Search for heavy Higgs bosons in top-antitop final states at ATLAS

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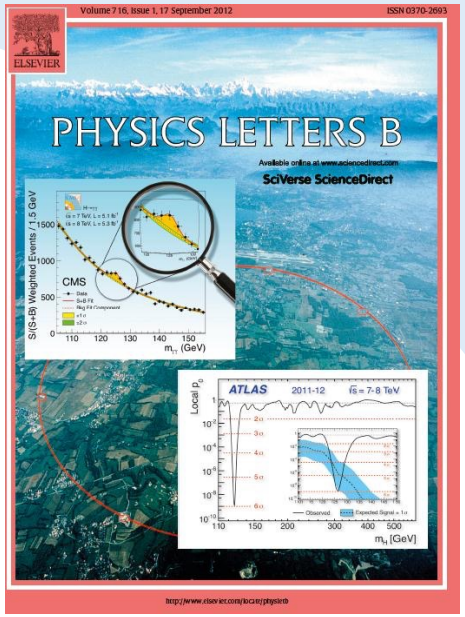
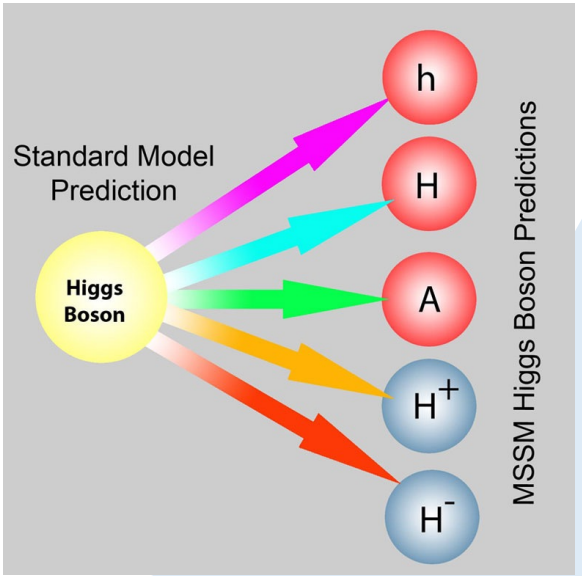
Motivation (1)

- The SM provides an effective description of nature up to the TeV scale
  - Minimal SM extensions are well motivated by BSM theories, such as supersymmetry and axion models
- 2HDM models, for example, generate new neutral pseudoscalar (A) and scalar (H) states as well as charged ($H^{\pm}$) states
  - m_A, m_H, $m_{H^{\pm}}$, m_{12}, α and $\tan\beta$ are free parameters





3 Higgs masses

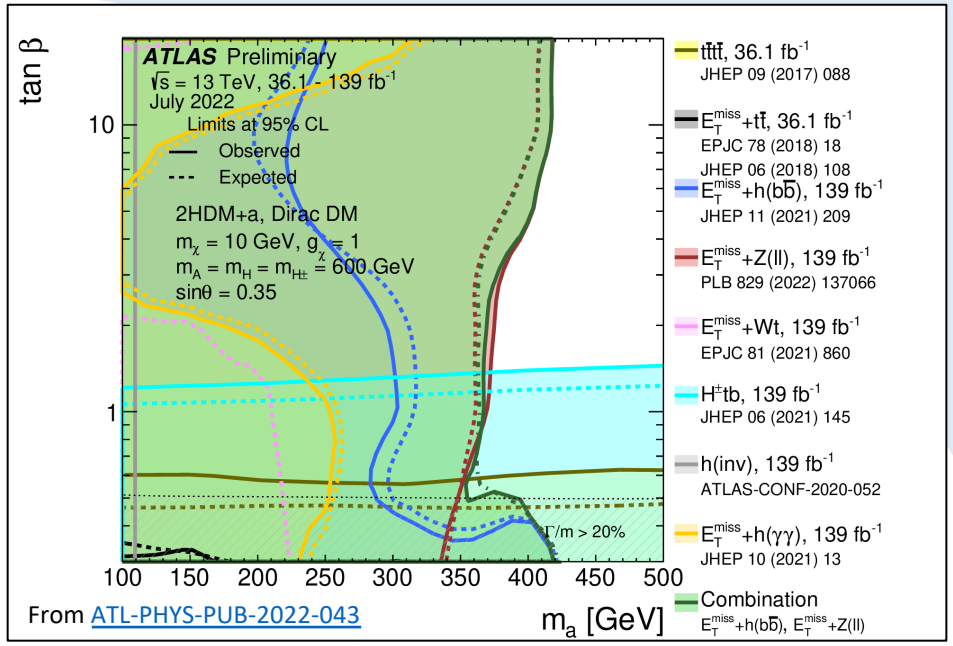
Parameter of the potential

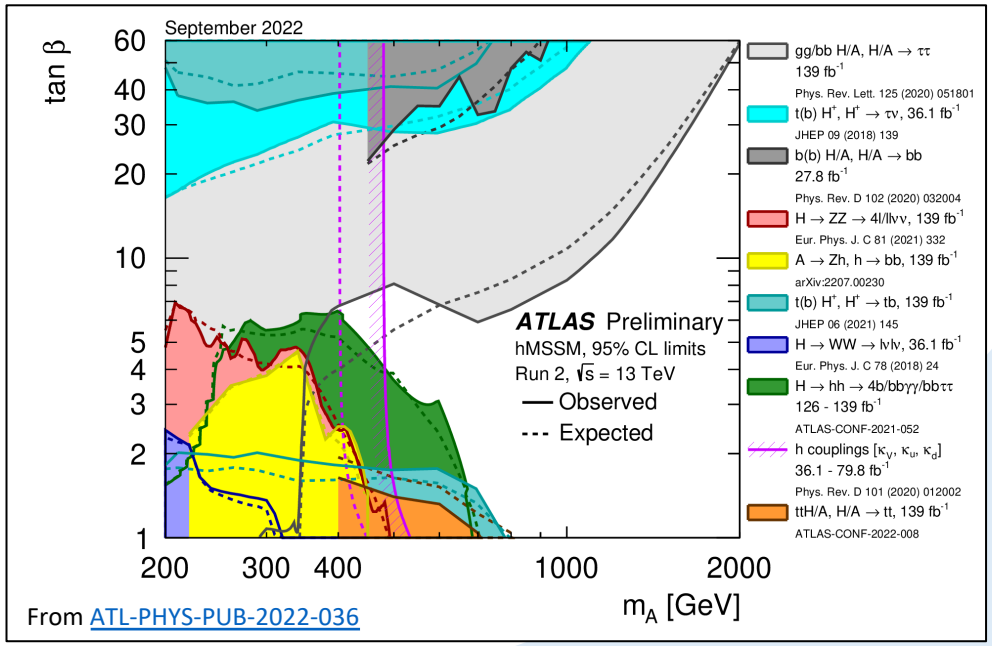
Mixing angle of h and H

Ratio of vacuum expectation values of A and H

Motivation (2)

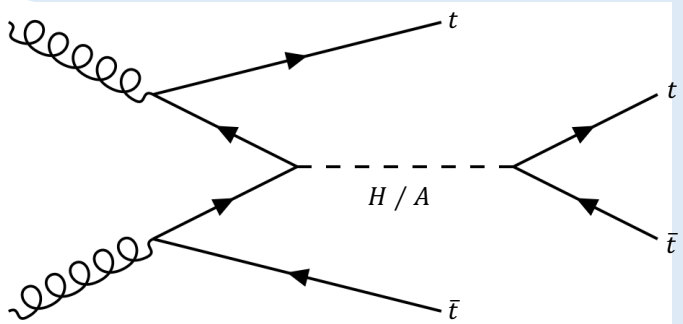
- In type-II 2HDM models, $t\bar{t}$ is the dominant decay if $m_{H/A} > 2m_t$ and $\tan\beta$ is small
  - The parameter region is not strongly constrained to date
- Inclusive searches are challenging due to destructive interference with SM $t\bar{t}$ production
- $t\bar{t}A$ / H production has a distinctive experimental signature, but a small cross section compared to gluon-initiated production





$gg \rightarrow t\bar{t}H\,/\,A \rightarrow t\bar{t}t\bar{t}$

arXiv:2211.01136



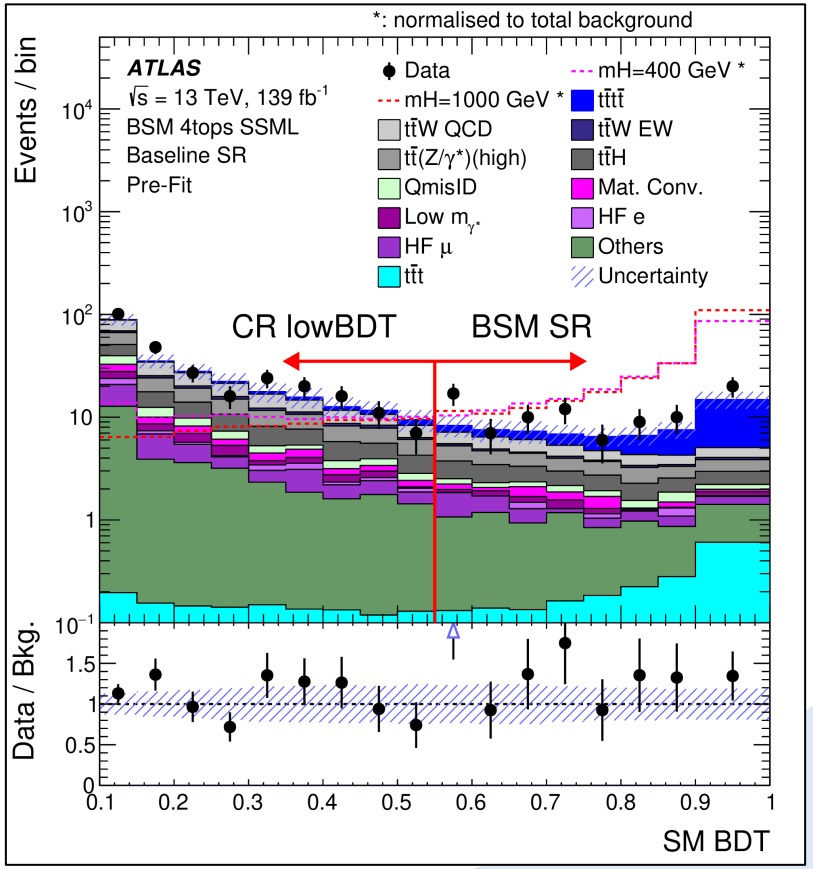
- Full Run 2 dataset: $139\ \text{fb}^{-1}$ at $\sqrt{s} = 13$ TeV
- Probed mass range of signal: $400 < m_{H/A} < 1000$ GeV
  - ✓ Large $H\,/\,A \rightarrow t\bar{t}$ branching fraction
  - ✓ Small $H\,/\,A$ widths
  - ✓ Above 1 TeV, interference becomes non-negligible
- Target final states: $= 2$ same-sign leptons or ≥ 3 leptons
  - ✓ Low-level of background contamination
  - ✓ Main backgrounds: $t\bar{t}W/t\bar{t}Z/\,t\bar{t}H$, charge-misidentification, fake/non-prompt leptons from $t\bar{t}$
- Binned likelihood fit to 1 signal region + 5 control regions simultaneously

Leptons = e or μ (including from τ decays)

$gg \rightarrow t\bar{t}H$ / $A \rightarrow t\bar{t}t\bar{t}$ selection

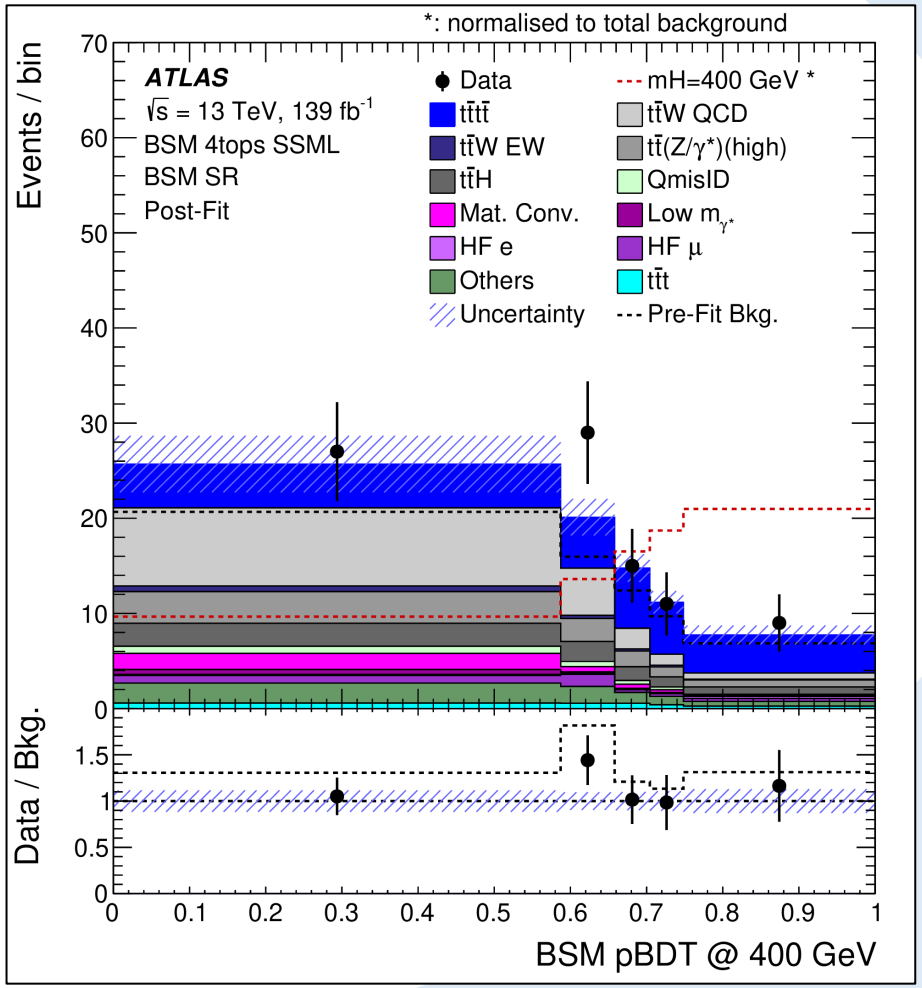
Baseline SR → Train 'SM BDT' → *BSM SR*

- 2 channels:
  - dilepton: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$
  - 3-lepton: eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$
- Electrons: $p_T > 28$ GeV
- Muons: $p_T > 28$ GeV
- Z-veto: $m_{ll} \in [81,101]$ GeV
- $R = 0.4$ jets: $p_T > 25$ GeV
  - $N_j \geq 6$ and $N_b \geq 2$



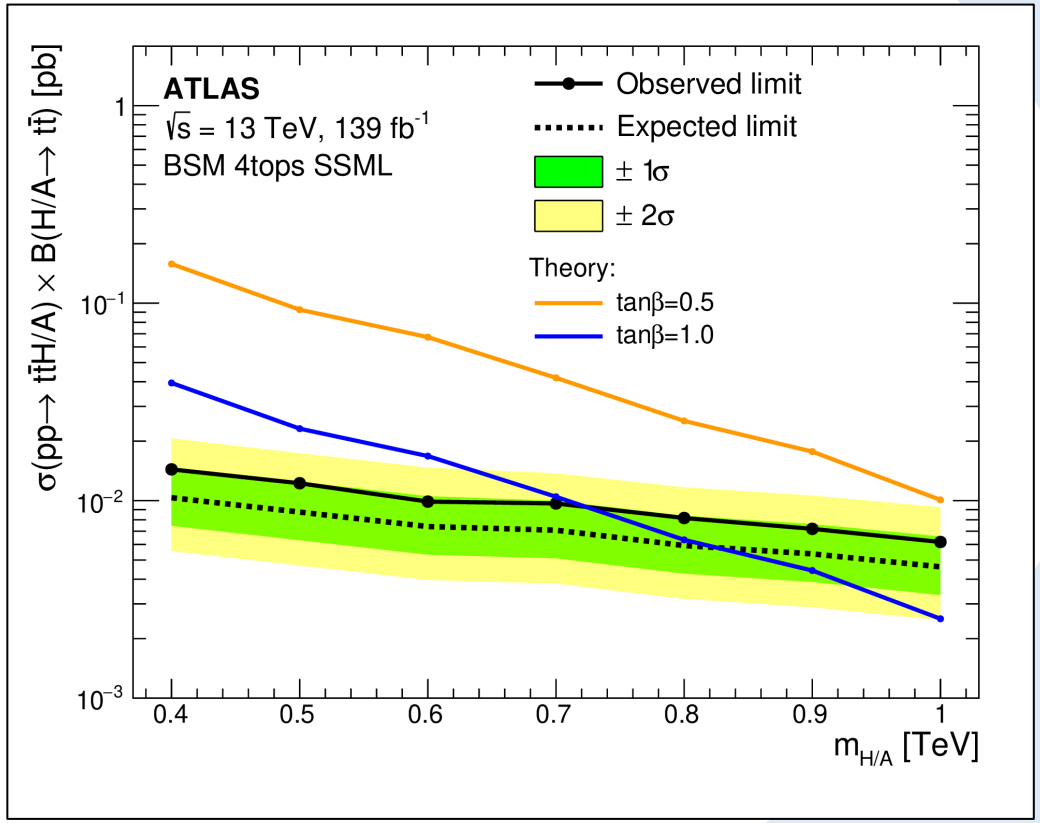
$gg \rightarrow t\bar{t}H$ / $A \rightarrow t\bar{t}t\bar{t}$ classification

- SM BDT: to separate SM $t\bar{t}t\bar{t}$ from other backgrounds
  - SM BDT > 0.55
- BSM pBDT: to separate signal from background
  - distribution of the BSM pBDT score is discriminating variable in *BSM SR*
  - binning optimised for each signal hypothesis



$gg \rightarrow t\bar{t}H$ / $A \rightarrow t\bar{t}t\bar{t}$ results (1)

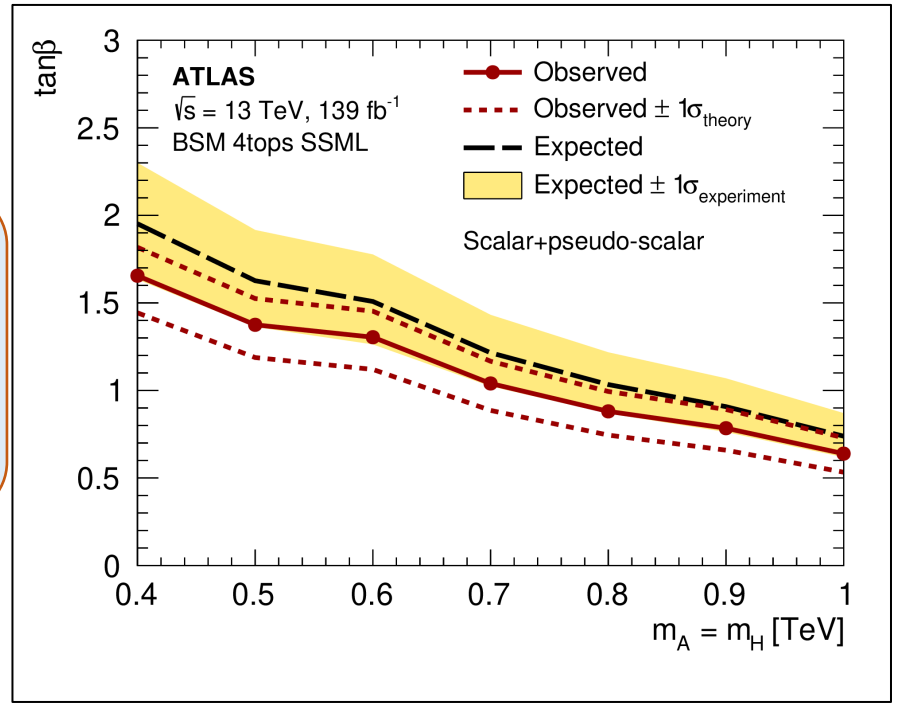
- Under the S+B hypothesis, no significant excess of events above the SM prediction is observed
- Results are interpreted in the context of a type-II 2HDM, assuming no interference

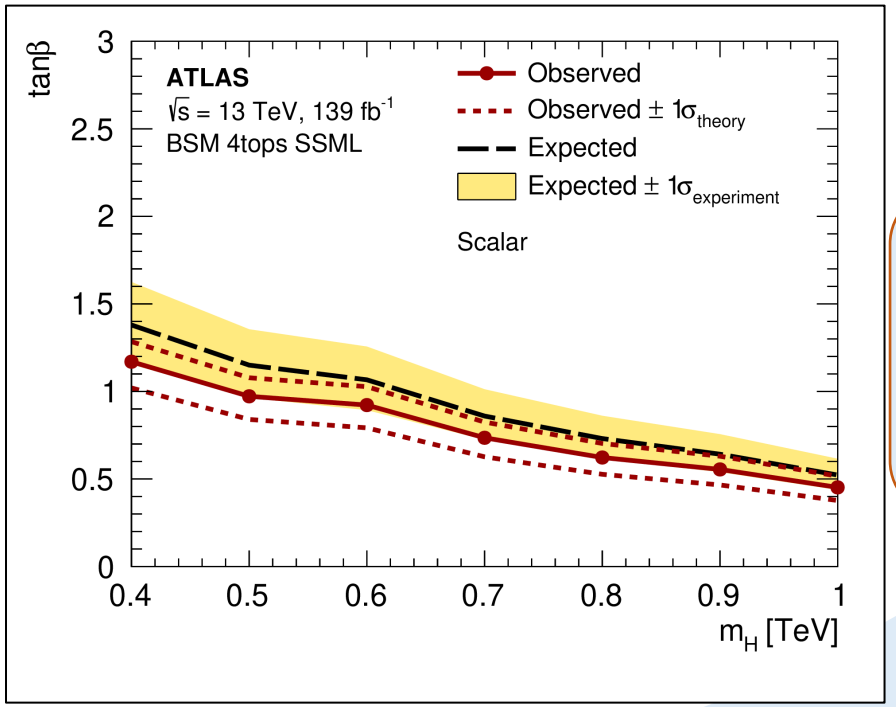


$gg \rightarrow t\bar{t}H$ / $A \rightarrow t\bar{t}t\bar{t}$ results (2)

- Upper limits on the cross section can be translated into limits in the tan β vs $m_{H/A}$ plane

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

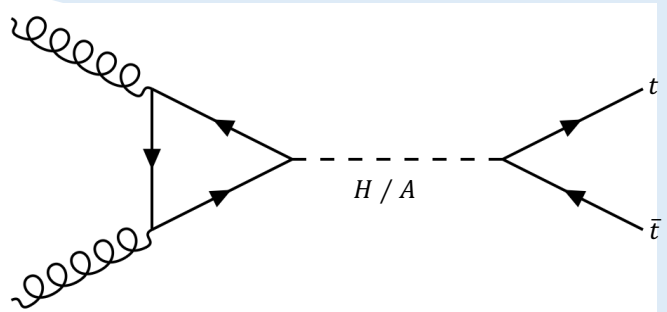


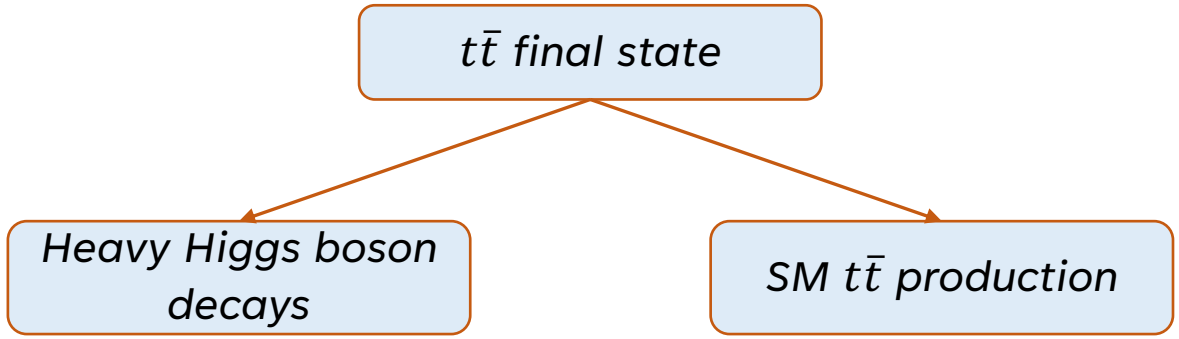


Only scalar particle contributes to BSM $t\bar{t}t\bar{t}$ production

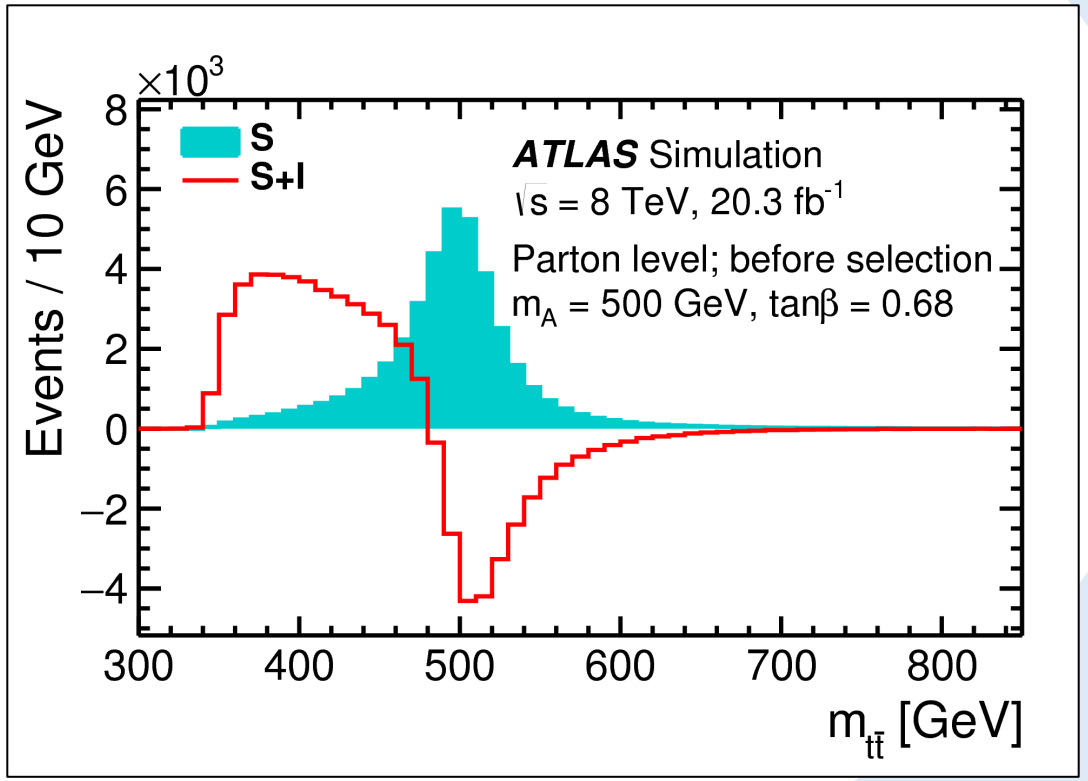
$gg \rightarrow H / A \rightarrow t\bar{t}$

Phys. Rev. Lett. **119,** 191803





- Invariant mass of the $t\bar{t}$ system reconstructed from:
  - 4 $R = 0.4$ jets with $p_T > 25$ GeV
  - 1 lepton (e or μ with $p_T > 25$ GeV)
  - E_T^{miss}

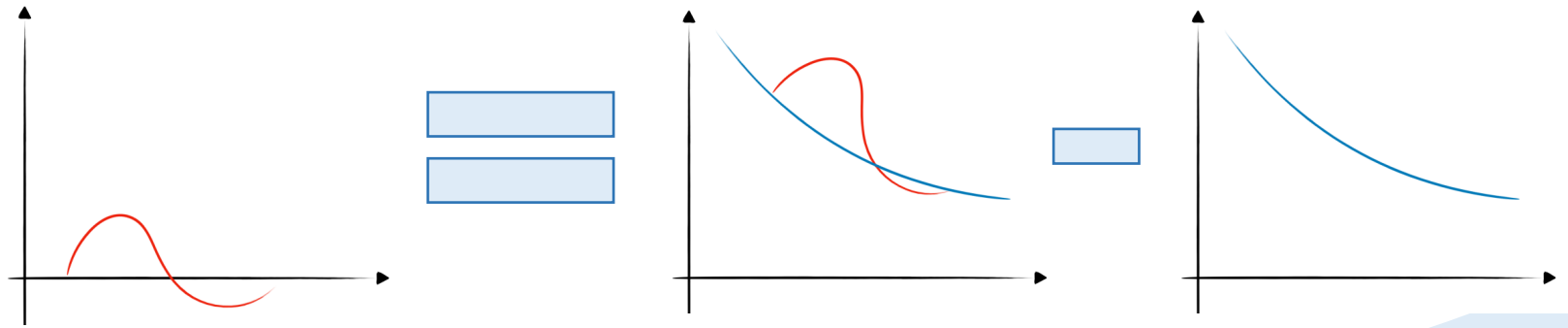


Complications of interference (1)

- Requires a quadratic parametrisation of the likelihood:

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

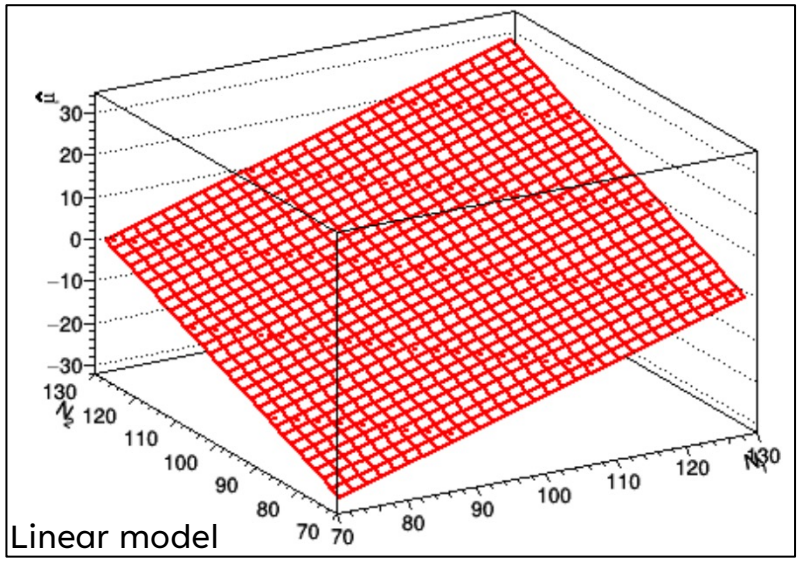
- Traditional statistical tools cannot handle bins with negative entries
- ‘Offset method’ developed in order to perform binned likelihood fit

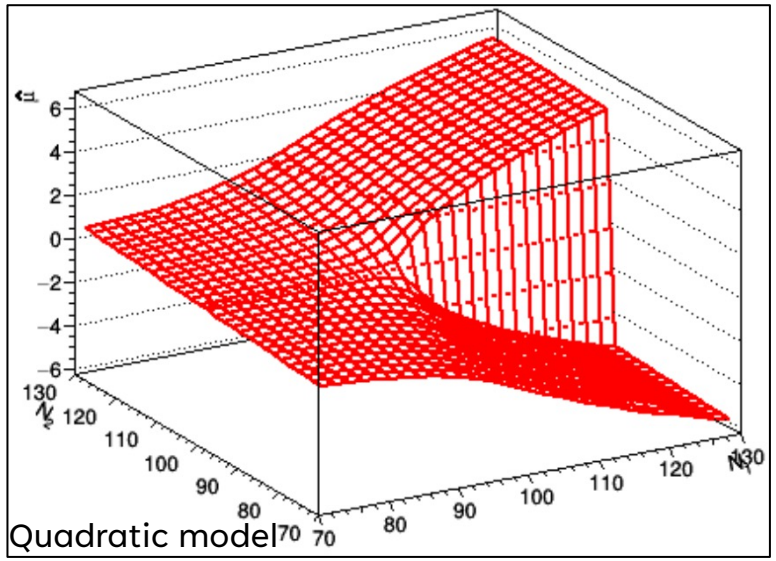


Complications of interference (2)

Full details

- Quadratic parametrisation can also lead to unexpected features in the likelihood scans





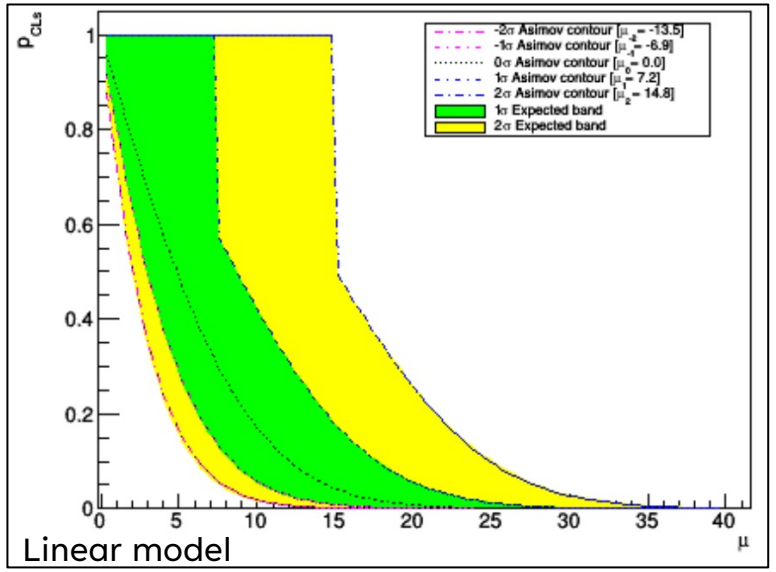
Current ATLAS default

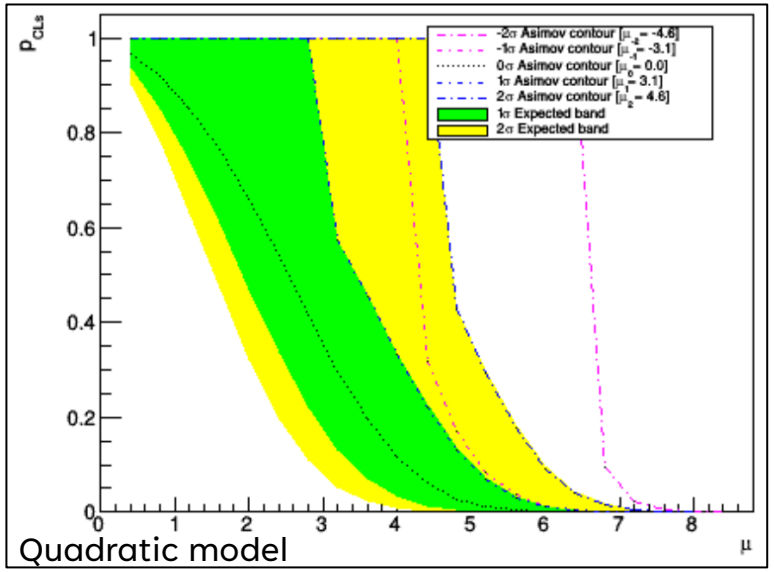
- Issues arise when determining the expected exclusion limits using limit contours, obtained from limits calculated with Asimov datasets

Limit contours vs limit bands

- A alternative method for limit bands: determined from the interval of values that would be excluded under the alternative hypothesis

In the absence of interference the edges of the limit bands correspond with the limit contours





In the quadratic model, the contours do not coincide with the band edges

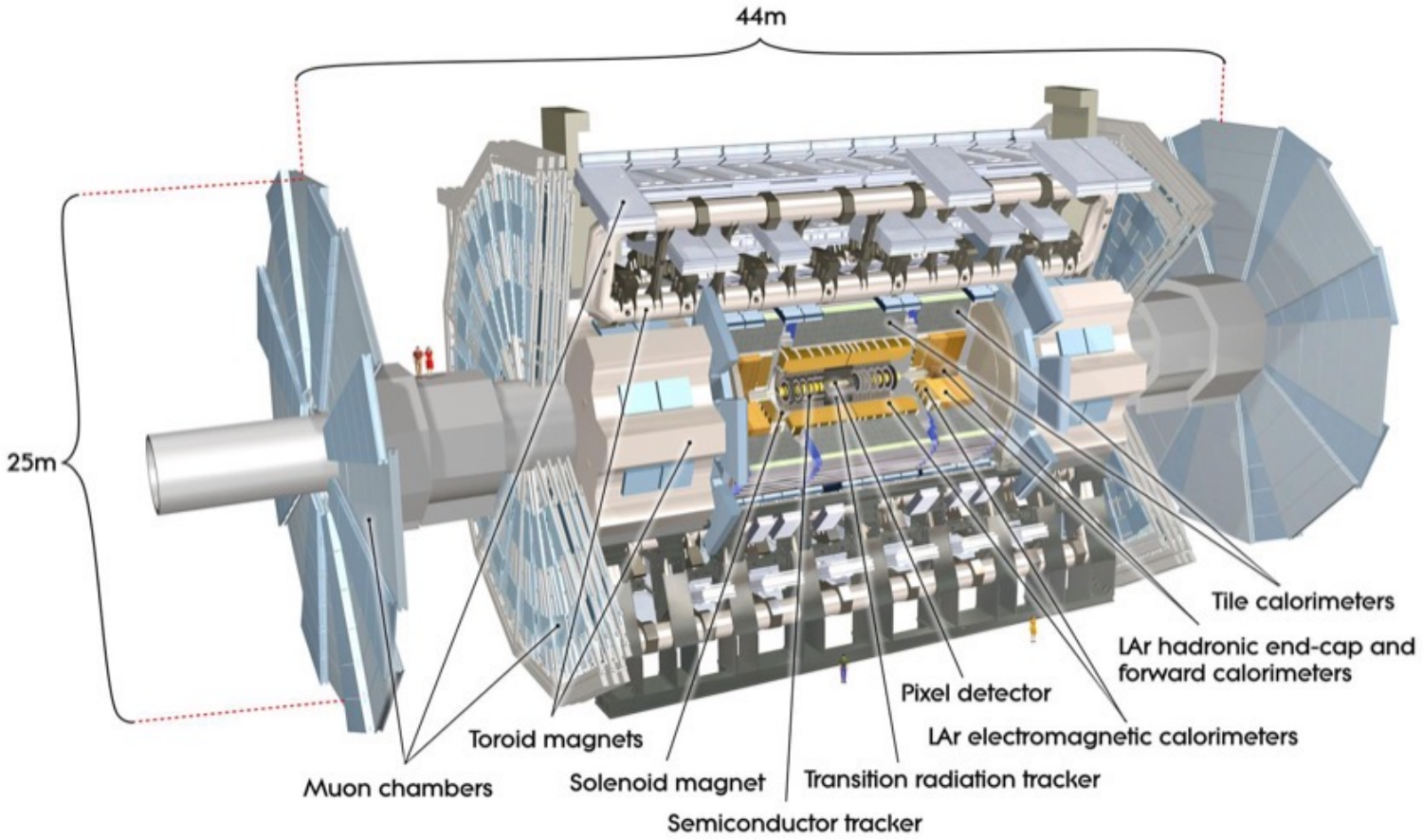
Asimov contours are not always appropriate to define the edges of exclusion bands

Summary

- Searches for heavy Higgs bosons decaying into a $t\bar{t}$ pair are motivated by several BSM models
- The associated production with a $t\bar{t}$ pair leads to a distinctive $t\bar{t}t\bar{t}$ final state, despite the small cross section
  - Constraints in the $\tan\beta$ vs $m_{H/A}$ plane have been presented for 2 possible mass scenarios
- Gluon-initiated production has the added complication of interference resulting in a distorted signal shape
  - This requires special treatment for the calculation of limit bands

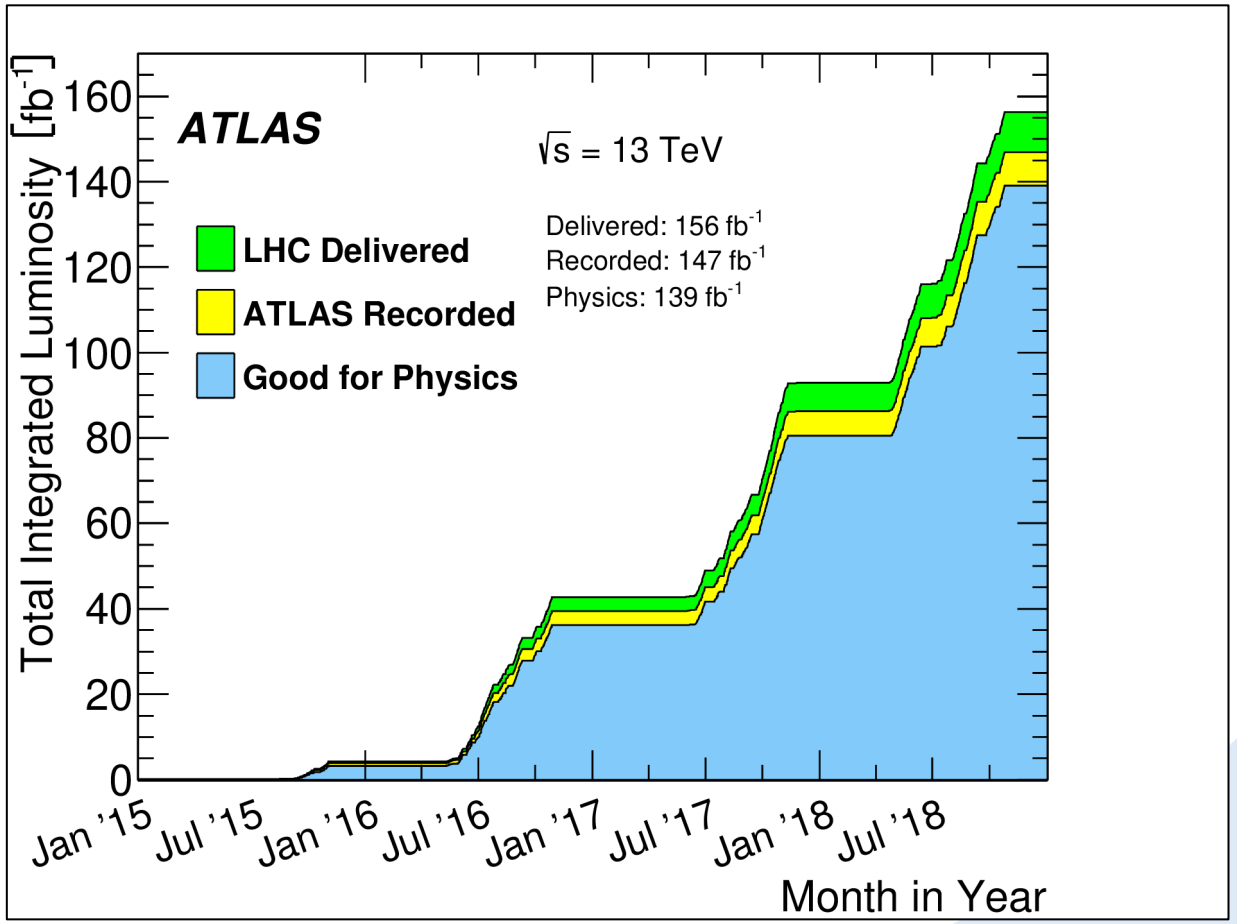
Additional Material

The ATLAS detector



Run 2 luminosity

- Preliminary ‘good-for-physics’ integrated luminosity is $139\ \mathrm{fb}^{-1}$ with an uncertainty of 1.7%
- Final ‘good-for-physics’ integrated luminosity is $140\ \mathrm{fb}^{-1}$ with an uncertainty of 0.83%

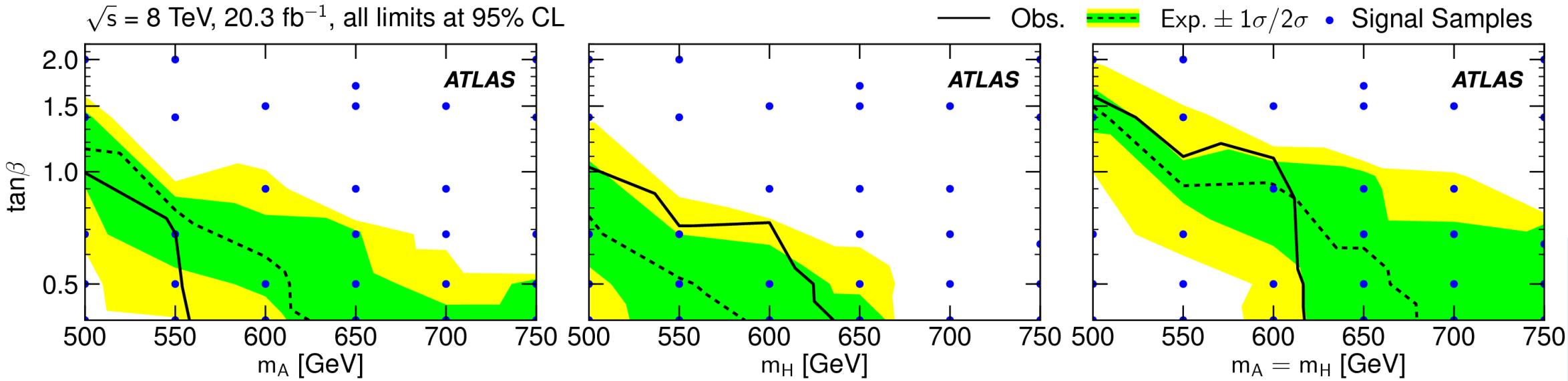


$gg \to t\bar{t}H$ / $A \to t\bar{t}t\bar{t}$ analysis regions

Region	Channel	N_j	N_b	Other selection requirements	Fitted variable
CR Conv	$e^{\pm}e^{\pm}$ || $e^{\pm}\mu^{\pm}$	$4 \leq N_j < 6$	≥ 1	$m_{ee}^{CV} \in [0, 0.1]$ GeV $200 < H_T < 500$ GeV	m_{ee}^{PV}
CR HF e	eee || $ee\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR HF μ	$e\mu\mu$ || $\mu\mu\mu$		$= 1$	$100 < H_T < 250$ GeV	Yield
CR $t\bar{t}W$	$e^{\pm}\mu^{\pm}$ || $\mu^{\pm}\mu^{\pm}$	≥ 4	≥ 2	$m_{ee}^{CV} \notin [0, 0.1]$ GeV, $\|\eta(e)\| < 1.5$ for $N_b = 2$, $H_T < 500$ GeV or $N_j < 6$; for $N_b \geq 3$, $H_T < 500$ GeV	$\sum p_T^{\ell}$
CR lowBDT	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT < 0.55	SM BDT
BSM SR	SS+3L	≥ 6	≥ 2	$H_T > 500$ GeV, SM BDT ≥ 0.55	BSM pBDT

$gg \rightarrow H / A \rightarrow t\bar{t}$ 8 TeV limits

- No significant deviation from the SM
  - Results interpreted within the type-II 2HDM model



Linear v quadratic

- Define 2 models, both representing simple Poisson counting experiments with two bins:

$\mu + b_1$: expectation in bin 1 in linear model

N_1, N_2: event yields in each bin

Linear: $p_1(N_1, N_2) = \frac{e^{-(\mu+b_1)}(\mu+b_1)^{N_1}}{N_1} \frac{e^{-(\mu+b_2)}(\mu+b_2)^{N_2}}{N_2}$

$\mu + b_2$: expectation in bin 2 in both models

Quadratic: $p_1(N_1, N_2) = \frac{e^{-(\mu^2+b_1)}(\mu^2+b_1)^{N_1}}{N_1} \frac{e^{-(\mu+b_2)}(\mu+b_2)^{N_2}}{N_2}$

$\mu^2 + b_1$: expectation in bin 1 in quadratic model