ATLAS Searches for Resonances Decaying to Boson Pairs

Jana Schaarschmidt (University of Washington) on behalf of the ATLAS collaboration

DIS2019 April 10 - Turin

Outline

(1) Search for heavy resonances

(2) Search for light resonances

(3) DiHiggs searches

More ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Searches for heavy resonances

The SM is not the final answer

Many BSM models have an extended Higgs sector (2HDM, MSSM, Triplets, Singlets, ...)

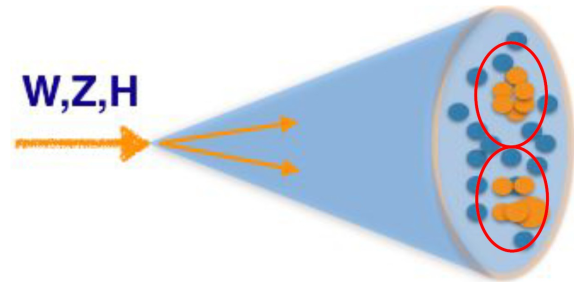
Other models suggest new heavy particles, such as Gravitons, or heavy vector bosons (Sequential Standard Model, E_6, Warped Extra Dimensions, Heavy Vector Triplets, ...)

$X \to VV \to JJ$ **Full Run-2 Dataset!** ATLAS-CONF-2019-003

Probes data for fully-hadronic boosted WW, WZ or ZZ resonances heavier than 1.3 TeV

Highly boosted jets → each vector boson candidate is contained in a single R=1.0 ("large-R") anti-kt calorimeter jet, and we require pT > 200 GeV and m > 50 GeV

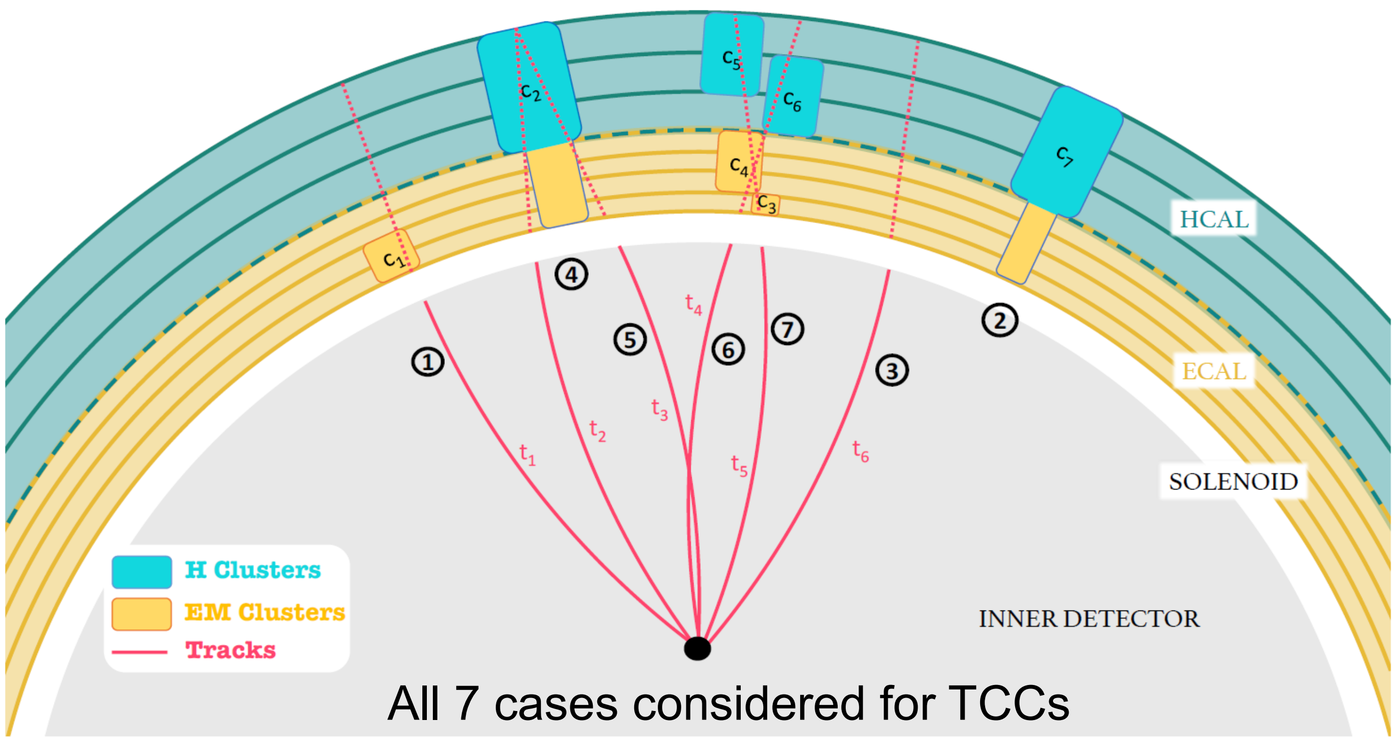
Substructure techniques applied to identify vector bosons and suppress background



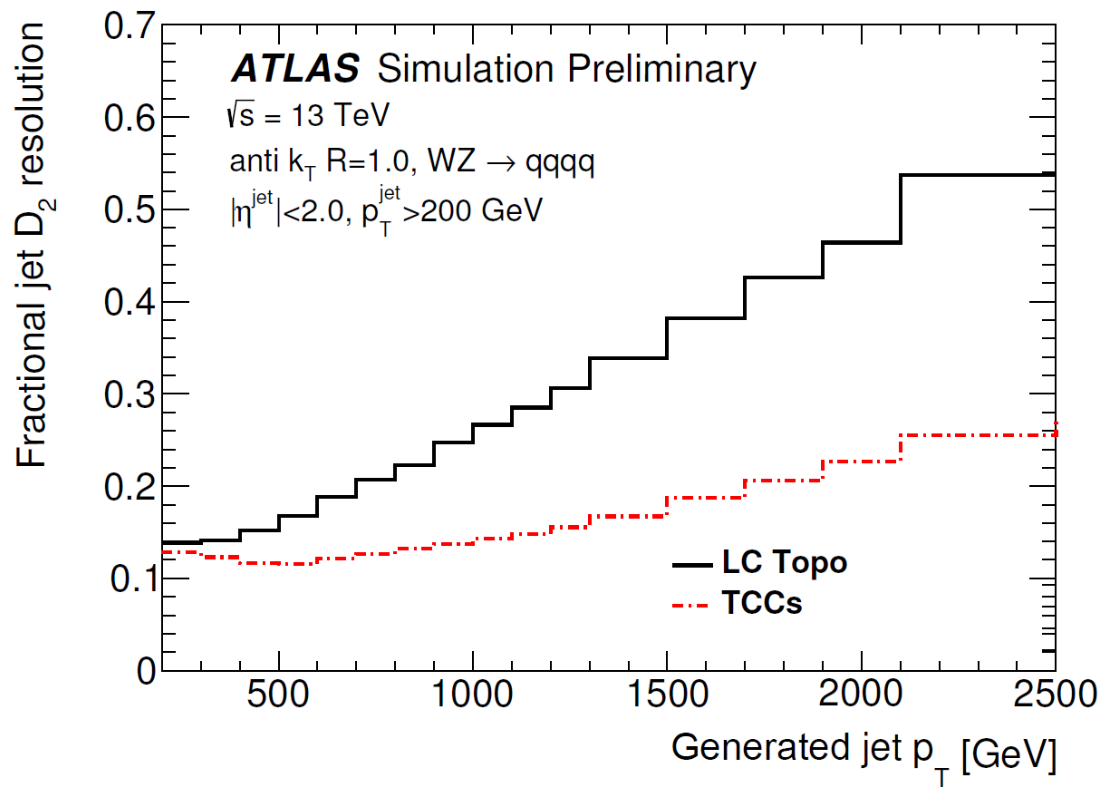
Track-Calo-Clusters (TCC): (more information: https://cds.cern.ch/record/2275636)

Combined object built from tracks and calorimeter clusters, that serve as input to the jet reconstruction algorithms

ATLAS calorimeter has great energy resolution, but lacks angular resolution. By combining the calorimeter clusters with the tracks, can notibly improve the angular resolution and two-particle separation

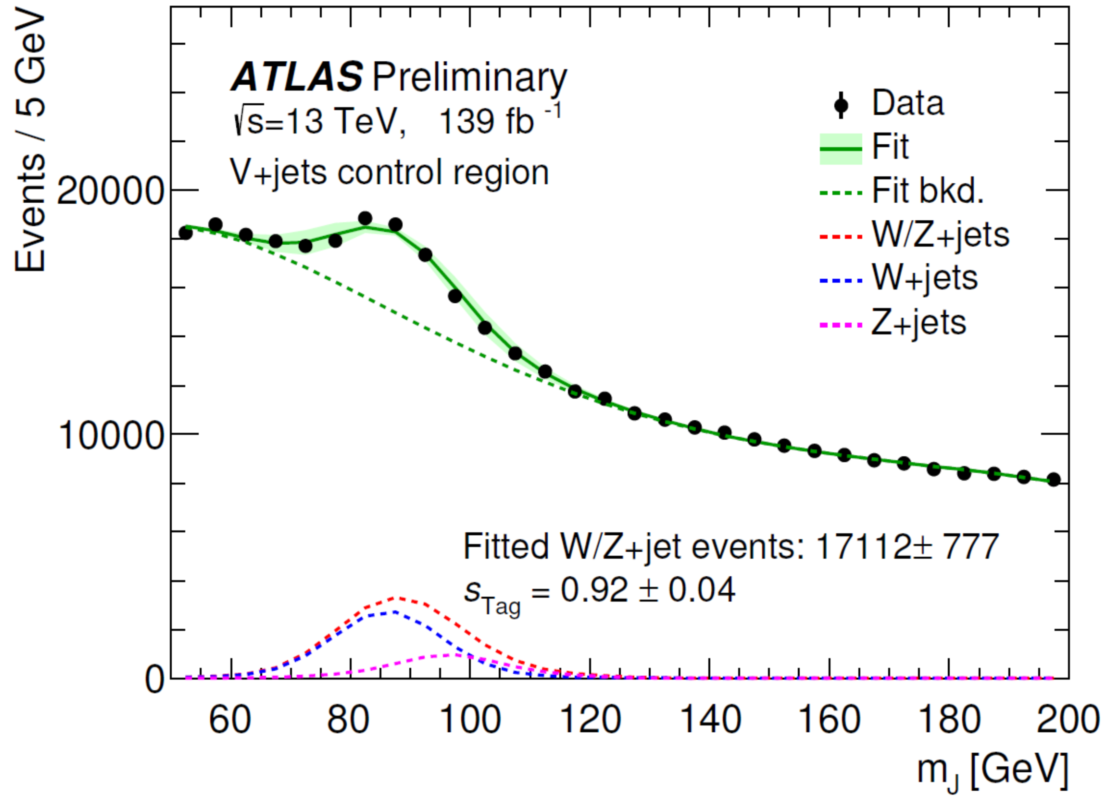


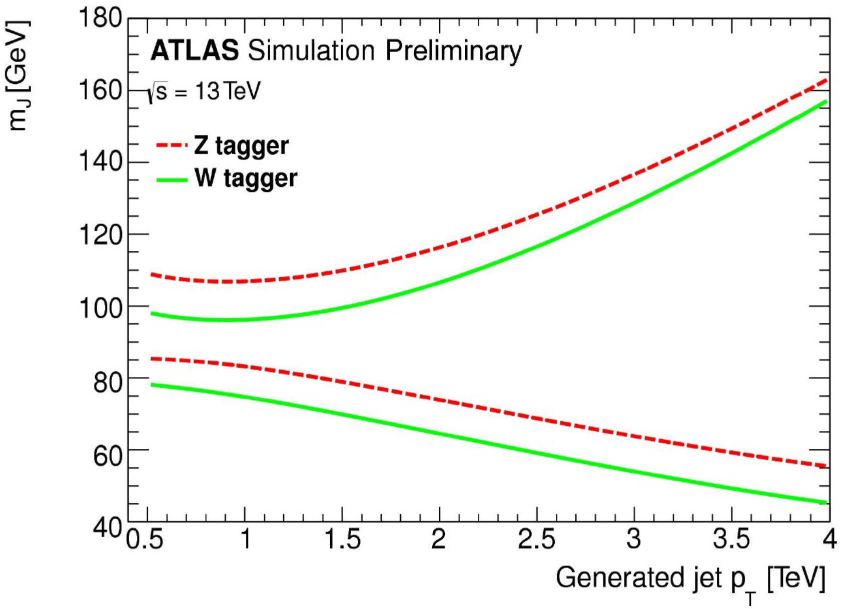
All 7 cases considered for TCCs

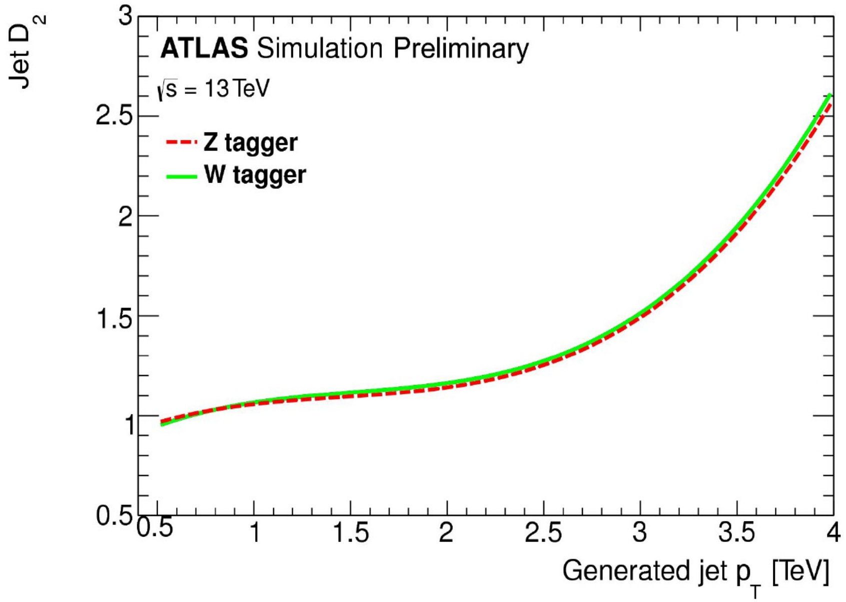


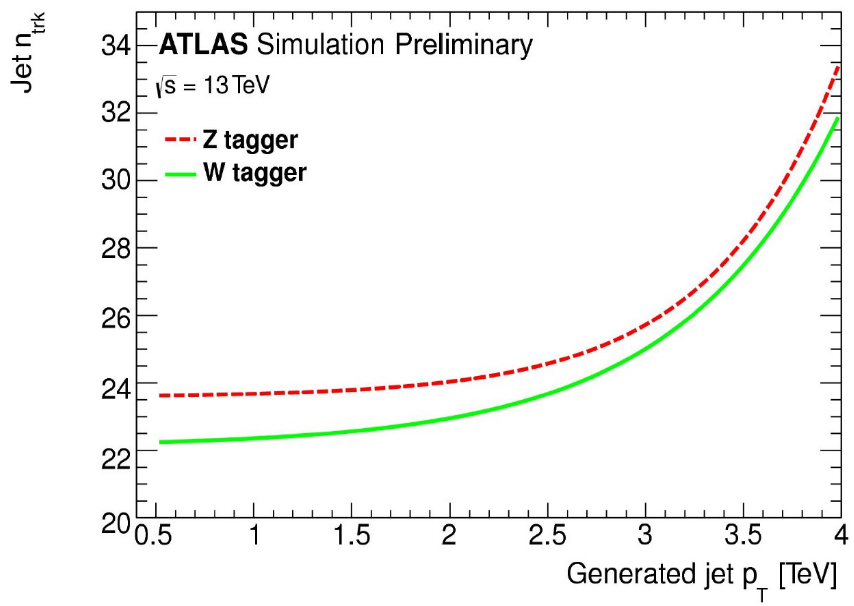
Improved V tagger:

- Three-dimensional tagger (jet mass, D_2, #tracks) using TCC jets
- Optimized to discriminate W/Z bosons from background jets
- Validation on SM V+jets processes:
  Require 2 large-R jets, one passes and one fails the tagger
- Selection efficiency in data relative to MC measured as 0.92±0.13
- Overlapping signal regions defined based on these taggers:
  2 large-R jets that pass some kinematic cuts, and are tagged as
  WZ or WW (SR1) or WW or ZZ (SR2)

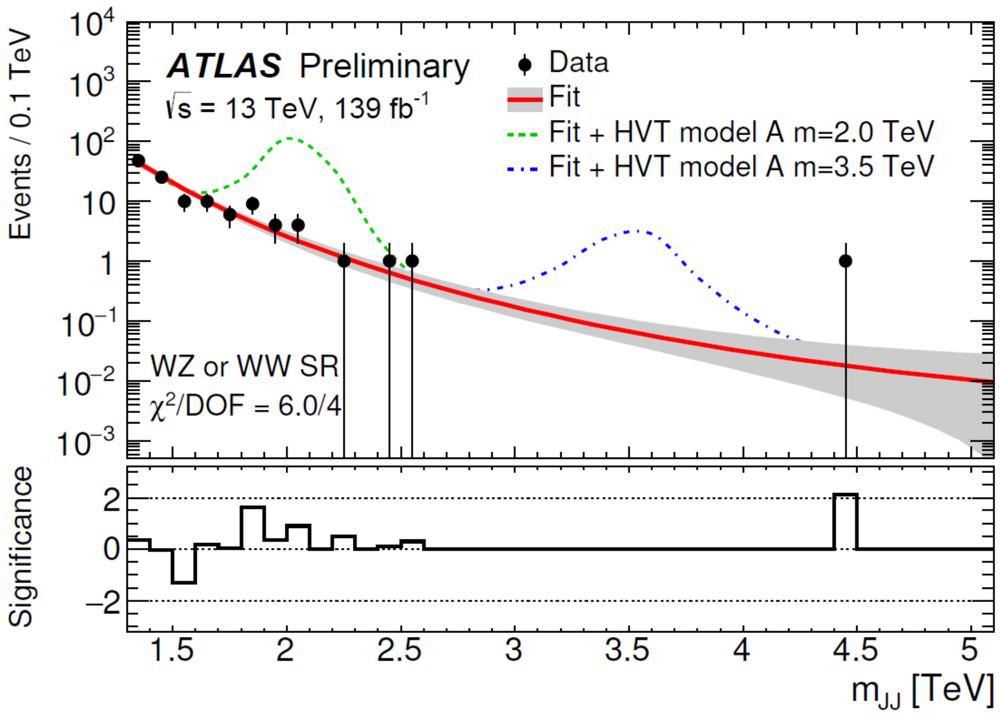


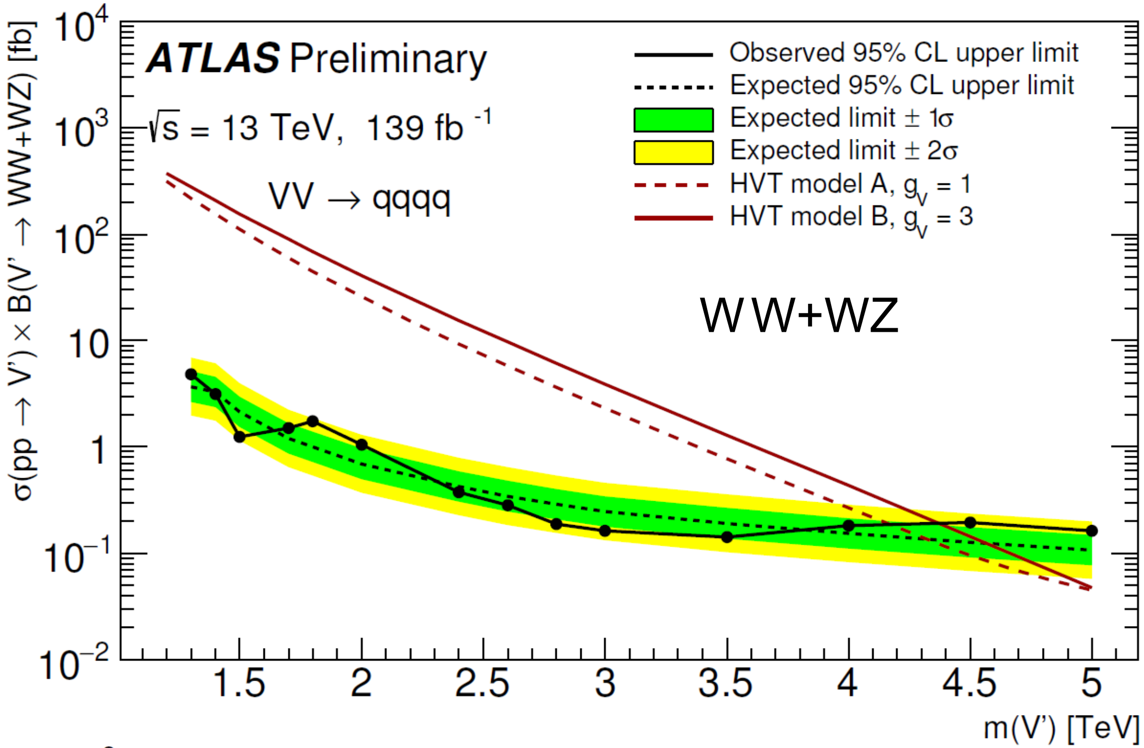


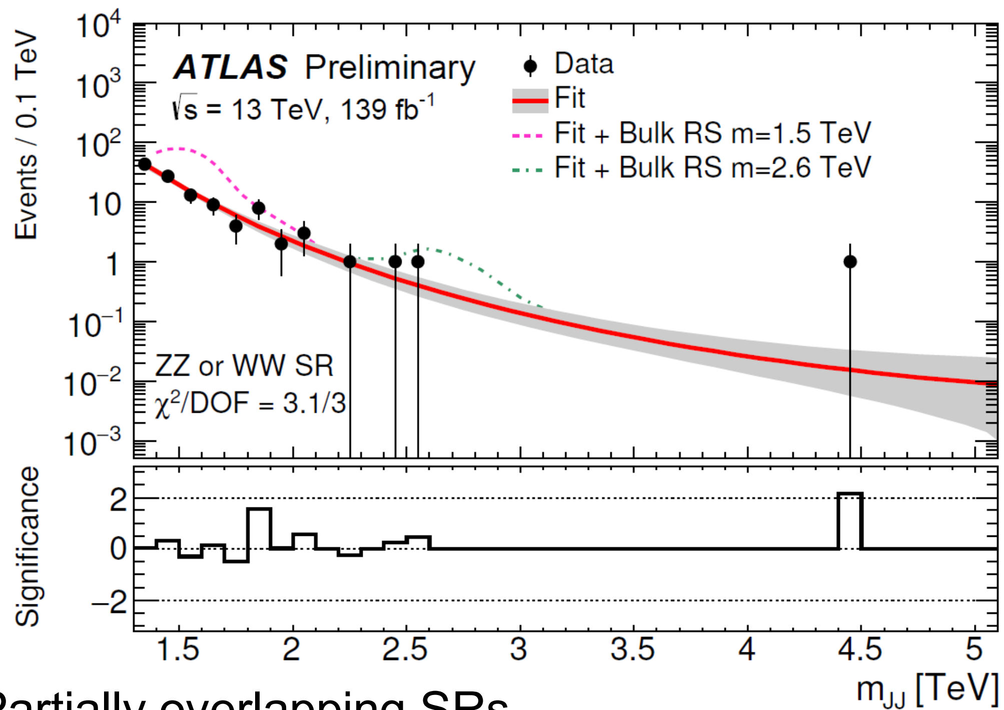


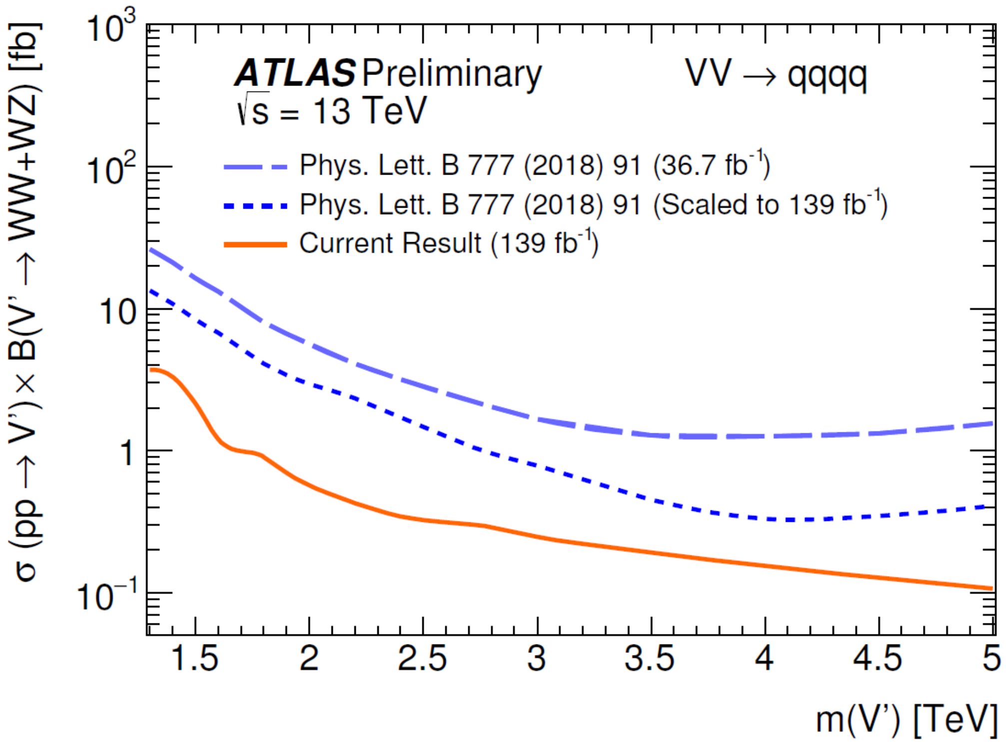


X → VV → JJ **Full Run-2 Dataset!** ATLAS-CONF-2019-003









Smallest p_0 at 4.5 TeV (1.8σ)

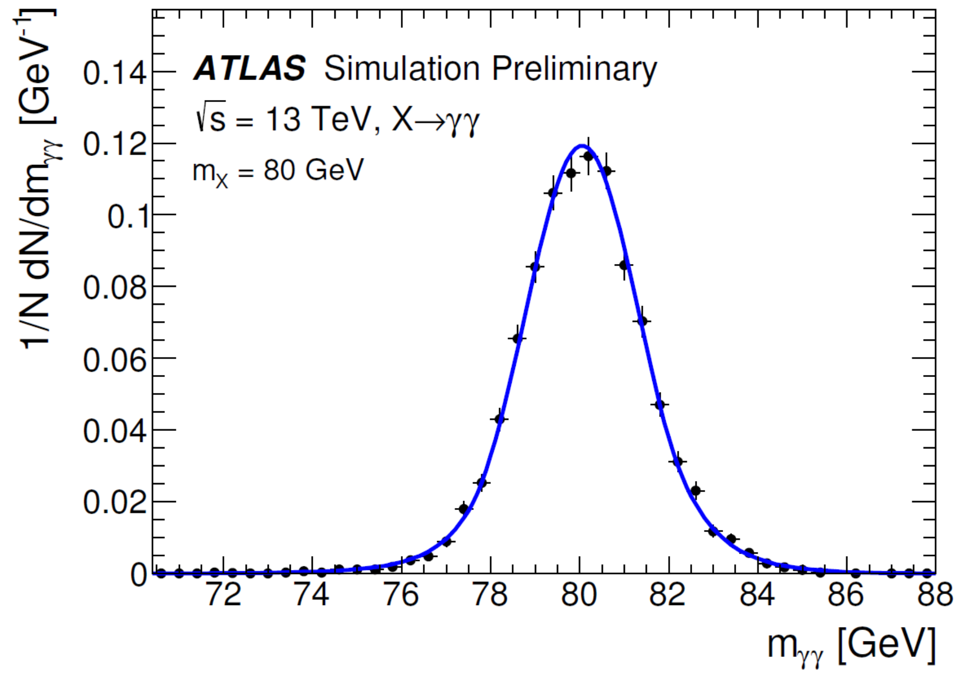
← Better than projected!

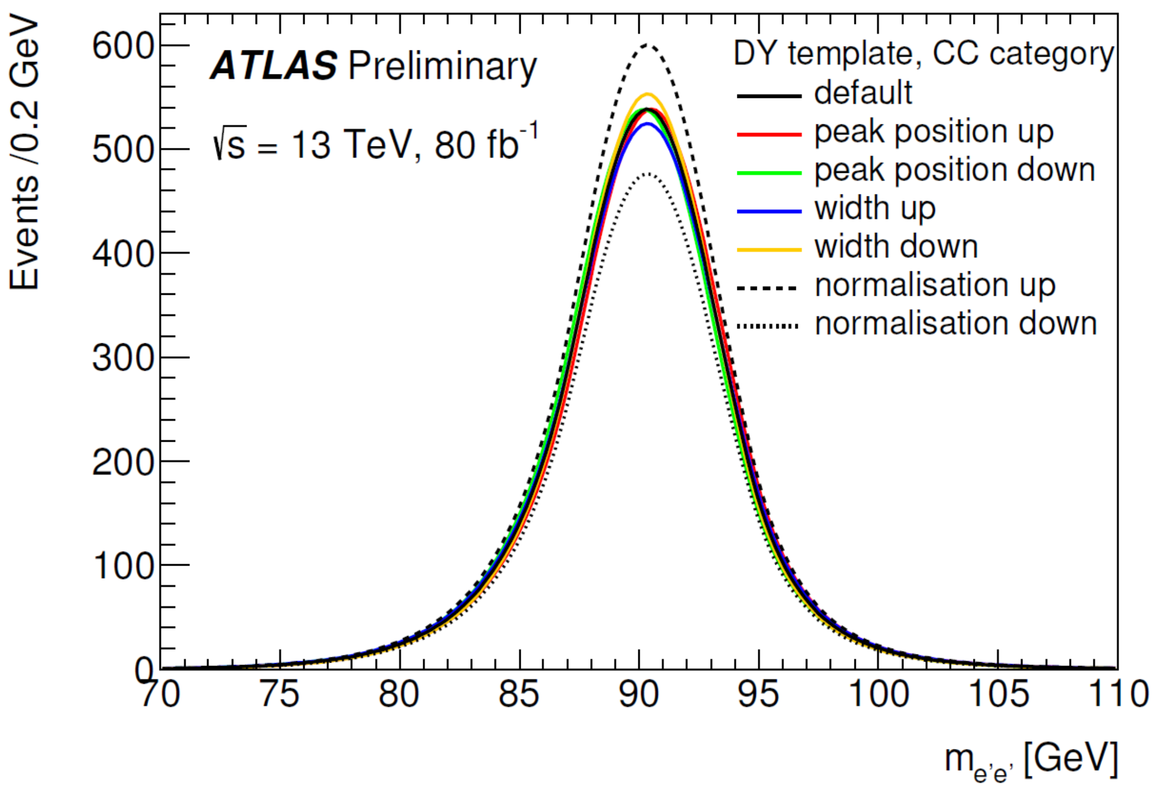
Partially overlapping SRs

Low mass $H \rightarrow \gamma\gamma$

ATLAS-CONF-2018-025 80/fb

- Search for diphoton resonances of mass **65 – 110 GeV**
- Diphoton trigger, photon E_T > 22 GeV
- Categories depending if photons are converted or unconverted
- Signal shape precisely modelled with Double Sided Crystal Ball function
- Continuum $pp \rightarrow \gamma\gamma$ background estimated from data with analytical functions (Bernstein polynomials or Landau+exponential)

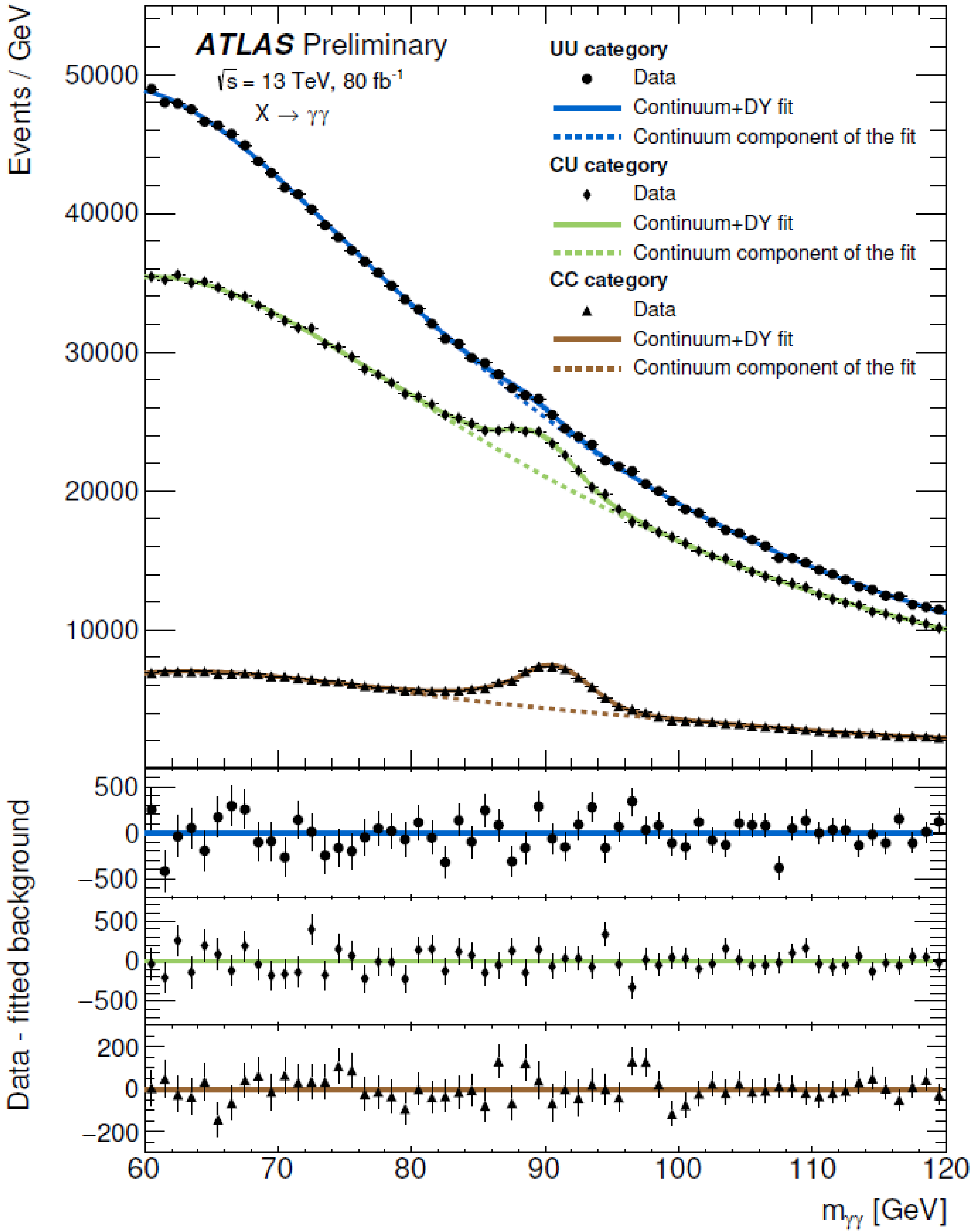


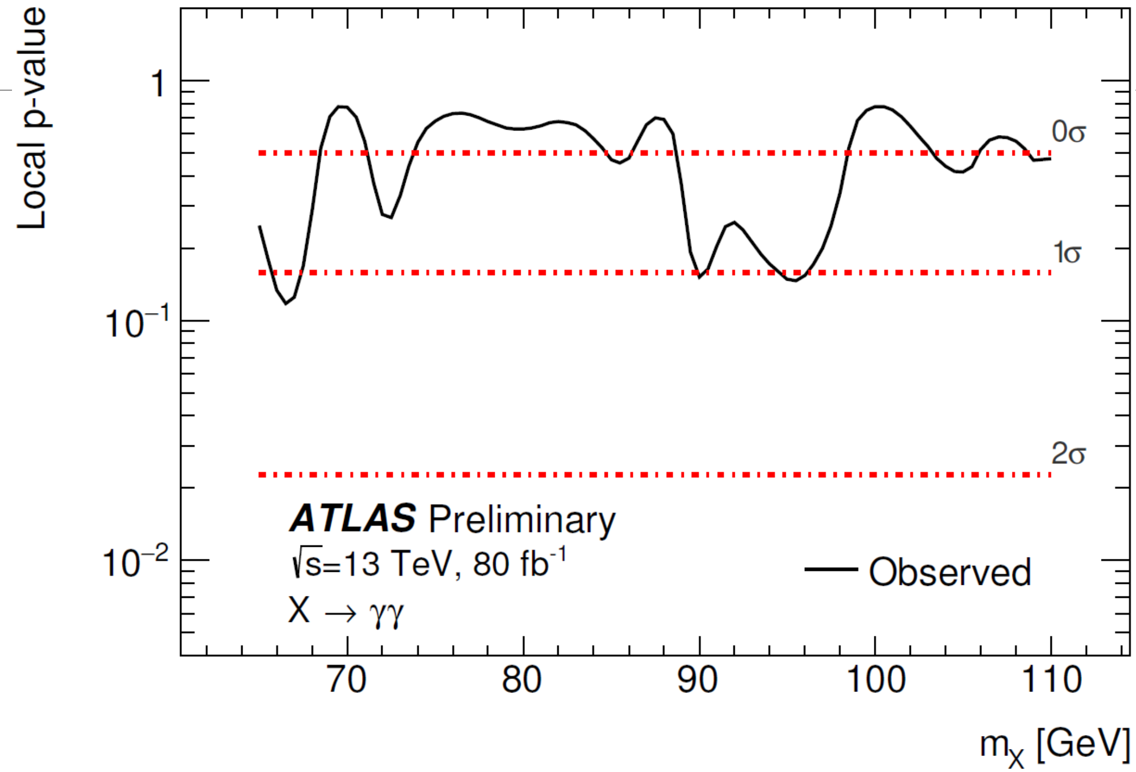


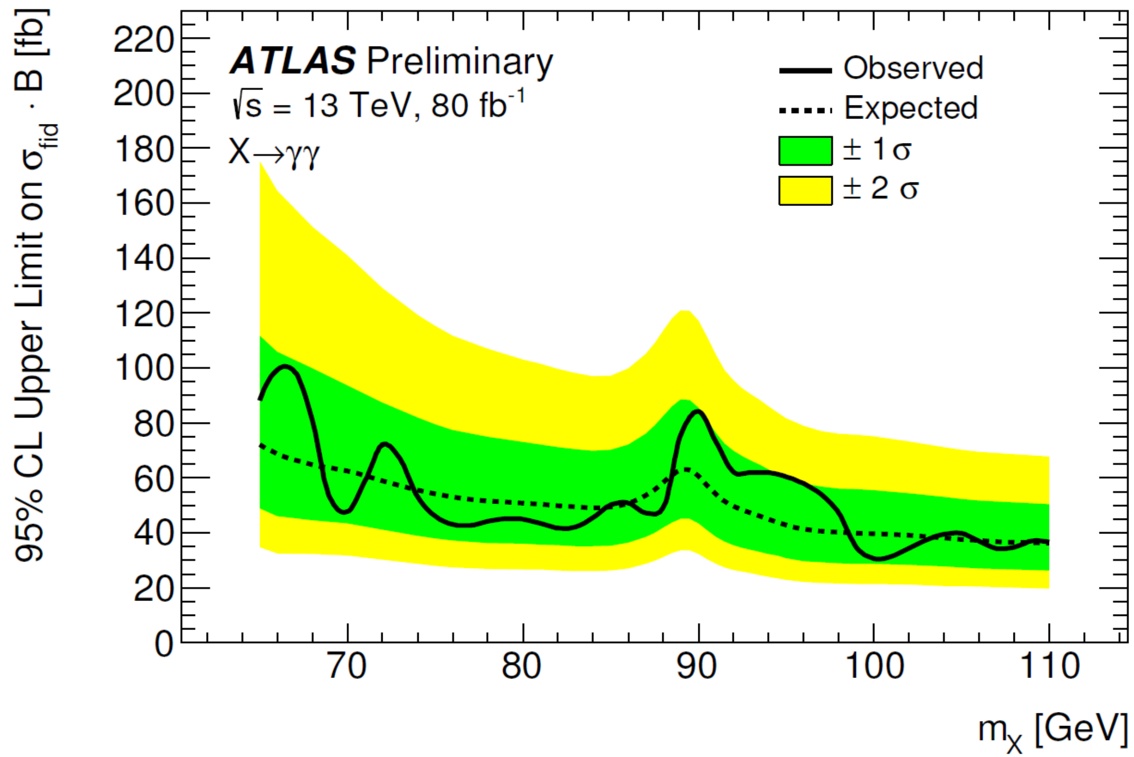
- Modelling the $Z \rightarrow ee$ backgrounds where e fake photons is a challenge, especially if selecting converted photons
- Data-driven template constructed from $Z \rightarrow ee$ data, electron's energy loss due to bremsstrahlung corrected for
- Shape modelled with Double Sided Crystal Ball fit to the data-driven template
- Normalisation of the template from data-driven $e \rightarrow \gamma$ fake rate measurements, large uncertainty (9-21%)

Low mass H → γγ

80/fb

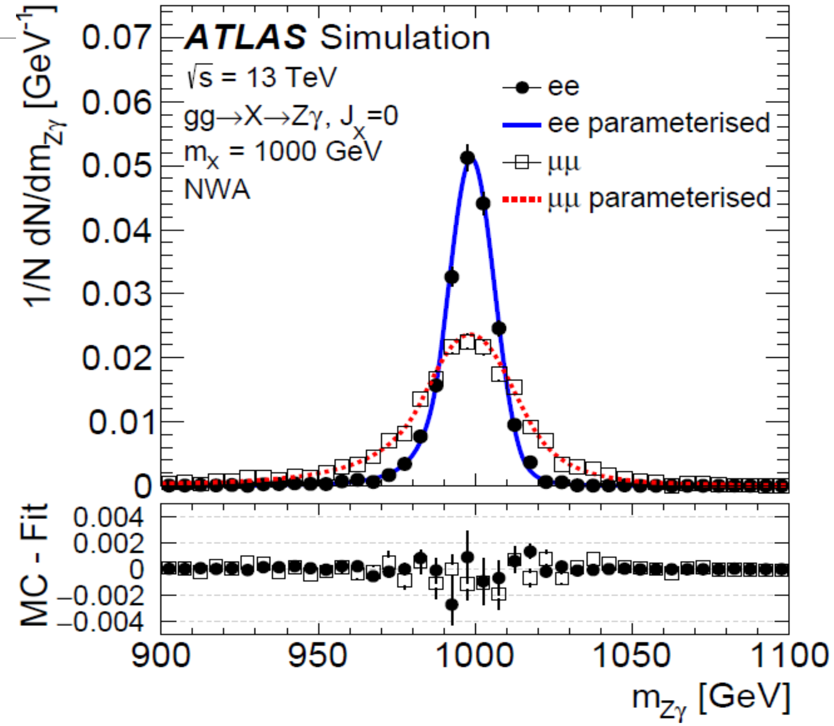


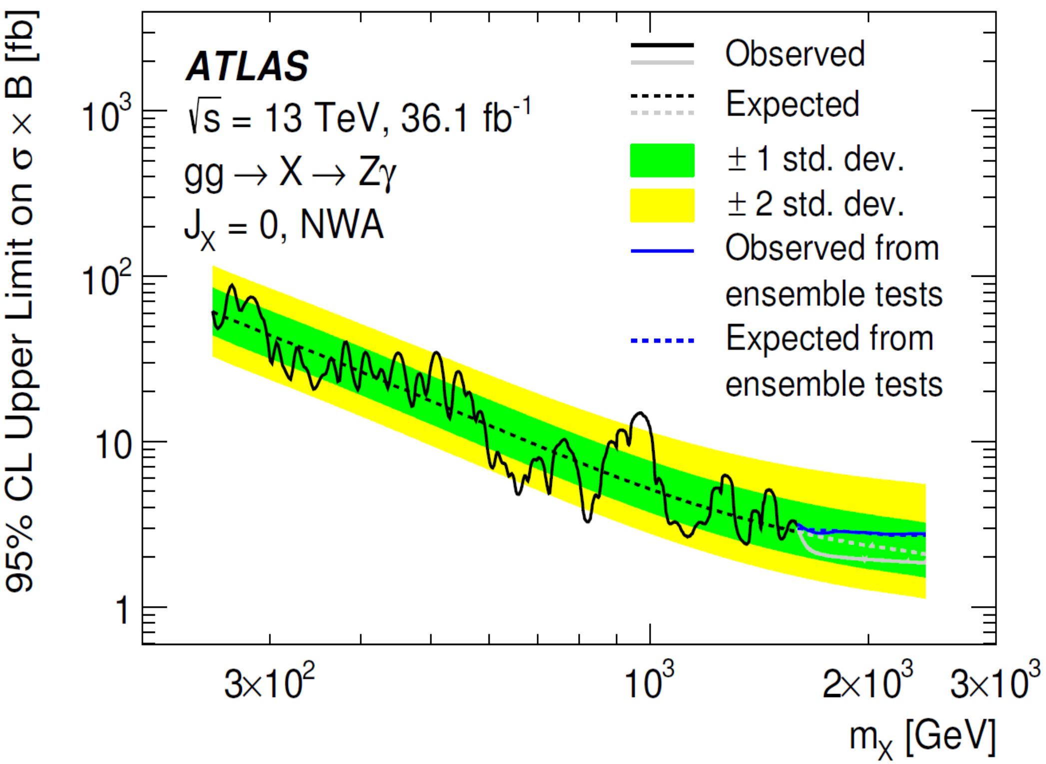


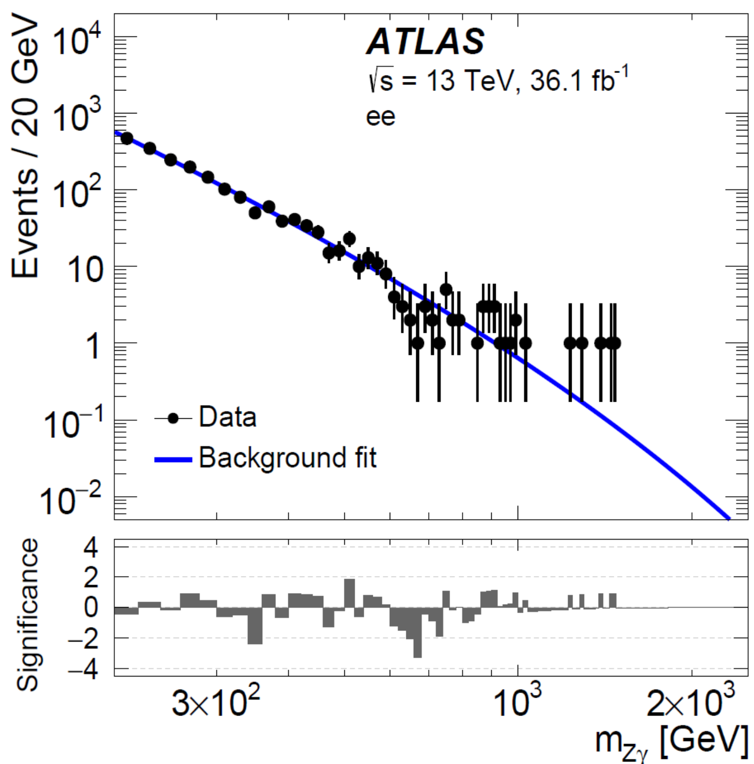


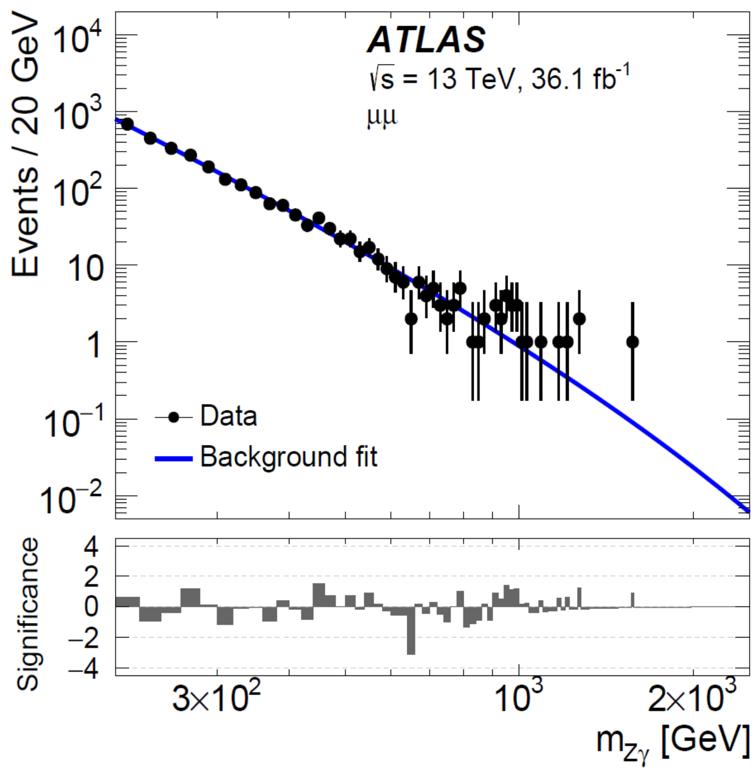
H → Zγ HIGG-2016-14

- X mass range 250 – 2400 GeV
- Two catgeories for the high mass search: Z → ee and Z → μμ, resolution of heavy resonances better in eeγ channel
- Signal shape modelled with Double Sided Crystal Ball
- Background shape model: $f^{k}_{\mathrm{bkg}}(x; b, a_k) = N(1 - x^{1/3})^{b} x^{\sum_{j=0}^{k} a_k \log(x)^{j}}$ (k=0)
  model has to pass spurious signal tests and also an F-test
- No significant excess found, global significance 0.8σ





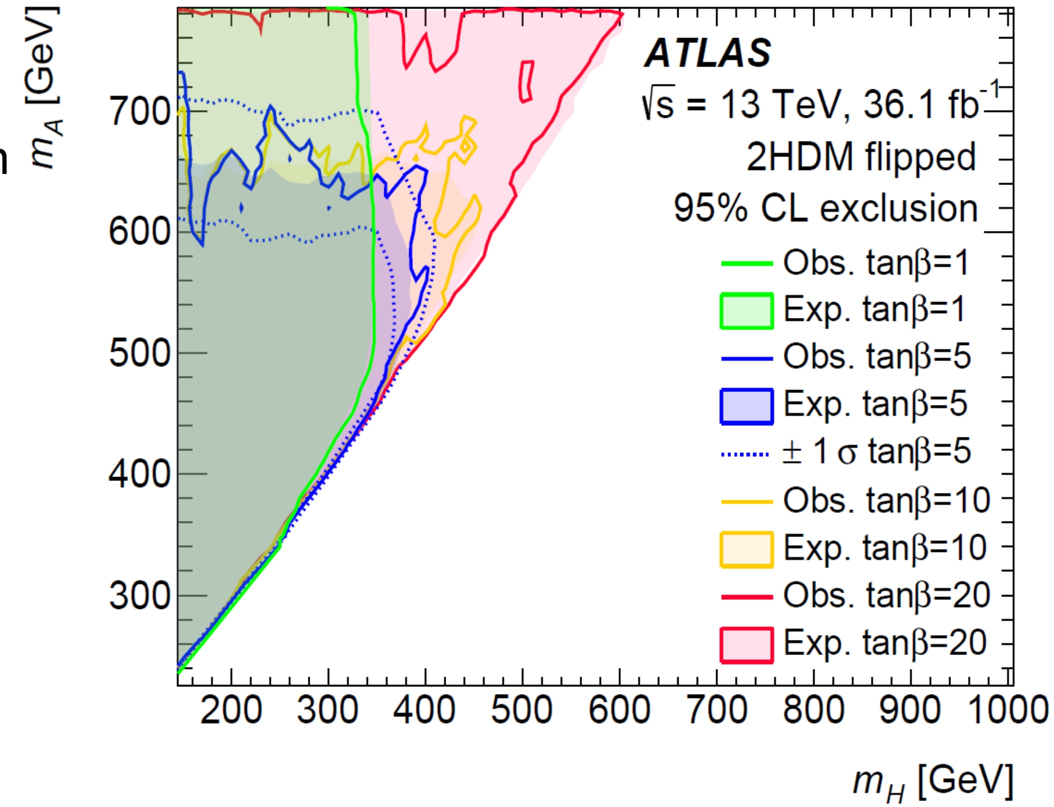


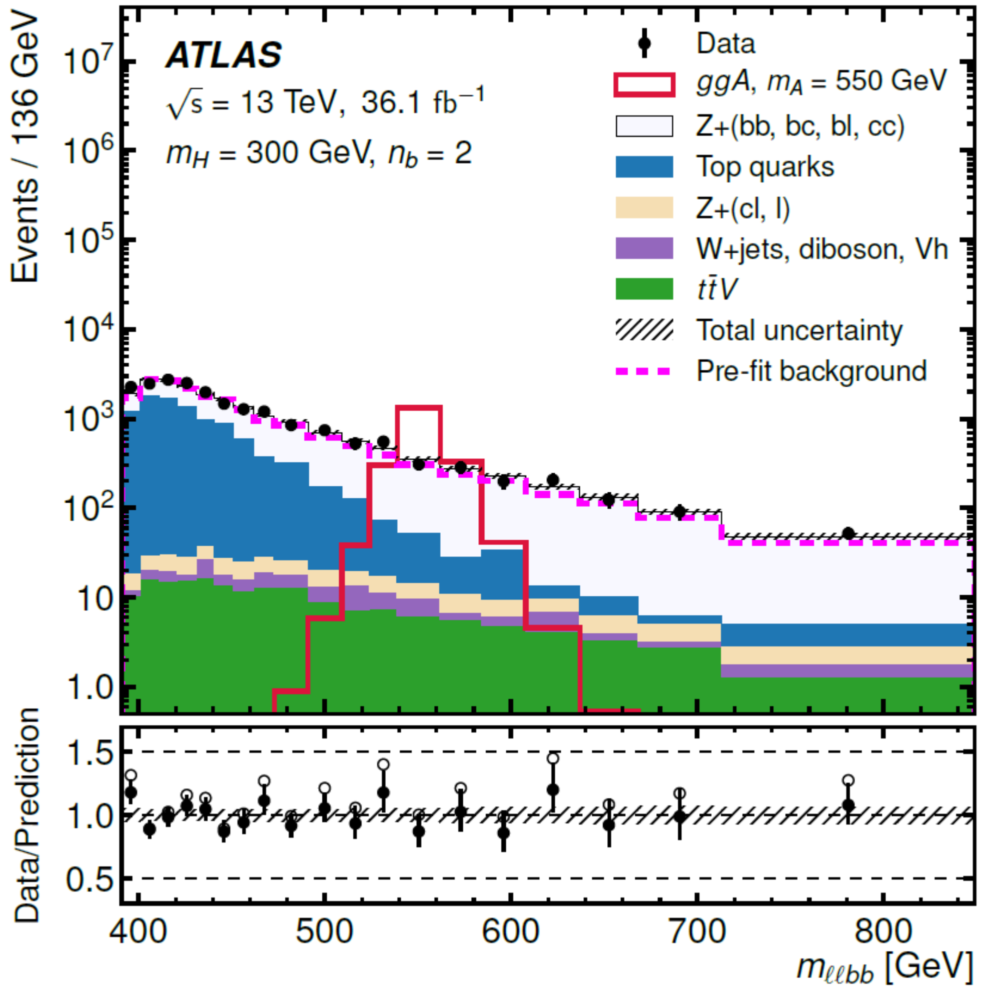


A → Z H → ll bb

EXOT-2016-34

- H is not limited to 125 GeV → 2D scan in A and H mass, **mA > mH**
- Signal produced in gluon-fusion and through b-associated production
- Categories: #b=2, #b>=3 to access both production modes
- 80 < mll < 100 GeV, mbb must be close to the hypothesized H mass





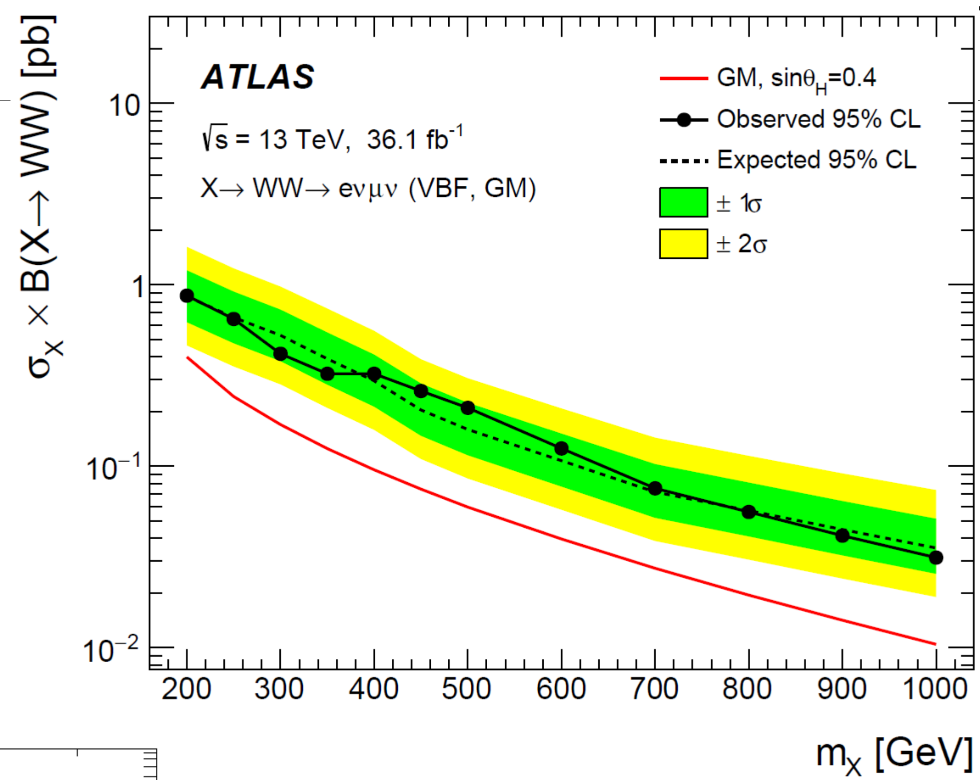
Background estimation:

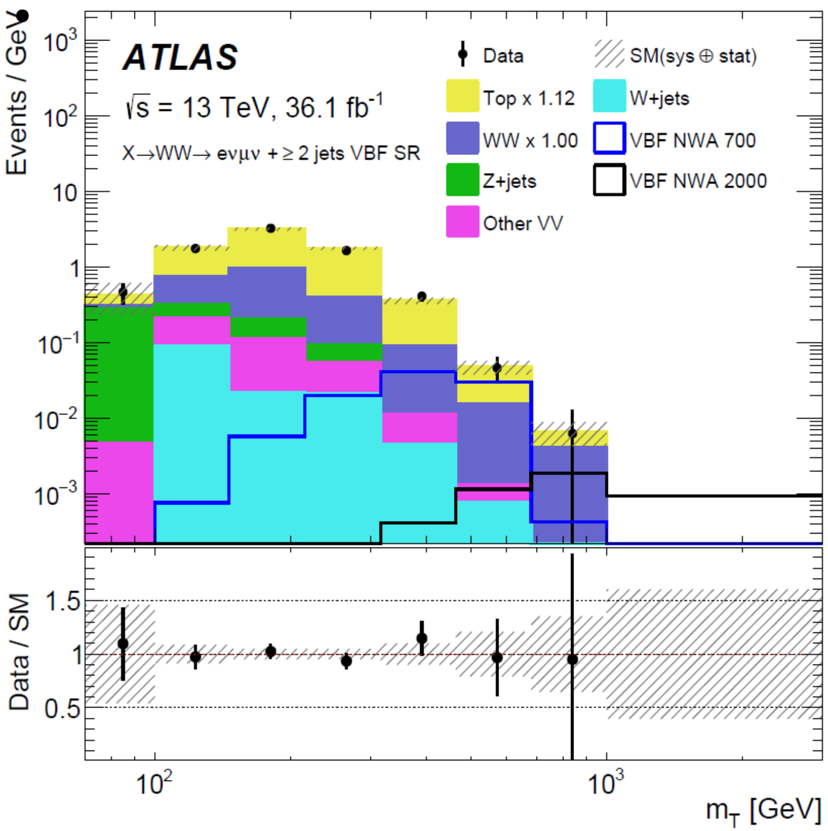
- ttbar: Shape taken from simulation, normalisation from data eμ control region (99% pure)
- Z+jets: Shape from simulation, normalisation obtained from signal region m_{llbb} fit (shapes are sufficiently different)
- Smaller backgrounds estimated entirely from simulation

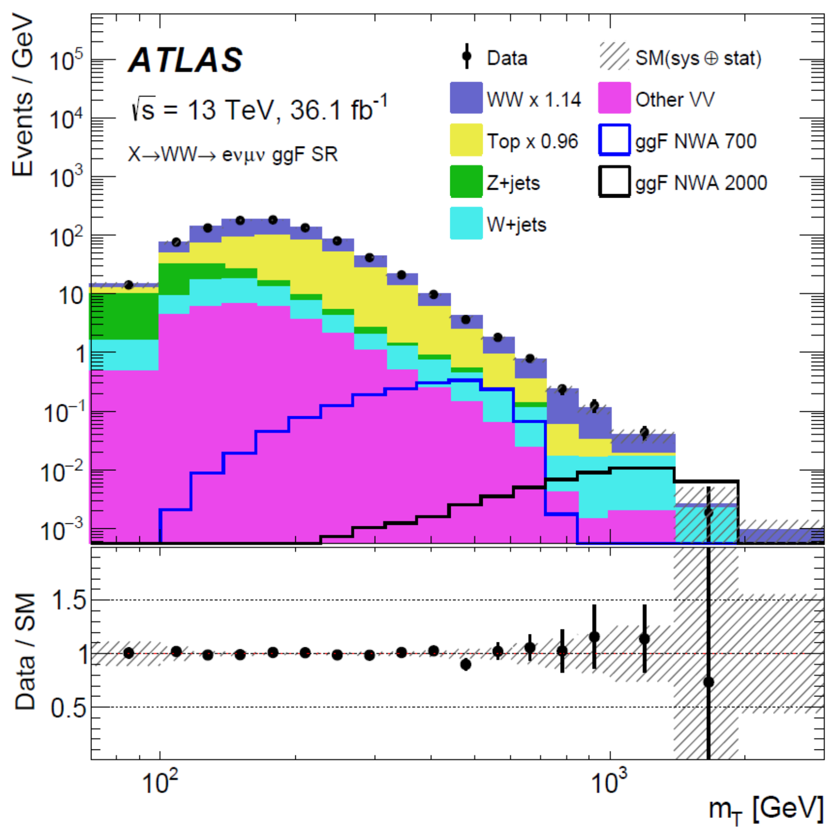
H → WW → eνμν

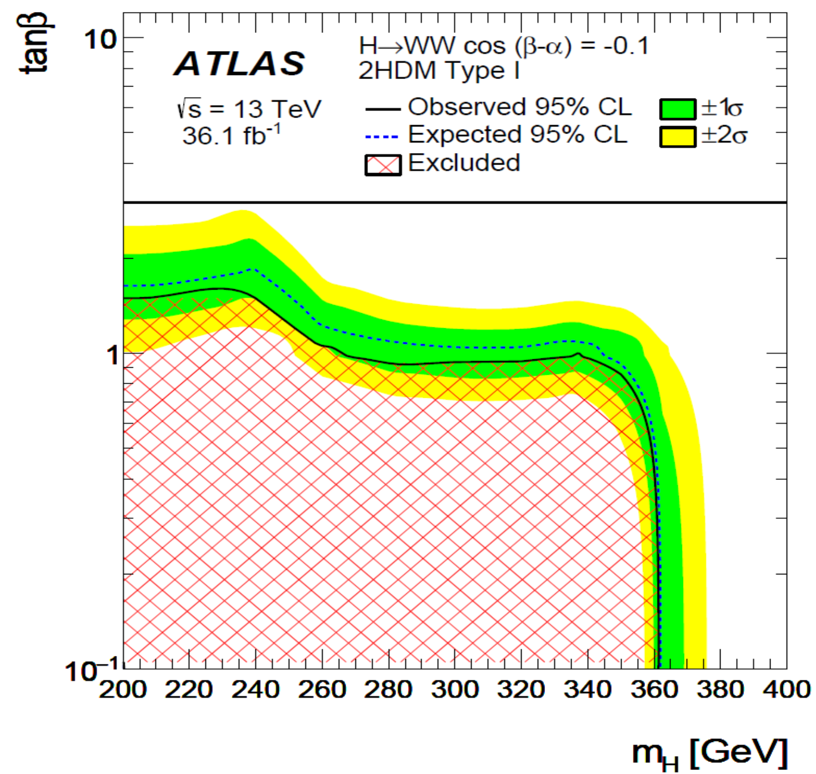
HIGG-2016-31

- 3 signal regions: VBF 1 jet, VBF 2 jets, ggF, all with b-jet veto
- WW background modelled with Sherpa, reweighted to NNLO theory
- SM Higgs is a background, interference of off-shell component with continuum background is considered
- ttbar and WW background normalised in data control regions
- Final discriminant $m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$





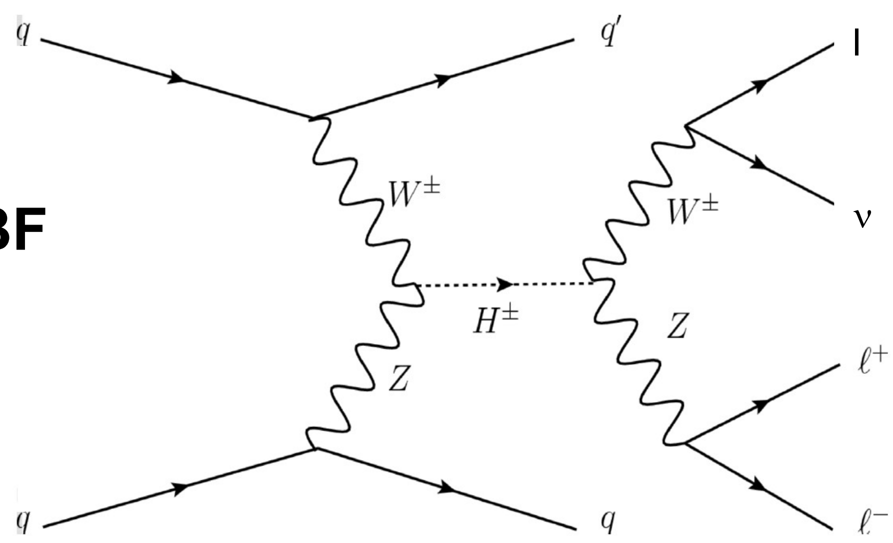


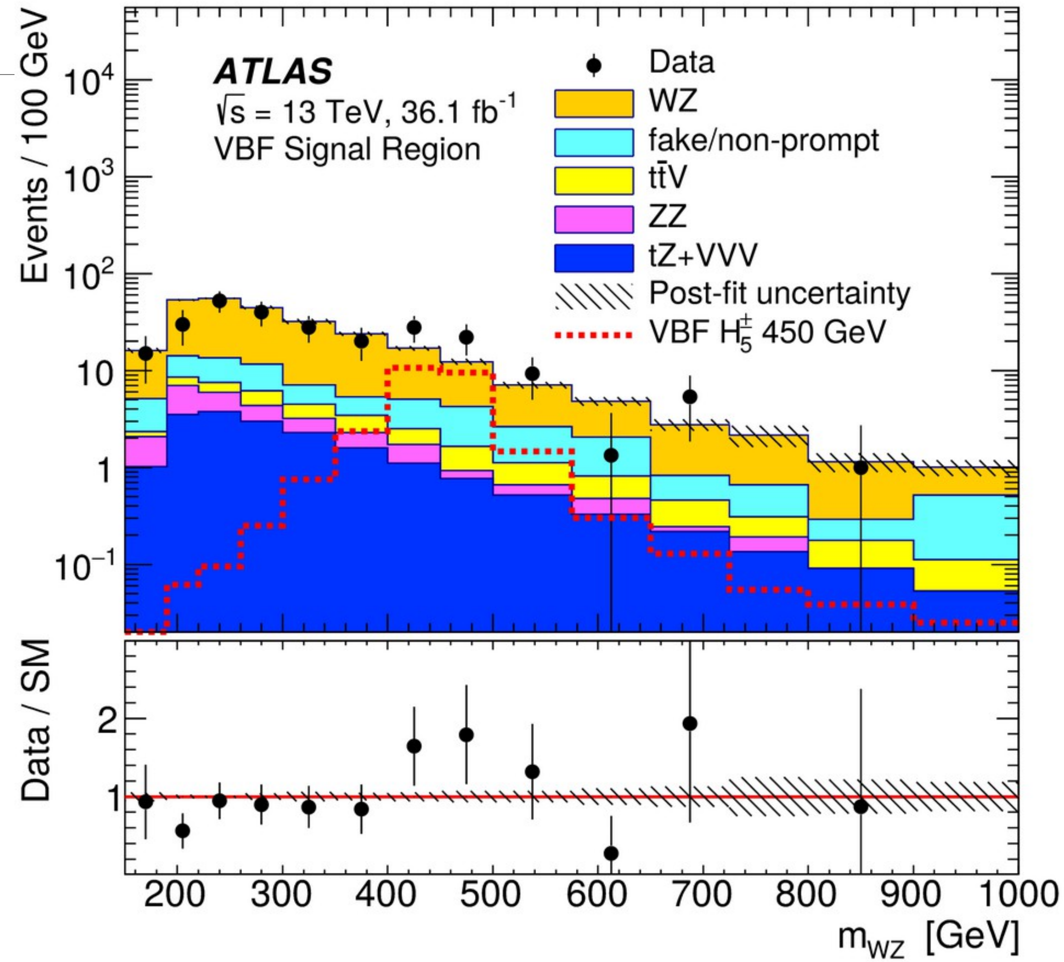


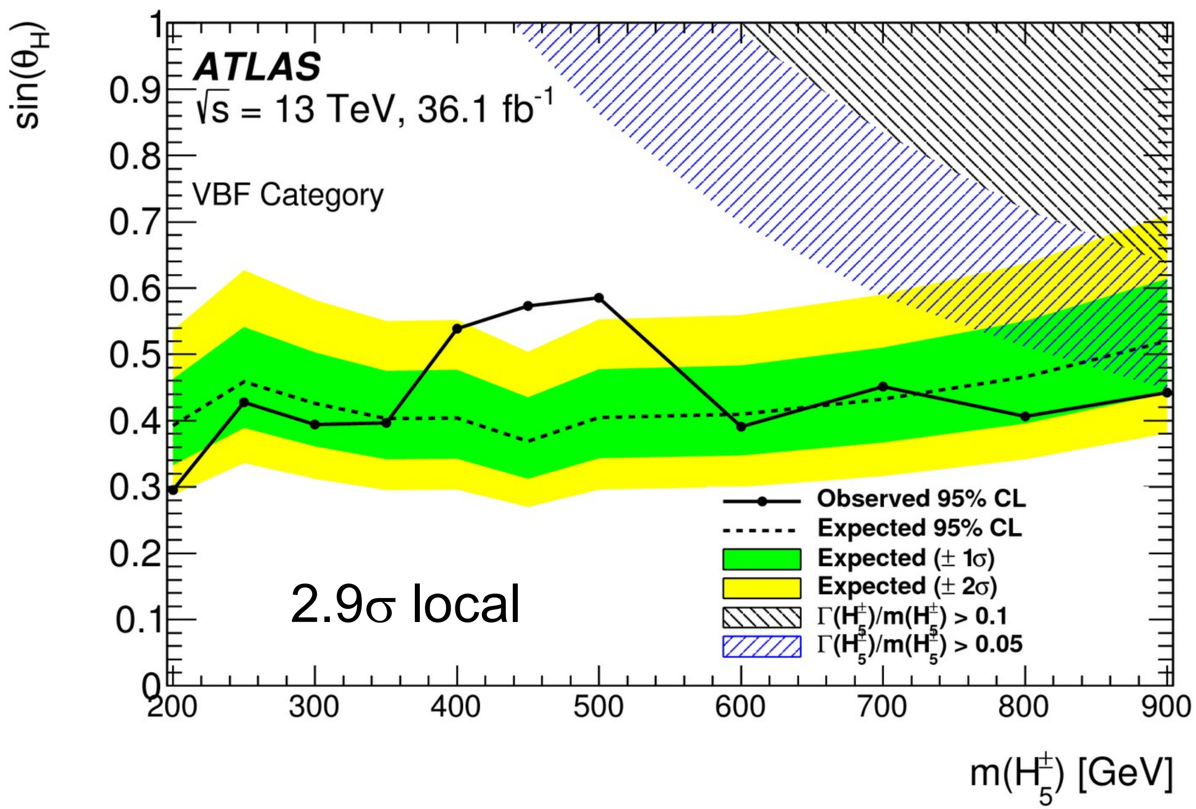
$H^+ \rightarrow WZ$

EXOT-2016-11

VBF



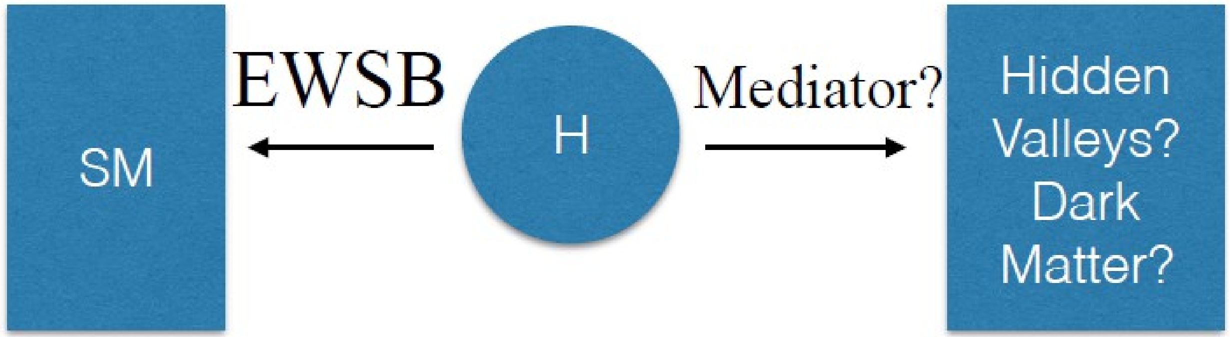




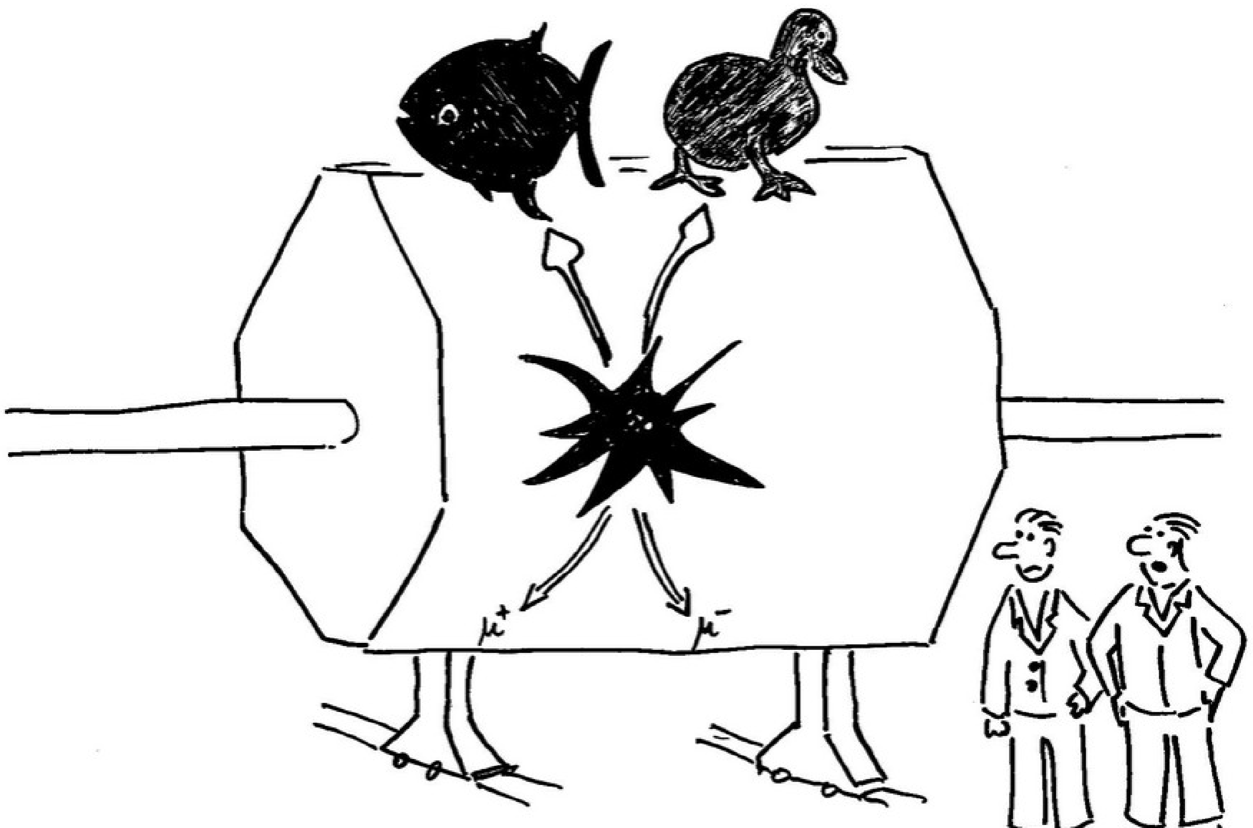
- 3 leptons, MET > 25 GeV, b-jet veto
- m(WZ) fully reconstructed, with the solution for neutrino p_z that gives W mass
- VBF selection on jets (m_{jj}>500 GeV, $|\Delta\eta_{jj}|$>3.5)
- Georgi Machacek model Nucl. Phys. B 262 (1985) 463
  10 Higgs bosons, fermiophobic 5-plet H_5^{++}, H_5^{+}, H_5

Search for light resonances

New particles might couple preferentially to the Higgs boson:

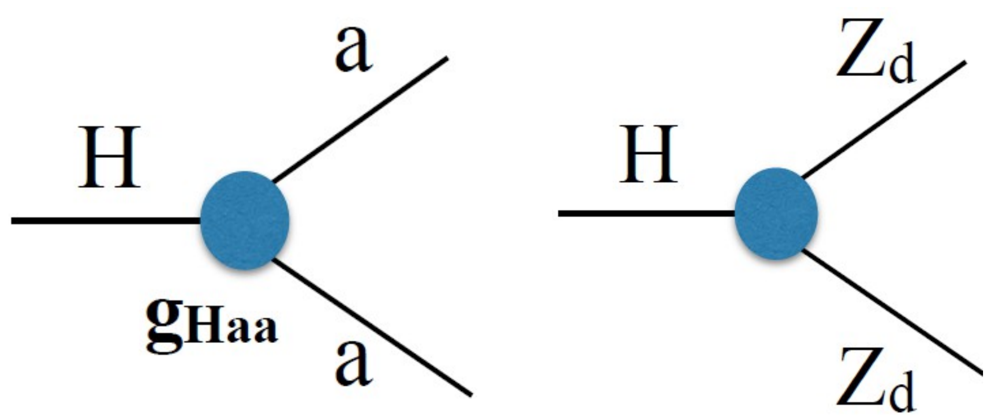


Typical benchmarks:
- SM + dark gauge symmetry $U(1)_d$
- 2HDM+S
- NMSSM



“This is not exactly, what theory predicted for the Higgs decay!”

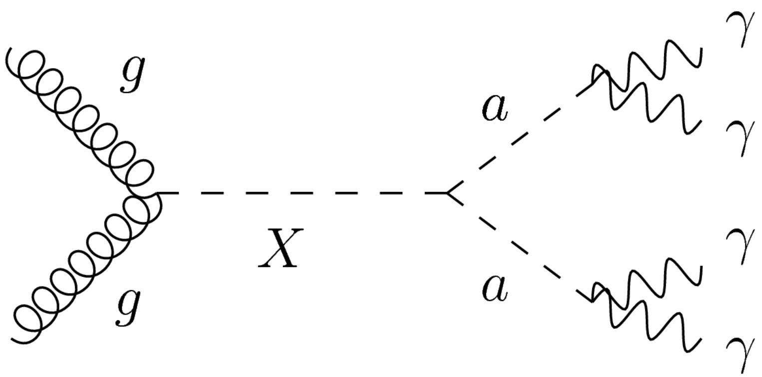
- Extended Higgs sector with a light singlet
- Hidden interactions, coupling to dark sector



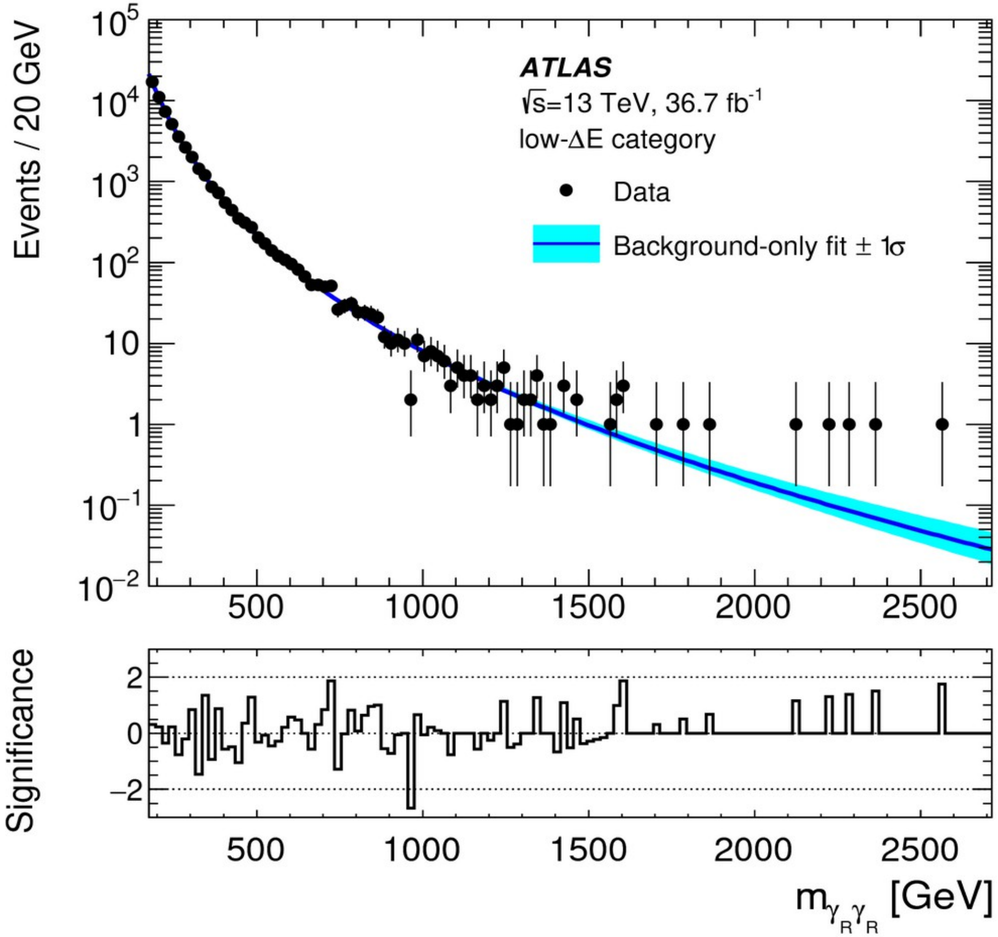
More results presented by Scott Snyder on Tuesday:
https://indico.cern.ch/event/749003/contributions/3343033/

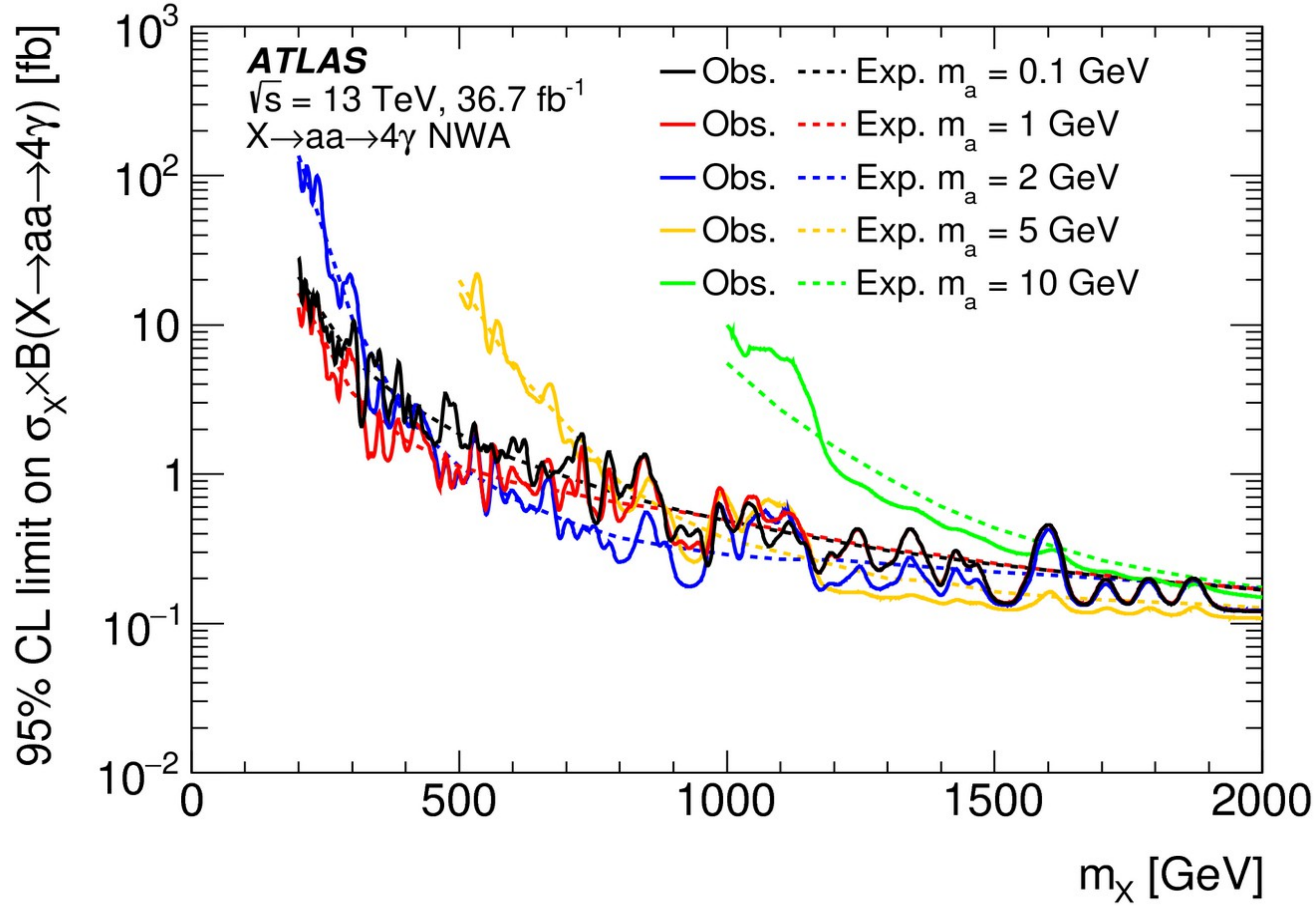
$X \to aa \to$ photon-jets

EXOT-2017-08



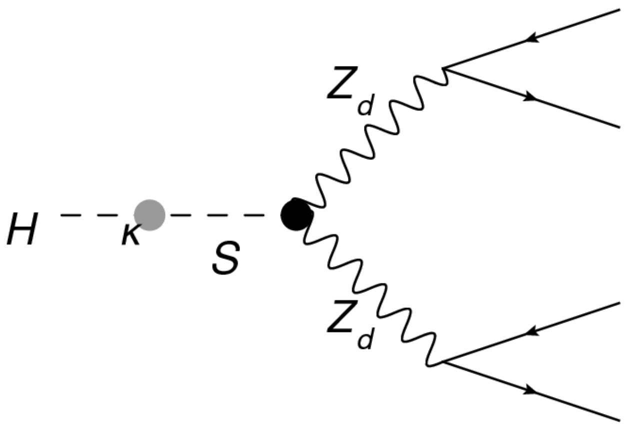
- Probed X mass range 0.2 - 2 TeV, a mass range 0.1-10 GeV
- Strongly boosted decay products → appear as a single photon-like energy cluster („photon-jet“), typically with $\Delta R_{\gamma\gamma}$<0.04
- Energy deposits in the strip layer used for categorising events
- Largest background: non-resonant pp → γγ





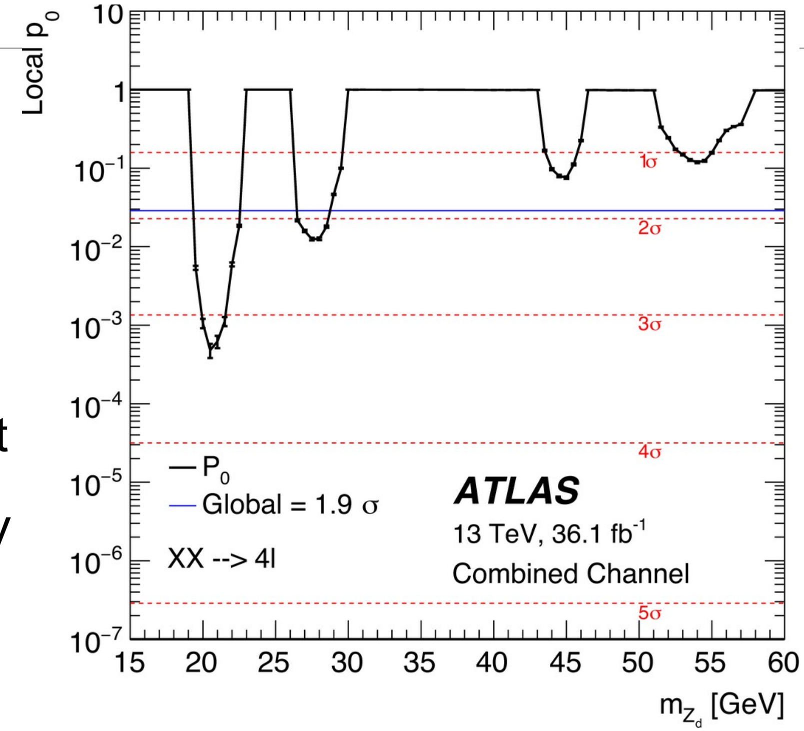
$H \rightarrow Z_{dark} Z_{dark} \rightarrow 4l$

EXOT-2016-22

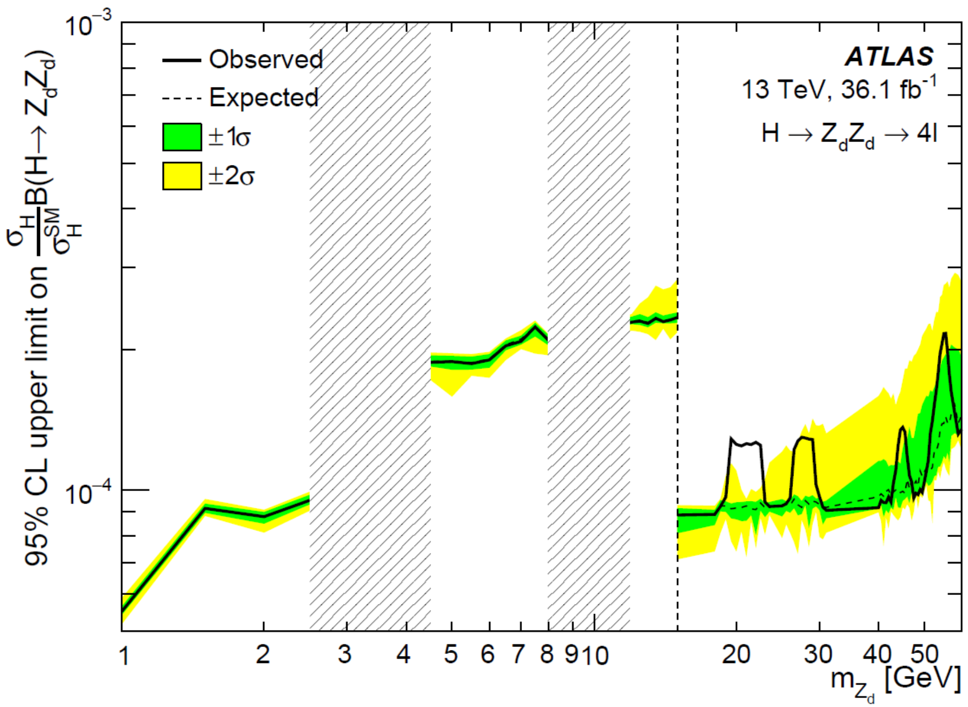


H: SM Higgs boson
κ: Higgs portal coupling
S: Dark Higgs boson
Zd: Dark vector boson

- Single, di- or tri-lepton triggers, ~100% efficient

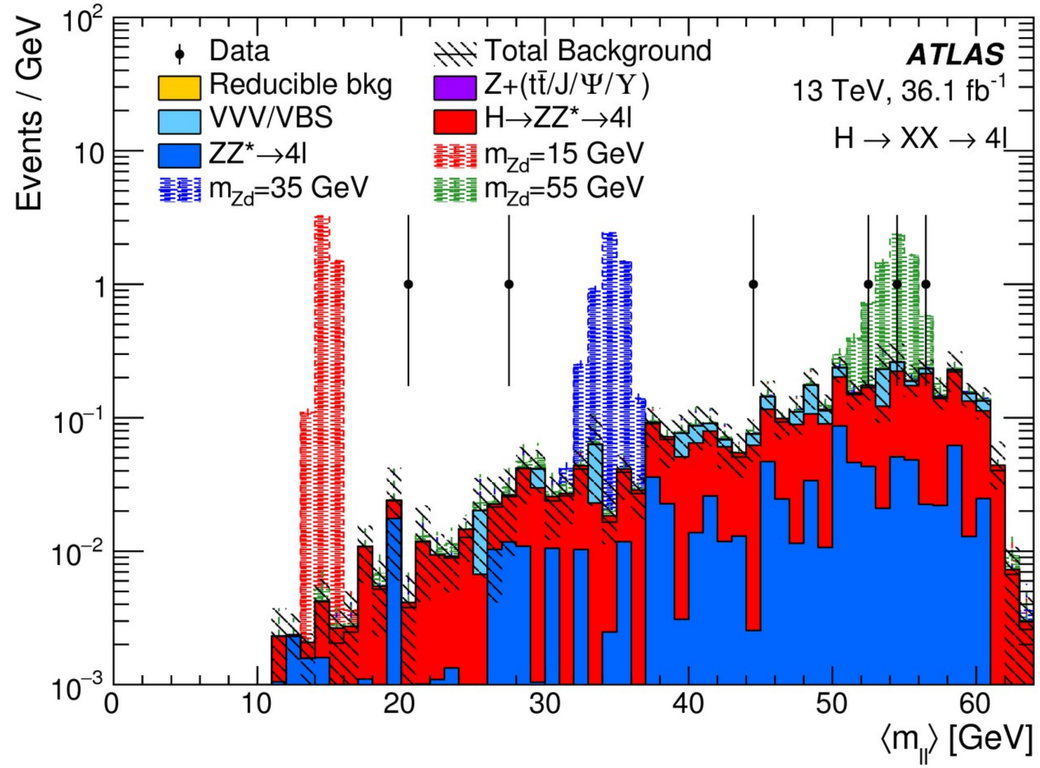


- Select events with 4e or 4μ, ie. 2 SFOS lepton pairs, lead lepton pT > 20 GeV
- m_{4l} must be close to Higgs mass 115 < m_{4l} < 130 GeV
- Select lepton quadruplet from combination that minimizes $|m_{12}-m_{34}|$



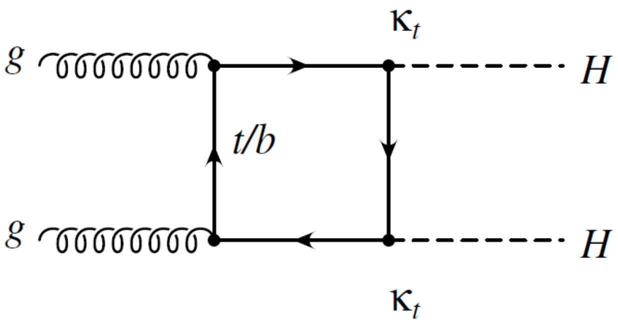
Largest excess at 20 GeV (1 event) 3.2σ local

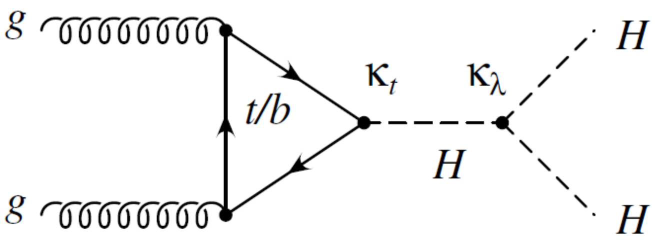
Quarkonia regions excluded (vetoed during selection)



DiHiggs Searches

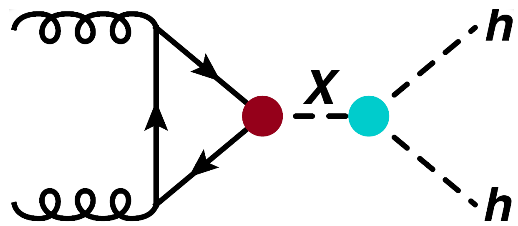
Non-resonant





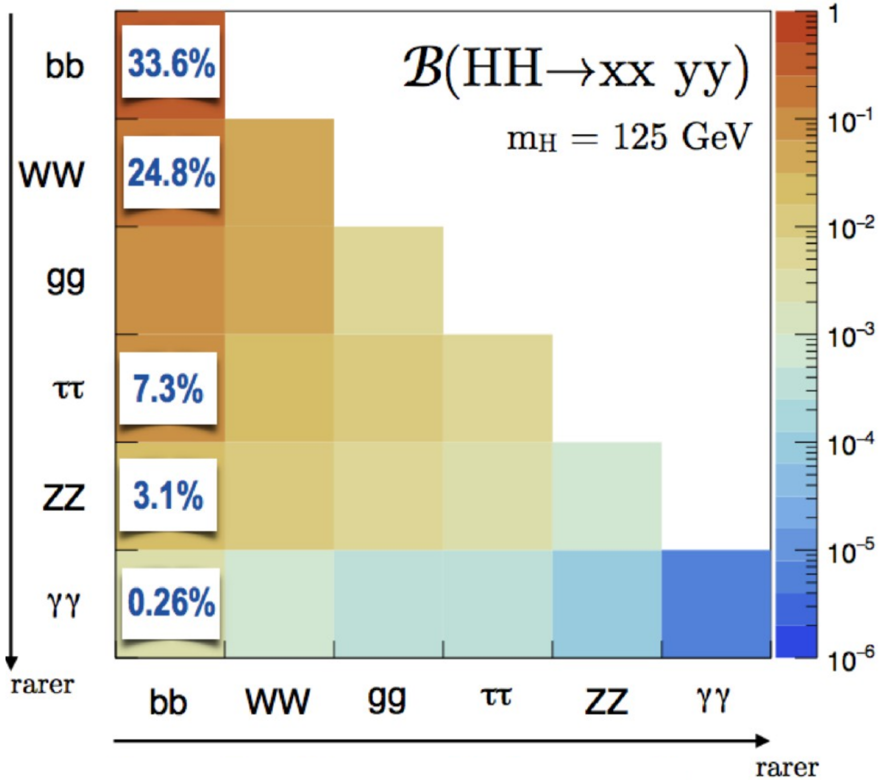
→ See the talk on non-resonant by Muhammad Kiani on Tuesday:
https://indico.cern.ch/event/749003/contributions/3343034/

Resonant

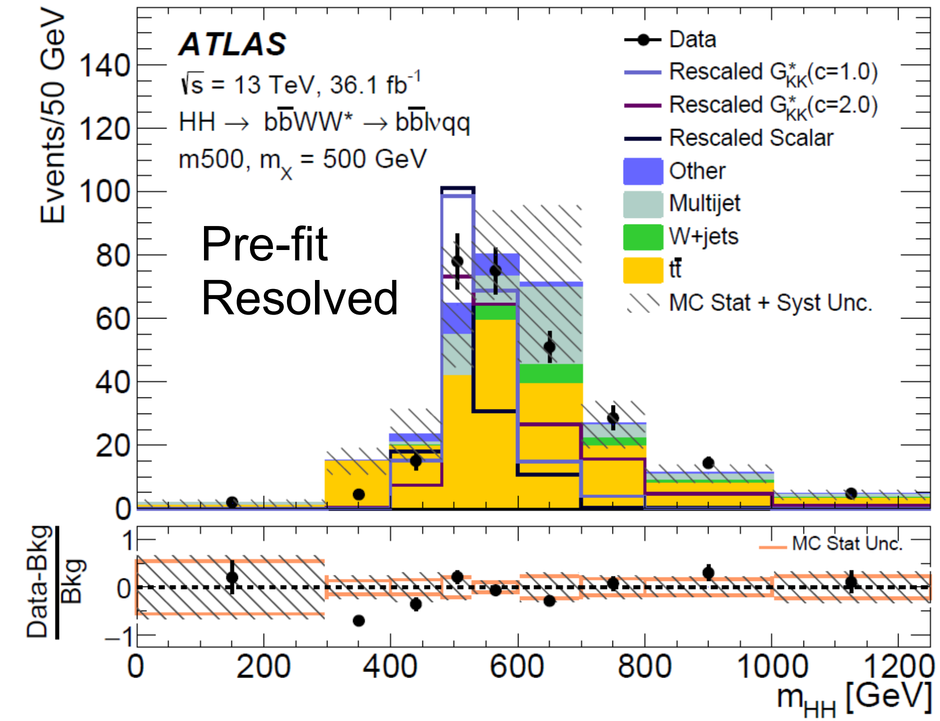


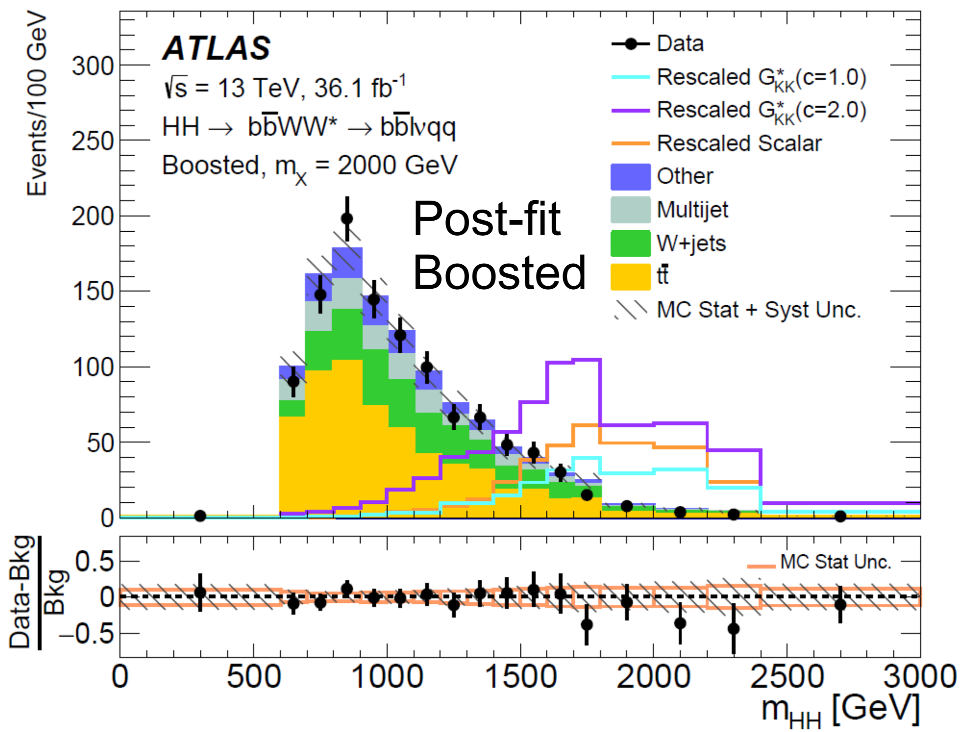
X can be a heavy Higgs (spin-0) or a Graviton (spin-2)

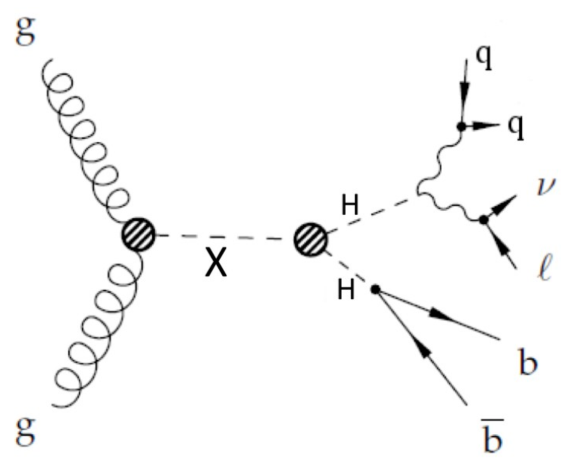
HH branching fractions:

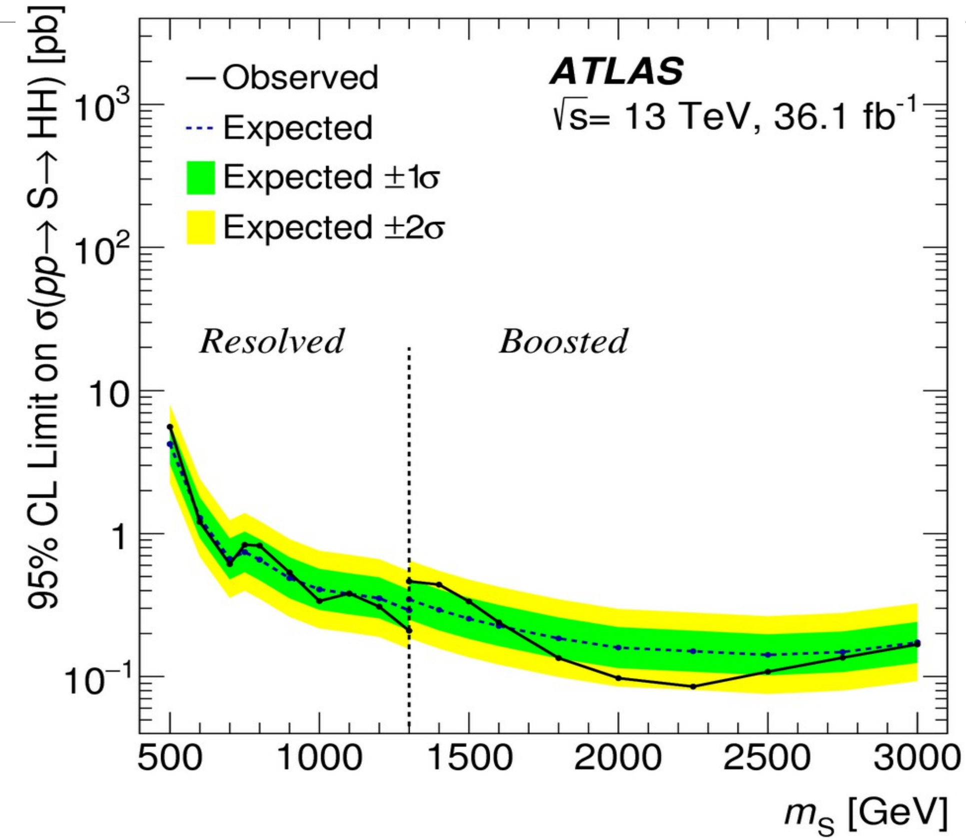


X → HH → WWbb (1-lepton) HIGG-2016-27



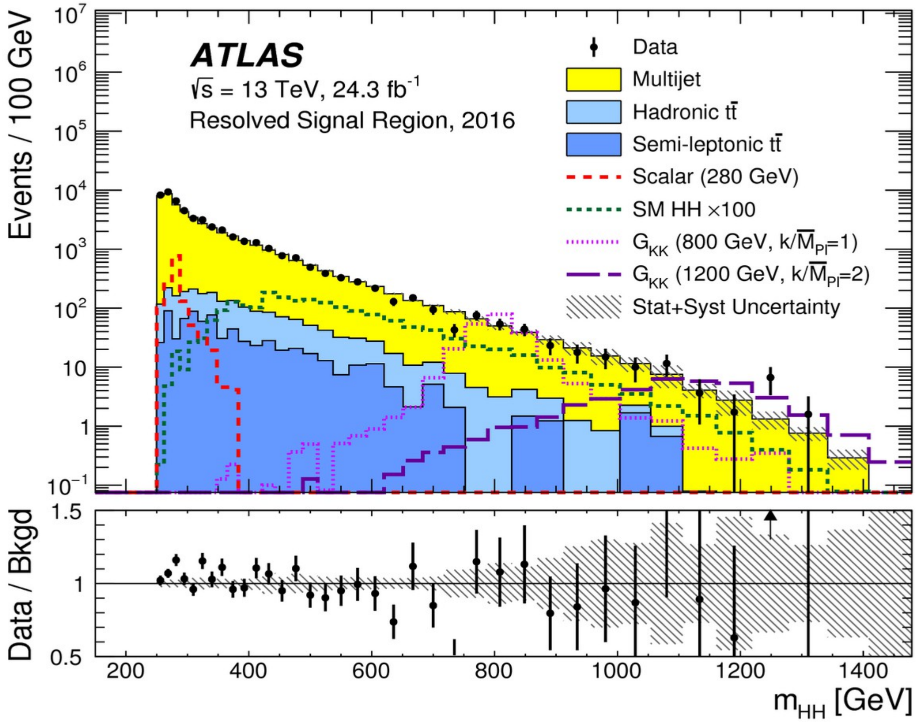


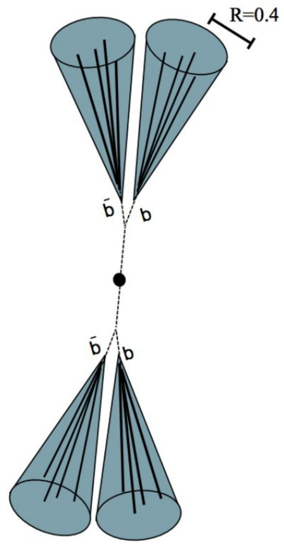




- W W→lνqq system fully reconstructed, pZ of the neutrino estimated from the visible information and using m_{WW}=125 GeV
- Resolved selection:
  2 b-tagged small-R jets,
  Kinematic cuts differently optimized in 3 different mass ranges and for the non-resonant signal (MET, m_{WW}, p_T^{bb}, p_T^{WW}, ΔR_{WW}, m_{bb})
- Boosted selection:
  A large-R jet that contains the H → bb candidate,
  two small-R jets to identify the jets from the WW system

X → HH → 4b EXOT-2016-31

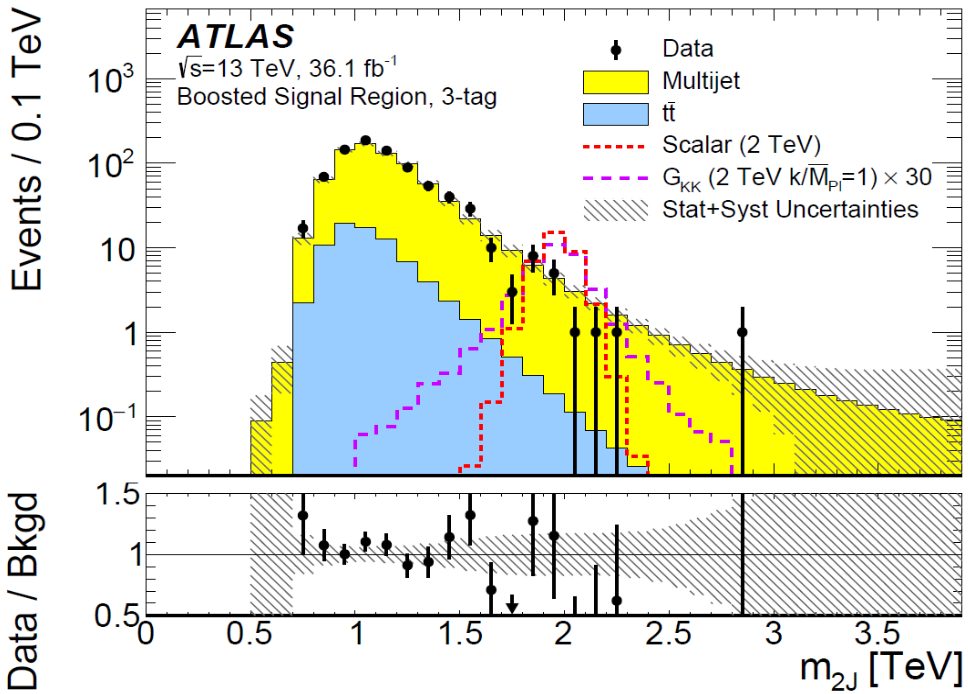


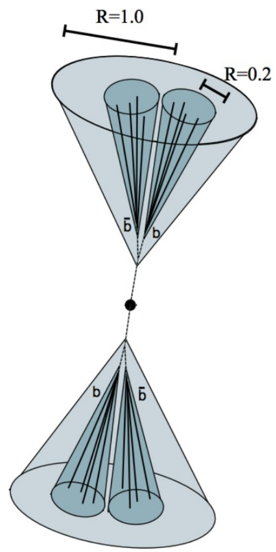


Resolved selection:
- 4 b-tagged small-R jets (R=0.4, 70%WP)
- Background modelled using events with 2 b-jets

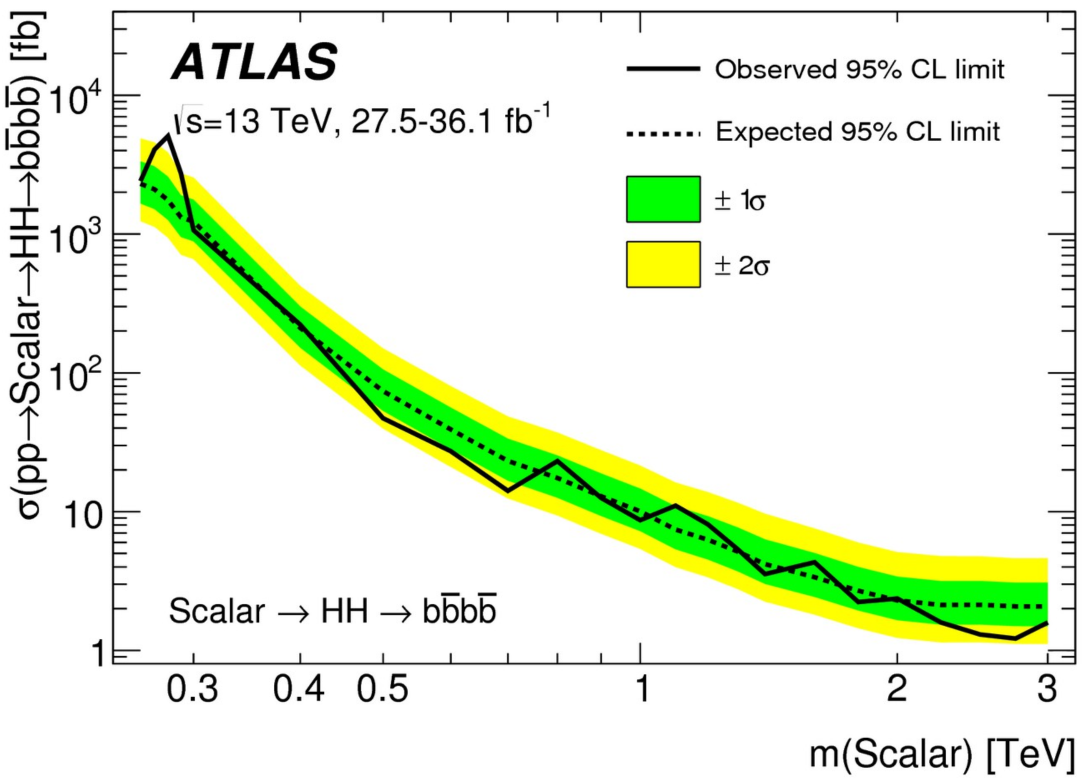
Boosted selection:
- 2 large-R jets (R=1.0)
- 3 categories with either 2, 3 or 4 b-tagged track-jets

Both channels were stat. combined for 800-1300 GeV



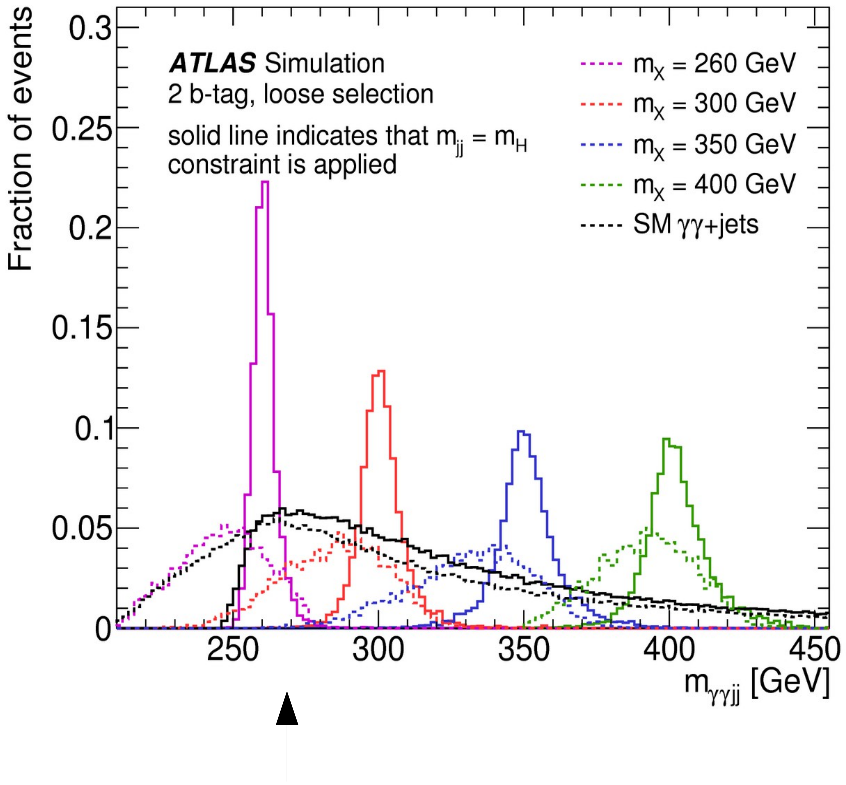


Best HH channel at high mass (>500 GeV)



$X \rightarrow HH \rightarrow bb\gamma\gamma$

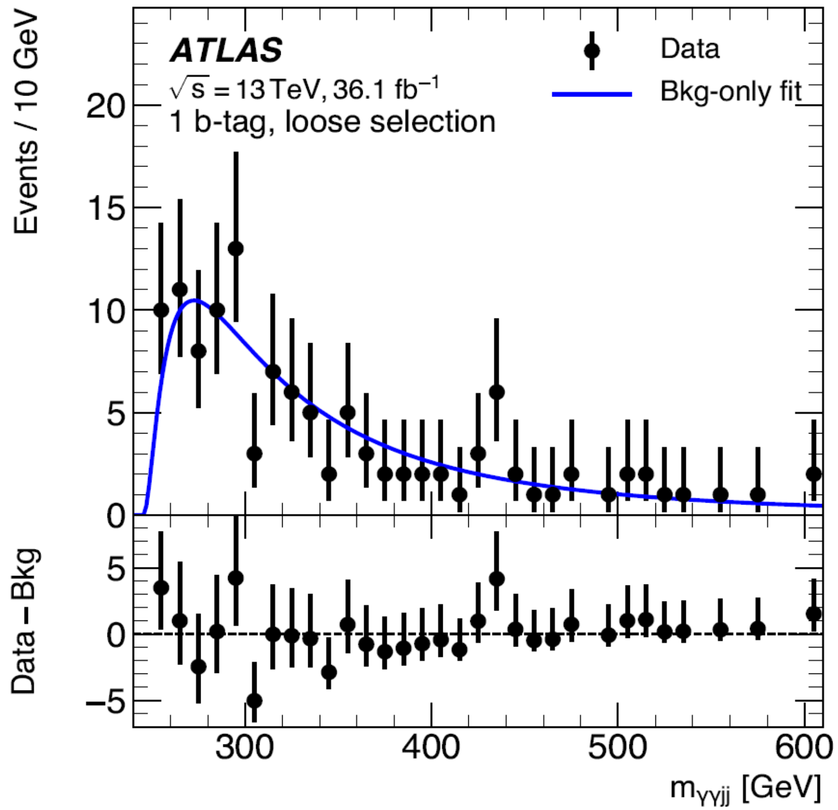
HIGG-2016-15

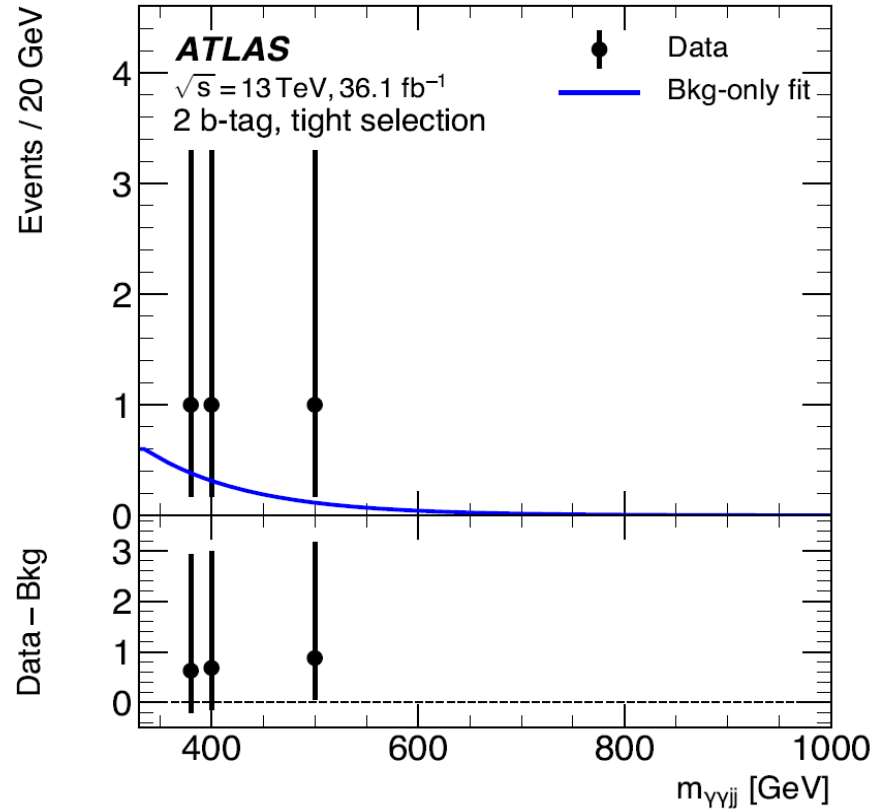


Nice improvement in γγjj mass resolution when applying 125 GeV constraint to the dijet mass

Statistics limited, expect huge improvements from full run-2 luminosity alone

- Categories: 1b/2b, each with loose/tight kinematic cuts (jet pT, mjj, mγγ) (where tight is a subset of loose, tight is used to set limits on mX>500 GeV, loose is used for mX<500 GeV)
- NN-based vertex selection algorithm using fine-granularity of strip calo layer
- In case of 1 b-jet: 2nd jet is selected based on BDT jet pairing algorithm (inputs: jet pT and η, dijet pT and η, Δηjj)
- Final discriminant is γγjj mass
- Best channel for resonances with mass 260 - 400 GeV





HH Combination (Resonant)

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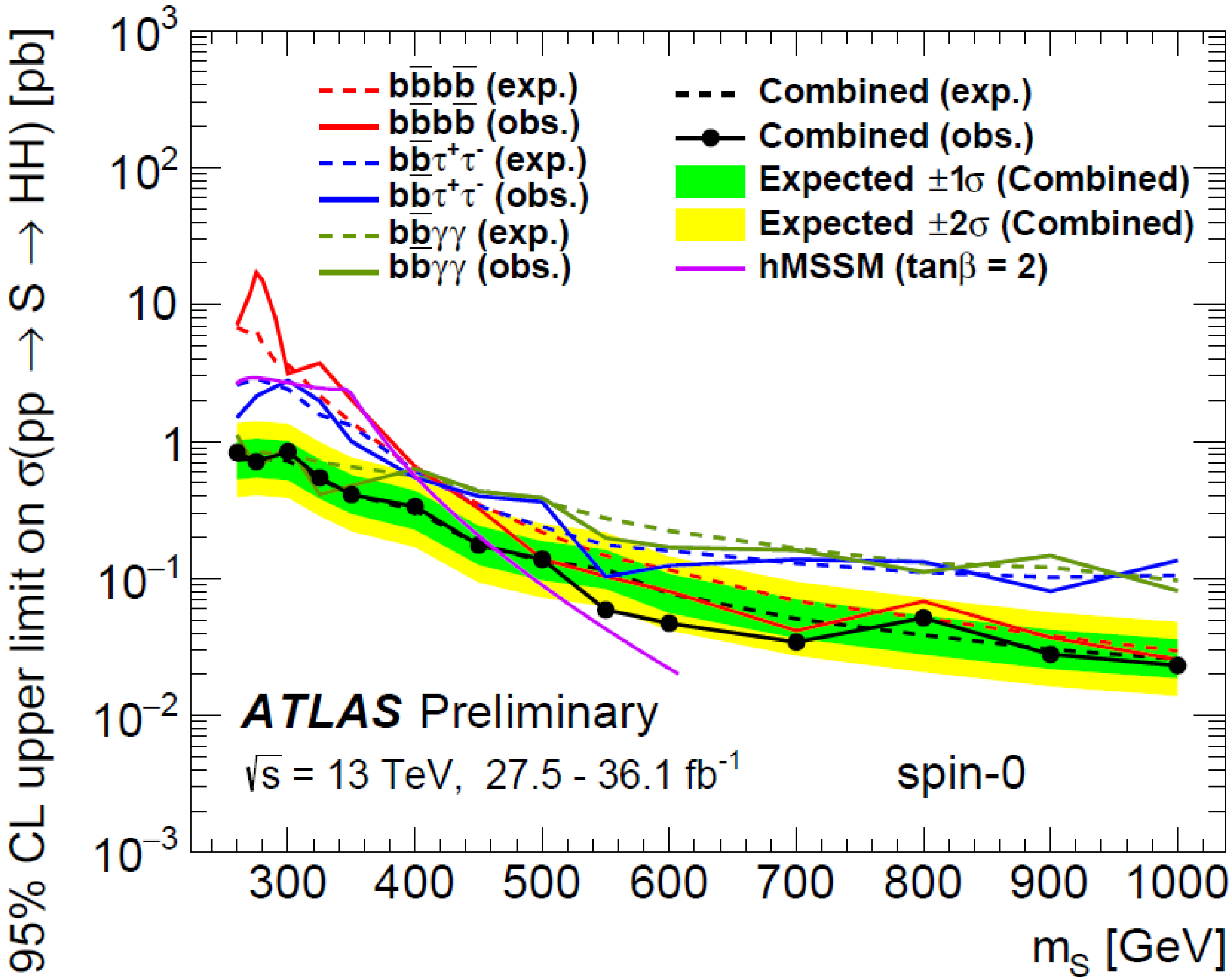
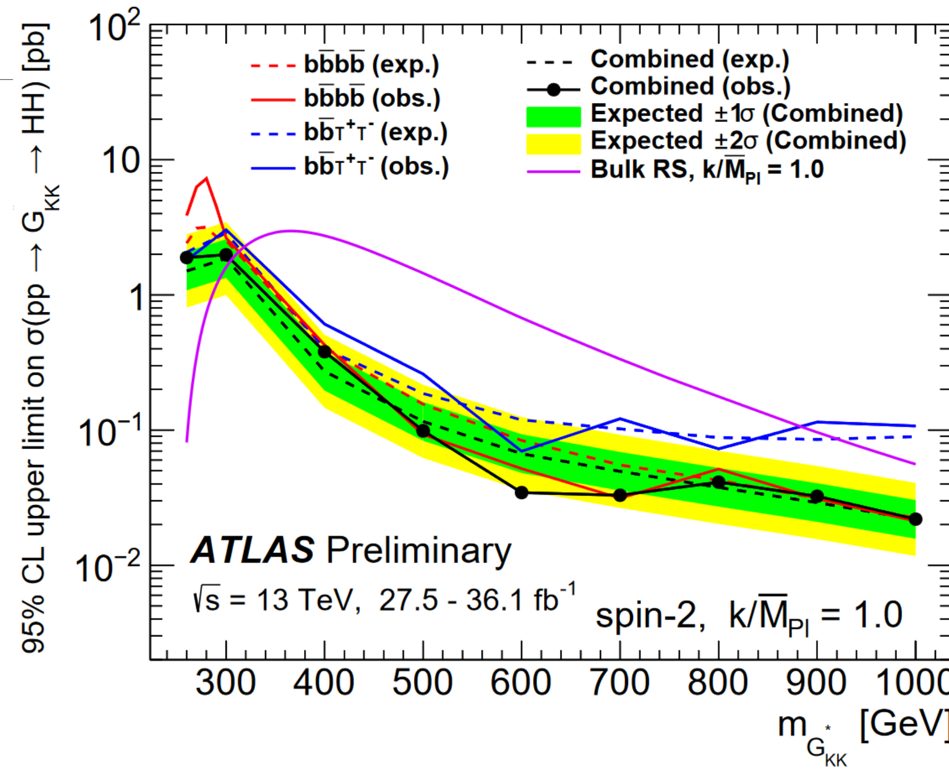
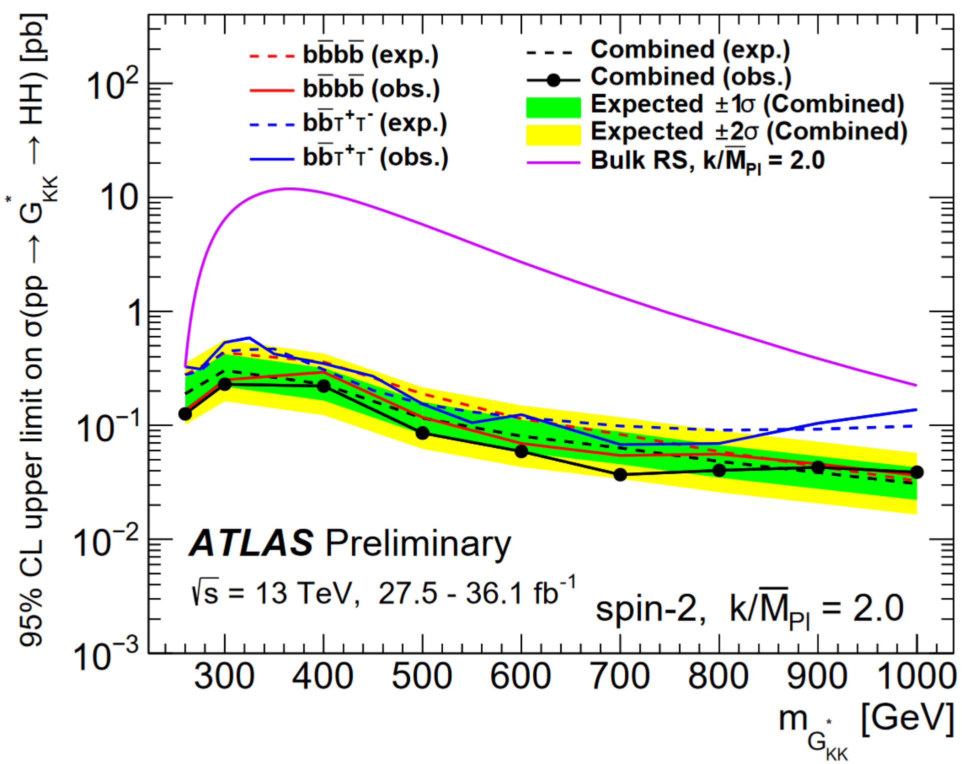
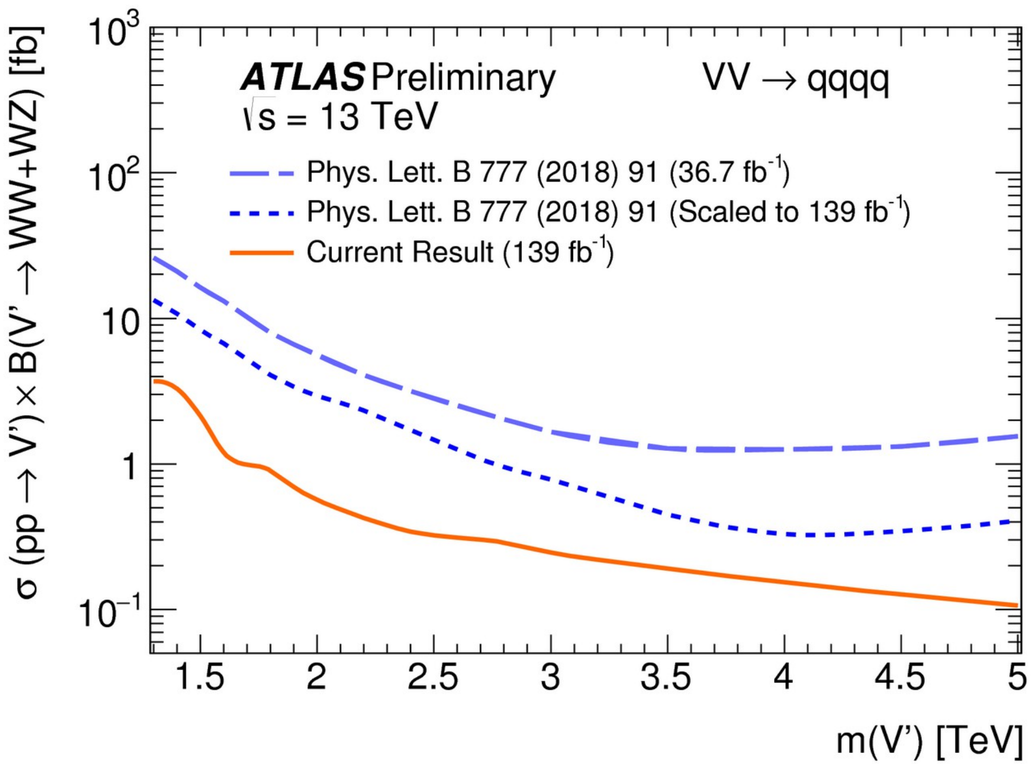


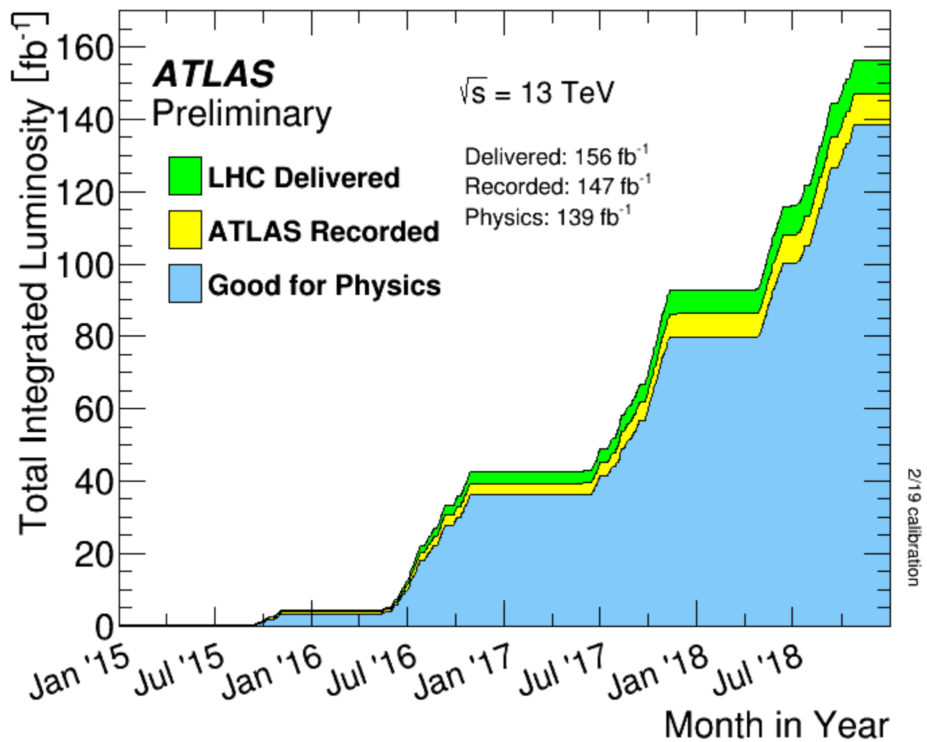




Summary

- First full run-2 ATLAS results are becoming available
- Recent improvements in analysis techniques used in boosted diboson searches increased the sensitivity much beyond what we had projected
- Many more exciting results will arrive gradually this year and in the next years
- No excesses found, no hint for new particles so far
- Most results presented here use only 1% of the total expected LHC dataset (3/ab)

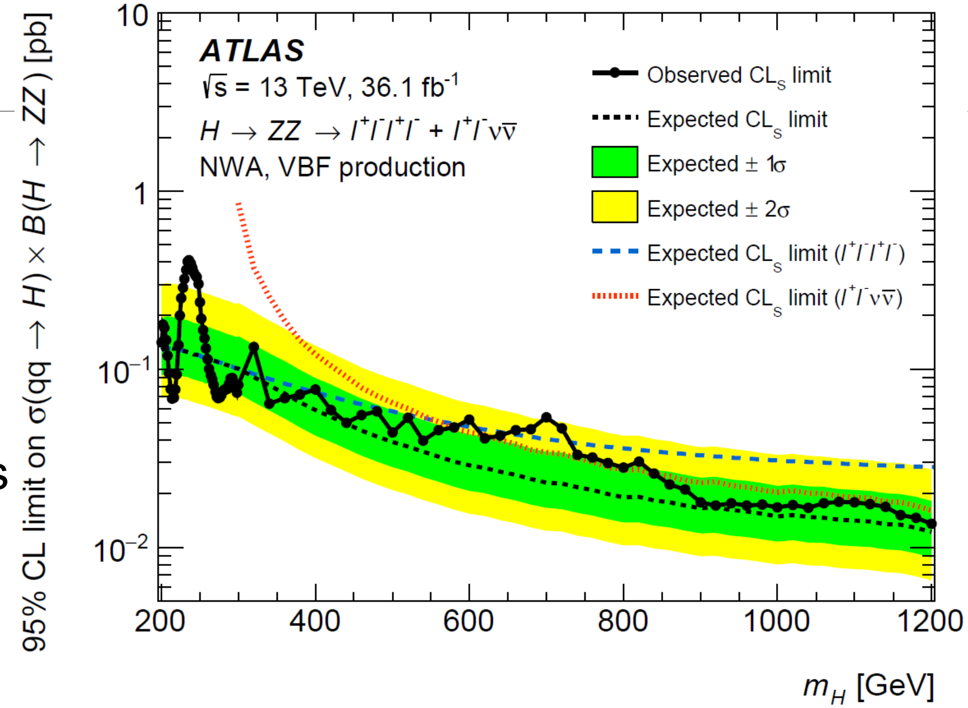


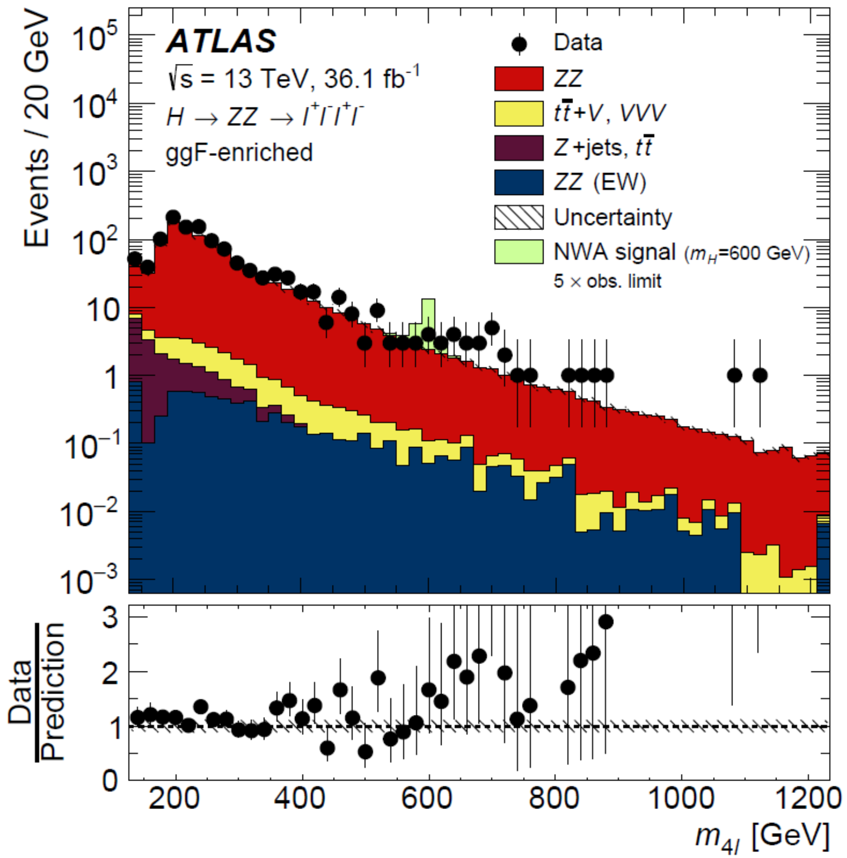


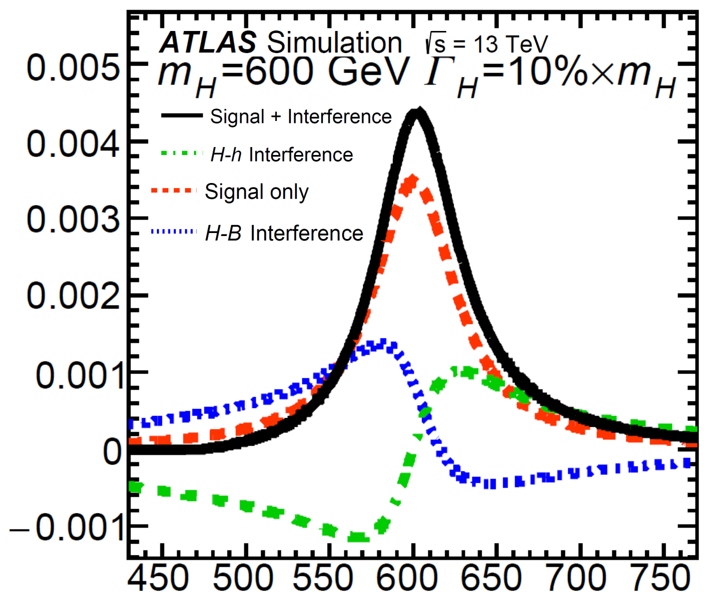
Backup

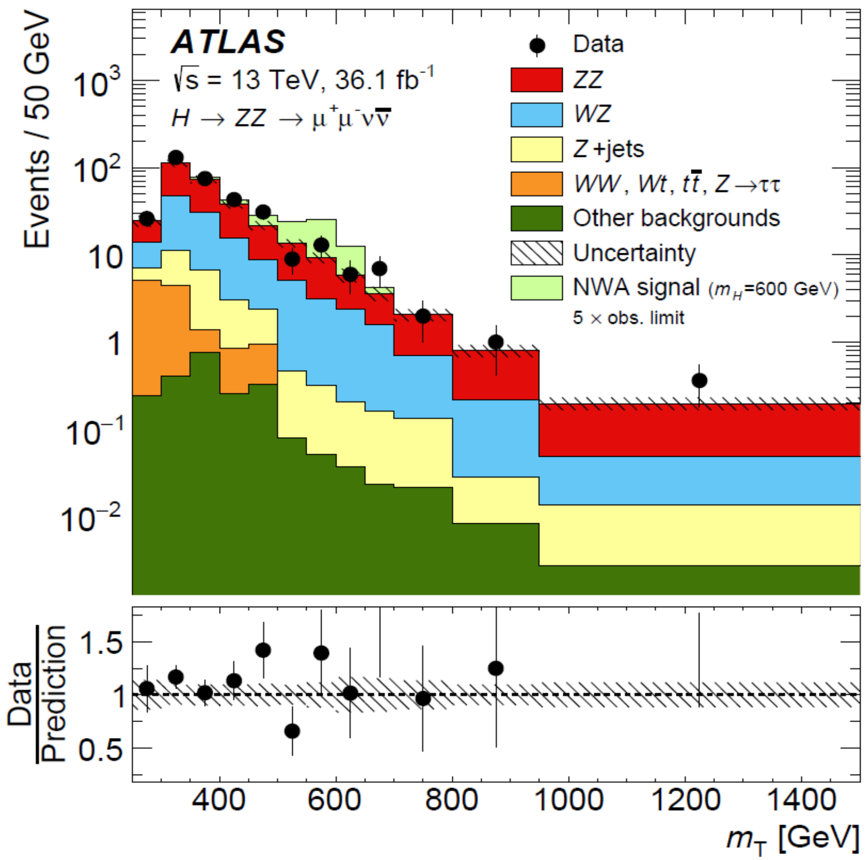
$H \rightarrow ZZ \rightarrow 4l$ or $ll\nu\nu$ HIGG-2016-19

- 4l channel: 4 categories (ggF 4e, ggF 4μ, ggF 2e2μ, VBF 4l)
- 2l2ν channel: 2 categories (ggF, VBF)
- 2 slight excesses in 4l: 240 GeV, 700 GeV (2.2σ global), 700 GeV excess excluded by llνν which is more sensitive at high mass
- Interference of signal with $gg \rightarrow ZZ$ continuum considerd, also interference of SM H with heavy new scalar considered







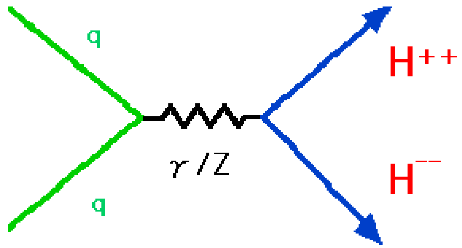


H$^{++}\to$WW

Theory: arXiv:1105.1925

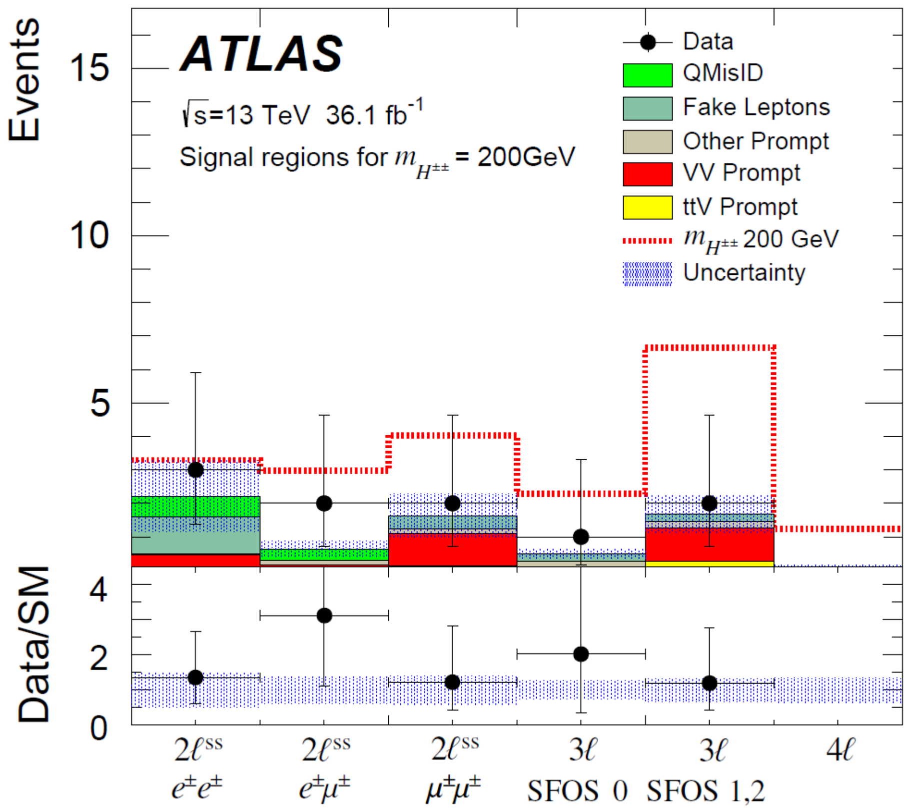
$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \quad \text{and} \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

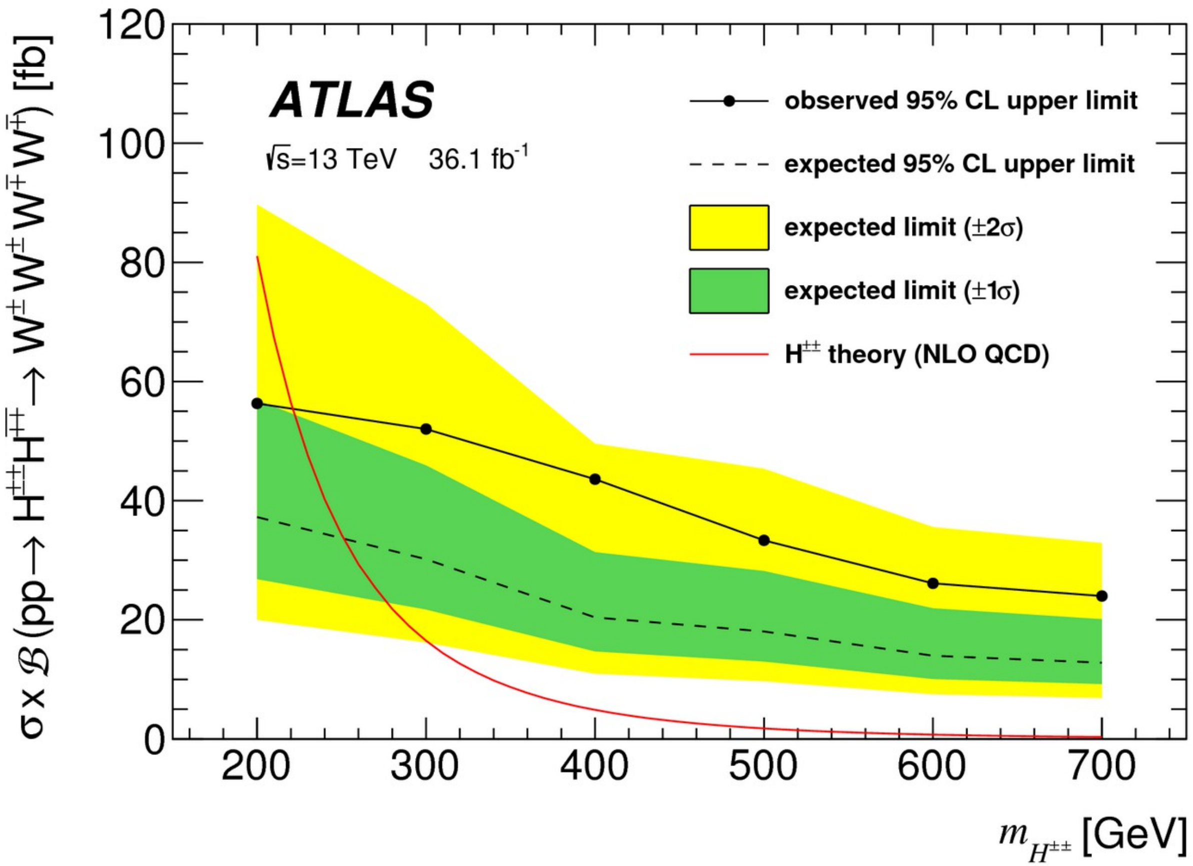
SM Higgs Doublet and additional hypercharge Y=2 scalar triplet
→ 7 Higgs bosons (H$^{\pm\pm}$, H$^{\pm}$, A, H, h), h is SM like
→ Triplet conveniently provides non-zero neutrino masses (type-II seesaw mechanism)



3 catgeories: 2l (same-sign), 3l, 4l   MET > 70 GeV (30 GeV) for 2l (3l, 4l)

Cut-based selection, optimized with TMVA

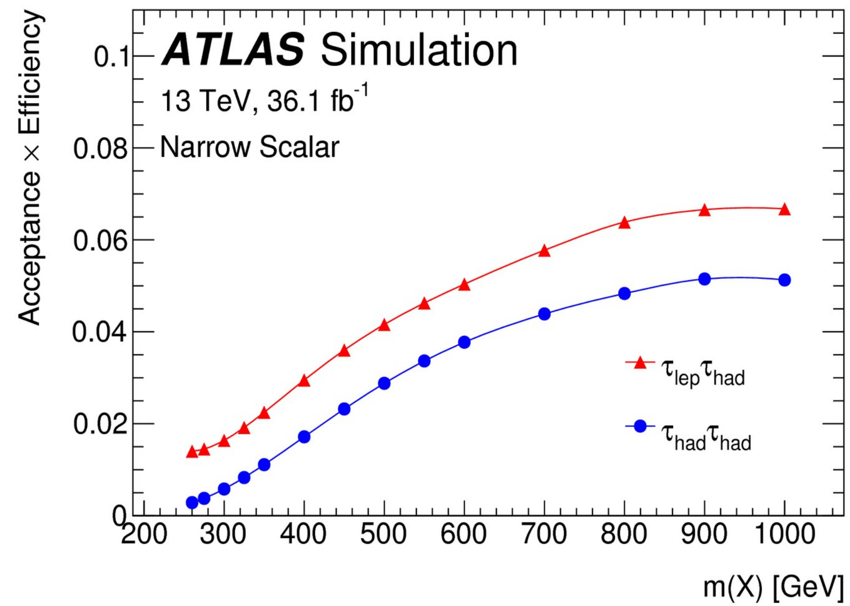




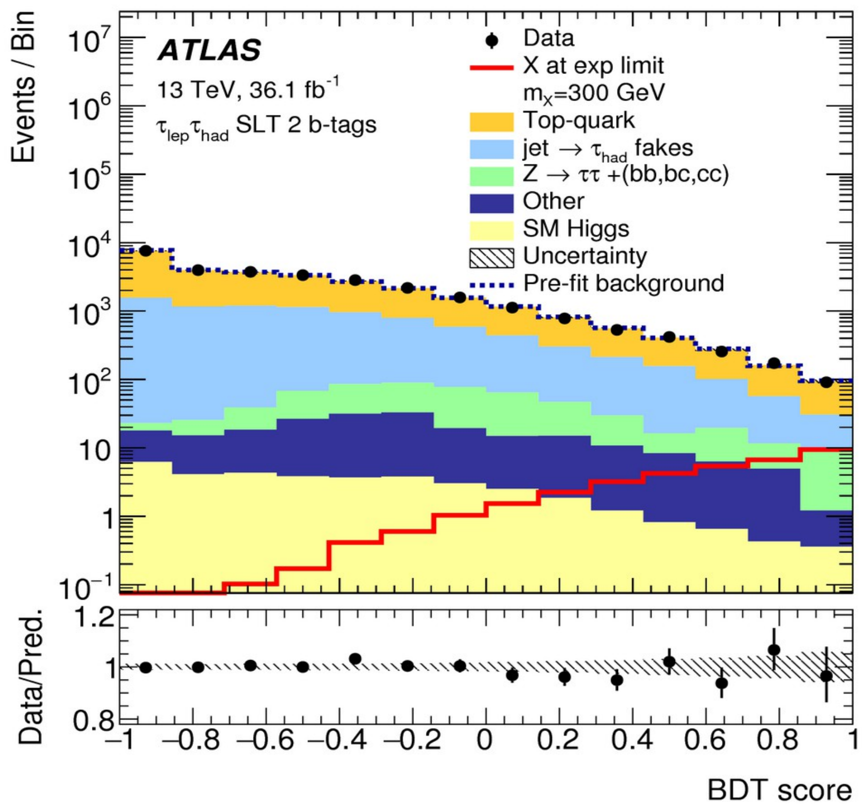
X → HH → bbττ

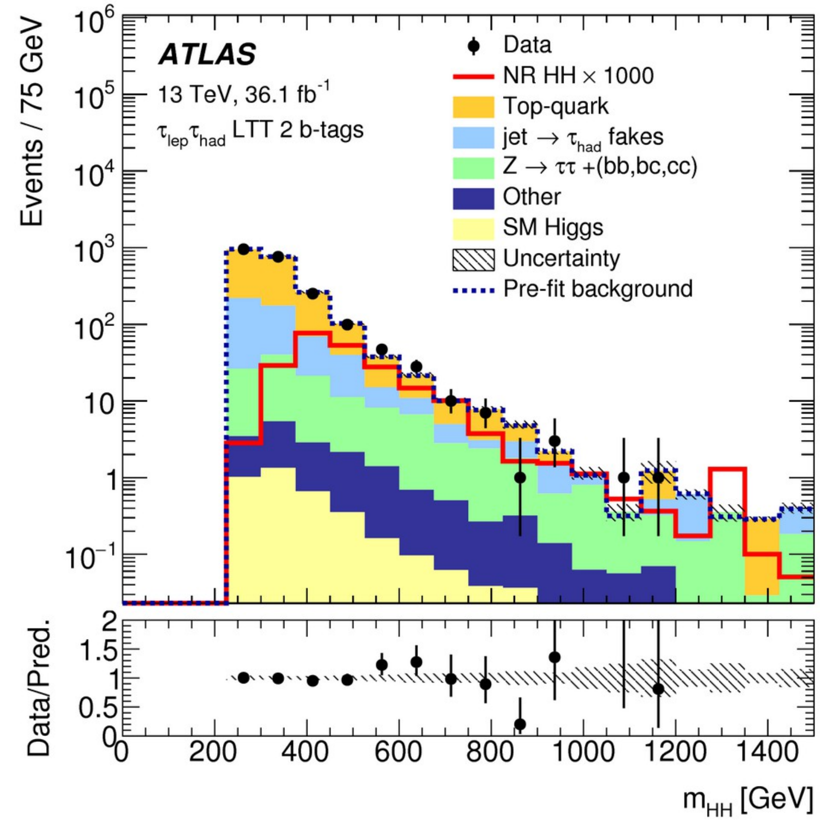
HIGG-2016-16

- ATLAS' best HH channel for non-resonant
- 3 categories: Had-had, lep-had (single lepton trigger), lep-had (lepton+tau trigger)
- 2 bjets required in the SR, 0 and 1 b-tag regions used for validation
- BDT trained in each category, for each mass hypothesis
- Fits performed to the BDT output



Variable
m_{HH}
$m_{\tau\tau}^{\mathrm{MMC}}$
m_{bb}
$\Delta R(\tau,\tau)$
$\Delta R(b,b)$
$E_{\mathrm{T}}^{\mathrm{miss}}$
$E_{\mathrm{T}}^{\mathrm{miss}}$ ϕ centrality
m_{T}^{W}
$\Delta\phi(H,H)$
$\Delta p_{\mathrm{T}}(\mathrm{lep},\tau_{\mathrm{had\text{-}vis}})$
Sub-leading b-jet p_{T}





HH Combination (Non-Resonant)

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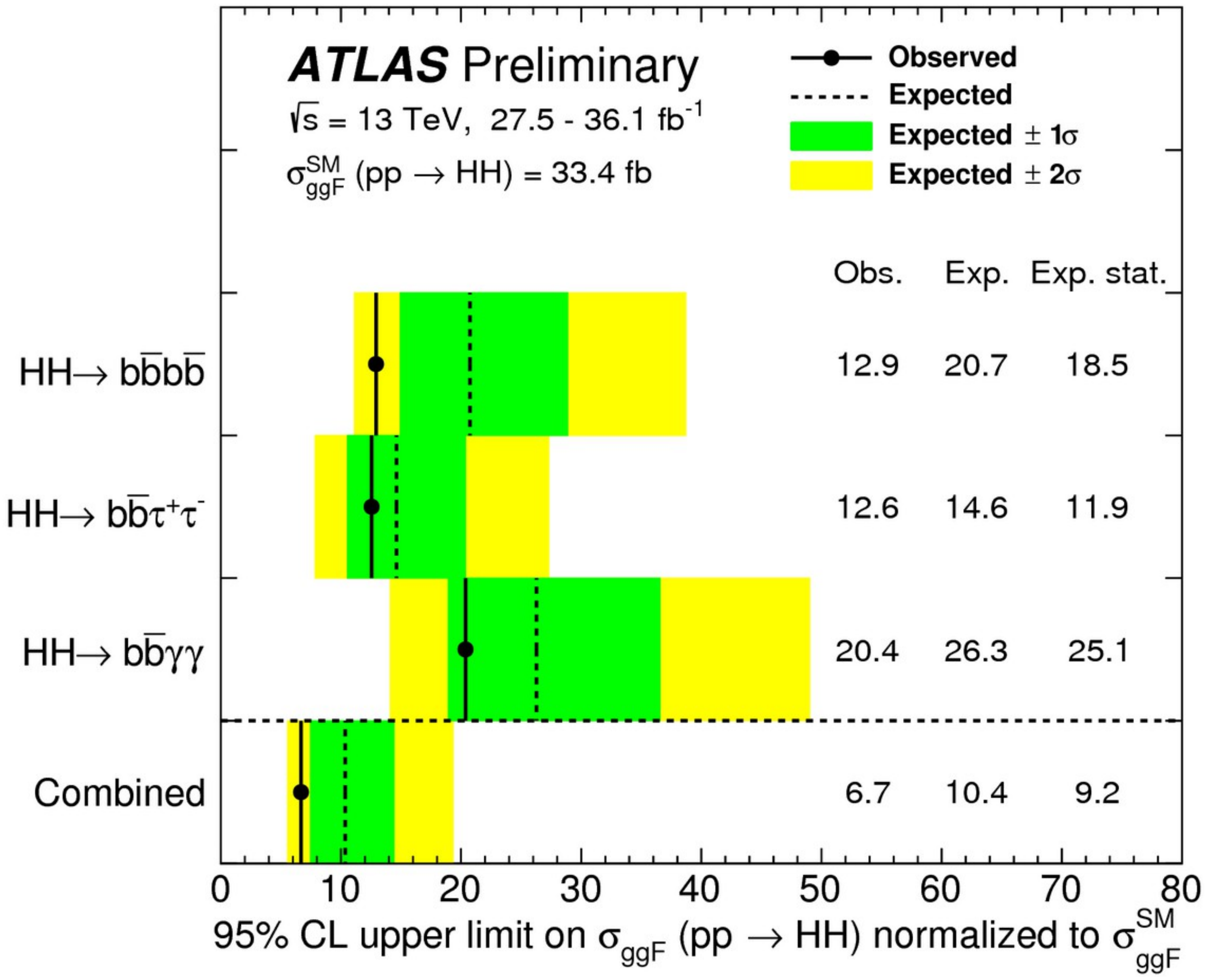
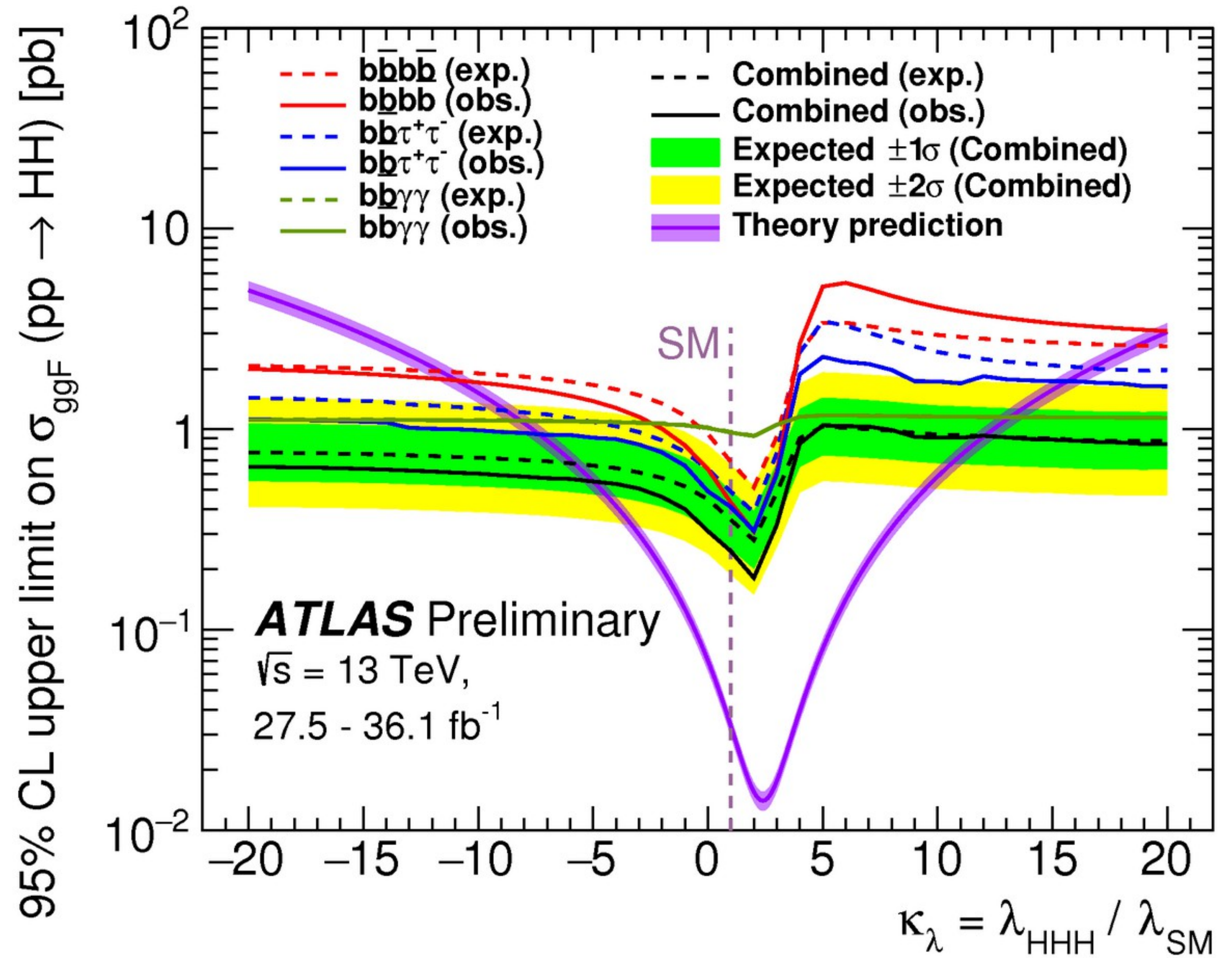
Worlds-best limit on non-resonant HH production:





6.7 x SM observed, 10.4 x SM expected

$$-5.0 < \kappa_\lambda < 12.1 \; (-5.8 < \kappa_\lambda < 12.0)$$