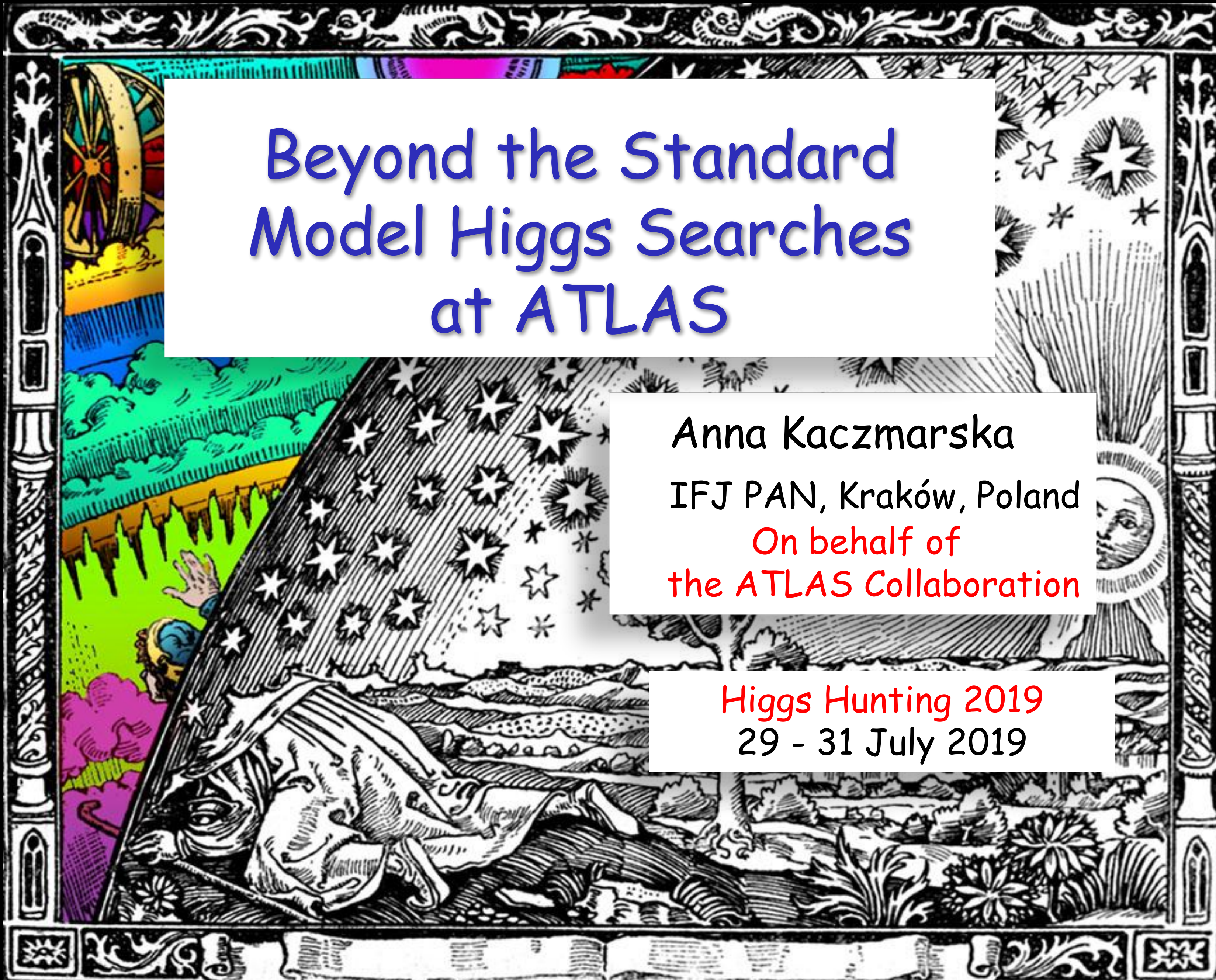


# Beyond the Standard Model Higgs Searches at ATLAS

Anna Kaczmarska

IFJ PAN, Kraków, Poland

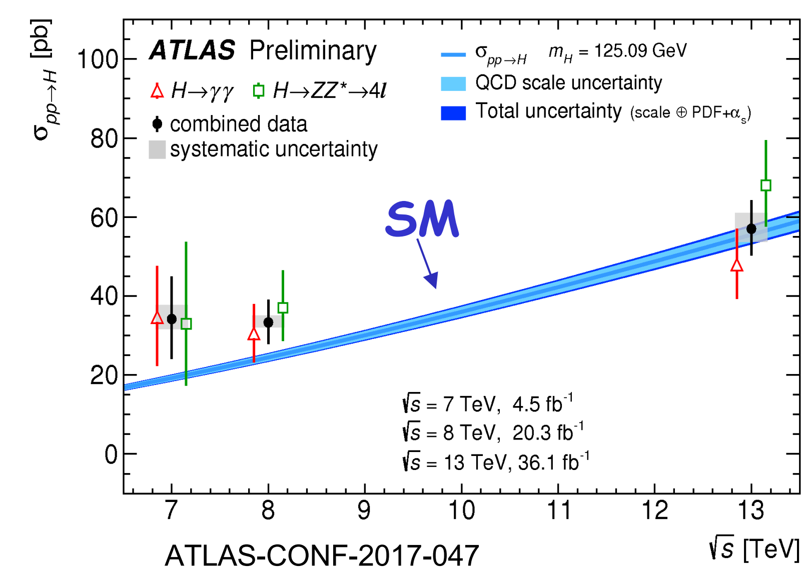
On behalf of
the ATLAS Collaboration

Higgs Hunting 2019
29 - 31 July 2019

# Standard Model Higgs

- So far…
  - Discovery of a neutral scalar particle of mass ~125 GeV confirmed the predicted electroweak symmetry breaking mechanism of the SM
  - Experimental results show consistency with the SM Higgs boson
- But the SM is not perfect…
  - Hierarchy problem, dark matter, unification of the forces etc.
- Fortunately consistency with SM doesn't exclude Beyond SM scenarios


- Extended scalar sector appears in many extensions of the SM
- They allow for SM-like Higgs phenomenology with smaller or larger modification of couplings



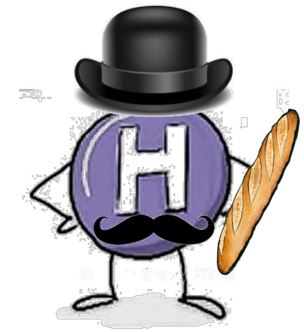
# Beyond the Standard Model Higgs

**General recipe: SM Higgs Doublet + Additional Field = Additional Higgs Bosons**

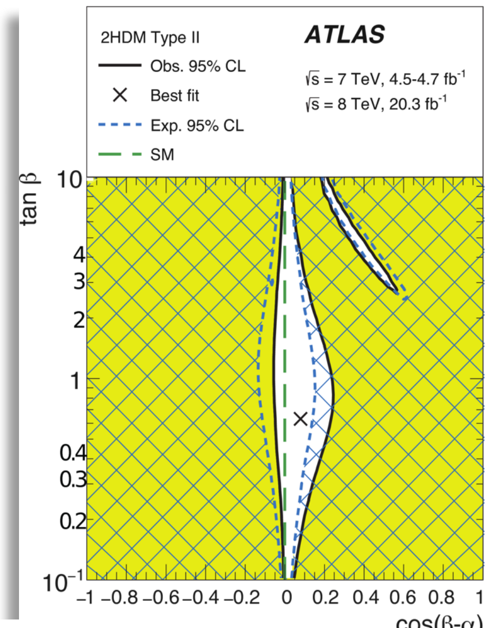
- SM + another Higgs doublet = **Two Higgs Doublet Model, 2HDM**
  - 5 Higgs bosons: h, H, A, $H^+$, $H^-$
  - Free parameters: tanβ, α and $m_A$
  - Four variants to couple SM fermions to the 2HDs

| Coupling scale factor | Type I | Type II | Lepton-specific | Flipped |
|---|---|---|---|---|
| $\kappa_V$ | $\sin(\beta-\alpha)$ | | | |
| $\kappa_u$ | $\cos(\alpha)/\sin(\beta)$ | | | |
| $\kappa_d$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ |
| $\kappa_\ell$ | $\cos(\alpha)/\sin(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $-\sin(\alpha)/\cos(\beta)$ | $\cos(\alpha)/\sin(\beta)$ |

Table 5: Couplings of the light Higgs boson $h$ to weak vector bosons ($\kappa_V$), up-type quarks ($\kappa_u$), down-type quarks ($\kappa_d$), and charged leptons ($\kappa_\ell$), expressed as ratios to the corresponding SM predictions in 2HDMs of various types.



  - Minimal Supersymmetric SM (MSSM)
    - "type II" 2HDM with fixed α
    - numerous benchmark models: hMSSM, $m_h^{mod+}$, etc.
  - SM Higgs Run1 results => strict constraints on 2HDM. Data prefers alignment limit: cos(β- α)=0
    - h recovers properties of the SM Higgs
- SM + triplet = **Higgs triplet models**
  - Double charged Higgs boson + 2HDM Higgses




JHEP11(2015)206

# Strategies using Higgs to find New Physics

Strategies that use Higgs to find new physics:

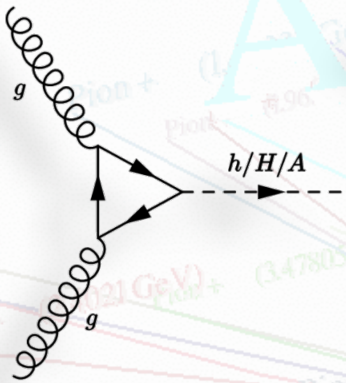
- Indirectly, by looking for non-standard properties of light Higgs (spin, CP, couplings, LFV decays etc.)
- **Directly, by explicit search for BSM objects**
  - Additional Higgs bosons (neutral and charged, decays to SM particles or to Higgs bosons)
  - Higgs decays to BSM states (light scalar resonances, invisible decays, long lived particles etc.)
    - see talks by L.Truong and Y.Gershtein

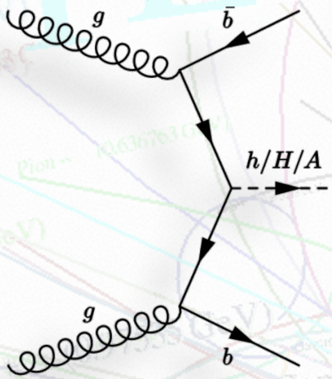
**Today:**

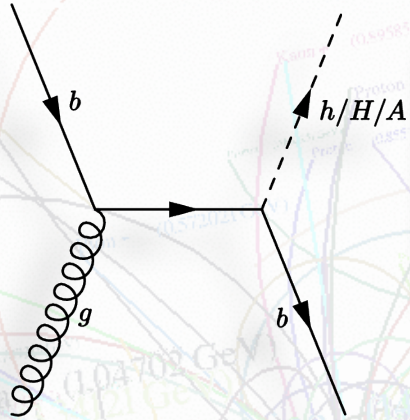
- Neutral Higgs to fermions
  - $H \to \tau\tau$ JHEP 01 (2018) 055
  - $bH \to bb$ arXiv:1907.02749
- Charged Higgs
  - $H^{\pm} \to \tau\nu$ JHEP 09 (2018) 139
  - $H^{\pm} \to tb$ JHEP 11 (2018) 085
  - $H^{\pm\pm} \to l^{\pm}l^{\pm}$ Eur. Phys. J. C78 (2018) 19
  - $H^{\pm\pm} \to W^{\pm}W^{\pm}$ Eur. Phys. J. C (2019) 79
- Higgs to dihiggs
  - see talk by S.Shrestha, C.Amendola
- Neutral Higgs to bosons
  - $H \to \gamma\gamma$ ATLAS-CONF-2018-025

Disclaimer:
Incomplete set of analysed Higgs channels. Only most recent results shown.
New results with full Run-2 dataset coming!

# Heavy neutral Higgs decays to fermions




Dominant production modes in the MSSM:

- gluon fusion (low tan$\beta$)
- b-associated production (high tan$\beta$)

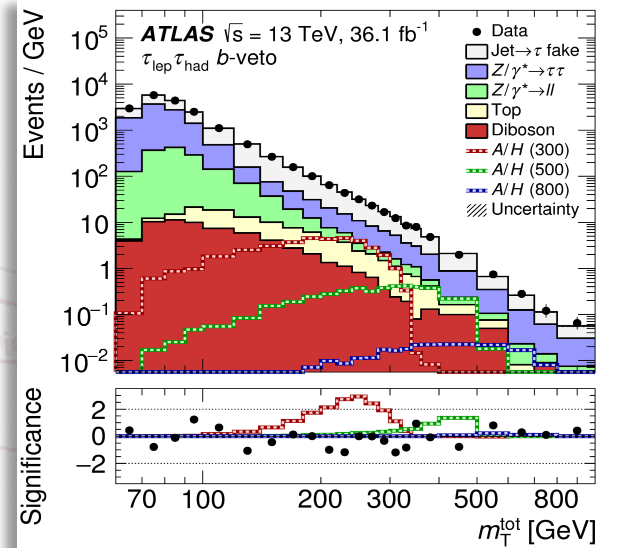
- In the MSSM, the heavy Higgs boson couplings to down-type fermions (τ,b) are strongly enhanced for a large part of the parameter space for large tanβ
  - increased BRs to τ- leptons and *b*-quarks
  - higher cross section for Higgs boson production in association with *b*-quarks
- Searches for both decays to b-quarks and τ- leptons needed to cover all 2HDM Types
  - τ- leptons sensitive to II and Lepton-specific Types
  - *b*-quarks sensitive to II and Flipped Types

- **H/A→ττ** JHEP 01 (2018) 055
- **bH/A→ bbb** arXiv:1907.02749

- H/A →ttbar ATLAS-CONF-2016-073, Run1
- H/A →$\mu\mu$ arXiv: 1901.08144

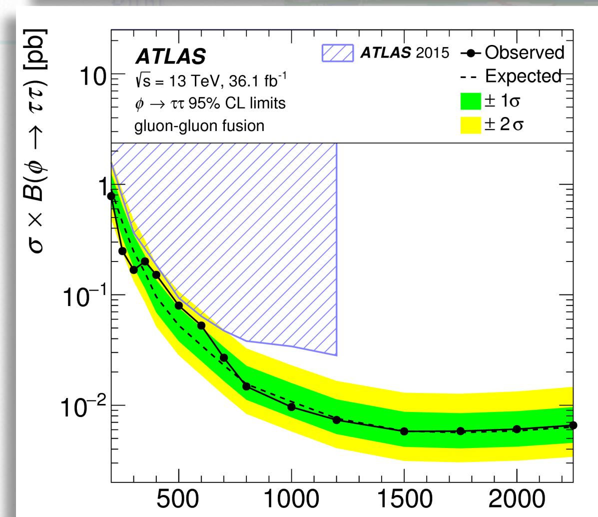
# Neutral Higgs searches: H/A→ττ

JHEP 01 (2018) 055

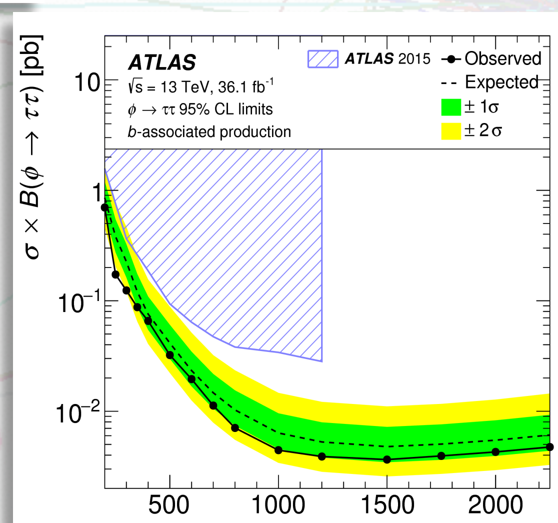



- Mass range 200 – 2250 GeV
- Final states: $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$
- Two categories: b-veto (gluon fusion) and b-tag (b-associated production)
- Discriminant: total transverse mass

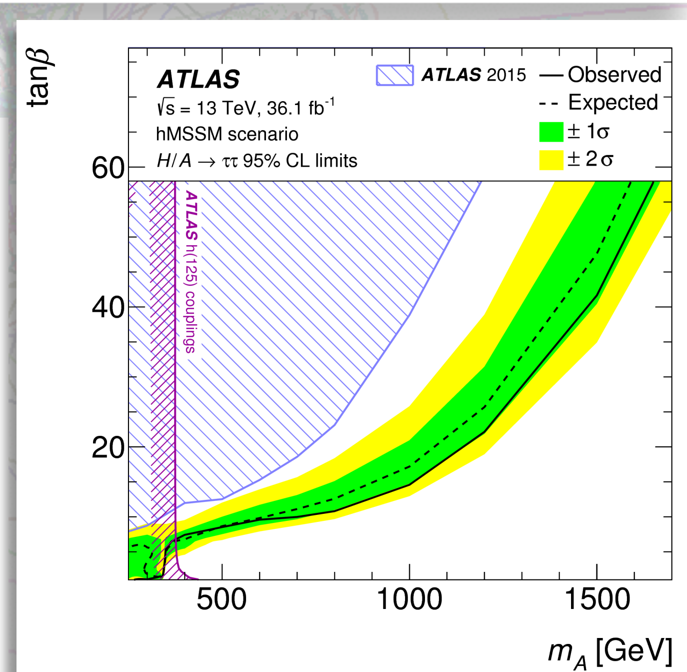
$$m_T^{\rm tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\rm miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{\rm miss})^2}$$




0.78-0.0058 pb



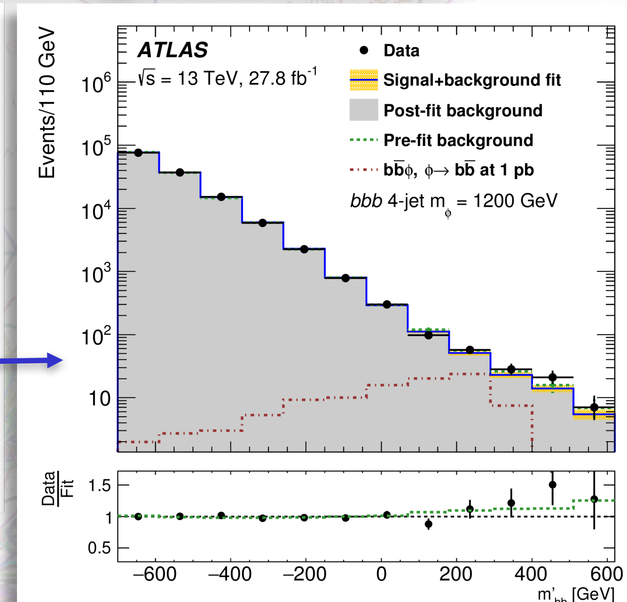

0.70-0.0037 pb

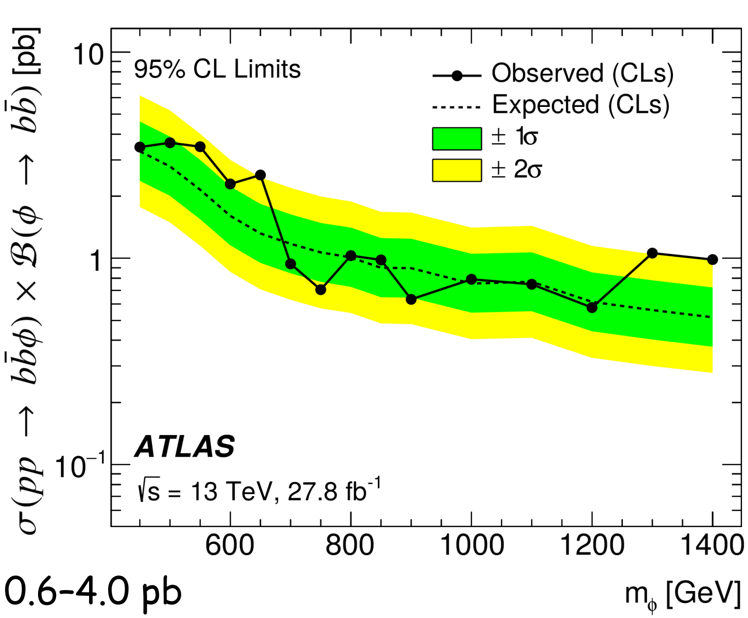


# Neutral Higgs searches: bH/A→bb

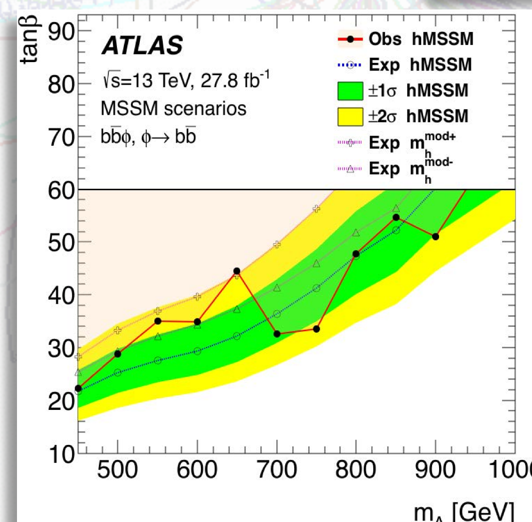
arXiv:1907.02749

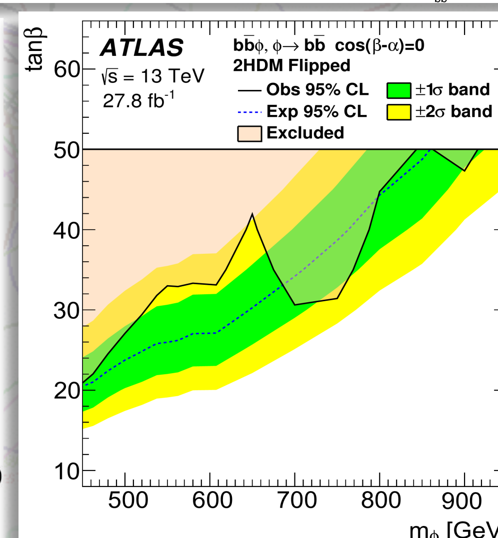
- Mass range 450 – 1400 GeV
- Targets Type II and Flipped 2HDM at high tan$\beta$ (where H/A mainly couple to b-quarks)
- Challenging b-jet trigger
- Events classified according to the number of jets and b-jets
- $m'_{bb}$ from diagonalized ($m_{bb}$, $PT_{b1}$,$PT_{b2}$) improves S/B separation
- Fully data driven background with bb(anti-b) CR




0.6–4.0 pb



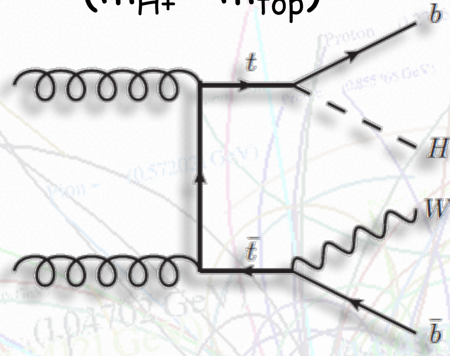



# Charged Higgs searches

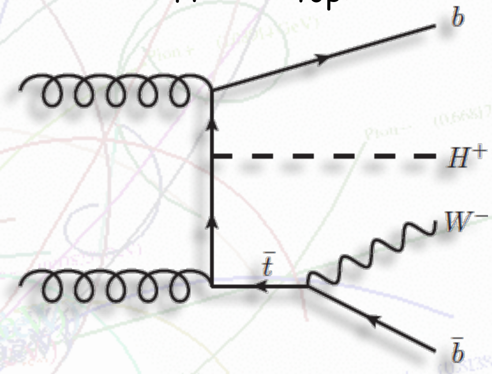
$H^{\pm}$ predicted by 2HDM, Higgs triplets,….
In Type II 2HDM:

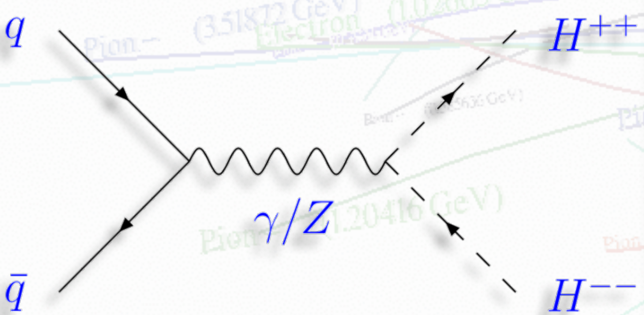
- Main production in association with a top quark
- At high mass $H^{\pm} \to tb$ is the dominant decay mode
- $BR(H^{\pm} \to \tau\nu)$ significant for a large range of masses for high $\tan\beta$

$(m_{H^+} < m_{top})$




$(m_{H^+} > m_{top})$




$H^{\pm\pm}$ predicted by Left-Right Symmetric Models (LRSM), Higgs Triplet Model (HTM), Zee-Babu and Georgi–Machacek models
In LRSM and HTM:

- Dominant production at the LHC: DY pair production
- Decays: $H^{\pm\pm} \to l^{\pm}l^{\pm}$ or $H^{\pm\pm} \to W^{\pm}W^{\pm}$
  - BR ~ f($m_{H^{\pm\pm}}$ , vev of Higgs triplet)
  - Low $m_{H^{\pm\pm}}$ and low vev : $H^{\pm\pm} \to l^{\pm}l^{\pm}$ dominates

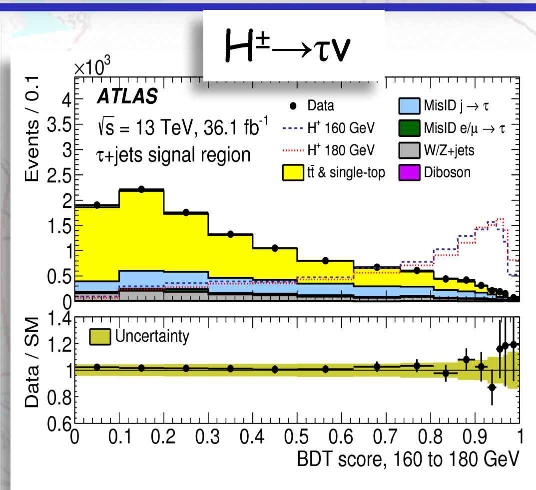
- $H^{\pm} \to \tau\nu$ JHEP 09 (2018) 139
- $H^{\pm} \to tb$ JHEP 11 (2018) 085
- $H^{\pm\pm}H^{\mp\mp} \to 4W$ Eur. Phys. J. C (2019) 79
- $H^{\pm\pm}H^{\mp\mp} \to 4l$ Eur. Phys. J. C78 (2018) 199

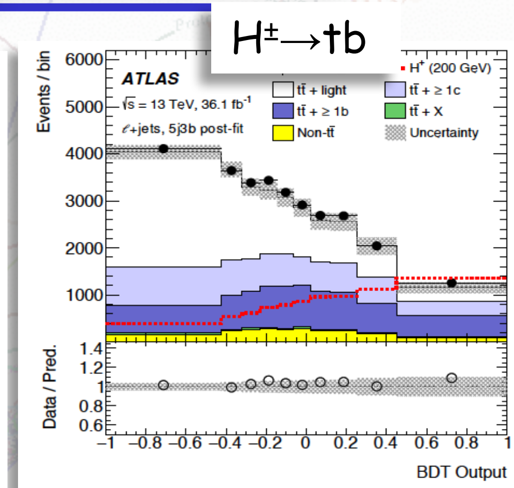
- $H^{\pm}$ -> $W^{\pm}Z$ Phys. Lett. B 787 (2019) 68
- $H^{\pm}$ -> cs Eur. Phys. J. C, 73 6 (2013) 2465, Run1

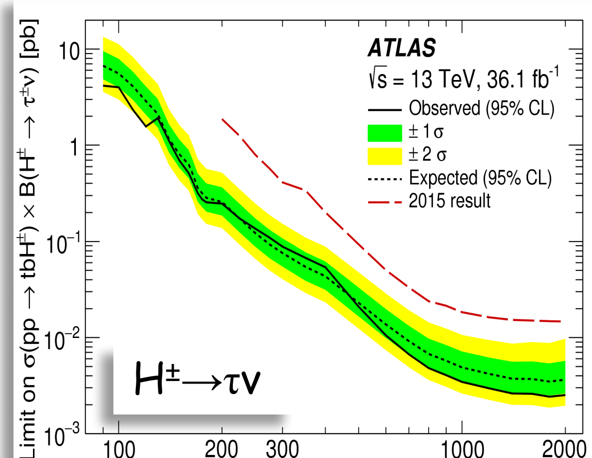
# Charged Higgs searches: $H^\pm \to \tau\nu$, tb

JHEP 09 (2018) 139
JHEP 11 (2018) 085

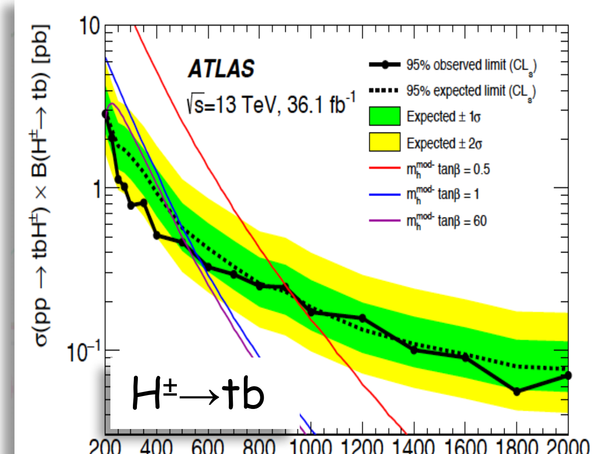
- $H^\pm \to \tau\nu$, mass range 90-2000 GeV
  - Final states $\tau_{had}$+jets, $\tau_{had}$+lep
  - Tau polarisation variable used
  - BDT trained in different mass bins
- $H^\pm \to tb$, mass range 200-2000 GeV
  - Final state single- and di-lepton (opposite-sign)
  - SR and CRs according to the number of jets and b-jets (7 regions)
  - BDT trained in each SR and for each signal mass hypothesis



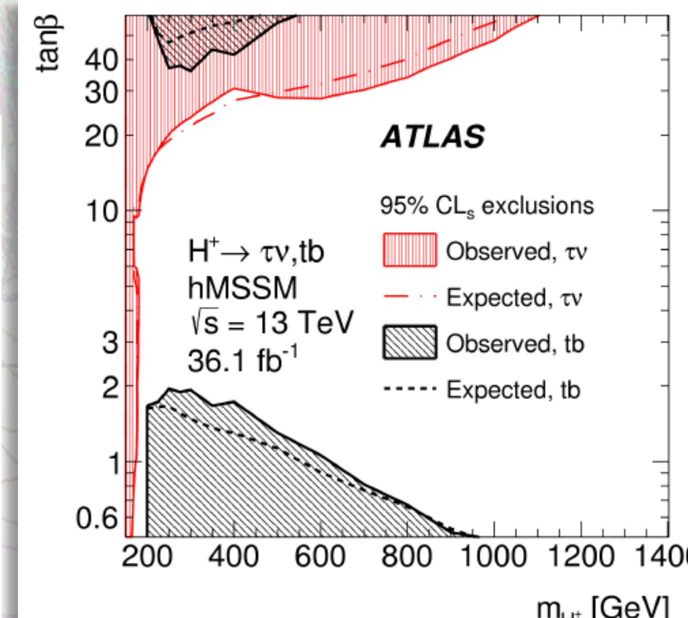




4.2 pb–2.5 fb




2.9 pb– 0.07 pb

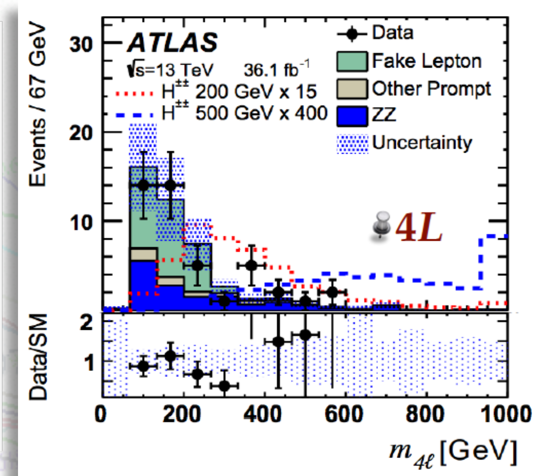


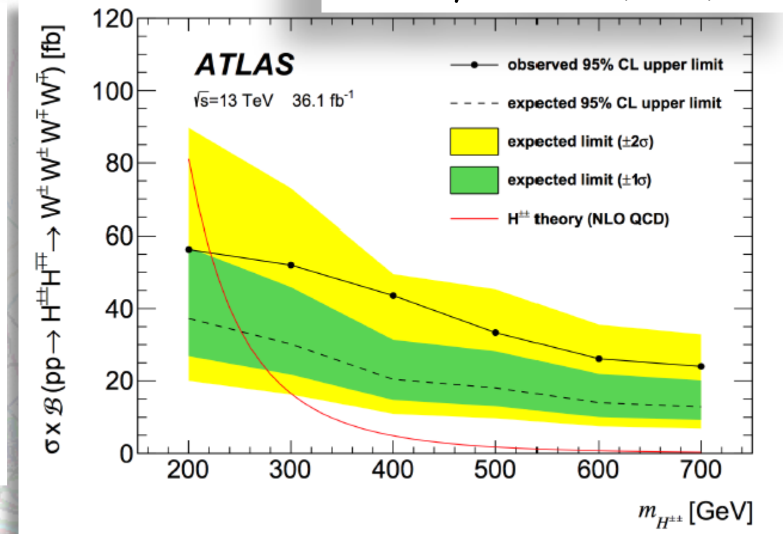
# Doubly charged Higgs searches: $H^{\pm\pm}H^{\mp\mp} \to 4W$, 4l

Eur. Phys. J. C (2019) 79
Eur. Phys. J. C78 (2018) 199

**$H^{\pm\pm}H^{\mp\mp} \to 4W$ (THM), mass range 200-700 GeV**

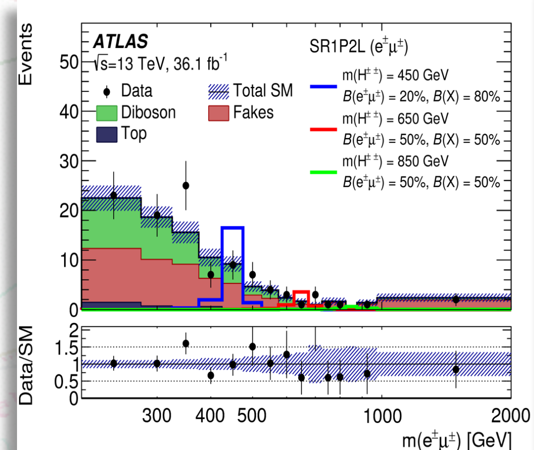
- Signature: $2l^{SS}$,3l,4l light leptons + missing $E_T$
- Mass- and channel-dependent cuts on discriminating variables
- Final fit based on six bin counting experiment

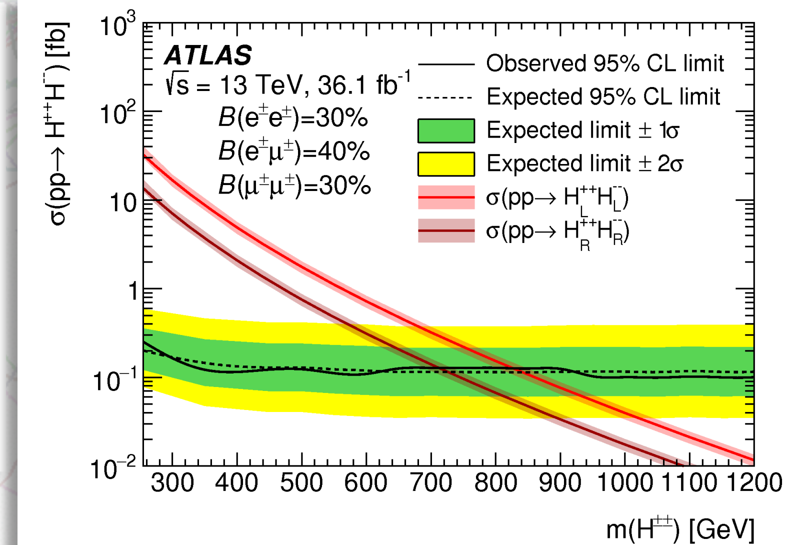



**$H^{\pm\pm}H^{\mp\mp} \to 4l$ (LRS), mass range 250-1300 GeV**

- Signature: isolated $2l^{SS}$,3l (1 pair SS), 4l (2 pairs SS) light leptons
- Discrimination: dilepton invariant mass, for SR with 4 leptons mean mass of two SS pairs

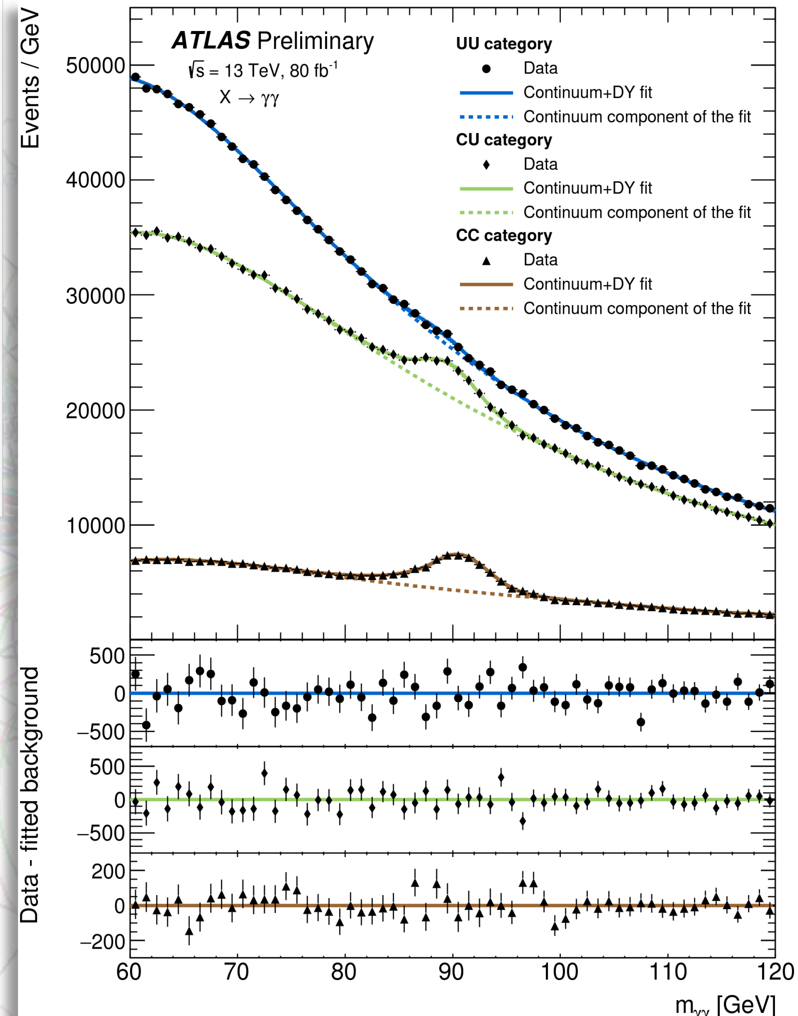


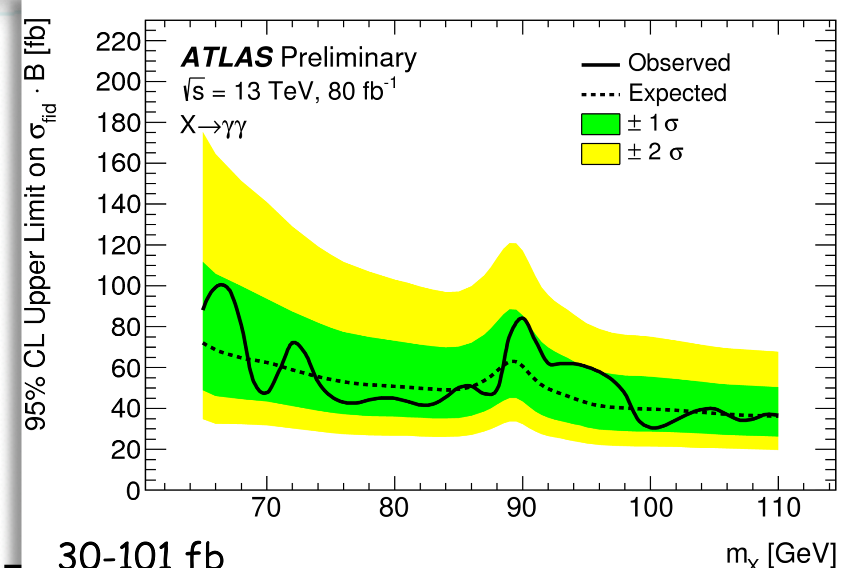



# Neutral Higgs decays to bosons: H→$\gamma\gamma$ (low-mass)

ATLAS-CONF-2018-025

- Generic search for diphoton resonances in mass range 65-110 GeV
- Three categories depending on how 2 $\gamma$'s candidates reconstructed (converted or not)
- Main backgrounds described with analytic functions validated on data
  - Continuum: $\gamma\gamma$, $\gamma$j, jj (jets misidentified as $\gamma$'s )
  - $Z/\gamma^* \to e^+e^-$ (Drell-Yan): e's reconstructed as $\gamma$'s
- The fit is performed to the m($\gamma\gamma$) spectra in the three conversion categories



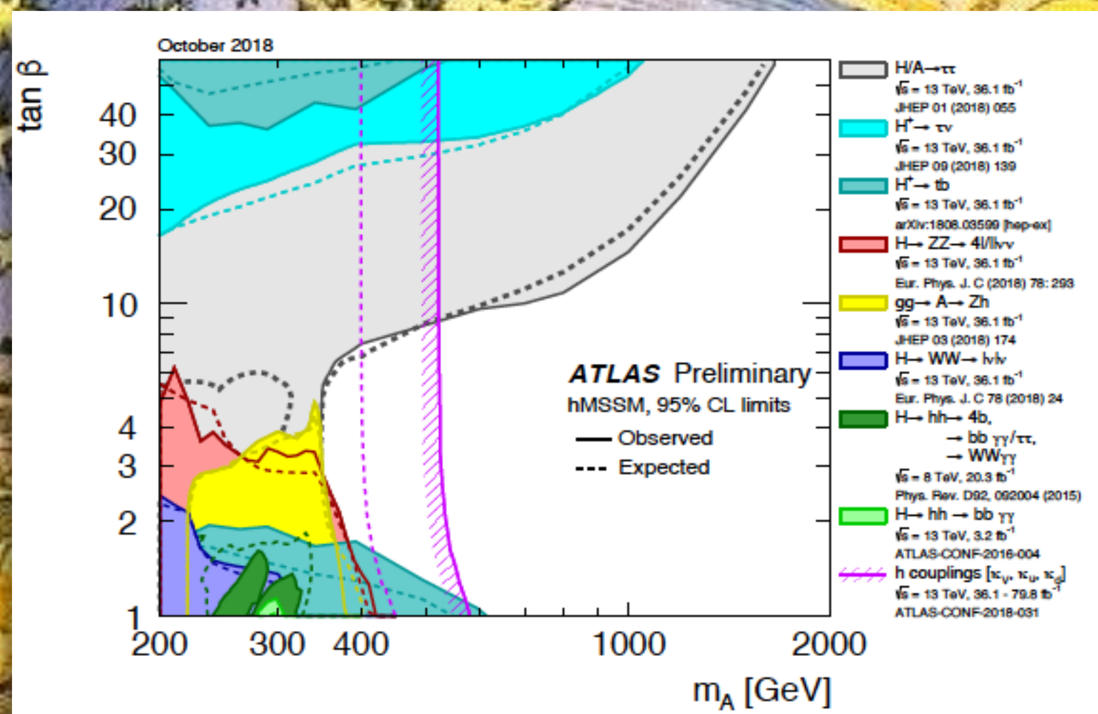




30-101 fb

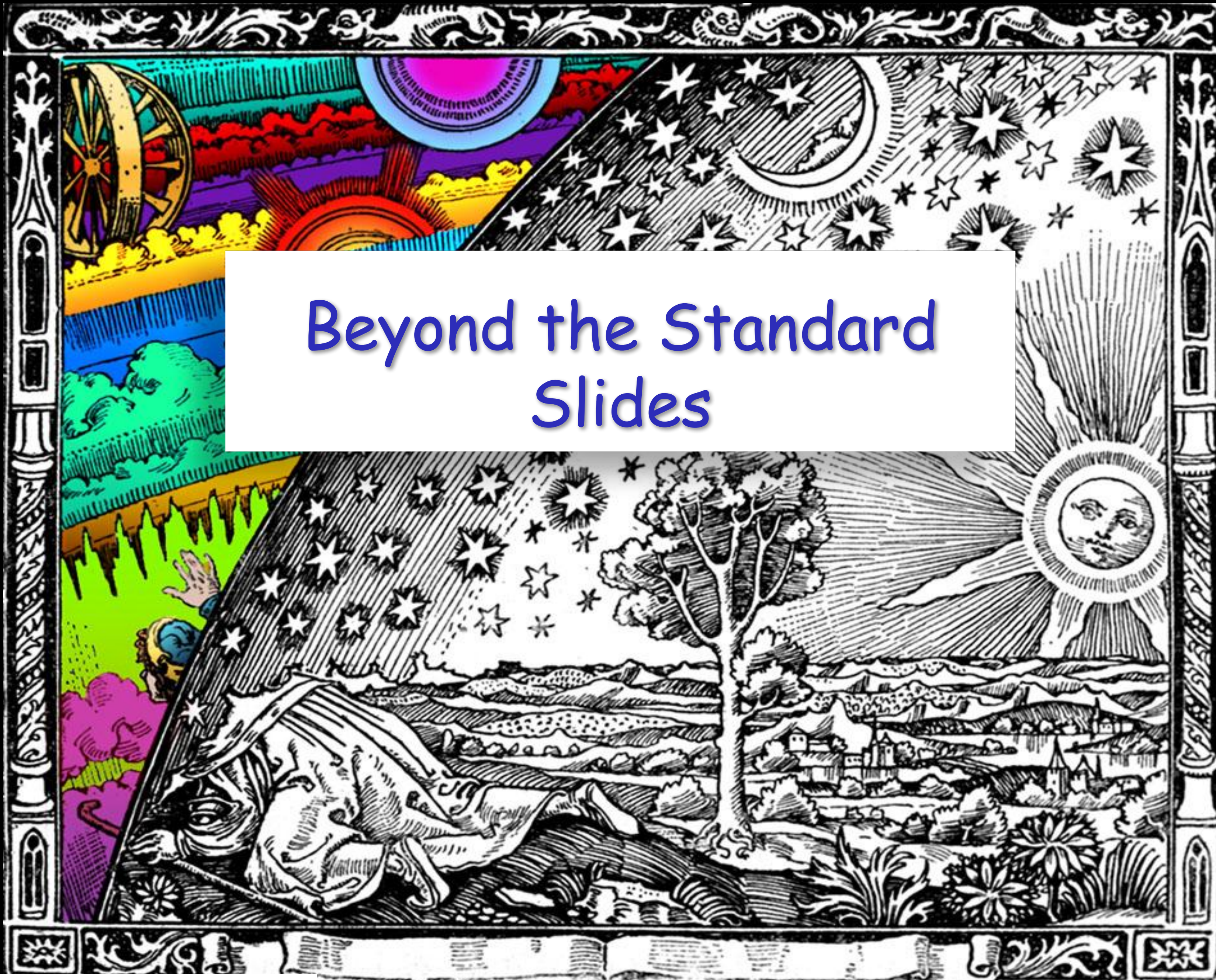
# Summary

- There is a plethora of searches for BSM physics in the Higgs sector at the LHC
- Only a small selection of results were presented here
- No evidence for any BSM Higgs Boson… yet
- Dedicated efforts in the combinations help improve sensitivity
- By now only impressive agreement with SM observed, instead of inspiring surprises
- But we have not yet finished! Much more Run2 data (140/fb) to analyse!

- We will turn every stone ☺ - but for now we need to wait a bit to tell an inspiring story to stimulate the HL-LHC and future experiments



# Beyond the Standard Slides



Courtesy of J. Keller

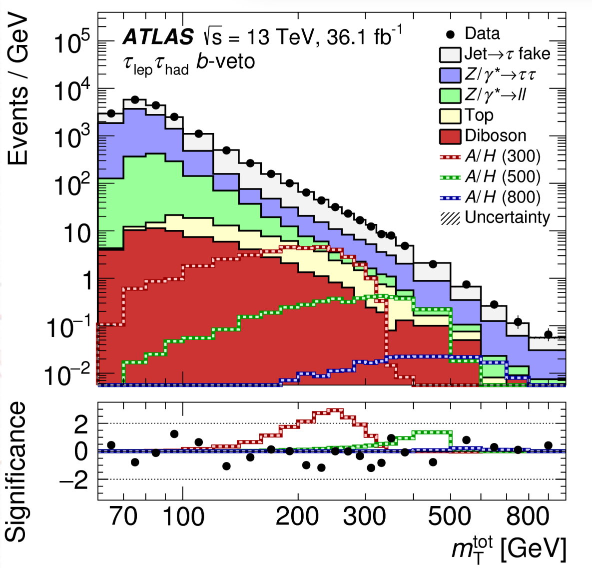
# Neutral Higgs decays to bosons

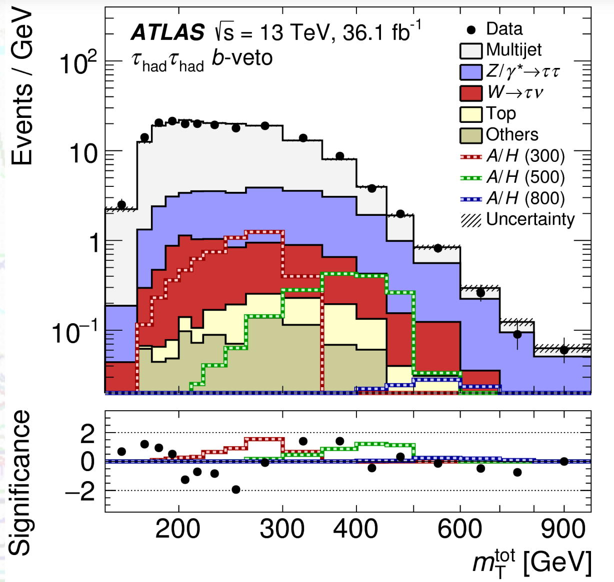
- BSM scenarios tested also for decay of neutral Higgs to di-boson final states
  - WW, WZ, ZZ, VH, $Z\gamma$ and $\gamma\gamma$
- Large variety of final states including leptonic and hadronic decays

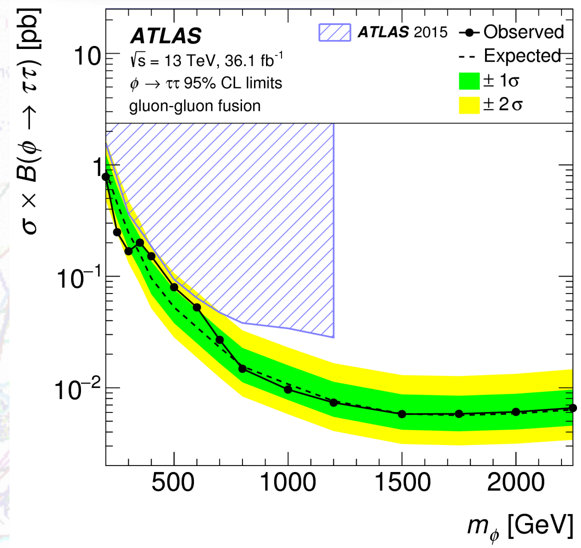
JHEP 03 (2018) 009, JHEP 03 (2018) 042, JHEP 03 (2018) 174, Phys. Lett.B 783 (2018) 392, Phys. Lett.B 775 (2017) 105, Phys. Lett.B 777 (2018) 91, Phys. Rev. D 98 (2018) 032015, Eur. Phys. J. C78 (2018) 24, Phys. Lett. B 793 (2019) 320

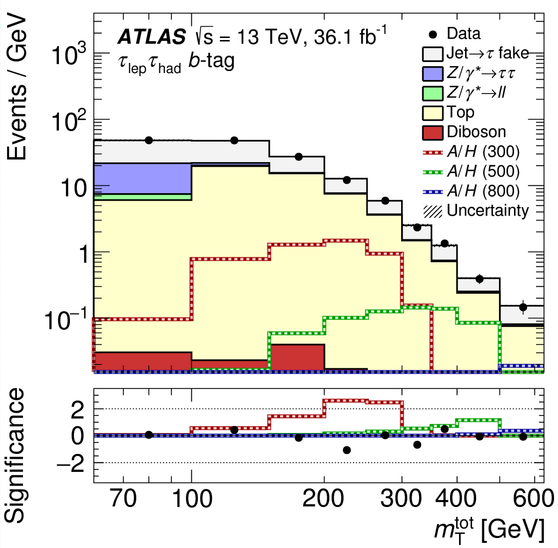
# Neutral Higgs searches: H/A→ττ

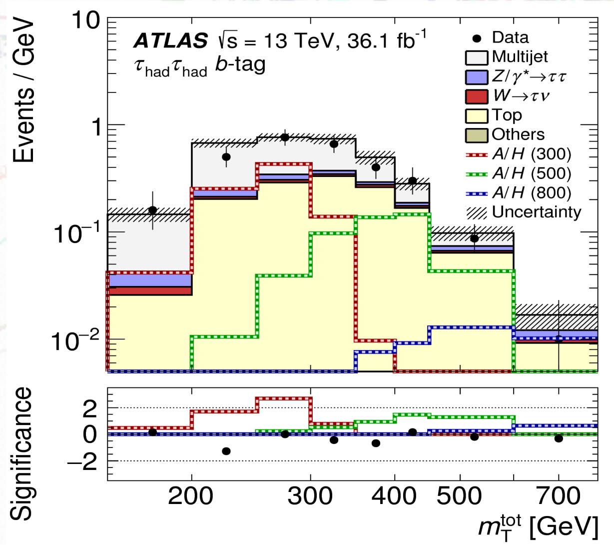
JHEP 01 (2018) 055

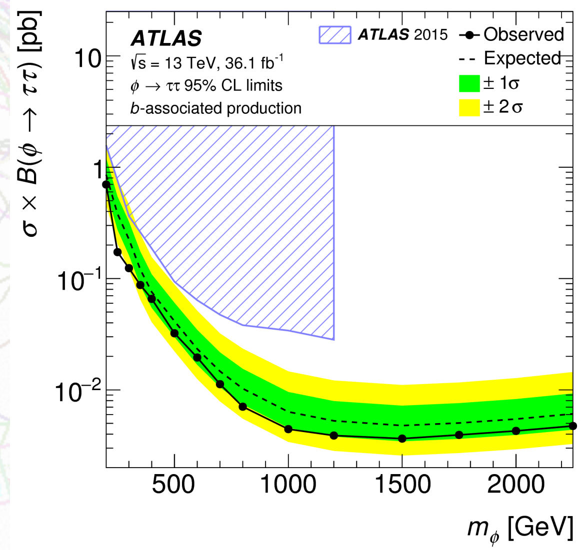


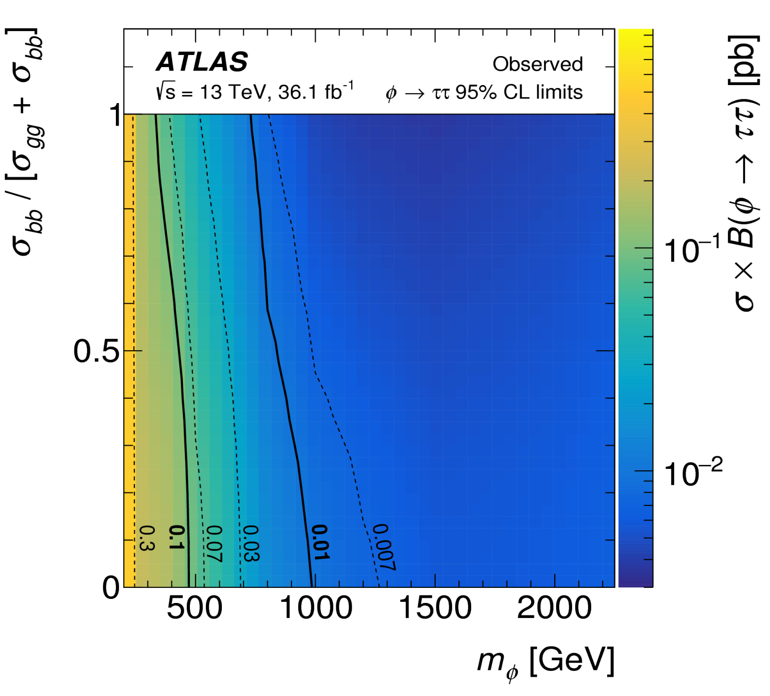



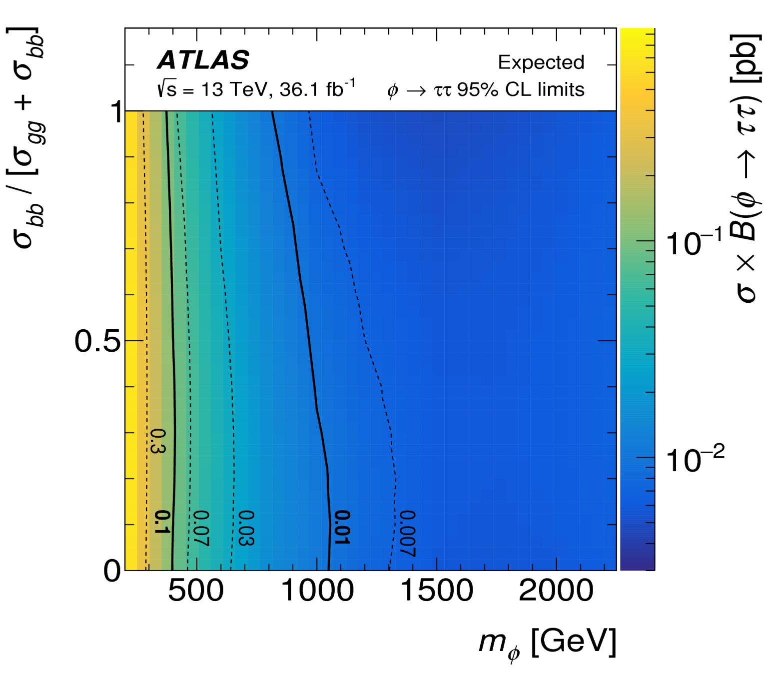



# Neutral Higgs searches: H/A→ττ

JHEP 01 (2018) 055

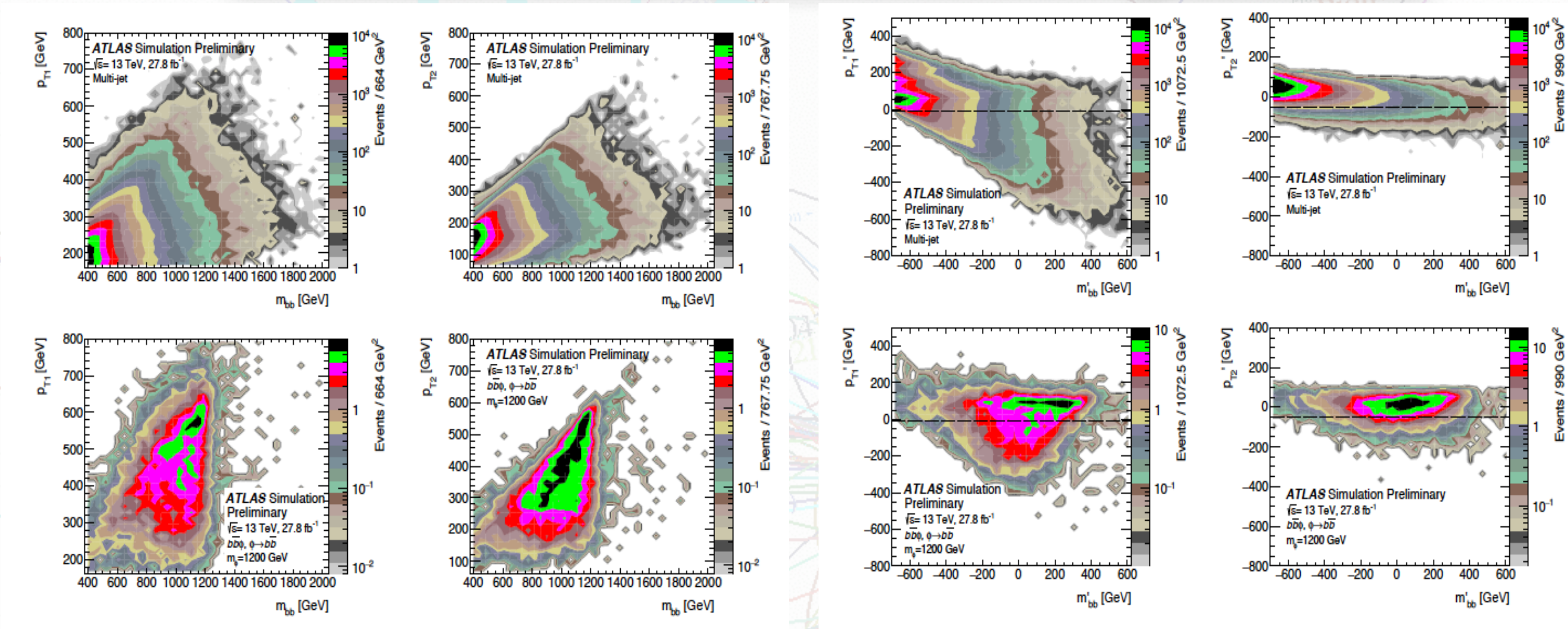



The observed and expected 95% CL upper limit on the production cross section times branching fraction for φ->tautau as a function of the fractional contribution from b -associated production and the scalar boson mass. The solid and dashed lines represent contours of fixed σ x B

# Neutral Higgs searches: bH/A→bb

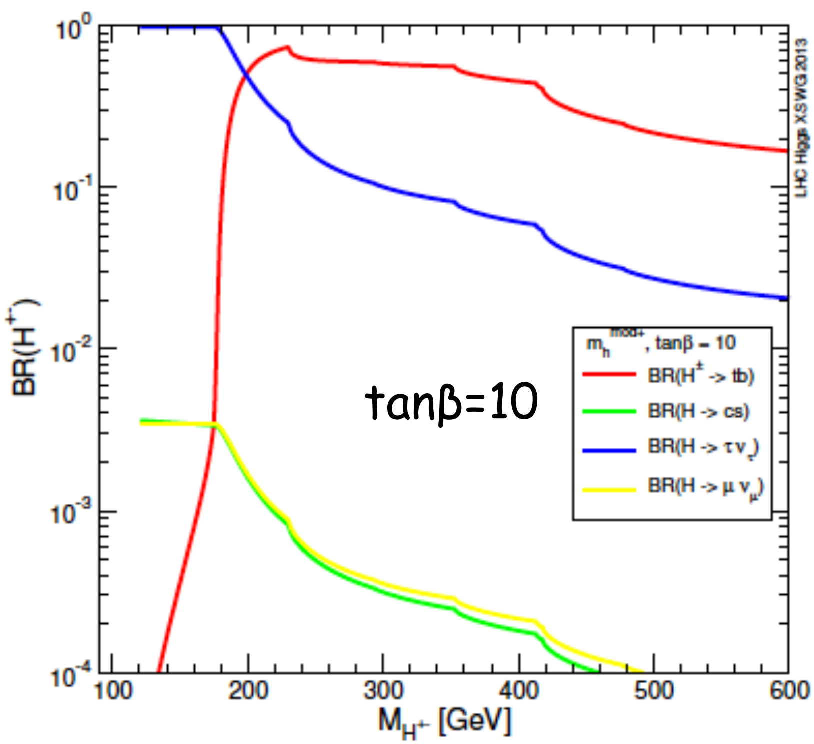
arXiv:1907.02749

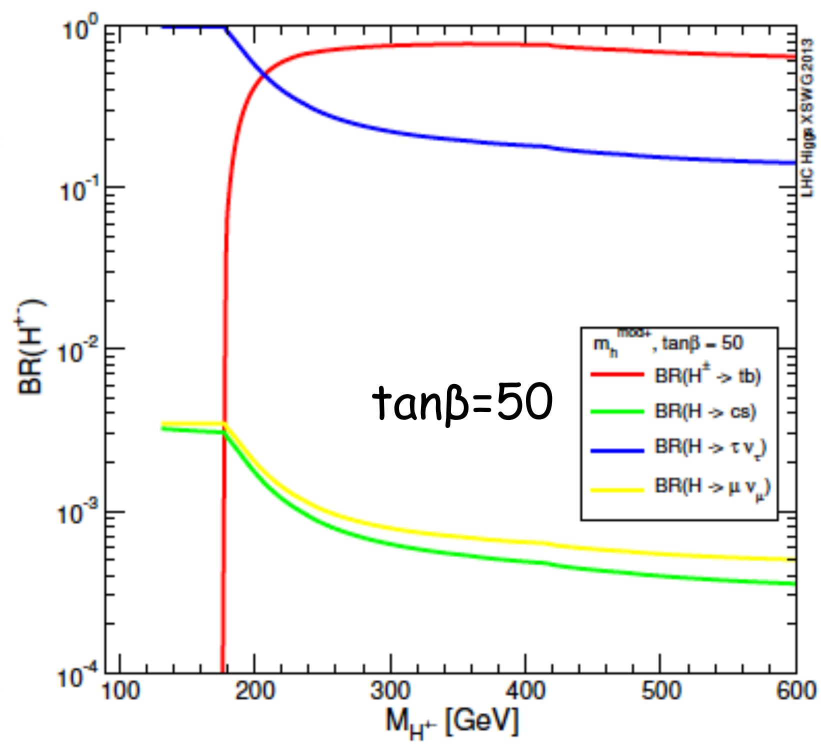



In order to isolate events with small FSR and good $m_\phi$ resolution, a principal component analysis (PCA) is performed on the three dimensional distribution of the variables $m_{bb}$, $p_{T1}$, and $p_{T2}$ using events drawn from the signal MC sample with the *bbb* classification following pre-selection. Separate PCA's are performed for each of the fifteen simulated values of $m_\phi$ and for each of the three *n*-jet regions. Upon diagonalization of the covariance matrix for $m_{bb}$, $p_{T1}$, and $p_{T2}$, the first, second and third principal components define the variables $m'_{bb}$, $p'_{T1}$, and $p'_{T2}$, respectively. The point $(m'_{bb}, p'_{T1}, p'_{T2}) = (0, 0, 0)$ corresponds to the vector of mean values for $m_{bb}$, $p_{T1}$, and $p_{T2}$. Two-dimensional distributions of $p'_{T1}$ versus $m'_{bb}$ and of $p'_{T2}$ versus $m'_{bb}$ are shown in Figure 4.

# $H^{\pm}$ decay modes

- For $m_{H+} < m_{top}$, the decay $H^{\pm} \rightarrow \tau\nu$ usually dominates in a type-II 2HDM
- For $m_{H+} > m_{top}$, the dominant decay is $H^{\pm} \rightarrow tb$, however the branching fraction of $H^{\pm} \rightarrow \tau\nu$ can reach 10–15% at large values of tanβ in a type-II 2HDM



# $H^{\pm}\rightarrow\tau\nu$: Selection

## $\tau_{had}$+jets: $pp\rightarrow bbWH^{\pm}\rightarrow bb(jj)(\tau_{had}\nu)$

**Sensitive at large $m_{H\pm}$**

- $E_T^{miss}$ trigger
- Select events with a $\tau_{had}$ and a hadronic top-quark decay:
  - 1 $\tau_{had}$ object with $p_T > 40$ GeV,
  - 3 jets with $p_T > 25$ GeV, including 1 b-tag
  - Electron and muon veto
  - $E_T^{miss} > 150$ GeV
  - $m_T > 50$ GeV

$$m_T = \sqrt{2p_T^{\tau}E_T^{miss}(1-\cos\Delta\phi_{\tau,miss})}$$

## $\tau_{had}$+lepton: $pp\rightarrow bbWH^{\pm}\rightarrow bb(l\nu)(\tau_{had}\nu)$

**Sensitive at low/intermediate $m_{H\pm}$**

- Single lepton trigger
- Select events with a $\tau_{had}$ and a leptonic top-quark decay:
  - 1 $\tau_{had}$ object with $p_T > 30$ GeV,
  - 1 lepton with $p_T > 30$ GeV
  - Two opposite sign channels: $e+\tau_{had}$, $\mu+\tau_{had}$
  - At least 1 b-tagged jet with $p_T > 25$ GeV
  - $E_T^{miss} > 50$ GeV

Dominant backgrounds: SM ttbar production, misidentified jets as fake $\tau_{had}$

| | |
|---|---|
| Backgrounds with a true $\tau_{had}$ : | MC |
| Backgrounds with e, $\mu$ faking $\tau_{had}$: | MC + data-driven corrections |
| Backgrounds with jets faking $\tau_{had}$ : | data-driven fake-factor method |

# H±→τν: Analysis Strategy

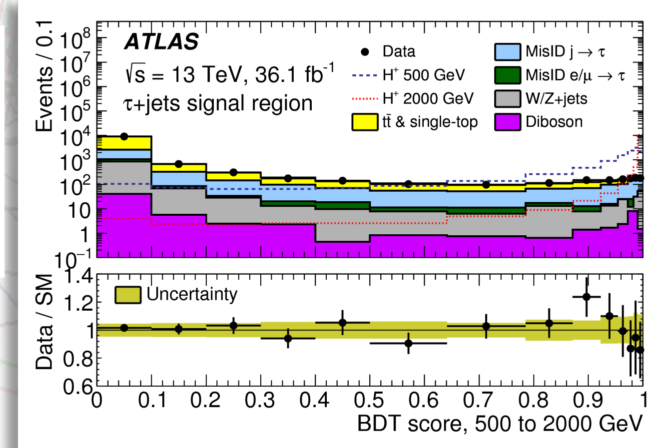
**Multivariate discriminant:**

- FastBDTs trained in 5 H± mass bins
- Separate training for $\tau_{had}$+jets and $\tau_{had}$+lepton final states
- Polarisation variable used for 1-prong $\tau_{had}$ objects when $m_{H+} < 500$ GeV
  - discrimination between H±→τν (signal) and W±→τν (top background)
  - increase of sensitivity for low H± masses

$$\Upsilon = \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{E_T^{\tau}} \simeq 2\frac{p_T^{\tau\text{-track}}}{p_T^{\tau}} - 1$$

| MVA input variable | $\tau$+jets | $\tau$+lepton |
|---|---|---|
| $E_T^{miss}$ | ✓ | ✓ |
| $p_T^{\tau}$ | ✓ | ✓ |
| $p_T^{b\text{-jet}}$ | ✓ | ✓ |
| $p_T^{\ell}$ | | ✓ |
| $\Delta\phi_{\tau,miss}$ | ✓ | ✓ |
| $\Delta\phi_{b\text{-jet},miss}$ | ✓ | ✓ |
| $\Delta\phi_{\ell,miss}$ | | ✓ |
| $\Delta R_{\tau,\ell}$ | | ✓ |
| $\Delta R_{b\text{-jet},\ell}$ | | ✓ |
| $\Delta R_{b\text{-jet},\tau}$ | ✓ | |
| $\Upsilon = 2\frac{p_T^{\tau\text{-track}}}{p_T^{\tau}} - 1$ | ✓ | ✓ |

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions




**Systematic uncertainties:**

- dominant at low $m_{H\pm}$ : fake factors method
- dominant at high $m_{H\pm}$ : signal modelling

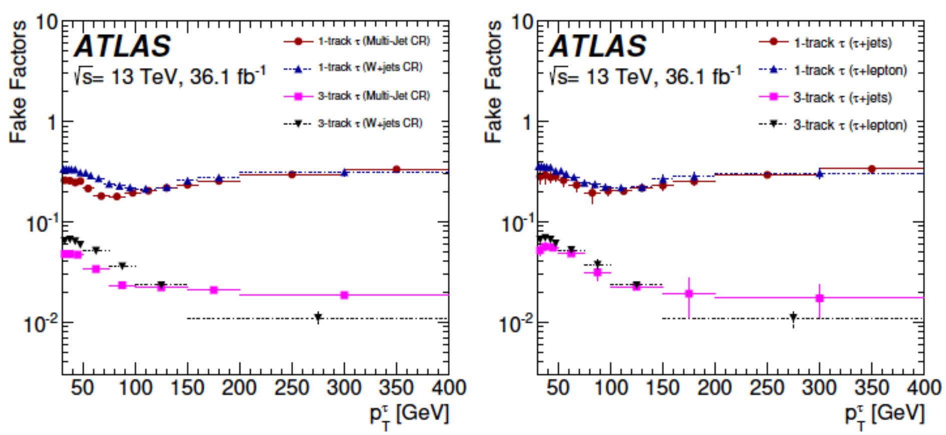
# $H^{\pm} \to \tau\nu$: Fake Factors method

- Define an anti-tau region, which is similar to the signal region but where a tau candidate fails the ID-tau requirement, instead of fullfiling it.

$$FF = \frac{N_{\tau-\mathrm{id}}}{N_{\mathrm{anti}-\tau-\mathrm{id}}}$$

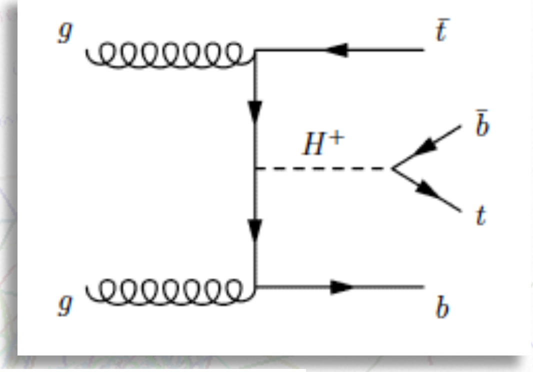
$$N^{\tau}_{\mathrm{fakes}} = N^{\mathrm{anti}-\tau}_{\mathrm{fakes}} \times FF$$

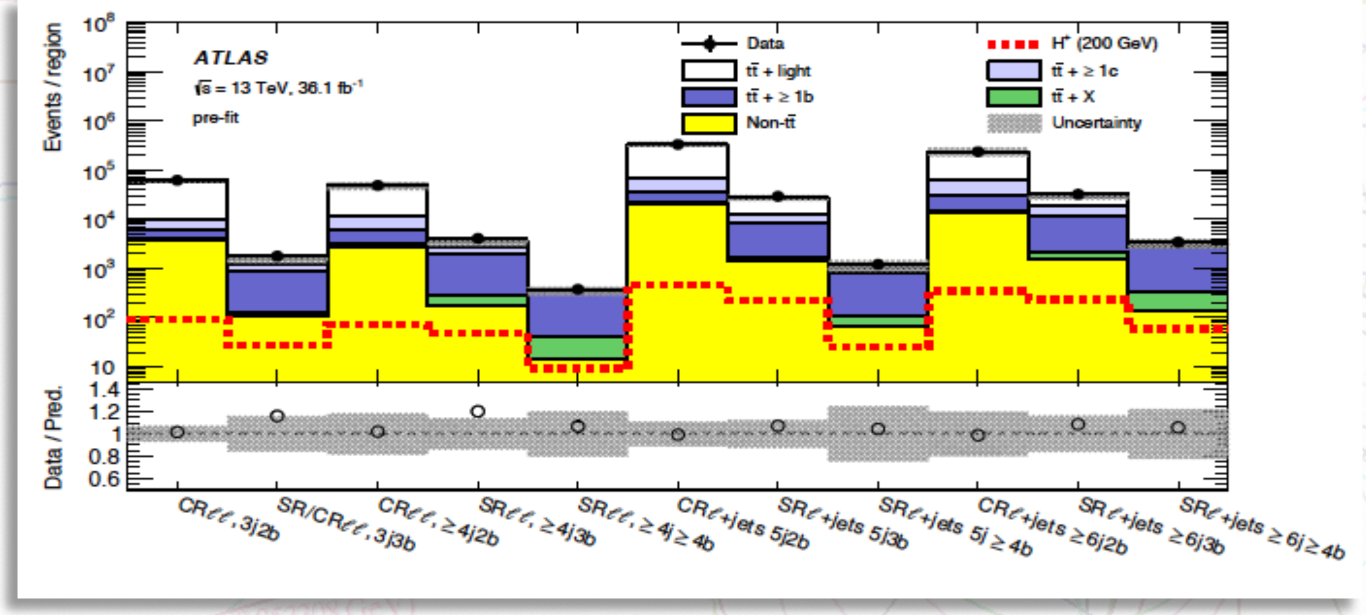
- Two control region with different jet compositions are used in order to determine the rate of the fake tau object
  - Multi-jet CR (dominated by gluon-initiated jets)
  - W+jet CR (dominated by quark-initiated jets)
- In the anti-tau regions, the fractions of quark- and gluon-initiated jets misidentified as tau candidates are measured using a template-fit approach, based on variables that are sensitive to the difference in quark- and gluon-fractions between these two types of jets



# $H^{\pm} \rightarrow tb$: Selection

- At least one leptonic top-quark decay
  - single-lepton triggers
- Considers 200 GeV < $m_{H+}$ < 2000 GeV
- Single- and di-lepton (OS) channels
- Z-veto in ee and $\mu\mu$ channels;
- Event categorisation in Signal and Control Regions according to the number of jets and b-jets



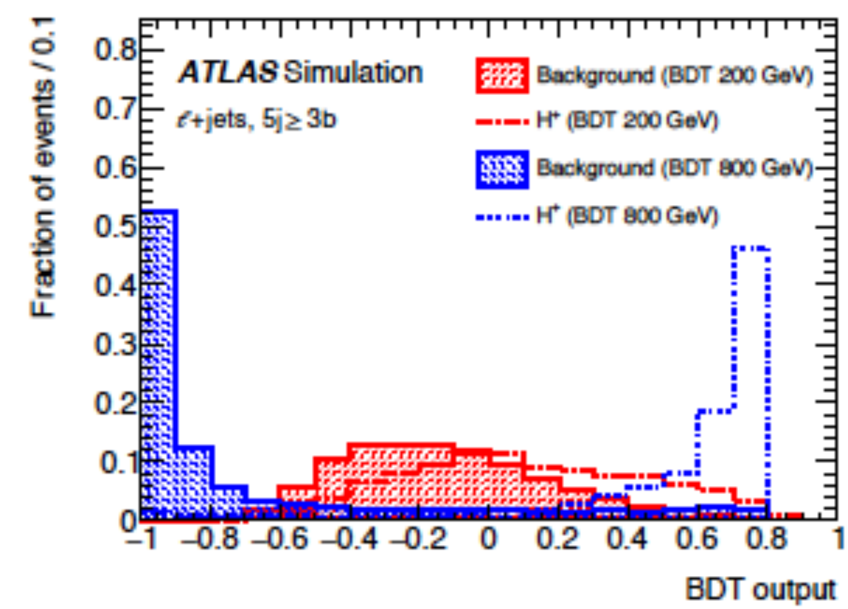

Single-lepton: CR 5j2b, SR 5j3b, SR 5j4b, CR 6j2b, SR 6j3b, SR 6j4b
Di-lepton: CR 3j2b, CR/SR 3j3b, CR 4j2b, SR 4j3b, SR 4j4b

# H±→tb: Analysis Strategy

- The dominating background: ttbar +jets
  - Model = Powheg+Pythia8
  - Categorised according to the flavour of additional jets (b/c/light)
- Prompt leptons modelled with MC
- Non-prompt leptons in ℓℓ modelled with MC and normalised with data in CR
- Non-prompt leptons in ℓ+jets modelled with a data-driven matrix method
  - Use sample with enhanced non-prompt leptons (use loose selection)
  - Weight events by efficiencies for prompt and non-prompt leptons to pass default tight selection

- Separate BDT trained in each SR and for each signal mass hypothesis
- Trained against all backgrounds in single lepton channel
- Trained against ttbar in di-lepton channel

- No statistically significant deviation from the SM predictions
- Exclusion limits obtained from a fit of the BDT distributions in SRs and a single bin in CRs




Dominant systematic uncertainties:
- Jet flavour tagging
- Background modelling

| $\ell$+jets channel | |
|---|---|
| $p_{\mathrm{T}}(j_1)$ | Leading jet transverse momentum |
| $m(b\text{-pair}^{\Delta R^{\min}})$ | Invariant mass of pair of $b$-tagged jets with smallest $\Delta R$ |
| $p_{\mathrm{T}}(j_5)$ | Transverse momentum of fifth jet |
| $H_2$ | Second Fox–Wolfram moment [128] calculated using all jets and leptons |
| $\Delta R^{\mathrm{avg}}(b\text{-pair})$ | Average $\Delta R$ between all $b$-tagged jet pairs in the event |
| $\Delta R(\ell, b\text{-pair}^{\Delta R^{\min}})$ | $\Delta R$ between the lepton and the $b$-tagged jet pair with smallest $\Delta R$ |
| $m(u\text{-pair}^{\Delta R^{\min}})$ | Invariant mass of the non-$b$-tagged jet-pair with minimum $\Delta R$ |
| $H_{\mathrm{T}}^{\mathrm{jets}}$ | Scalar sum of all jets transverse momenta |
| $m(b\text{-pair}^{p_{\mathrm{T}}^{\max}})$ | Invariant mass of the $b$-tagged jet pair with maximum transverse momentum |
| $m^{\max}(b\text{-pair})$ | Largest invariant mass of any two $b$-tagged jets |
| $m^{\max}(j\text{-triplet})$ | Largest invariant mass of any three jets |
| $D$ | Kinematic discriminant based on mass templates (for $m_{H^+} \leq 300\,\mathrm{GeV}$) |

| $\ell\ell$ channel, $m \leq 600\,\mathrm{GeV}$ | | 3j3b | ≥4j3b | ≥4j≥4b |
|---|---|---|---|---|
| $m((j,b)^{p_{\mathrm{T}}^{\max}})$ | Inv. mass of the jet and $b$-tagged jet with largest $p_{\mathrm{T}}$ | ✓ | | |
| $\Delta E(j_3, \ell_2)$ | Energy difference between the third jet and the subleading lepton | ✓ | | |
| $E(j_3)$ | Energy of third jet | ✓ | | |
| $\Delta m(j_1+j_2, j_1+j_3+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Inv. mass difference between $j_1+j_2$ and $j_1+j_3+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | ✓ | | |
| $\Delta R(j_2, j_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Angular difference between subleading jet and $j_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | ✓ | | |
| $p_{\mathrm{T}}(b_1)$ | $p_{\mathrm{T}}$ of leading $b$-tagged jet | ✓ | | |
| $p_{\mathrm{T}}((\ell,b)^{\Delta\eta^{\max}})$ | $p_{\mathrm{T}}$ of the pair of lepton and $b$-tagged jet with largest $\Delta\eta$ | ✓ | | |
| $m((\ell,b)^{\Delta\phi^{\min}})$ | Inv. mass of the pair of lepton and $b$-tagged jet with smallest $\Delta\phi$ | | ✓ | |
| $\Delta E(b_1, \ell_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | Energy difference between the leading $b$-tagged jet and $\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $\Delta m(j_2+j_3, j_1+\ell_1+\ell_2)$ | Inv. mass difference between $j_2+j_3$ and $j_1+\ell_1+\ell_2$ | | ✓ | |
| $\Delta m(\ell_1+j_3+E_{\mathrm{T}}^{\mathrm{miss}}, j_1+j_2+\ell_2)$ | Inv. mass difference between $\ell_1+j_3+E_{\mathrm{T}}^{\mathrm{miss}}$ and $j_1+j_2+\ell_2$ | | ✓ | |
| $\Delta p_{\mathrm{T}}(j_1, j_3)$ | $p_{\mathrm{T}}$ difference between leading and third jet | | ✓ | ✓ |
| $m^{\min}(b\text{-pair})$ | Smallest invariant mass of any $b$-tagged jet pair | | ✓ | ✓ |
| $m^{\min}(\ell, b)$ | Smallest invariant mass of any pair of lepton and $b$-tagged jet | | ✓ | ✓ |
| $p_{\mathrm{T}}(b_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ of $b_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | | ✓ |
| $\Delta R(\ell_2, j_2+j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | Angular difference between $\ell_2$ and $j_2+j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | | ✓ |
| $H_{\mathrm{T}}^{\mathrm{all}}$ | Scalar sum of all jets and leptons transverse energy | | | ✓ |

| $\ell\ell$ channel, $m > 600\,\mathrm{GeV}$ | | 3j3b | ≥4j3b | ≥4j≥4b |
|---|---|---|---|---|
| $p_{\mathrm{T}}((\ell,b)^{\Delta\eta^{\min}})$ | $p_{\mathrm{T}}$ of the pair of lepton and $b$-tagged jet with smallest $\Delta\eta$ | ✓ | | ✓ |
| $\Delta p_{\mathrm{T}}(j_1, j_3)$ | $p_{\mathrm{T}}$ difference between leading and third jets | ✓ | | ✓ |
| $\Delta m(j_2+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}, j_1+j_3+\ell_1)$ | Inv. mass difference between $j_2+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ and $j_1+j_3+\ell_1$ | ✓ | | |
| $p_{\mathrm{T}}((\ell,b)^{\Delta R^{\min}})$ | $p_{\mathrm{T}}$ of the pair of lepton and $b$-tagged jet with smallest $\Delta R$ | ✓ | | |
| $m(j\text{-pair}^{\Delta\eta^{\min}})$ | Inv. mass of the jet pair with smallest $\Delta\eta$ | ✓ | | |
| $\Delta p_{\mathrm{T}}(j_1, j_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between leading jet and $j_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | ✓ | | |
| $p_{\mathrm{T}}(j_1+j_2+j_3+\ell_1)$ | $p_{\mathrm{T}}$ of $j_1+j_2+j_3+\ell_1$ | ✓ | | |
| $\Delta E(\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}, j_1+j_2)$ | Energy difference between $\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ and $j_1+j_2$ | ✓ | | |
| $E(j_1)$ | Energy of the leading jet | ✓ | ✓ | |
| $p_{\mathrm{T}}^{\max}(j\text{-pair})$ | Maximum $p_{\mathrm{T}}$ of any jet pair | ✓ | ✓ | |
| $m(b_1+b_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Inv. mass of $b_1+b_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $p_{\mathrm{T}}((\ell,b)^{\Delta\eta^{\min}})$ | $p_{\mathrm{T}}$ of the lepton-$b$-jet pair with smallest separation in $\eta$ | | ✓ | |
| $\Delta p_{\mathrm{T}}(\ell_2, u_1+b_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between subleading lepton and $u_1+b_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $\Delta p_{\mathrm{T}}(\ell_2, u_1+b_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between subleading lepton and $u_1+b_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $\Delta p_{\mathrm{T}}(\ell_2, \ell_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between subleading lepton and $\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $\Delta p_{\mathrm{T}}(j_1, j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between leading jet and $j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $\Delta E(\ell_1, j_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Energy difference between leading lepton and $j_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | ✓ | |
| $m^{\min}(b\text{-pair})$ | Smallest invariant mass of any $b$-tagged jet pair | | ✓ | ✓ |
| $H_{\mathrm{T}}^{\mathrm{all}}$ | Scalar sum of all jets and leptons transverse momenta | | | ✓ |
| $p_{\mathrm{T}}(j_3+\ell_1)$ | $p_{\mathrm{T}}$ of $j_3+\ell_1$ | | | ✓ |
| $\Delta p_{\mathrm{T}}(b_2, b_1+\ell_2)$ | $p_{\mathrm{T}}$ difference between subleading $b$-tagged jet and $b_1+\ell_2$ | | | ✓ |
| $\Delta p_{\mathrm{T}}(j_2, j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}})$ | $p_{\mathrm{T}}$ difference between subleading jet and $j_3+\ell_1+E_{\mathrm{T}}^{\mathrm{miss}}$ | | | ✓ |
| $\Delta E(j_3, j_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Energy difference between third jet and $j_2+\ell_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | | ✓ |
| $\Delta m(j_2+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}, j_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}})$ | Inv. mass difference between $j_2+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ and $j_1+\ell_2+E_{\mathrm{T}}^{\mathrm{miss}}$ | | | ✓ |

The BDT variables include various kinematic quantities with the optimal discrimination against the ttbar + >=1b background.

For H+ masses above 400 GeV the most important variables are the scalar sum of the pT of all jets and the leading jet pT.

For a mass at or below 300 GeV, a kinematic discriminant, D is used as an input variable for the BDT.

# Kinematic Discriminant $D$

- $D = P_{H^+}(\mathrm{x})/(P_{H^+}(\mathrm{x}) + P_{t\bar{t}}(\mathrm{x}))$
- $P_{H^+}(\mathrm{x})$ and $P_{t\bar{t}}(\mathrm{x})$ are probability density functions for x under signal and background hypotheses
- x is $E_{\mathrm{T}}^{\mathrm{miss}}$ and four-momentum of $e$, $\mu$, and jets
- $P_{H^+}(\mathrm{x})$ defined as the product of probability density functions for:
    - the mass of the semileptonically decaying top quark, $m_{b_\ell \ell \nu}$
    - the mass of the hadronically decaying W boson, $m_{q_1 q_2}$
    - the difference between the masses of the hadronically decaying top quark and the hadronically decaying W boson, $m_{b_h q_1 q_2} - m_{q_1 q_2}$
    - the difference between the mass of the charged Higgs boson and the mass of the leptonically or hadronically decaying top quark, $m_{b_{H^+} b_\ell \ell \nu} - m_{b_\ell \ell \nu}$ or $m_{b_{H^+} b_\ell q_1 q_2} - m_{b_\ell q_1 q_2}$, depending on whether or not the top quark from the charged Higgs boson decays leptonically or hadronically

- Where:
    - $q_1$ and $q_2$ are quarks from the hadronic $W$ decay
    - $\ell$ and $\nu$ are from the leptonic $W$ decay
    - $b_h$ is the $b$-quark from the hadronic top quark decay
    - $b_\ell$ is the $b$ quark from the leptonic top quark decay
    - $b_{H^+}$ is the $b$-quark from the $H^+$ decay

courtesy of B. Burghgrave

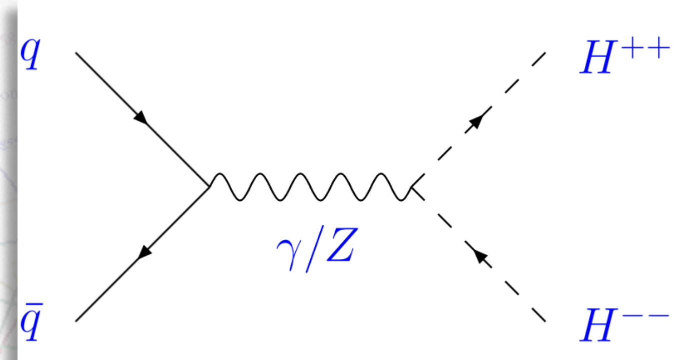
# $H^{\pm\pm}$: Production and Decays

$H^{\pm\pm}$ predicted by variety of BSM models:
- Left-Right Symmetric Models (LRSM)
  - addition of two triplets, L and R
- Higgs Triplet Model (HTM)
  - addition of one triplet, L
- Zee-Babu models, Georgi-Machacek models

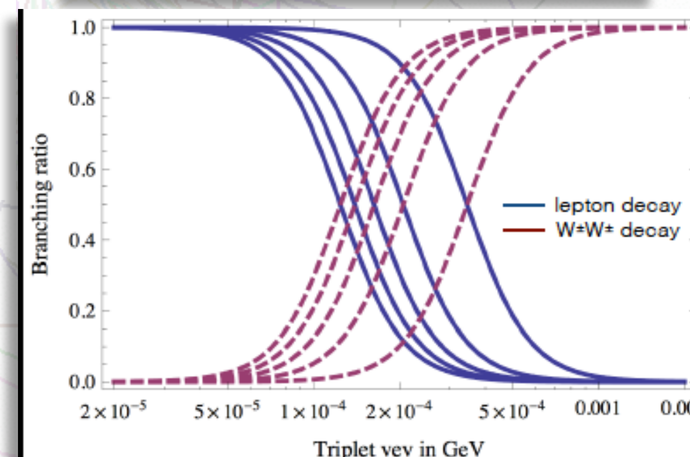
Motivations
- Restoring parity symmetry in weak interactions at higher energy (LRSM)
- Explain light neutrino masses through Type II See-Saw mechanism

Most unique feature of such models: **$H^{\pm\pm}$**
- left and right-handed in LRSM or left-handed only in HTM

Decays: $H^{\pm\pm} \to l^{\pm}l^{\pm}$ or $H^{\pm\pm} \to W^{\pm}W^{\pm}$
- BR ~ f($m_{H^{\pm\pm}}$ , vev of Higgs triplet)
- Low $m_{H^{\pm\pm}}$ and low vev : $H^{\pm\pm} \to l^{\pm}l^{\pm}$ dominates

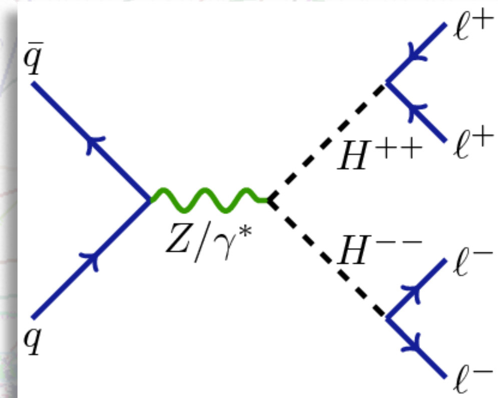



Production at the LHC:
pair-produced $H^{\pm\pm}$ via the Drell-Yan process
(dominant in LRSM and HTM)



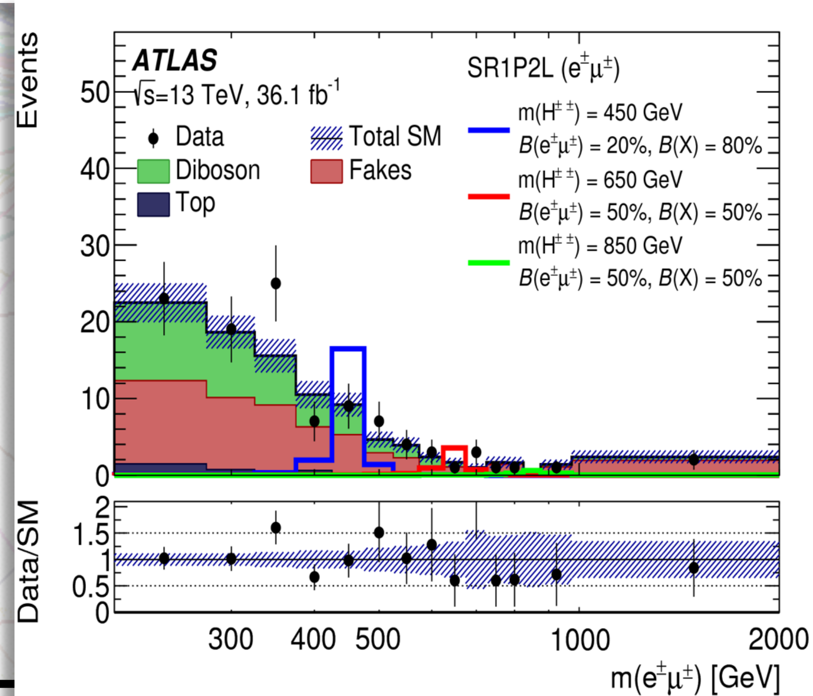
# $H^{\pm\pm} \to l^{\pm}l^{\pm}$ : Selection and Backgrounds

- Considered decays: $H^{\pm\pm} \to e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm}, \mu^{\pm}\mu^{\pm}$
  - no preference for decays into taus - coupling not proportional to $m_{lept}$ like for the SM Higgs
- Masses studied: 250 - 1300 GeV
- Search for isolated, same sign lepton pairs
- Discrimination observable
  - dilepton invariant mass distribution in all CRs and SRs
  - For SR with 4 leptons $\bar{M} \equiv (m^{++} + m^{--})/2.$




**Backgrounds:**

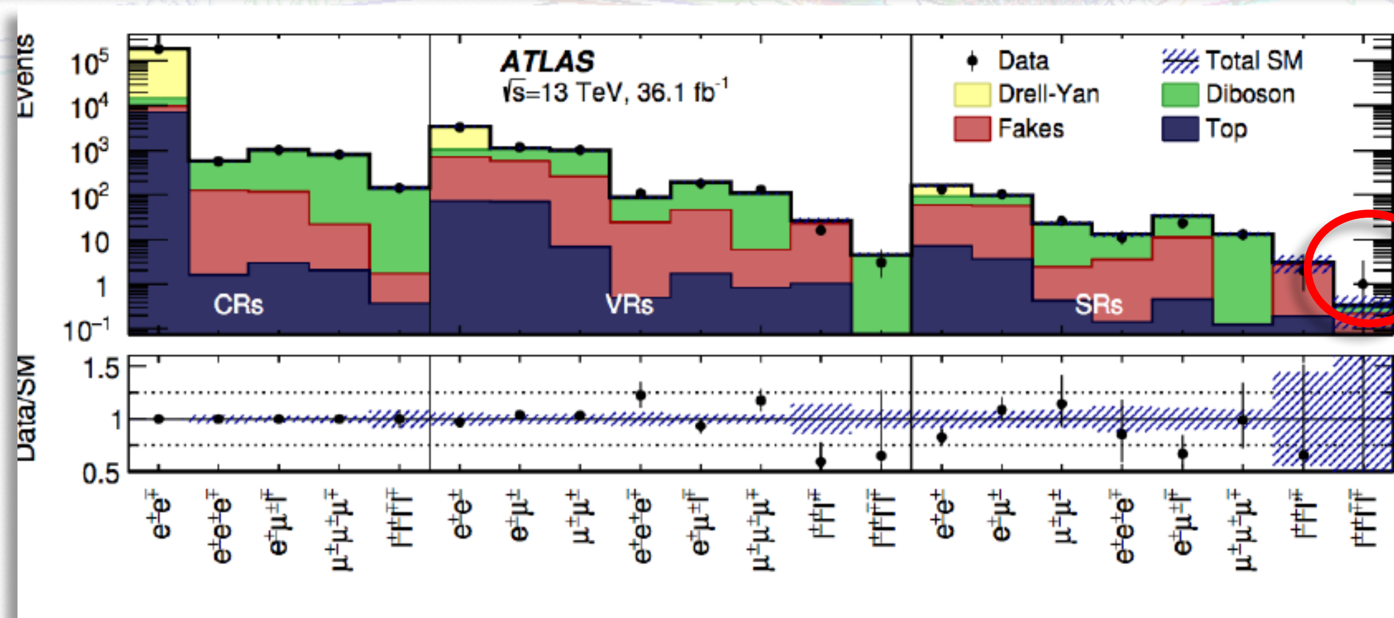
- real prompt leptons
  - estimated with MC
- oppositely charged leptons with charge mis-ID
  - estimated with MC but with data-driven correction factors
- non-prompt
  - estimated from data
  - real e or μ from non-prompt decays, e.g. from heavy flavoured mesons
  - jets mis-reconstructed as electrons



# $H^{\pm\pm} \to l^{\pm}l^{\pm}$ : Signal and Control Regions

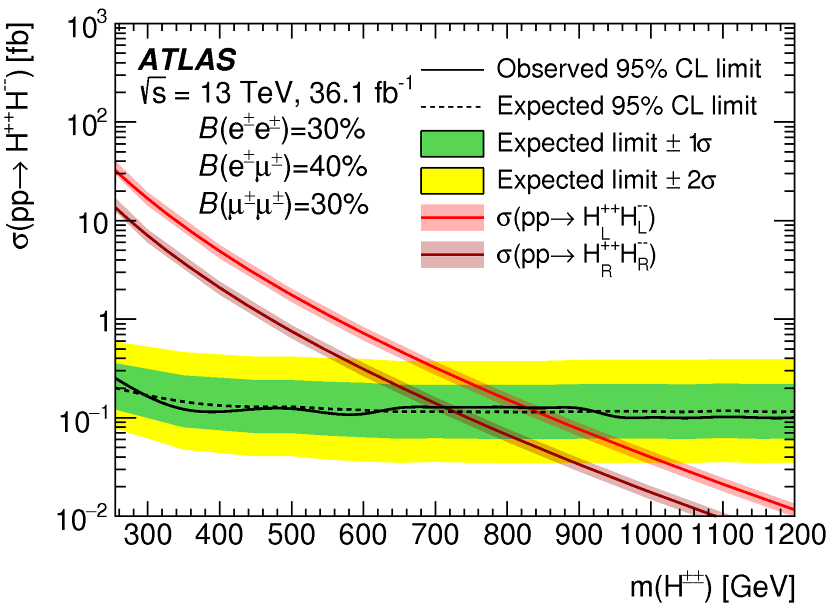
- SRs with 2-, 3-, and 4-leptons and flavour categories
- Control Regions (CRs) to constrain background parameters in the statistical analysis
- Validation Regions (VRs) to check background model against data
- Regions defined by $m(l^{\pm}l^{\pm}) > 200$ GeV in SRs and below 200 GeV in most CRs and VRs

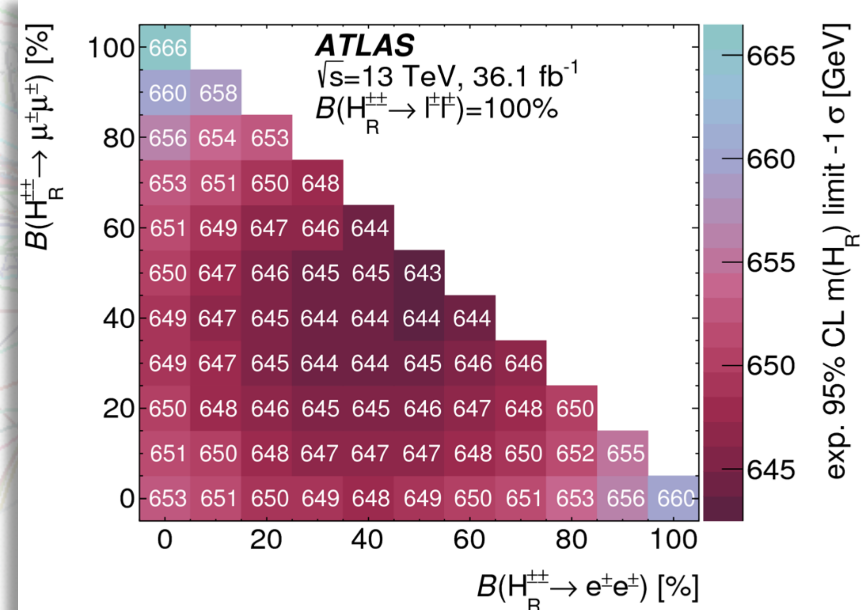
| Region / Channel | Control Regions | | | Validation Regions | | | Signal Regions | | |
|---|---|---|---|---|---|---|---|---|---|
| | OCCR | DBCR | 4LCR | SCVR | 3LVR | 4LVR | 1P2L | 1P3L | 2P4L |
| Electron channel | $e^{\pm}e^{\mp}$ | $e^{\pm}e^{\pm}e^{\mp}$ | | $e^{\pm}e^{\pm}$ | $e^{\pm}e^{\pm}e^{\mp}$ | | $e^{\pm}e^{\pm}$ | $e^{\pm}e^{\pm}e^{\mp}$ | |
| Mixed channel | - | $e^{\pm}\mu^{\pm}\ell^{\mp}$ | $\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$ | $e^{\pm}\mu^{\pm}$ | $e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$ | $\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$ | $e^{\pm}\mu^{\pm}$ | $e^{\pm}\mu^{\pm}\ell^{\mp}$ $\ell^{\pm}\ell^{\pm}\ell'^{\mp}$ | $\ell^{\pm}\ell^{\pm}$ $\ell^{\mp}\ell^{\mp}$ |
| Muon channel | - | $\mu^{\pm}\mu^{\pm}\mu^{\mp}$ | | $\mu^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}\mu^{\mp}$ | | $\mu^{\pm}\mu^{\pm}$ | $\mu^{\pm}\mu^{\pm}\mu^{\mp}$ | |



# $H^{\pm\pm} \to l^{\pm}l^{\pm}$ : Results

- No significant excesses observed
- Lower limit evaluated as a function of the branching into electrons and muons
- Separate limits for $H^{\pm\pm}_L$ and $H^{\pm\pm}_R$
- Limits on $H^{\pm\pm}_L$ vary from 770 GeV to 870 GeV, and 660 GeV to 760 GeV for $H^{\pm\pm}_R$ (depending on BR composition)

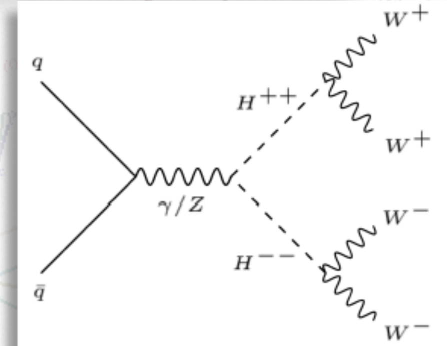


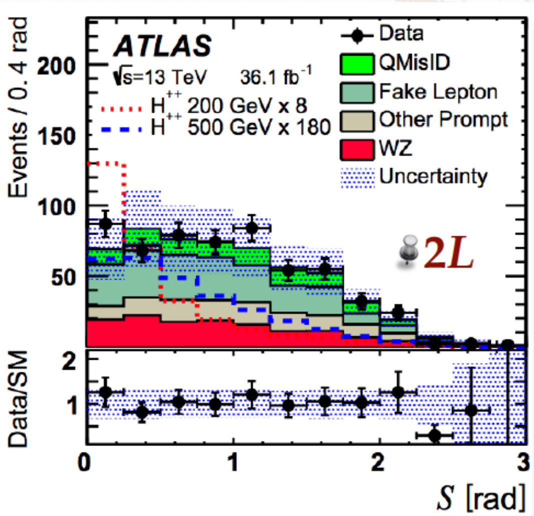



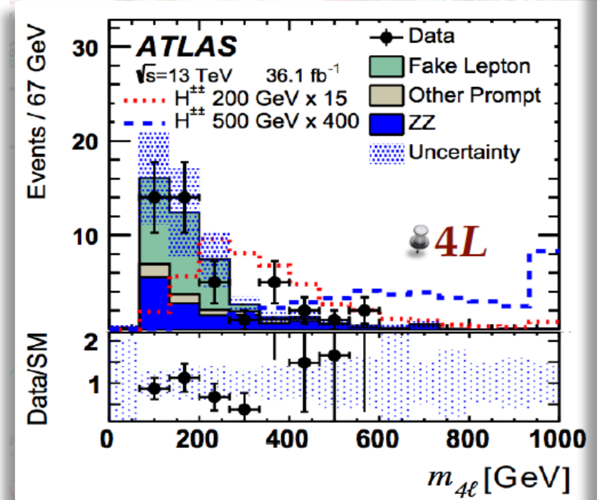

Systematic uncertainties: fake factor method, statistical uncertainty, theory description

# $H^{\pm\pm} \to W^{\pm}W^{\pm}$ : Selection and Backgrounds

- Signature: $2L^{SS}$,3L,4L light leptons + missing $E_T$
- Masses studied: 200-700 GeV
- Dominant backgrounds: dibosons, Z+jets, ttbar
  - Prompt sources estimated from MC
  - Fake estimation: data-driven fake factor method
  - Charge misID: data-driven method



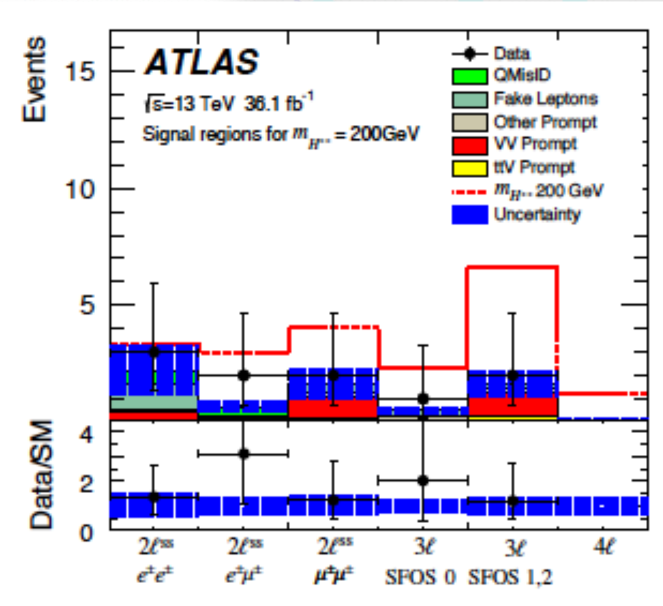



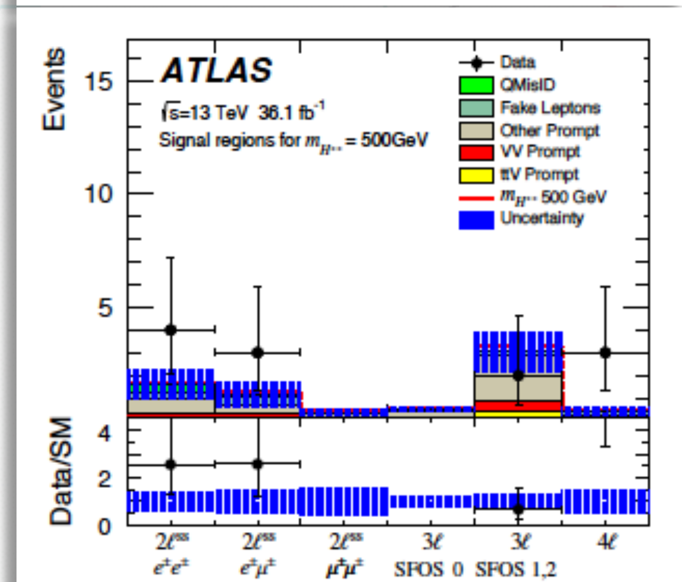




Mass-dependent and channel-dependent cuts on discriminating variables:

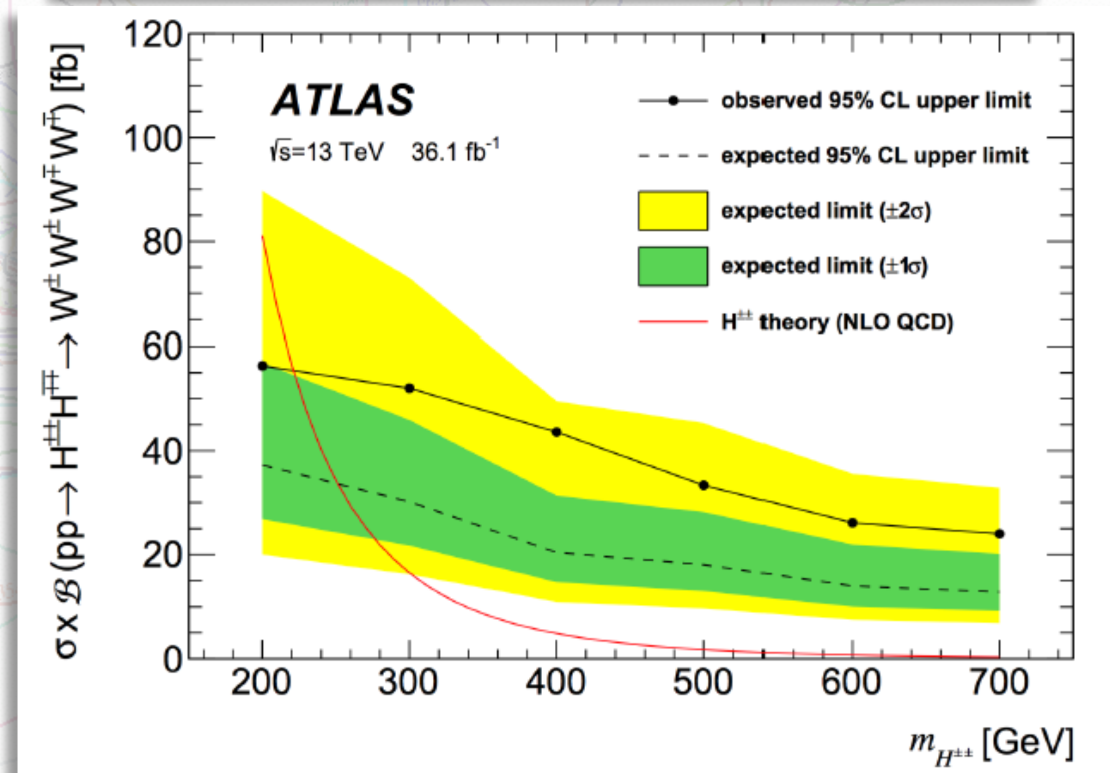
- $m_{Xl}$ of all leptons in the event;
- $\Delta R(l^{\pm}l^{\pm})$
- $m_{jets}$ only in the 2L channel
- $p_T^{\text{leading jet}}$
- $\Delta\varphi(l^{\pm}l^{\pm}, E_T^{miss})$ in the 2L channel
- $\Delta R(l, \text{jet})$ any lepton and its closest jet in the 3L channel
- $S$, used in $2L^{SS}$ channel, describes the event topology in the transverse plane, defined using the spread of the φ angles of the leptons, $E_T^{miss}$ and jets

# $H^{\pm\pm}\rightarrow W^{\pm}W^{\pm}$ : Results




Final fit based on six bin counting experiment



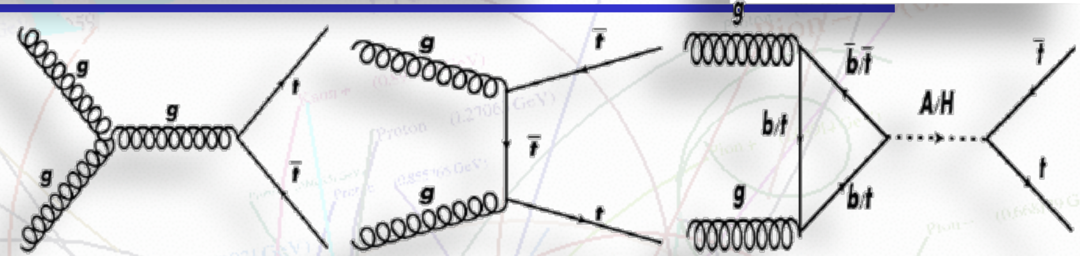

Dominating uncertainties: statistics, data-driven fakes and charge mis-ID

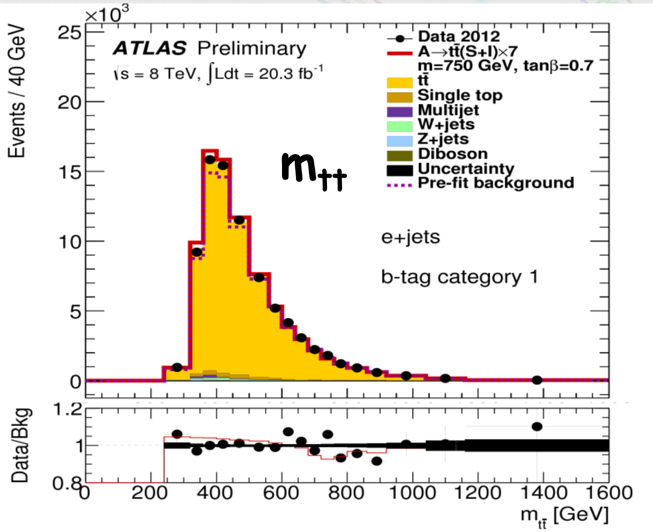
# Neutral Higgs searches: H/A→ttbar

ATLAS-CONF-2016-073

8 TeV results

- ttbar lepton+jets channel (one W to hadrons, one to leptons)
- re-interpretation for the ttbar resonance search (JHEP 08 (2015) 148)

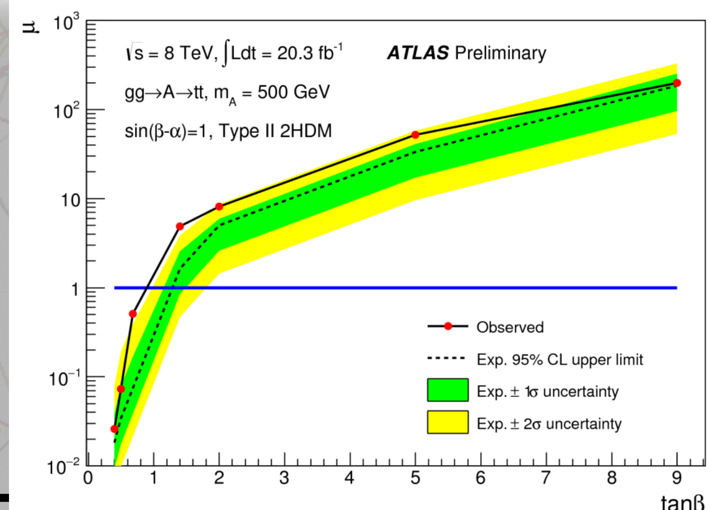





- interference between the signal and ttbar background production modes taken into account for the first time
  - the MadGraph code is modified to remove the SM ttbar matrix element to yield the pure signal + interference contribution on an event-by-event basis.

- For a neutral pseudoscalar A (scalar H) with a mass of 500 GeV, the parameter values tan$\beta$ < 0.85 (< 0.45) are excluded in the type-II 2HDM at 95% confidence level

- No tanβ values can be excluded for the higher mass point at 750 GeV



# Neutral Higgs searches: H/A→mu mu

arXiv: 1901.08144