# Latest Results on the Beyond the Standard Model Higgs Searches from ATLAS and CMS

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On behalf the of the ATLAS and CMS collaborations

In Search of New Paradigms

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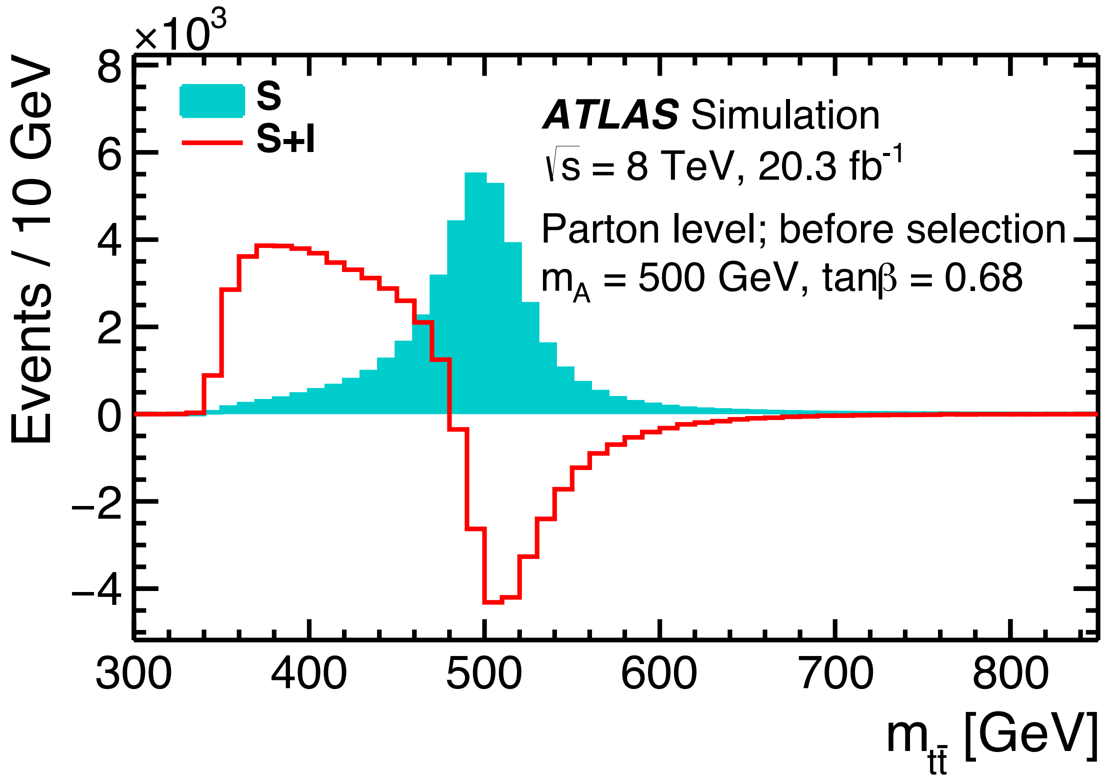
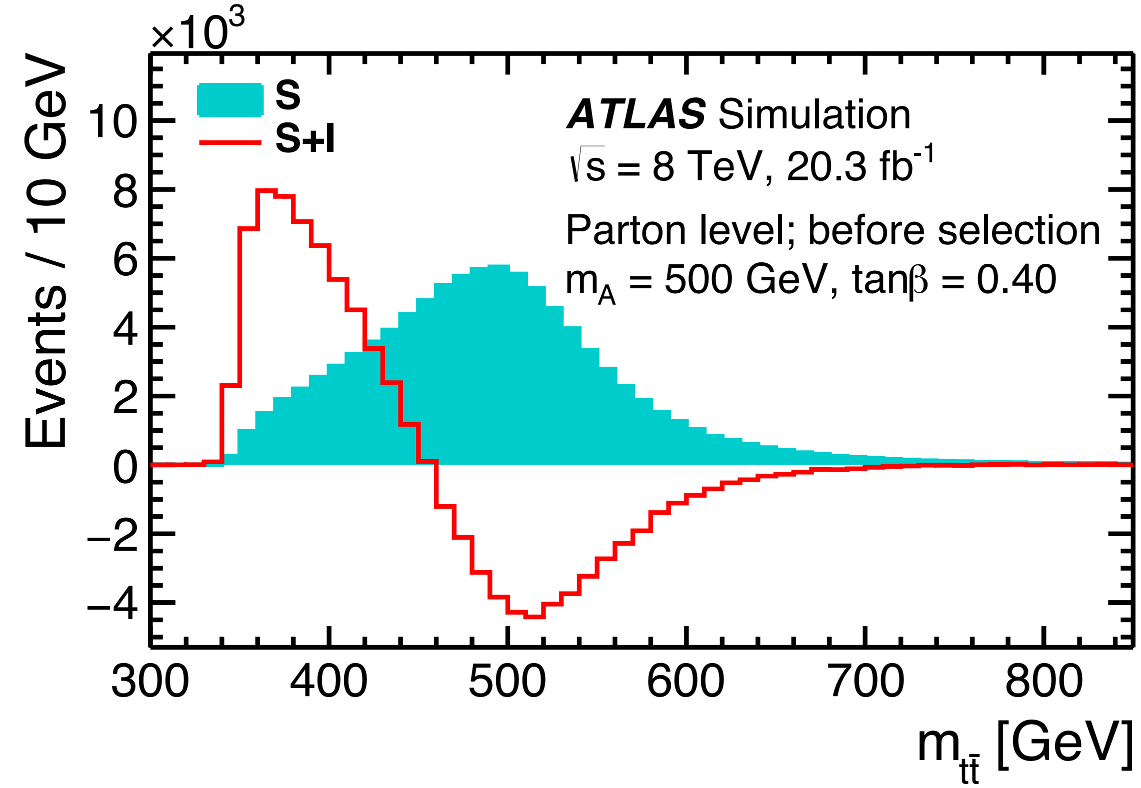
- Theory hypothesises several extensions of the Standard Model (SM).
- In the Higgs sector, hypothesised additional Higgs bosons
  - Minimal super symmetric Standard Model (MSSM)
    - Ex: CP even neutral doublet $(h, H)$ and CP odd pseudo scalar $A$ and two scalars $H^{\pm}$
  - Two Higgs doublet model (2HDM)
    - motivated also by dark matter axion models
- Outline:

1. $A/H \rightarrow t\bar{t}$, $A/H \rightarrow \tau\bar{\tau}$ and $HH \rightarrow b\bar{b}\ \tau\bar{\tau}$
2. Heavy $ZZ$ resonances in the $4\ell$ and $\ell\bar{\ell}\nu\bar{\nu}$ final states
3. Exotic Higgs boson decays

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

- In 2HDM decays of $A/H$ to $t\bar{t}$ enhanced for $\tan\beta < 3$ and $m_{A/H}$ > 500 GeV.
  - Parameter region not probed by previous searches.

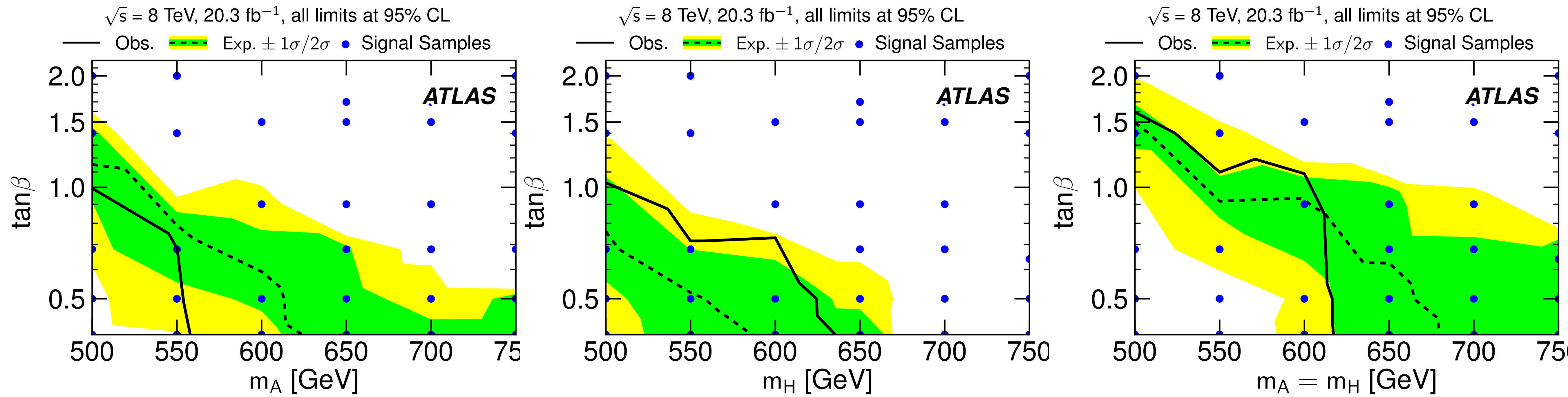



- Significant interference between $gg \rightarrow t\bar{t}$ production and $A/H \rightarrow t\bar{t}$
  - for $m_{A/H}$ above $t\bar{t}$ threshold, for LHC $t\bar{t}$ main production
  - Resonant shape distorted to a peak-dip structure.
- Considering only resolved kinematics
  - Most efficient strategy for $m_{A/H} < 800$ GeV
- Event classification into six categories
  - Kinematic $\chi^2$ for jet association to $W$

# $A/H \to t\bar{t}$

arXiv:1707.06025



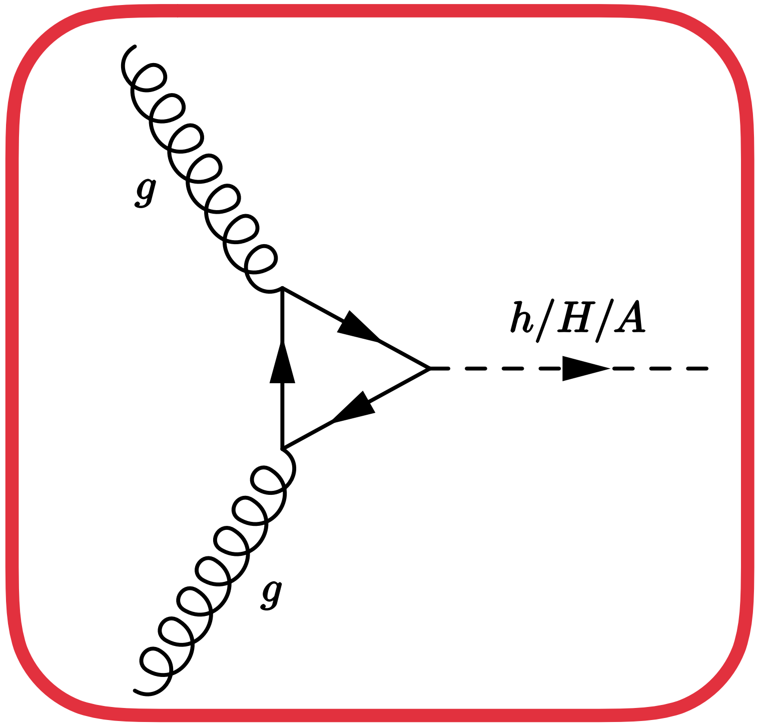

Pseudo scalar    Scalar    Degenerate

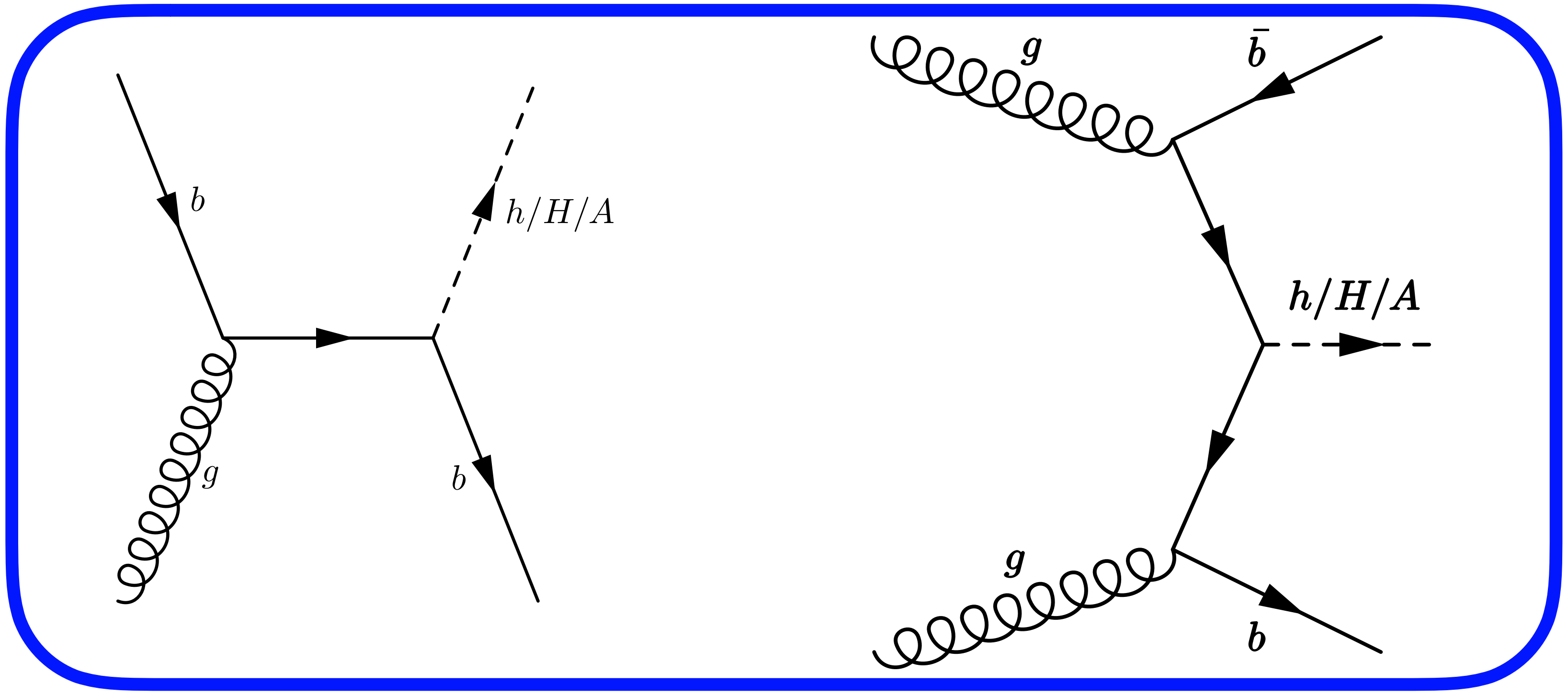
$$\mu \cdot S + \sqrt{\mu} \cdot I + B = \sqrt{\mu} \cdot (S + I) + (\mu - \sqrt{\mu}) \cdot S + B.$$

- $CL_s$ limits taking into account signal (S), background (B) and interference (I)
  - $\tan\beta < 0.7$ for $m_A$=550 GeV and $\tan\beta$ < 0.72 for $m_H$=550 GeV
- First and strictest limits in this parameter region

# $A/H \to \tau\overline{\tau}$ and $HH \to b\overline{b}\ \tau\overline{\tau}$

- For large tan$\beta$, $A/H$ couplings to leptons and down quarks enhanced.
  - Particular for hMSSM models.
  - Increased branching fractions to $\tau$-leptons
- Dominant production modes:
  - gluon gluon fusion for low tan$\beta$,
  - $b$-associated production for high tan$\beta$



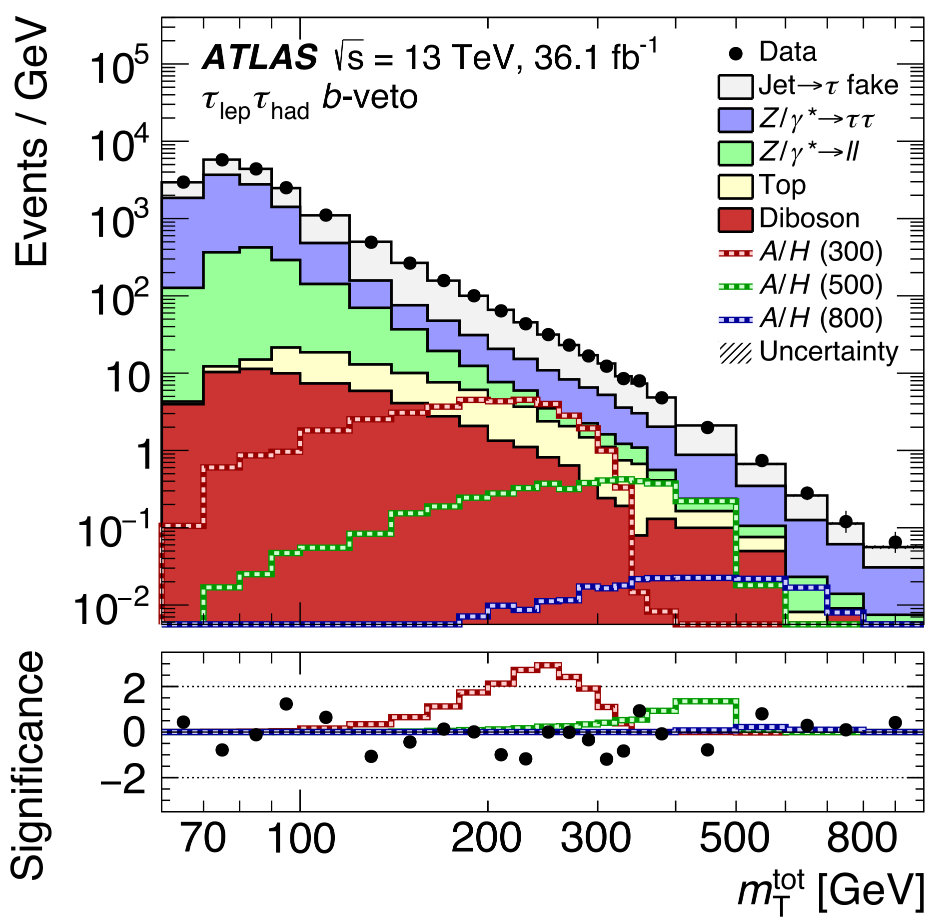

- Events are split into two categories:
  - $b$-tag veto category: no $b$-jets in production.
  - $N(b\text{-jets}) > 0$ associated b-jet production.

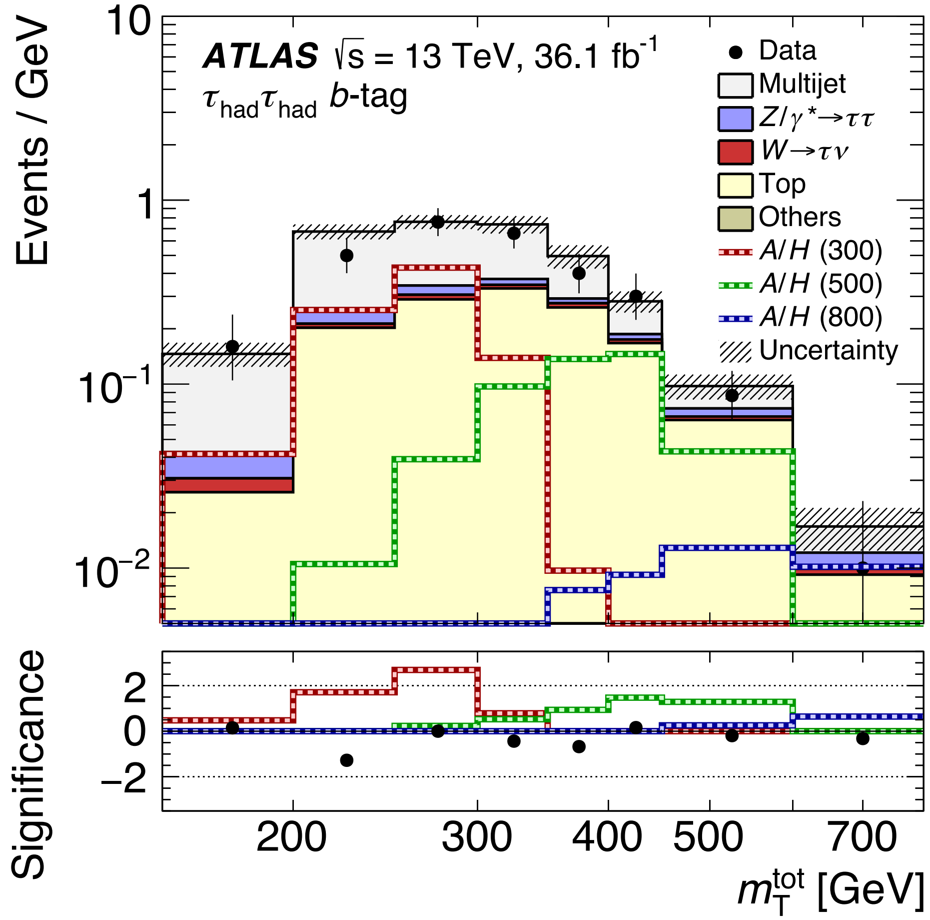
- Reconstruction of $\tau\overline{\tau}$ final states.
  - Two $\tau$ decay modes are considered:
    - All hadronic final state ($\tau_{had}\tau_{had}$) both $\tau$ decay hadronically.
    - Semileptonic final state ($\tau_{lep}\tau_{had}$) one $\tau$ decays hadronically and one leptonically.

- Discriminant is total transverse mass:

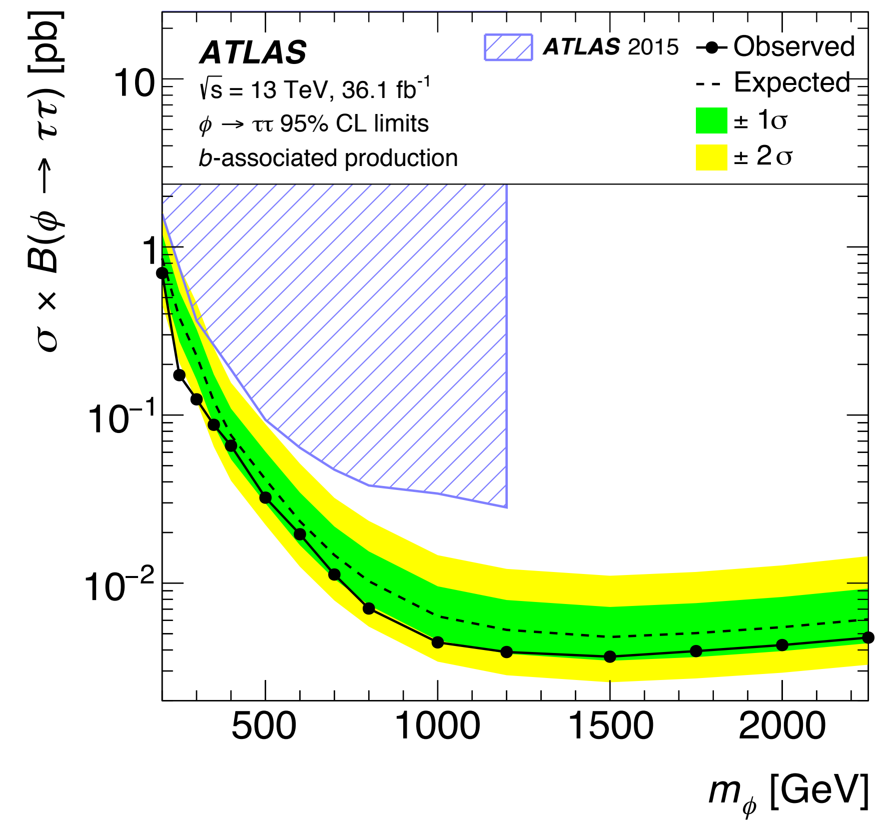
$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

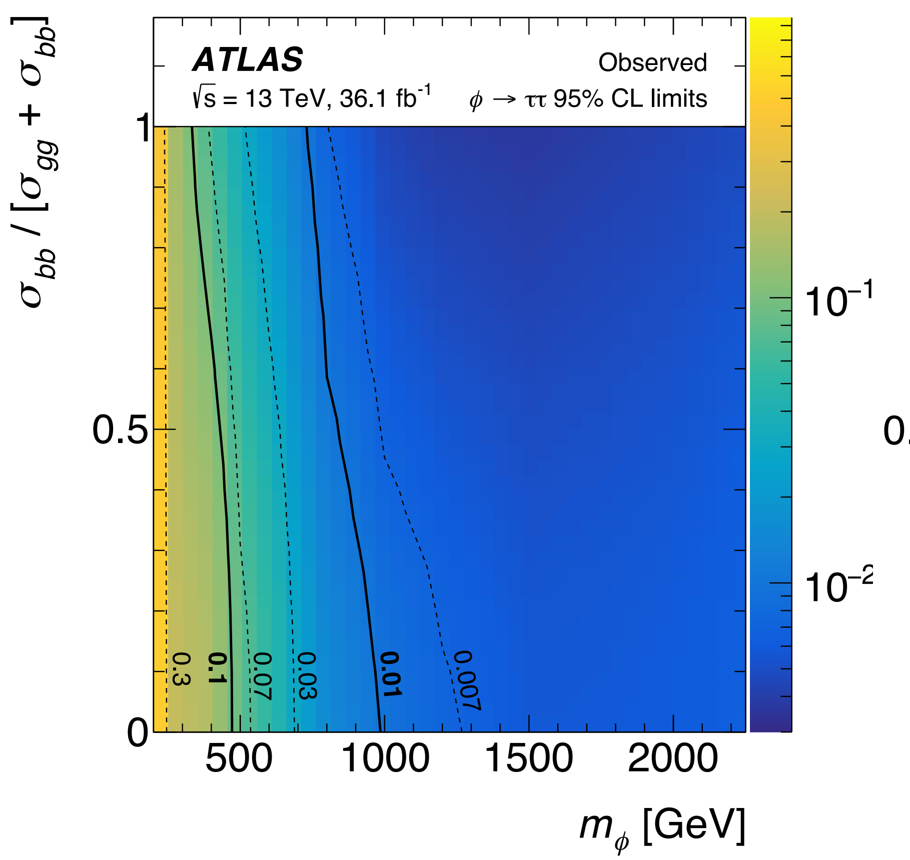
  - Missing energy challenges $m_{\tau\tau}$.
  - Backgrounds larger component in longitudinal axis.

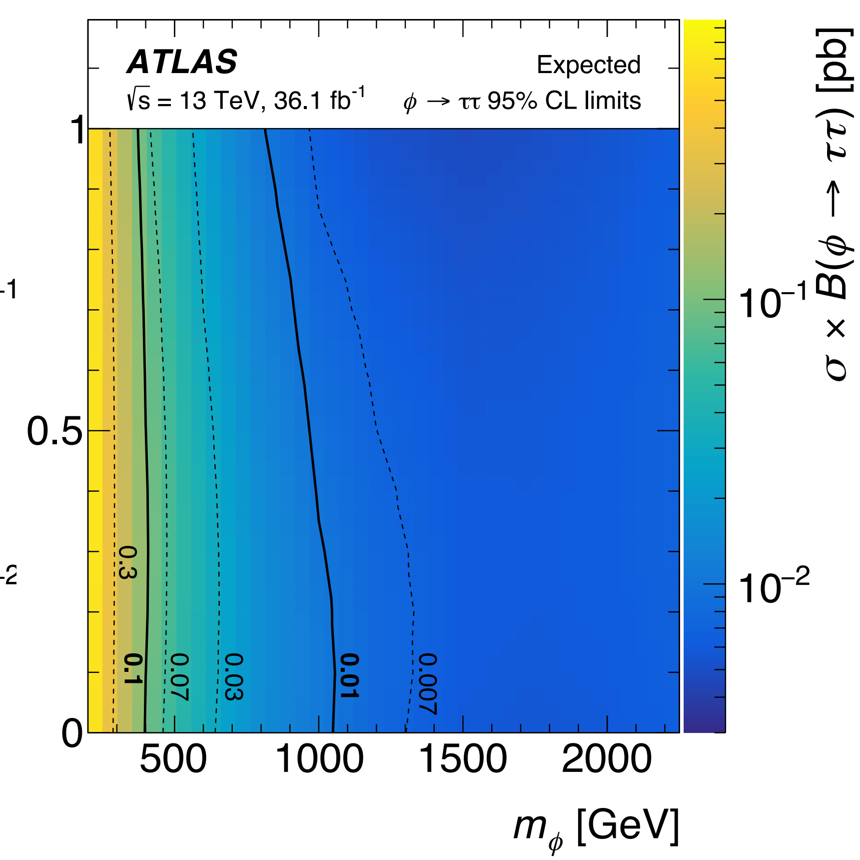


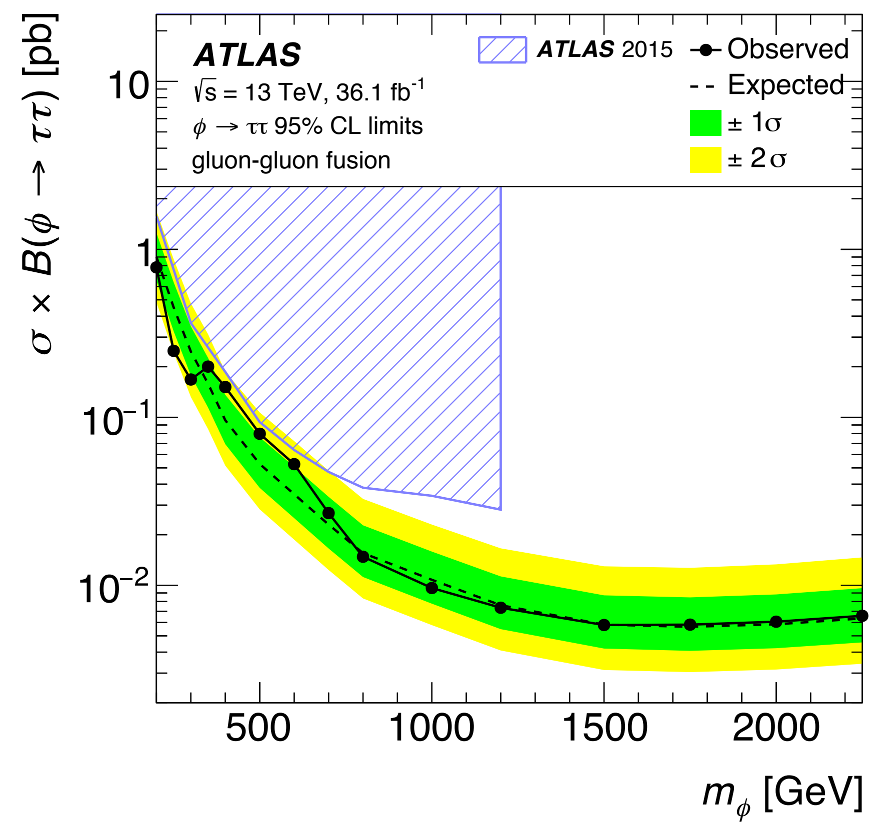



- Results from profile likelihood fit on transverse mass $m_T^{tot}$
- Model independent limits on $\sigma$ x *BR* (H/A) production
  - Separately for *gg*F production and *b*-associated production.
  - Limits from 200 GeV to > 2.0 TeV on $m_\phi$
  - Narrow-width assumption of $\phi$

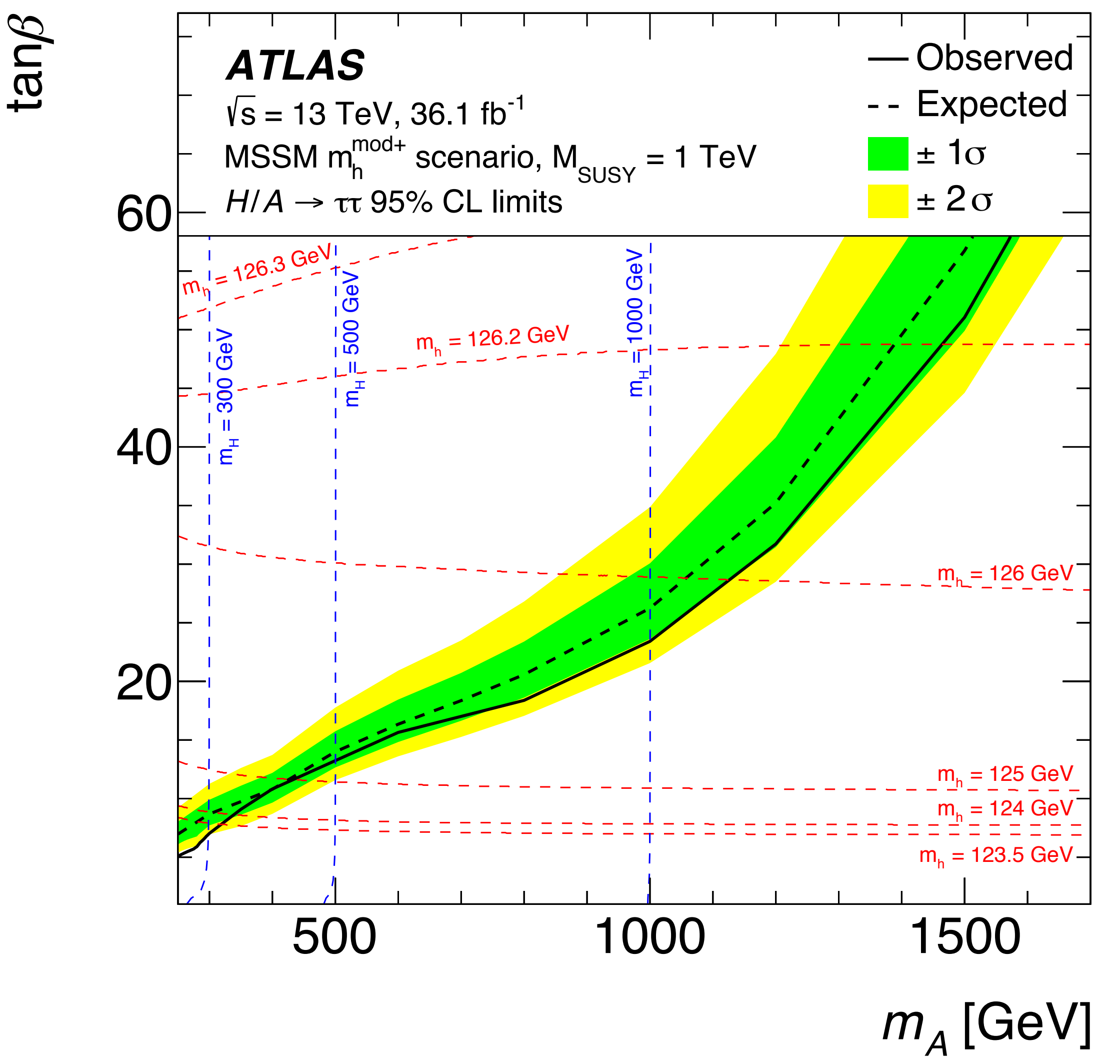


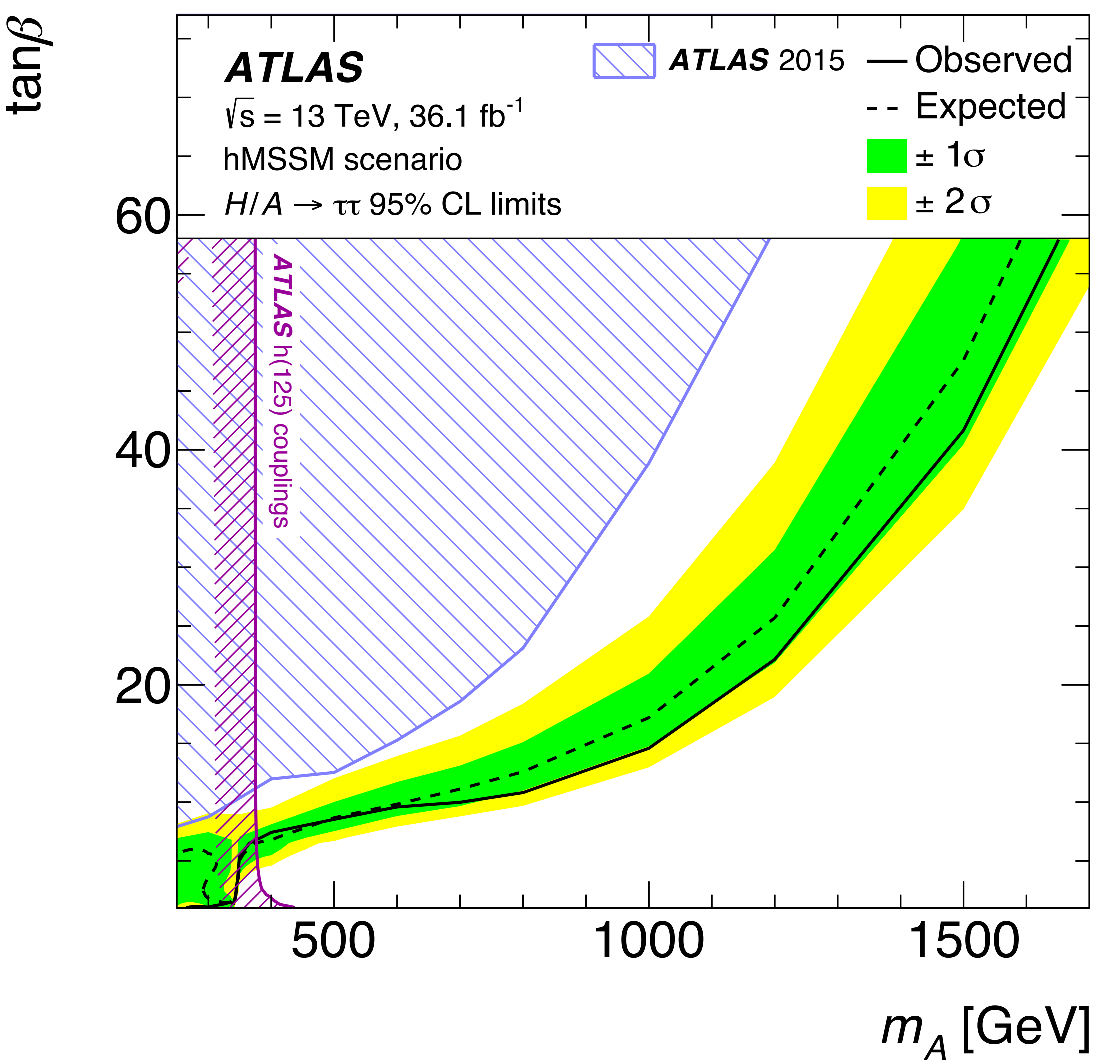



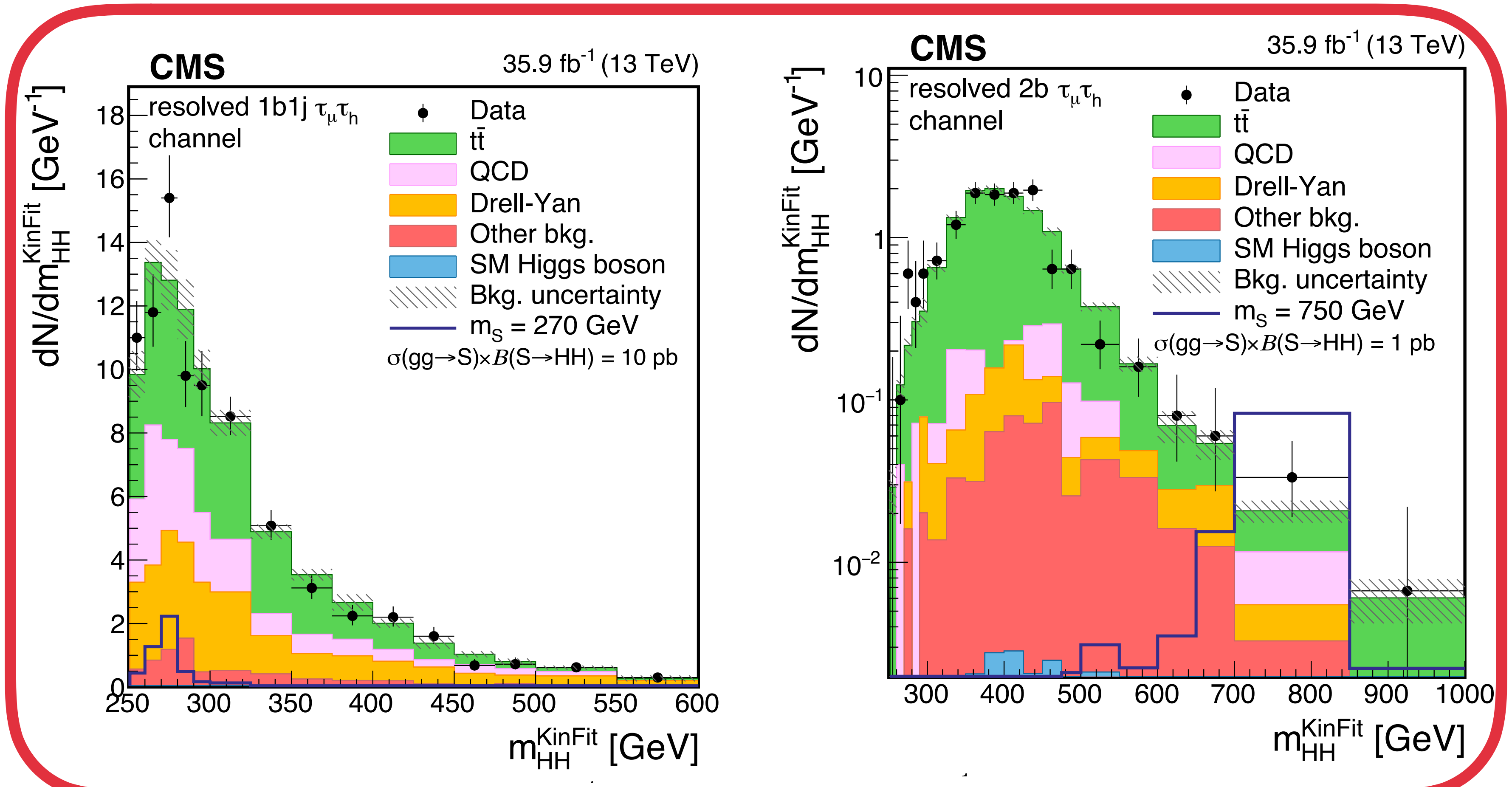



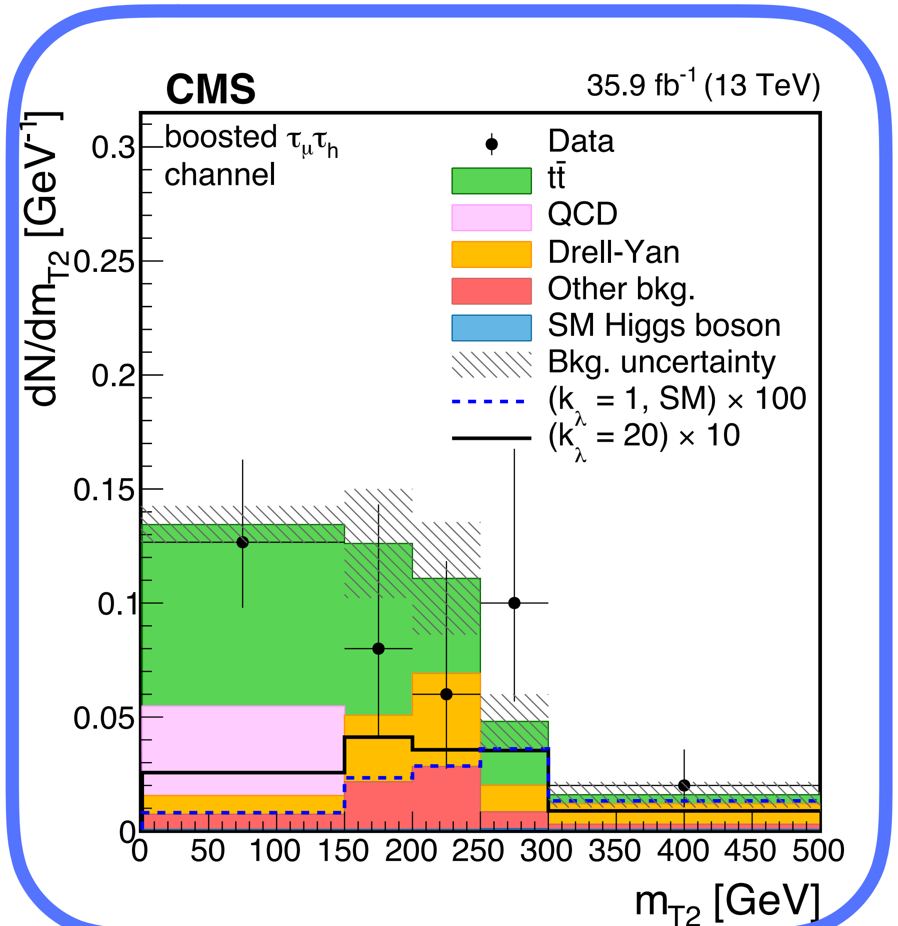
- Results interpreted as limits on MSSM models
  - $\tan\beta$ > 1.0 for $m_A$=0.25 TeV and $\tan\beta$ > 45 for $m_A$=1 TeV excluded.
  - For $m_h^{\text{mod+}}$ $\tan\beta$ > 5.3 for $m_A$=0.25 TeV and $\tan\beta$ > 54 for $m_A$=1 TeV excluded
    - ✦ Presence of low mass neutralinos decrease $A/H\rightarrow\tau\tau$ branching fraction



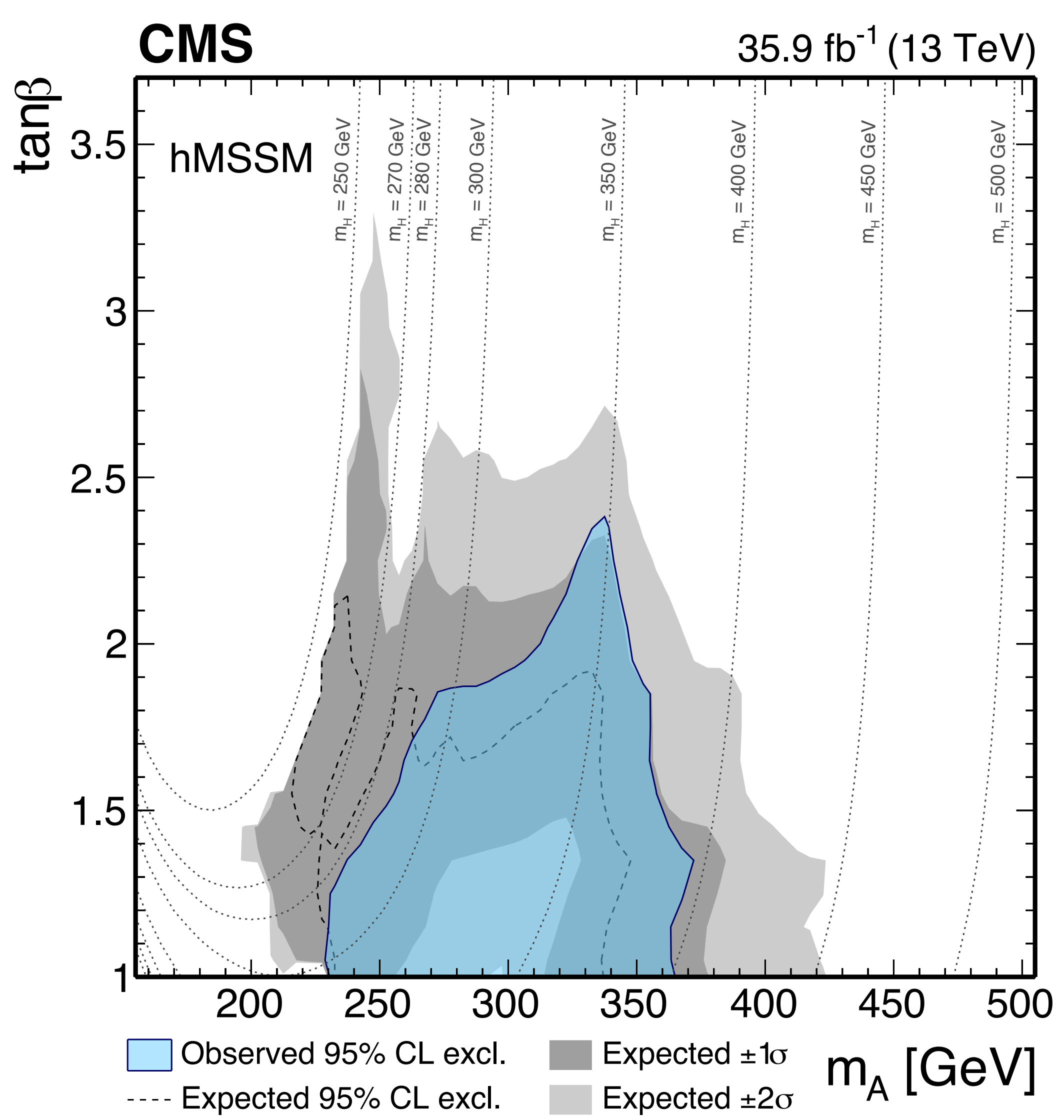



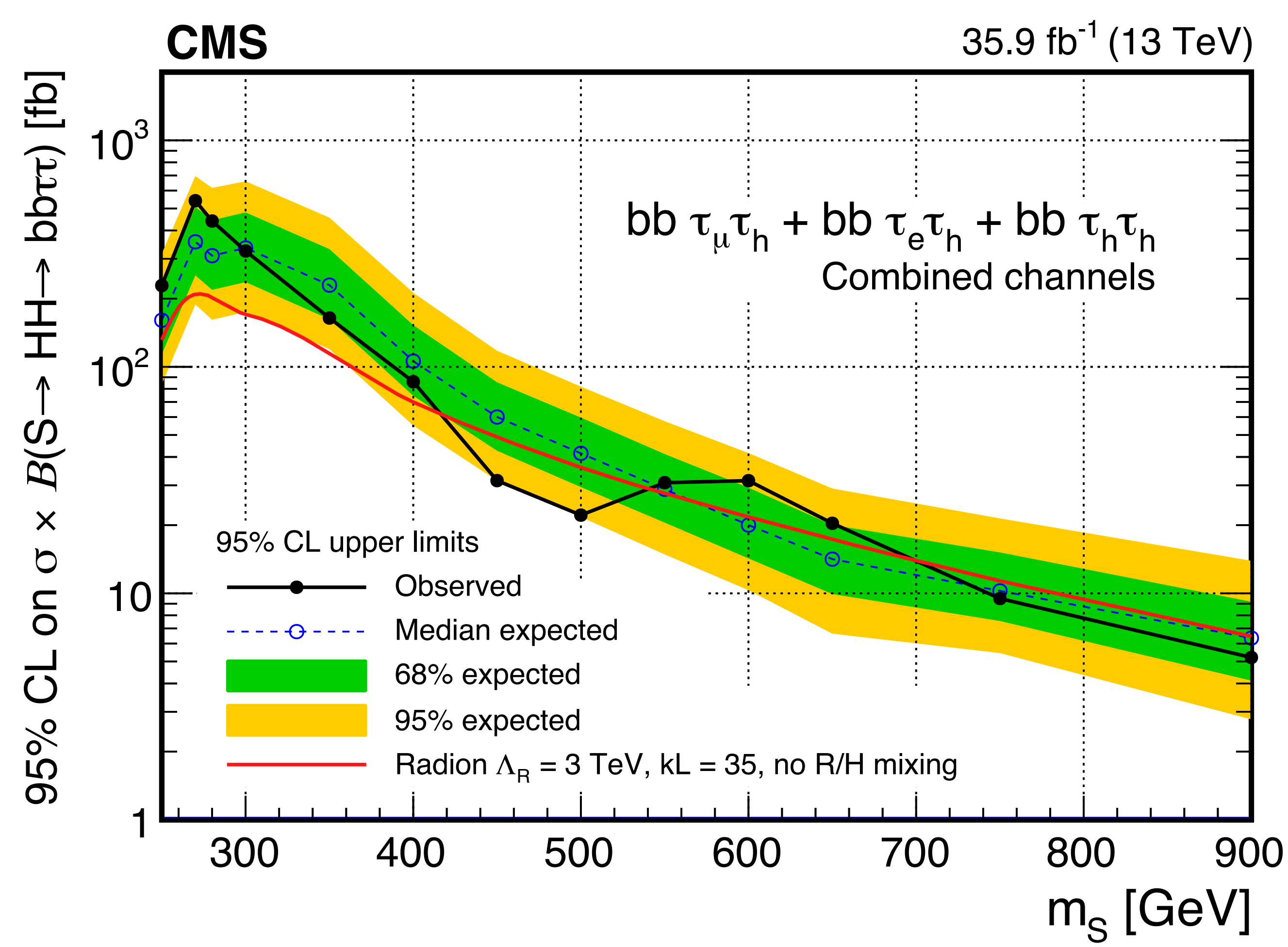
- Search for resonant Higgs pair production
  - CP-even scalar decaying into a HH pair.
  - One pair into $b\bar{b}$ and one into $\tau\bar{\tau}$
    - $\tau$ modes similar to what discussed above.
    - $m_{\tau\tau}$ reconstructed with kinematic likelihood
  - Splitting in resolved and boosted topologies for $b\bar{b}$ kinematics
  - Multivariate discriminant to reject $t\bar{t}$ processes.



- Model independent limits as a function of resonance mass
  - Narrow width hypothesis.
- Limits interpreted in the hMSSM model in the tanβ plane
  - with the resonance interpreted as A and h(SM Higgs at 125 GeV).
  - limits from $m_A$ = 270 GeV to 370 GeV.

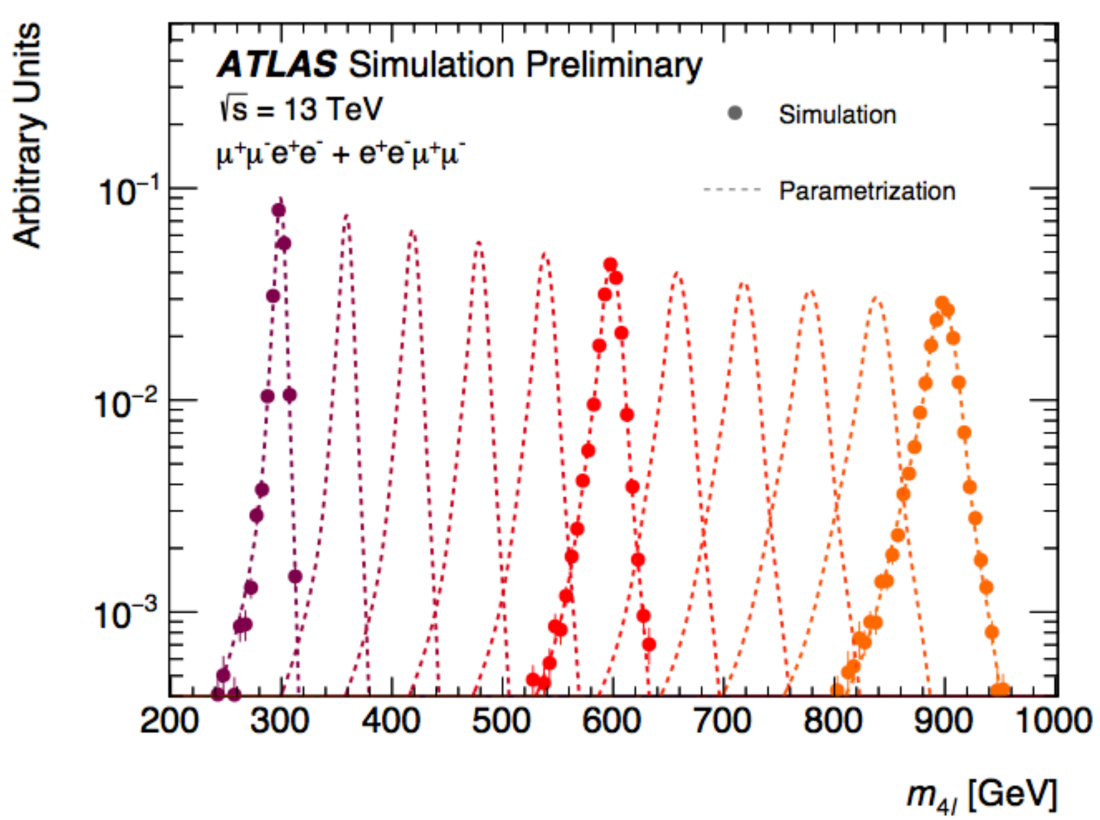


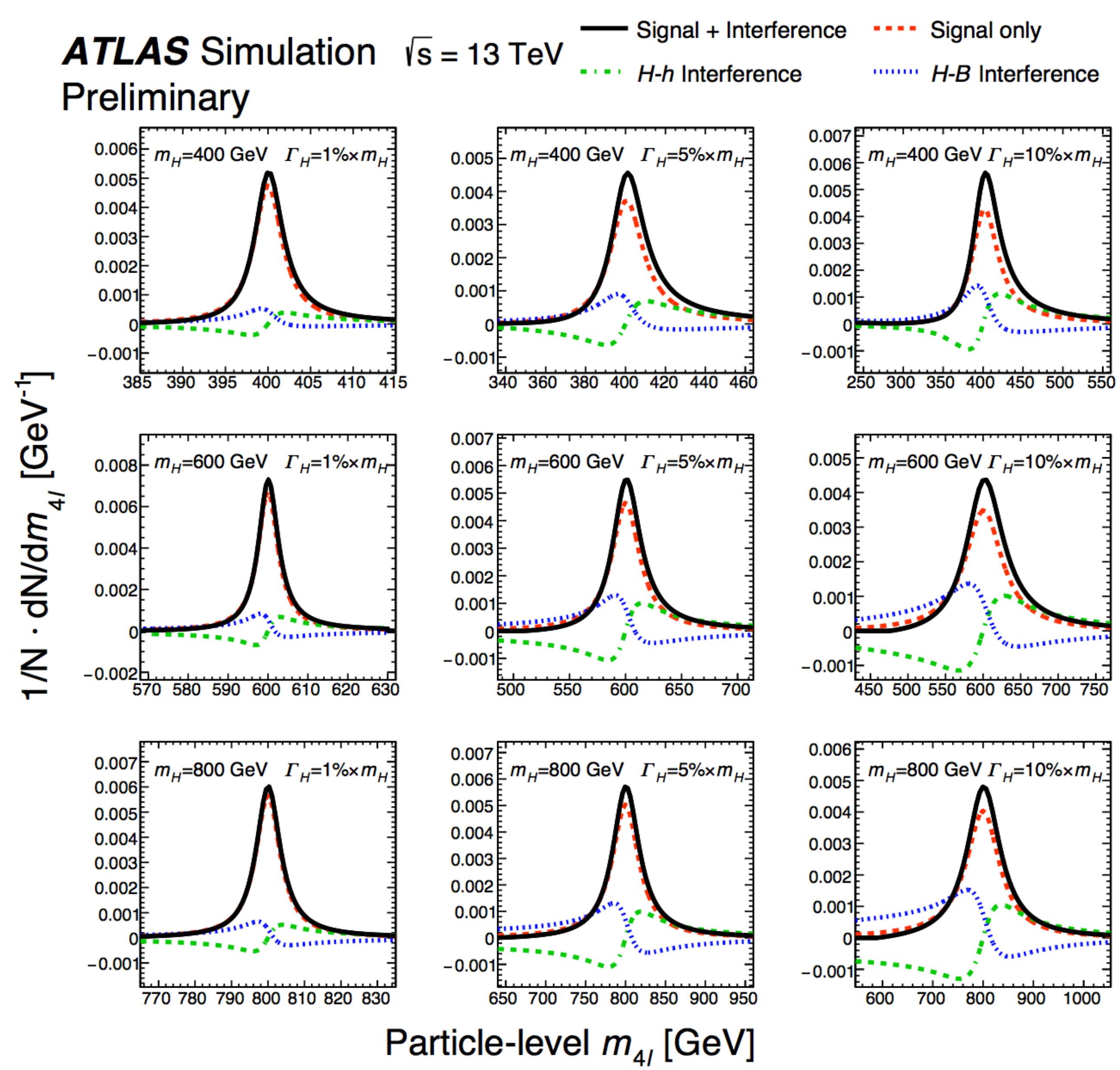



# *Heavy $ZZ$ resonances in the $4\ell$ and $\ell\overline{\ell}\nu\overline{\nu}$ final states*

# $ZZ \to 4\ell$ and $\ell\bar{\ell}\nu\bar{\nu}$ ATLAS-CONF-2017-058, B2G-16-023 and B2G-16-033

- Searches for spin-0 and spin-2 resonances in the $ZZ \to 4\ell$ and $\ell\bar{\ell}\nu\bar{\nu}$ final states.
  - Upper limits for Type-I and II two-Higgs double models (spin-0) and for RS models (spin-2)
  - Separate sensitivity for ggF and VBF productions (both ATLAS and CMS)
    - ✦ Typical VBF selection: at least two jets with $p_T(j)$ > 30 GeV, $\Delta\eta$ > 3.3 and $m_{jj}$ > 400 GeV
- Resonances searched in $m_{4\ell}$ and $m_T$
  - Analytical parametrisation of signal.
  - *h-H* interference taken into account in the large width approximation



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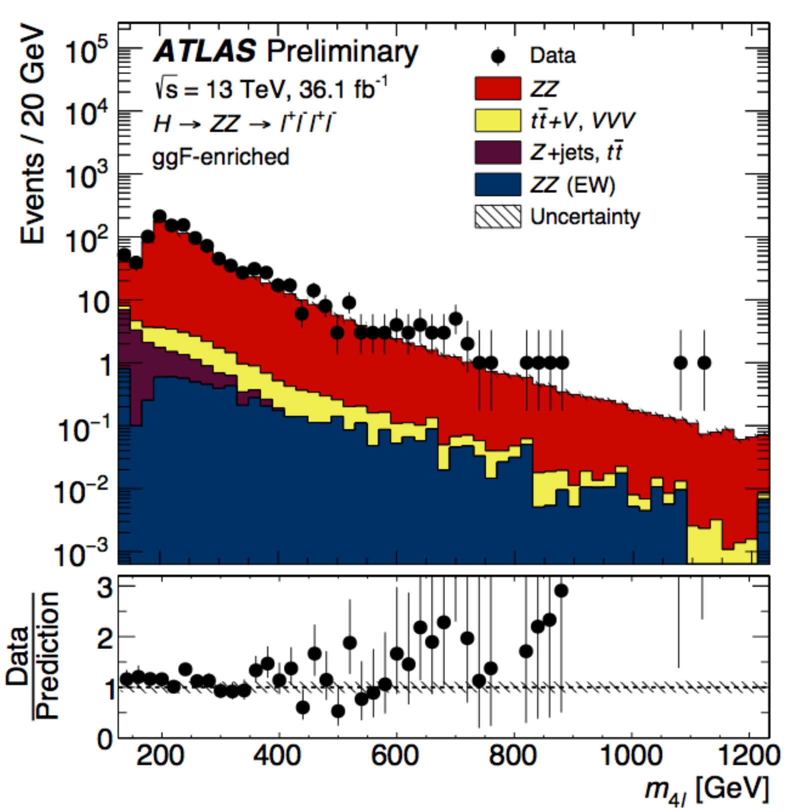
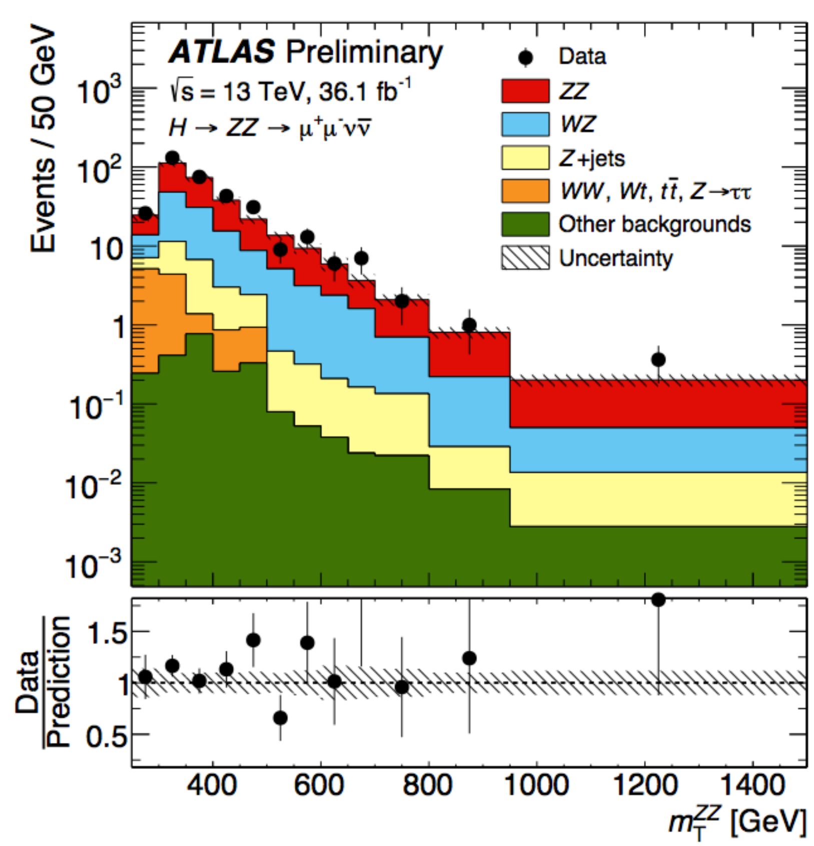
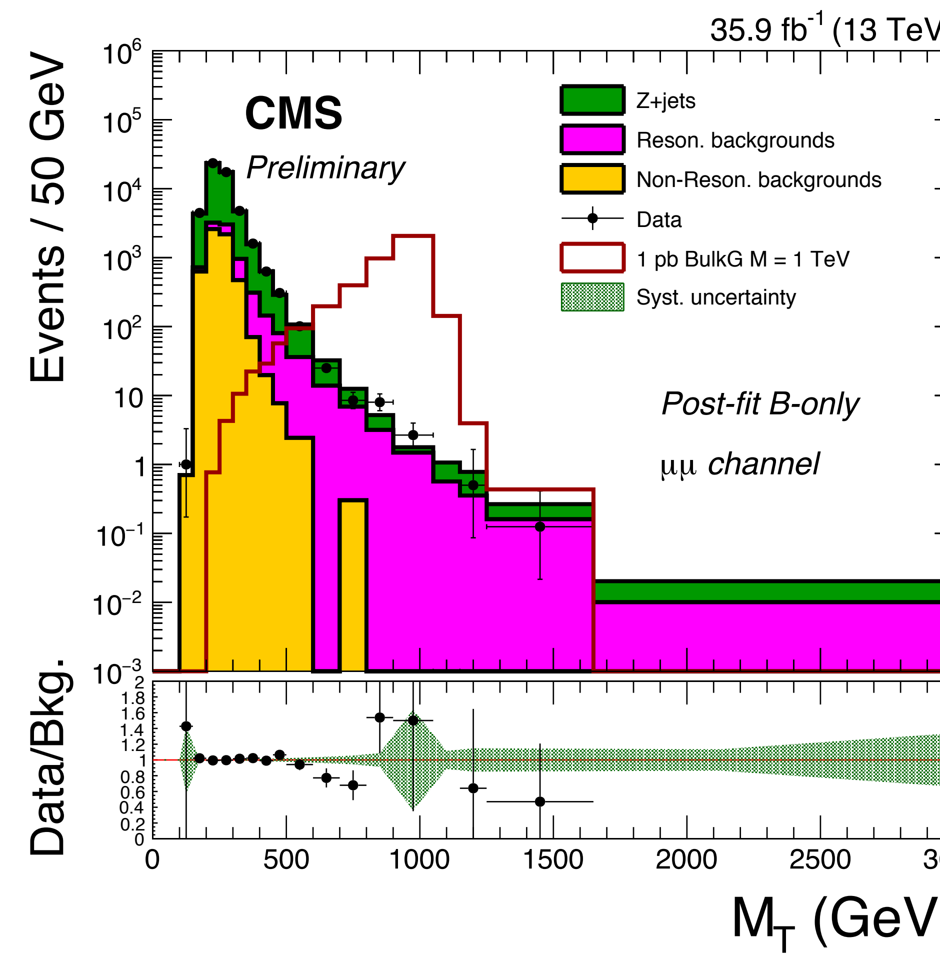
  - Upper limits for Type-I and II two-Higgs double models (spin-0) and for RS models (spin-2)
  - Separate sensitivity for ggF and VBF productions
    - ✦ At least two jets with $p_T(j) > 30$ GeV, $\Delta\eta > 3.3$ (4.4) and $m_{jj} > 400$ (550) GeV

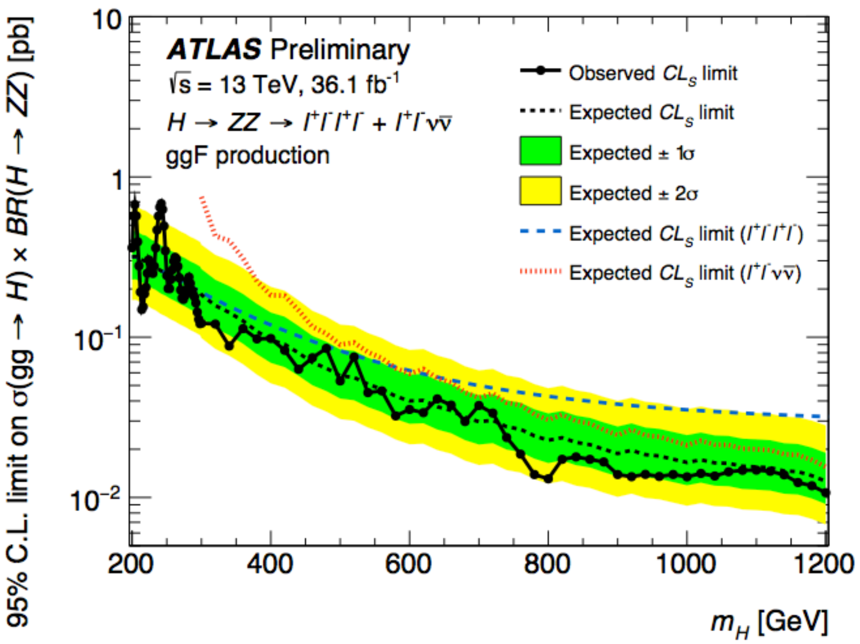


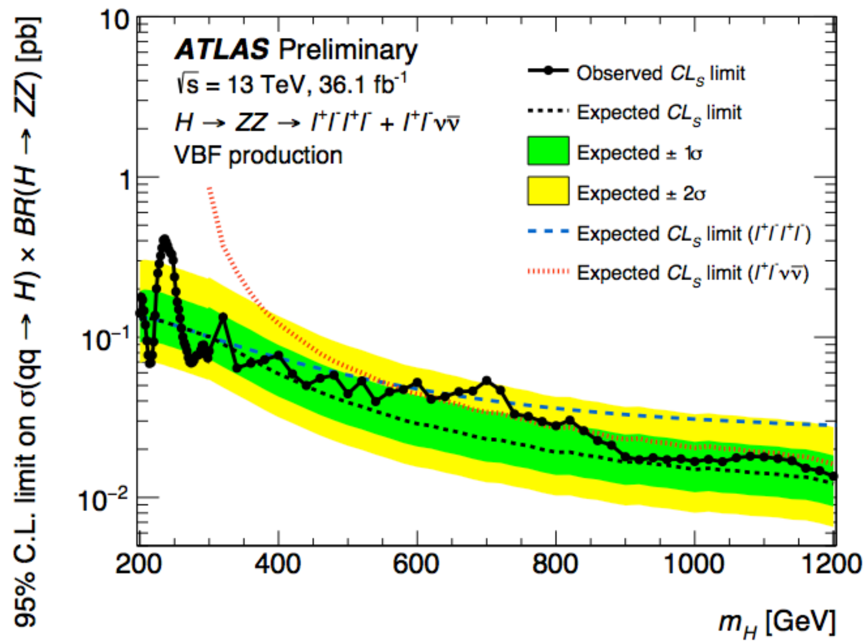



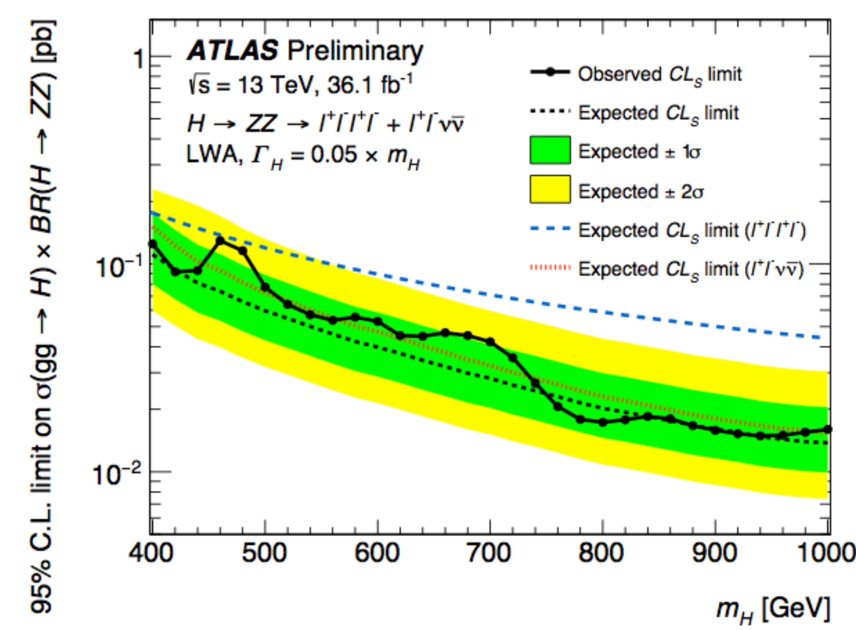



# $ZZ \to 4\ell$ and $\ell\bar{\ell}\nu\bar{\nu}$

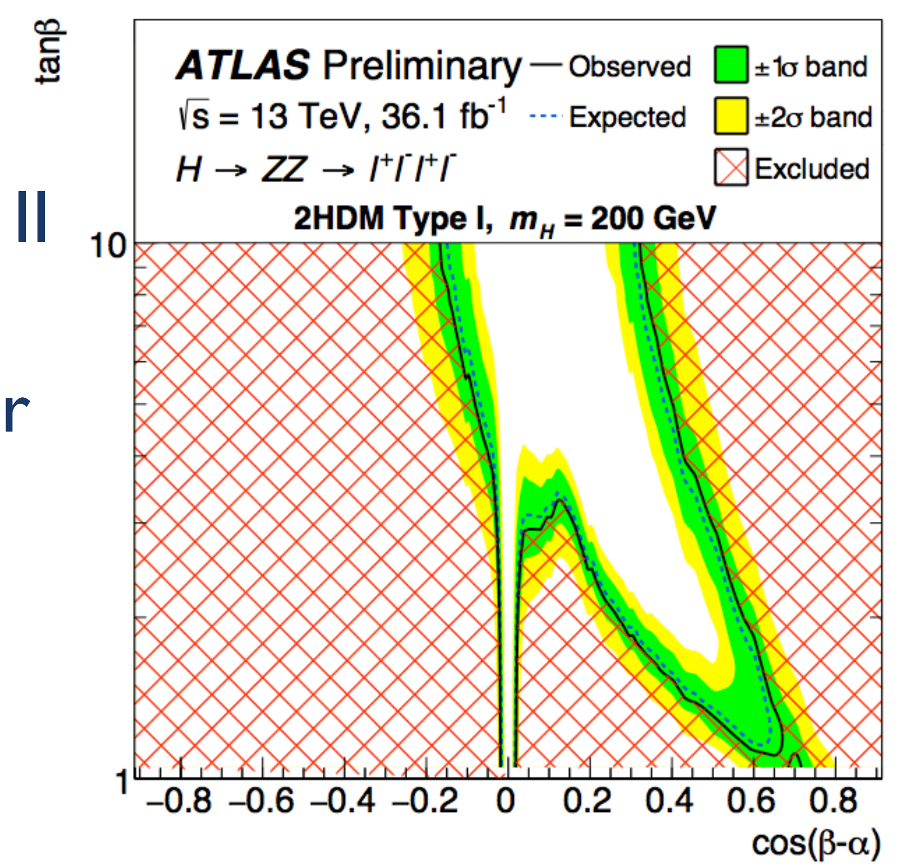
- Spin-0 resonance limits
  - Narrow width: 0.68 pb at $m_H$= 242 GeV to 11 fb at $m_H$= 1.2 TeV
  - Large width as a function of 1%, 5% and 10% of $m_H$



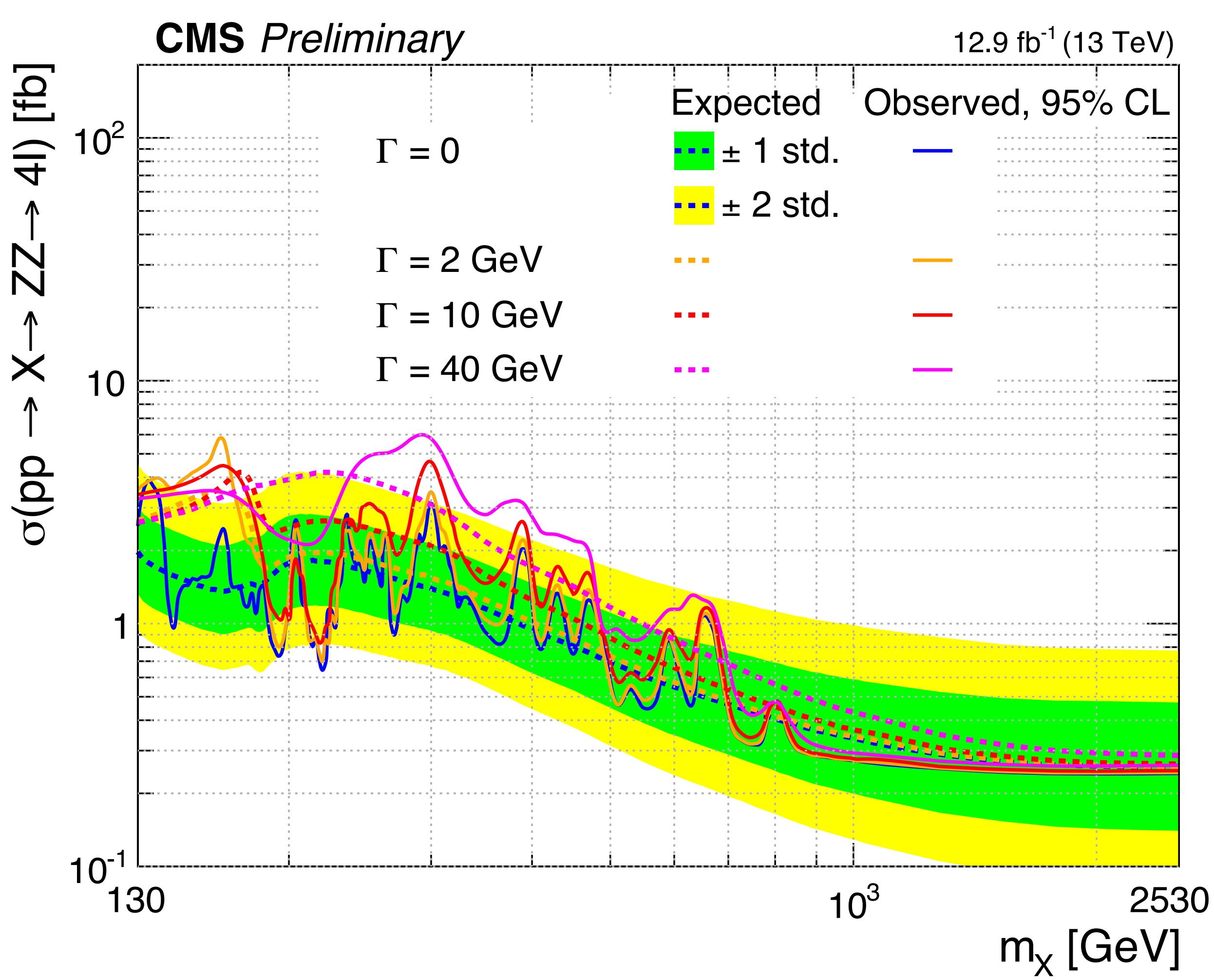



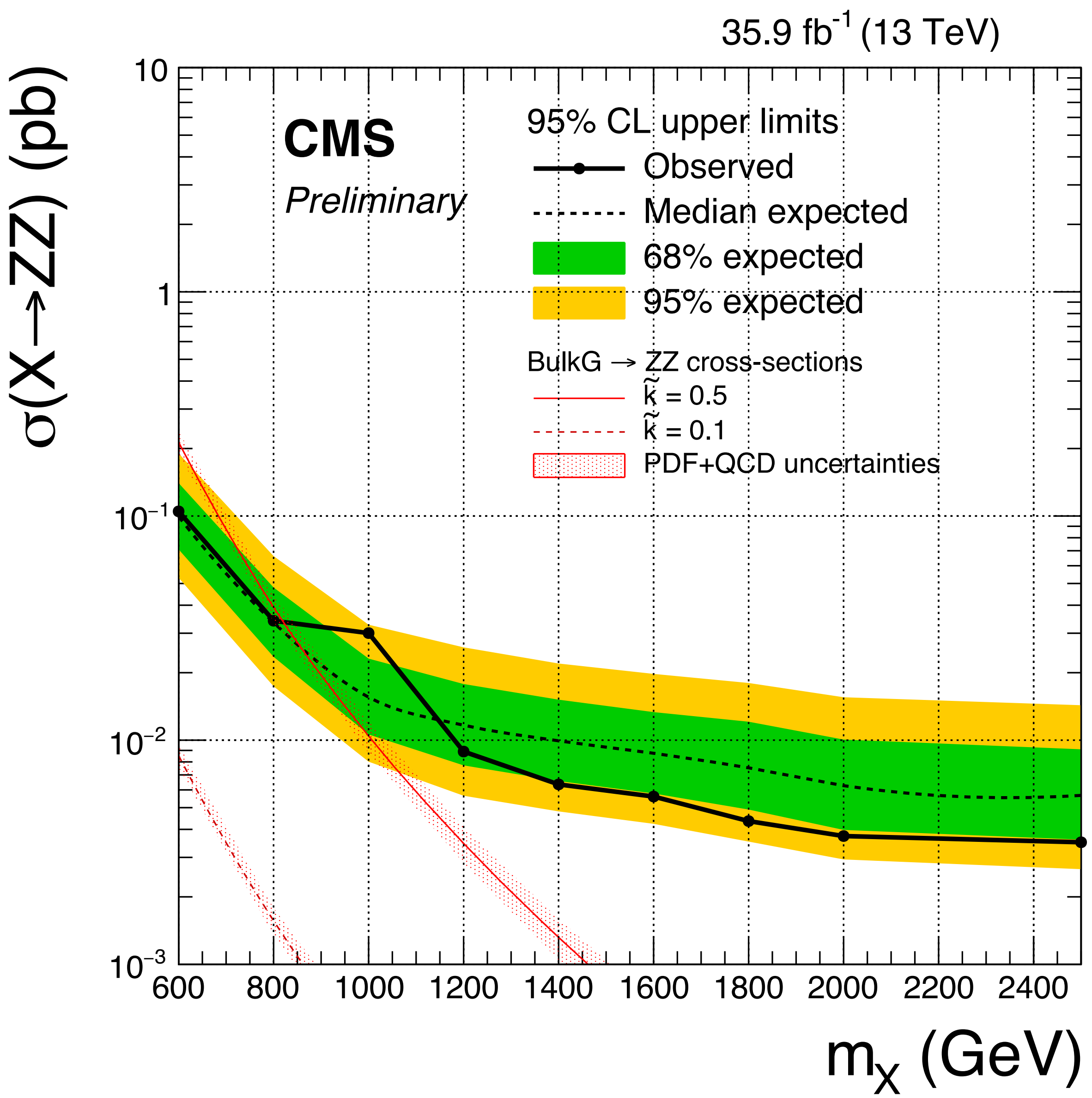




- Interpretation in context of 2HDM
  - No direct coupling of Higgs to leptons, only Type II and II considered.
  - Relative ggF to VBF rates fixed to 2HDM predictions for *$m_H$= 200 GeV.*
    - ✦ *NWA* valid across wide range and maximal experimental sensitivity



- Separates searches in each final state.
- $ZZ\to 4\ell$, search as function of $\Gamma$ (with $\Gamma < m_X$) on $m_{4\ell}$
  - Separate ggF / VBF categorisation
    - Parametrisation based on MCFM within MELA, incorporation of interference effects
- $ZZ\to \ell\bar{\ell}\nu\bar{\nu}$

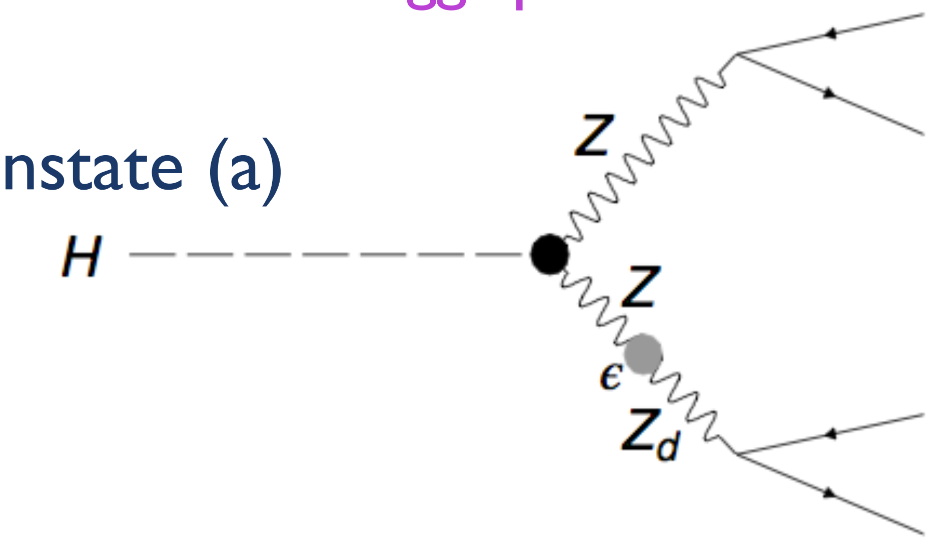


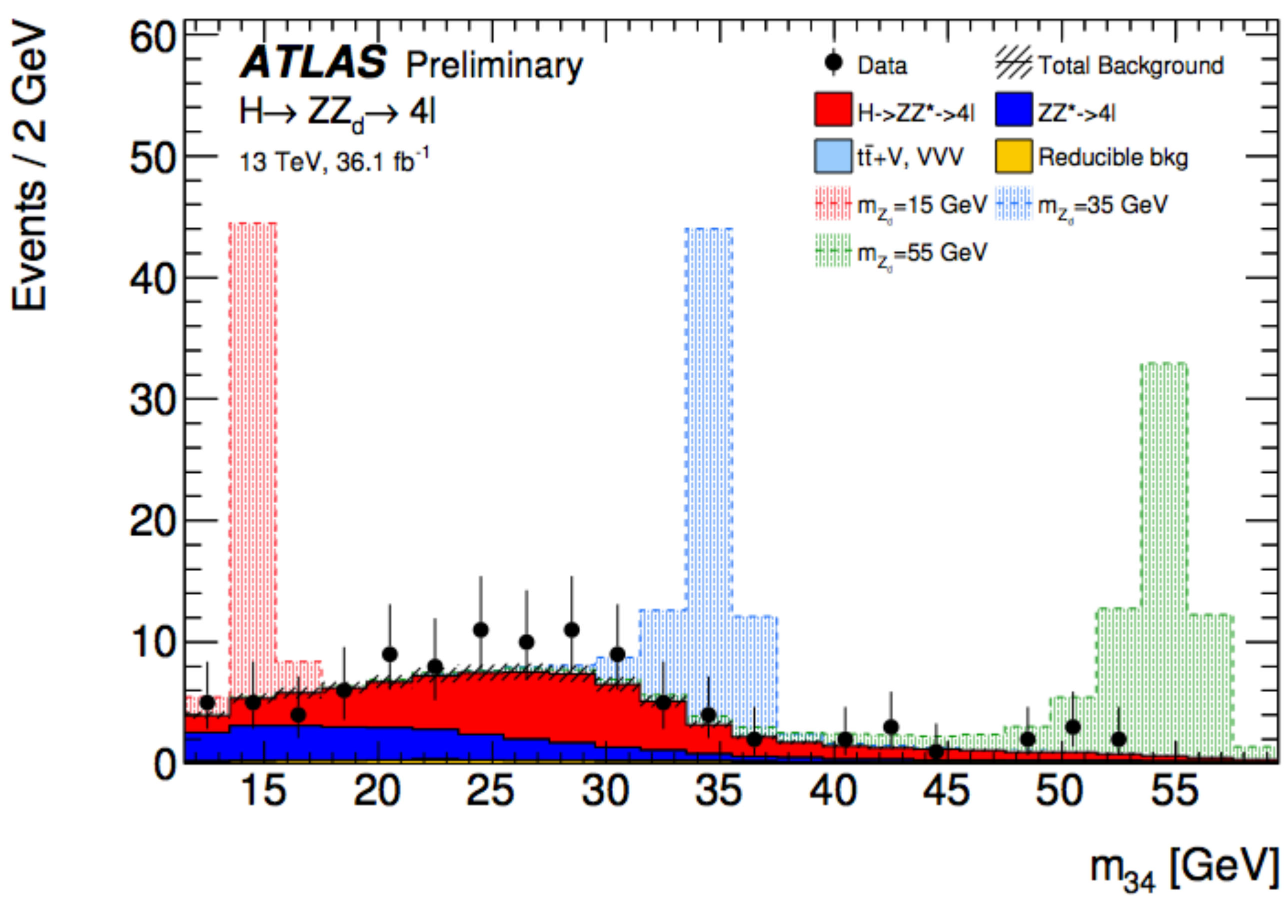



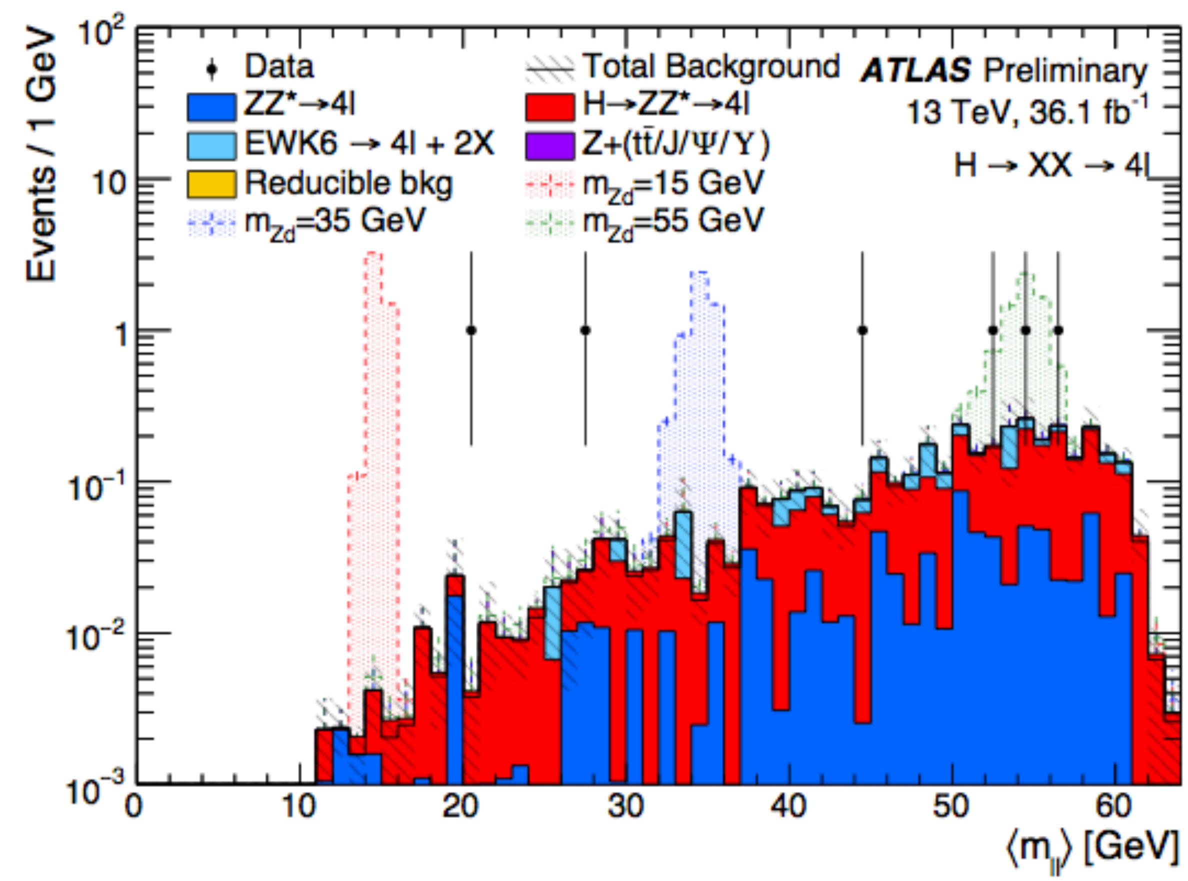
# Exotic Higgs boson decays

# $H \rightarrow ZZ_d$ and $Z_dZ_d$

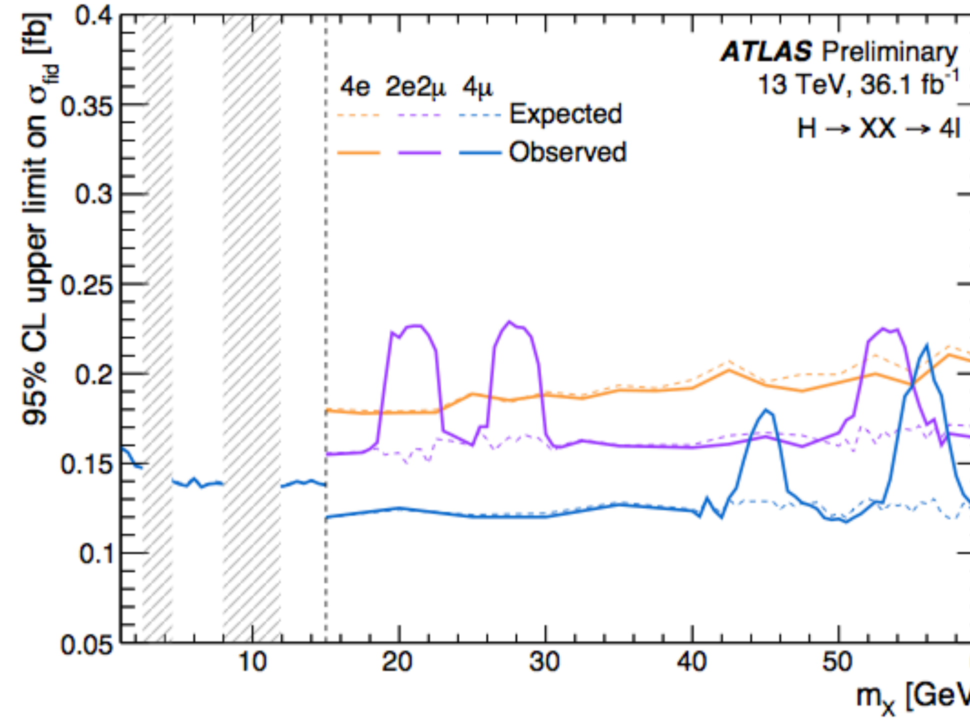
- Search for BSM dark vector or pseudoscalar bosons in $4\ell$ final states
  - Probe ε and $m_{Zd}$ (of the $U(1)_d$) independently of mixing with SM Higgs
    - ✦ Signal is indistinguishable from $H \rightarrow ZZ^*$, must emerge above SM Higgs production
  - 2HDM+S allows for a light pseudoscalar mass eigenstate (a)
    - ✦ Yukawa-like couplings to fermions, though smaller BR to lepton pairs

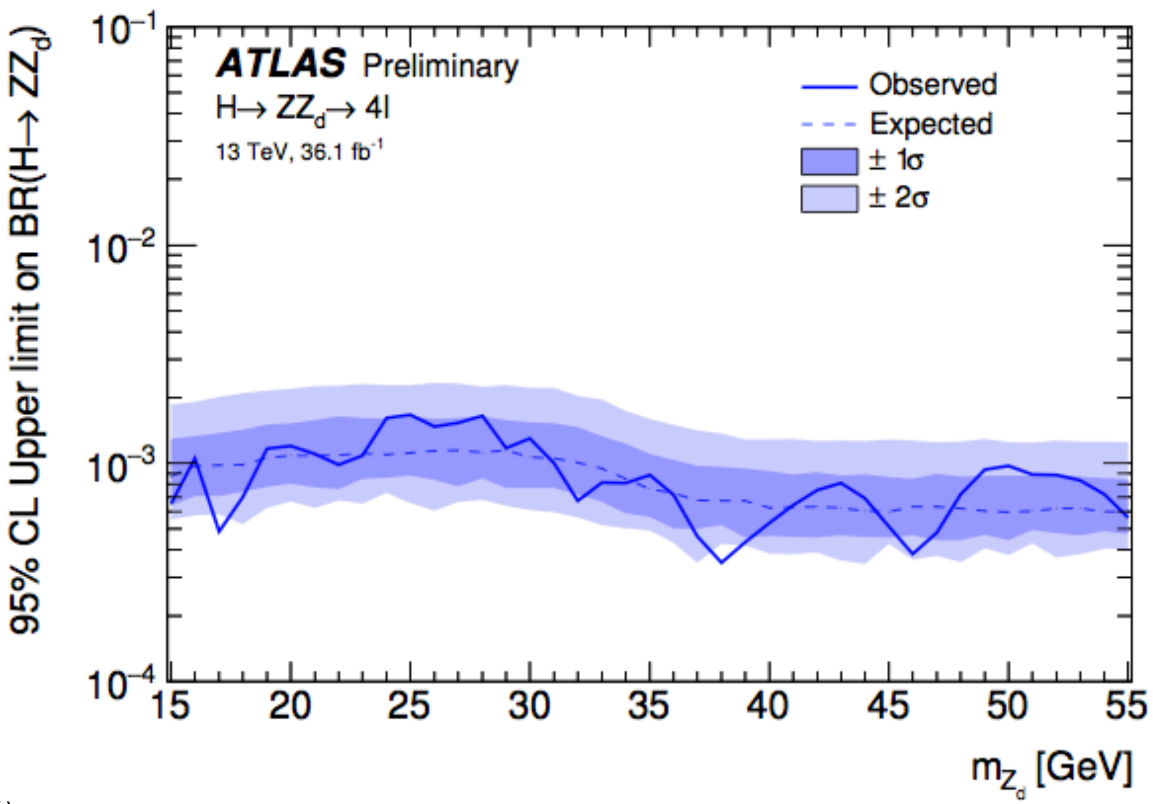


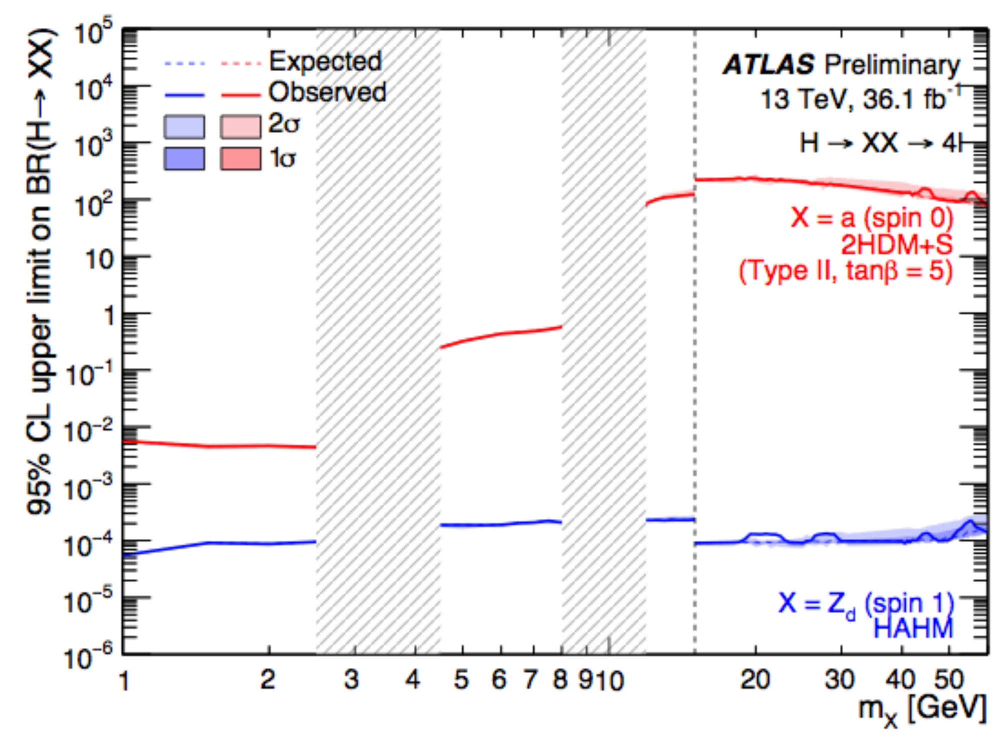



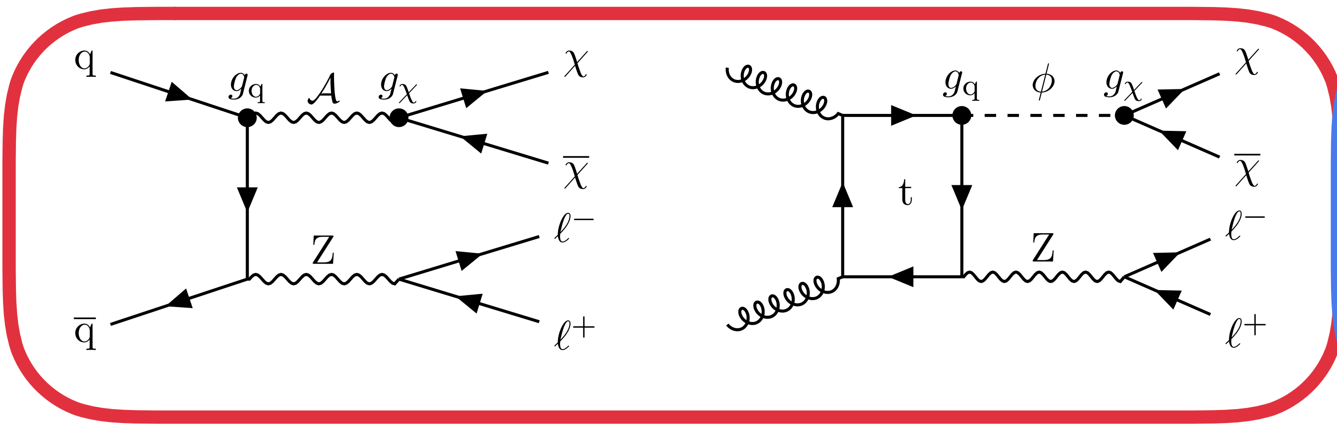
- Generic limits on $H \to XX \to 4\ell$
  - model independent within fiducial phase-space
    - $\sigma_H$ fixed to expectation at $m_H$=125 GeV
    - Signal modelled by Gaussian pdf
- Interpreted as limits $Z_dZ_d$ and 2HDM+S
  - on BR($H \to Z_dZ_d$) and BR($H \to aa$)
  - factor two improvement w.r.t previous result
- Limits on $ZZ_d$

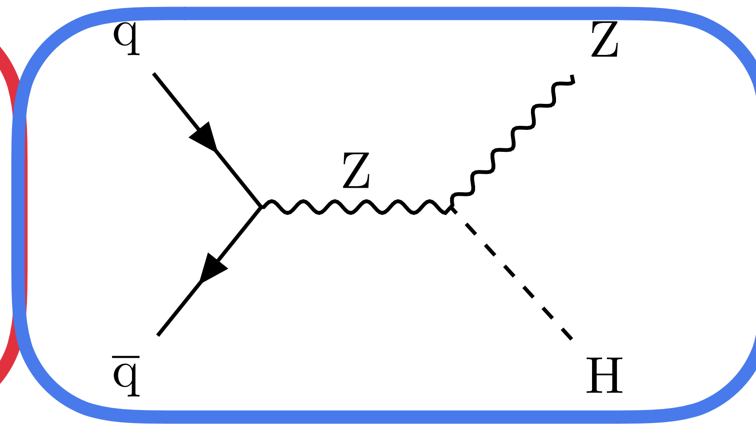


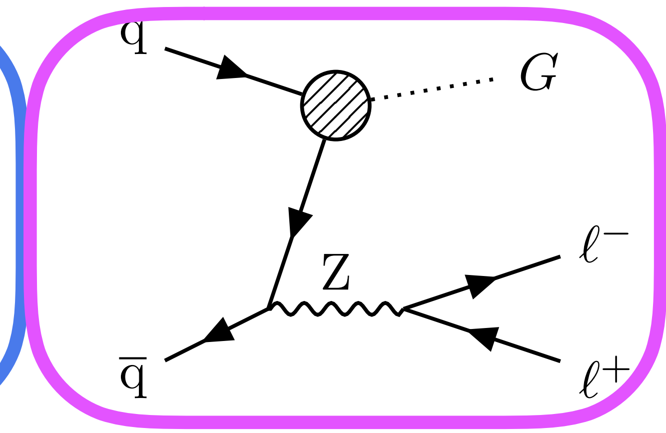



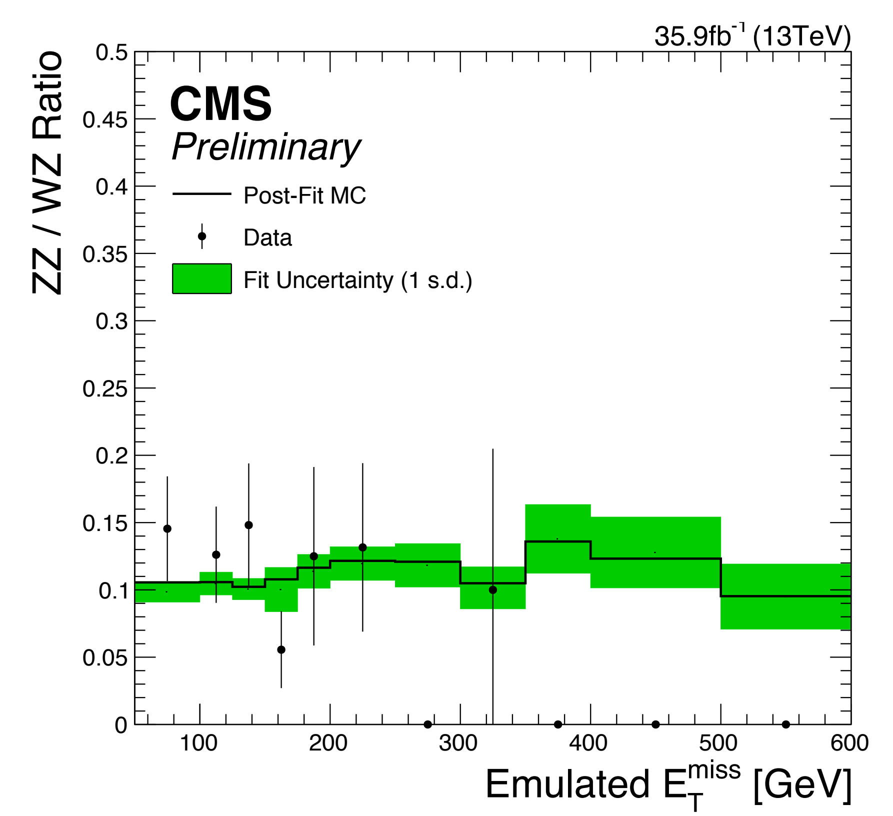
- Dilepton from Z boson production in association with large $E_T^{miss}$ probes
  - Dark matter production, spin-0- and spin1- mediated
  - Higgs decays into invisible particles
  - Graviton production in the context of large extra dimensions



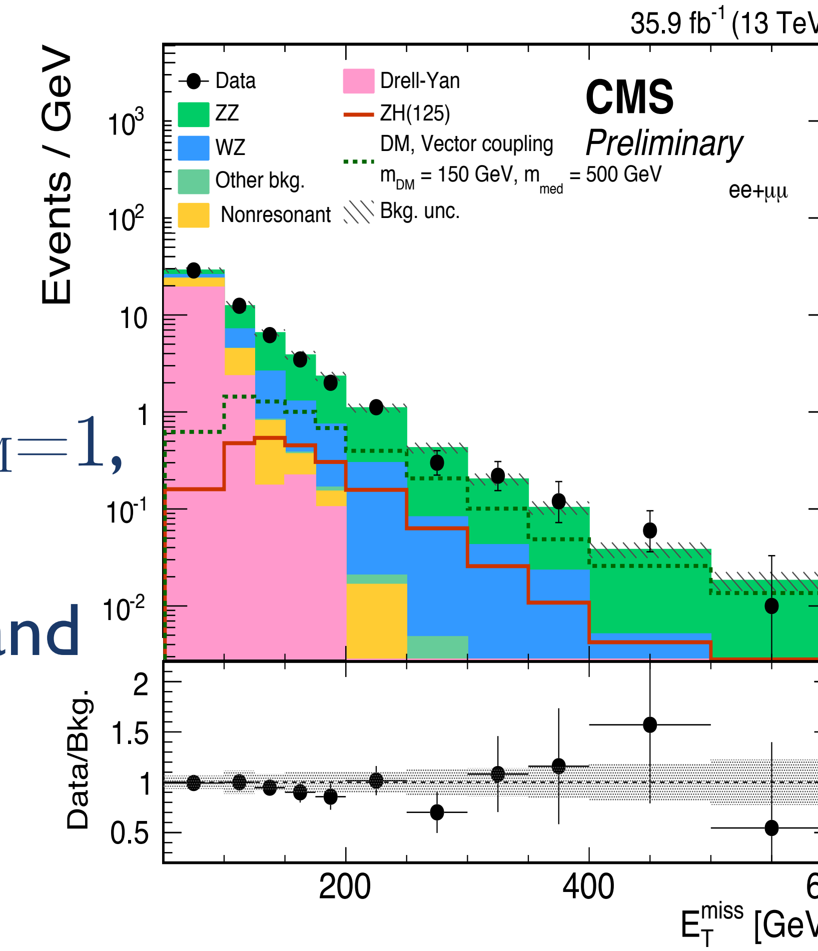

- Non resonant signal search → understanding of background
  - $ZZ \to 2\ell 2\nu$ same final state about 60% of tot. bck.
  - $WZ \to \ell\nu\ell\bar{\ell}$ with one lepton failing identification, about 25% of tot. bck.
  - $W(Z)$ traverse momentum: emulation of $E_T^{miss}$
    - sum of extra lepton and measured $E_T^{miss}$



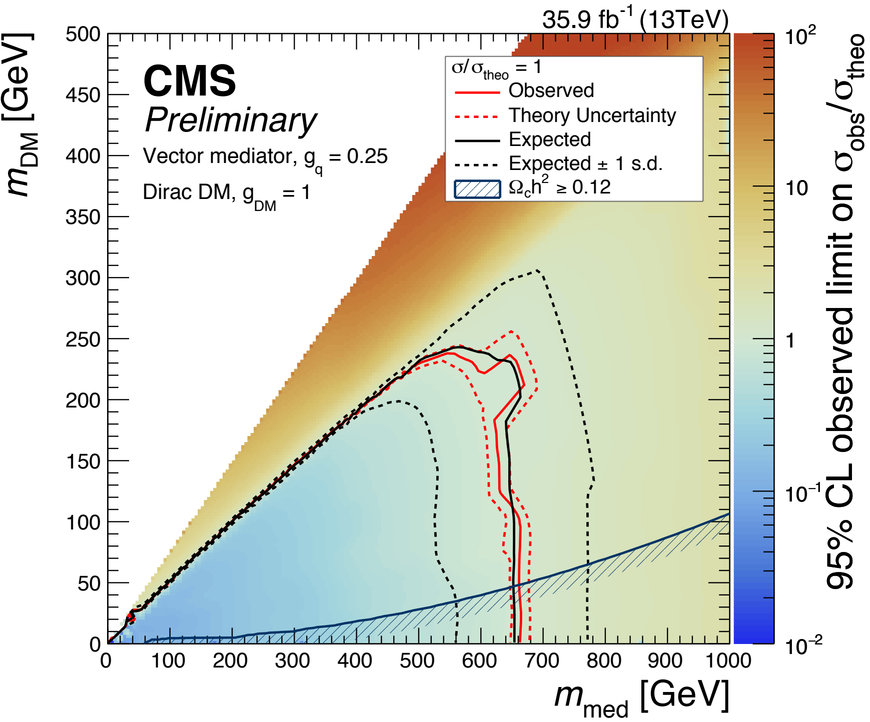
# $\ell\bar{\ell}+E_T^{miss}$

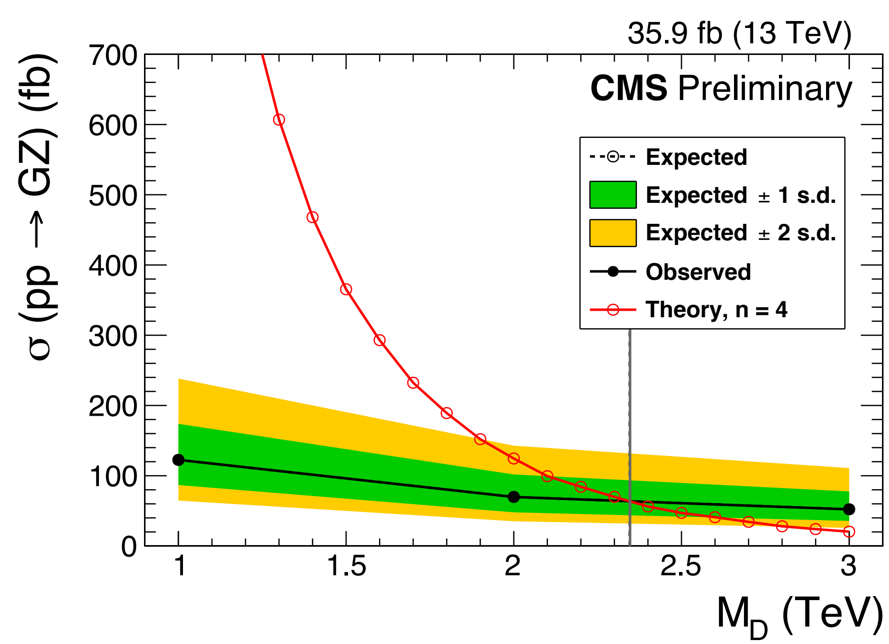


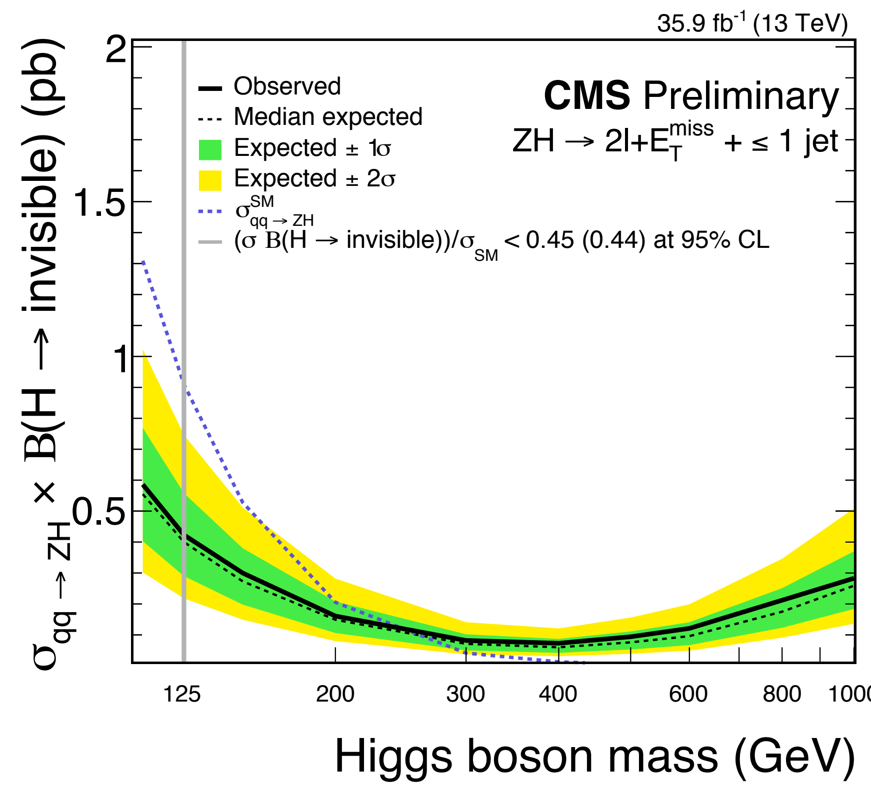
- Classification of events with multivariate technique
  - Enhances sensitivity of the analysis
  - Signal emulated with $q\bar{q}$ and $gg$ $H$ invisible process




- Extraction from yield analysis in the $E_T^{miss}$ spectrum
  - Dark matter: limits on vector and axial-vector with $g_{DM}=1$, $g_q=0.25$ and $g_q=1$
  - Extra dimensions: limits on the number of dimensions and graviton masses
  - Invisible decays: limits on $\sigma_{ZH}\times BR(H\rightarrow$ inv.)
    - ✦ under $m_H$=125 GeV, shape analysis



# Conclusions

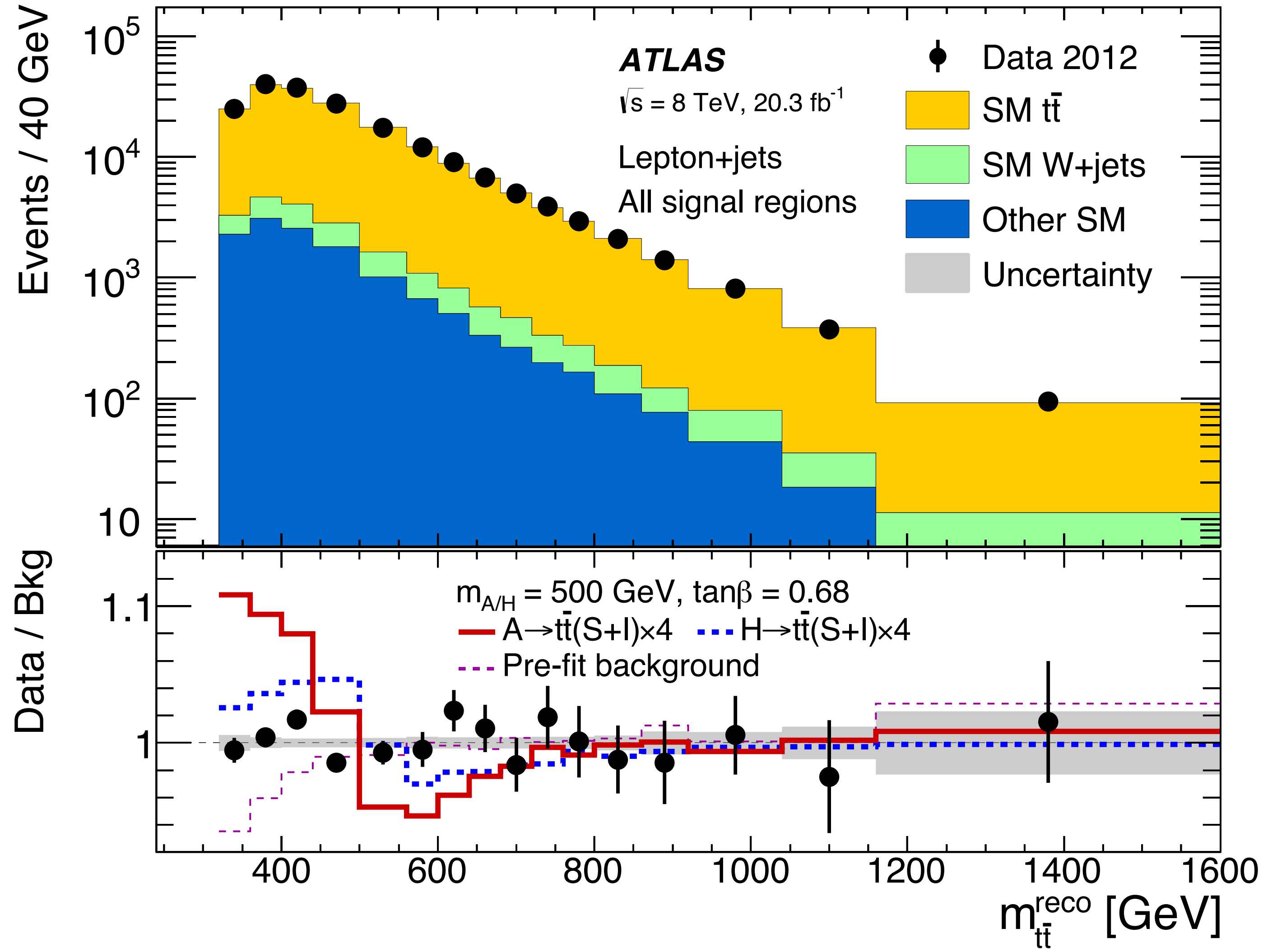
# Conclusion

- ATLAS and CMS have good sensitivity to standard models extensions
  - In particular BSM physics in the Higgs sector
- Searches for new phenomena a involving heavy neutral scalar production
  - Decaying into quarks, leptons and bosons ($Z$)
- Carried novel experimental techniques to constrain the background.

- Only a selection shown here, more results and details:
  - CMS results
  - ATLAS results

# Additional material

- Analysis in the lepton ($\ell$) plus jets ($j$) final state
  - One lepton ($e$ or $\mu$) with $p_T(\ell) > 25$ GeV.
  - At least four anti-$k_T$(4) jets with $p_T(j) > 25$ GeV.
  - $E_T^{miss} > 20$ GeV and $E_T^{miss} + m_T^W > 60$ GeV.




- Considering only resolved kinematics
  - Most efficient strategy for $m_{A/H} < 800$ GeV
- Event classification into six categories
  - Kinematic $\chi^2$ for jet association to $W$
- $W$+jets and Multijet contributions estimated from data.
- Leading uncertainties
  - Jet modelling ~6% on $B$ and ~9% on $S+I$
  - $t\bar{t}$ modelling ~7% ($m_t$ and pdf)

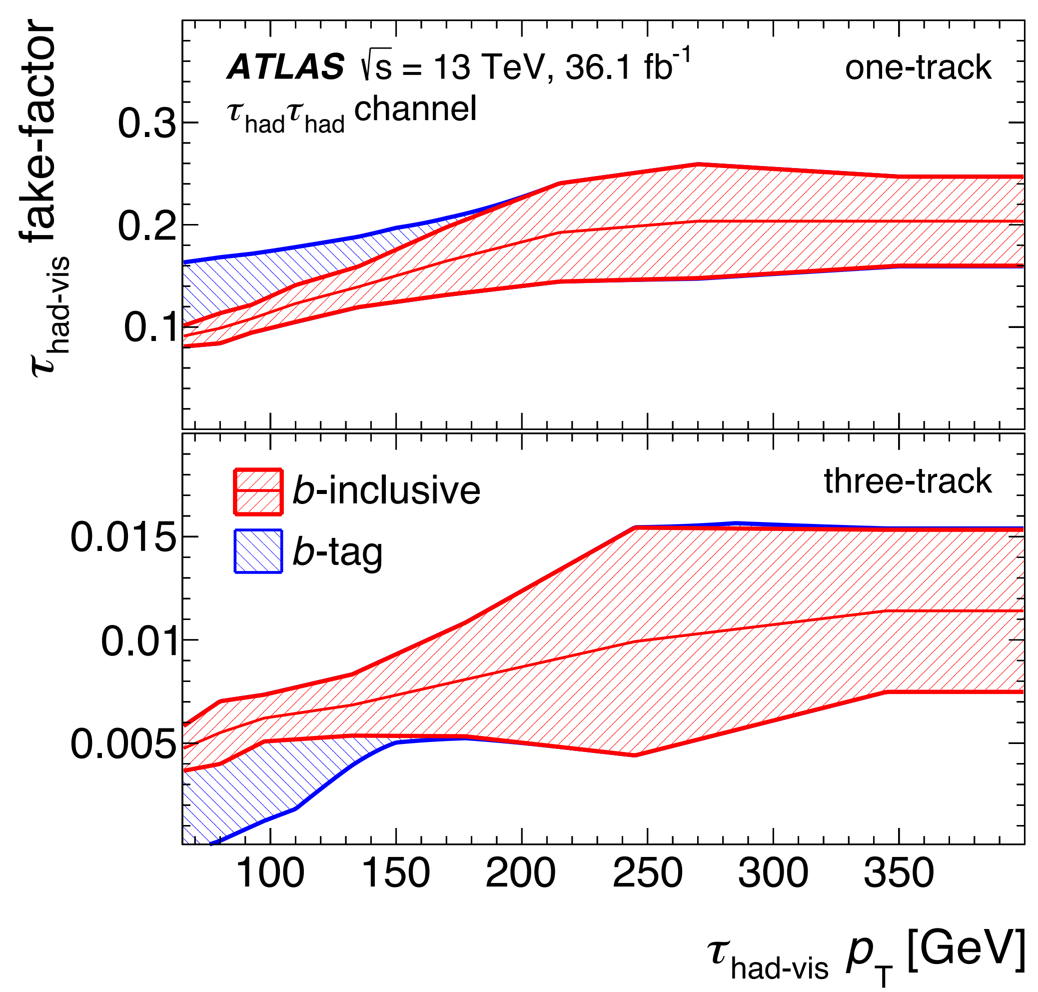
- $\tau$ reconstruction and event selection
  - Two $\tau$ decay modes are considered:
    - All hadronic final state ($\tau_{had}\tau_{had}$).
    - Semileptonic final state ($\tau_{lep}\tau_{had}$).

| $\tau_{lep}\tau_{had}$ | $\tau_{had}\tau_{had}$ |
|---|---|
| One $\tau_{had}$ with $p_T$ >25 GeV<br>$\lvert\Delta\varphi(\ell, \tau_{had})\rvert > 2.4$ rad<br>$m_T(\ell, E_T^{miss}) < 40$ GeV | At least two $\tau_{had}$ with $p_T$ >65 GeV<br>$\lvert\Delta\varphi(\tau_{had}, \tau_{had})\rvert > 2.7$ rad |

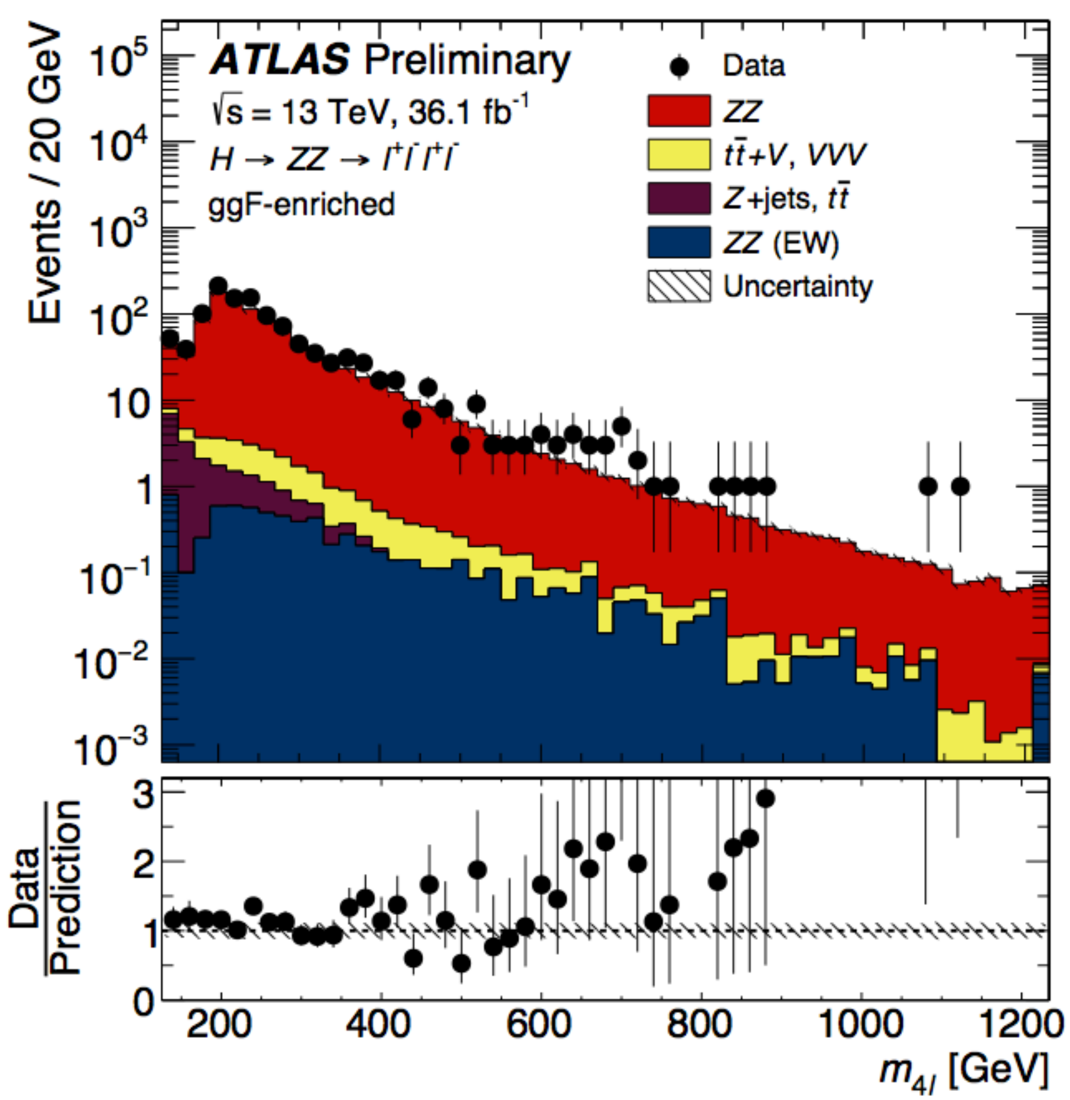
- Dominant backgrounds estimated from data
  - Estimate rates of jets faking taus by inverting identification criteria

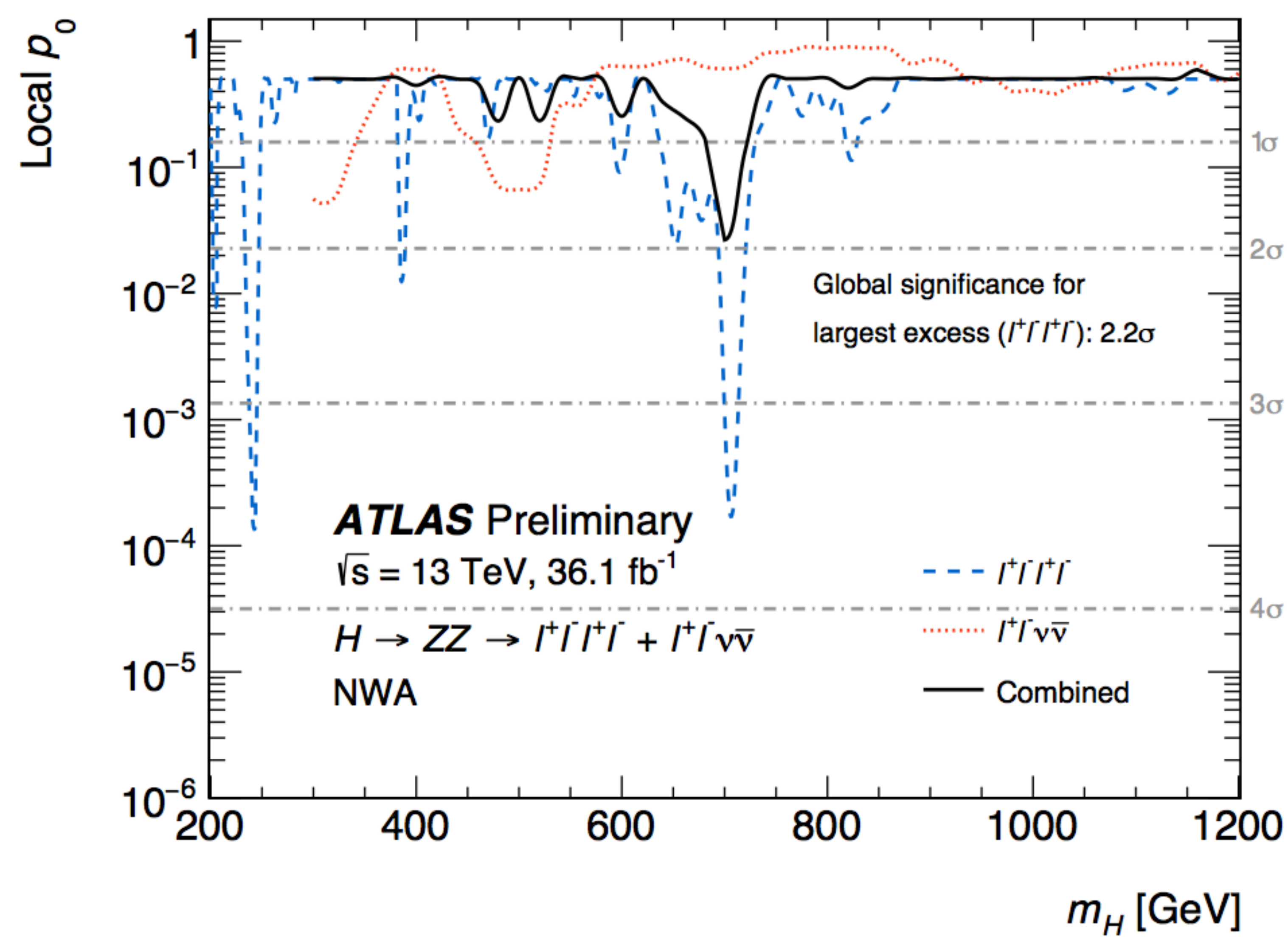
$$f(\mathbf{x}) \equiv \frac{N^{\text{pass}}_{\text{data}}(\mathbf{x}) - N^{\text{pass}}_{\text{bkg}}(\mathbf{x})}{N^{\text{fail}}_{\text{data}}(\mathbf{x}) - N^{\text{fail}}_{\text{bkg}}(\mathbf{x})}$$

  - from regions in data enhancing the Mulitjet background, $t\bar{t}$ and $W$+jets



- Local $p_0$ scan.
  - Largest excess at 2.2 σ

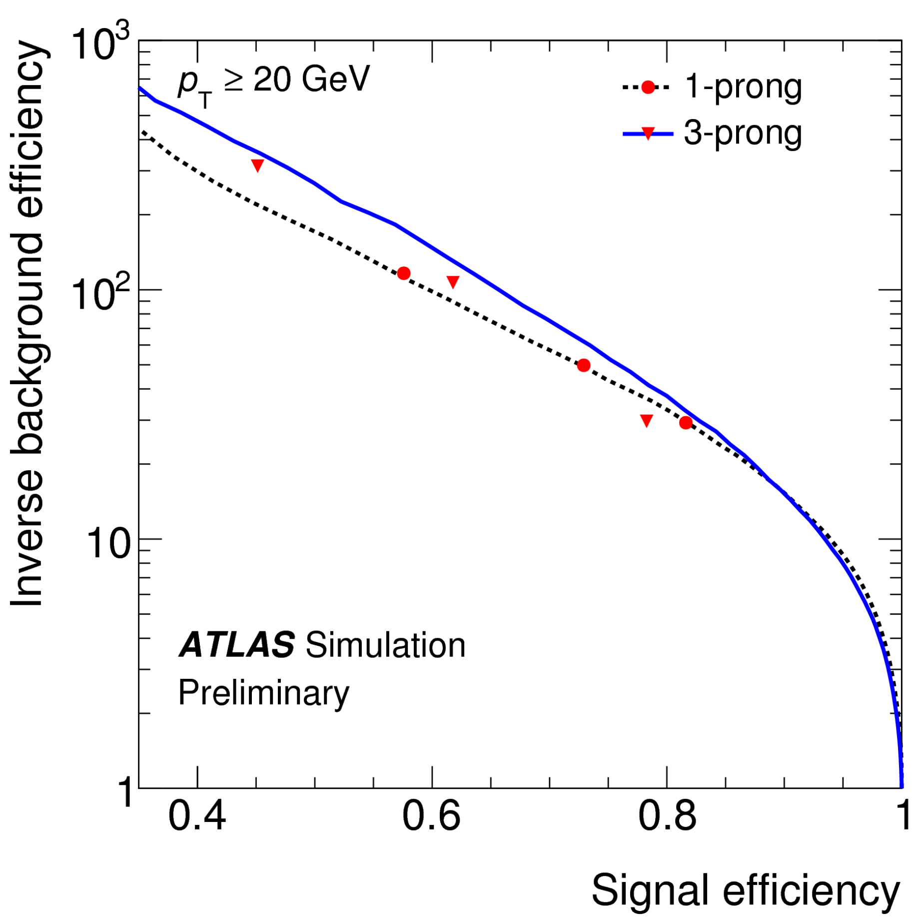


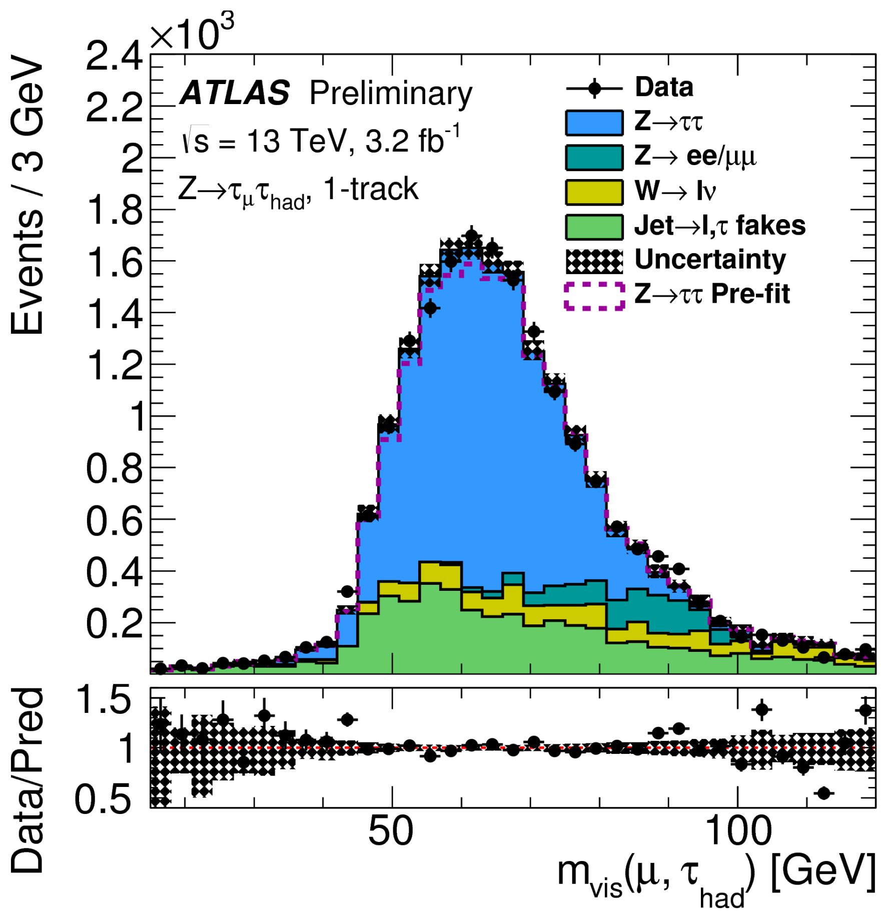



- τ reconstruction and event selection

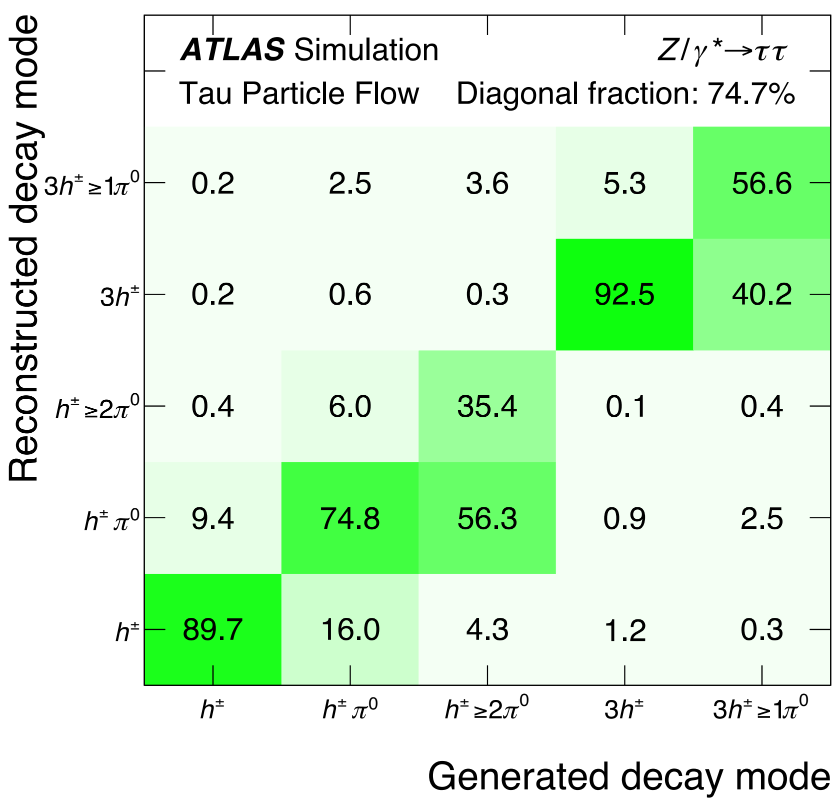
| $\tau_{lep}\tau_{had}$ | $\tau_{had}\tau_{had}$ |
|---|---|
| One $\tau_{had}$ with $p_T$ >25 GeV<br>$\lvert\Delta\varphi(\ell, \tau_{had})\rvert > 2.4$ rad<br>$m_T(\ell, E_T^{miss}) < 40$ GeV | At least two $\tau_{had}$ with $p_T$ >65 GeV<br>$\lvert\Delta\varphi(\tau_{had}, \tau_{had})\rvert > 2.7$ rad |

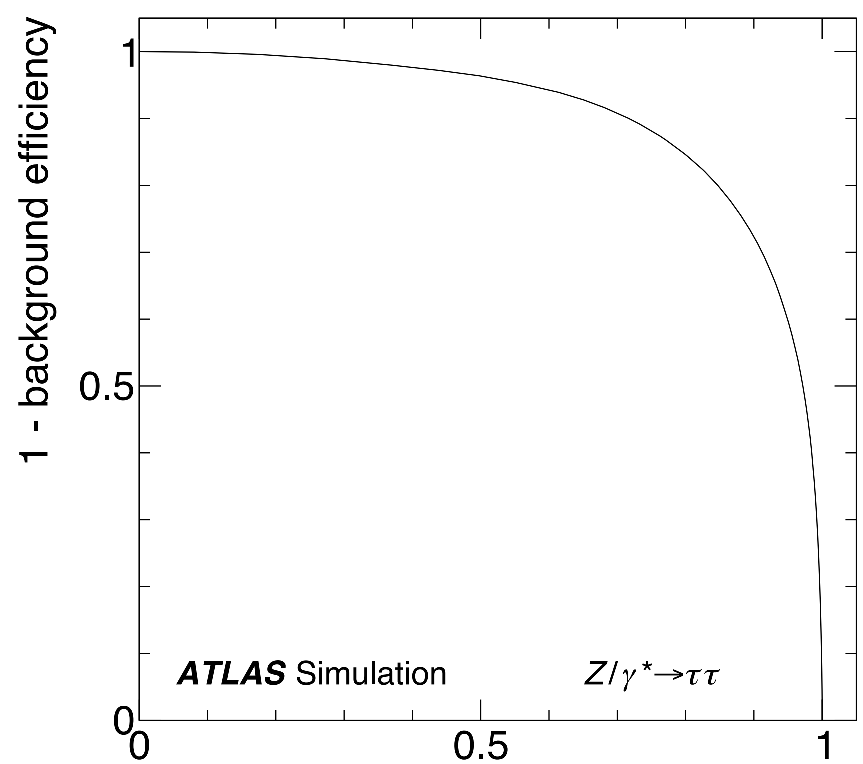
- Hadronic τ decays: one or more charged particles, a neutrino and $\pi^0$
- Visible decay products identification based on multivariate technique
- 50% to 60% identification efficiencies measured on $Z \rightarrow \tau\tau$

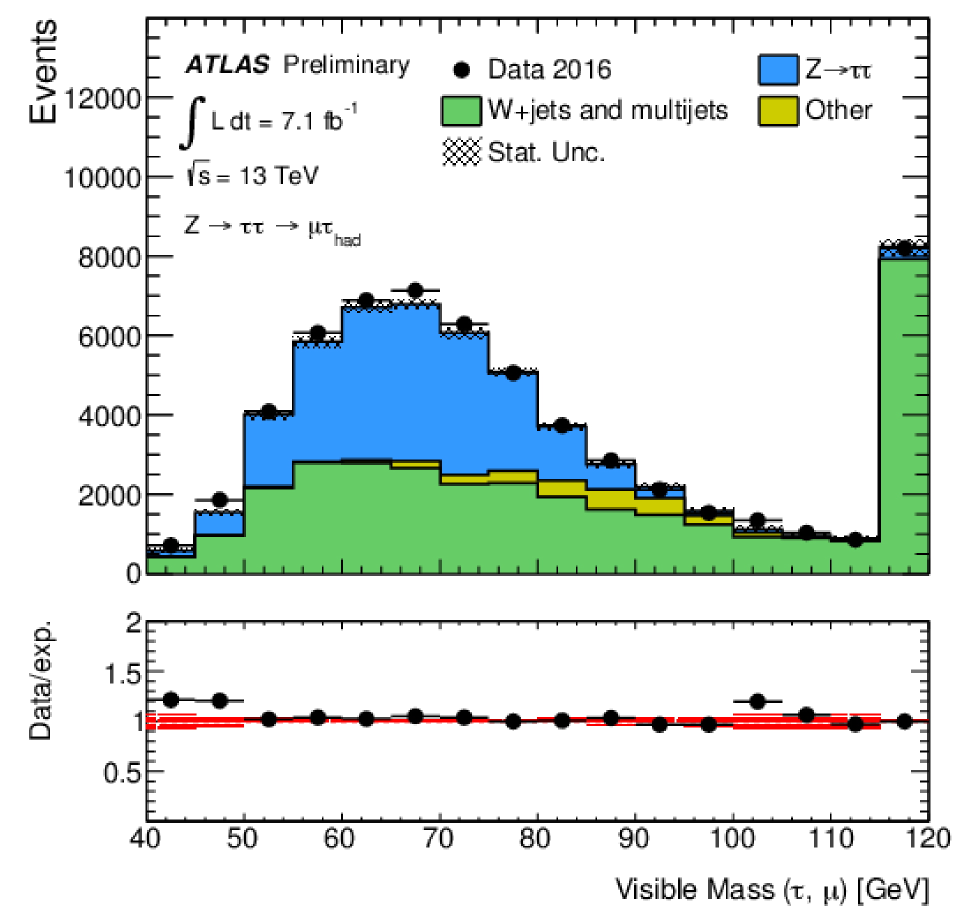


- Hadronic tau decays: one or more charged particles, a neutrino and $\pi^0$
- Visible decay products ID based on multivariate technique
  - Rejection of jets faking a tau lepton.
    - Shower shapes and track multiplicities.
  - 50% to 60% identification efficiencies measured on $Z \to \tau\tau$

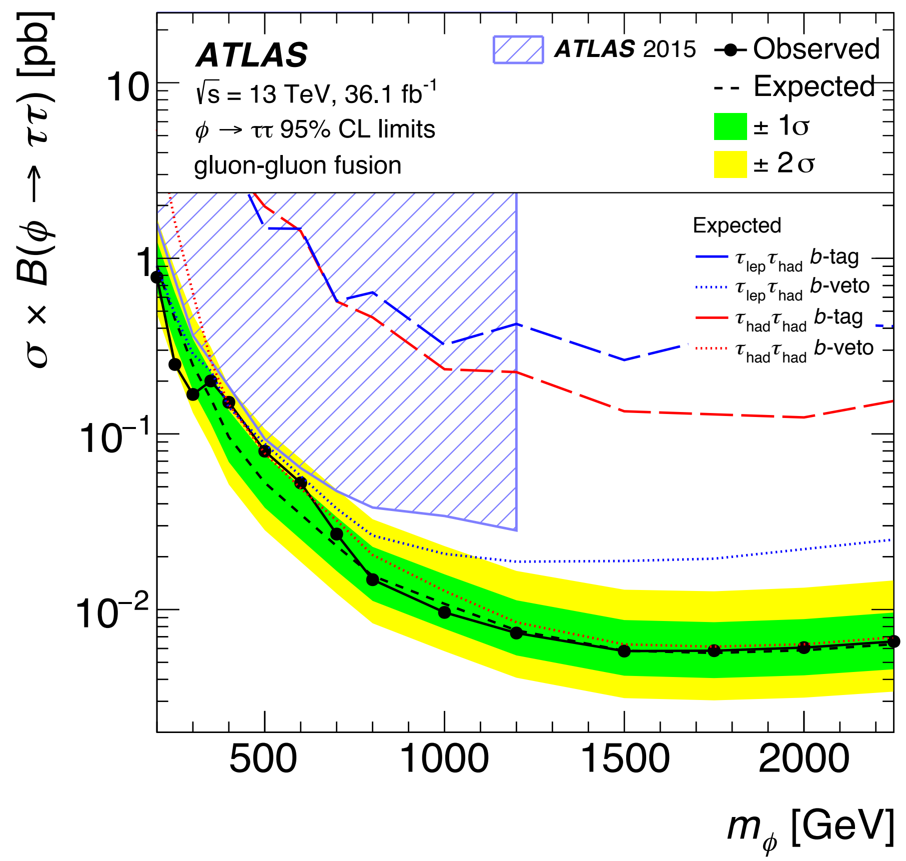


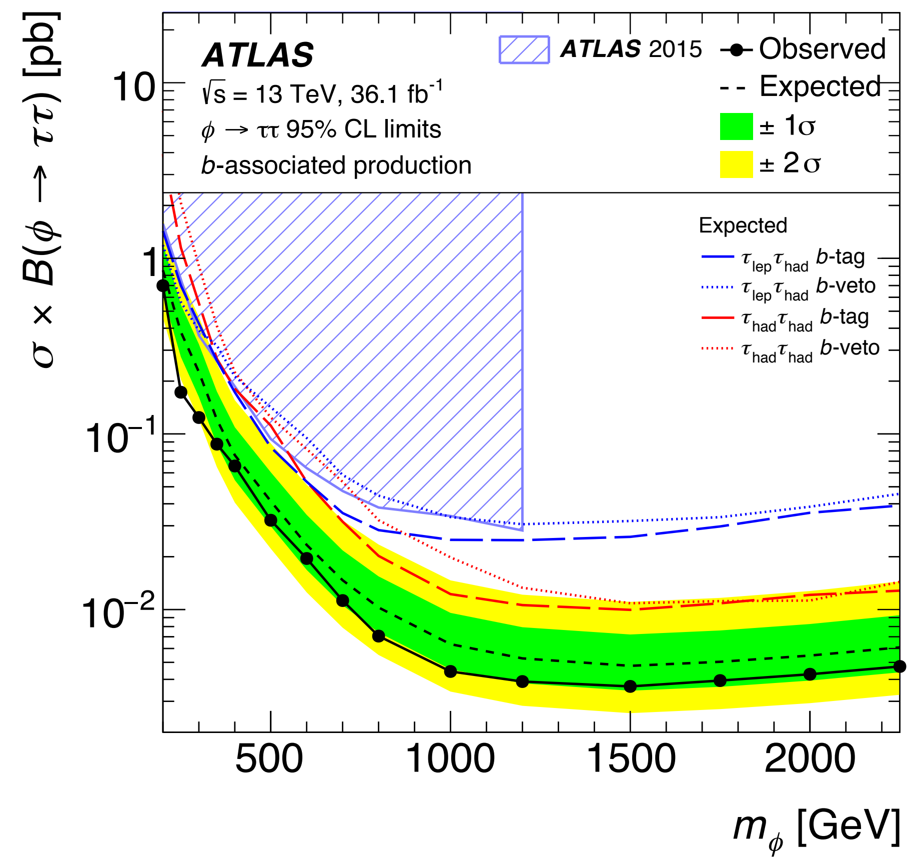



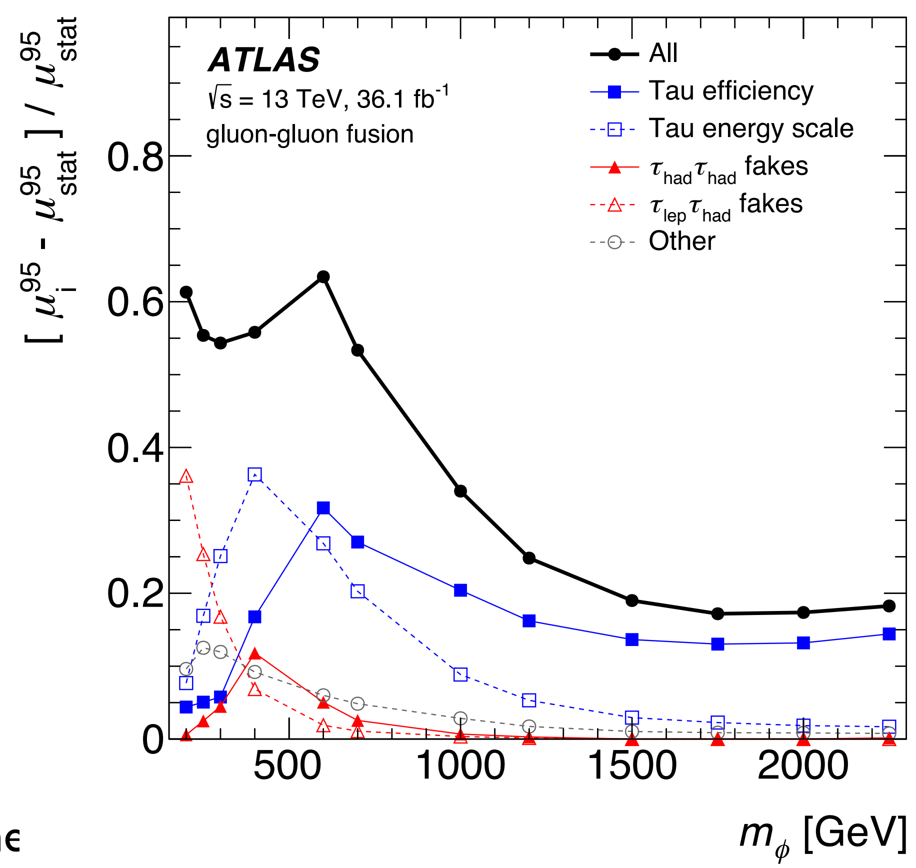



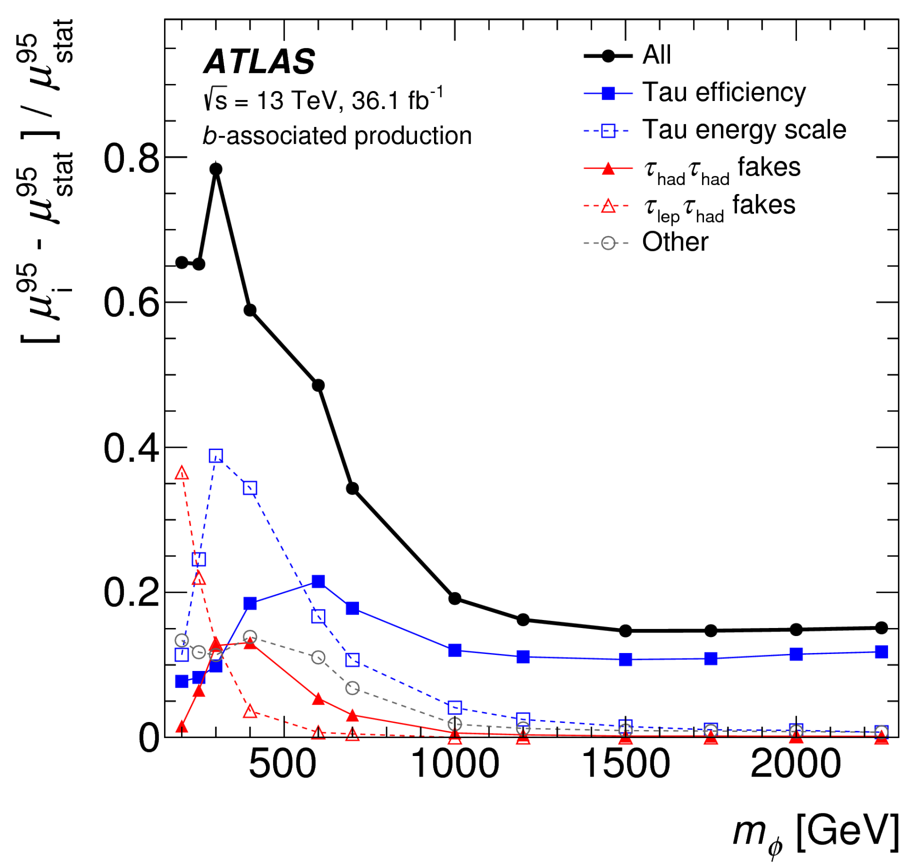

- In $\tau$ leptonic decays $E_T^{miss}$ stringent requirements

- Results from profile likelihood fit on transverse mass $m_T^{tot}$



# h→ BSM

- Combined run I limit on h→ BSM