BSM resonance to ttbar search at ATLAS and CMS

Jialin Li
Shanghai Jiao Tong University
for the ATLAS and CMS collaborations

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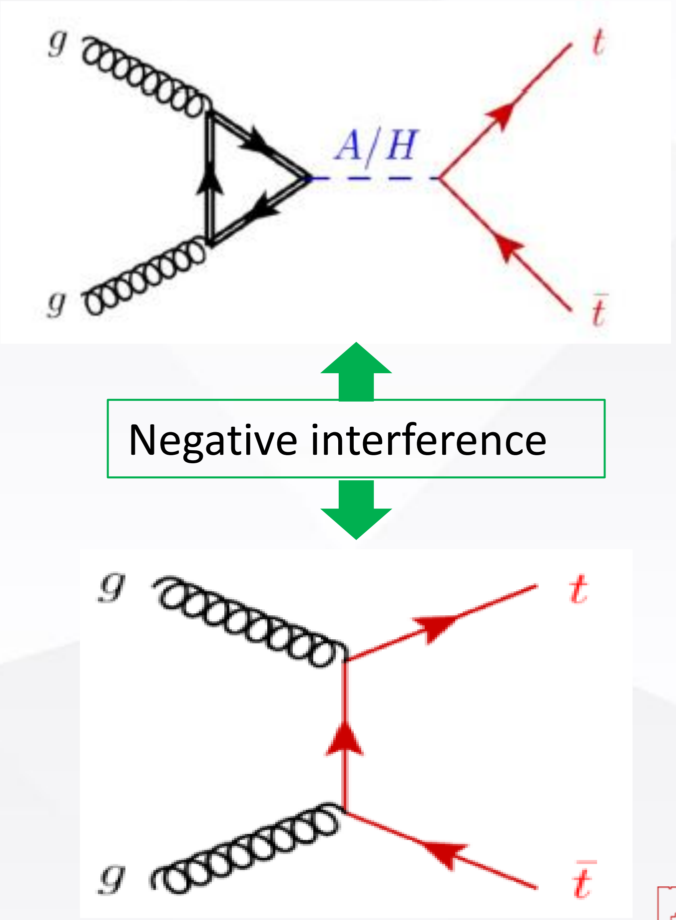
ATLAS EXPERIMENT

CMS

Physics Motivation

- Explore Beyond the Standard Model:
  - Two-Higgs-Doublet Model (2HDM) and Minimal Supersymmetric Standard Model(MSSM)
- Direct insight of Higgs-top yukawa coupling
- Understand Electroweak Symmetry Breaking
- **Challenges**:
  - Strong interference between signal and SM ttbar background

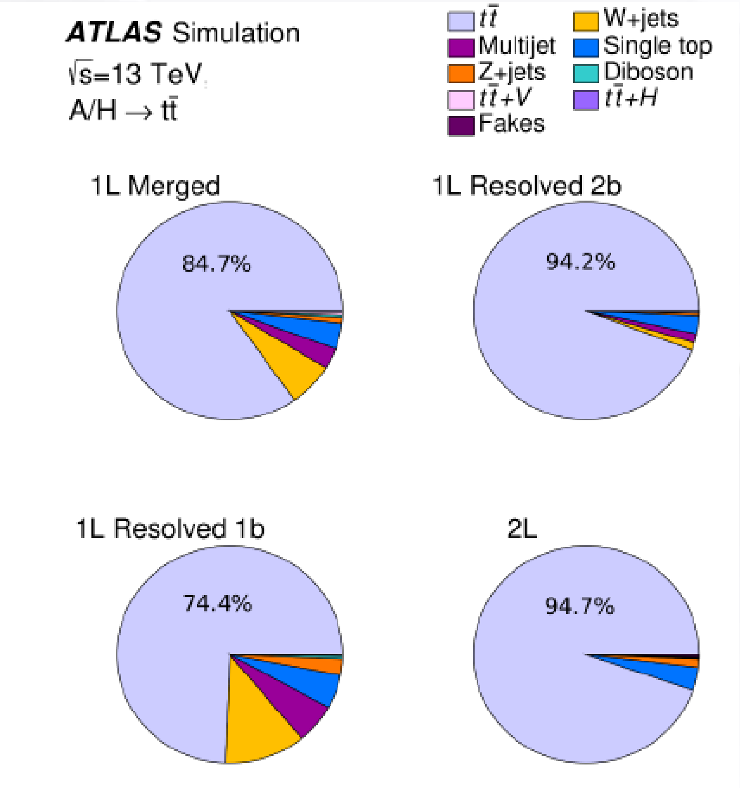


- Two Higgs Doublet Model (2HDM) and its variation:
- ◆ e.g: MSSM, hMSSM
- ◆ 5 Higgs Bosons: h,H,A,$H+$,$H-$
- ◆ 7 free parameters: **5** Higgs masses, **α**, ***tan β***
- ◆ Widely used as a benchmark for BSM Higgs searches

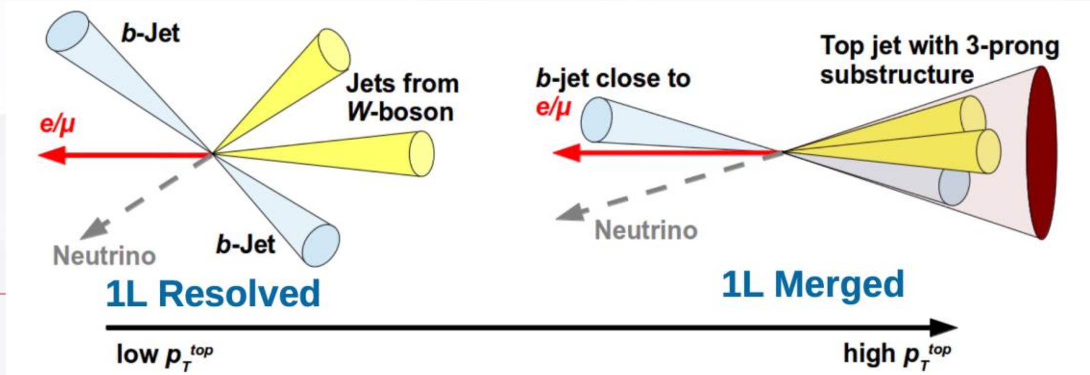
ATLAS: Analysis Strategy

JHEP08(2024)013

- Full run 2 dataset (140 fb^{-1})
- High mass($m_{A/H}$) : 400-1400GeV
- Large cross section when tanβ is small and mA is large
- **Two orthogonal channels: 1L (e or μ) + 2LOS**
  - 2L channel: $m_{llbb,}$ ≥2 small-R jets , ≥1 b-tagged jets
  - 1L channel: $m_{t\bar{t}}$
    - Resolved: ≥4 small-R jets and well reconstructed $t\bar{t}$ system
    - Merged: ≥1 large -VR jet



- CR_Z and CR_f to evaluate small backgrounds: e.g Z+jets, fake leptons



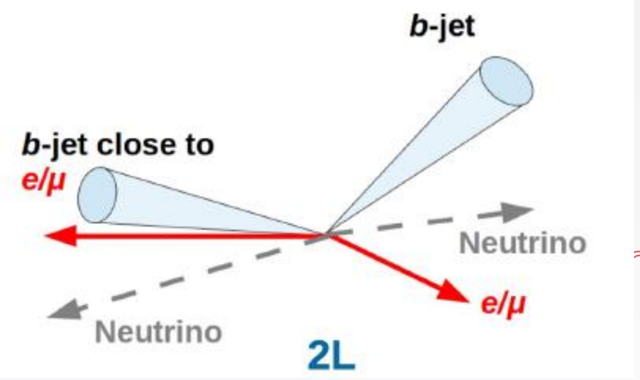
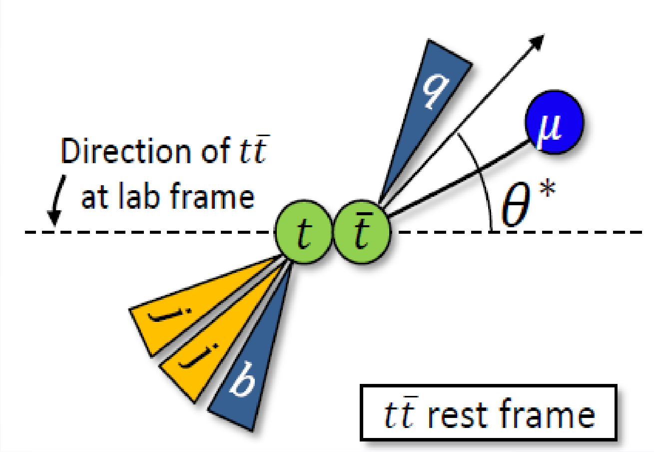
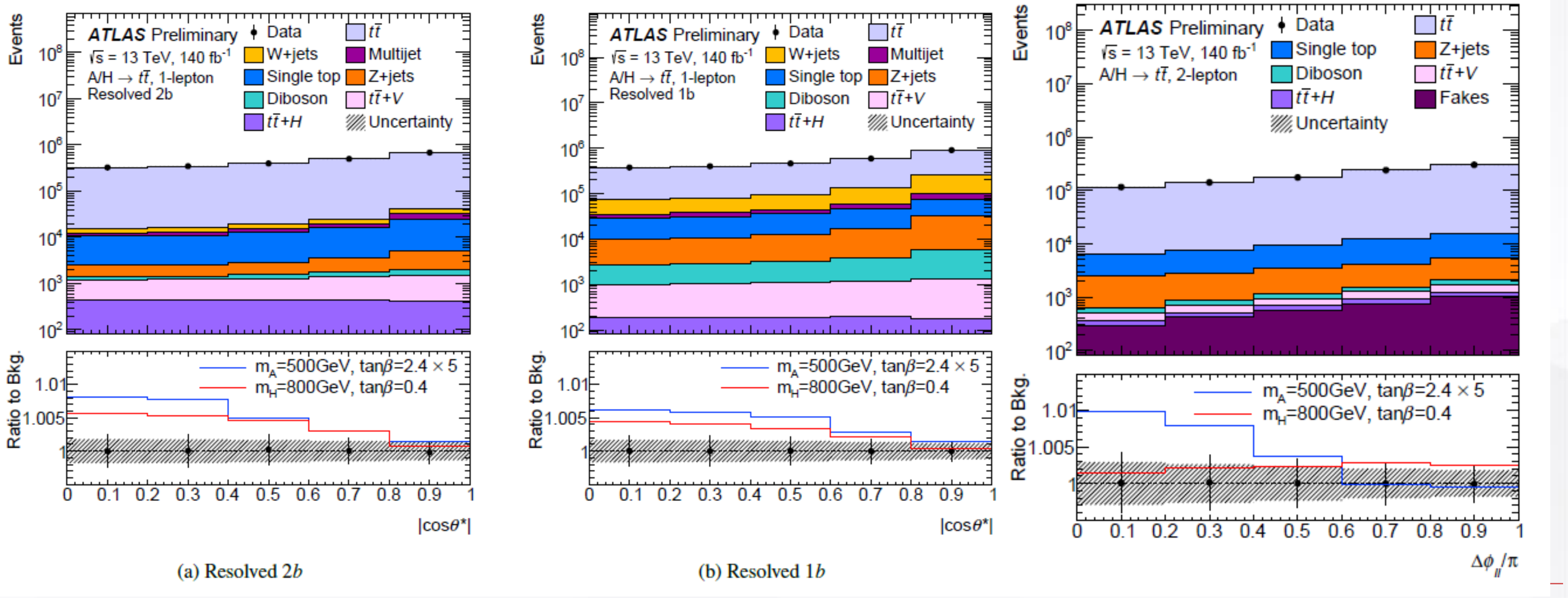


Figure from Yizhou Cai

Channel Categorization

- Split resolved ***1l region*** into **5** bins of ***cos θ****
  - ➢ Exploit the flat signal and peaked background distributions in *cos θ**
- Split resolved ***2l region*** into **5** bins of $\Delta\phi_{ll}$
  - ➢ Enhance the sensitivity to spin-0 states
- 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





(a) Resolved 2b

(b) Resolved 1b

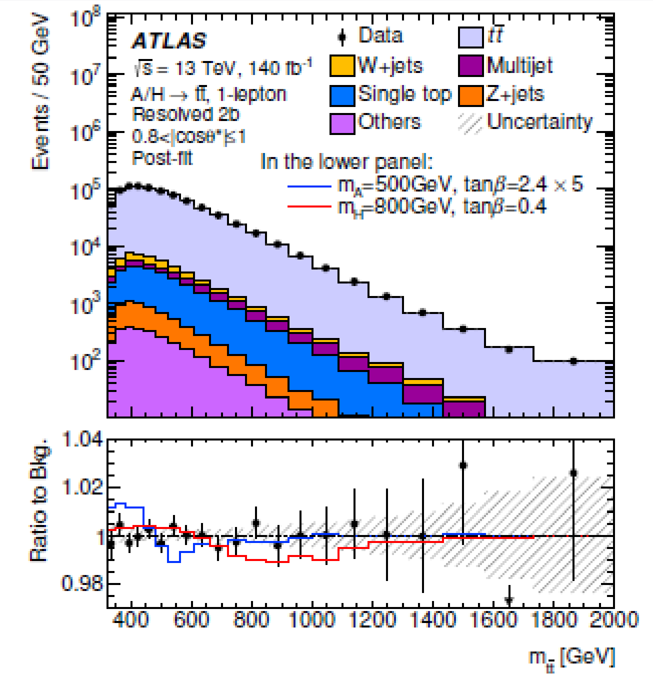
Systematic uncertainties

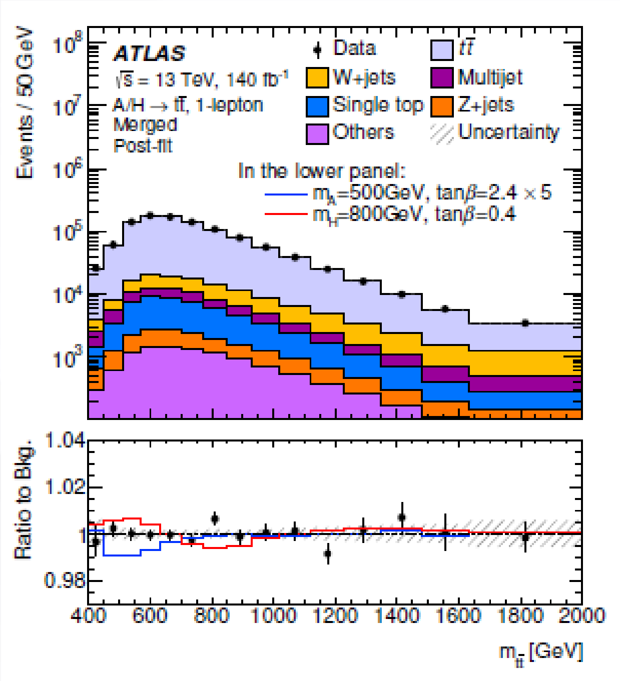
- Main syst. uncert. from SM $t\bar{t}$ modeling
  - NLO MC sample reweighting
  - SM $t\bar{t}$ MC samples comparison
  - NLO+PS prediction
- JES and JER are dominant experimental uncertainties.
  - Reduce the JES affect by re-calibrating to remove the MC dependence

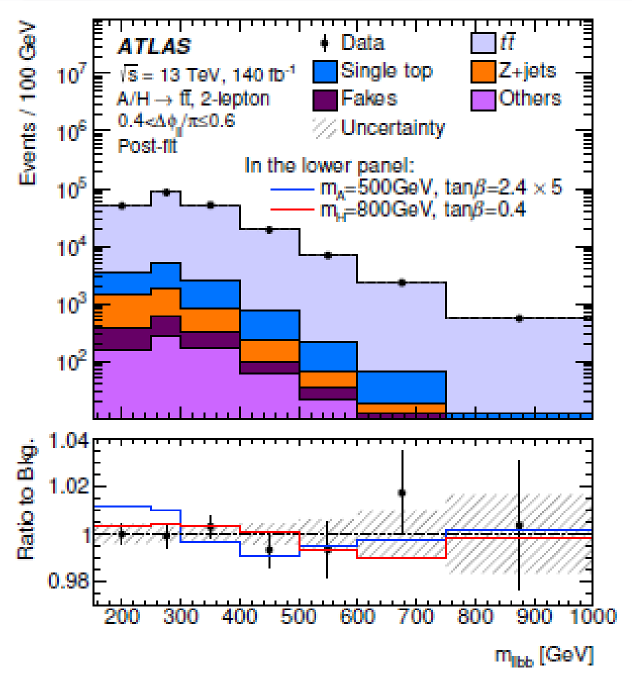
Uncertainty component	Fractional contribution [%] $m_A = 800$ GeV $\tan\beta = 0.4$	Fractional contribution [%] $m_A = m_H = 500$ GeV $\tan\beta = 2.0$
Experimental	**30**	**42**
Small-R jets (JER, JES)	22	29
Large-VR jets	11	20
Flavour tagging	13	17
Leptons	4	5
Other (E_T^{miss}, luminosity, pile-up, 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**

Post fit results

- background-only hypothesis (μ = 0)
- No significant interference pattern is found in the data
- Most significant deviation from SM-only: **2.3σ** at m_A = 800GeV, Γ/m = 10%

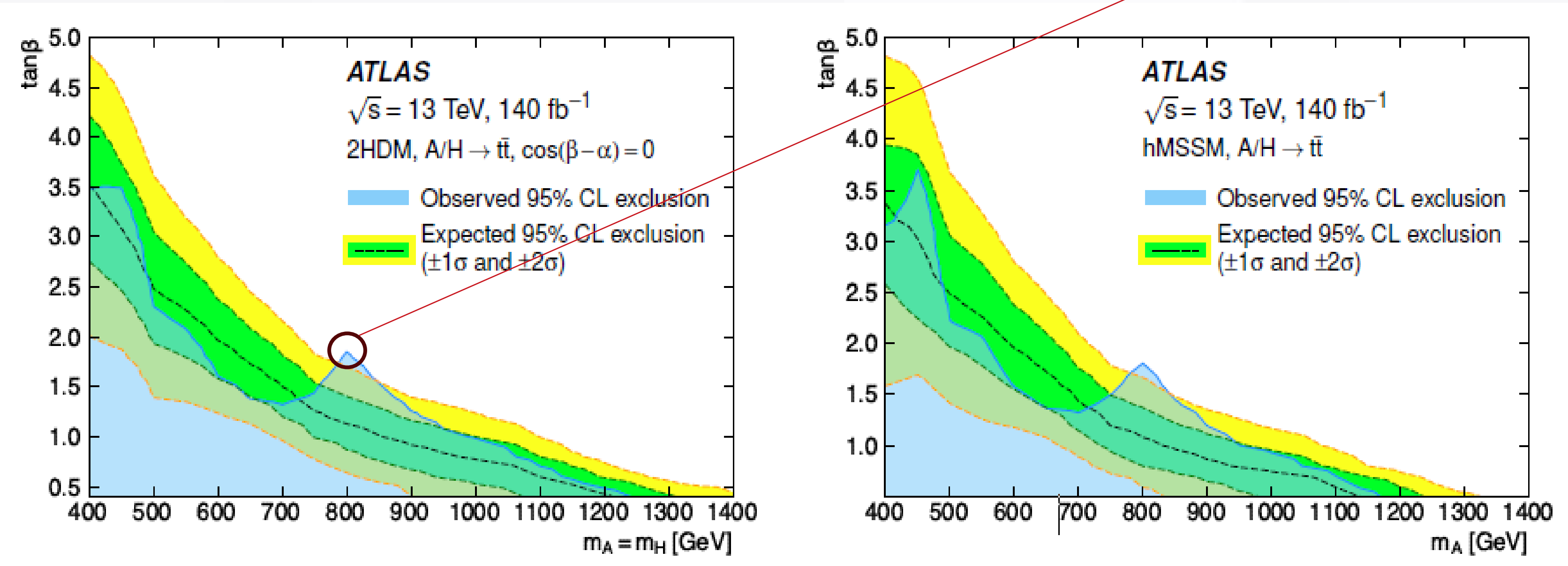






Exclusion on 2HDM and hMSSM

- $\tan\beta < 3.49$ (3.52) are observed (expected) to be excluded for $m_A = m_H = 400$ GeV in the 2HDM
- $\tan\beta < 3.16$ (3.37) are observed (expected) to be excluded for mA = 400 GeV in hMSSM
- The observed exclusion is stronger than the expected exclusion by about **2σ** in the mass region $m_A = m_H \approx 850$ GeV.

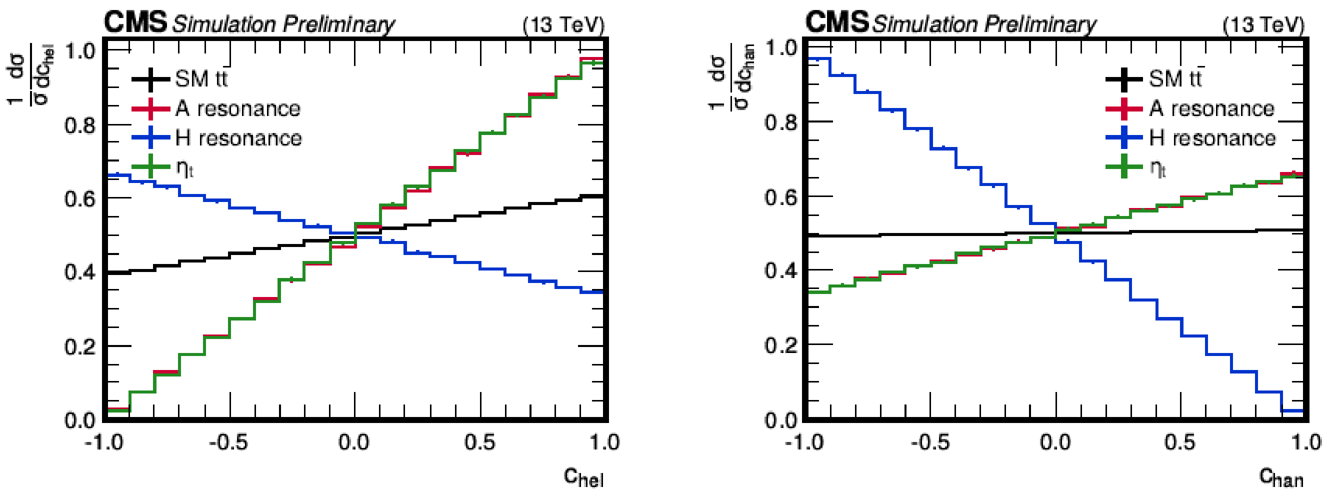


CMS: Analysis Strategy

CMS-PAS-HIG-22-013

- Full run 2 dataset (138 fb^{-1})
- High mass($m_{A/H}$) : 365-1000GeV with relative widths of 0.5-25%
- 2LOS channel :
  - 2 OS ℓ ($ee/e\mu/\mu\mu$)
  - ≥ 2 jets
  - ≥ 1 jets tagged b
- 1l channel :
  - 1ℓ (e/μ)
  - ≥ 3 jets
  - ≥ 2 jets tagged b
- Observables:
  - 1l channel: $m_{t\bar{t}}$, $\cos\theta^*$
  - 2lOS channel: $m_{t\bar{t}}$, c_{hel}(cosφ), c_{han} (cos'φ)

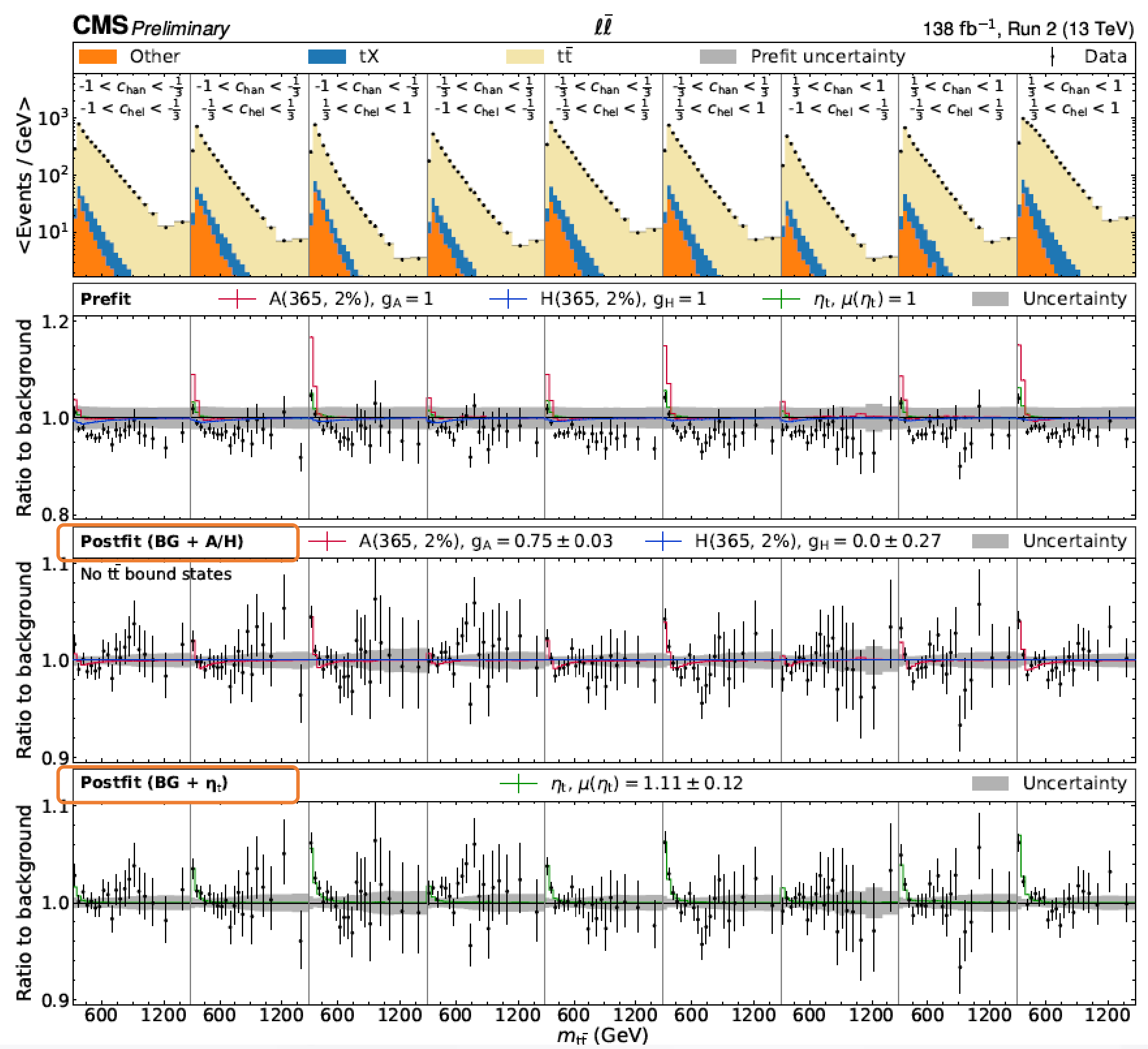
where φ denotes the angle between the direction of flight of the lepton ℓ^+ (or jet j_1) and of ℓ'^- (or j_2), defined in the t or $\bar{t}$ rest frames, respectively.



C_{han}:obtained by flipping the sign of the component parallel to the top quark direction

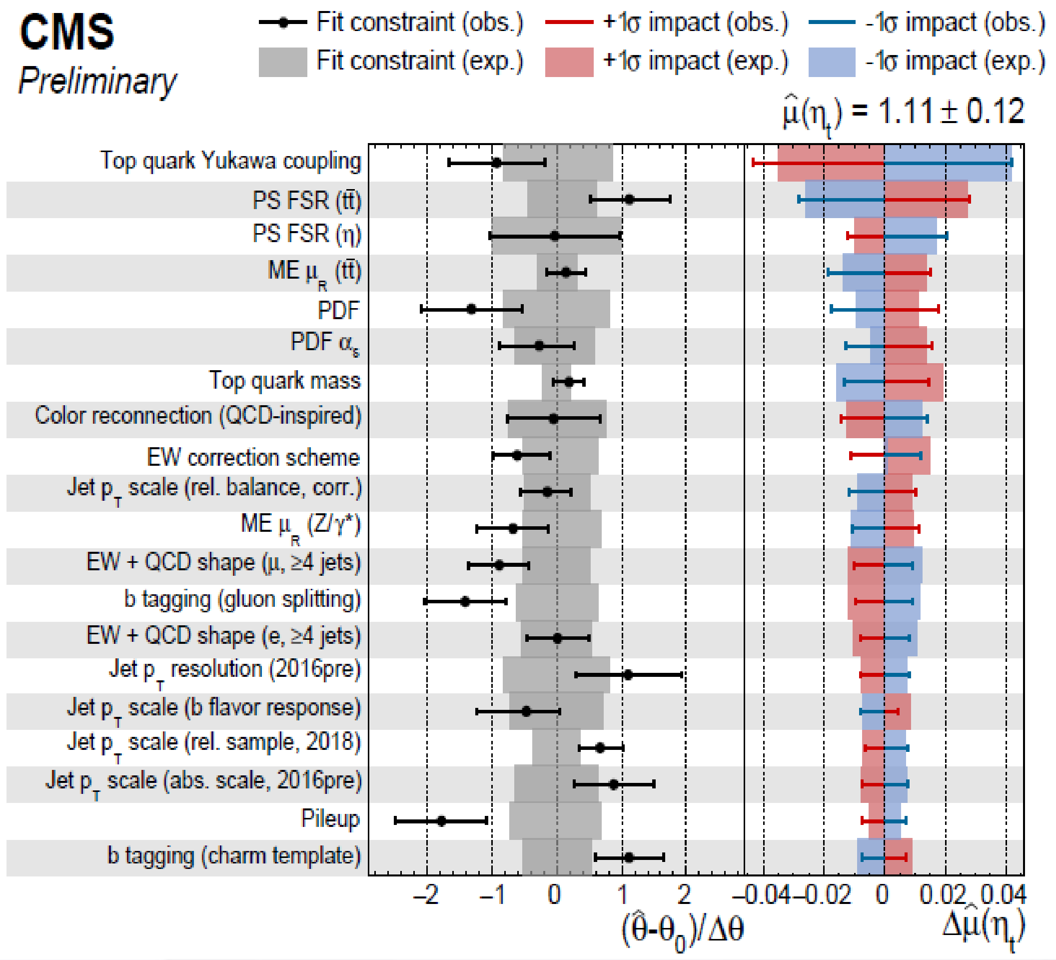
CMS Results

- Data vs. perturbative QCD (pQCD) bkg-only + A/H boson
- Data vs. pQCD bkg-only + pseudoscalar color-singlet $t\bar{t}$ bound state (η_t)
- > 5σ significance for A(365,2%) with respect to bkg-only hypos



CMS: Model interpretation

- **Cross section measurement for the η_t signal model**
  - $\sigma(\eta_t)$ = 7.14 ± 0.77pb (theory 6.42 pb)
- Dominant NPs arise from the top-Yukawa coupling and modeling systematics affecting the $m_{t\bar{t}}$ threshold region.

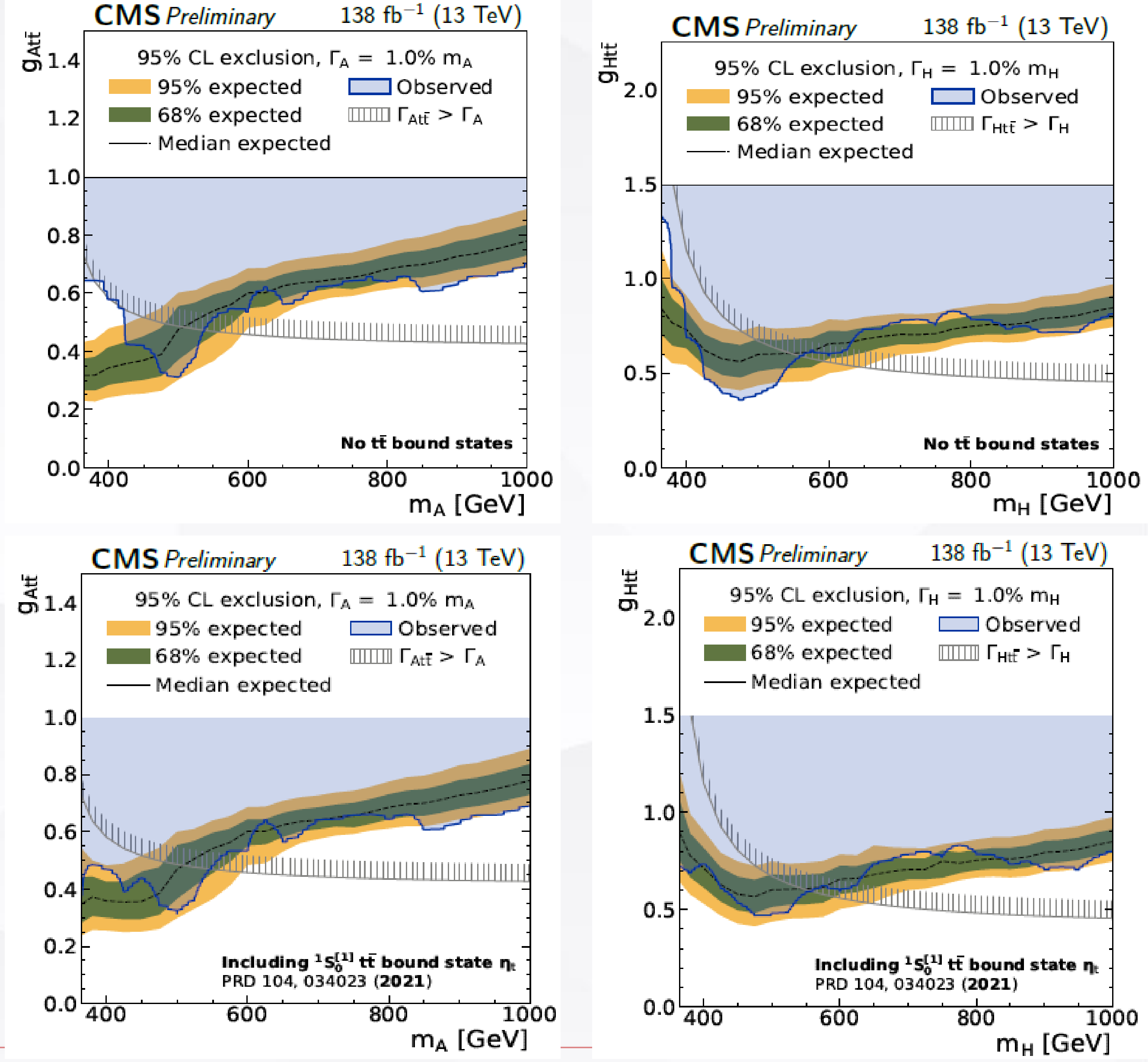


CMS: Model interpretation

$$\mathcal{L}_{\text{Yukawa,A}} = i g_{\text{A}t\bar{t}} \frac{m_t}{v} \bar{t}\gamma_5 t\text{A}, \qquad \mathcal{L}_{\text{Yukawa,H}} = -g_{\text{H}t\bar{t}} \frac{m_t}{v} \bar{t}t\text{H},$$

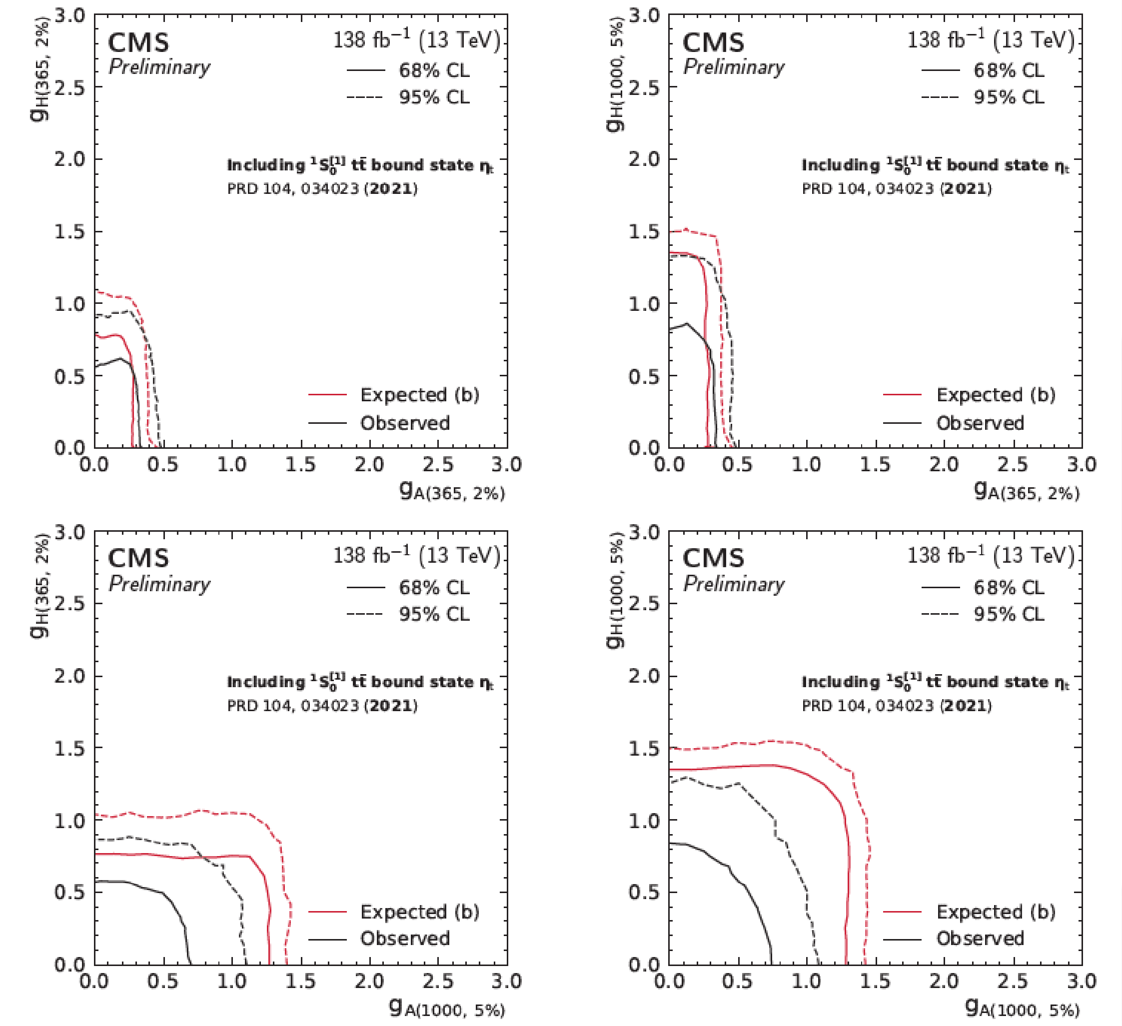
- **Single A/H interpretation**
  - ➢ Top row: pQCD SM background only
  - ➢ Bottom row: pQCD + η_t (as bkg)

- Including η_t production in the background leads to a **good** description of the observed data
- No hint for new A/H
- Excluded real-valued coupling modifier $g_{At\bar{t}}$ ($g_{Ht\bar{t}}$) is **0.4 (0.6)** for masses in 365-1000 GeV and widths 0.5-25%



CMS: Model interpretation

- **Simultaneous A+H interpretation**
- Consider η_t as background
- The observed exclusion contours are compatible with zero A+H contribution in all cases.



Summary

- Search for ttbar decayed from heavy Higgs boson with interference in ATLAS and CMS
- Several benchmark models very well physics motivated are tested
- Most stringent constraints on the 2HDM, hMSSM and pQCD parameter space

Thanks for your listening!

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Backup

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- 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, …

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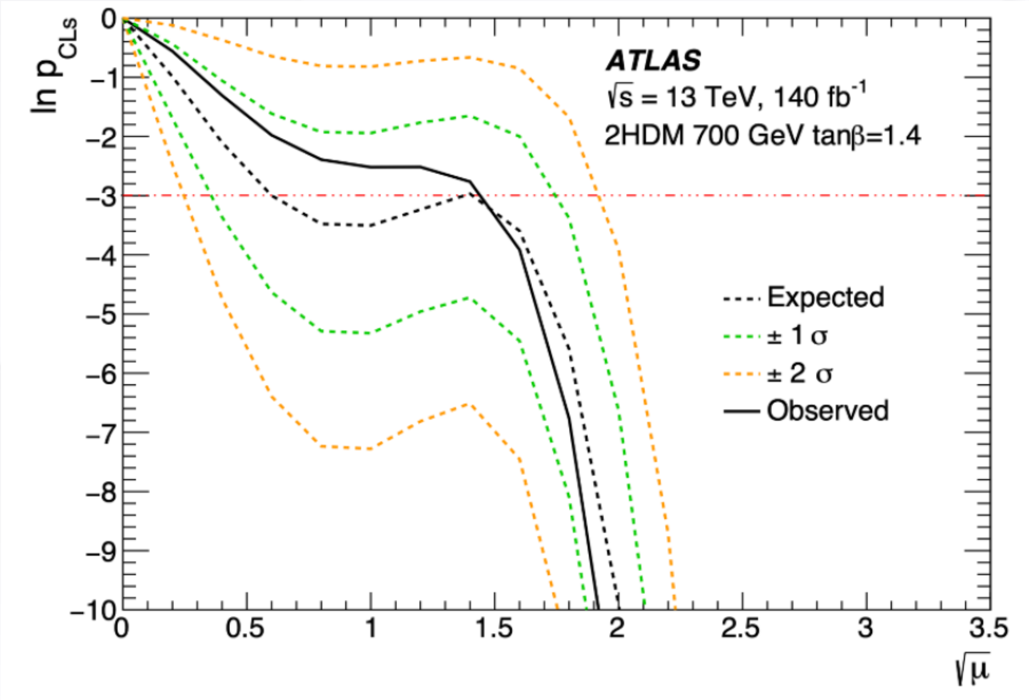
Statistical Analysis

- Extend likelihood to include interference term
- $\mu\, S + \sqrt{\mu}\, I + B = (\mu - \sqrt{\mu})\, S + \sqrt{\mu}\, (S + I) + B.$
- Quadratic dependence on μ
  - 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 $q_{1,0} = -2\ln\frac{\mathcal{L}(1, \hat{\hat{\theta}}_1)}{\mathcal{L}(0, \hat{\hat{\theta}}_0)}$
- Interpolate $\ln p_{\mathrm{CLs}}$ between signal hypotheses



Extended Higgs Sector Models

arXiv:2209.07510

Additional Singlet

- Simplest extension: $\mathcal{L} \supset \lambda_{\phi S}\phi^2 S^2$, S: real singlet scalar
- **Higgs portal** → connection to dark sector
- With Z_2 symmetry, **3 new free parameters**: mass of the scalar, mixing angle α, ratio of two VEVs $\tan\beta$
- Couplings inherited from SM h_{125} suppressed by $\sin\alpha$

Additional Singlet + Doublet

- 2HDM+S: 2HDM extended with a complex singlet
- Additional CP-odd/even scalars wrt pure 2HDM
- Required by next-to-minimal supersymmetric SM (**NMSSM**)

Additional Doublet

- Two Higgs Doublet Models (**2HDMs**): additional SU(2) doublet → Richer phenomenology
- **Required by SUSY** → received a lot of attention over time
- Standard parametrization: $\tan\beta$, α, masses
- **5 physical scalar states**: two neutral CP-even (H, h), one neutral CP-odd (A) and two charged ($H^{\pm}$)
- In the *alignment limit* ($\cos(\beta-\alpha) \to 0$) : h≡ h_{125}
- Yukawa couplings: $\lambda_f^{SM} = \frac{\sqrt{2}}{v} m_f$, $\lambda_f^{BSM} = \frac{\eta_f}{\tan\beta}\lambda_f^{SM}$

	Type-I	Type-II	Type-L	Type-F
η_u	1	1	1	1
η_d	1	$-\tan^2\beta$	1	$-\tan^2\beta$
η_l	1	$-\tan^2\beta$	$-\tan^2\beta$	1

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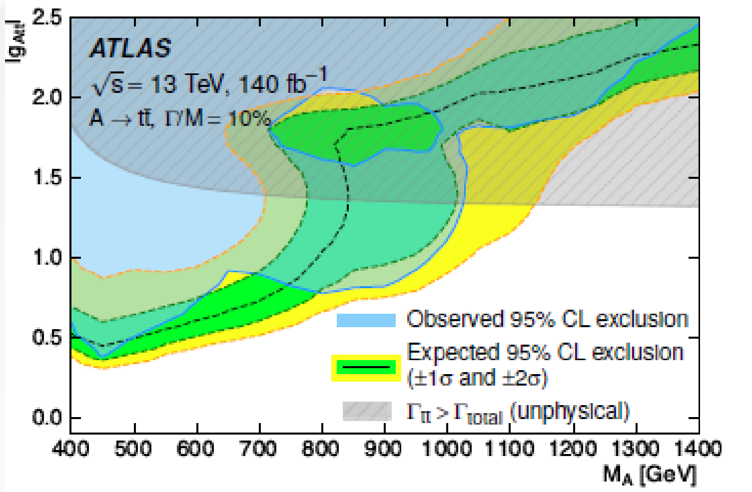
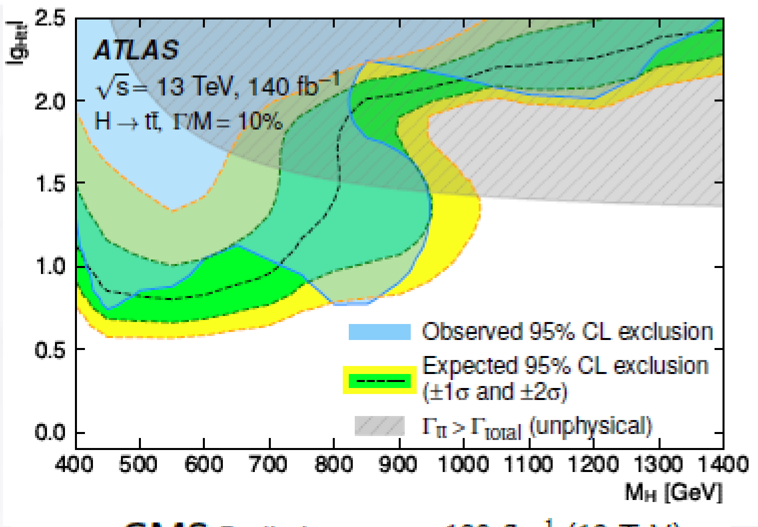
ATLAS: statistical data analysis

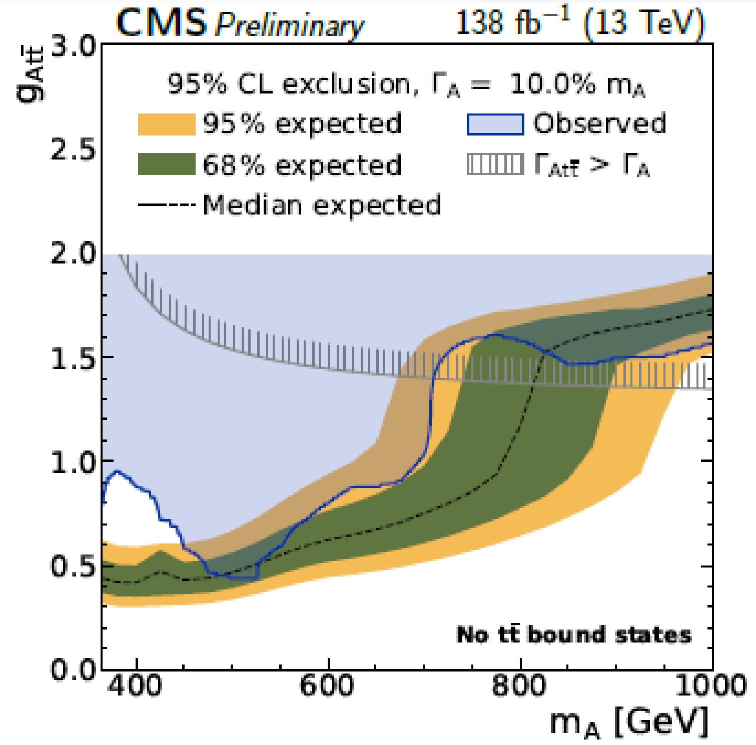
of $m_{A/H}$ and $\tan\beta$. In a type-II 2HDM, the
$\tan\beta$: $g_{At\bar{t}} = 1/\tan\beta$ and $g_{Ht\bar{t}} = -1/\tan\beta$.

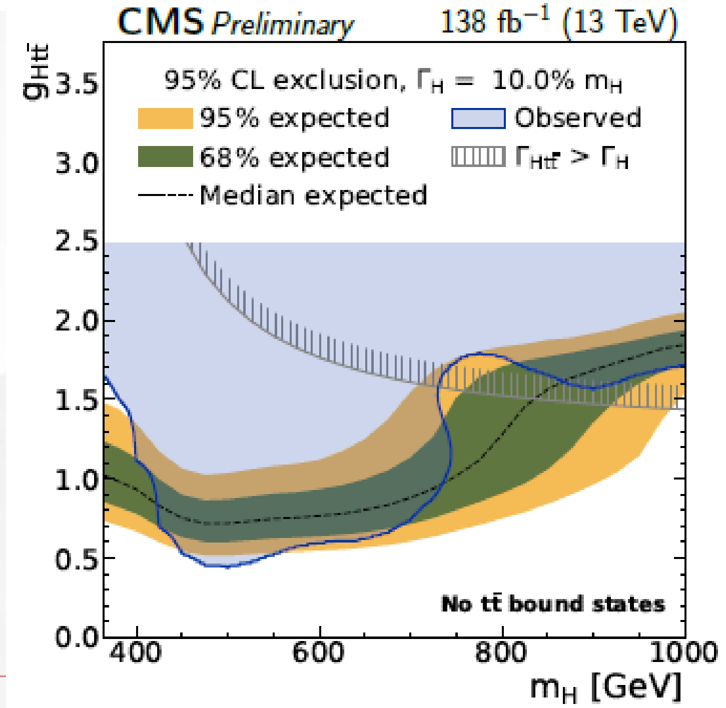
$$
\begin{aligned}
(S+I)_{g^2_{A/Ht\bar{t}}} &= g^4_{A/Ht\bar{t}} \cdot S + g^2_{A/Ht\bar{t}} \cdot I \\
&= (g^4_{A/Ht\bar{t}} - g^2_{A/Ht\bar{t}}) \cdot S + g^2_{A/Ht\bar{t}} \cdot (S+I).
\end{aligned}
$$

CMS and ATLAS comparison









ATLAS Selection table

- resolved and merged signal regions in the 1-lepton channel

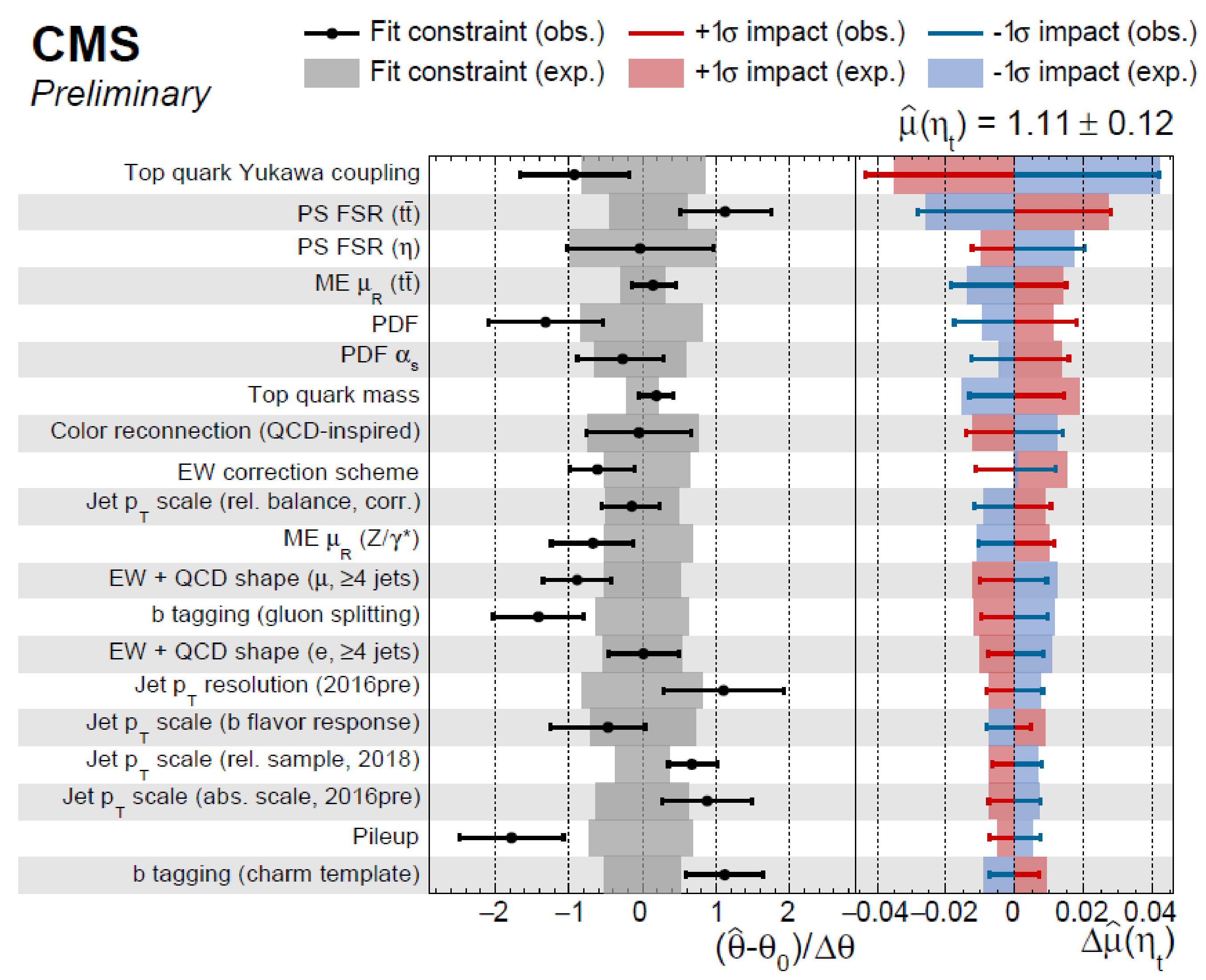
Selection	Criteria
Common selection	
Run and event cleaning	All detector components with acceptable conditions
Single lepton trigger	Separate single-electron or single-muon triggers
Exactly one lepton	Exactly one e or μ with $p_{\mathrm{T}} > 28$ GeV.
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} + W$ transverse mass	$E_{\mathrm{T}}^{\mathrm{miss}} + m_T^W > 60$ GeV
b-tagging	≥ 1 b-tagged jet
Merged-topology selection	
Large-VR jet	≥ 1 large-VR jet, $p_{\mathrm{T}} > 200$ GeV
Top tagging (hadronic decay)	Large-VR jet mass consistent with m_{top}: $m > 100$ GeV
Candidate b-jet (leptonic decay)	≥ 1 jet with ΔR (ℓ, R=0.4 jet) < 2.0
	ΔR (candidate b-jet, ℓ) < 2.0
Back-to-back $t\bar{t}$ topology	ΔR (large-VR jet, candidate b-jet) > 1.5
	ΔR (large-VR jet, ℓ) > 1.5
Matching of b-jets and top candidates	≥ 1 top candidate reconstructed with exactly one b-jet
Resolved-topology selection	
Small-R jets	≥ 4 jets, $p_{\mathrm{T}} > 25$ GeV
Well-reconstructed $t\bar{t}$ system	$\log_{10}(\chi^2) < 0.9$
Matching of b-jets and top candidates	≥ 1 top candidate reconstructed with exactly one b-jet
Veto events passing merged-topology selection	

A χ^2 minimisation approach is used to select the four jets from the $t\bar{t}$ decay from all selected small-R jets and assign them to the leptonically- and hadronically- decaying top quarks. It is defined as follows:

$$\chi^2 = \left[\frac{m_{jj} - m_{W_h}}{\sigma_{W_h}}\right]^2 + \left[\frac{(m_{jjb} - m_{jj}) - m_{t_h - W_h}}{\sigma_{t_h - W_h}}\right]^2 + \left[\frac{m_{jl\nu} - m_{t_l}}{\sigma_{t_l}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,jl\nu}) - (p_{T,t_h} - p_{T,t_l})}{\sigma_{\mathrm{diff}p_T}}\right]^2. \quad (7.1)$$

CMS Ranking

- The dominant contributions arise from modeling uncertainties, particularly those affecting the mtt threshold region.



CMS: A+H interpretation

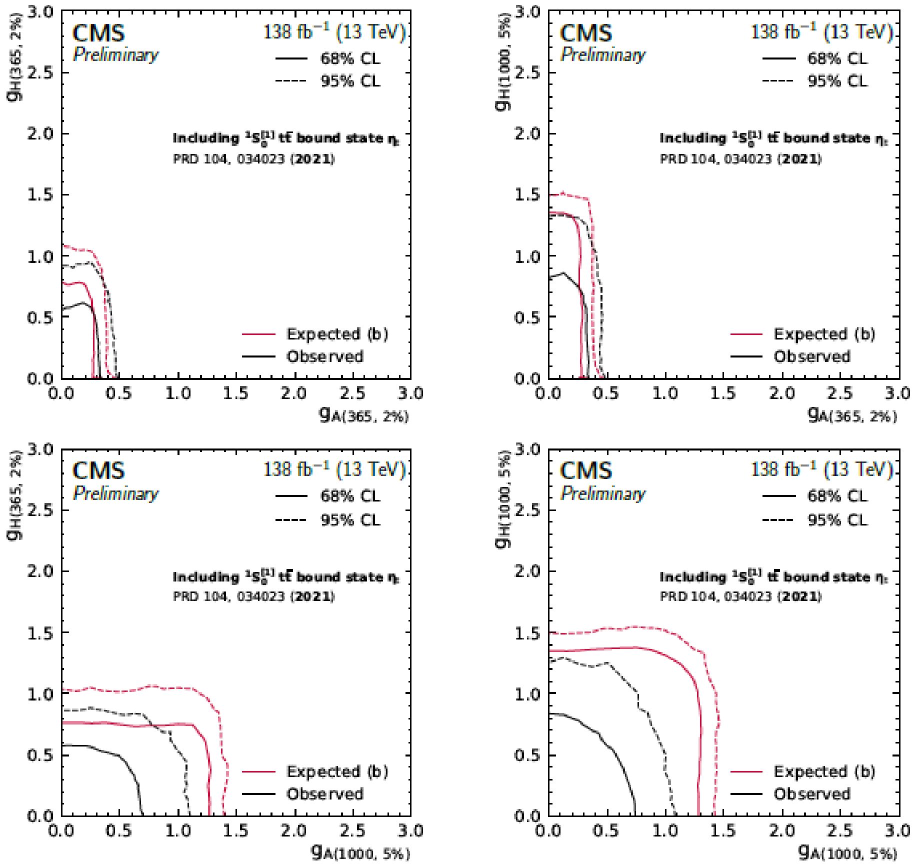


Figure 12: Frequentist 2D exclusion contours for $g_{\mathrm{At\bar{t}}}$ and $g_{\mathrm{Ht\bar{t}}}$ in the A+H interpretation for four different signal hypotheses: A(365, 2%) + H(365, 2%) (upper left), A(365, 2%) + H(1000, 5%) (upper right), A(1000, 5%) + H(365, 2%) (lower left), and A(1000, 5%) + H(1000, 5%) (lower right). The expected and observed contours, evaluated with the Feldman–Cousins prescription [108], are shown in black and red, respectively, with the solid and dashed lines corresponding to exclusions at 68 and 95% CL, and the respective best-fit points for $g_{\mathrm{At\bar{t}}}$ and $g_{\mathrm{Ht\bar{t}}}$ are shown as the colored crosses. In all cases, the η_t contribution is considered as part of the background.

- $\mu_{10Pb}^{A(365,2\%)}$ is far from the origin of zero signal contribution, with a local significance beyond five standard deviations.