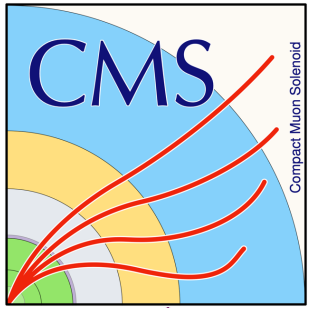


Searches for Neutral Higgs Bosons at LHC

Yizhou Cai (Nanjing University)

22nd December 2024

Higgs Potential 2024, Hefei

Introduction

- **The Higgs sector in the Standard Model is the simplest solution to achieve electroweak symmetry breaking**
  - But no guarantee that the Higgs sector must be minimal
- **BSM models can be constructed by extending the Higgs sector**
  - With additional singlets/doublets/triplets/combinations of them/…
  - While keeping prediction compatible with the observed 125GeV boson
  - Help explain baryogenesis, hierarchy problem, …
  - Bring new Higgs bosons after EWSB
    - 2HDM/MSSM: h, H, A, H^+, H^-
    - 2HDM+S/NMSSM: $h, H_1, H_2, A, a, H^+, H^-$
    - …
  - A broad search program is required
    - scaler/pseudoscalar, neutral/charged, light/heavy, narrow/broad…

or

?

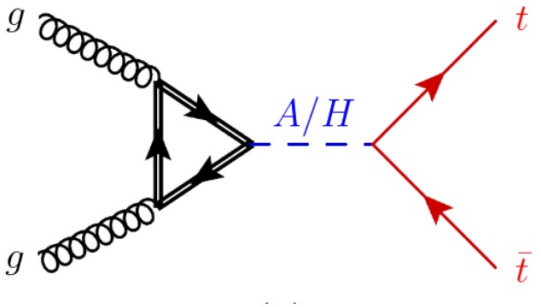
- **Most ATLAS/CMS analyses using Run-2 dataset have been released**
  - Lots of interesting searches for neutral Higgs boson!

Neutral Higgs Searches at LHC

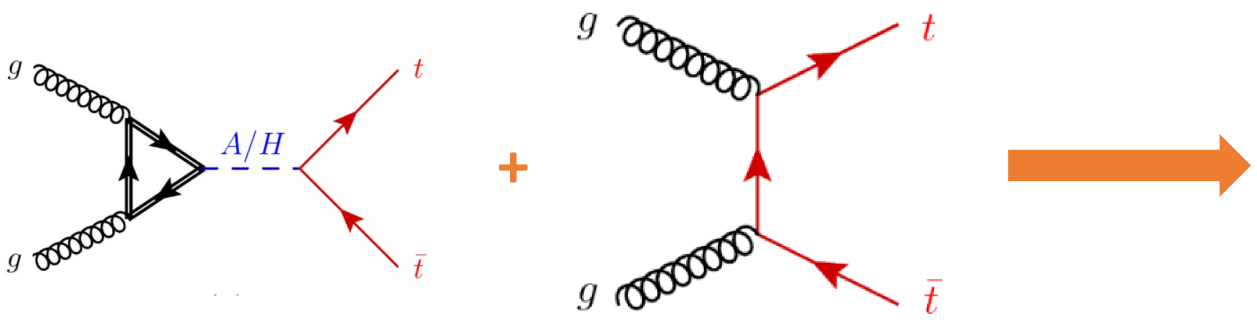
- **Resonance searches**
  - $X \to \gamma\gamma$
  - $X \to \tau\tau$
  - $A/H \to t\bar{t}$
  - $A \to Zh$
  - $X \to hh$
  - …
- **Exotic decays**
  - $h \to aa$
  - $h \to Za$
  - …
- **Multi-BSM searches**
  - $X \to Yh$
  - $A \to ZH$
  - …

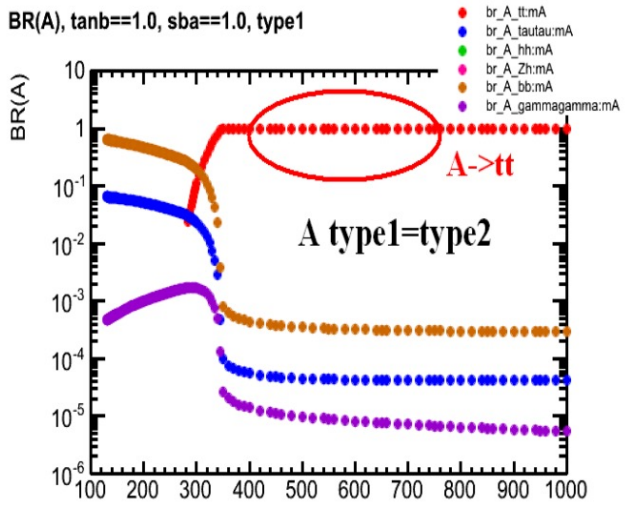
- Complete review has been shown by Zirui Wang
- I will present selected two recent searches
  - $A/H \to t\bar{t}$ (ATLAS: JHEP08(2024)013, CMS: CMS-PAS-HIG-22-013)
  - Low mass $X \to \gamma\gamma$ (CMS: arXiv:2405.18149, ATLAS: arXiv:2407.07546)

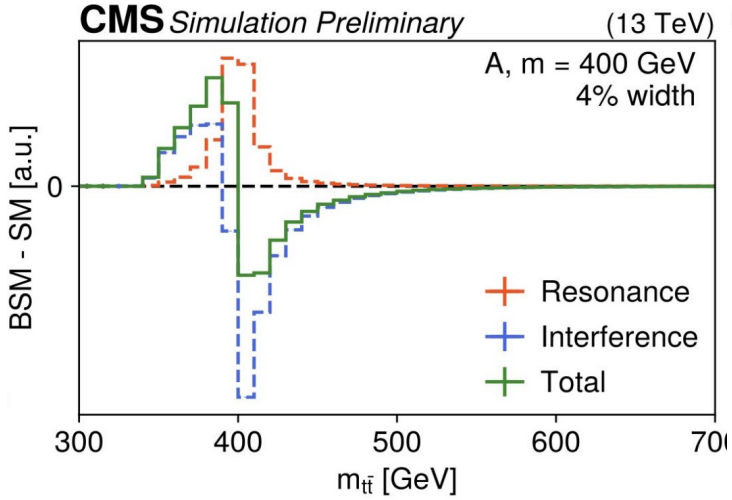
$A/H \rightarrow t\bar{t}$



- Search for ggF produced A/H decaying to ttbar
  - 1-lepton and 2-leptons final states
  - Assume m_t 172.5GeV in CMS but 173.3GeV in ATLAS
- **Motivation**
  - Dominant decay channel across large regions of parameter space in type-II 2HDM (MSSM-like)
- **Challenge:**
  - Large irreducible SM ttbar background
  - Strong interference between signal and SM ttbar
    - Lead to peak-dip(peak) structure in $m_{t\bar{t}}$ spectrum

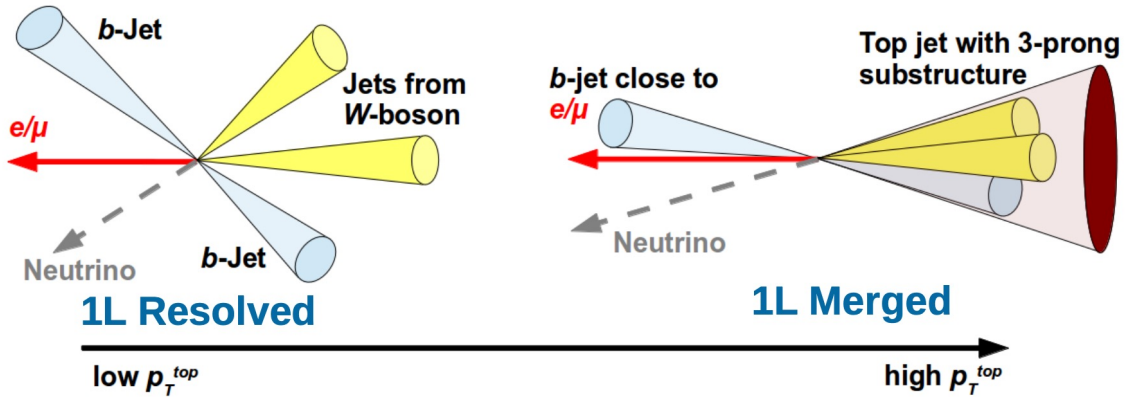


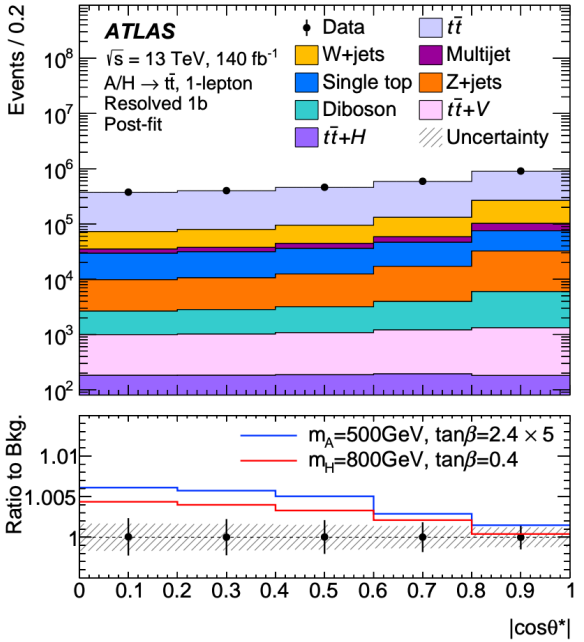


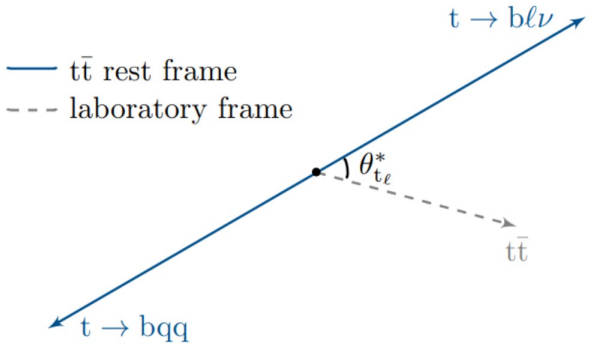


$A/H \rightarrow t\bar{t}$: ATLAS 1L Strategy

- Two topologies
  - == 1 lepton
  - Resolved
    - ≥4 small-R jets, ≥1 b-tagged jet
  - Merged
    - ≥1 vRC jets, ≥1 b-tagged jet
- Reconstruct $t\bar{t}$ system by χ^2 algorithm
  - Fit on $m_{t\bar{t}}$
- Category resolved region by b-tag
  - == 1b, ≥ 2b
- Spilt resolved region by 5-bins $|\cos\theta^*|$
  - Sensitive to resonance decay

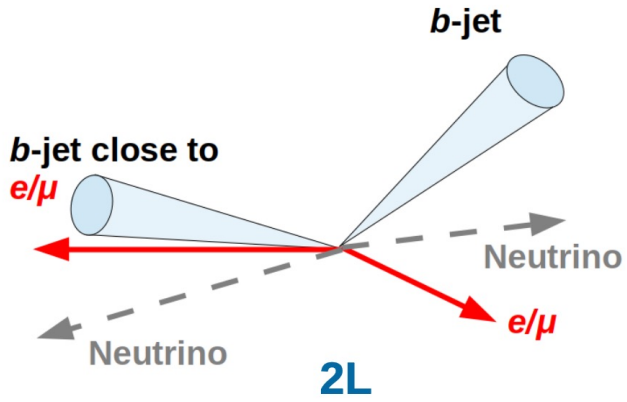


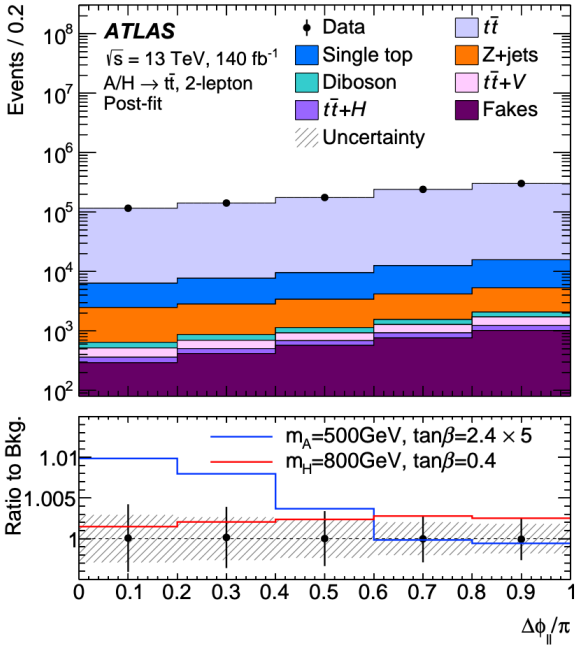




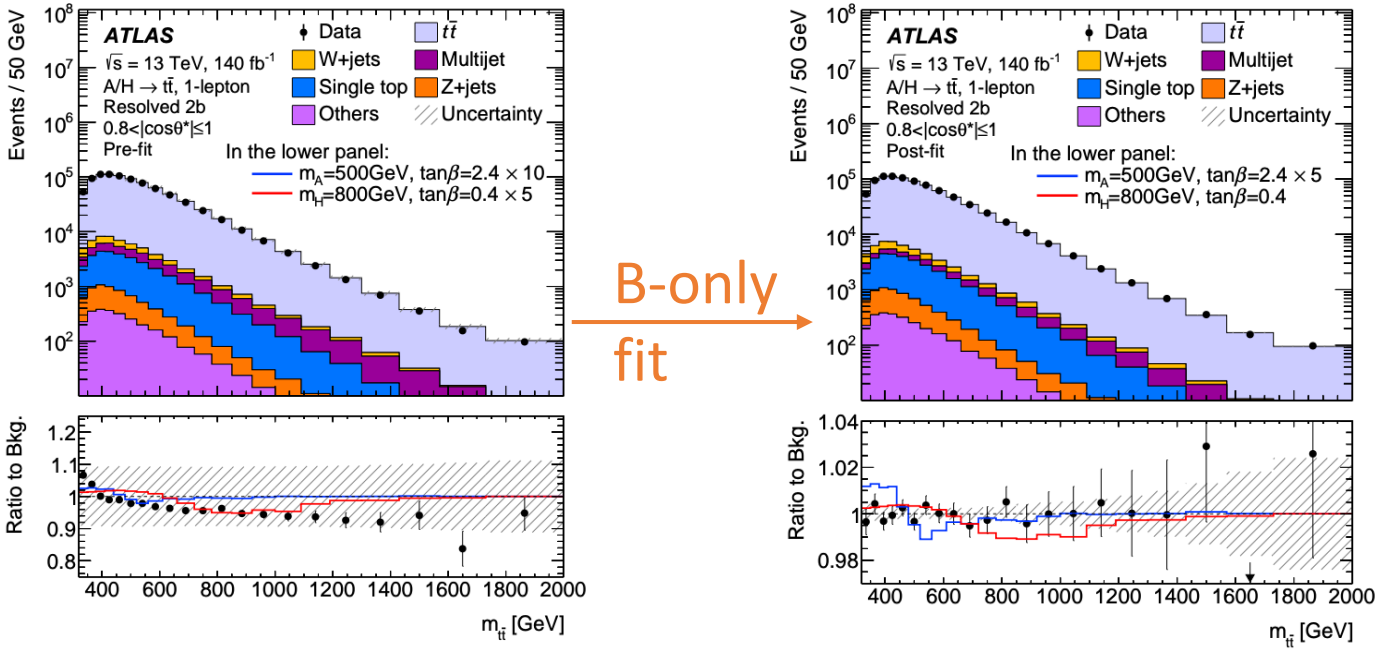
$A/H \rightarrow t\bar{t}$: ATLAS 2L Strategy

- One topology
  - ≥2 small-R jets, ≥1 b-tagged jet, == 2 OS leptons
- Reconstruct visible term in $t\bar{t}$ system
  - Fit on m_{llbb}
- Spilt into 5 bins by $\Delta\phi_{ll}$
  - Sensitive to spin state of the ttbar system
  - Also provide discrimination between A and H



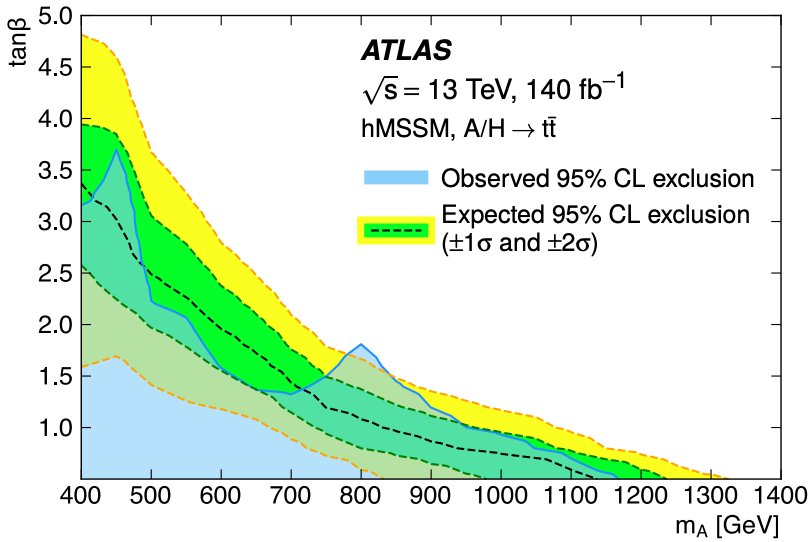


$A/H \to t\bar{t}$: ATLAS Results

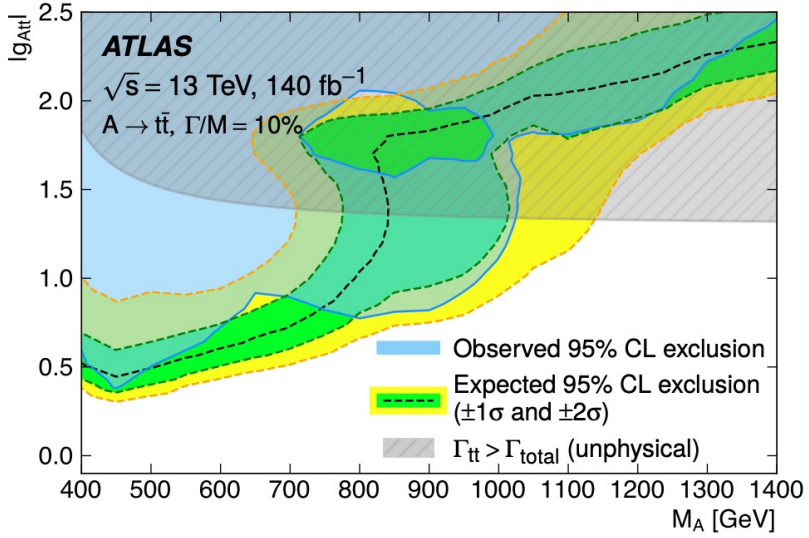


- Most constrained NP: ttbar PS
- Top ranked NP: ttbar NNLO
- Strongest constraints in high mass, low $\tan\beta$ region in some interpretation including hMSSM
- Not significant deviation from SM observed in physical region of model-independent interpretation

hMSSM

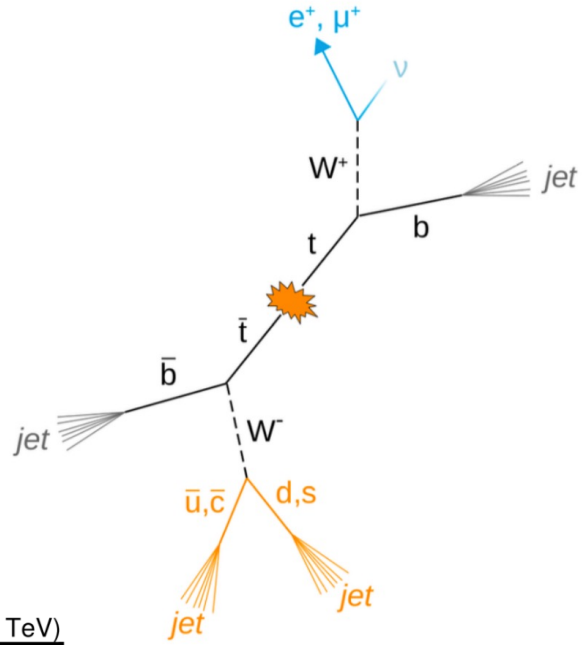


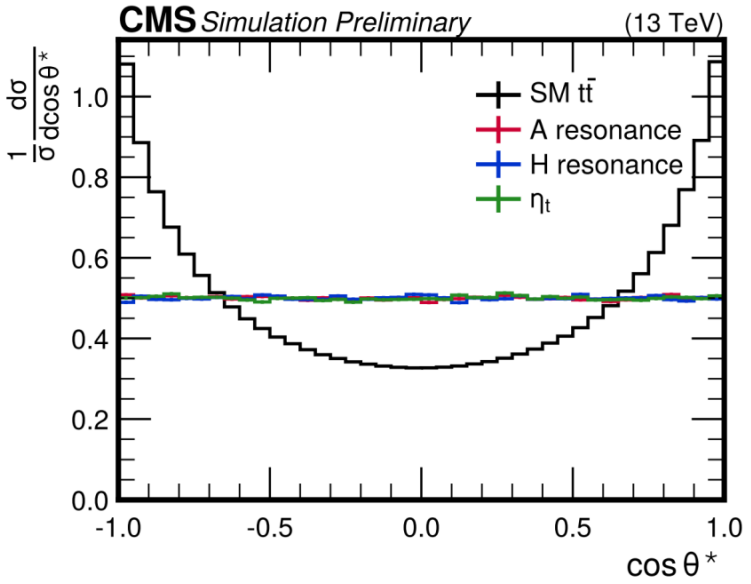
Generic pseudoscalar



$A/H \rightarrow t\bar{t}$: CMS 1L Strategy

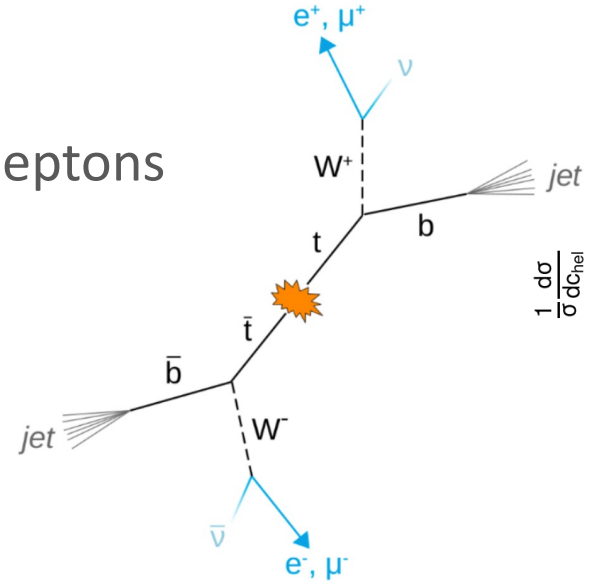
- One topology
  - ≥3 small-R jets, ≥2 b-tagged jets, == 1 lepton
- Reconstruct $t\bar{t}$ system using NeutrinoSolver algorithm
  - Fit on $m_{t\bar{t}}$
- Categorized by number of jets
  - == 3j, ≥ 4j
- Categorized by lepton flavor
  - e, μ
- Also spilt by 5-bins $|\cos\theta^*|$
  - Non-uniform

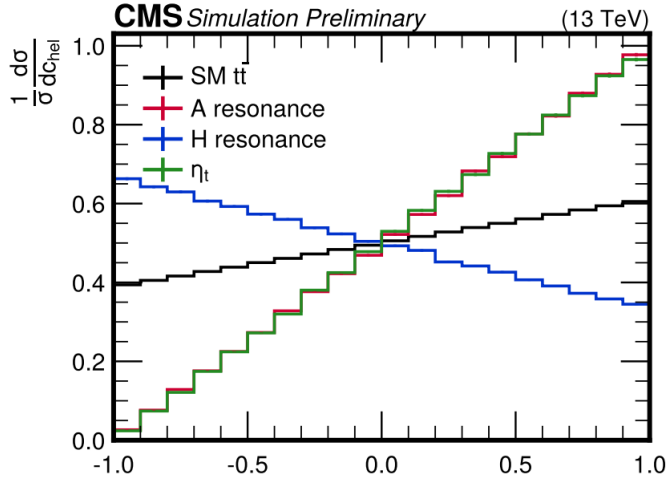


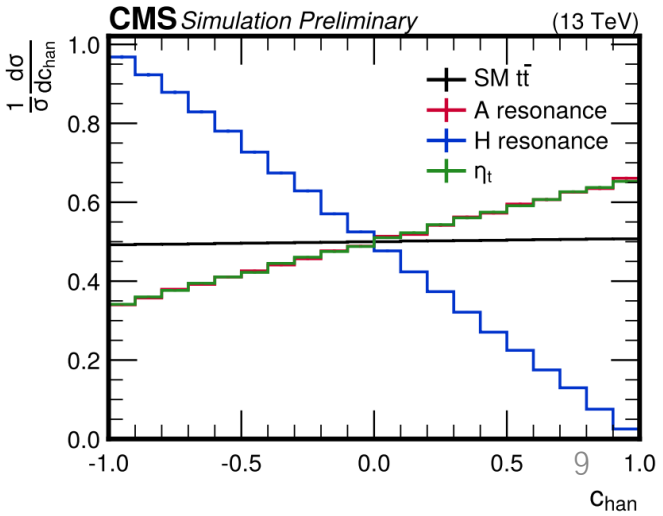


$A/H \rightarrow t\bar{t}$: CMS 2L Strategy

- One topology
  - ≥2 small-R jets, ≥1 b-tagged jet, == 2 OS leptons
- Analytic reconstruction of $t\bar{t}$ system
  - Fit on fully reconstructed $m_{t\bar{t}}$
- Categorized by lepton flavor
  - $ee, e\mu, \mu\mu$
- Split into 9 bins by more sophisticated angular variables
  - c_{hel}: $l^+ \cdot l^-$, lepton directions in their helicity frames
  - c_{han}: $l^+ \cdot P_3 l^-$, same as c_{hel} but flip the sign of the component parallel to one top quark direction
  - Both sensitive to the spin and CP state of the ttbar system
  - Provide discrimination between A, H and SM ttbar

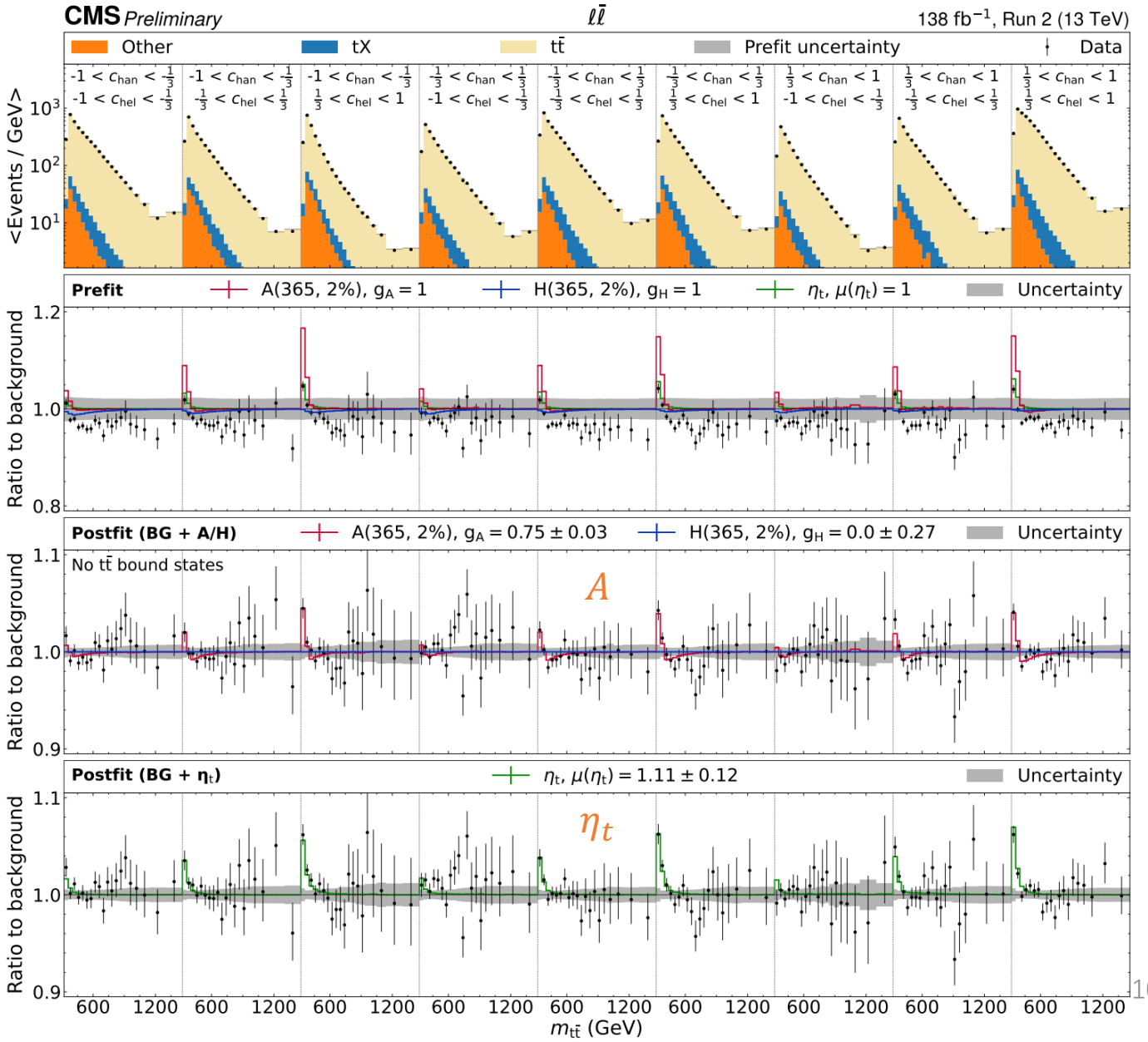




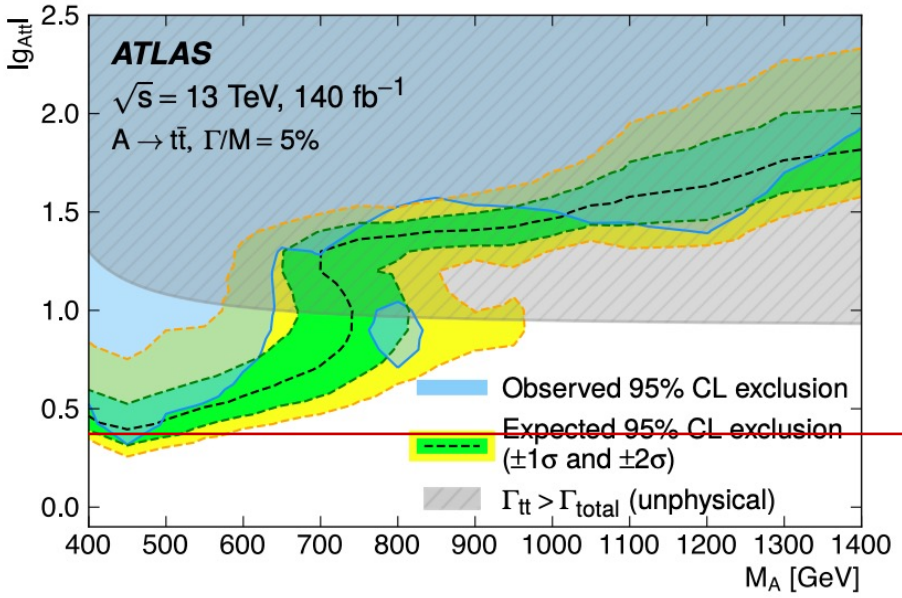


$A/H \to t\bar{t}$: CMS Results

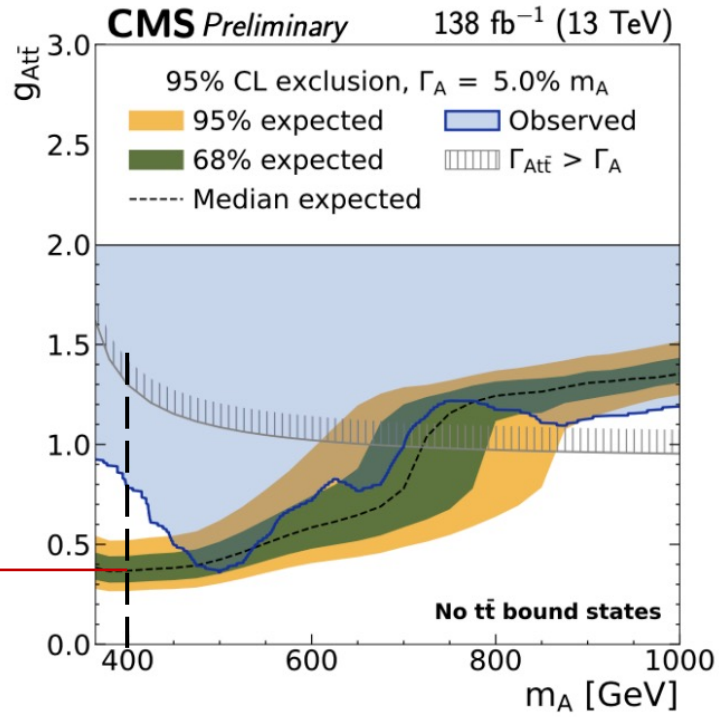
- Most constrained NP: top mass
- Top ranked NP: tH Yukawa
- > 5σ deviation from SM observed, most compatible with the A signal hypothesis at $(365\ \mathrm{GeV}, 2\%)$
- Extract cross section using the top bound state η_t color-singlet model $\sigma = 7.1 \pm 0.8\ \mathrm{pb}$
  - Compatible with NRQCD prediction $\sigma(\eta_t) = 6.43\ \mathrm{pb}$



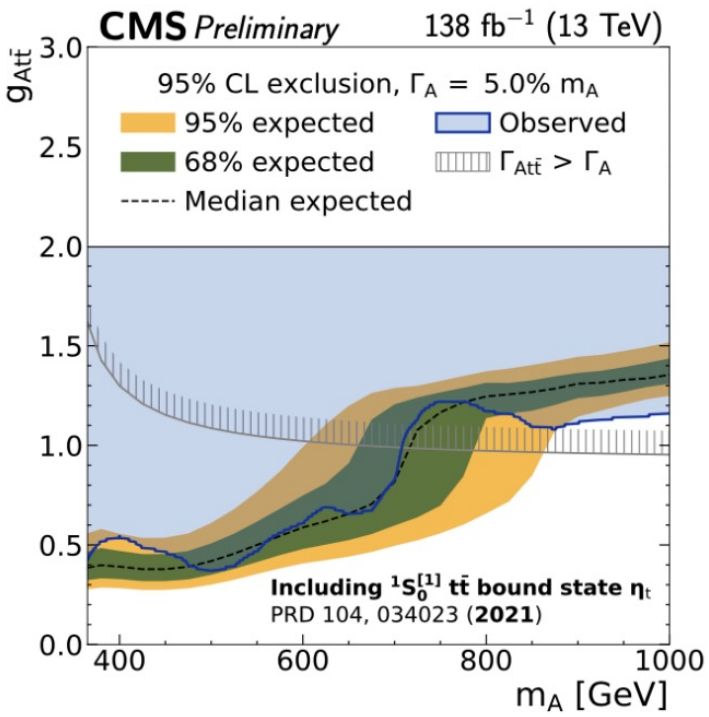
$A/H \to t\bar{t}$: Results



No Toponium in SM bkg



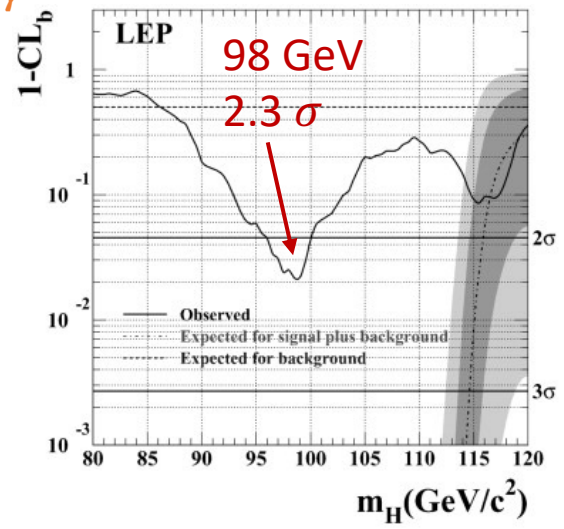
With Toponium in SM bkg

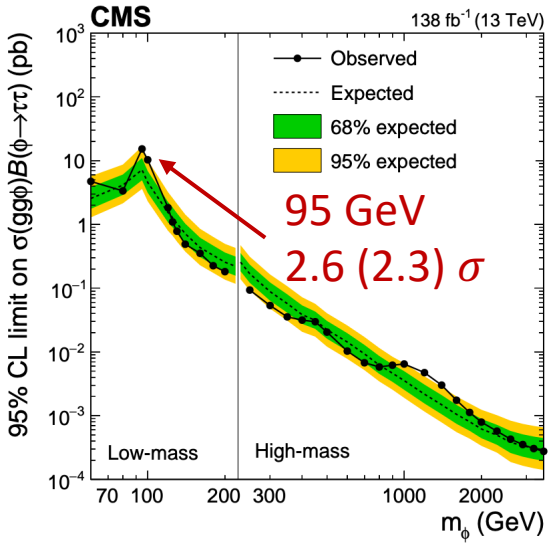


- Similar expected limit between ATLAS and CMS
- CMS observe a pseudo-scalar/toponium excess while ATLAS doesn't
- More checks/re-interpretations/specialized-analysis are proceeding in ATLAS and CMS internally

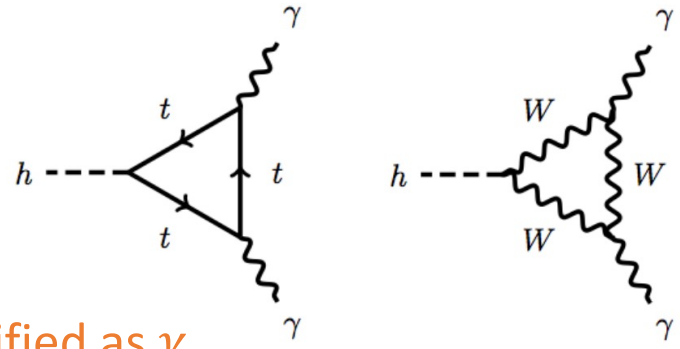
Low Mass $X \to \gamma\gamma$

- Search for narrow width scalar signal on $m_{\gamma\gamma}$
- **Motivation**
  - Small excess observed by LEP Higgs search and CMS Run2 $X \to \tau\tau$ search



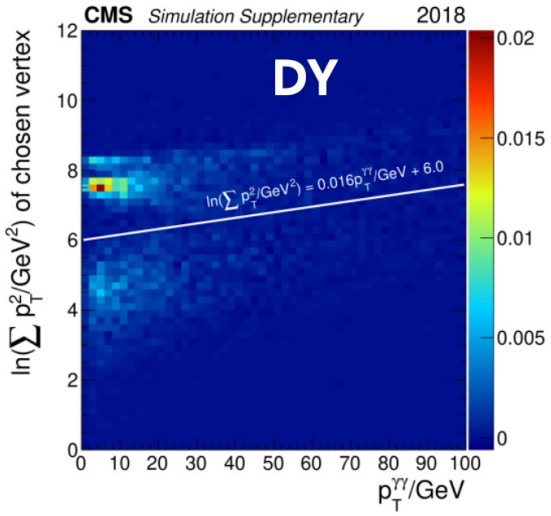


  - Potential BSM Higgs boson is usually able to decay to $\gamma\gamma$ due to loops of both f and V
  - $\gamma\gamma$ channel provides a clean final-state topology
- Signal production modes involve ggH, VBF, VH, and ttH
- **Main background**
  - Continuum process: non-resonant $\gamma\gamma, \gamma j, jj$ → dominant
  - Resonant Drell-Yan: $Z \to ee$ → mis-identified as γ



Low Mass $X \to \gamma\gamma$: CMS Strategy

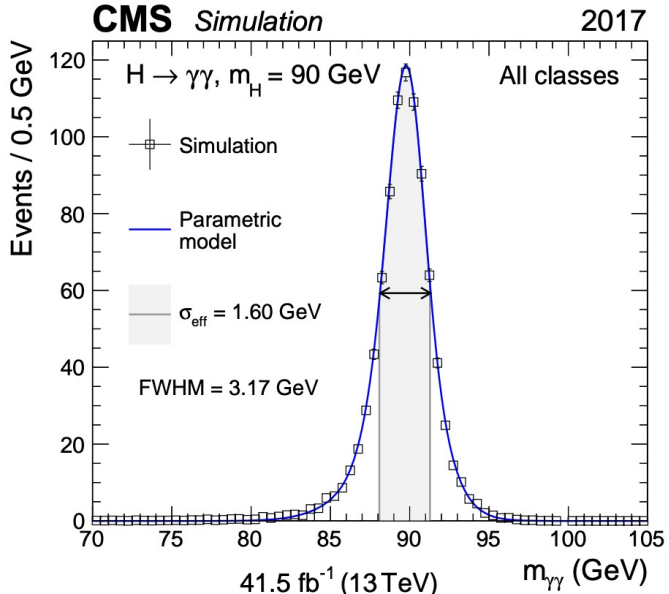
- Assume the ratios between different production modes are the same as in SM
- Photon identified by a BDT
- Require $p_T^{\gamma 1(2)} > 30(18)$ GeV, $\frac{p_T^{\gamma 1(2)}}{m_{\gamma\gamma}} > 0.47(0.28)$ for ideally falling $m_{\gamma\gamma}$ spectrum
- Veto-e and cut on $\ln(\sum_{\text{tracks}} p_T^2)$ as function of $p_T^{\gamma\gamma}$ to suppress DY
- Two more BDTs for better discrimination power
  - Di-photon BDT trained between Higgs decayed $\gamma\gamma$ and continuum bkg
  - Combined BDT used to tag VBF events in 2017 and 2018
- Categorization
  - 3 classes for 2016
  - 3 untagged classes + 1 VBF-tagged class for 2017 and 2018

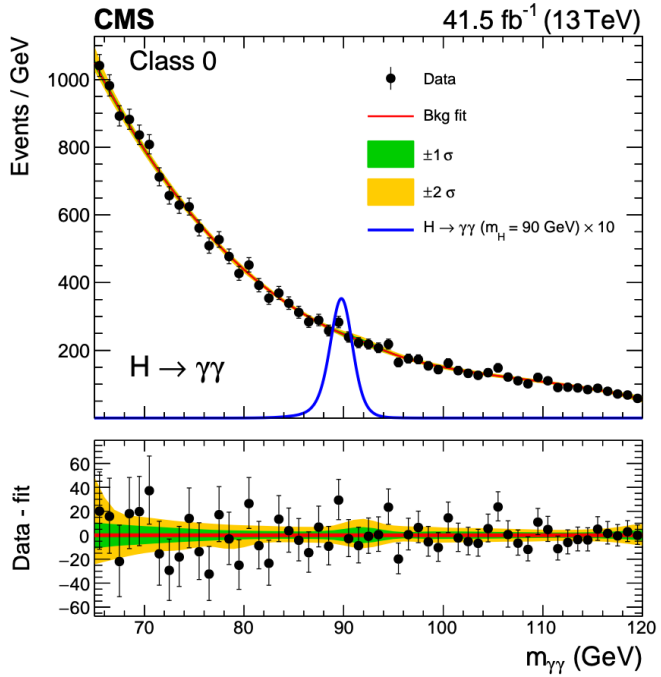


Low Mass $X \to \gamma\gamma$: CMS Strategy

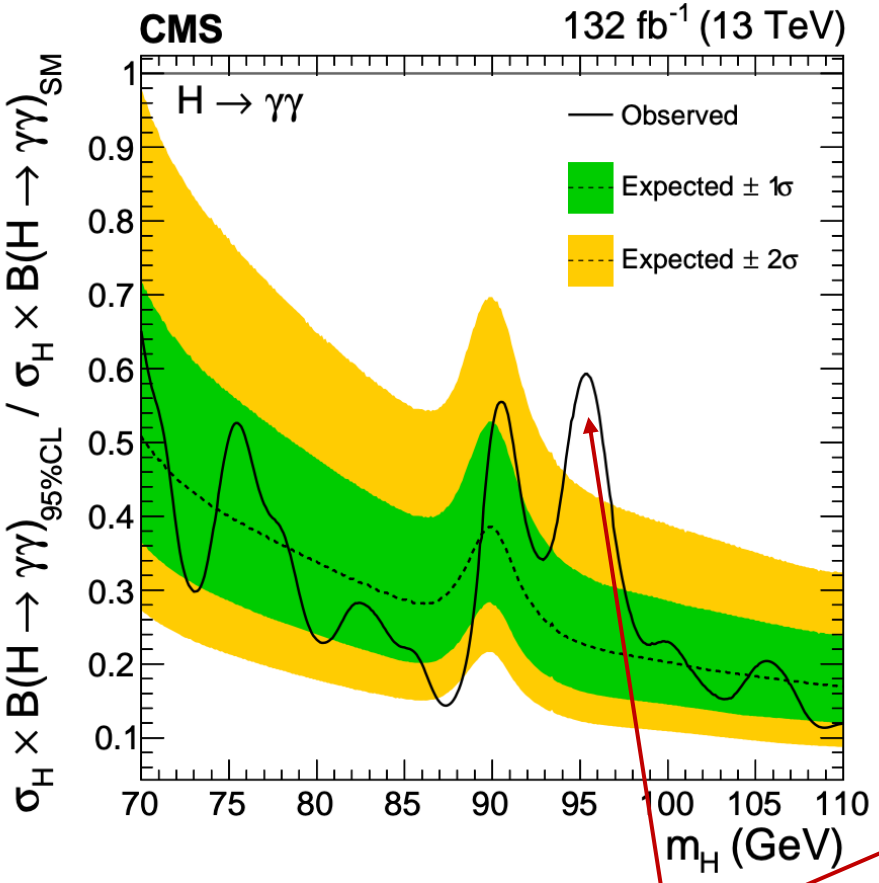
- **Signal modelling**
  - Combine all production modes together
  - Described as sum of Gaussian functions depending on if candidate di-photon match correct primary vertex
  - Fit to the shape of the signal in each event class

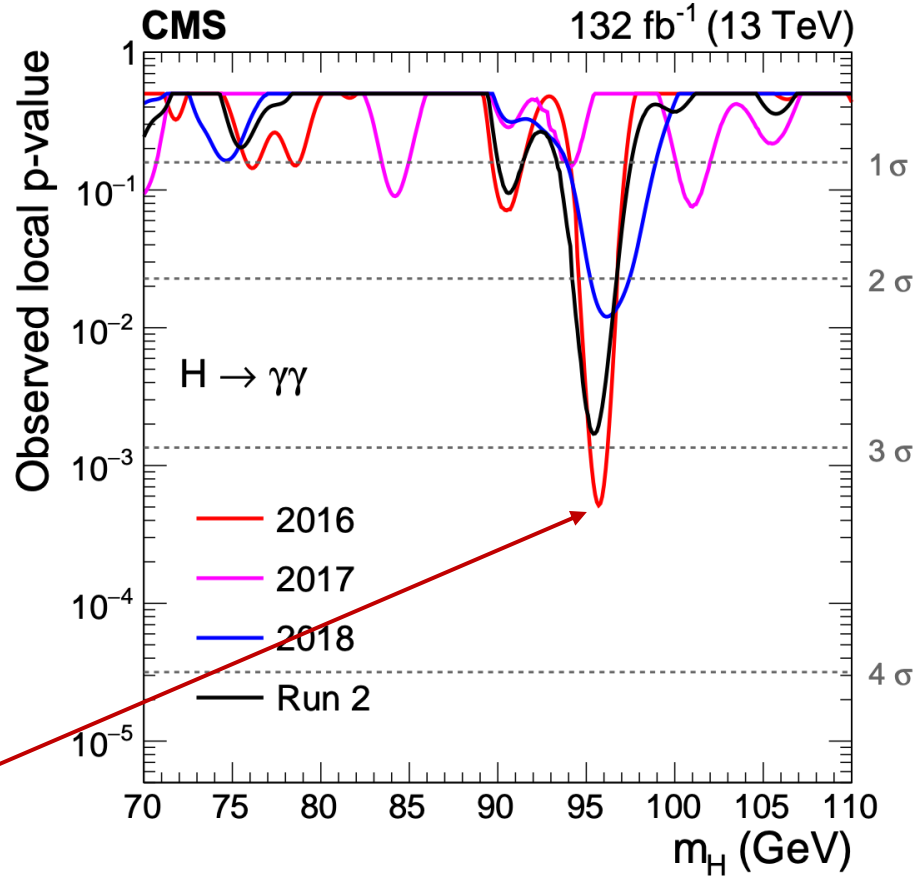
- **Background modelling**
  - Continuum background: Discrete profiling method
    - Treat the choice of function as a discrete parameter
  - DY background: Double-sided Crystal Ball function + exponential





Low Mass $X \to \gamma\gamma$: CMS Results

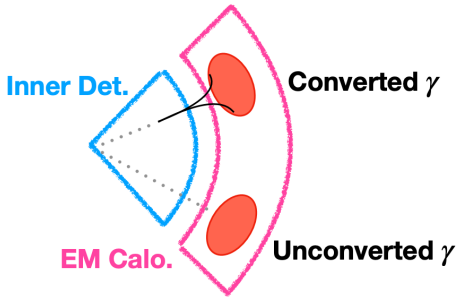




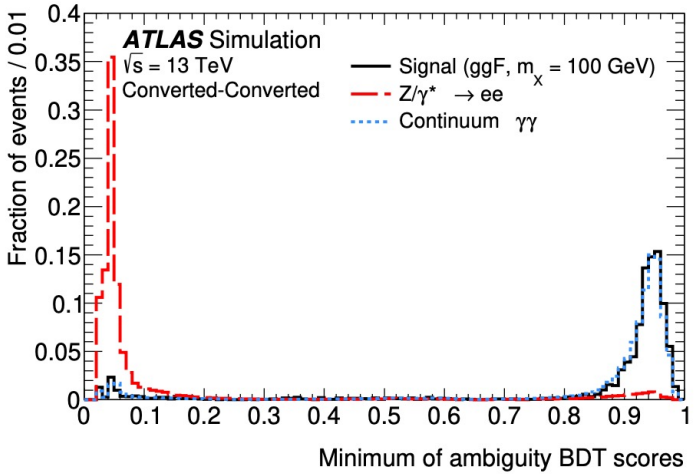
- Largest excess with ~2.9σ local (1.3σ global) significance at $m_H = 95.4$ GeV

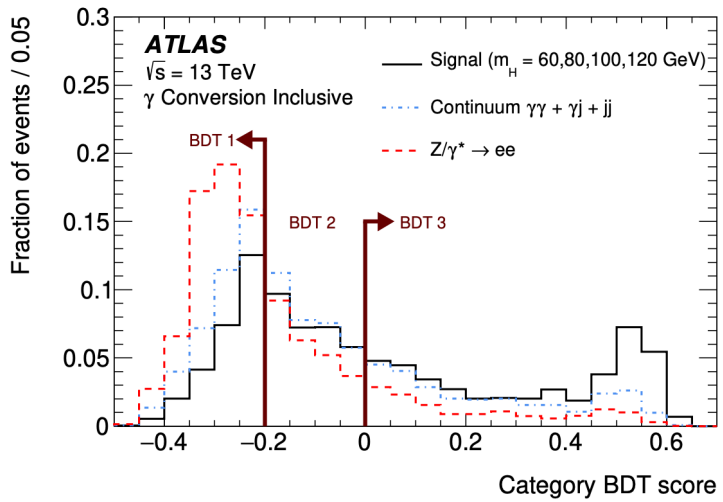
Low Mass $X \to \gamma\gamma$: ATLAS Strategy

- Consider ggF only and take envelope of other production modes as uncertainty
  - Additionally consider model-dependent interpretation using CMS assumption
- e/γ ambiguity BDT to reject electron-fakes
- Require $\frac{E_T^\gamma}{m_{\gamma\gamma}} > 0.38$ for ideally falling $m_{\gamma\gamma}$ spectrum
- Categorized by conversion to further suppress DY impact
  - UU (both unconverted), CC (both converted), UC



- Train category BDT for model-dependent result
  - 9/3 categories for model-dependent/independent

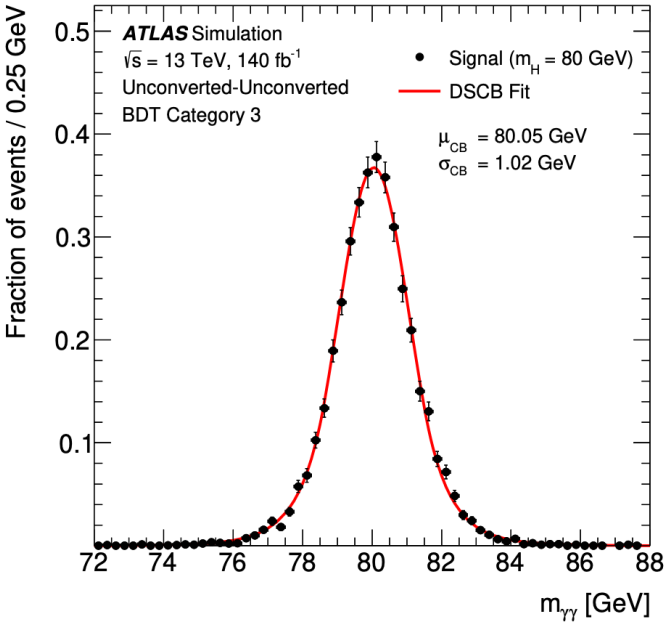


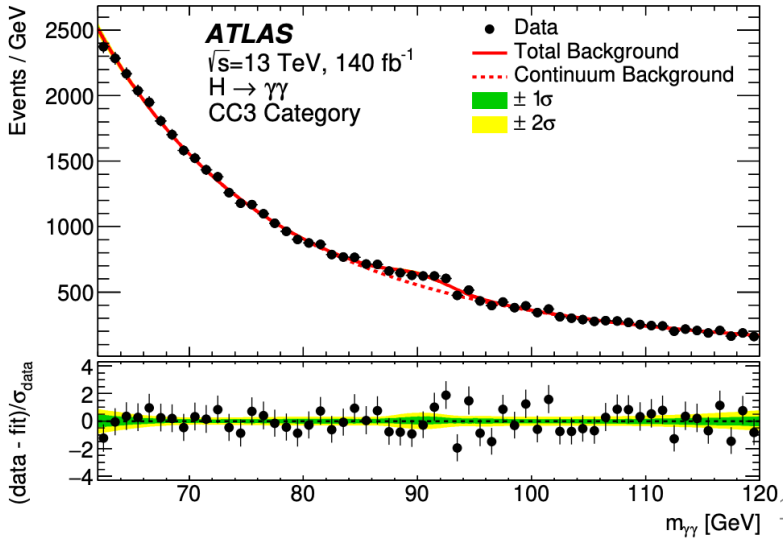


Low Mass $X \rightarrow \gamma\gamma$: ATLAS Strategy

- **Signal modelling**
  - Combine all modes for model-dependent result
  - Modelled as a DSCB function
  - Fit to the shape of the signal in each category

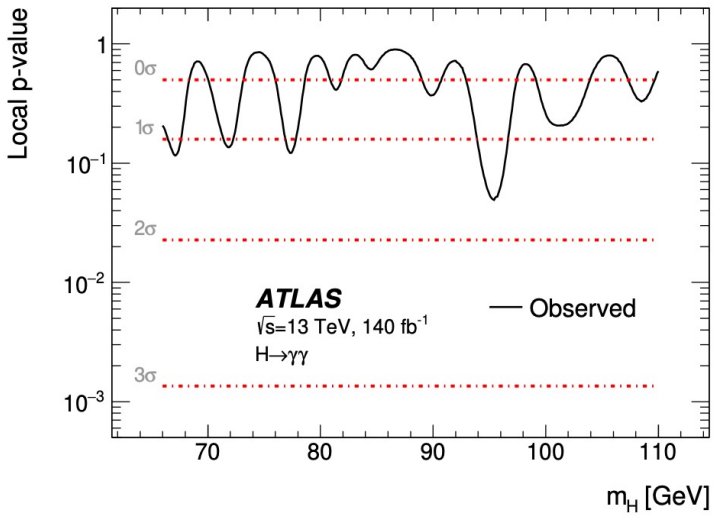
- **Background modelling**
  - Continuum background: analytic function
    - Composition estimated by 2D side-bands method
    - Smooth MC prediction by Gaussian Process
    - Bias from function choice covered by spurious signal
  - DY background: DSCB function

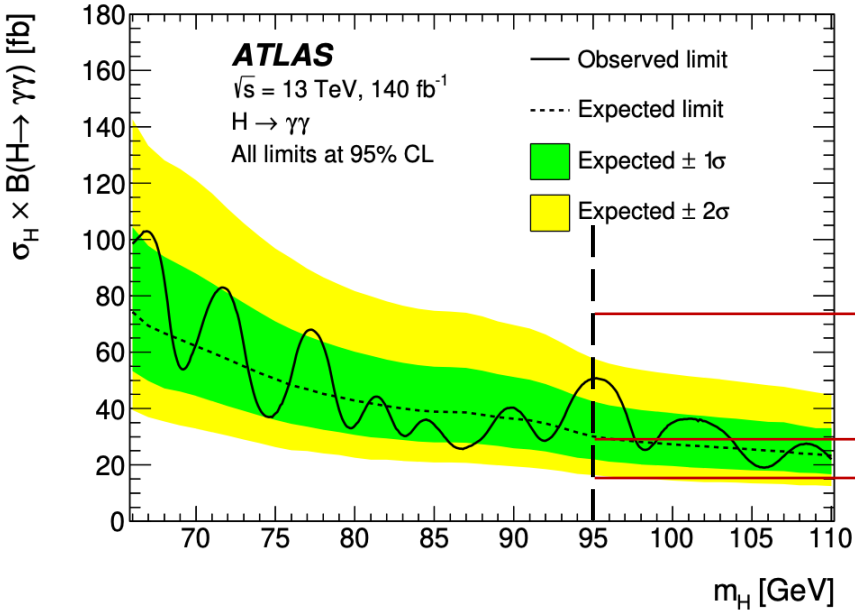


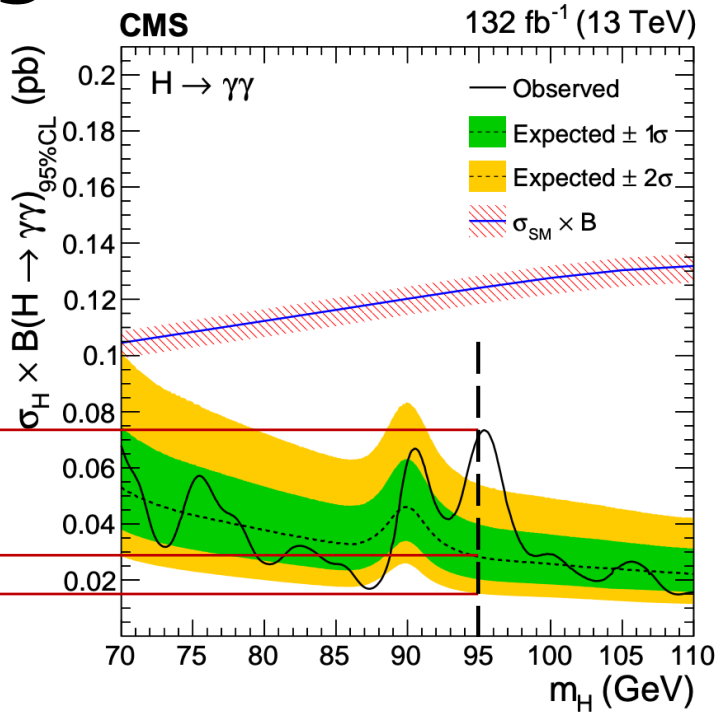


Low Mass $X \to \gamma\gamma$: ATLAS Results

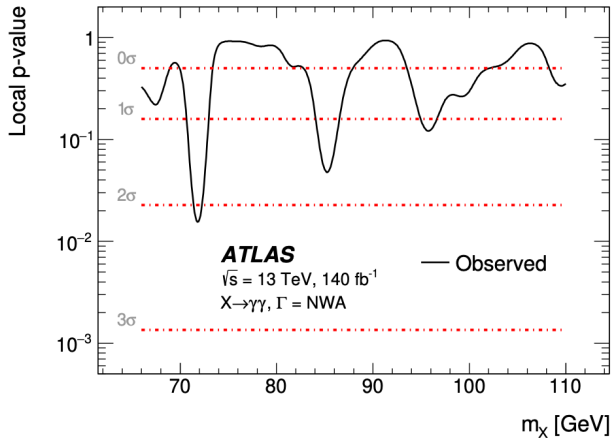
Model-dependent

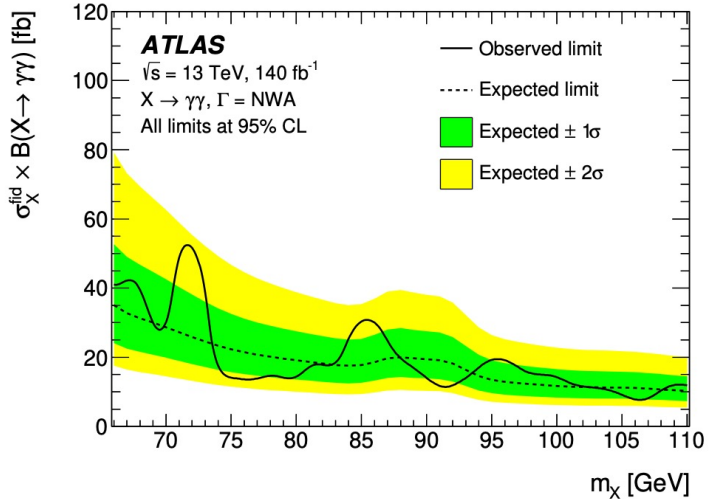






Model-independent





- Similar sensitivity as CMS, but much low significance
- 1.7σ local significance at $m_H = 95.4$ GeV
  - Interesting to follow up!

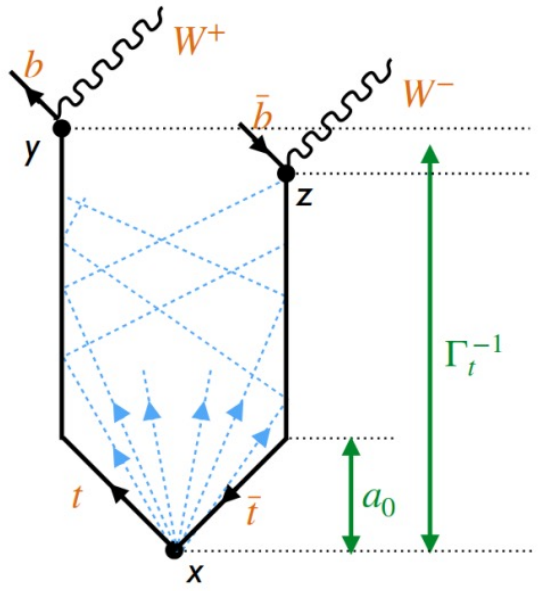
Summary

- Extensive efforts by ATLAS and CMS have not (yet) significantly hinted any extension in Higgs sector
  - Still many valuable contributions I couldn’t cover in this talk
- Tighter experimental constraints on model parameters are derived
- Interesting excesses could be followed up
- Stay tuned for more searches in the future!

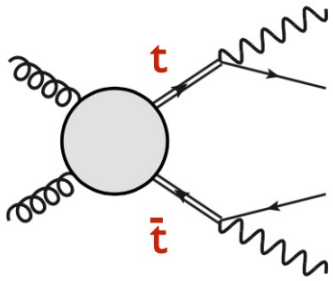
Thank you for your attention!

Backup

Ttbar Bound State

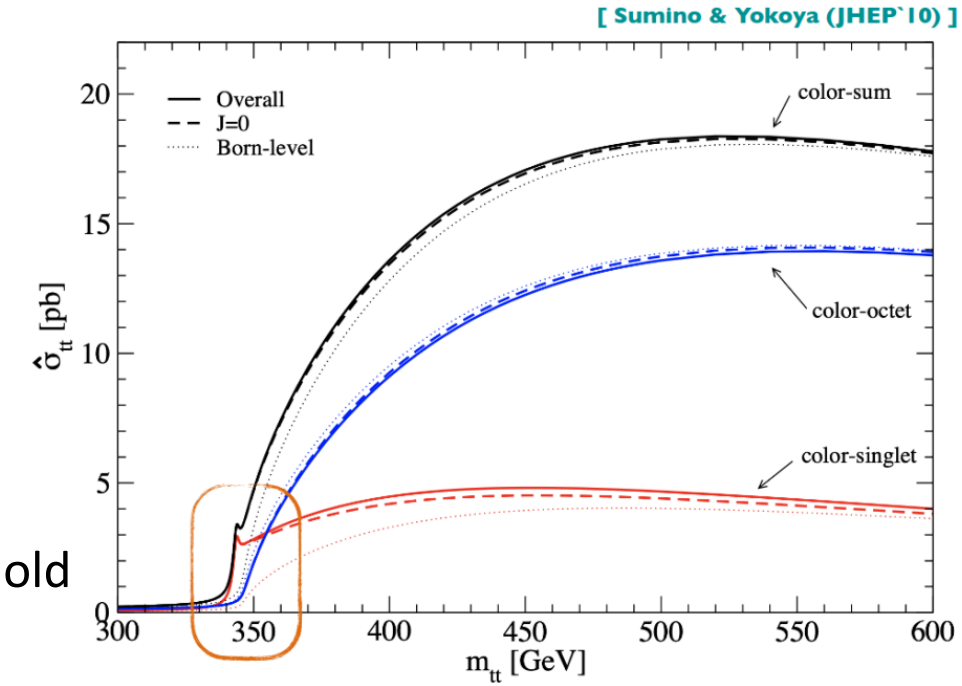


- The top Bohr radius $a_0 = \frac{2}{G_F \alpha_S m_t} \sim \frac{1}{20}\mathrm{GeV}^{-1}$
- Lifetime of top $\sim\Gamma_t^{-1} = 1.5\mathrm{GeV}^{-1}$
- Possible gluon exchanges before the top decay
- Bound state -- toponium?
  - Probe of the QCD potential



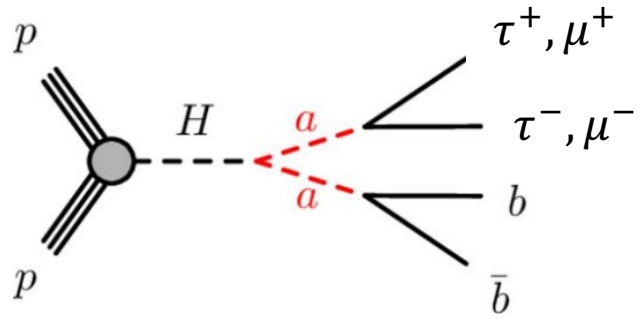
From theory calculation:

- Color-singlet
  - ${}^1S_0^{[1]}$
  - Peak below the ttbar threshold
- Color-octet
  - ${}^1S_0^{[8]}$ or ${}^3S_1^{[8]}$
  - Expected to be small below the ttbar threshold

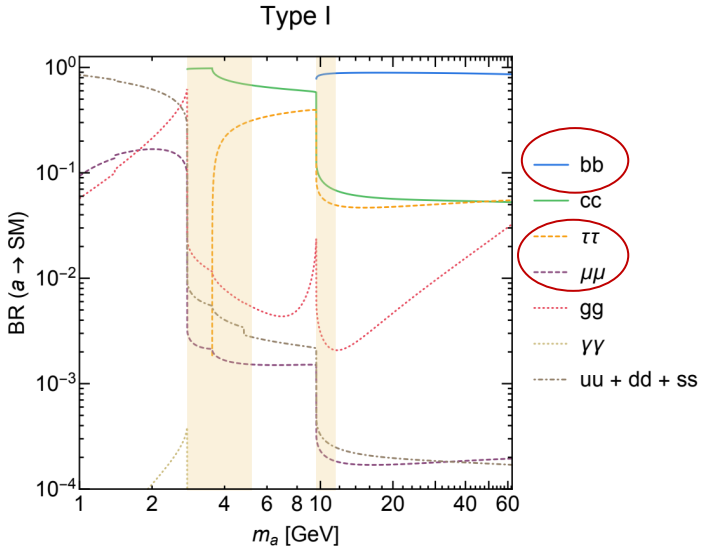


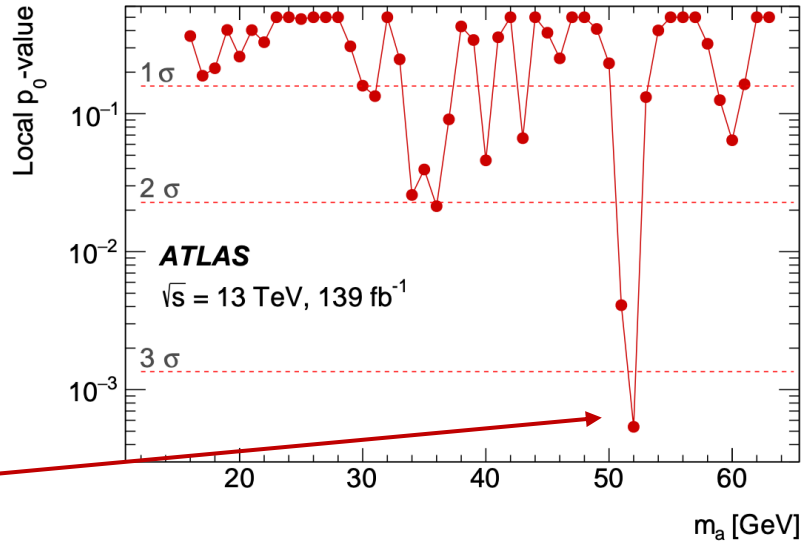
$H \to aa \to bb\tau\tau(bb\mu\mu)$

- $h \to aa \to bb\tau\tau(bb\mu\mu)$ (CMS: EPJC84(2024)493, ATLAS: PRD.110.052013)
  - Decay of SM 125 GeV Higgs boson into 2 light pseudoscalars
    - One a decay into $b\bar{b}$, another a decay into $\tau^+\tau^-$ or $\mu^+\mu^-$



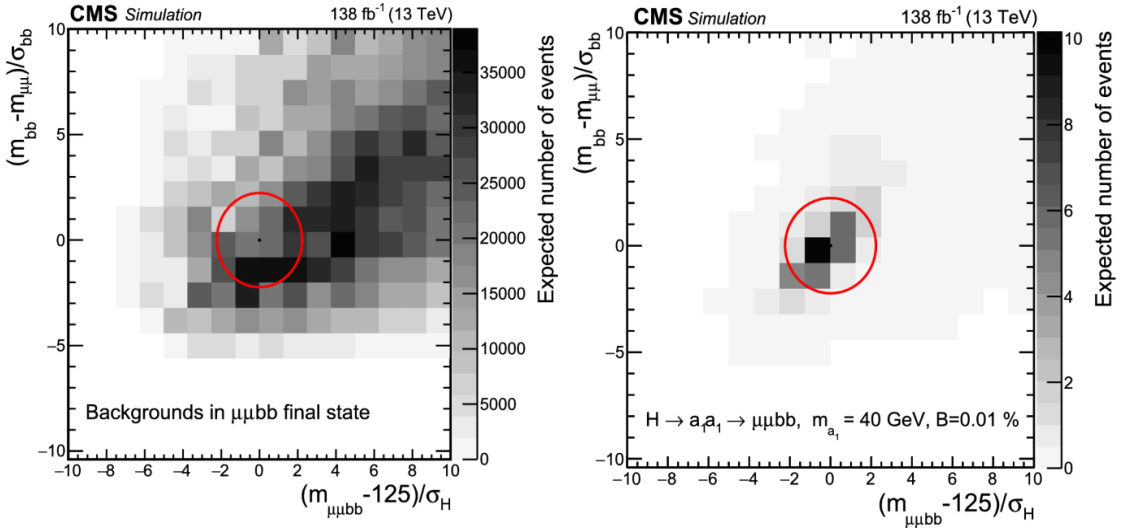
  - **Motivation**
    - ~ 10% room in Higgs BR for exotics decay
    - Light pseudoscalars appear in 2HDM+S/NMSSM/…
      - Coupling with SM Higgs by cubic term in the potential
      - Coupling with SM particles by mixing with $\phi_{1,2}$
    - Relatively large BR with clean final states of aa decay
    - Observe a bump in ATLAS $H \to aa \to bb\mu\mu$ search
      - Significance at 3.3σ local (1.7σ global)

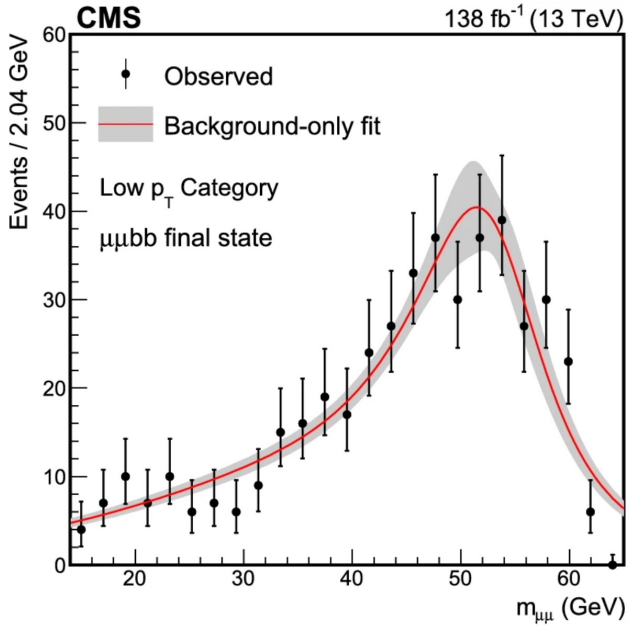




$H \to aa \to bb\mu\mu$: CMS Strategy

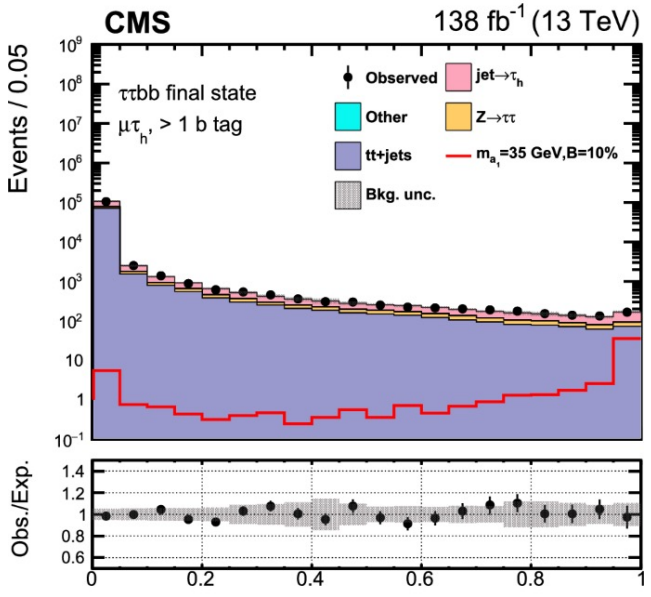
- Dominant background
  - Drell-yan process and $t\bar{t}$
- Selection conditions
  - == 2 OS μ, ≥ 2 b-tagged jets
  - Require $p_T^{\text{miss}} < 60\text{GeV}$ to reduce $t\bar{t}$ + jets
  - χ^2 cut to further suppress background
    - Exploiting $m_{bb\mu\mu} \simeq 125\text{GeV}, m_{bb} \simeq m_{\mu\mu}$
    - Taking correlation into account
- Categorized by jet p_T, b-tag score, VBF signature
- Fit on $m_{\mu\mu}$
  - Background completely estimated from data
    - Discrete profiling method
  - Signal modelled as weighted sum of a Voigt profile and a Crystal Ball function

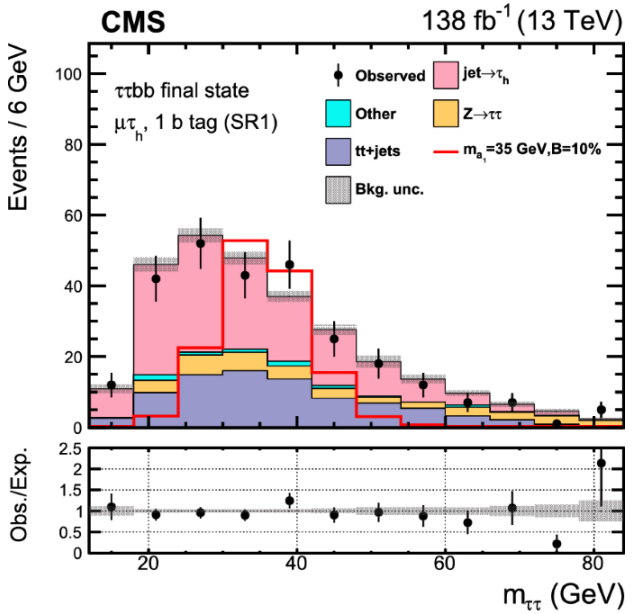




$H \to aa \to bb\tau\tau$: CMS Strategy

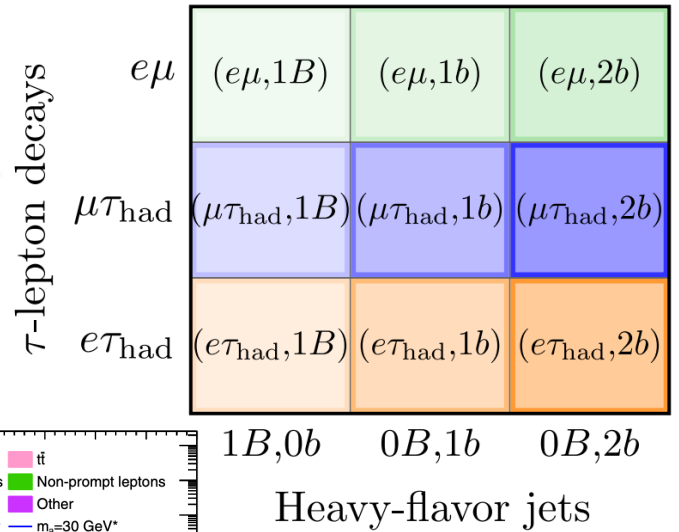
- Dominant background
  - $t\bar{t}$, Drell-yan τ's + jets, jet fakes processes
- Selection conditions
  - ≥ 1 b-tagged jet
  - Exact one OS $e\mu$ or $e\tau_{had}$ or $\mu\tau_{had}$ pair
- Categorized by b-tag and τ decay mode
- Train pNN in each category for discrimination
  - Used as a reference to define sub-regions
- Fit on $m_{\tau\tau}$
  - Reconstructed via SVfit algorithm

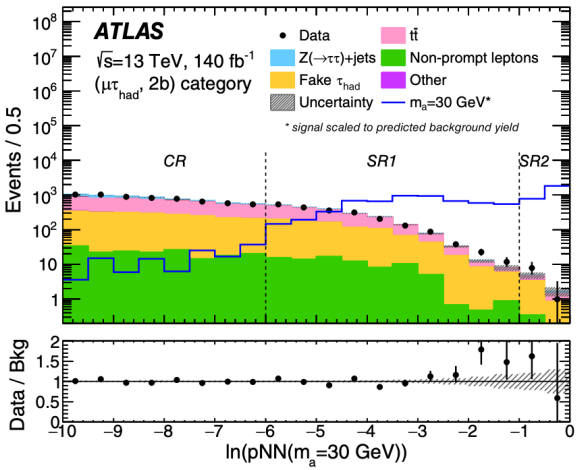


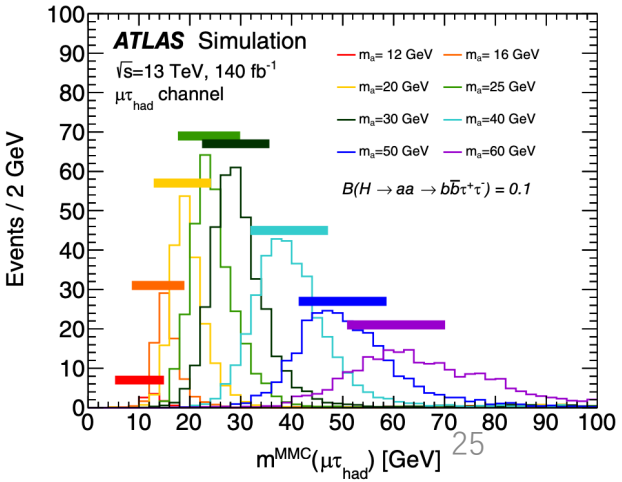


$H \to aa \to bb\tau\tau$: ATLAS Strategy

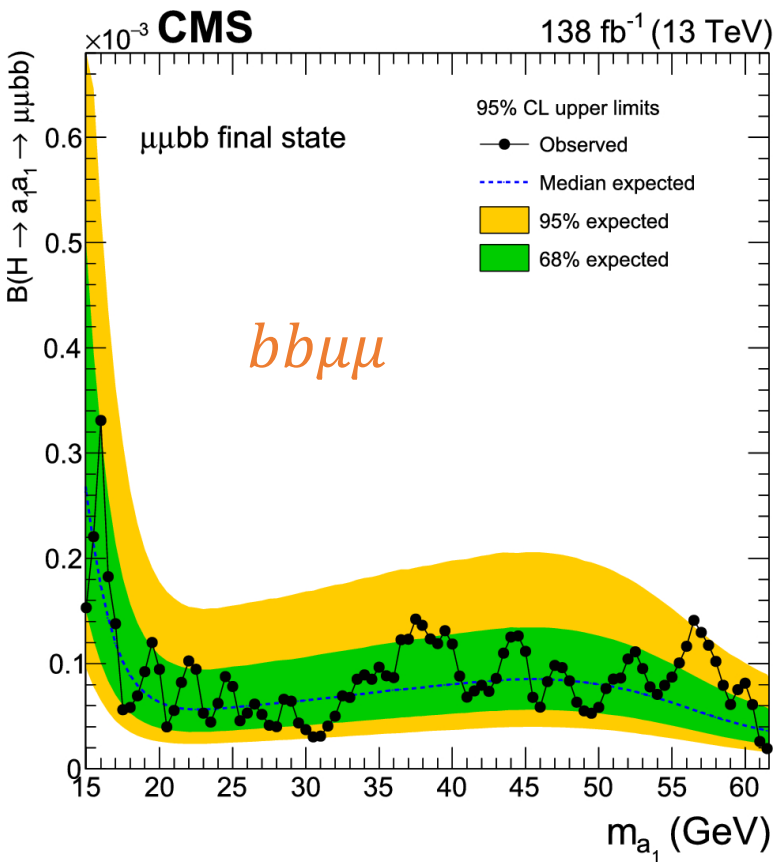
- The same dominant background
- Dedicated merged B-tagger for low m_a
  - Based on DeXTer deep sets
- Selection conditions
  - ≥ 1 b-tagged jet or B-tagged RC jet
  - Exact one OS $e\mu$ or $e\tau_{had}$ or $\mu\tau_{had}$ pair
- Categorized by b/B-tag and τ decay mode
- Reconstruct neutrinos 4-momenta by MMC
- Train pNN as final discriminant in fit
  - Possibility to treat m_a hypothesis as input
- Only events satisfying $m_{\tau\tau}^{\mathrm{MMC}}$ cut used to fit
  - To reduce the correlation among different hypothesis

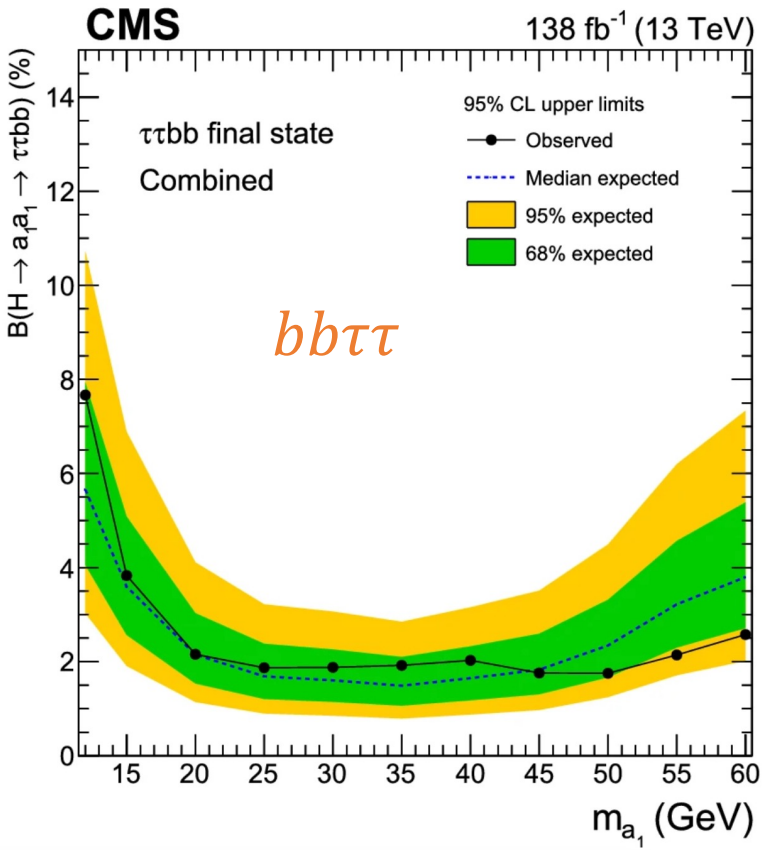


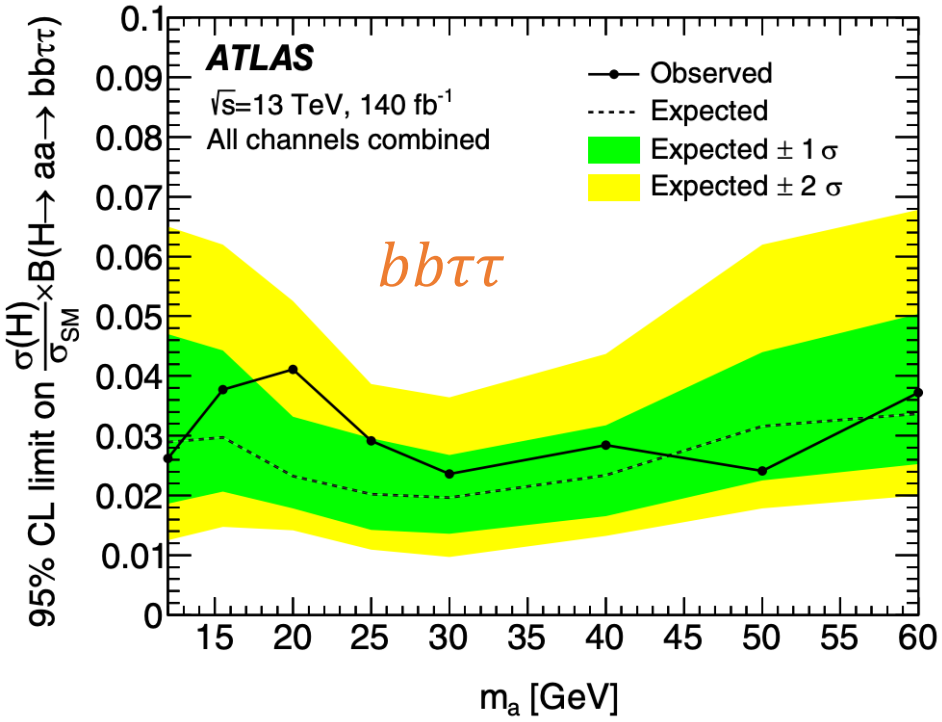




$H \to aa \to bb\tau\tau(bb\mu\mu)$: Results







- No excess found over SM prediction
- Boosted B-tagger help ATLAS improve the limit at low mass a lot