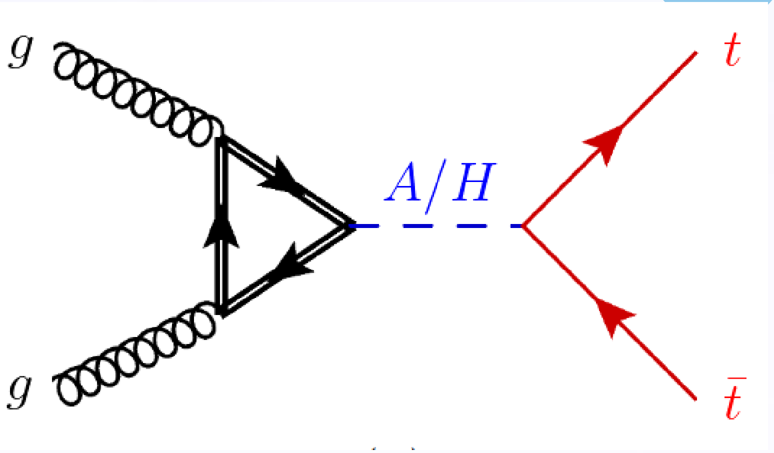
Results from the ATLAS $A/H \to t\bar{t}$ search

Dr Eleanor Jones

17th January 2025

DESY FH Particle Physics Seminar



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All figures including auxiliary figures available at:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2020-25/

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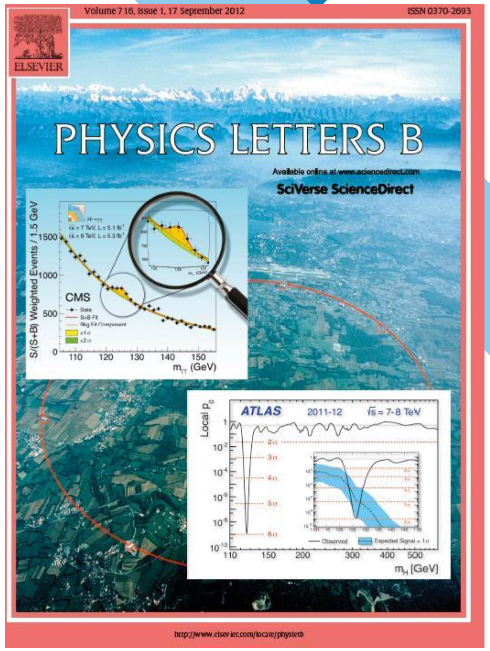
Motivation (1)

- 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



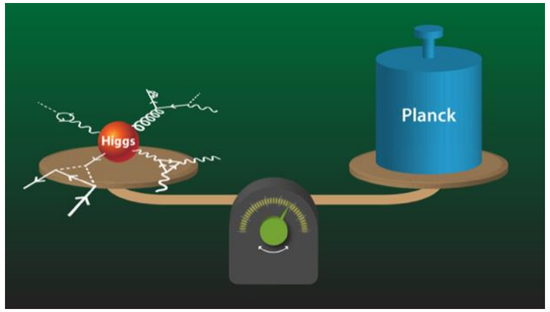


Photo: Alan Stonebraker

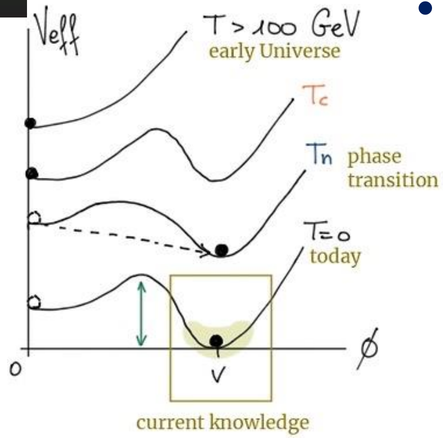
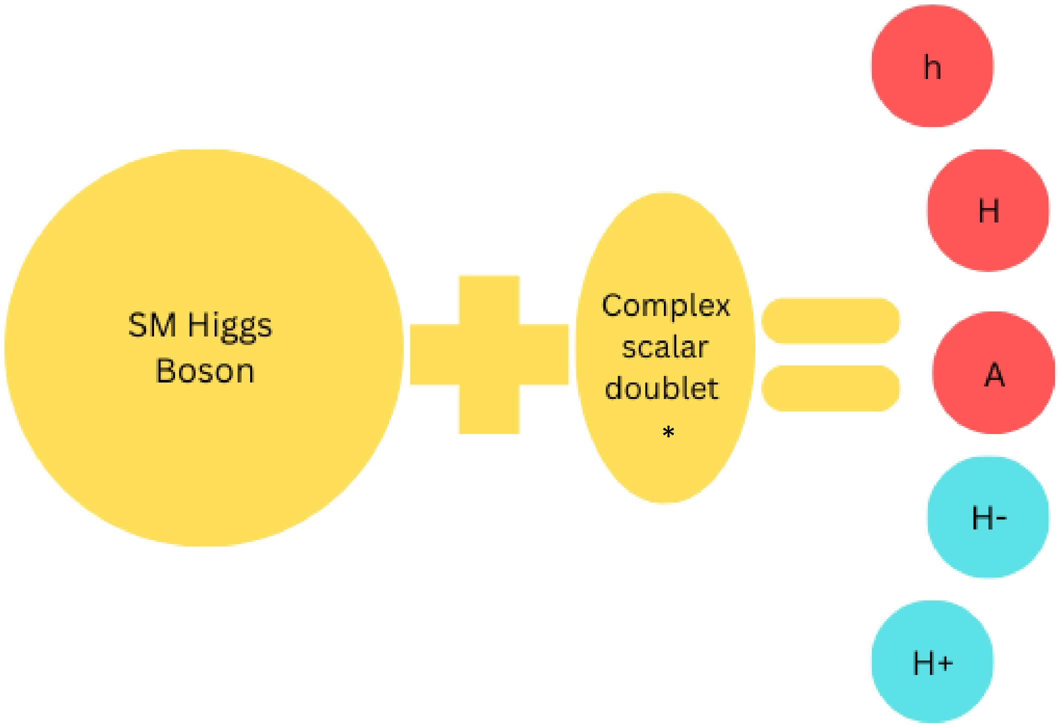


Photo: Kateryna Radchenko Serdula

- 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

* with CP conserving potential

Benchmark scenarios

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

- **hMSSM**

- **2HDM+a**

Benchmark scenarios

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

Requires $\mathbb{Z}_2$ symmetry
Describes which fermion couples to which doublet

- **hMSSM**
- **2HDM+a**

Benchmark scenarios

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

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Describes which fermion couples to which doublet

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

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

- **hMSSM**

- **2HDM+a**

Benchmark scenarios

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- **hMSSM**

Simplified SUSY benchmark, deriving from MSSM

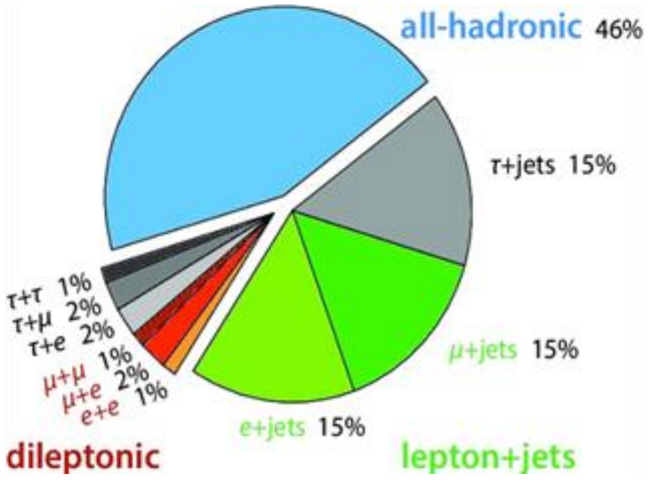
$h = h_{\mathrm{SM}}$
$\Longrightarrow$
only $\tan\beta$ and m_A are free parameters

- **2HDM+a**

Additional fermionic DM particle, χ, with CP-odd mediator, a

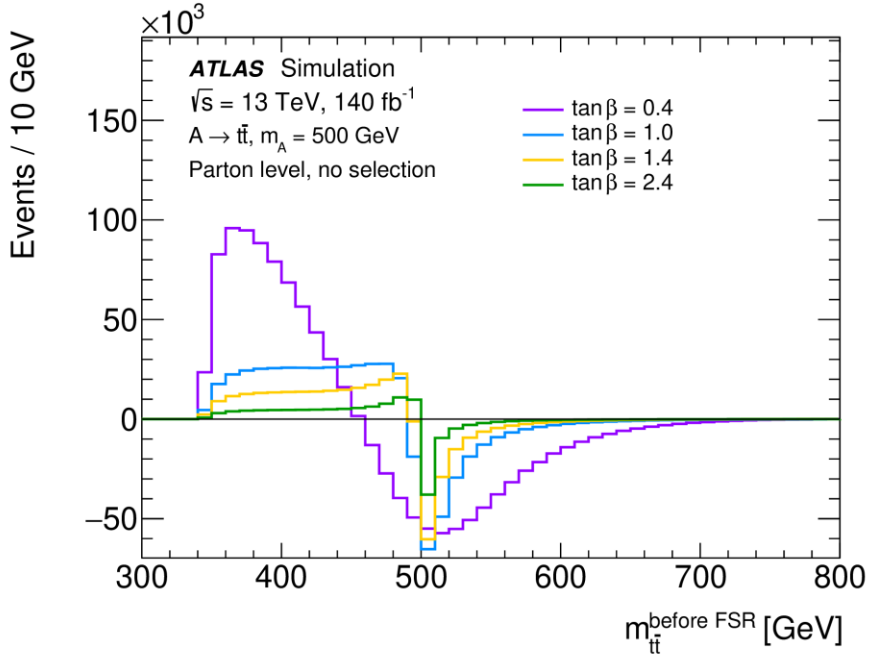
Overview

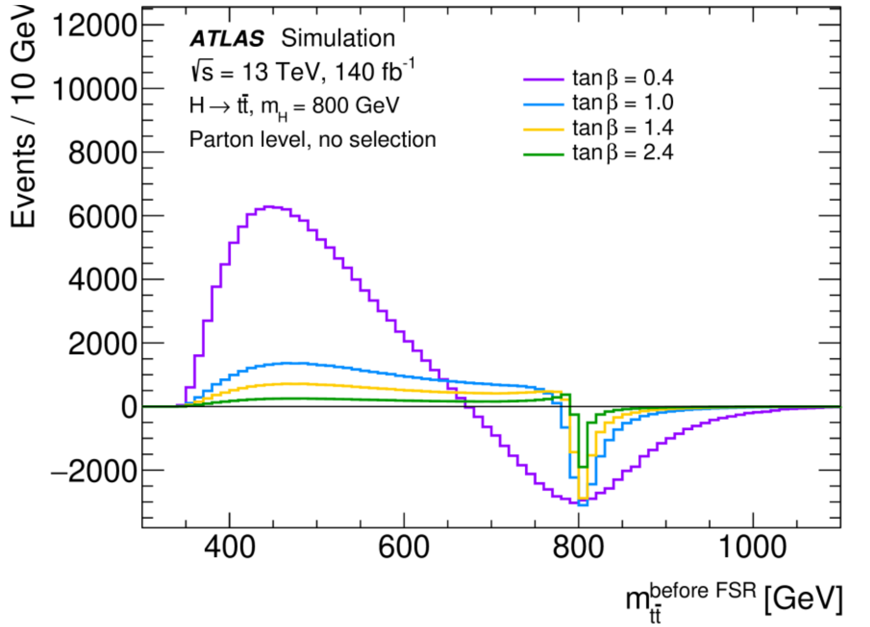
- Strong interference between the signal and the SM $t\bar{t}$ process leads to a peak-dip structure
  - A and H do not interfere since they are orthogonal CP states
  - The peak-dip structure is strongly model dependent



From arXiv:2007.14701

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





Event selection: 1L

- Standard run and event cleaning
- Single-lepton trigger (e or μ)
- 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%)

CMS ask for ≥ 2 *b*-tagged jets

CMS split into 3 or ≥ 4 jets

Total of 11 orthogonal signal regions

CMS have 10 signal regions in total

CMS do not include a merged region

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
- $\Delta R(l, b_l) < 2.0$
- $\Delta R(l, t_h) > 1.5$
- $\Delta R(b_l, t_h) > 1.5$

Event selection: 2L

- Standard run and event cleaning
- Single-lepton trigger (e or μ)
- == 2 leptons (ee, $\mu\mu$, $e\mu$) with $p_{\mathrm{T}} > 25$ GeV (orthogonality with 1L)
  - Leading one: $p_T > 28$ GeV (trigger)
- ≥ 2 small-R jets and ≥ 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 ≥ 1 b-jet assignment

CMS use spin correlation variables

$m_{\ell\ell bb}$ is the discriminating variable

- If ≥ 2 b-jets: use the 2 leading b-jets
- If $== 2$ b-jet: use the b-jet + the leading non-b-jet

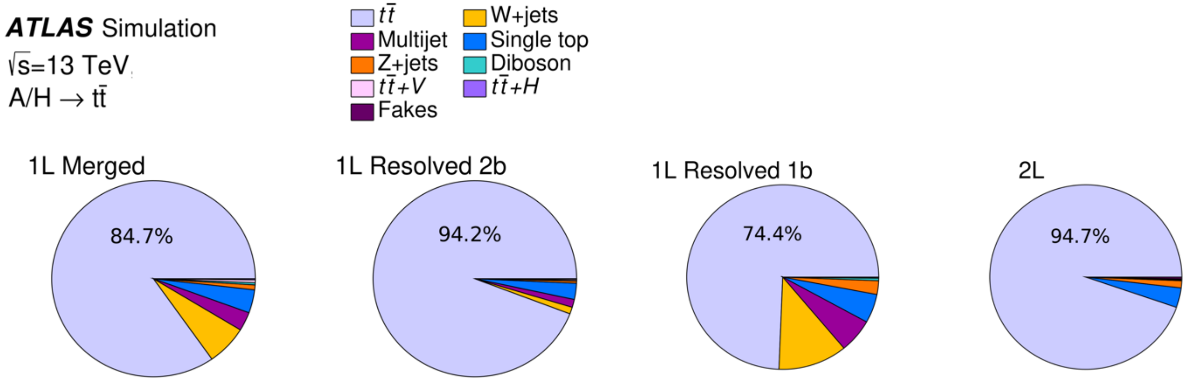
CMS use $m_{t\bar{t}}$

Additionally binned in $\Delta\phi_{\ell\ell}$

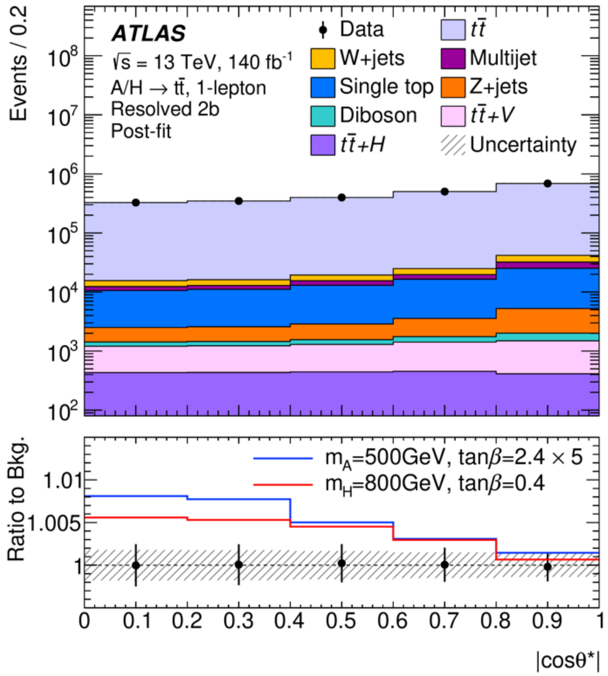
Backgrounds

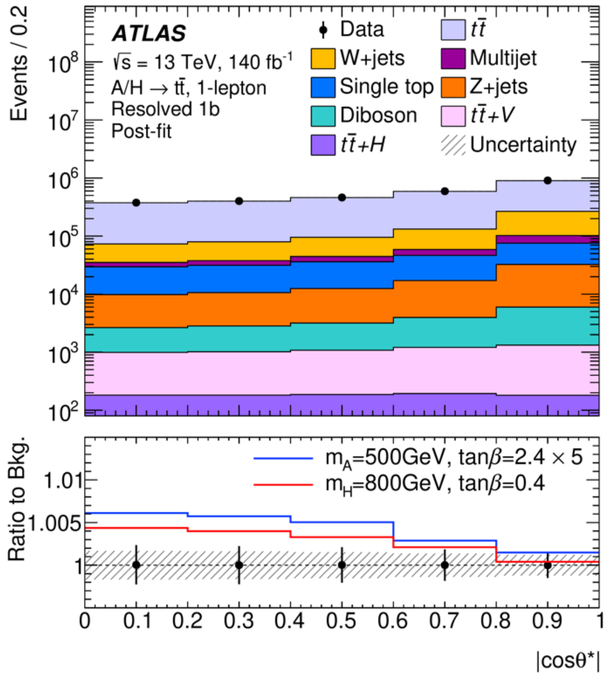
Different methods and different top quark mass used by ATLAS and CMS

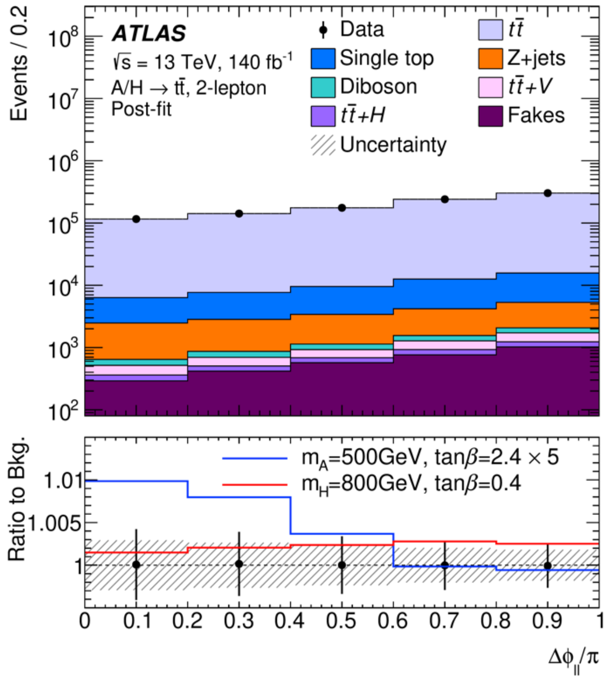
- Dominant and irreducible background: SM $t\bar{t}$ reweighted to NNLO-QCD+NLO-EW predictions



- Single-top production, $t\bar{t}V$, di-boson (all 1L and 2L), $t\bar{t}H$, $Z+$jets (1L), fakes (2L): directly from MC
- Multijet (1L): data-driven estimate
- W $+$ jets (1L), $Z+$jets (2L): MC with data-driven correction



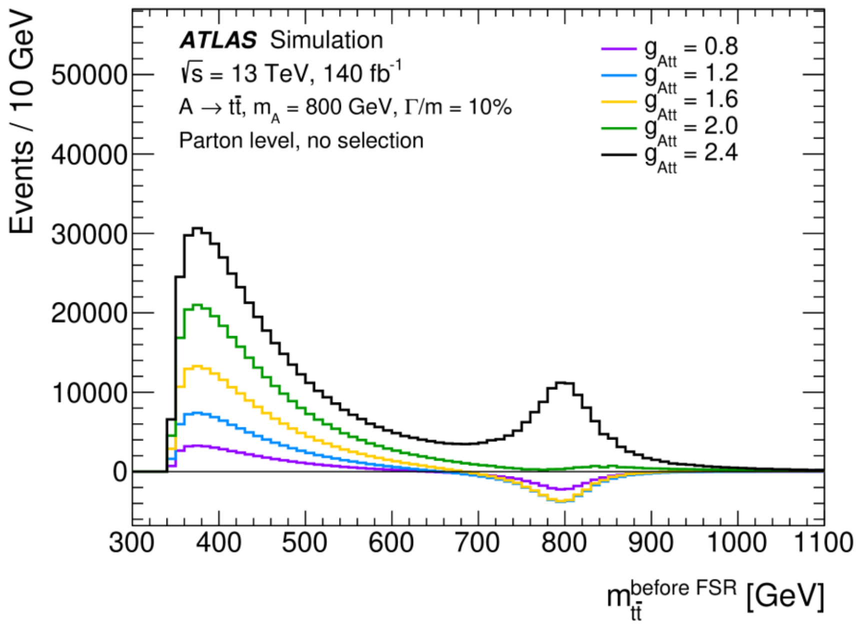




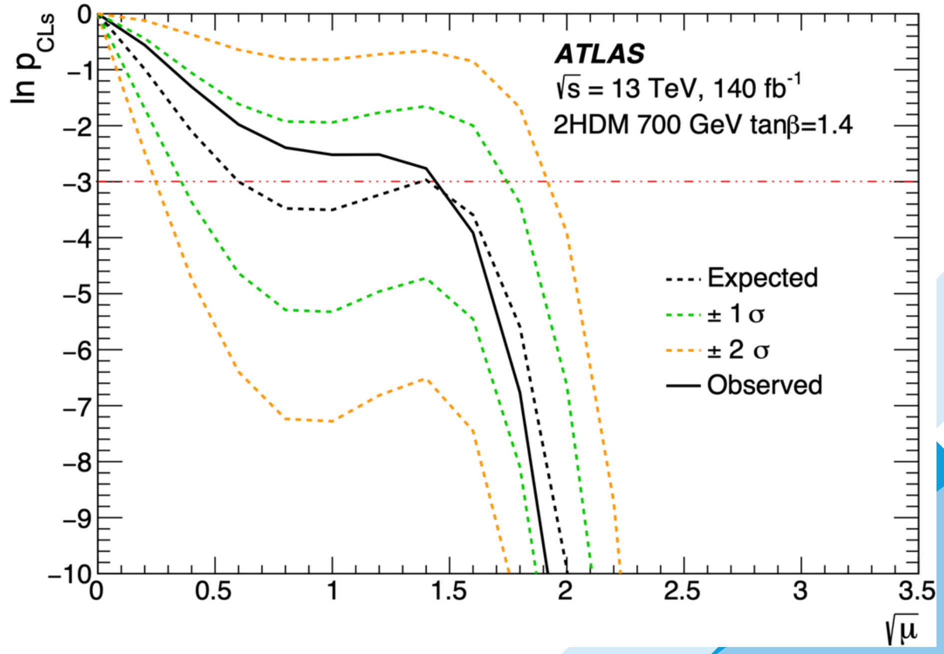
Statistical analysis

- 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



Choice of test statistic

CMS compare to global minimum instead of $\mu = 0$, leading to slightly more optimistic constraints at the cost of interpretability

- 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

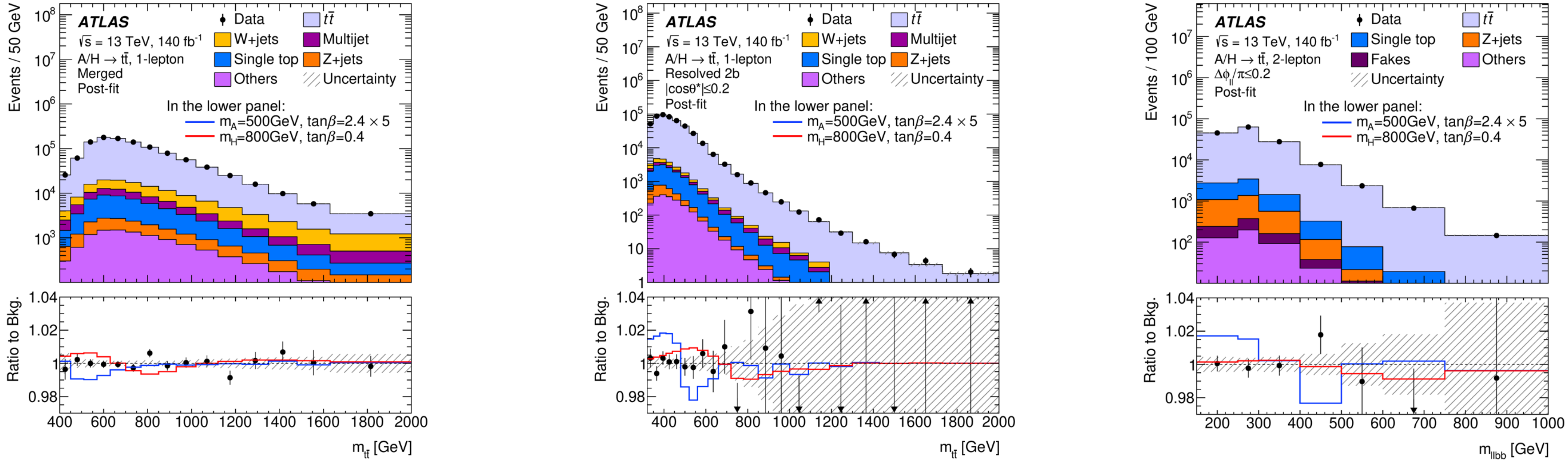
$$q_{1,0} = -2\ln\frac{\mathcal{L}\left(1, \hat{\hat{\theta}}_1\right)}{\mathcal{L}\left(0, \hat{\hat{\theta}}_0\right)}$$

Should we reject the BSM hypothesis under consideration?

- Test (dis)agreement of data with specific interference pattern of tested signal hypothesis
- Always testing against the SM for the sake of interpretability leading to slightly less optimistic constraints

Results: Search stage

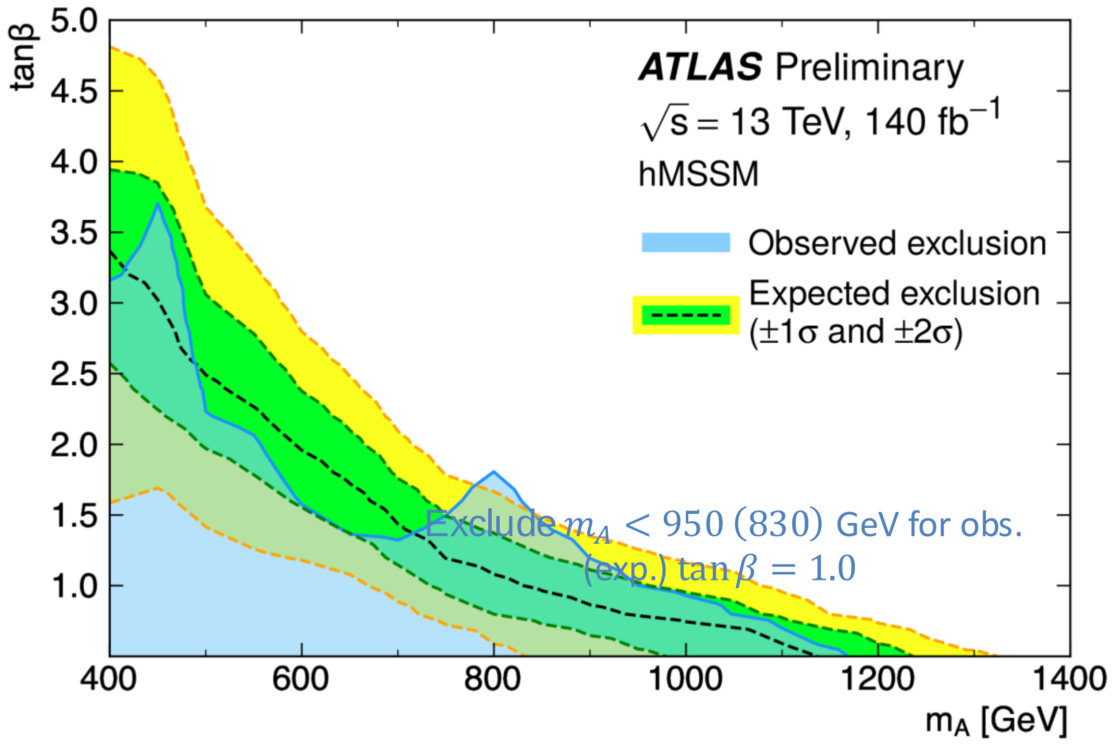
- Tested agreement between data and S+I+B hypotheses with $m_{A/H} \in [400{,}1400]$ GeV and $\Gamma_{A/H} \in [1{,}40]\%$
  - Most significant deviation from SM ($2.3\ \sigma$ local): $m_A = 800$ GeV, $\Gamma_A = 10\%$ and $\sqrt{\mu} = 4.0$



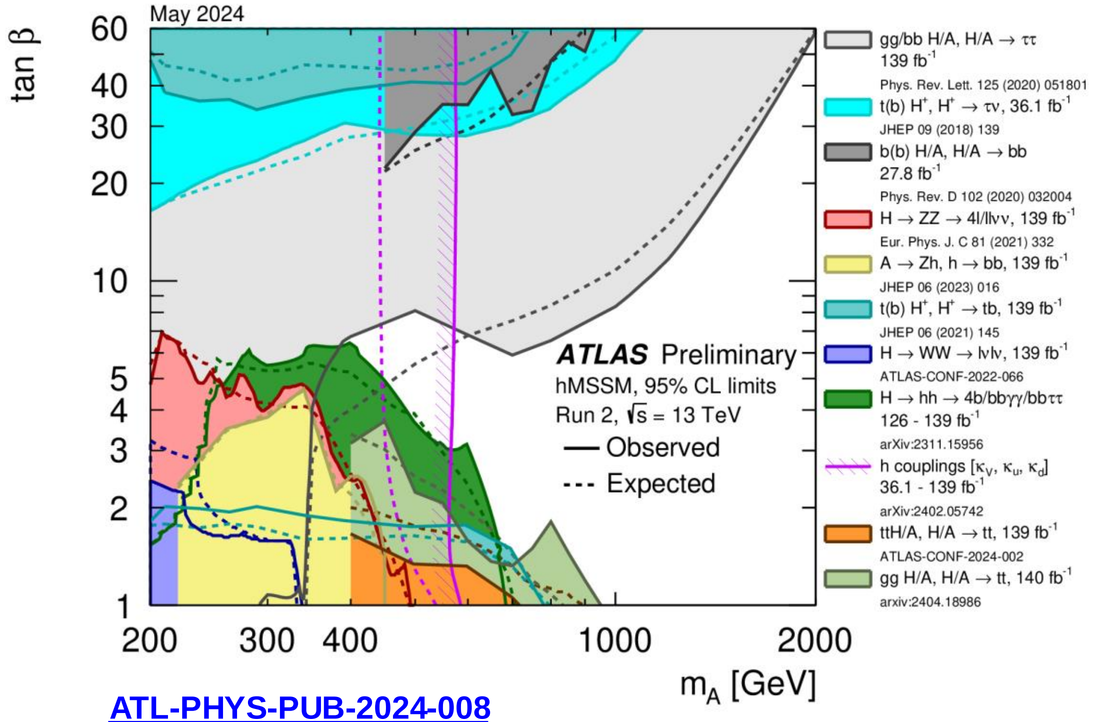
Results: hMSSM

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

Exclude $\tan\beta < 3.16$ for $m_A = m_H = 400$ GeV in the hMSSM



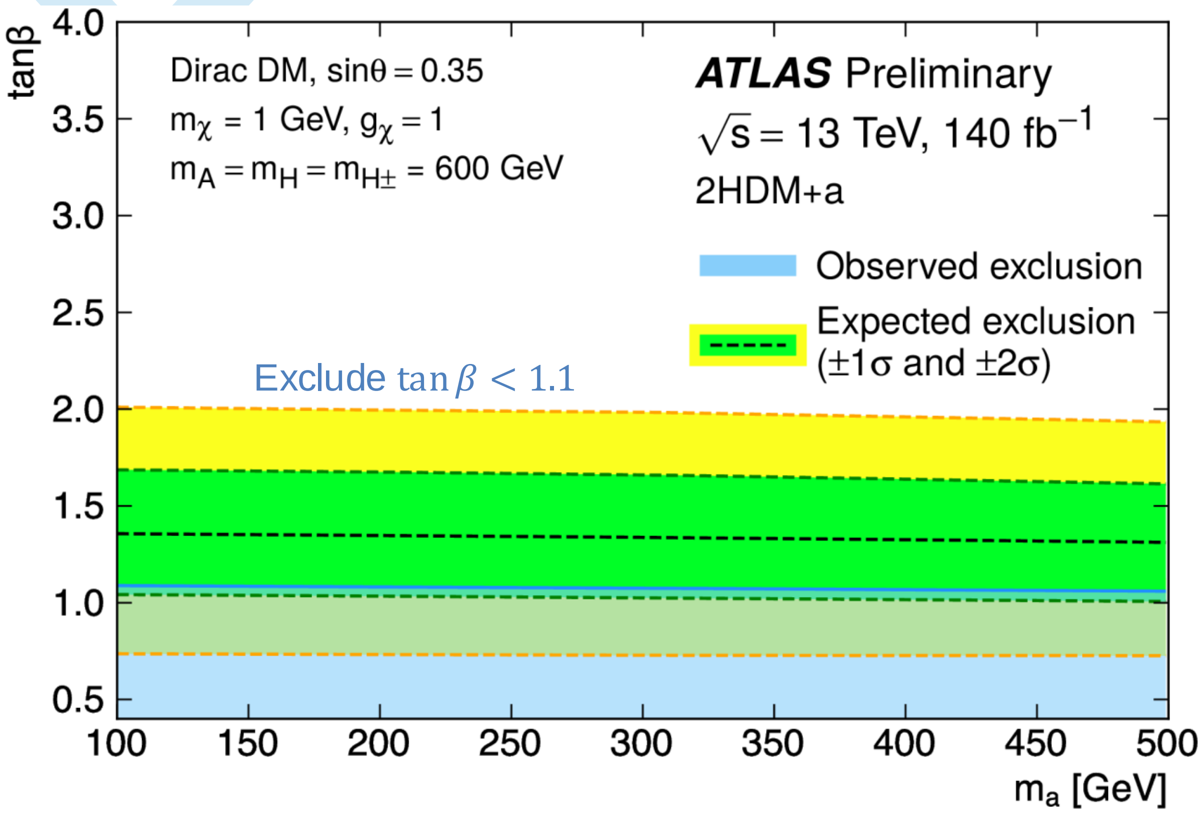
Exclude $m_A < 950\ (830)$ GeV for obs. (exp.) $\tan\beta = 1.0$

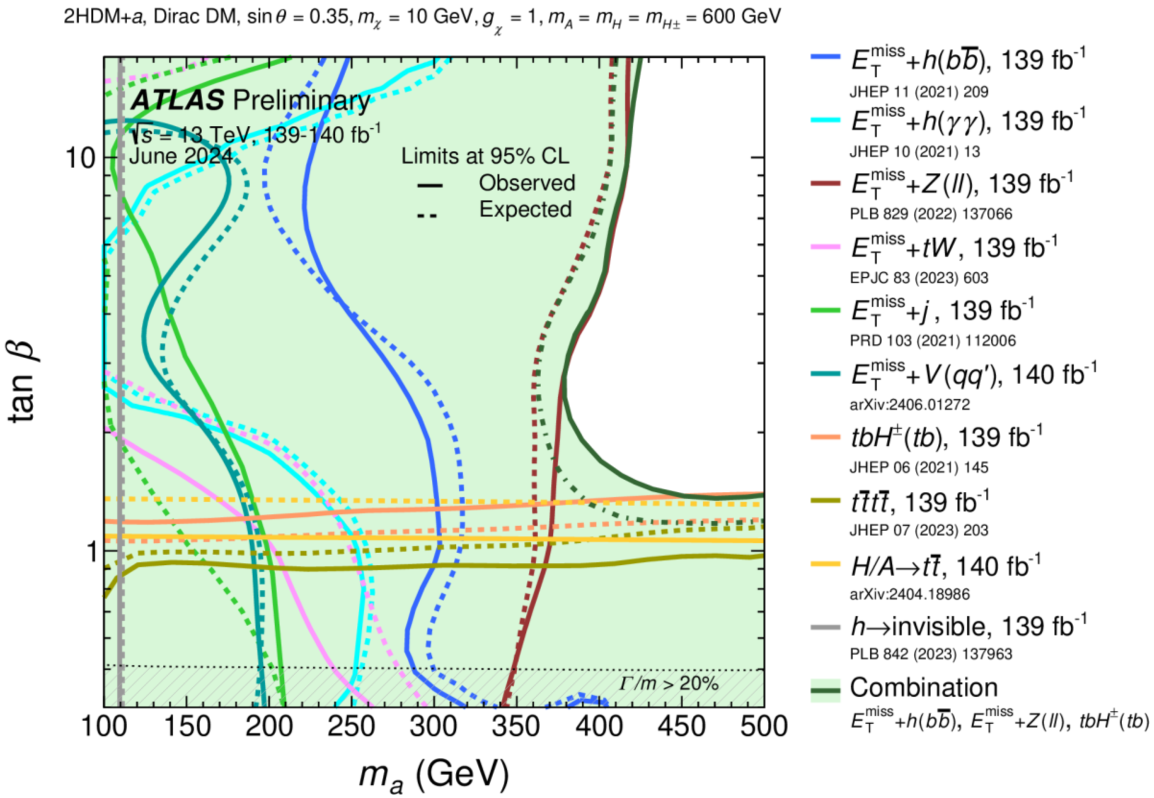


ATL-PHYS-PUB-2024-008

Results: 2HDM+a

First dark matter interpretation of an interference search!





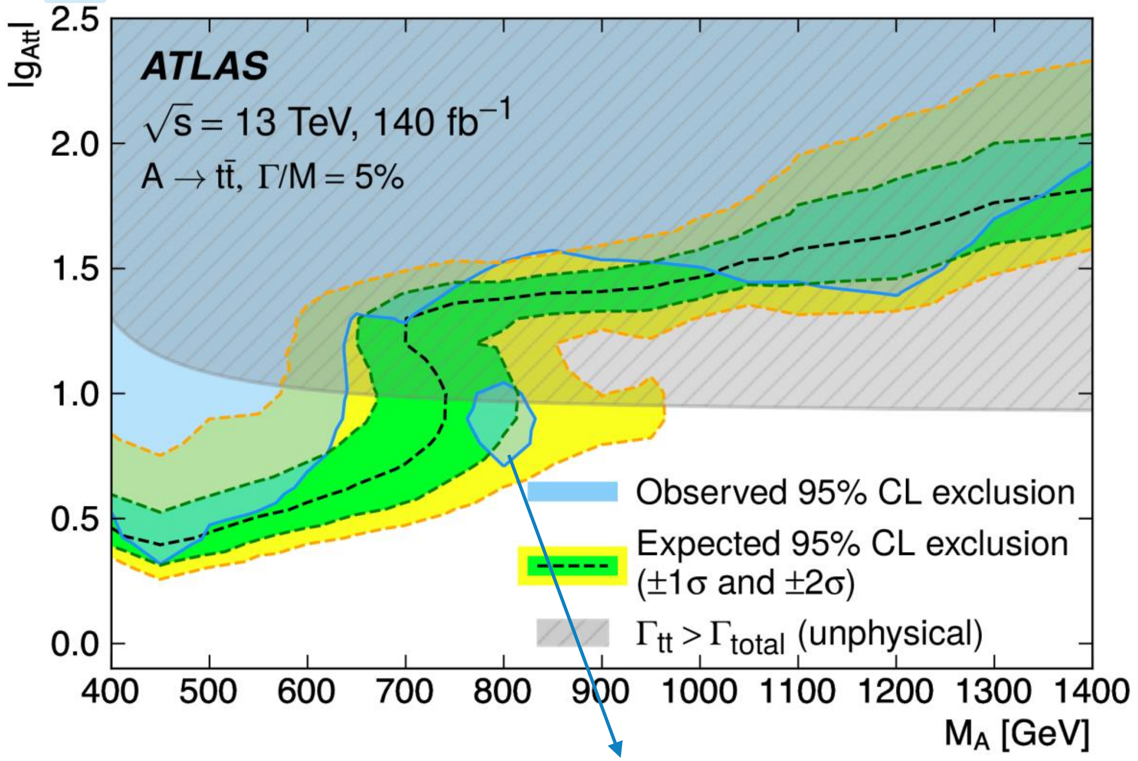
ATL-PHYS-PUB-2024-010

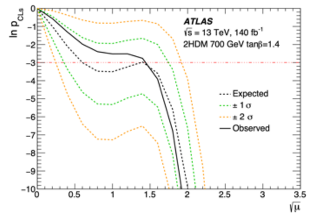
Strongest expected limits at high mediator mass to date!

Results: Model-independent

Constraints on the coupling strength modifier

- Most comparable with CMS results



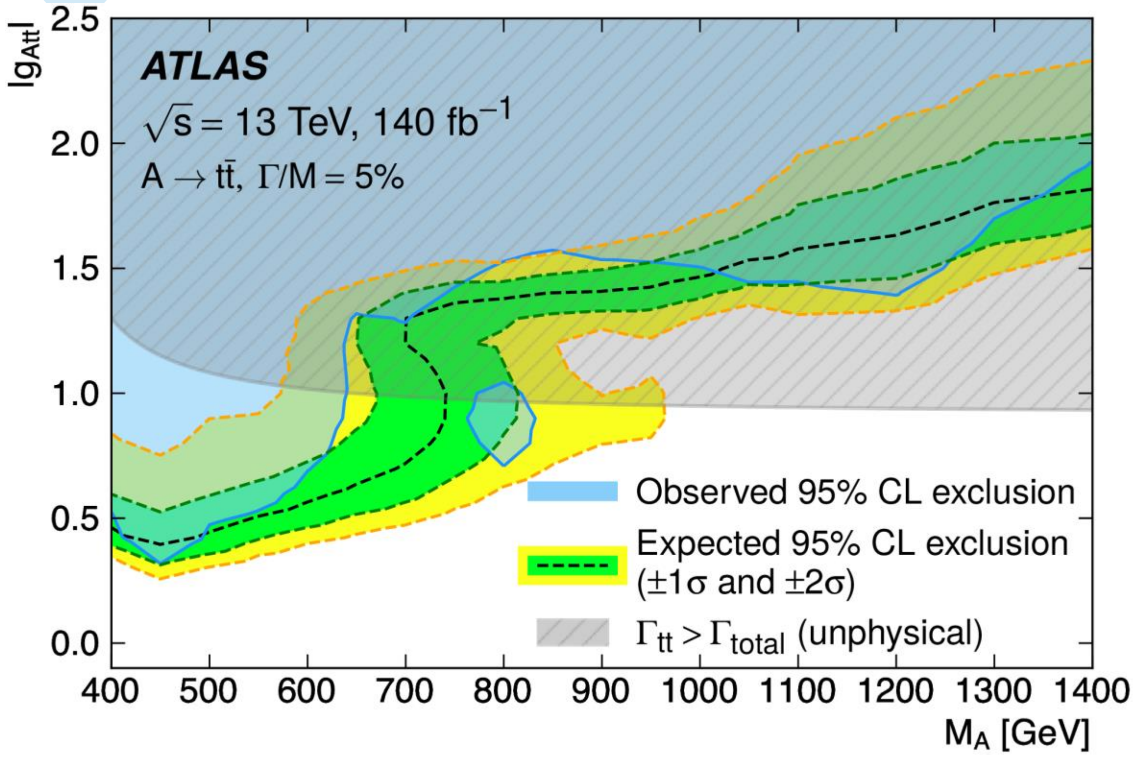


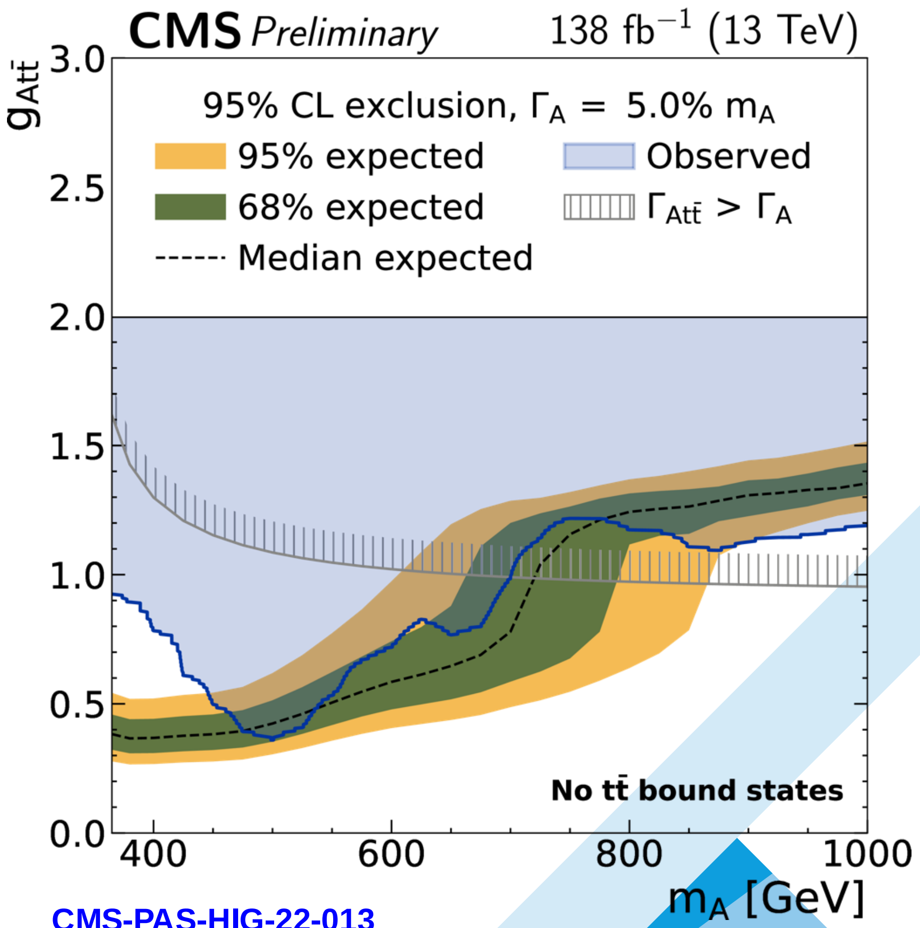
- No exclusion regions calculated for masses < 400 GeV
  - LO signal model is a poor approximation of the actual interference pattern in this region
  - Large k-factors are observed for signals in this region

- "Islands" and "holes" observed in limit plots due to double minima in likelihood scan
  - More appropriate for the treatment of the interference

Results: Model-independent

- Above ~ 450 GeV, very similar sensitivity observed
  - Is the much better ATLAS 1L sensitivity compensating for the much better CMS 2L sensitivity?





CMS-PAS-HIG-22-013

Summary

- ATLAS analysis has set constraints on a variety of BSM models including:
  - strongest constraints on m_A at $\tan\beta = 1.0$ in the hMSSM to date!
  - first dark matter interpretation of an interference search, giving the strongest expected limits at high mediator mass to date!

- Comparable sensitivities observed by ATLAS and CMS for $m_{A/H}$ above ~ 450 GeV

So… what next?

- What is the origin of the CMS excess? Why does ATLAS not see this excess?
  - Is it Toponium?
  - Is it BSM?
  - Is it background (mis)modelling?

- Many investigations are already ongoing jointly between ATLAS and CMS
  - The spin correlation observables used by CMS in the 2L channel dramatically increase sensitivity at threshold
  - CMS and ATLAS see similar behaviour pre-fit, but not post-fit
  - CMS do not see the same large impact from $t\bar{t}$ modelling uncertainties that dominate the ATLAS search

- An exciting prospect lies in wait…

Thank You

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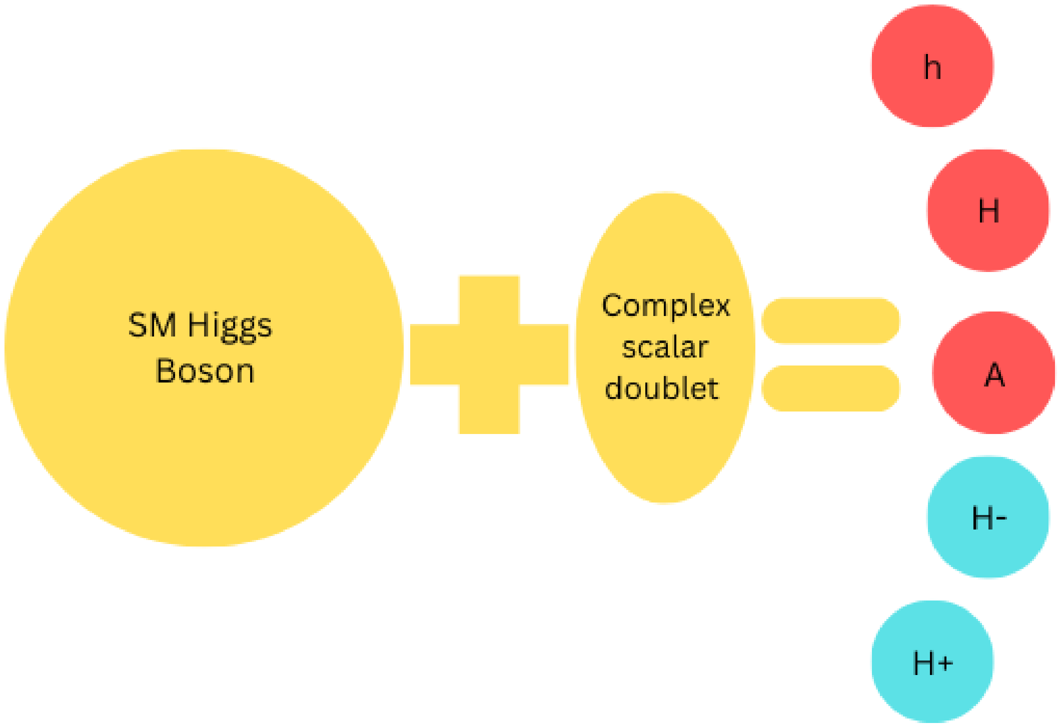
Backup

2HDMs

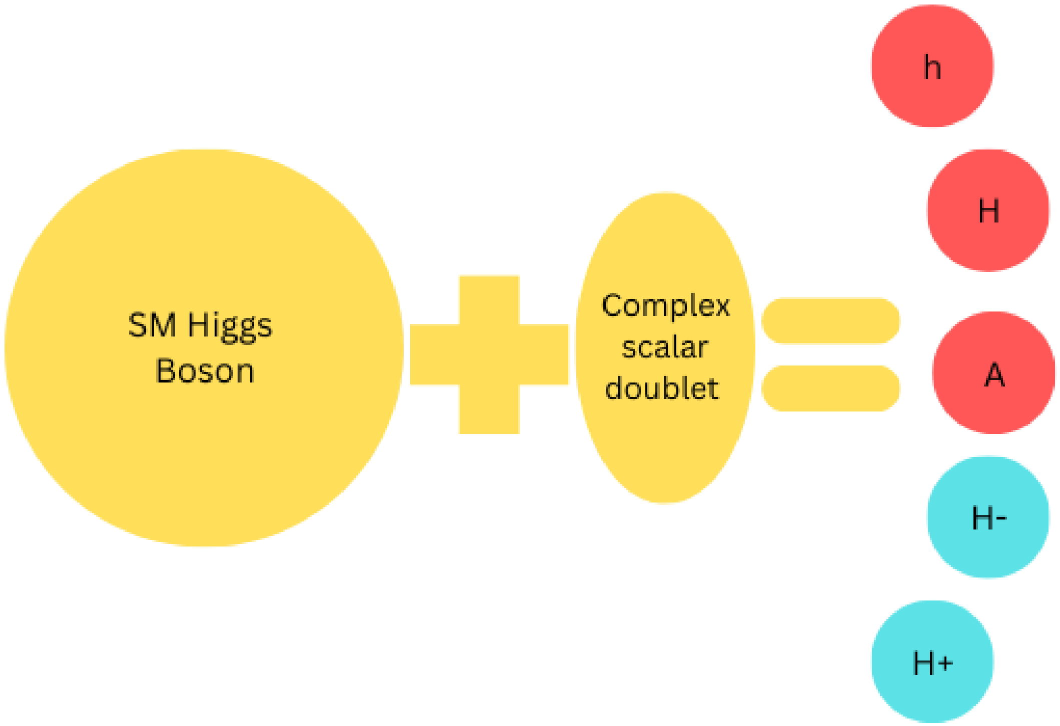
- Introduce second complex scalar SU(2) doublet
- CP-conserving scalar potential
- $\mathbb{Z}_2$ symmetry



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

2HDMs

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



$\underbrace{m_A, m_H, m_{H^\pm}}_{\text{3 Higgs masses}}, m_{12}, \alpha$ and $\tan\beta$ are free parameters

2HDMs

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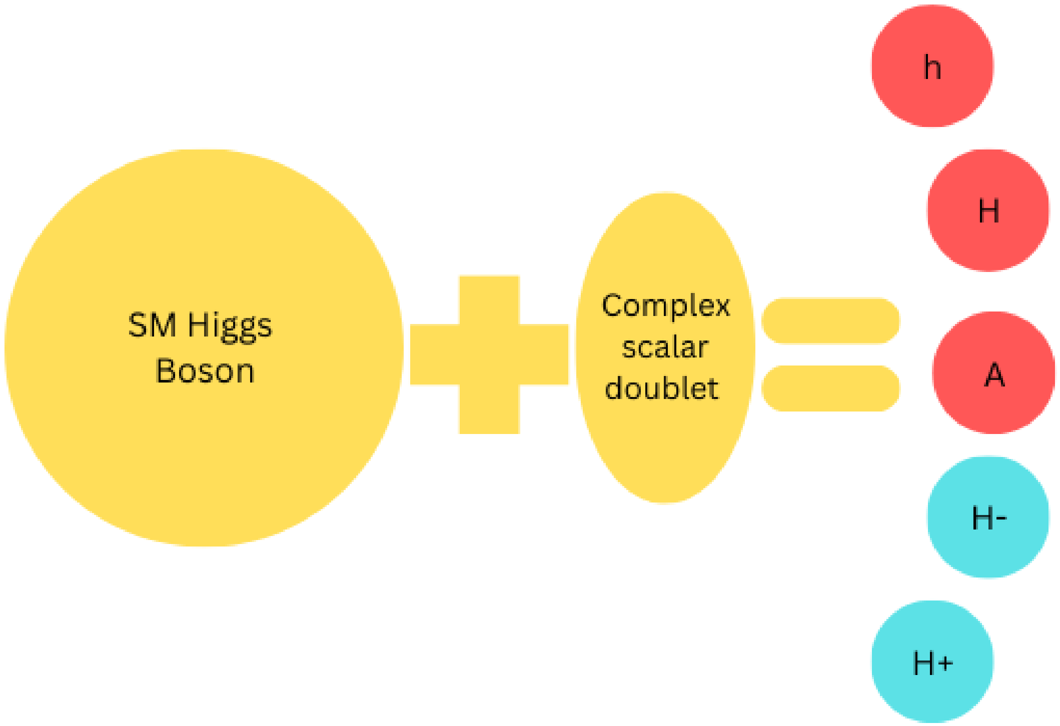
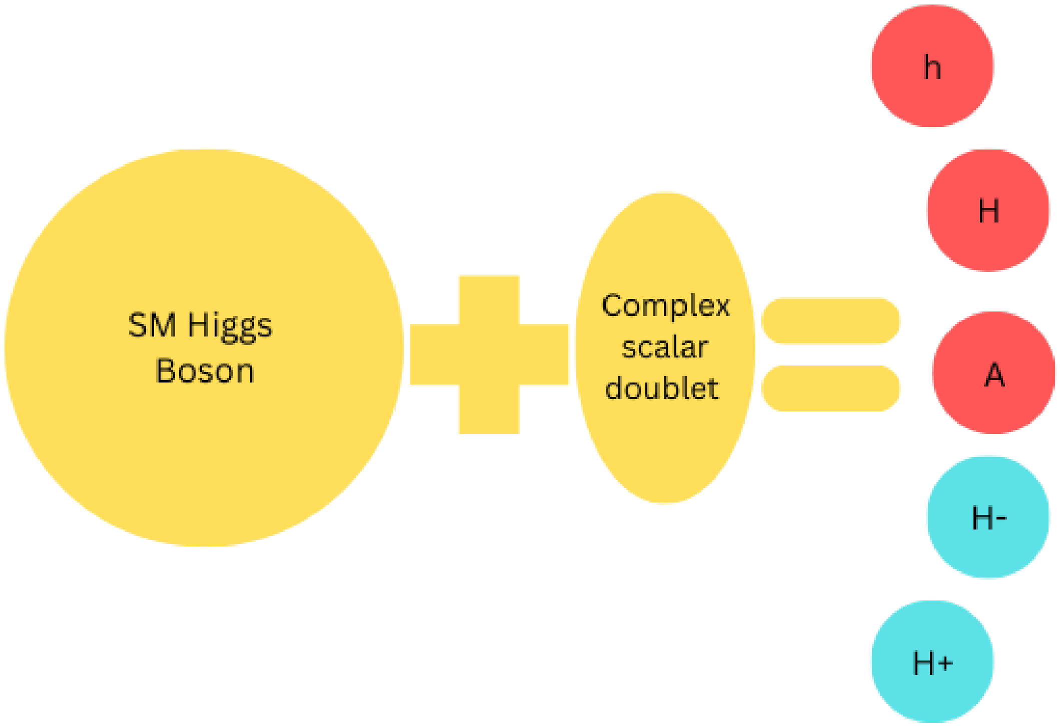


$\underbrace{m_A,\, m_H,\, m_{H^\pm}}_{\text{3 Higgs masses}},\, \underbrace{m_{12}}_{\text{Soft } \mathbb{Z}_2 \text{ symmetry-breaking term}},\, \alpha$ and $\tan\beta$ are free parameters

2HDMs

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



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

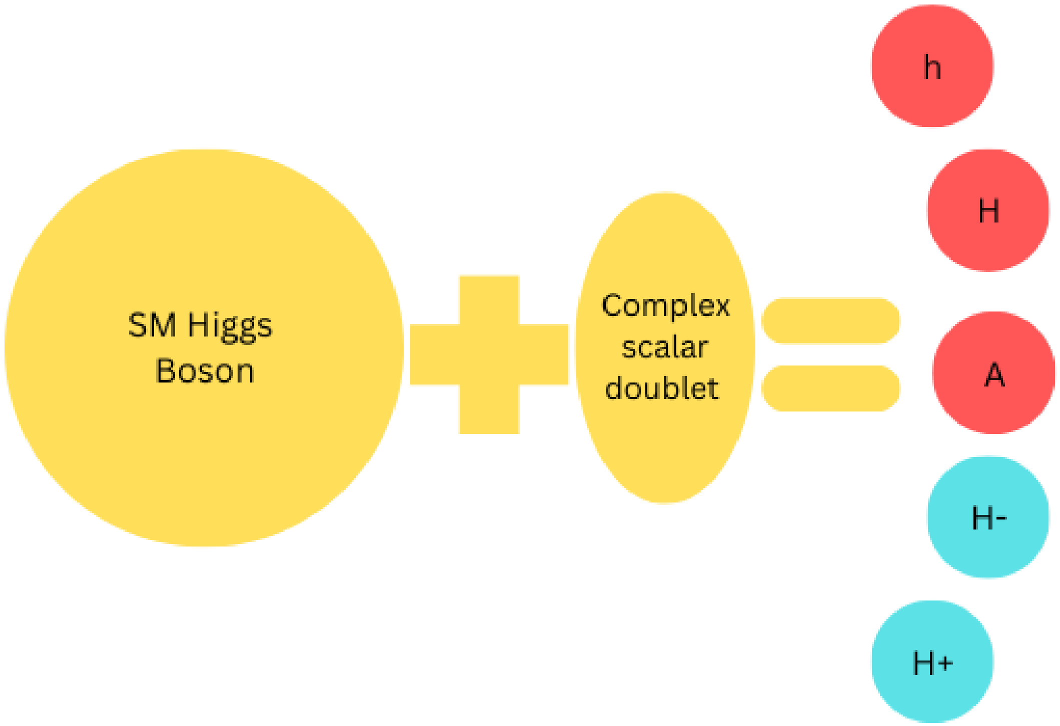
3 Higgs masses

Soft $\mathbb{Z}_2$ symmetry-breaking term

Mixing angle of h and H

2HDMs

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



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

3 Higgs masses

Soft $\mathbb{Z}_2$ symmetry-breaking term

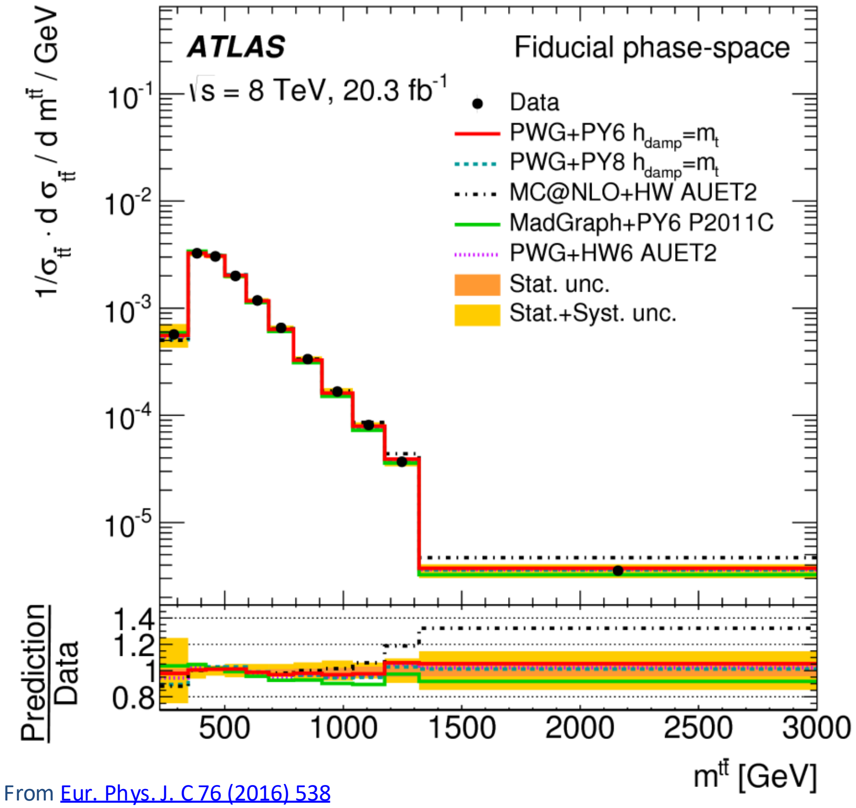
Mixing angle of h and H

Ratio of vacuum expectation values of Higgs fields

NNLO reweighting for SM $t\bar{t}$

- The generated MC (Powheg + Pythia) for SM top quark pairs is at NLO in QCD, with no higher-order corrections for EW

- Higher-precision differential predictions at NNLO-QCD+NLO-EW have been calculated by Mitov et al.



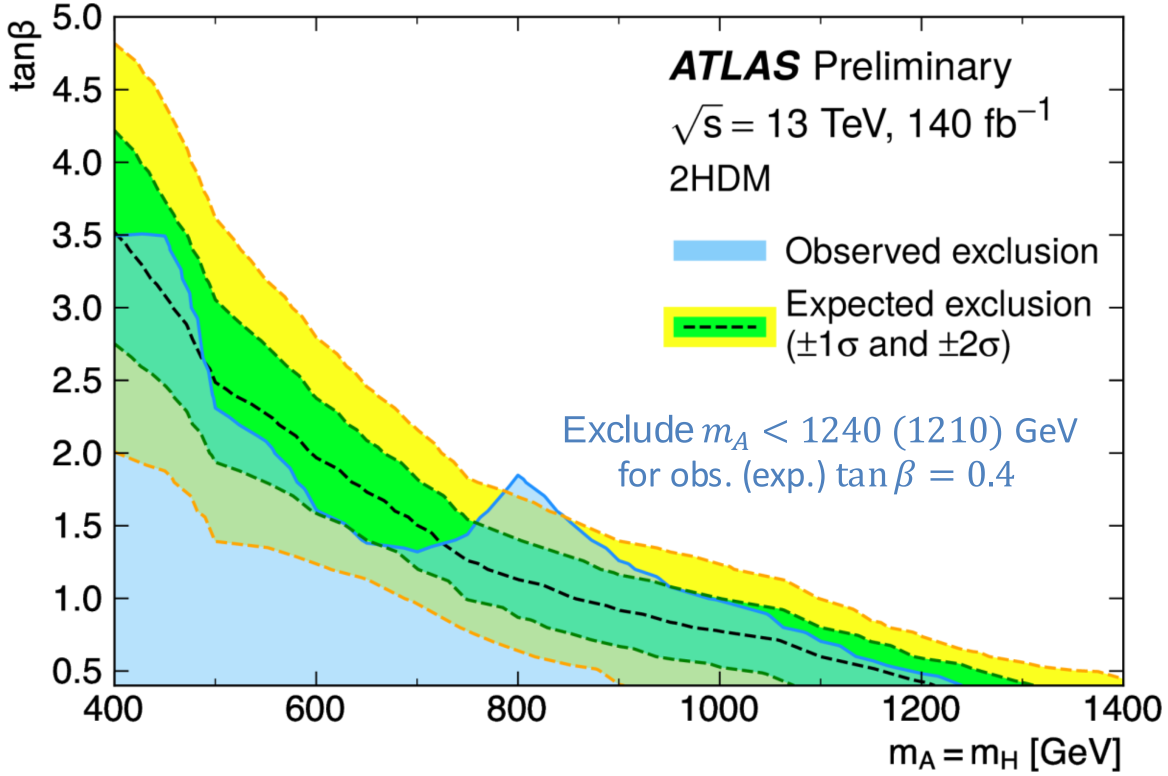
From Eur. Phys. J. C 76 (2016) 538

- Reweight generated MC samples to these higher-order predictions
  - Iterative recursive reweighting in m_{tt} and p_T(top, avg) (parton-level momentum after FSR)
  - Calculate correction factors from all MC samples and implement on events in SR

Results: Model-independent

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

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

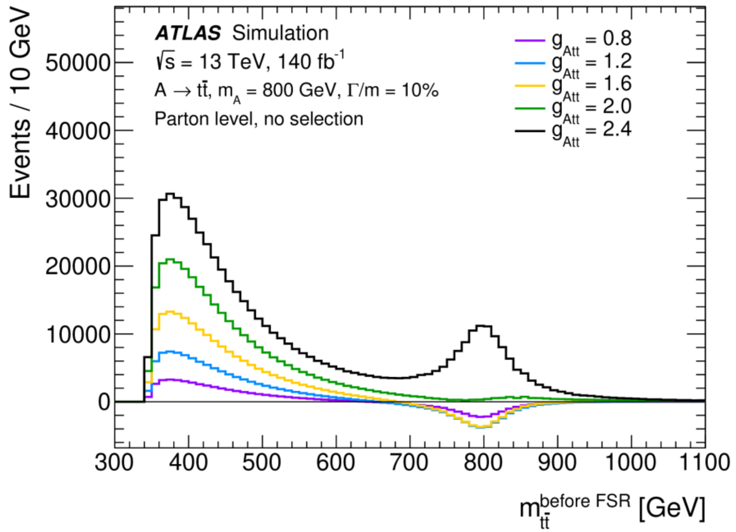


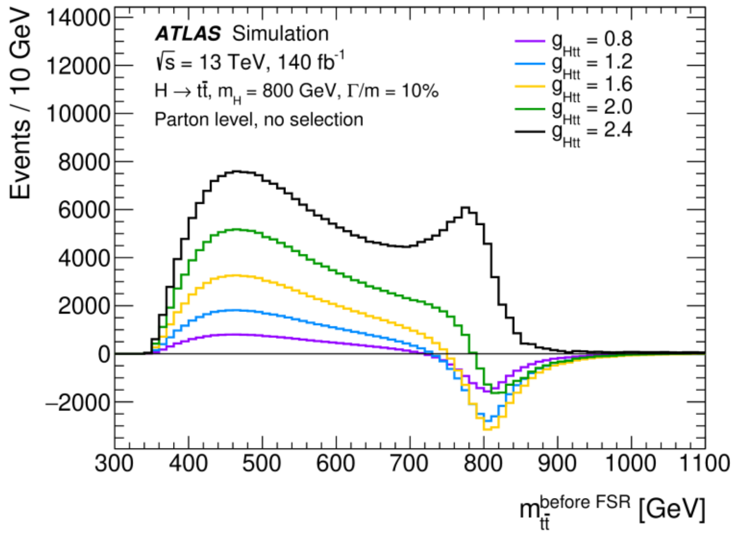
Model independent

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

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

  - Very few assumptions so can derive model-agnostic constraints
  - $A\ /\ Ht\bar{t}$ coupling and $A\ /\ H \rightarrow t\bar{t}$ 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)





Results: Model-independent