BSM Higgs searches in ATLAS

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for the ATLAS Collaboration

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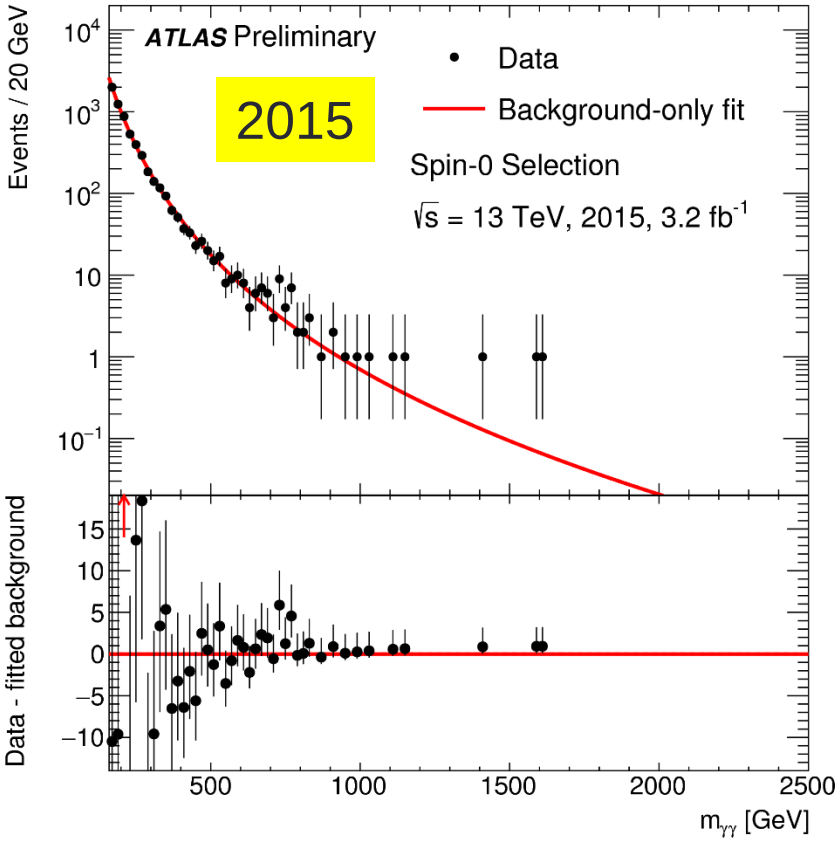
Beyond Standard Model Higgs

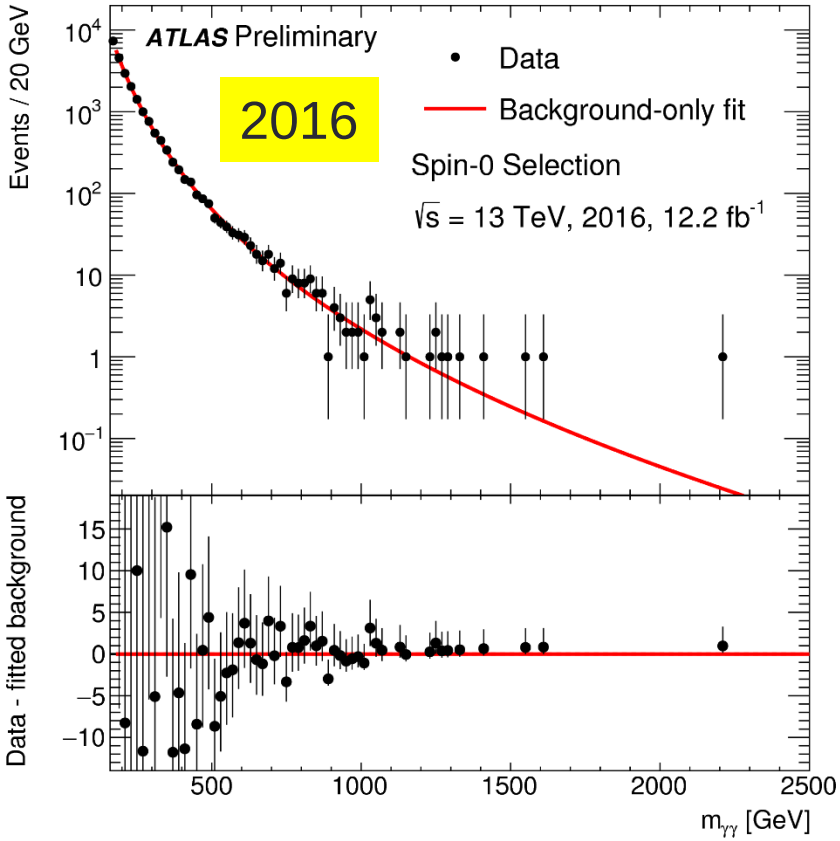
- New heavy scalar particle
  - $\gamma\gamma,\ Z\gamma,\ ZZ,\ WW, ZV$ channels in various subsequent decay modes
- Two Higgs doublet model (2HDM)
  - Five Higgs bosons ($h, H, A, H^{\pm}$)
  - Charged Higgs
  - $H/A \rightarrow \tau\tau$
  - $H \rightarrow hh$
  - Minimal Supersymmetric Standard Model (MSSM)
    - Similar to 2HDM plus superpartners of SM particles
- Dark matter candidate
  - Associated production of dark matter candidate and Higgs boson
- Most of the results shown are based on 2016 data

$H \to \gamma\gamma$

ATLAS-CONF-2016-059

- Two isolated photons
  - $E_T^{\gamma} > 40, 30$ GeV for leading and 2nd leading photons
- An excess of events at $m_{\gamma\gamma}$~730 GeV was observed at the end of 2015
- However, no such excess was observed with more data





$H \to \gamma\gamma$

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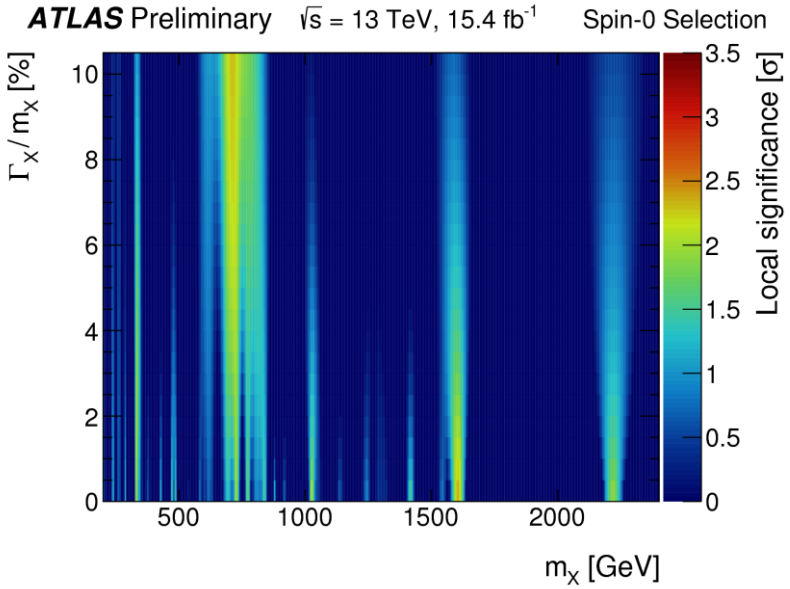
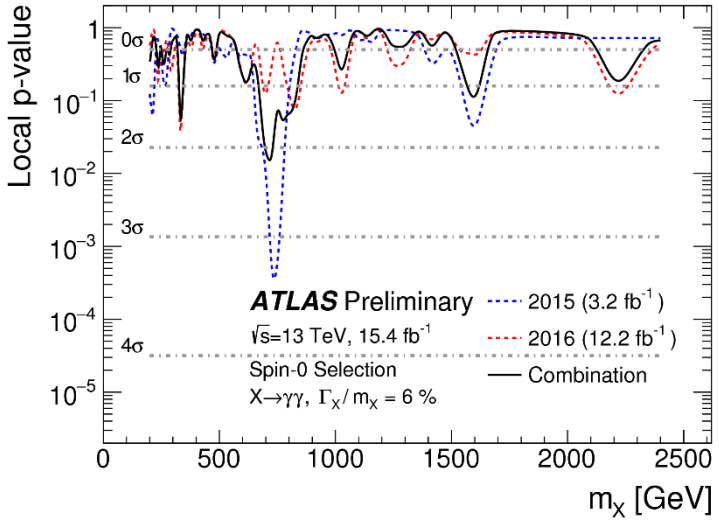




2015 analysis

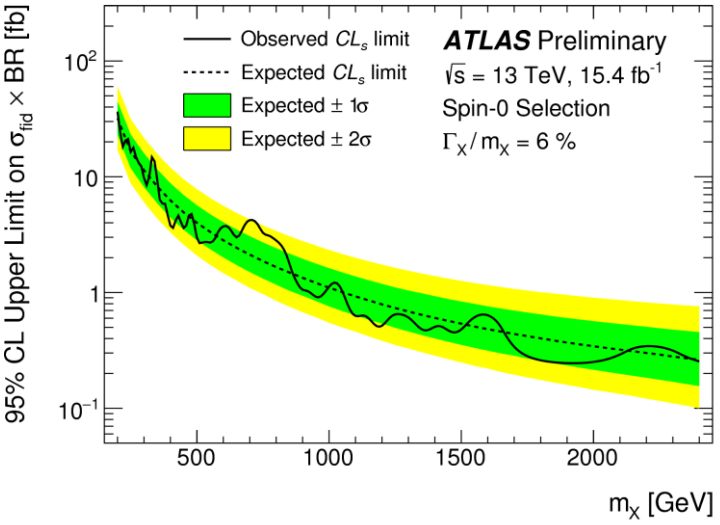
- $m_{\gamma\gamma} = 750$ GeV, $\Gamma/m = 6$ %, 3.9σ

After analysis improvement (calibration, photon conversion)

- $m_{\gamma\gamma} = 730$ GeV, $\Gamma/m = 8$ %, 3.4σ

Combination of 2015 and 2016 results

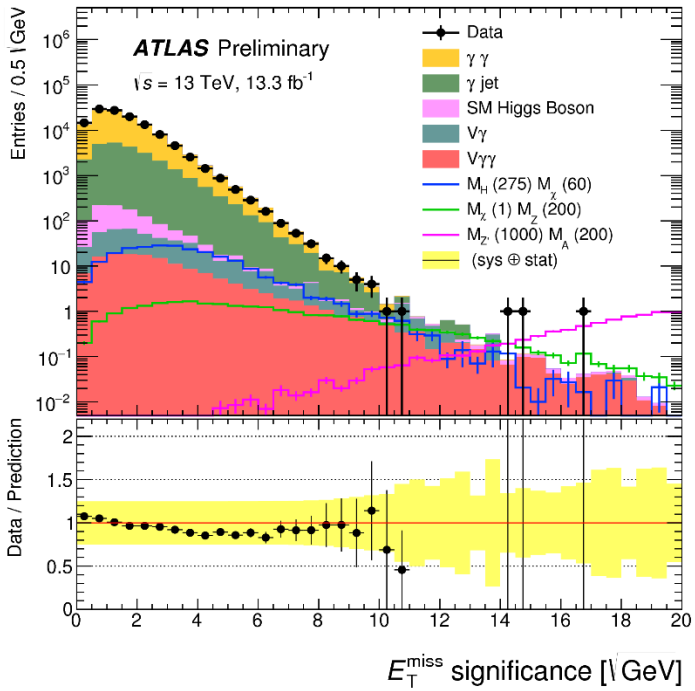
- Largest deviation with 2.3σ excess at 710 GeV with $\Gamma/m = 10$ %

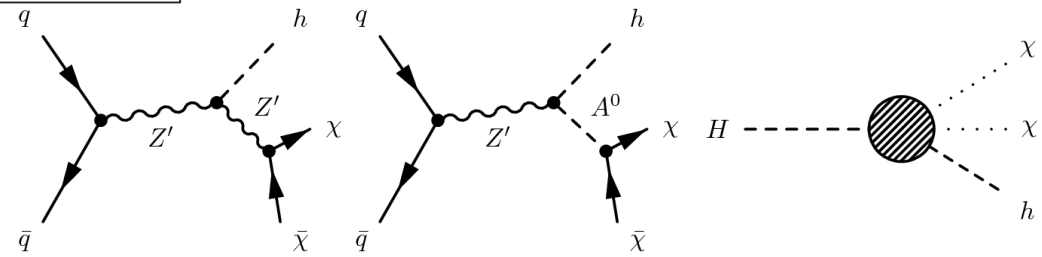


$\gamma\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$ final state

Event selection
- 2 photons with $p_T > 25$ GeV
- $E_T^{\gamma}/m_{\gamma\gamma} > 0.35, 0.25$ for leading/sub-leading photons
- $105 < m_{\gamma\gamma} < 160$ GeV
- 4 categories based on $E_{\mathrm{T}}^{\mathrm{miss}}$ significance and $p_T^{\gamma\gamma}$

Dark matter models
- Z' mediator coupling to dark matter fermion and SM Higgs
- Heavy scalar particle decaying into Higgs and a pair of dark matter candidates



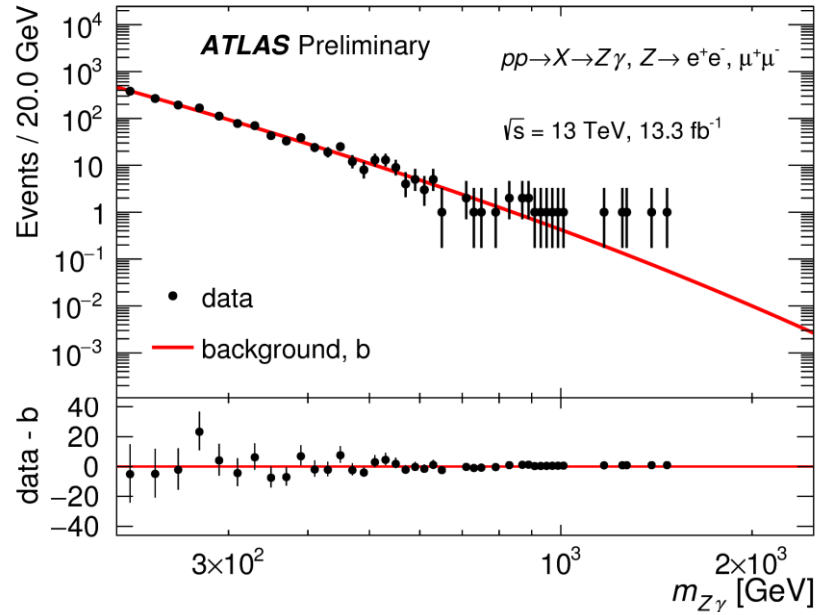


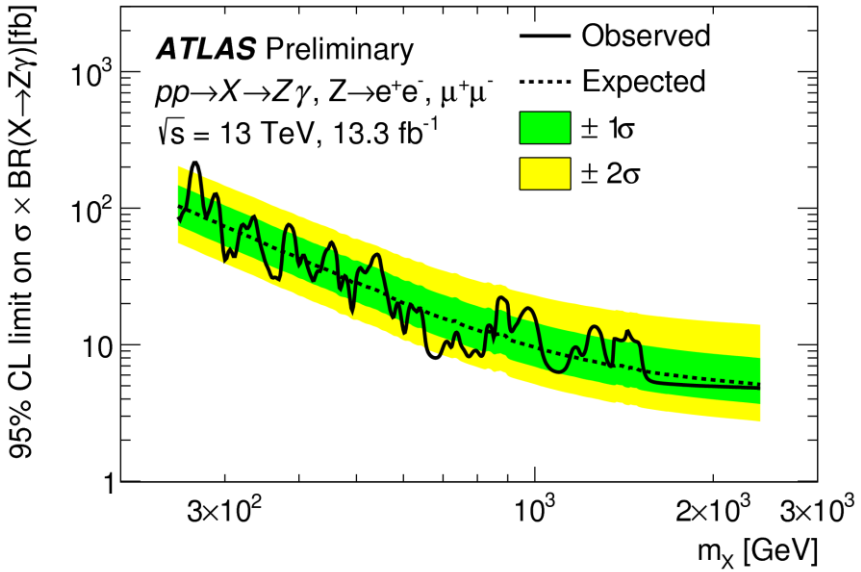
Upper limits on $\sigma \cdot BR$
- $m_{Z'} = 10$ GeV, $m_{\chi} = 1$ GeV: 2.87 fb
- $m_{Z'} = 2000$ GeV, $m_{\chi} = 1$ GeV: 0.87 fb
- $m_H = 260$ GeV, $m_{\chi} = 50$ GeV: 18.2 fb

$H \to Z\gamma$

ATLAS-CONF-2016-044

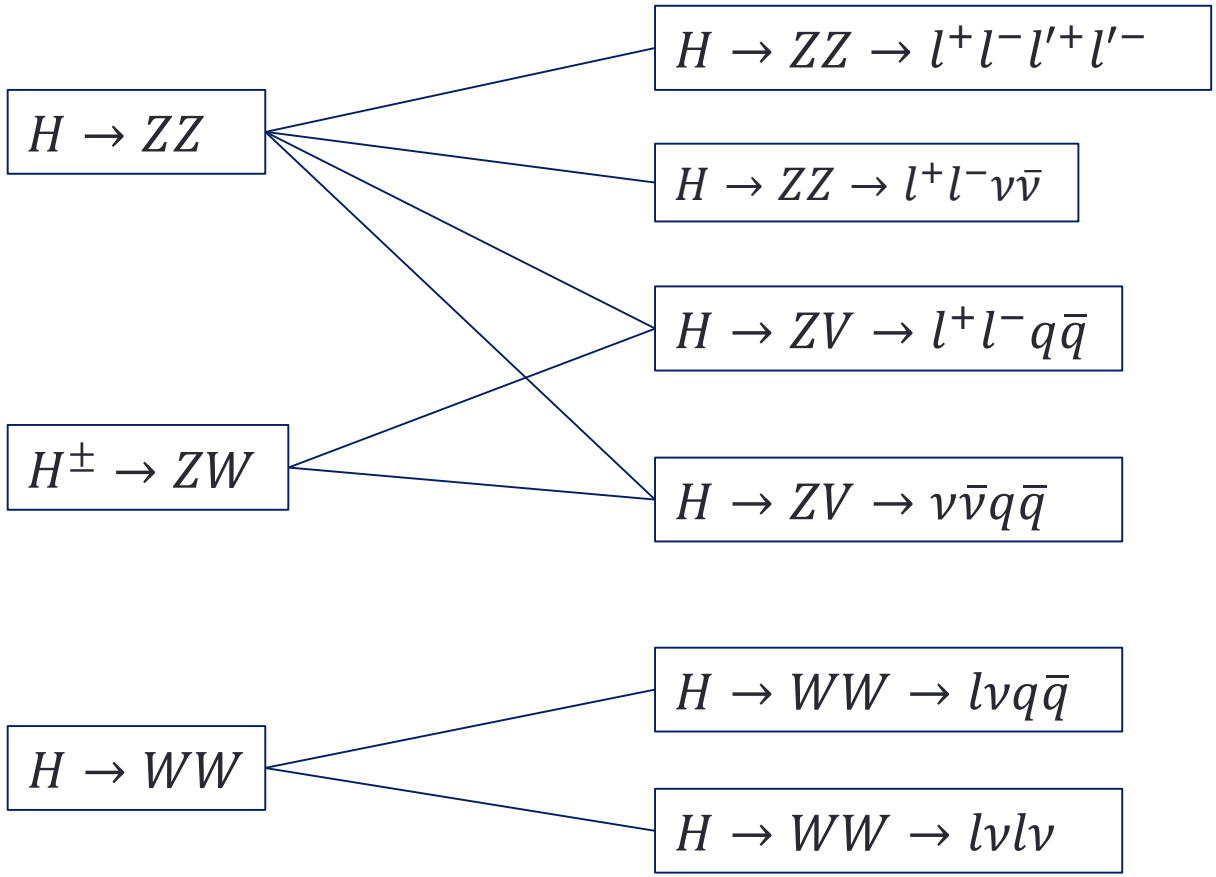
- $H \to Z\gamma \to l^+l^-\gamma$
- Many extensions of the SM Higgs sector introduces new massive bosons which may decay to SM gauge bosons
- The decay occurs in the Standard Model via top or W loop
  - BR(SM)=1.54×10^{-3}
- Measurement using leptons and photon is experimentally very clean
  - Analysis with hadronic Z decay with 3.2 fb-1 has also been performed (arXiv:1607.06363)
- No significant excess is observed in the mass range 250 – 2.4 TeV
- Upper limits on $\sigma \cdot BR$ range from 215 fb to 5 fb in the mass range between 250 GeV and 2.4 TeV





$H \to VV$

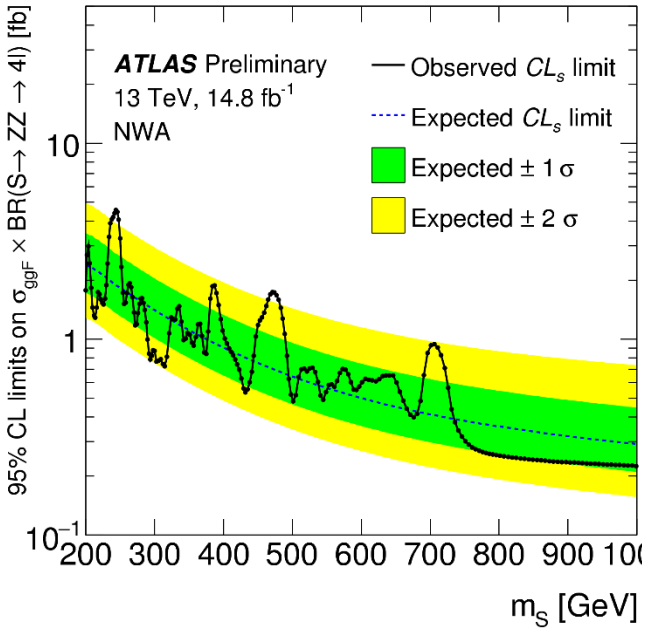
- Various final states are possible in decay modes with two massive gauge bosons

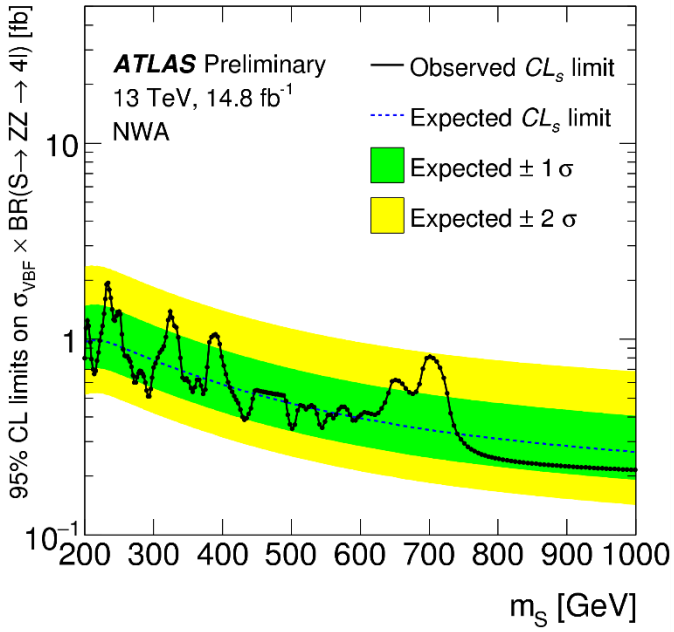


$H \to ZZ \to 4l$

ATLAS-CONF-2016-079

- High mass resonance search in $m_{4l} > 140$ GeV
- Event categories
  - VBF (vector boson fusion):
    - More than 2 jets with $m_{jj} > 400$ GeV, $|\Delta\eta_{jj}| > 3.3$
  - ggF (gluon-gluon fusion):
    - Events which fail the VBF criteria



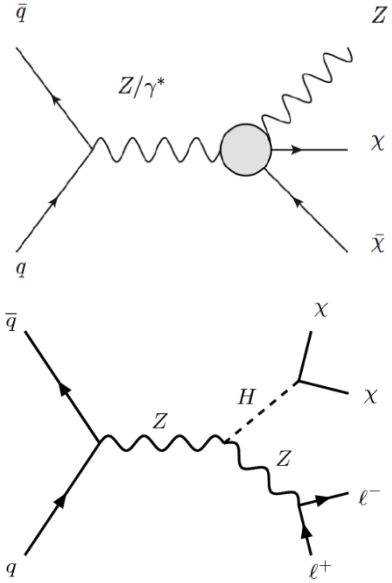


- Narrow width approximation
- Also used a larger width Γ/m =1, 5 and 10%
- No significant excess is observed

$l^+l^- + E_{\mathrm{T}}^{\mathrm{miss}}$ final state

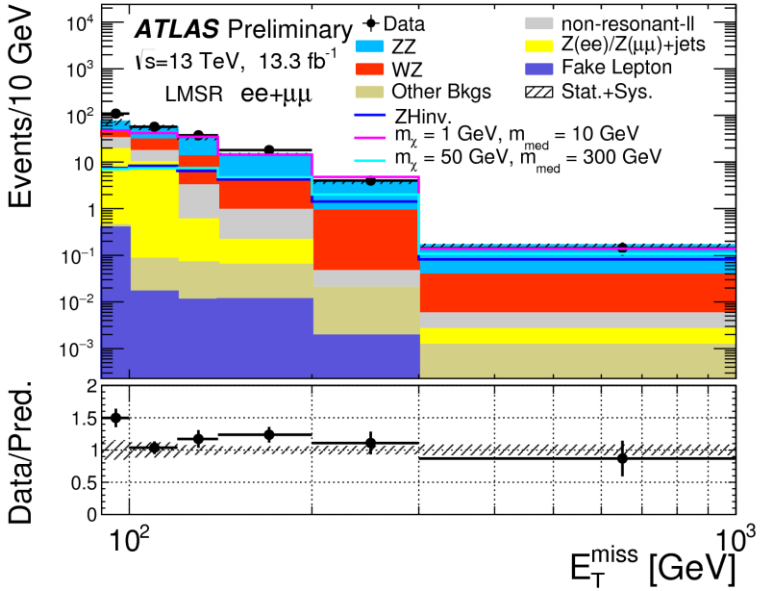
ATLAS-CONF-2016-056

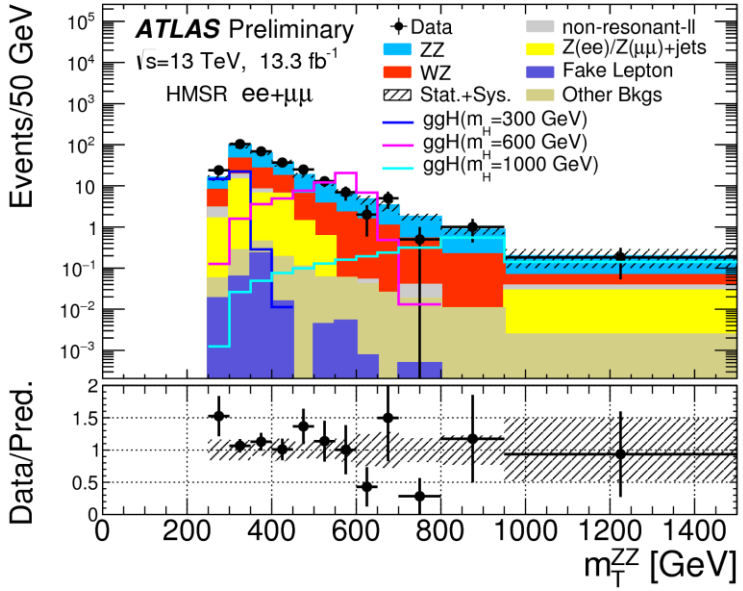
Several processes may produce this final state
- $H \to ZZ \to l^+l^-\nu\bar{\nu}$
- $Z + \chi \to l^+l^- + \chi$ (χ undetectable, mono-Z)
- $ZH \to l^+l^- + X$ (X undetectable, invisible Higgs)



Final discriminant:
- $E_{\mathrm{T}}^{\mathrm{miss}}$ in low-mass region
- m_T in the high-mass region

Backgrounds:
- ZZ, WZ and Z+jets





Results of $l^+l^- + E_{\mathrm{T}}^{\mathrm{miss}}$ channel

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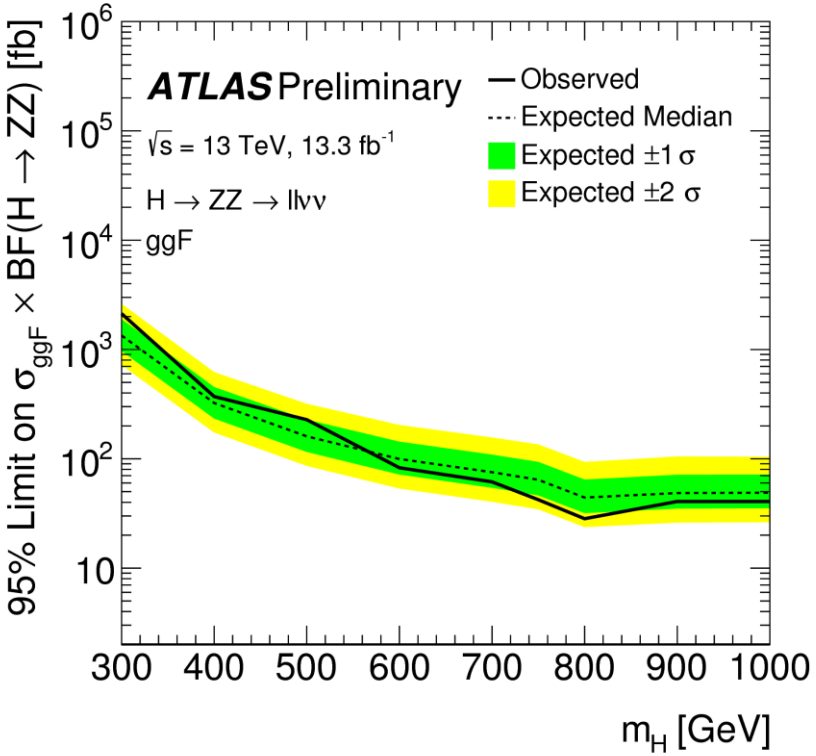
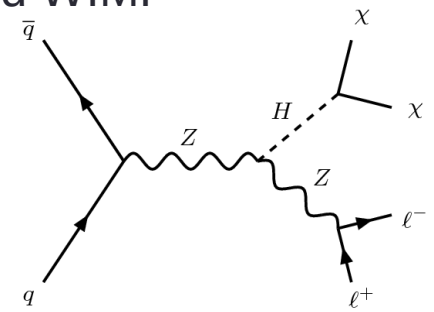
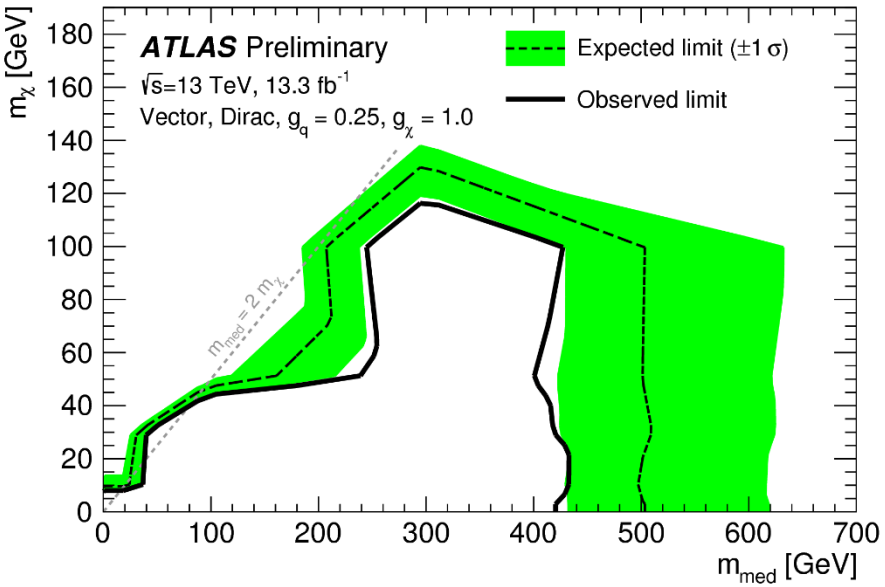


- Limit on dark matter candidate from mono-Z search
  - Vector mediator between SM particles and WIMP



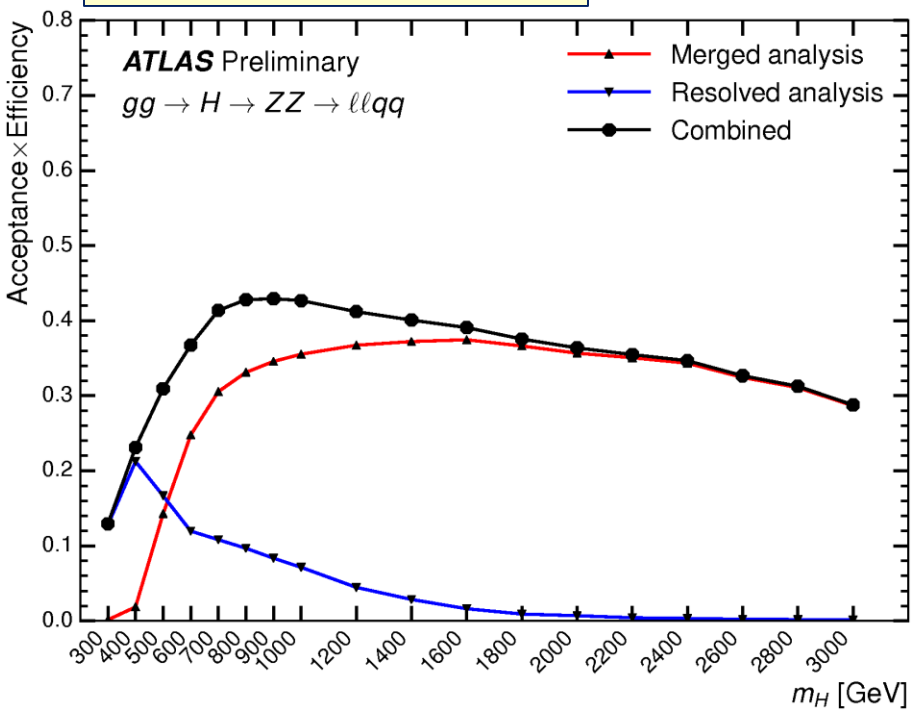


$\sigma\left(Z(\rightarrow ll)H(\rightarrow \text{invisible})\right) < 88$ fb at 95% CL

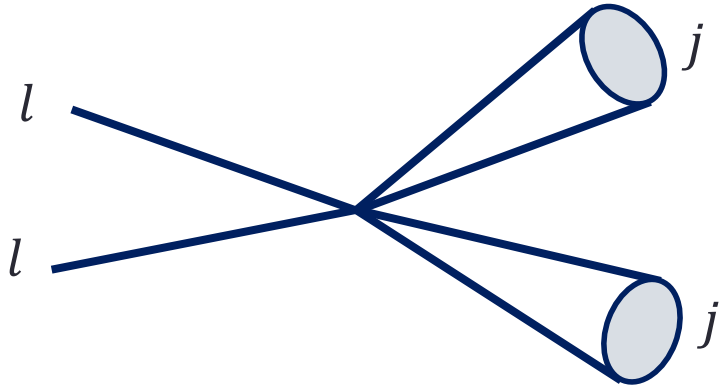
$H \to ZV \to llqq$

- A heavy object decaying into two vector bosons which further produces two jets
- Two analysis strategies for resolved and merged jets

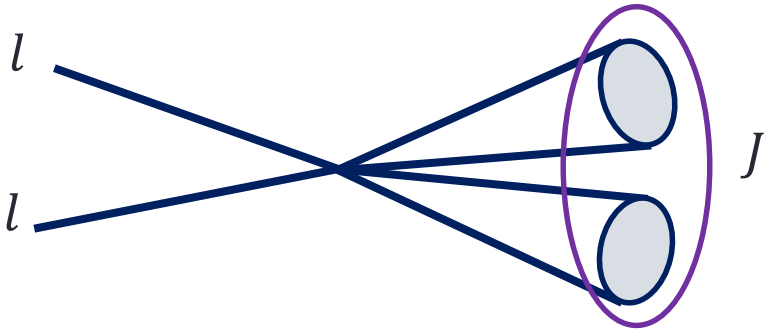
ATLAS-CONF-2016-082



Resolved analysis



Merged analysis



Large R (R=1) anti-k_T jet

$H \to ZV \to llqq$

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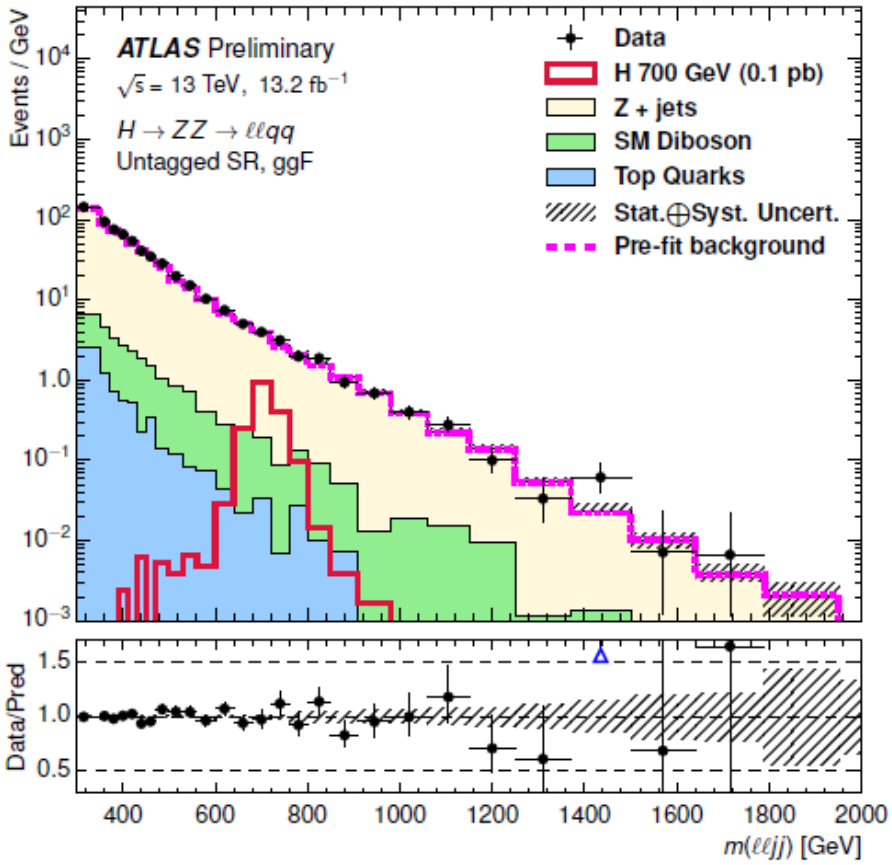
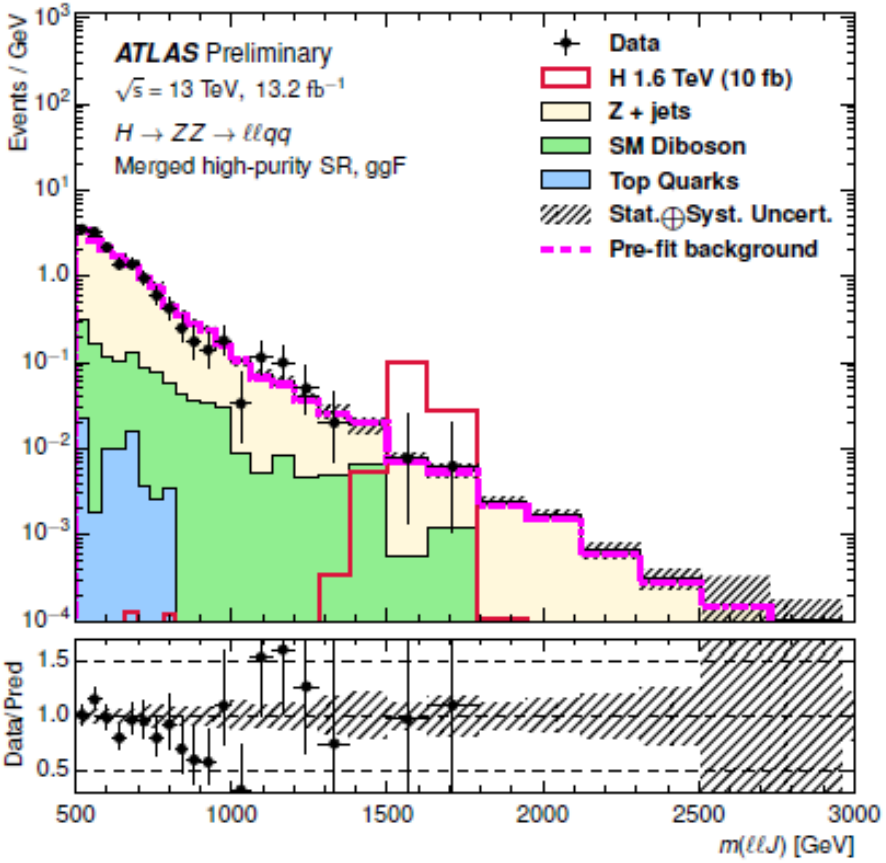
Resolved analysis



Merged analysis



Largest deviation is observed around 500 GeV in the resolved analysis
2.75σ (local) and 1.4σ (global)

$H \to ZV \to llqq$

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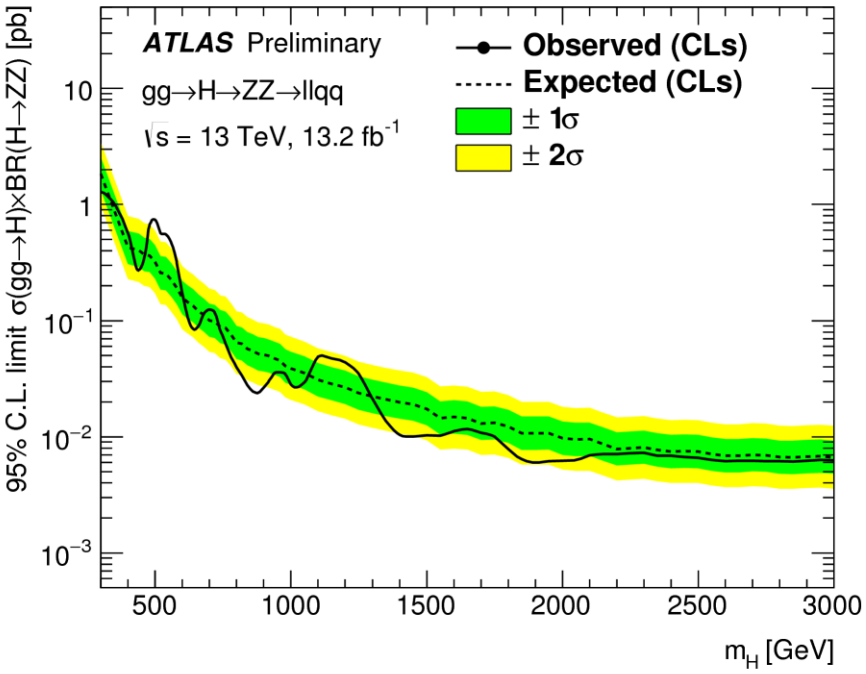
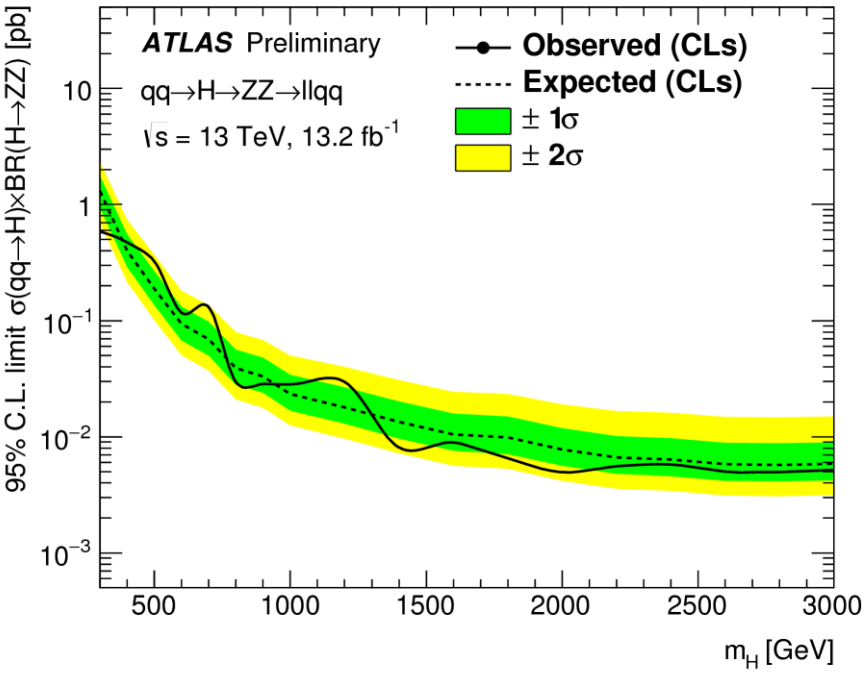
ggF



VBF



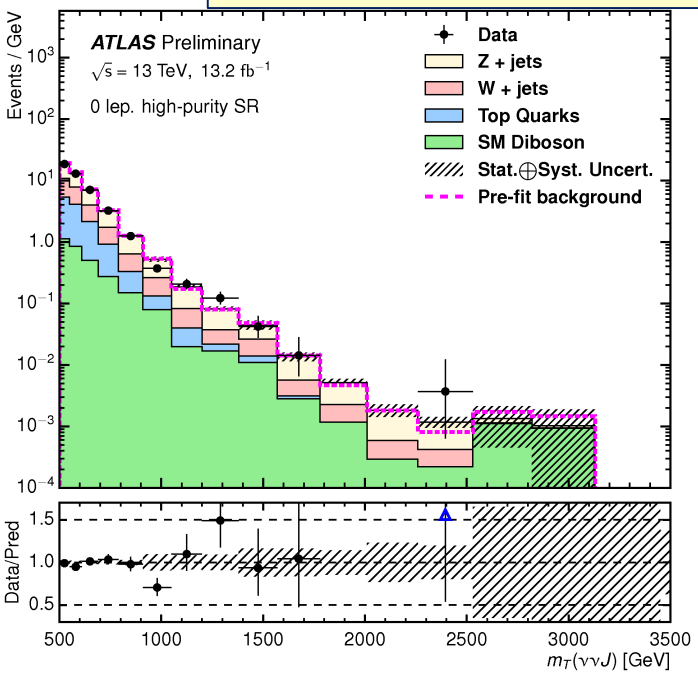
Upper limits on observed cross sections

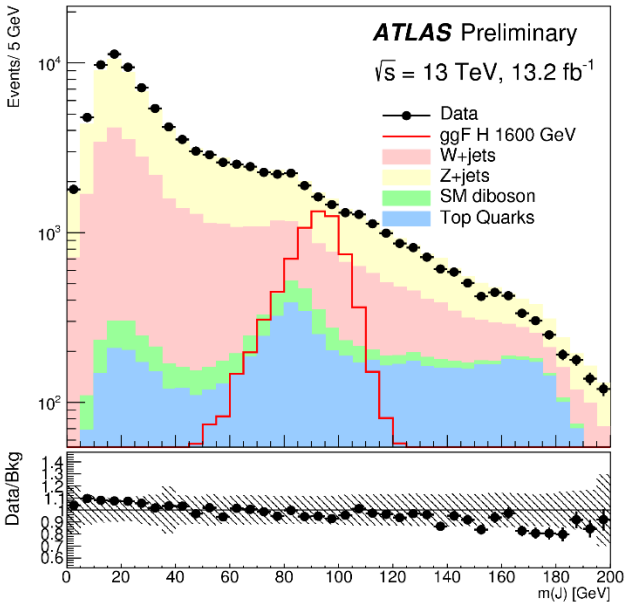
- ggF: $\sigma \cdot BR$ =1.28 pb – 6.2 fb in the mass range 300 – 3000 GeV
- VBF: $\sigma \cdot BR$ =0.6 pb - 5.2 fb in the mass range 300 – 3000 GeV

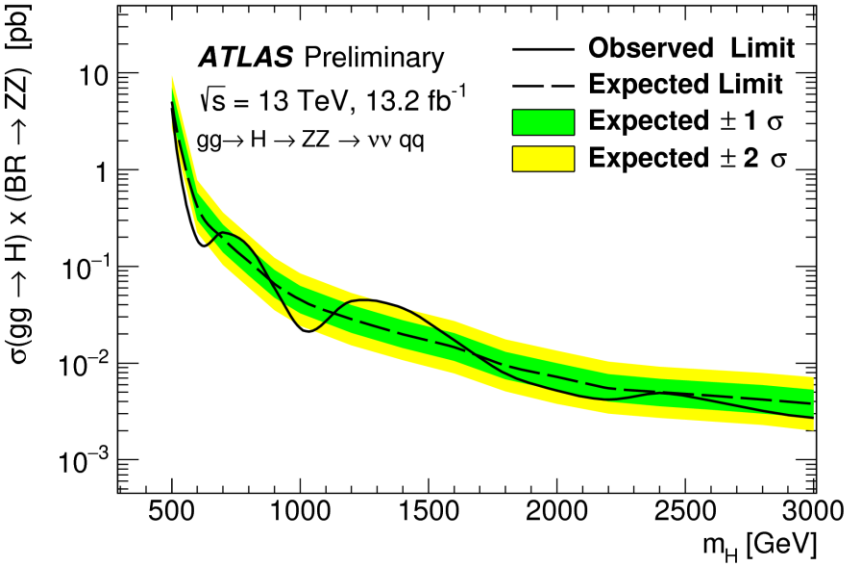
$H \to ZZ \to \nu\bar{\nu}q\bar{q}$

ATLAS-CONF-2016-082

- Require that qq system to be consistent with either W or Z
- $E_{\mathrm{T}}^{\mathrm{miss}}$>250 GeV
- Upper limit on $\sigma(gg \to H) \cdot BR(H \to ZZ)$ is given

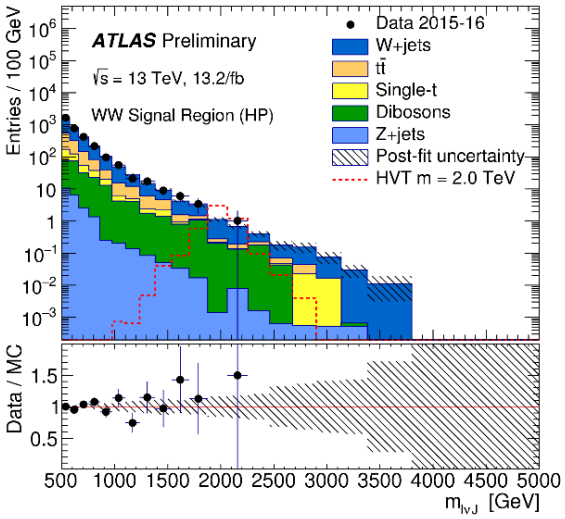


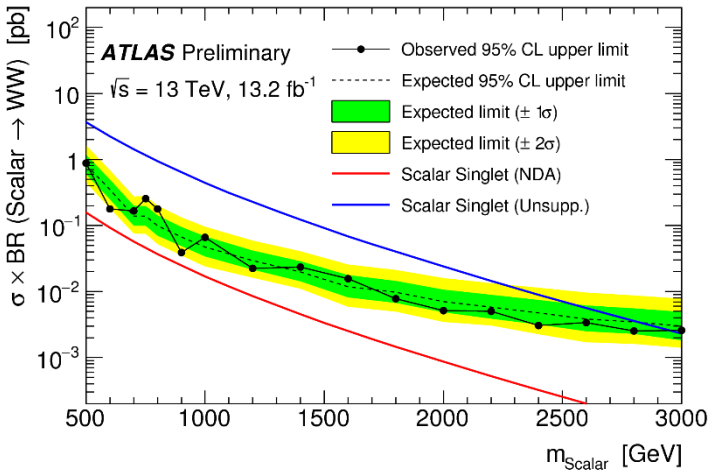




$H \to WW \to l\nu q\bar{q}$

ATLAS-CONF-2016-062





Event selection

- $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV, $p_T(l\nu) > 200$ GeV
- Large-R jet (J)
  - Selection for 2-prong sub-structure
    - high-purity and low-purity samples depending on the sub-structure
  - $p_T(J)/m_{l\nu J} > 0.5, p_T(l\nu)/m_{l\nu J} > 0.5$

Backgrounds

- Main backgrounds are W+jets and $t\bar{t}$
- Separate signal and background using N_b, m_J
  - $N_b \geq 1$ → $t\bar{t}$ and in W mass window
  - $N_b = 0$ and $50 < m_J < 68.2$ or $m_J > 108.4$ GeV → W control region

Exclusion limits

- masses below 2500 – 2810 (2400 - 2540) GeV for neutral (charged) scalar

$H \to WW \to l\nu l\nu$

Event selection
- Different flavor, opposite sign leptons ($p_{\mathrm{T}}^{l} > 25, 15$ GeV),
- $|\Delta\eta_{ll}| < 1.8$, $m_{ll} > 10$ GeV
- No b-jet

Backgrounds
- $t\bar{t}$: control region (CR) with b-jes
- WW: CR with reversed $\Delta\eta_{ll}$ cut

Event categories
- VBF1J (vector boson fusion):
  - $N_{jet}=1$, $m_{jj} > 400$ GeV, $|\eta_j| > 2.4$
- VBF1J (vector boson fusion):
  - $N_{jet} \geq 2$, $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 4$
- ggF (gluon-gluon fusion):
  - Events which fail the VBF criteria

ggF category

$$m_T = \sqrt{\left(E_T^{ll} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\vec{p}_T^{\,ll} + \vec{p}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

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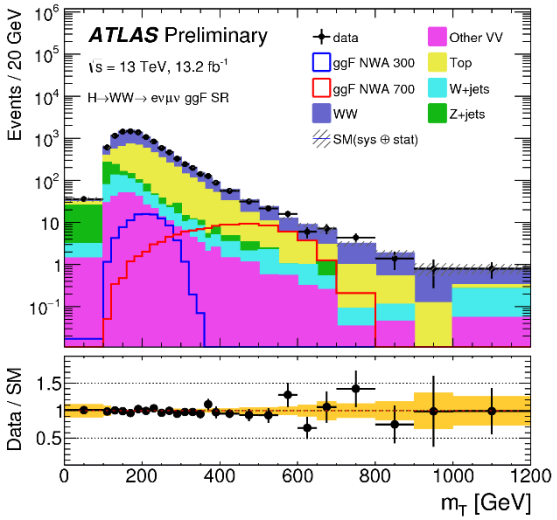
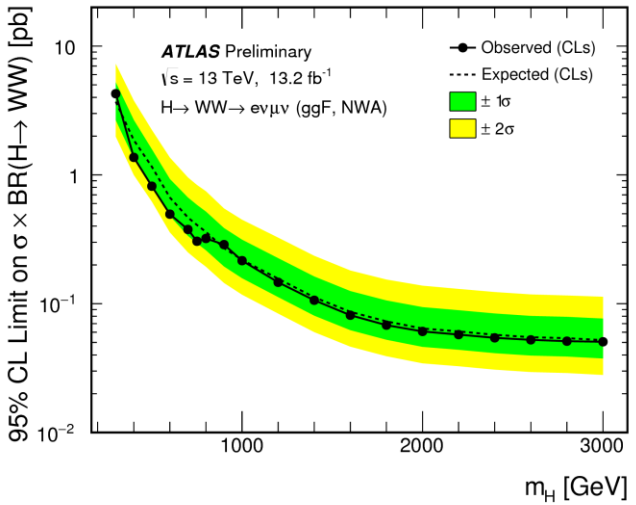




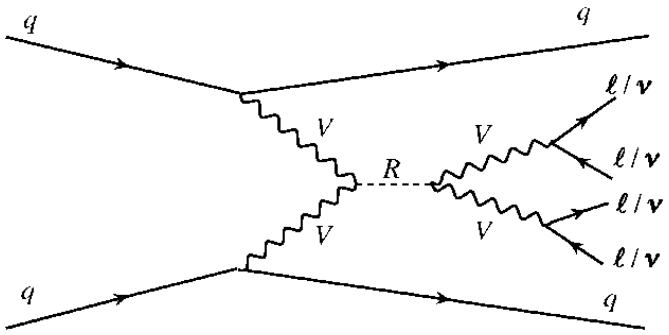
- No significant excess in the mass range 300 – 3000 GeV
- $\sigma \cdot BR < 4.3$ pb at $m_H = 300$ GeV and $\sigma \cdot BR < 0.051$ pb at $m_H = 3$ TeV

VBF $R \rightarrow WW \rightarrow l\nu l\nu$

ATLAS-CONF-2016-053

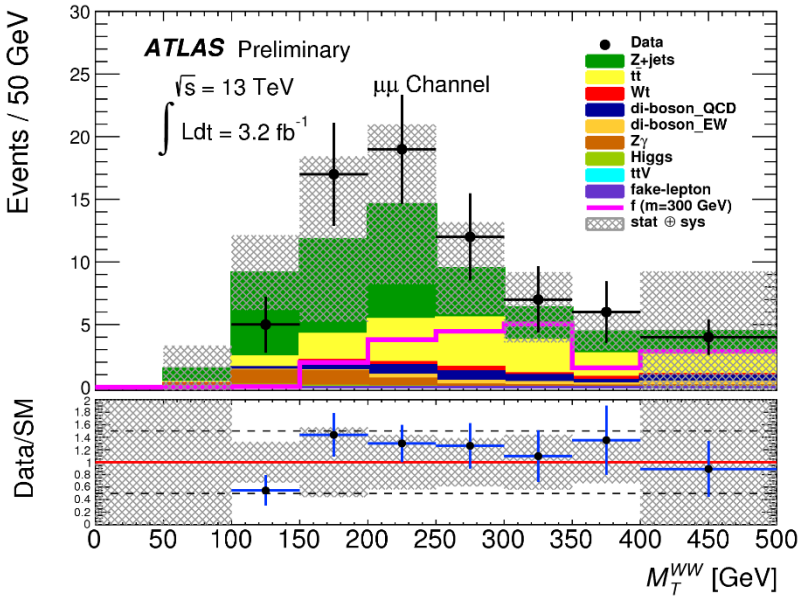
Search for a heavy neutral resonance

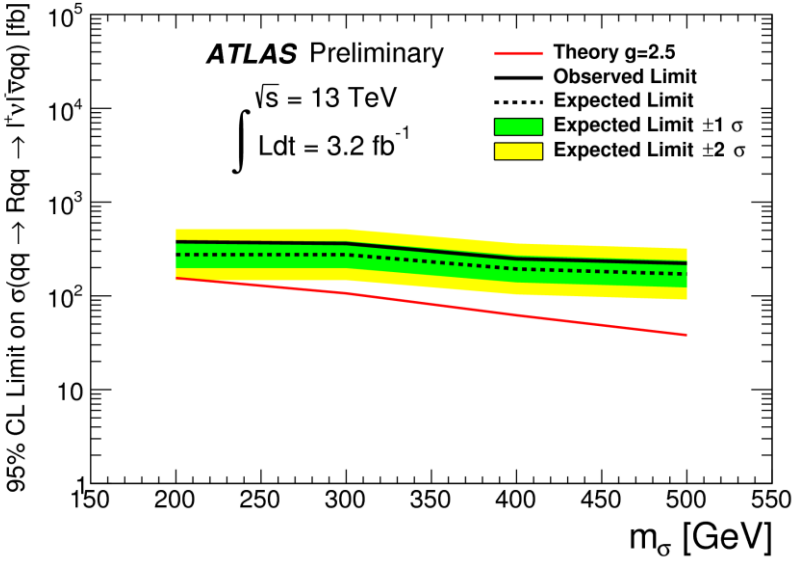
- An extension of the Higgs sector with a tensor resonance in effective field theory (Phys. Rev. D93, 036004)
- In such models, additional contributions arises in VBF



$$(M_{\mathrm{T}}^{WW})^2 = (P_{\ell_1} + P_{\ell_2} + P^{\mathrm{miss}})(P_{\ell_1} + P_{\ell_2} + P^{\mathrm{miss}})$$

Observed cross section limits are betweer 460 – 220 fb for resonance mass of 200 – 500 GeV





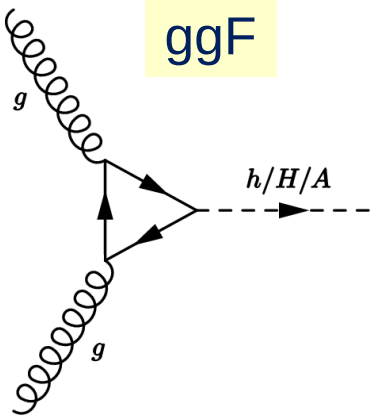
Two Higgs Doublet Model (2HDM)

- Standard Model has only one $SU(2)_L$ Higgs doublet
  - 4 degrees of freedom → 3 for longitudinal components of gauge bosons + 1 Higgs particle
- Two Higgs $SU(2)_L$ doublets
  - Straightforward extension of SM, but in some models this is a necessary requirement (e.g. MSSM)
  - 8 degrees of freedom → 3 for longitudinal components of gauge bosons + 5 Higgs particles
    - h, H (neutral, CP-even), A (neutral, CP-odd), $H^{\pm}$
    - Two vacuum expectation values v_1 and v_2
    - $v_1^2 + v_2^2 = (246\ \mathrm{GeV})^2$, $\tan\beta = v_2/v_1$
    - α: mixing angle between the CP-even states (h and H)
  - Coupling between Higgs and up-type (down-type) particles is proportional to v_1 (v_2)

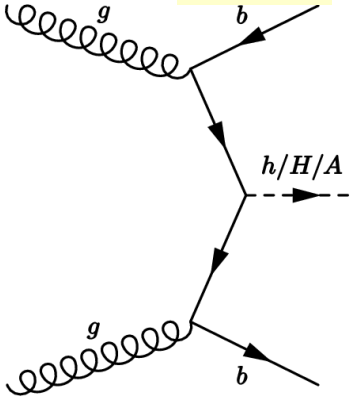
$H/A \to \tau\tau$

ATLAS-CONF-2016-085

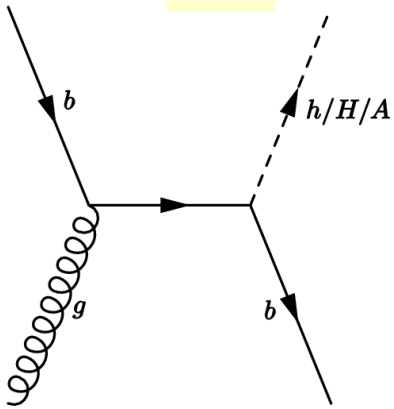
ggF

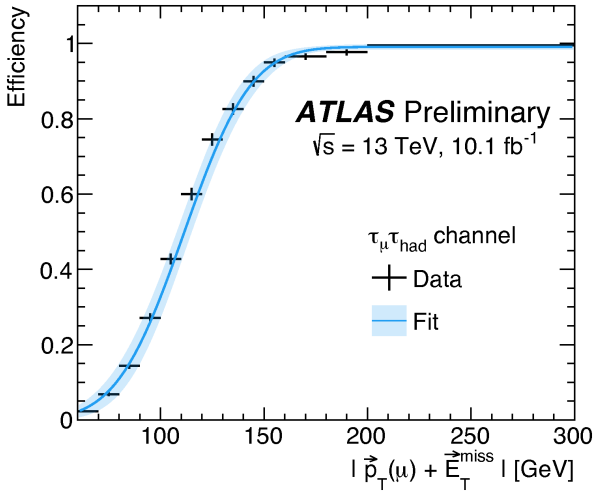


$b\bar{b}H$



bH





- Analysis aimed at large $\tan\beta$
- Require at least one τ to be decayed hadronically
  - $\tau_{\text{lep}}\tau_{\text{had}}$ channel
    - b-veto category, b-tag category (single-lepton trigger)
    - High $E_{\text{T}}^{\text{miss}}$ category ($E_{\text{T}}^{\text{miss}}$>150 GeV or $\left|\vec{p}_T^{\,\mu} + \vec{E}_{\text{T}}^{\text{miss}}\right|$>150 GeV)
  - $\tau_{\text{had}}\tau_{\text{had}}$ channel
    - b-veto category, b-tag category

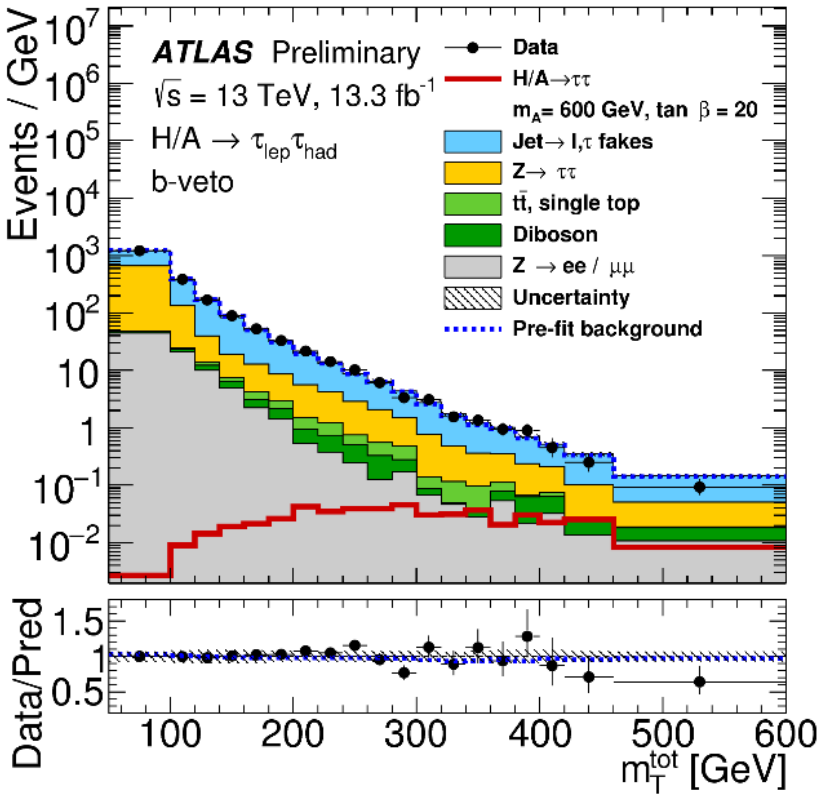
Final discriminant

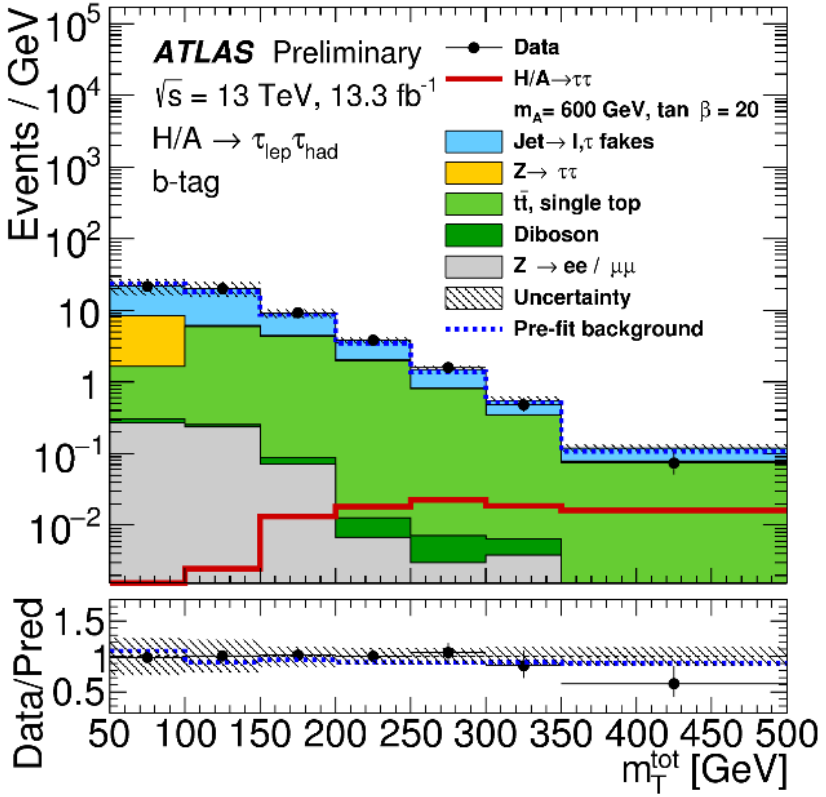
$$m_{\text{T}}^{\text{tot}} = \sqrt{m_{\text{T}}^2(E_{\text{T}}^{\text{miss}}, \tau_1) + m_{\text{T}}^2(E_{\text{T}}^{\text{miss}}, \tau_2) + m_{\text{T}}^2(\tau_1, \tau_2)},$$

$$m_{\text{T}}(a, b) = \sqrt{2p_{\text{T}}(a)p_{\text{T}}(b)[1 - \cos\Delta\phi(a, b)]}$$

$H/A \to \tau\tau$ signal region

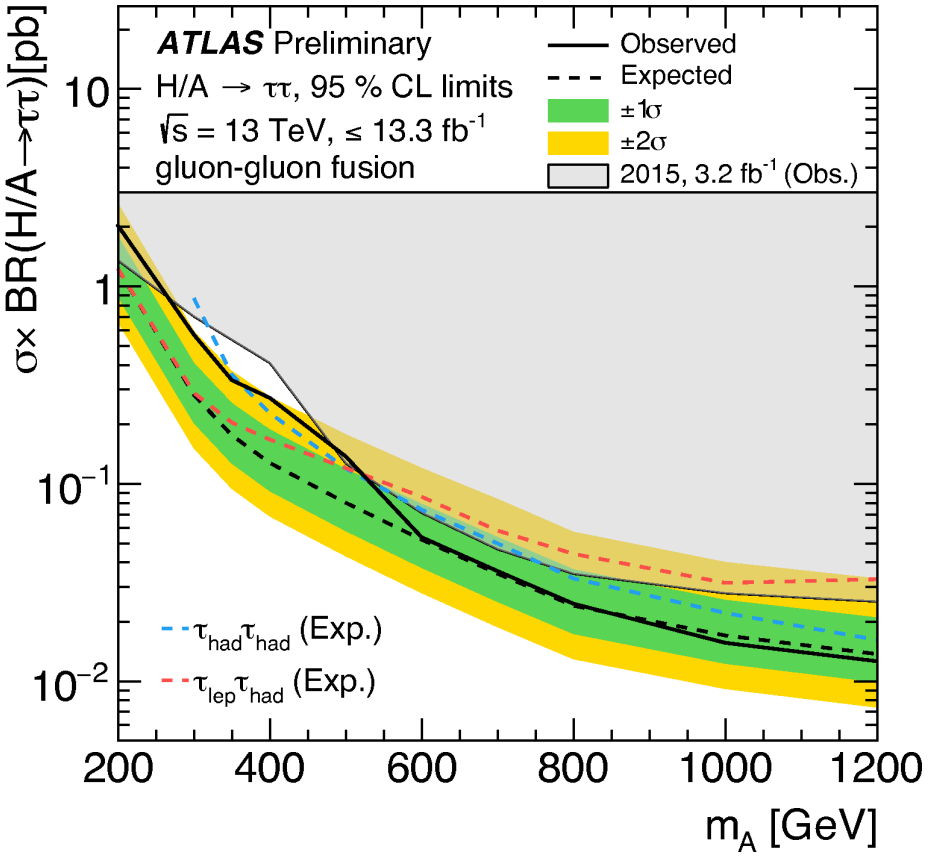
ATLAS-CONF-2016-085

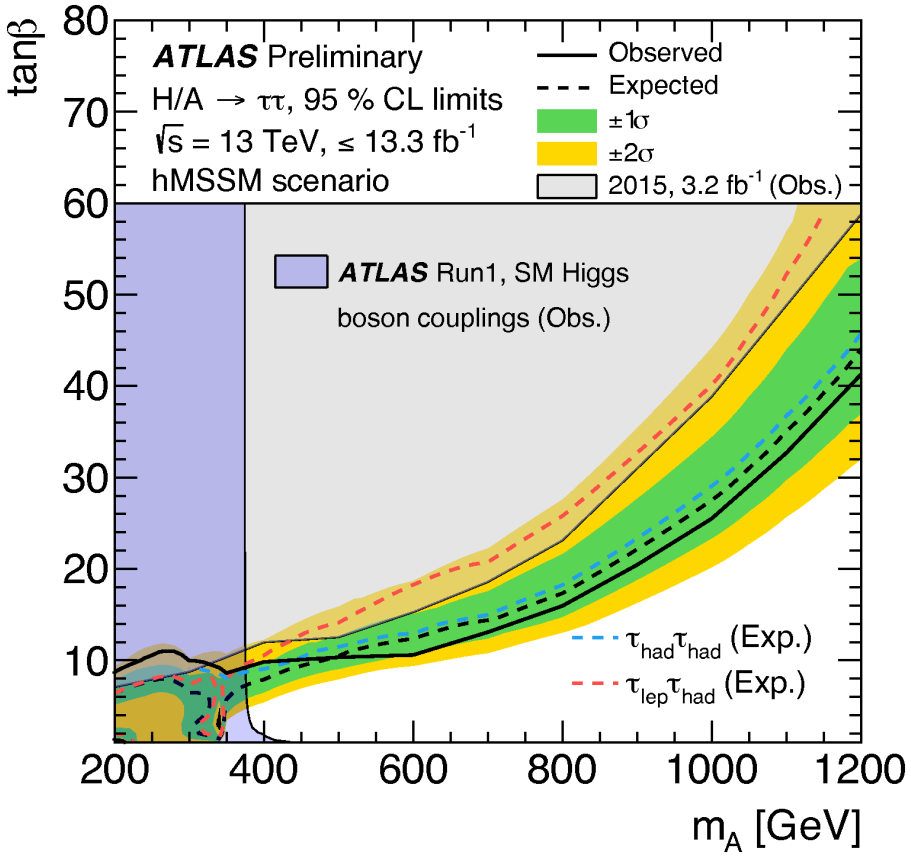




- m_T distribution for 2 categories (lep/had b-veto and b-tag)
- Main backgrounds are $Z \to \tau\tau$ and $t\bar{t}$
- Data is described well by SM prediction (also for other categories)

$H/A \to \tau\tau$ results



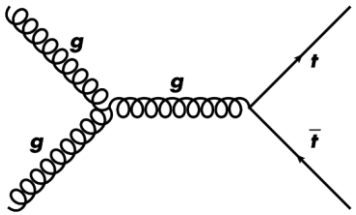


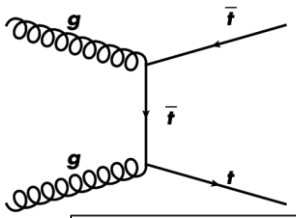
Excluded region

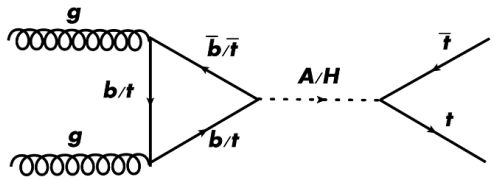
- $\tan\beta$>9 for m_A=200 GeV
- $\tan\beta$>42 for m_A=1.2 TeV
- Exceeds the previous results for m_A=350 GeV

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

ATLAS-CONF-2016-073



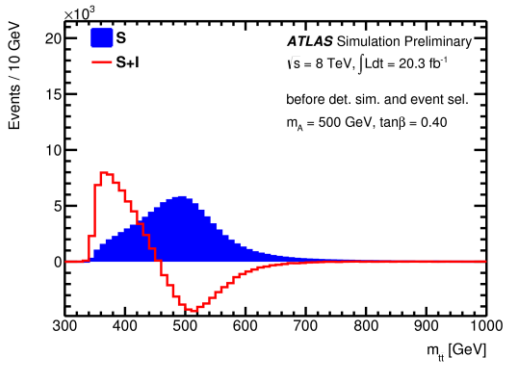


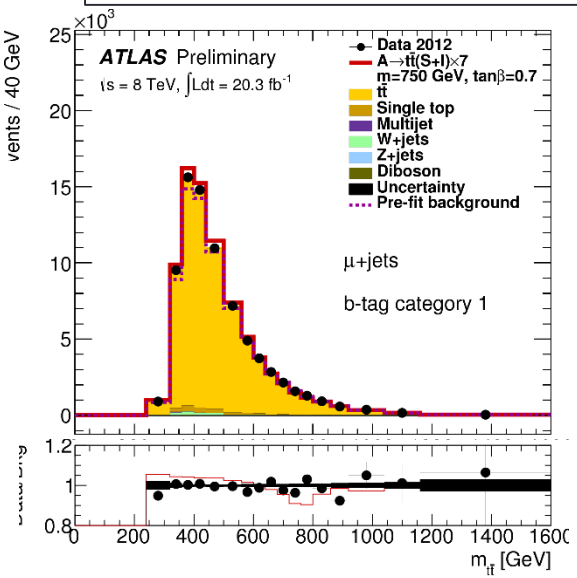


- $H/Z \to t\bar{t}$ is enhanced at low $\tan\beta$
- Interference between SM continuum $gg \to t\bar{t}$
- Event selection
  - 1 lepton + ≥ 4 jets (≥2 b-tag)
- $\tan\beta < 0.85\ (< 0.45)$ are excluded for $m_A = 500$ GeV $(m_H = 500$ GeV$)$

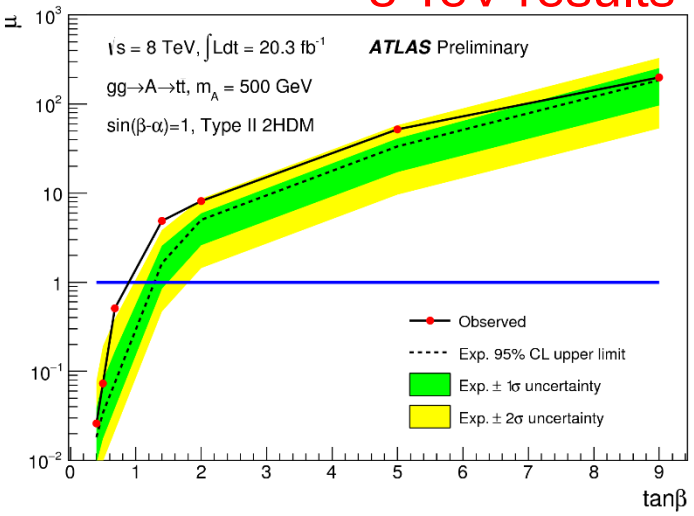
$\sigma = S + I + B$
(signal, interference, bg)

- MadGraph5_aMC had been used to generate the S+I contribution

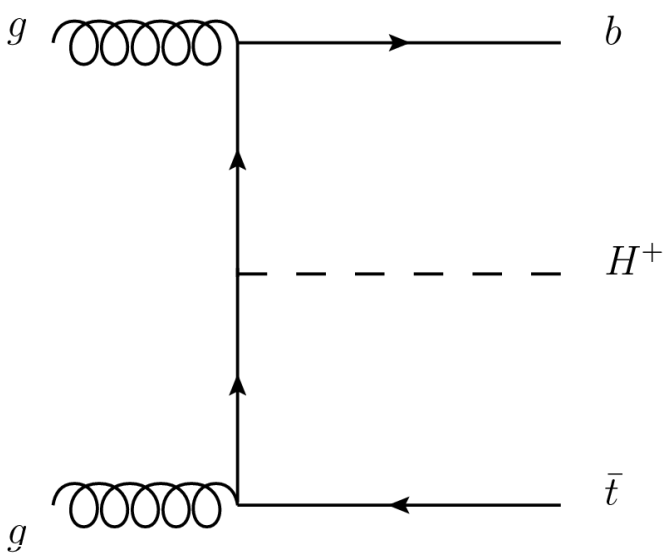




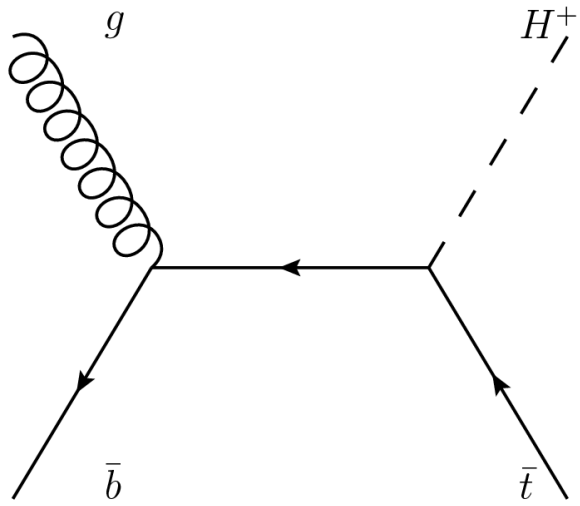
8 TeV results



Charged Higgs



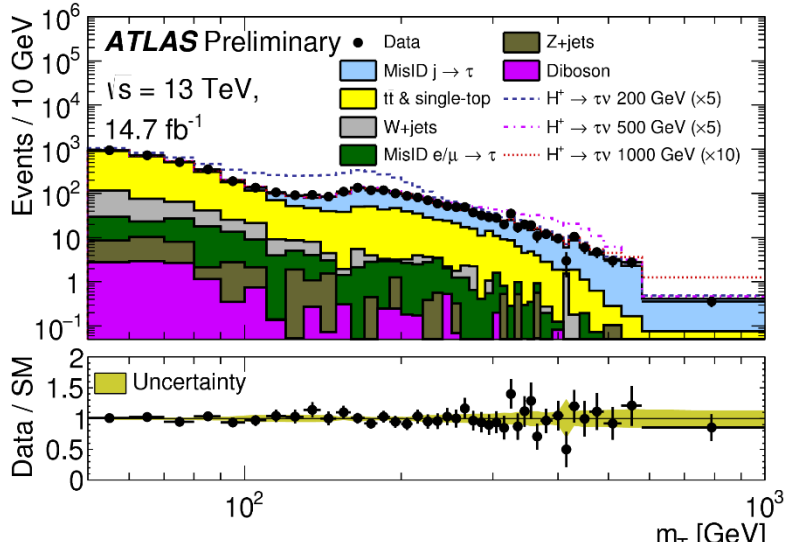
4-flavor scheme

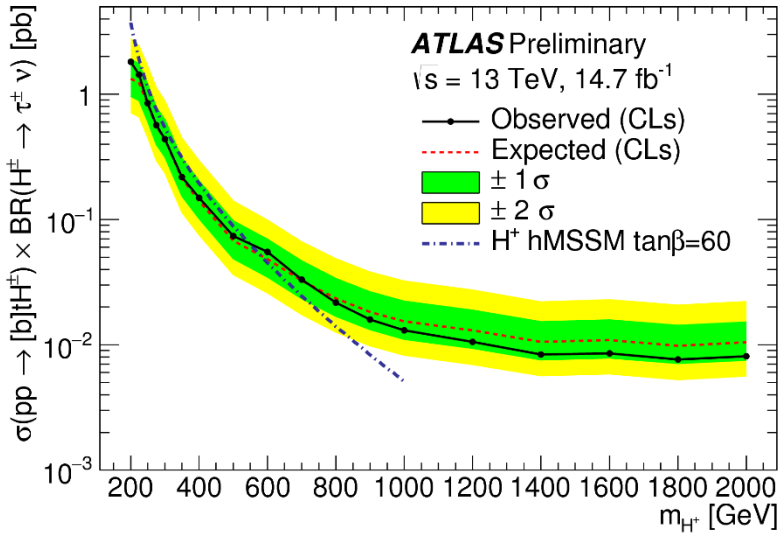


5-flavor scheme

- Main production mechanism is the associated production with a top quark
- The coupling depends on the value of $\tan\beta$
- Searches are performed in the mass range of 200 - 2000 GeV
  - $H^+ \to \tau^+\nu_\tau$ channel → τ +jets (from associated production)
  - $H^+ \to t\bar{b}$ channel (dominant at $m_{H^+} > m_t$)

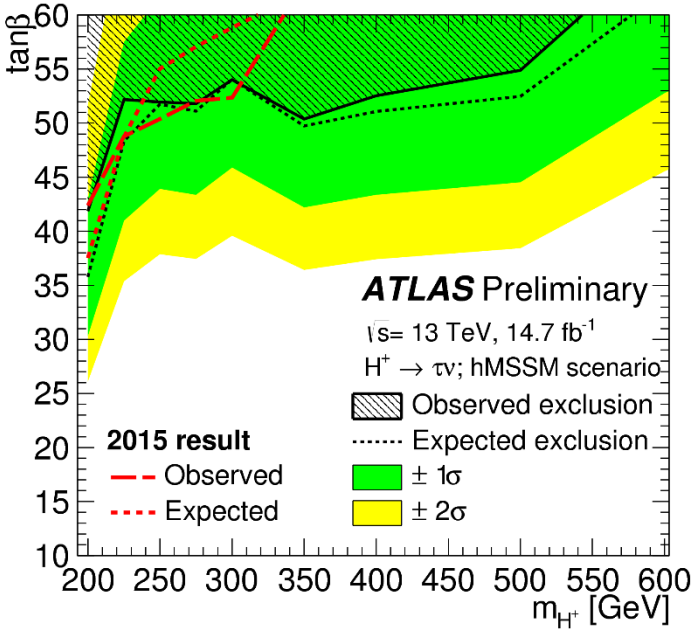
$H^+ \to \tau^+ + \bar{\nu}_\tau$(+jets) channel





- $H^+(\to \tau^+\nu_\tau) + \text{jets}$
- $42 < \tan\beta < 60$ is excluded for charged Higgs mass of 200 GeV
- At $\tan\beta = 60$, the charged Higgs mass from 200 to 540 GeV is excluded

ATLAS-CONF-2016-088

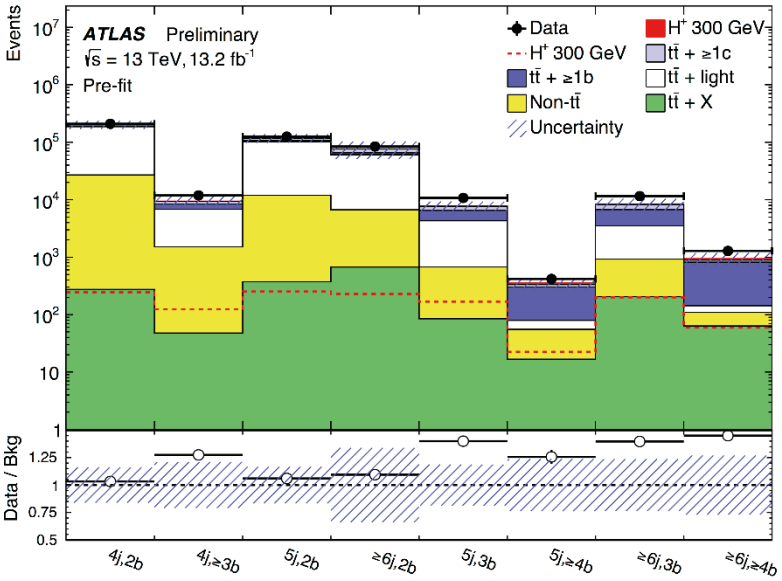


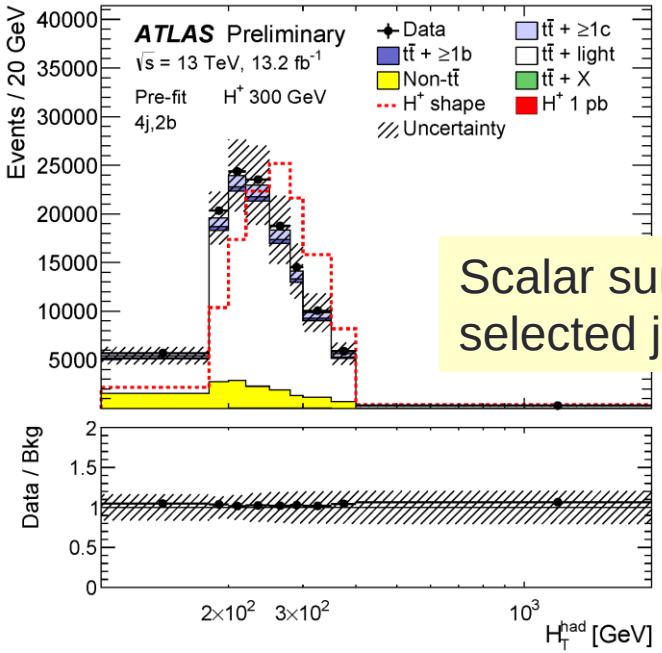
$H^+ \to t\bar{b}$ channel

ATLAS-CONF-2016-089

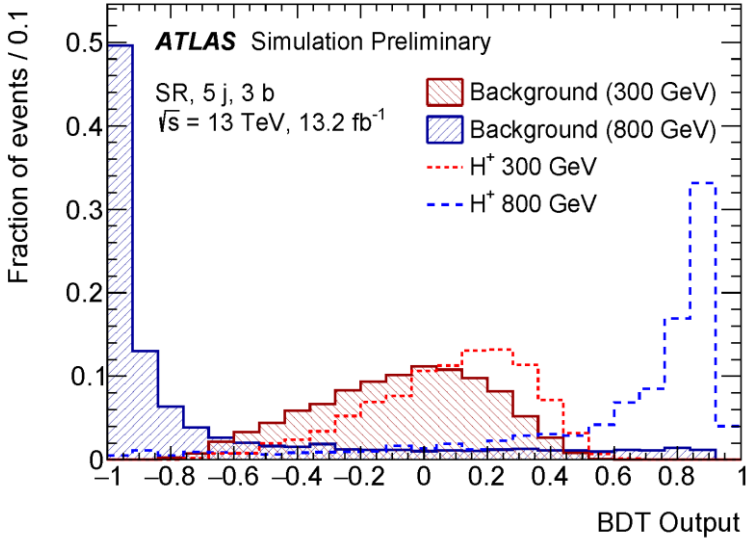
Search in semileptonic $t\bar{t}$ channel

- 1 lepton, ≥ 4 jets (≥ 2 b-tag)
- Signal/control regions based on N_{jet}, N_b
  - CR: 4j2b, 4j≥3b, 5j2b, ≥6j2b
  - SR: 5j3b, 5j≥4b, ≥6j3b, ≥6j≥4b
- Maximum Likelihood to all regions
- BDT in the signal region



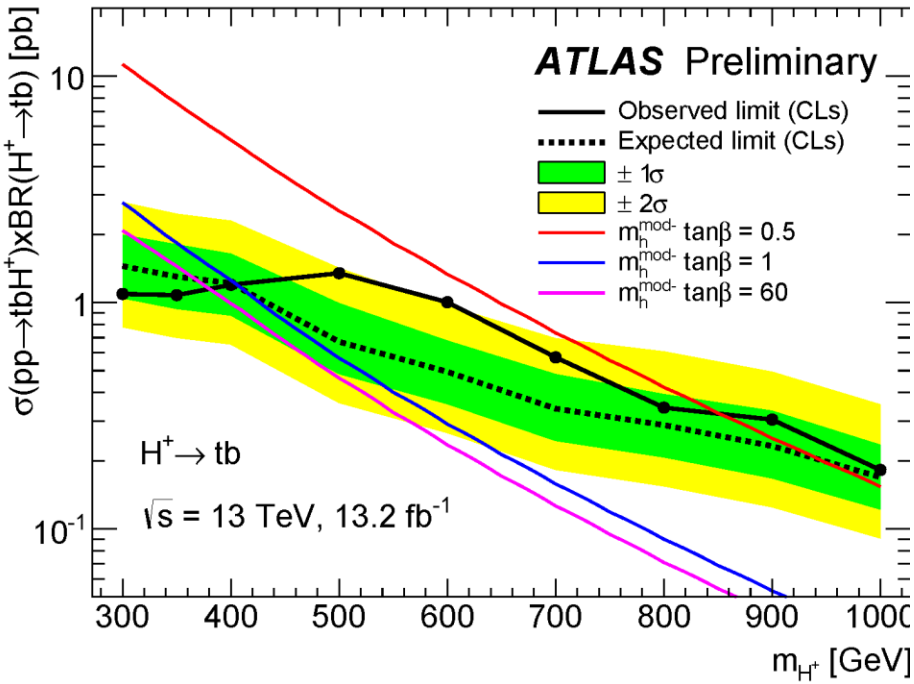


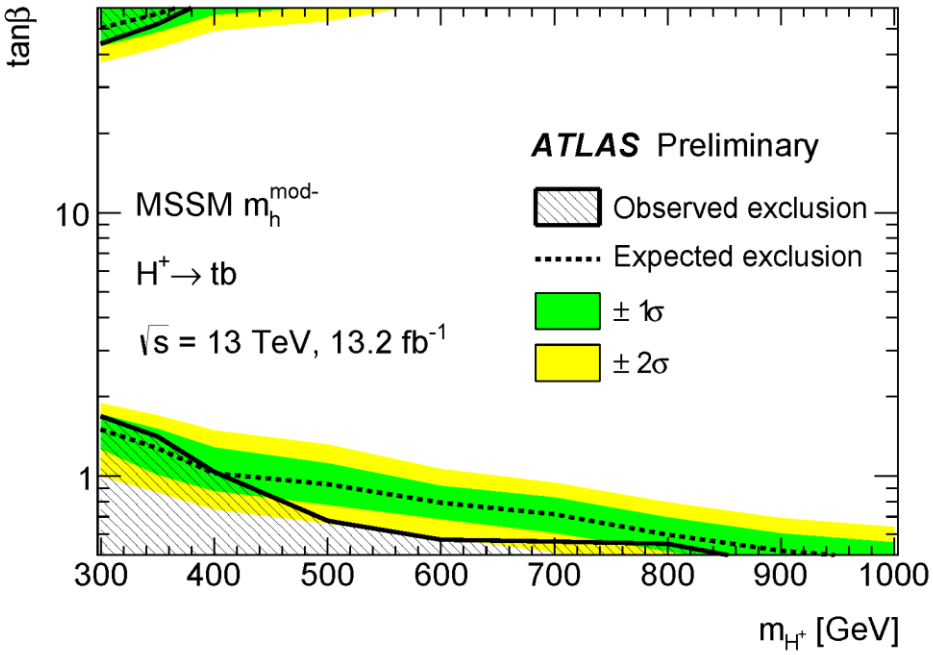
Scalar sum of p_T of selected jets



$H^+ \to t\bar{b}$ results

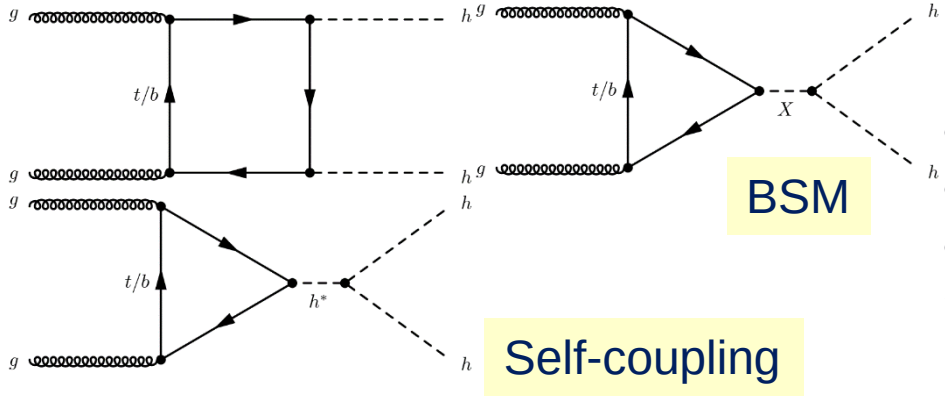
ATLAS-CONF-2016-089





- Limit on the cross section × branching ratio
  - $\sigma \cdot \mathrm{BR}$= 1.09 pb for m_{H^+}=300 GeV and
  - $\sigma \cdot \mathrm{BR}$ =0.18 pb for m_{H^+}=1000 GeV
- $\tan\beta$ in the range 0.5 – 1.7 are excluded for $300 < m_{H^+} < 855$ GeV
- $\tan\beta > 44$ at m_{H^+}=300 GeV and $\tan\beta > 60$ at m_{H^+}=366 GeV are excluded

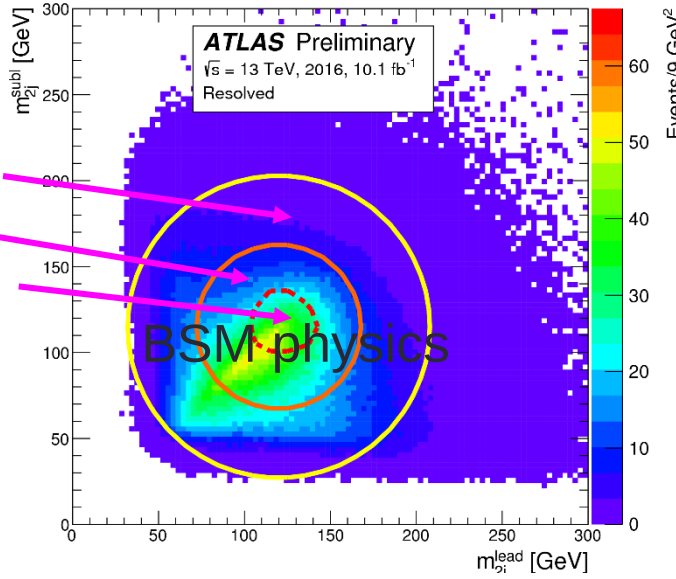
$hh \to b\bar{b}b\bar{b}$



BSM

Self-coupling

ATLAS-CONF-2016-049

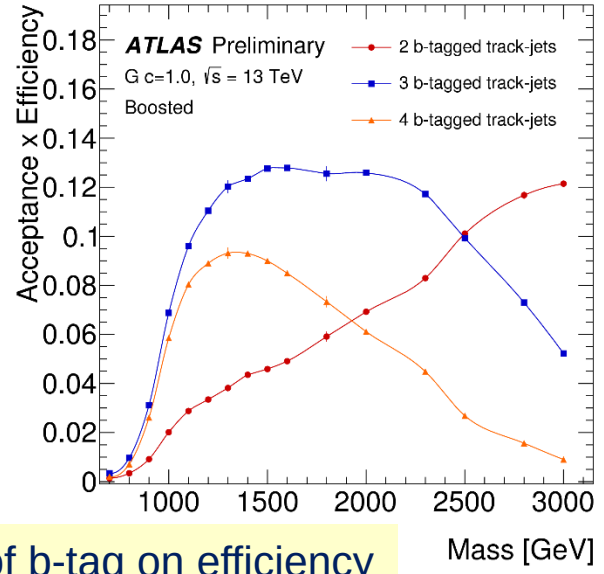


- side-band,
- control
- and signal

regions

$hh \to b\bar{b}b\bar{b}$

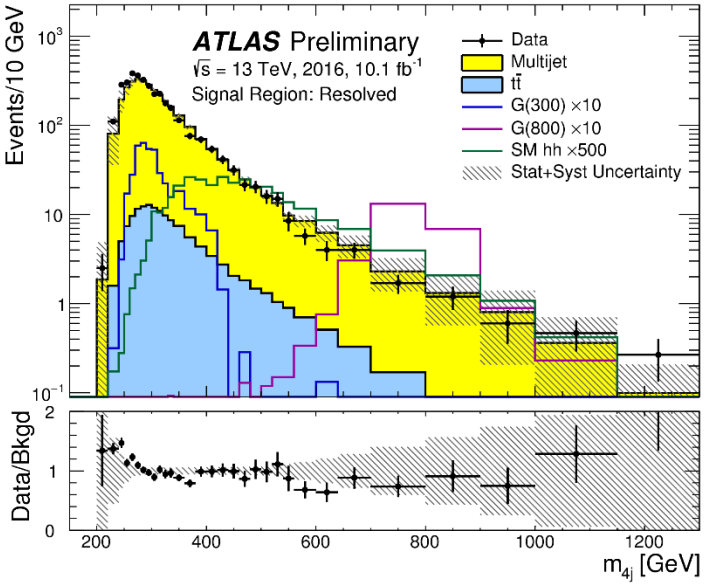
- Resolved analysis
  - anti-k_T jet (R=0.4)
  - Pair of b-jets to form Higgs candidate
  - Invariant mass of two Higgs candidates
  - Background: multijet (98%) and $t\bar{t}$ (2%)
- Boosted analysis
  - anti-k_T jet (R=1.0) p_T>250 GeV, m_J>50 GeV
  - 2, 3 or 4 b-tagged track jets
  - Invariant mass of the two large-R jets
  - Background: multijet (83-87%) and $t\bar{t}$

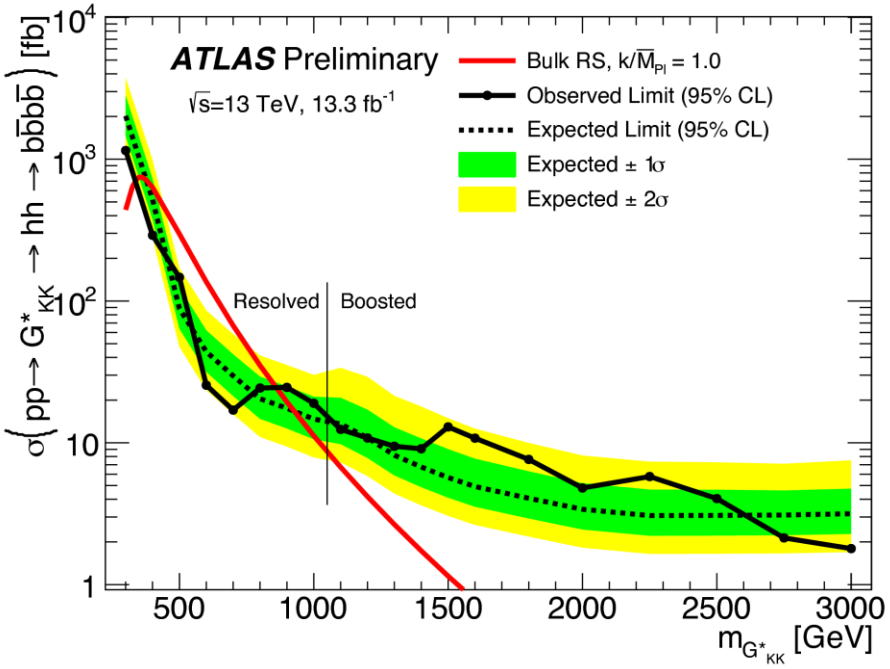


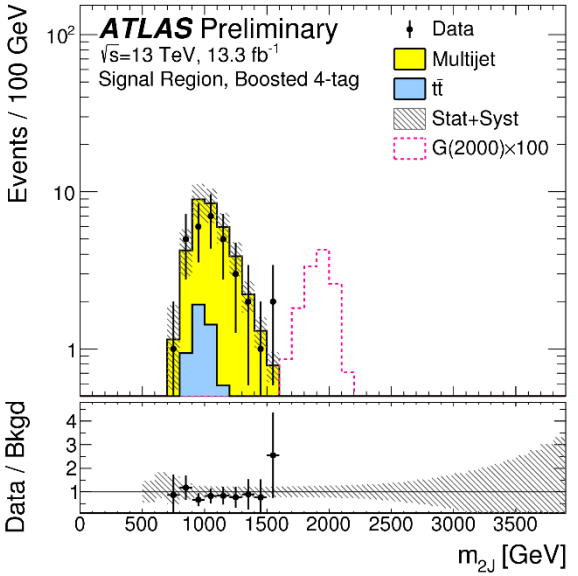
Effect of b-tag on efficiency

$hh \to b\bar{b}b\bar{b}$

- Dominant background is multijet and $t\bar{t}$
- Limit on spin-2 resonance
  - σ =1000 – 2 fb in the mass range of 300 – 3000 GeV
- Limit on non-resonant production
  - 330 fb (95% C.L.)







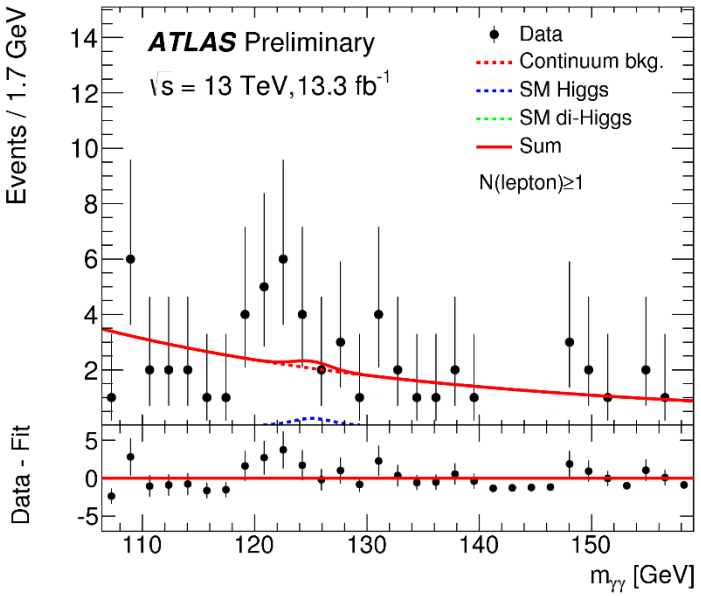
$hh \to \gamma\gamma WW \to \gamma\gamma l\nu jj$

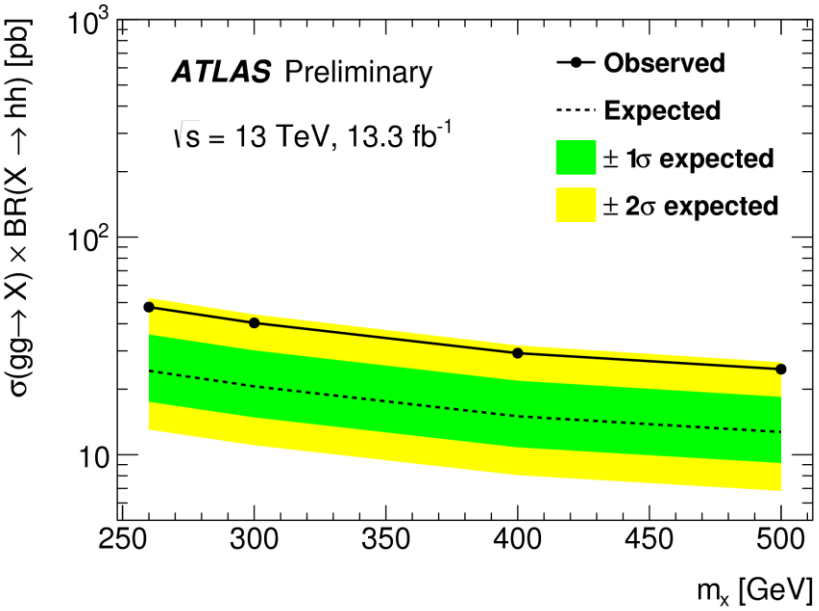
ATLAS-CONF-2016-071

- Clean signal from $h \to \gamma\gamma$
- Large branching ratio of $h \to WW$

Event selection

- Two photons ($p_T^{\gamma} > 35, 25$ GeV)
- $105 < m_{\gamma\gamma} < 160$ GeV
- Require 1 charged lepton





Limits

- Non-resonant production
  - observed: 25.0 pb (95% C.L.)
  - expected: 12.9 pb
- Narrow resonance
  - In the range between 47.7 pb and 24.7 pb for a resonance mass of 260 – 500 GeV

Conclusion

- Searches for BSM Higgs has been performed in various channels have been performed
  - High mass resonances
  - Heavy particles decaying into SM Higgs
  - Associated production of Higgs and DM candidate
- No significant excess is observed
  - Excess at 750 GeV in diphoton channel became less significant with 2016 data
- Expectation for results from LHC Run-2
  - So far in 2016, ATLAS has collected ~20 fb^{-1} of data at 13 TeV
  - By the end of Run-2 (2015 - 2018), 100 fb^{-1} is expected

Backup slides