New ATLAS results in monoHiggs to tau tau and combination for DM limits

14.06.2023

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ATLAS EXPERIMENT

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Dark matter at the LHC

- The presence of Dark Matter (DM) has been unequivocally established from experimental observations
- Basic DM requirements (so far):
  - Electrically neutral
  - Colorless
  - Stable (Over the lifetime of the universe)
  - (Very) Weakly interacting
- Significant number of particle-DM candidates from BSM theories
  - Share some common distinctive properties that can be exploited in the search for DM
- Colliders: DM particles expected to be produced via the mediated interaction with SM particles
  - **Minimal experimental signature:** Excess of events with a visible final state particle, X, recoiling against E_T^{miss} —> Mono-X

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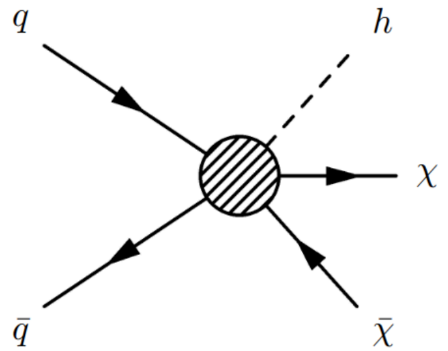
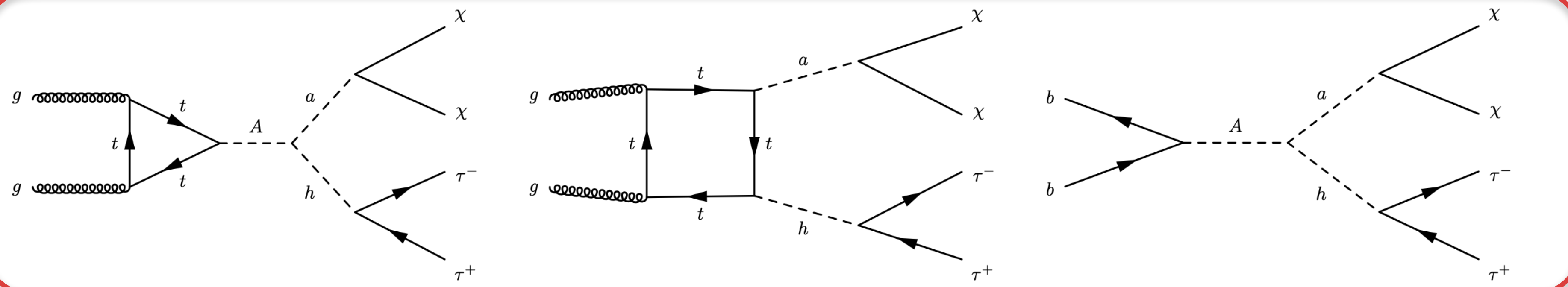
Mono-Higgs searches

- Visible SM particle can be jet, photon, W/Z, top quark or a Higgs boson
  - Typically stronger couplings to light quarks and gluons than DM particles
  - Suppressed for Higgs —> Mono-Higgs topologies are only significantly sensitive to scenarios where a Higgs boson couples directly to some BSM particle participating in the DM production
  - Mono-Higgs searches therefore give access to the structure of the BSM physics responsible for DM production —> Of interest at the LHC
- Many mono-Higgs searches have been performed by ATLAS and CMS in different Higgs decay channels for LHC Run 2:
  - $h \to b\bar{b}$ (ATLAS, CMS)
  - $h \to \tau^+\tau^-$ (CMS)
  - $h \to \gamma\gamma$ (ATLAS, CMS)
  - $h \to VV$ (CMS)
- **Focus of this talk:** Recent ATLAS result in $\tau^+\tau^-$ hadronic channel and combination
  - Results can be found here: 2305.12938
- The design of these experimental searches can in general be kept independent of theoretical models
- Some theoretical benchmarks still needed



Benchmark model: 2HDM+a

- One straightforward extension of the SM is the SM with two Higgs doublets. (2HDM)
- Gives 5 physical Higgs states after electroweak symmetry breaking:
    - Two neutral scalar states: h and H
    - A neutral psuedoscalar state: A
    - Two charged scalar states: $H^{\pm}$
- The 2HDM+a model further extends the baseline 2HDM with an additional pseuodoscalar singlet: a
    - Mediates the interactions between the visible and dark sector
- Model also includes a DM candidate (χ) which is a singlet under the SM Gauge group
- Simplest Gauge-invariant renormalisble extension of psuedoscalar mediator models
- Model leads to $h + E_T^{miss}$ signature through gluon-gluon fusion and $b\bar{b}$ production modes.

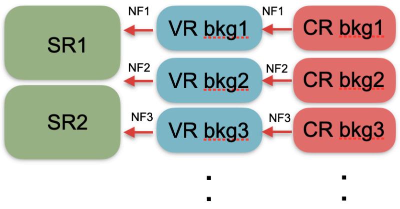


2HDM+a: Benchmark parameters used in searchers

- The 2HDM+a model is described by 12 new parameters
- Following the LHC DM working group recommendations 2-dimensional parameter scans are performed with the following choices:
  - Masses of CP-odd Higgs Boson, A, CP-even Higgs boson H and charged Higgs bosons, $H^{\pm}$: $m_A = m_H = m_{H^{\pm}}$
  - DM dark fermion mass: $m_\chi = 10$ GeV
  - DM Yukawa coupling to pseudoscalar a: $y_\chi = 1$
  - Mixing angle α (between h and H) and β ($\tan\beta = \frac{v_1}{v_2}$) satisfies: $\cos(\alpha - \beta) = 0$
  - Quartic couplings of the pseudo scalar potential and the Higgs potential: $\lambda_{1P} = \lambda_{2P} = \lambda_3 = 3$
  - Mass of the lightest Higgs boson: $m_h = 125$ GeV
  - Mixing angle between the two pseudoscalars satisfies: $\sin\theta = 0.35$ or $\sin\theta = 0.7$
- Scans are performed in the following planes keeping all other parameters fixed:
  - $m_A - m_a$ plane for $\tan\beta = 1.0$ and $\sin\theta = 0.35$ (34 signal points)
  - $m_A - \tan\beta$ plane for $m_a = 250$ GeV and $\sin\theta = 0.7$ (72 signal points)

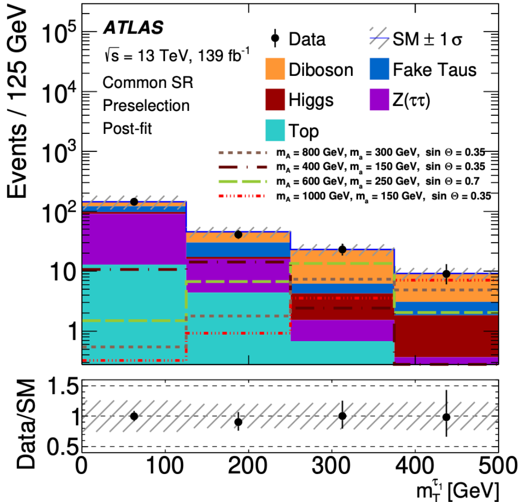
Analysis strategy and event selection

- Select events in three types of regions:
  1. Define Signal regions (SRs) by selecting events where signal sensitivity is optimised
  2. Define Control regions (CRs) enriched in events of a particular background process
     —> Fit to data to ensure proper normalisation of dominant backgrounds
  3. Define Validation regions (VRs) in between SRs and CRs to validate extrapolation of background normalisation factors from the CRs to the SRs.



- Signal signature is two tau leptons + E_T^{miss}
- Further event requirements to suppress different background sources
  - Selection optimised with Asimov significance
- Two **SRs** defined to target different parts of the parameter space:
  - SR low m_A (4 bins)
  - SR high m_A (2 bins)
- Both SRs binned in $m_T(\tau_1, E_T^{miss}) + m_T(\tau_2, E_T^{miss})$

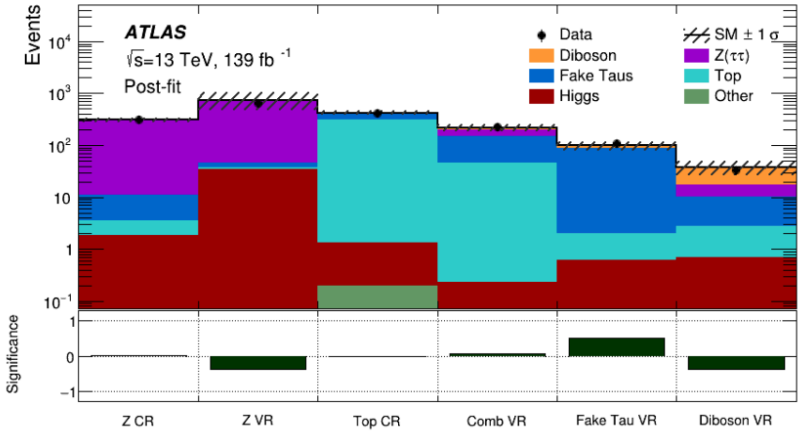
$$m_T(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2p_{\mathrm{T}}(\tau_1)E_{\mathrm{T}}^{\mathrm{miss}}(1 - cos\Delta\Phi(\tau_1, p_{\mathrm{T}}^{miss}))}$$



Background estimation

- **Two types of backgrounds:**
  - Events where both taus are true: Estimated with MC and referred to as the original process, e.g $Z(\tau\tau)$
  - Events with at least one fake tau: Modelled using the data-driven fake factor method, collectively referred to as “Fake taus”. E.g $W(\tau\nu)$ and QCD background.

- **Dominant backgrounds:**
  - After preselection: $Z(\tau\tau)$ and to a lesser extent $t\bar{t}$ and fake background
  - Higgs and diboson contribution become more relevant as selection gets tighter
- **CR defined for:**
  - $Z(\tau\tau)$ and top ($NF_{top} = 0.82, NF_{Z(\tau\tau)} = 1.04$)
- **VR defined for:**
  - $Z(\tau\tau)$, top, Diboson/Higgs and fake taus and combined total background
- All VRs show agreement within one standard deviation between SM prediction and data —> Good modelling observed for SM backgrounds



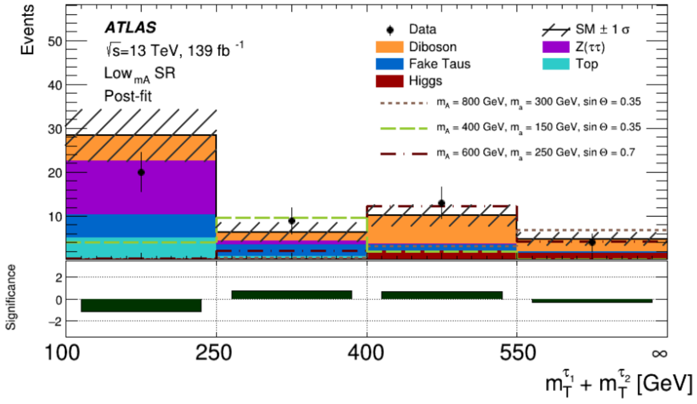
Uncertainties

- **Uncertainties considered:**
  - **Statistical**: Statistical uncertainties in signal and background modelling
  - **Theoretical**: Generator-modelling-related uncertainties, cross-section uncertainties, and uncertainties related to the choice of PDF set. Assumed to be uncorrelated
  - **Experimental**: Uncertainties related to reconstruction, identification, correction and calibration of the various physics objects. Assumed to be correlated
  - **Fake taus:** Uncertainties on the fake modelling
- Included in Likelihood fits as nuisance parameters with Gaussian probability densities.

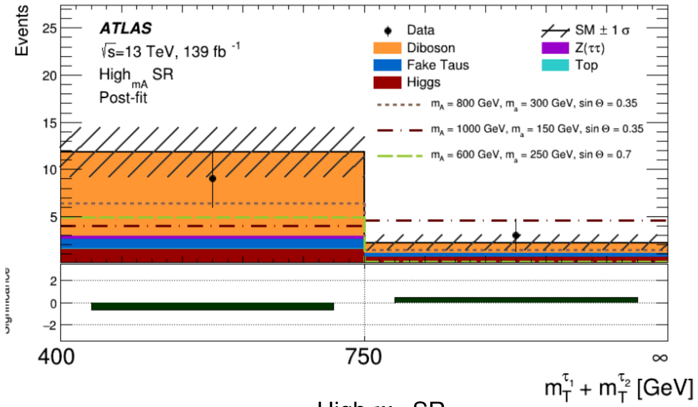
Region $m_T^{\tau_1} + m_T^{\tau_2}$ [GeV]	Low_{m_A} $\in [100, 250]$	Low_{m_A} $\in [250, 400]$	Low_{m_A} $\in [400, 550]$	Low_{m_A} > 550	High_{m_A} $\in [400, 750]$	High_{m_A} > 750
Theoretical	15.9%	20.9%	15.4%	13.3%	14.2%	21.7%
Fake τ-leptons	6.2%	19.1%	6.0%	3.0%	4.0%	13.2%
Jets	6.2%	7.9%	5.2%	11.0%	3.4%	7.9%
True τ-leptons	1.6%	3.1%	7.0%	10.6%	4.8%	5.0%
Normalisation	4.5%	4.0%	4.8%	8.1%	4.8%	6.1%
MC statistical	7.6%	13.2%	9.3%	15.6%	9.2%	22.2%
Cross-section	2.7%	4.7%	10.0%	9.8%	11.3%	8.5%
Other	4.1%	2.7%	5.3%	6.3%	4.9%	4.5%
Total	20.8%	32.8%	23.8%	28.3%	22.2%	36.3%

Results and fit models

- No significant excess observed —> Setting limits
- In addition to background-only fit two additional fits are performed for the signal in the SRs:
  - **Model dependent (exclusion) fit:** All CRs and (Multibin) SRs participate in the fit. Signal strength is a free parameter and fit is performed for each signal point individually —> Exclusion contour
  - **Model independent fit:** All CRs and each (single-bin) SR used in the fit. A generic signal model is assumed with free floating normalisation in the SR —> Upper limit on signal strength



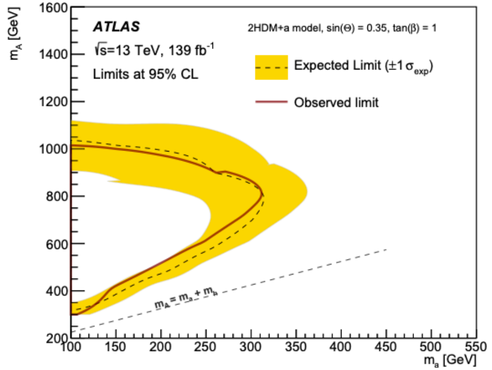
Low m_A SR

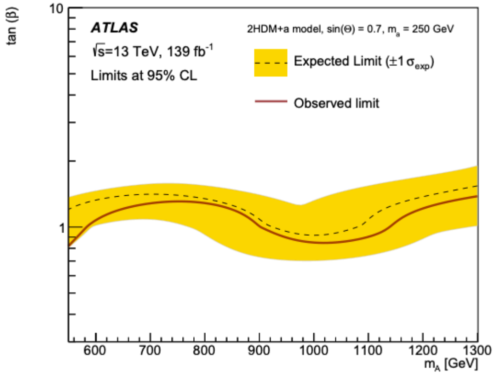


High m_A SR

Limits

- **Model dependent exclusion contours**
  - Results obtained using the CL$_s$ prescription —> Points within the contour excluded at 95% confidence level (CL)
  - $m_A - m_a$ plane: Models with m_a up to 300 GeV excluded at $m_A = 800$ GeV
  - $m_A - \tan\beta$ plane: Models with $\tan\beta \leq 1$ excluded for m_A up to 900 GeV
- **Model independent upper limits**
  - Depending on the bin: upper limits on the visible cross section (σ_{vis}) is set between 0.04 and 0.08 fb at 95% confidence level (CL)

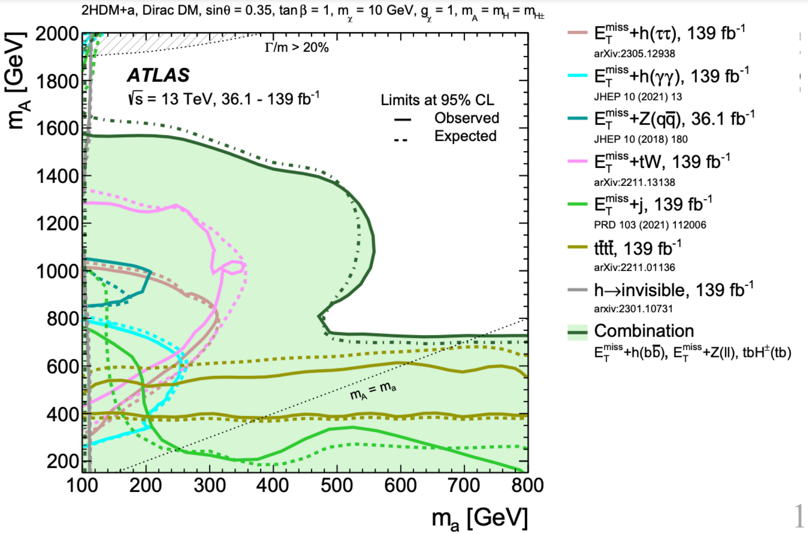


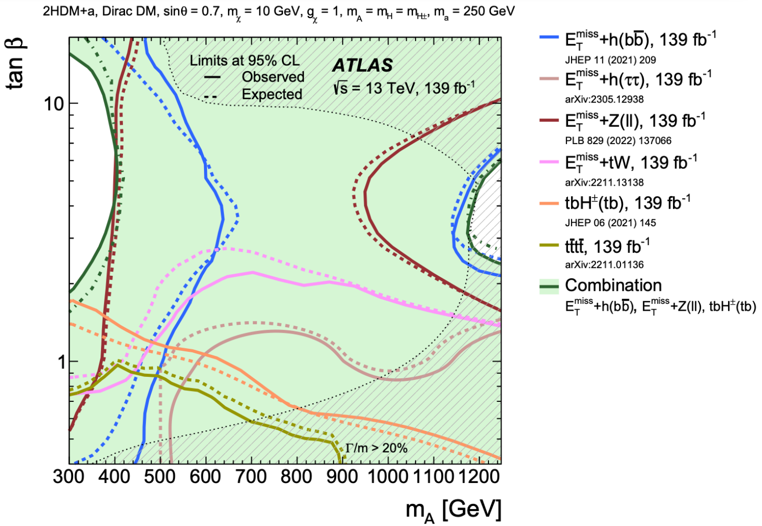


Signal region	σ_{vis} [fb]	S^{95}_{obs}	S^{95}_{exp}	CL$_b$	p_0 (Z)
Low$_{m_A}$ SR $m_T^{\tau_1} + m_T^{\tau_2}$					
[100, 250] GeV	0.08	10.7	$12.5^{+5.2}_{-3.5}$	0.27	0.86 (−1.07)
[250, 400] GeV	0.07	9.1	$7.6^{+3.1}_{-1.6}$	0.72	0.30 (0.53)
[400, 550] GeV	0.08	10.8	$8.9^{+3.4}_{-2.3}$	0.75	0.26 (0.65)
> 550 GeV	0.04	5.8	$6.0^{+2.6}_{-1.6}$	0.42	0.61 (−0.29)
High$_{m_A}$ SR $m_T^{\tau_1} + m_T^{\tau_2}$					
[400, 750] GeV	0.05	7.6	$8.8^{+3.1}_{-2.4}$	0.34	0.85 (−1.03)
> 750 GeV	0.04	5.4	$4.6^{+1.8}_{-0.8}$	0.67	0.34 (0.42)

Combination with other channels

- ATLAS recently published a statistical combination of multiple channels: [2306.00641]
- Statistical combination performed by constructing a combined likelihood and maximising the profile likelihood ratio
- $Z(\ell\ell) + E_T^{miss}$ and $h(b\bar{b}) + E_T^{miss}$ dominate the sensitivity across the mass plane, complimentary sensitivity from $tbH^{\pm}(tb)$
  - Only these channels used for combination contour
- $h(\tau\tau) + E_T^{miss}$ show similar $m_A - m_a$ dependence to $h(b\bar{b}) + E_T^{miss}$, but notably lower significance due to smaller branching ratio
  - Comparable sensitivity in low m_A region
  - Offers some sensitivity in the low $\tan\beta$ region





Summary

- Presented the search for $E_T^{miss} + h(\tau\tau)$
  - New analysis in ATLAS —> First exploration of mono-Higgs signature in hadronic ditau decays
  - No excess of data found over predicted SM background
  - 95% CL limits set in in the $m_a - m_A$ plane and $m_A - \tan\beta$ plane
  - Model independent limits set on the visible cross section of BSM physics with $E_T^{miss} + h(\tau\tau)$ signature
- Analysis included in the combination paper:
  - Similar dependence on $m_A - m_a$ as $h(b\bar{b}) + E_T^{miss}$, but lacking sensitivity due to smaller branching ratio
  - $E_T^{miss} + h(\tau\tau)$ offers comparable sensitivity in low m_A region in the $m_A - m_a$ plane and low $\tan\beta$ region in the $\tan\beta - m_A$ plane

Thank you!

BACKUP

Some variable definitions

- Transverse mass m_T:

$$m_T(\tau_1, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2p_{\mathrm{T}}(\tau_1)E_{\mathrm{T}}^{\mathrm{miss}}(1 - cos\Delta\Phi(\tau_1, p_{\mathrm{T}}^{miss}))}$$

- m_T^{tot}:

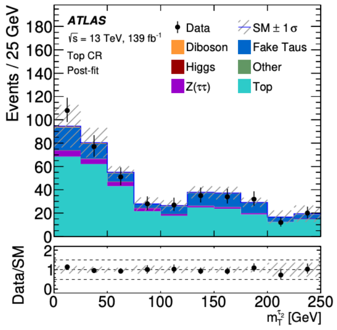
$$m_T^{tot} = \sqrt{(p_{\mathrm{T}}(\tau_1) + p_{\mathrm{T}}(\tau_2) + p_{\mathrm{T}}^{miss})^2 - (p_x(\tau_1) + p_x(\tau_2) + p_x^{miss})^2 - (p_y(\tau_1) + p_y(\tau_2) + p_y^{miss})^2}$$

- Asimov significance:

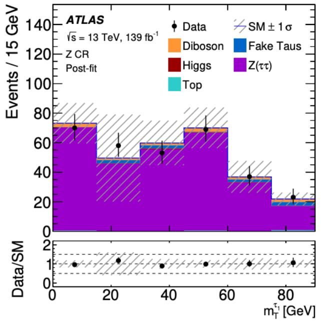
$$Z_A = \left[2\left((s+b)\ln[\frac{(s+b)(b+\sigma_b^2)}{b^2+(s+b)\sigma_b^2}] - \frac{b^2}{\sigma_b^2}\ln[1+\frac{s\sigma_b^2}{b^2+b\sigma_b^2}]\right)\right]^{\frac{1}{2}}$$

CR/VR selections

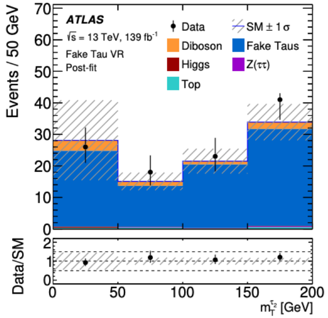
Variable	Z CR	Z VR	Fake Tau VR	Top CR	Comb VR	Diboson VR
Charge(τ_1, τ_2)	OS	OS	**SS**	OS	OS	OS
$N_{b\text{-jet}}$	0	0	0	**1**	0	0
$\Delta R(\tau_1, \tau_2)$	< 2	< 2	$\mathbf{> 2}$	> 1	$\mathbf{> 2}$	< 2
$m_{\text{vis}}(\tau_1, \tau_2)$	**< 40 GeV**	[40, 75] GeV	-	-	> 125 GeV	**[40, 75] GeV**
$m_{\text{T}}^{\text{tot}}$	> 50 GeV	> 50 GeV	-	-	-	**[50, 400] GeV**
$m_{\text{T}}^{\tau_1}$	-	-	-	-	-	> 60 GeV
$m_{\text{T}}^{\tau_2}$	-	-	-	-	-	> 20 GeV
$m_{\text{T}}^{\tau_1} + m_{\text{T}}^{\tau_2}$	-	**< 100 GeV**	-	-	-	> 140 GeV
$p_{\text{T}}^{\tau_1+\tau_2}$	-	-	-	-	< 125 GeV	-



(b) $m_{\text{T}}^{\tau_2}$ in Top CR



(d) $m_{\text{T}}^{\tau_1}$ in Z CR



(b) $m_{\text{T}}^{\tau_2}$ in Fake Tau VR

Ditau+MET triggers

Running period	Trigger name	L1	Lumi
2015 – 2017	HLT_tau35_medium1_tracktwo_tau25_medium1_tracktwo_xe50	L1_TAU20IM_2TAU12IM_XE35	77.2 fb^{-1}
parts of 2017	HLT_tau60_medium1_tracktwo_tau25_medium1_tracktwo_xe50	L1_TAU40_2TAU12IM_XE40	3.3 fb^{-1}
2018 period B-K	HLT_tau60_medium1_tracktwoEF_tau25_medium1_tracktwoEF_xe50	L1_TAU40_2TAU12IM_XE40	18.3 fb^{-1}
2018 from period K on	HLT_tau60_medium1_tracktwoEF_tau25_medium1_tracktwoEF_xe50 OR HLT_tau60_mediumRNN_tracktwoMVA_tau25_mediumRNN_tracktwoMVA_xe50	L1_TAU40_2TAU12IM_XE40	40.2 fb^{-1}

- HLT_tau35 trigger is used for the majority of 2015-2017, 3.3 fb^{-1} are recovered with HLT_tau60
- Trigger plateau (leading tau p_T) dependent on the period
- Scale factors from tau trigger group, binned in tau p_T and number of charged tracks
- Derive additional SFs as a function of E_T^{miss} for 2015 – 2017/mc16a-d
- 2018/mc16e agreement is reasonable
- Offline taus are geometrically matched to the trigger ones.