Search for new scalars → $t\bar{t}$ in Atlas

(inspired from slides by Katharina Behr, CERN seminar)

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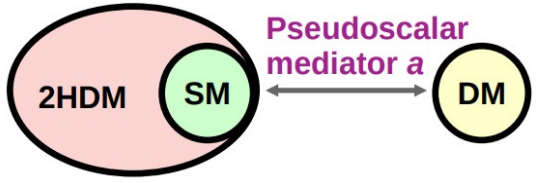
ATLAS-CONF-2024-001
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-001/

Motivations

- Many BSM theories involve extended Higgs sectors
  - Supersymmetry, WIMP DM models, axion DM models
- Simplest extensions consistent with existing constraints: 2HDM
  - After EWSB:
    - 2 neutral scalars : h (likely the discovered Higgs), H
    - 1 pseudo-scalar: A
    - 2 charged : $H^{\pm}$

… Or with an additional mediator: 2HDM+a



Decay into $t\bar{t}$

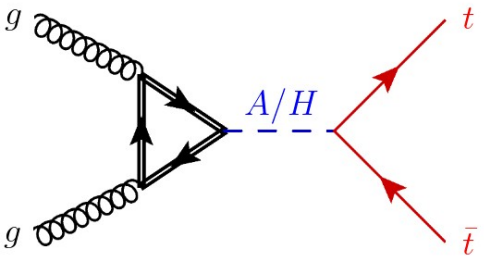
- Assume type 2 couplings

Model	Up quarks	Down quarks	Leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

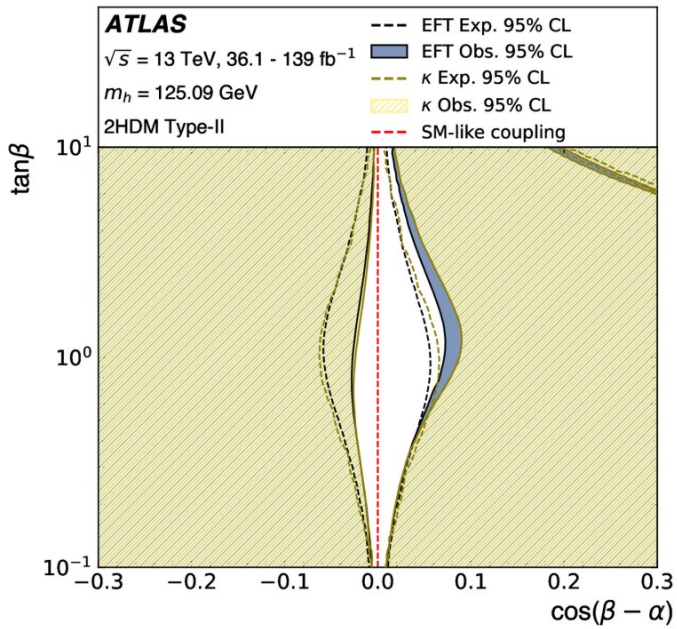
Φ_1, Φ_2: Higgs fields before EWSB

- And alignment: cos (β-α)=0
  - tanβ=v2/v1
  - α: mixing angle btw/ Higgs doublet

- A/H → $t\bar{t}$, dominant BR (for m>350GeV)

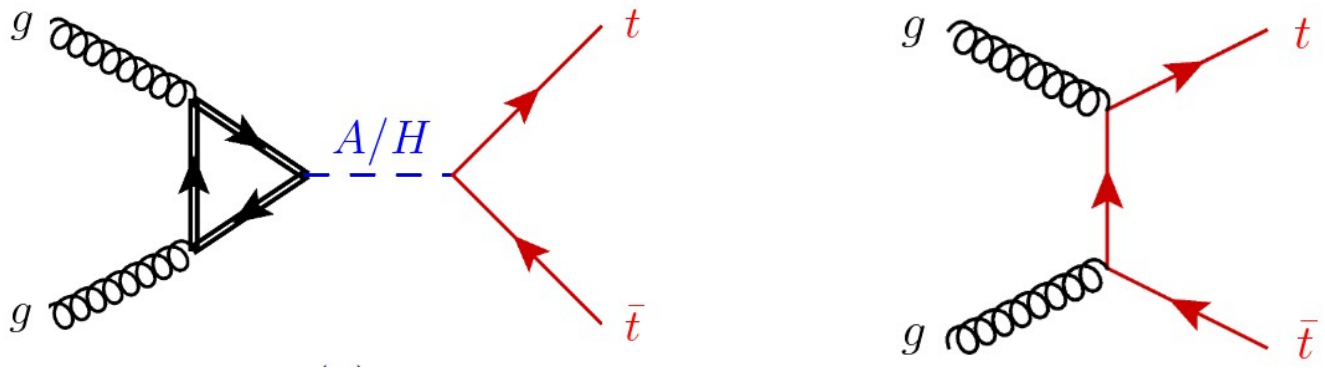


arXiv:2402.05742



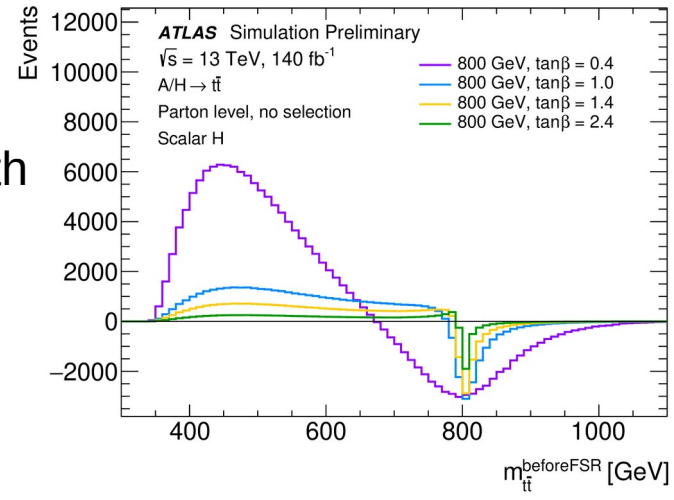
Strong interference

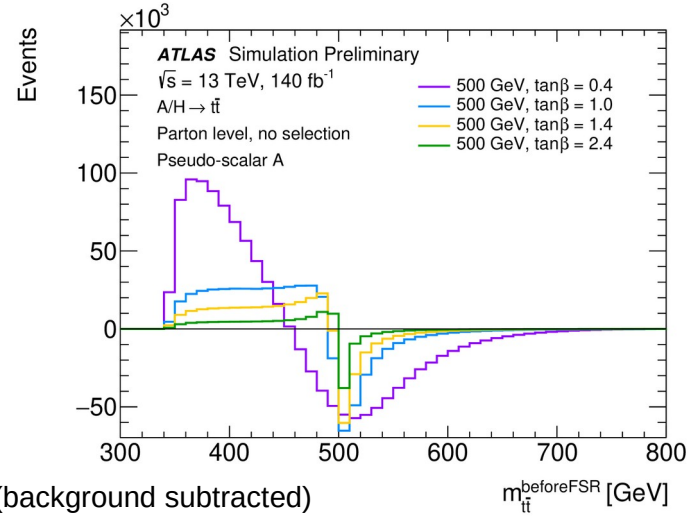
- Strong interference due to on-shell top quark in the loop



- Depend on the models, and their parameters

Larger tanβ
→ smaller total width
→ narrower pattern





S+I (background subtracted)

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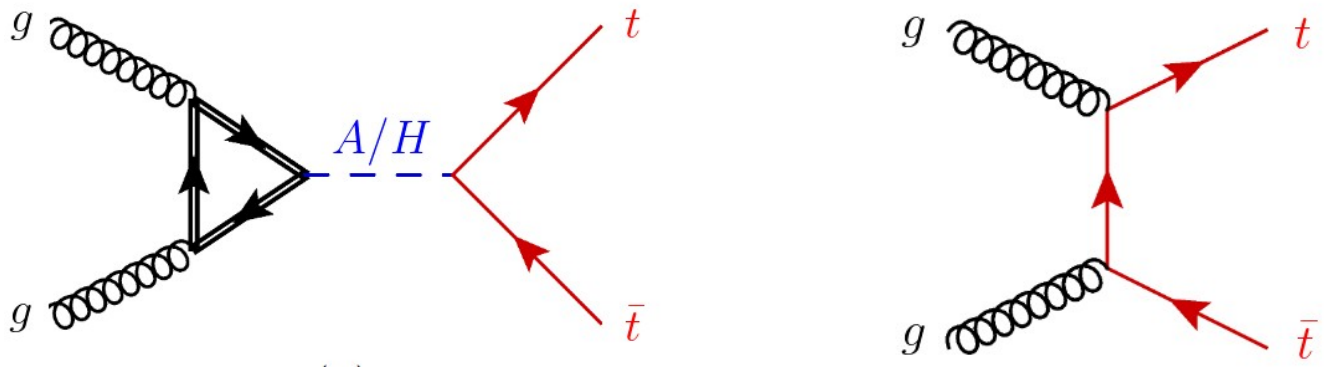
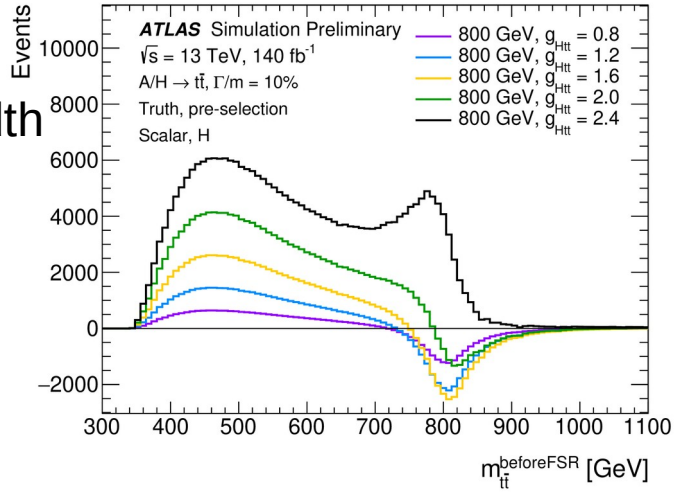
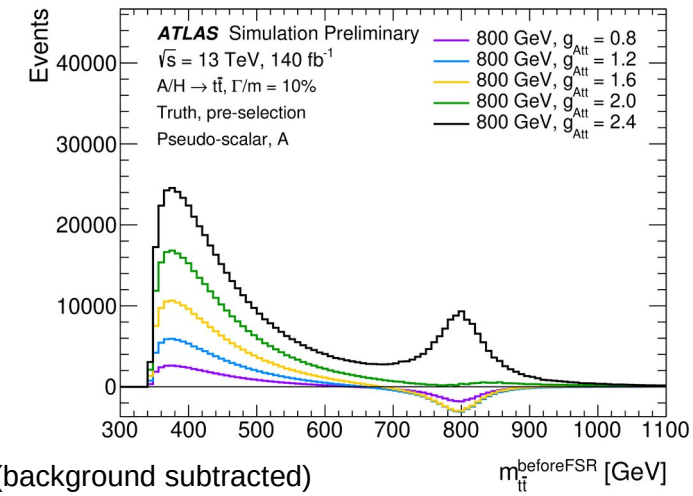


- Depend on the models, and their parameters

Assume 10% total width and vary couplings:
S scale as g^4
I scale as g^2

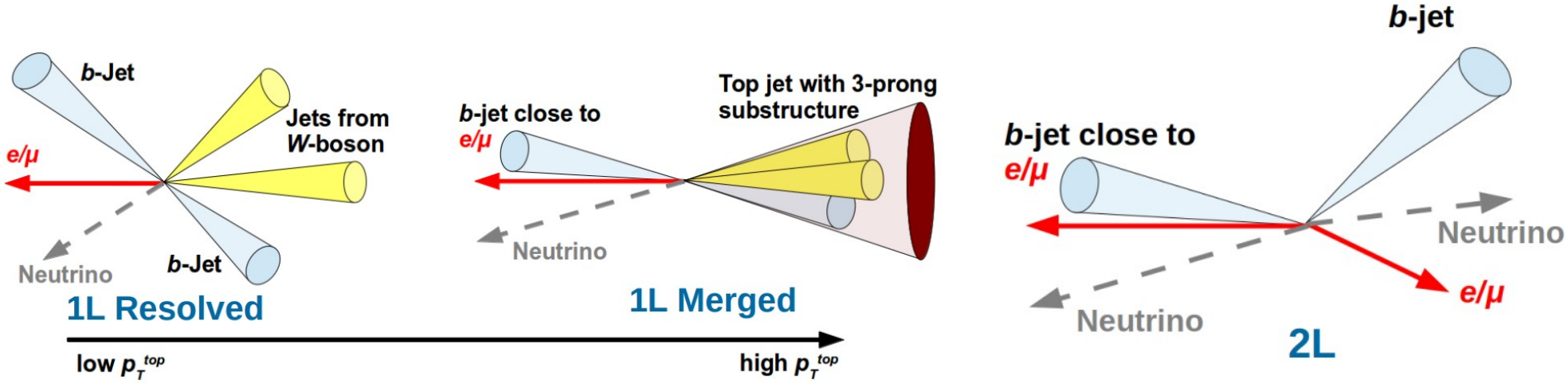




S+I (background subtracted)

Search strategy

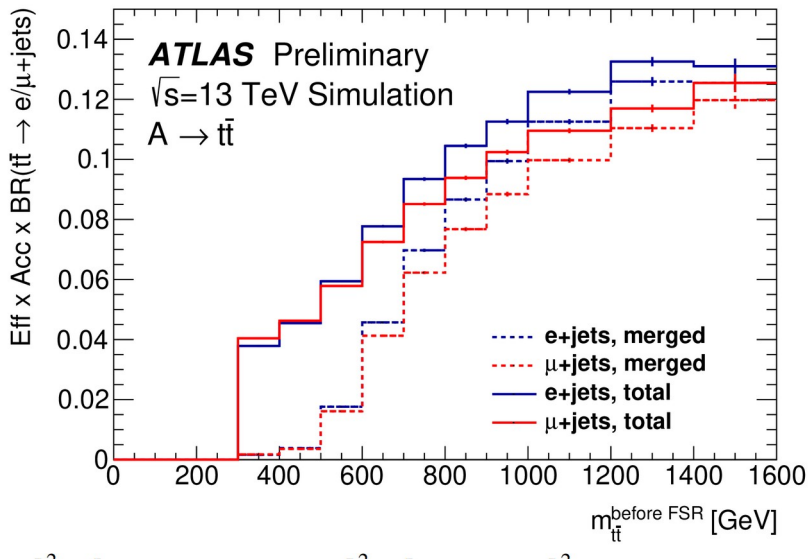
- Select $t\bar{t}$ events
  - 1 ou 2 lepton (e or mu) decays
  - Resolved or merged topologies
    - Allow leptons to be close to jets
    - Large-R jet with substructure
  - Look at mass spectra. SR's split using angular variables, (pseudo-)scalar!



Selections (1L)

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	$== 1$ 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 Selection
Large-VR jet	≥ 1 large-VR jet, $p_{\mathrm{T}} > 200$ GeV
Top tagging (hadronic decay)	Large-VR jet mass consistent with top quark mass: $m > 100$
Candidate b-jet (leptonic decay)	≥ 1 jet with ΔR (ℓ, R=0.4 jet) < 2.0
	ΔR (lep-b-cand-jet, ℓ) < 2.0
Back-to-back $t\bar{t}$ topology	ΔR (large-VR jet, lep-b-cand-jet) > 1.5
	ΔR (large-VR jet, ℓ) > 1.5
Matching of b-jets and top candidates	≥ 1 top candidate reconstructed using $== 1b$-tagged jet
	Resolved Selection
At least four 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 using $== 1b$-tagged jet
Veto events passing the merged selection	

Re-clustered anti-kt Variable-R jet
Dynamic radius:
R(pT)=600 GeV/pT



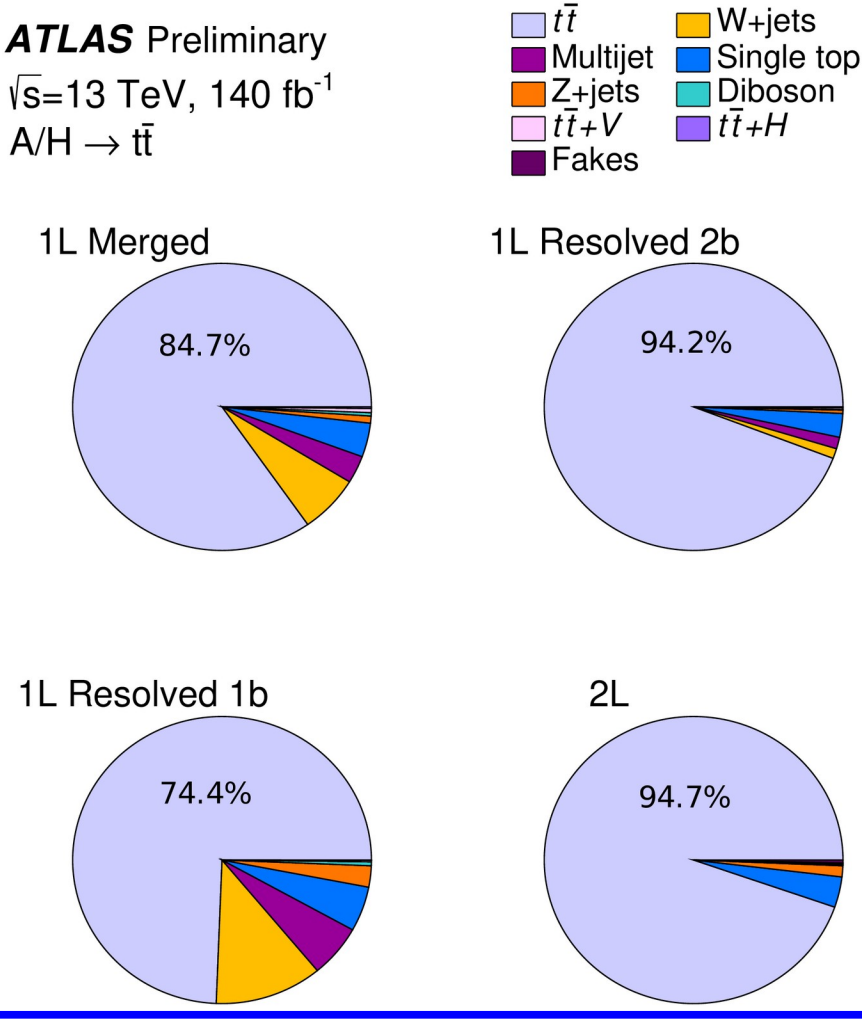
Reconstruction based on minimization of:

$$\chi^2 = \left[\frac{m_{jj} - m_{W_{\mathrm{h}}}}{\sigma_{W_{\mathrm{h}}}}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_{\mathrm{h}}-W_{\mathrm{h}}}}{\sigma_{t_{\mathrm{h}}-W_{\mathrm{h}}}}\right]^2 + \left[\frac{m_{b\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{\mathrm{T},jjb} - p_{\mathrm{T},b\ell\nu}) - (p_{\mathrm{T},t_{\mathrm{h}}} - p_{\mathrm{T},t_\ell})}{\sigma_{p_{\mathrm{T},t_{\mathrm{h}}}-p_{\mathrm{T},t_\ell}}}\right]^2.$$

Selections (1L&2L)

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 two leptons	2 (ee, $\mu\mu$, $e\mu$) with $p_{\mathrm{T}} > 25$ GeV. Leading one with $p_{\mathrm{T}} > 28$ GeV.
At least two jets	≥ 2 jets
b-tagging	≥ 1 b-tagged jet
Signal Selection	
Opposite-sign leptons	e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, $e^-\mu^+$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV (ee and $\mu\mu$ channels only)
Dilepton invariant mass	$m_{ll} > 15$ GeV
Dilepton invariant mass	$m_{ll} < 81$ GeV or > 101 GeV (ee and $\mu\mu$ channels only)
Lepton-plus-b-jet invariant mass	$m_{lb} < 150$ GeV

2L: Quite pure! (but small BR)



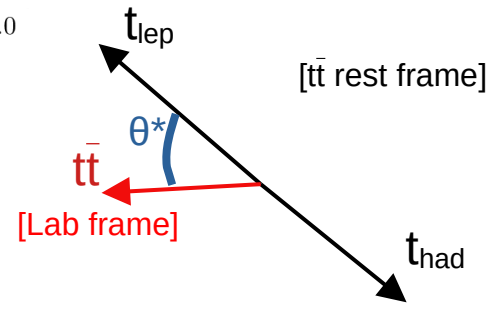
Signal Regions & discriminating variables

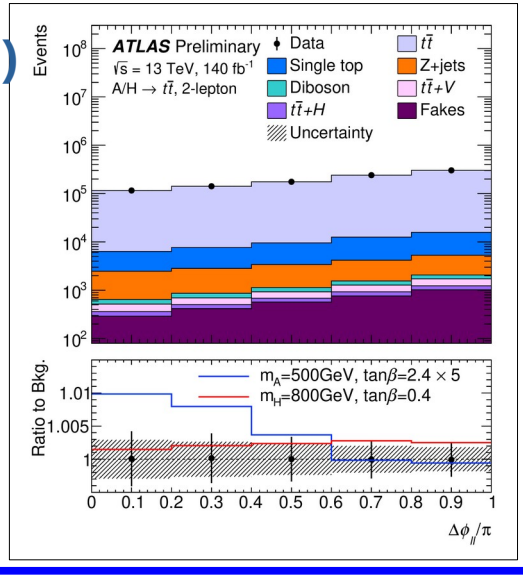
- 1L (11 SR):
  - Merged: use VR-jet for top_{had} + blv
  - Resolved:
    - Mass($t\bar{t}$), from χ^2
    - **In-situ calibration** for jet assigned to top_{had} → improves resolution

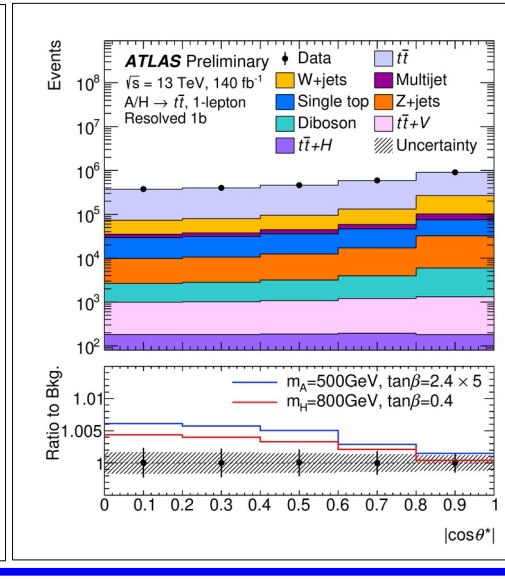
      (W- and top-mass constraints)
    - Split SR according to number of top candidates with b-tagged jet (1 or 2)
    - 5 bins in **cosθ***
- 2L (5 SR): m_{llbb}
  - 5 bins in **Δϕ(ll)**

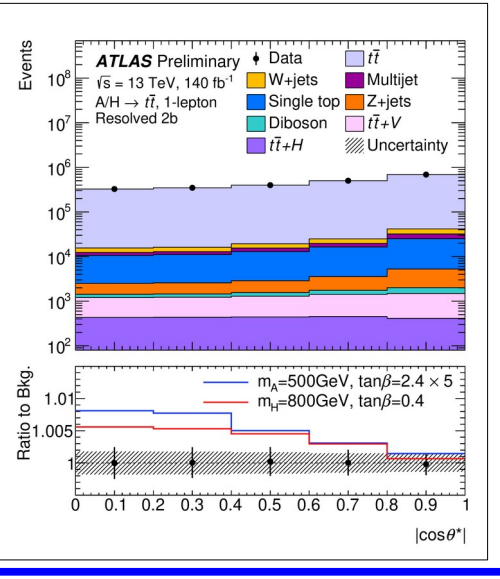
Candidate b-jet (leptonic decay) | ≥ 1 jet with ΔR (ℓ, R=0.4 jet) < 2.0; ΔR (lep-b-cand-jet, ℓ) < 2.0

$$\chi^2 = \left[\frac{m_{jj} - m_{W_h}}{\sigma_{W_h}}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h - W_h}}{\sigma_{t_h - W_h}}\right]^2 + \left[\frac{m_{b\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,b\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{p_{T,t_h} - p_{T,t_\ell}}}\right]^2.$$









Signal & Background modelings

Process	ME generator	ME order	PDF set	PS and hadronisation	UE tune
Signal	MadGraph5_aMC@NLO 2.6.7	LO	NNPDF3.0nlo	Pythia [8.244]	A14
$t\bar{t}$	Powheg Box v2	NLO, rew. to NNLO + NLO EW	NNPDF3.0nlo	Pythia 8.230	A14
Single top	Powheg Box v2	NLO	NNPDF3.0nlo	Pythia 8.230/8.235	A14
Diboson	Sherpa 2.2.1/2.2.2	MEPS@NLO	NNPDF3.0nnlo	Sherpa	internal
W+jets	Sherpa 2.2.11	MEPS@NLO	NNPDF3.0nnlo	Sherpa	internal
Z+jets	Sherpa 2.2.1	MEPS@NLO	NNPDF3.0nnlo	Sherpa	internal
$t\bar{t}+V$	MadGraph5_aMC@NLO 2.3.3	NLO	NNPDF3.0nlo	Pythia 8.210	A14

- Signal:
  - ggHFullLoop model
    - Width from 2HDMC v1.8.0
    - MadSpin
  - **Generate S, Reweighting → S, S+I**
    modified MG code!
  - k_S: LO → NNLO k-factor (SUSHI)

$$k_I = \sqrt{k_S \cdot k_B^{\mathrm{LO}}}$$

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- SM tt:
  - Correct NLO Powheg+Pythia MC → **NNLO-QCD+NLO-EW** iterative reweighting in $m_{t\bar{t}}$, pT_t, $pT_{\bar{t}}$
- W+jets (1L):
  - Normalisation corrected from Charge Asymmetry (asymmetry in data driven by W+jets)
- Z+jets (2L):
  - Correction on m_{llbb} shape. Reweighting derived in Z-peak CR
- Fake leptons
  - 1L: from data (matrix method)
  - 2L: from MC (mostly $t\bar{t}$, W+jets)

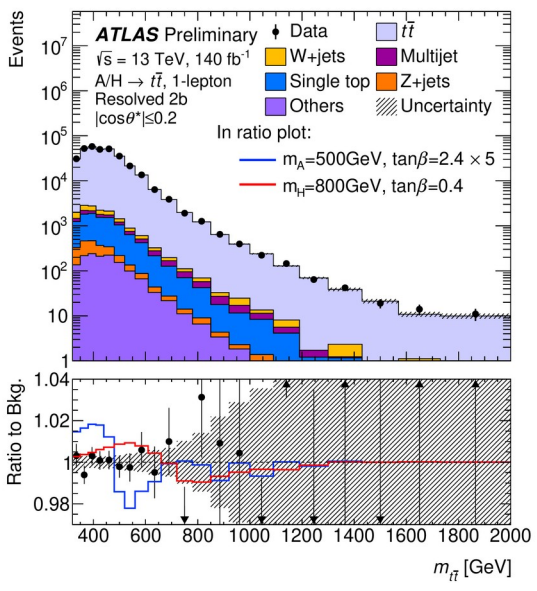
Systematic uncertainties

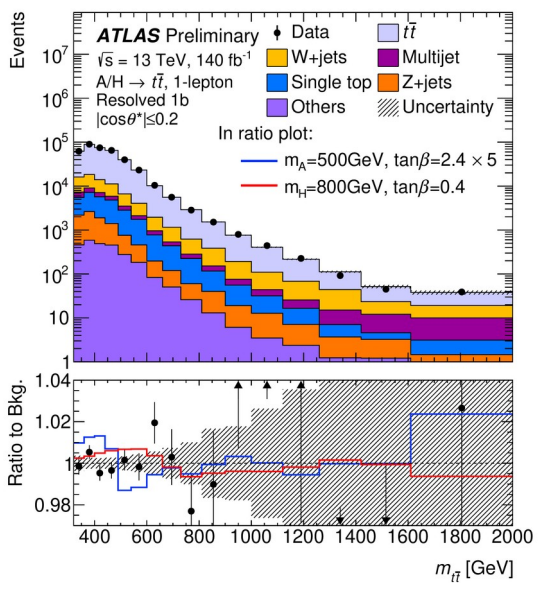
- Complex fit:
  - Many systematics, 16 SR's, millions of events
- Correlation scheme:

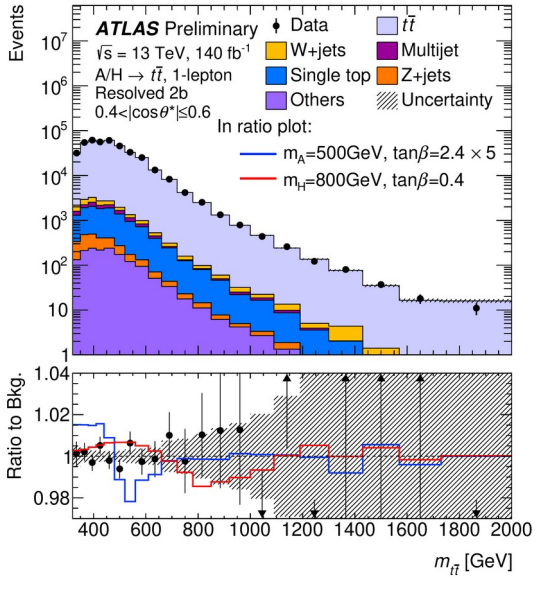
	1 L Resolved, 10 SR										1 L Merged	2 L 5 SR				
$t\bar{t}$ modelling [1] (h_{damp}, PS, PS-ME match.)																
$t\bar{t}$ modelling [2] (I/FSR, cross-sections, $\mu_{R,F}$)																
top mass																
Other backgrounds																
Experimental uncertainties																

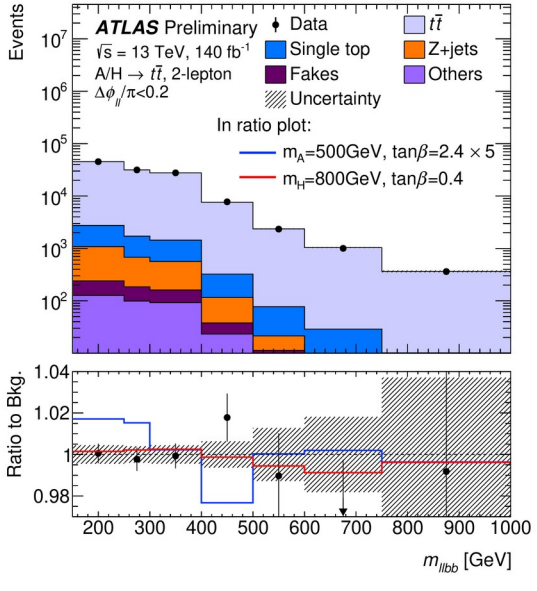
[1]: large 2-point systematics → prevent constraints to propagate across SR
[2]: decorrelate different kinematic regimes
Top mass: correlated btw/ B and S+I

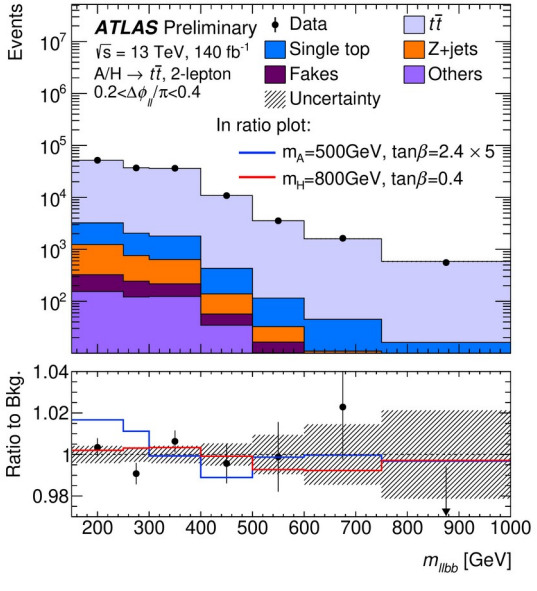
Good agreement

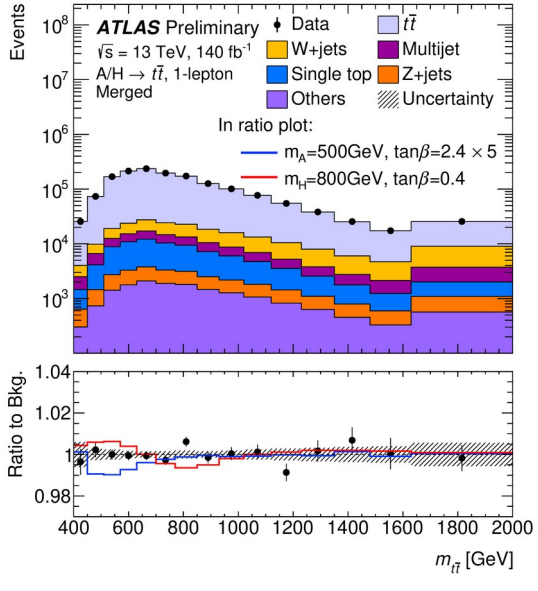












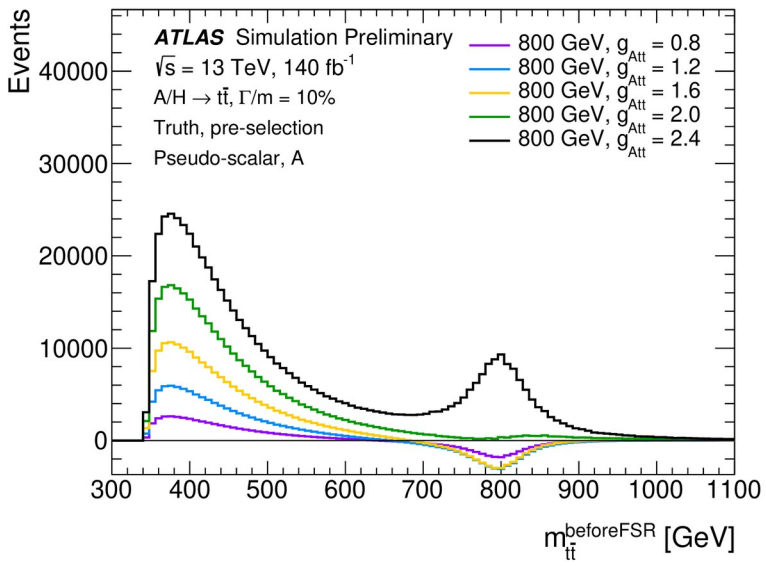
6 SR's among 16

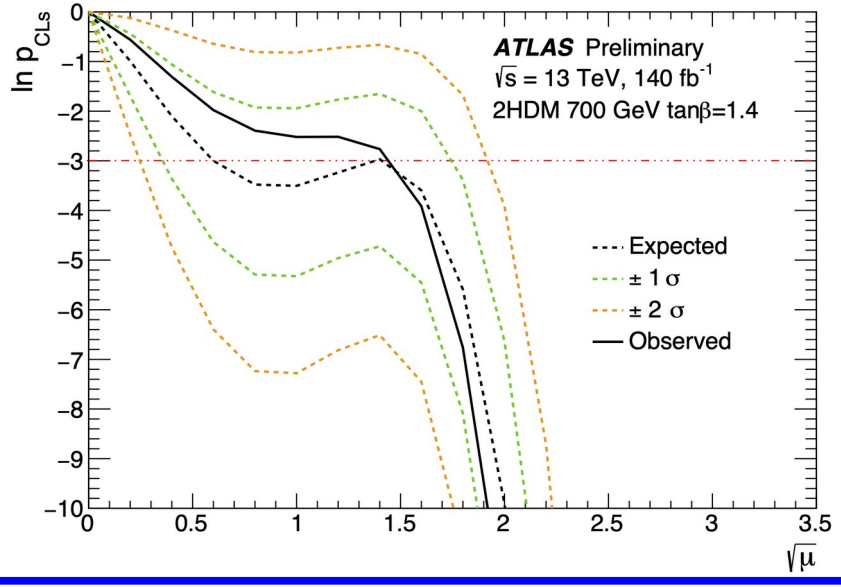
Statistical analysis with interference

- Likelihood: √μ=g as parameter of interest

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

- Local minima can appear in CLS scan
  - Upper limits not well defined!
  - Requires going beyond common statistical approaches





Choice of test statistic

- Search stage
  - Should we reject SM in favour of (any) BSM hypothesis?

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

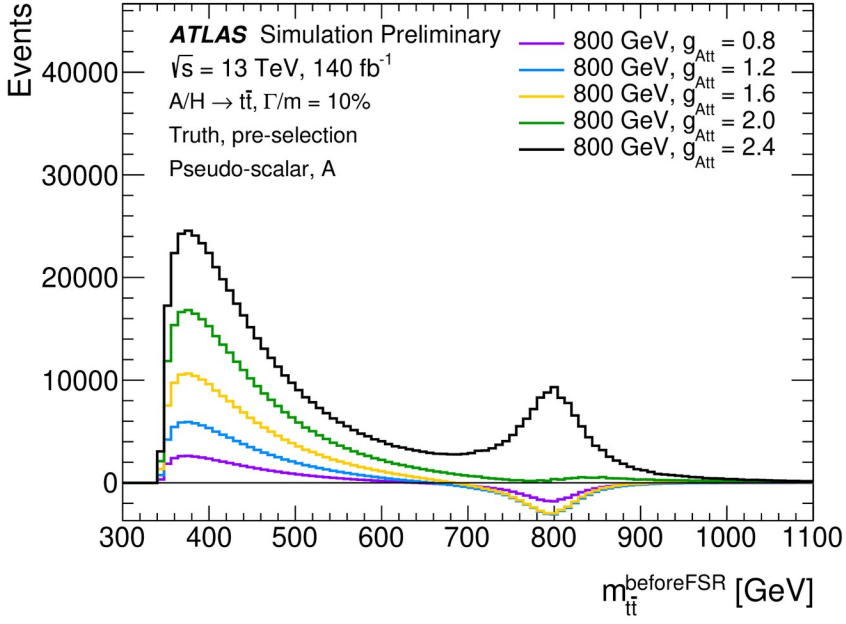
- Exclusion stage:
  - Should we reject the BSM hypothesis under consideration?

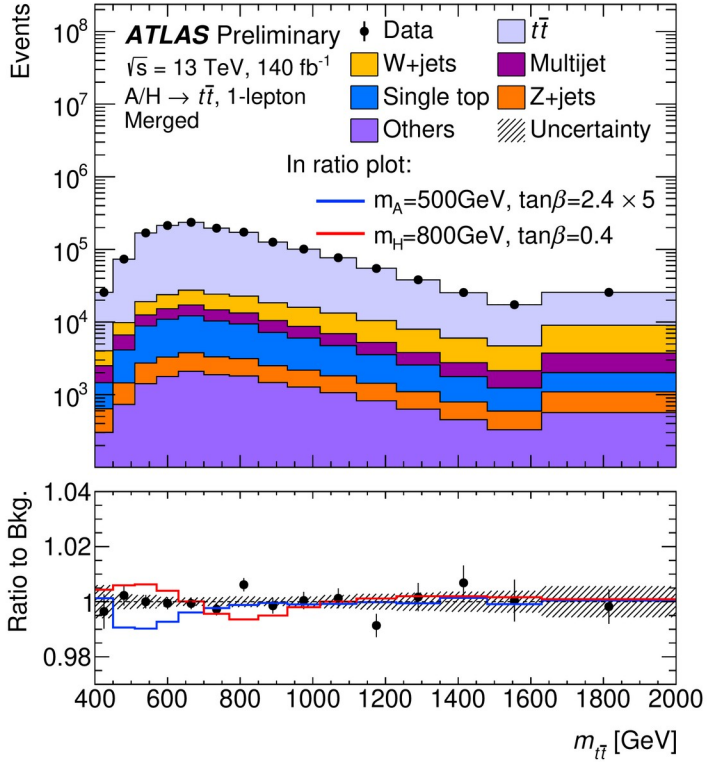
$$q_{1,0} = -2\ln\frac{\mathcal{L}(1,\hat{\hat{\boldsymbol{\theta}}}_1)}{\mathcal{L}(0,\hat{\hat{\boldsymbol{\theta}}}_0)}$$

Search stage

- Tested agreement between data and S+I+B hypotheses
  - For masses [400,1400] GeV and widths [1, 40]%
  - Most significant deviation from SM-only (2.3σ local): mA = 800 GeV, Γ_A/m_A = 10% and **√μ = 4.0 (→ peak)**
    - Driven by narrow upward fluctuation around 800 GeV in merged region

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



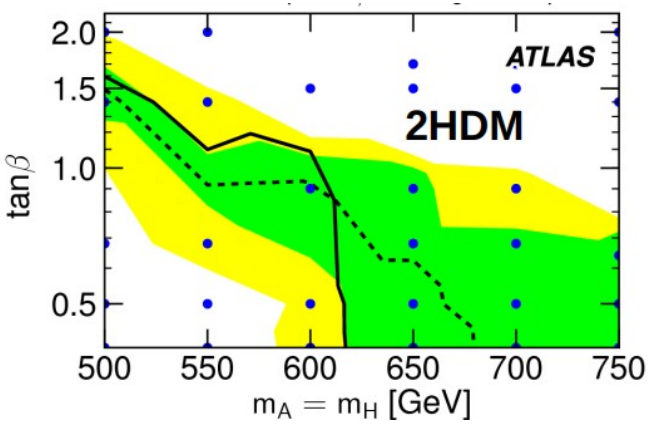


Exclusion regions: 2HDM

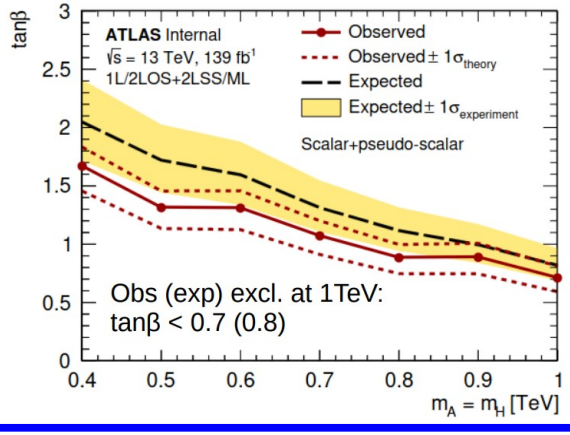
$$q_{1,0} = -2\ln\frac{\mathcal{L}(1,\hat{\hat{\theta}}_1)}{\mathcal{L}(0,\hat{\hat{\theta}}_0)}$$

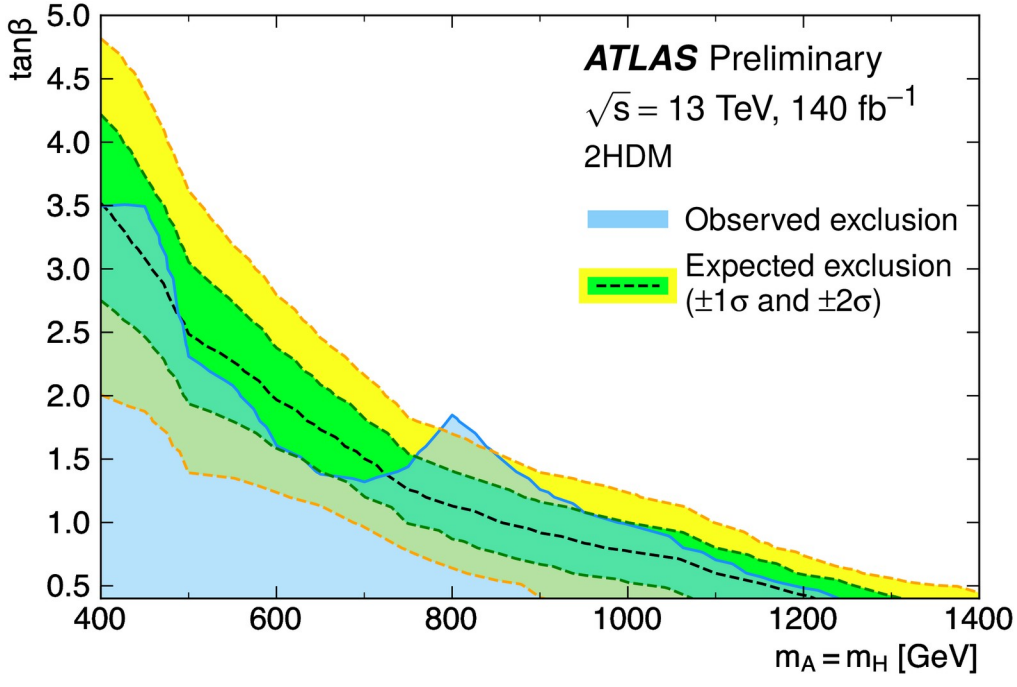
- Test “each” point of the plan: $p_{CLs}(\sqrt{\mu}=1)<0.05$?
- Strongest mass exclusion at low tanβ to date

tt, 8TeV result



4tops, 13TeV result

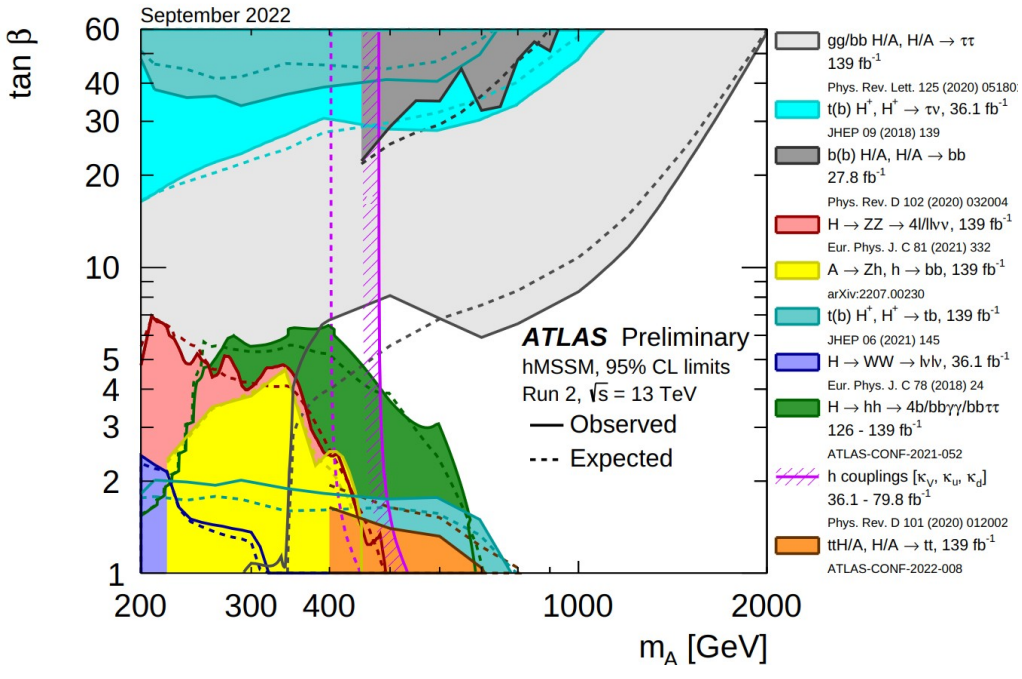


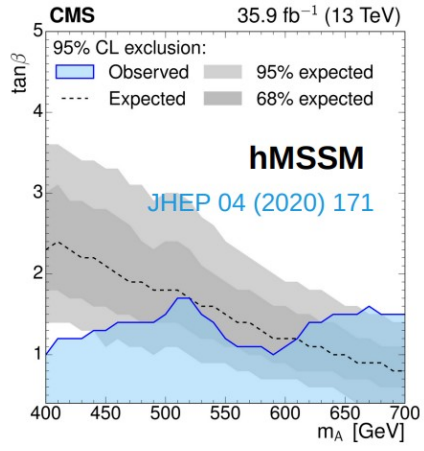


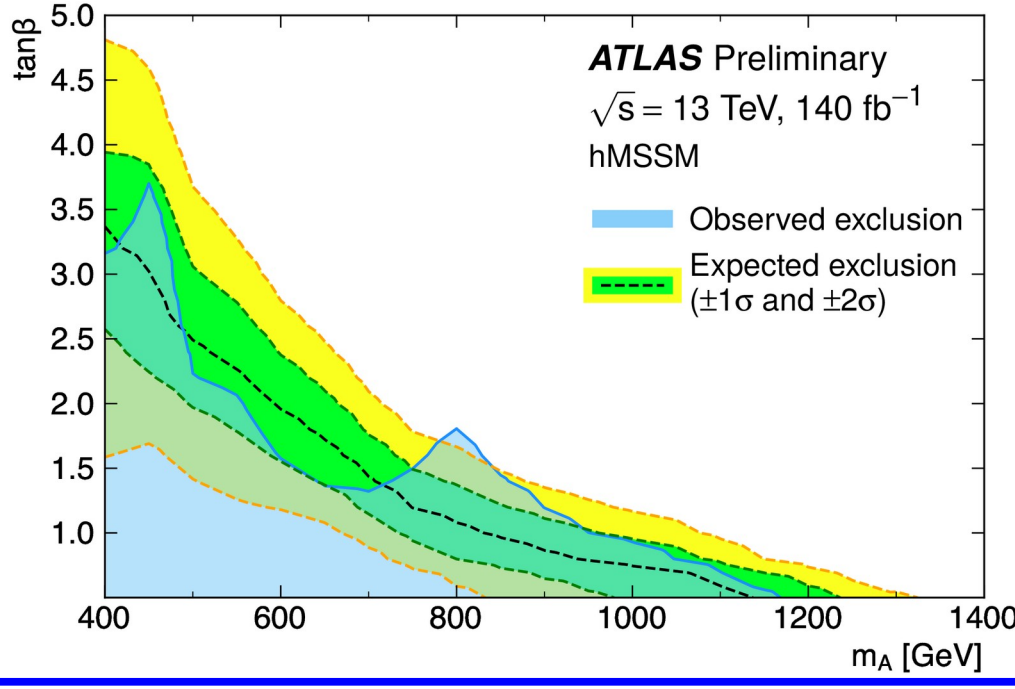
Exclude mA=mH < 1240 GeV for tanβ = 0.4

Exclusion regions: hMSSM

- Low mass deviation seen by CMS not confirmed

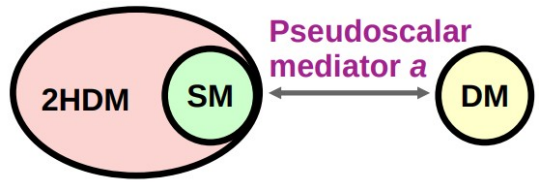


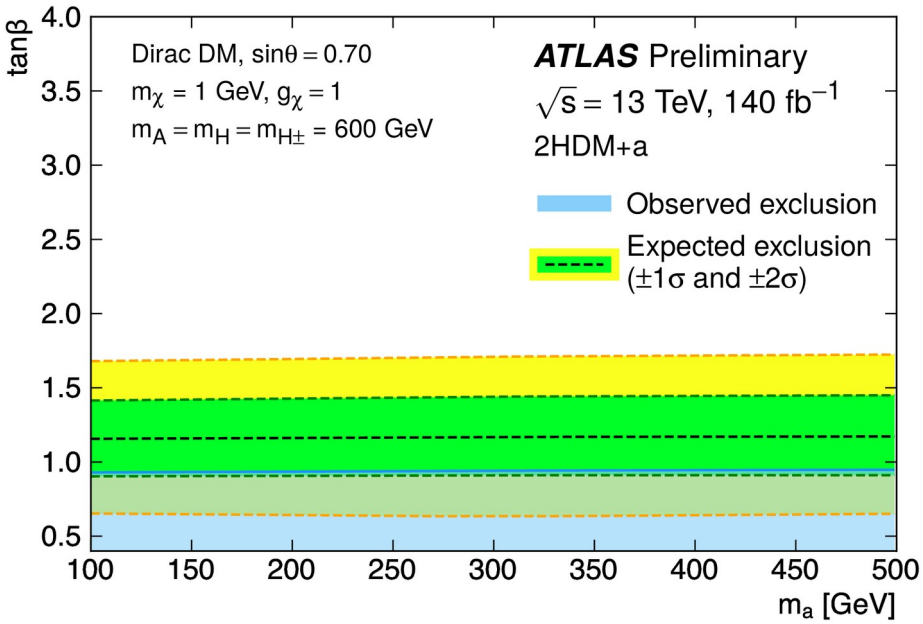


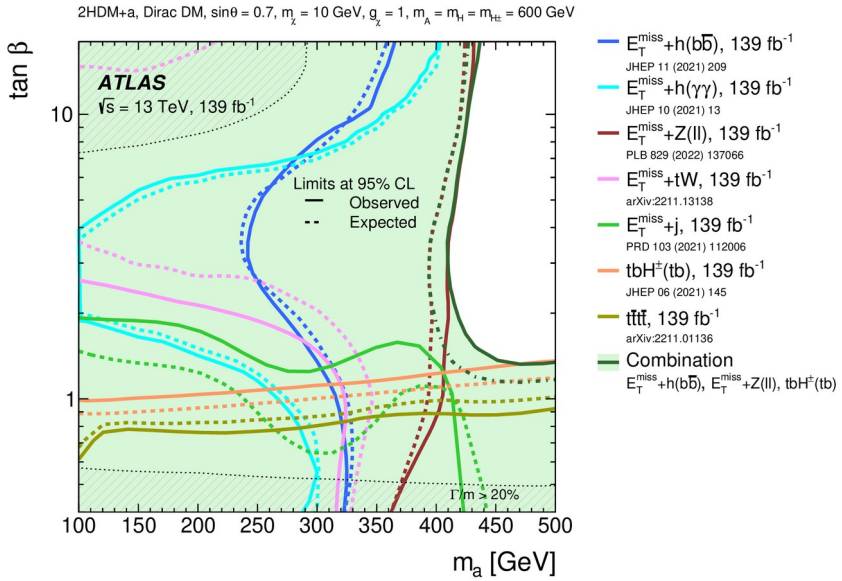


Exclusion regions: 2HDM+a

- Benchmark scenario 3a in LHC DM WG recommendations
- Observed exclusion slightly weaker than H+ → tb result due to downward fluctuation
  - Similar conclusion for sin(θ)=0.35

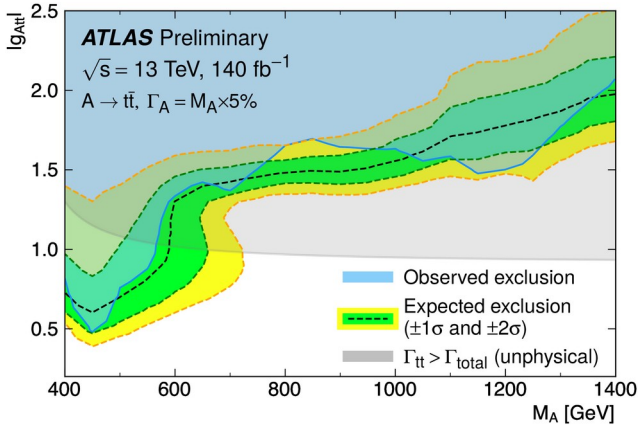


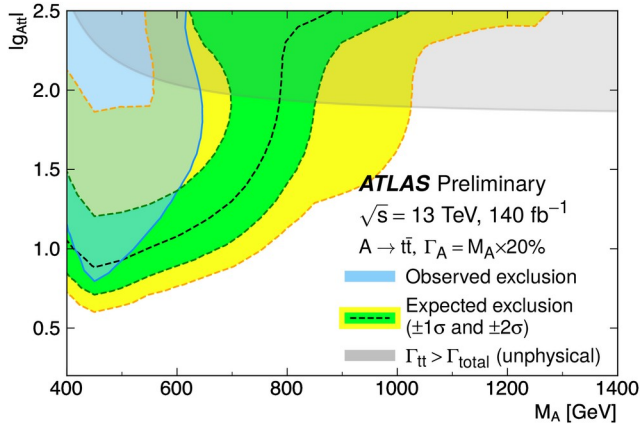


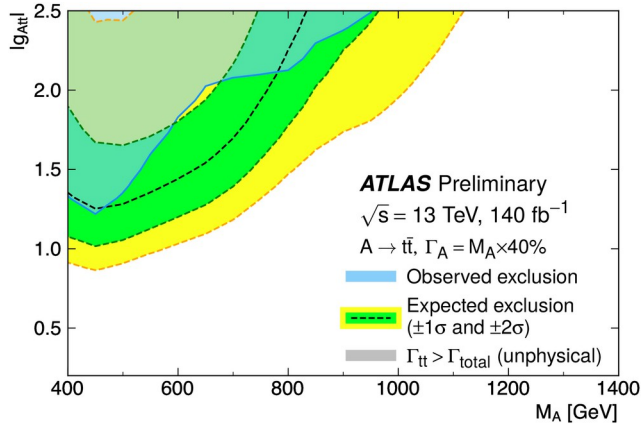


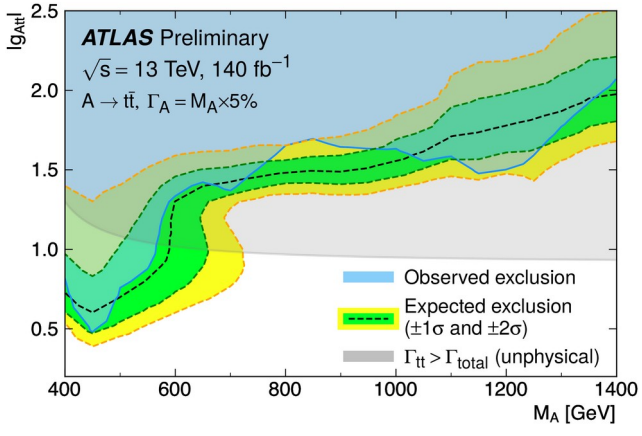
Model-agnostic

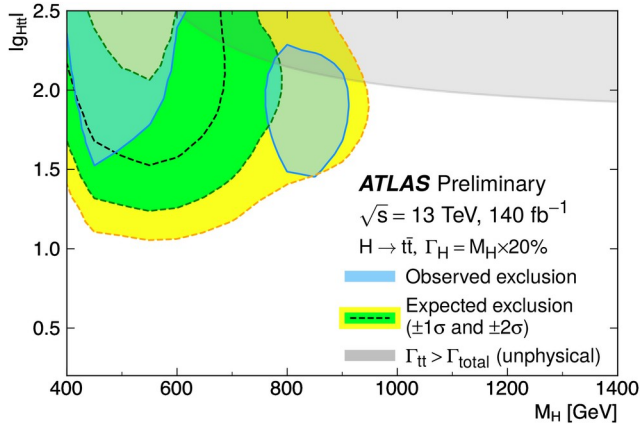
- Constrain single (pseudo-)scalar production
- Upper limits on coupling modifier g_{Att} or g_{Htt} as function of mass for **fixed total width**
  - Different from 2HDM where width depends on mass and coupling (tanβ)

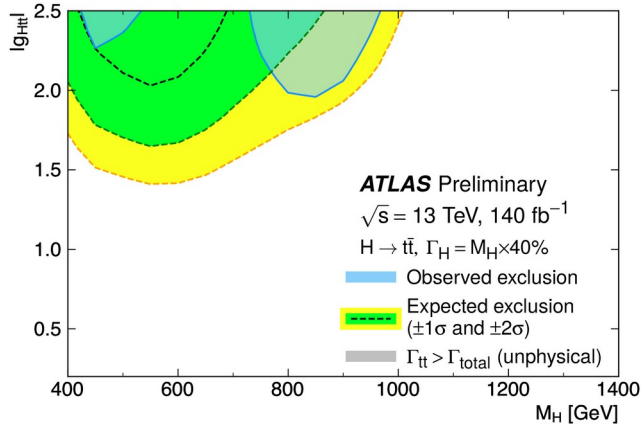






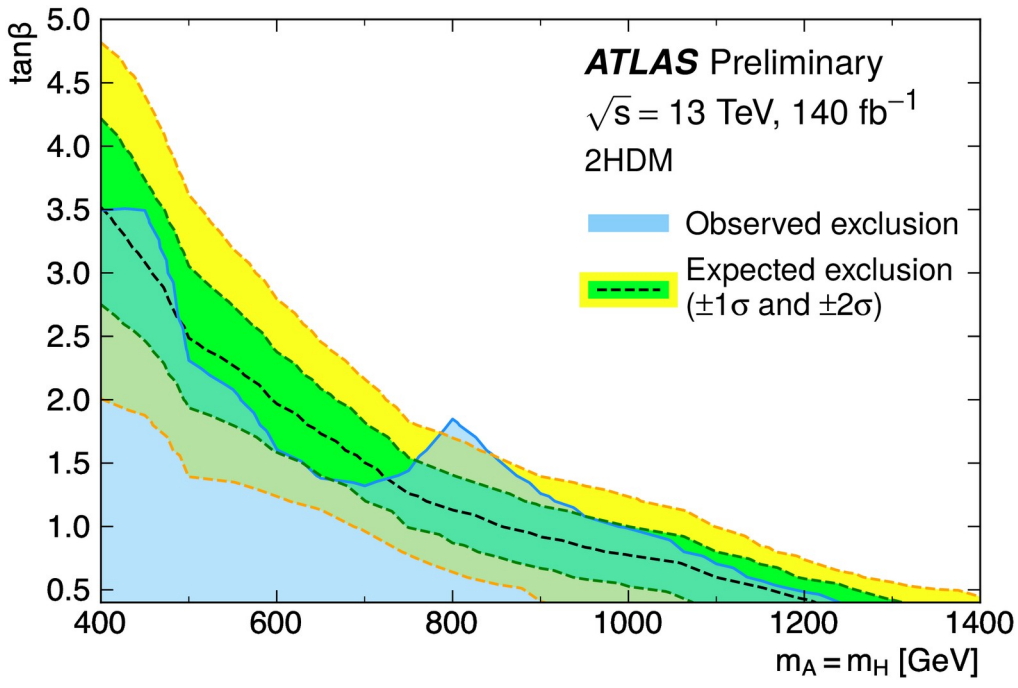






Conclusions

- Interference pattern:
  - Fun !
  - Difficult (modeling, limit setting)
  - Refreshing (limit setting)
- Strongest limits for low tanβ for 2HDM/hMSSM
- No sign of new physics
  - In agreement with search for tt(H/A) → 4 tops



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