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Search for A/H Decaying to $t\bar{t}$ in ATLAS

CLHCP Conference

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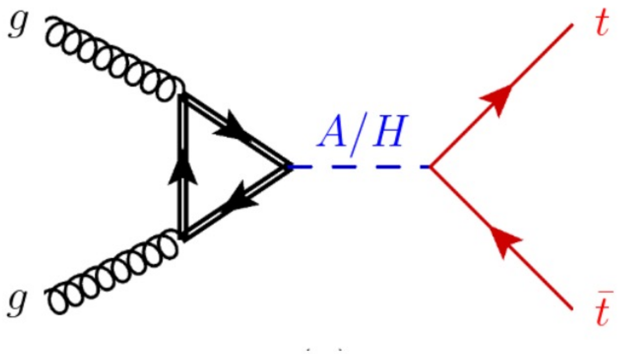
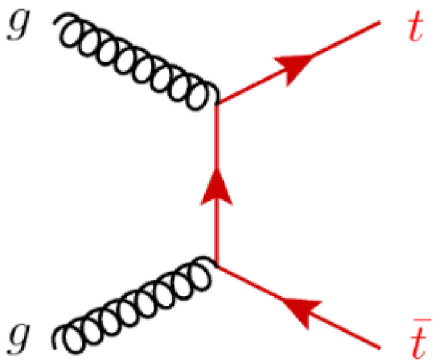
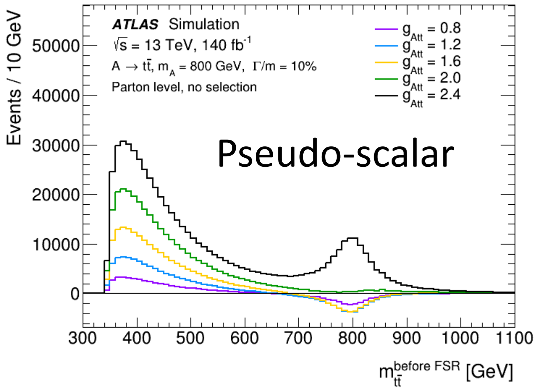
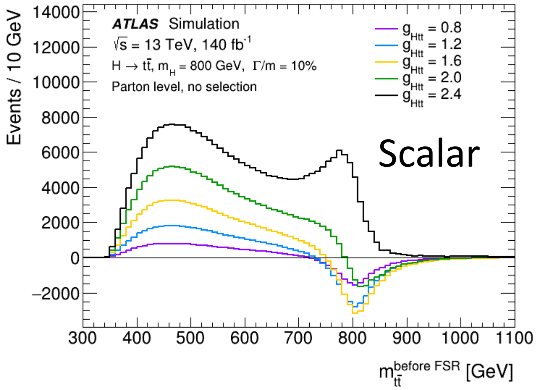
Introduction

- Search for production of new heavy scalars and pseudoscalars decaying to ttbar
  - $g\, g\ \rightarrow A/H\ \rightarrow t\, \bar{t}$
- Full Run2 dataset at ATLAS, 140 ifb
- **Motivation:**
  - Predicted in 2HDM, hMSSM, 2HDM+a, ALPs, …
    - Many BSM solutions involve extended Higgs sectors
  - Sensitive in general for high-mass spin-0 resonance
- **Challenge:** strong interference between signal and SM ttbar background
  - Non-trivial to model and treat statistically
  - Interference pattern depends strongly on signal parameters



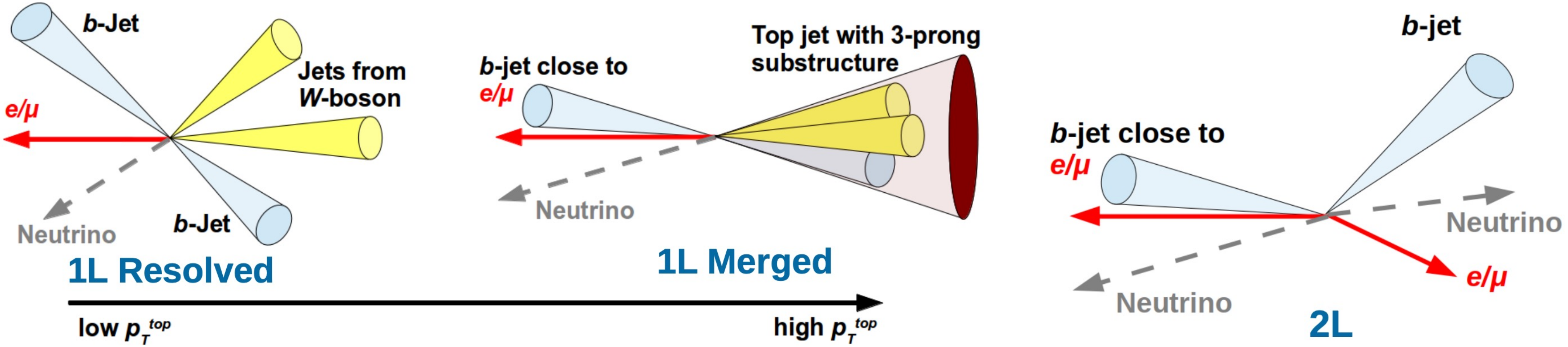






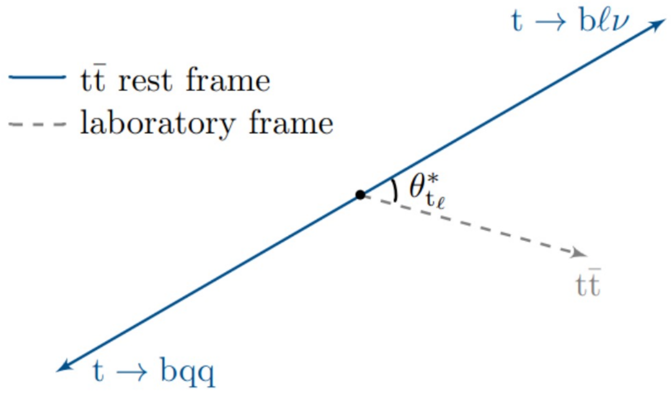
Analysis Strategy

- Two orthogonal analysis channels: 1L (e or μ) + 2L (e^-e^+, $e\mu$, $\mu^-\mu^+$)
- **Final discriminant:**
  - 2L channel: m_{llbb} as proxy of $m_{t\bar{t}}$
  - 1L channel: reconstruct full ttbar system and use $m_{t\bar{t}}$
    - Resolved: ≥4 small-R jets assigned via χ^2 algorithm
    - Boosted: large variable-R jet optimised for intermediate top boosts

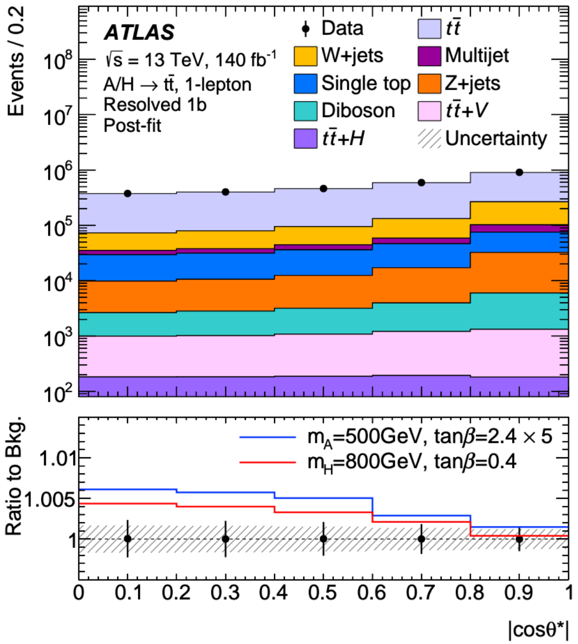


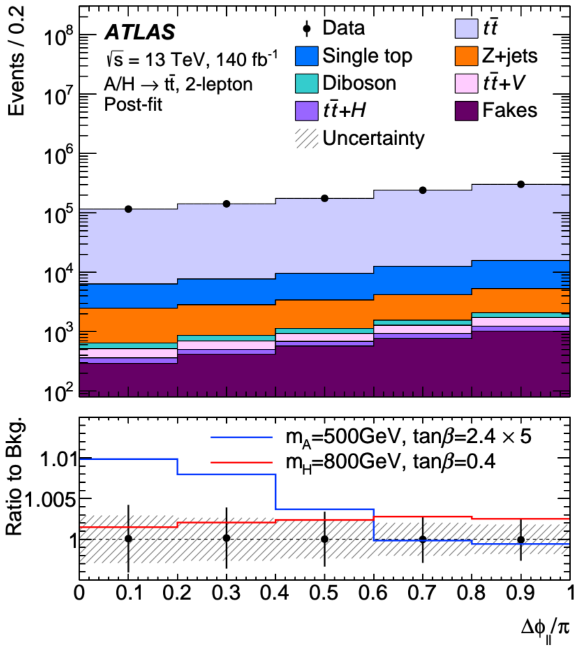
Categorization

- Categorize 1L channel with b-tagging for higher ttbar purity
- Split resolved signal regions into bins of angular variables
  - 1L: $\cos\theta^*$ 2L: $\Delta\phi_{ll}$
  - Sensitive to spin state of the ttbar system
  - Improved signal-background discrimination

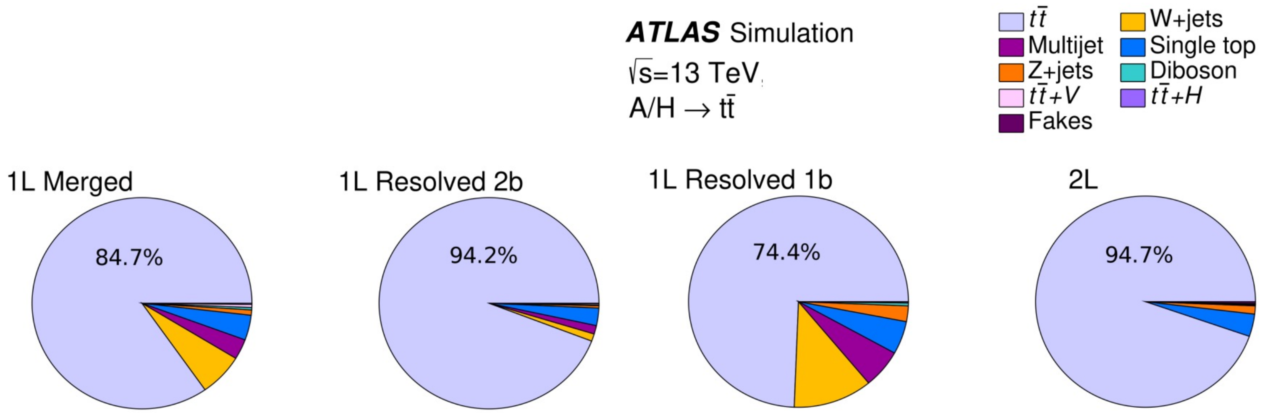


- 16 signal regions in total
  - 1L merged
  - 1L resolved 1b in 5 $\cos\theta^*$ bins
  - 1L resolved 2b in 5 $\cos\theta^*$ bins
  - 2L in 5 $\Delta\phi_{ll}$ bins

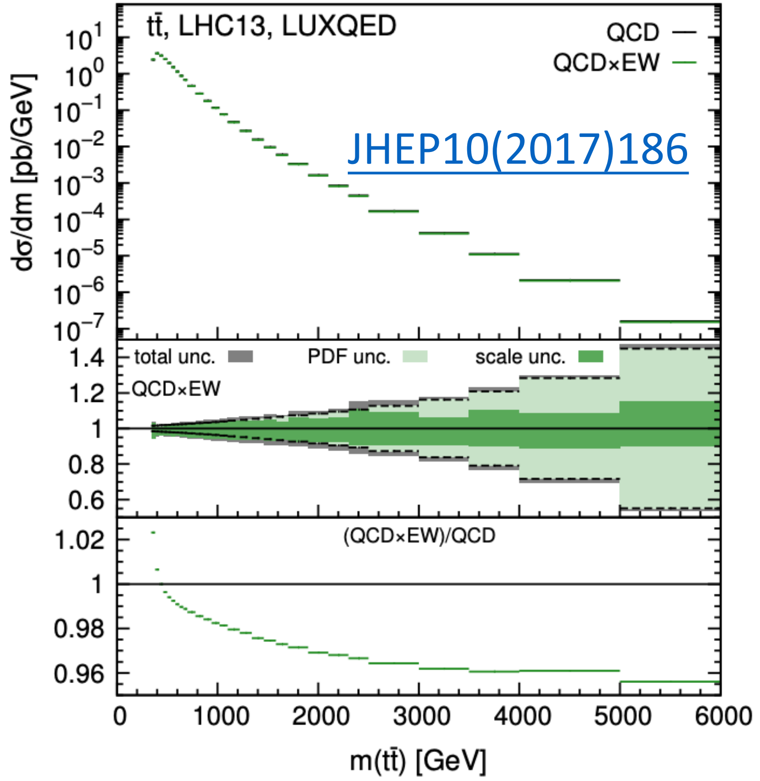




Modelling



- **Signal**
  - Implemented at LO using MadGraph5
  - Scaled to NNLO prediction from SusHi
  - Employ a MadGraph hack by subtracting B contribution from ME to produce S+I samples
- **Background**
  - ttbar: dominant and irreducible background
    - Correct NLO Powheg+Pythia MC to NNLO-QCD+NLO-EW
    - Via Iterative recursive reweighting in $m_{t\bar{t}}, p_T(t), p_T(\bar{t})$
  - W+jets, Z+jets
    - Data-driven correction on MC
  - Multi-jet
    - Estimated from data using matrix-method
  - Other small bkgs
    - MC



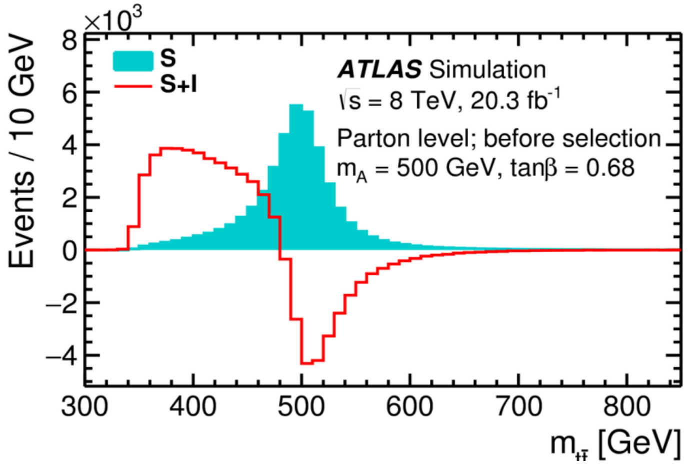
Systematic Uncertainties

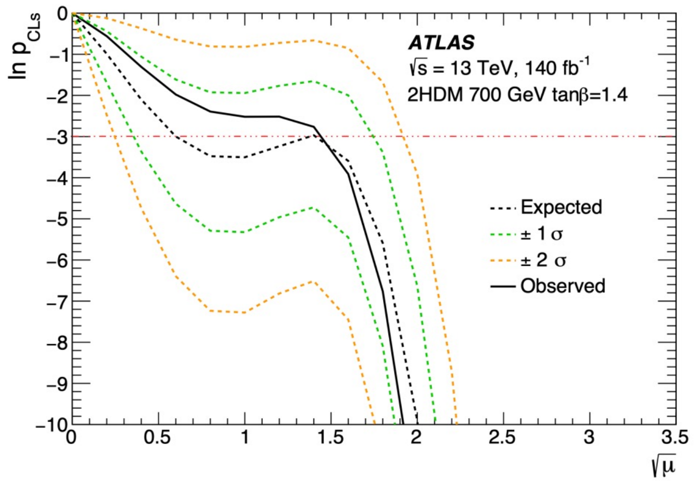
- Largest source from SM ttbar modelling
  - **NNLO:**
    - Uncertainties in reweighting
    - Scale and PDF uncertainties on calculation
    - Uncertainty on EW component from PDFs
  - **Line-shape:** comparison with MadSpin
  - **PS:** Pythia vs Herwig
    - Strongest constraint as observed in other ATLAS Top analyses
- Uncertainties from alternative samples with non-negligible constraints are treated un-correlated across SRs and split into shape/normalization component
  - Considered to be conservative
  - Including PS, ME-PS, …

Uncertainty component	Fractional contribution [%] $m_A = 800$ GeV $\tan\beta = 0.4$	Fractional contribution [%] $m_A = m_H = 500$ GeV $\tan\beta = 2.0$
Experimental	**30**	**42**
Small-R jets (JER, JES)	22	29
Large-VR jets	11	20
Flavour tagging	13	17
Leptons	4	5
Other (E_T^{miss}, luminosity, pile-up, JVT)	10	14
Modelling: SM $t\bar{t}$ and signal	**91**	**79**
$t\bar{t}$ NNLO	49	28
$t\bar{t}$ lineshape	27	29
$t\bar{t}$ ME-PS (p_T^{hard})	36	30
$t\bar{t}$ ME-PS (h_{damp})	41	25
$t\bar{t}$ ISR& FSR	9	13
$t\bar{t}$ PS	29	41
$t\bar{t}$ cross-section	21	31
$t\bar{t}$ Scales & PDF	21	16
m_t	6	4
Signal	19	9
Modelling: other	**41**	**16**
W+jets	11	8
Z+jets	1	2
Multijet	27	10
Fakes	<1	1
Other bkg.	29	10
MC statistics	**18**	**26**
Total systematic uncertainty	**±100**	**±100**
Total statistical uncertainty	**< 1**	**< 1**

Statistical Analysis

- Extend likelihood to include interference term
  - $\mu\, S + \sqrt{\mu}\, I + B = (\mu - \sqrt{\mu})\, S + \sqrt{\mu}\, (S + I) + B$
  - Quadratic dependence on $\sqrt{\mu}$
- Design interference-specified statistical method
  - Including offset to handle the negative histograms
  - Choice of test statistics:
    - Search stage $q_0 = -2\ln \frac{\mathcal{L}(0, \hat{\hat{\theta}}_0)}{\mathcal{L}(\hat{\sqrt{\mu}}, \hat{\theta}_{\hat{\sqrt{\mu}}})}$
    - Exclusion stage $q_{1,0} = -2\ln \frac{\mathcal{L}(1, \hat{\hat{\theta}}_1)}{\mathcal{L}(0, \hat{\hat{\theta}}_0)}$
  - New ATLAS baseline limit band calculation
    - Previous method using $\pm N\sigma$ Asimov give asymmetry bands and unphysical crossing
      - $\sigma^2 S - \sigma I + B$ vs. B vs. $\sigma^2 S + \sigma I + B$
    - Directly represent the hypotheses that have an exclusion rate between $\phi(\pm N)$
      - Assuming standard Gaussian distribution
  - Interpolate $\ln p_{CLs}$ between signal hypotheses





Search Stage

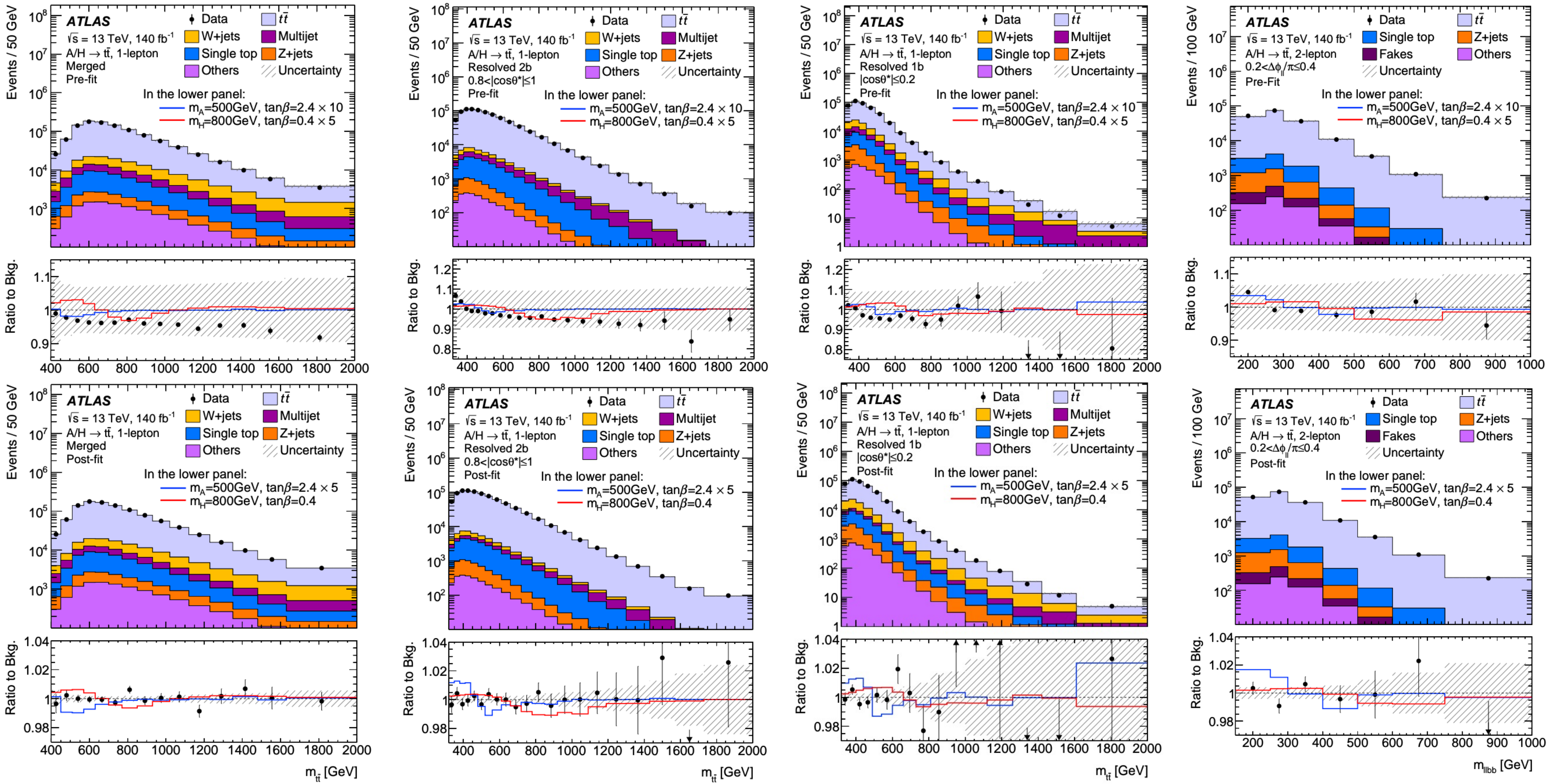
Tested agreement between data and S+I+B hypotheses with masses [400,1400] GeV and widths [1,40]%

- Most significant deviation from SM-only: 2.3σ at $m_A = 800\text{GeV}, \Gamma/m = 10\%, \sqrt{\mu} = 4.0$

1L merged | 1L resolved 2b | 1L resolved 1b | 2L

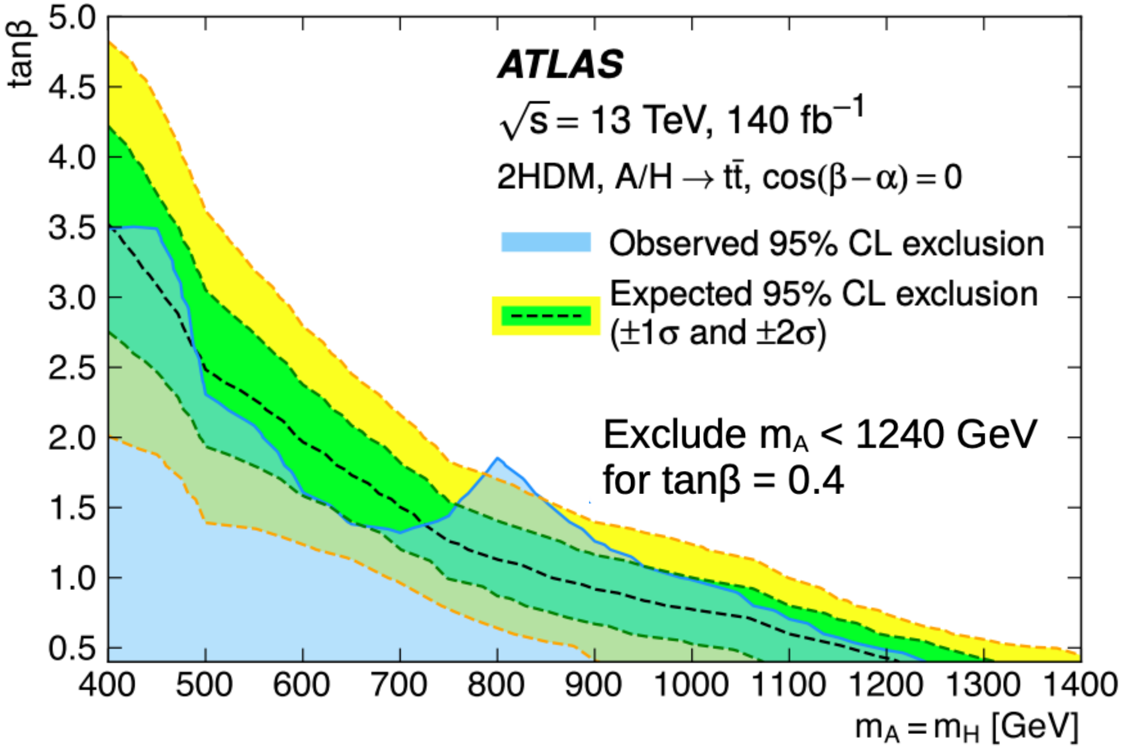
Pre-fit

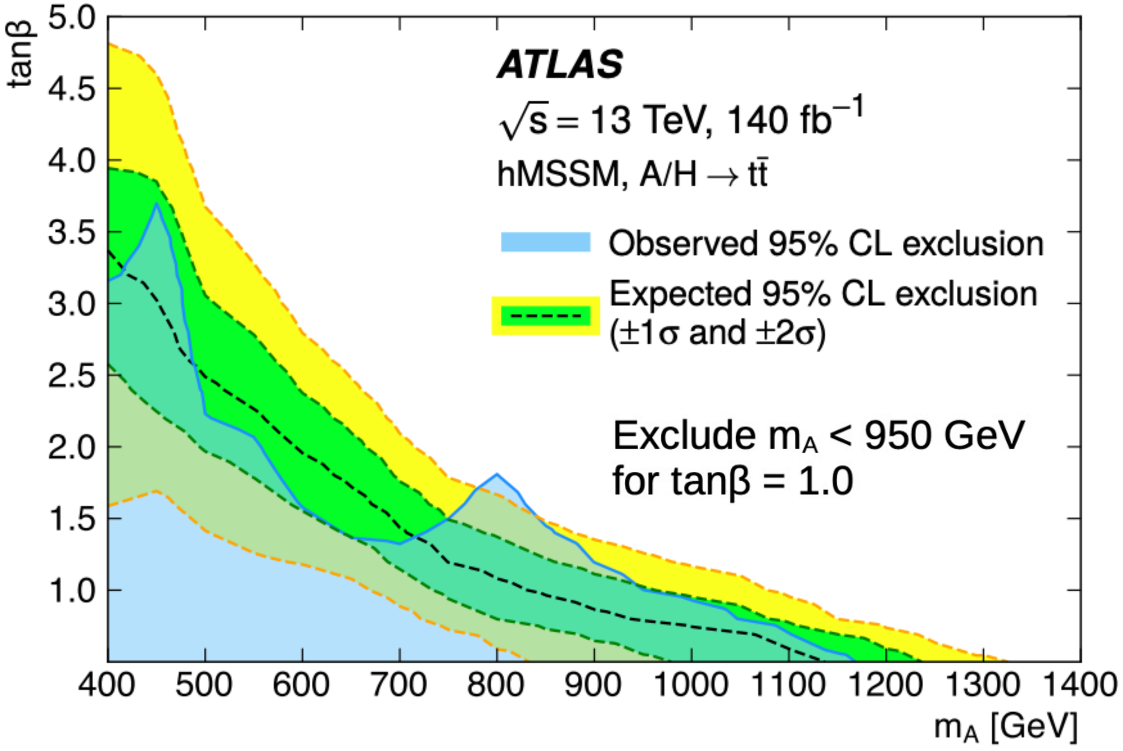
Post-Bonly-fit



Exclusion on 2HDM and hMSSM

- Strongest mass exclusion at low $\tan\beta$ to date
- Stop at 400GeV because the signal k-factor for NNLO prediction become large
  - LO signal model considered bad approximation of actual interference pattern



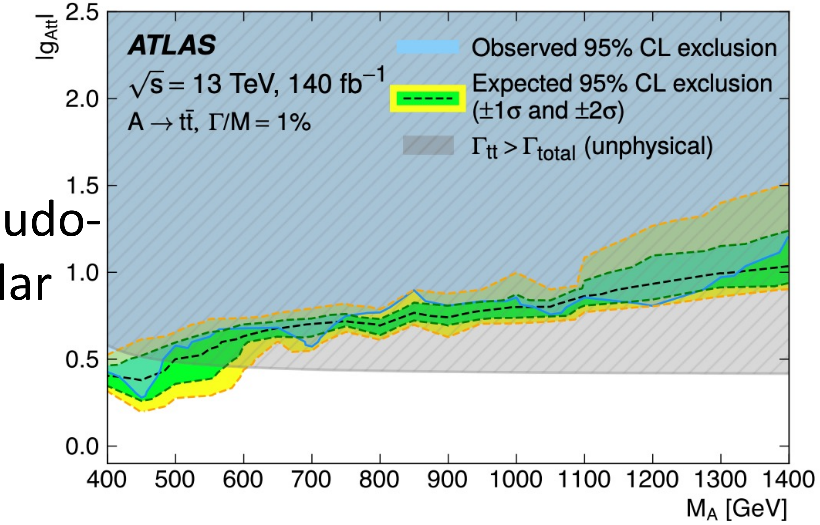


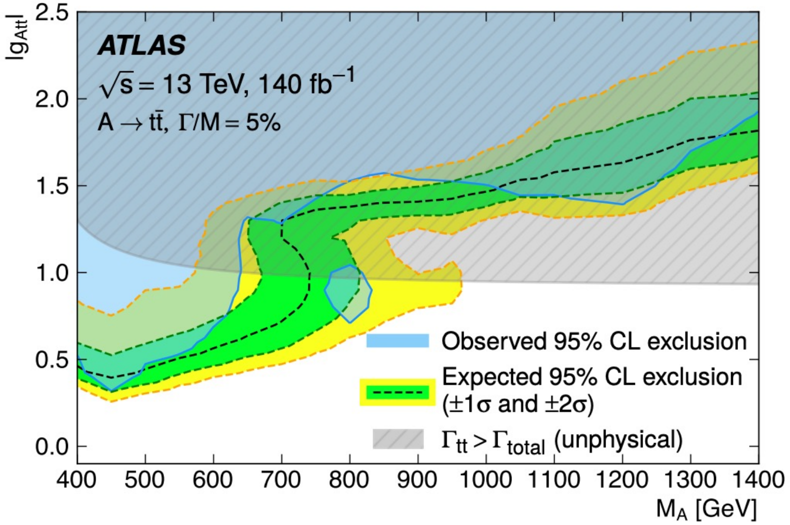
Exclusion on Coupling

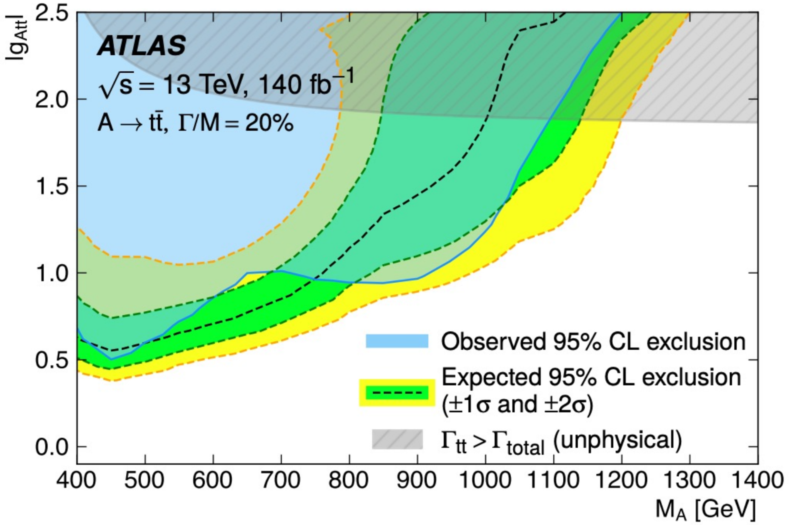
$g^2_{\phi t\bar{t}} = \sqrt{\mu}$

Width = 1%   Width = 5%   Width = 20%

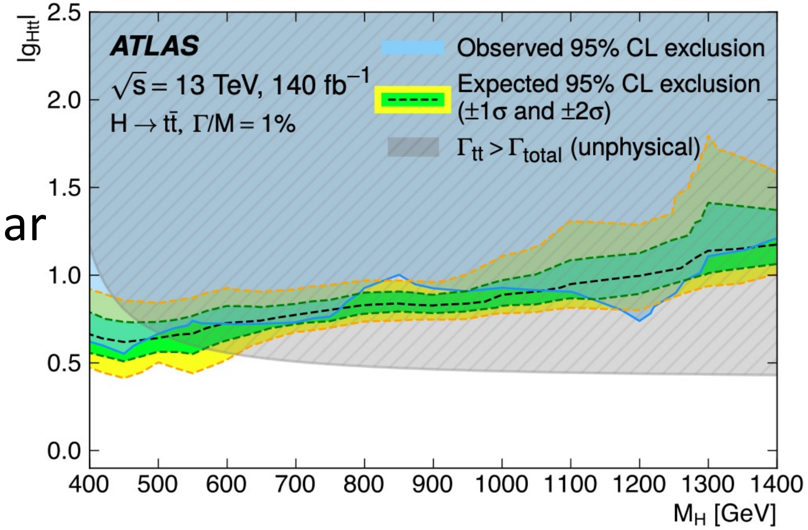
Pseudo-scalar

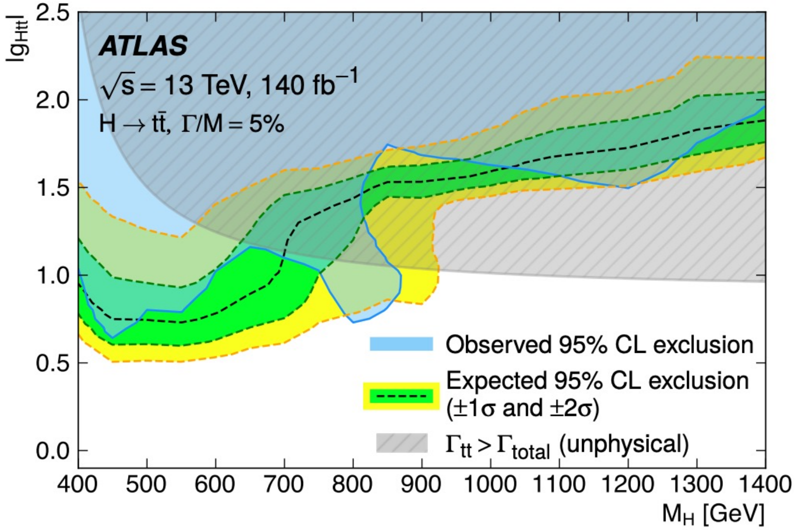


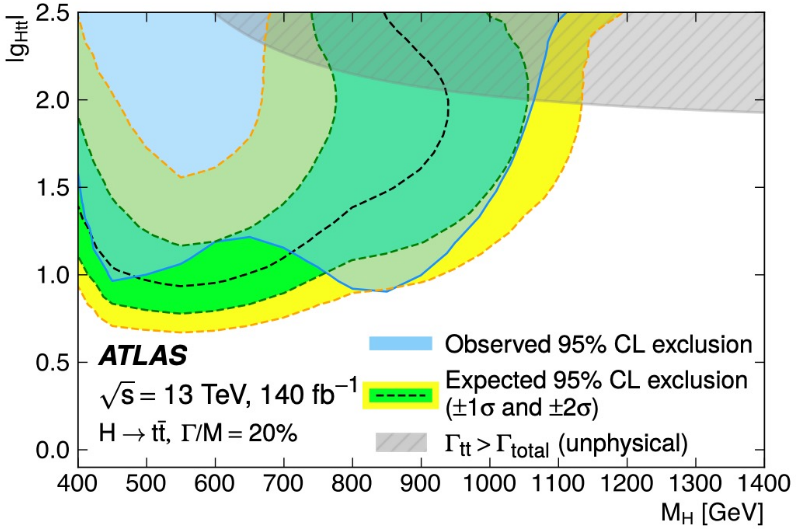




Scalar







Conclusion

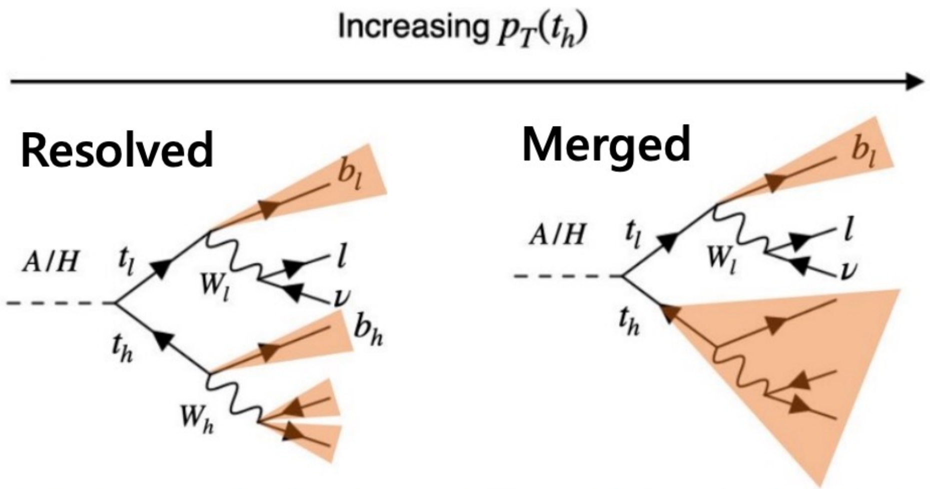
- Search for ttbar decayed from heavy Higgs boson with interference
  - 1-lepton, 2-leptons channels
- Results interpreted in various benchmark models
  - 2HDM, hMSSM, 2HDM+a
- Most stringent constraints on the 2HDM and hMSSM parameter space in the region of high m_A and low $\tan\beta$ to date
- No significant deviation from the SM prediction is observed
  - Did we consider too much flexibility in terms of systematic uncertainty?
  - Further study on-going in reply to CMS' latest result

Backup

Event Selection 1L

Pre-selection:

- Standard run and event cleaning
- Single-lepton trigger, trigger matching
- Exactly 1 lepton with $p_{\mathrm{T}} > 28\mathrm{GeV}$
- $E_{\mathrm{T}}^{\mathrm{miss}} > 20\mathrm{GeV}$, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60\mathrm{GeV}$
- $\geq$ 1 b-tagged jet (DL1r 77% WP)



Resolved topology

- **Number of jets:**
  - $\geq$ 4 small-R jets
- **Well-reconstructed $t\bar{t}$:**
  - $\log_{10}(\chi^2) < 0.9$

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h\text{-}W}}{\sigma_{t_h\text{-}W}}\right]^2 + \left[\frac{m_{jl\nu} - m_{t_l}}{\sigma_{t_l}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,jl\nu}) - (p_{T,t_h} - p_{T,t_l})}{\sigma_{diff\, p_T}}\right]^2$$

- **Orthogonality:**
  - Veto events passing merged selection

Merged topology

- **Top tagging**
  - $\geq$ 1 large-R jet with $p_{\mathrm{T}} > 300\mathrm{GeV}$ and $m > 100\mathrm{GeV}$
  - Didn't use DNN top tagged jets
    - Our main sensitivity is < 1 TeV (intermediate boosts)
    - DNN top tagger is aimed at high boosts
- **Close-to-lepton jet**
  - $\geq$ 1 small-R jet with $\Delta R(l, \mathrm{jet}) < 2.0$
- **Avoid overlap between objects**
  - $\Delta R(l, t_h) > 1.5$
  - $\Delta R(b_l, t_h) > 1.5$

Event Selection 2L

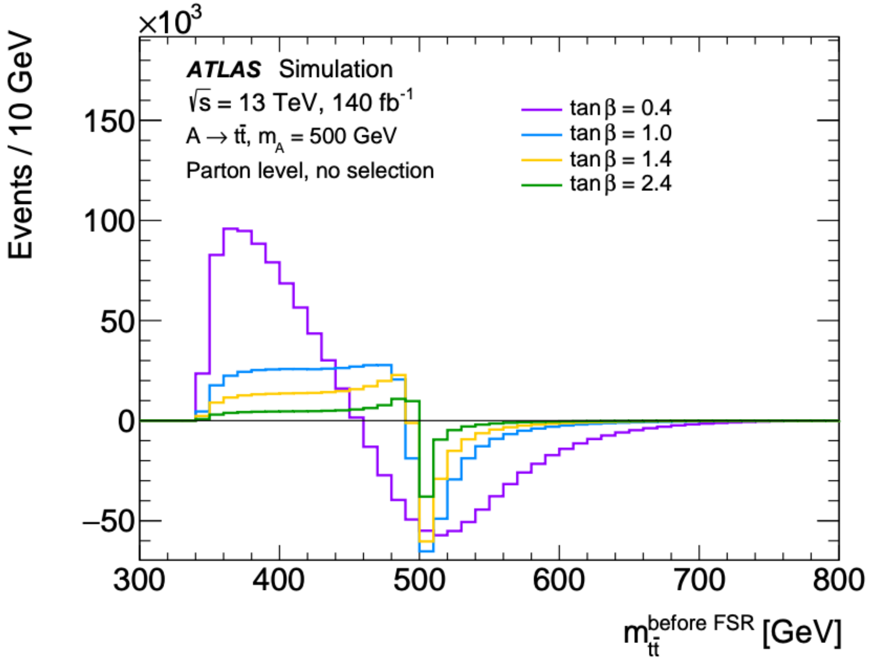
Pre-selection:

- Standard run and event cleaning
- Single-lepton trigger, trigger matching
- Exactly 2 leptons (ee, eμ, μμ)
- $\geq$ 2 small-R jets, $\geq$ 1 b-tagged jet
- $m_{ll} > 15$ GeV (for ee and μμ)

Signal region

- **Opposite-sign (OS) lepton pair**
- **Z-veto (for ee and μμ)**
  - $m_{ll} < 81$ GeV or $m_{ll} > 101$ GeV, $E_T^{\mathrm{miss}} > 45$ GeV
- **Lepton-b-jet pairs compatibility:**
  - $m_{l^+b} < 150$ GeV or $m_{l^-b} < 150$ GeV for at least one b-jet assignment

Choice of Test Statistics



Search stage:

- Should we reject SM in favour of (any) BSM hypothesis?
- Test agreement of data with range of interference patterns
- Consider all possible values of POI

$$q_0 = -2\ln\frac{\mathcal{L}(0,\hat{\hat{\theta}}_0)}{\mathcal{L}(\sqrt{\hat{\mu}},\hat{\theta}_{\sqrt{\hat{\mu}}})}$$

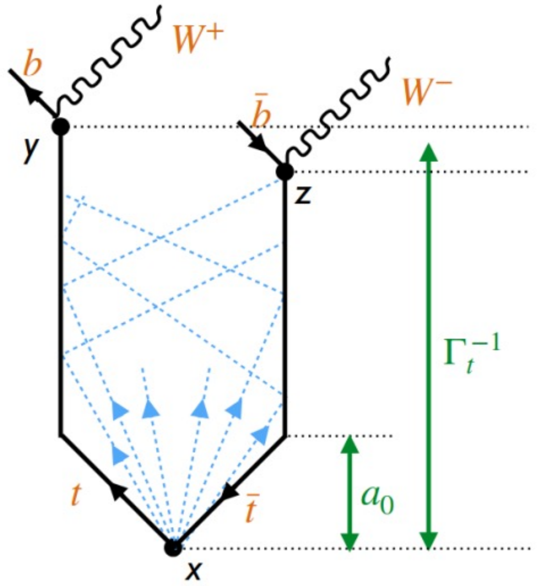
Exclusion stage:

- Should we reject the BSM hypothesis under consideration?
- Test (dis)agreement of data with specific interference pattern of tested signal hypothesis
- $\sqrt{\mu} = g^2_{\phi t\bar{t}}$: $\sqrt{\mu}$ change ⇒ $g_{\phi t\bar{t}}$ change ⇒ width change ⇒ shape change

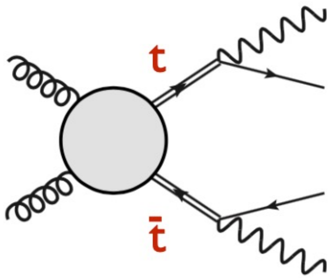
$$q_{1,0} = -2\ln\frac{\mathcal{L}(1,\hat{\hat{\theta}}_1)}{\mathcal{L}(0,\hat{\hat{\theta}}_0)}$$

Both are well defined in [1007.1727]

Ttbar Bound State



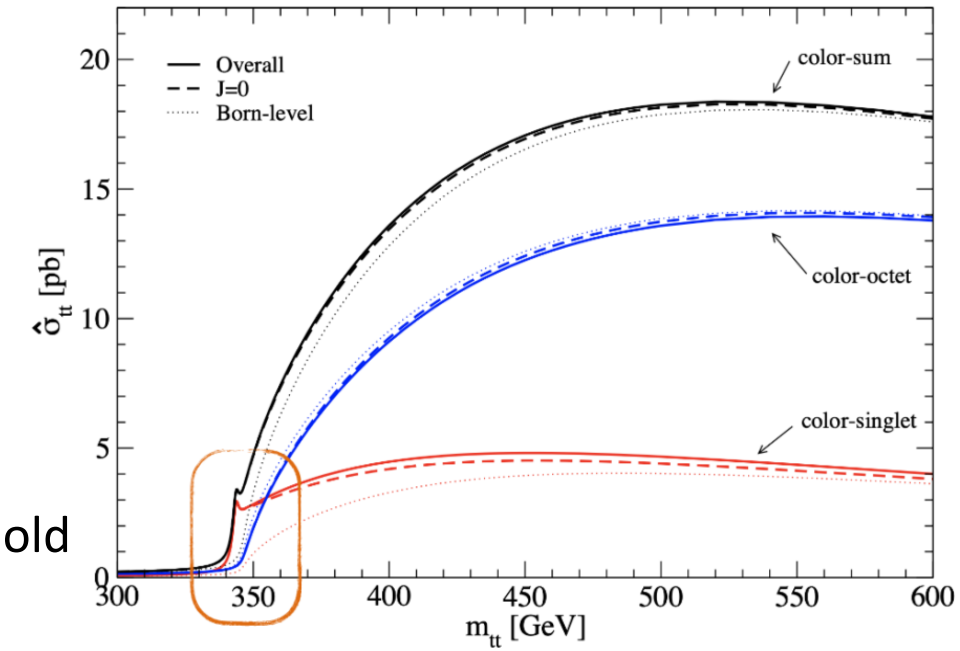
- The top Bohr radius $a_0 = \frac{2}{G_F \alpha_S m_t} \sim \frac{1}{20}\mathrm{GeV}^{-1}$
- Lifetime of top $\sim \Gamma_t^{-1} = 1.5\mathrm{GeV}^{-1}$
- Possible gluon exchanges before the top decay
- Bound state -- toponium?
  - Probe of the QCD potential



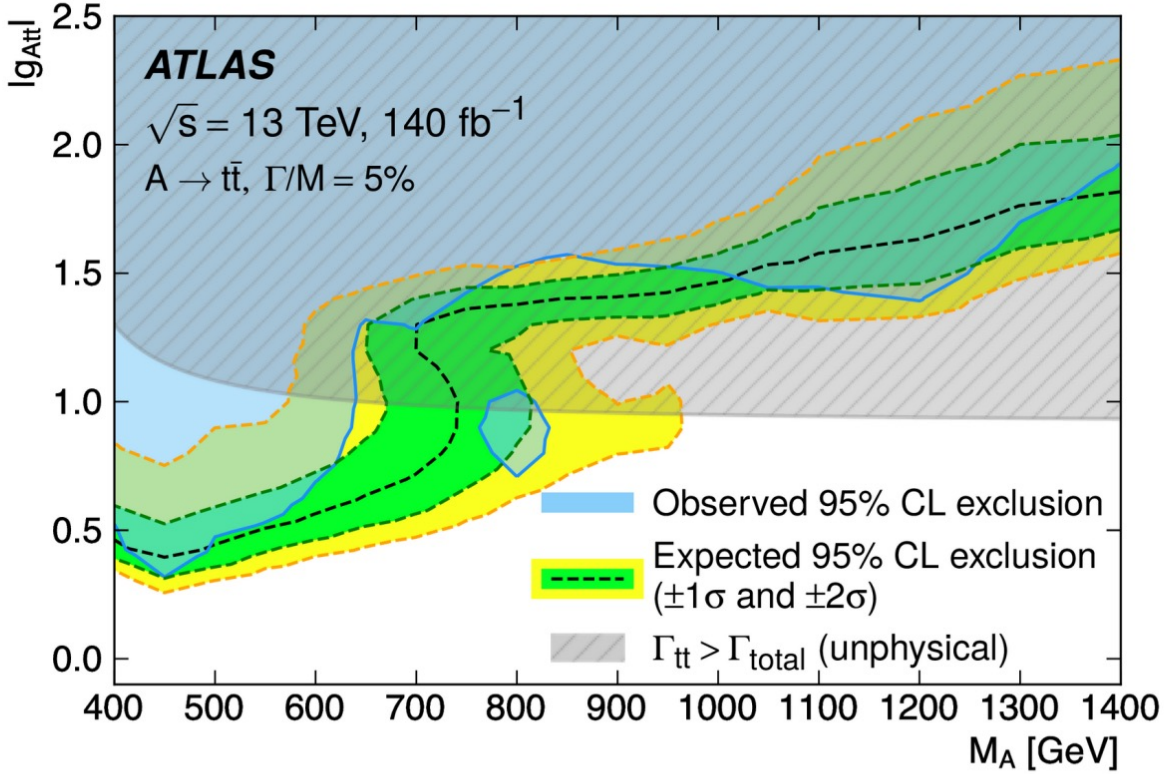
From theory calculation:

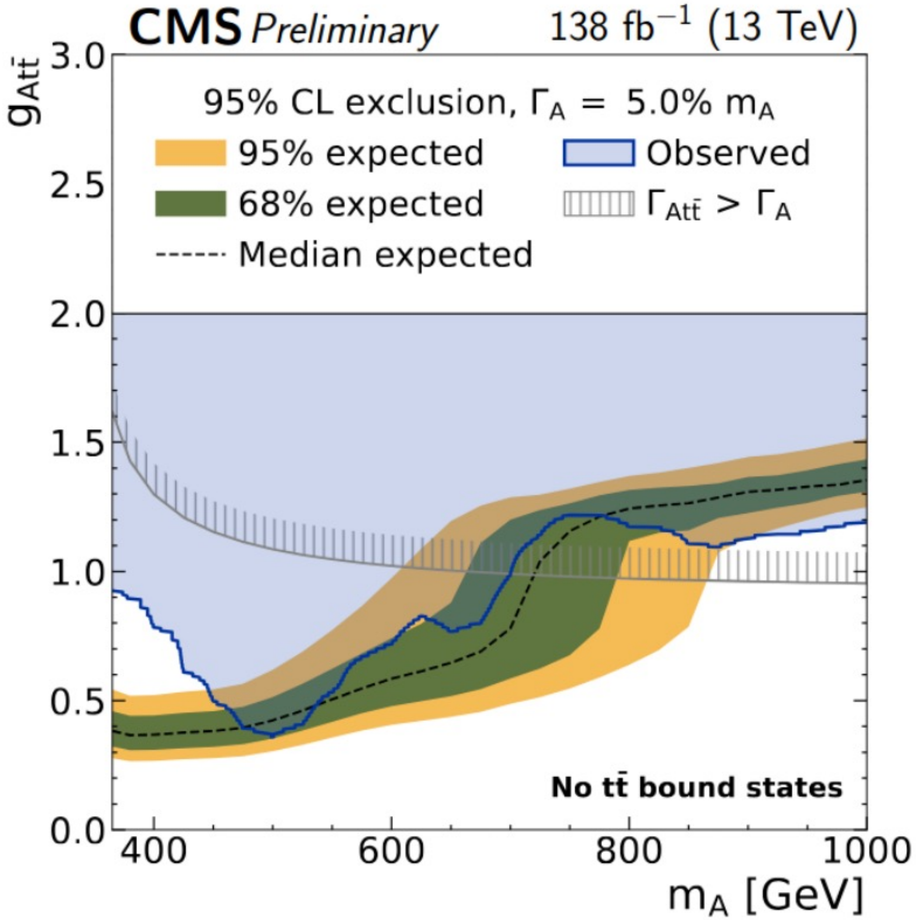
- Color-singlet
  - ${}^1S_0^{[1]}$
  - Peak below the ttbar threshold
- Color-octet
  - ${}^1S_0^{[8]}$ or ${}^3S_1^{[8]}$
  - Expected to be small below the ttbar threshold

[Sumino & Yokoya (JHEP`10)]



Comparing with CMS





Excess found in ~400GeV
Sensitivity mostly come from 2L channel

Comparing with CMS

CMS

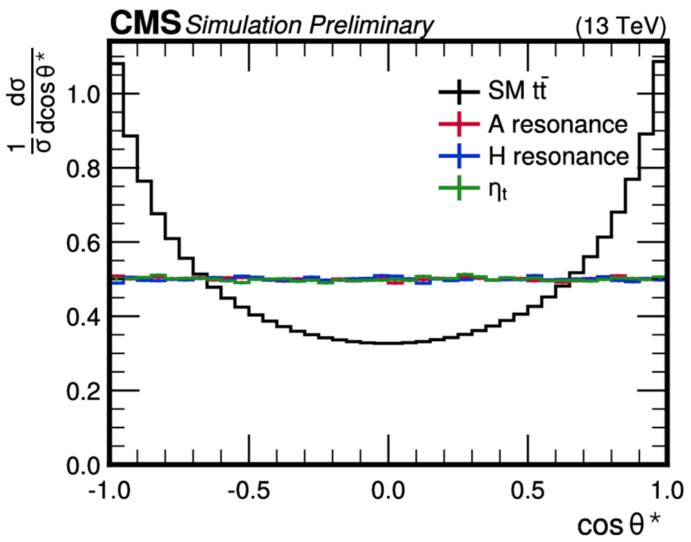
- 1L and 2L channel
- Split by lepton flavor
- 1L:
  - Not merged region
  - 5 bins in $\cos\theta^*$ (>=4j, >=2b)
  - 5 bins in $\cos\theta^*$ (==3j, >=2b)
- 2L:
  - Binned by c_{hel} and c_{han}

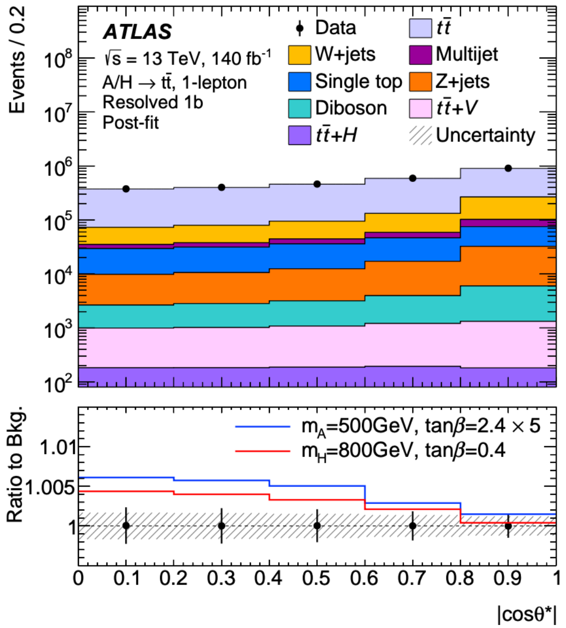
ATLAS

- 1L and 2L channel
- Not split by lepton flavor
- 1L:
  - Have merged region
  - 5 bins in $\cos\theta^*$ (>=4j, ==1b)
  - 5 bins in $\cos\theta^*$ (>=4j, >=2b)
- 2L:
  - Binned by $\Delta\phi_{ll}$

Angular Distribution

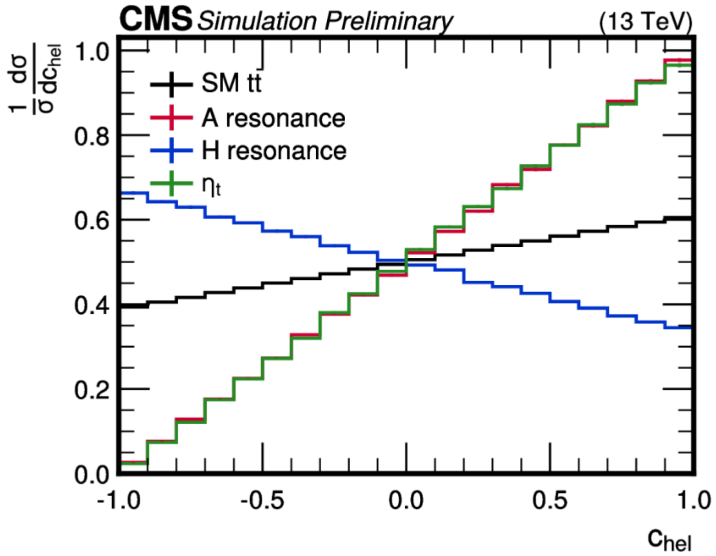
1L

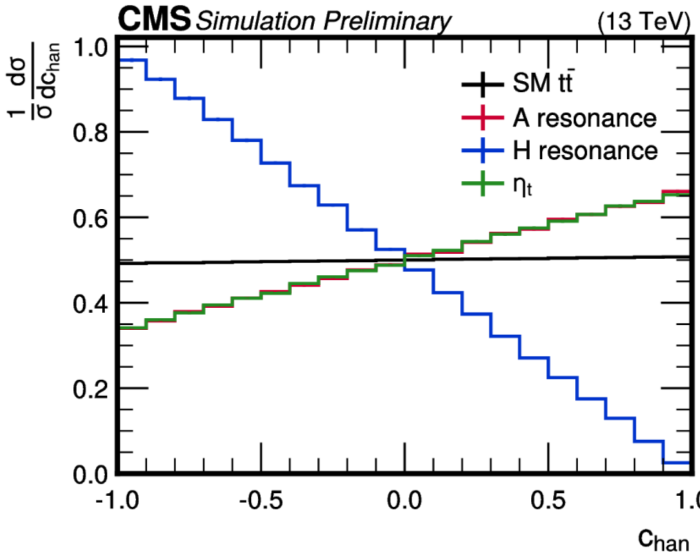


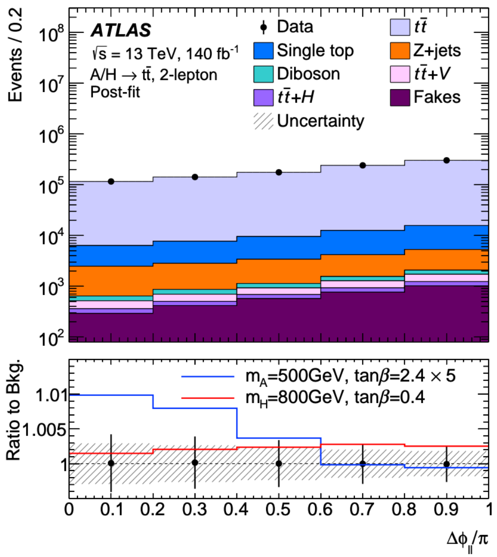


Similar observation

2L



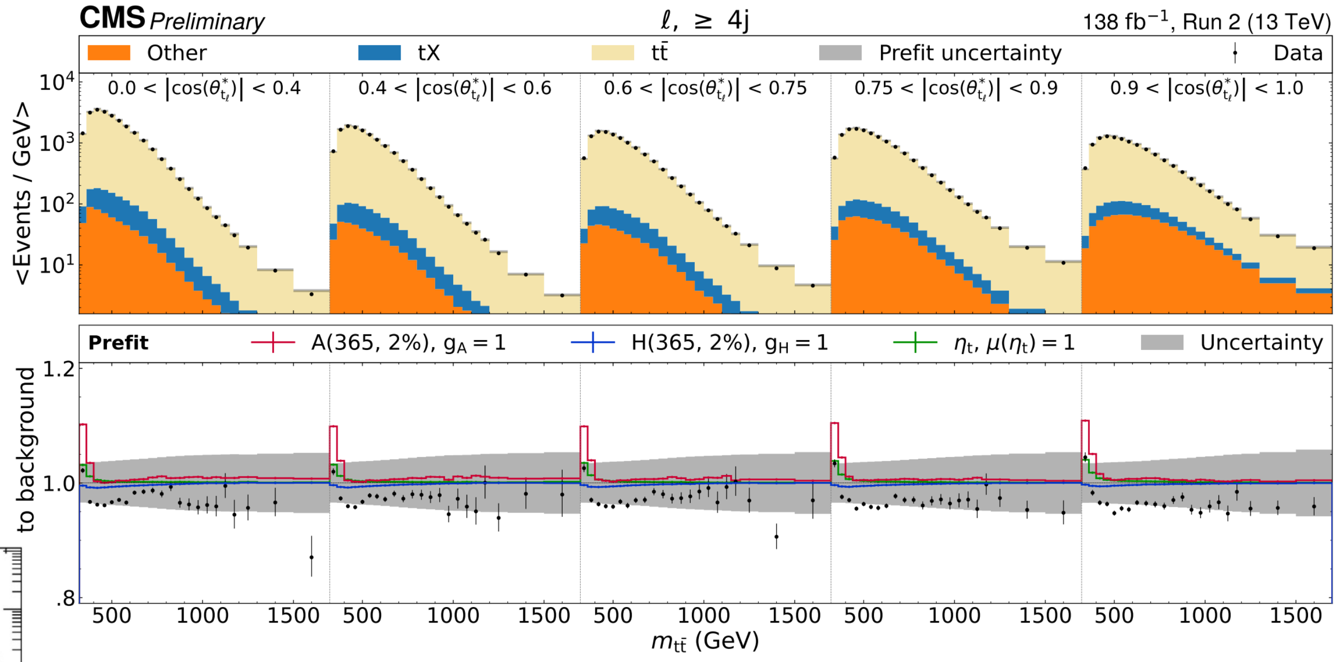


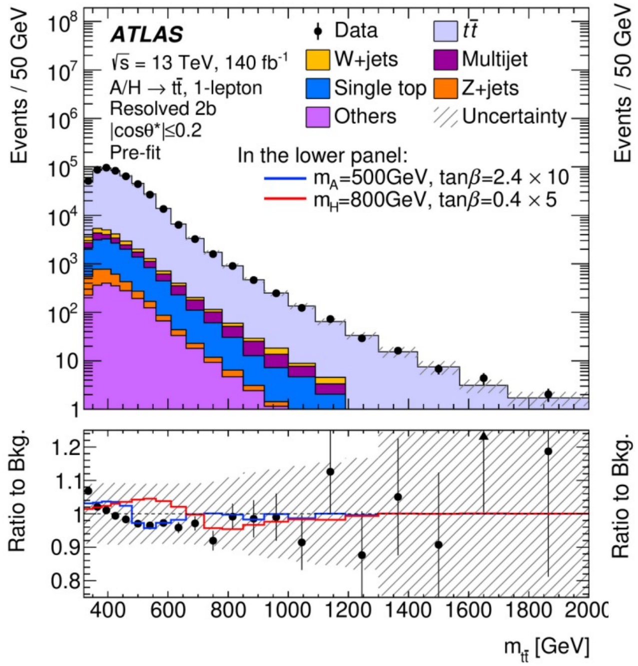


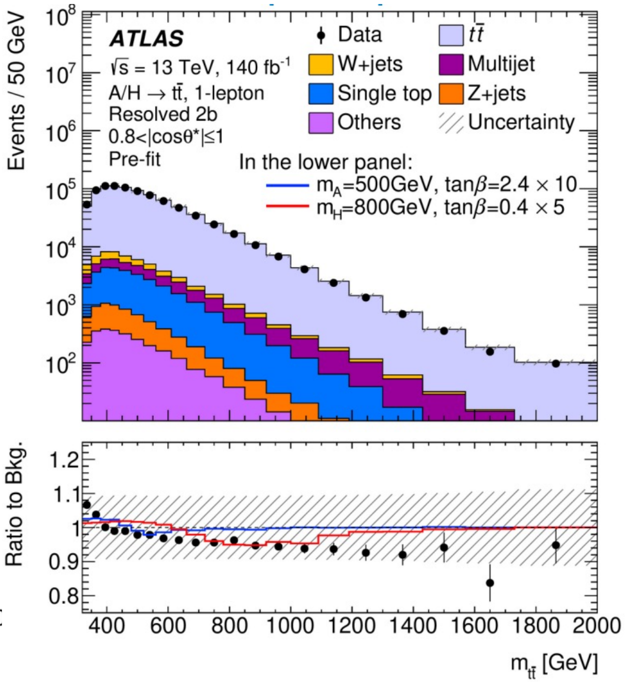
CMS' setup may be more powerful

Comparing with CMS – 1l

CMS



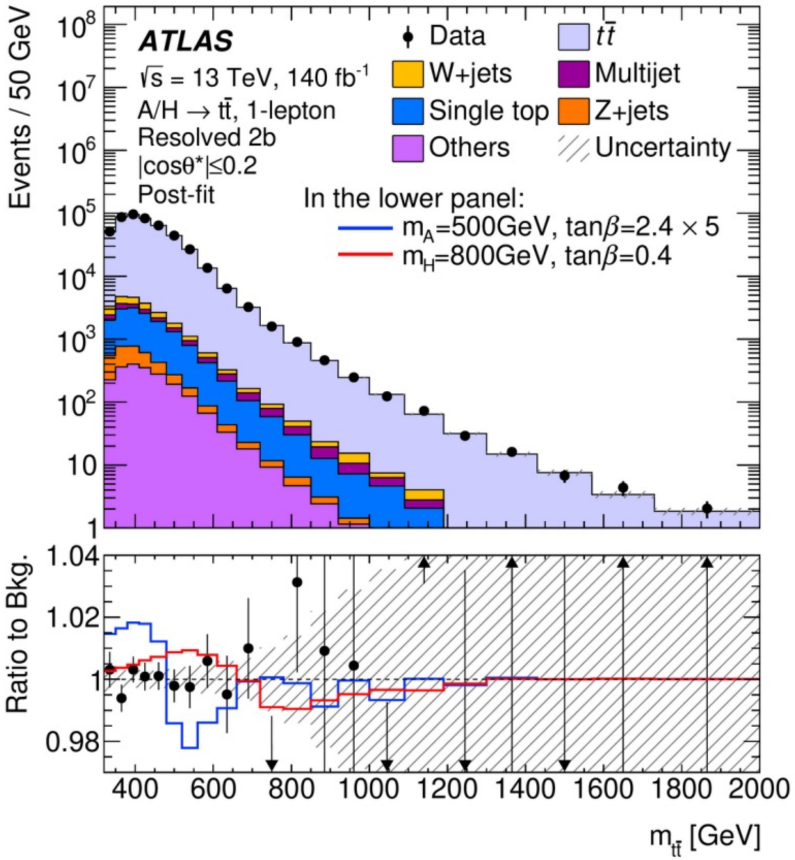


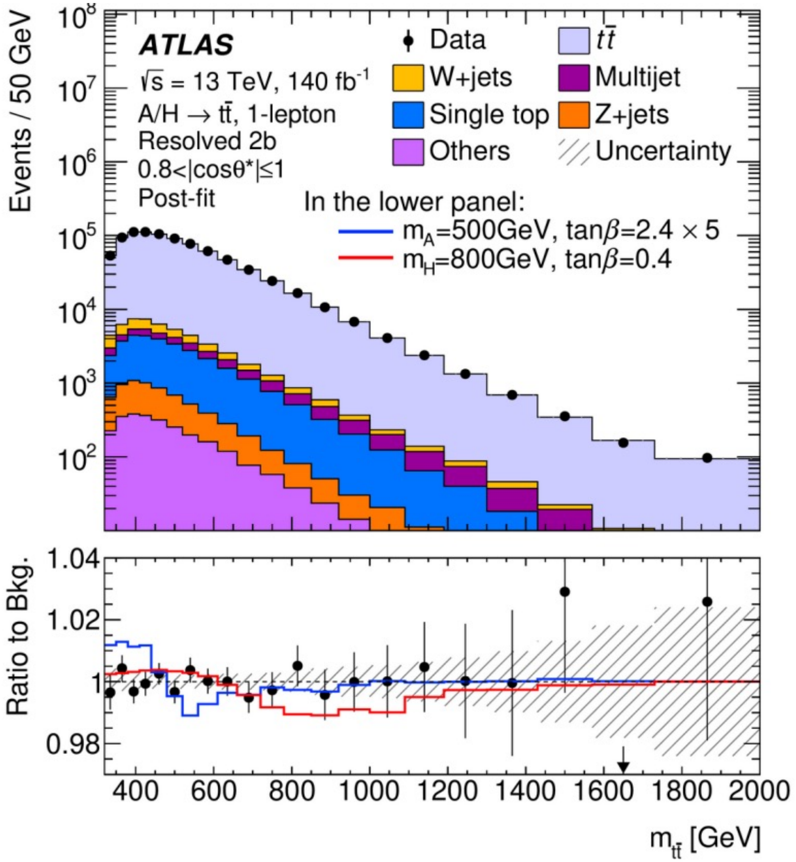


ATLAS:

- Observe similar disagreement between data and background prediction

Comparing with CMS – 1l



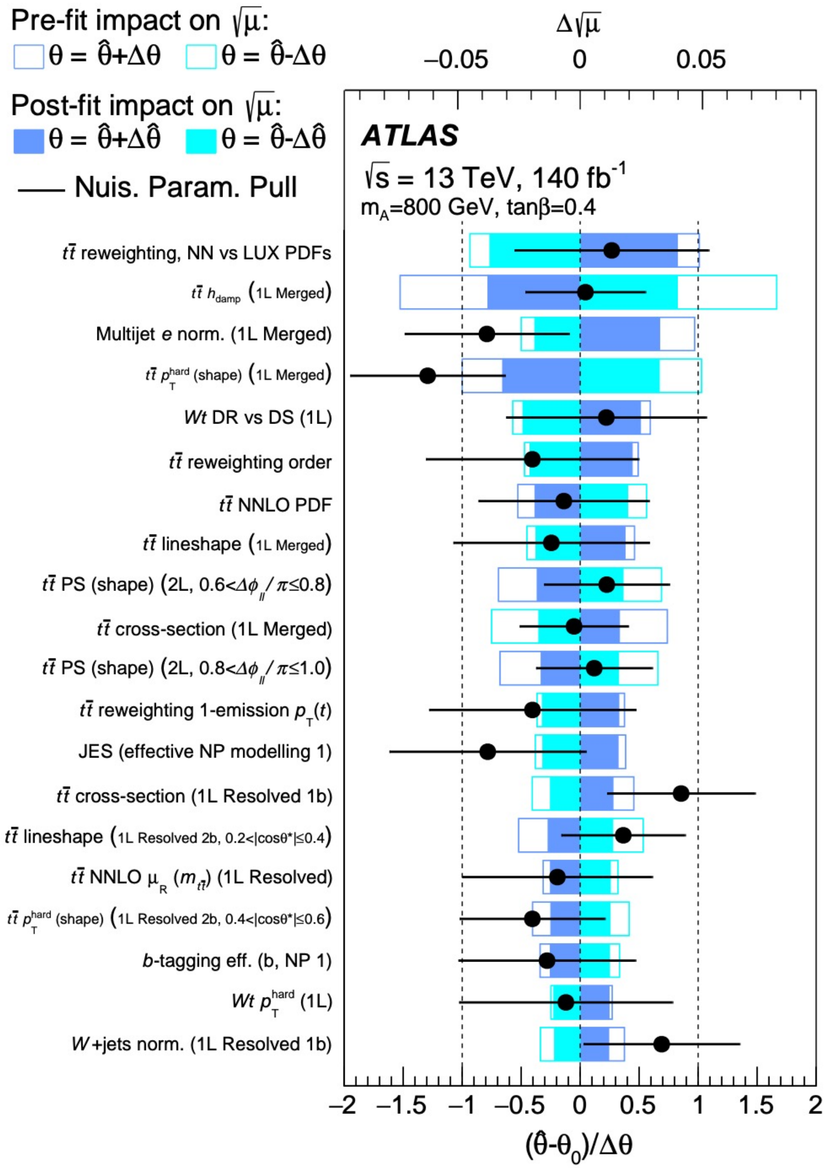


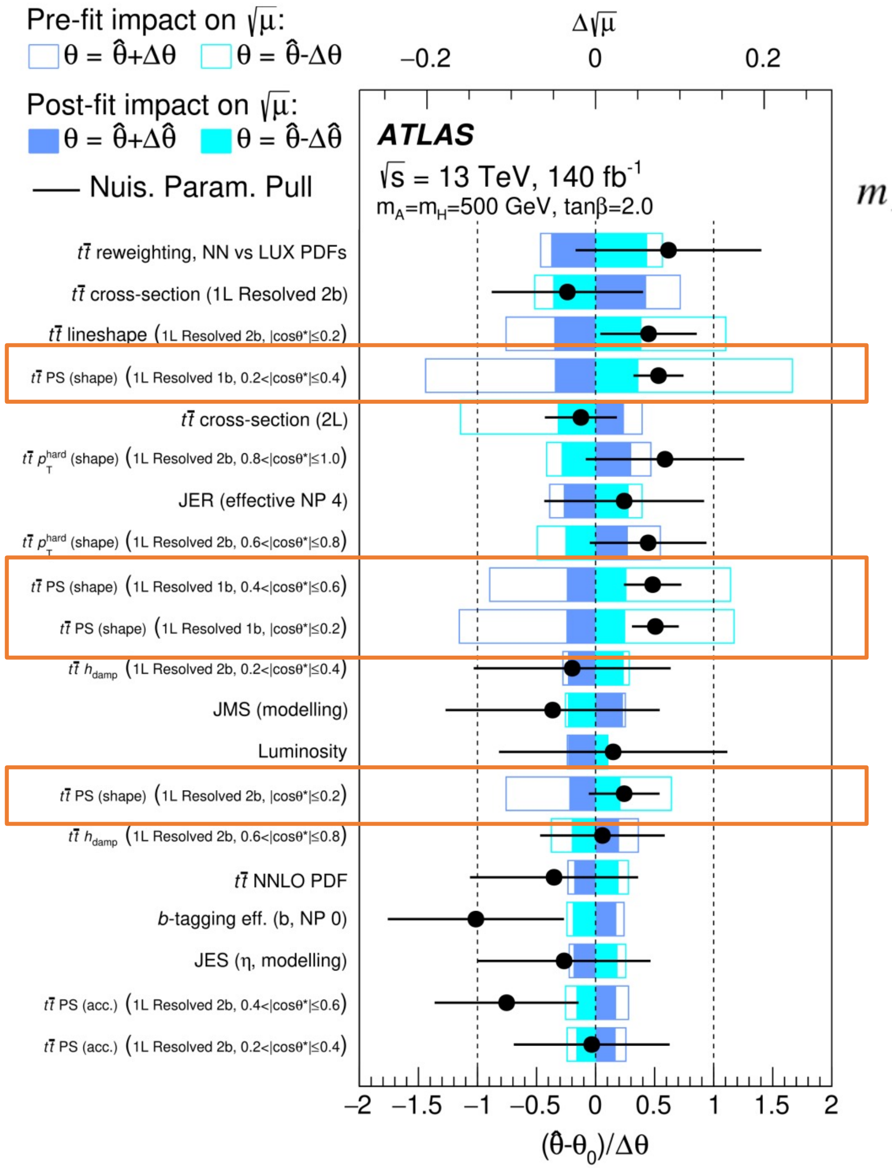
ATLAS:

- The disagreement disappear after Bonly fit

Ranking/Pull Plots

$m_A = 800$ GeV
$\tan\beta = 0.4$





$m_A = m_H = 500$ GeV
$\tan\beta = 2.0$

CMS Impact of NPs

In the toponium interpretation

- Top Yukawa has highest impact
- Top mass NP heavily constrained
- PS not included