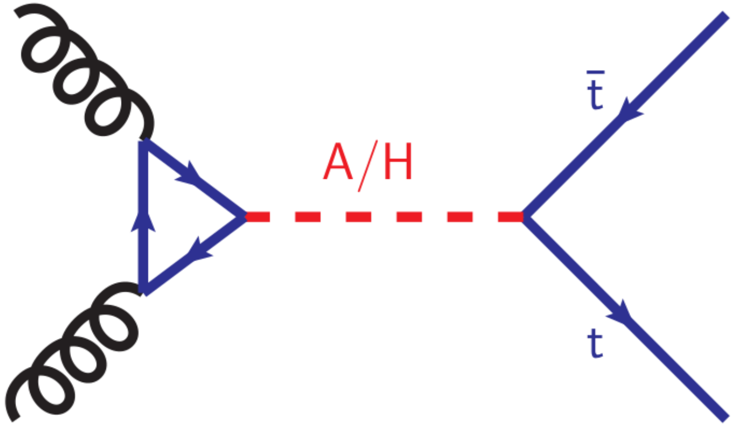
Interference modeling for A/H → ttbar

ATLAS vs CMS



LHC Higgs W3 Meeting
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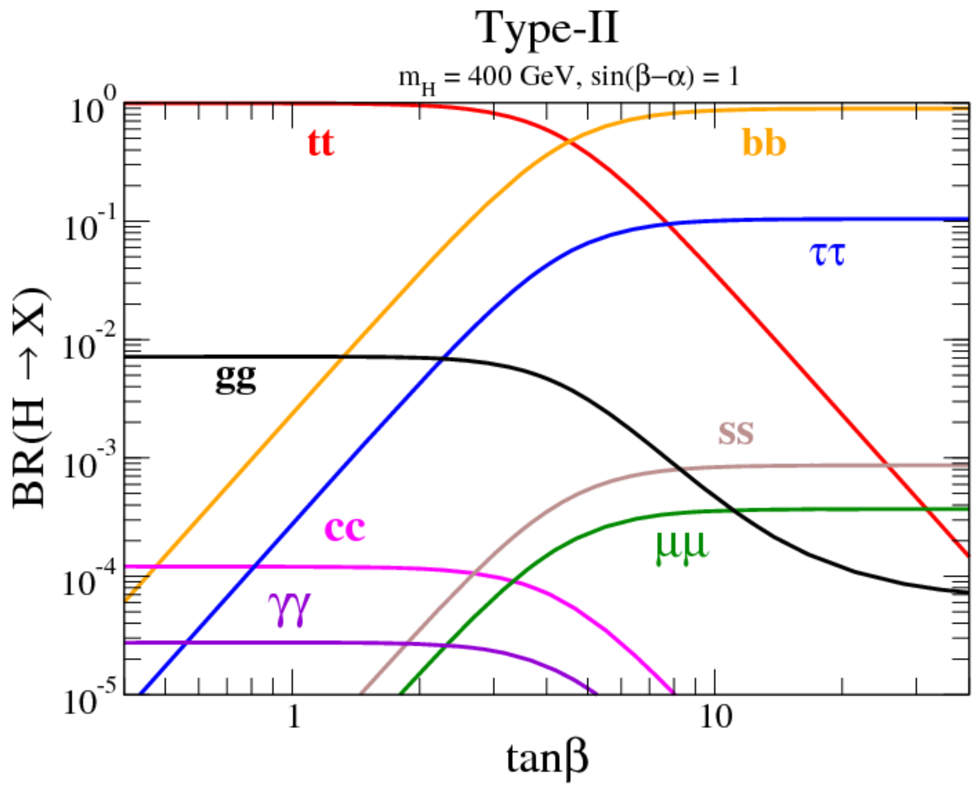
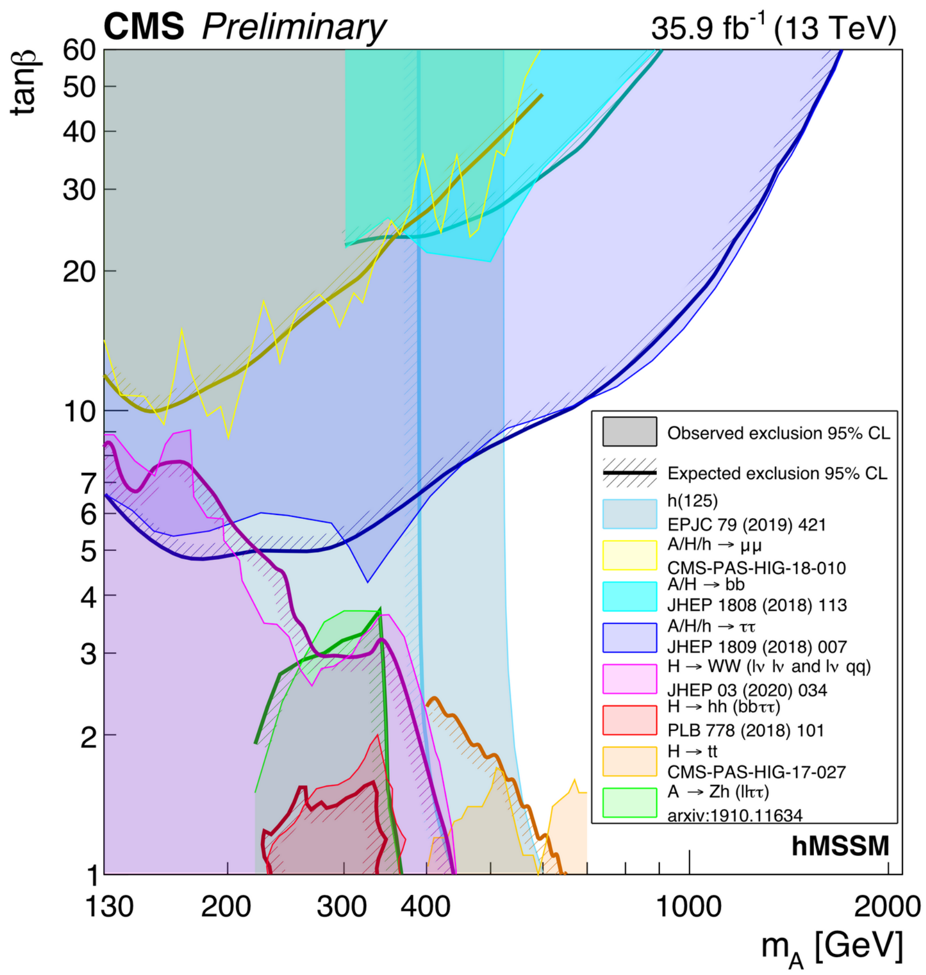
Motivation

- A/H decay almost exclusively to ttbar for $m_{A/H} > m_{ttbar}$ and small tanβ in type-II 2HDMs
- Searches for A/H → ttbar crucial to probe uncovered parameter regions in 2HDM-type models



ILC Higgs White Paper, arXiv:1310.0763

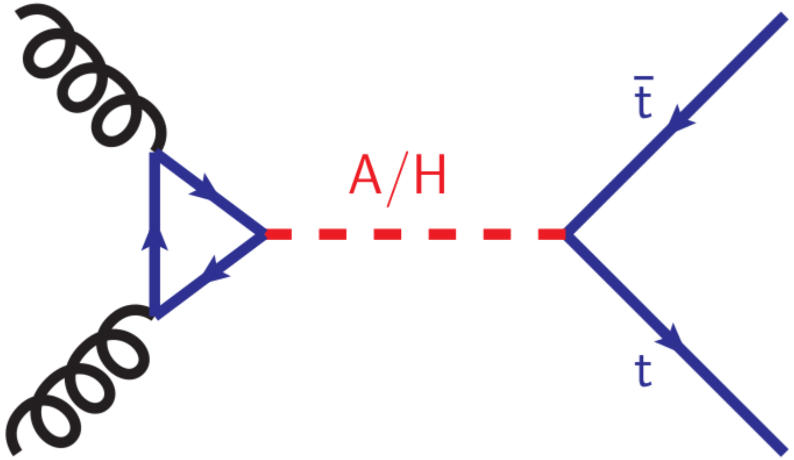


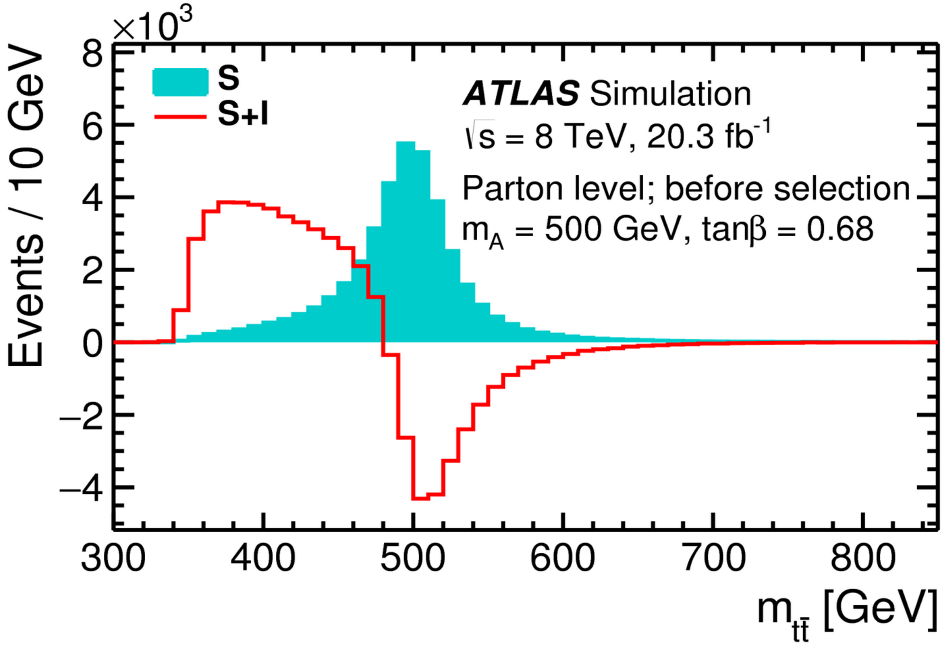
Interference

> Dominant production mode: gluon fusion via triangular loop
  - Loop dominated by tops and bottoms (depending on tanβ)
  - BSM particles could also contribute, e.g. VLQs or stops (not considered here)

> Strong interference of this process with SM ttbar background due to imaginary phase from production loop

> Complex, model-dependent signal shape: peak-dip structure instead of Breit-Wigner peak

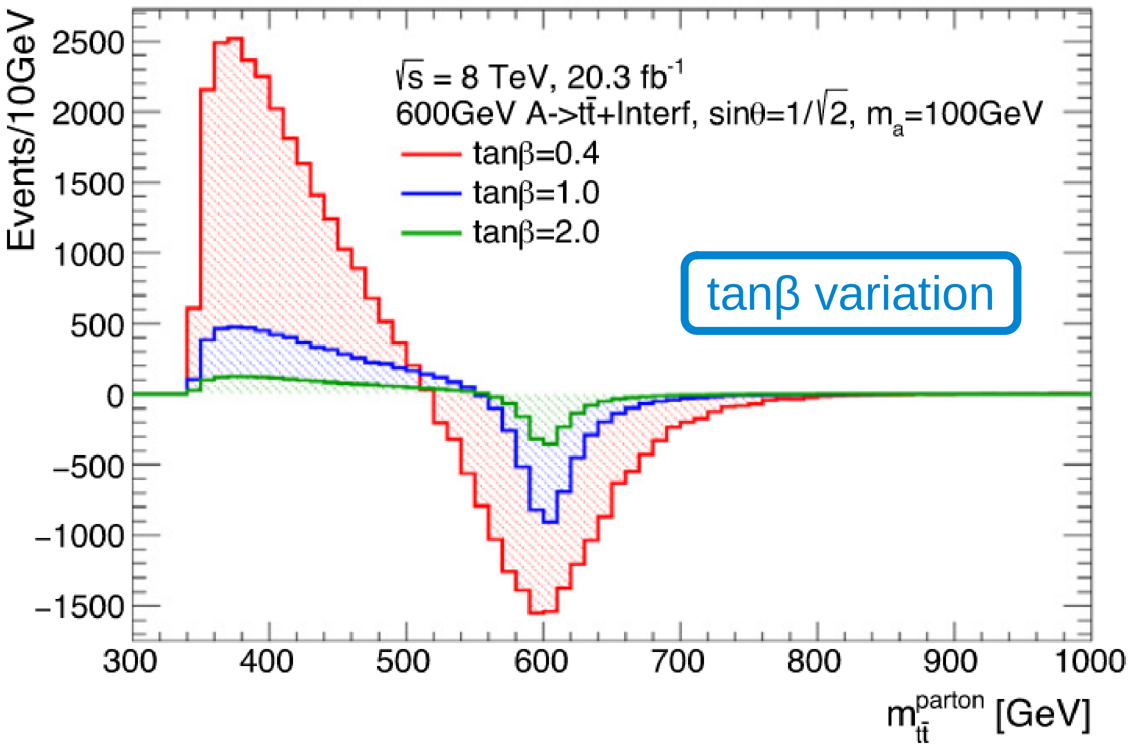


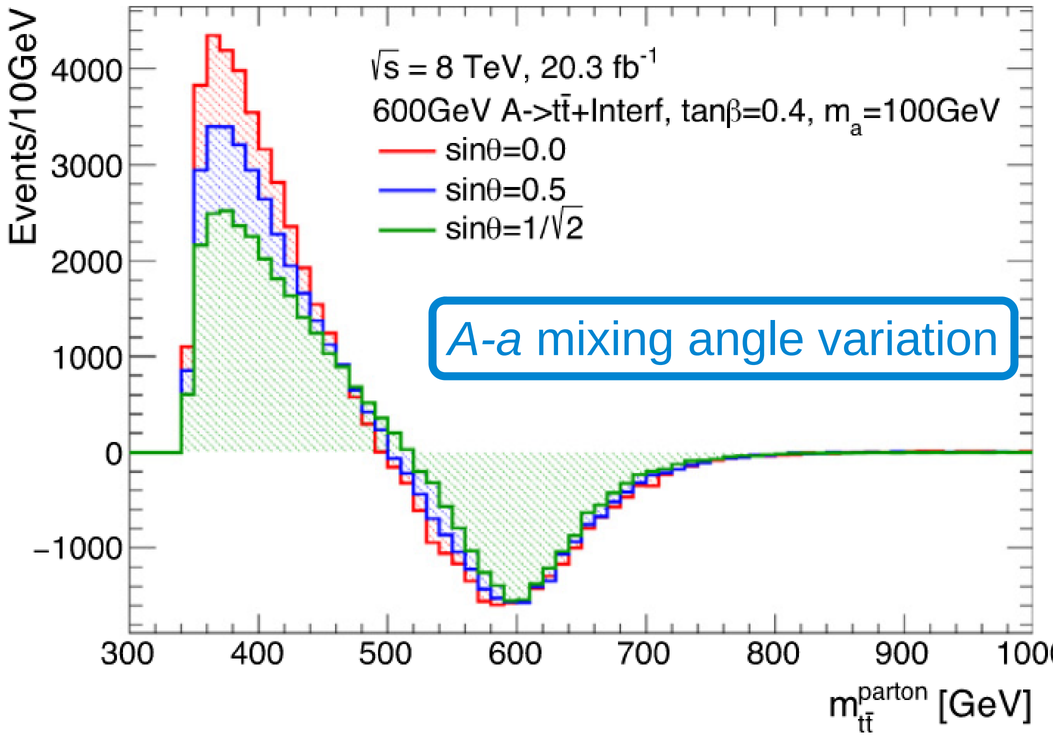


Model dependence of interference pattern

- <u>Example</u>: 2HDM with a pseudoscalar mediator *a* to DM (2HDM+*a*)
- Simple case: S+I pattern for *single* pseudoscalar *A* at fixed mass

LHC DM WG, Phys. Dark. Univ. 27 (2020) 100351





Challenges

> **Modeling**
  - Interference between LO loop process and LO tree-level background
  - Separation of S+I or I components from inclusive S+I+B process

> **Reconstruction**
  - Sensitivity depends strongly on:
    - Resolution of reconstructed variables of interest, e.g. m(ttbar)
    - Instrumental and modeling uncertainties affecting the shape of reconstructed variables
  - Treatment of modeling uncertainties for the interference component I

> **Statistical interpretation**
  - Issues arising due to likelihood parameterisation in terms of $\sqrt{\mu}$: $\mu S + \sqrt{\mu}\, I + B$

Challenges

- **Modeling**
  - Interference between LO loop process and LO tree-level background
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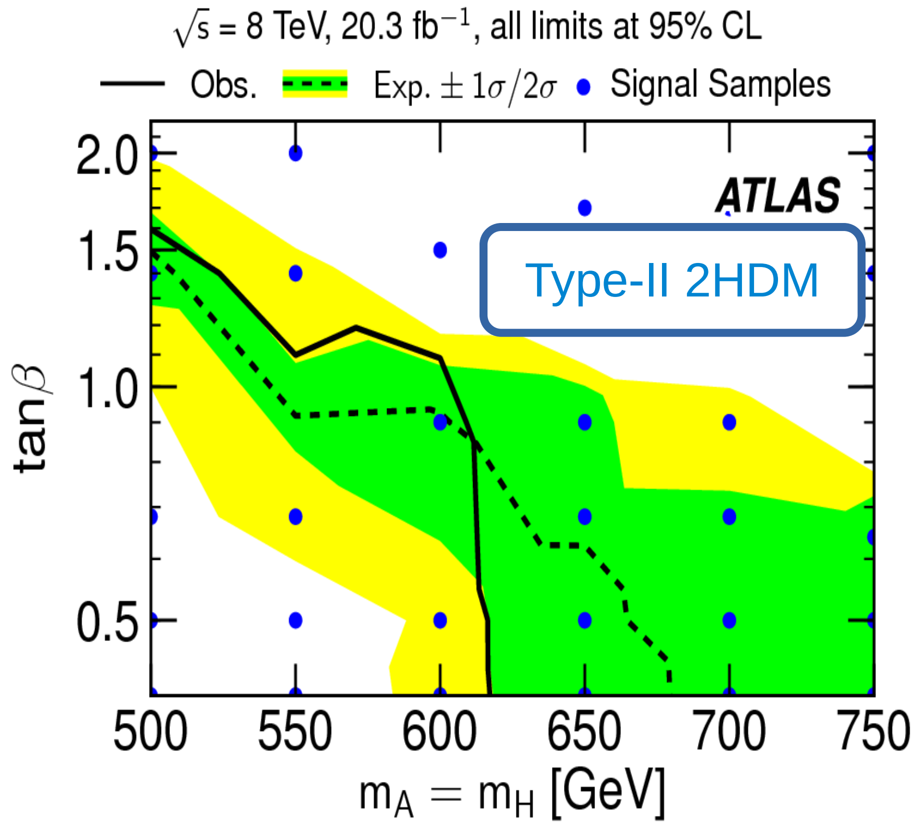
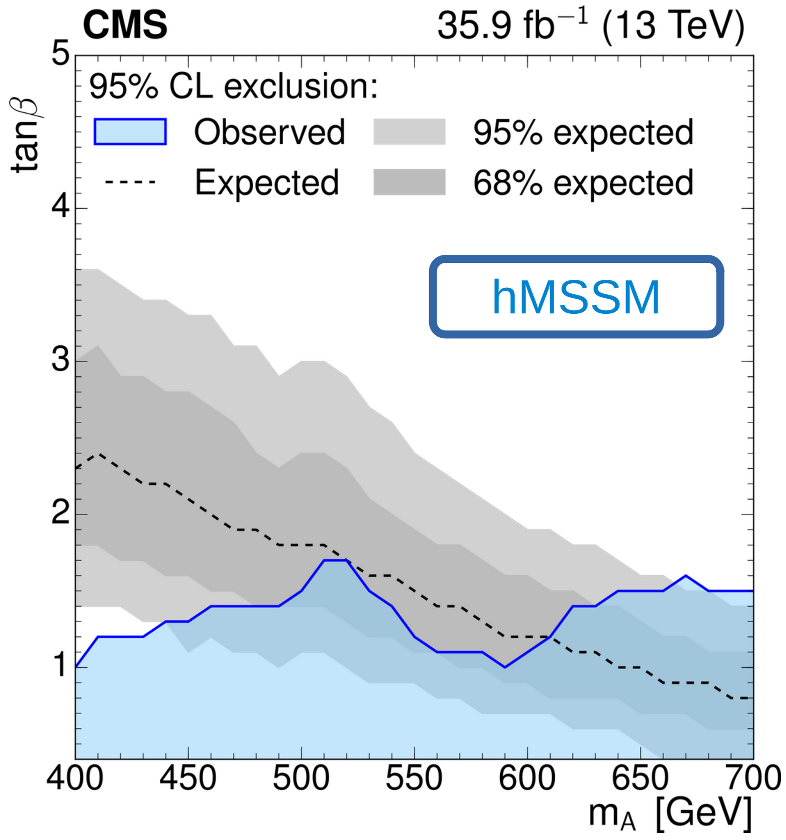
- **Statistical interpretation**
  - Issues arising due to likelihood parameterisation in terms of $\sqrt{\mu}$:

Current results

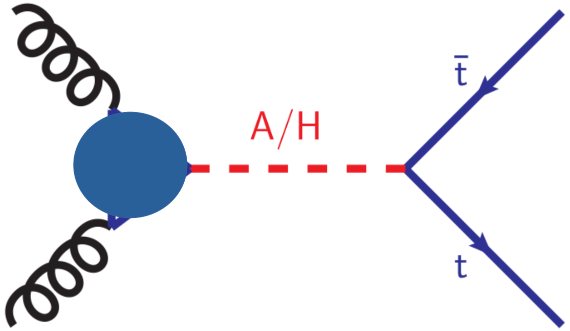
- ATLAS: result based on 20.3 fb^{-1} of 8 TeV data [Phys. Rev. Lett. 119 (2017) 191803]
- CMS: result based on 36.9 fb^{-1} of 13 TeV data [JHEP 04 (2020) 171]
- Searches on full Run 2 dataset on-going





UFO implementation(s)

- Signal process and interference generated at LO with MadGraph
- Problem: Interference cannot be generated between loop-induced process and tree-level background
- Solution: Reduce loop to effective vertex with effective coupling
- Different UFO implementations used in ATLAS and CMS
  - ATLAS: Higgs_Effective_Couplings_FormFact [link]
  - CMS: Massive_Higgs_v2 [link]

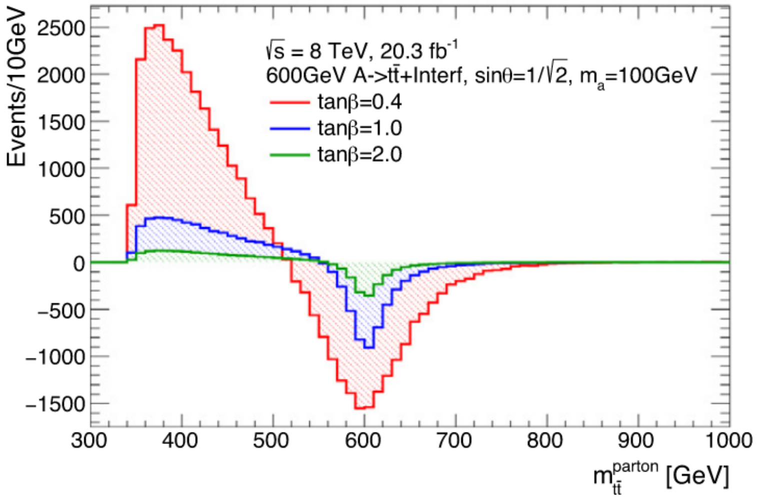


- Note aside: interference at NLO difficult due to presence of two loops

Subtraction of background component (1)

> By default, can only generate pure signal or inclusive S+I+B processes

> Problem: would need to generate large S+I+B samples for each signal hypothesis because σ(S) << σ(B)



> Solution: hack MadGraph to remove background component in generation

> Different hacks used in ATLAS and CMS

- Both validated against S+I sample obtained by subtracting B sample from S+I+B sample
- Both discussed with MadGraph authors [launchpad]

Subtraction of background component (2)

> ATLAS:
  - At the matrix element level, subtract B from inclusive process: (S+I+B) - B
  - Modify: `madgraph/iolibs/template_files/matrix_madevent_group_v4.inc`

```
+
+    MATRIX_BKG = 0.D0
+  DO M = 1, NAMPSO
+      DO I = 1, 2
+        ZTEMP = (0.D0,0.D0)
+        DO J = 1, 2
+          ZTEMP = ZTEMP + CF(J,I)*JAMP(J,M)
+        ENDDO
+    DO N = 1, NAMPSO
+          IF (CHOSEN_SO_CONFIGS(SQSOINDEX%(proc_id)s(M,N))) THEN
+         MATRIX_BKG = MATRIX_BKG + ZTEMP*DCONJG(JAMP(I,N))/DENOM(I)
+      ENDIF
+    ENDDO
+      ENDDO
+  ENDDO
+      MATRIX%(proc_id)s = MATRIX%(proc_id)s - MATRIX_BKG
```

Subtraction of background component (2)

> CMS:
  - At the matrix element level, subtract S-I+B from inclusive process: (S+I+B) – (S-I+B)
  - Subtraction sample obtained by reverting sign of effective coupling (GC_85 → -GC_85)
    - GC_85^2 * ME(S) - GC_85 * ME(I) + ME(B)
  - Modify: `SubProcesses/*/matrix1.f`

```
# A0 Interference
  for file in `find ${name}/SubProcesses/. -name matrix1.f`; do
    sed -i "/INCLUDE 'coupl.inc'/d" $file
    sed -i "/IMPLICIT NONE/a\      INCLUDE 'coupl.inc'" $file
    sed -i '/T=MATRIX1(P ,NHEL(1,I),JC(1))/a\          GC_85=-GC_85' $file
    sed -i '/T=MATRIX1(P ,NHEL(1,I),JC(1))/a\          T=5D-1*(T-MATRIX1(P ,NHEL(1,I),JC(1)))' $file
    sed -i '/T=MATRIX1(P ,NHEL(1,I),JC(1))/a\          GC_85=-GC_85' $file
  done
```

Summary of ATLAS/CMS differences

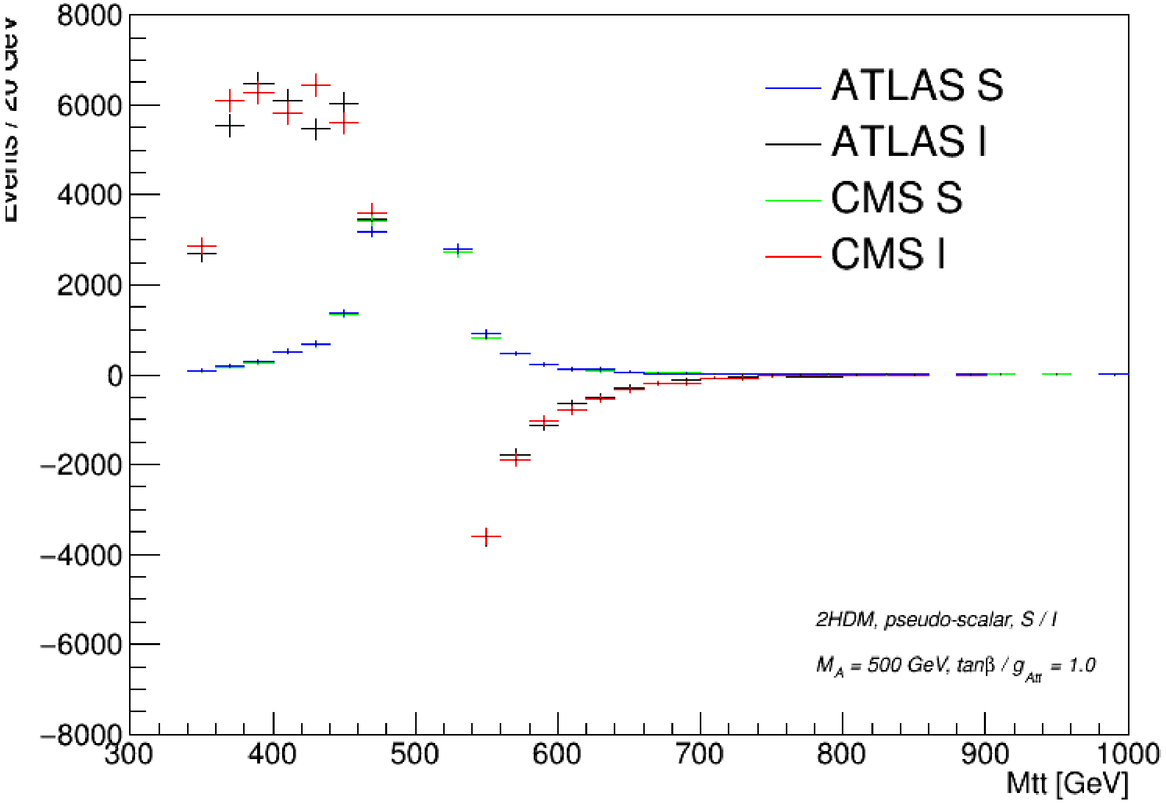
- Different LO UFO implementations
- Different approach to remove background component
  - ATLAS: (S+I+B) – B
  - CMS: 0.5 * [(S+I+B) - (S-I+B)]
- Different components being generated directly
  - ATLAS: S+I
  - CMS: I

Many thanks to Alexander Grohsjean and Afiq Anuar for providing the details about the CMS UFO and hacks!

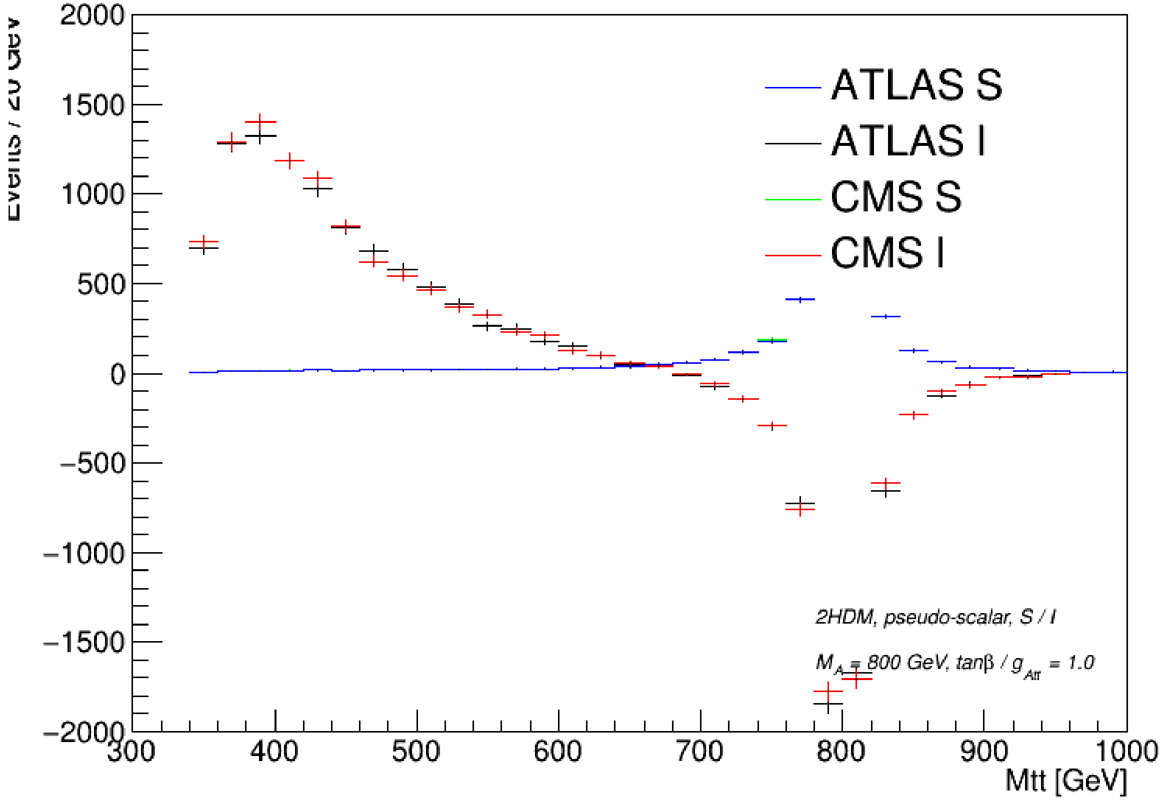
S and I shape comparisons for A

> Compare separately the pure signal shape S and interference shape I

m_A = 500 GeV, tanβ = 1.0



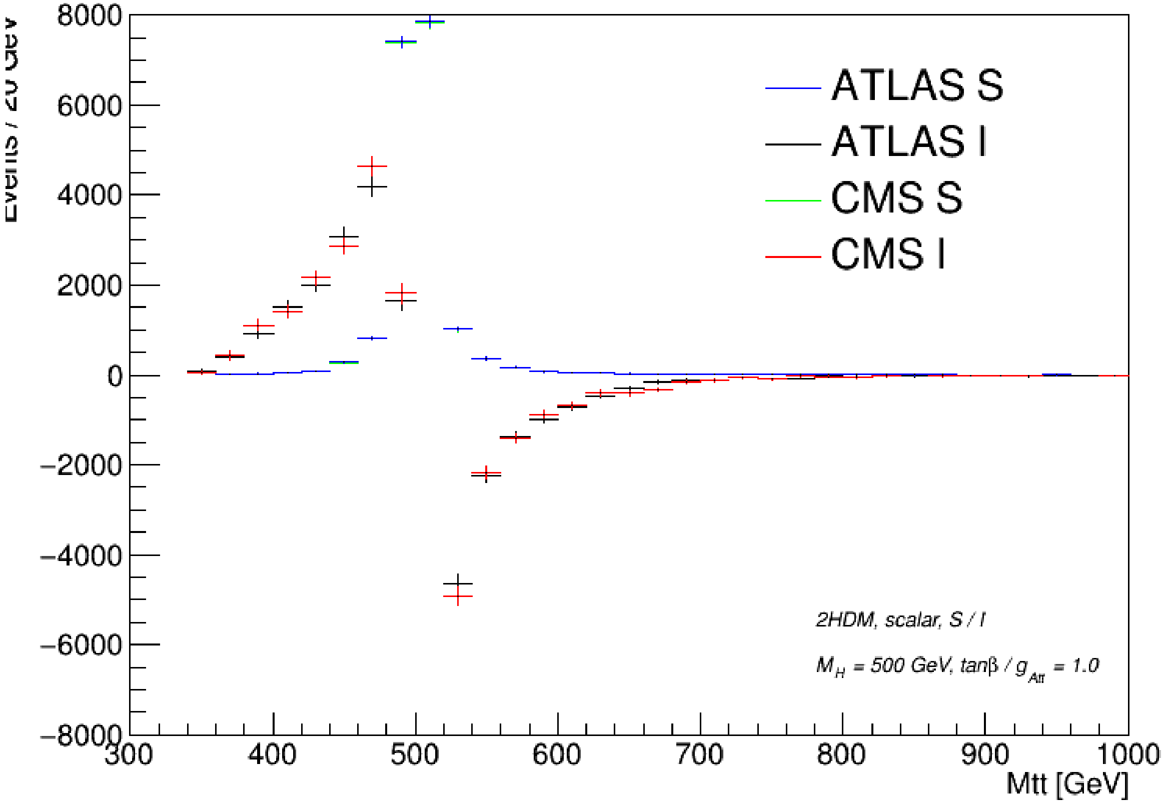
m_A = 800 GeV, tanβ = 1.0



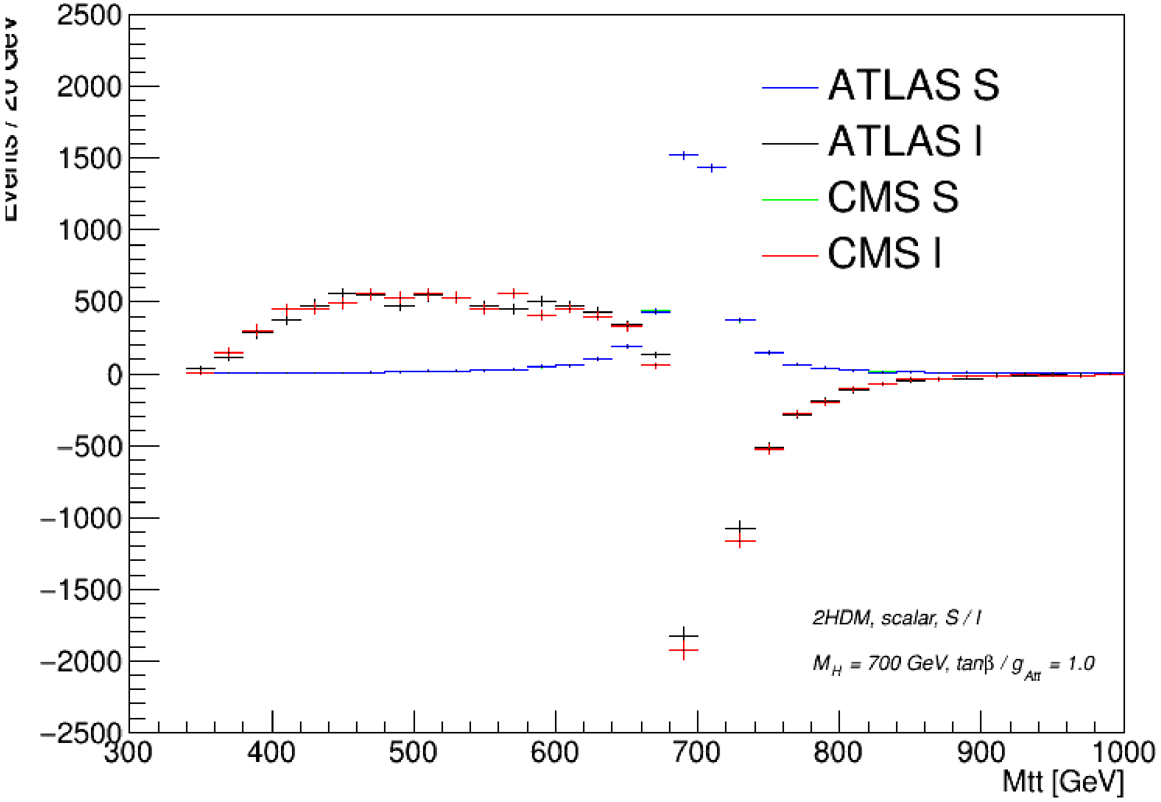
S and I shape comparisons for H

> Compare separately the pure signal shape S and interference shape I

m_H = 500 GeV, tanβ = 1.0



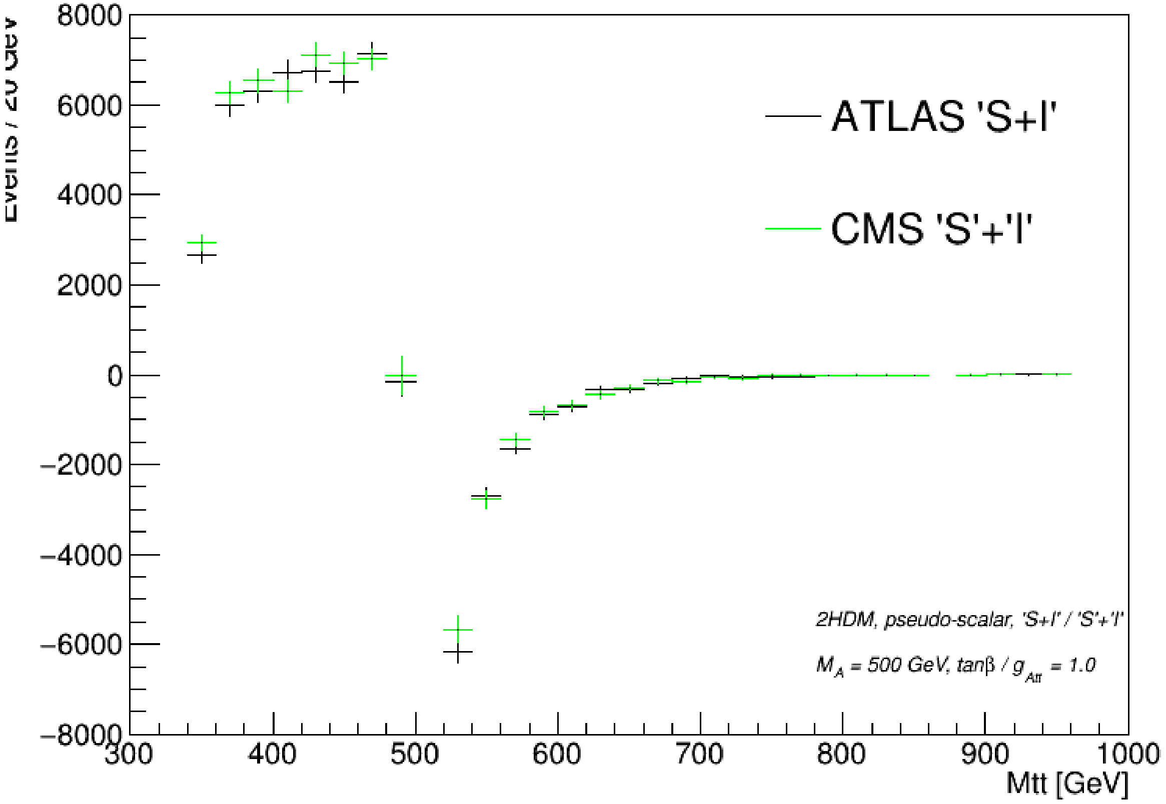
m_H = 800 GeV, tanβ = 1.0



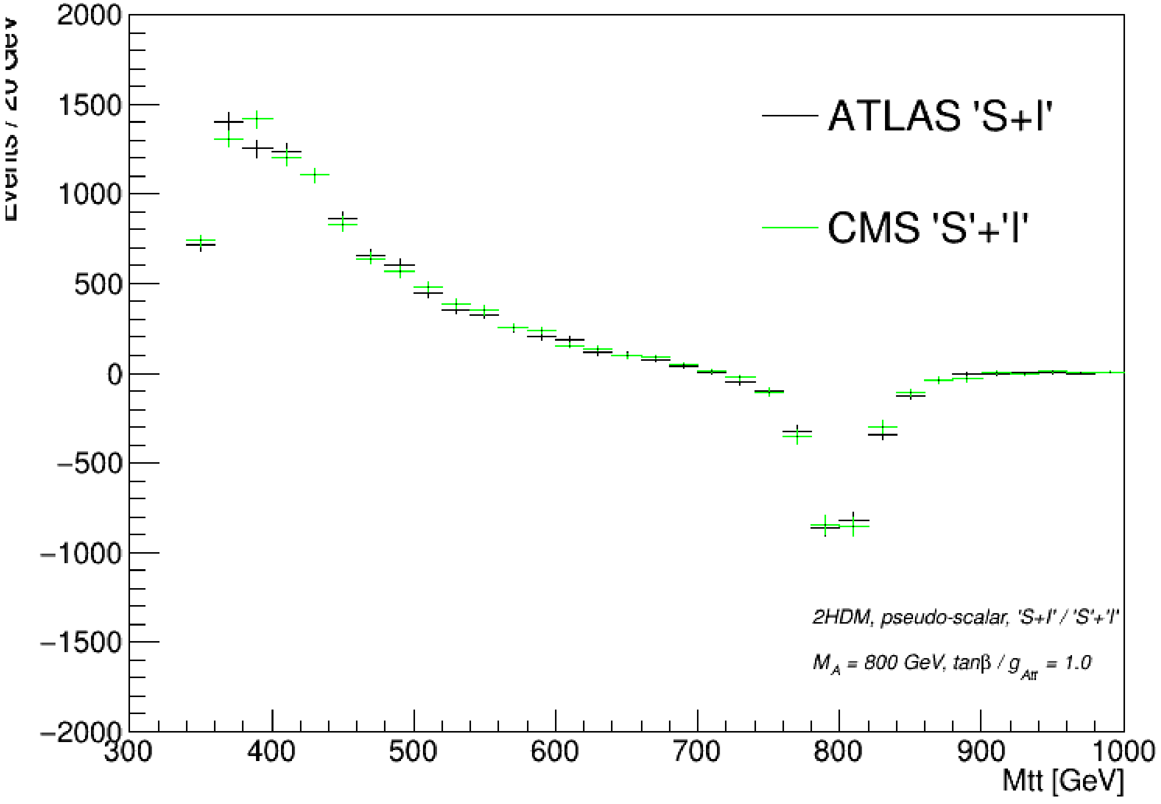
S+I shape comparison for A

> Final signal+interference shapes:
  - ATLAS: “S+I”
  - CMS: “S”+”I”

mA = 500 GeV, tanβ = 1.0



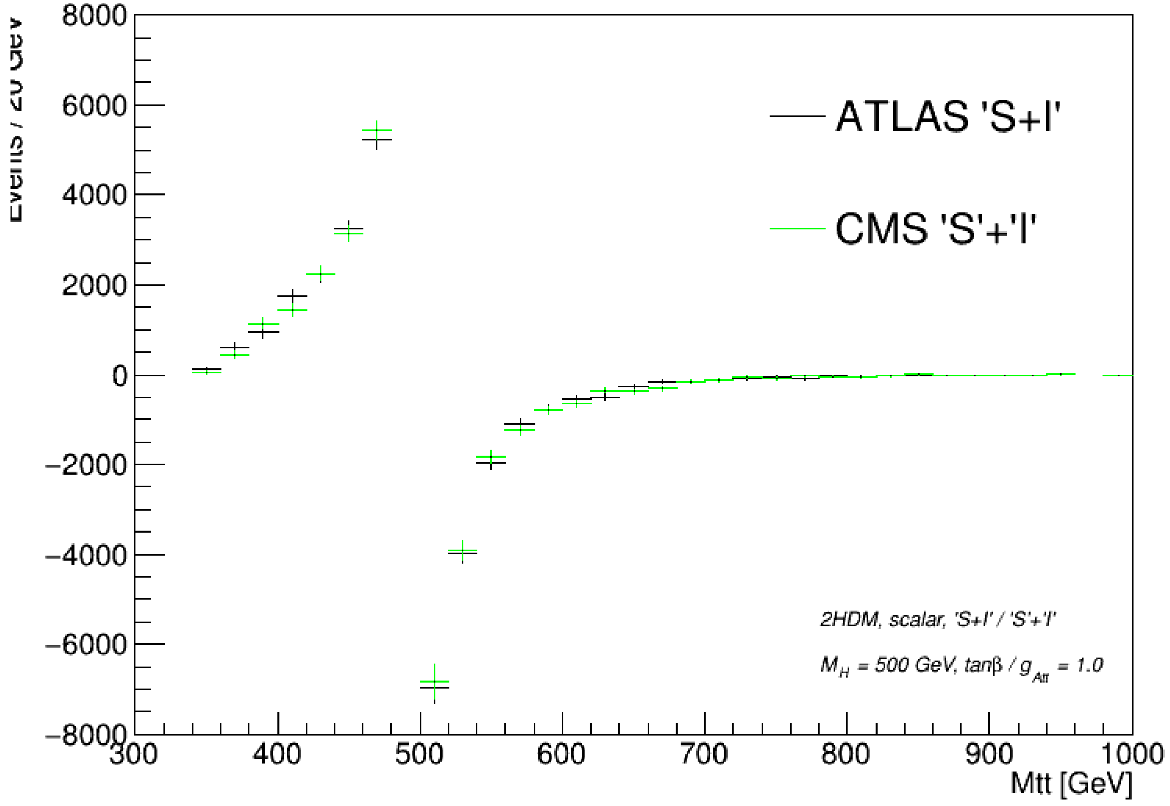
mA = 800 GeV, tanβ = 1.0



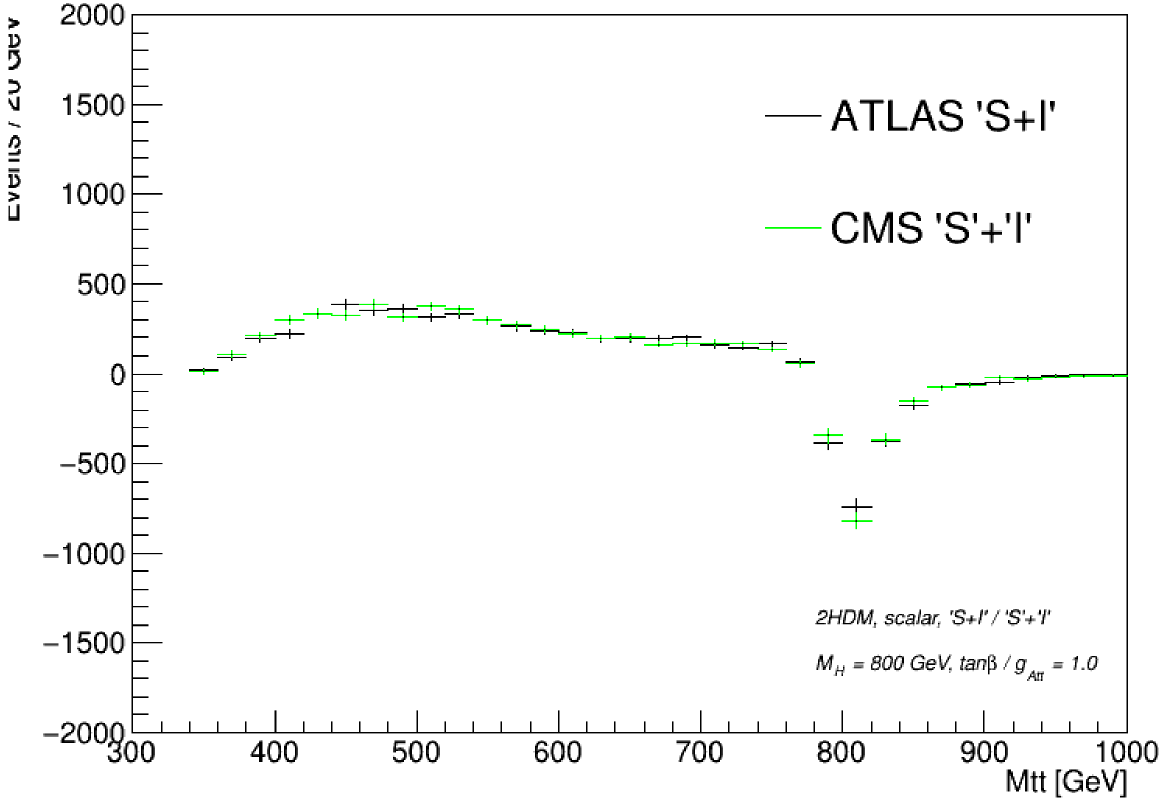
S+I shape comparison for H

> Final signal+interference shapes:
  - ATLAS: "S+I"
  - CMS: "S"+"I"

m_H = 500 GeV, tanβ = 1.0



m_H = 800 GeV, tanβ = 1.0



Widths calculations

> Excellent shape agreement in all relevant distributions (S, I, S+I)...

> … but only if A/H width set to the same calculated input value! (internal width calculations differ)

> Both experiments rely on 2HDMC to calculate A/H widths and branching ratios
  - ATLAS: central recommendations based on 2HDMC v1.8.0
  - CMS: no central recommendations; A/H→ttbar search also uses 2HDMC v1.7.0

Cross-sections corrections

- Higher-order cross-section calculations available for resonant A/H production (no interference)
- Corrections applied consistently in ATLAS and CMS:

$$K_S\, S + \sqrt{K_S K_B}\, I$$

- Where $K_S = \sigma_{calc}(S)/\sigma_{gen}(S)$ and $K_B = \sigma_{calc}(B)/\sigma_{gen}(B)$
- Approach for interference term correction based on Hespel, Maltoni, Vryonidou [JHEP 10 (2016) 016]

- Both experiments rely on SusHi to calculate A/H cross-sections
  - ATLAS: central recommendations based on latest SusHi v1.7.0
  - CMS: no central recommendations; A/H→ttbar search also uses SusHi v1.7.0

Comparison of calculated width and cross-section values

- Compared values obtained with setups described in previous slides
- Many thanks to Afiq Anuar for providing the CMS values!
- Agreement within 1%
  - Small differences probably due to differences in SusHi/2HDMC setups, e.g. different choice of PDF set

		ATLAS	CMS		ATLAS	CMS	
mA	tanb	width [GeV]			xsec [GeV]		
400	0.4	93.8	93.7	0.1%	173.5	173.2	0.2%
400	1.0	15.0	15.0	0.0%	27.8	27.7	0.4%
600	0.4	182.3	180.7	0.9%	19.1	19.3	-1.0%
600	1.0	29.2	28.9	1.0%	3.1	3.1	0.0%
800	0.4	248.1	245.8	0.9%	3.6	3.6	0.0%
800	1.0	39.7	39.3	1.0%	0.6	0.6	0.0%

- Note aside: CMS assumes BR(A/H→ttbar) = 100%, while ATLAS also considers couplings to bbar
  - Expect no significant impact for the currently probed tanβ values

Summary

- Searches for A/H $\rightarrow$ ttbar crucial to probe uncovered parameter regions of 2HDMs
- Strong model-dependent signal-background interference complicates analysis
- Different modeling approaches used in ATLAS and CMS

- Compared different aspects of interference modeling
  - Consistent interference shapes ✓
  - Consistent choice of widths ✓
  - Consistent signal and interference normalisation ✓
- ATLAS and CMS model predictions are consistent, so results will be comparable. ✓