Searching for Beyond the Standard Model Physics using Tau Leptons

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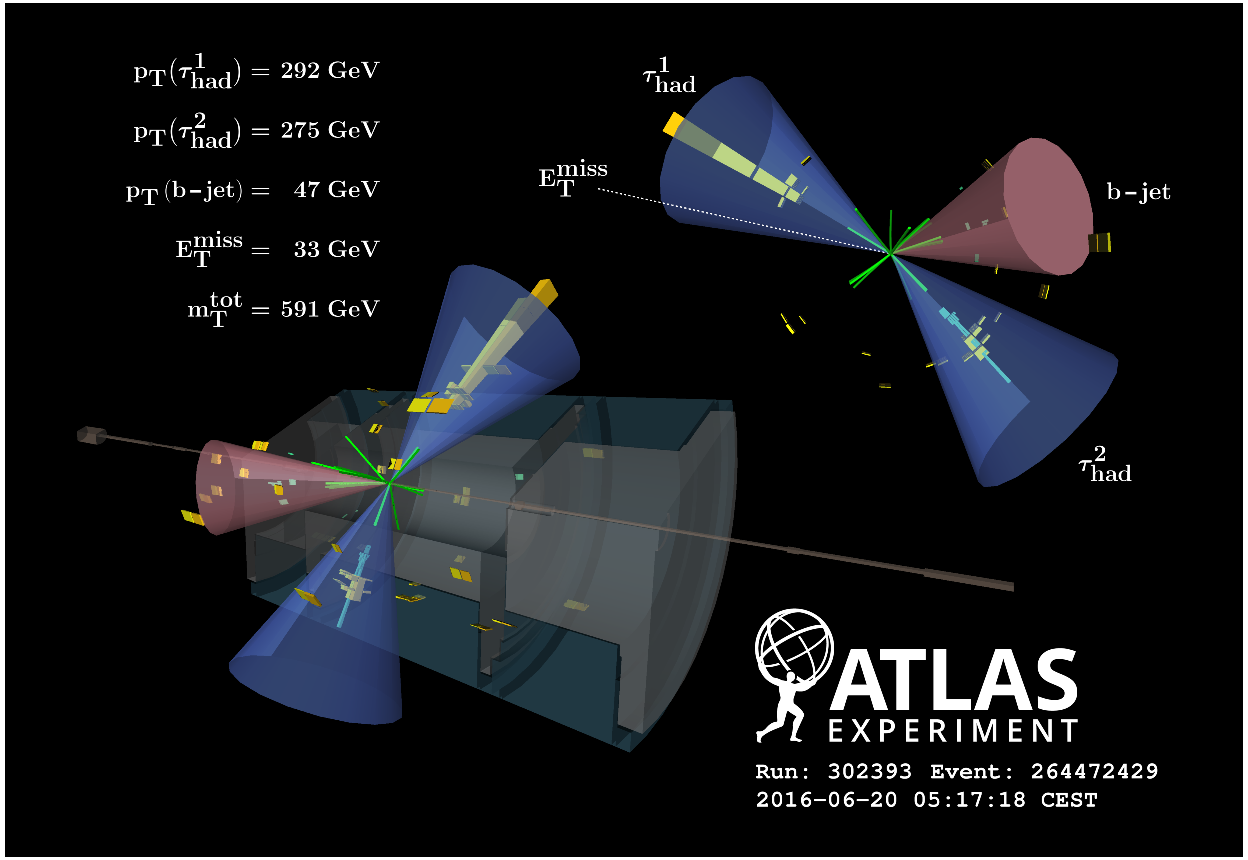
ATLAS EXPERIMENT

- Taus and Ditau Final State
- Minimally Supersymmetric Standard Model (MSSM)
  - Motivation
  - Event Selection and Backgrounds
  - Signal Region
  - Exclusion Limit
- Z' Interpretation
  - Motivation & Limits
- Leptoquark (LQ) Interpretation
  - Motivation & Strategy
  - Exclusion Limits
- Conclusion



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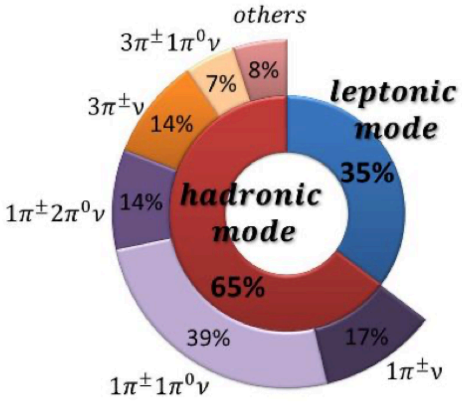
Using Taus

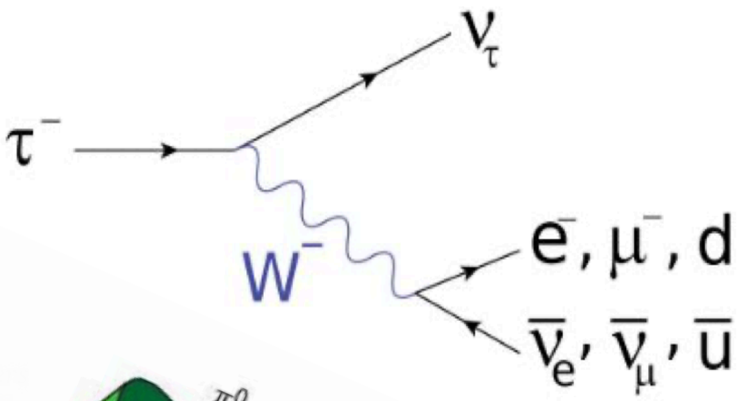
- Mass: 1.777 GeV
  Mean lifetime: 2.903×10^{-13} s
  Typically decay in the beampipe, only detect their products

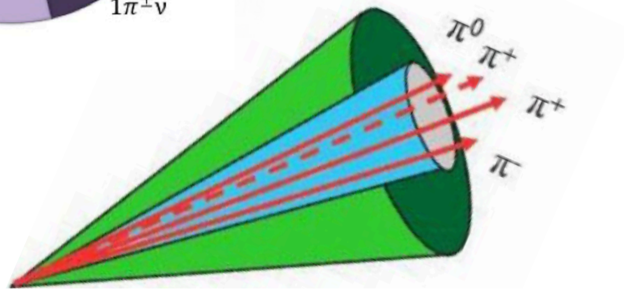
- Taus decay hadronically 65% of the time, forming narrow and collimated jets of pions. Decay leptonically 35% of the time

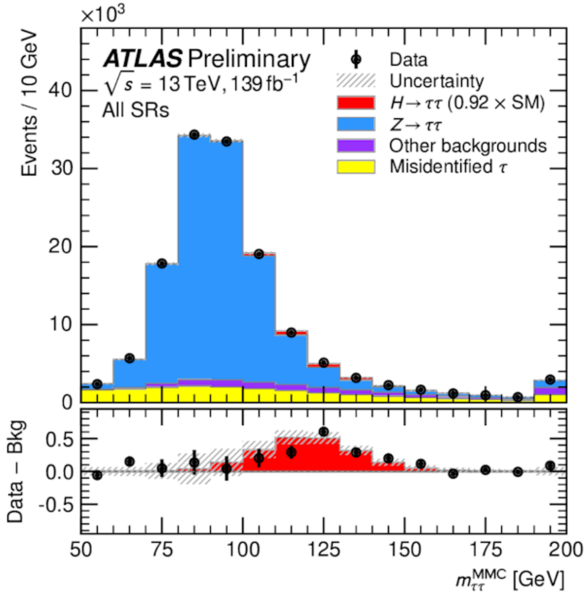
- Taus have the largest branching fraction of all leptonic Higgs decays (6.3% for $m_H = 125.09$ GeV). Leading to $\approx$ 500 000 Run-2 $H \rightarrow \tau\tau$ decays

- Neutrinos in the final state degrade the resolution. Separation from other backgrounds ($\mathrm{Z} \rightarrow \tau\tau$, Fakes, etc.) is difficult





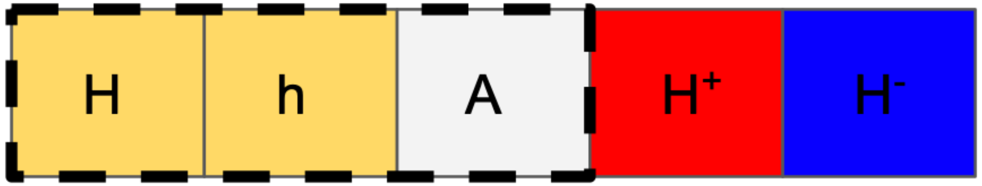




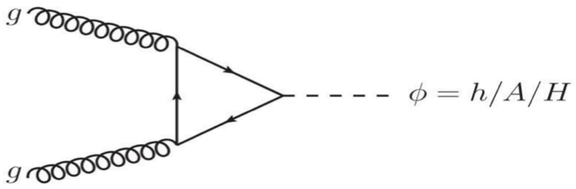
arXiv:2201.08269

Minimally Supersymmetric Standard Model

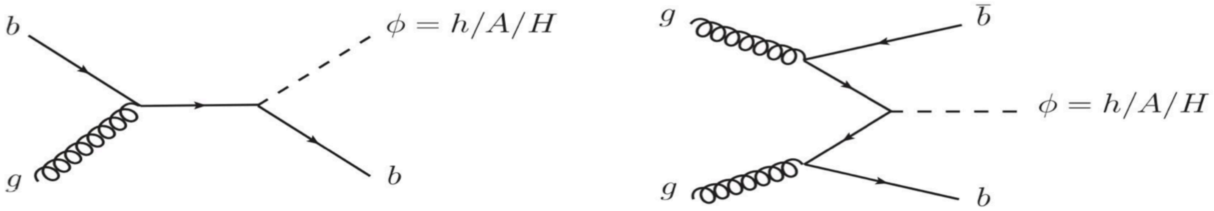
- A proposed extension to the SM predicting a Two Higgs Doublet Model (2HDM). Resulting in 3 neutral Higgs bosons and 2 oppositely charged
- The Higgs sector at tree level is described by two parameters: m_A and $tan\beta$ (β = Ratio of vacuum expectation values of the two doublets)
- Predicts larger coupling to τ and b-quarks at high $tan\beta$
  - Search in the ditau final state and tag b-quarks



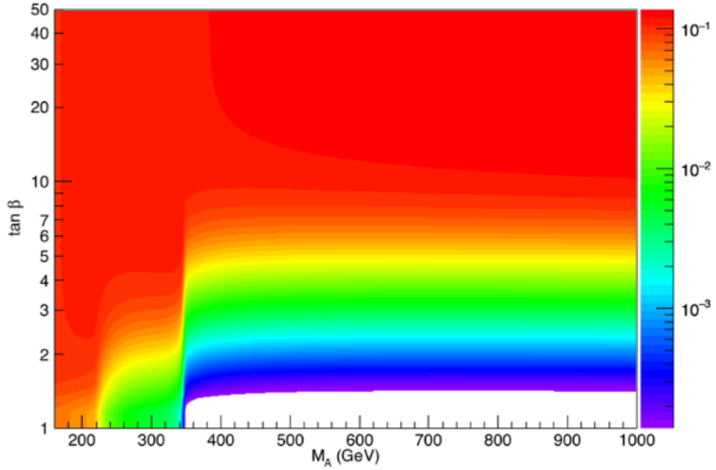
gluon-gluon fusion

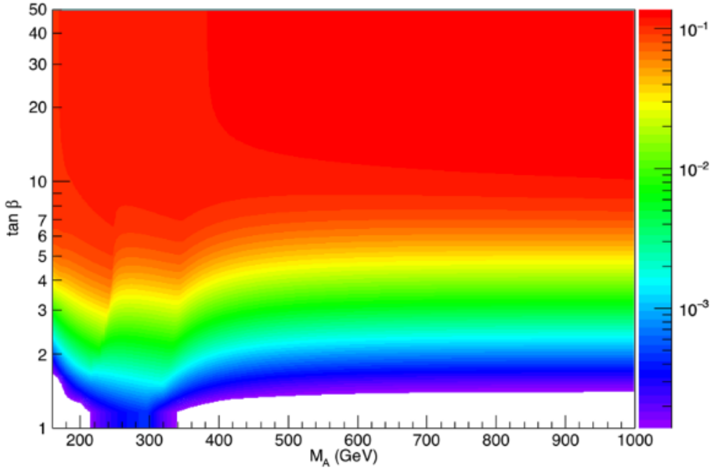


b-associated production



BR(A → ττ) *arXiv:1502.05653v2* BR(H → ττ)





- 4 analysis channels:
  - $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
  - Further split into *b*-tag and *b*-veto regions

- Signal regions selected to enhance the signal to background ratio, control regions used to constrain and correct the large backgrounds

- Background composition:

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Region	Selection
SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell) \times q(\tau_1) < 0$, $\lvert\Delta\phi(\ell, \tau_1)\rvert > 2.4$, $m_T(\ell, E_T^{miss}) < 40$ GeV, veto $80 < m(\ell, \tau_1) < 110$ GeV (ehad 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)
W-CR	Pass SR except: $60 < m_T(\ell, E_T^{miss}) < 150$ GeV in ehad (muhad) channel for b-veto
	Pass SR except: $60 < m_T(\ell, E_T^{miss}) < 110$ GeV in ehad (muhad) channel for b-tag
T-CR	Pass SR except: $m_T(\ell, E_T^{miss}) > 110$ GeV in the ehad (muhad) channel, *b*-tag category only
L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{had\text{-}vis}$, $m_T(\ell, E_T^{miss}) < 30$ GeV

Region	Selection
SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 2.7$
CR-1	Pass SR except: τ_2 (fail loose)
DJ-FR	jet trigger, τ_1+τ_2 (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 2.7$, $p_T^{\tau_2}/p_T^{\tau_1} > 0.3$
W-FR	μ (trigger, isolated), τ_1 (no identification), $\lvert\Delta\phi(\mu, \tau_1)\rvert > 2.4$, $m_T(\mu, E_T^{miss}) > 40$ GeV *b*-veto category only
T-FR	Pass W-FR except: *b*-tag category only

$Z/\gamma^* \to \tau^+\tau^-$ (real tau)
Top (real tau)
Diboson (real tau)

→ Estimated with MC simulation

QCD multijet (Jet fakes lepton and/or tau)
W + jets (b-veto) (Jet fakes tau (lephad))
Top processes (Jet fakes tau (lephad))

→ Estimated with data driven fake factor technique for each sub process, using dedicated control regions

$$f(\mathbf{x}) \equiv \frac{N_{data}^{pass}(\mathbf{x}) - N_{bkg}^{pass}(\mathbf{x})}{N_{data}^{fail}(\mathbf{x}) - N_{bkg}^{fail}(\mathbf{x})}$$

$Z/\gamma^* \to \ell\ell$ (Lepton fakes tau (lephad))
W + jets and top (true tau and fake tau (hadhad))

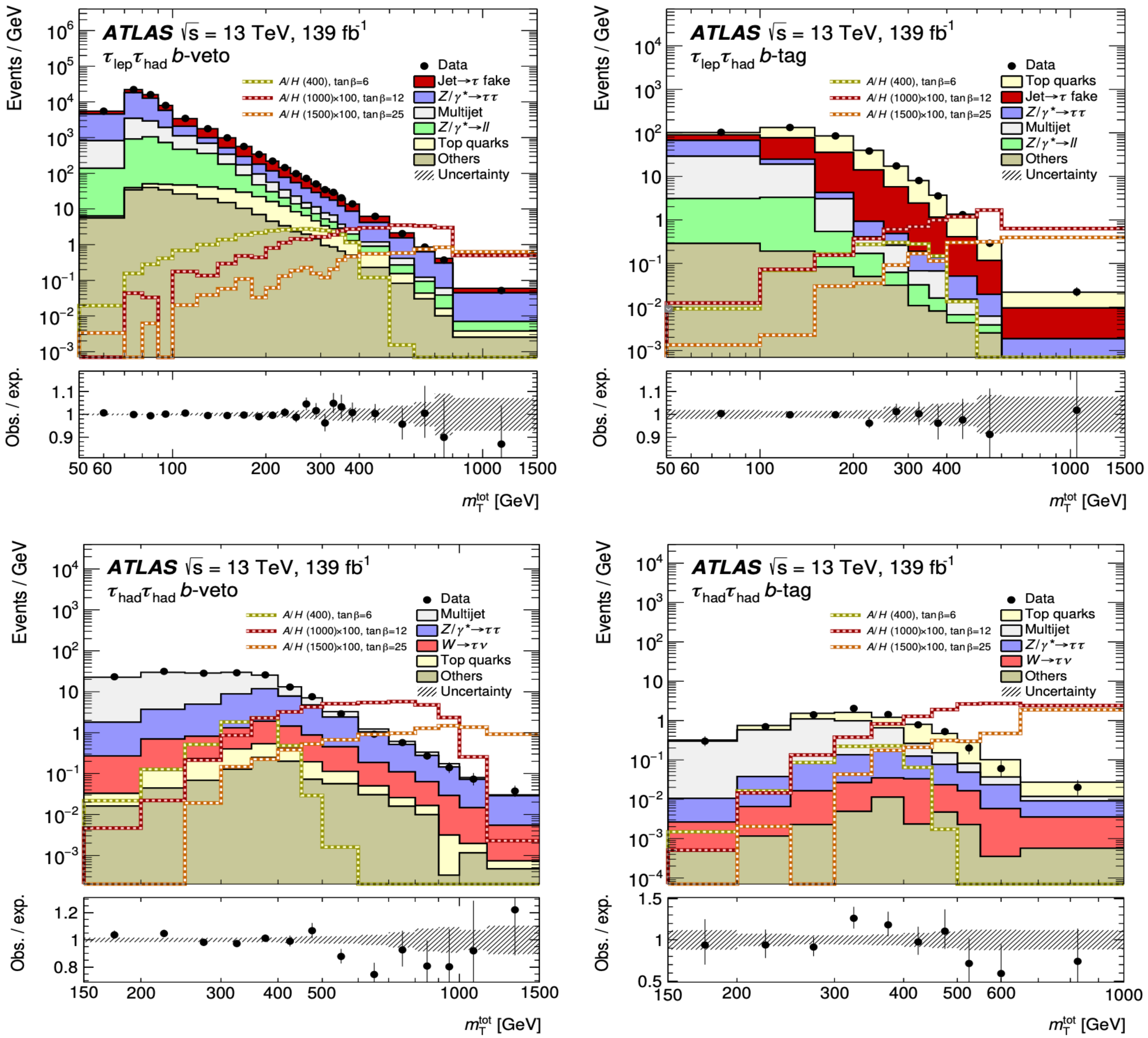
→ Estimated using MC simulation and data driven corrections

Unblinded signal region

- Basic search conducted for full Run-2 dataset (139 fb^{-1})
- Final discriminant:

$$M_T^{TOT} = \sqrt{\left(p_T^{\tau_1} + p_T^{\tau_1} + E_T^{miss}\right)^2 - \left(\boldsymbol{p}_T^{\tau_1} + \boldsymbol{p}_T^{\tau_1} + \boldsymbol{E}_T^{miss}\right)^2}$$

- No deviation from the Standard Model prediction observed
  - Signals shown: 400 GeV, $tan\beta = 6$, 1 TeV, $tan\beta = 12$, 1.5 TeV, $tan\beta = 25$



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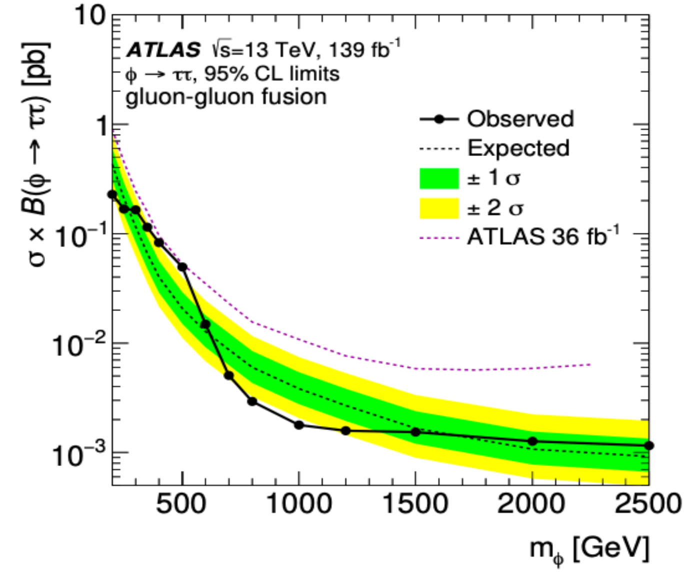
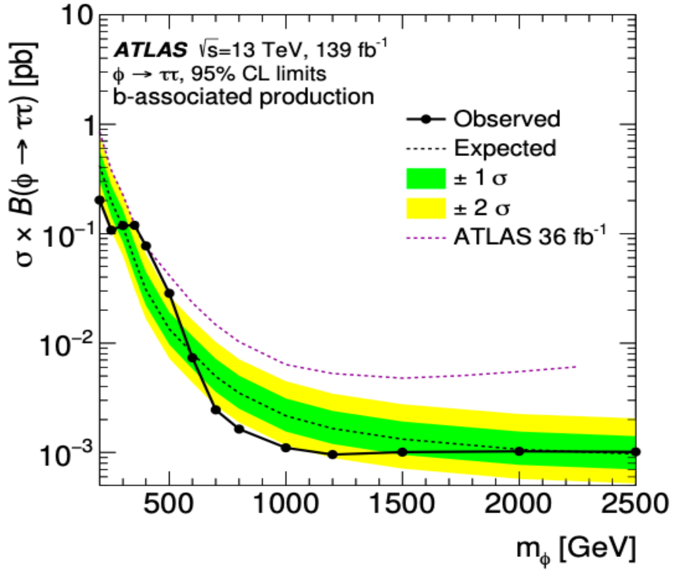
If no excess observed, limits can be set on the maximum possible cross section × branching ratio of each production mode

Model independent limits

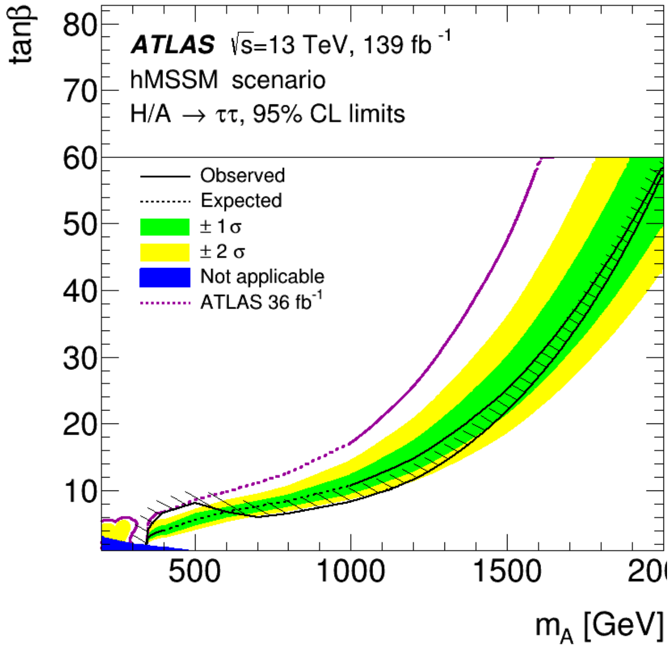
- Set a limit for a generic heavy Higgs decaying via *gluon-gluon* fusion and *b*-associated production
- Improvement from last result (36 fb^{-1}) is visible

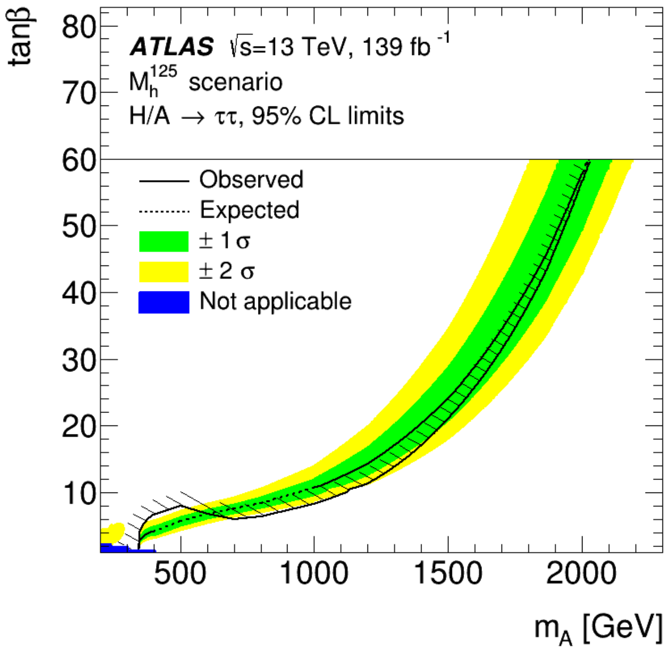




Model dependent limits

- Use the cross section predicted by the benchmark models for each mass point and $tan\beta$ to construct a limit across the two parameters
- Improvement on past benchmark scenarios (hMSSM) and first limits on new m_H^{125} scenario are shown





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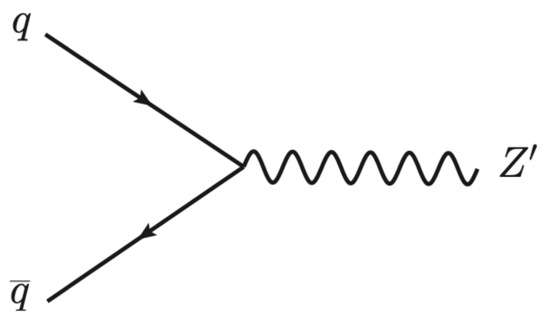
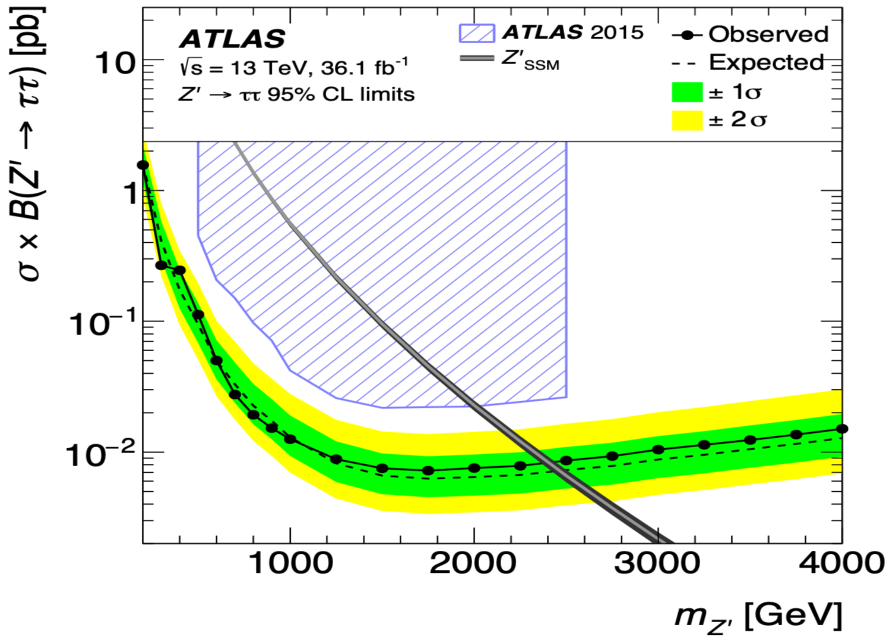
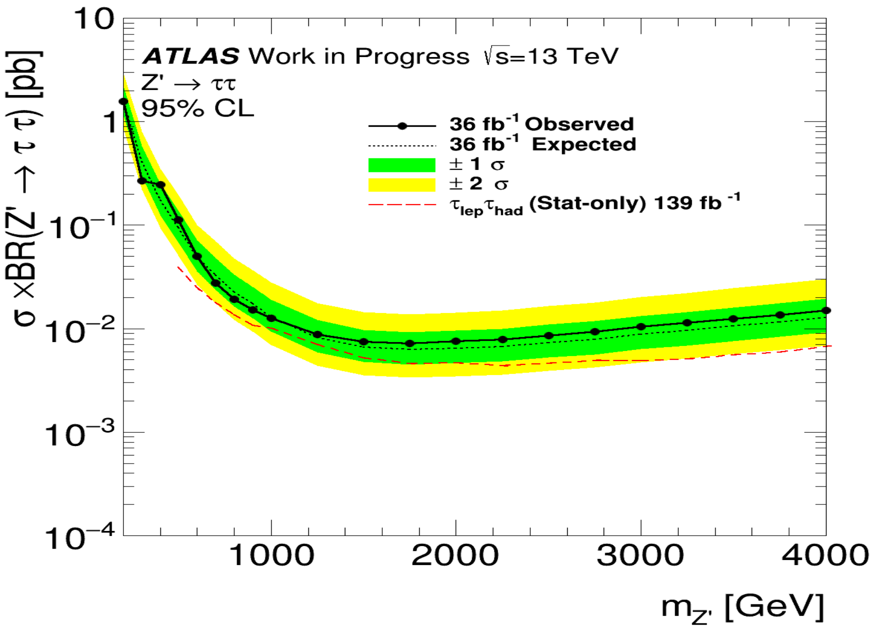
- Many extensions to the SM predict heavy Z' gauge bosons. Models in which Z' couple preferentially to a 3rd generation fermion may be linked to the high top mass
- Sequential Standard Model predicts a single Z' with the same couplings as the SM Z' boson, serving as a benchmark
- Latest ATLAS public limit from 36 fb^{-1} result. Full Run-2 result available in next publication. *JHEP 01 (2018) 055*
- Full Run-2 $\tau_{lep}\tau_{had}$ expected limit only considering statistical uncertainty shown, expect greater improvement with channel combination and neural network discriminator







Analysis in progress – blinded

- The singly produced third generation leptoquark is predicted to couple to both leptons and quarks. Could be responsible for latest hints (3.1σ) of lepton universality violation *arXiv:2103.11769*

- $\widetilde{S}_1$ model used, $3B + 2L = -2$, $Q = -\frac{4}{3}$. Scan over Coupling (λ) of LQ-τ-b

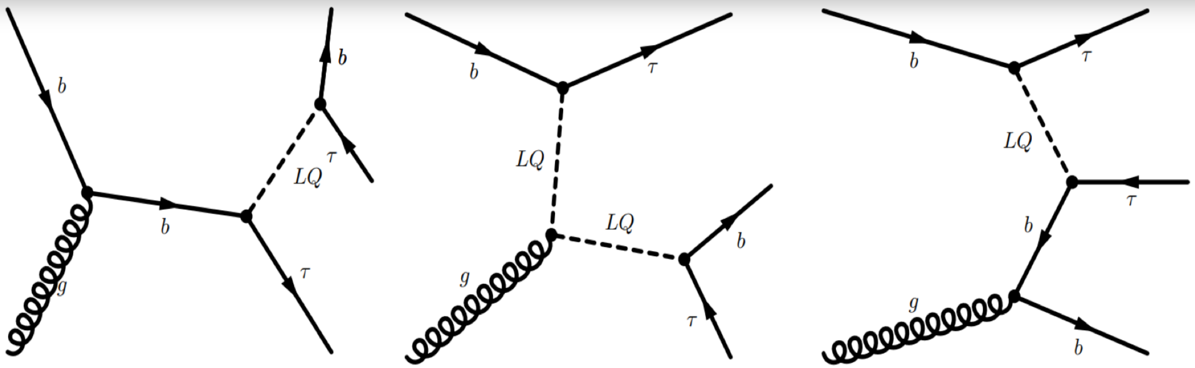
- Similar strategy to MSSM and Z' but slightly different selection due to different topology.

- Discriminant:

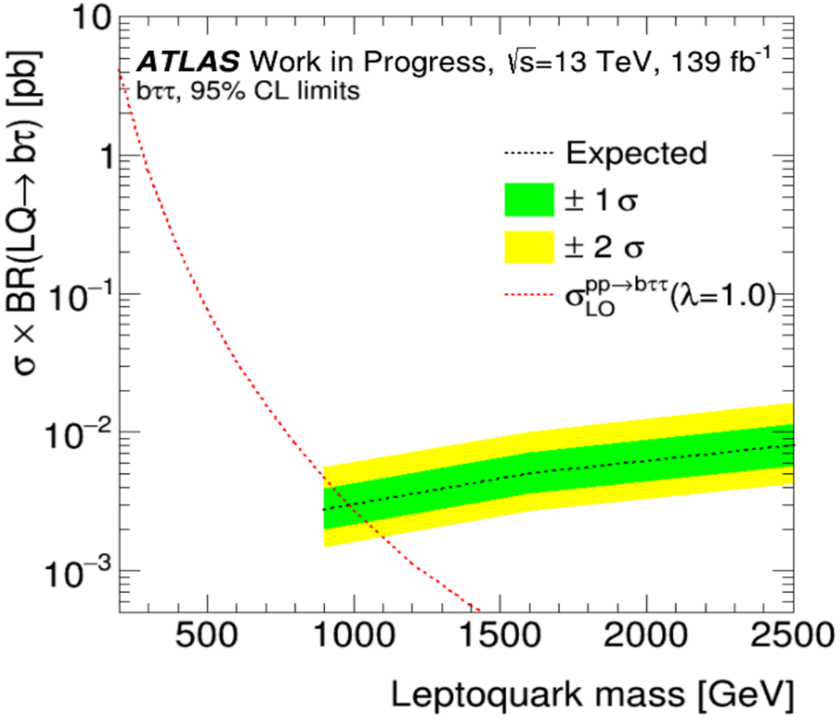
$$S_T = p_T^{\tau_1} + p_T^{\tau_1} + \mathrm{p}_T^{\mathrm{bjet}}$$

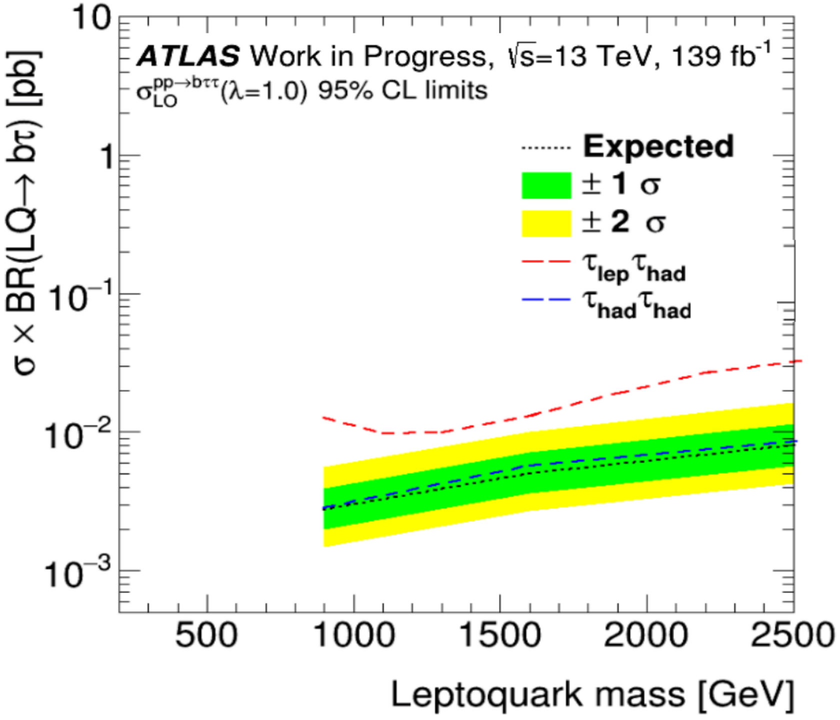
Region	Selection
SR	ℓ (trigger, isolated), τ_{had} (medium), $q(\ell) \times q(\tau) < 0$, $\Delta\phi(\ell, E_T^{\mathrm{miss}}) < 1.5$, at least one b-jets, $m_{\mathrm{vis}}(\ell, \tau) > 100$ GeV, $S_T > 300$ GeV
Multijet-CR	ℓ (trigger, passes or fails offline isolation), $m_T(\ell, E_T^{\mathrm{miss}}) < 30$ GeV, Exactly one b-jets, RNN τ identification score < 0.01, $E_T^{\mathrm{miss}} < 50$ GeV
T-CR	Pass SR except: remove S_T cut, $\Delta\phi(\ell, E_T^{\mathrm{miss}}) > 2.5$
VR	Pass SR except: $1.5 < \Delta\phi(\ell, E_T^{\mathrm{miss}}) < 2.5$
SS-CR	Pass SR except: remove $\Delta\phi(\ell, E_T^{\mathrm{miss}})$ and S_T cut, $q(\ell) \times q(\tau) > 0$
FT-CR	Pass SR except: $S_T < 300$ GeV, $m_T(\ell, E_T^{\mathrm{miss}}) \geq 50$

Region	Selection
SR, low b-jet p_T	τ_1 (trigger, med.), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $S_T > 300$ GeV, $m_{vis} > 100$ GeV, 25 GeV < lead b-jet p_T < 200 GeV
SR, high b-jet p_T	Same as previous line, but with b-jet $p_T > 200$ GeV
DJ-FR	Jet trigger, τ_1+τ_2 (very loose identification), $q(\tau_1) \times q(\tau_2) < 0$
CR-1	Pass SR except: τ_2 (fail loose)
SS-SR	Same as the SRs, except $q(\tau_1) \times q(\tau_2) == 1$
T-VR	40 GeV < $m(b, \tau)$ < 150 GeV, $E_T^{\mathrm{miss}} > 40$ GeV, $\Sigma(\mathrm{b-jet}p_T) > 50$ GeV



- Expected limits shown for $\lambda = 1$, showing an expected upper limit on the cross section $\times$ branching fraction for $LQ \to b\tau\tau$
    - The expectation shows an intersection with the theoretical prediction
- A comparison of the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels is shown with the latter being the more sensitive channel
- First result of this type





A search for three well motivated extensions to the SM using the ditau final state

MSSM interpretation

- Limits shown for full Run-2 dataset (139 fb^{-1})

Z' interpretation

- Limits shown for partial Run-2 dataset (36 fb^{-1})
- Full Run-2 result coming soon. Expected 139 fb^{-1} stat only limit shown for $\tau_{lep}\tau_{had}$ channel

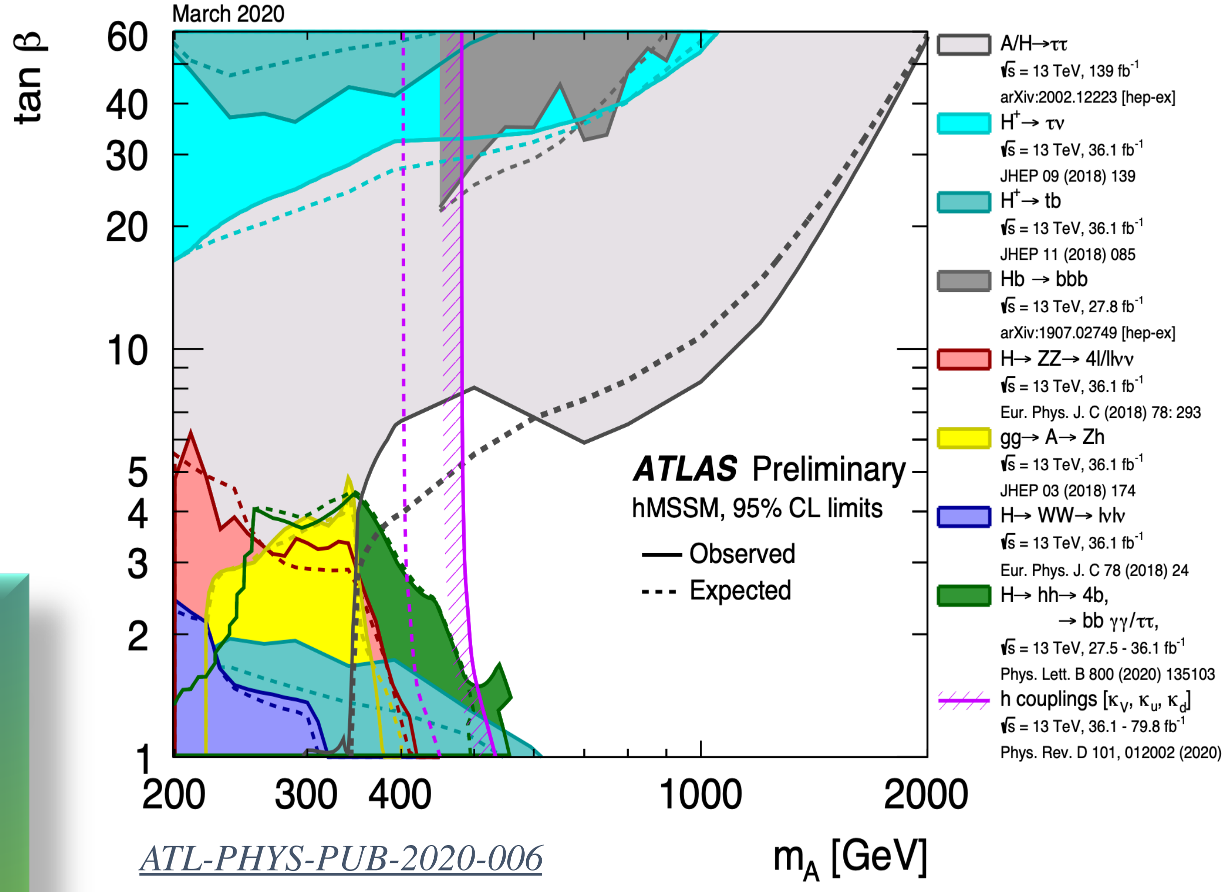
Future plans

Working on improved Run-2 combined MSSM and Z' analysis with following improvements…

- Neural network to replace m_T^{TOT} as final discriminant
- Neural network to reject jets faking taus
- Region optimization
- Improved *b*-tagging
- Other *ATLAS* improvements

LQ interpretation

- Expected limits shown for full Run-2 dataset (139 fb^{-1})



ATL-PHYS-PUB-2020-006

Future plans

Working on first Run-2 analysis for singly produced 3rd generation leptoquark $LQ \rightarrow b\tau\tau$ under the $\tilde{S}_1$ model

Backup

MSSM Interpretation + Z’ Interpretation + LQ Interpretation

More information on backgrounds - lephad

<u>Backgrounds estimated by data driven technique</u>

- QCD multijet (jet fakes tau/lepton) estimated by lepton fake factor in fake region enriched with these events
- W + jets / top (jet fakes tau but lepton genuine) estimated by W+jets fake factor in fake region enriched with these events

Region	Selection
SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell)\times q(\tau_1) < 0$, $\lvert\Delta\phi(\ell,\tau_1)\rvert > 2.4$, $m_T(\ell, E_T^{miss}) < 40$ GeV, veto $80 < m(\ell,\tau_1) < 110$ GeV (ehad 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)
W-CR	Pass SR except: $60 < m_T(\ell, E_T^{miss}) < 150$ GeV in ehad (muhad) channel for b-veto
	Pass SR except: $60 < m_T(\ell, E_T^{miss}) < 110$ GeV in ehad (muhad) channel for b-tag
T-CR	Pass SR except: $m_T(\ell, E_T^{miss}) > 110$ GeV in the ehad (muhad) channel, b-tag category only
L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{had\text{-}vis}$, $m_T(\ell, E_T^{miss}) < 30$ GeV

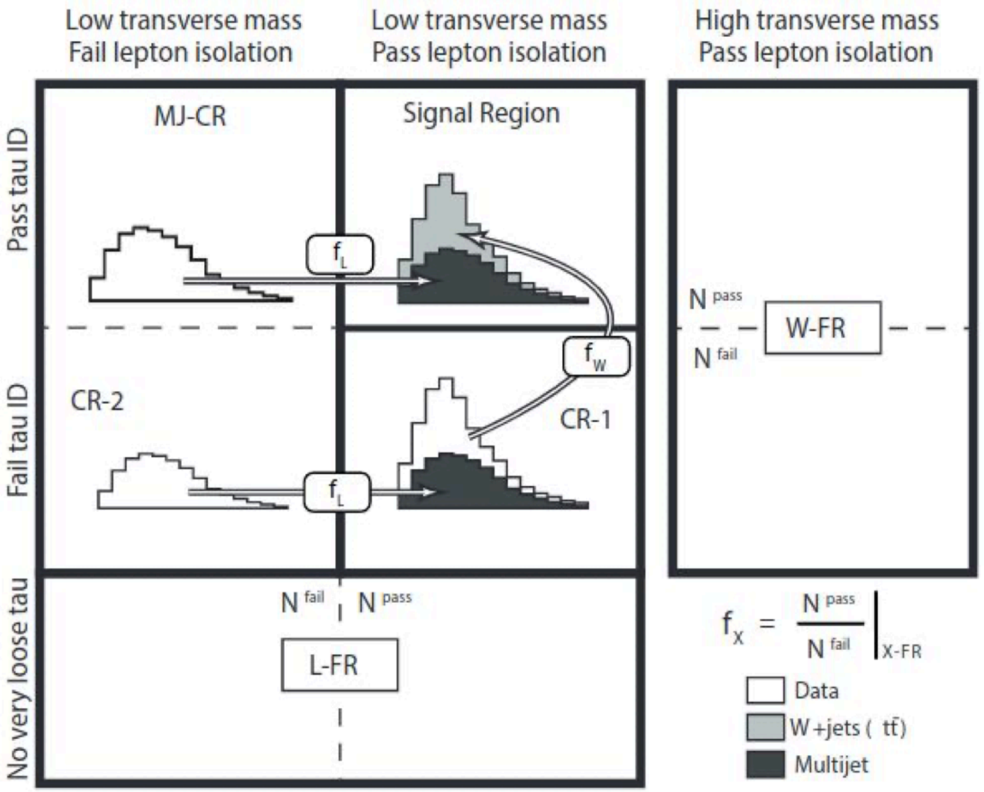


Figure 11: A schematic overview of the background estimation used in this analysis.

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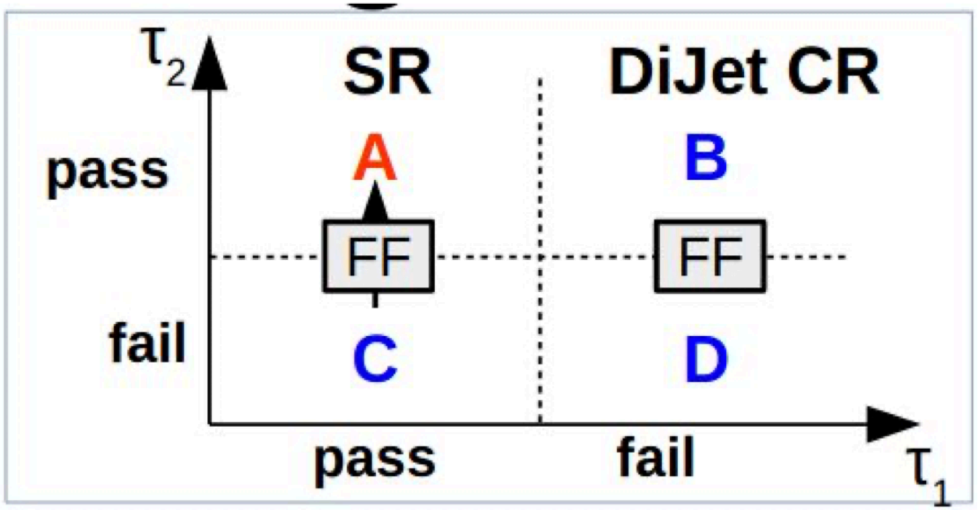
More information on backgrounds - hadhad

Similar story to lephad

- QCD multijet contribution estimated using di-jet control region
- W -> $\tau\nu$, ttbar and single top, give true and fake tau estimated using data driven fake rate method



Region	Selection
SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1)\times q(\tau_2) < 0$, $\|\Delta\phi(\tau_1,\tau_2)\| > 2.7$
CR-1	Pass SR except: τ_2 (fail loose)
DJ-FR	jet trigger, τ_1+τ_2 (no identification), $q(\tau_1)\times q(\tau_2) < 0$, $\|\Delta\phi(\tau_1,\tau_2)\| > 2.7$, $p_T^{\tau_2}/p_T^{\tau_1} > 0.3$
W-FR	μ (trigger, isolated), τ_1 (no identification), $\|\Delta\phi(\mu,\tau_1)\| > 2.4$, $m_T(\mu, E_T^{miss}) > 40$ GeV *b*-veto category only
T-FR	Pass W-FR except: *b*-tag category only

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Table 2: Relative increase in the expected 95% CL upper limits for the production cross section times branching fraction relative to the statistical only expected limit for each systematic uncertainty under consideration, shown for scalar bosons with mass of 400 GeV and 1 TeV produced via ggF and bbH production.

Source	ggF (400 GeV)	ggF (1 TeV)	bbH (400 GeV)	bbH (1 TeV)
Tau id. efficiency	0.14	0.16	0.12	0.08
Tau energy scale	0.33	0.09	0.22	0.03
Z+jets bkg. modeling	0.27	0.19	0.08	0.04
Mis-id. $\tau_{\text{had-vis}}$ bkg.	0.22	0.01	0.14	0.03
Others	0.09	0.04	0.11	0.02
Total	0.54	0.28	0.45	0.13

Low mass:

- ggF: Dominant background is ***Z+jets*** and **fakes**
- bbH: Dominant background is $t\bar{t}$ and **fakes**

High mass:

- ggF: Some ***Z+jets,*** Signal efficiency is the more important
- bbH: Almost background free, Signal efficiency most important

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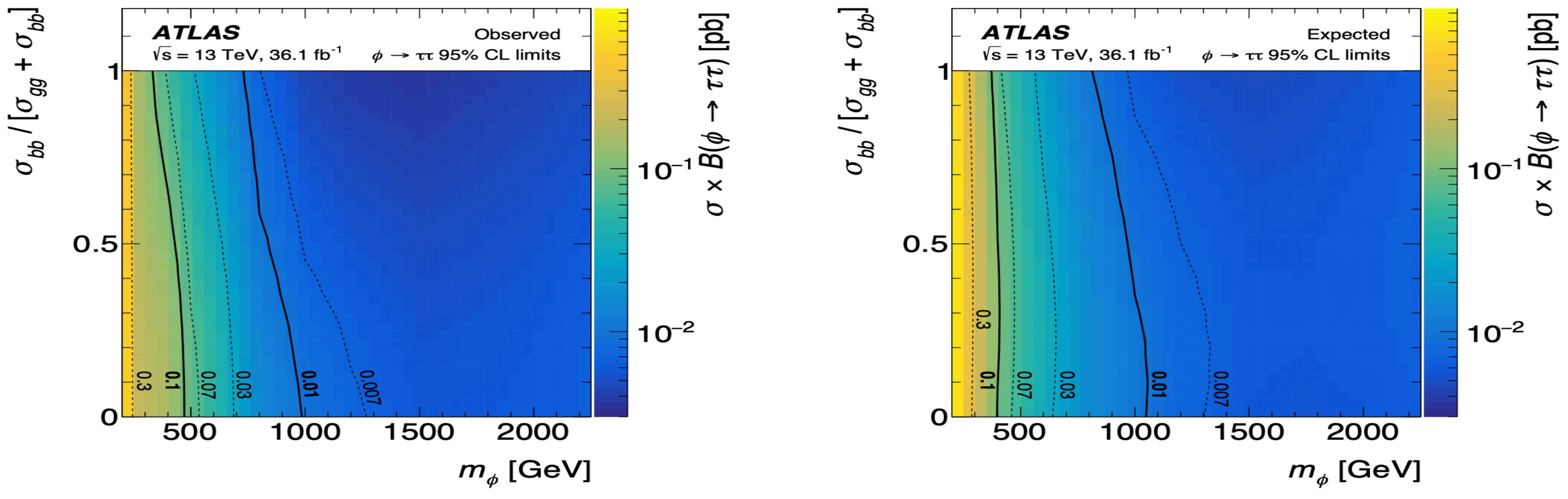

(a) Observed (b) Expected

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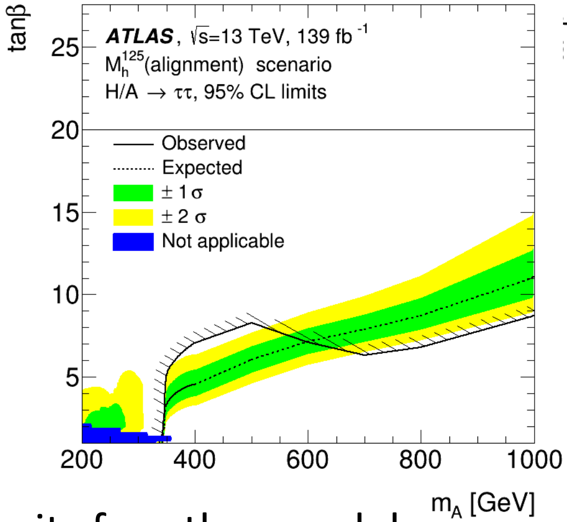

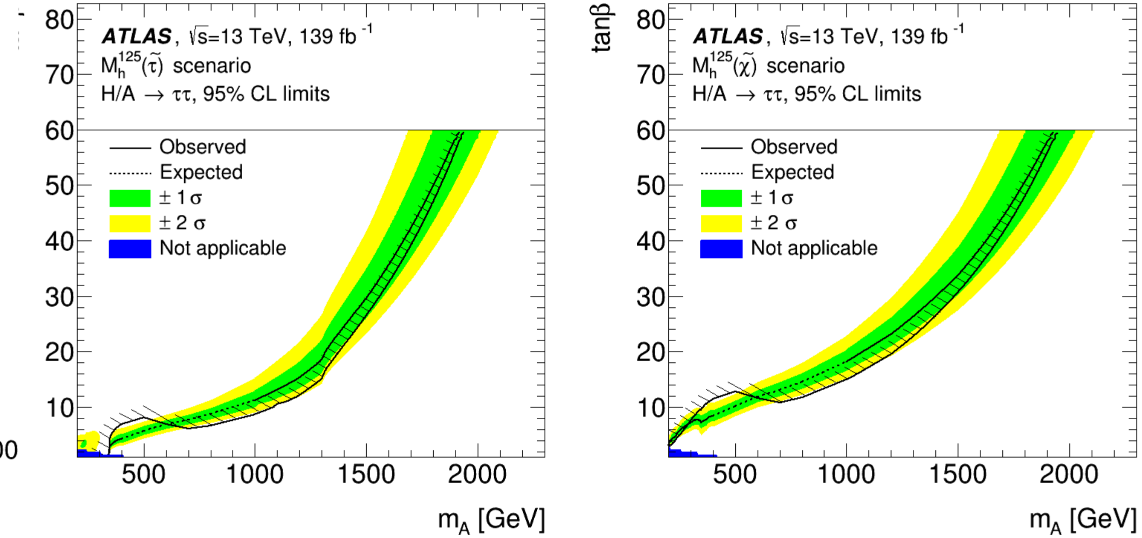

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Limits for other models

The upper limit on the cross section × branching fraction for $\phi \rightarrow \tau\tau$ as a function of the fractional contribution from *b*-associated production and the scale boson mass

$$\mathcal{L}(\mu, \vec{\theta}) = \prod_{i=1} e^{-(\mu s_i + b_i)} \frac{(\mu s_i + b_i)^{n_i}}{n_i!} \cdot \prod_{j=1} G(\theta_j)$$

- Binned likelihood function constructed as the product of Poisson probability terms
- Parameter of interest, $\mu =$ Ratio of the fitted signal cross section × branching ratio to the signal cross section × branching fraction predicted by the MSSM signal assumption
  - $\mu = 0$: Absence of signal
  - $\mu = 1$: Signal presence as predicted by the theoretical model under study
- Results from all channels combined
- Simultaneous signal + background fit done
- CLs method used to construct 95% CL limits