# *Searches for scalar particles in top quark topologies in ATLAS and CMS*

Dr Eleanor Jones

on behalf of the ATLAS and CMS collaborations

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17th International Workshop on Top Quark Physics

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# *Agenda Overview*

01 Motivation

02 Theoretical overview of 2HDMs

03 Analysis results

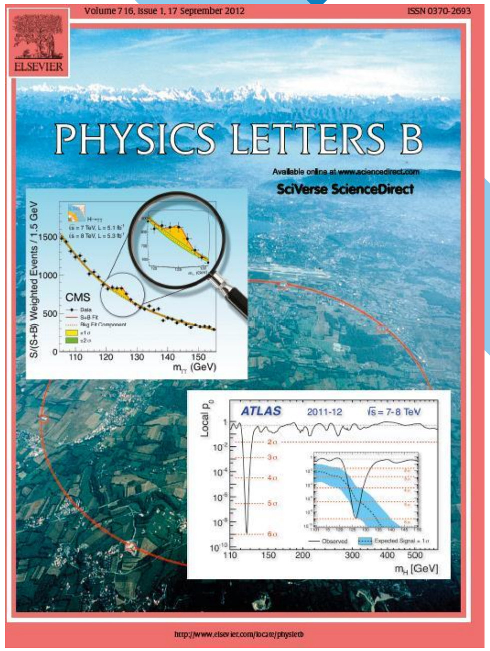
04 Theoretical overview of VLQs

05 Analysis results

06 Summary

# *Motivation (1)*

- The SM provides an effective description of nature up to the TeV scale
  - The discovery of a Higgs-like particle in 2012 marked a major milestone for ATLAS and CMS
  - Electroweak symmetry breaking remains the simplest hypothesis



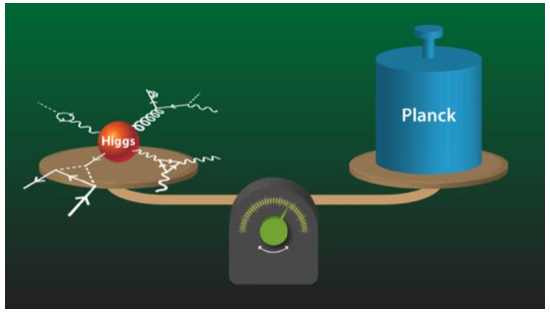




Photo: Alan Stonebraker

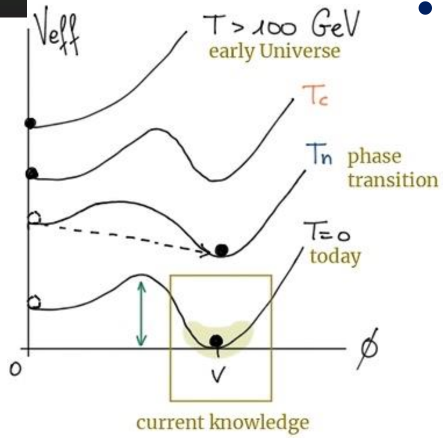
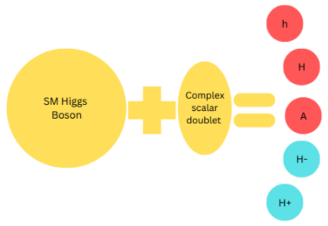



Photo: Kateryna Radchenko Serdula

- However, there are many unexplained observations remaining
  - Why is the observed Higgs mass so small?
  - What is the nature of the electroweak phase transition in the early Universe?

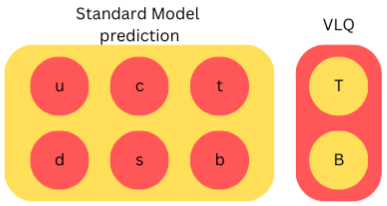
# *Motivation (2)*

- Many BSM models have been proposed to explain the observations
  - Minimal extensions to the SM are well-motivated by theories such as supersymmetry or axion models




**2 Higgs Doublet Models**

- Simple extension that is consistent with existing constraints
- Introduces a second complex scalar doublet to the SM Lagrangian

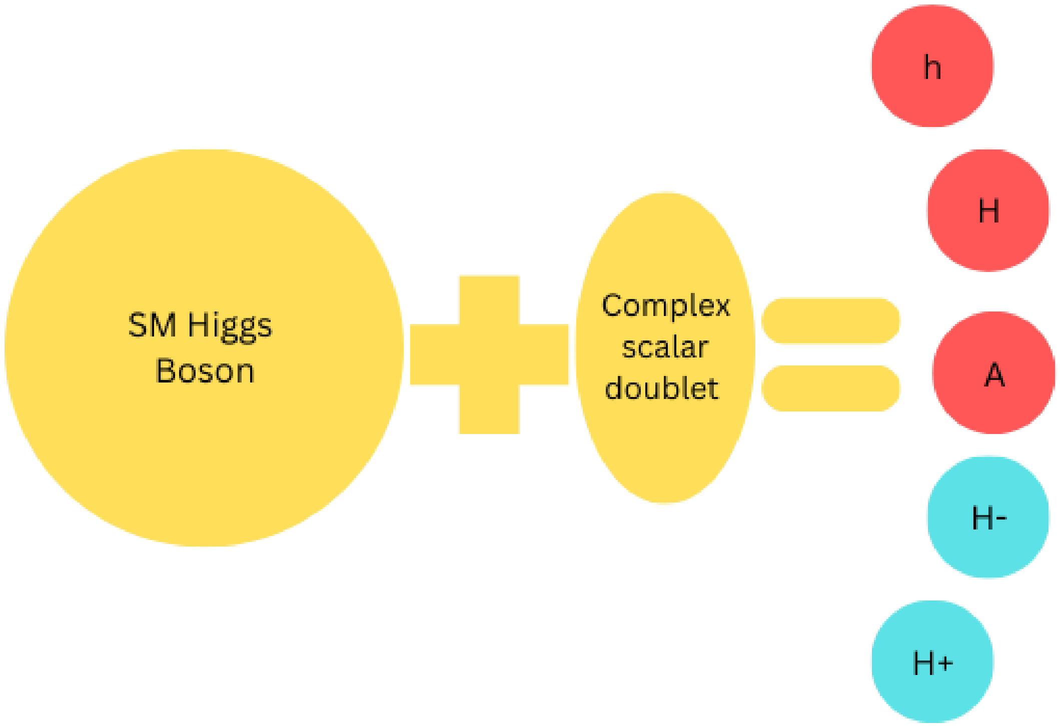



**Vector-like Quarks**

- New generation of spin-$^1/_2$ particles
- Equal left- and right-handed couplings to the weak sector

# *2HDMs*

- Introduce second complex scalar SU(2) doublet
- CP-conserving scalar potential
- $\mathbb{Z}_2$ symmetry

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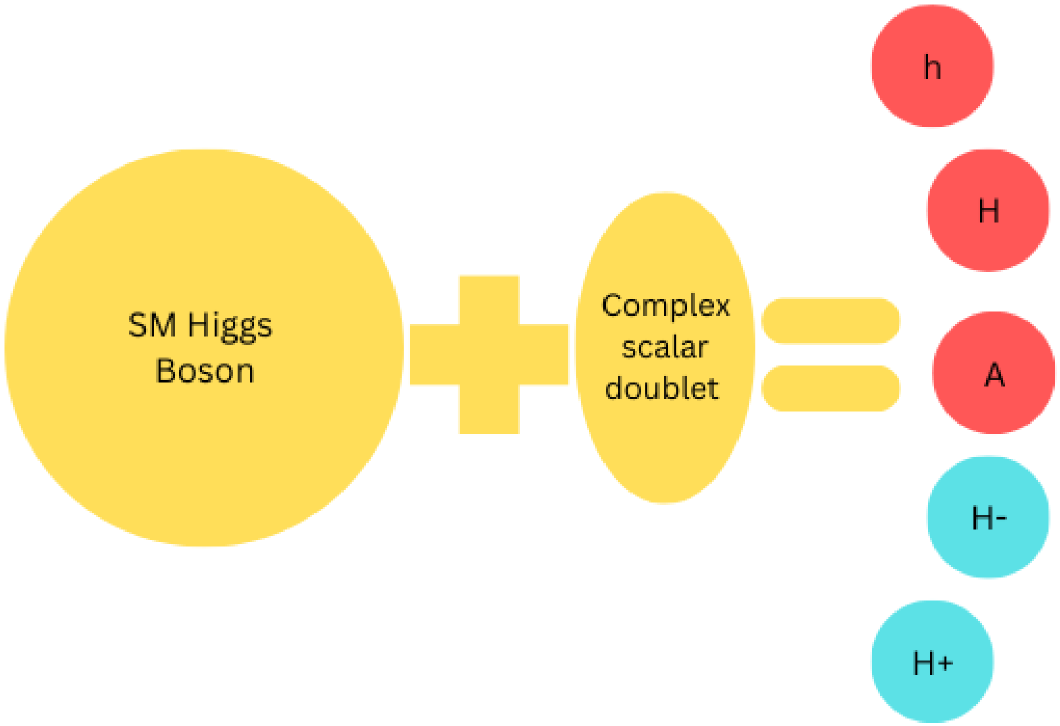


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3 Higgs masses ($m_A$, $m_H$, $m_{H^\pm}$)

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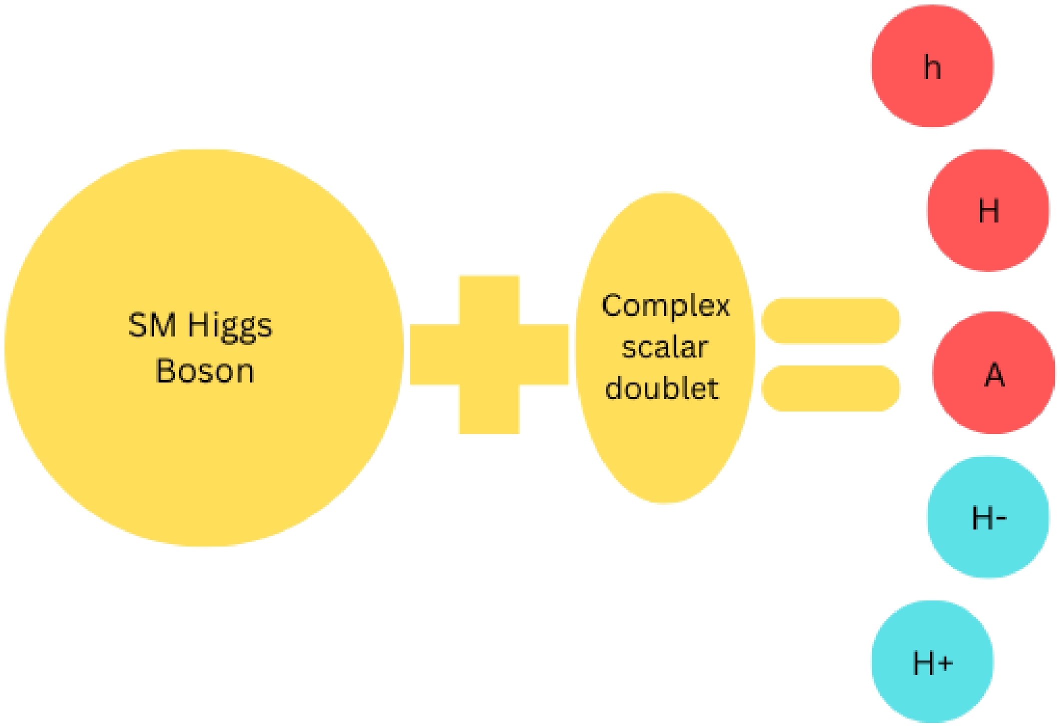


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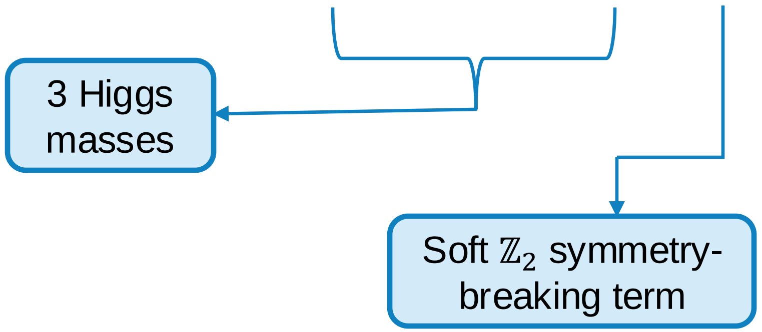

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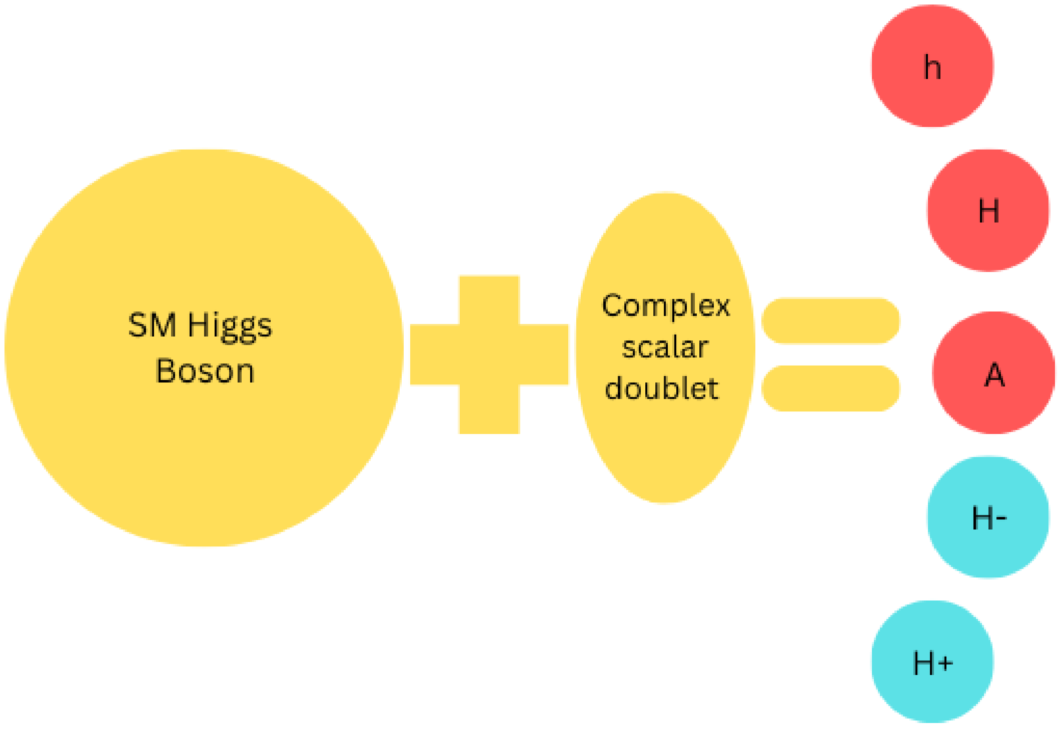


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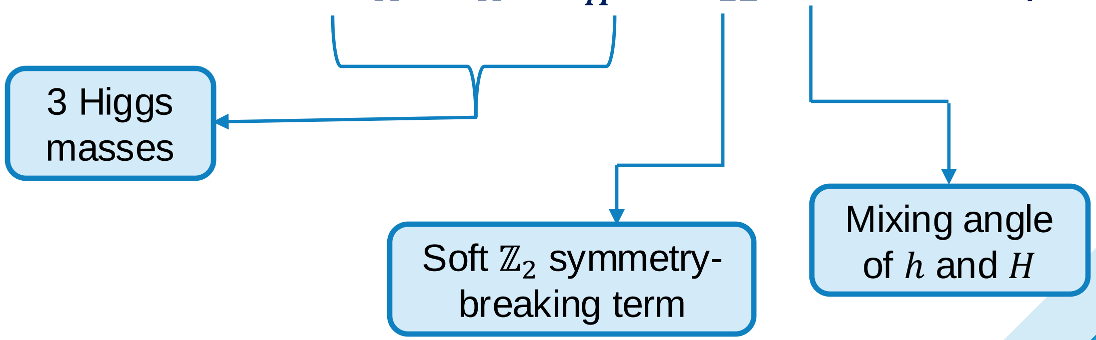

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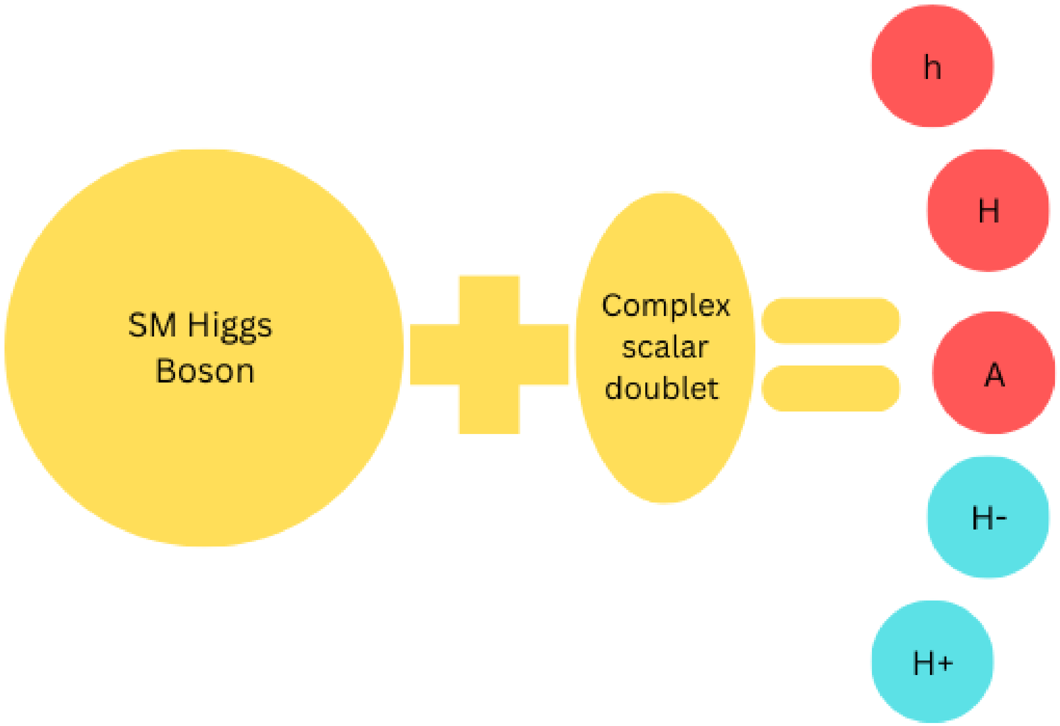


$m_A, m_H, m_{H^\pm}, m_{12}, \alpha$ and $\tan\beta$ are free parameters

- $m_A, m_H, m_{H^\pm}$: 3 Higgs masses
- $m_{12}$: Soft $\mathbb{Z}_2$ symmetry-breaking term
- $\alpha$: Mixing angle of $h$ and $H$
- $\tan\beta$: Ratio of vacuum expectation values of Higgs fields

# *Benchmark scenarios*

- **Type-II 2HDM in the alignment and decoupling limit**

- **g2HDM in the alignment limit and decoupling limit**

- **hMSSM**

- **2HDM+a**

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Describes which fermion couples to which doublet

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$\cos(\beta - \alpha) = 0$
couplings of $h =$ couplings of $h_{SM}$

$h \ll \Lambda_{2HDM}$ and $\Lambda_{2HDM} \gg v$

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generalized 2HDM
=
no $\mathbb{Z}_2$ symmetry
+
extra Higgs quartic couplings $\sim \mathcal{O}(1)$

new Yukawa couplings $\sim \mathcal{O}(1)$,
e.g.
$\rho_{\tau\mu}, \rho_{tu}, \rho_{tc}, \rho_{tt}$

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    $\Longrightarrow$
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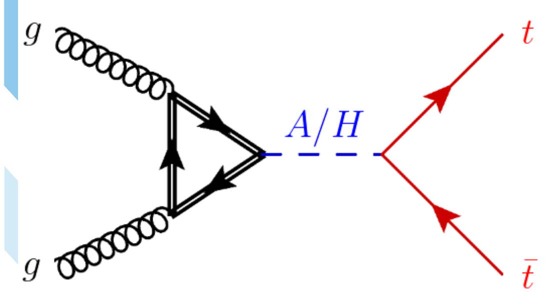
  - Additional fermionic DM particle, $\chi$, with CP-odd mediator, $a$

# *2HDM analyses*



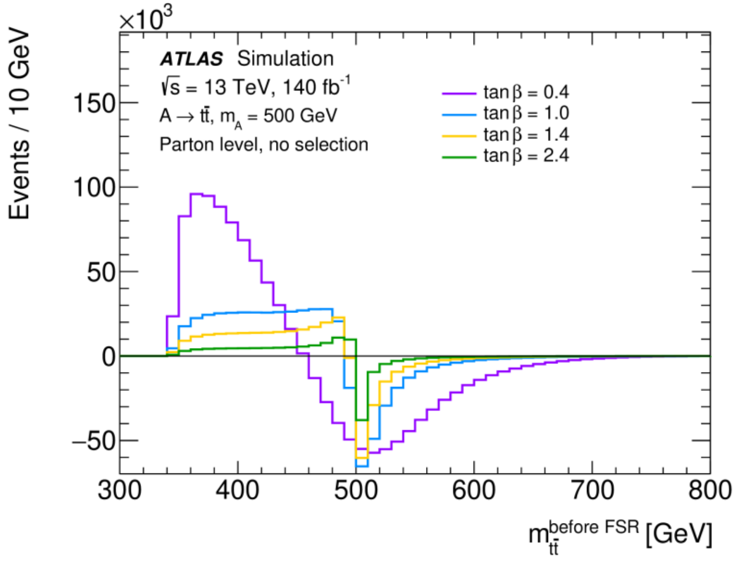

# Search for $gg \to H/A \to t\bar{t}$

ATLAS EXPERIMENT

[JHEP08(2024)013](JHEP08(2024)013)

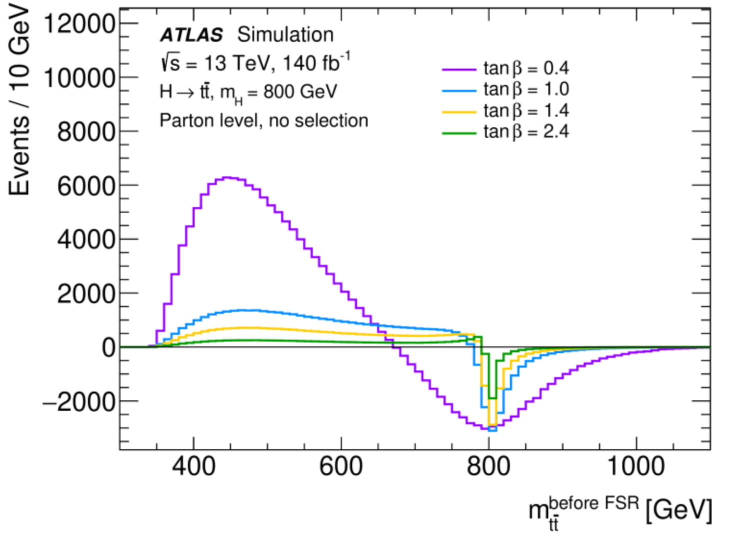
## Overview

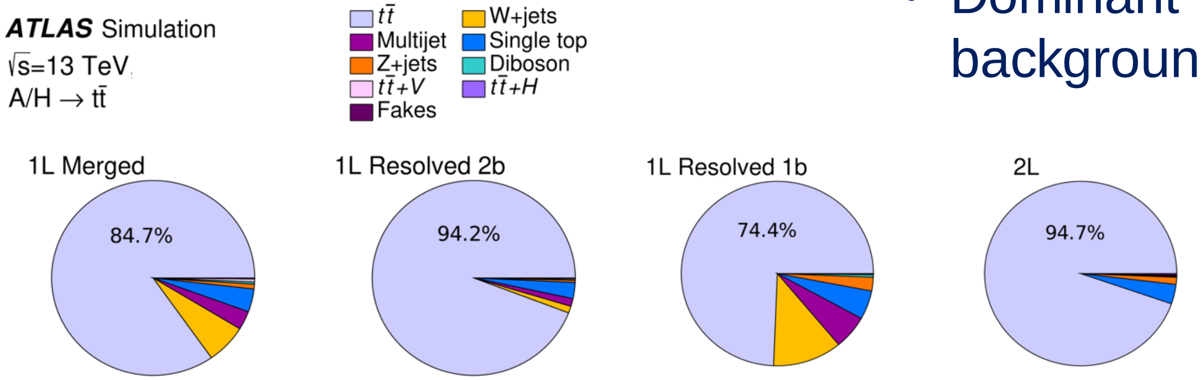
- Strong interference between the signal and the SM $t\bar{t}$ process leads to a peak-dip structure
  - $A$ and $H$ do not interfere since they are orthogonal CP states
  - The peak-dip structure is strongly model dependent

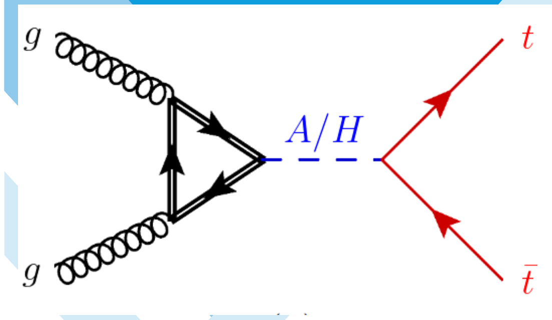



- Two orthogonal channels considered:
  - lepton+jets (1L) and dileptonic (2L)

- Dominant background: SM $t\bar{t}$






# Search for $gg \to H / A \to t\bar{t}$

ATLAS EXPERIMENT

JHEP08(2024)013

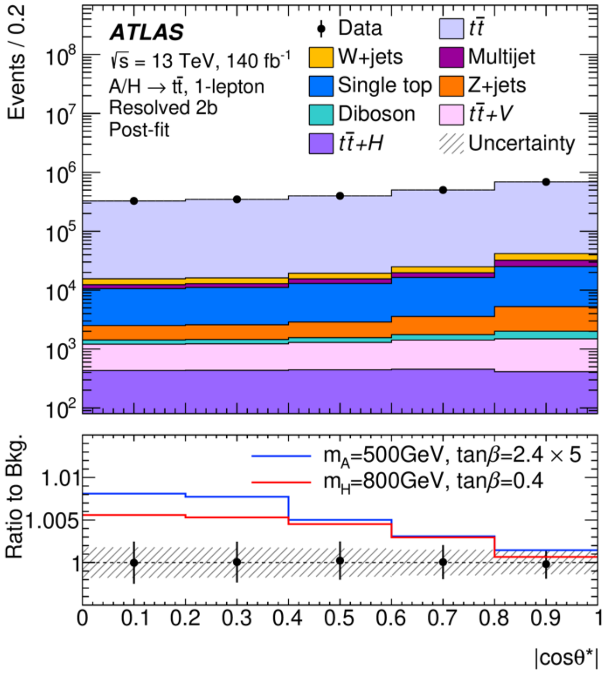
## Analysis strategy

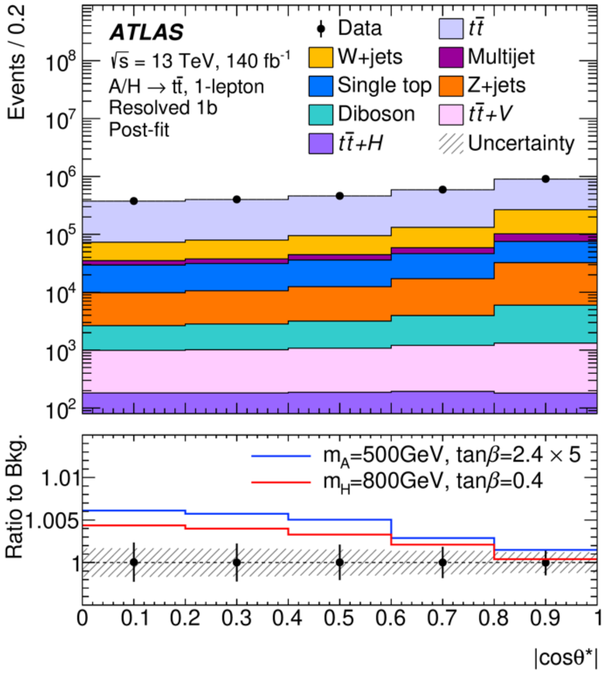
### 1L

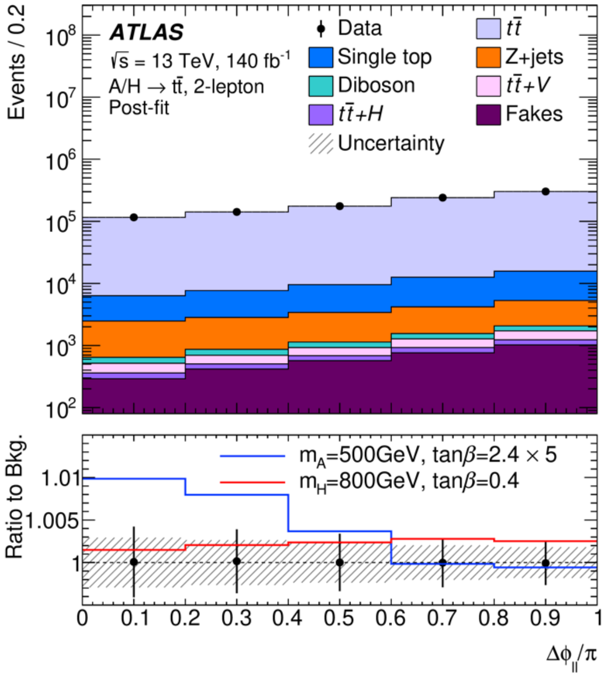
- Invariant mass spectrum of the top pair, $m_{t\bar{t}}$
- Additionally binned in $\cos\theta^*$

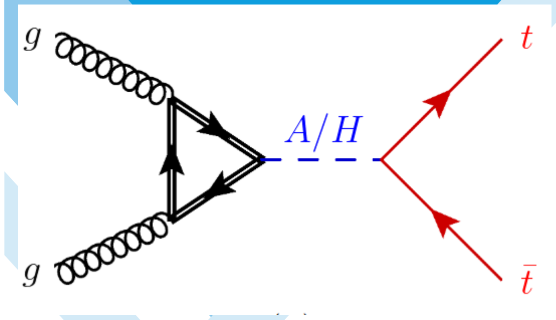
### 2L

- Invariant mass spectrum of the di-$b$-plus-di-lepton system, $m_{llbb}$
- Additionally binned in $\Delta\phi(l, l)$






# Search for $gg \to H / A \to t\bar{t}$

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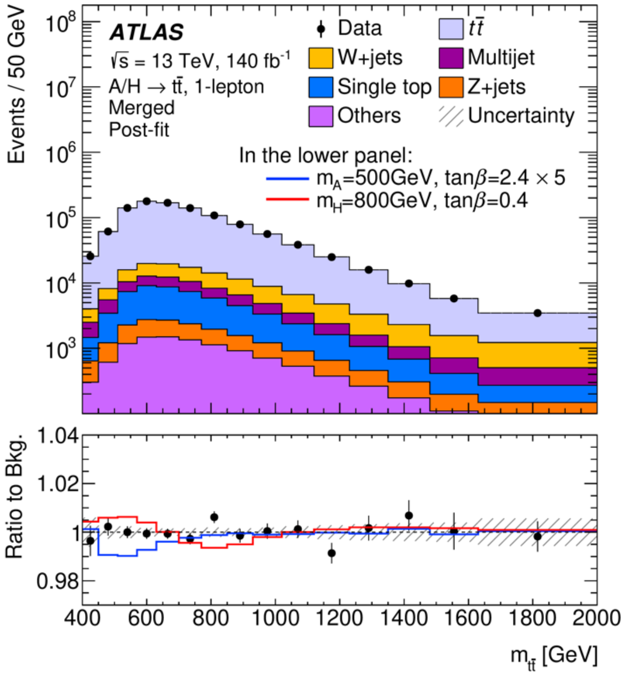
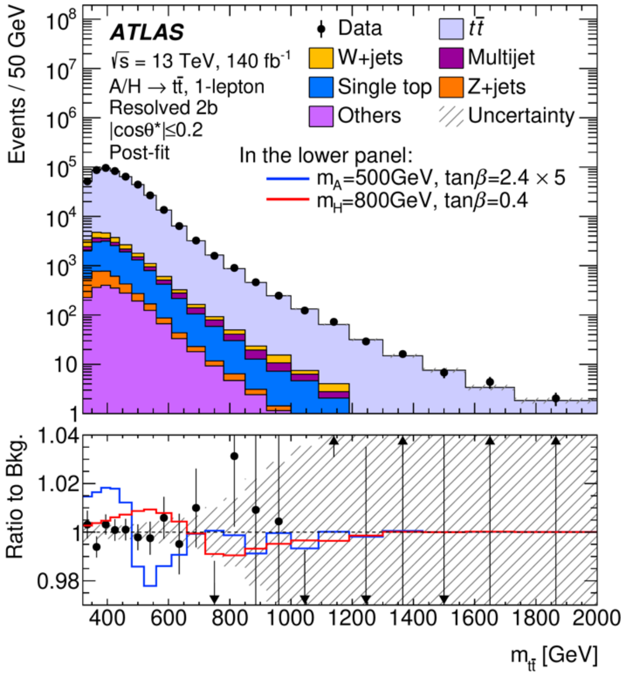
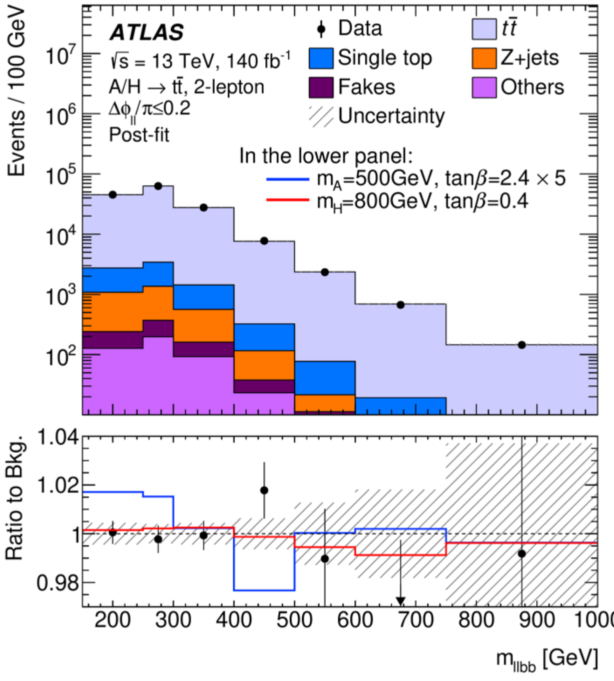
## Results: Search stage

- Tested agreement between data and S+I+B hypotheses with $m_{A/H} \in [400,1400]$ GeV and $\Gamma_{A/H} \in [1,40]\%$
  - Most significant deviation from SM ($2.3\ \sigma$ local): $m_A = 800$ GeV, $\Gamma_A = 10\%$ and $\sqrt{\mu} = 4.0$



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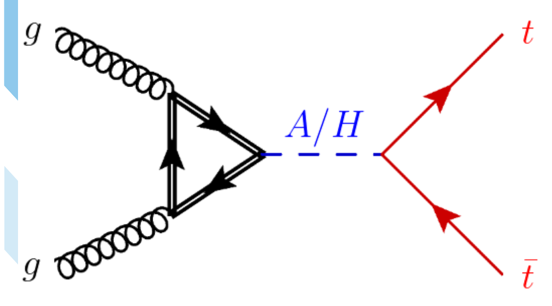



# Search for $gg \to H / A \to t\bar{t}$

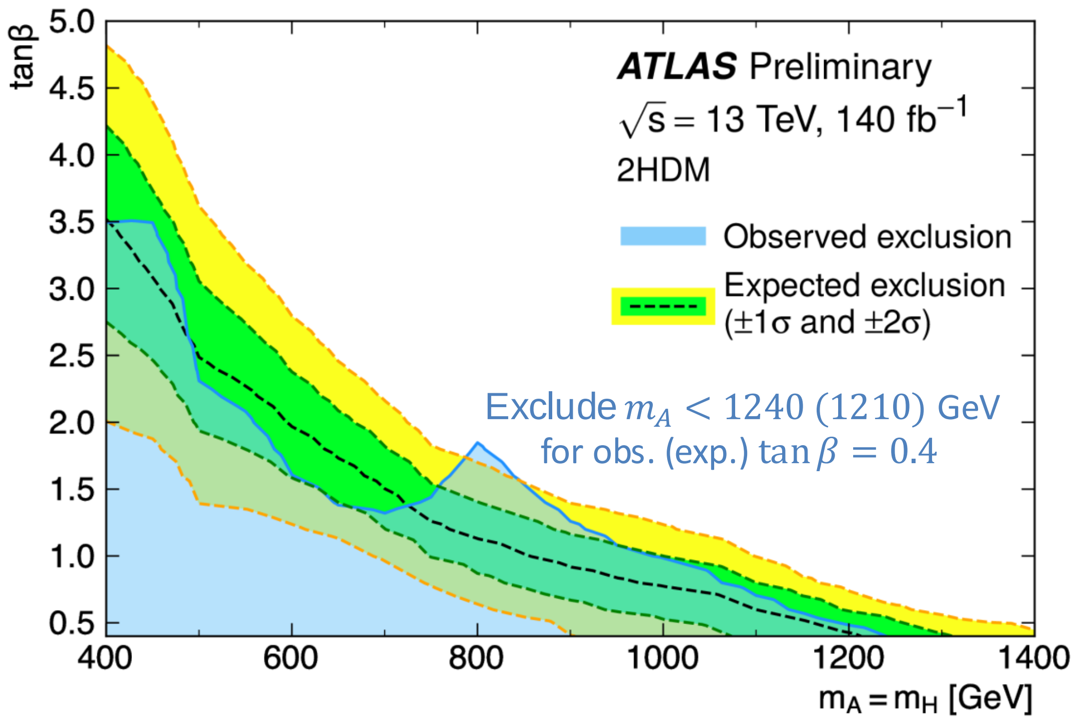
JHEP08(2024)013

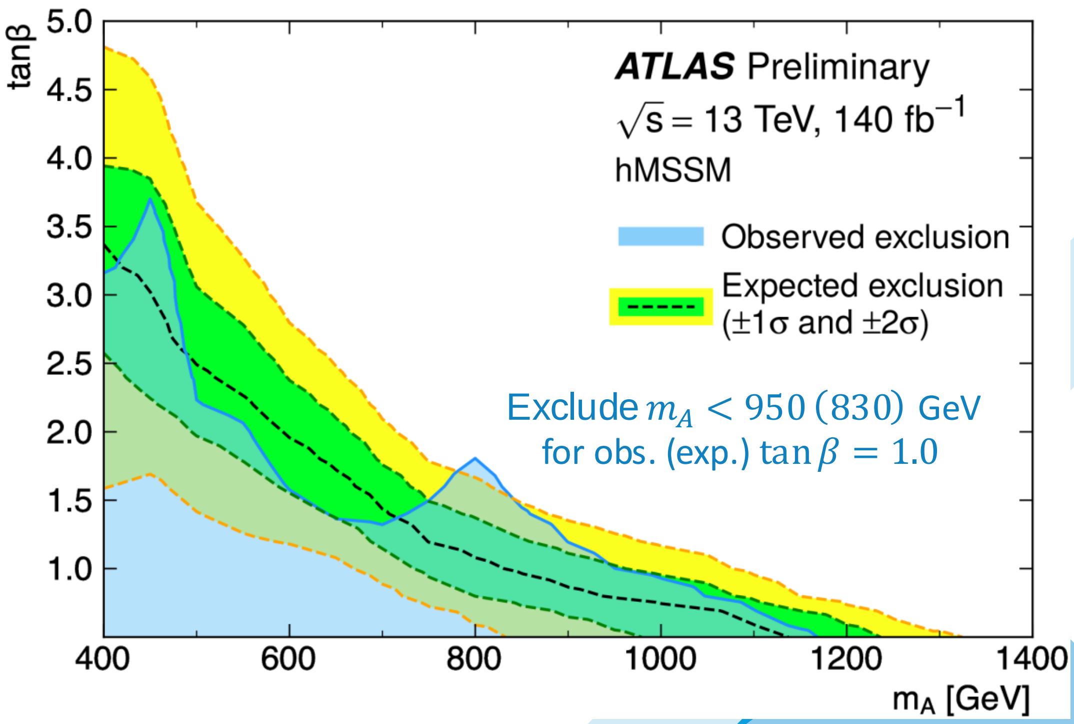
## Results: Exclusion stage

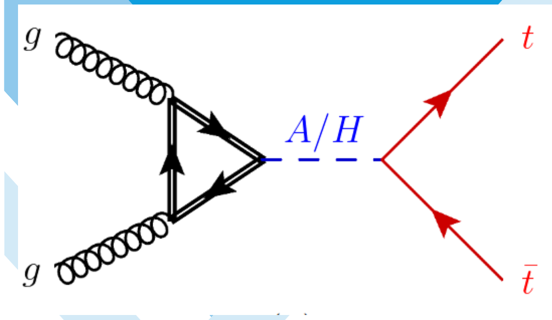
In the 2HDM interpretation, we test hypotheses for $\tan\beta > 0.4$, whereas for the hMSSM interpretation, we test hypotheses for $\tan\beta > 1.0$.

Strongest mass exclusion at low $\tan\beta$ to date!

Exclude $\tan\beta < 3.5(3.16)$ for $m_A = m_H = 400$ GeV in the 2HDM (hMSSM)






# Search for $gg \to H/A \to t\bar{t}$

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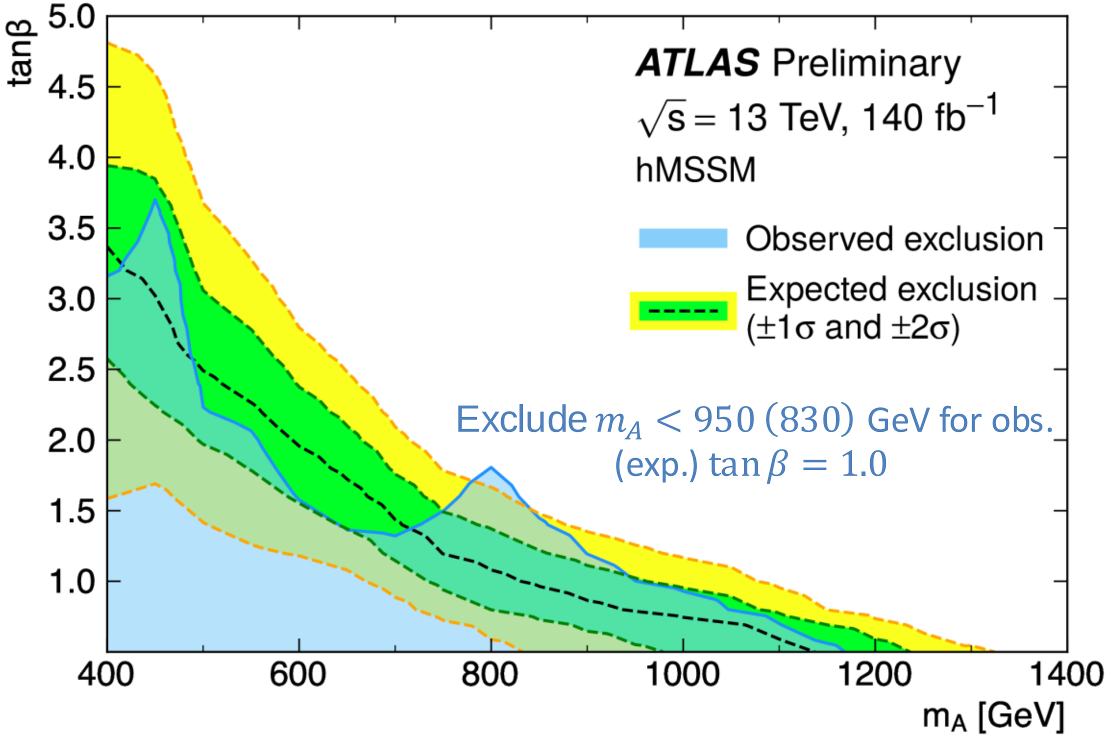
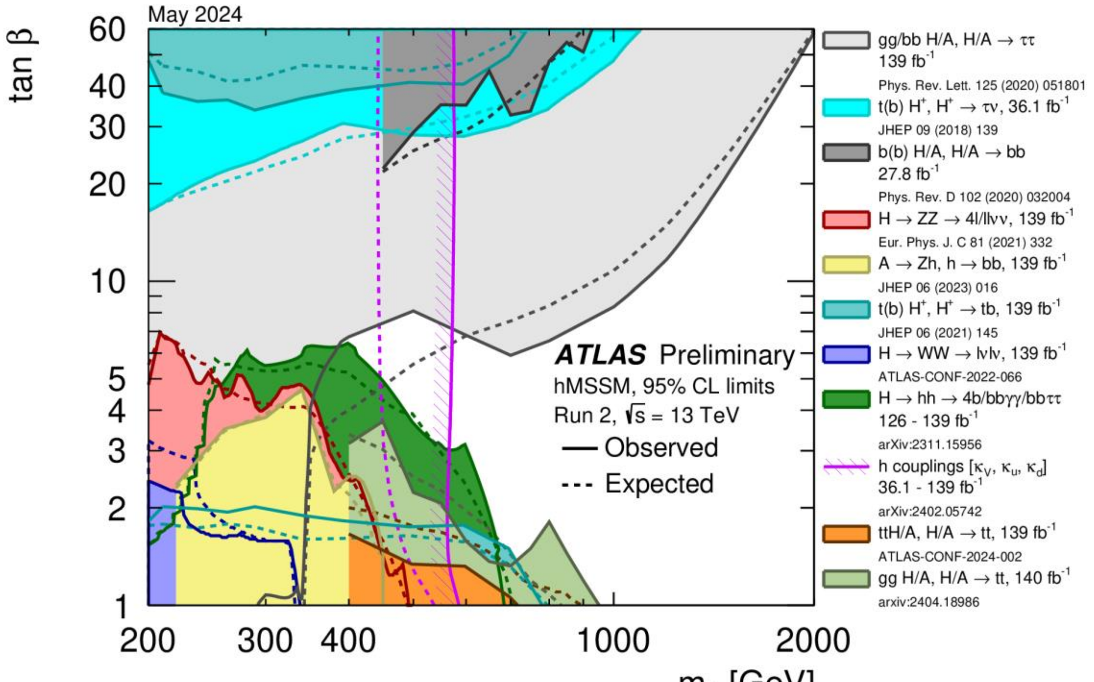
## Results: hMSSM comparison

Strongest constraints on $m_A$ at $\tan\beta = 1.0$ to date!




ATL-PHYS-PUB-2024-008

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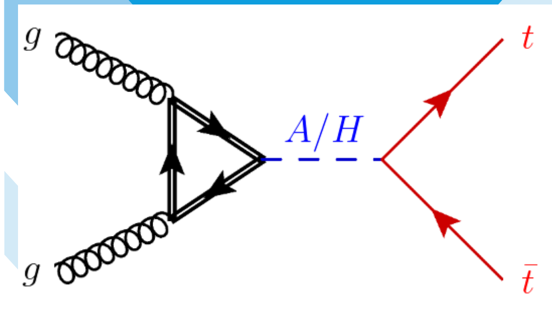


# Search for $gg \to H / A \to t\bar{t}$

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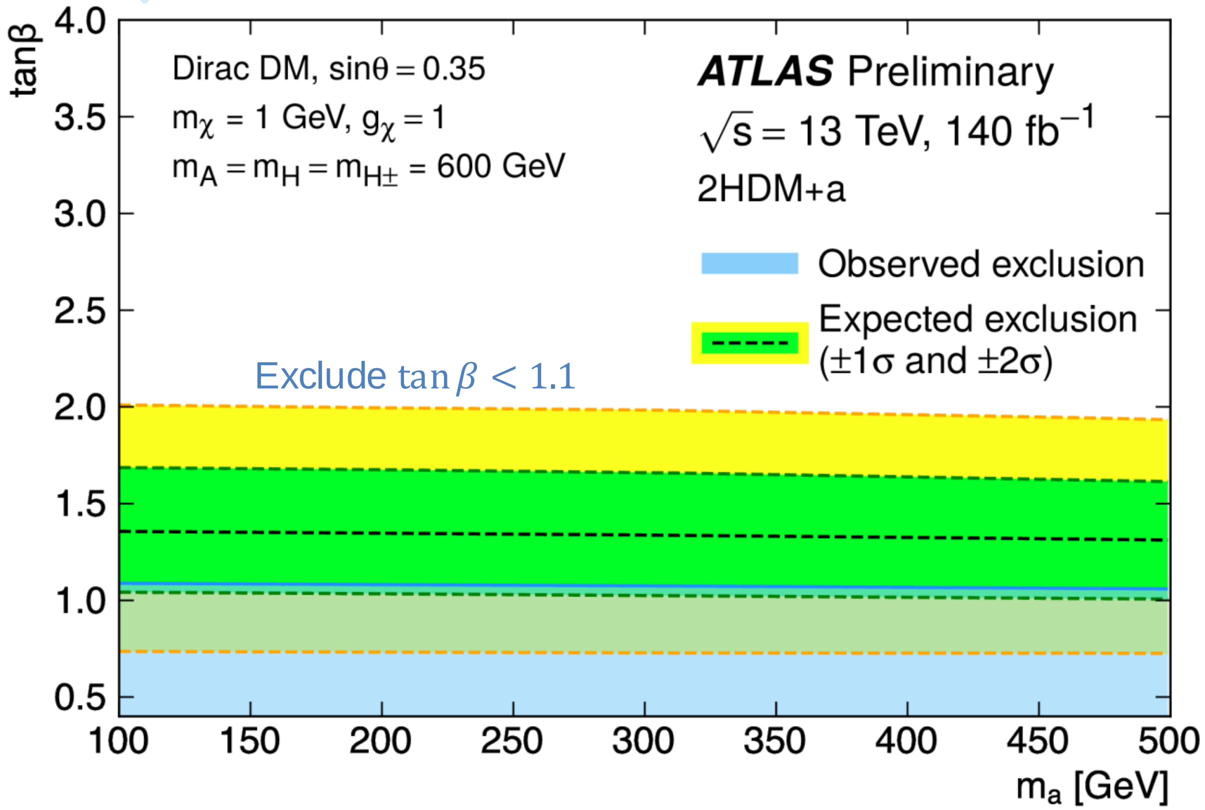
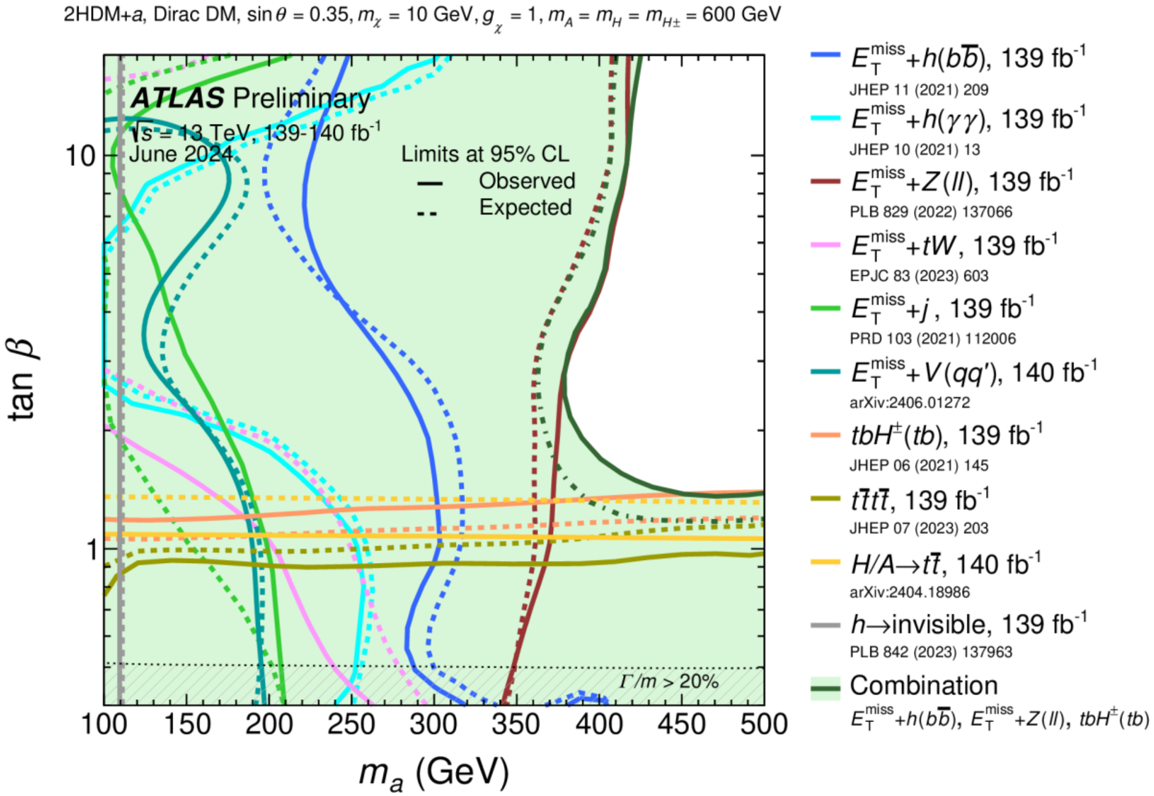
## Results: 2HDM+a

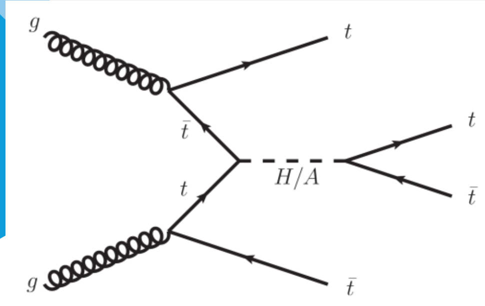
First dark matter interpretation of an interference search!




ATL-PHYS-PUB-2024-010

Strongest expected limits at high mediator mass to date!




# Search for $t\bar{t}H / A \rightarrow t\bar{t}t\bar{t}$

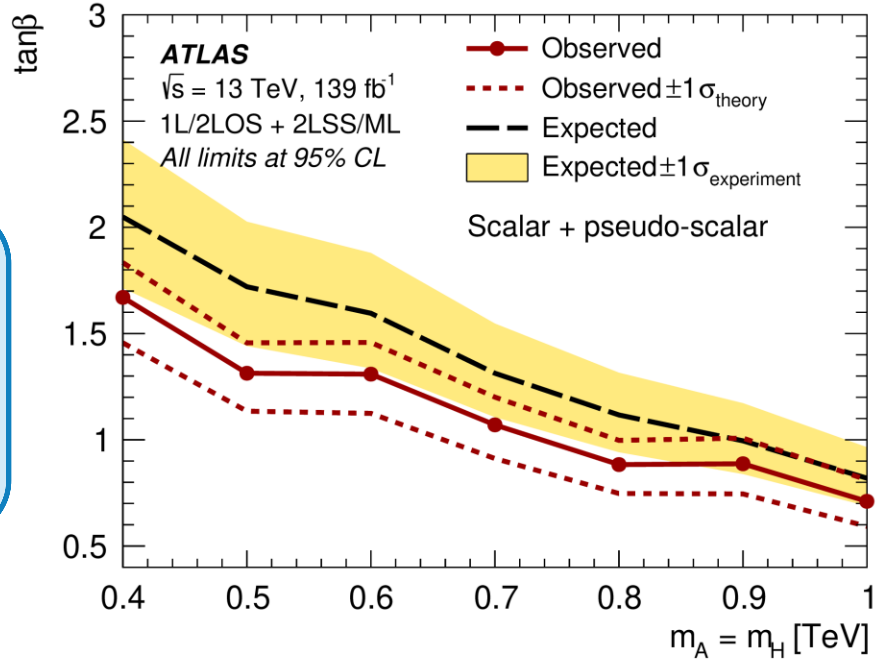
ATLAS EXPERIMENT

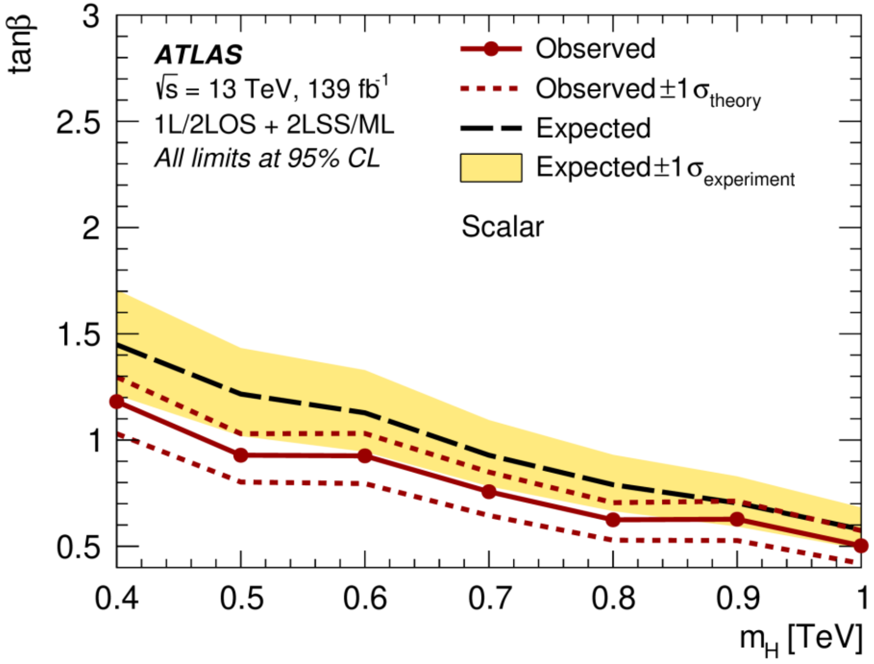
## Results: 2D limits

arXiv: 2408.17164

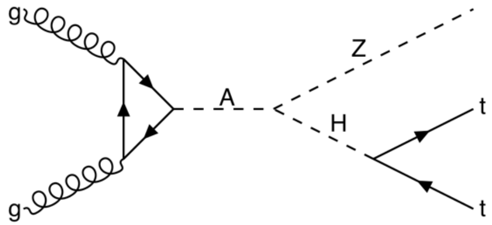
- Upper limits on the cross-section can be translated to constraints in the $\tan\beta - m_{A/H}$ plane

$m_H = m_A$
Both particles contribute to BSM $t\bar{t}t\bar{t}$ production




Only scalar particle contributes to BSM $t\bar{t}t\bar{t}$ production




# Search for $A \rightarrow ZH, H \rightarrow t\bar{t}$

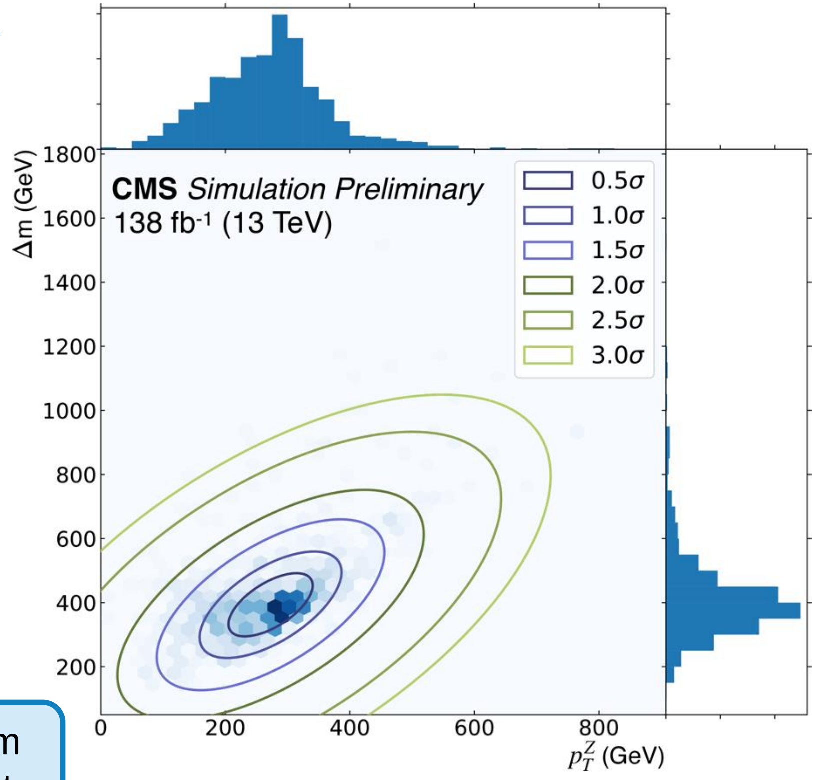
CMS-PAS-B2G-23-006

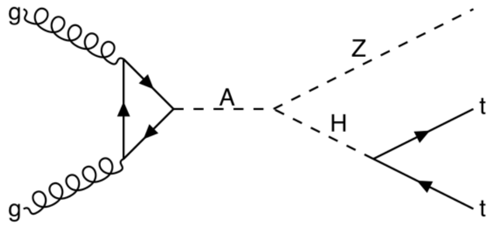
## Overview

- Full CMS Run 2 dataset: $138\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Probed kinematic range of signal: $m_A > m_H + m_Z$
  - $A \rightarrow ZH$ becomes dominant in a wide range of 2HDM parameter space
  - For $m_A > 400$ GeV, $H \rightarrow t\bar{t}$ is dominant decay
  - Above $1$ TeV, interference becomes non-negligible
- Target final state: $Z \rightarrow ee/\mu\mu$ and all-jet decays of $t\bar{t}$
  - First time this final state has been considered
- Discriminating observable: 2D-distribution of $\Delta m$ and $p_T^Z$
  - Reduced to a 1D-distribution, $p_T^Z \times \Delta m$

Mass difference of the $A$ and $H$ boson candidates

Transverse momentum of the $Z$ boson candidate



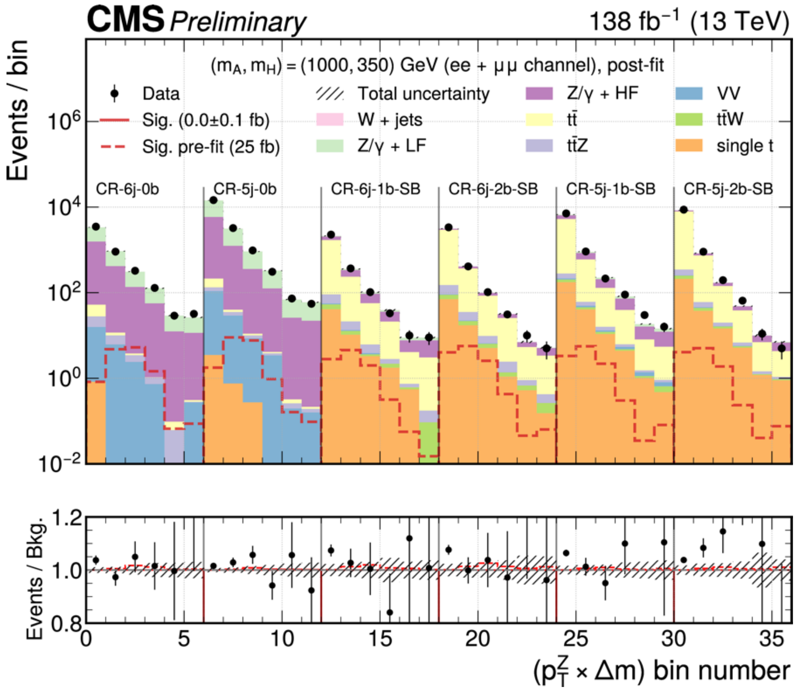


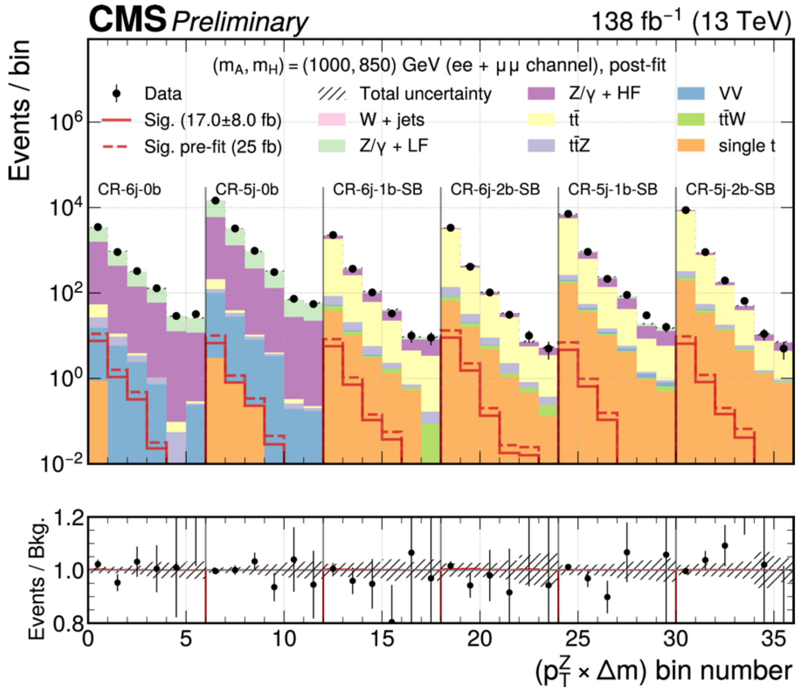

# Search for $A \to ZH, H \to t\bar{t}$

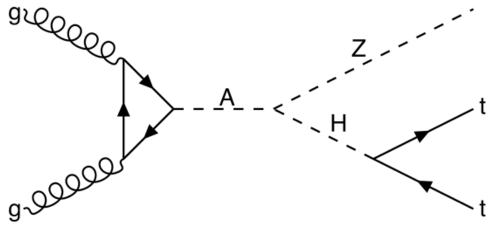
CMS-PAS-B2G-23-006

## Analysis strategy

- 6 bins corresponding to 6 quantiles of the $p_T^Z \times \Delta m$ distribution in each of 20 regions :
  - binning is optimised for each signal hypothesis
- Simultaneous binned profile likelihood fit in all channels and categories
- Separate fits for each $(m_A, m_H)$ hypothesis



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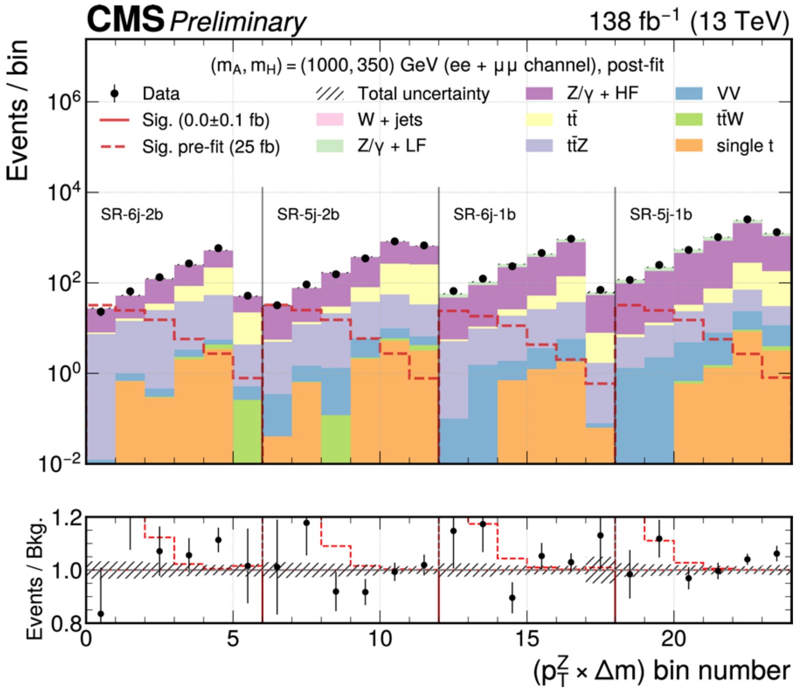
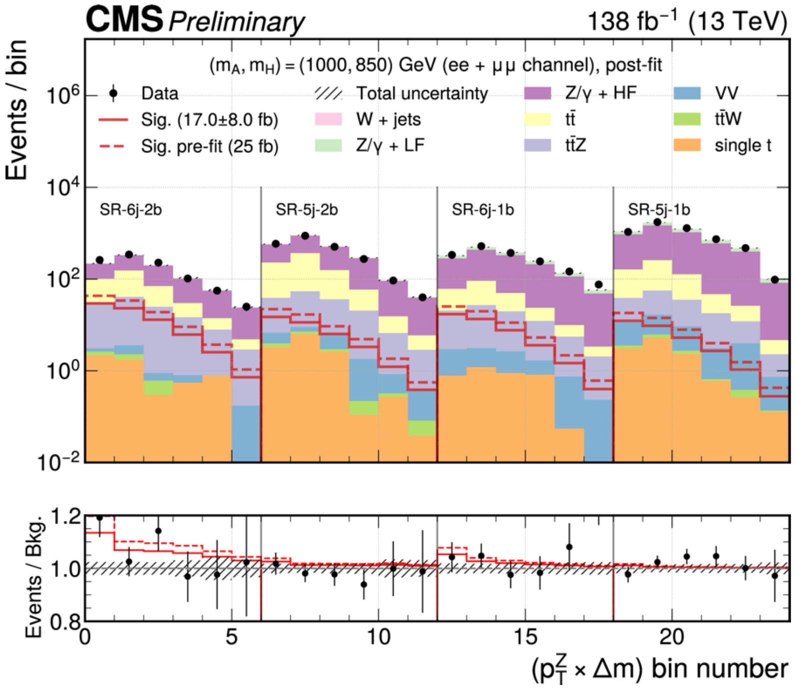
CMS-PAS-B2G-23-006

## Results: SR fits

- Post-fit background normalisation parameters are consistent for all tested hypotheses
  - $0.82 - 0.94$ with uncertainties of $\sim 0.1$ for $t\bar{t}$
  - $0.81 - 0.97$ with uncertainties of $\sim 0.14$ for $Z/\gamma + jets$
- No significant signal excess
- Largest fluctuation ($2.1\sigma$) observed for:

  $m_A = 1000$ GeV and $m_H = 850$ GeV



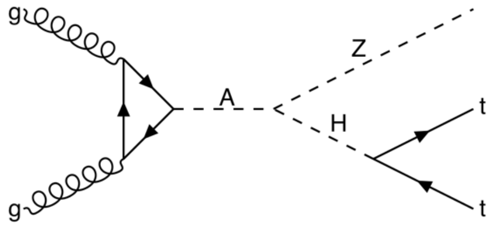
# *Benchmark scenarios*

- **Type-II 2HDM in the alignment and decoupling limit**
  - Requires $\mathbb{Z}_2$ symmetry. Describes which fermion couples to which doublet
  - $\cos(\beta - \alpha) = 0$ couplings of $h$ = couplings of $h_{SM}$
  - $h \ll \Lambda_{2HDM}$ and $\Lambda_{2HDM} \gg v$

- **g2HDM in the alignment limit and decoupling limit**
  - generalized 2HDM = no $\mathbb{Z}_2$ symmetry + extra Higgs quartic couplings $\sim \mathcal{O}(1)$
  - new Yukawa couplings $\sim \mathcal{O}(1)$, e.g. $\rho_{\tau\mu}, \rho_{tu}, \rho_{tc}, \rho_{tt}$

- **hMSSM**
  - Simplified SUSY benchmark, deriving from MSSM
  - $h = h_{\text{SM}}$ $\Longrightarrow$ only $\tan\beta$ and $m_A$ are free parameters

- **2HDM+a**
  - Additional fermionic DM particle, $\chi$, with CP-odd mediator, $a$

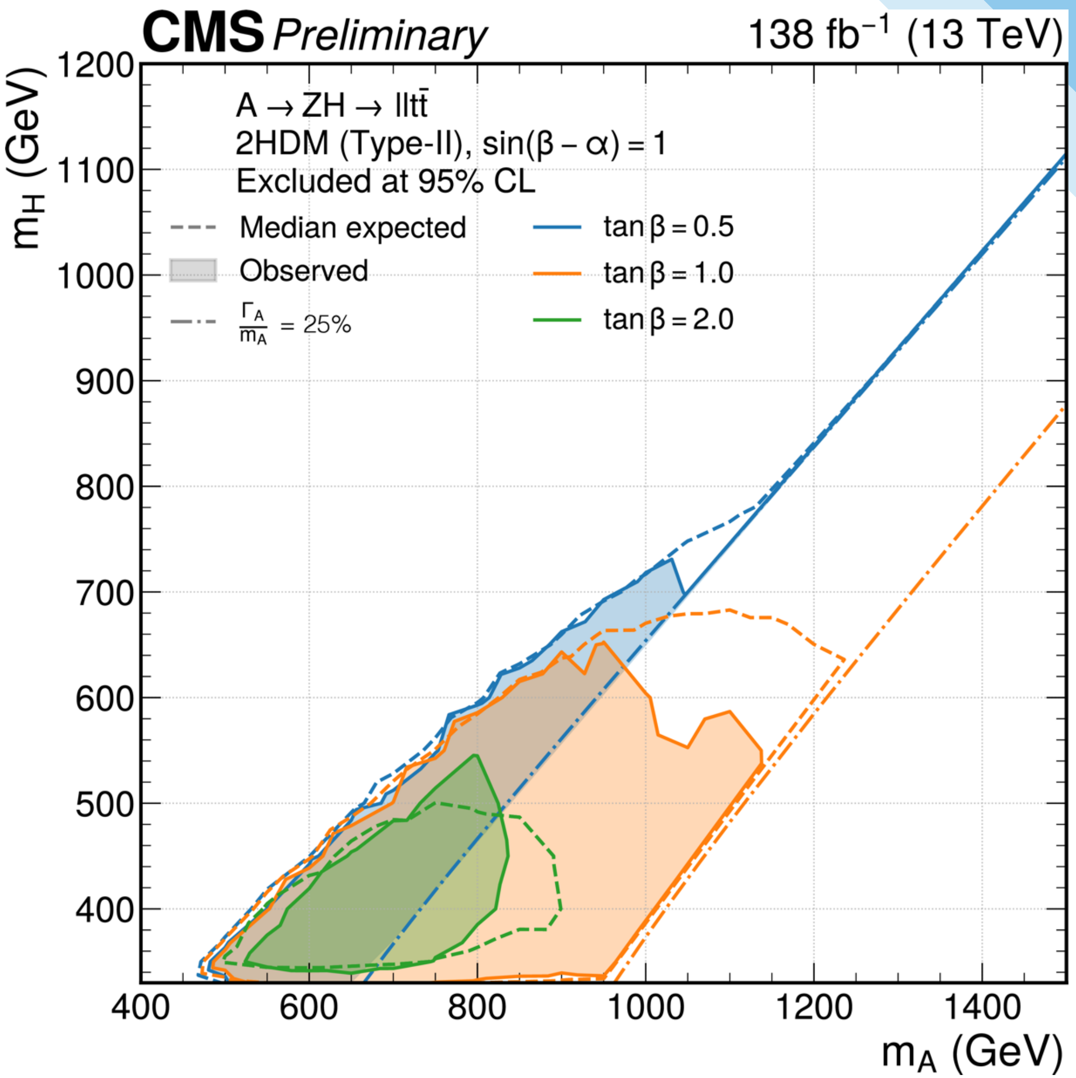


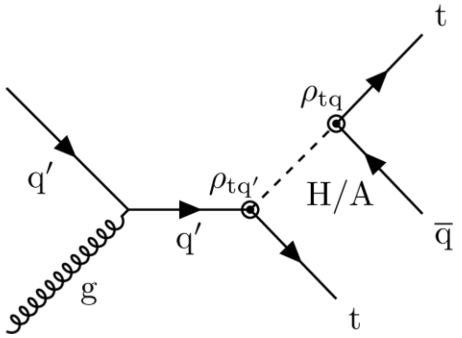

# Search for $A \rightarrow ZH, H \rightarrow t\bar{t}$

CMS-PAS-B2G-23-006

## Results: 2D limits

- Interpreted in the context of type-II 2HDM
  - Interpretation is limited to the 2HDM parameter space where $\Gamma_A < 25\%$
- Exclude, depending on the value of $\tan\beta$:
  - $m_A$ between $550 - 1500$ GeV
  - $m_H$ between $350 - 700$ GeV






# Search for $pp \to tH / A \to tt\bar{q}$

[Phys. Lett. B 850 (2024) 138478](Phys. Lett. B 850 (2024) 138478)

## Overview

- First search based on g2HDM model considering $A$-$H$ interference
  - 2023 ATLAS analysis has similar limits for the non-interference case
- Mass difference of $m_A - m_H = 50$ GeV assumed

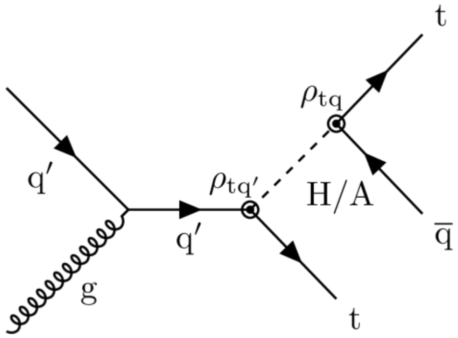
If $m_A - m_H \gtrsim 100$ GeV, effectively no interference

- Full CMS Run 2 dataset: $138$ fb$^{-1}$ at $\sqrt{s} = 13$ TeV
- Probed mass range of new Higgs bosons: $200 - 1000$ GeV
- Probed range of new Yukawa couplings, $\rho_{tu}$ and $\rho_{tc}$: $0.1 - 1.0$

All other new Yukawa couplings assumed to be $0$

- Final state signature: two same-sign leptons with at least three jets
- Dominant background: events with non-prompt leptons

Estimated using fake factor method

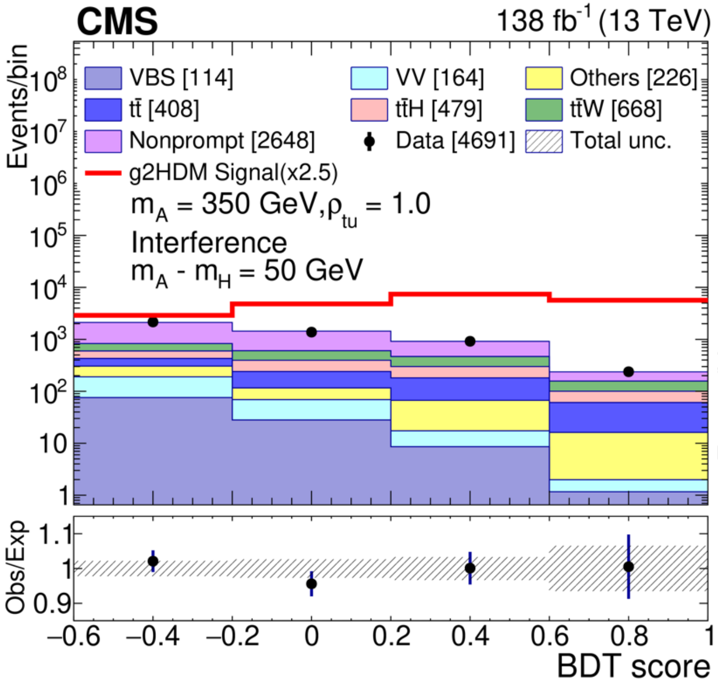


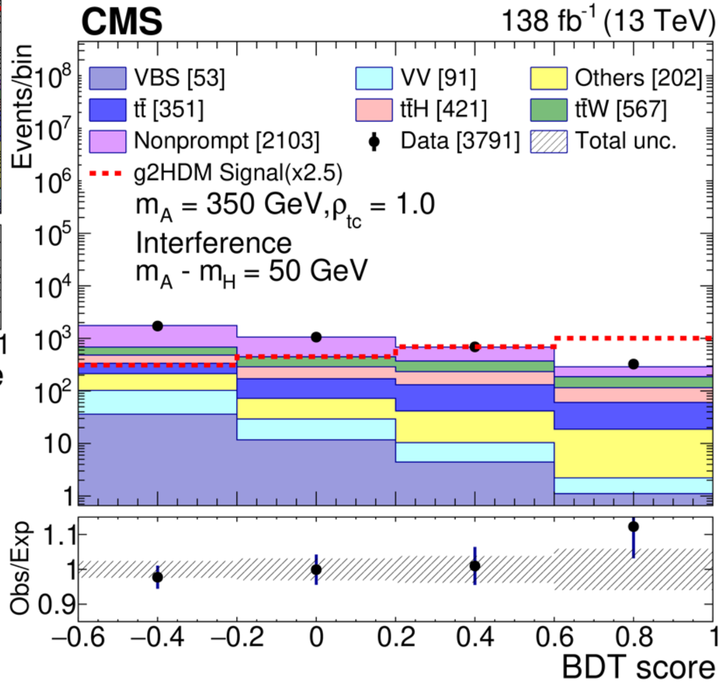

# Search for $pp \to tH\,/\,A \to tt\bar{q}$

[Phys. Lett. B 850 (2024) 138478](Phys. Lett. B 850 (2024) 138478)

## Signal extraction

- BDT discriminant used to distinguish signal and background
- 152 BDTs trained in total:
  - independently for four data-taking periods
  - in each data-taking period, independently for each mass assumption of $m_A$
  - for each mass assumption, independently for $\rho_{tu} = 0.4$ and $\rho_{tc} = 0.4$




- Signal strength, $\mu$, extracted with a simultaneous maximum likelihood fit for each signal mass-coupling assumption independently in 12 categories:
  - 3 decay modes in the 4 data-taking periods

# *Benchmark scenarios*

- **Type-II 2HDM in the alignment and decoupling limit**
  - Requires $\mathbb{Z}_2$ symmetry
    Describes which fermion couples to which doublet
  - $\cos(\beta - \alpha) = 0$
    couplings of $h$ = couplings of $h_{SM}$
  - $h \ll \Lambda_{2HDM}$ and $\Lambda_{2HDM} \gg v$

- **g2HDM in the alignment limit and decoupling limit**
  - generalized 2HDM
    =
    no $\mathbb{Z}_2$ symmetry
    +
    extra Higgs quartic couplings $\sim \mathcal{O}(1)$
  - new Yukawa couplings $\sim \mathcal{O}(1)$, e.g.
    $\rho_{\tau\mu}, \rho_{tu}, \rho_{tc}, \rho_{tt}$

- **hMSSM**
  - Simplified SUSY benchmark, deriving from MSSM
  - $h = h_{\text{SM}}$
    $\Longrightarrow$
    only $\tan\beta$ and $m_A$ are free parameters

- **2HDM+a**
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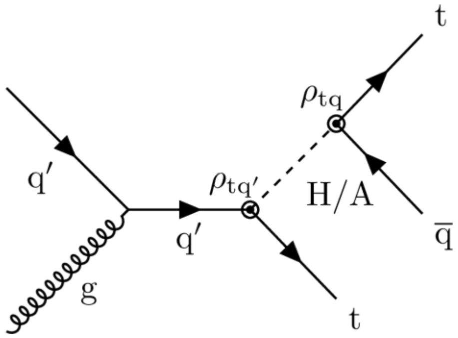
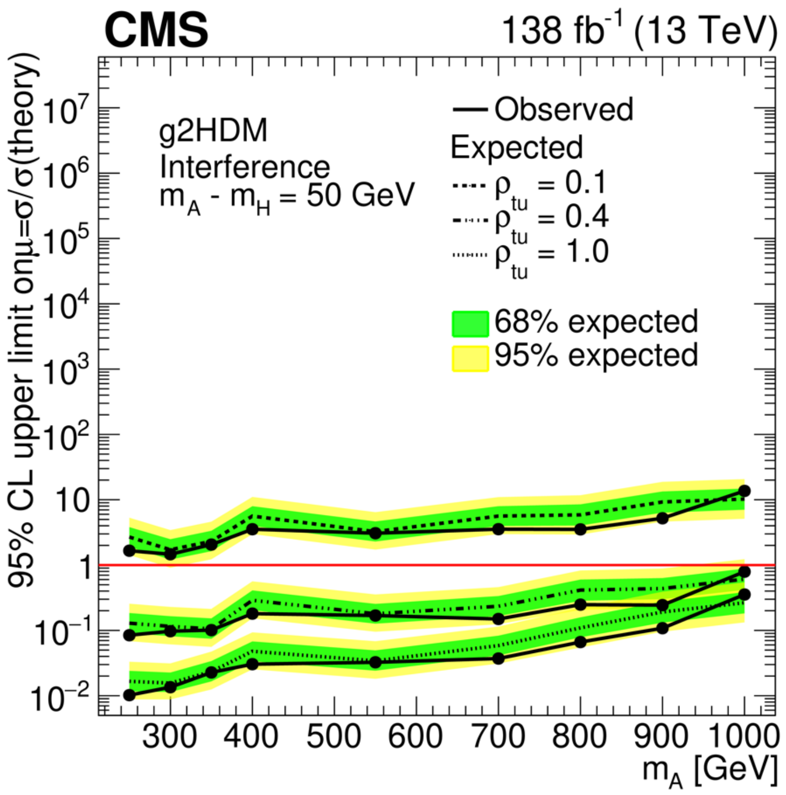



# *Search for* $pp \to tH\ /\ A \to tt\bar{q}$

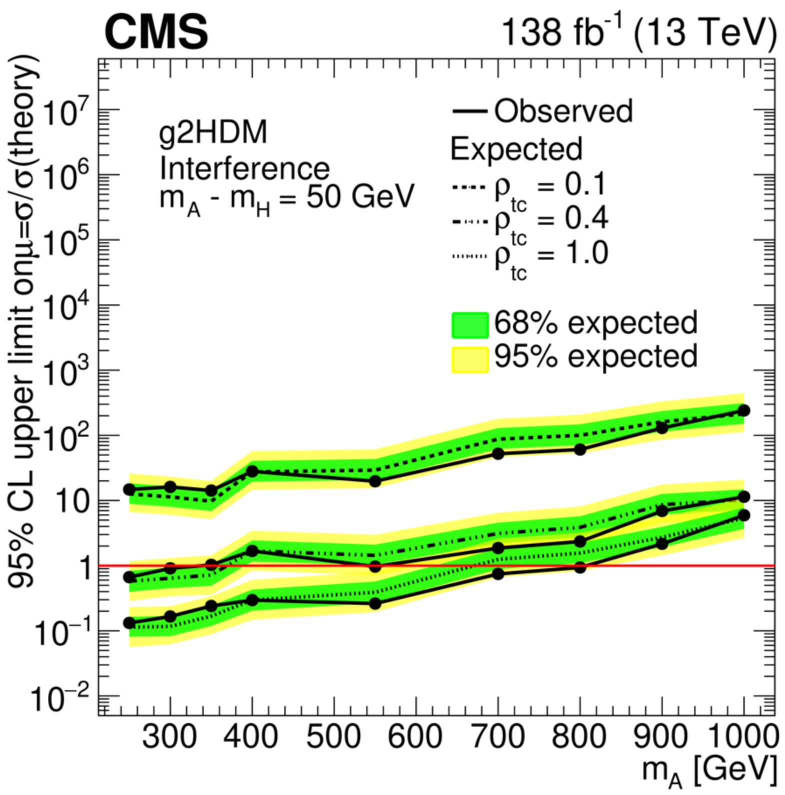
Phys. Lett. B 850 (2024) 138478

## Results: 1D limits

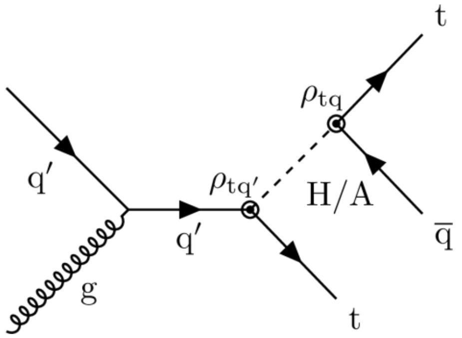
- No significant excess over the expected SM background
  - interpreted as upper limits on $\mu$ as a function of $m_A$




Exclude $m_A < 1000$ GeV for $\rho_{tu} > 0.4$




Exclude $m_A < 340(810)$ GeV for $\rho_{tc} = 0.4(1.0)$



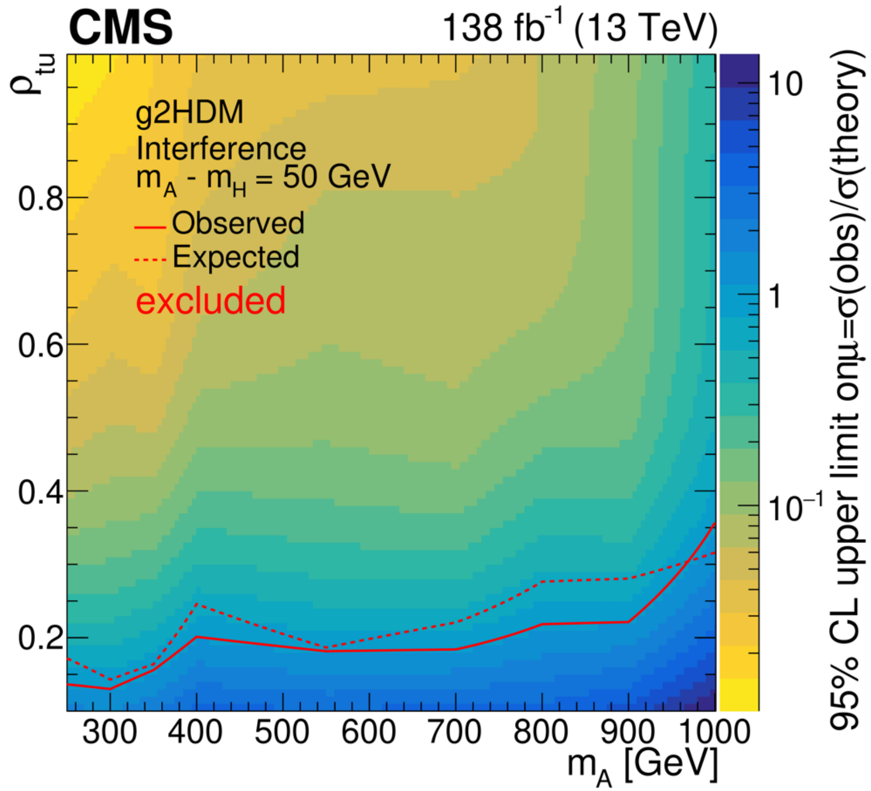

# Search for $pp \to tH / A \to tt\bar{q}$

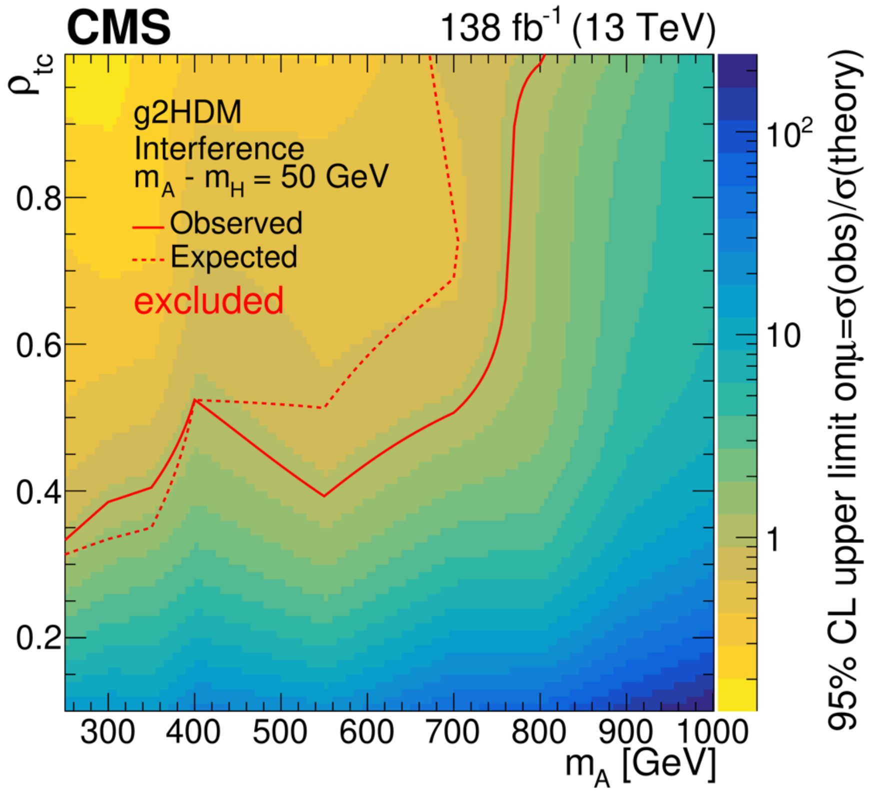
Phys. Lett. B 850 (2024) 138478

## Results: 2D limits

- No significant excess over the expected SM background
  - interpreted as upper limits on $\mu$ as a function of $m_A$ and $\rho_{tu}$ / $\rho_{tc}$

$\rho_{tu}$ largely excluded

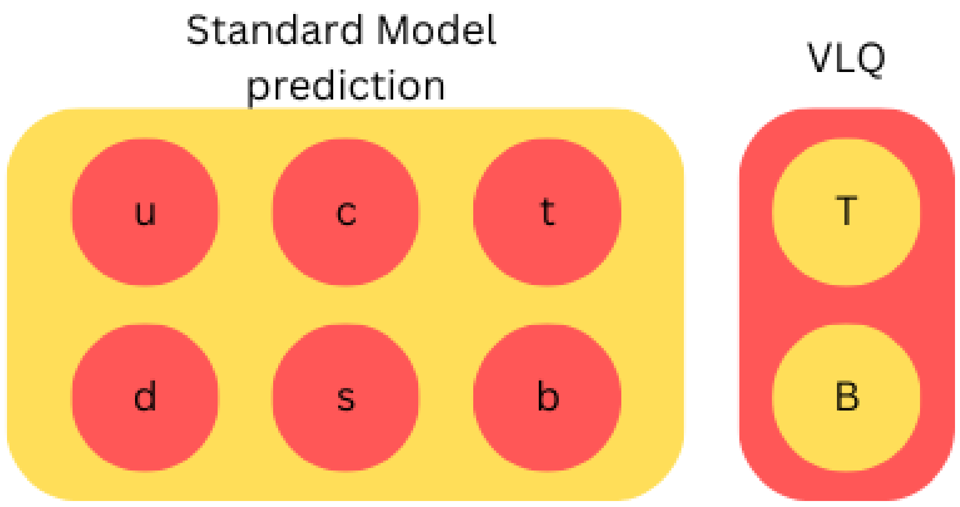



Large area of unconstrained phase space for $\rho_{tc}$

# *VLQs*

- Color-triplet, spin-$^1/_2$ fermions
- Left- and right-handed chiral components transform identically under the weak-isospin gauge group
- Can be singly- or doubly- produced

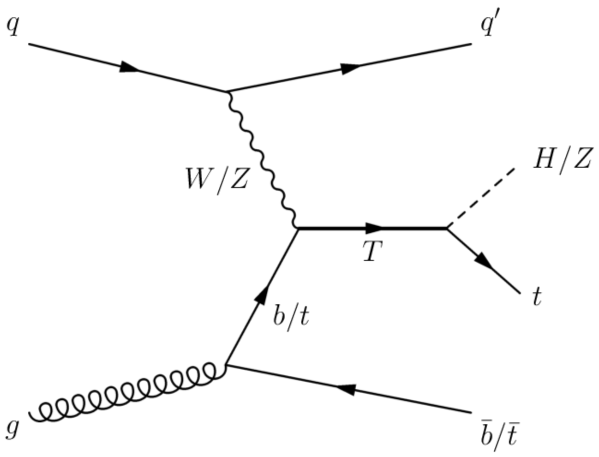


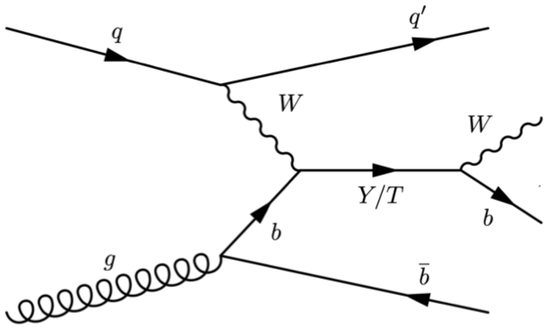

| VLQ | $(T)$ | $(B)$ | $\begin{pmatrix}T\\B\end{pmatrix}$ | $\begin{pmatrix}X\\T\end{pmatrix}$ | $\begin{pmatrix}B\\Y\end{pmatrix}$ | $\begin{pmatrix}X\\T\\B\end{pmatrix}$ | $\begin{pmatrix}T\\B\\Y\end{pmatrix}$ |
|---|---|---|---|---|---|---|---|
| **Isospin** | 0 | 0 | 1/2 | 1/2 | 1/2 | 1 | 1 |
| **Hypercharge** | +2/3 | −1/3 | +1/6 | +7/6 | −5/6 | +2/3 | −1/3 |

- Couple to SM quarks via exchange of $W^{\pm}$, $Z$ or $H$ with electroweak couplings, $\kappa$, $\tilde{\kappa}$ and $\hat{\kappa}$
- VLQs couple preferentially to third-generation SM quarks
  - other couplings set to 0
  - no additional mediators

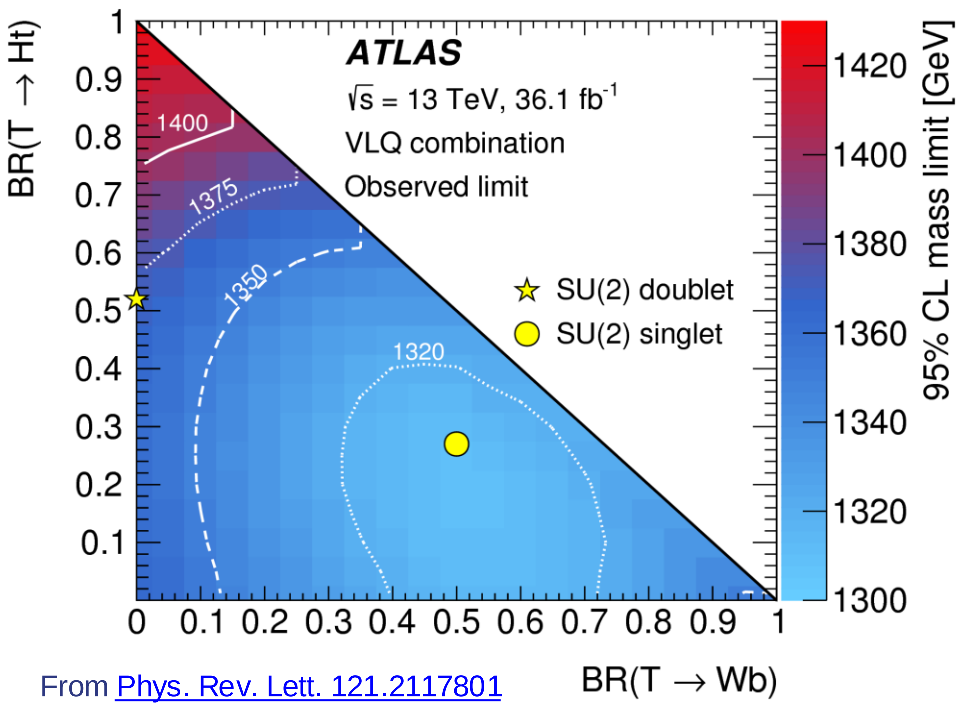
- Could mix with like-charge SM quarks
  - 7 renormalizable possibilities generate Yukawa terms without changing the scalar sector

# VLQs




- Relative couplings of VLQs to $W$, $Z$ and $H$ bosons given in terms of $\xi_W$, $\xi_Z$ and $\xi_H \approx$ branching ratios of the decays to $W$, $Z$ and $H$ bosons




From Phys. Rev. Lett. 121.2117801

**T quark decays**

- $T$ $SU(2)$ singlet:
  50% to $Wb$, 25% to $Zt$ and 25% to $Ht$
- $T$ $SU(2)$ doublet:
  50% to $Zt$ and 50% to $Ht$

# *VLQ analyses*

# *Combination of searches for singly-produced VLQs*

## Overview

arXiv:2408.08789

- Combination of 3 orthogonal analyses, targeting different leptonic ($e$ or $\mu$) final states
  - `MonoTop`: $0$ leptons (JHEP 05 (2024) 263)
  - `HTZT`: $1$ lepton (Phys. Rev. D (2024) 109 112012)
  - `OSML`: $\geq 2$ leptons (JHEP 08 (2023) 153)

- Full ATLAS Run 2 dataset: $139\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV

- Combination performed considering correlations in the background modelling and systematic uncertainties

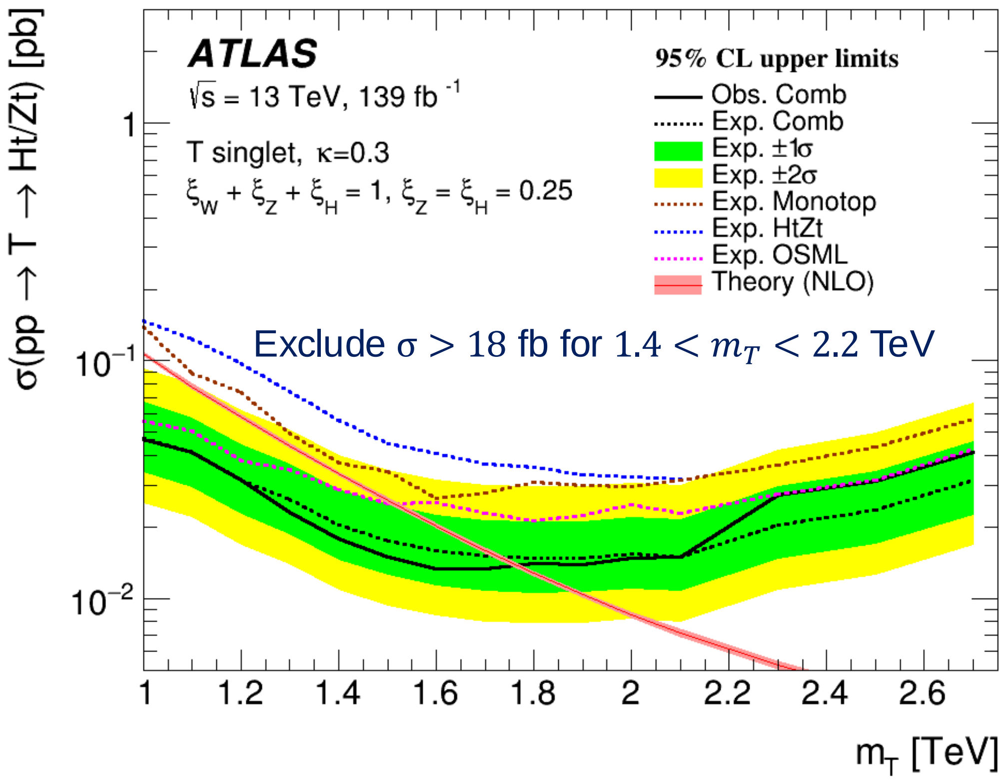
- First combination of searches single $T$-quark production in ATLAS
  - Most restrictive bounds to date!

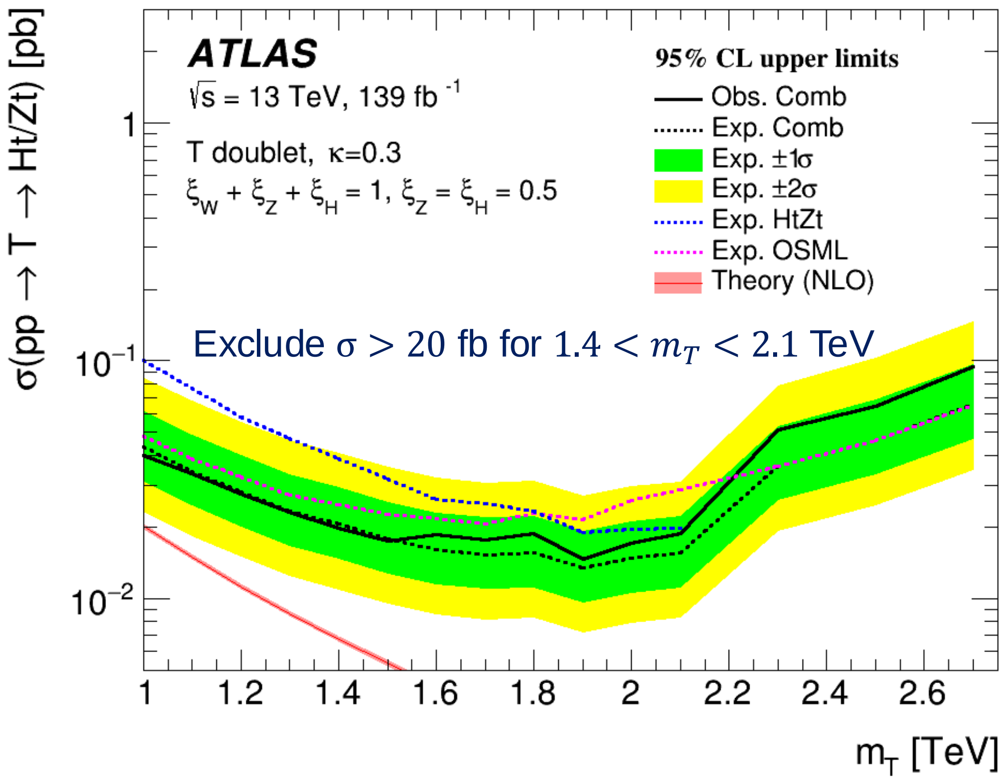
# Combination of searches for singly-produced VLQs

## Results: $\kappa = 0.3$

arXiv:2408.08789

- No significant excess over the expected SM background
  - most significant local $p_0$-value of $0.14(0.10)$ for the $SU(2)$ singlet (doublet) interpretation at $m_T = 2.1$ TeV, $\kappa = 0.1$



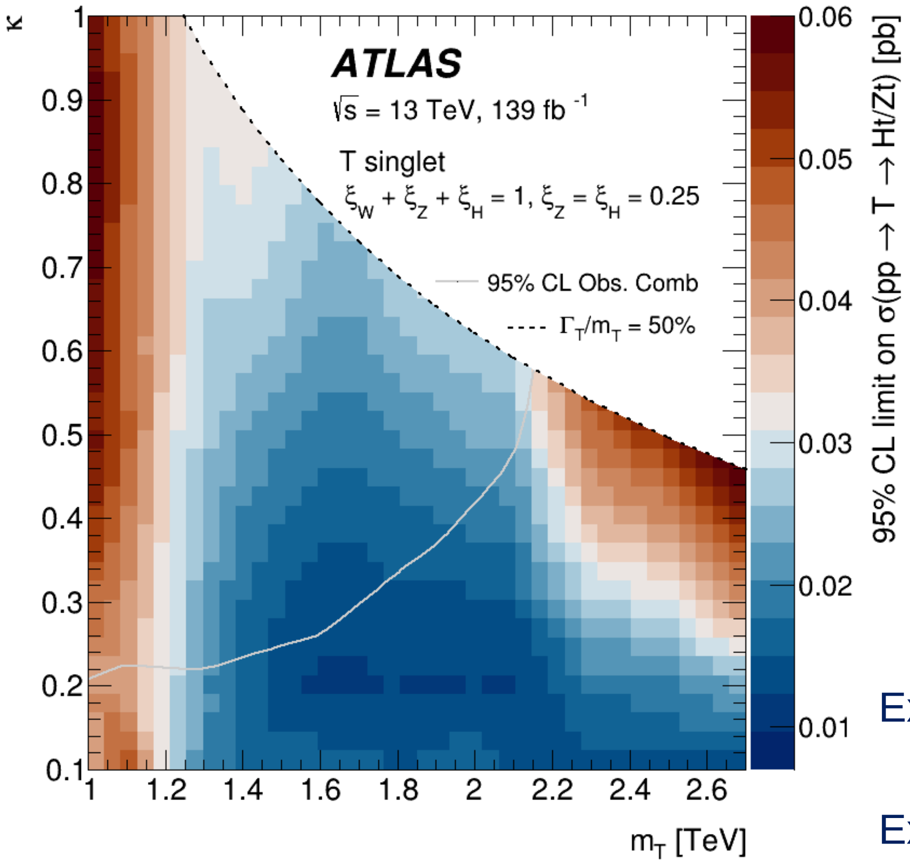

- Combination improves the limits over the individual results for *all* masses and couplings by up to a 2x!

# Combination of searches for singly-produced VLQs

## Results: $T$ $SU(2)$ singlet

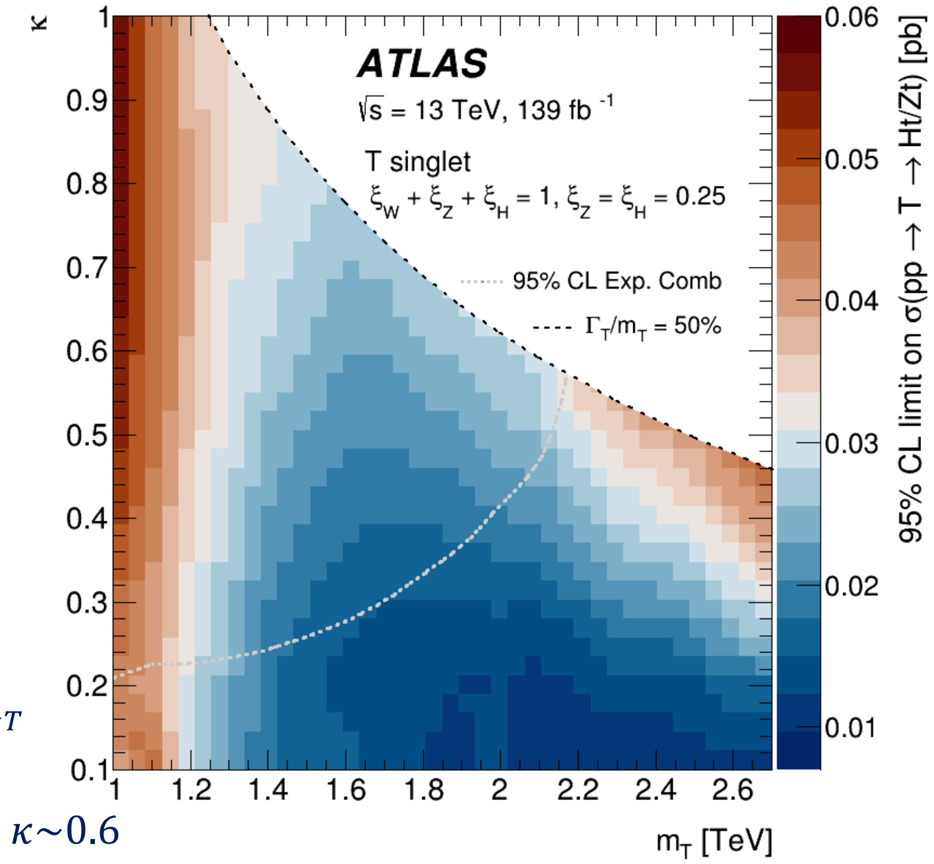
arXiv:2408.08789

- Combination increases sensitivity to a wider range of model parameters beyond existing parameters
  - Also interpreted as exclusion limits on the total cross section as a function of $m_T$ and $\kappa$




Exclude $\kappa > 0.2$ for low $m_T$

Exclude $m_T < 2.1$ TeV for $\kappa \sim 0.6$



# *Combination of searches for singly-produced VLQs*

## Overview

arXiv:2405.17605

- Combination of 3 orthogonal analyses, targeting different final states
  - \`ZT$\upsilon\upsilon$\`: 2 neutrinos (JHEP 05 (2022) 093)
  - \`HT$\gamma\gamma$\`: 2 photons (JHEP 09 (2023) 057)
  - \`HTZT\`: all-hadronic (arXiv:2405.05071)

- Full CMS Run 2 dataset: $138$ fb$^{-1}$ at $\sqrt{s} = 13$ TeV

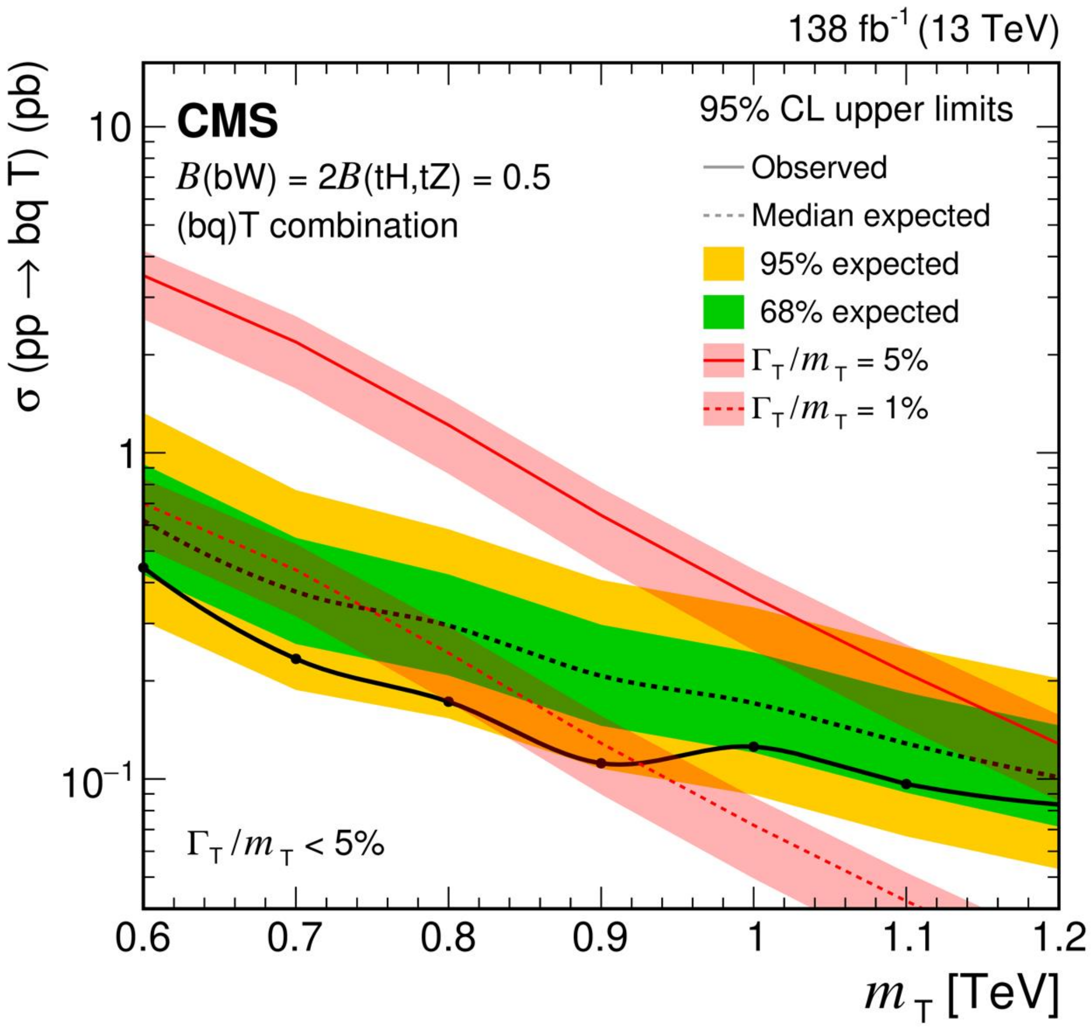
- Combination performed considering correlations in the background modelling and systematic uncertainties

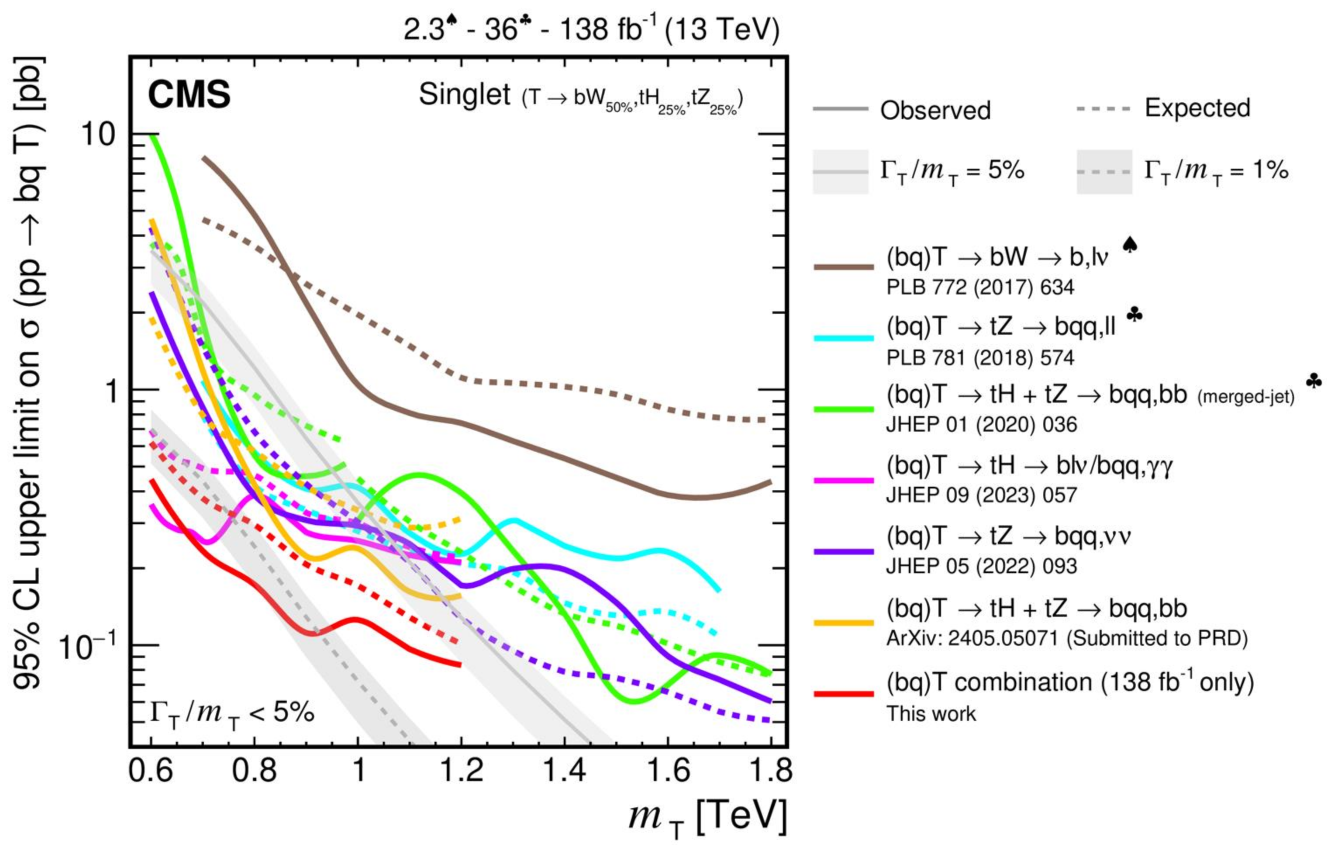
# Combination of searches for singly-produced VLQs

## Results: Upper limits

arXiv:2405.17605

- Combination significantly improves limits compared to a single analysis

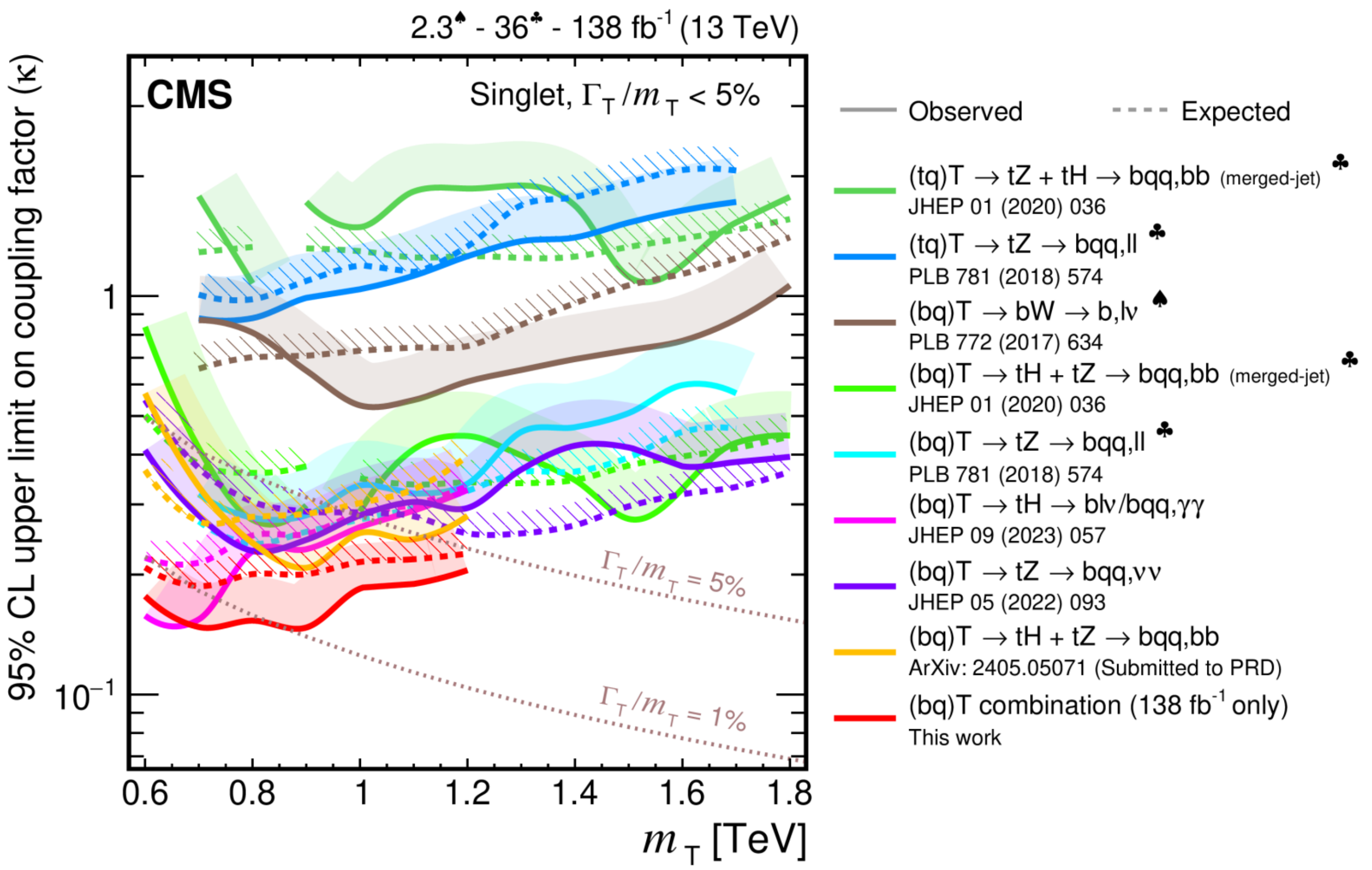


# Combination of searches for singly-produced VLQs

## Results: $T\ SU(2)$ singlet

arXiv:2405.17605




- Also interpreted as exclusion limits on $\kappa$
  - Couplings $\kappa > 0.4$ excluded at 95% confidence level across entire $m_T$
  - For $m_T = 600$ GeV, $\kappa > 0.15$ excluded

# Summary

- Presented an overview of recent ATLAS and CMS results in the context of $t\bar{t}$ final states
- Explored 2HDM models and VLQ models
- Currently no significant excesses have been observed, but stringent limits have been set
- An exciting search program for Run 3 awaits…

# *Thank You*

Dr Eleanor Jones
eleanor.jones@cern.ch

# *Backup*

# Search for $gg \to H / A \to t\bar{t}$

## Event selection: 1L

- Standard run and event cleaning
- Single-lepton trigger ($e$ or $\mu$)
- Exactly 1 lepton with $p_T > 25$ GeV (orthogonality with 2L)
  - Selected lepton $p_T > 28$ GeV (trigger)
- $E_T^{miss} > 20$ GeV
- $E_T^{miss} + m_T^W > 60$ GeV
- ≥ 1 *b*-tagged jet (DL1r 77%)

Total of 11 orthogonal signal regions

### Resolved

- ≥ 4 jets with $p_T > 25$ GeV
- $\log_{10} \chi^2 < 0.9$
- Veto on events passing boosted selection
- Split into 1 *b*-tag and 2 *b*-tag categories
- Split into equal bins of $|\cos \theta^*|$

### Merged

- ≥1 VRC jet with $p_T > 300$ GeV and $\mathrm{m} > 100$ GeV
- $\Delta R(l, b_l) < 2.0$
- $\Delta R(l, t_h) > 1.5$
- $\Delta R(b_l, t_h) > 1.5$

# Search for $gg \to H / A \to t\bar{t}$

## Event selection: 2L

- Standard run and event cleaning
- Single-lepton trigger ($e$ or $\mu$)
- == 2 leptons ($ee$, $\mu\mu$,$e\mu$) with $p_T$ > 25 GeV (orthogonality with 1L)
  - Leading one: $p_T > 28$ GeV (trigger)
- $\geq 2$ small-*R* jets and $\geq 1$ *b*-tagged jet (DL1r 77%)
- $m_{\ell\ell} > 15$ GeV for $ee$ and $\mu\mu$

Total of 5 orthogonal signal regions

- Opposite sign lepton pair
- *Z*-veto for $ee$ and $\mu\mu$
  - $E_T^{miss} > 45$ GeV, $m_{\ell\ell} < 81$ GeV or $m_{\ell\ell} < 101$ GeV
- Lepton-*b*-jet compatibility
  - $m_{l^+b} < 150$ GeV, $m_{l^-b} < 150$ GeV for $\geq 1$ *b*-jet assignment

- $m_{\ell\ell bb}$ is the discriminating variable
  - If $\geq 2$ *b*-jets: use the 2 leading *b*-jets
  - If $== 2$ *b*-jet: use the *b*-jet + the leading non-*b*-jet
- Additionally binned in $\Delta\phi_{\ell\ell}$

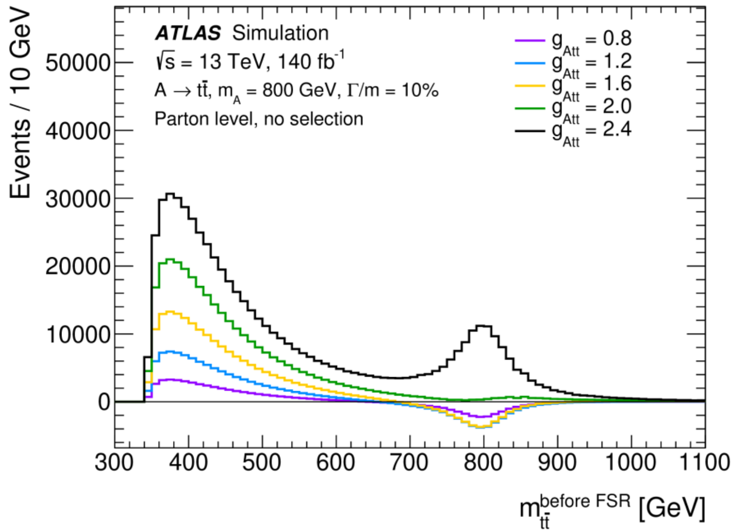
# Search for $gg \to H / A \to t\bar{t}$

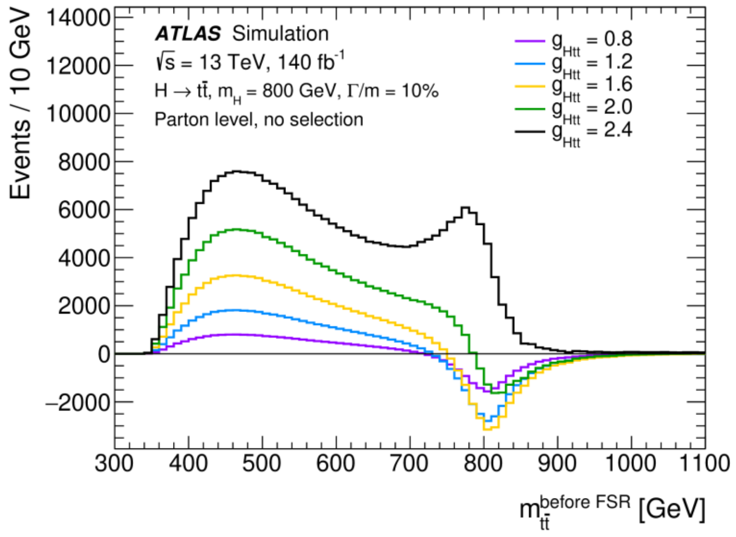
## Overview: “model-independent”

- Can also extend the SM with generic (pseudo)scalars with terms:

$$\mathcal{L}_H = -g_{Ht\bar{t}} \frac{m_t}{v} t\bar{t}H, \mathcal{L}_A = i g_{At\bar{t}} \frac{m_t}{v} \bar{t}\gamma^5 tA$$

  - Very few assumptions so can derive model-agnostic constraints
  - $A / Ht\bar{t}$ coupling and $A / H \to t\bar{t}$ decay width vary independently
- The peak-dip structure is still strongly model dependent
  - Higher coupling does not always mean bigger deviation from SM (unlike resonances)



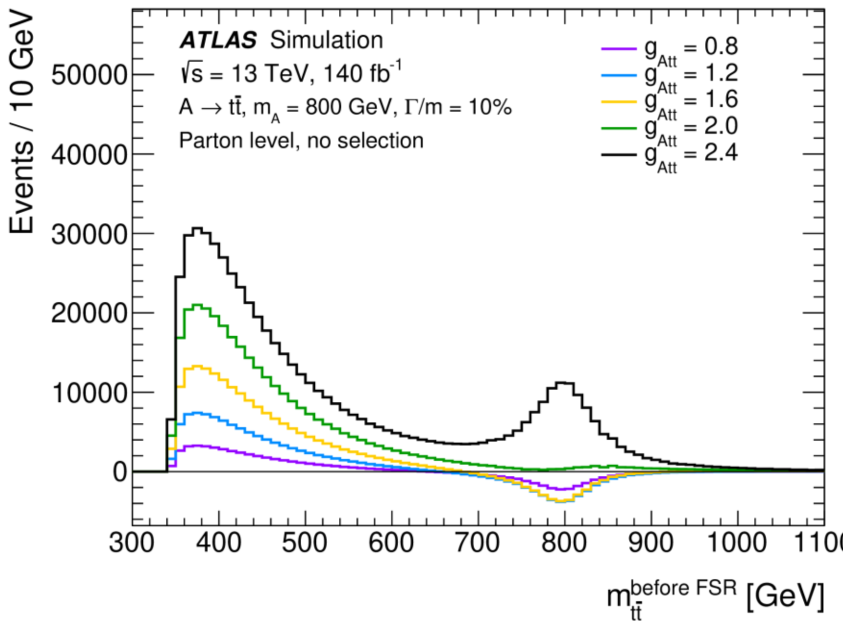
# Search for $gg \rightarrow H / A \rightarrow t\bar{t}$

## Statistical analysis overview

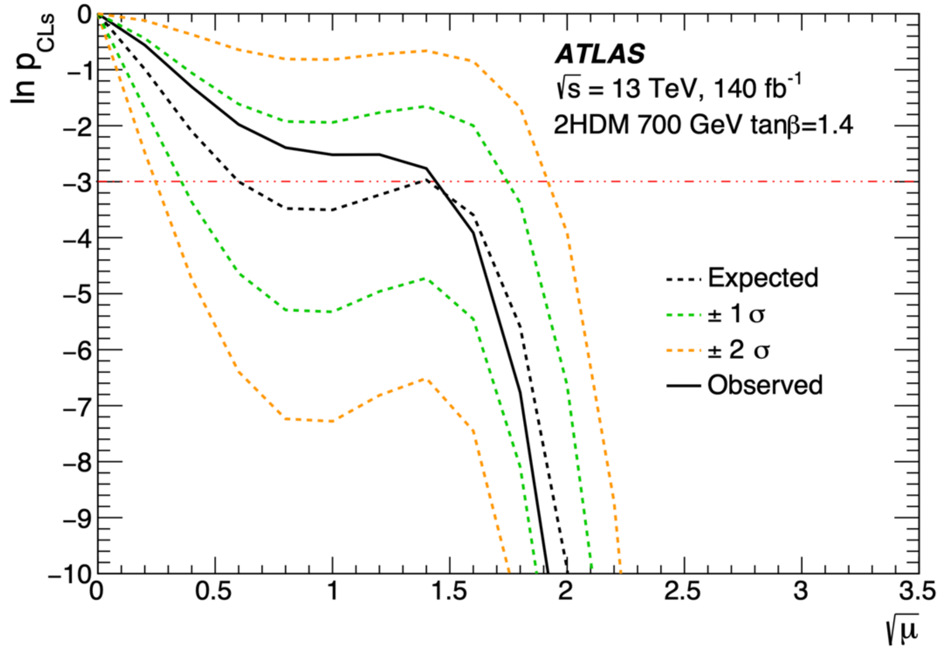
- Binned profile likelihood fit parametrised in $\sqrt{\mu}$:

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

- $\sqrt{\mu}$ is equivalent to the coupling, $g$
  - The interference shape depends on $\sqrt{\mu}$




- Upper limit on $\sqrt{\mu}$ is not always well-defined
  - Double minima can appear in the likelihood scan



# Search for $gg \to H / A \to t\bar{t}$

## Choice of test statistic

- Different test statistics are used for the search and exclusion stages:

Search stage

$$q_{\sqrt{\mu}} = \frac{\mathcal{L}\left(\sqrt{\mu}, \hat{\hat{\theta}}_{\sqrt{\mu}}\right)}{\mathcal{L}\left(\widehat{\sqrt{\mu}}, \hat{\theta}_{\widehat{\sqrt{\mu}}}\right)}$$

Should we reject the SM in favour of (any) BSM hypothesis?

- Test agreement of data with a range of interference patterns
- Consider all possible values of $\sqrt{\mu}$

Exclusion stage

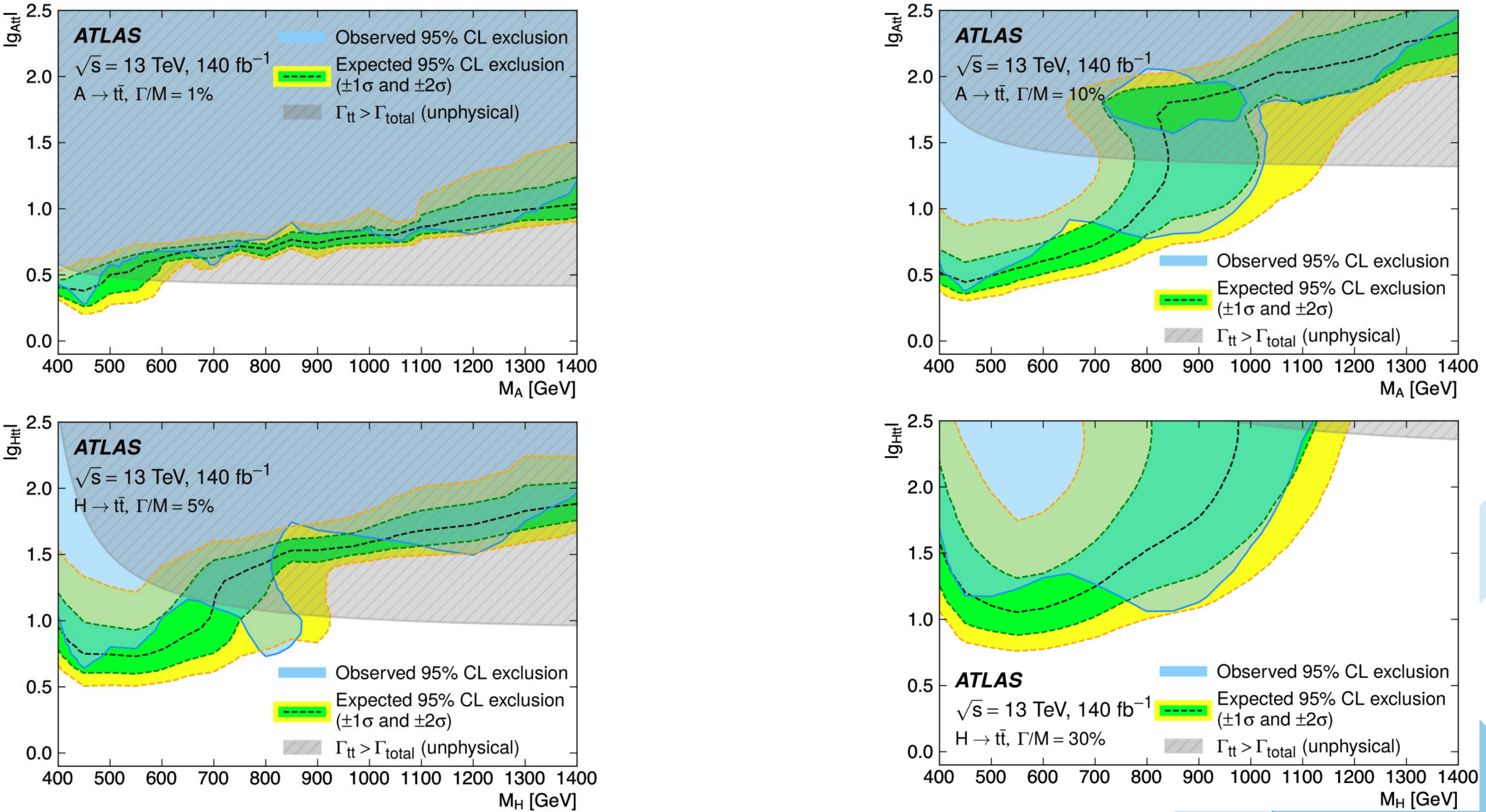
$$q_{1,0} = -2\ln\frac{\mathcal{L}\left(1, \hat{\hat{\theta}}_1\right)}{\mathcal{L}\left(0, \hat{\hat{\theta}}_0\right)}$$

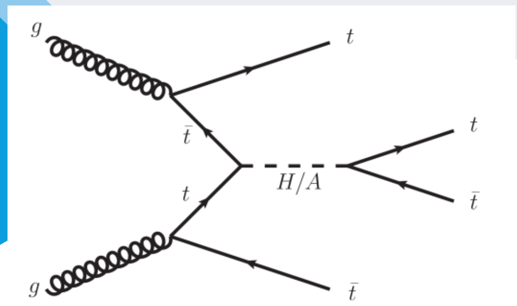
Should we reject the BSM hypothesis under consideration?

- Test (dis)agreement of data with specific interference pattern of tested signal hypothesis

# *Search for* $gg \to H / A \to t\bar{t}$

## Results: “model-independent”






Full details in Quake Qin's talk

# Search for $t\bar{t}H / A \rightarrow t\bar{t}t\bar{t}$

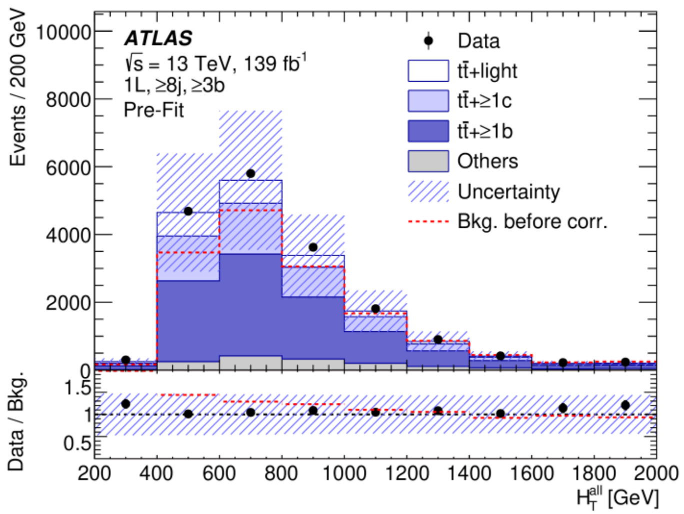
arXiv: 2408.17164

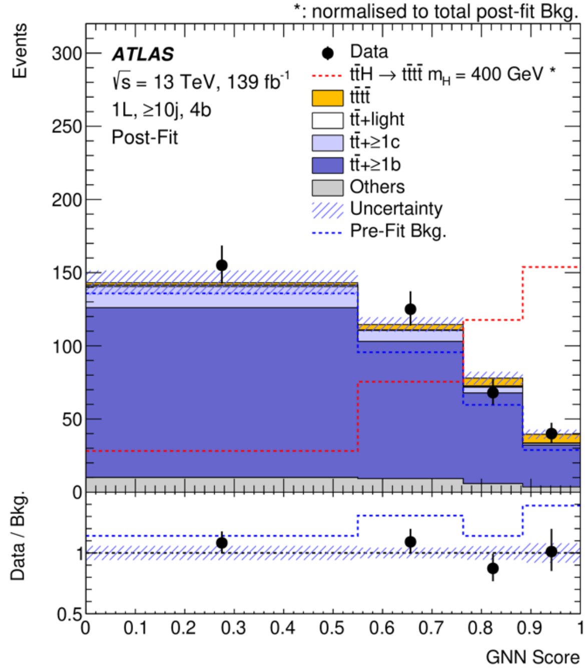
## Overview

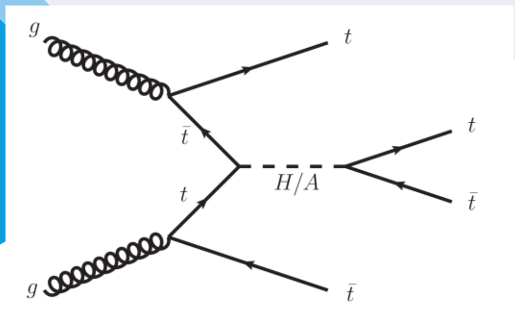
- Full ATLAS Run 2 dataset: $139\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
  - Combination with previous 2 lepton same-sign and multilepton result
- Probed mass range of signal: $400 < m_{H/A} < 1000$ GeV
  - Large $H / A \rightarrow t\bar{t}$ branching fraction
  - Above 1 TeV, interference becomes non-negligible

Leptons = $e$ or $\mu$ (including from $\tau$ decays)

- Target final states: = 1 lepton or = 2 opposite-sign leptons
  - Main background: $t\bar{t} + jets$
- Simultaneous profile likelihood fit to $H_T$ distributions in the CRs and GNN output distributions in the SRs






# Search for $t\bar{t}H\ /\ A \rightarrow t\bar{t}t\bar{t}$

ATLAS EXPERIMENT

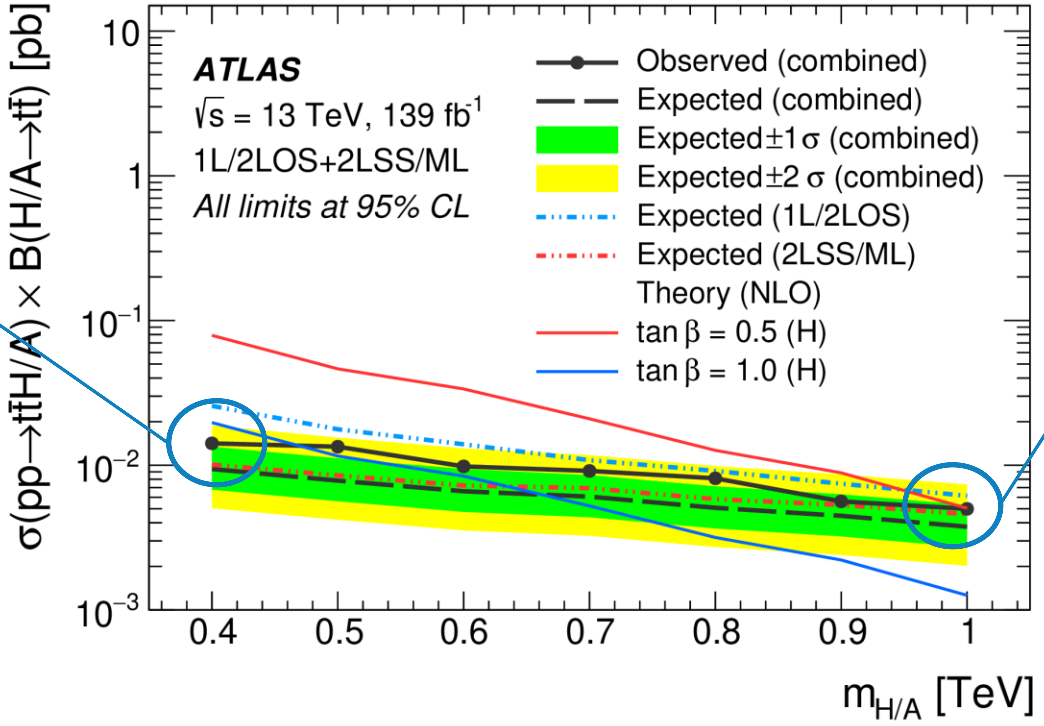
Full details in Quake Qin's talk

arXiv: 2408.17164

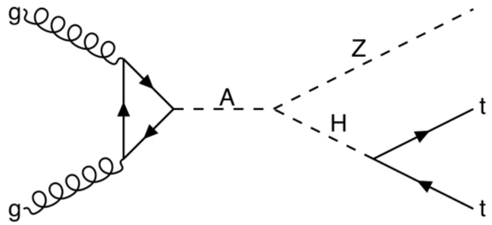
## Results: 1D limits

- No significant excess above the SM prediction is observed under the S+B hypothesis
- Results are interpreted in the context of a type-II 2HDM model, assuming no interference
  - Combination results with the previous 2LSS/ML shown here.

14 fb at $m_{A/H} = 400$ GeV




5.0 fb at $m_{A/H} = 1000$ GeV

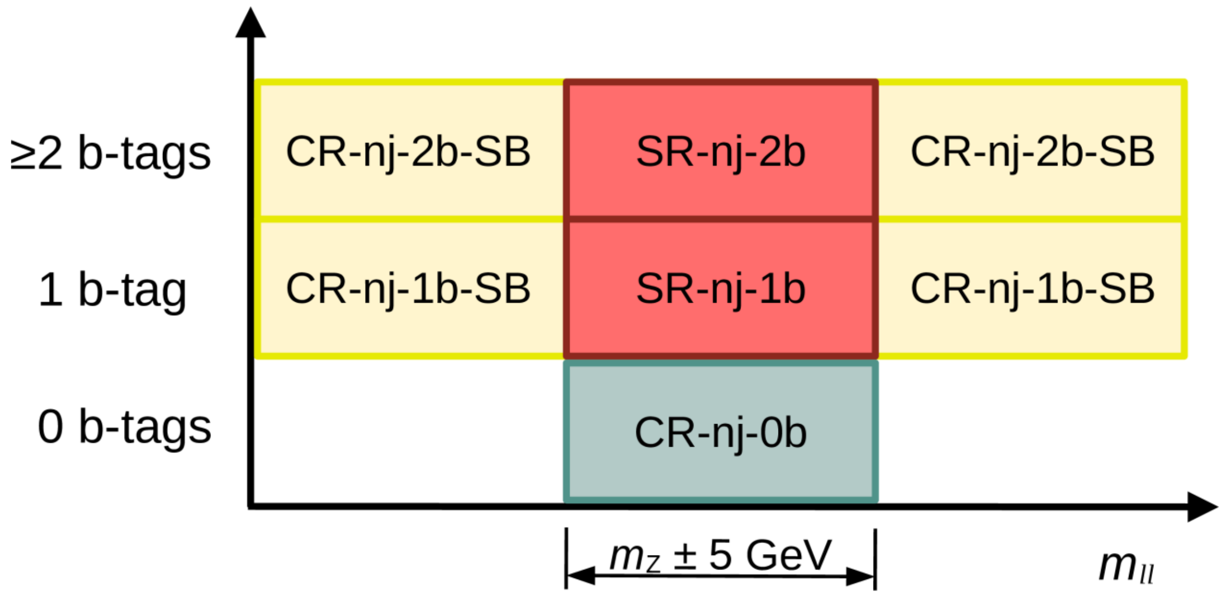



# Search for $A \to ZH, H \to t\bar{t}$

CMS-PAS-B2G-23-006

## Analysis strategy

- 20 analysis regions in total:
  - 10 per lepton-flavour channel, of which 2 SRs and 3 CRs per jet multiplicity




with n = 5, ≥6

- Selection efficiency for signal events:
  - above $99\%$ in the $\mu\mu$ channel across $(m_A, m_H)$ plane
  - above $99\%$ in the $ee$ channel for $m_H > 300$ GeV
  - above $97\%$ in the $ee$ channel for $m_H < 300$ GeV

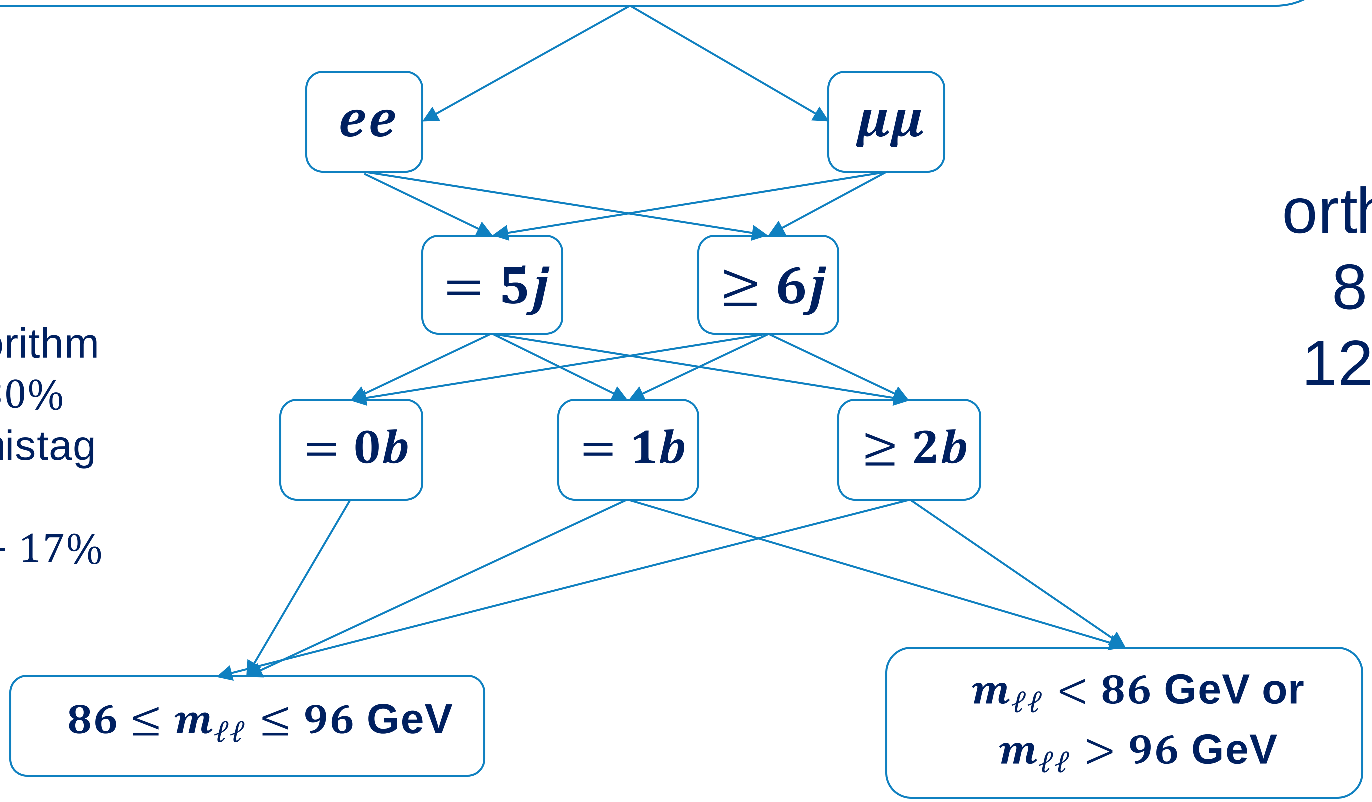
- Signal selection efficiency in all SRs is between $3-13\%$

- CRs constrain the dominant $t\bar{t}$ and Drell-Yan backgrounds

# Search for $A \to ZH, H \to t\bar{t}$

## Event selection

- \`OR\` combination of triggers:
  - di-muon, di-electron, single-lepton, single- or di-photon
- == 2 leptons ($ee$ or $\mu\mu$) with $|\eta| < 2.4$ and $p_T > 35(20)$ GeV for leading (sub-leading)
- $\geq 5$ anti-$k_T$, $R = 0.4$ jets with $|\eta| < 2.4$ and $p_T > 30$ GeV
- $m_{\ell\ell} > 30$ GeV and $p_T(\ell\ell) > 15$ GeV




Total of 20 orthogonal regions:
8 signal regions
12 control regions

*b*-tagging with DeepJet algorithm
- *b*-tag efficiency: $75 - 80\%$
- light-flavour and gluon mistag rate: $1.5 - 2\%$
- c quark mistag rate: $15 - 17\%$

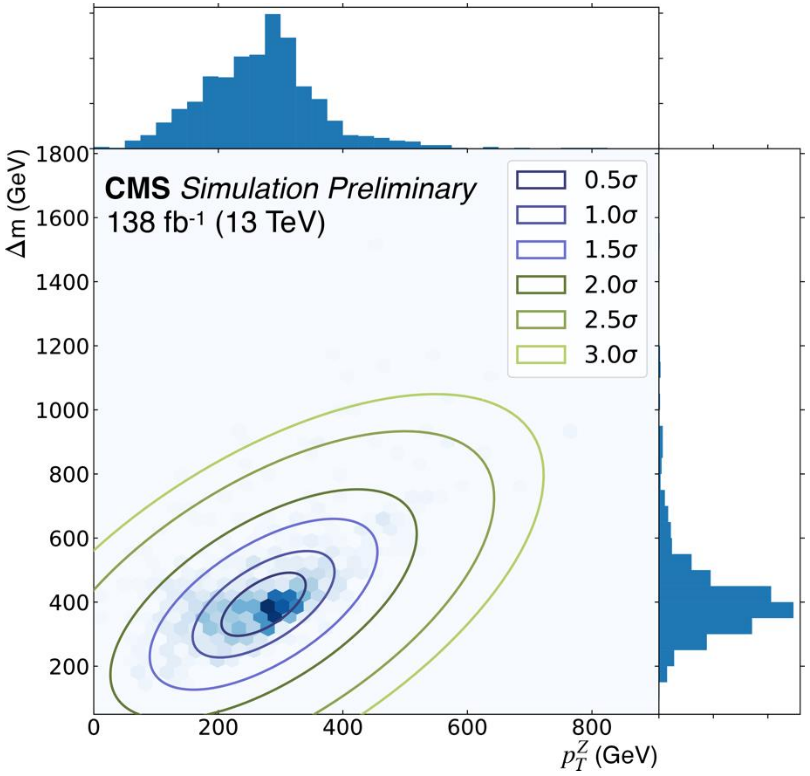
# Search for $A \to ZH, H \to t\bar{t}$

## Reconstruction

- $m_H$ is reconstructed as the invariant mass of the $t\bar{t}$ system:
  - if there are 5 or 6 jets, $m_{t\bar{t}}$ is computed as the invariant mass of the jets
  - if there are $\geq 6$, the six jets are chosen as the $t\bar{t}$ decay products that minimise a $\chi^2$ function under the $t\bar{t} \to b\bar{b}q\bar{q}q\bar{q}$ hypothesis
- $m_A$ is reconstructed as the invariant mass of the $t\bar{t}Z$ system:
  - $m_{t\bar{t}}$ is computed as the invariant mass of the selected jets
  - $m_Z$ is computed as the invariant mass of the two leptons

- Two observables of interest:
  - difference between the Breit-Wigner peaks $\Delta m = m_{t\bar{t}Z} - m_{t\bar{t}} \approx m_A - m_H$
  - $p_T(\ell\ell) \approx p_T^Z$ spectrum, which has a characteristic shape with a kinematic edge

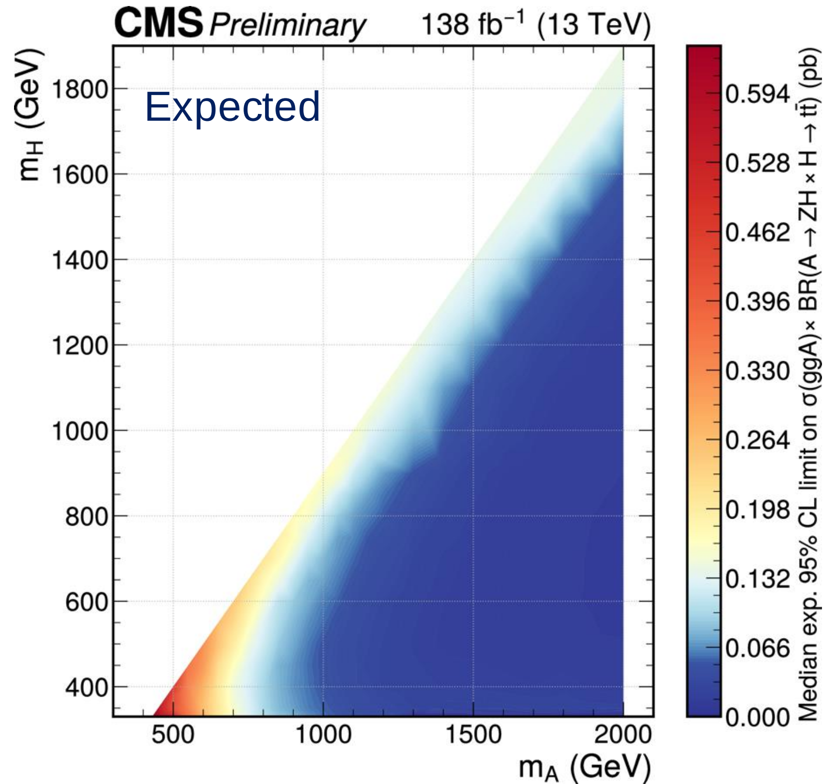
- Final discriminant: $p_T^Z \times \Delta m$
  - reduced to 1D-distribution using concentric elliptical bins in the $(p_T^Z, \Delta m)$ plane
  - angles and proportions of axes obtained by diagonalising the covariance matrix of $p_T^Z$ and $\Delta m$, assuming normal distributions
  - In the SR, the ellipses are centred around the mean of the signal distribution and chosen specifically for each tested hypothesis
  - In the CR, the ellipses are centred around the mean of the total expected background distribution, so the same for each hypothesis

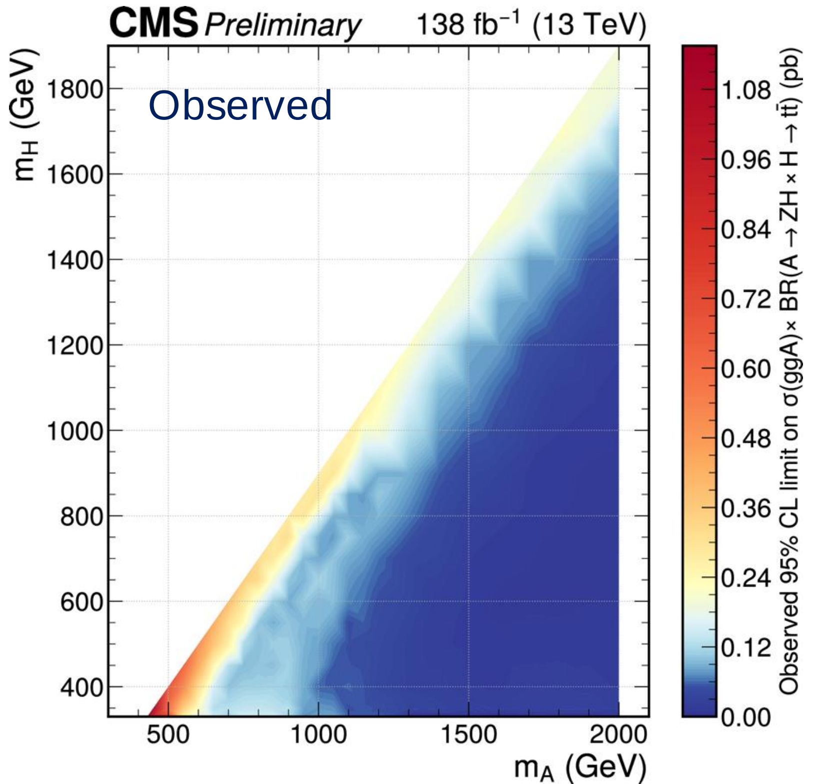


# Search for $A \to ZH, H \to t\bar{t}$

## Model independent limits

- Model independent limits on $\sigma(pp \to A \to ZH) \times \mathcal{B}(H \to t\bar{t})$ of generic Higgs-like narrow resonances
- Results do not confirm previous $2.85\sigma$ excess reported by ATLAS in the region around $(m_A, m_H) = (650{,}450)$ GeV
  - Local significance here is $0.4\sigma$
- Exclude $A \to ZH \to Zt\bar{t}$ signal with a cross section $> 0.25$ pb at $95\%$ CL

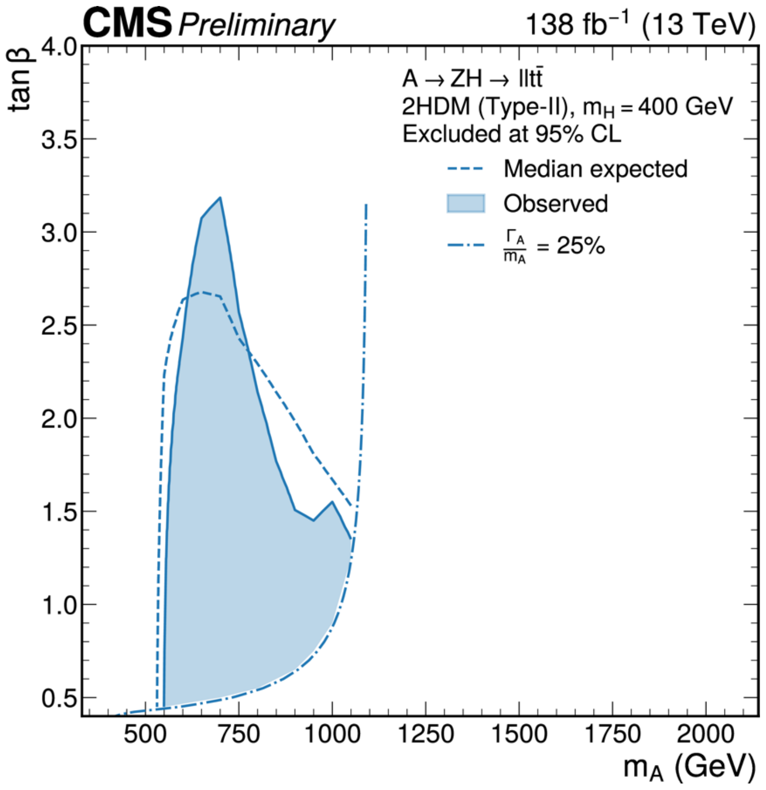


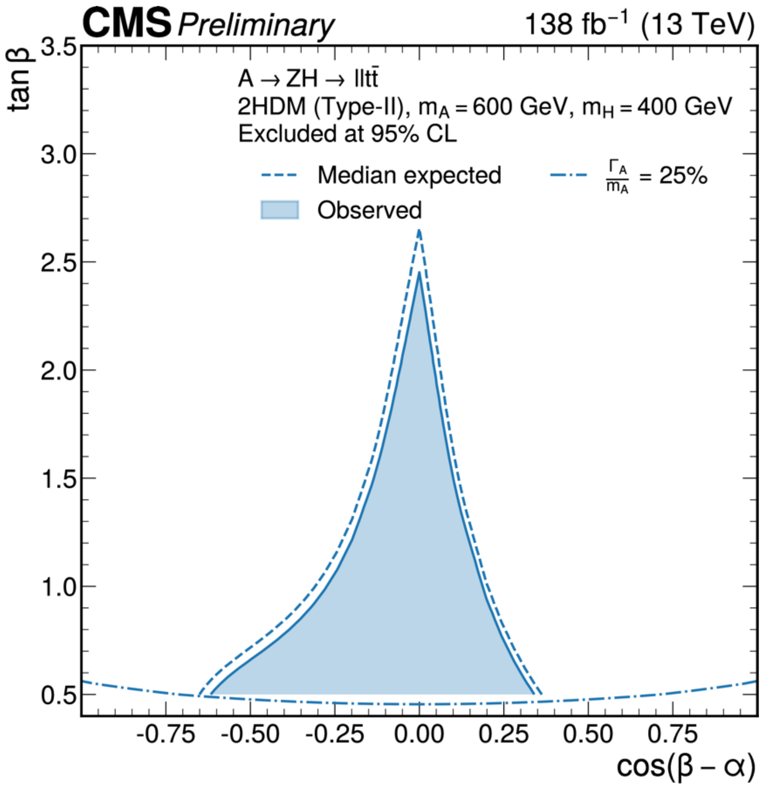



# Search for $A \to ZH, H \to t\bar{t}$

## 2HDM limits

- Limits interpreted in the context of a type-II 2HDM in the:
  - $(\tan\beta, m_A)$ parameter space at $m_H = 400$ GeV
  - $(\tan\beta, \cos(\beta-\alpha))$ parameter space at $m_A = 600$ GeV and $m_H = 400$ GeV



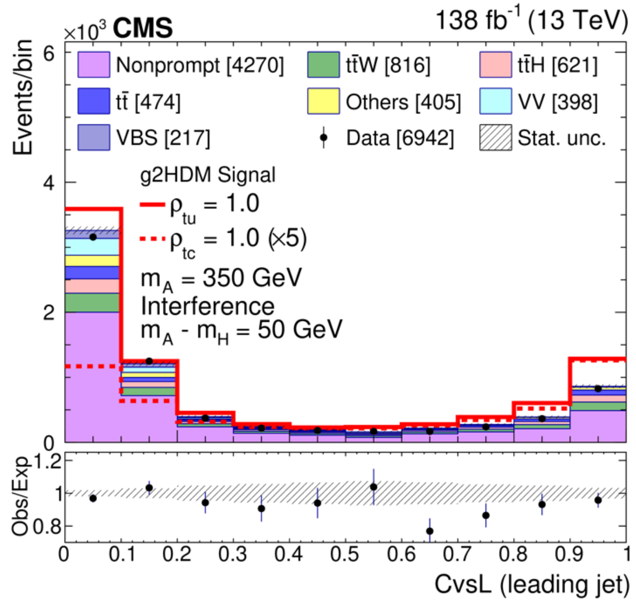



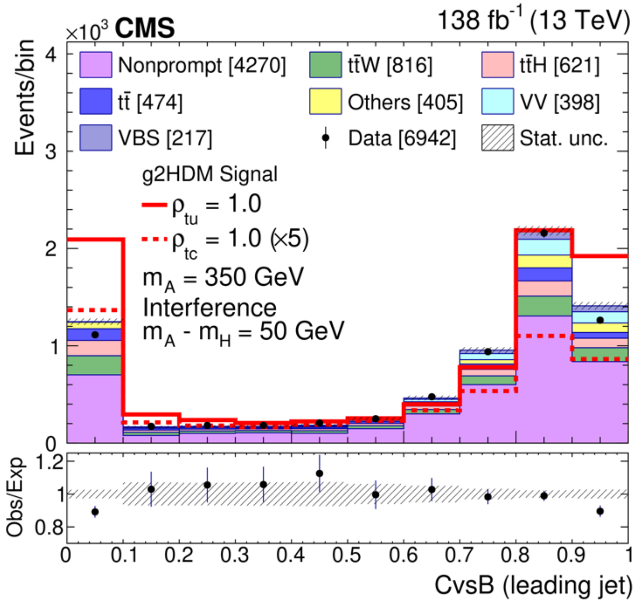
# Search for $pp \to tH\ /\ A \to tt\bar{q}$

## Event selection

- Combination of di-lepton and single-lepton triggers
- Exactly 2 same-sign leptons ($ee$, $\mu\mu$, $e\mu$) with $p_T > 30\ (20)$ GeV for the leading (sub-leading) lepton
- $\geq 30$ anti-$k_T$, $R = 0.4$ jets with $|\eta| < 2.4$ and $p_T > 30$ GeV
- $p_T^{miss} > 30$ GeV
- $\Delta R(\ell_1, \ell_2) > 0.3$
- $m_{\ell\ell} > 20$ GeV and not $60 < m_{\ell\ell} < 120$ GeV for $ee$
- BDT score $> 0.6$

- Different flavour jets distinguished through ratios of corresponding jet flavour probabilities obtained from DEEPJET



# Search for $pp \to tH / A \to tt\bar{q}$

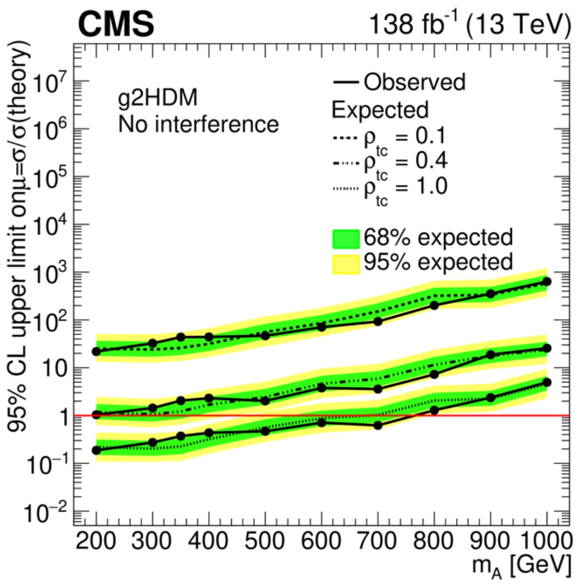
## BDT

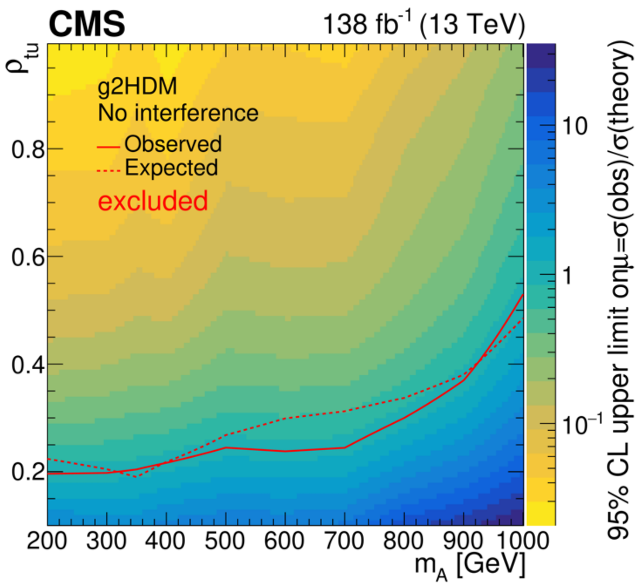
| Input variables of the BDT | | |
|---|---|---|
| $\mathrm{CvsL}(j_a)$ | $a = 1, 2, 3$ | Charm- vs light-quark jet identification variable |
| $\mathrm{CvsB}(j_a)$ | $a = 1, 2, 3$ | Charm- vs bottom-quark jet identification variable |
| $\Delta R(j_a, j_b)$ | $1 \leq a < b \leq 3$ | Angular separation between jets |
| $m(j_a, j_b)$ | $1 \leq a < b \leq 3$ | Invariant mass of jet pairs |
| $\Delta R(j_a, l_b)$ | $a = 1, 2, 3; b = 1, 2$ | Angular separation between jet and lepton |
| $m(j_a, l_b)$ | $a = 1, 2, 3; b = 1, 2$ | Invariant mass of jet-lepton pairs |
| $p_\mathrm{T}(\ell_a)$ | $a = 1, 2$ | Transverse momentum of leptons |
| $m(\ell_1, \ell_2, j_a)$ | $a = 1, 2, 3$ | Invariant mass of the two leptons plus the highest $p_\mathrm{T}$ jet |
| $m(\ell_1, \ell_2)$ | | Invariant mass of the two leptons |
| $H_\mathrm{T}$ | | Scalar $p_\mathrm{T}$ sum of the jets |
| $p_\mathrm{T}^\mathrm{miss}$ | | Missing transverse momentum |

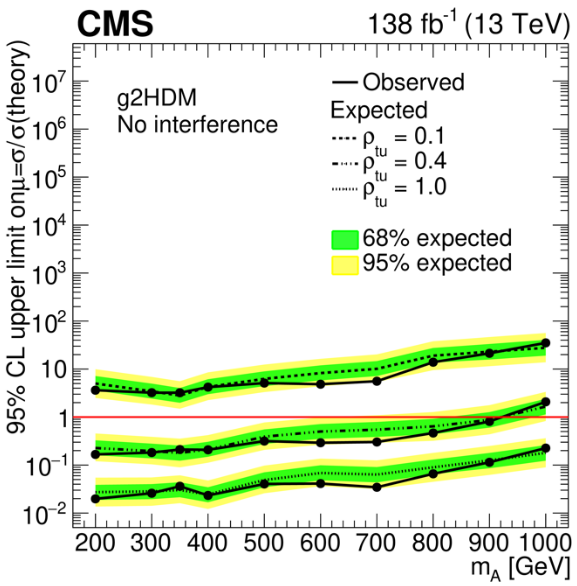
- Half of the available simulated events used for training
- Backgrounds added according to their cross sections: $tt\bar{c}$, $tt\bar{u}$, semi- and di-leptonic $t\bar{t}$, $t\bar{t}V$, $VV$, $VVV$, $t\bar{t}H$, $t\bar{t}VH$, $t\bar{t}tj$, $t\bar{t}tW$, $t\bar{t}t\bar{t}$ and VBS
  - 3 values of couplings used for $\rho_{tu}$ and $\rho_{tc}$: 0.1, 0.4 and 1.0
  - For each coupling value, 10 values of $m_A$: 200, 300, 350, 400, 500, 600, 700, 800, 900, 1000 GeV
  - For each coupling value, also consider the more realistic case with $A - H$ interference assuming a fixed mass difference of 50 GeV, with 9 $m_A - m_H$ combinations: $250 - 200$, $300 - 250$, $350 - 300$, $400 - 350$, $550 - 500$, $700 - 650$, $800 - 750$, $900 - 850$, $1000 - 950$ GeV

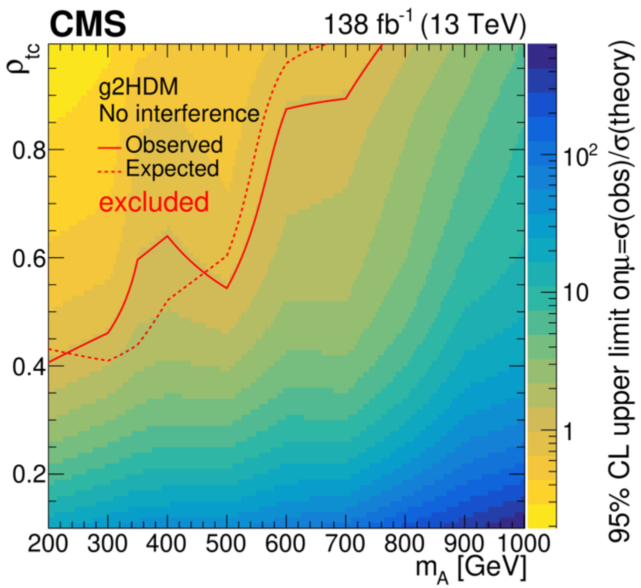
# Search for $pp \to tH / A \to tt\bar{q}$

## Results without interference



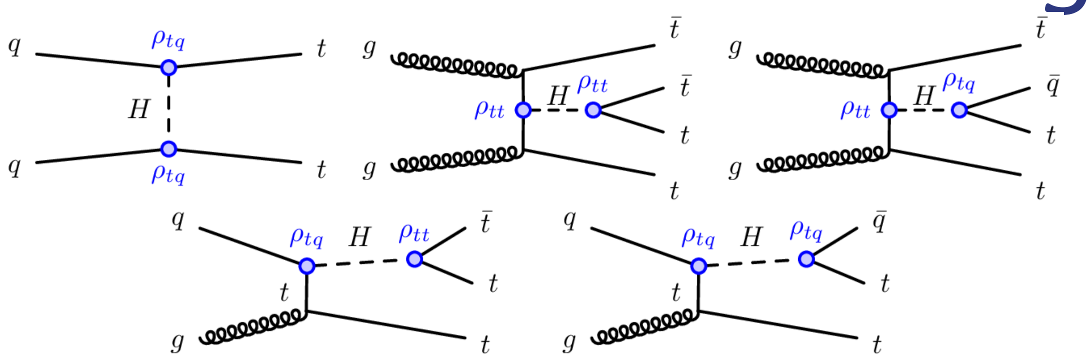
# Search for $pp \rightarrow tH\ /\ A \rightarrow tt\bar{q}$

## Results summary

| | Observed (expected) mass limit [GeV] | | |
|---|---|---|---|
| | without interference | with interference | with interference |
| | $m_A$ or $m_H$ | $m_A$ | $m_H$ |
| $\rho_{tu}$ | | | |
| 0.4 | 920 (920) | 1000 (1000) | 950 (950) |
| 1.0 | 1000 (1000) | 1000 (1000) | 950 (950) |
| $\rho_{tc}$ | | | |
| 0.4 | no limit | 340 (370) | 290 (320) |
| 1.0 | 770 (680) | 810 (670) | 760 (620) |

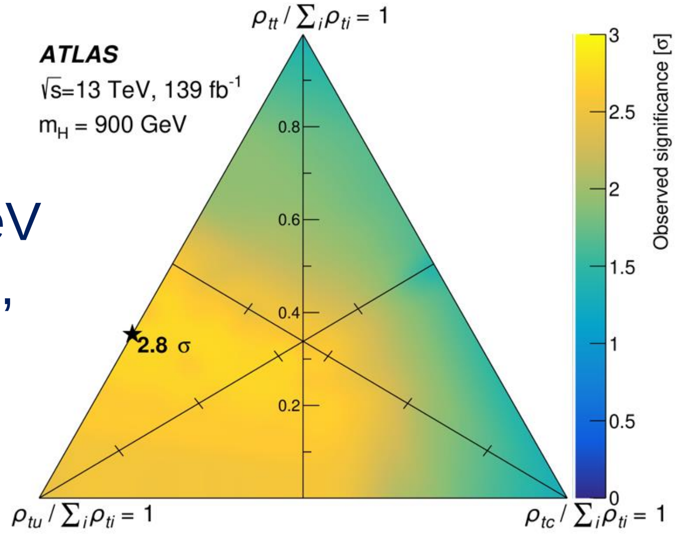
# ATLAS g2HDM analysis

[JHEP 12 (2023) 081](#)



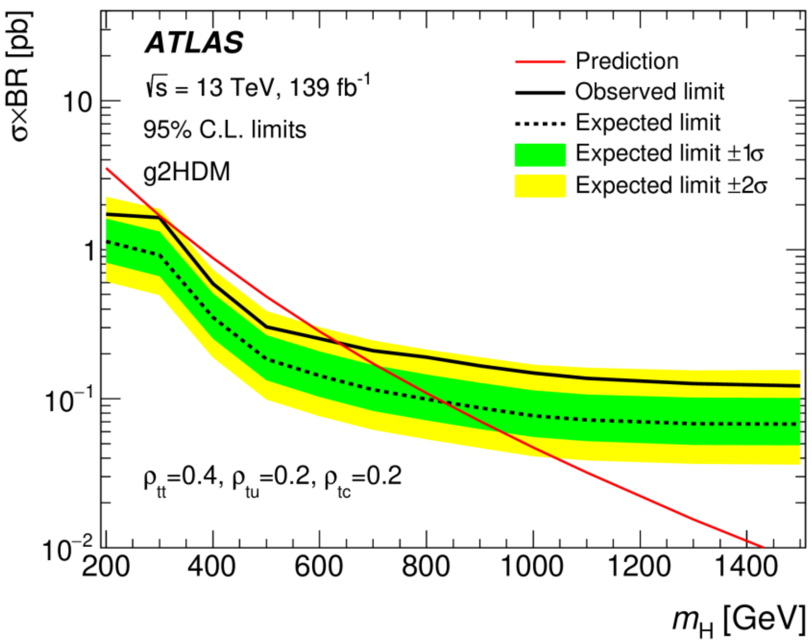
- No $A$-$H$ interference considered

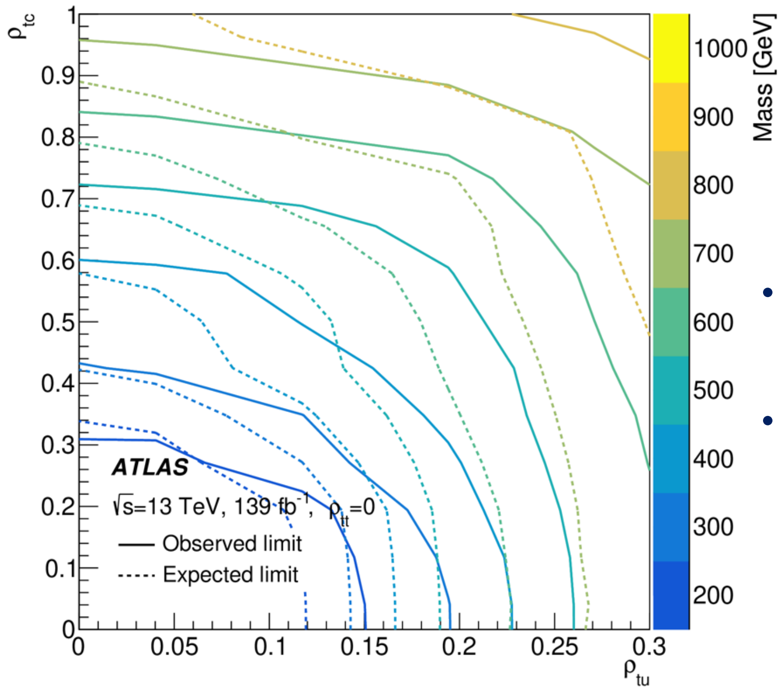
- Largest significance ($2.8\sigma$) for $m_H = 900$ GeV and $\rho_{tt} = 0.4$, $\rho_{tc} = 0.2$, $\rho_{tu} = 0.2$




Normalised to the sum of the couplings

- Considered also $\rho_{tt} \neq 0$
  - Limits only when $\rho_{tc} = \rho_{tu} = 0.2$




- Exclusion limits set for different choices of couplings
- For $\rho_{tt} = 0$, $\rho_{tc} = 0.2$ and $\rho_{tu} = 0.2$:
  - Observed (expected) limit for $m_H$ of 200-320 (200-560) GeV

# *Combination of searches for singly-produced VLQs*

## Input searches

| Analysis | Target signal | Decay channels | Discriminants |
|---|---|---|---|
| MONOTOP | $Wb/Zt \to T \to Zt$ | $Zt \to \nu\nu bqq$ ($0\ell$) | BDT score |
| HTZT | $Wb/Zt \to T \to Ht/Zt$ | $Ht/Zt \to bbb\ell\nu/qqb\ell\nu$ ($1\ell$) | $m_{\text{eff}}$ |
| OSML | $Wb/Zt \to T \to Zt$ | $Zt \to \ell\ell b\ell\nu$ ($3\ell$), $Zt \to \ell\ell bqq$ ($2\ell$) | $Z$ boson $p_{\text{T}}$ |

**MonoTop**
- Boosted hadronically-decaying top quark
- Large missing $p_T$
- 1 forward ($2.5 < |\eta| < 4.5$) anti-$k_T$, $R = 0.4$ jets
- Discriminating variable: BDT output score

**HTZT**
- Single lepton
- Multiple anti-$k_T$, $R = 0.4$ jets and *b*-tagged jets
- 1 forward ($2.5 < |\eta| < 4.5$) anti-$k_T$, $R = 0.4$ jets
- Discriminating variable: scalar sum of $p_T$ of all central jets, leptons and $E_T^{miss}$, $m_{eff}$

**OSML**
- Pair of leptons with opposite charge
- Multiple anti-$k_T$, $R = 0.4$ *b*-tagged jets
- 1 forward ($2.5 < |\eta| < 4.5$) anti-$k_T$, $R = 0.4$ jets
- Discriminating variable: $p_T^Z$

# Combination of searches for singly-produced VLQs

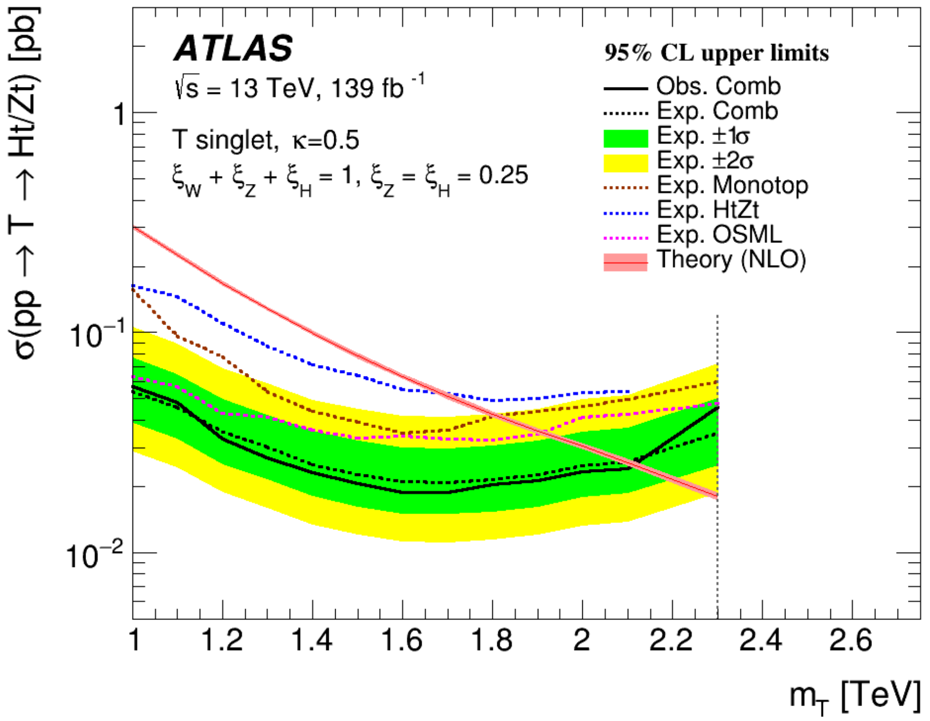
## Uncertainties

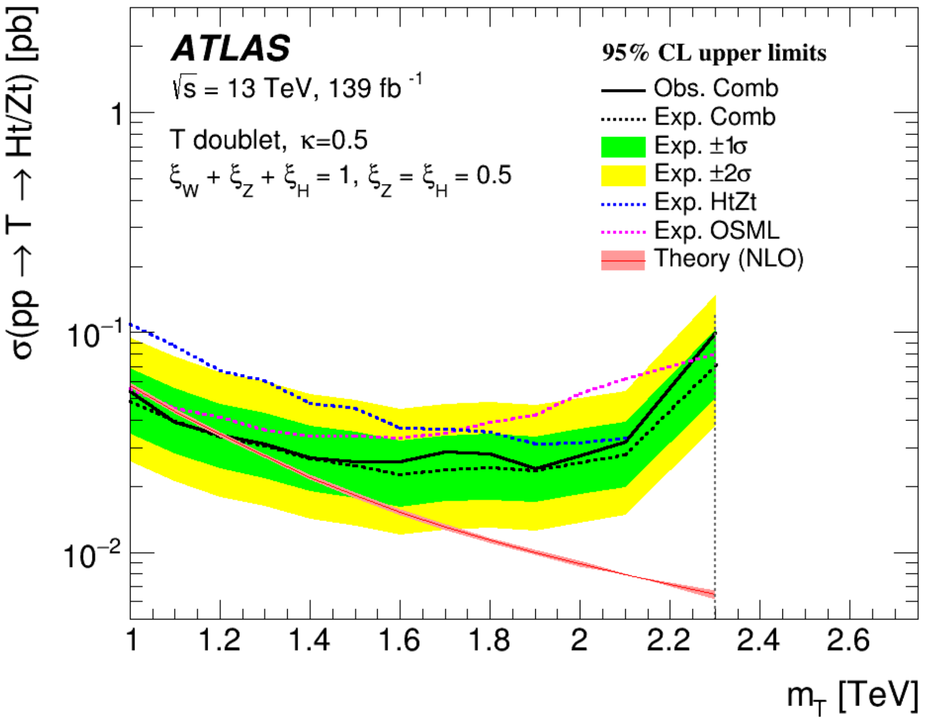
| Category | MONOTOP | HTZT | OSML | Correlating |
|---|---|---|---|---|
| Lepton and $E_{T}^{miss}$ uncertainties | | | | |
| Electron uncertainties | | ✓ | ✓ | All |
| Muon uncertainties | | ✓ | ✓ | All |
| $E_{T}^{miss}$ uncertainties | ✓ | ✓ | ✓ | All |
| Jet uncertainties | | | | |
| JES uncertainties | ✓ | ✓ | ✓ | All |
| JER uncertainties | ✓ | ✓ | ✓ | HTZT and OSML |
| JMS uncertainties | | ✓ | | None |
| JMR uncertainties | ✓ | ✓ | | None |
| Tagging uncertainties | | | | |
| Flavor-tagging uncertainties | ✓ | ✓ | ✓ | MONOTOP and OSML |
| Top-tagging uncertainties | ✓ | | | None |
| $W/Z$-tagging uncertainties | ✓ | | | None |
| Background modeling uncertainties (constrained) | ✓ | ✓ | ✓ | None |
| Background normalization factors (unconstrained) | | | | |
| $t\bar{t}$ normalization | ✓ | | | None |
| $V$+jets normalization | ✓ | | | None |
| $Z$+light-jets normalization | | | ✓ | None |
| $Z$+heavy-flavor normalization | | | ✓ | None |
| $t\bar{t}V$ normalization | | | ✓ | None |
| $VV$ normalization | | | ✓ | None |

# Combination of searches for singly-produced VLQs

## Limits: $\kappa = 0.5$

- Limits are calculated for the sum of the production cross sections times branching ratio of the four production and decay modes considered
- Comparing the obtained cross section limits with the theoretical cross section, limits are derived on $m_T$ and $\kappa$
  - signal efficiencies for the considered models are generally different, so limits are independently determined for combinations of $m_T$, $\kappa$ and branching ratios

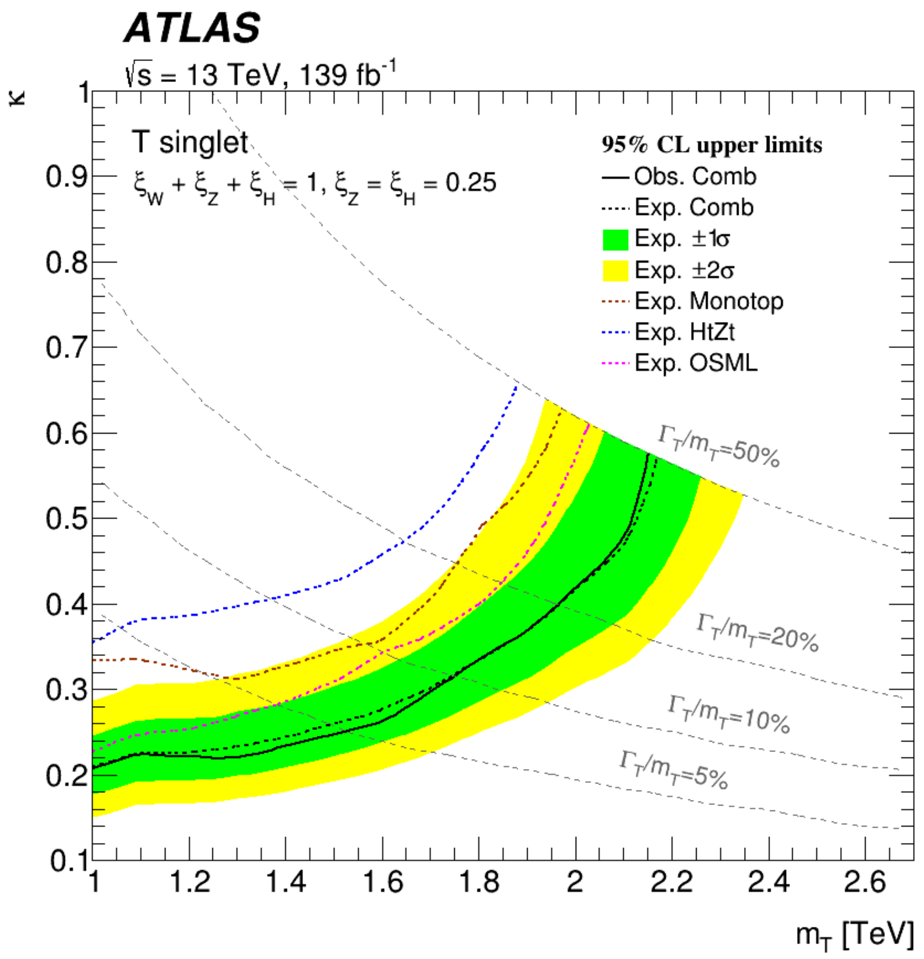


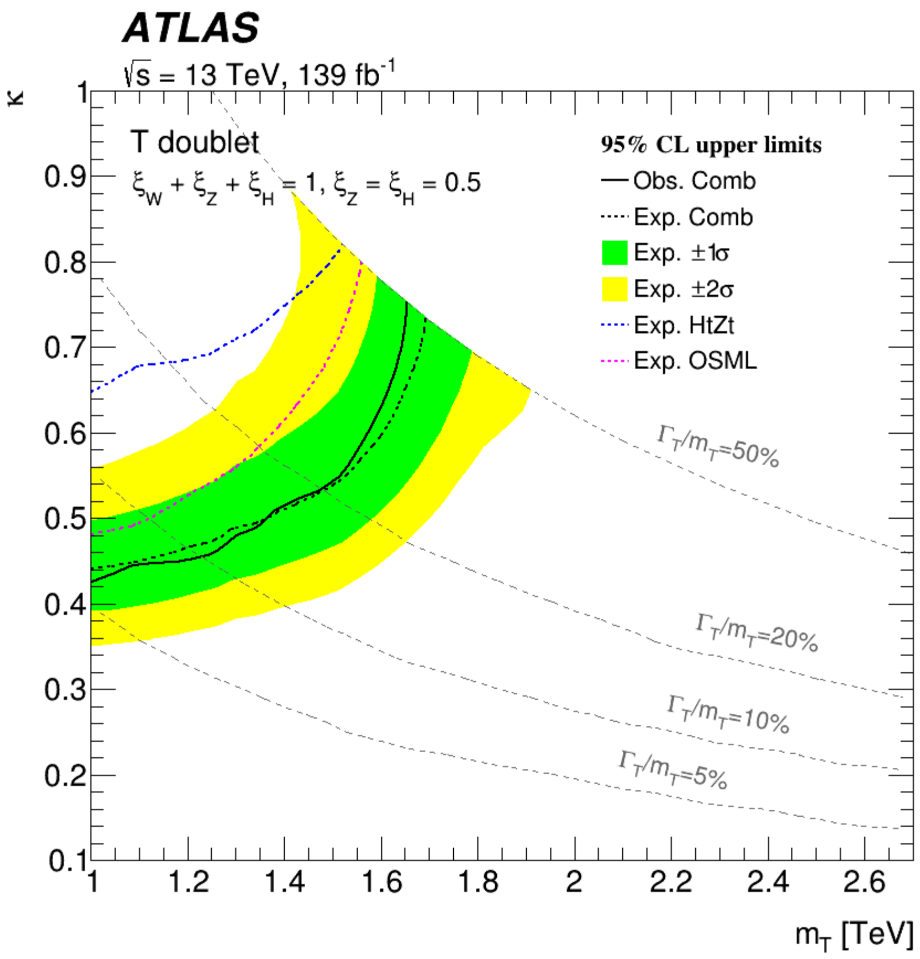



# *Combination of searches for singly-produced VLQs*

## Excluded regions

- Limits are computed for a finite number of points in the $m_T - \kappa$ plane
  - interpolated using a piecewise function between the measured points to obtain a continuous shape in the exclusion contours



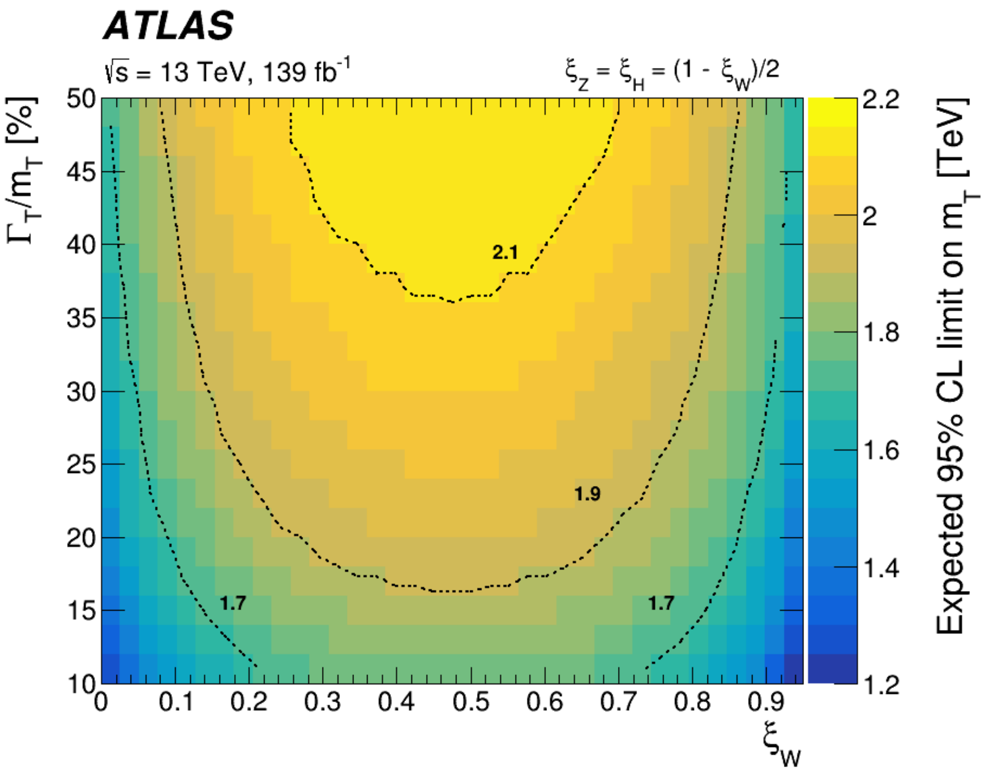



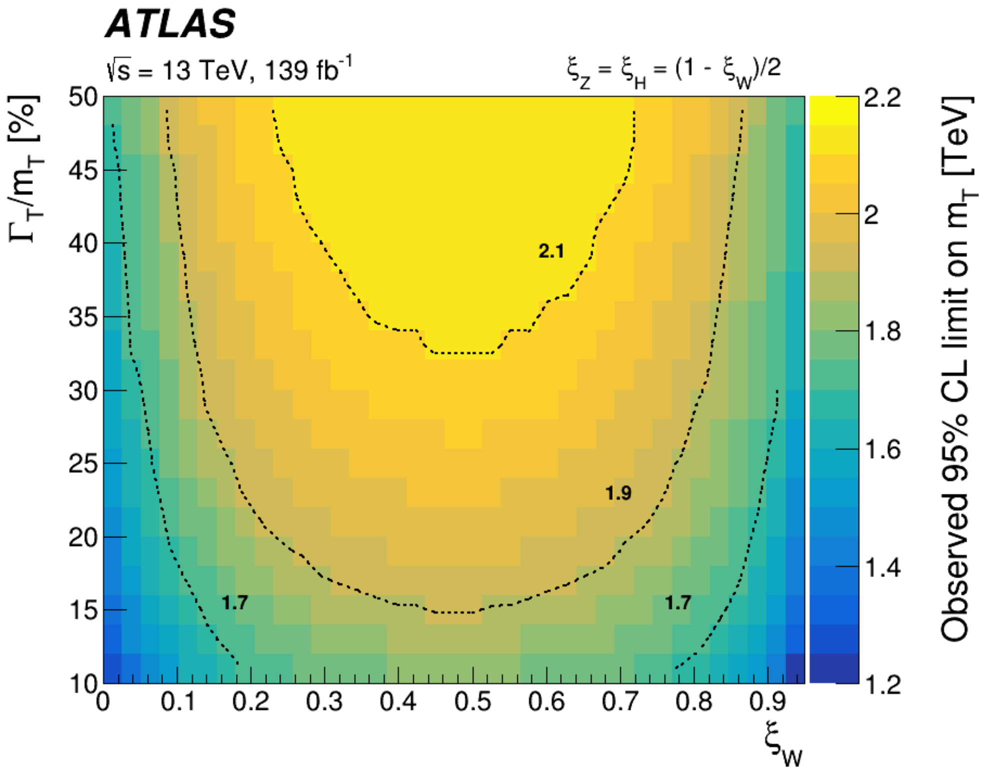
# Combination of searches for singly-produced VLQs

## Limits in mass plane

- Limits can be generalised for arbitrary values of $\xi_W$
- Relative width of $T$, $\Gamma_T/m_T$, is completely determined by $m_T$ and $\kappa$

| Representation | $\Gamma_T/m_T$ [%] | Obs./Exp. mass limit [TeV] |
|---|---|---|
| SU(2) singlet ($\xi_W = 0.5$) | 20 | 2.0 / 2.0 |
| SU(2) singlet ($\xi_W = 0.5$) | 50 | 2.1 / 2.1 |
| SU(2) doublet ($\xi_W = 0.0$) | 20 | 1.4 / 1.4 |
| SU(2) doublet ($\xi_W = 0.0$) | 50 | 1.6 / 1.7 |



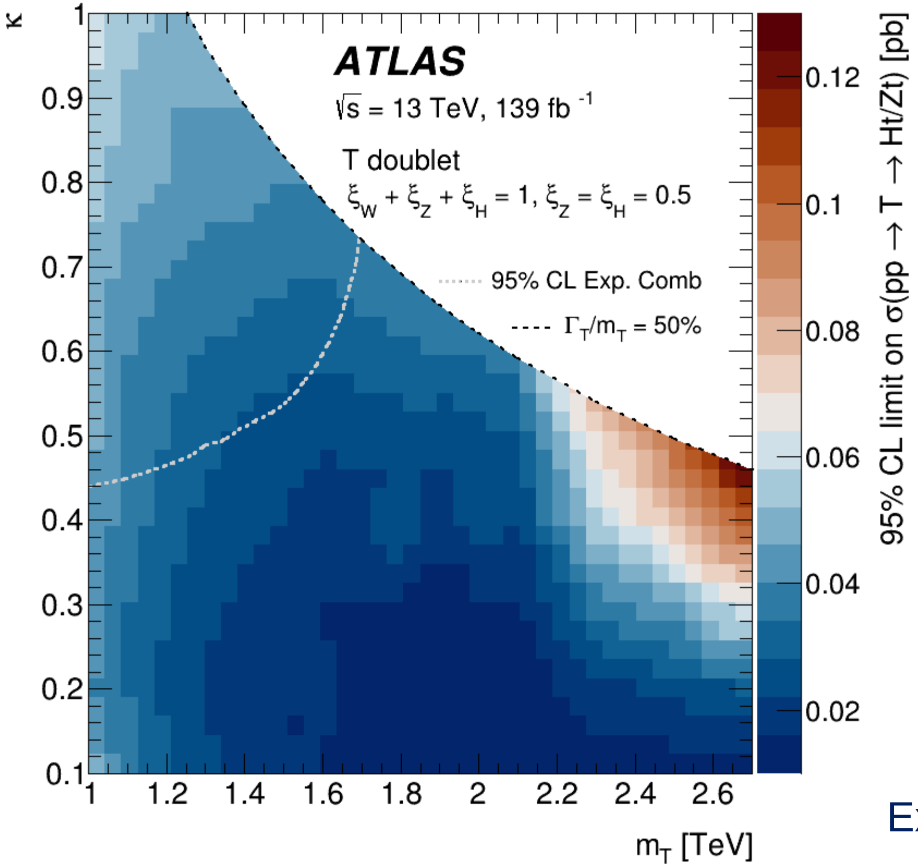



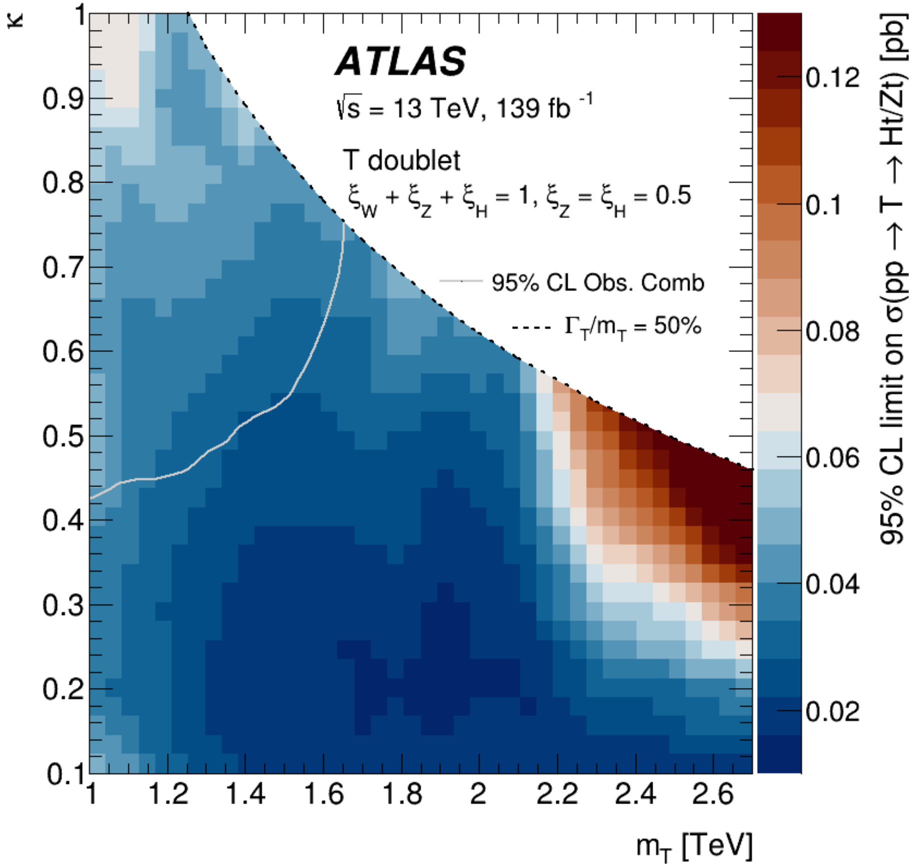

- Largest excluded mass is 2.1 TeV for large $\Gamma_T/m_T$ and $\xi_W = 0.5$
  - equivalent to $SU(2)$ representation with a branching ratio to $Wb$ of 50%

# Combination of searches for singly-produced VLQs

## Results: *T SU(2)* doublet

- Also interpreted as exclusion limits on the total cross section as a function of $m_T$ and $\kappa$



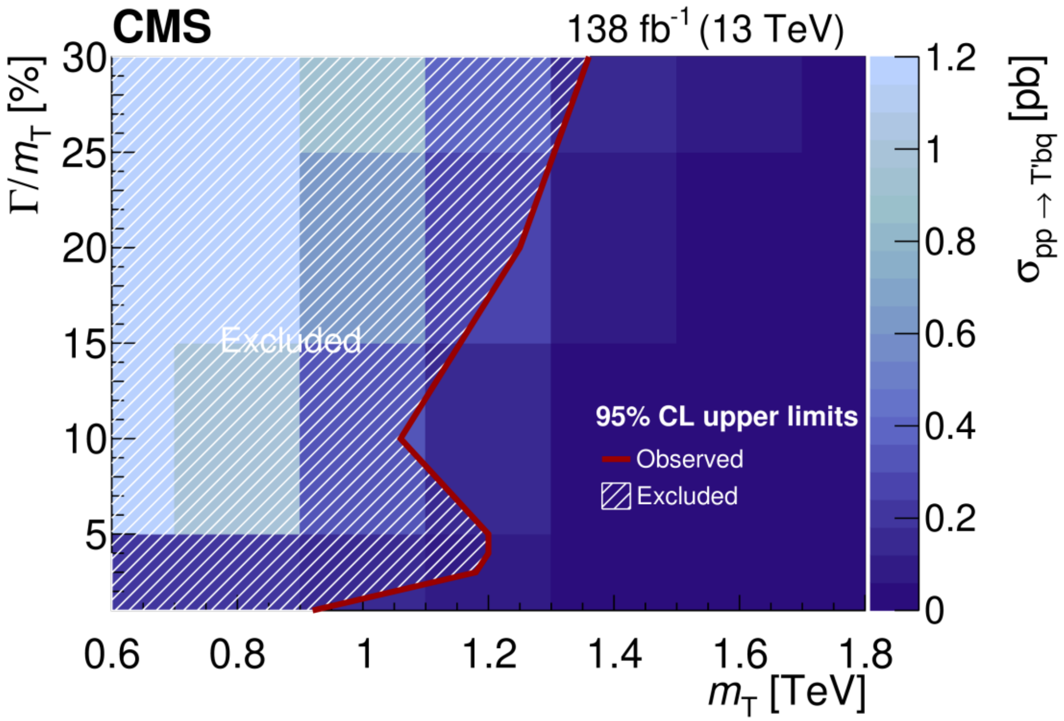

Exclude $\kappa > 0.4$ for low $m_T$

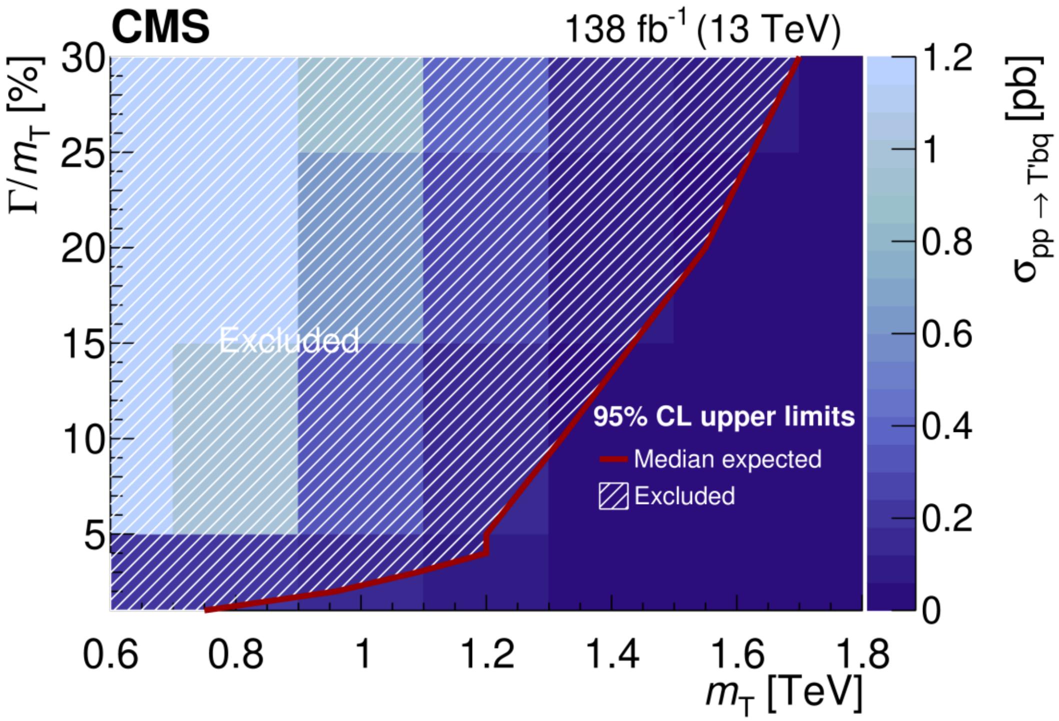
Exclude $m_T < 1.7$ TeV for $\kappa \sim 0.7$

# Combination of searches for singly-produced VLQs

## Results: Different widths

- Also interpreted as exclusion limits on the total cross section as a function of $m_T$ and $\Gamma/m_T$




Exclude $m_T < 1.20$ TeV for $\Gamma/m_T = 5\%$

Exclude $m_T < 1.06$ TeV for $\Gamma/m_T = 10\%$

Exclude $m_T < 1.25$ TeV for $\Gamma/m_T = 20\%$

Exclude $m_T < 1.36$ TeV for $\Gamma/m_T = 30\%$