Search for heavy Higgs bosons A/H decaying to a top quark pair in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Motivation

- New (pseudo)scalar states coupling strongy to $t\bar{t}$ predicted by many BSM models
- Benchmark: **Two-Higgs-Doublet Models (2HDM)**
  - Higgs sector extended to include **second Higgs doublet**
  - E.g. in SUSY (MSSM) or axion models

5 physical Higgs bosons after EWSB

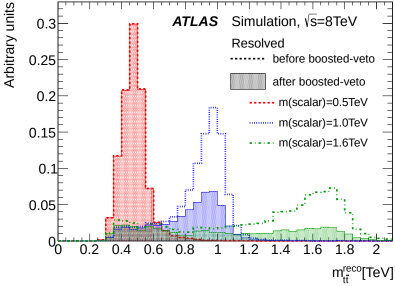
- CP-even: h^0, H^0
- CP-odd: A^0
- Charged: $H^{\pm}$

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
flipped	u,l	d
lepton-specific	u,d	l

- Search for $gg \to A/H \to t\bar{t}$
- ICHEP'16 CONF note: ATLAS-CONF-2016-073
- Re-interpretation of published ATLAS search for $t\bar{t}$ resonances (JHEP 08 (2015) 148)
  - Full $\sqrt{s} = 8$ TeV dataset ($\int \mathcal{L} = 20.3$ fb^{-1})
  - Final state: ℓ+jets

Why a re-interpretation?

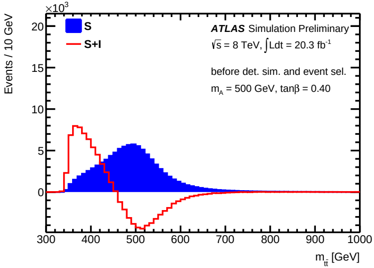
- Standard approach: JHEP 08 (2015) 148
- "Bump hunt": Excess on top of background spectrum



- Generic scalar resonance decaying to $t\bar{t}$
- $\frac{d\sigma}{dm_{t\bar{t}}} \sim S + B$
- No interference between signal and background

Why a re-interpretation?

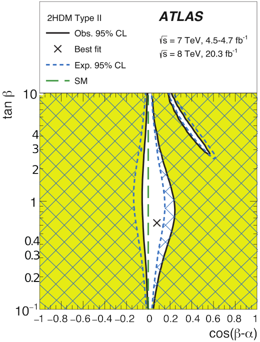
- Our generalised approach: ATLAS-CONF-2016-073
- **Interference** between $gg \to A/H \to t\bar{t}$ signal and SM $t\bar{t}$ background
  - SM $t\bar{t}$ production $\approx$ 90% via $gg \to t\bar{t}$ at 13 TeV LHC
- Not considered in any previous search for $t\bar{t}$ resonances at the LHC



- $\frac{d\sigma}{dm_{t\bar{t}}} \sim |\mathcal{A}_S + \mathcal{A}_B|^2 = S + I + B$
- Peak-dip structure (or pure dip)

Choice of Model Parameters

- Two mixing angles α and β:
  - $\tan\beta$: ratio of vacuum expectation values of Φ_1 and Φ_2
  - α: diagonalises mass matrix of h and H
- Couplings to W/Z and fermions depend only on difference $(\beta - \alpha)$ and $\tan\beta$



- Alignment limit: $\cos(\beta - \alpha) = 0$
  - Assume h is boson discovered at 125 GeV with SM couplings
  - No couplings between A/H and W/Z!
- Low $\tan\beta$ range: 0.4–9.0
  - A/H to $t\bar{t}$ couplings $\sim 1/\tan\beta$.
  - High $\tan\beta$ range constrained by searches in $\tau\tau$ final states
- Mass points $m_{A/H} = 500$ GeV and 750 GeV
  - > 400 GeV, i.e. well above $t\bar{t}$ production threshold
  - < 800 GeV such that cross-section is sufficiently large

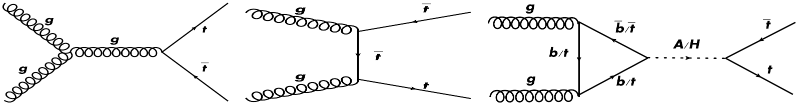
Signal Modelling

Samples

- 24 signal parameter points
- Need both $S + I$ and S samples (for limit setting)
  $\Rightarrow$ 48 samples required
  $\Rightarrow$ ATLFAST-II

Model

- **Higgs Effective Couplings Form Factor** model in MadGraph v.5.2
- Leading order in QCD
- Cross-section corrected to calculations with 2HDMC/SusHi
  - Note: signal k-factor applied to both S and $S + I$ samples



(a) SM $gg \to t\bar{t}$ (s-channel) (b) SM $gg \to t\bar{t}$ (t-channel) (c) $gg \to A/H \to t\bar{t}$

Sample Generation

A. Indirect approach

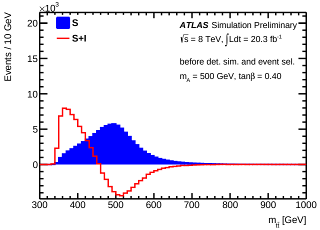
- Generate: $(S + I + B)$ and B
- Subtract $m_{t\bar{t}}^{\mathrm{reco}}$ histograms after selection
- Need large $(S + I + B)$ sample for each signal point ($\approx$ 600 M events)

$\Rightarrow$ Challenging due to large CPU and storage requirements

B. Direct approach (adopted strategy)

- Generate: S, $(S + I)$ and B
- Modify MadGraph code:
  Remove ME for SM $t\bar{t}$ production
- Pure $(S + I)$ samples ($\approx$ 1 M events each)
- Both positive and negative event weights

$\Rightarrow$ Significantly lower CPU/storage requirements
$\Rightarrow$ Can use most accurate description of SM $t\bar{t}$ bgr.

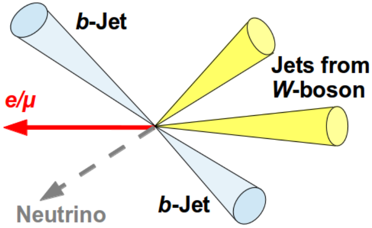


- **Difference taken as systematic uncertainty (flat $\pm 0.4\%$ uncertainty)**

Event Selection

Identical to "resolved" selection in JHEP 08 (2015) 148

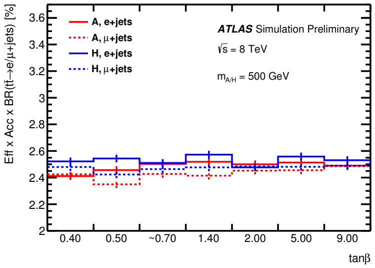
- $==1$ electron or muon
  - $p_T > 25$ GeV, $|\eta| < 2.5$
  - tight, mini-isolated
- $E_T^{\mathrm{miss}} > 20$ GeV
- $E_T^{\mathrm{miss}} + m_T^W > 60$ GeV
- ≥ 4 anti-k_t $R = 0.4$ jets
  - $p_T > 25$ GeV, $|\eta| < 2.5$
- $\geq 1 b$-tagged jets
  - MV1 70% operating point



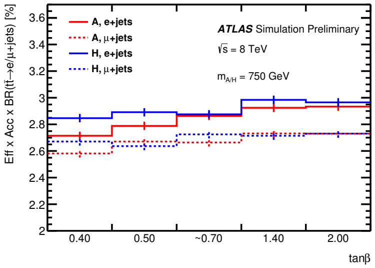
Six mutually exclusive signal regions

- 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

Selection efficiencies (pure signal)



(d) $m_{A/H} = 500$ GeV

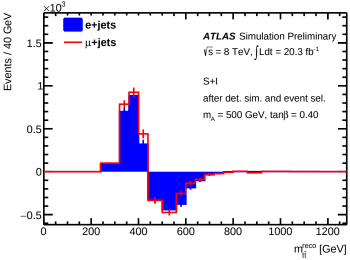


(e) $m_{A/H} = 750$ GeV

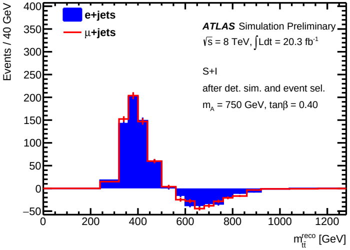
Signal shape for pseudoscalar A (after selection)

Event 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



(f) $m_A = 500$ GeV, $\tan\beta = 0.40$



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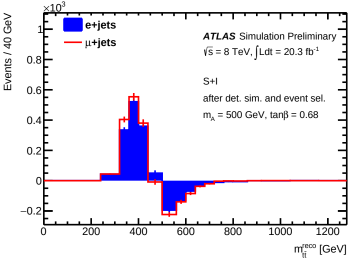
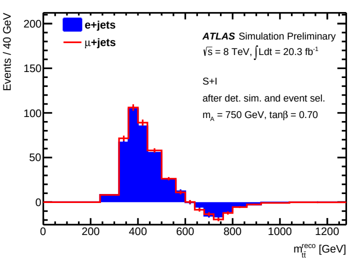


(h) $m_A = 500$ GeV, $\tan\beta = 0.70$



(i) $m_A = 750$ GeV, $\tan\beta = 0.64$

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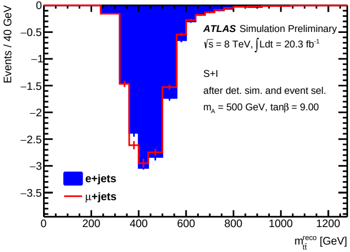
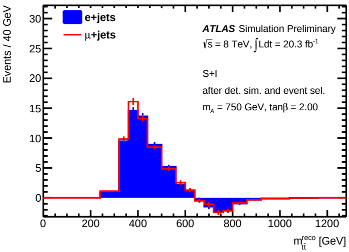


(j) $m_A = 500$ GeV, $\tan\beta = 9.00$



(k) $m_A = 750$ GeV, $\tan\beta = 2.00$

Results: Hypothesis test

- Binned profile likelihood ratio fit
  - Simultaneously in all signal regions
  - Systematic/statistical uncertainties $\longrightarrow$ nuisance parameters
- Parameterise shape of binned $m_{t\bar{t}}^{\mathrm{reco}}$ distribution in terms of signal strength μ

$$\mu \cdot S + \sqrt{\mu} \cdot I + B = \sqrt{\mu} \cdot (S + I) + (\mu - \sqrt{\mu}) \cdot S + B$$

- Based on amplitudes defined in MadGraph model (provided by D. Franzosi)

Scalar

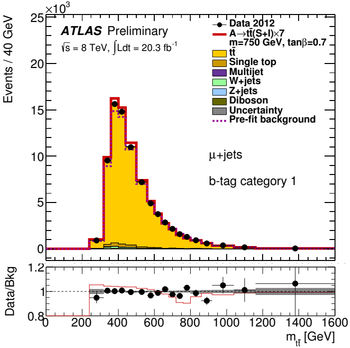
$$\frac{d\sigma}{ds} = \underbrace{\frac{\alpha_s^2 G_F^2 c_t^2 m_t^2 s^2}{1536\pi^3}\beta^3 \left| \frac{\sum_f c_f A_S(\tau_f)}{s - m_H^2 + i m_H \Gamma_H(s)} \right|^2}_{S} \underbrace{- \frac{\alpha_s^2 G_F c_t m^2}{66\pi\sqrt{2}}\beta^2 \log\left(\frac{1+\beta}{1-\beta}\right) \mathrm{Re}\left[\frac{\sum_f c_f A_S(\tau_f)}{s - m_H^2 + i m_H \Gamma_H(s)}\right]}_{I} \underbrace{+ \frac{d\sigma_{QCD}}{ds}}_{B}$$

Pseudo-scalar

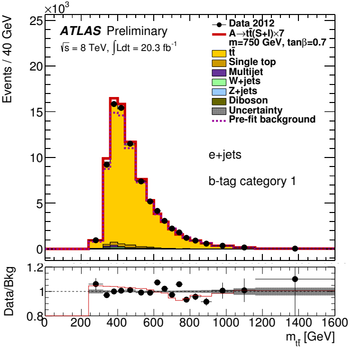
$$\frac{d\sigma}{ds} = \underbrace{\frac{3\alpha_s^2 c_t^2 G_F^2 m^2 s^2}{2048\pi^3}\beta \left| \frac{\sum_f c_f f(\tau_f)/\tau_f}{s - m_A^2 + i m_A \Gamma_A(s)} \right|^2}_{S} \underbrace{- \frac{\alpha_s^2 c_t G_F m^2}{64\pi\sqrt{2}} \log\left(\frac{1+\beta}{1-\beta}\right) \mathrm{Re}\left[\frac{\sum_f c_f f(\tau_f)/\tau_f}{s - m_A^2 + i m_A \Gamma_A(s)}\right]}_{I} \underbrace{+ \frac{d\sigma_{QCD}}{ds}}_{B} .$$

Post-fit $m_{t\bar{t}}$ distributions

- Background-only fit: $\mu = 0$
- Finer binning compared to 8 TeV Z' analysis



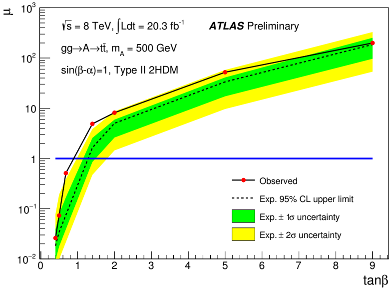
(a) μ+jets, 2b-tags



(b) e+jets, 2b-tags

Exclusion limits on μ for pseudoscalar A

- The blue line at $\mu = 1$ corresponds to the signal strength in the type-II 2HDM.
- Exclusion for 2HDM ($\mu = 1$) at 95% confidence level
  - $\tan\beta < 0.85$ for $m_A = 500$ GeV



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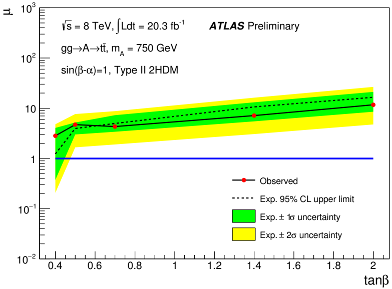
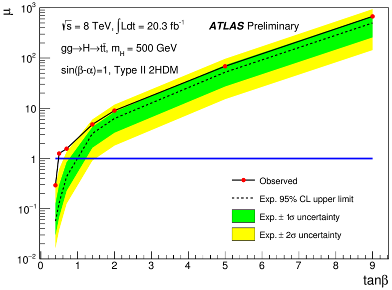


(b) $m_A = 750$ GeV

Exclusion limits on μ for scalar H

- The blue line at $\mu = 1$ corresponds to the signal strength in the type-II 2HDM.
- Exclusion for 2HDM ($\mu = 1$) at 95% confidence level
  - $\tan\beta < 0.45$ for $m_H = 500$ GeV



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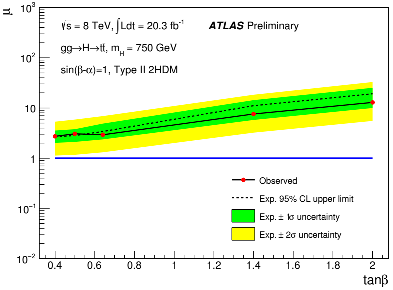

(b) $m_H = 750$ GeV

Conclusion

- Search for $gg \to A/H \to t\bar{t}$ in type-II 2HDM
  - $m_{A/H} = 500$ GeV, 750 GeV
  - $0.4 < \tan\beta < 9.0$
  - $\sin(\beta - \alpha) = 1.0$
- First LHC search to include interference between signal and SM $t\bar{t}$ background
- Met and solved a number of technical challenges
  - Signal modelling
  - Variable binning
  - Statistical analysis
- Significant improvements w.r.t. previous constraints for $m_{A/H} > 2 \cdot m_{\text{top}}$ and low $\tan\beta$
- Note: *A* and *H* considered separately!

Next steps

- Include more signal mass points $\Rightarrow$ Reweighting method
- Consider higher-order corrections (Peter's talk)

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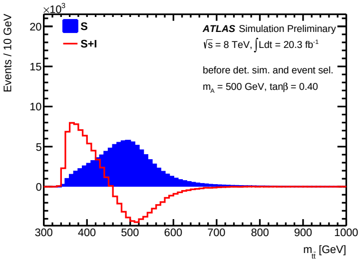
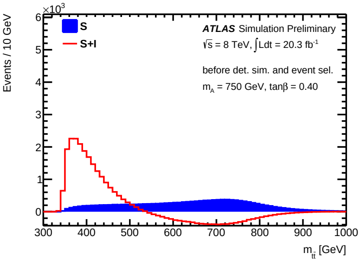
Thank you!

BACKUP

Signal shape for pseudoscalar A (parton level, no selection)



(c) $m_A = 500$ GeV, $\tan\beta = 0.40$



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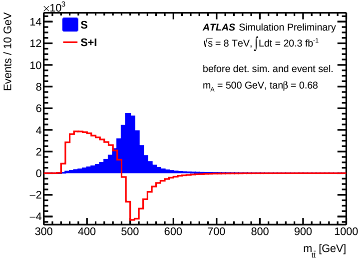

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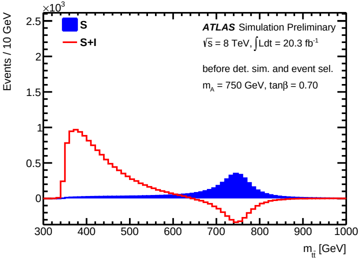

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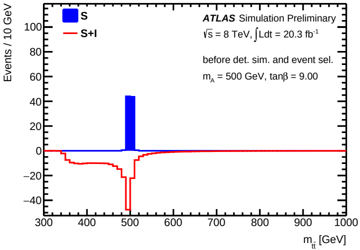

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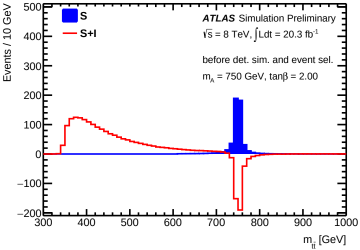
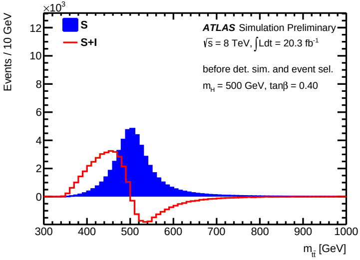


(h) $m_A = 750$ GeV, $\tan\beta = 2.00$

Signal shape for scalar H (parton level, no selection)



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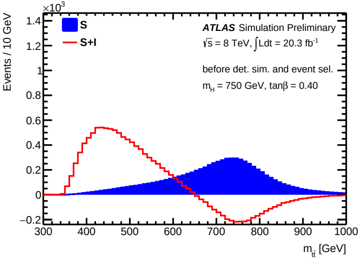

(b) $m_H = 750$ GeV, $\tan\beta = 0.40$

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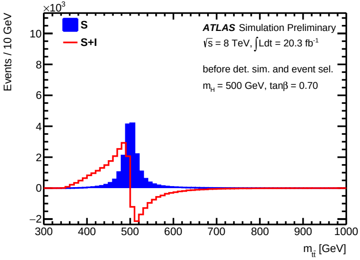

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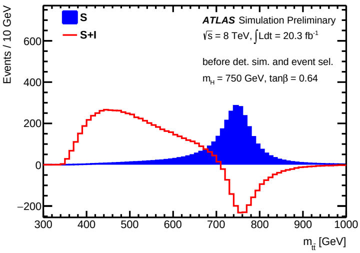

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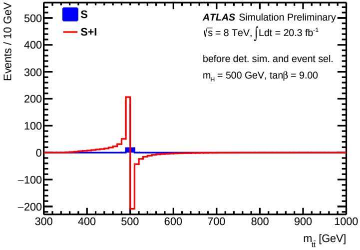

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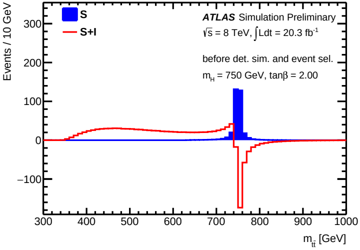

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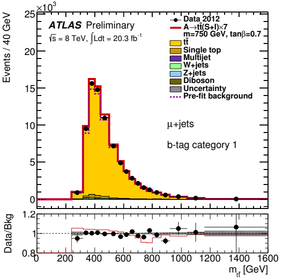
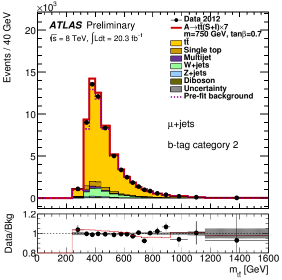
Post-fit $m_{t\bar{t}}$ distributions (μ+jets)

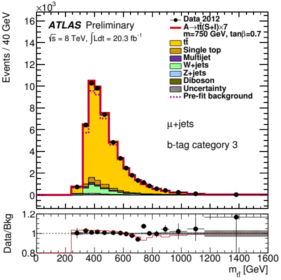
- Background-only fit: $\mu = 0$
- Finer binning compared to 8 TeV Z' analysis



(a)



(b)



(c)

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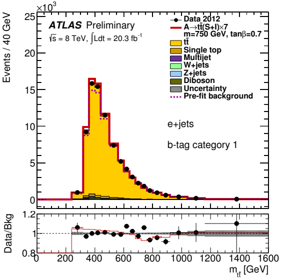

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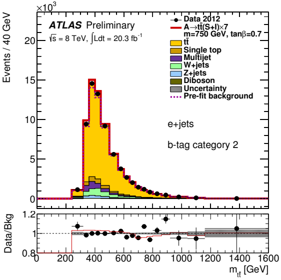

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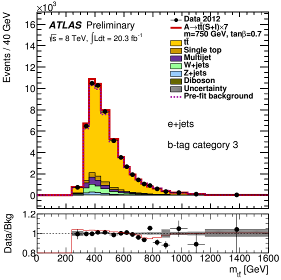

(c)