IOP APP/HEPP Bristol 2018:

Latest results in the search for $H/A/Z^{\prime} \rightarrow \tau^{-}\tau^{+}$

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Introduction and the 2HDM

- Analysis searching for **heavy neutral** resonances **beyond** the Standard Model (SM), produced in the **ATLAS** detector around CERN's Large Hadron Collider, decaying into a pair of **tau leptons**
  - Recent publication featuring **2015+2016** datasets, containing **36.1** $\mathbf{fb^{-1}}$ of integrated luminosity [1]
- Mainly focus on searching for heavy Higgs' proposed by two-Higgs-doublet Model (**2HDM**) extensions of the SM [2]
  - Minimal Supersymmetric Standard Model (**MSSM**) facilitates such a 2HDM:

***h*: Light** **_H_: Heavy** **_A_: CP-odd** **$H^{\pm}$: Charged**

- **Two** benchmark scenarios assuming *h* mass is (or approximately) the same as SM Higgs:

***h*MSSM**	$m_h \equiv 125$ GeV, the experimentally-observed value
$\mathbf{m_h^{mod+}}$	$m_h \simeq 125$ GeV, by tuning stop squark mixing parameter X_t

- Each Higgs doublet eigenstate, H_u and H_d, couple to isospin up- and down-type fermions
  - Benchmark models can be constrained by **two** parameters:

$\mathbf{m_A}$	Mass of the *A* boson
tan β	Ratio of vacuum expectation values between H_u/H_d

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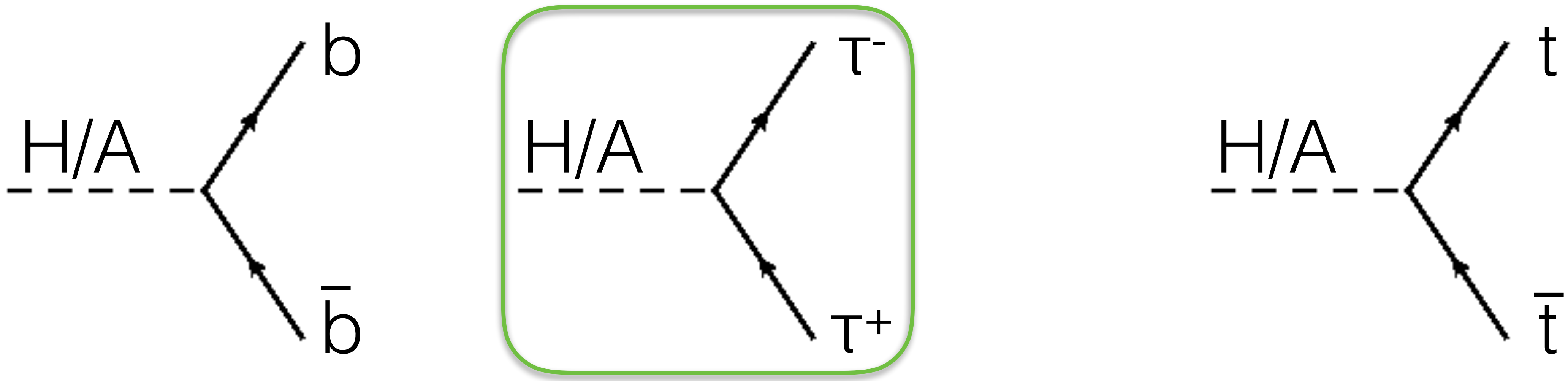
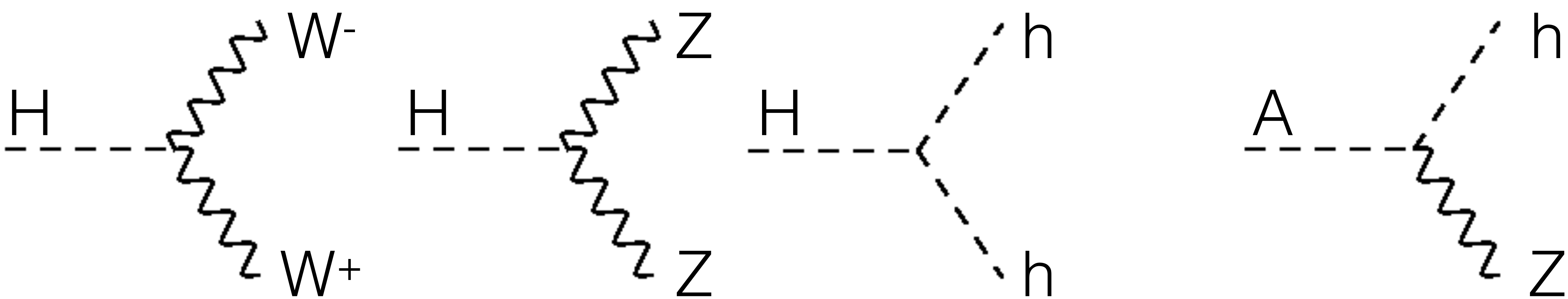
Heavy neutral Higgs decays

- At **high** tan β (>10), neutral H/A couples more strongly to **down**-type fermions relative to SM Higgs, exclusively decaying to $b\bar{b}$ (~90%) and $\tau^- \tau^+$ (~10%)
    - **Di-tau** offers an albeit **rarer** but comparatively **cleaner** channel
- At **low** tan β, H/A couples strongly to **up**-type fermions, exclusively decaying to $t\bar{t}$

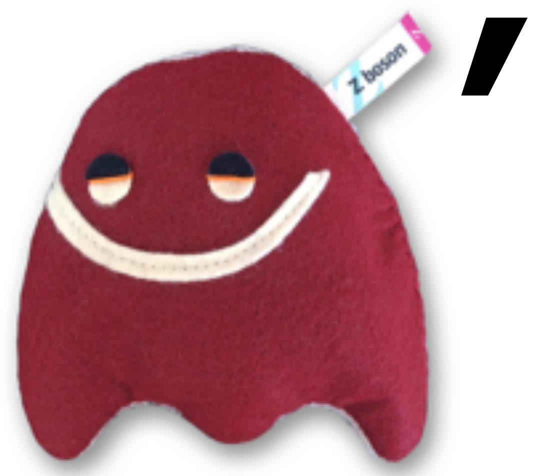


- There is a **small** chance that H may decay into W^-W^+/ZZ/hh, while A may decay into hZ. These are enhanced to a few % (comparable to SM Higgs decay to ZZ) at **low** tan β for **lower** masses of H/A (<500 GeV) [3]



Additional SU(2) bosons

- Similarly to the 2HDM, there are models which propose **additional SU(2)** gauge groups, for example from Grand Unified Theories (**GUT**) [4]
  - Result in additional **heavy** $\boldsymbol{Z'}$ and $\boldsymbol{W'^{\pm}}$ bosons



$\boldsymbol{Z'}$

$\boldsymbol{W'^{-}}$

$\boldsymbol{W'^{+}}$

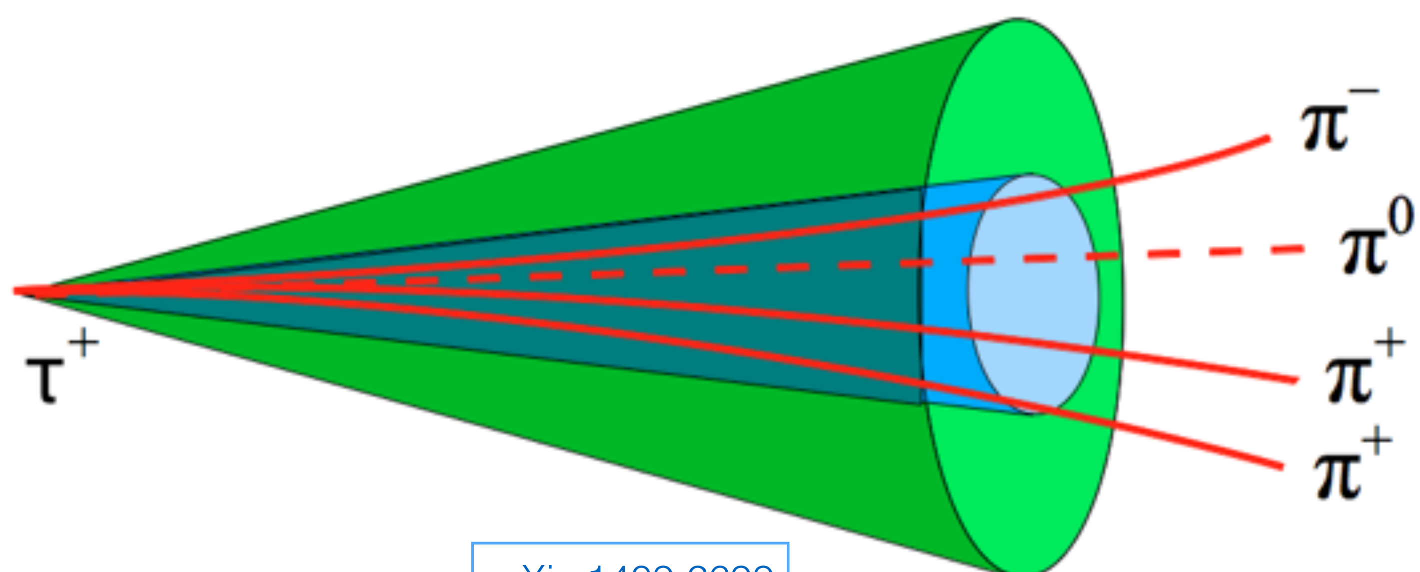
- Results may be interpreted in **two** benchmark scenarios:

SSM (Sequential Standard Model)	Couplings of Z' boson identical to those of SM Z boson
SFM / NU G(221) (Strong Flavour Model / Non-Universal G(221))	Z' favours coupling to third-generation fermions (ie. tau leptons) (possibly explains the large mass increase of the third-generation)

  - **SFM** can be constrained by a $\boldsymbol{\sin^2 \phi}$ mixing parameter between generations
    - For example, $\sin^2 \phi$ **< 0.5** corresponds to stronger coupling with **third**-generation fermions, for a **TeV**-scale Z' boson

Tau decay modes

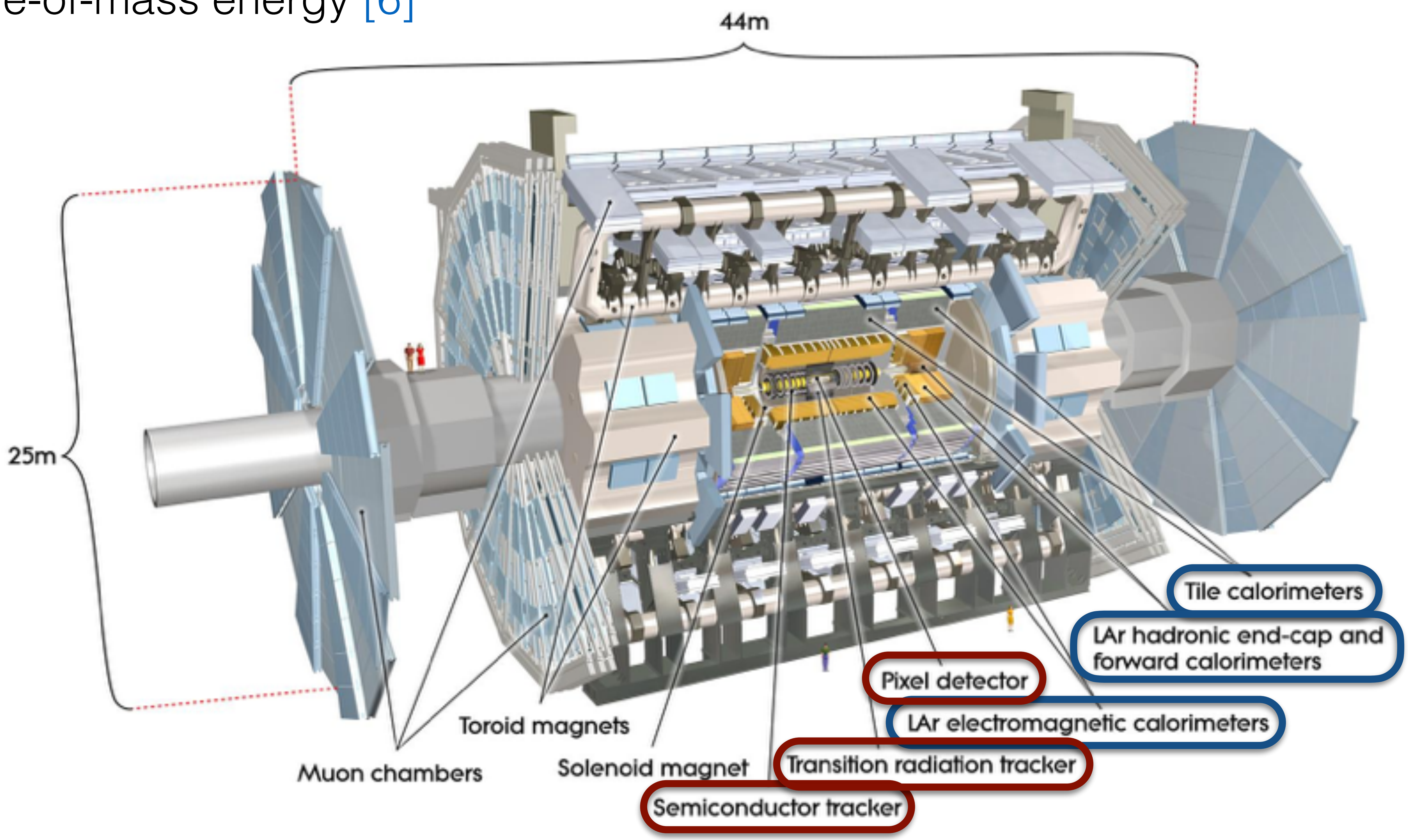
- The **tau** (τ) is a third-generation charged lepton with mass 1.7768 GeV and lifetime 290 fs (relativistic decay length 87 μm) [5]
- Has **two** primary decay modes:
  - **Leptonic** (~35%): electron or muon (~17.5% each due to lepton universality)
  - **Hadronic** (~65%): mainly 1 charged pion, mostly likely with 1 additional neutral pion, sometimes additional charged/neutral pions (**1-** and **3-prong** tracks)
    - Plus lepton number conserving neutrinos all round
- **Hadronic** taus are reconstructed as an **isolated conical jet**



arXiv:1409.2699

The ATLAS detector

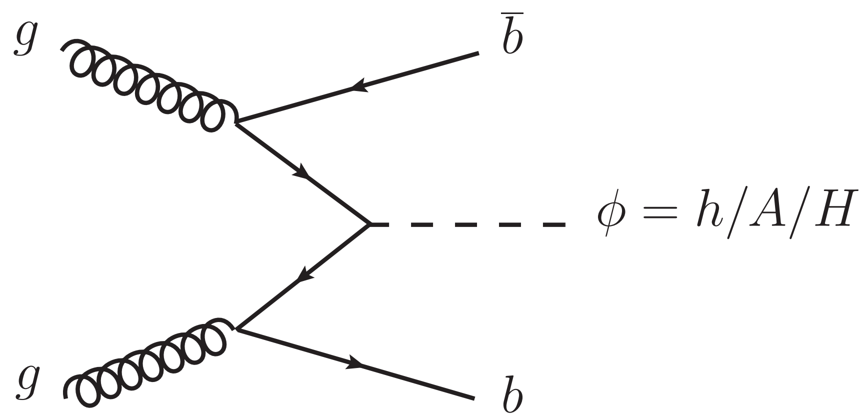
- CERN's **Large Hadron Collider** produces **proton-proton** collisions at **13 TeV** centre-of-mass energy [6]



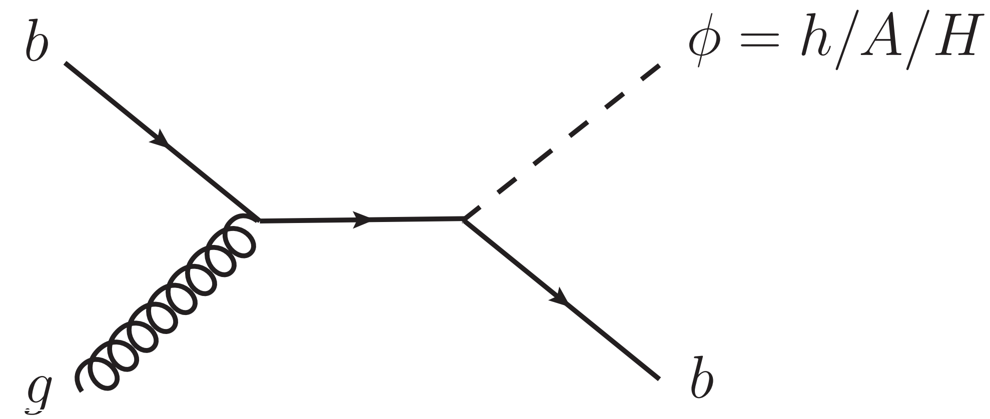
- Tau decay **tracks** are reconstructed in the **Inner Detector**
- **Leptonic/Hadronic** modes are identified from energy deposits in the **Calorimeters**

Production mechanisms

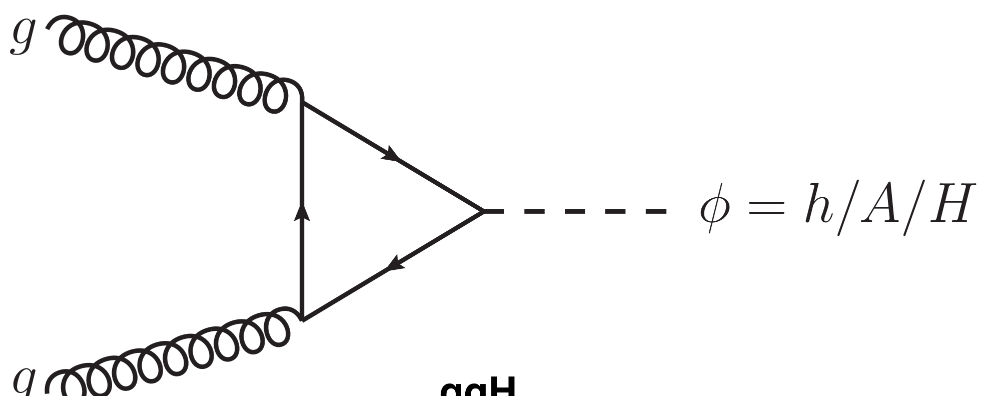
- For the **heavy neutral Higgs** search, we mainly focus on the b-associated production (**bbH**) and gluon-gluon fusion (**ggH**) mechanisms:



Four-flavour bbH scheme

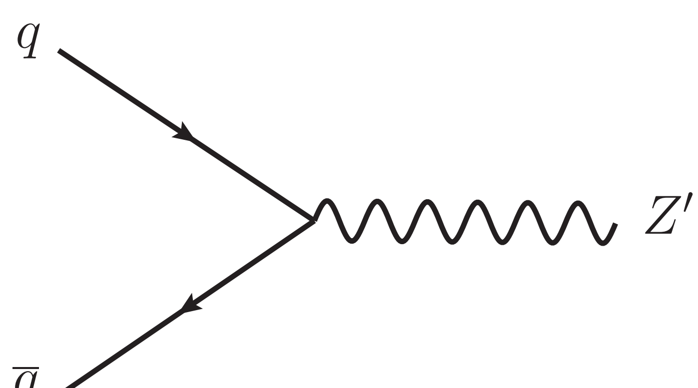


Five-flavour bbH scheme



ggH

- For the ***Z′*** search, we focus on **Drell-Yann** production:



arXiv:1709.07242

Analysis sub-channels

- With resonances decaying **back-to-back** into a pair of taus, and each tau decaying **lep**tonically/**had**ronically, our analysis is divided into **two** main **sub-channels**:

LepHad	46% probability (for Lep = *e/μ*)
HadHad	42% probability

$N = 0, 1, 2, \ldots$
$X = 0, 1, 2, \ldots$

Had

$\bar{\nu}_\tau + X\pi^0\, N(\pi^-\pi^+) + \pi^+$

Had

$\pi^- + N(\pi^-\pi^+)\, X\pi^0 + \nu_\tau$

H/A/Z′

Lep

$\bar{\nu}_\tau + \nu_\mu\, \mu^+ / \nu_e\, e^+$

Lep

$e^-\, \bar{\nu}_e / \mu^-\, \bar{\nu}_\mu + \nu_\tau$

- Each sub-channel also considers **two** different **categories** of events:

b-tag	Event contains at least 1 bottom quark
b-veto	Event contains no bottom quarks

  - **b-tag** category strongly synonymous with **bbH** production
  - Use b-tagging algorithm with a **70% efficiency** working point

Channel event selection

LepHad

- Opposite charge taus
- 1 tau jet, 1 lepton
- Single lepton triggers (20-140 GeV)
- $\Delta\phi(\tau_1,\tau_2) > 2.4$ (back-to-back)
- Lepton $p_T > 30$ GeV
- Tau $p_T > 25$ GeV
- Tau ID “Medium” BDT working point
- e-had channel: $m(e,\tau_{had}) < 80$, $m(e,\tau_{had}) > 110$ GeV (avoid Z peak)
- $m_T < 40$ GeV (suppresses W+jets)

$$m_T(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{miss}) \equiv \sqrt{2p_T^{\ell} E_T^{miss}[1 - \cos\Delta\phi(\mathbf{p}_T^{\ell}, \mathbf{E}_T^{miss})]}$$

BDT = Boosted Decision Tree
where **tighter** working points correspond to a **reducing** efficiency of **identification** but with an **increasing** factor of **rejection**

HadHad

- Opposite charge taus
- 2 tau jets, no leptons
- Single tau triggers (80/125/160 GeV)
- $\Delta\phi(\tau_1,\tau_2) > 2.7$ (back-to-back)

Leading tau (highest p_T):

- Matches single tau triggers
- p_T threshold per trigger +5 GeV ($p_T > 85/130/165$ GeV)
- Jet ID “Medium” BDT working point

Subleading tau:

- $p_T > 65$ GeV
- Jet ID “Loose” BDT working point

Background estimation: LepHad

Main backgrounds:

- $Z \to \tau^-\tau^+$ *(b-veto)*
- Single top *(b-tag)*
- $Z \to e^-e^+$
- W+jets *(b-veto)*
- $t\bar{t}$ *(b-tag)*
- Multijet

τ_{had} candidate:

Genuine τ_{had}

e faking τ_{had} (**L**)

Jet faking τ_{had} (**W/MJ**)

Estimation:

Based on MC simulation with data-driven correction

Data-driven

Estimate τ_{had} misidentifications using **fake factor** methods for each sub-process ***f_X*** in each of their own fake regions **X-FR** (**X** ∊ [**L**, **W**, **MJ**]):

$$f_X = \left. \frac{N_{\rm data}^{\rm pass} - N_{\rm bkg}^{\rm pass}}{N_{\rm data}^{\rm fail} - N_{\rm bkg}^{\rm fail}} \right|_{\rm X\text{-}FR}$$

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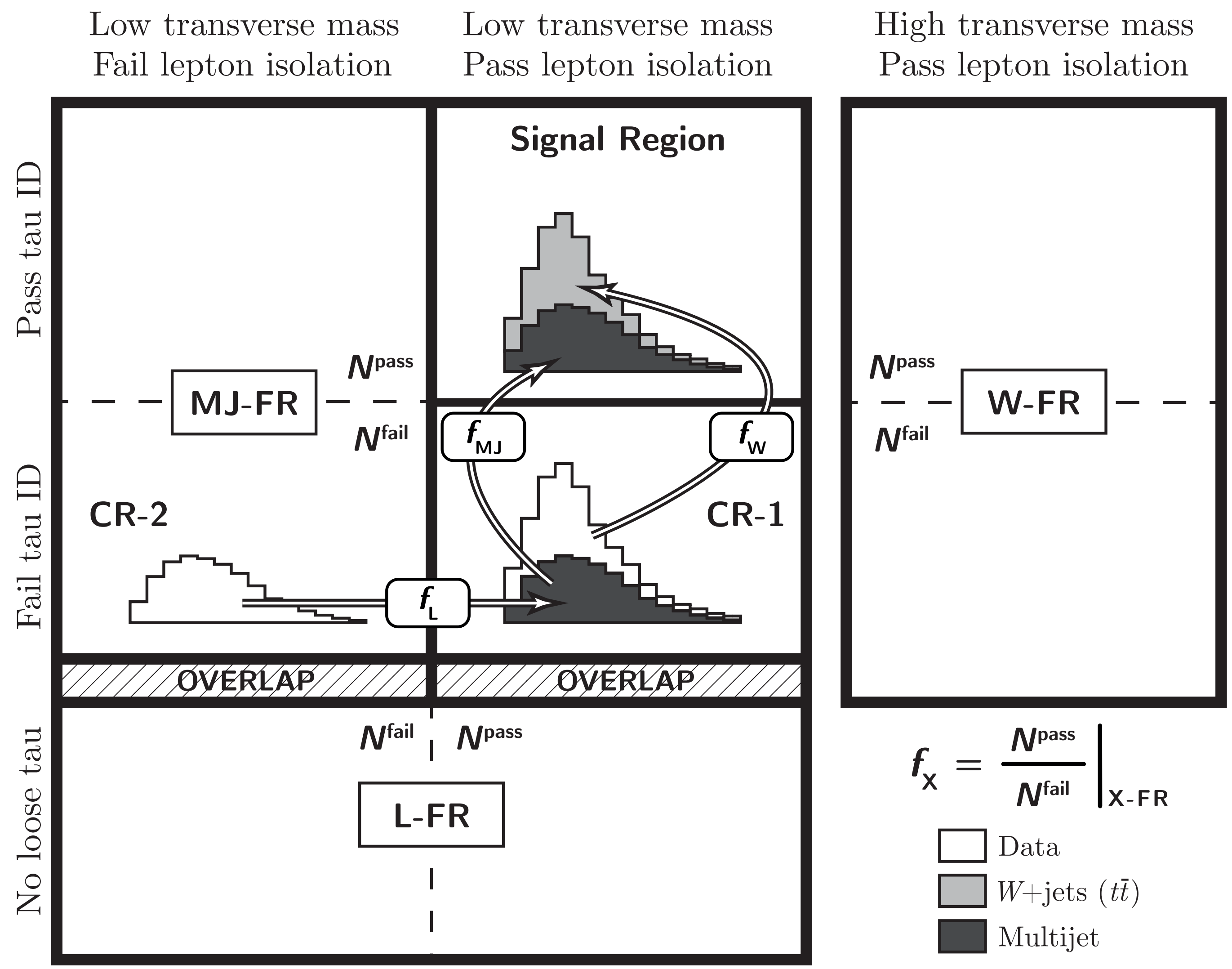
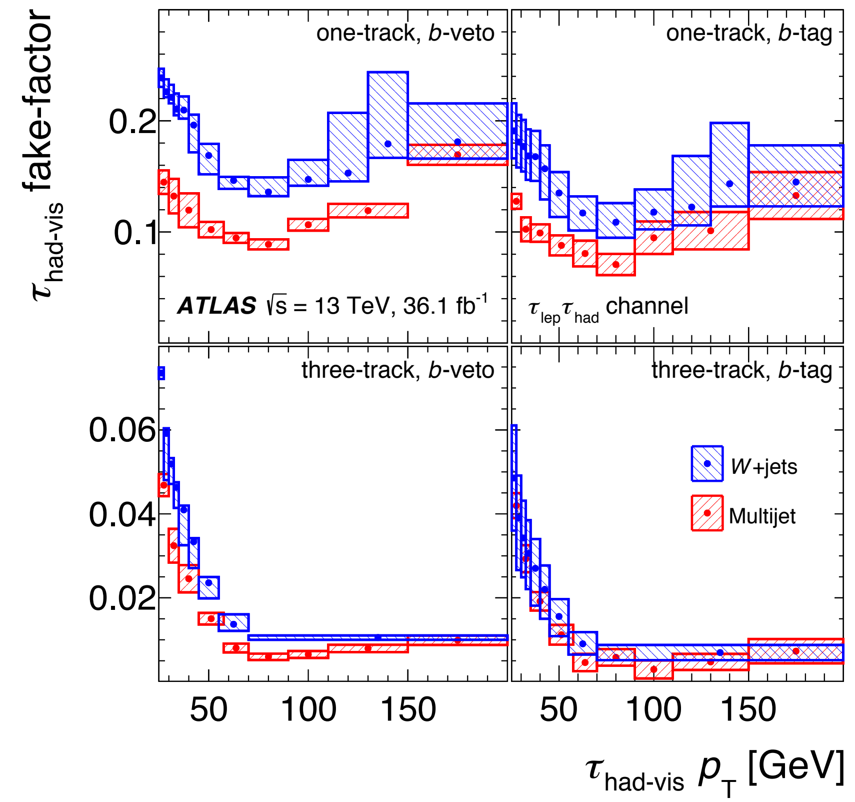
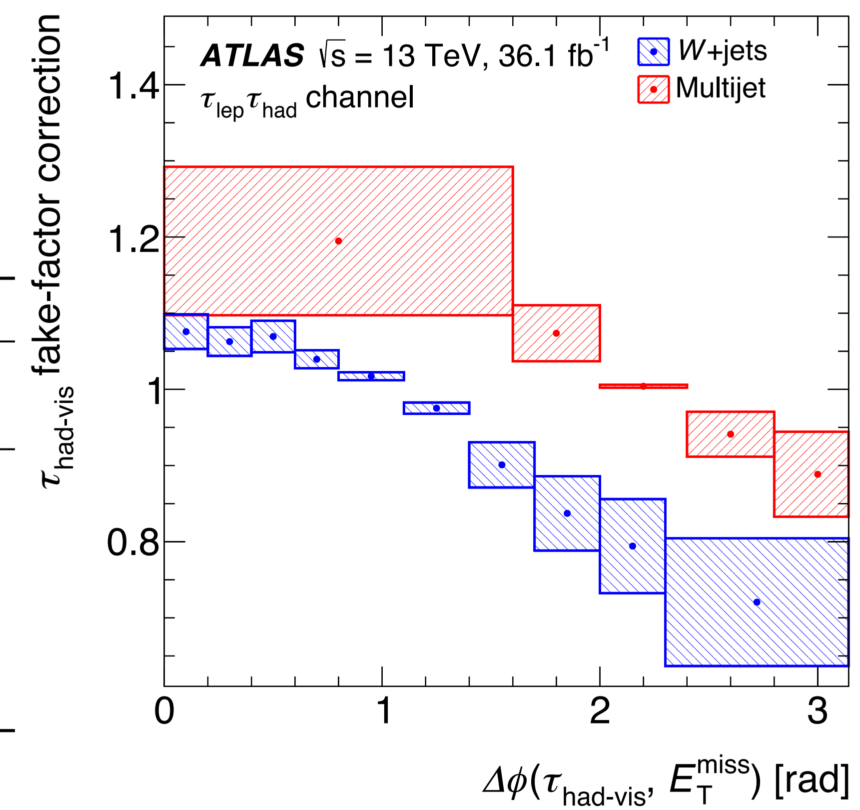
LepHad fake factors







Region	Selection
SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell)\times q(\tau_1)<0$, $\lvert\Delta\phi(\mathbf{p}_T^\ell,\mathbf{p}_T^{\tau_1})\rvert>2.4$, $m_T(\mathbf{p}_T^\ell,\mathbf{E}_T^{miss})<40$ GeV, veto $80<m(\mathbf{p}^\ell,\mathbf{p}^{\tau_1})<110$ GeV ($\tau_e\tau_{had}$ channel only)
CR-1	Pass SR except: τ_1 (very-loose, fail medium)
CR-2	Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)
MJ-FR	Pass SR except: τ_1 (very-loose), ℓ (fail isolation)
W-FR	Pass SR except: $70\,(60)<m_T(\mathbf{p}_T^\ell,\mathbf{E}_T^{miss})<150$ GeV in $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$) channel
CR-T	Pass SR except: $m_T(\mathbf{p}_T^\ell,\mathbf{E}_T^{miss})>110\,(100)$ GeV in the $\tau_e\tau_{had}$ ($\tau_\mu\tau_{had}$) channel, b-tagging category only
L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{had\text{-}vis}$, $m_T(\mathbf{p}_T^\ell,\mathbf{E}_T^{miss})<30$ GeV

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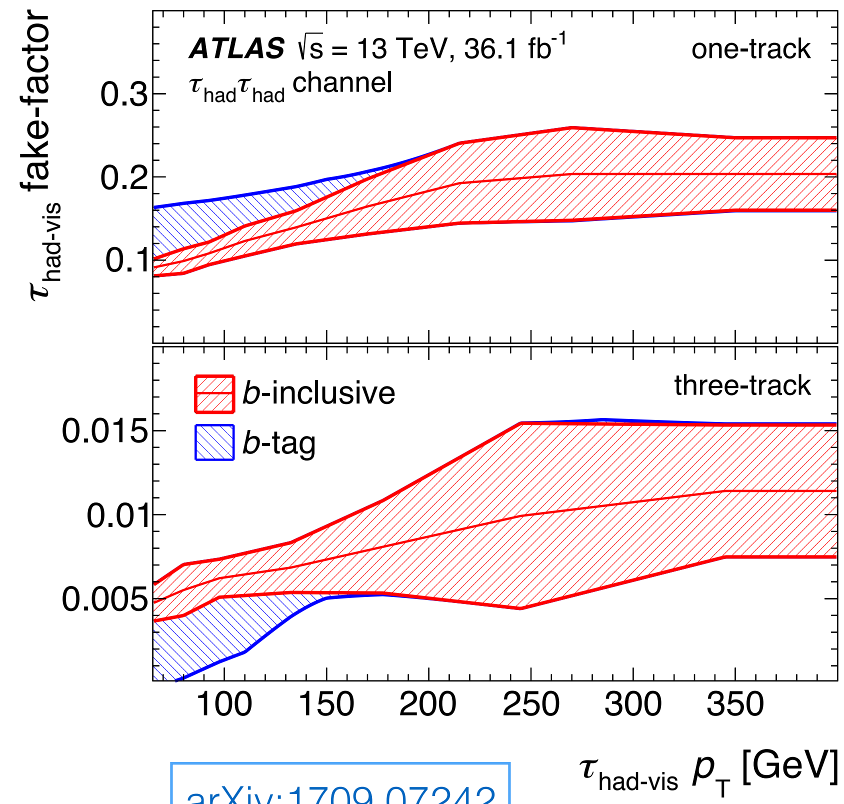
Background estimation: HadHad

- Mostly **similar** to **LepHad**
- **Main backgrounds:**
  - b-tag: Multijet and top
  - b-veto: $Z \rightarrow \tau^{-}\tau^{+}$
- Backgrounds with **true** hadronic tau decays (top/Z) are directly estimated from MC **simulation**
- **Multijet faking** taus purely estimated from **data** using a similar **fake factor** technique to LepHad
- **Other** backgrounds with **jets faking** taus (W+jets and single top/ttbar) are estimated from MC simulation, but with a data-driven **fake rate** correction, measured in μν+jets events where the rate is defined as the **ratio** of probe jets **passing loose ID** to the **total number** of probe jets



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$$f_R = \frac{N_{\mathrm{data}}^{\mathrm{pass}}}{N_{\mathrm{data}}}$$

Analysis strategy

- Distinguish SM background against BSM signal by observing results between data and MC prediction using the the **total transverse mass** of the di-tau system, $\mathbf{m_T^{tot}}$:

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

- Reconstructed using **kinematics** rather than complex **algorithm** techniques
  - Previous studies have shown these have difficulty handling undetected **neutrinos**, thus providing **no improvement** to sensitivity

Results

- The **discriminant** total transverse mass represents a **generic** scan for new heavy resonances, **without** yet applying model-specific **interpretations**

- Latest results show data are in agreement with the SM background, with **no significant excess** observed

- Apply **exclusion limits** in order to supply theorists with up-to-date constraints on the various models

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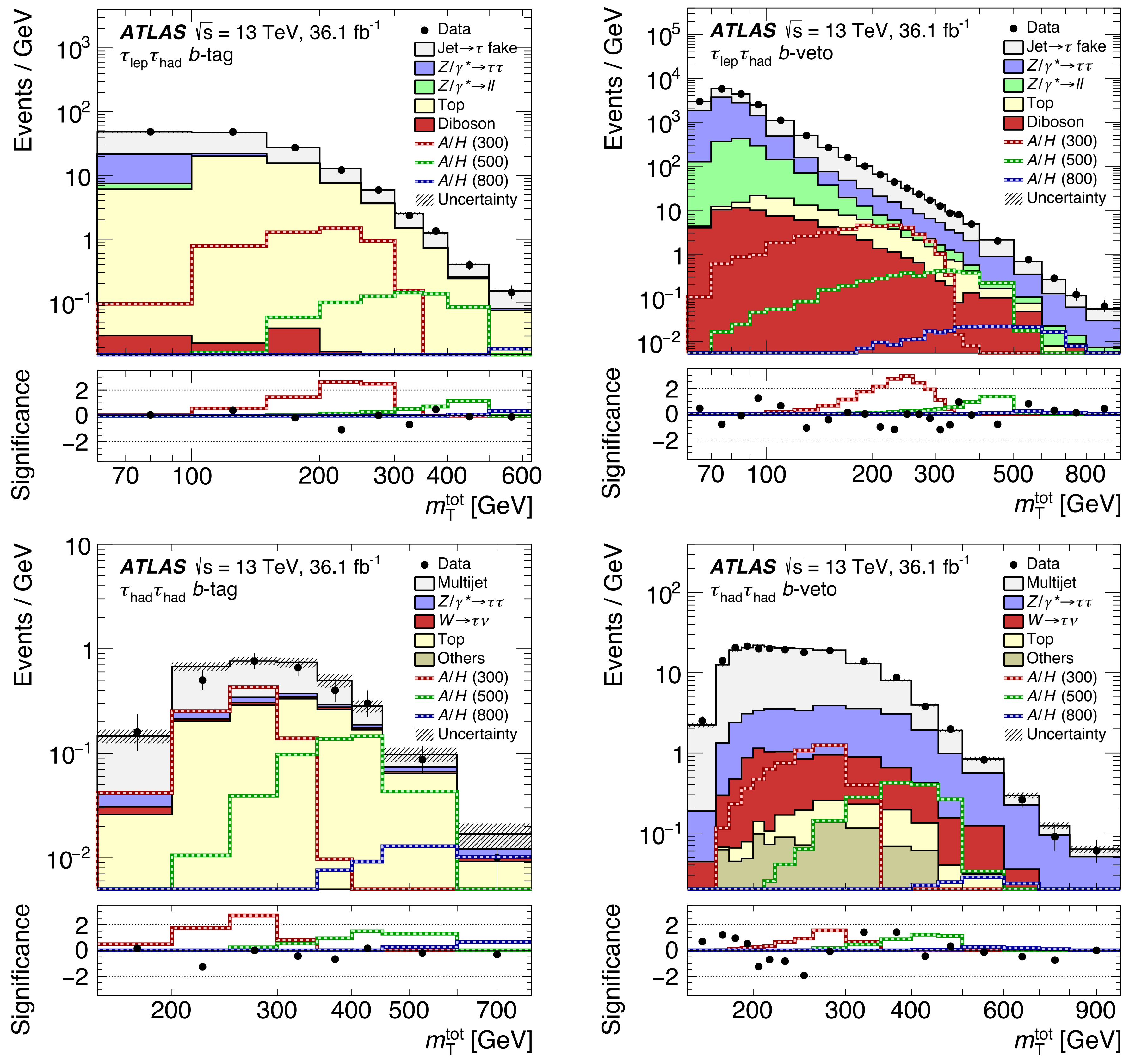
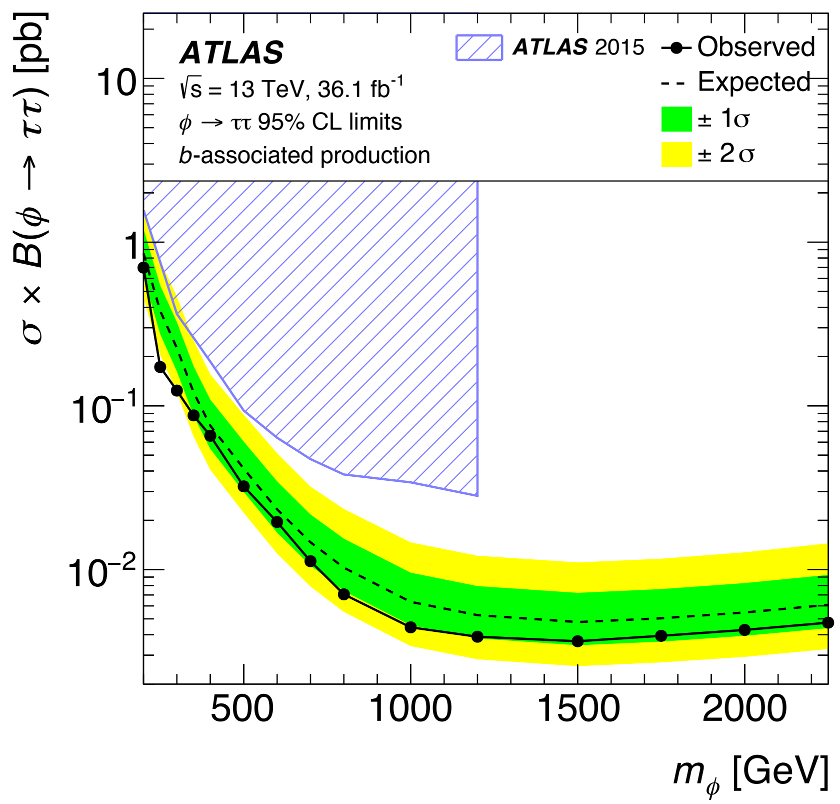


Exclusion limits

- Apply **exclusion limits** based on each of the **production mechanisms**:



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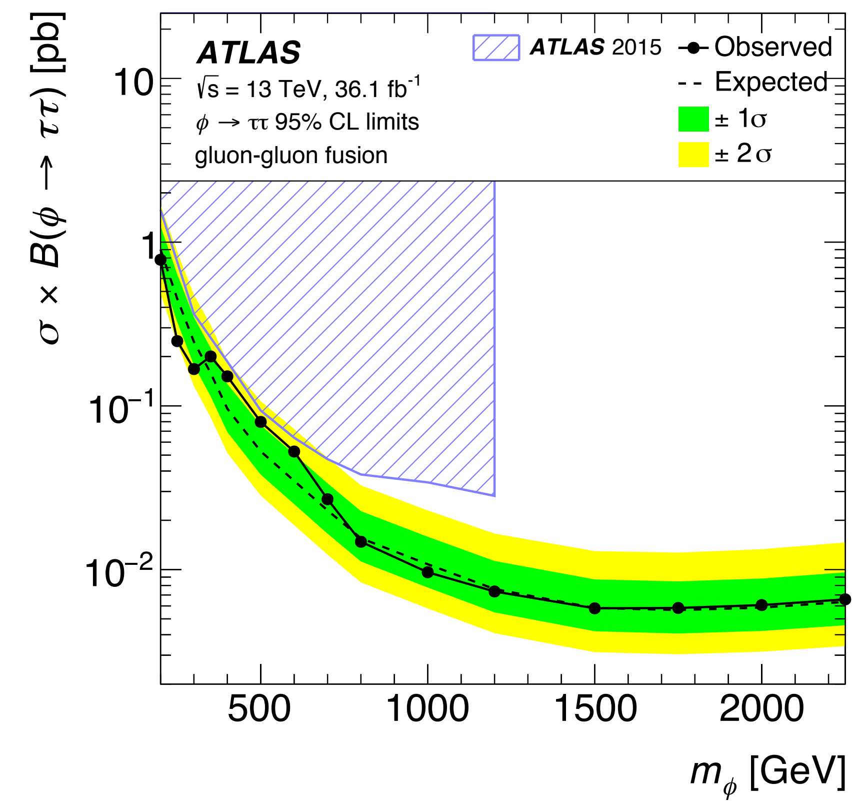

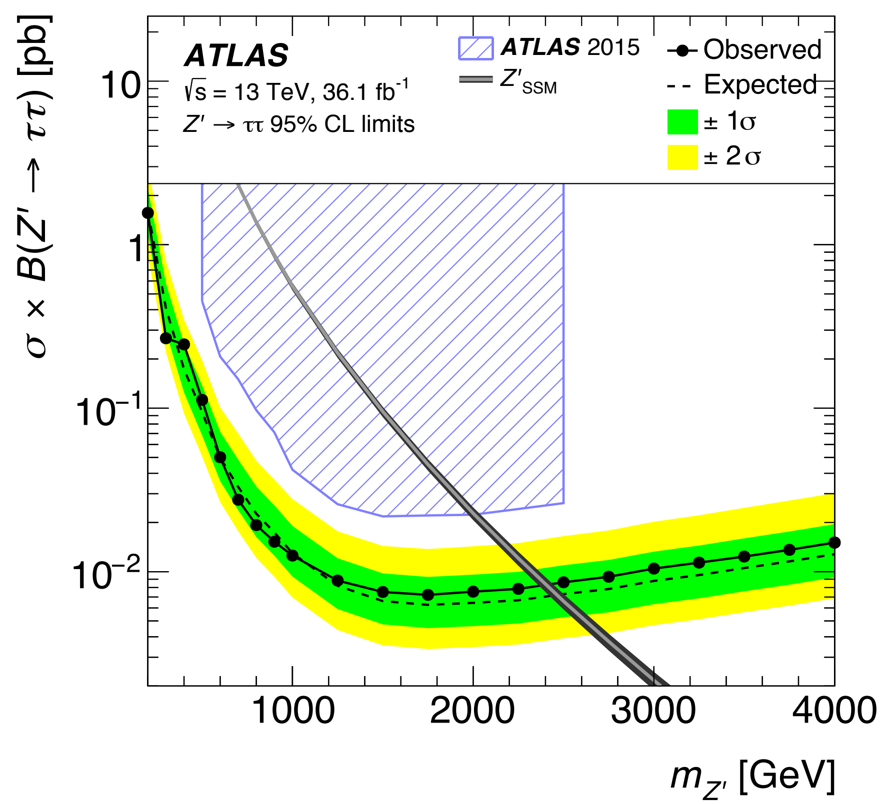

Exclusion limits

- Also apply **exclusion limits** based on each of the **model benchmark scenarios**:
  - For **Higgs**:

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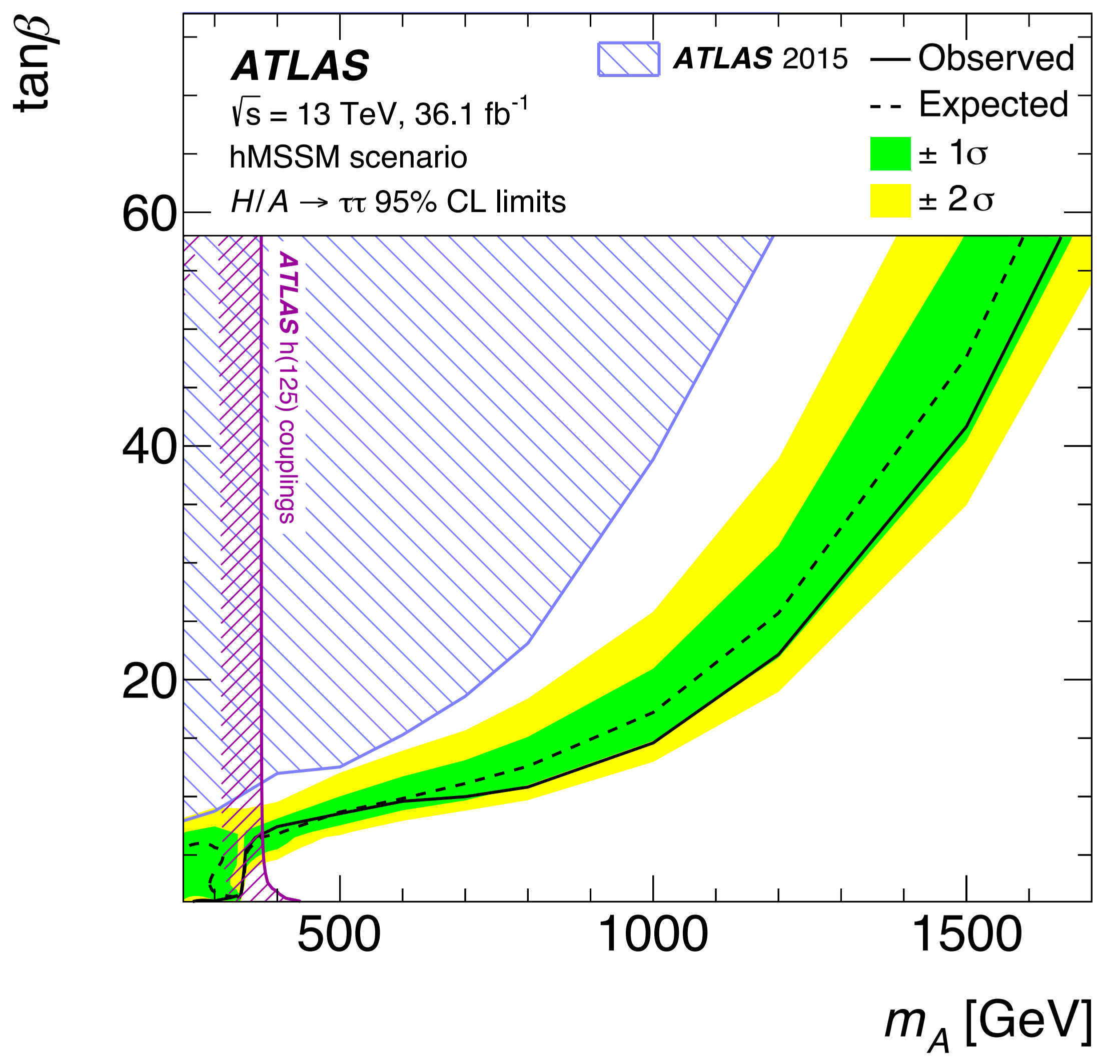
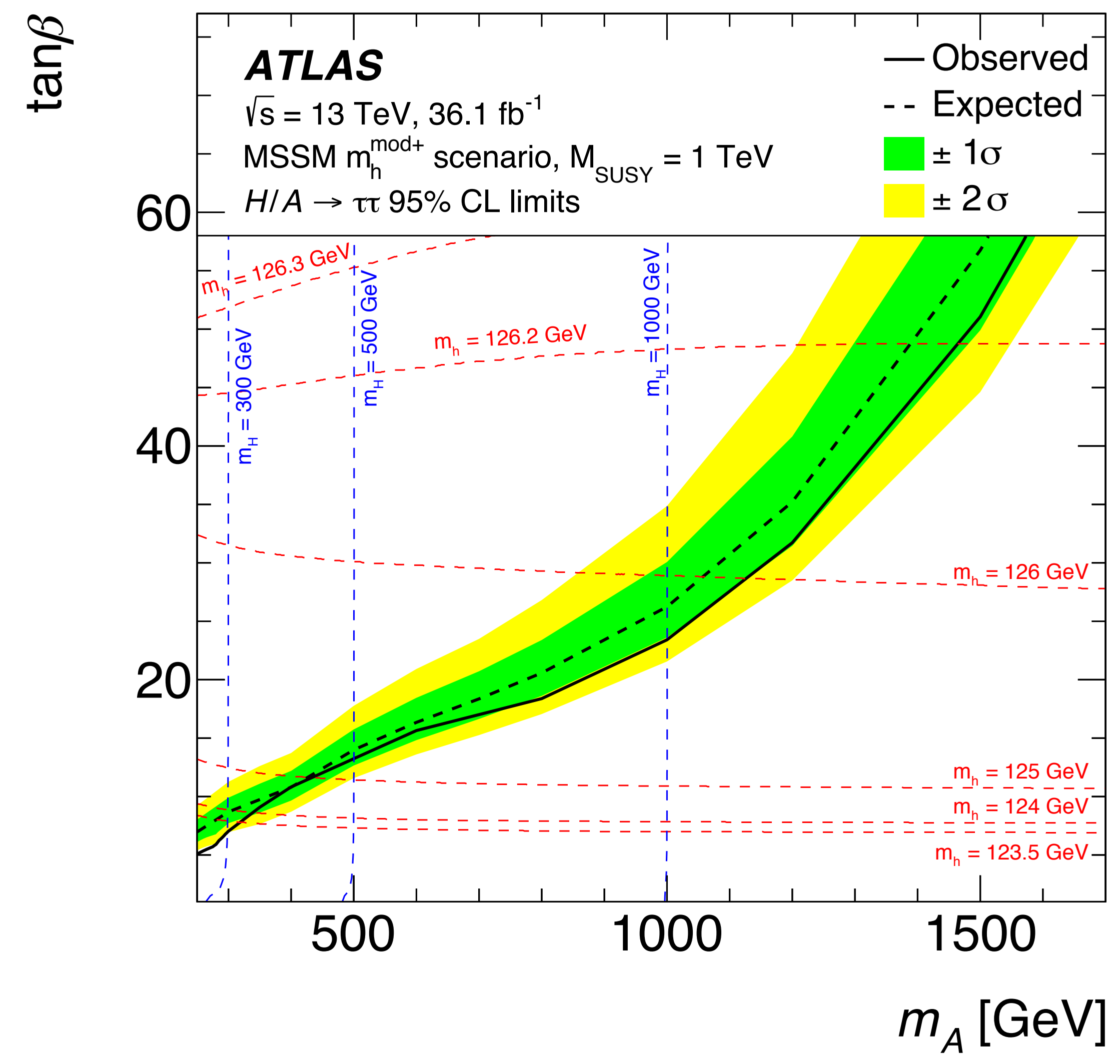
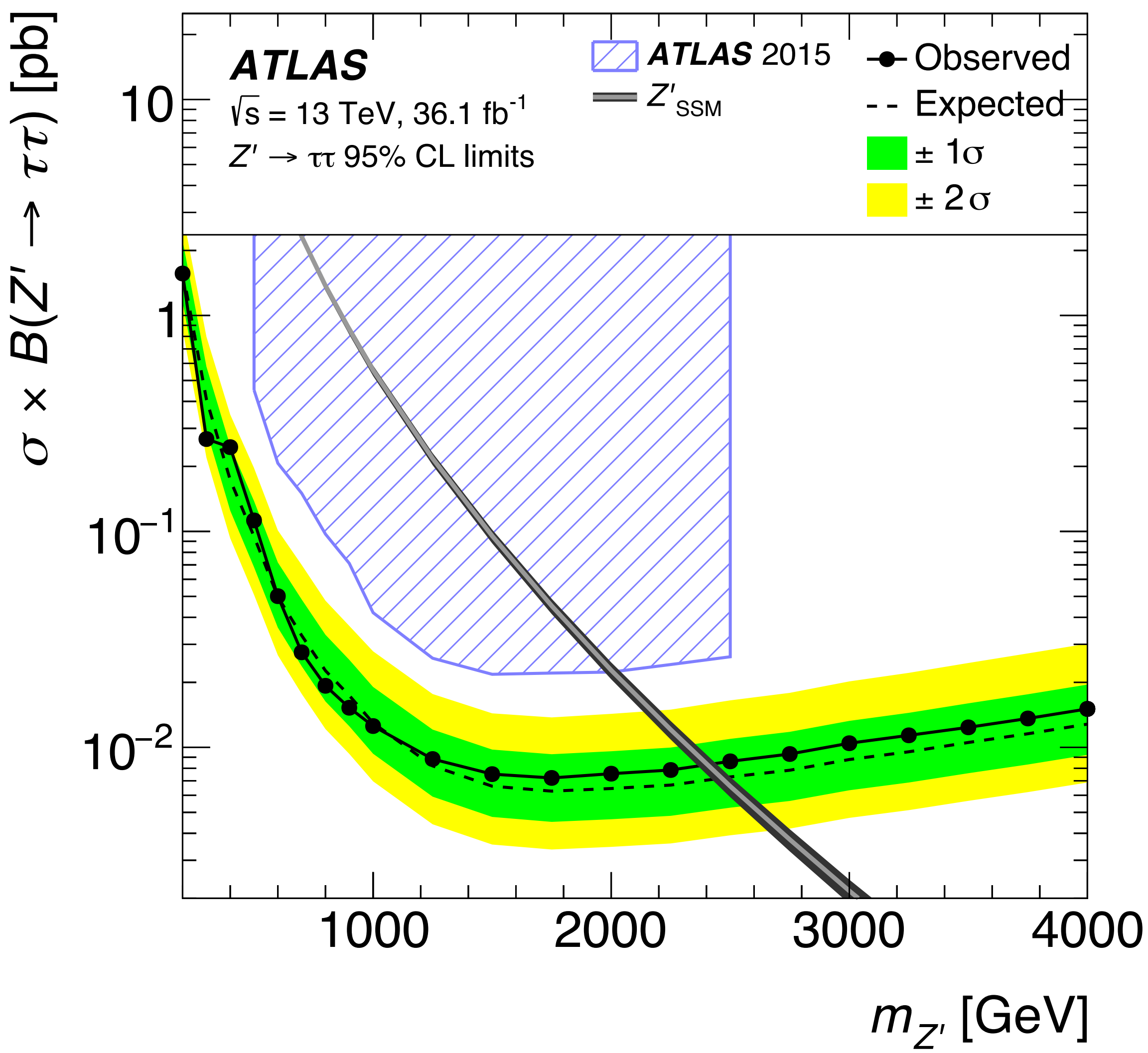


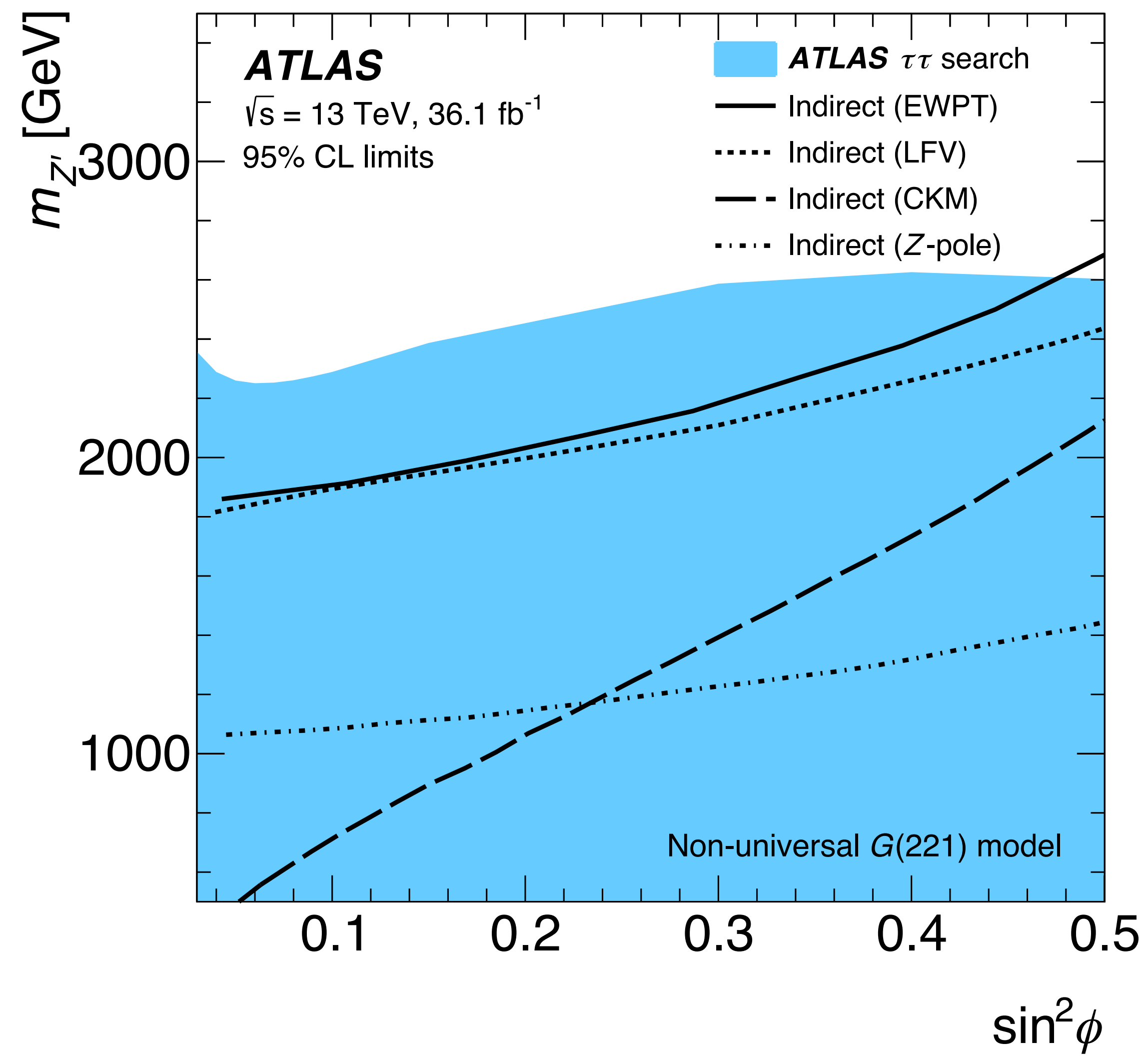


Exclusion limits

- Also apply **exclusion limits** based on each of the **model benchmark scenarios**:
  - For **Z′**:

arXiv:1709.07242





- As demonstrated, these have set **record exclusion limits** in our analysis, as well as significantly **extending** our sensitive **mass range** since previous publications

Future features

General improvements:

- Software upgrades in **tau reconstruction**, energy scale and identification
- Optimise **event selection** criteria
- Improve **trigger** menu
- Improve **fake factor** estimation techniques
- Studies improving **MC signal generators**

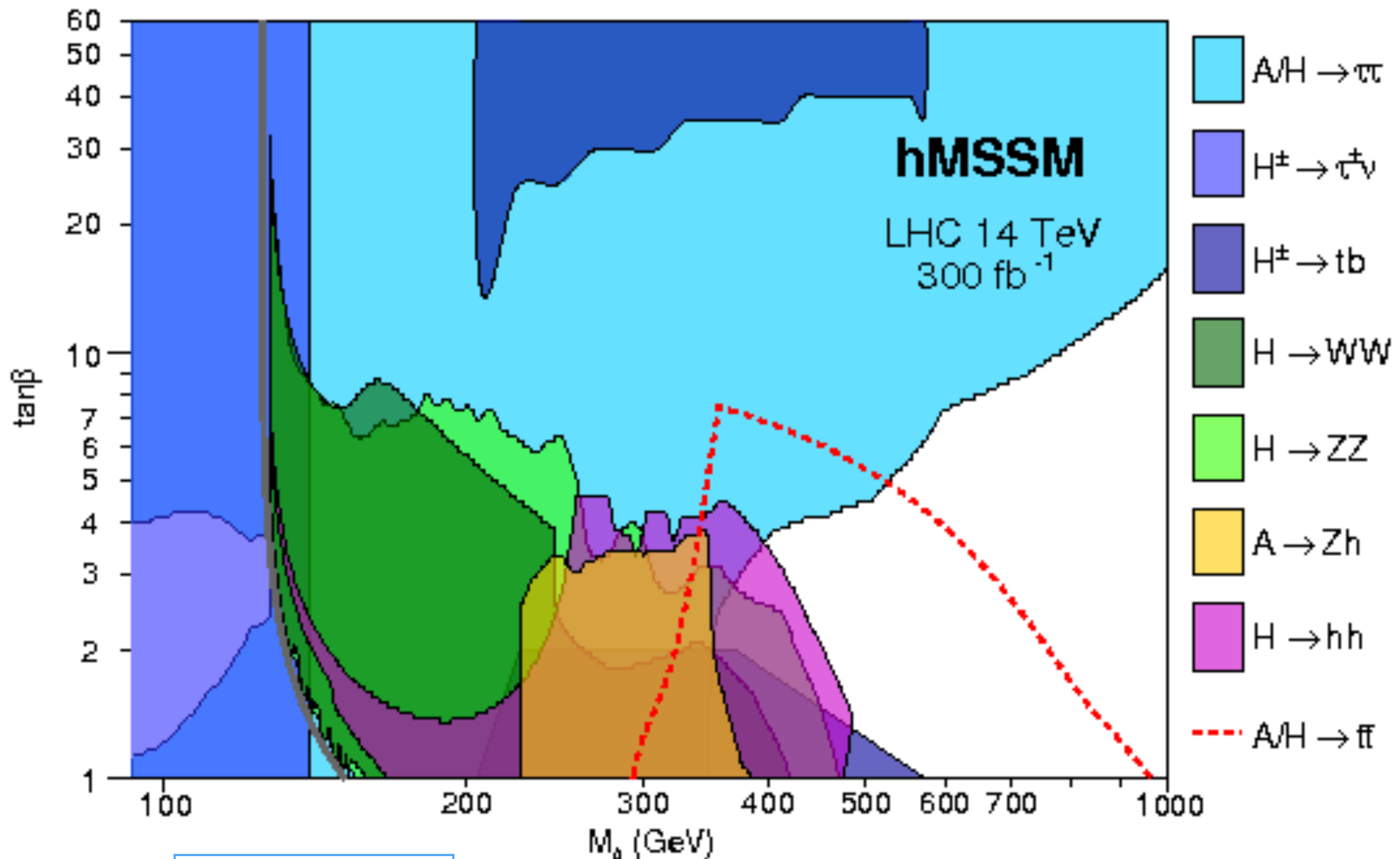
More specific studies:

- Include **2-prong** taus (3-prong decays only partially identified)
- Use a **continuous tau ID** with binned BDT efficiencies rather than fixed BDT working points
- Revisit using **discriminant mass algorithms** again
- Include a new **LepLep** channel (12% probability)
- Possibly extend our analysis to cover **more resonances**, such as charged Higgs and di-Higgs production (4-tau) - relax the back-to-back tau criteria

Stay tuned!

Fortune-telling

- **Prospect** with dataset including **Run-3** luminosity by the end of **2023**
  - We are a **flagship** analysis channel in **excluding** much of the **hMSSM** parameter space, especially at **high** values of tan β
  - Compared to **current** results, expecting **large** improvements **<1 TeV**
  - Keen to see how other channels can **fill the gaps**!



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References

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Thanks for listening!

Any questions?