Search for pseudoscalars and scalars decaying to top quark pairs with CMS Run 2

Samuel Baxter on behalf of the CMS Collaboration

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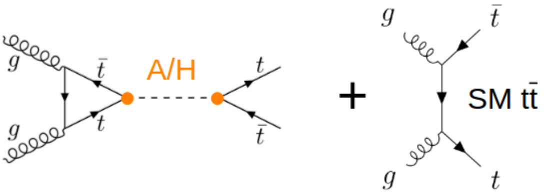
Theoretical Motivation

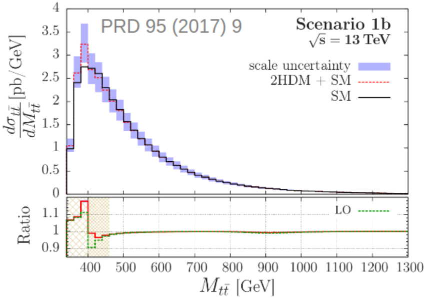
- Many extensions to the Standard Model rely on an extended Higgs sector
- Among the most popular SM extensions with an exteded Higgs sector are the 2HDM and MSSM
- We make the assumptions that the mass of the new (pseudo)scalar is more than twice the mass of the top quark, which it couples to exclusively

$$\mathcal{L}_A^{\text{int}} = i g_{\mathrm{At\bar{t}}} \frac{m_{\mathrm{t}}}{v} \bar{\mathrm{t}} \gamma_5 \mathrm{t} \mathrm{A} \qquad \mathcal{L}_H^{\text{int}} = -g_{\mathrm{Ht\bar{t}}} \frac{m_{\mathrm{t}}}{v} \bar{\mathrm{t}} \mathrm{t} \mathrm{H}$$



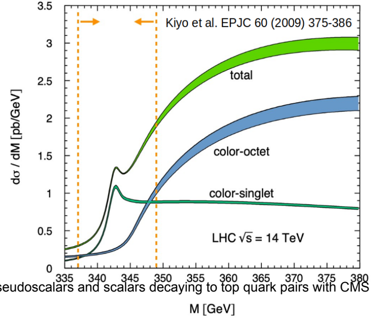
Signal Model

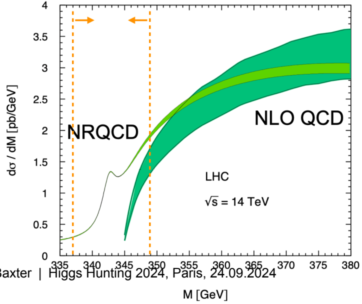
- In our search, we use a model-independent approach, where we consider the mass, CP parity, width and the coupling modifiers $g_{\mathrm{A}}/g_{\mathrm{H}}$ as free parameters for the new scalar/pseudoscalar
- In addition to the $\mathrm{t\bar{t}}$ resonance, the interference with Standard Model $\mathrm{t\bar{t}}$ production is also considered, resulting in a peak-dip structure in the $m_{\mathrm{t\bar{t}}}$ distribution
- The signal samples are generated at LO with NNLO QCD k-factors applied



Model of the $t\bar{t}$ Bound State (η_t)

- At the $m_{t\bar{t}}$ threshold, non-perturbative QCD effects start to play a role
- These effects inculde a bound state of $t\bar{t}$, appearing as a pseudoscalar resonance
- We model this effect with the following assumptions and parameters suggested by Fuks et al. (PRD 104 (2021) 3, 034023):
  - Color-singlet pseudoscalar particle η_t coupling to gluons and top quarks
  - $m_{\eta_t} = 343$ GeV, $\sigma_{\eta_t} = 6.43$ pb
  - Generated in MadGraph, filtering out events outside $m_{\eta_t} = 343 \pm 6$ GeV





Selections

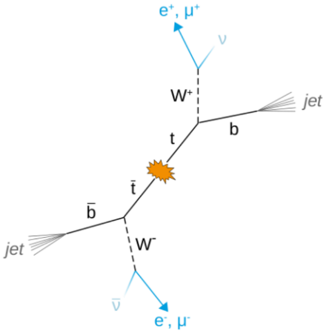
Dileptonic Channel

Two oppositely charged leptons (ee/eμ/$\mu\mu$)

At least two jets

At least one jet b tagged

At least one solution to the $t\bar{t}$ reconstruction is required

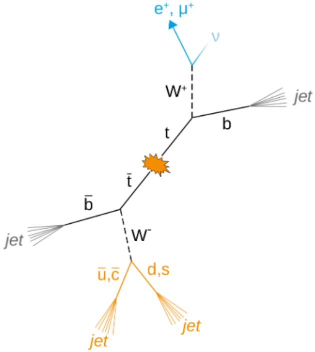


Semileptonic Channel

Only one lepton (e/μ)

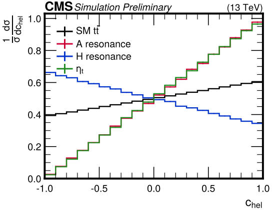
Three or more jets

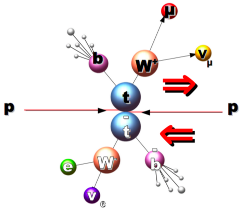
At least two jets b tagged

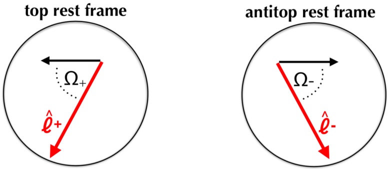


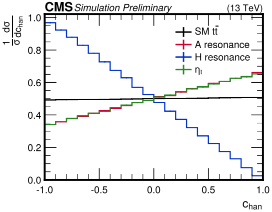
Dileptonic Channel

- The search variables are $m_{t\bar{t}}$, c_{hel} and c_{han}
- The c_{hel} variable is defined by taking the scalar product of the lepton unit vectors, boosted to the zero mass frame of the $t\bar{t}$ system and further boosted to their respective parent top quark
- The c_{han} variable has a similar definition, just has a flipped sign for the coordinate in the direction of the parent top quark for one of the leptons









Semileptonic Channel Variables

- The search variables in the semileptonic channel are $m_{t\bar{t}}$ and $|\cos(\theta^*)|$
- θ^* is the angle between the leptonically decaying top quark in the zero mass frame of the $t\bar{t}$ system and the diraction of the $t\bar{t}$ system in the laboratory frame
- For SM $t\bar{t}$ production, $|\cos(\theta^*)|$ peaks at $|\cos(\theta^*)| = 1$, whereas both the scalar and pseudoscalar signals are flat in comparison

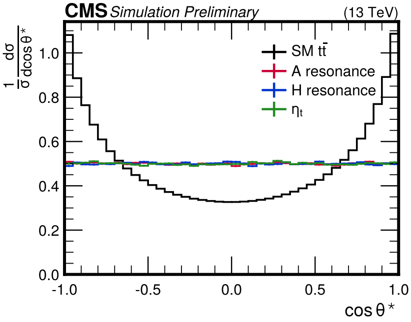
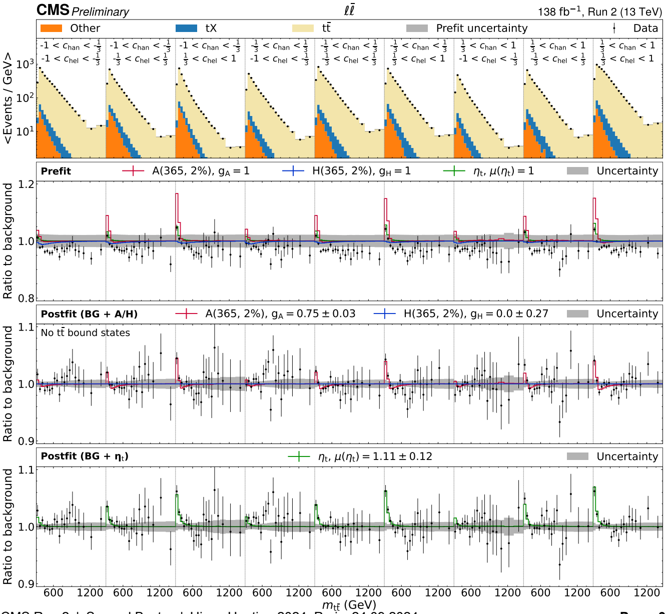


Figure: Gen-level distribution of the spin-correlation variable $\cos(\theta^*)$.

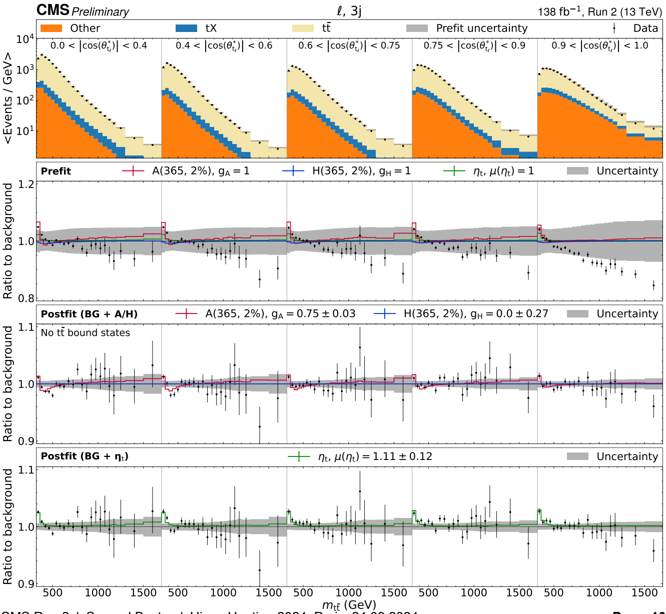
Backgrounds

- **SM $t\bar{t}$** is an irreducable background - the best possible precision and accuracy is needed
  - Generated at NLO
  - Shape reweighted to NNLO QCD + NLO EW, normalized to NNLO + NNLL
- **Single top and tW**, generated at NLO, present in both the single leptonic and dileptonic searches
- **Z+jets**, present in the dileptonic search, mainly the ee and $\mu\mu$ channels
  - MiNNLO samples for better data/MC agreement at low m_{ll}
  - Normalisation from Z window using an R_{in}/R_{out} method
- **QCD and EW**, data-driven estimate - semileptonic only
  - Sideband regions, where no jets pass the b-tagging
  - Transfer factors on W+jets and QCD MC simulations, shapes are corrected as well
- tt+X and Diboson MC simulations are included in the dileptonic search

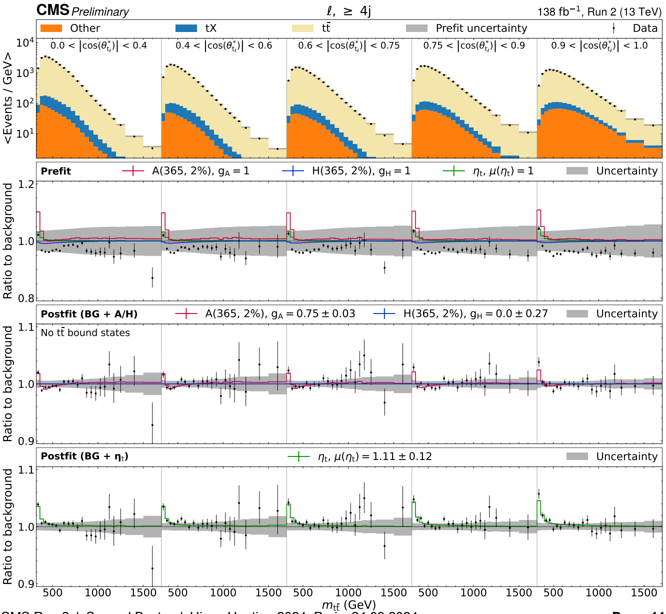
Prefit/Postfit Dilepton



Prefit/Postfit Lepton+3Jets

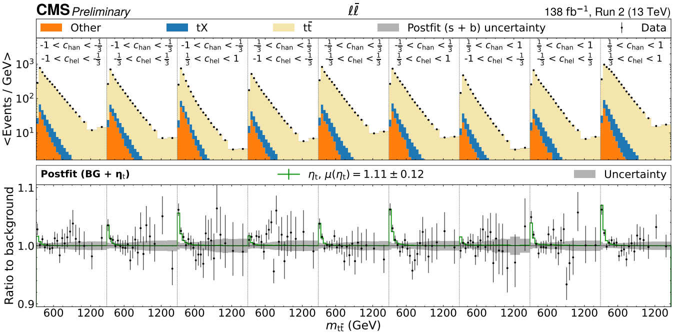


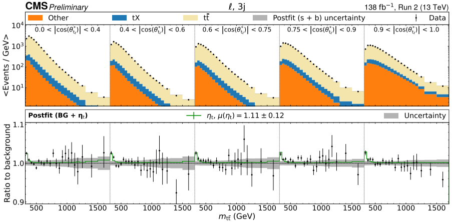
Prefit/Postfit Lepton+$\geq$4Jets

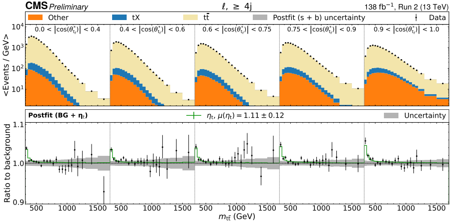


Best fit for η_t

- As seen in the postfit plots with the SM+η_t interpretation, data fits η_t well, and a cross section of **7.1 pb±11 %** is determined

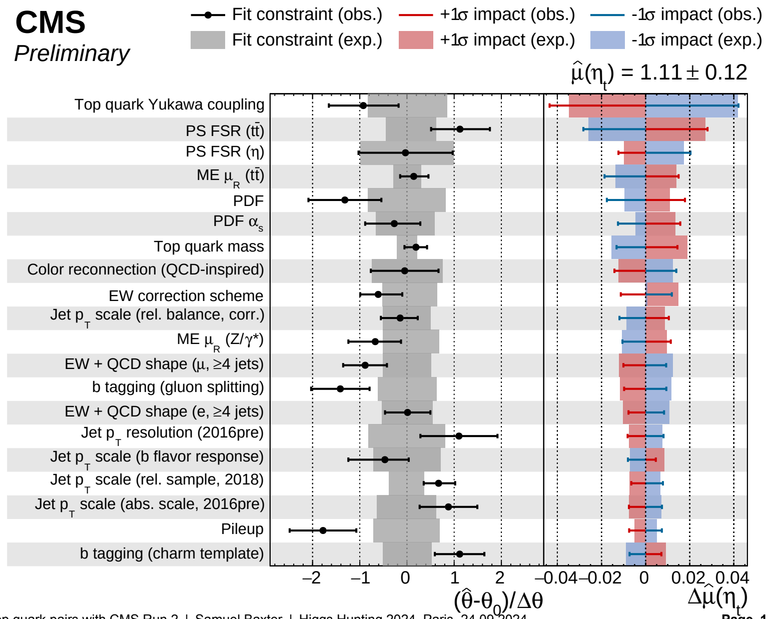






Uncertainties

> Modelling uncertainties have the dominating impact on fitting the η_t model



Combined Limit

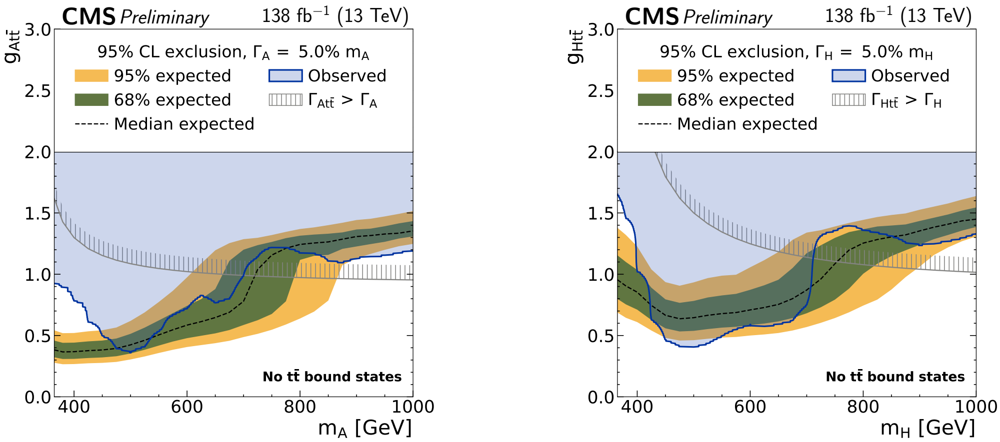


Figure: Limits for pseudoscalar(left) and for scalar(right), perturbative QCD SM background

Combined Limit with η_t

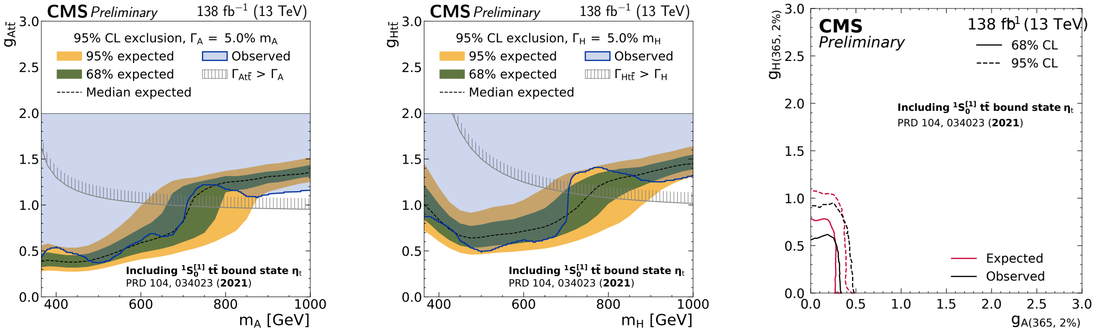


Figure: Limits for pseudoscalar(left), for scalar(centre) and 2-dimensional for both scalar and pseudoscalar (right), SM background with a model of the $t\bar{t}$ bound state

Summary

- **A search for a scalar or pseudoscalar has been peformed** in the dileptonic and semileptonic final states of $\mathrm{t\bar{t}}$ using the full Run2 dataset of CMS
- The analysis targets the $m_{\mathrm{t\bar{t}}}$ distribution along with angular and spin observables
- **A local excess, at low $m_{\mathrm{t\bar{t}}}$, has been observed in data with >5σ significance**, which fits better to **pseudoscalar** than scalar hyptheses
- Excess also fits best to a model of **the $\mathrm{t\bar{t}}$ bound state η_{t}**, a cross section has been determined
- **Stringent limits have been set** on the scalar and pseudoscalar signal models, with a floating normalisation of η_{t} included

Reference: CMS-PAS-HIG-22-013

Thank you!

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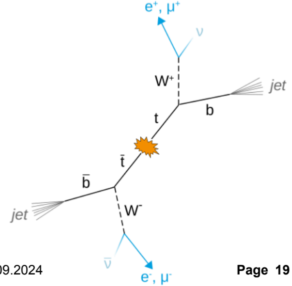
Backup

Dileptonic Channel Selection

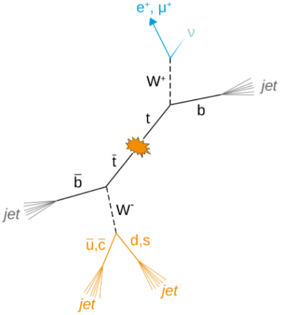
- **Two oppositely charged leptons** with $p_T > 25(20)$ GeV for the leading (subleading) lepton, $|\eta| < 2.4$, Split into three channels: ee eμ and $\mu\mu$
  - Muon: tight cut-based ID & ISO, Electrons: tight WP of MVA+ISO ID
  - Remove $m_{ll} < 20$ GeV, Z-window ($M_Z \pm 15$ GeV), along with a $p_T^{miss} > 40$ GeV requirement, in ee/$\mu\mu$
  - Pass any single lepton or dilepton trigger and veto additional leptons with $p_T > 20$ GeV
- **At least two jets** with $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R > 0.4$ to leptons, tight ID
- **At least one jet b tagged** with a likelihood-based method, medium WP

- A reconstruction of the $t\bar{t}$ system is done analytically, **at least one solution to the reconstruction is required**
  - Assigning p_T^{miss} to the two neutrinos, assuming on-shell tops and Ws
  - Selecting the best fitting jets to the m_{lb} systems
  - Smeared masses, use weighted average of 100 variations

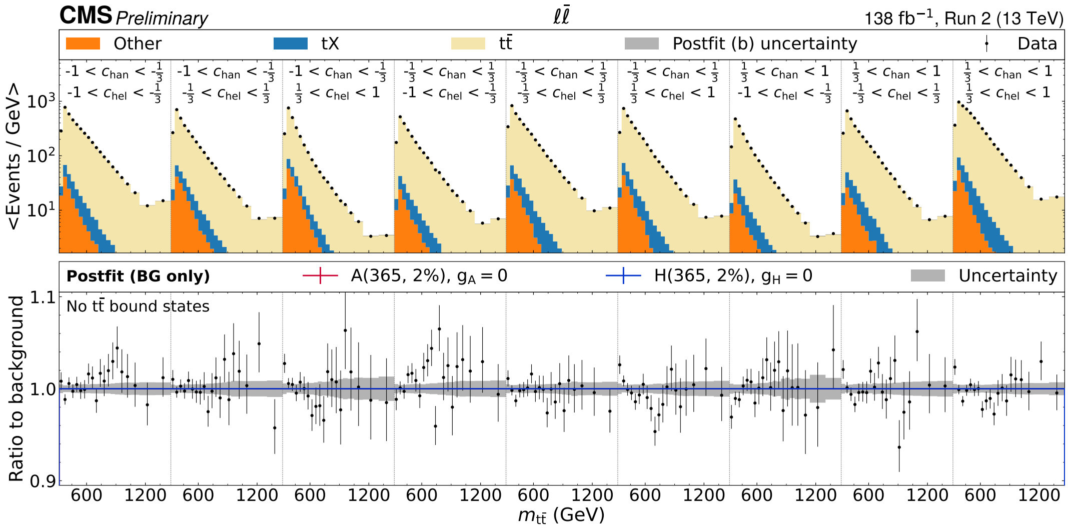


Semileptonic Channel Selection

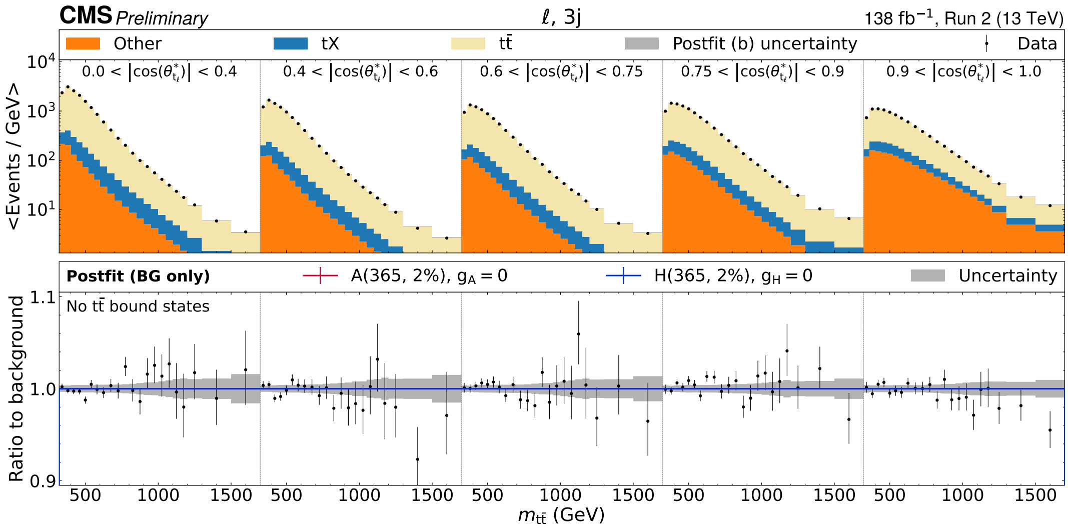
- **Require only one lepton (e/μ)** with $p_T > 30$ GeV, $|\eta| < 2.4$ with tight cut-based ID
  - Pass a single lepton trigger, veto additional leptons with $p_T > 20$ GeV and loose ID
  - For muon: tight PF ISO
- **Three or more jets**: $p_T > 30$ GeV, $|\eta| < 2.4$, $\Delta R > 0.4$ to leptons, tight ID
- **At least two jets b tagged** with a likelihood based method, medium WP
- Split in four channels: e vs μ and 3 jets vs ≥ 4 jets
- The $t\bar{t}$ system is reconstructed using an algorithm that applies:
  - B-jet assignment by maximum likelihood
  - Energy correction factor for 3 jet events to compensate for a missing jet in the event



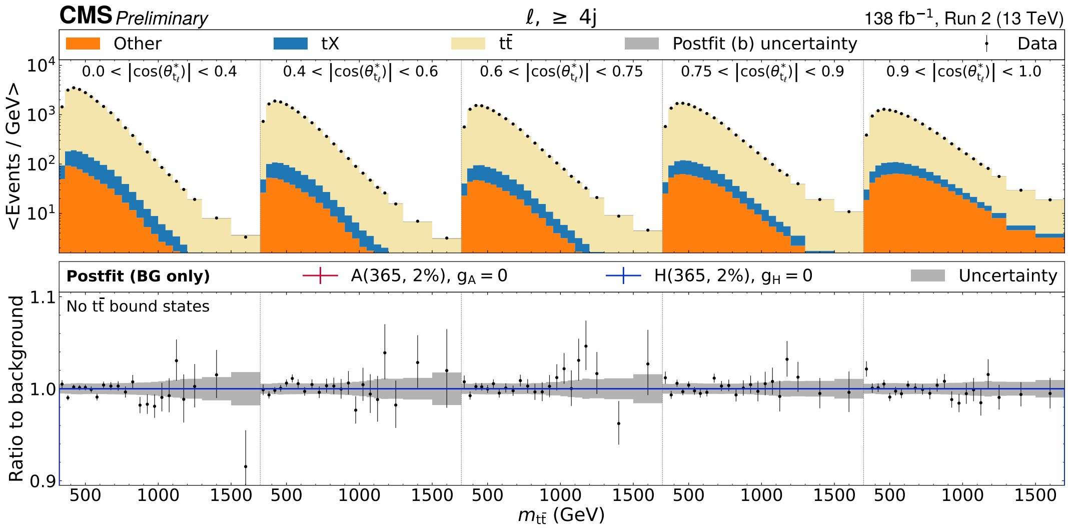
Postfit Pertubative SM Background Dilepton



Postfit Pertubative SM Background Lepton+3Jets

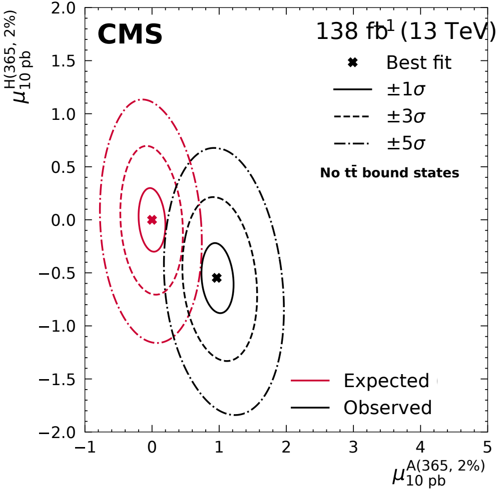


Postfit Pertubative SM Background Lepton+$\geq$4Jets



Testing the Result: Scalar vs Pseudoscalar

- To test whether the result fits better with a scalar or pseudoscalar, a simultaneus 2D fit is performed
- The fitted signals are resonant components of H and A with a mass of 365 GeV and a width of 2 %
- both cross sections are normalized to the same value (10 pb)
- As seen in the figure, data favours the pseudoscalar hypothesis



Hypothesis test

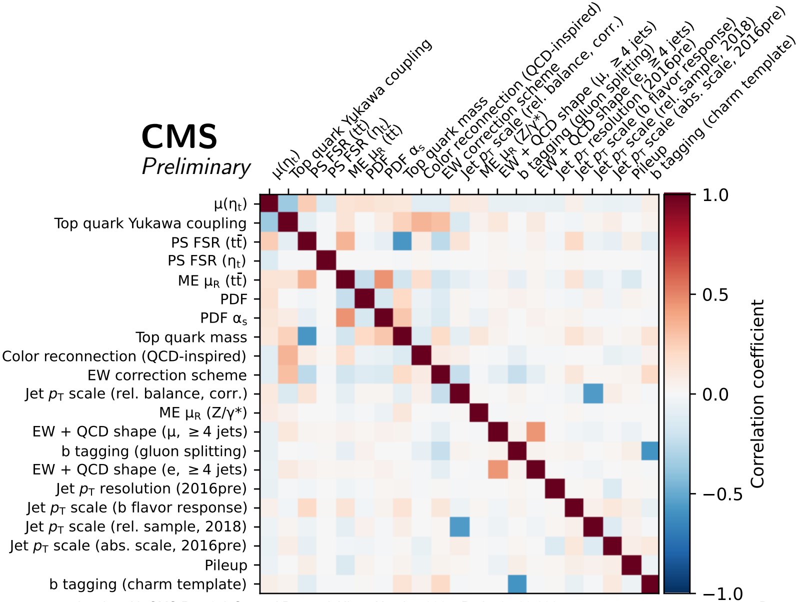
	Best-fit point	Difference in $-2\ln L$
η_t interpretation	$\mu(\eta_t) = 1.11$	-86.2
Single A interpretation	$m_A = 365\,\text{GeV}, \Gamma_A/m_A = 2\%, g_{At\bar{t}} = 0.78$	-72.6
Single H interpretation	$m_H = 365\,\text{GeV}, \Gamma_H/m_H = 2\%, g_{Ht\bar{t}} = 1.45$	-10.4

- When comparing the best fitting generated scalar and pseudoscalar signal ($m_A = 365$ GeV, $\Gamma_A = 2\%$) to SM with our η_t toy model, data prefers η_t
- One needs to keep in mind that signal samples were only generated down to $m_{A/H} = 365$ GeV so far, and that interference is included

Table B.1: Results on the η_t cross section, using only the $\ell\bar{\ell}$ channels, for the b_bbar_4l background prediction and for the default setup. The quoted uncertainty for b_bbar_4l assumes the same uncertainty as for the nominal result.

Prediction for SM $t\bar{t}$ and tW	Extracted η_t cross section	Uncertainty
b_bbar_4l (POWHEG vRES)	5.9 pb	18%
Default (POWHEG v2)	7.5 pb	13%

Correlation Matrix



Related Searches

Recent full Run 2 result by ATLAS

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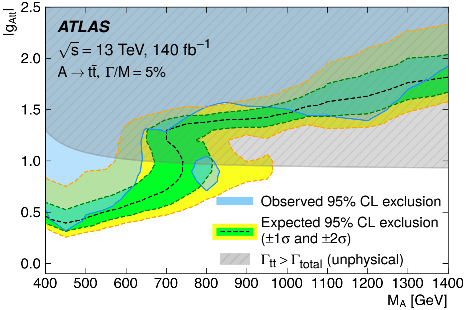

Previous CMS A/H search:
CMS-HIG-17-027 (35.9 fb^{-1})

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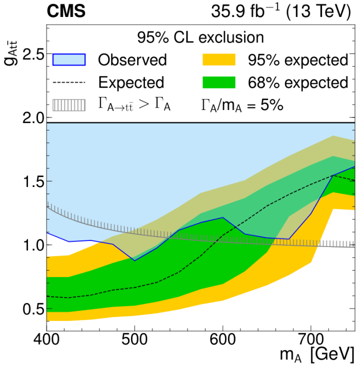

ATLAS Prefits

ATLAS prefit example lj channel

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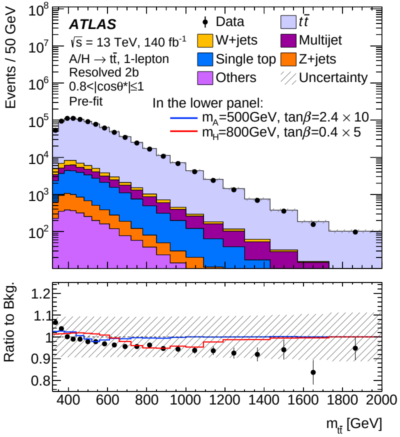

ATLAS prefit example ll channel

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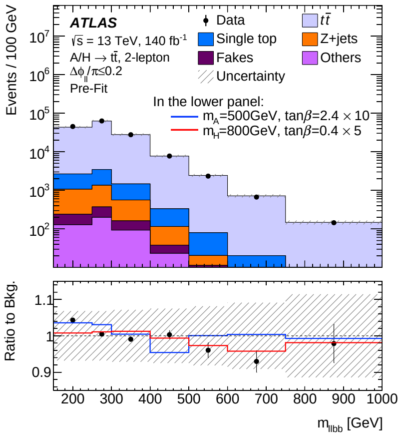

ATLAS Postfits

ATLAS postfit example lj channel

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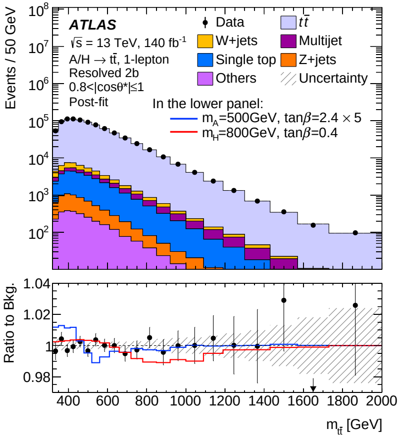

ATLAS postfit example ll channel

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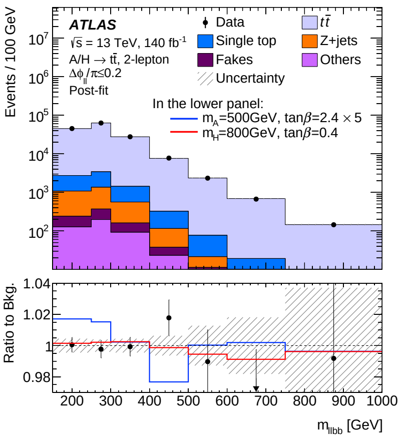


Combined Limit

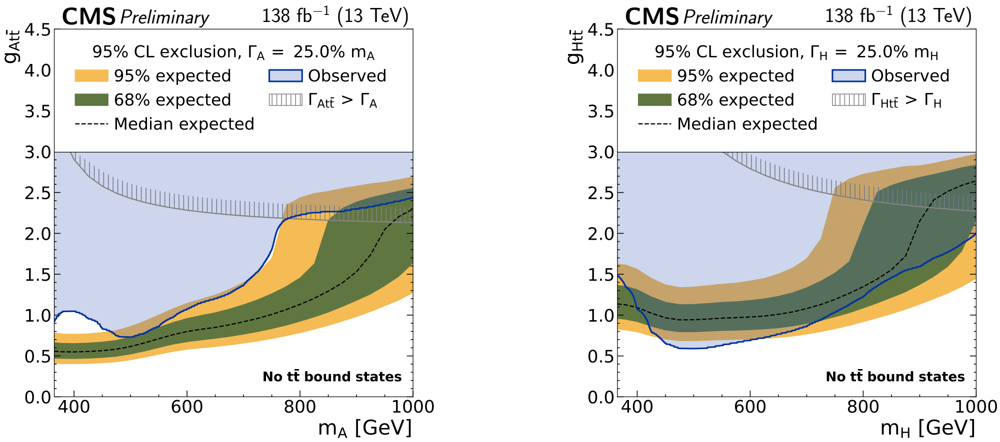
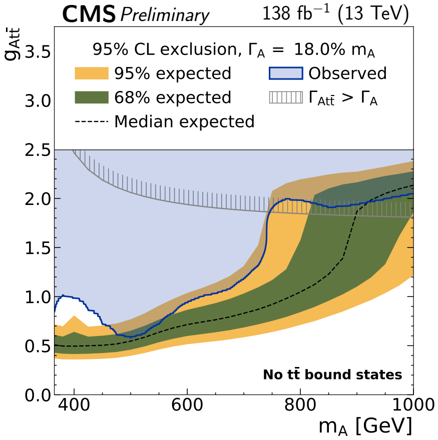
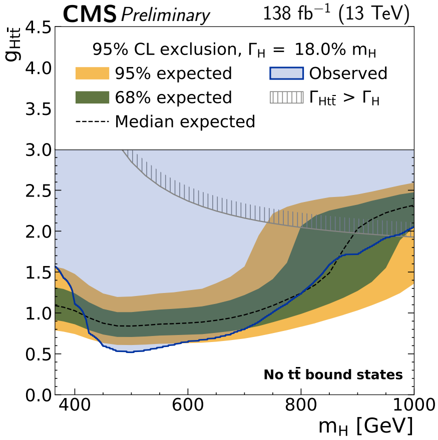


Figure: Limits for pseudoscalar(left) and for scalar(right), perturbative QCD SM background

Combined Limit





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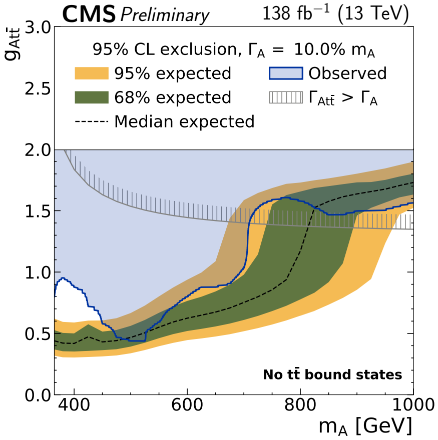

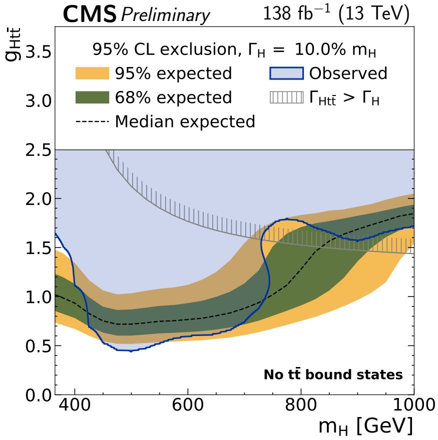

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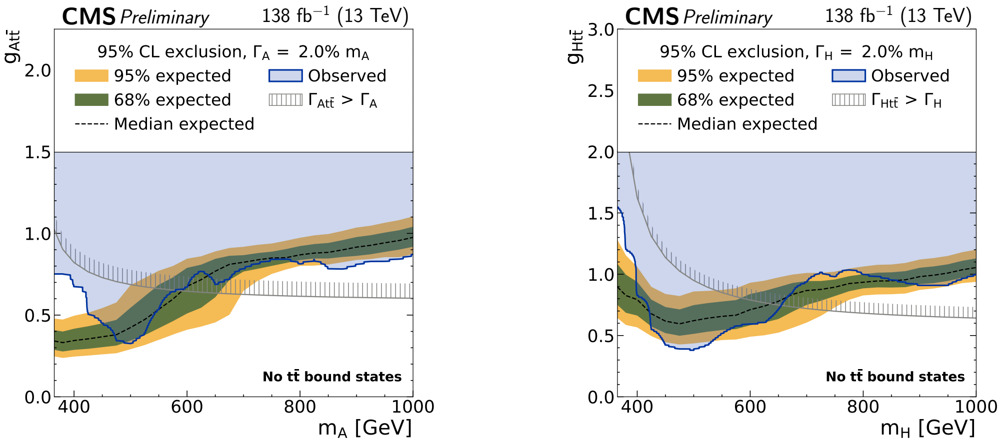

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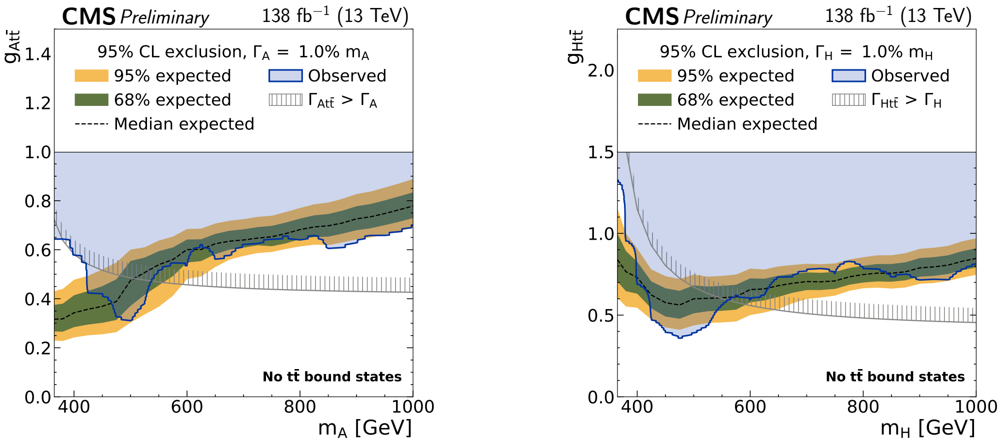

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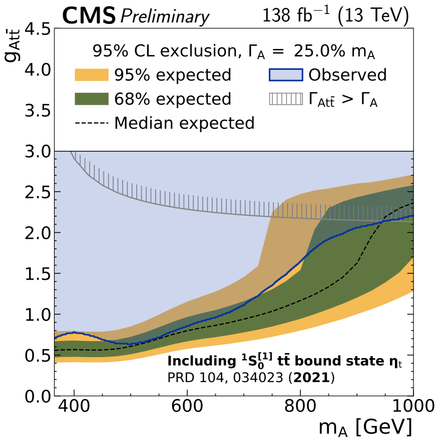
Combined Limit with η_t



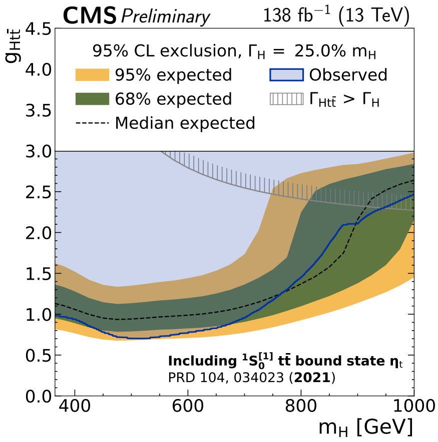
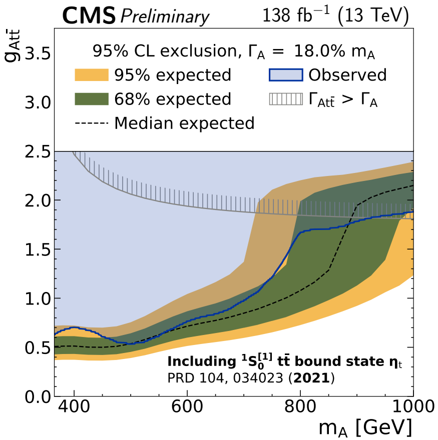
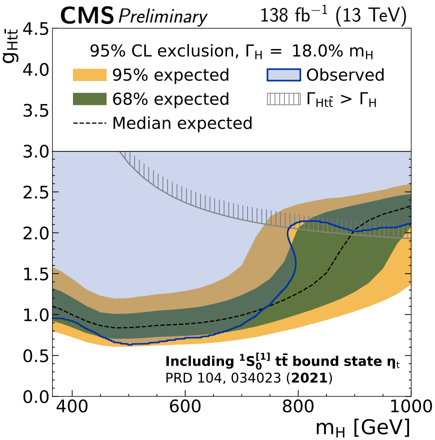


Figure: Limits for pseudoscalar(left) and for scalar(right), SM background with non-perturbative toy-model

Combined Limit with η_t





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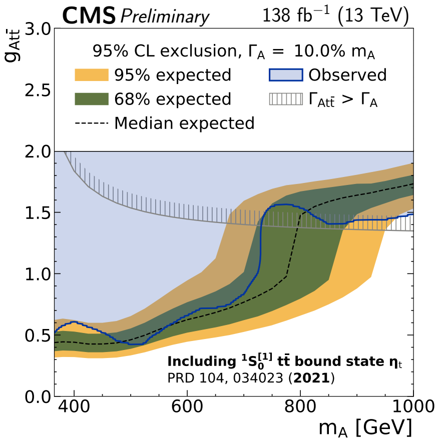

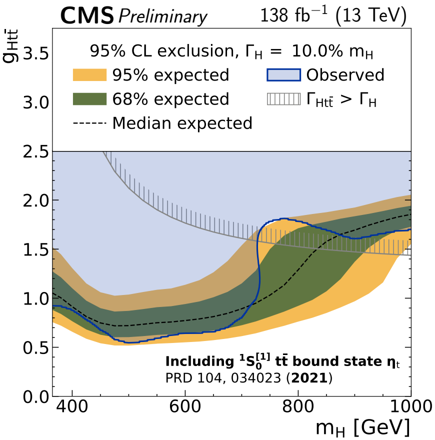

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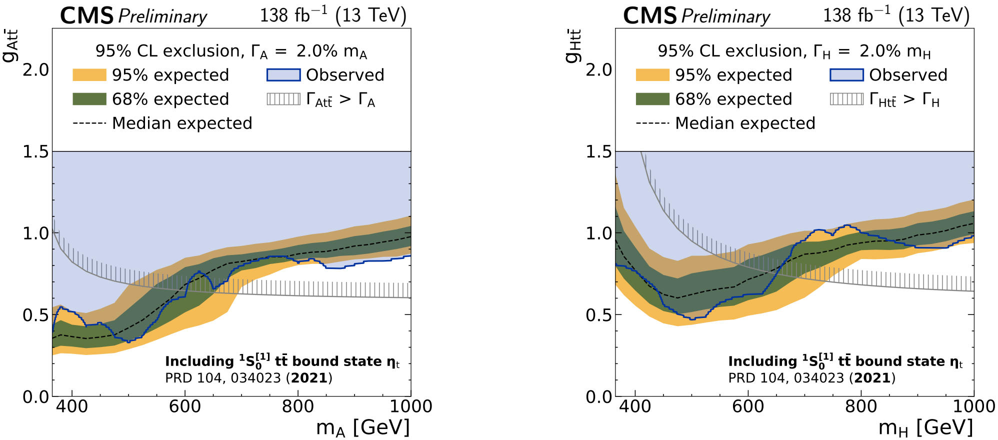

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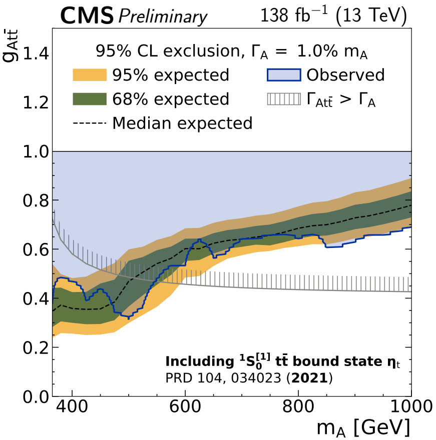
Combined Limit with η_t



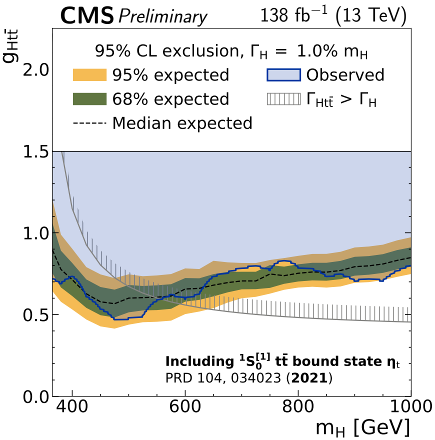


Figure: Limits for pseudoscalar(left) and for scalar(right), SM background with non-perturbative toy-model

Combined contours with η_t

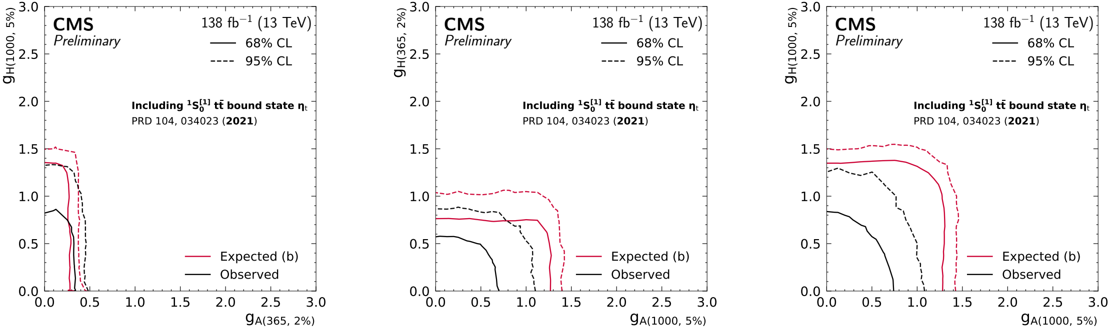


Figure: Contours for pseudoscalar and for scalar simultaneously, SM background with non-perturbative toy-model