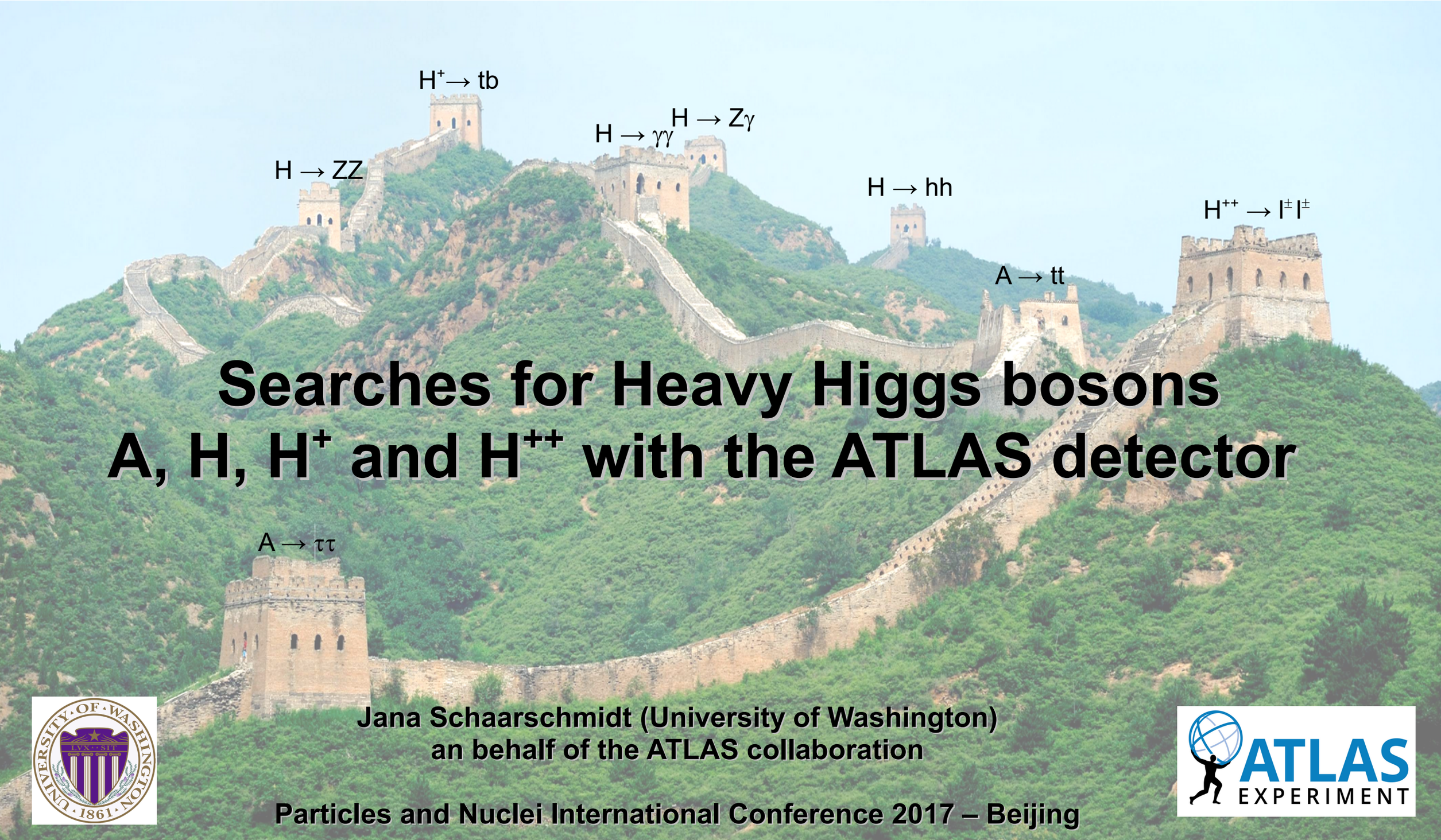
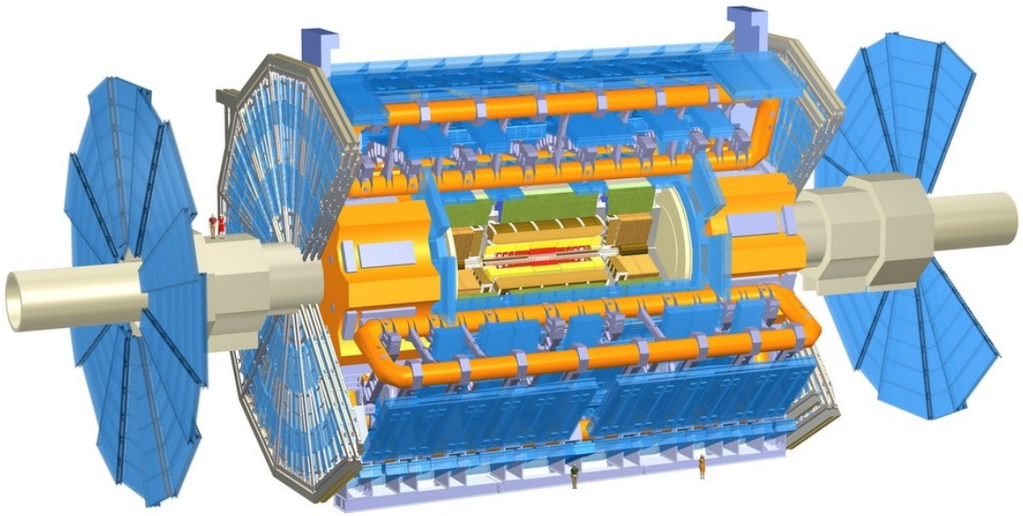


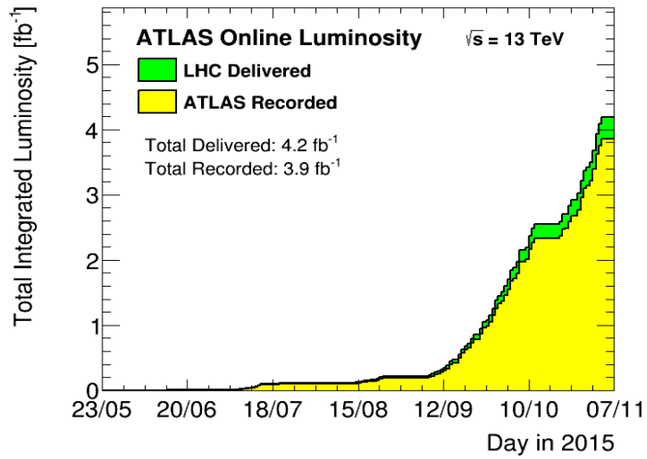
Searches for Heavy Higgs bosons A, H, H^+ and H^{++} with the ATLAS detector

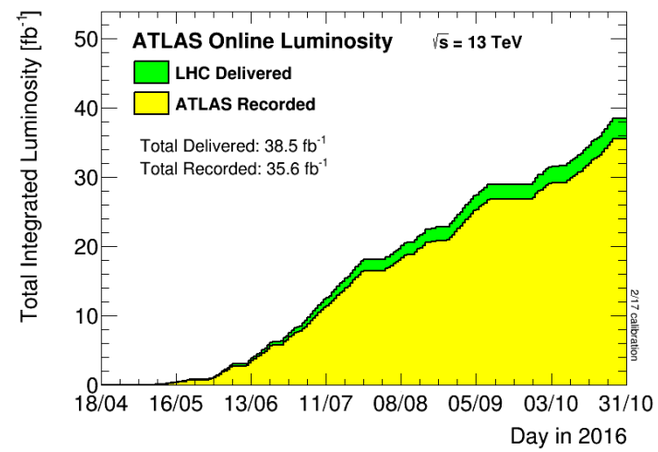
Jana Schaarschmidt (University of Washington)
an behalf of the ATLAS collaboration

Particles and Nuclei International Conference 2017 – Beijing

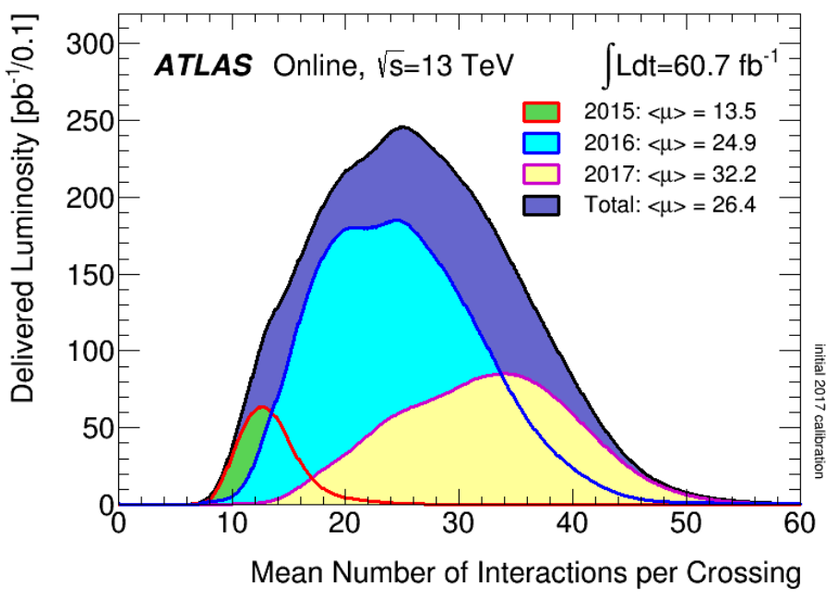
Overview







The talk contains 13 TeV ATLAS result with up to 36/fb of 2015/2016 data. ATLAS already recorded ~17/fb of 2017 data!

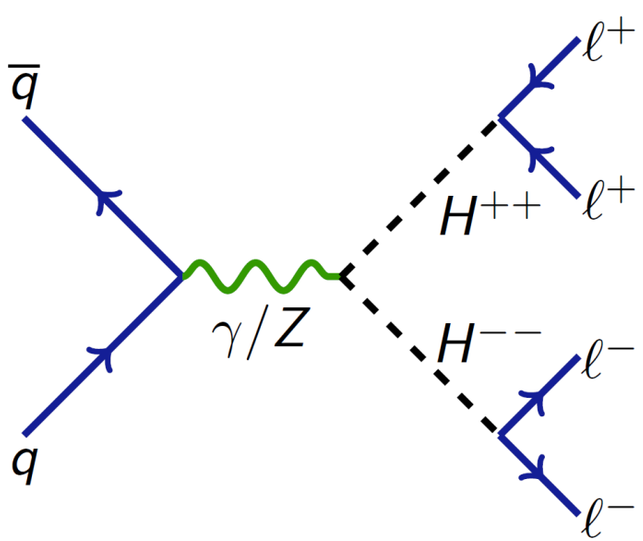


BSM Heavy Higgs results presented here:

- Charged Higgs ($H^+ \to tb, \tau\nu, H^{++} \to ll$)
- Neutral Higgs to fermions ($\tau\tau$, $t\bar{t}$)
- Neutral Higgs to bosons ($\gamma\gamma$, $Z\gamma$, Vh, ZZ, WW, hh)

Check out Katherine's talk on non-standard and rare Higgs decays!

Search for $H^{++} \rightarrow l^{\pm} l^{\pm}$



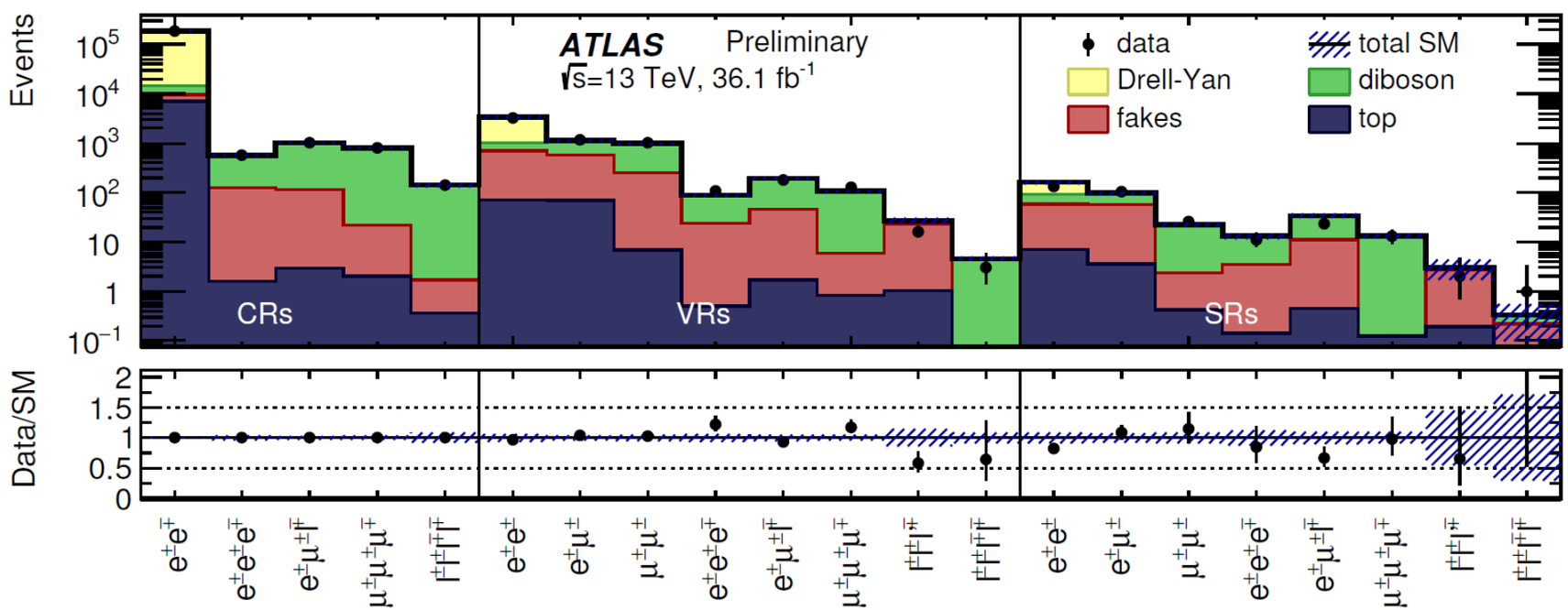
- Signal production in pairs, by Drell Yan process
- Signal process modelled with Pythia8 with left-right symmetry package
- Signal regions: Two, three or four leptons
- Main prompt backgrounds: WW, ZZ, WZ, ttW, ttZ, ttH (estimated using MC)
- Charge-fake background: $Z/\gamma^* \rightarrow ll$, $t\bar{t}$ (estimated with data-driven method)

Selection:
- Electrons and muons: $p_T > 30$ GeV
- Veto on b-jets
- Veto on OS leptons close to Z mass

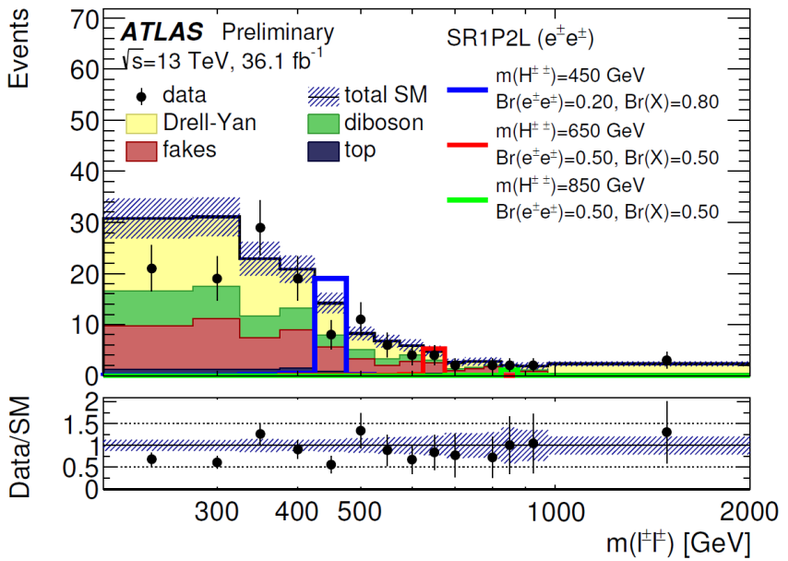
electron charge mis-ID:

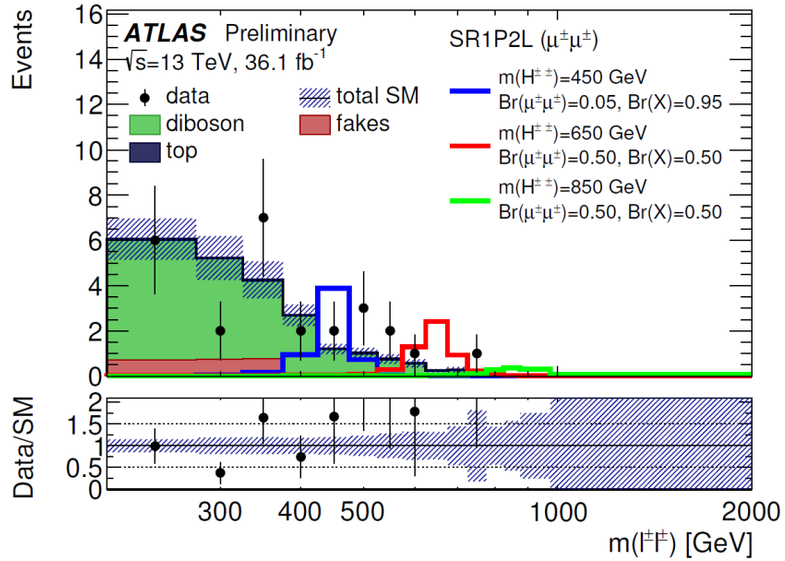
Predominantly by bremsstrahlung:
- the photon converts
- the electron calorimeter cluster is matched to the wrong-charge track

- measured in $Z \rightarrow ee$ data



Search for $H^{++} \rightarrow l^{\pm} l^{\pm}$



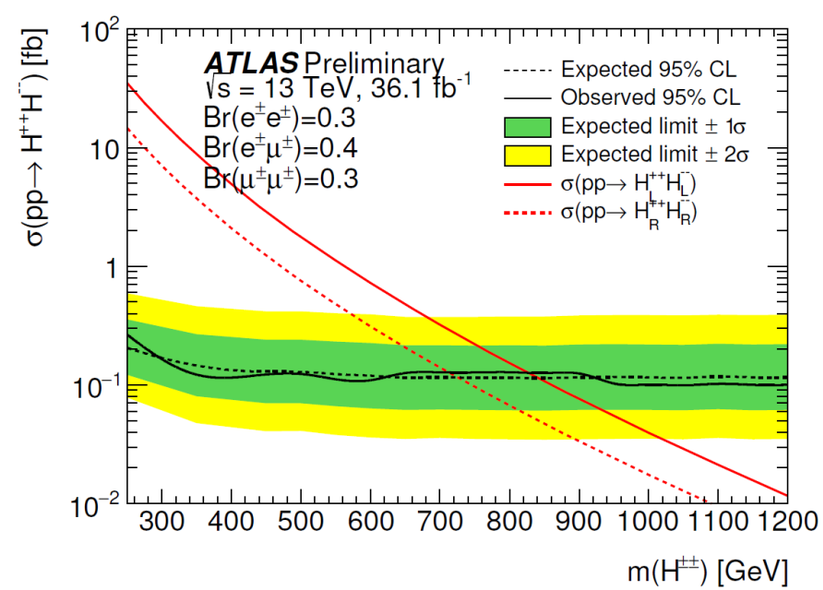


Final discriminant used in the fit:

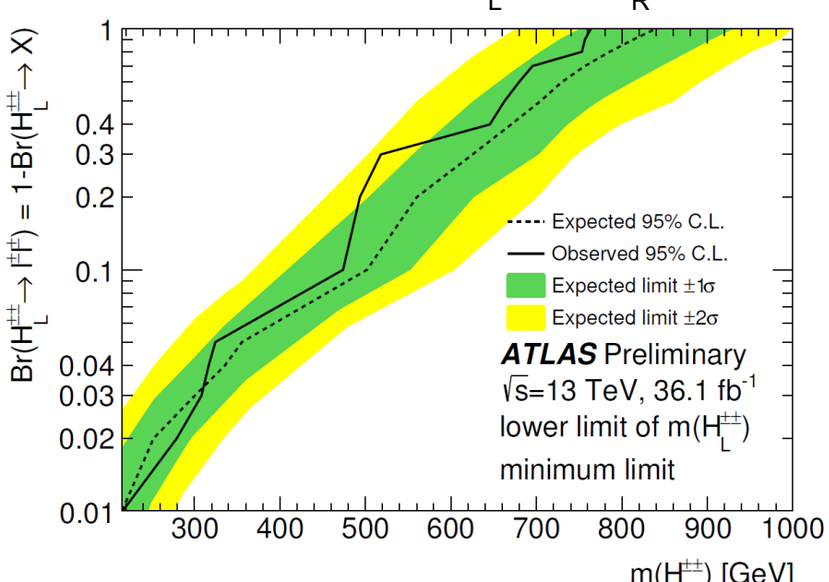
- m_{ll} of the SS lepton pair (for 2 or 3 leptons)
- averaged mass of the 2 lepton pairs (for 4l)

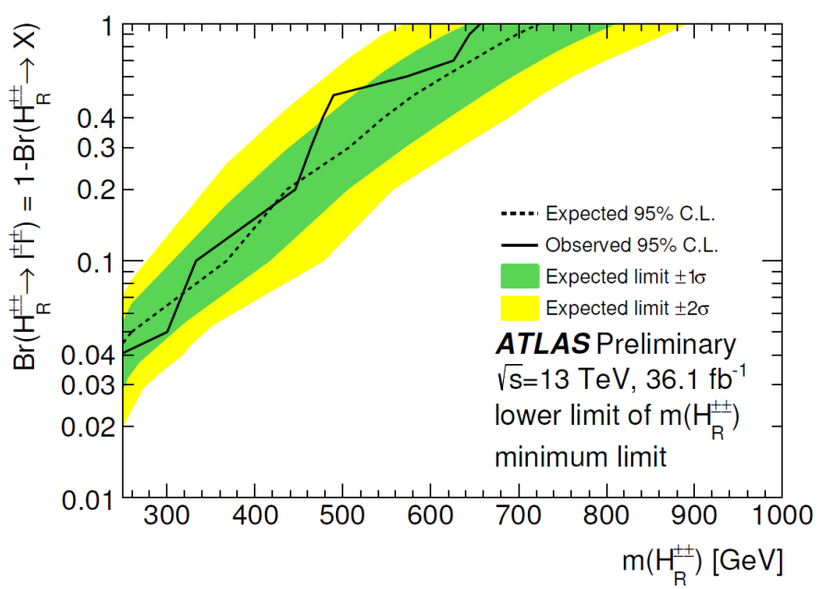
No excess observed in any of the SR.

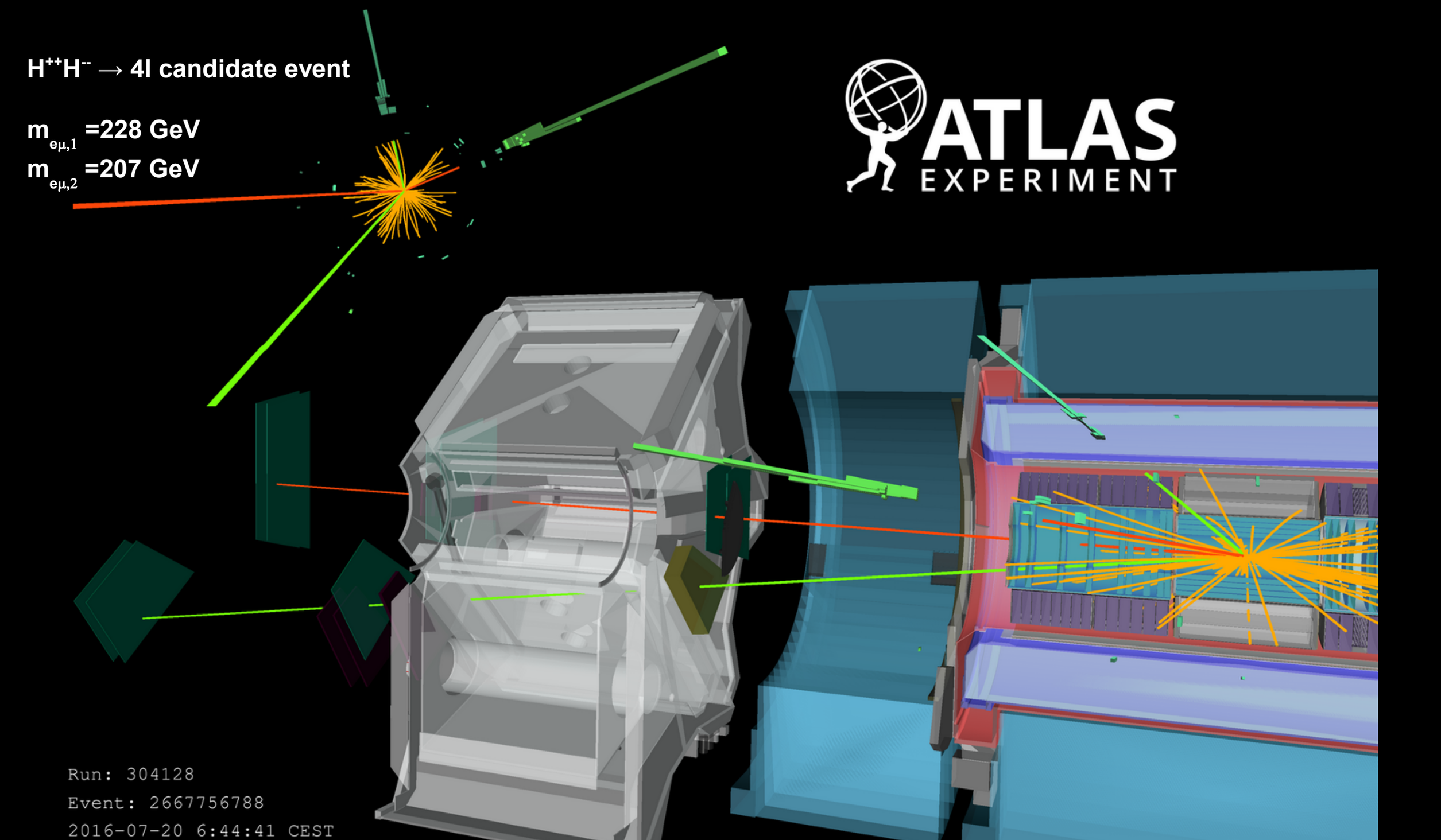
Limits on $H^{++}H^{--}$ production:



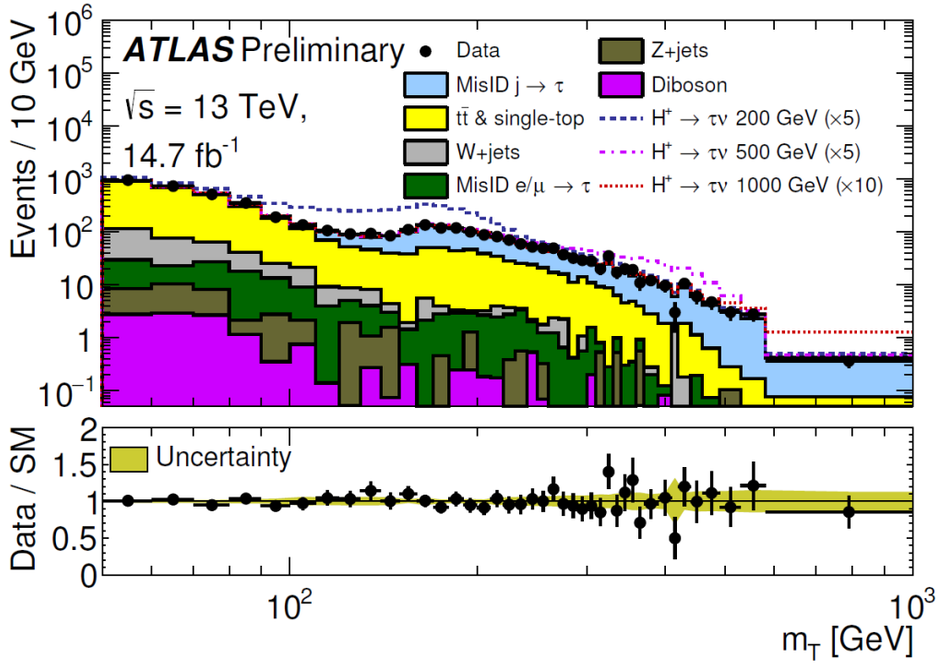
Limits on H_L and H_R masses as a function of the BR($H^{\pm\pm} \rightarrow l^{\pm} l^{\pm}$):

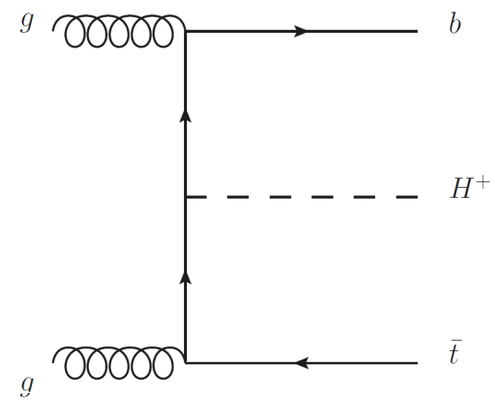





$H^{++}H^{--} \rightarrow 4l$ candidate event
$m_{e\mu,1}$ =228 GeV
$m_{e\mu,2}$ =207 GeV
ATLAS
EXPERIMENT
Run: 304128
Event: 2667756788
2016-07-20 6:44:41 CEST

Search for $H^+ \rightarrow \tau\nu$





4FS tb associated H^+ production

Signal modelled with MG5_aMCatNLO (NLO 4FS implementation)

H^+ produced with zero width

Model-independent limits on production of masses of 2 TeV
Limits set on high tanβ in MSSM for masses up to 550 GeV

- Etmiss trigger (70 or 90 GeV)

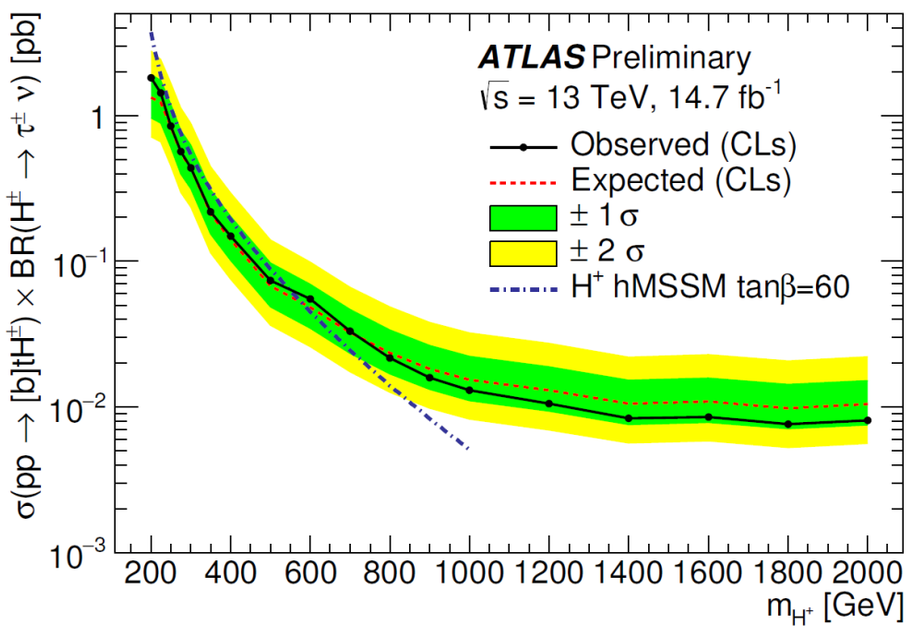
- At least three jets, one of them b-tagged

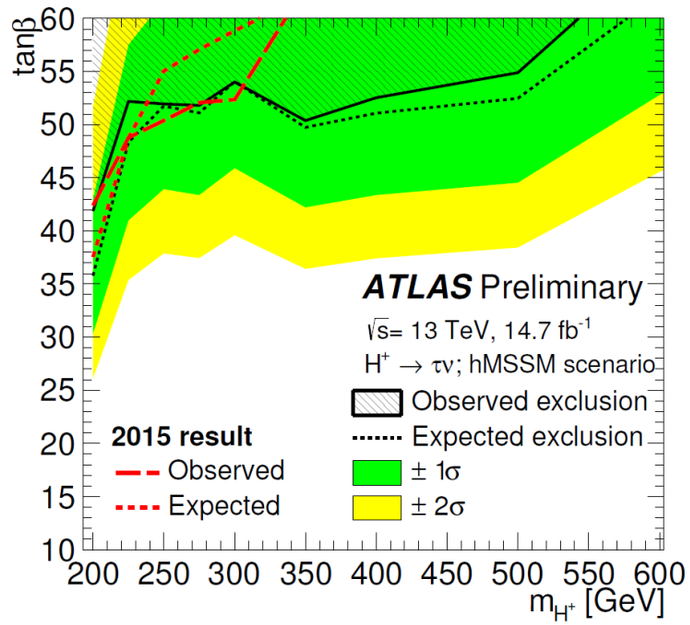
- veto on leptons (e/μ)

- Largest background: jets faking τ_{had}, estimated from data in bins of τ p_T

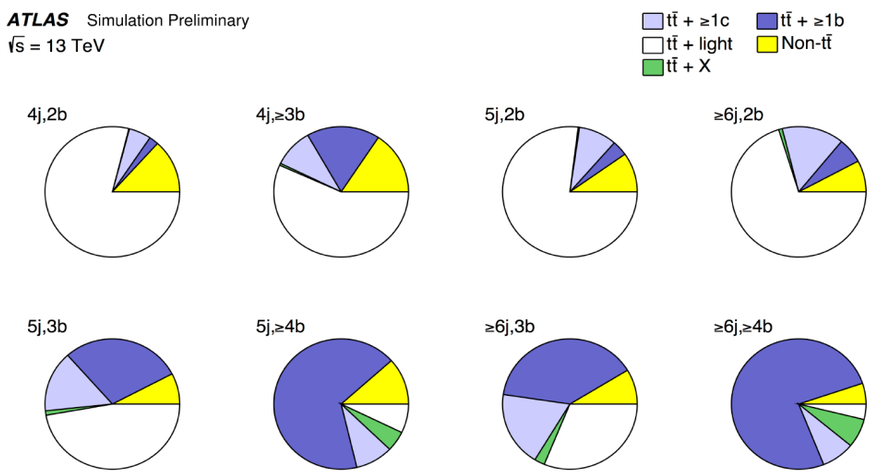
- Final discriminant: m_T

$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\tau}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi_{\tau,E_{\mathrm{T}}^{\mathrm{miss}}})}$$

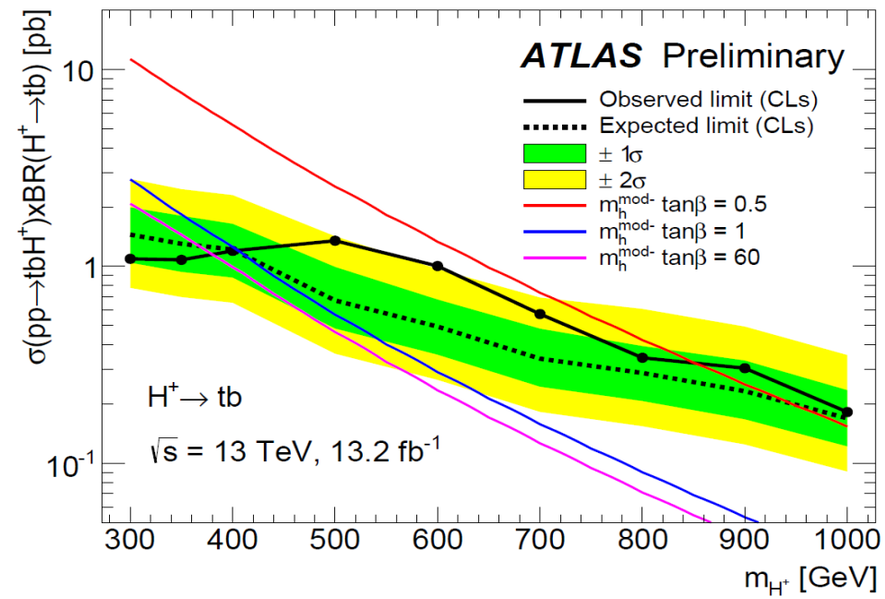




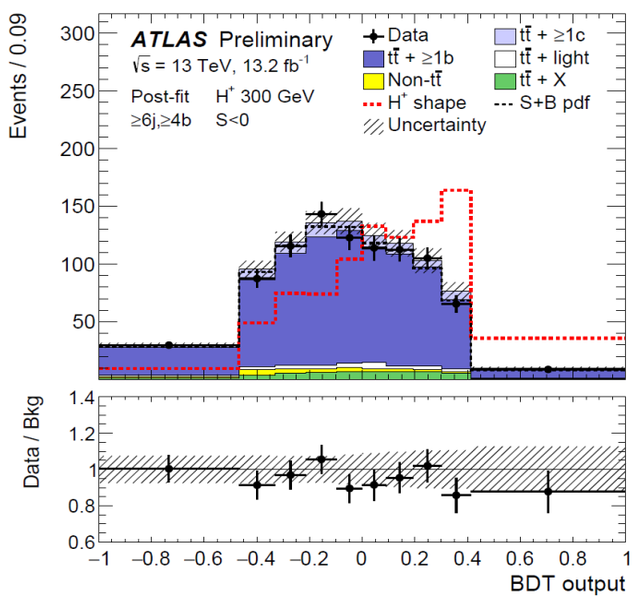
Search for $H^+ \rightarrow tb$

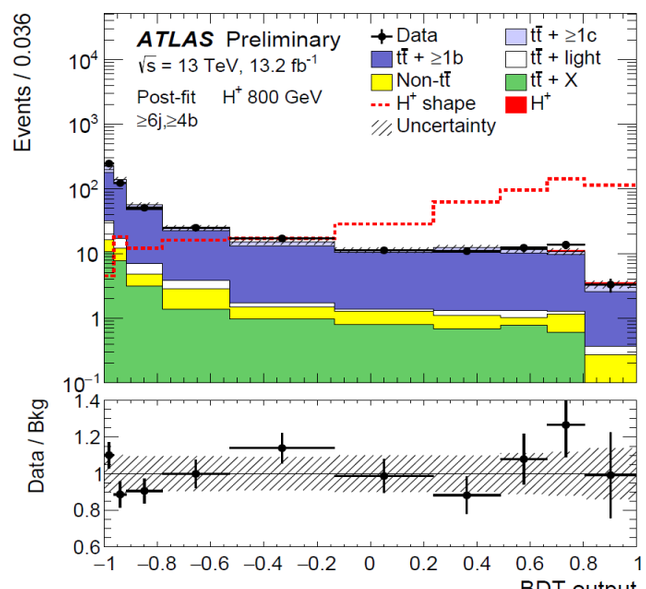


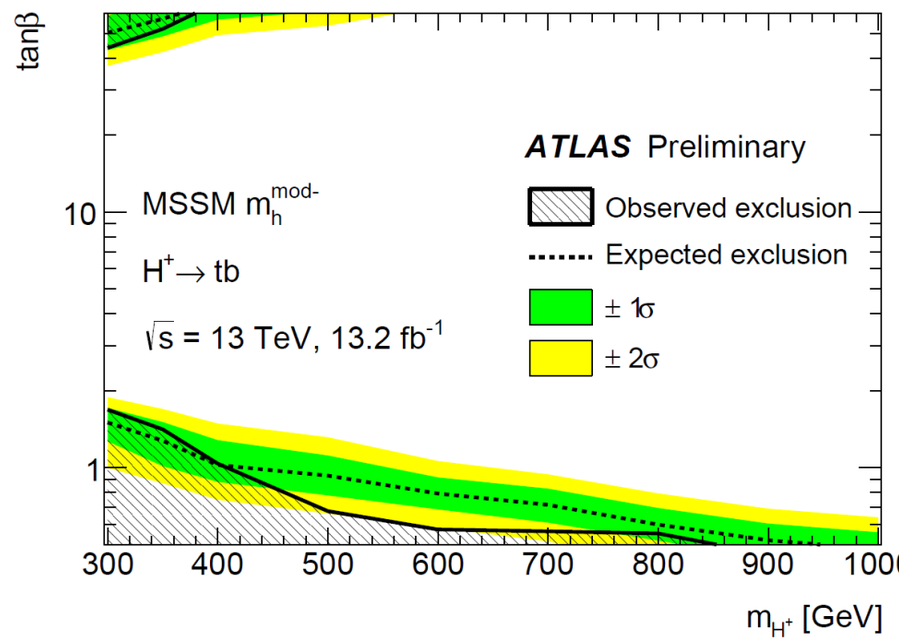
- Very challenging!
- Produced in 4FS together with a top and a bottom quark
- Dominated by systematics, in particular tt + bb, tt + cc
- Floating tt+HF normalisations
- Setting limits on low and high tanβ in MSSM models



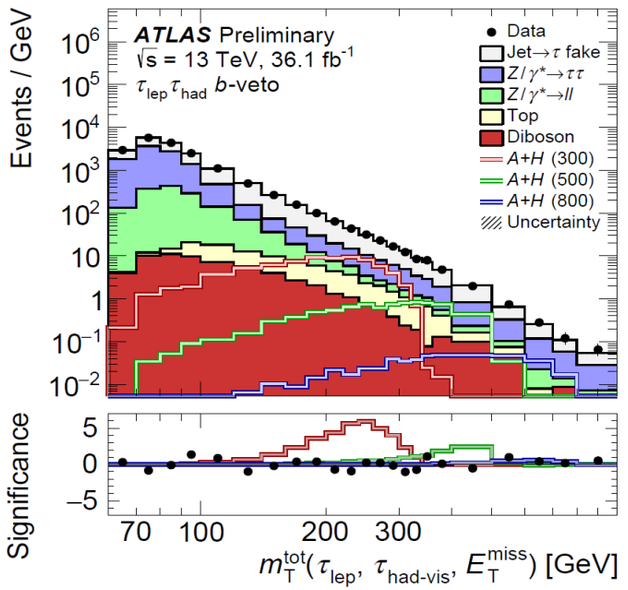
Four signal regions employed, and four control regions to constrain systematics
BDT trained for each mass hypothesis in each SR (5j3b, 5j≥4b, ≥6j3b, ≥6j≥4b)

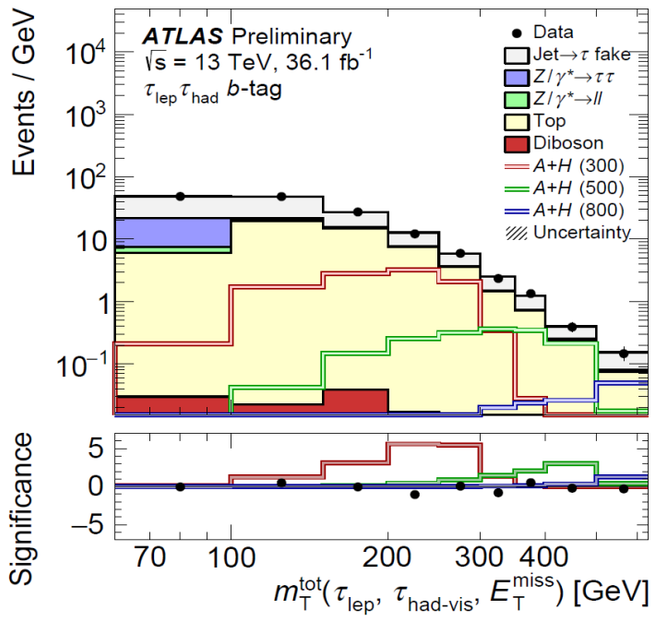


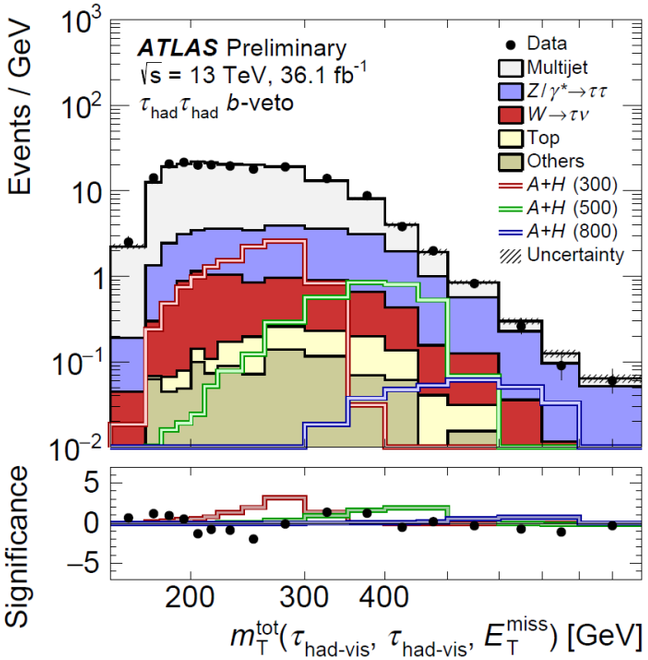


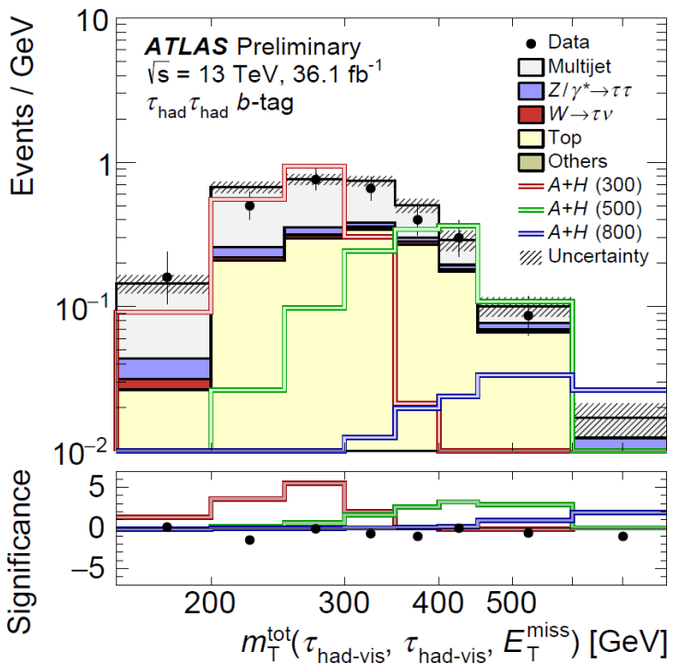


Search for A/H → ττ









Most powerful channel in the MSSM

Lephad and hadhad channels considered

b-tag and b-veto categories to enhance for b-associated or gluon fusion produced signal

ggF modelled with Powheg-Box,
bbA modelled with MG5_aMCatNLO

Ditau mass reconstruction in transverse plane:

$$m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(\mathrm{p}_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau_1} + \mathbf{p}_{\mathrm{T}}^{\tau_2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

Dominant backgrounds:

jets faking taus, estimated via data-driven fake-factors

Z→ττ estimated from simulation

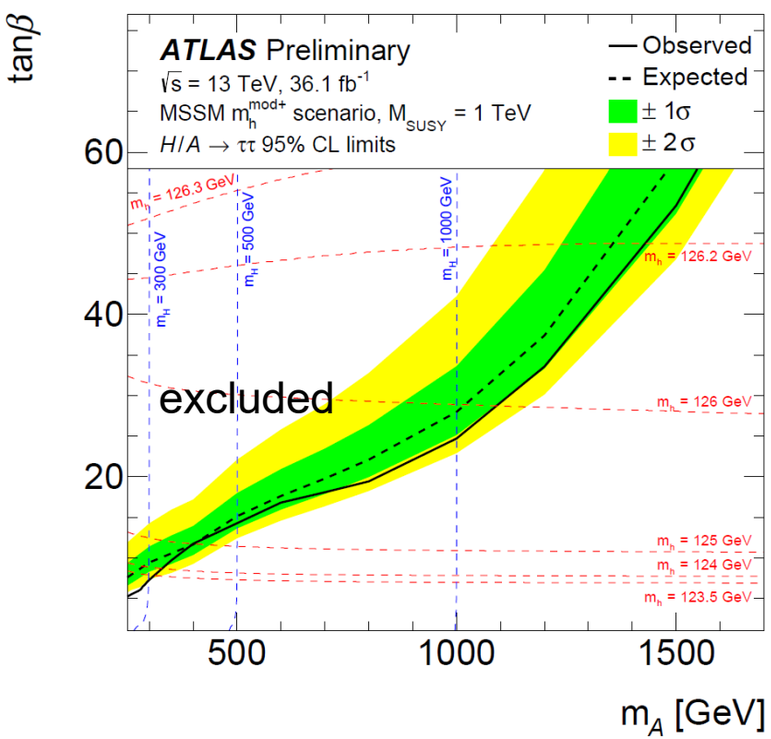
Search for A/H → ττ

No excess, but substantial improvement over 2015 sensitivity

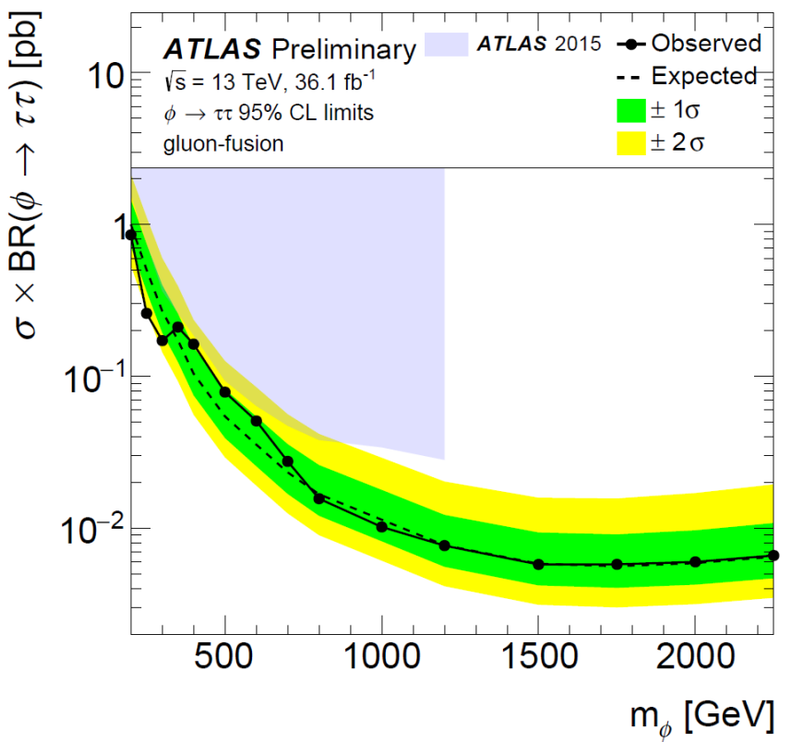
Deficit at low mass (statistical fluctuation)

Exclude mhmod+ model points with tanβ > 5 at 250 GeV up to tanβ > 50 at 1.5 TeV

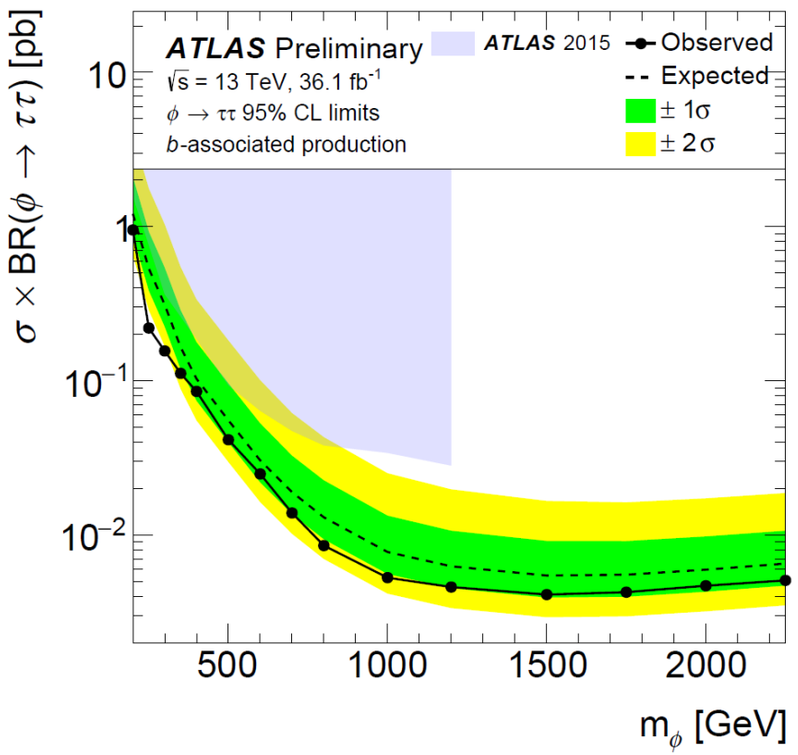
mhmod+



ggF

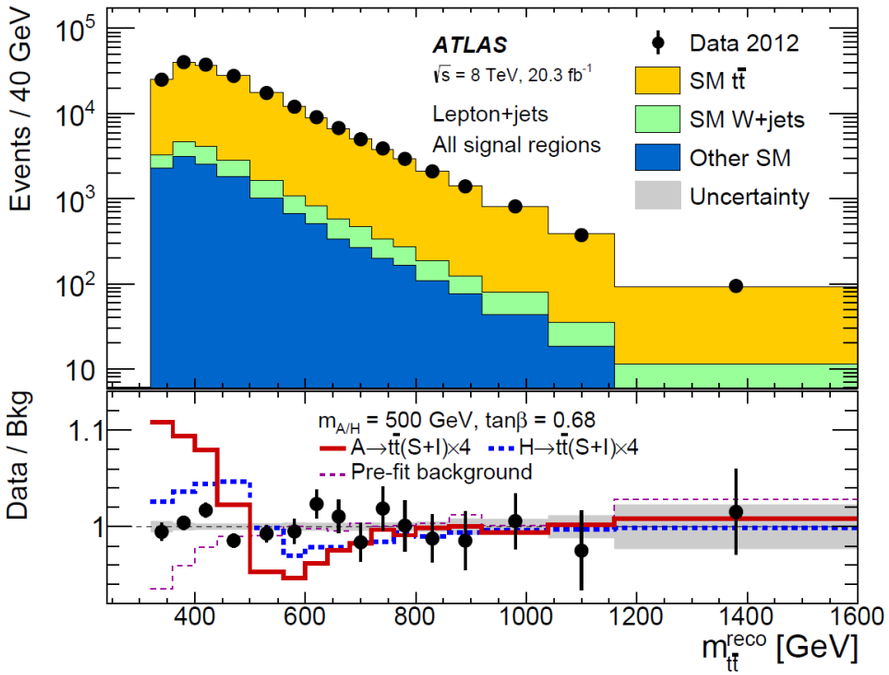


b-associated

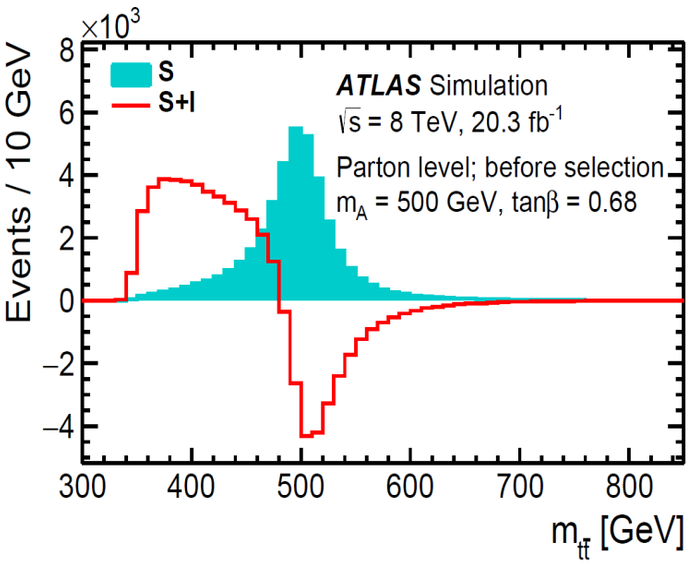


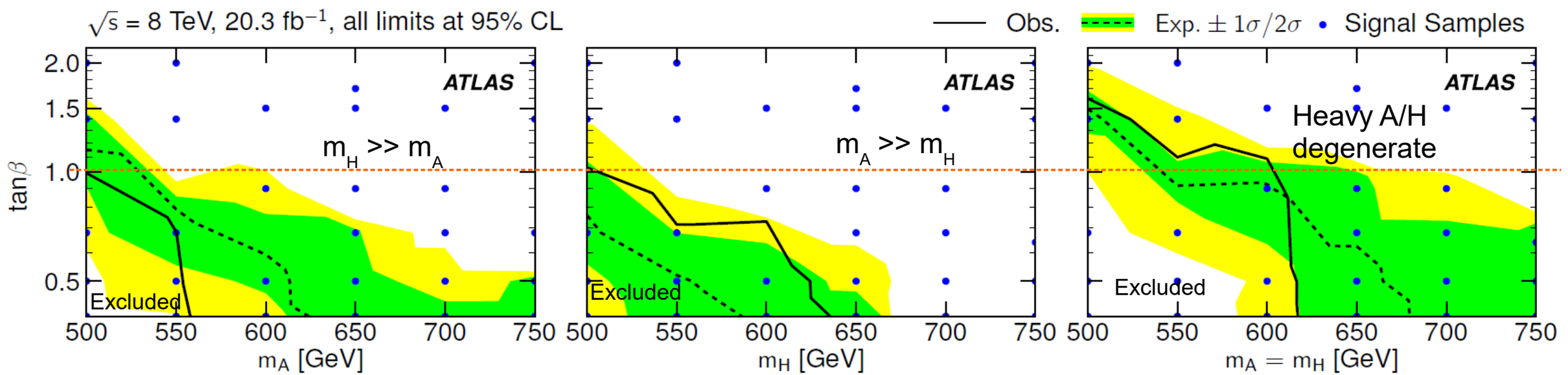
Search for A/H → $t\bar{t}$

arXiv:1707.06025

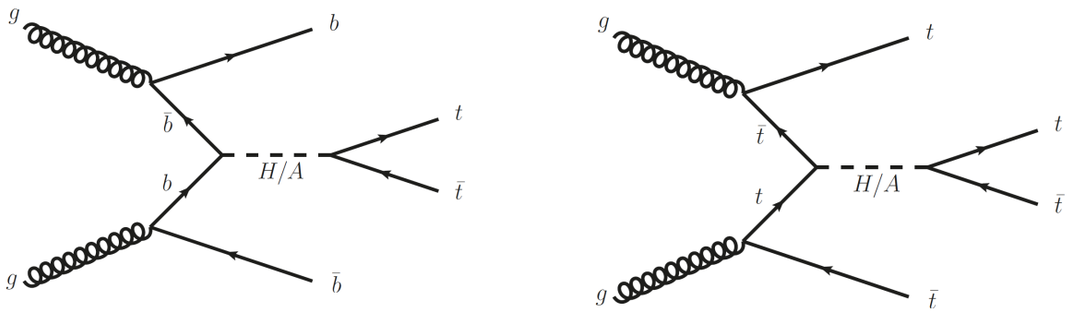


- Challenge: Interference between signal gg→A→tt and gg → tt background
- Signal has peak-dip shape
- Largest signal uncertainty: 1GeV m_{top}
- Final states with one lepton considered, four resolved jets, three of them b-tagged
- Mass reco via χ^2 algorithm matching objects to the tt system
- Limits set on low tanβ type-II 2HDM

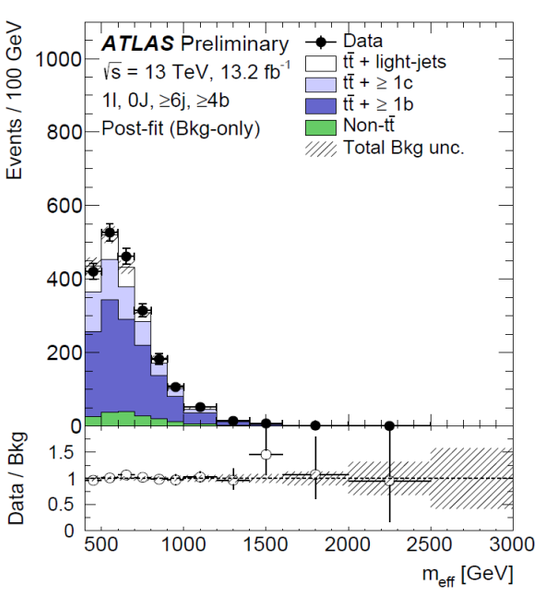


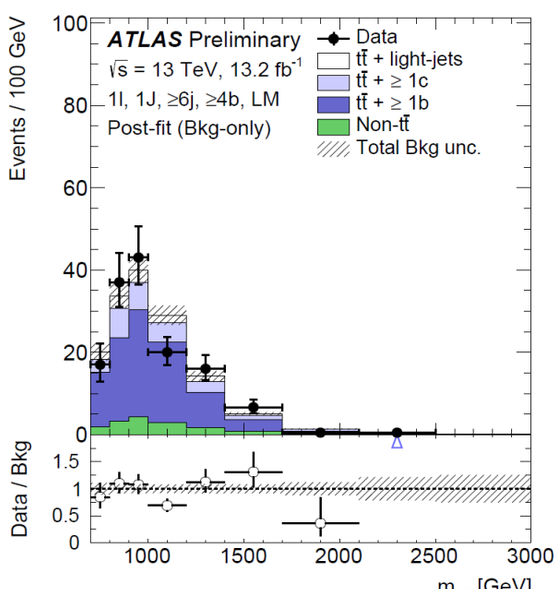


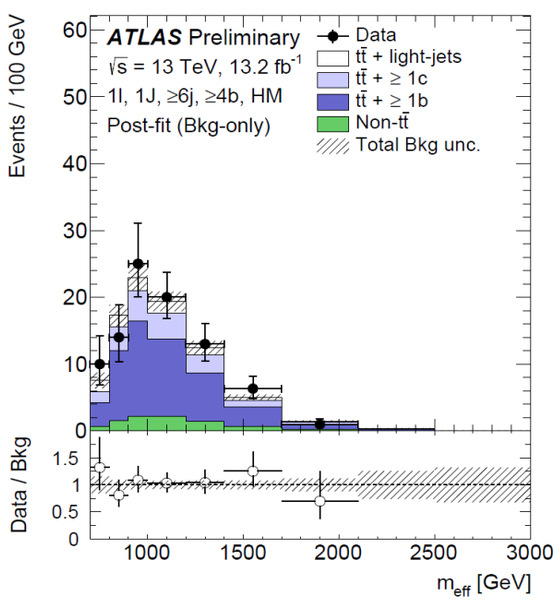
Search for ttH / bbH → $t\bar{t}$

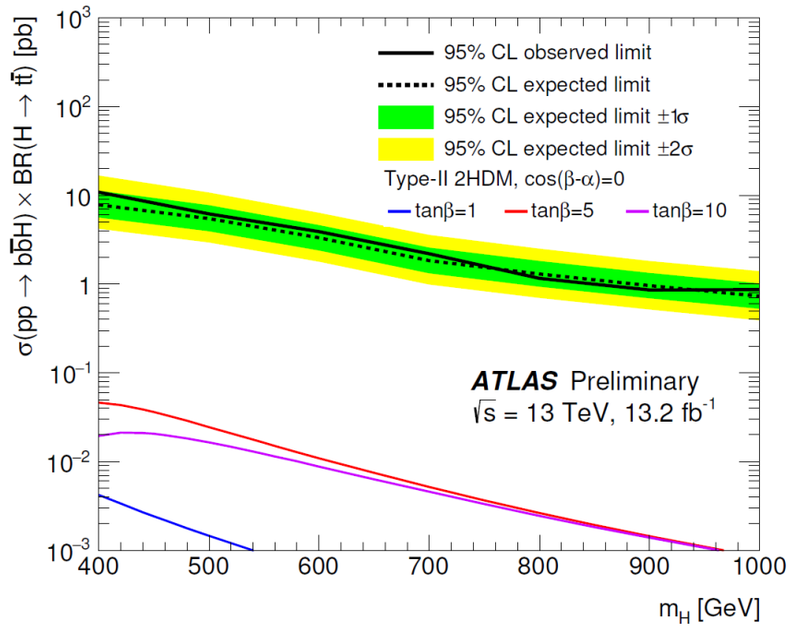


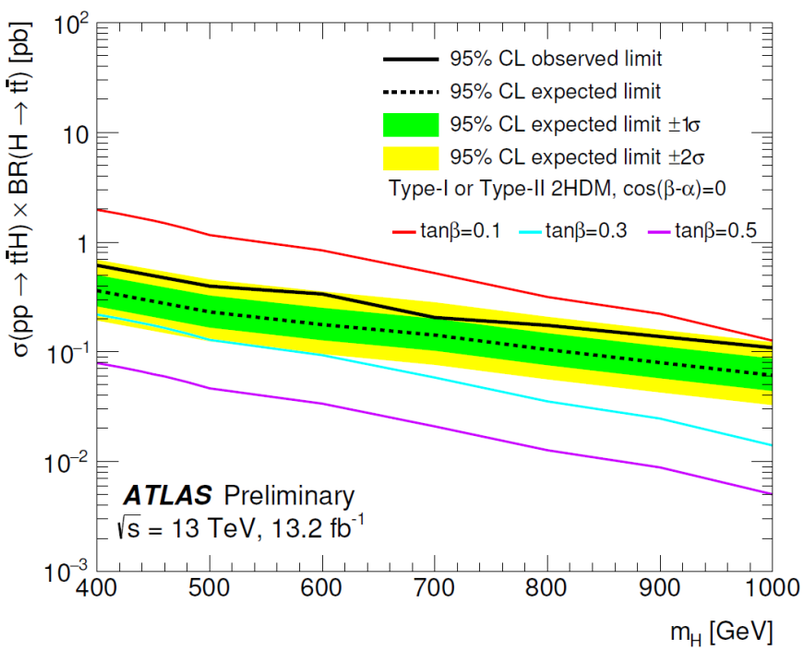
- No interference of heavy Higgs signal with background
- Selection optimized for search for vector-like quark T
- Events categorized by jet and b-jet multiplicity, and presence of large-R jets, and mass of b-quark pair $m_{bb}^{\min\Delta R}$ (8 categories simultaneously fit)
- Final discriminant: m_{eff} (scalar sum of p_T of lepton, jets and $p_{T,miss}$)







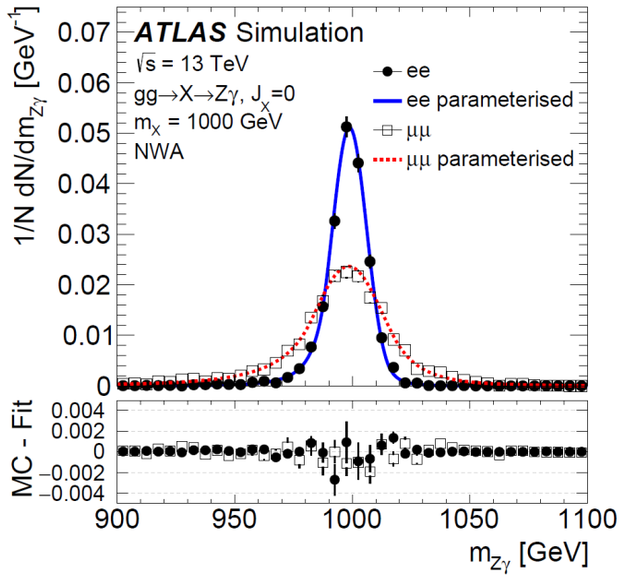


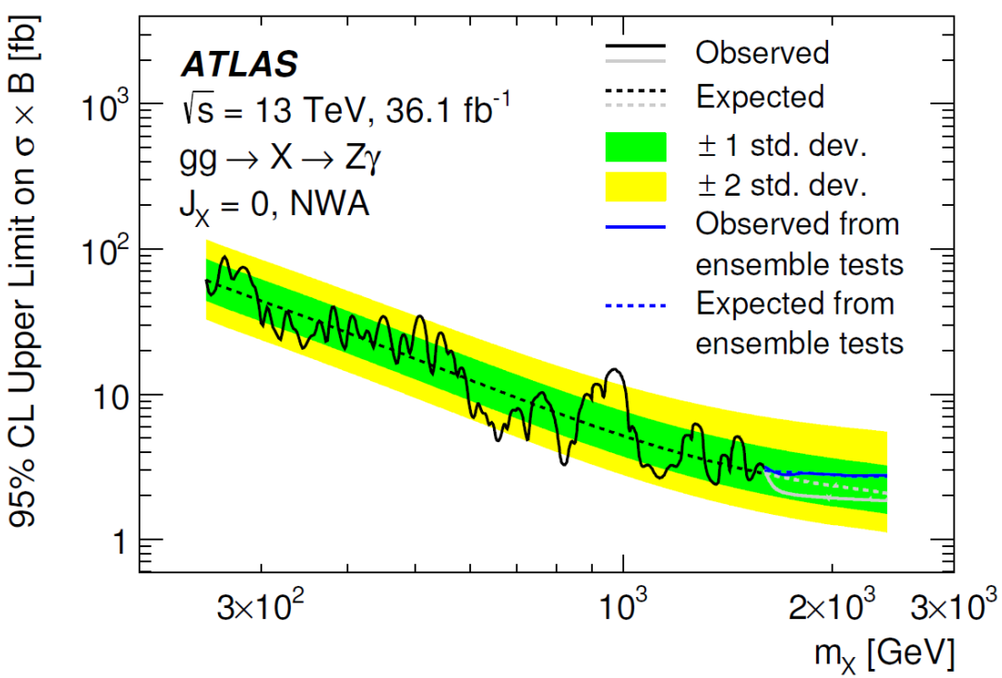


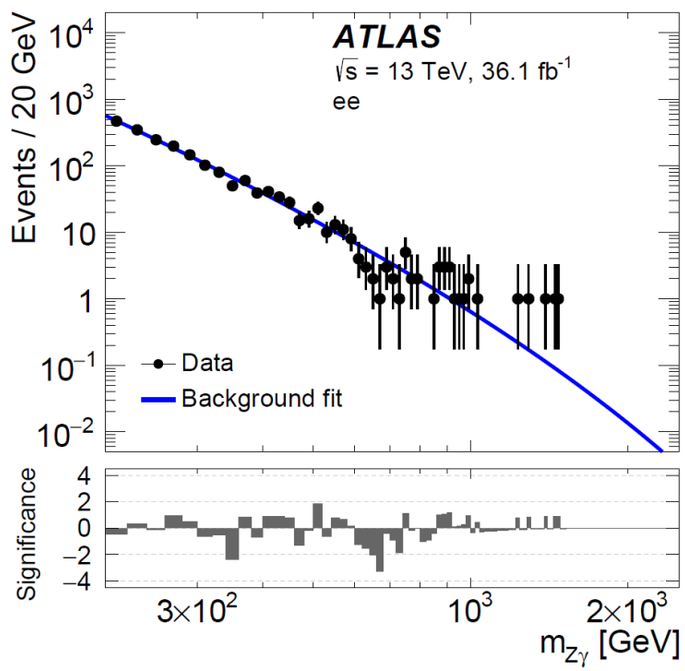
Search for X → Zγ

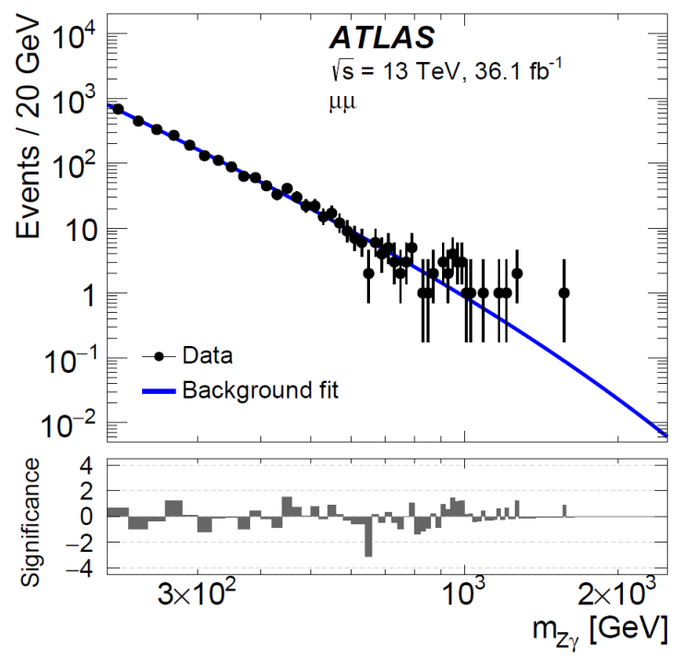
arXiv:1708.00212

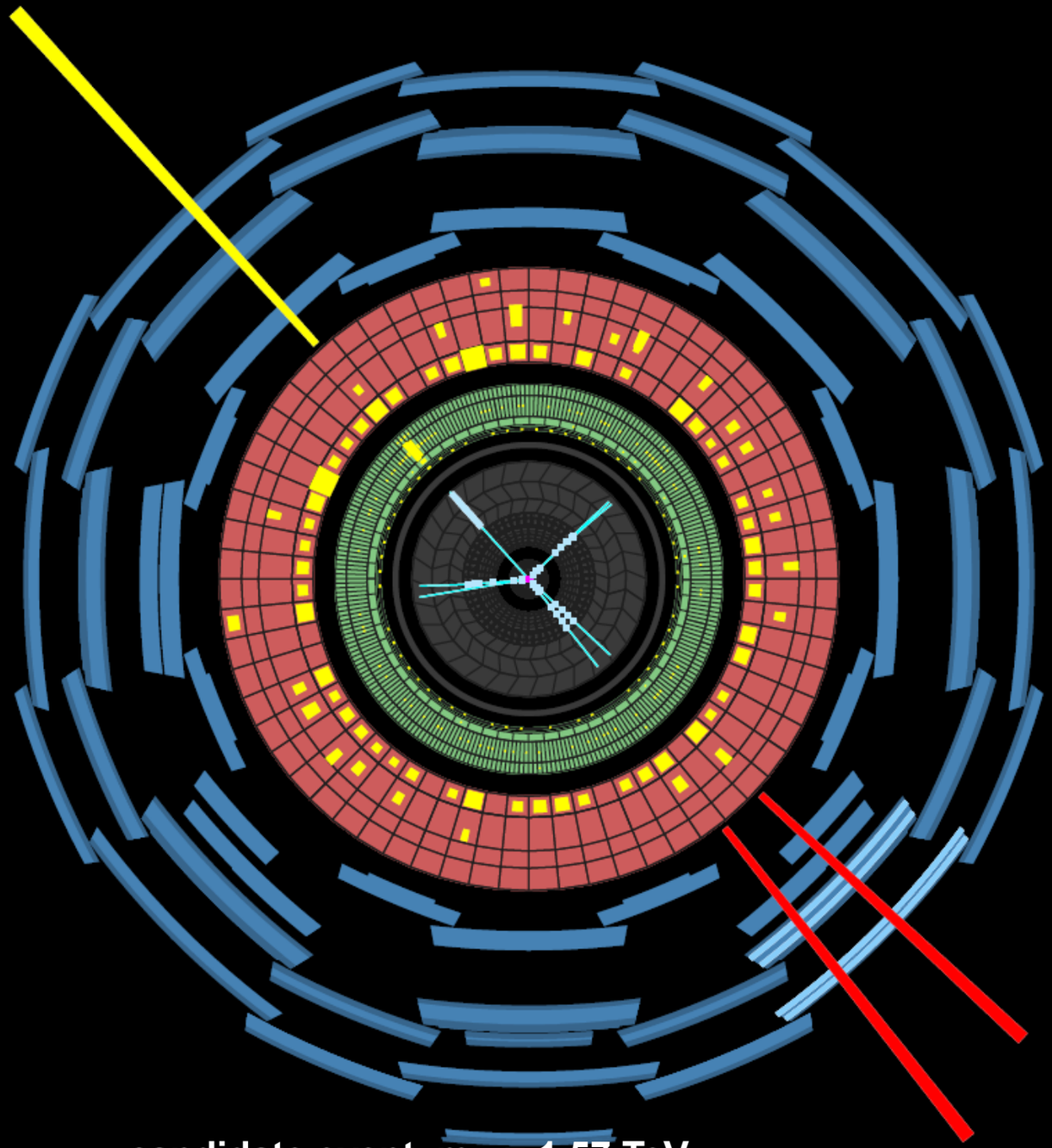
- Signal is narrow width scalar, produced in gluon fusion
- Z decays to two same-flavor OS leptons (ee, μμ categories)
- Fully analytical fit to parametrized signal and background
- Background modelled by $f^{k}_{\mathrm{bkg}}(x; b, a_k) = N(1 - x^{1/3})^{b} x^{\sum_{j=0}^{k} a_k \log(x)^j}$ with k=0
- Upper limits on heavy scalar set between 250 GeV – 2.4 TeV, though no events observed above ~1.5 TeV
- Largest local excess of 2.7σ at 960 GeV, global significance 0.8σ









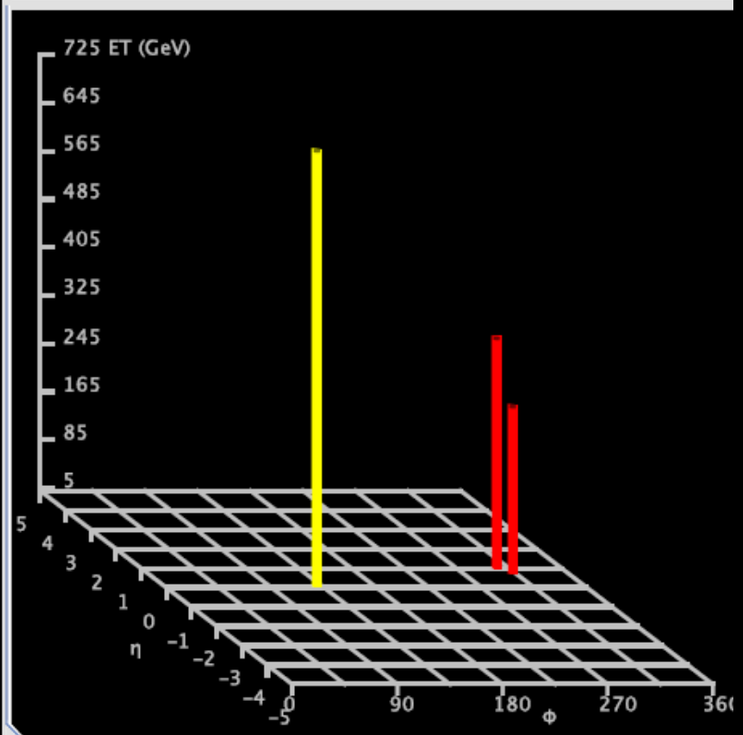


$H \rightarrow Z\gamma \rightarrow \mu\mu\gamma$ candidate event. $m_{Z\gamma}$ = 1.57 TeV

ATLAS EXPERIMENT

Run Number: 309759, Event Number: 3797573939

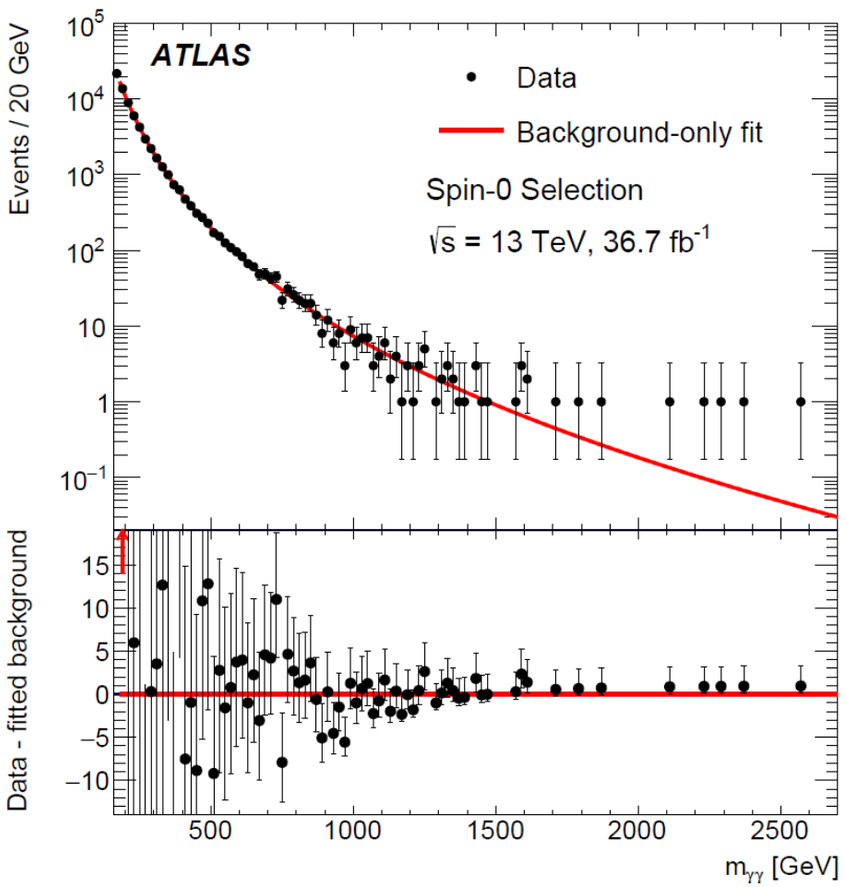
Date: 2016-10-03 03:27:33 UTC



Search for H → γγ

arXiv:1707.04147

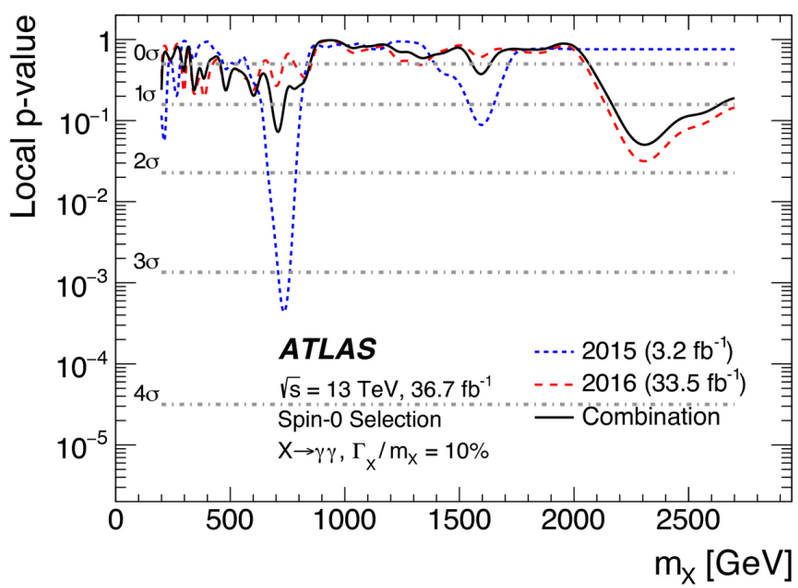
- Improved reconstruction of converted photons wrt. preliminary result
- Retrained regression algorithm for the energy determination
- E_T cuts: 0.4*$m_{\gamma\gamma}$ (leading), 0.3*$m_{\gamma\gamma}$ (sub-leading)
- Excess at 750 GeV in 2015 not seen in 2016 dataset, combined significance <1σ

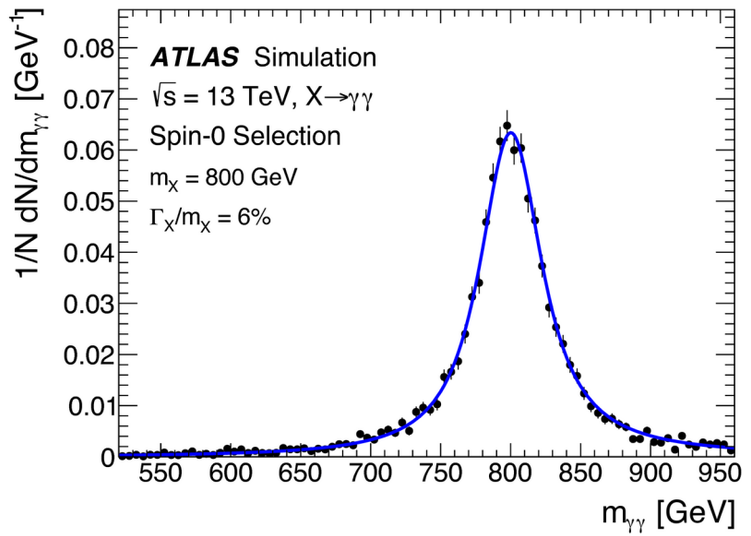


Background function:

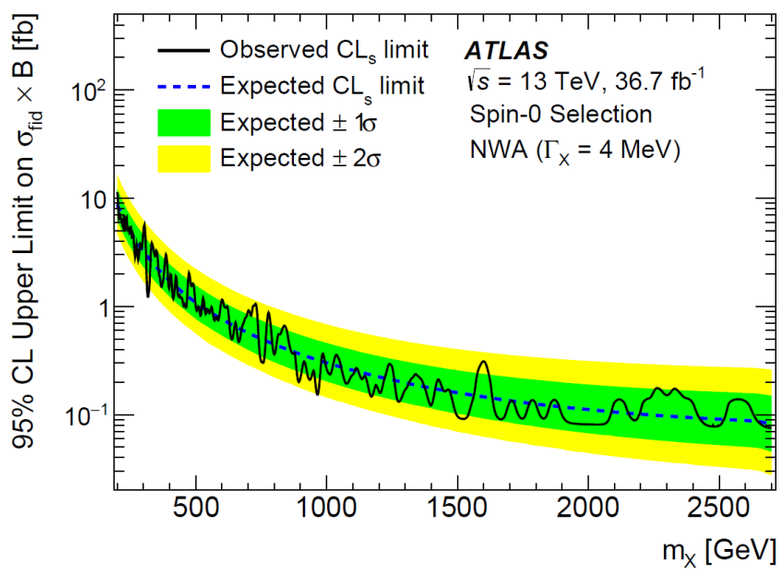
$$f_{\mathrm{bkg}}^{k}(x;b,a_k) = N(1-x^{1/3})^{b} x^{\sum_{j=0}^{k} a_k \log(x)^j}$$

with k=0



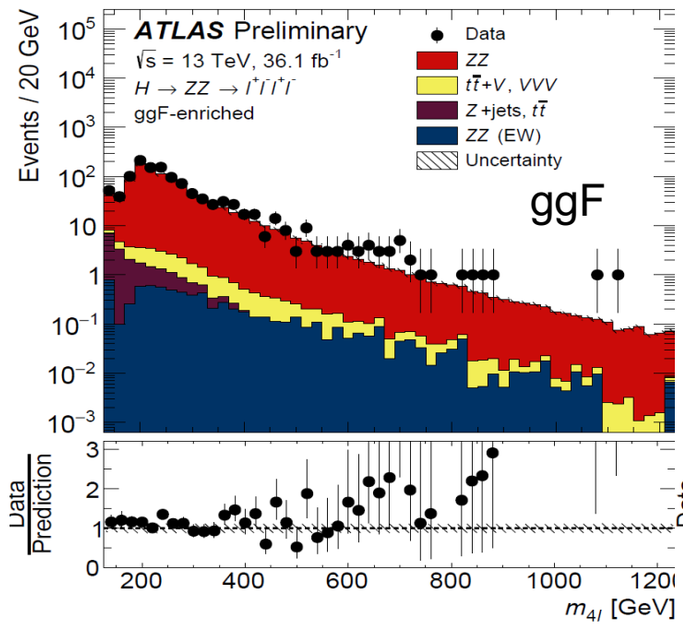


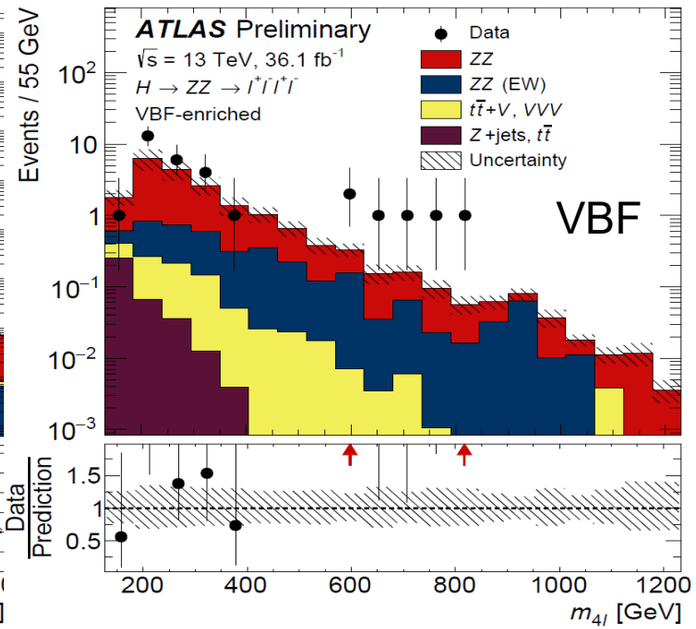
Signal model:
Double-sided Crystal Ball

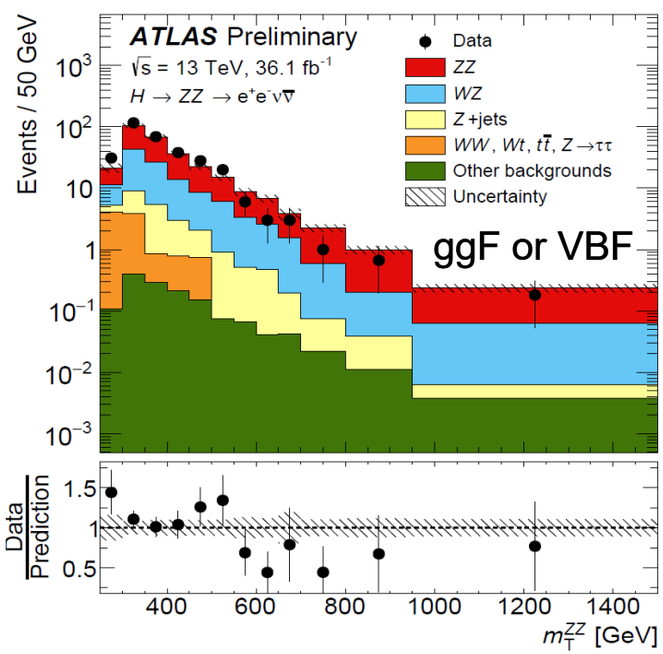


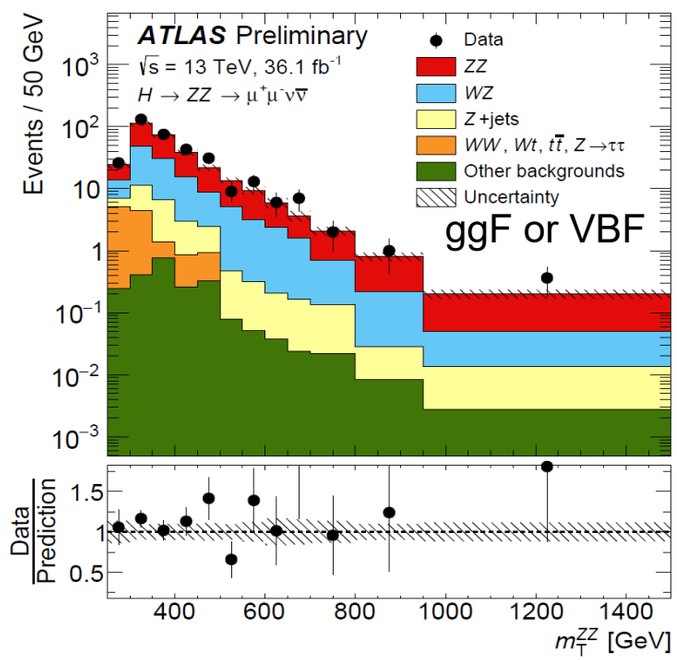
Search for H → ZZ → llll / llνν

ATLAS-CONF-2017-058



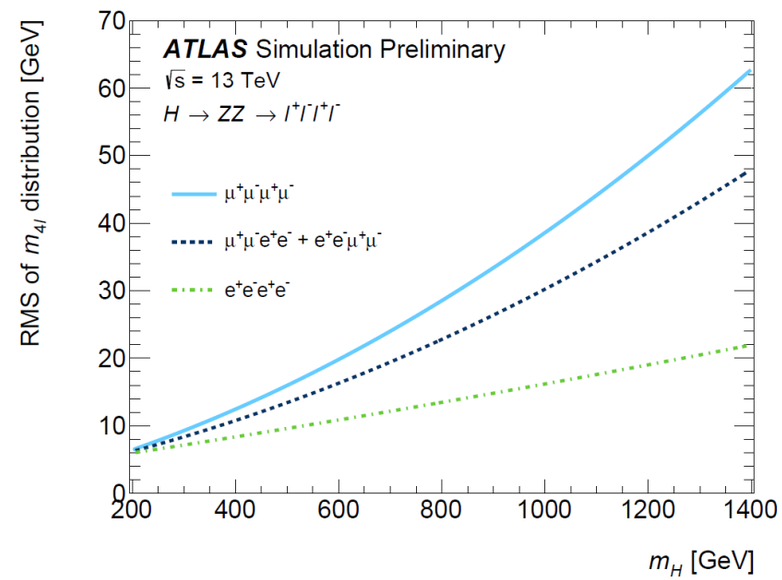






- Production via ggF or VBF
- Interferences: h_{125} and H, gg→H and gg→ZZ both are taken into account

ZZ → 4l mass resolution:

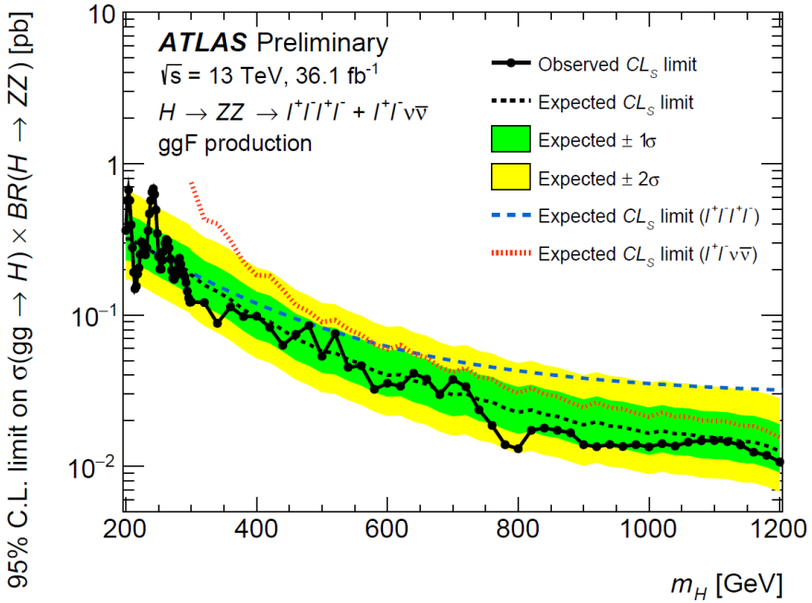


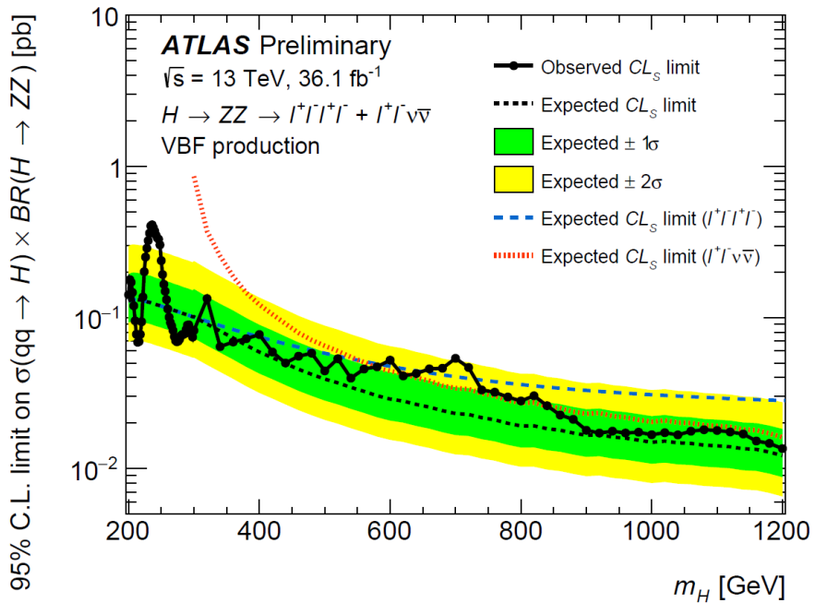
Final discriminant for ZZ → llνν:

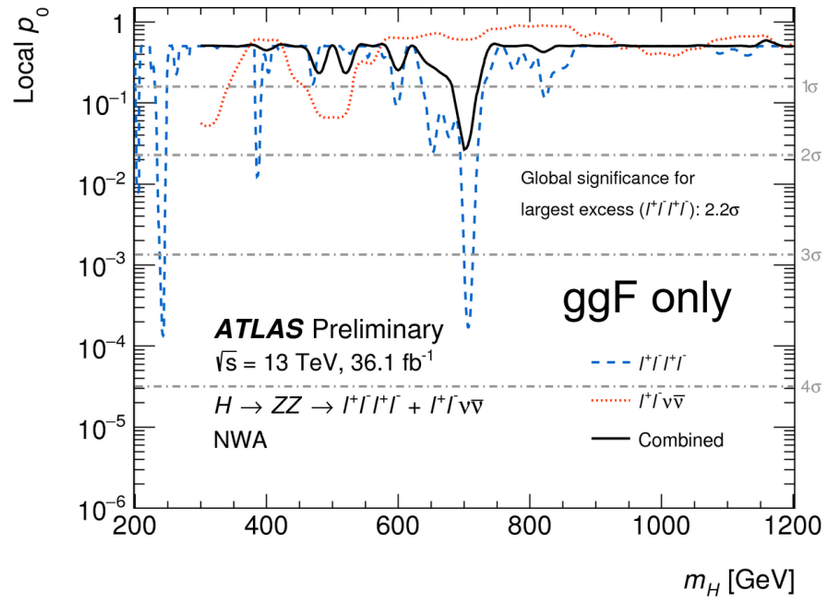
$$m_{\mathrm{T}} \equiv \sqrt{\left[\sqrt{m_Z^2 + \left(p_{\mathrm{T}}^{\ell\ell}\right)^2} + \sqrt{m_Z^2 + \left(E_{\mathrm{T}}^{\mathrm{miss}}\right)^2}\right]^2 - \left|\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

Search for H → ZZ → llll / llνν

ATLAS-CONF-2017-058





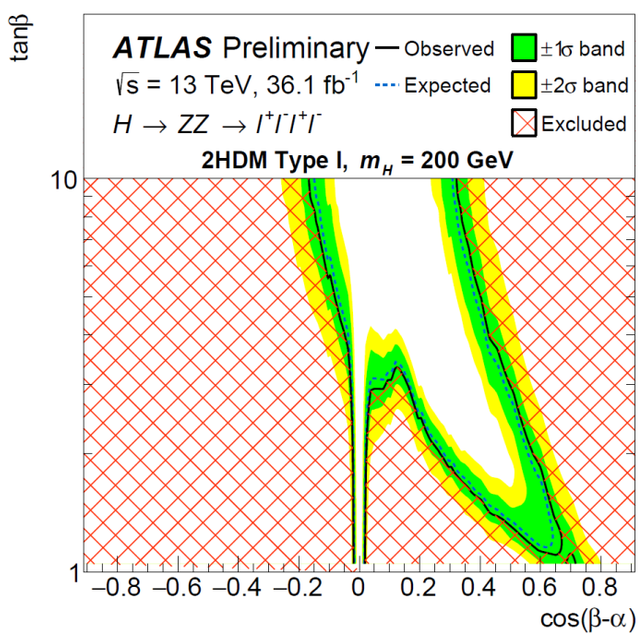


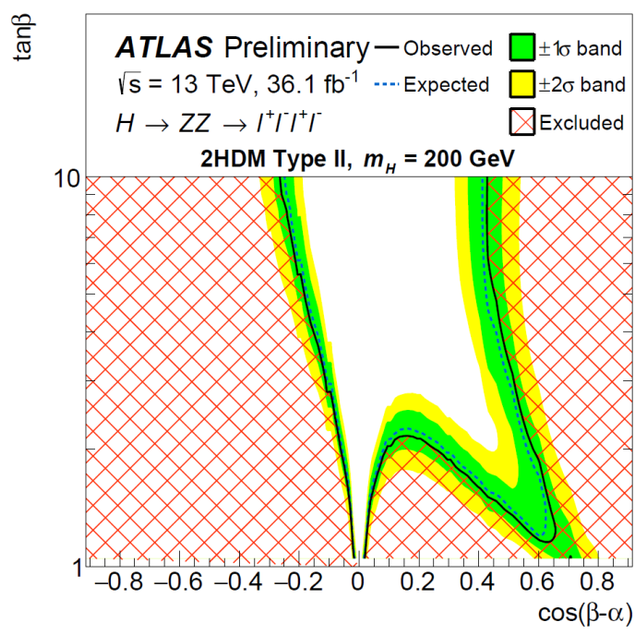
Two small excesses in 4l channel:

- 240 GeV (3.6σ), 700 GeV (3.6σ)
- 2.2σ global significance

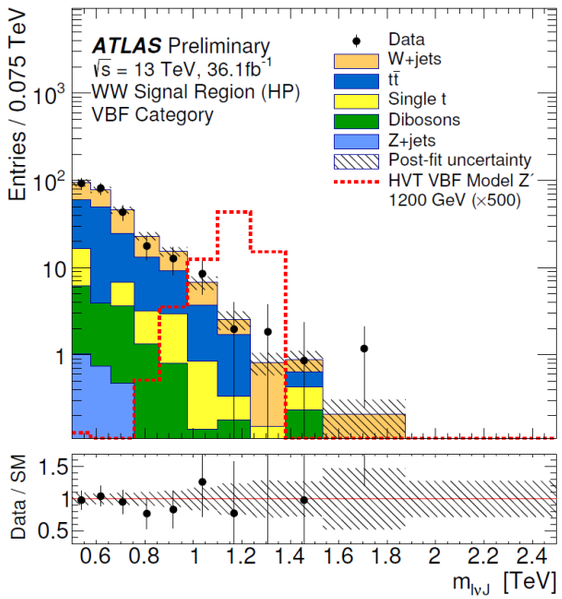
2HDM interpretations in type-I and type-II:

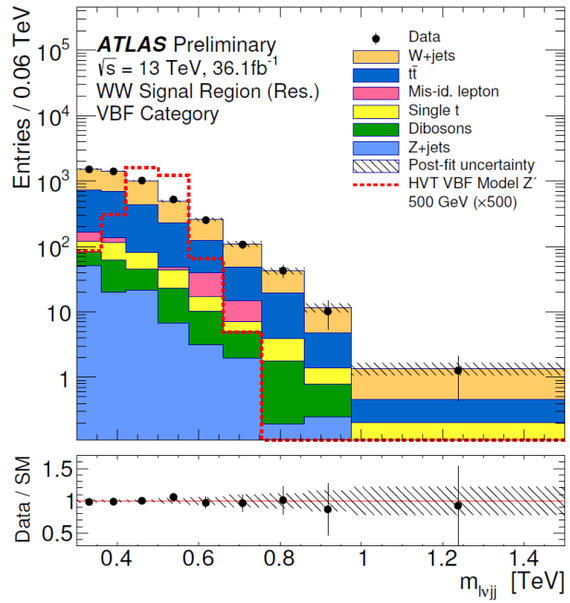
- ggF and VBF production as predicted by model
- NWA valid for 200 GeV mass point

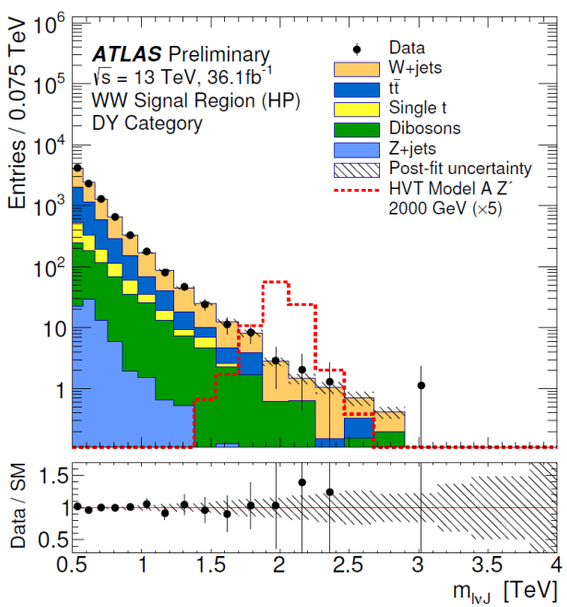


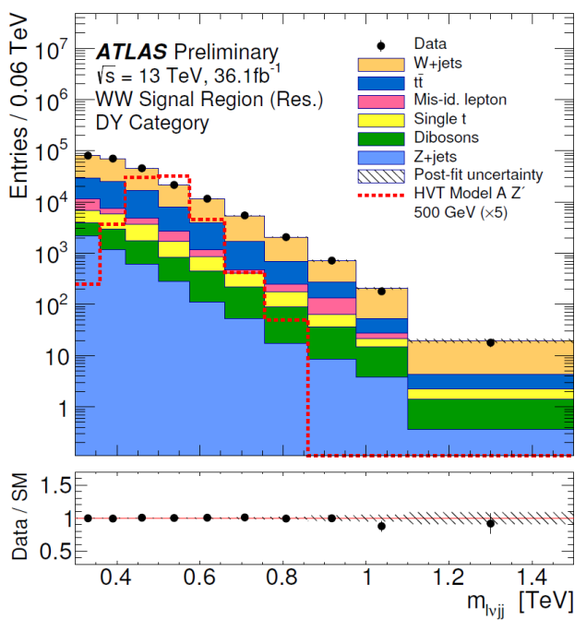


Search for H → WW → lνqq









Production via ggF or $q\bar{q}$ (Drell Yan category) or via VBF

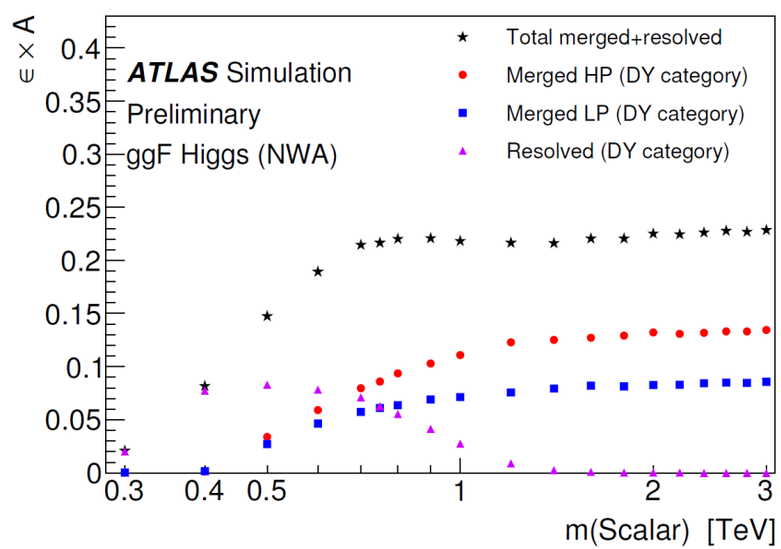
VBF category: m_{jj}>770 GeV, $|\Delta\eta_{jj}|$>4.7 (small-R tag jets)

DY category: events that fail the VBF selection

qq either merged (large-R jet) or resolved (jj)

Large-R jet mass combines calorimeter and track information

Merged category further subdivided into low and high purity, defined by cut on D2 substructure variable

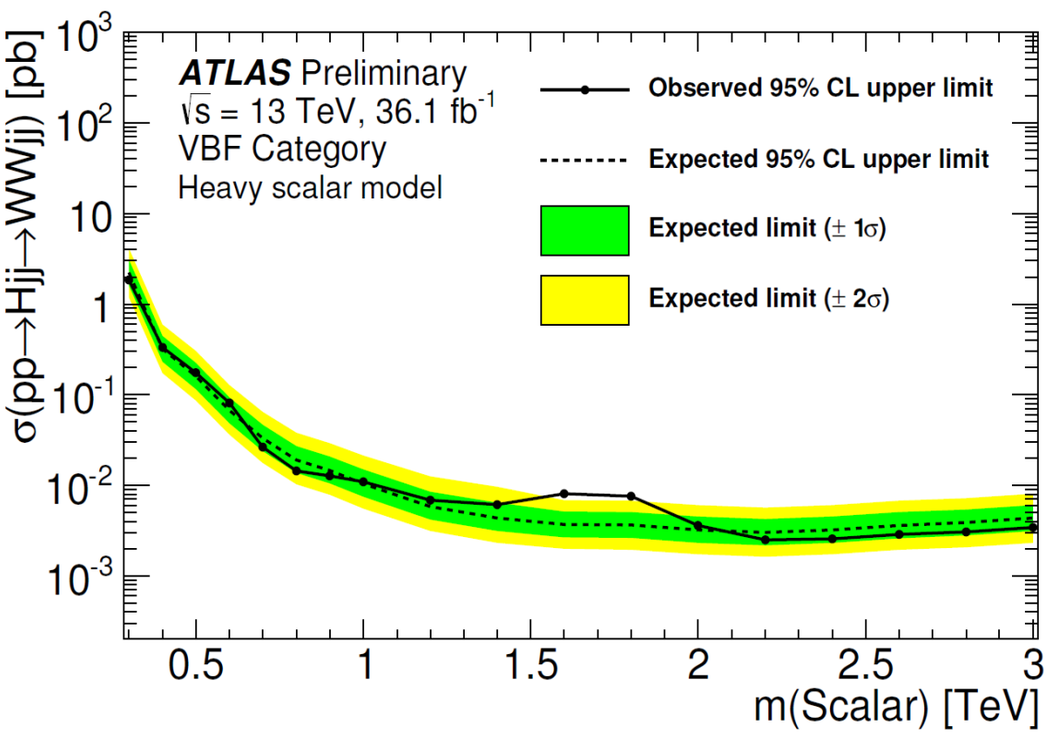


Search for H → WW → lνqq

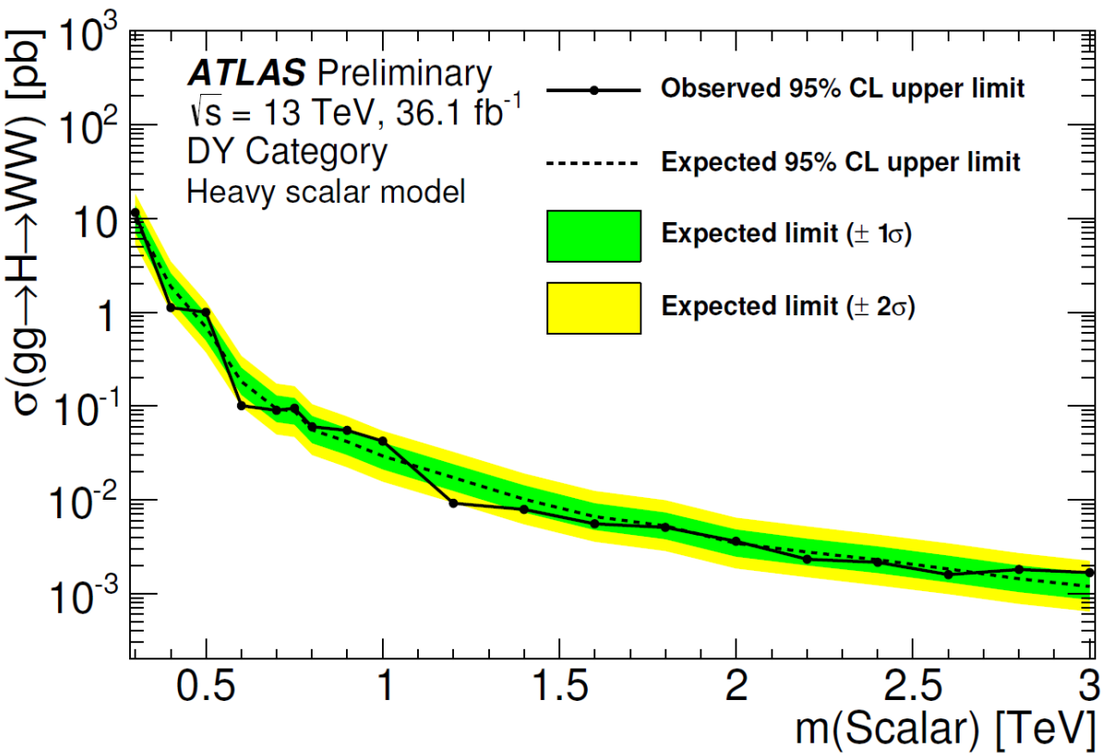
- No significant excess

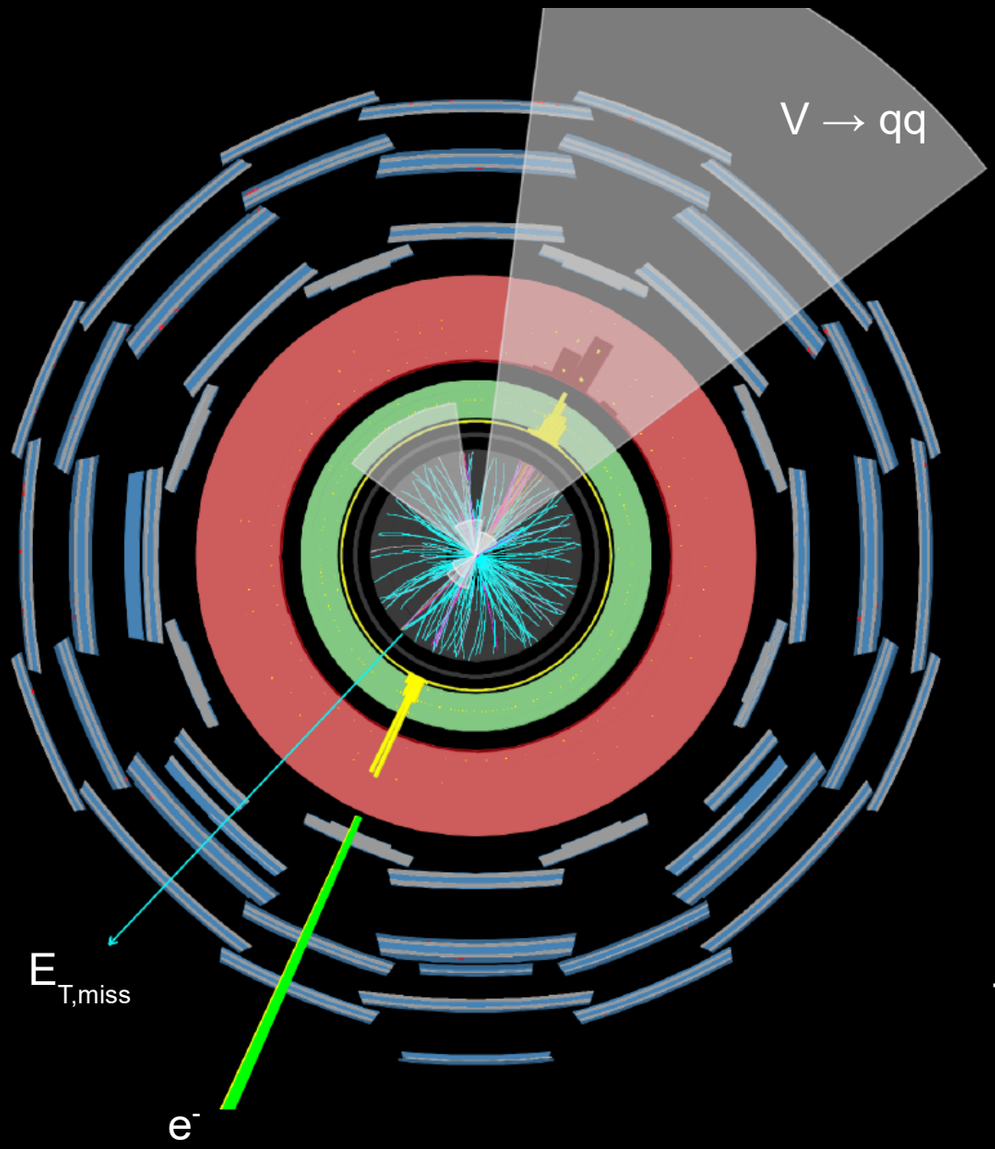
- Small fluctuation around 1.7 TeV in VBF category, due to one event in tail of merged high-purity category

VBF category



Drell Yan category

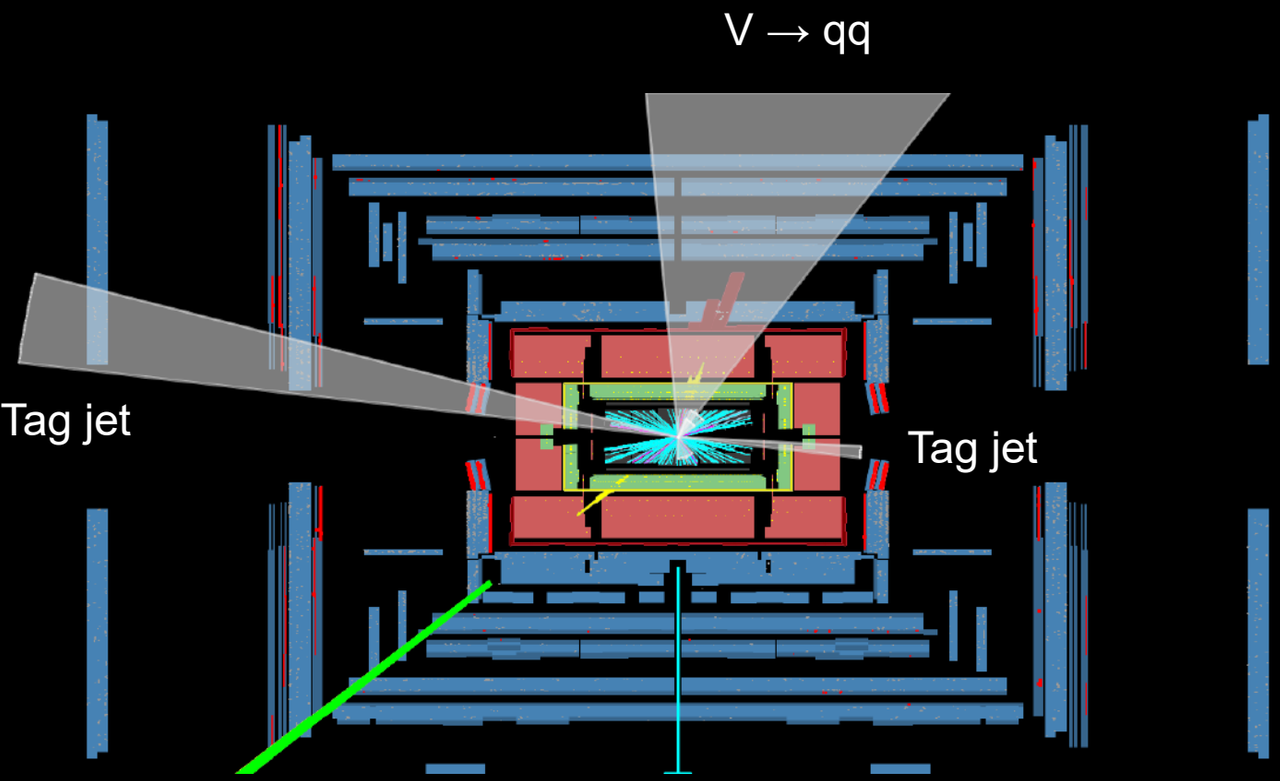




ATLAS EXPERIMENT

Run Number: 308047, Event Number: 969360152

Date: 2016-09-08 12:58:28 CEST



VBF WV candidate event

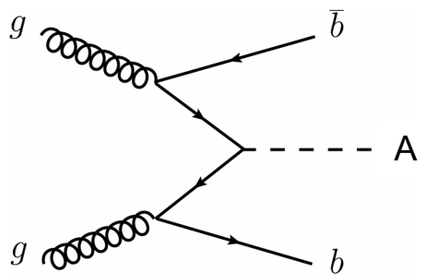
WV mass 2.76 TeV

Search for A → Zh$_{125}$ → νν**bb** / ll**bb**

ATLAS-CONF-2017-055

0 or 2 lepton categories

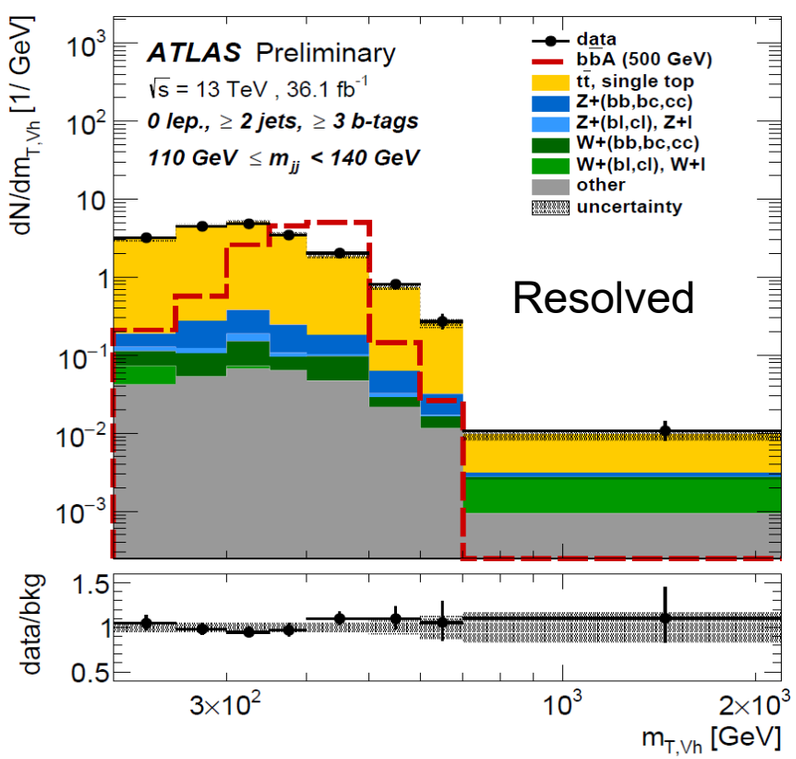
Merged and resolved categories

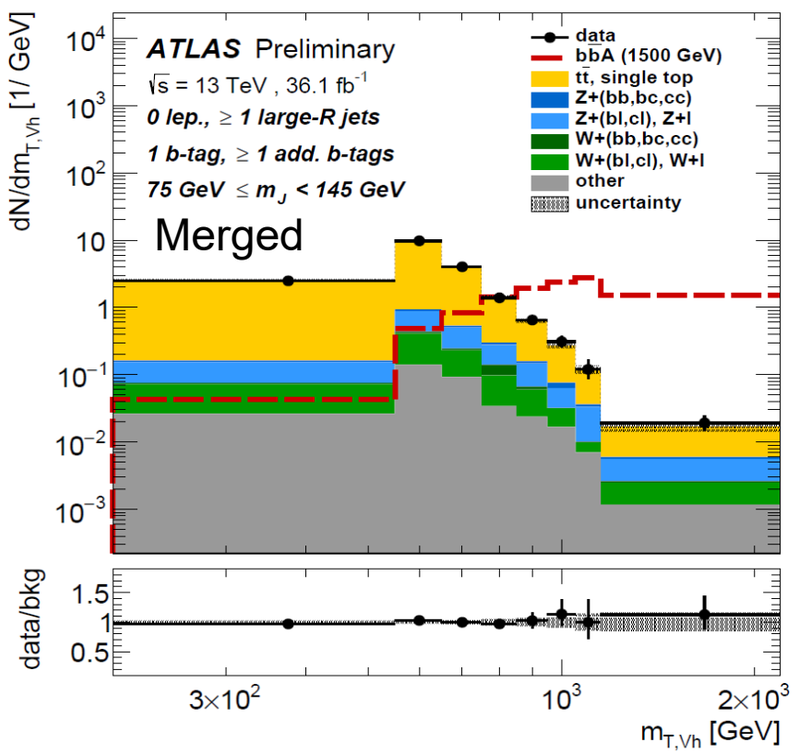


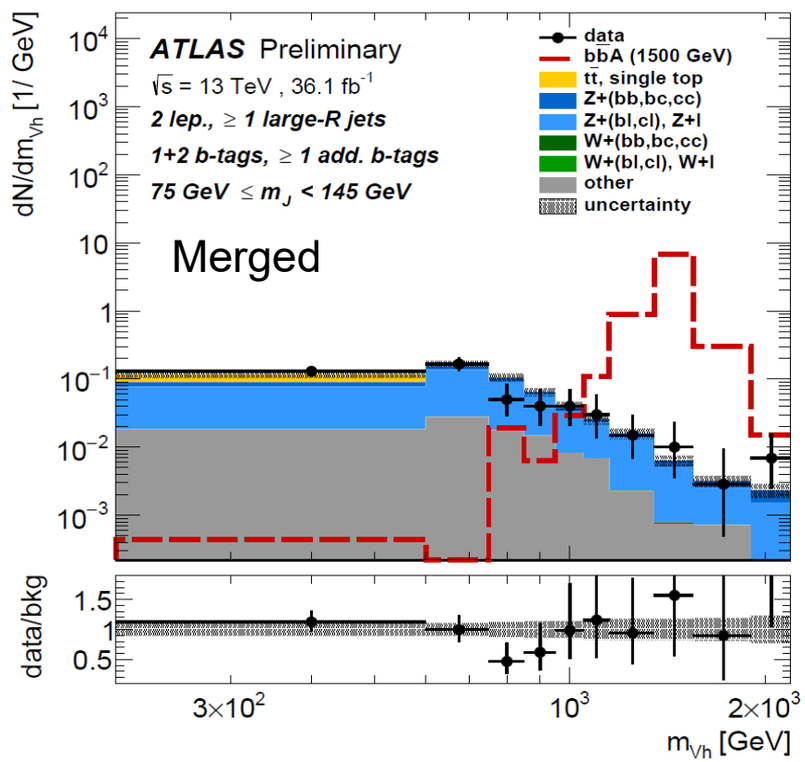
Z→νν or Z→ll, and h→bb

Channel	Resolved Signal regions	Merged Signal regions	Resolved Control regions
0-lepton	1, 2, 3+ *b*-tag	1, 2 *b*-tag, and 1, 2 *b*-tag add. b-tag	–
2-lepton	1, 2, 3+ *b*-tag	1, 2 *b*-tag, and 1+2 *b*-tag add. b-tag	1+2 *b*-tag , 3+ *b*-tag $e\mu$ CR

Categories with additional b-tags to enhance bbA process

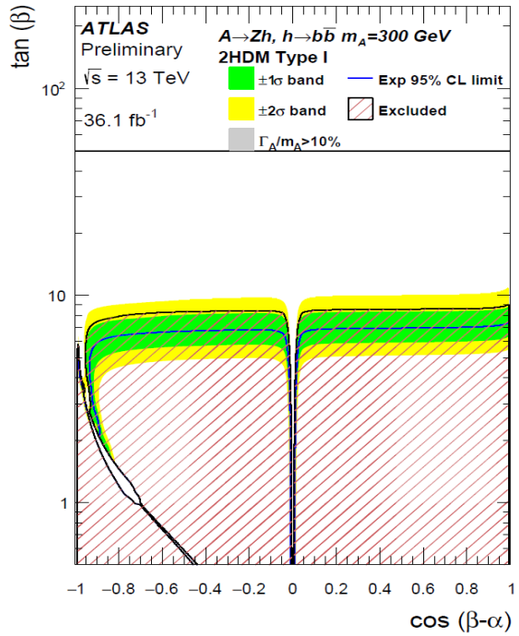


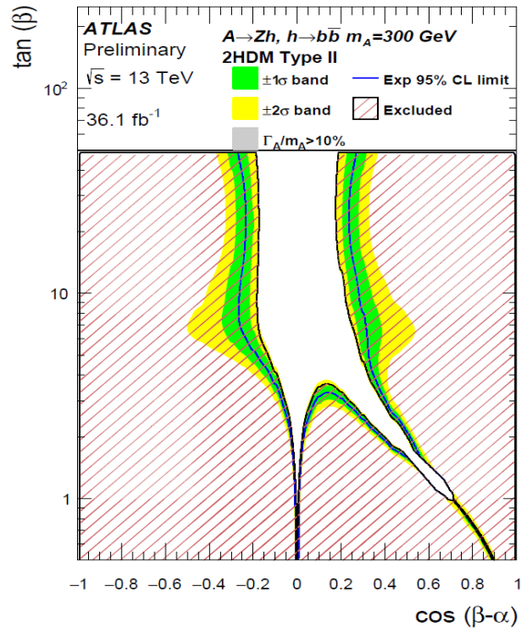


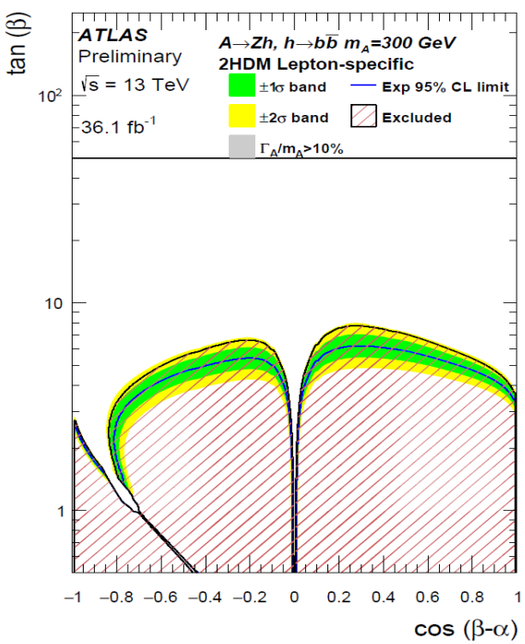


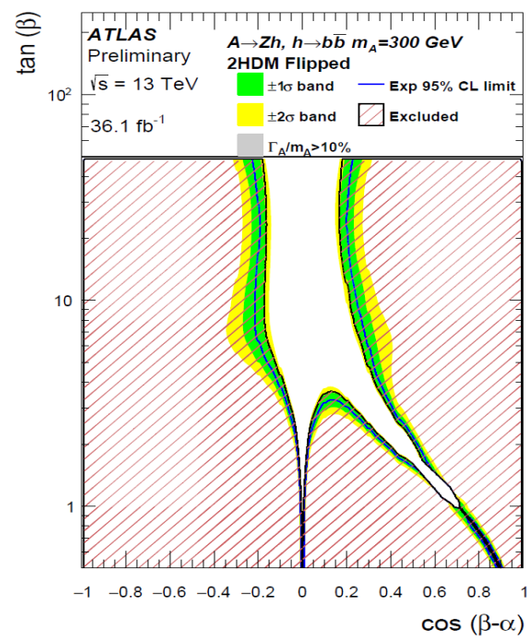
Search for $A \rightarrow Zh_{125} \rightarrow \nu\nu bb$ / $llbb$

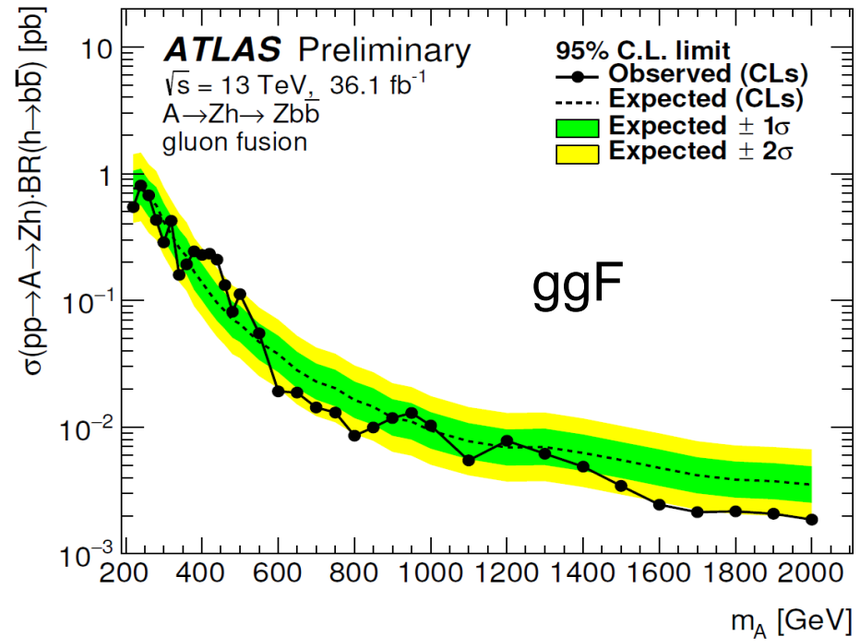
ATLAS-CONF-2017-055

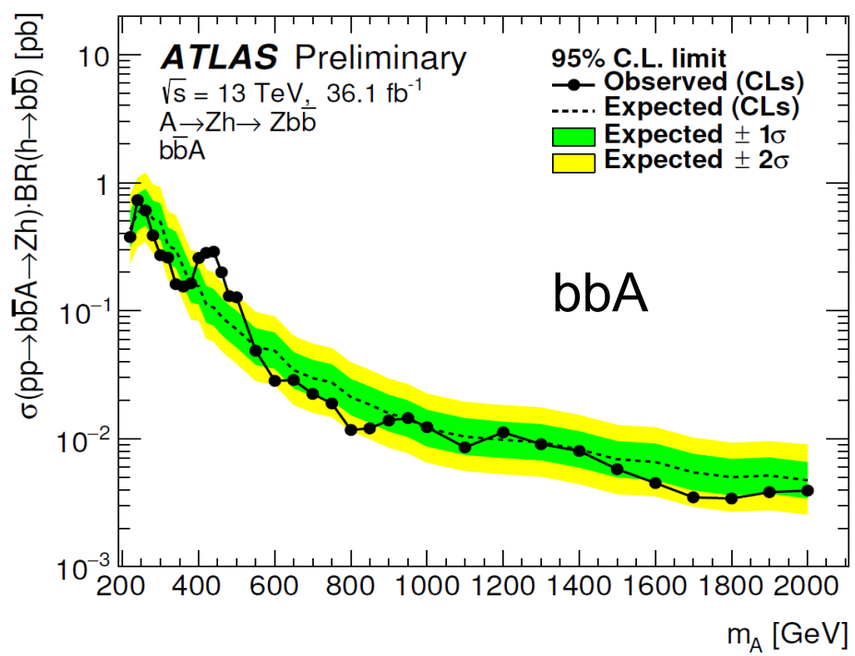












2.4σ global excess at 440 GeV

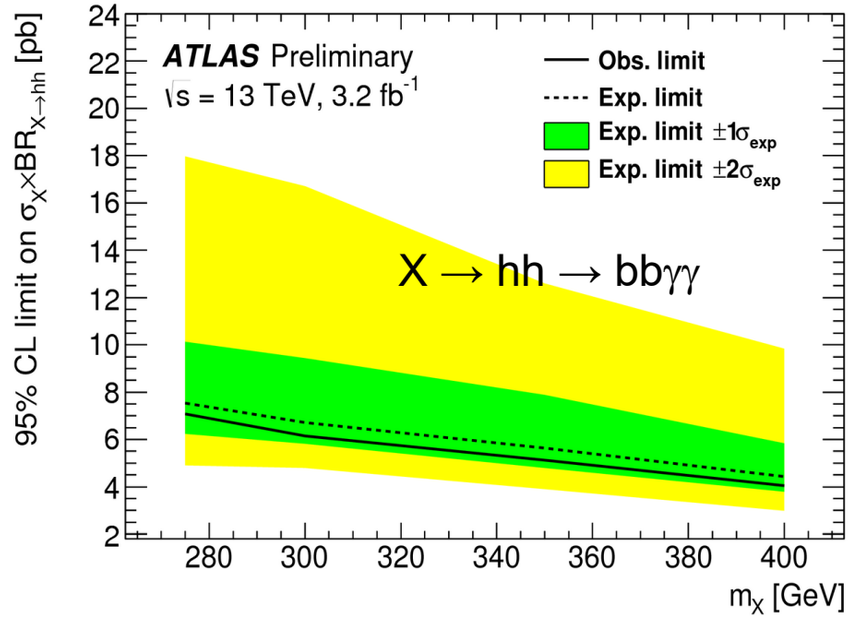
driven by dimuon resolved 3+ btags category

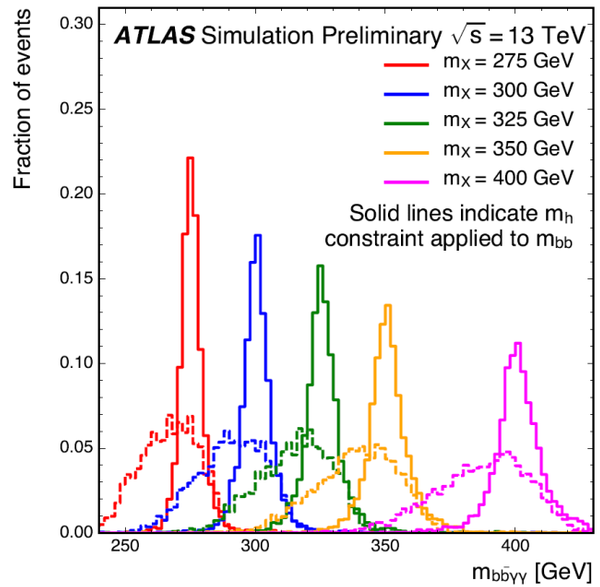
Searches for H/X → $h_{125}h_{125}$

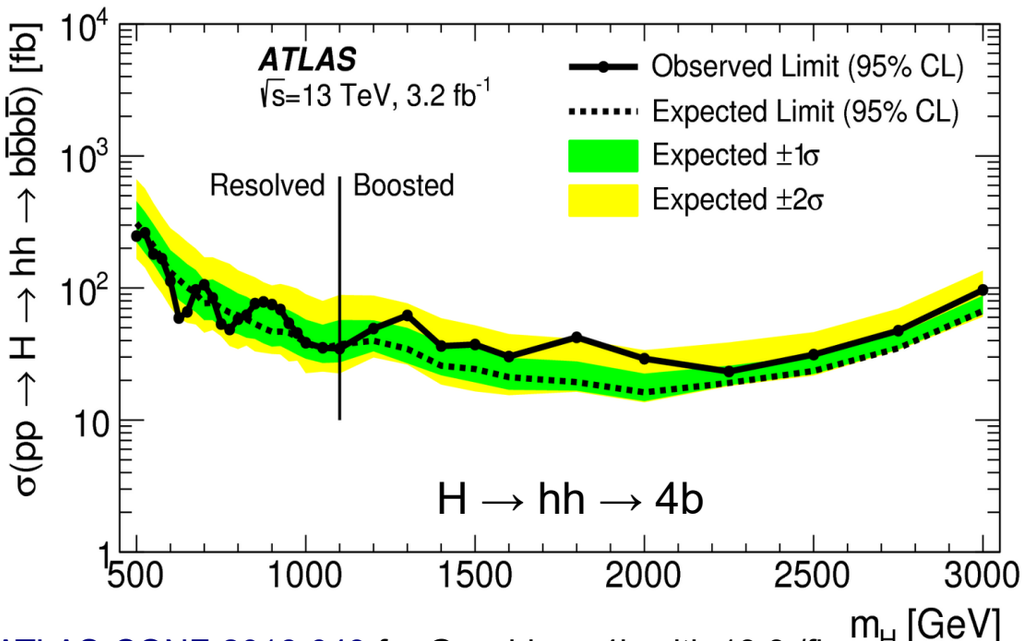
Using the SM Higgs boson as a tool to search for new resonances

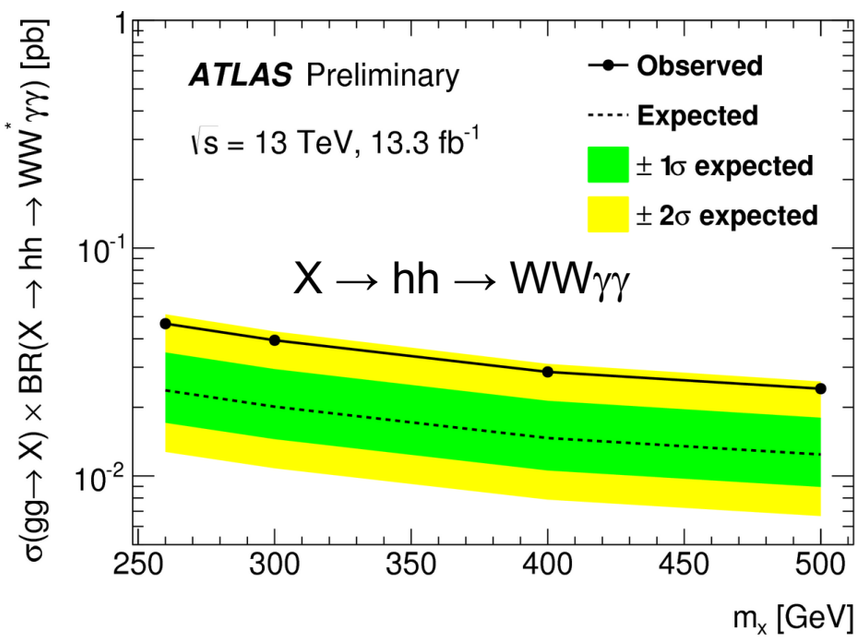
Limits on non-resonant hh production:

bbbb: 430fb obs. (330fb exp.)
ie. 29 x SM (using 13.3 /fb)
bbγγ: 3.9pb observed (5.4pb expected)
γγWW: 25.0pb observed (12.9 expected)









ATLAS-CONF-2016-049

arXiv:1606.04782

ATLAS-CONF-2016-071

ATLAS-CONF-2016-004

See ATLAS-CONF-2016-049 for G → hh → 4b with 13.3 /fb

Summary

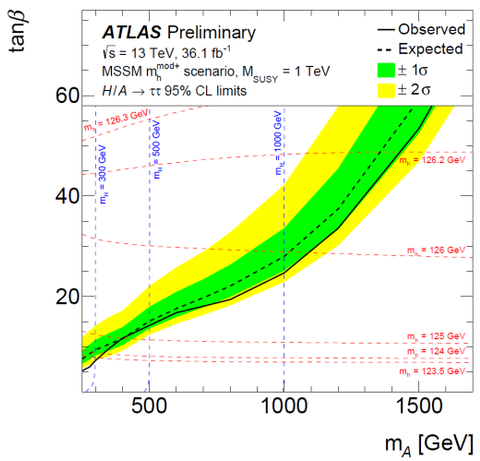
Large variety of BSM Heavy Higgs searches presented

Sophisticated analysis techniques employed: Different production modes, multi-variate techniques, sub-structure, many simultaneously fitted categories

Challenging channels tackled, eg. H/A → tt, H^+ → tb, bbH(→tt), ...

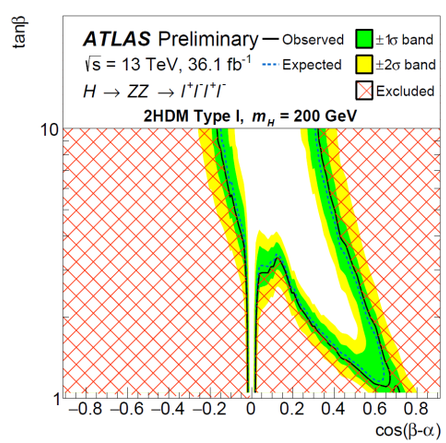
No significant excess observed

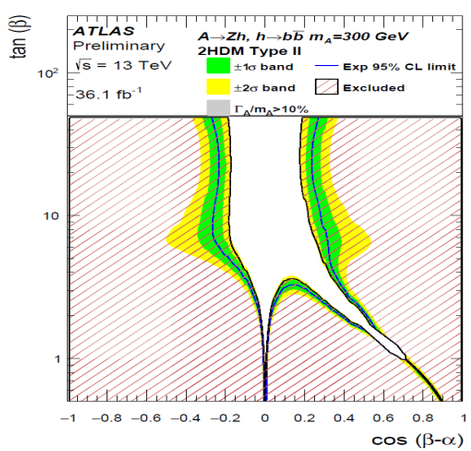
Limits considerably improved wrt. previous analyses, mass ranges expanded



2017 data not yet analysed

Total Run-2 luminosity expected to be ~100 /fb.
We will turn every stone!





Backup

Two Higgs Doublet Model (2HDM)

Extremely rich phenomenology, countless models.

→ Only specific class of models considered:

- No FCNC on tree level
- CP conservation in the Higgs sector

Review: Branco et al
arXiv:1106.0034

4 Types defined with different couplings of the particles to the doublets:

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

One doublet is fermiophobic

One doublet couples to up, other to down-type (=MSSM like)

One doublet couples to quarks as type-I, other with leptons as type-II

One doublet couples to quarks as type-II, other with leptons as type-I

- Five Higgs bosons: h, H, A, H^+, H^-
- Free parameters: tanβ, m_h, m_A, m_H, m_{H+}, α (mixing of h and H)
- Fixing m_h=125 GeV and other theoretical considerations about valid mass splittings reduce the phase space of these parameters in reality → m_A, tanβ, cos(β–α)

MSSM bechmark scenarios for the LHC

arXiv:1302.7033

- mhmaxup — Higher order corrections maximize the h mass
- mhmod± — Reduced stop mixing wrt. mhmax

  In mhmod+ the predictions are more in agreement with (g-2)μ, in mhmod- with b→sγ
- light stop — ggh suppressed
- light stau — Enhanced h → γγ at high tanβ
- tauphobic — Suppressed couplings of h to down-type fermions
- Low m_H — $m_h > m_H$, m_H = 125 GeV fixed