Search for Higgs boson exotic decays into new light bosons in the four-τ final state

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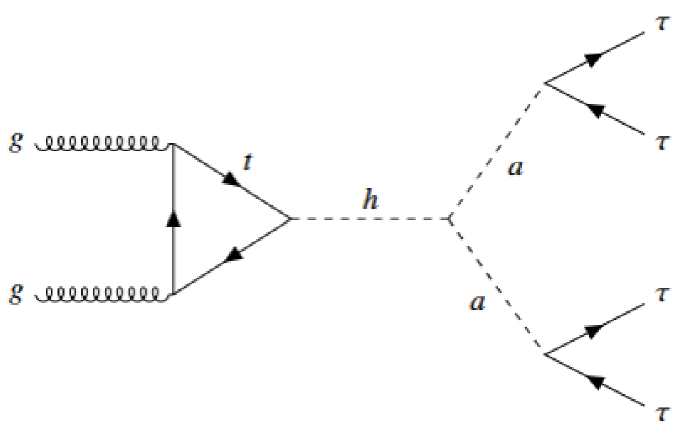
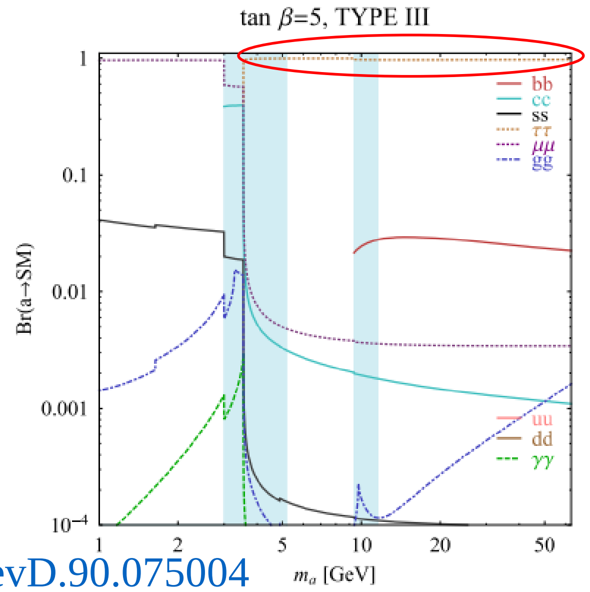
Motivation

- Search for Higgs boson (125 GeV) exotic decays into new light bosons ($\boldsymbol{a}$) in the four-tau final state
  - $H \to 2a \to 4\tau$
- This search is generic but the 2HDM + S model is used as a benchmark for the analysis optimization and limit extraction
  - The branching ratio of $a \to \tau^+\tau^-$ are dominant in the 2HDM + S for type-III Yukawa couplings with $\tan\beta > 1$
- 4τ channel has not been covered by ATLAS (first boosted 4τ search at ATLAS).





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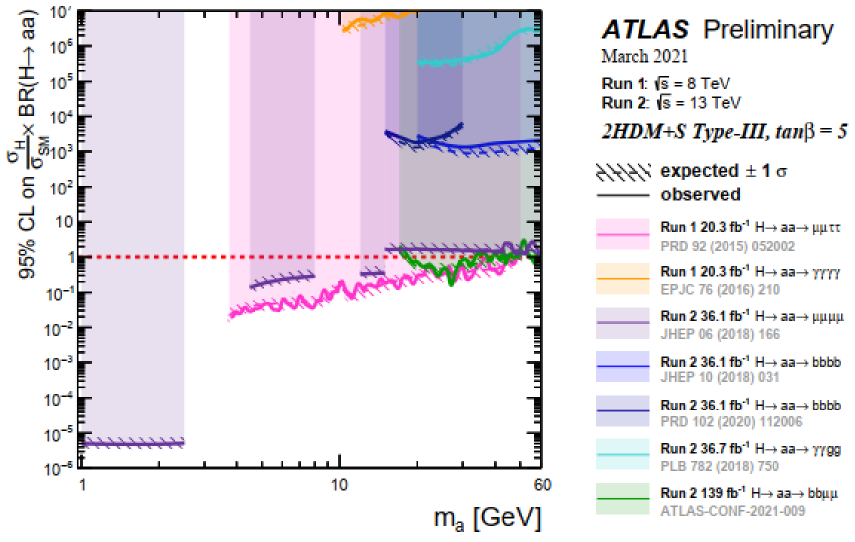
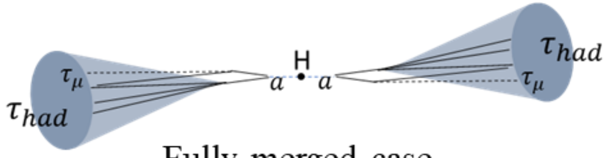


$H \to 2a \to 4\tau$ searches at ATLAS

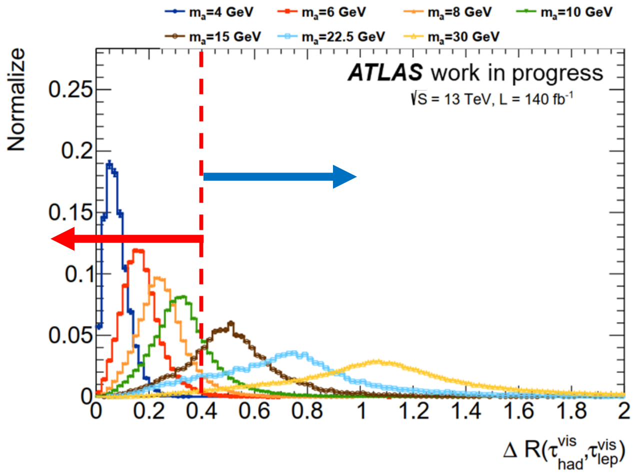
- Two $H \to 2a \to 4\tau$ searches in ATLAS using run 2 data

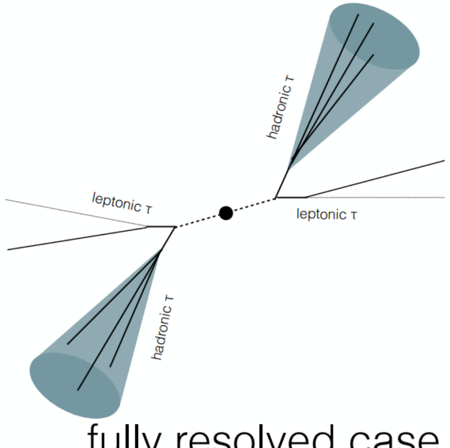
- Merged analysis:
  - Today's focus
  - ***a*** mass range [4,15] GeV
  - di-muon + single muon triggers
  - Boosted ***a*** decays into merged di−τ
  - Dedicated muon removal technique is developed to recover the tau performance
  - Only covering $\tau_\mu \tau_h \tau_\mu \tau_h$ final state
  - Selecting $2\mu\tau_h$ pairs
  - SSμ and OSμ channels



Fully merged case

- Resolved analysis:
  - ***a*** mass range [15,60] GeV
  - $2l2\tau_h$ and $3l1\tau_h$ $(l = e, \mu)$ channels
  - Select SS dilepton to reduce backgrounds

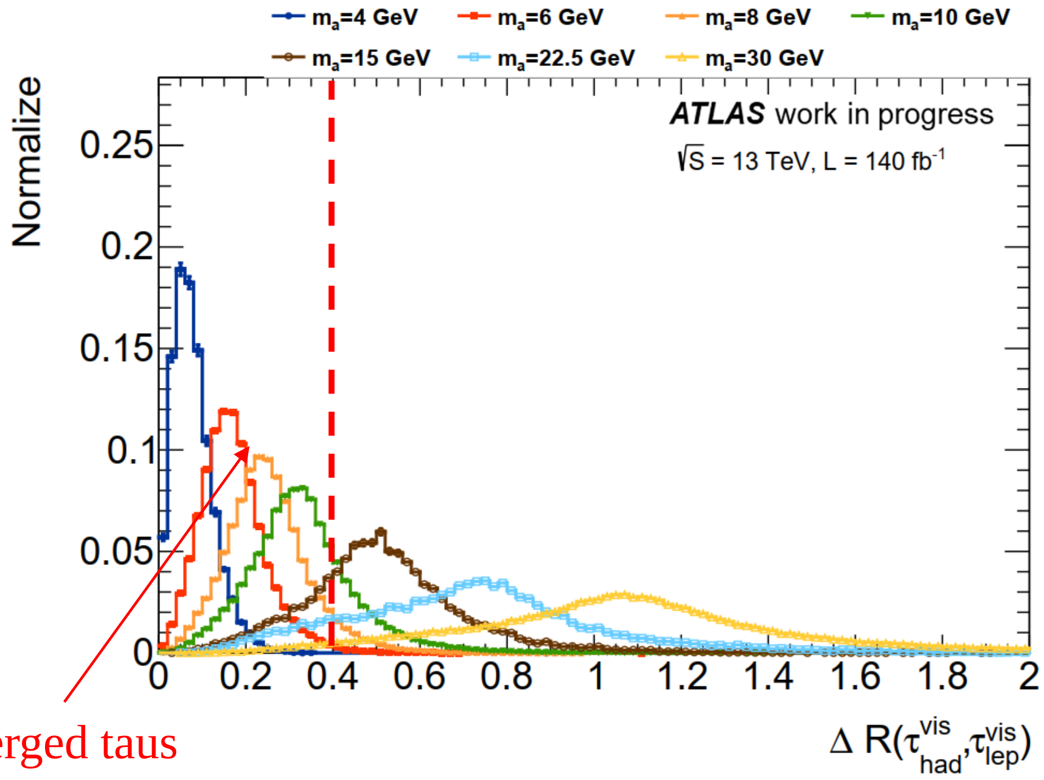




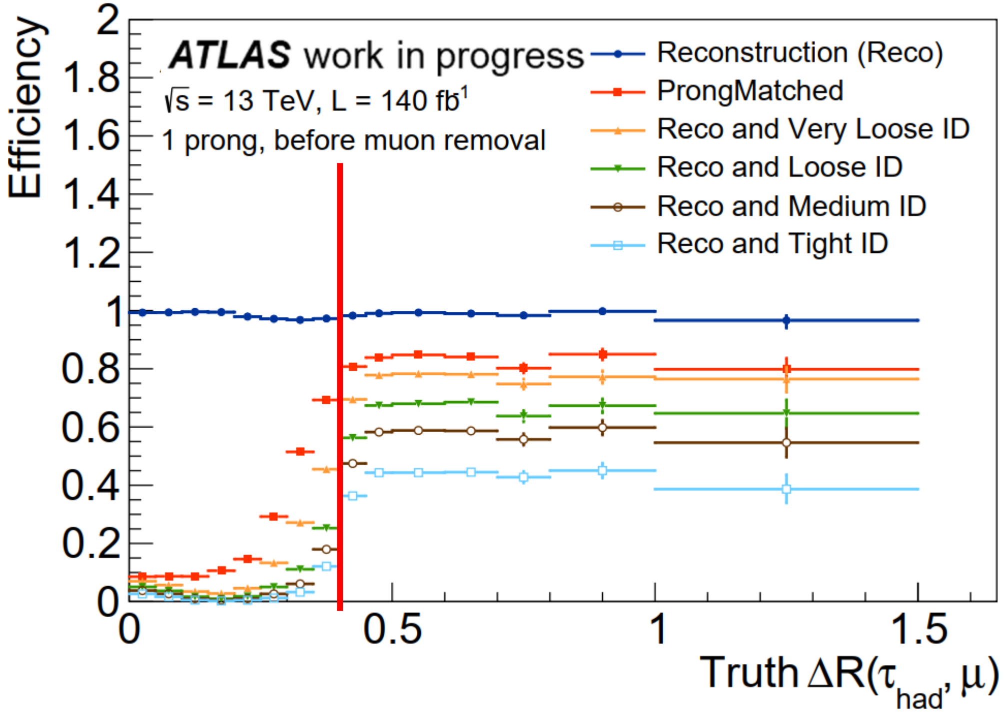
fully resolved case

Boosted low pt had-mu di-tau

- Because of the low mass of a, the distance between τ_l and τ_{had} will be very small even for low p_T
  - $\Delta R(\tau_l, \tau_{had}) \approx 2m_a/p_T^a$
- The decay products of τ_l and τ_{had} are mixed in the detector.
- The standard tau identification will no longer work



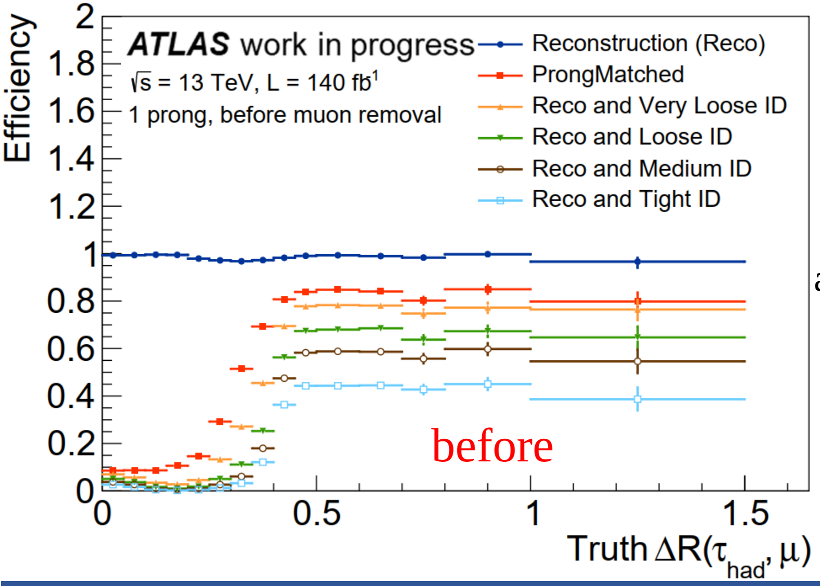
Merged taus



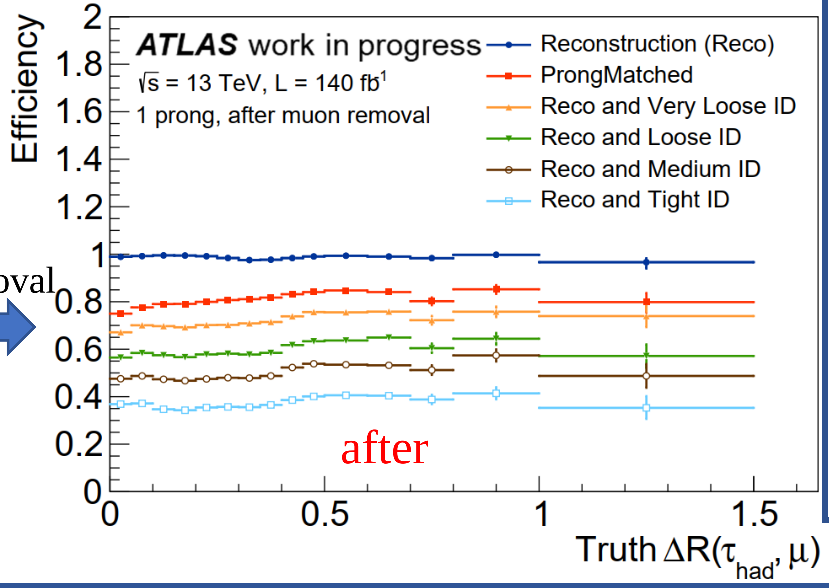
Standard tau identification efficiency

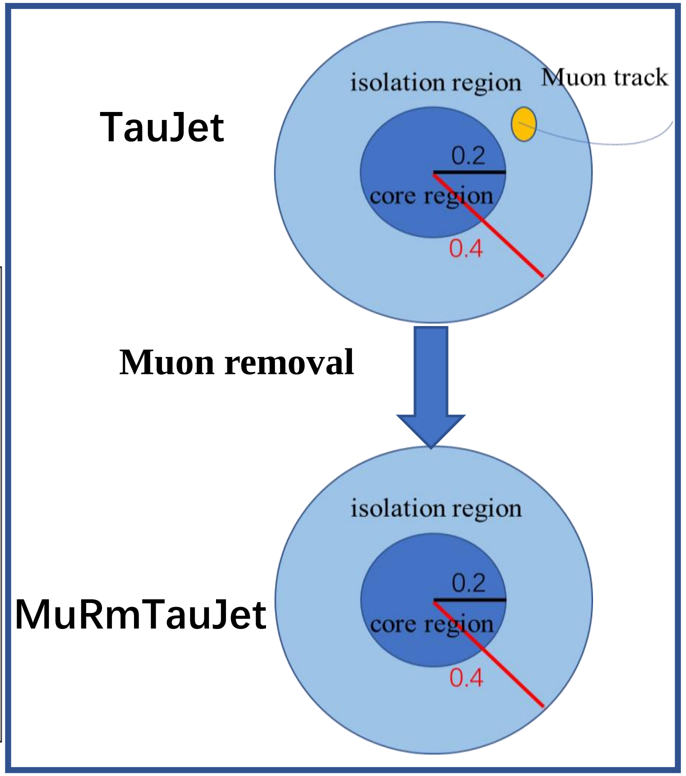
Muon removal technique

- Merged $\tau_\mu \tau_{had}$ correction algorithm: muon removal technique
  - Overlapped muons were removed from tau jet before the standard tau reconstruction and identification procedures.
    - **Muon tracks** and **associated energy** will be removed
  - Rerun the relevant official tau reconstruction and identification algorithm after muon removal.
  - Use the official tau performance results after proper muon removal
  - An extra efficiency uncertainty was extracted for the muon removal method
  - The τ_{had} four-momentum is corrected to the same energy scale as isolated τ_{had} using a MC-based correction method.
- Tau id efficiency was recovered after muon removal



after Muon removal

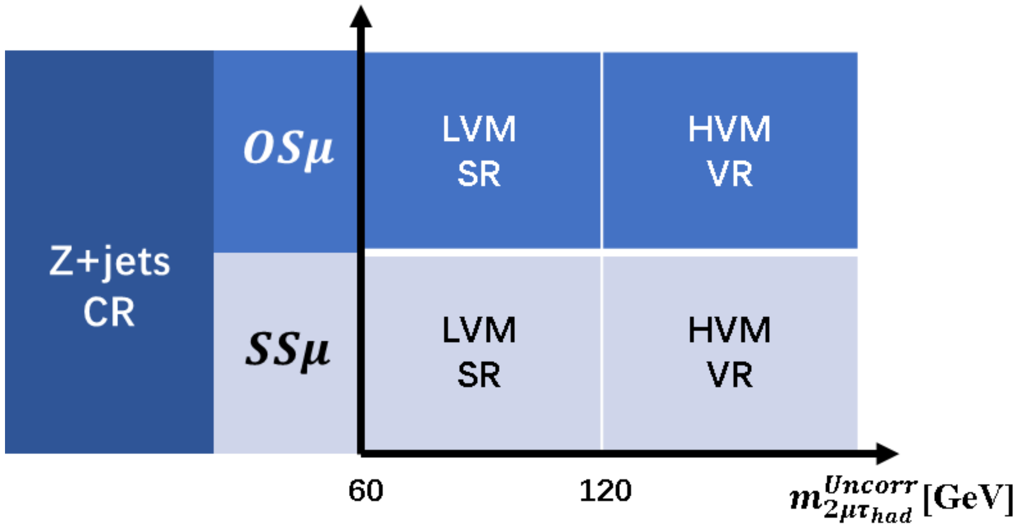




Region definition

- The events pass the preselection are then assigned to different regions:

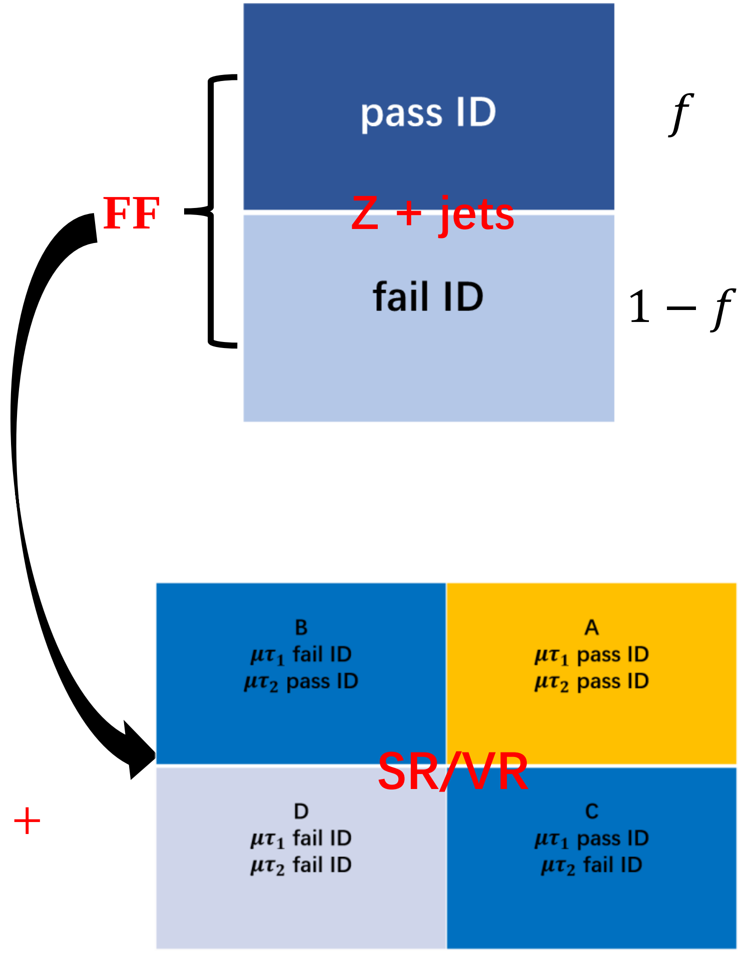
	$SS\mu$		$OS\mu$		CRZ
	SR(LVM)	VR(HVM)	SR(LVM)	VR(HVM)	
Number of muons	2	2	2	2	3
Number of $\mu\tau$ pairs	2	2	2	2	1
m_H^{vis} (GeV)	[60,120]	> 120	[60,120]	> 120	—
$m_{\mu\mu}$ (GeV)	—	—	< 50	< 50	[71,111]
Sign of muons	SS	SS	OS	OS	OS[5]



- Two channels: $SS\mu$ and $OS\mu$
  - $SS\mu$ channel is more sensitive to lower masses ($m_a = [4{,}10]$GeV)
  - $OS\mu$ channel is to enhance the sensitivity for higher masses ($m_a = [10{,}15]$ GeV)
- Each channel has one signal region with Low Visible Mass ($60 < m_{2\mu\tau_{had}} < 120$ GeV) and one validation region with High Visible Mass ($m_{2\mu\tau_{had}} > 120$ GeV).
- Z + Jets control region is defined to measure the $\mu\tau$ fake factors.

Background estimation

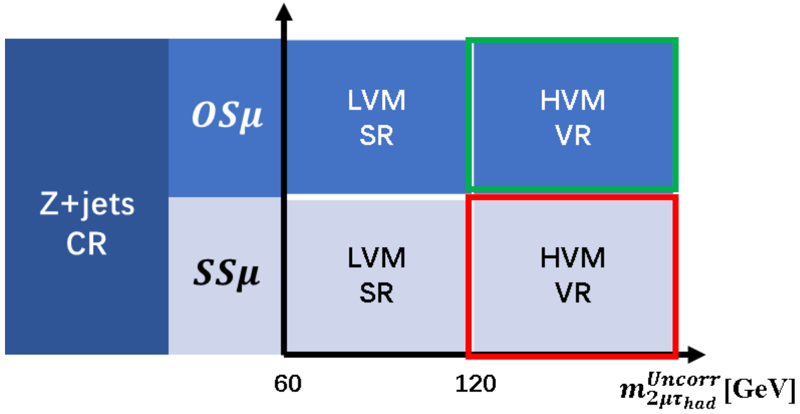
- Prompt background
  - Estimate using MC: $q\bar{q}/gg \to ZZ, H \to ZZ4l$
- Non-prompt/fake background
  - Data-driven fake factor method
  - Measure the FF of $\mu\tau$ in the $Z(\mu\mu)$ + jets($\mu\tau_{had}$) control region
  - $FF = \frac{N^{Z+\mu\tau}_{pass\ RNNLoose,Data} - N^{Z+\mu\tau}_{pass\ RNNLoose,truth\ matched\ MC}}{N^{Z+\mu\tau}_{fail\ RNNLoose,Data} - N^{Z+\mu\tau}_{fail\ RNNLoose,truth\ matched\ MC}} = f/(1-f)$
  - FF parameterized as function of p_T^{Uncorr} and prongness (FF(p_T^{Uncorr}, prongness))
  - Apply the FFs to $2\mu\tau_{had}$ regions by using the events with at least one $\mu\tau_{had}$ candidate failing ID
    - $Fake(\mu\tau_1^P\mu\tau_2^P) = [\boldsymbol{FF_2\mu\tau_1^P\mu\tau_2^F + FF_1\mu\tau_1^F\mu\tau_2^P - FF_1FF_2\mu\tau_1^F\mu\tau_2^F}]_{data} - [\boldsymbol{FF_2\mu\tau_1^P\mu\tau_2^F + FF_1\mu\tau_1^F\mu\tau_2^P - FF_1FF_2\mu\tau_1^F\mu\tau_2^F}]_{truth\ matched\ MC}$
    - $\boldsymbol{FF_2\mu\tau_1^P\mu\tau_2^F,\ FF_1\mu\tau_1^F\mu\tau_2^P}$: estimate the single fake $\mu\tau$ events, fake $\mu\tau_1$ and fake $\mu\tau_2$
    - $\boldsymbol{FF_1FF_2\mu\tau_1^F\mu\tau_2^F}$: estimate the double fake $\mu\tau$, minus sign is to remove the double counting double-fake-$\mu\tau$ events



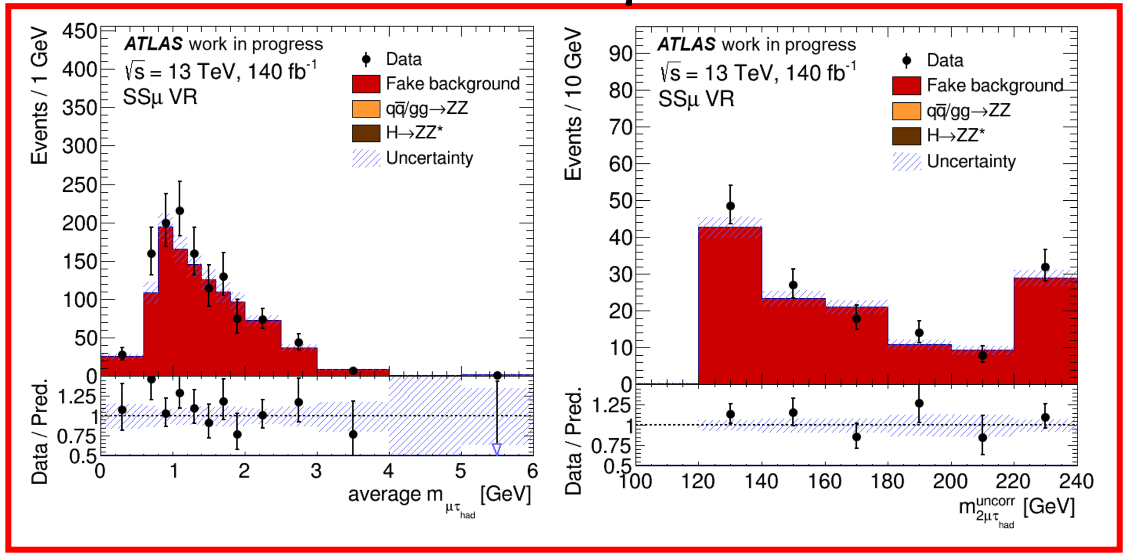
A: $\mu\tau_1$ pass ID, $\mu\tau_2$ pass ID (SR,VR)
B: $\mu\tau_1$ fail ID, $\mu\tau_2$ pass ID
C: $\mu\tau_1$ pass ID, $\mu\tau_2$ fail ID
D: $\mu\tau_1$ fail ID, $\mu\tau_2$ fail ID

Fake validation in HVM region

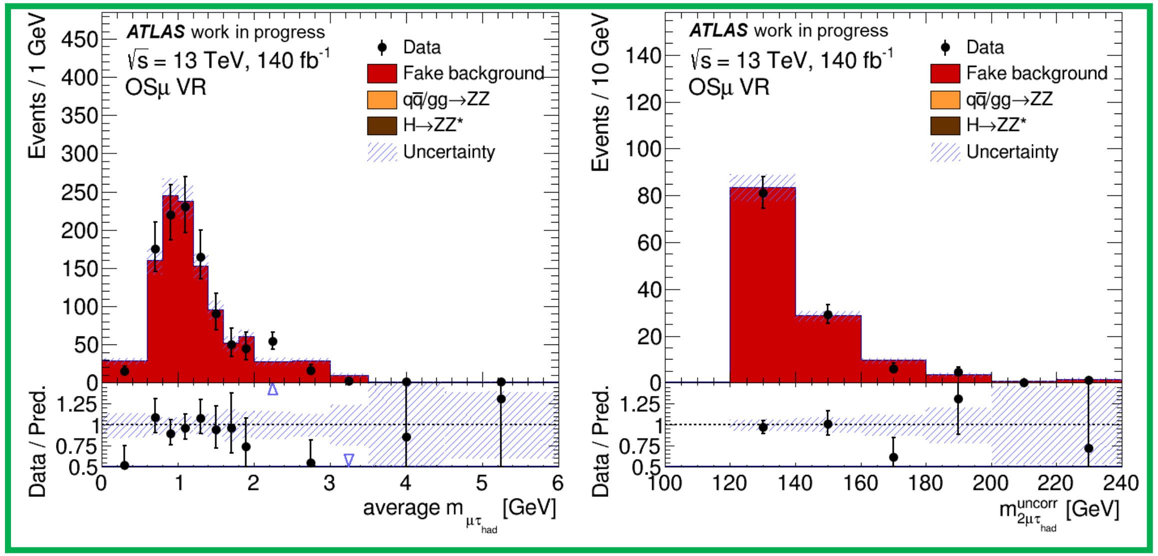
- Apply the fake factor (parametrized as $f(p_T^{\tau}, \tau_{prongness})$) to the HVM region using the two-object fake estimation equation
- Testing the fake factor method in the HVM validation region
- The fake prediction is agreed with data within the uncertainties
- The relative difference between background prediction and observed data is considered as non-closure uncertainty (8%).



$SS\mu$



$OS\mu$



Systematic Uncertainties

Standard systematics

- Experimental uncertainties (from CP group)
  - Muon
  - Tau
  - Jet
  - Lumi
  - Pileup
- Theoretical uncertainties
  - QCD (renormalization and factorization) scale uncertainties
    - Cross-section k-factor normalization uncertainty
    - QCD scale shape uncertainty
  - PDF set uncertainties

Custom systematics

- Fake uncertainties
  - Statistic
    - fake_FF_1prong_stat_up
    - fake_FF_1prong_stat_down
    - fake_FF_3prong_stat_up
    - fake_FF_3prong_stat_down

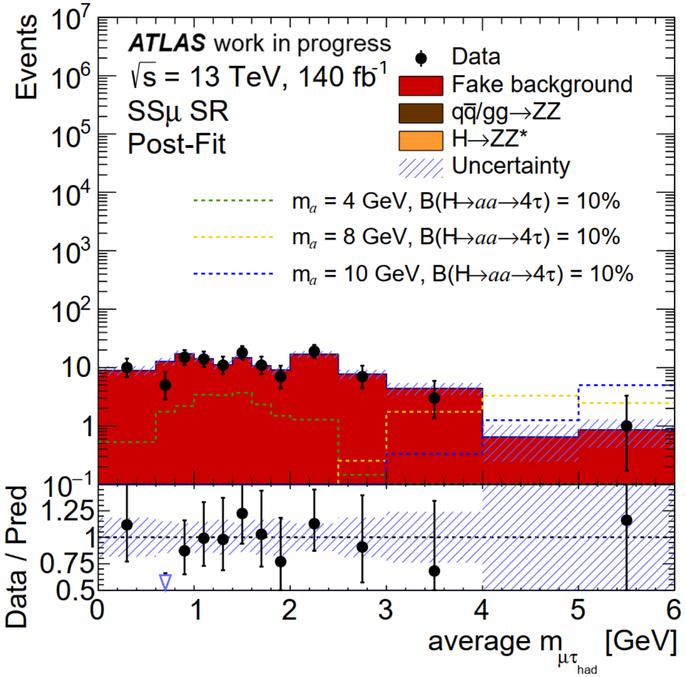
    Limited number of events in Z+jets CR
  - Parametrization
    - fake_FF_EtaBinning
    - fake_FF_dRBinning
    - fake_FF_MuTauPtBinning
  - Composition
    - fake_FF_Bcomposition
    - fake_FF_2MuTau
    - fake_FF_1jet
    - fake_FF_2jets
    - fake FF dRCut
  - Non-closure
    - fake FF Validation

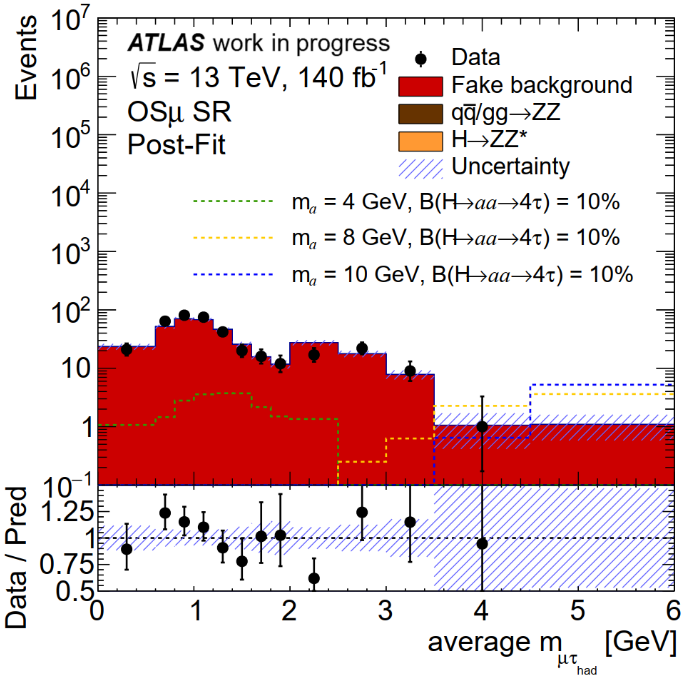
  Dominant uncertainty for background
- Moun Removal Technique Uncertainties
  - Additional Reco+Id efficiency uncertainties

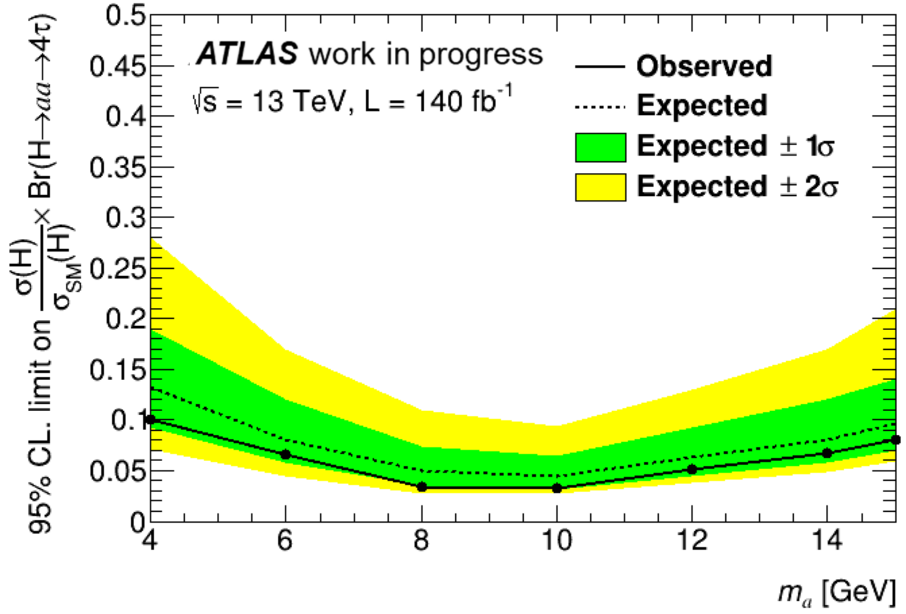
  Dominant uncertainty for signal

Results

- The observed number of events in data is consistent with the background prediction within 1σ in both $SS\mu$ and $OS\mu$ channels.
- No excess is found. The fake prediction shows very good agreement with the data.
- 95% CL upper limits are set on $(\sigma(H)/\sigma SM(H))$(B$(H \rightarrow aa \rightarrow 4\tau)$ using the CL_S method.
- The upper limits for each signal mass are obtained by using pseudo-experiment method.
- The observed (expected) limit ranges from 0.033 (0.044) to 0.10 (0.13) for $m_a = 10$ GeV and $m_a = 4$ GeV.





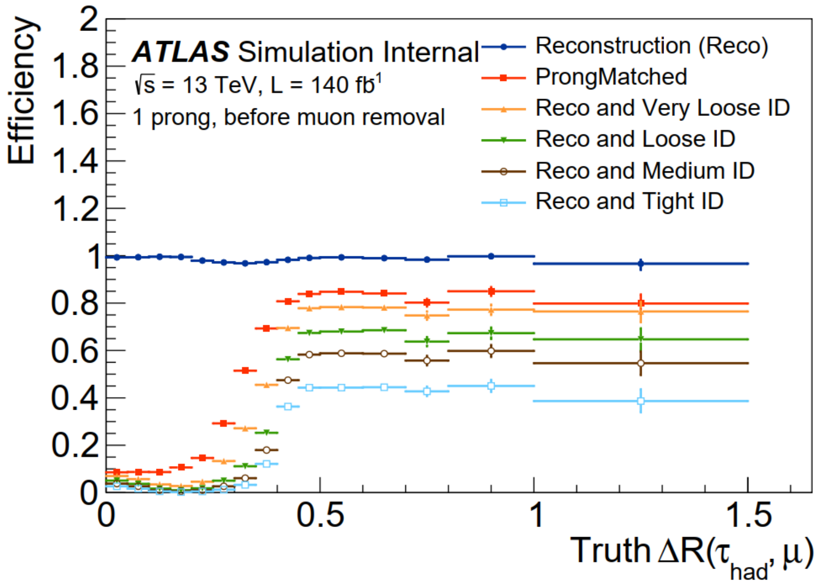


Summary

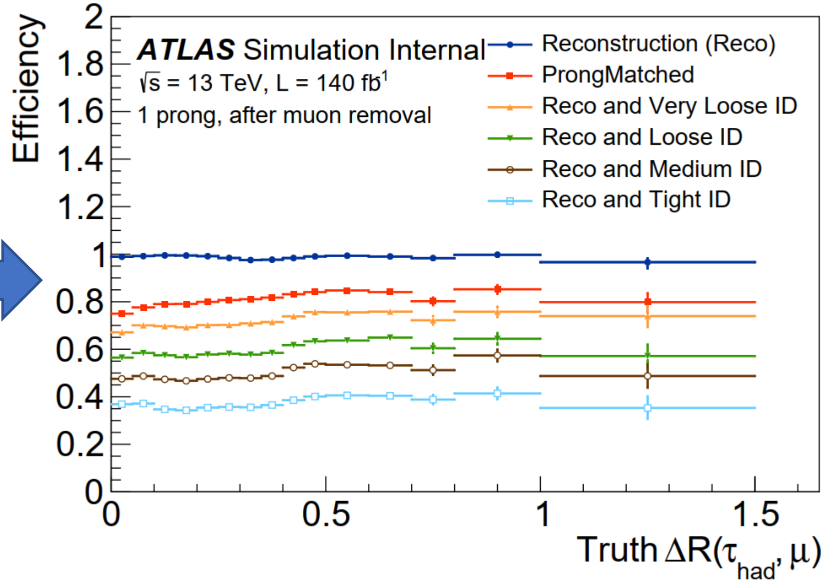
- The ATLAS search for Higgs exotic decays in the four-τ final state has been presented
  - A muon removal technique is the first time used in an ATLAS analysis to reconstruct merged di-τ decays.
  - The efficiencies of merged taus are improved by an order of magnitude.
  - No significant excess of data over the SM background expectation is observed.
  - Upper limits at 95% CL. are set on $(\sigma(H)/\sigma_{SM}(H))\mathrm{B}(H \rightarrow aa \rightarrow 4\tau)$, ranging from 3.3% at $m_a = 10$ GeV to 10% at $m_a = 4$ GeV.
- The analysis has been already pre-approved (unblinded) and will get group approval in the next couple of weeks.
- We are planning to publish this analysis in the end of this year.

Backup

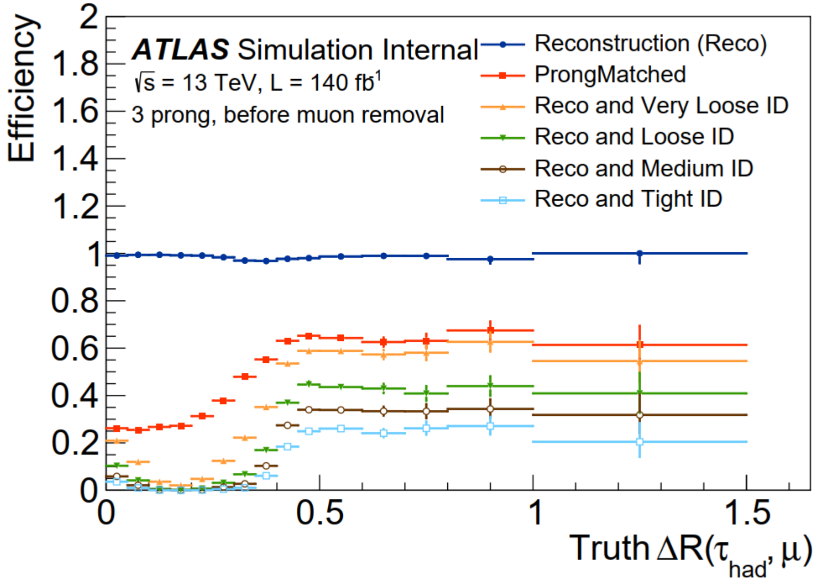
Tau Reco and ID Efficiency after Muon Removal



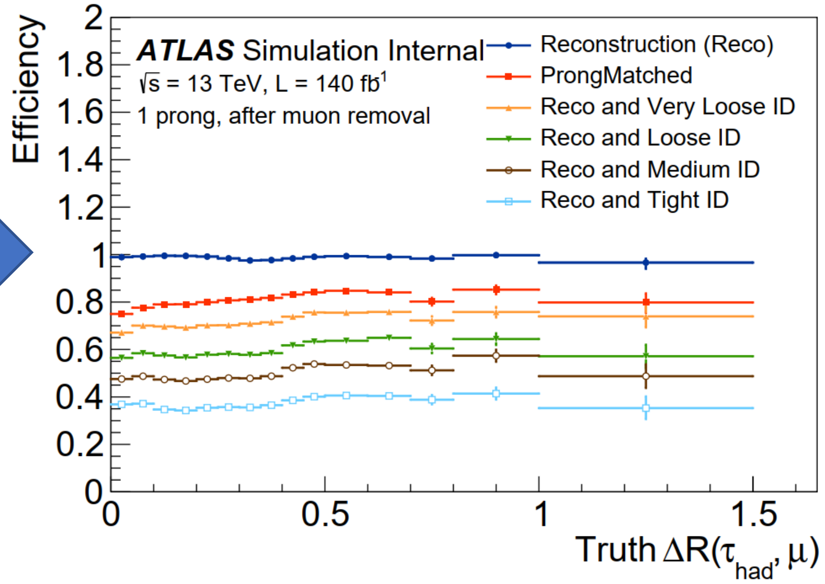
Muon Removal



- The efficiencies of merged taus were recovered (improved by an order of 10)
- ΔR has very small effect on the tau efficiencies after the muon removal

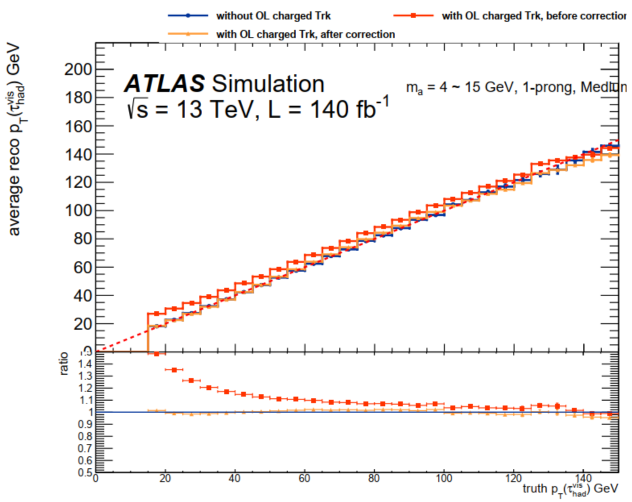


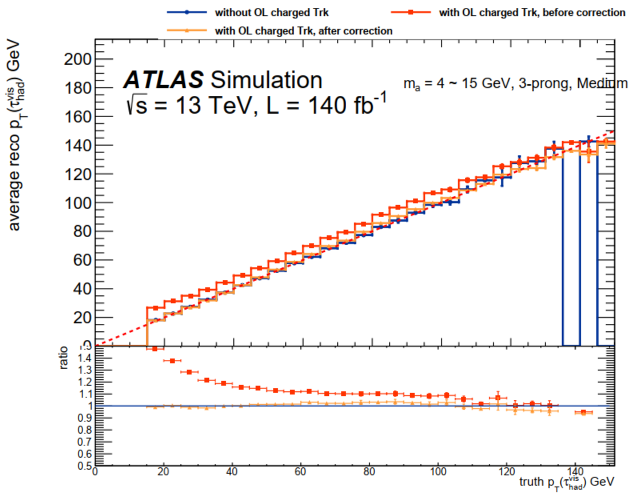
Muon Removal

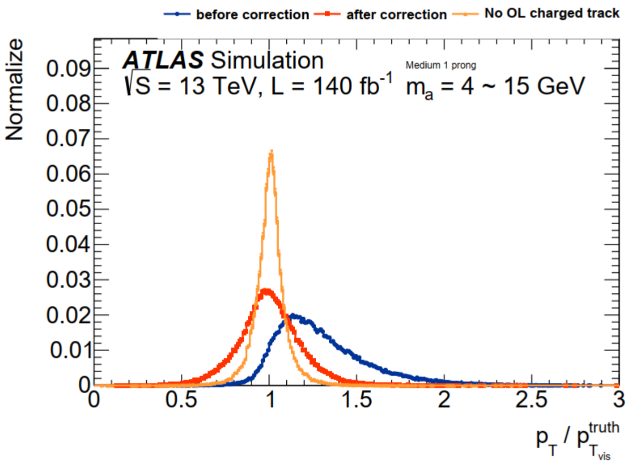


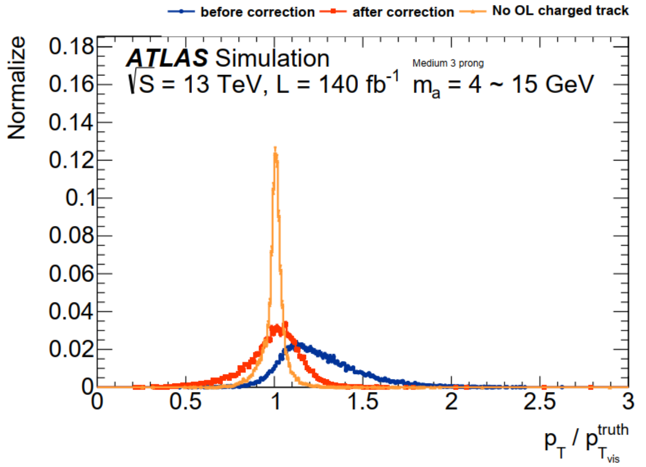
Tau momentum correction results

- The corrected p_T is calculated:
  - $p_T^{OL,Corr} = p_T^{OL,UnCorr} / R(p_T^{OL,UnCorr}, n_p, p_T^{\mu})$
  - where the R is the ratio of reco p_T^{OL} to reco p_T^{iso} in the same truth p_T, parameterized as function of $p_T^{OL,UnCorr}$, n_p and p_T^{μ}.
- After correction, the average reco p_T^{OL} is consistent with average reco p_T^{UnOL}
- After the p_T correction, the mean value of p_T^{reco}/p_T^{truth} is moving to 1, which means the average p_T^{reco} is corrected to p_T^{truth}.
- The resolution of p_T^{OL} also improves a lot after the correction.





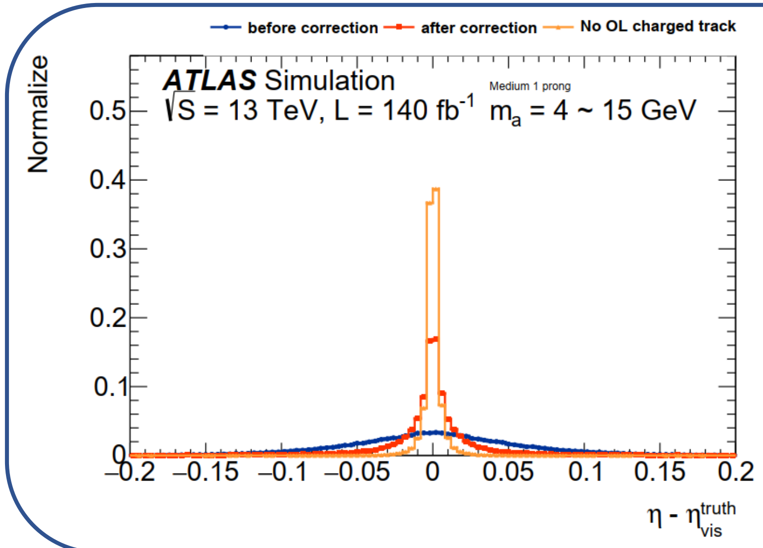




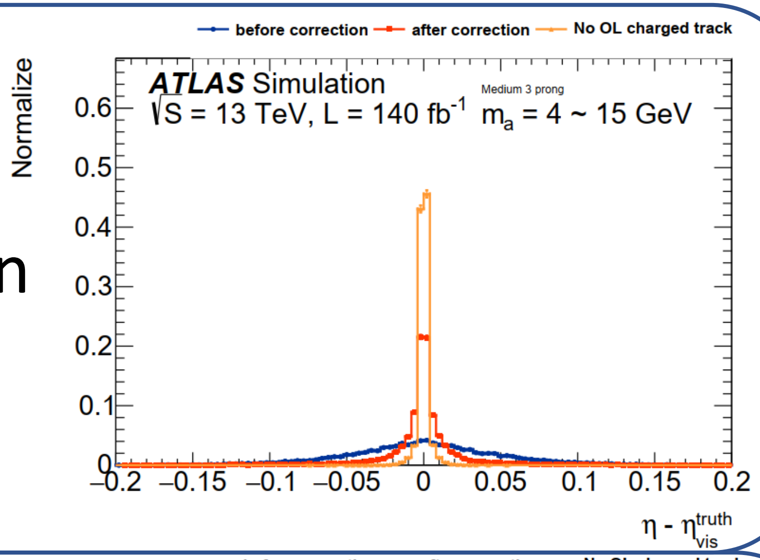
η and ϕ correction results

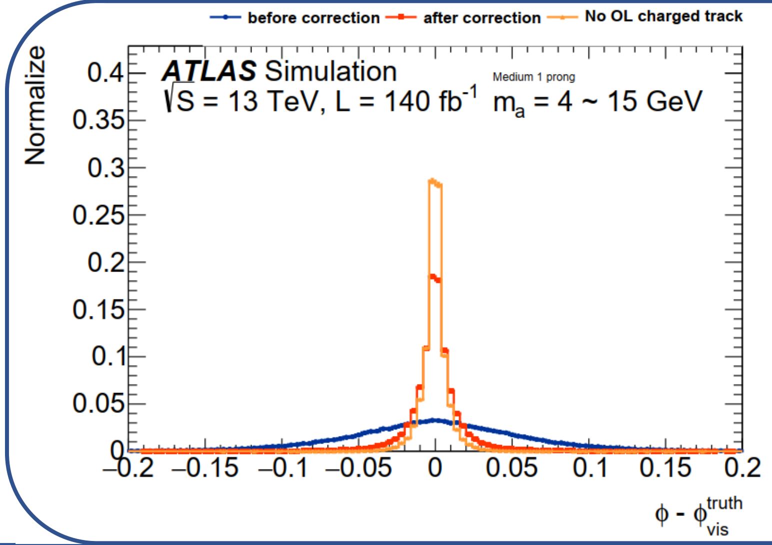
- The η and ϕ resolutions are improved very significantly after the correction.

figures for approval

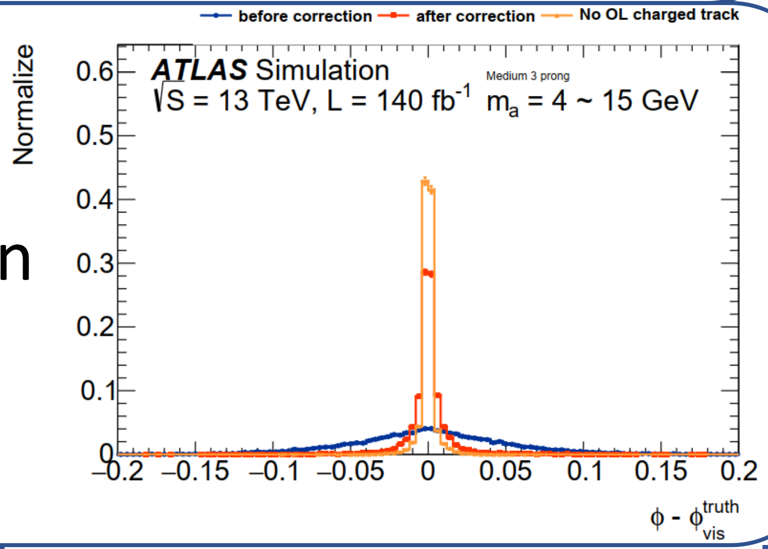


η resolution





ϕ resolution



Analysis strategy

- Signal selection:
  - Focusing on the mass range of $4 < m_a < 15$ GeV
  - Only considering $a \rightarrow \tau_\mu \tau_h$ decay mode (23% branching ratio of di-τ decay)
  - Using the muon removal technique to resolve the merged di-τ identification
  - Select two $\mu\tau_{had}$ pairs with $60 < m_{2\mu\tau_{had}} < 120$ GeV
  - SSμ and OSμ channels are considered based on the sign of final two μ to improve the sensitivity
- Background estimation:
  - Prompt background are estimated from MC
  - Non-prompt/fake background are estimated using a data-driven Fake Factor Method
  - Background model is verified in signal-like validation regions (VRs)
- Interpretation:
  - Upper limits on $\frac{\sigma_H}{\sigma_{SM}} \times BR(H \rightarrow aa \rightarrow 4\tau)$ are extracted from benchmark 2HDM + S model by using CLs method and pseudo-experiment method.

Data and simulated samples

- Data:
  - Full pp collision dataset collected by ATLAS during Run 2 of LHC (L = 140 fb^{-1})
- Signal simulation:
  - Powheg + Pythia8 + AFII, ggF production, $H \rightarrow aa \rightarrow 4\tau$
  - 2lep2had tau filter
  - m_a= 4, 6, 8, 10, 12, 14, 15 GeV
- Background simulation:
  - Prompt background
    - $q\bar{q}/gg \rightarrow ZZ^*$: Sherpa 2.2.2
    - $H \rightarrow ZZ^*$: Powheg + Pythia8
    - Triboson, $t\bar{t} + Z/W$: Sherpa
  - Non-prompt background (only used for fake composition study and signal optimization)
    - $t\bar{t}$: Powheg + Pythia8
    - Z/W + jets: Sherpa
    - Single top: Powheg + Pythia8
    - Semi-leptonic diboson: Sherpa
    - Dijet: Powheg + Pythia8
- Derivation:
  - Customized TAUP6

Trigger

- Combination of single muon and di-muon triggers:

Trigger Type	Year	HLTs
Single Muon	2015-2018	HLT_mu50
Di-muon	2015	HLT_mu18_mu8noL1
		HLT_2mu10
	2016-2018	HLT_mu22_mu8noL1
		HLT_2mu14

cut name	4 GeV	6 GeV	8 GeV	10 GeV	15 GeV
FullTrig	54	58	56	68	84
ResolvedTrig	42	44	40	46	53
AllmuTrig	50	55	52	63	82
AlltauTrig	23	13	11	25	52
AllmuOrtauTrig	53	56	53	64	84
DoubleMuTrig	39	40	35	40	43
SingleDoubleMuTrig	40	44	39	46	53
SingleDoubleMuNonIsoTrig	39	42	37	43	47
SingleDoubleTriMuTrig	41	45	40	47	53
SingleDoubleTriMuTauTrig	49	50	46	60	79

- FullTrig: full un-prescaled triggers in run2
- CurrentTrig: the triggers currently in use, from the resolved analysis
- AllmuTrig: all the triggers including mu in run2
- AlltauTrig: all the triggers including tau in run2
- AllmuOrtauTrig: all the triggers including mu or tau in run2
- DoubleMuTrig: hand-picked dimu triggers
- SingleDoubleMuTrig: hand-picked single muon and dimu triggers
- SingleDoubleMuNonIsoTrig: hand-picked single non-isolated muon and dimu triggers
- SingleDoubleTriMuTrig: hand-picked single muon, dimu and triple muon triggers
- SingleDoubleTriMuTauTrig: hand-picked single muon, dimu, and triple muon triggers + tau triggers

The efficiency of different trigger set in run2 trigger menu (in percent %)

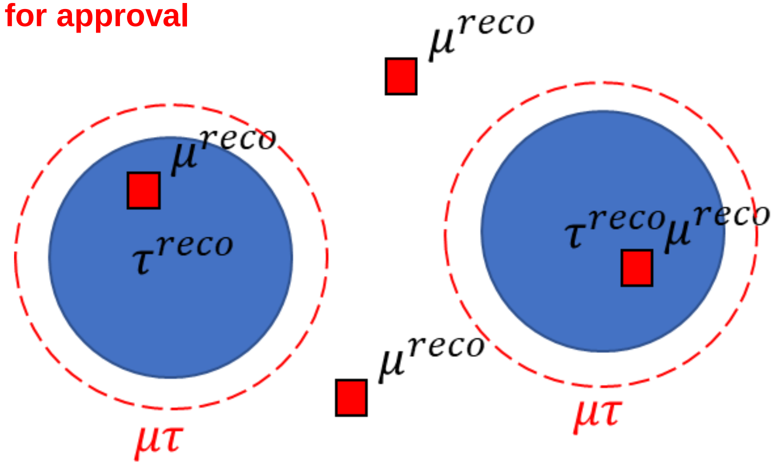
- Since the muons in the signals are close to the hadrons, only triggers without isolation requirements are considered.
- The proposed trigger set efficiency is comparable with other trigger sets.
- The combined trigger efficiency SF is directly obtained from the official TrigGlobalEffciencyCorrectionTool (twiki).

Object definition

- The requirements of the baseline and signal objects are summarized:

Category	Cut name	Baseline requirement	Signal requirement
Muons	p_T	> 5 GeV	same as baseline
	η	$\|\eta\| < 2.5$	same as baseline
	ID	Medium	same as baseline
	$z_0 \sin\theta$	< 0.5 mm	same as baseline
	d_0/σ_{d_0}	< 7	< 4
	Isolation	—	PflowLoose_VarRad WP
Taus	p_T	> 20 GeV	same as baseline
	η	$\|\eta\| < 2.5$ and exclude $1.37 < \|\eta\| < 1.52$	same as baseline
	ID	$RNN > 0.01$	Medium JETIDRNN WP
	Number of tracks	1 or 3 associated tracks	same as baseline
Jets	p_T	$> 20GeV$	—
	η (b-jet)	$\|\eta\| < 4.5(2.5)$	—
	jet type	AntiKt4EMPFlow	—
	b-jet tagger	DL1r	—
	b-jet WP	FixedCutBEff_85	—

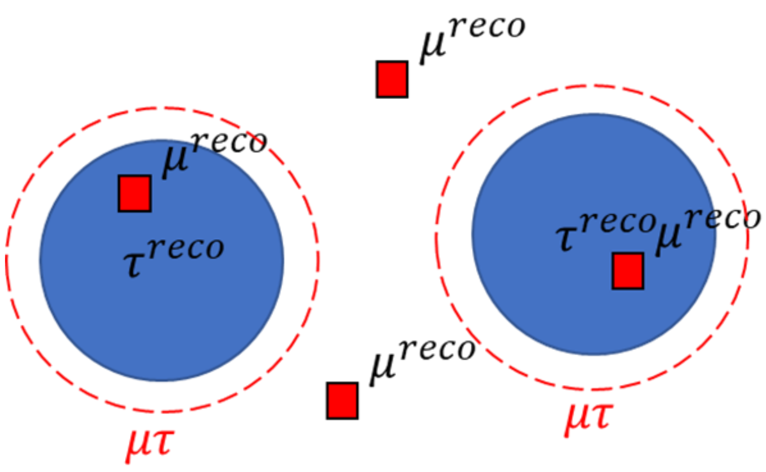
table for approval



- The standard Overlap Removal was skipped for muons and taus. The taus with $\Delta R(\tau_{had}, \mu) < 0.001$ were removed to save the signal efficiency and to delete τ_{had} reconstructed from μ track.
- The baseline d_0/σ_{d_0} requirement is looser than usual to increase the muon efficiency from tau decay.
- No isolation requirement for the signal muons.
- Uncorrected tau momentum is used in the tau object selection.
- $RNN > 0.01$ for the baseline tau is to increase the statistics for fake estimation.
- Selecting the closest $\mu\tau_{had}$ pairs with $\Delta R(\mu, \tau) < 0.4$ and $m_{\mu\tau_{had}} < 15$ GeV.

Event selection

- Trigger:
  - Combination of single muon and di-muon triggers
- Object selection:
  - Non-isolated muons with loose $d_0/\sigma_{d_0} < 7$ requirement
  - Baseline tau (RNN > 0.01) for fake estimation
  - Signal tau requires Medium RNN ID working points



- Event selection in the SRs:
  - Leading $p_T^{\mu} > 14$ GeV
  - Leading $p_{T,\tau}^{Uncorr} > 30$ GeV, subleading $p_{T,\tau}^{Uncorr} > 25$ GeV
  - 2 signal $\mu\tau_{had}$ pairs ($\Delta R(\mu, \tau_{had}) < 0.4$, $m_{\mu\tau_{had}} < 15$ GeV and τ_{had} passing Medium RNN ID)
  - $60 < m_{2\mu\tau_{had}}^{Uncorr} < 120$ GeV
  - $SS\mu$ channel: same-sign charge muons
  - $OS\mu$ channel: opposite-sign charge muons and $m_{\mu\mu} < 50$ GeV

Event selection (1)

- Event selection in the SRs:
  - Leading $p_T^{\mu} > 14$ GeV
  - Leading $p_{T,\tau}^{Uncorr} > 30$ GeV, subleading $p_{T,\tau}^{Uncorr} > 25$ GeV
  - 2 signal $\mu\tau_{had}$ pairs ($\Delta R(\mu, \tau_{had}) < 0.4$, $m_{\mu\tau_{had}} < 15$ GeV and τ_{had} passing Medium RNN ID)
  - $60 < m_{2\mu\tau_{had}}^{Uncorr} < 120$ GeV
  - $SS\mu$ channel: same-sign charge muons
  - $OS\mu$ channel: opposite-sign charge muons and $m_{\mu\mu} < 50$ GeV

cut name	4 GeV	6 GeV	8 GeV	10 GeV	12 GeV	14 GeV	15 GeV
AOD generation	5.5e+05	3.2e+05	2.7e+05	2.4e+05	2.3e+05	2.3e+05	2.2e+05
Preselection	5707.6	2773.7	2222.1	1955.2	1725.5	1561.7	1493.3
N(baseline μ) ≥ 2	5289.1	2554.3	2020.8	1785.3	1587	1441.8	1372
N(baseline τ) ≥ 1	5276.2	2546.2	2014.3	1779.4	1579.5	1432.1	1364
N(baseline τ) ≥ 2	2441	1200	872	683	524	456	410
2 baseline $\mu\tau$	2332.6	1135.4	818	576	334	222	176
μ leadpt > 14 GeV	2319.6	1128.2	813	573	334	222	176
2 OS $\mu\tau$	2229	1092.7	784	556	323	215	168
2 mVis15 $\mu\tau$	2229	1092.7	784	556	323	215	168
Lead $p_T^{\tau} > 30$ GeV	2047.7	1010.3	706	500	299	207	164
Sublead $p_T^{\tau} > 25$ GeV	1678.8	845	581	417	260	184	149
2 signal $\mu\tau$	477	231	167	141	86	67	54
60 GeV < $m_{2\mu\tau}^{vis}$ < 120 GeV	420	206	150	128	77	60	49
2 SS μ	202±9.0	97±4.8	78±4.4	66±3.7	37±2.5	31±2.3	24±2.0

table for approval

$SS\mu$ channel cutflow table

Event selection (2)

- Cutflow table for $OS\mu$ channel:

table for approval

cut name	4 GeV	6 GeV	8 GeV	10 GeV	12 GeV	14 GeV	15 GeV
AOD generation	5.5e+05	3.4e+05	2.7e+05	2.4e+05	2.3e+05	2.3e+05	2.3e+05
Preselection	5707.6	2773.7	2222.1	1955.2	1725.5	1561.7	1493.3
N(baseline μ) ≥ 2	5289.1	2554.3	2020.8	1785.3	1587	1441.8	1372
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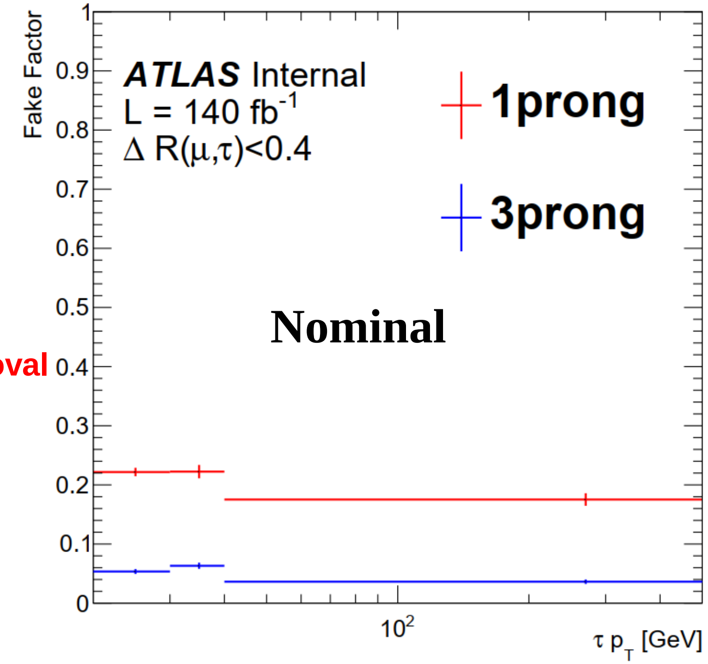
Lead $p_T^\tau > 30$ GeV	2047.7	1010.3	706	500	299	207	164
Sublead $p_T^\tau > 25$ GeV	1678.8	845	581	417	260	184	149
2 signal $\mu\tau$	477	231	167	141	86	67	54
60 GeV $< m_{2\mu\tau}^{vis} <$ 120 GeV	420	206	150	128	77	60	49
2 OS μ	218	109	72	62	40	29	24
$m_{\mu\mu} <$ 50 GeV	214±9.1	107±5.0	69±4.0	60±3.3	39±2.6	27±2.2	24±2.0

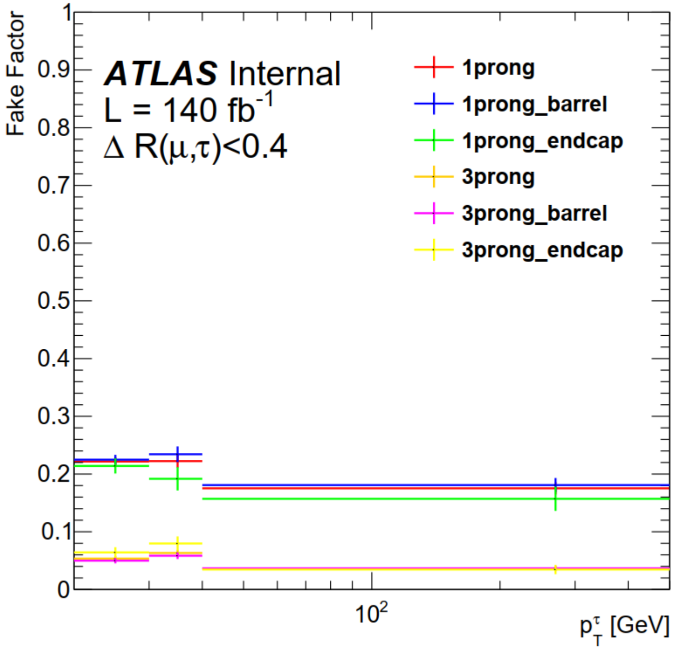
Table 10: A summary of weighted cutflow of signal region in OSμ channle for m_a = 4, 6, 8, 10, 12, 14, 15 GeV (BR($H \to 2a \to 4\tau$) = 1.0 at 140 fb^{-1}), starting from the AOD generation level.

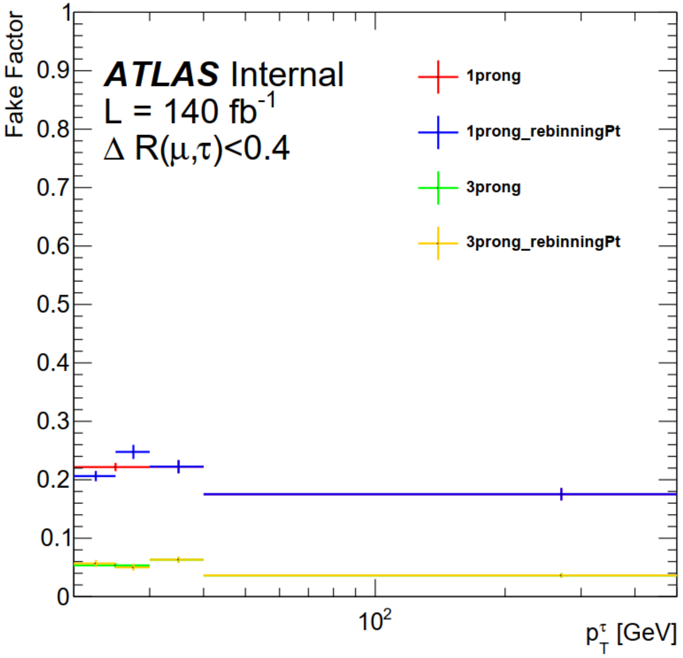
Fake factor measurement in Z + jets region

- Fake Factor parameterized as $f(p_T^{Uncorr}, \tau_{prongness})$
- Nominal binning:
  - p_T^{Uncorr}: (20,30), (30,40), (40,500) GeV
  - prongness: 1 prong, 3 prong
- Other parameterization and binning strategies are used to estimate the FF shape uncertainties
  - $|\eta|^{Uncorr}$: barrel (0,1.37), endcap (1.52,2.5)
  - $p_T^{Uncorr}, p_T^{\mu\tau}$

figure for approval

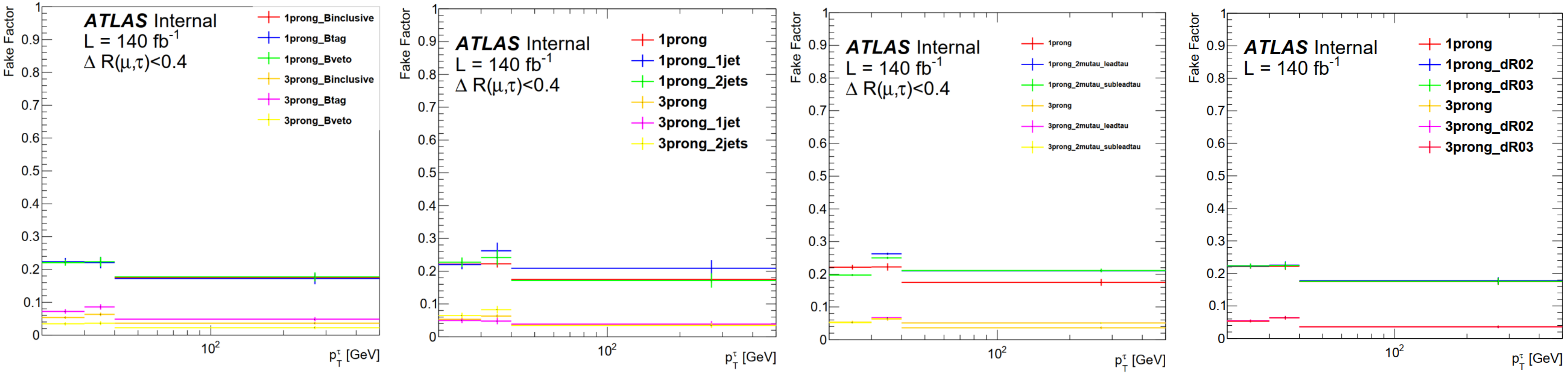






Fake composition uncertainties

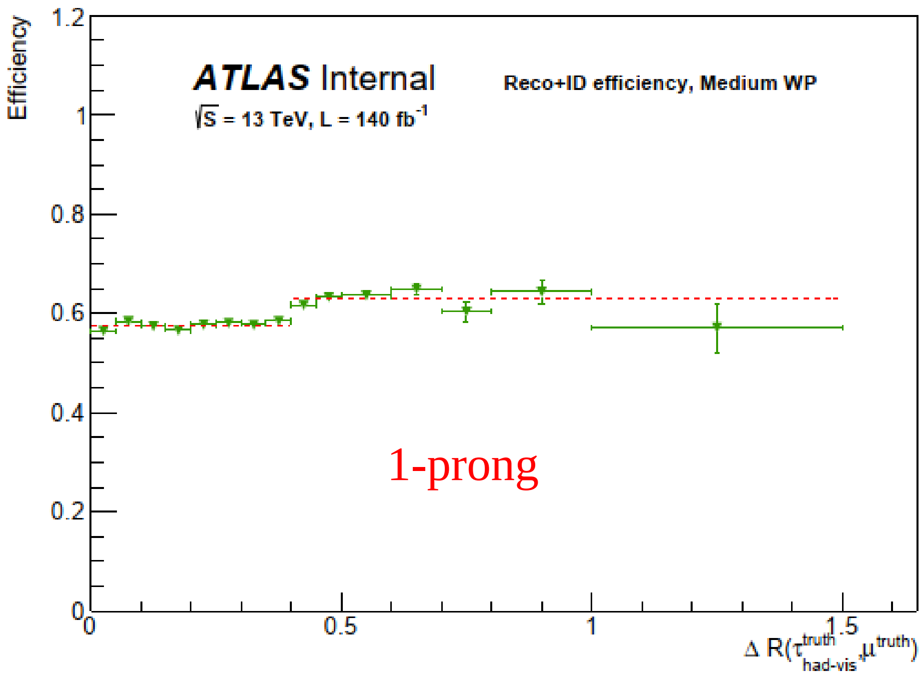
- Due to the fake composition difference between Z + jets CR and SR/VR
- Estimated by measuring the FFs in regions with different fake composition
  - With/without Bjets
  - With 1 or 2 jets
  - $2\mu\tau_{had}$ region
  - $\Delta R < 0.4(0.2)$
- Apply the new FFs to SR/VR using the same fake estimation equation

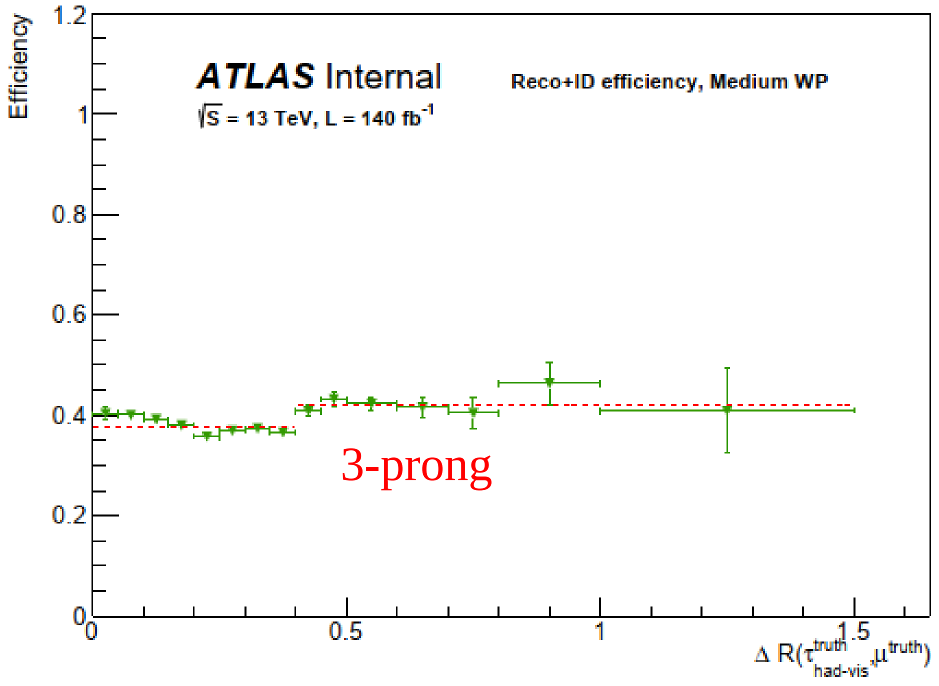


Additional tau efficiency SF uncertainty

- Taking the average difference between merged tau and standard taus
- Medium RNN
  - Object level uncertainty: 1-prong: ±8%, 3-prong: ±10%
  - Event level uncertainty: take into account two merged taus

	$Eff_{\Delta R<0.4}$	$Eff_{\Delta R>0.4}$	$Eff_{\Delta R<0.4}/Eff_{\Delta R>0.4}$	Uncertainty
1-prong	0.576	0.629	0.92	0.08
3-prong	0.378	0.420	0.90	0.10

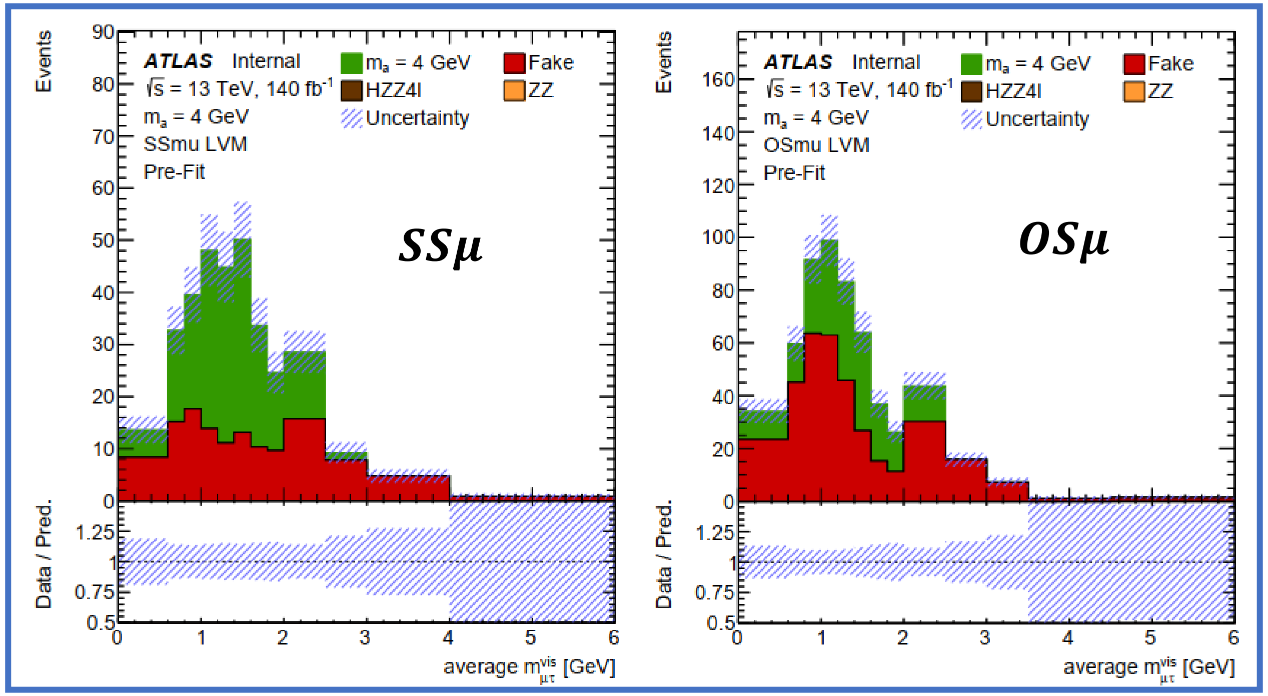




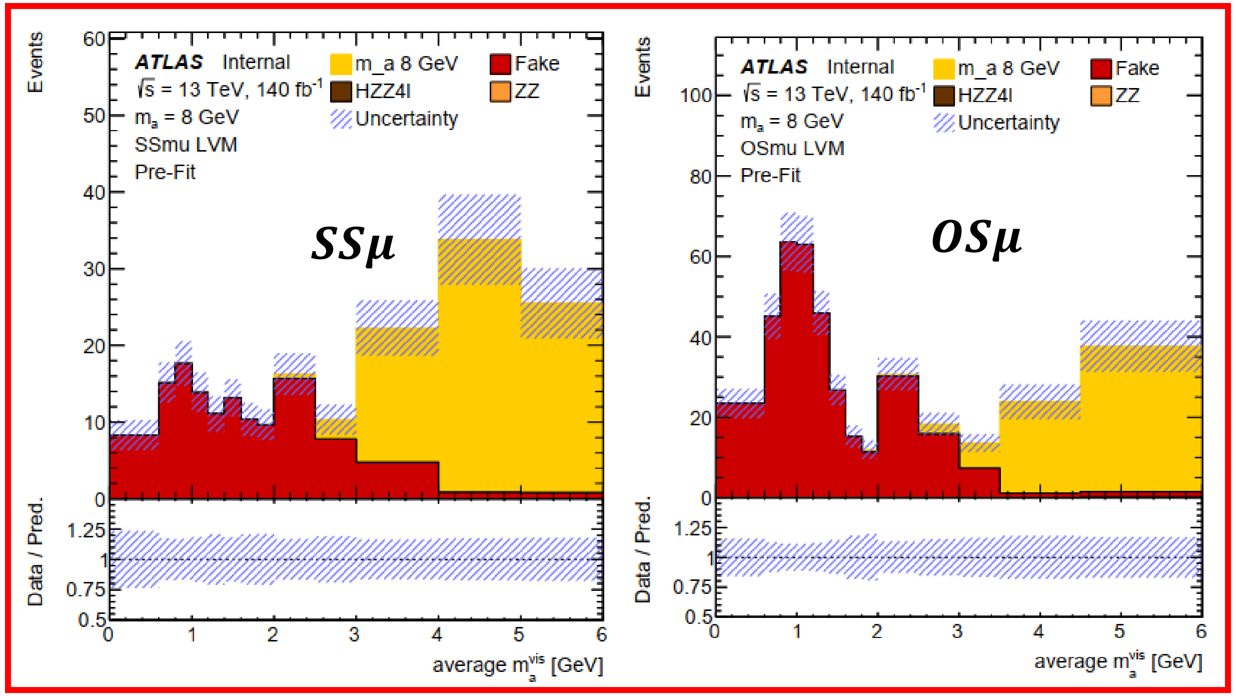
Average $m_{\mu\tau_{had}}$ distributions in SRs

- The binning of each signal mass point is optimized to make the statistical error of signal + background of each bin around 20% and never 0 background events in each bin.
- The edge of each bin is manually chosen to separate the shape of the signal and background.
- The overflow bin is added to the rightmost bin of each distribution.

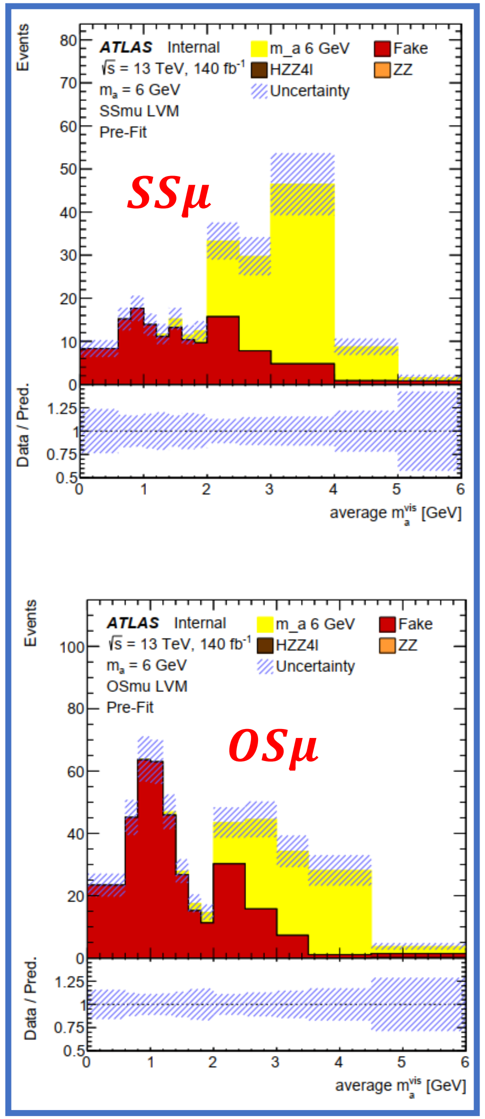
$m_a = 4$ GeV



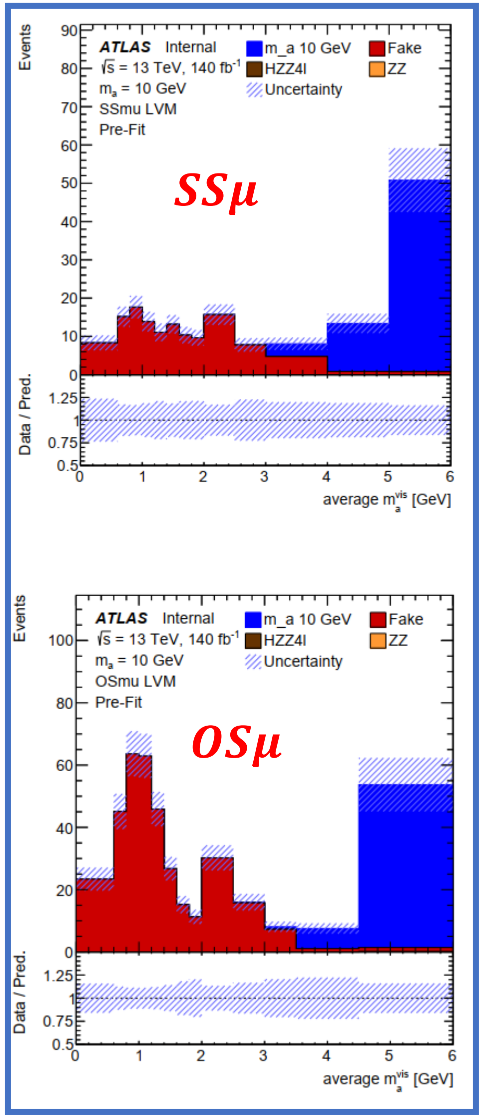
$m_a = 8$ GeV



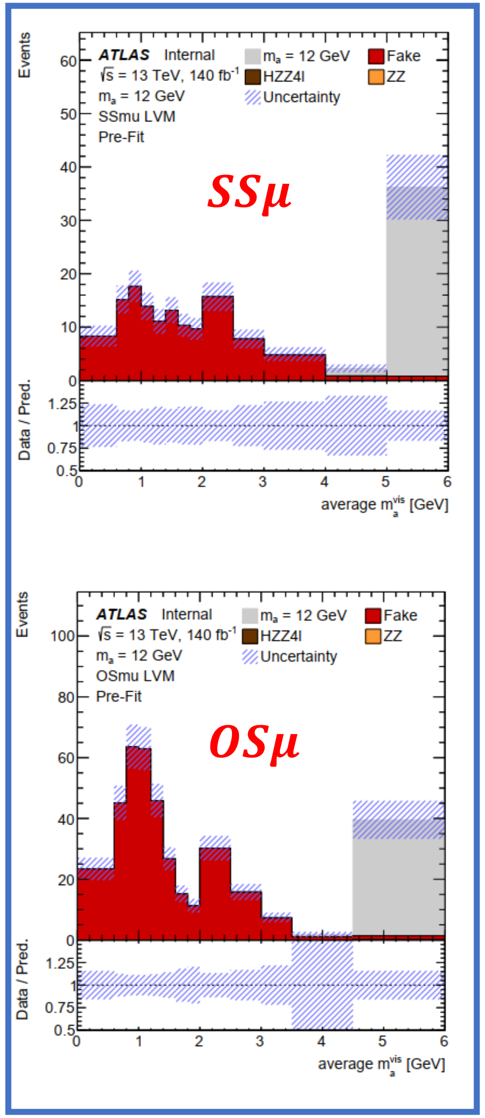
Average $m_{\mu\tau_{had}}$ distributions in SRs



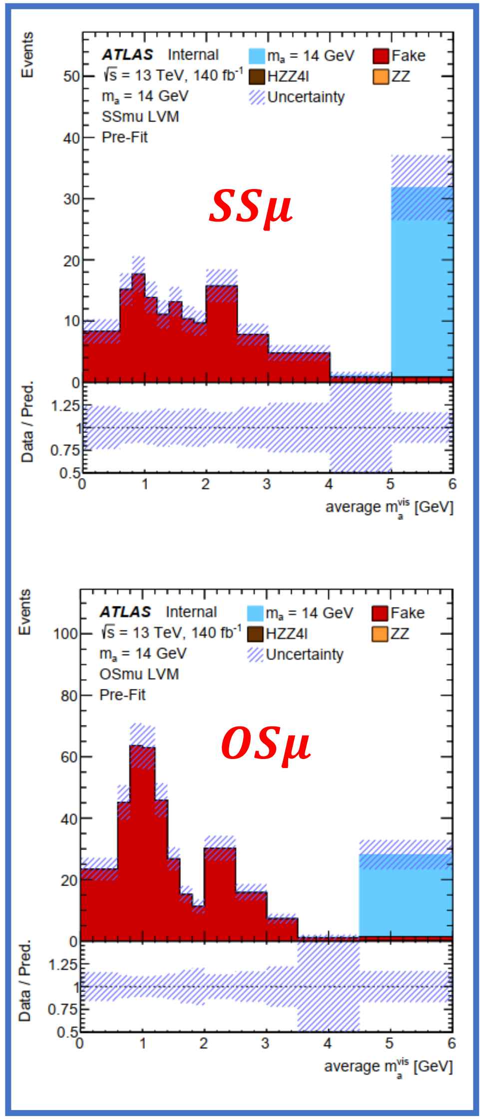
$m_a = 6$ GeV



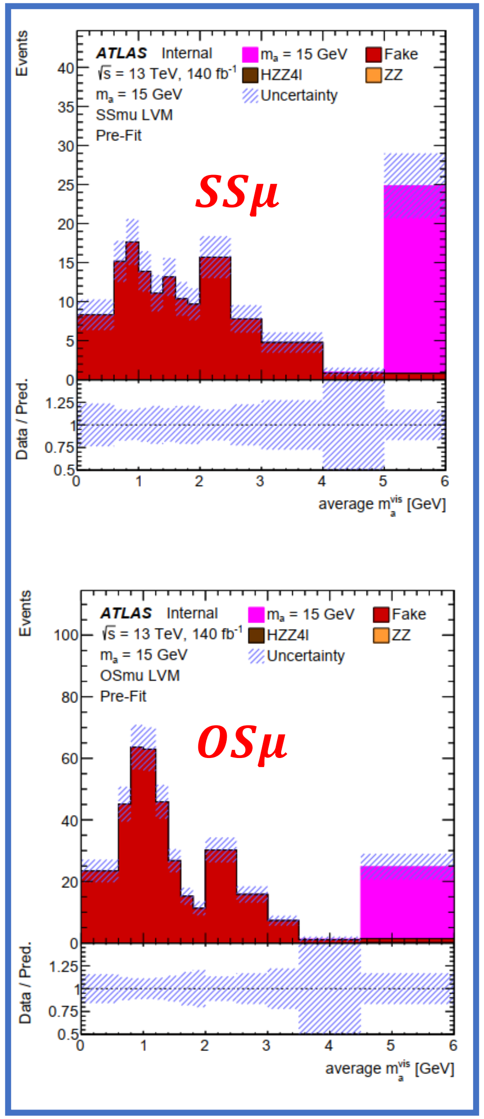
$m_a = 10$ GeV



$m_a = 12$ GeV



$m_a = 14$ GeV

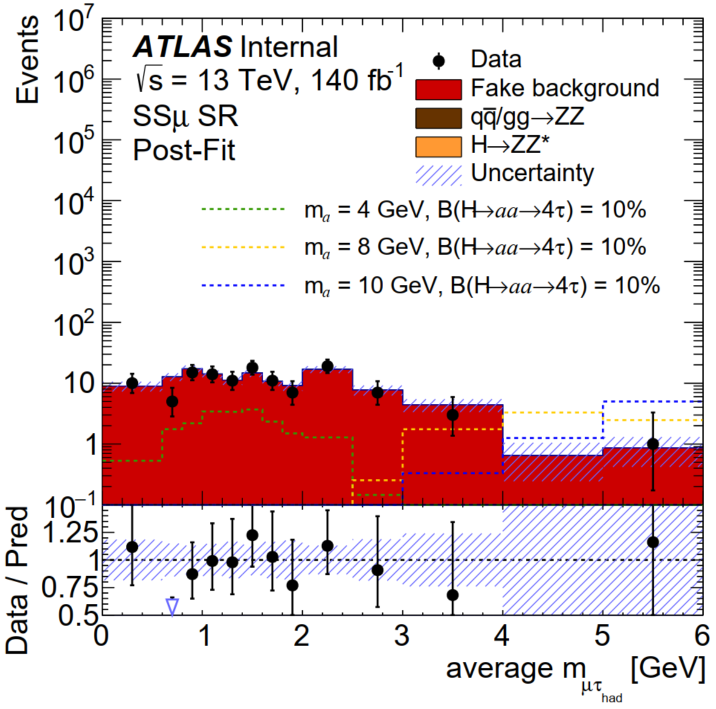


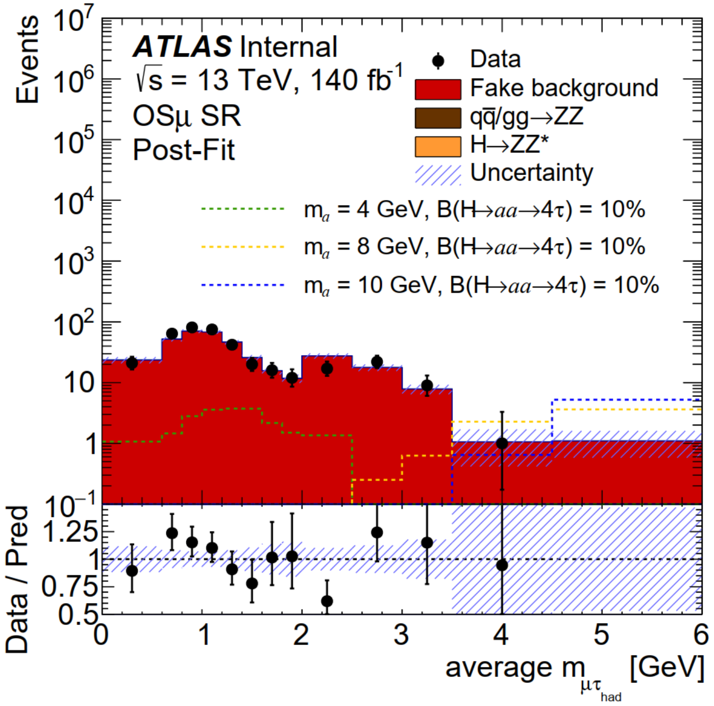
$m_a = 15$ GeV

Observed yields in SRs

- The observed number of events in data is consistent with the background prediction within 1σ in both $SS\mu$ and $OS\mu$ channels.
- No excess is found. The fake prediction shows very good agreement with the data.

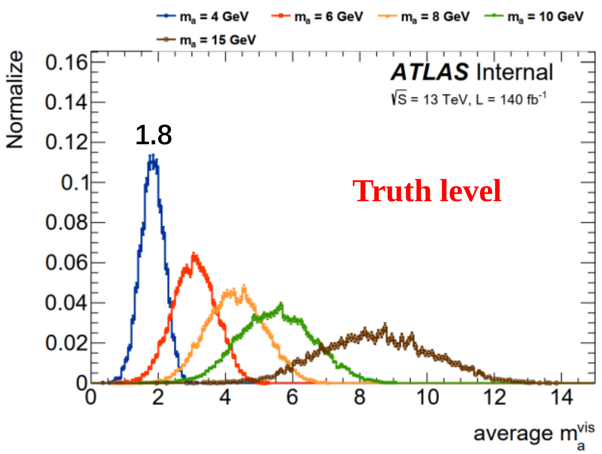
Process	SSμ region	OSμ region
Data	121	380
Fake background	129.1 ± 11.5	349.7 ± 31.4
$q\bar{q} \to ZZ$ and $gg \to ZZ$	< 0.01	< 0.01
$H \to ZZ^*$	0.01 ± 0.01	0.09 ± 0.04
Total background	129.1 ± 11.5	349.8 ± 31.4
$H \to aa \to 4\tau$ (m_a = 4 GeV)	20.2 ± 3.2	21.4 ± 3.3
$H \to aa \to 4\tau$ (m_a = 6 GeV)	9.7 ± 1.5	10.7 ± 1.7
$H \to aa \to 4\tau$ (m_a = 8 GeV)	7.8 ± 1.3	6.9 ± 1.1
$H \to aa \to 4\tau$ (m_a = 10 GeV)	6.6 ± 1.1	6.0 ± 1.0
$H \to aa \to 4\tau$ (m_a = 12 GeV)	3.7 ± 0.6	3.9 ± 0.6
$H \to aa \to 4\tau$ (m_a = 14 GeV)	3.1 ± 0.5	2.7 ± 0.5
$H \to aa \to 4\tau$ (m_a = 15 GeV)	2.4 ± 0.4	2.4 ± 0.4

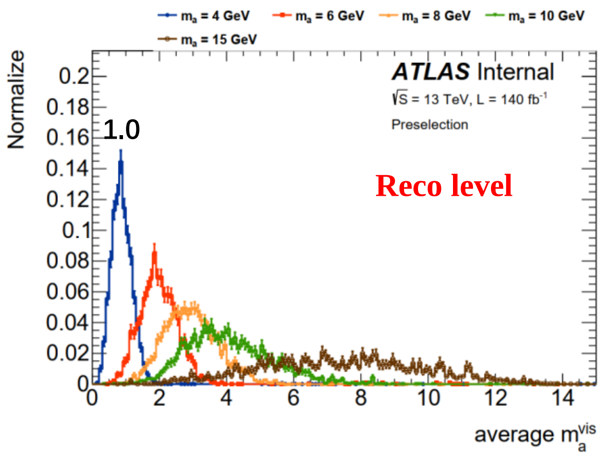


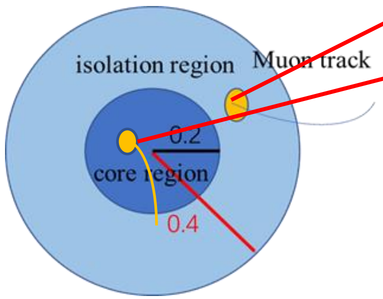


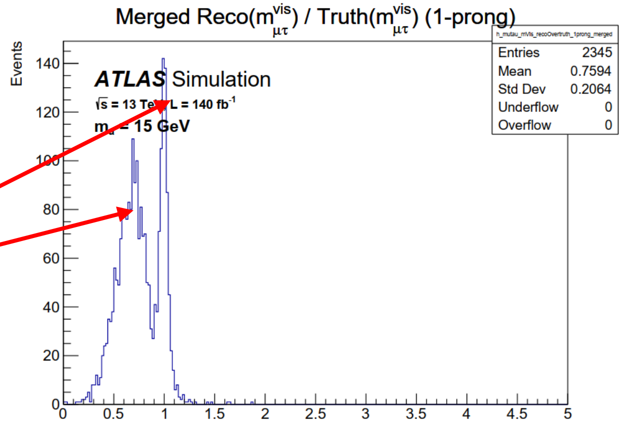
The discrepancy between truth and reco visible mass

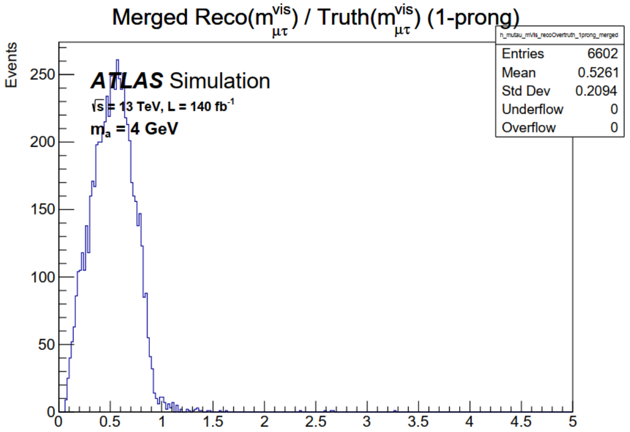
- The variable "average $m_{\mu\tau}^{vis}$" is used for the final fitting.
  - average $m_{\mu\tau}^{vis} = (m_{\mu\tau_1}^{vis} + m_{\mu\tau_2}^{vis})/2$,
  - $m_{\mu\tau}^{vis} = \sqrt{2p_T^{\mu}p_T^{\tau}(\cosh(\eta^{\mu}-\eta^{\tau}) - \cos(\phi^{\mu}-\phi^{\tau}))}, (m=0, E \gg m)$
- The reco average $m_{\mu\tau}^{vis}$ shifts to lower value compared to the truth value.
- The reason is because we only re-calculate the RNN ID variables in the muon removal algorithm, but not re-calculate the tau momentum variables (p_T, η, ϕ).
- Solution : Correct the tau momentum in the SR and VR.
  - Only taus having charged tracks overlapped with muon should be corrected
  - The total number of events for each region keeps the same





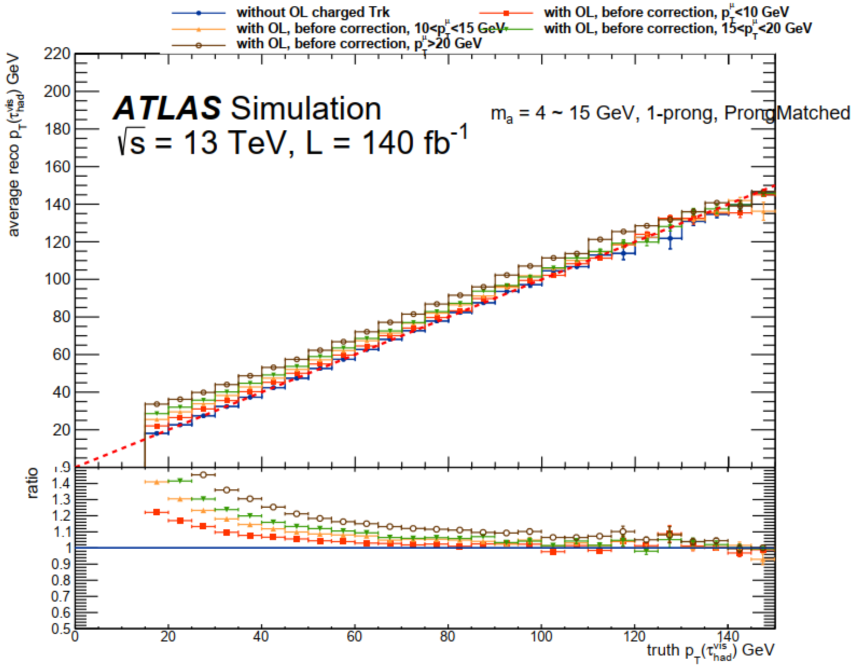


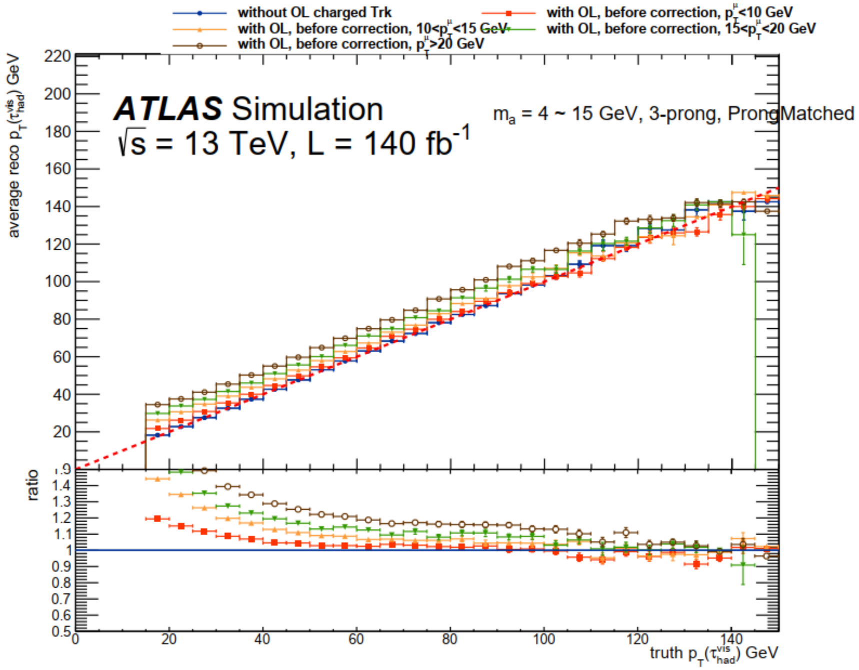




How to correct the tau momentum

- Step 1: Correct the p_T^τ
  - In the same truth p_T bin, the average reco p_T are different for the taus with OL muon and without OL muon.
  - We can make the ratio of overlapped tau p_T to unoverlapped tau:
    - OL taus: having charged track overlapped with muon; UnOL: no charged track overlapped with muon
    - $R(p_T^{OL}, p_T^{\mu}, n_p, \eta) = p_T^{OL}/p_T^{UnOL}$
    - Fit the ratio with a function
  - Correct the p_T^{OL} to p_T^{UnOL} using p_T^{OL}/R



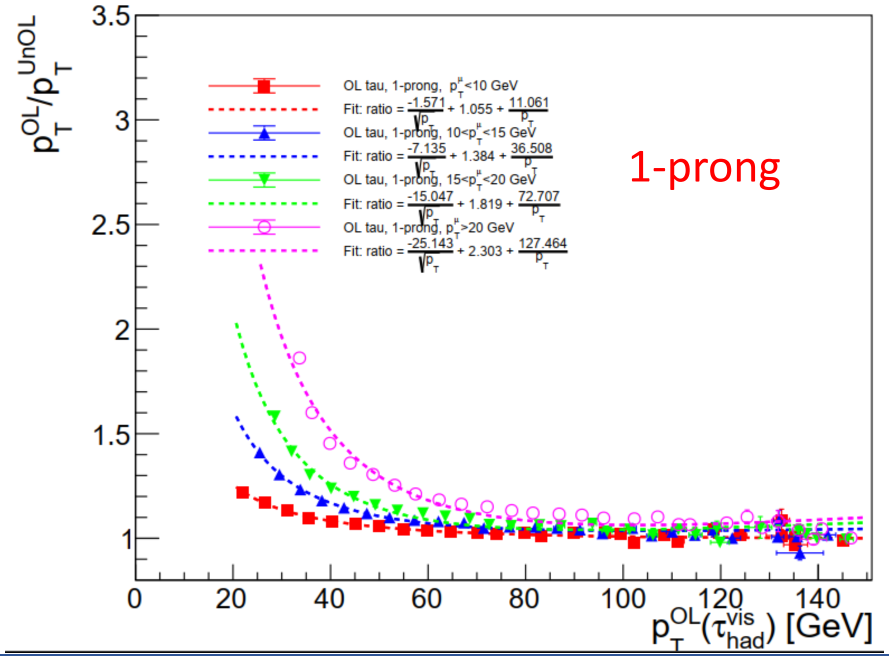


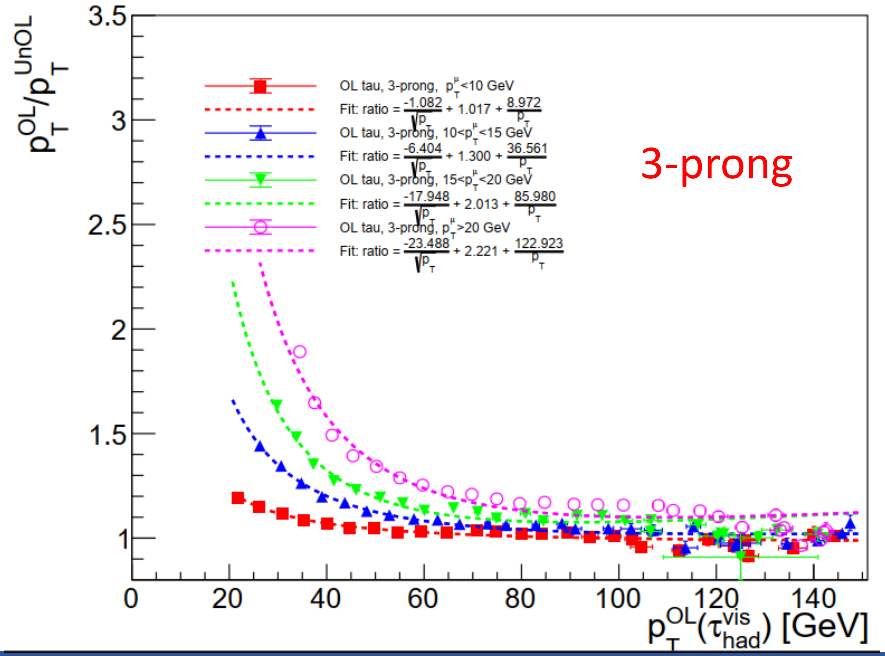
How to correct the tau momentum

- Step 2: Correct the η^{τ} and ϕ^{τ}
  - After correcting the p_T , we have:
    - $\vec{p}_{\mu\tau}(p_T^{\mu\tau}, \eta^{\mu\tau}, \phi^{\mu\tau})$
    - $\vec{p}_{\tau}(p_T^{\tau}, \eta^{\tau}, \phi^{\tau})$
    - $\vec{p}_{\mu}(p_T^{\mu}, \eta^{\mu}, \phi^{\mu})$
    - Where variables marked with green color are already known, variables marked with red color are unknown
  - According to the momentum conservation, we have $\vec{p}_{\mu\tau} = \vec{p}_{\mu} + \vec{p}_{\tau}$
  - We solve the equation:
    - $\phi^{\tau} = \phi^{\mu\tau} - sin^{-1}[p_T^{\mu} / p_T^{\tau} \, sin(\phi^{\mu} - \phi^{\mu\tau})]$
    - $p_T^{\mu\tau} = (p_T^{\tau} \cos\phi^{\tau} + p_T^{\mu} \cos\phi^{\mu}) / cos\phi^{\mu\tau}$
    - $\eta^{\tau} = tanh^{-1}[(p_T^{\mu\tau} tanh(\eta^{\mu\tau}) - p_T^{\mu} tanh(\eta^{\mu})) / p_T^{\tau}]$
  - Finally, we can correct η^{τ} and ϕ^{τ} using the above formulas.

Fit the ratio p_T^{OL}/p_T^{UnOL}

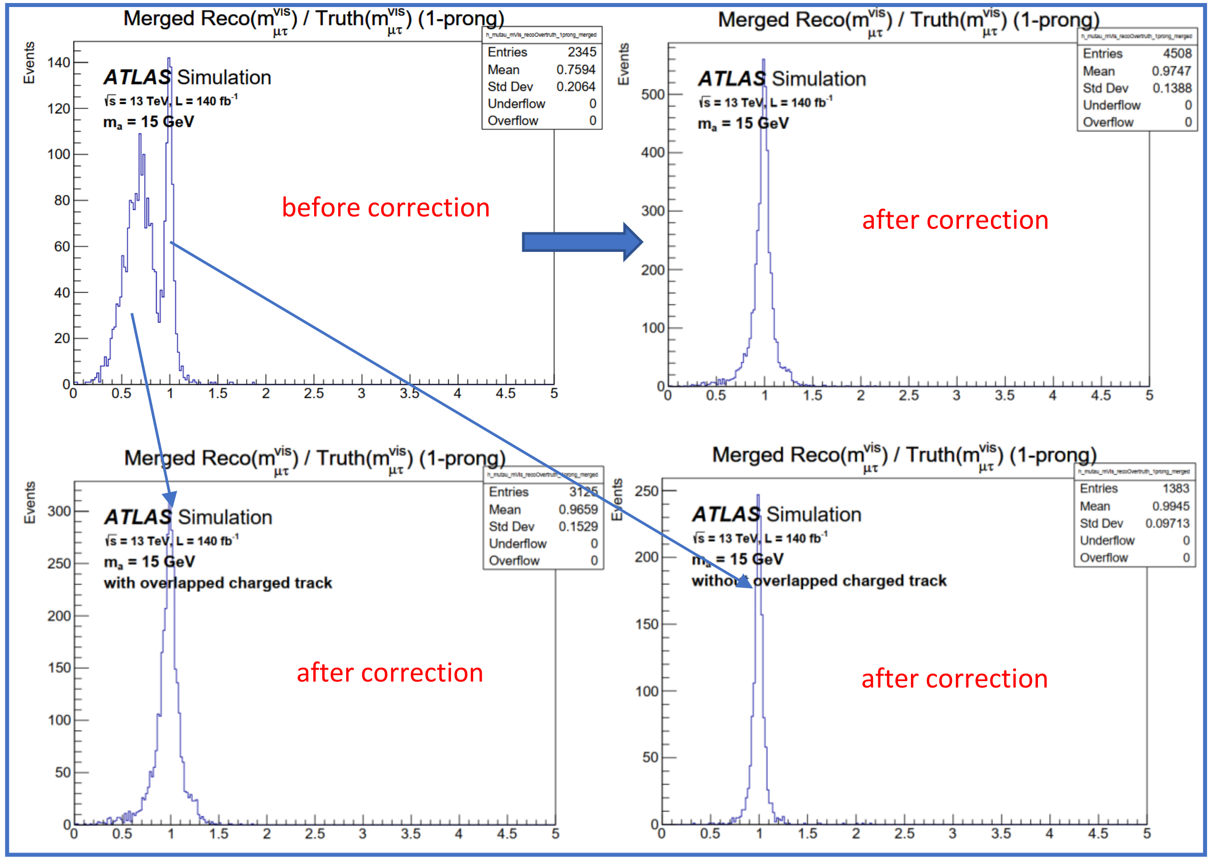
- The function used to fit the p_T ratio is the energy resolution parametrization function:
  - energy resolution parameterization: $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} + b + \frac{c}{E}$
  - $R(p_T^{OL}, p_T^{\mu}, \eta, n_p) = p_T^{OL}/p_T^{UnOL} = \frac{a}{p_T^{OL}} + b + \frac{c}{p_T^{OL}}$
- The barrel and endcap have almost the same ratio curves, so I merged them into one ratio curve for final parameterization:
  - $R(p_T^{OL}, p_T^{\mu}, n_p) = p_T^{OL}/p_T^{UnOL} = \frac{a}{p_T^{OL}} + b + \frac{c}{p_T^{OL}}$

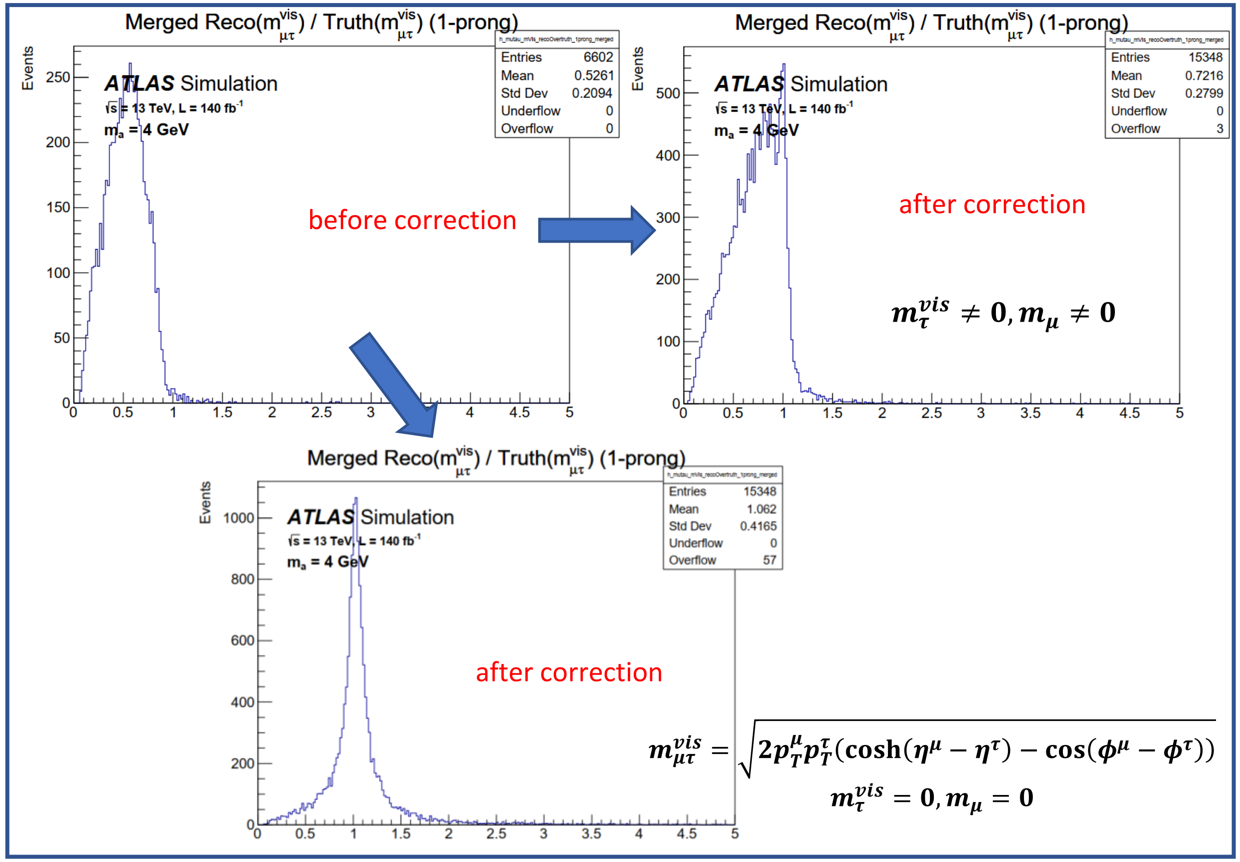




Visible mass $m_{\mu\tau}^{vis}$ correction results

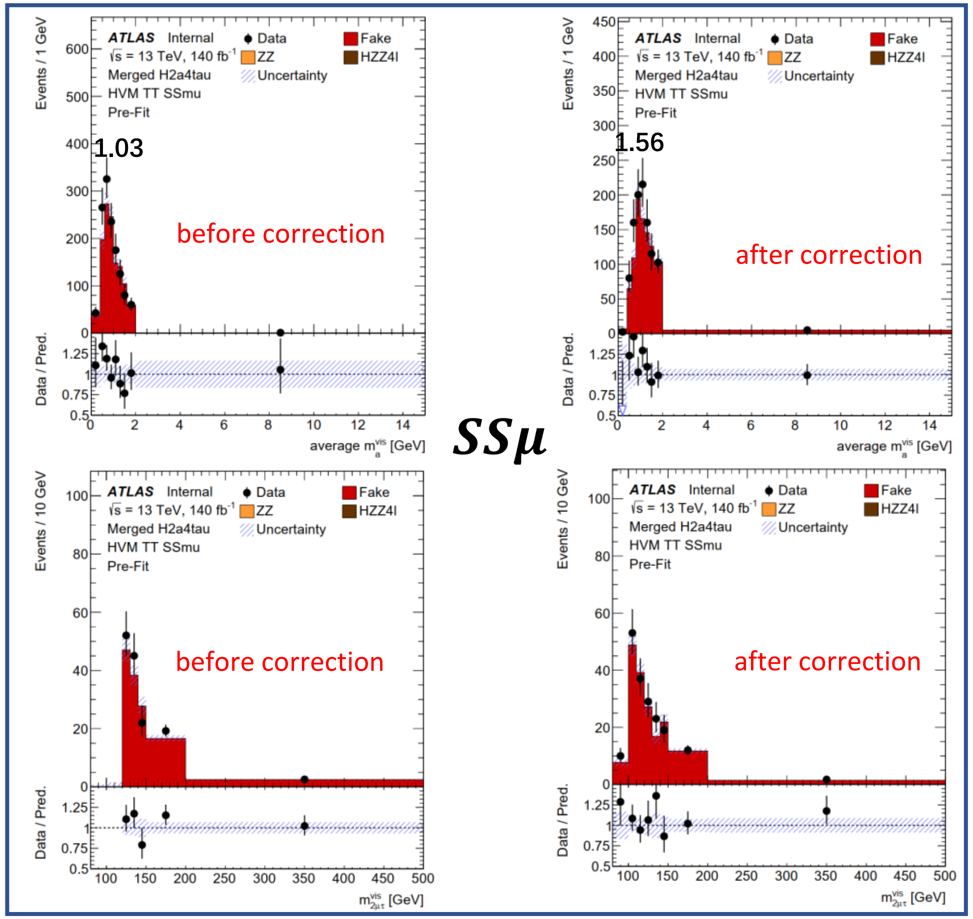
- The reco $m_{\mu\tau}^{vis}$ is consistent with truth $m_{\mu\tau}^{vis}$ after tau momentum correction.
- The m_{τ}^{vis} has a relatively large effect on $m_{\mu\tau}^{vis}$ for the lower mass signal. If we consider truth $m_{\tau}^{vis} = 0$, reco $m_{\mu\tau}^{vis}$ is also consistent with truth $m_{\mu\tau}^{vis}$ for lower masses after correction.

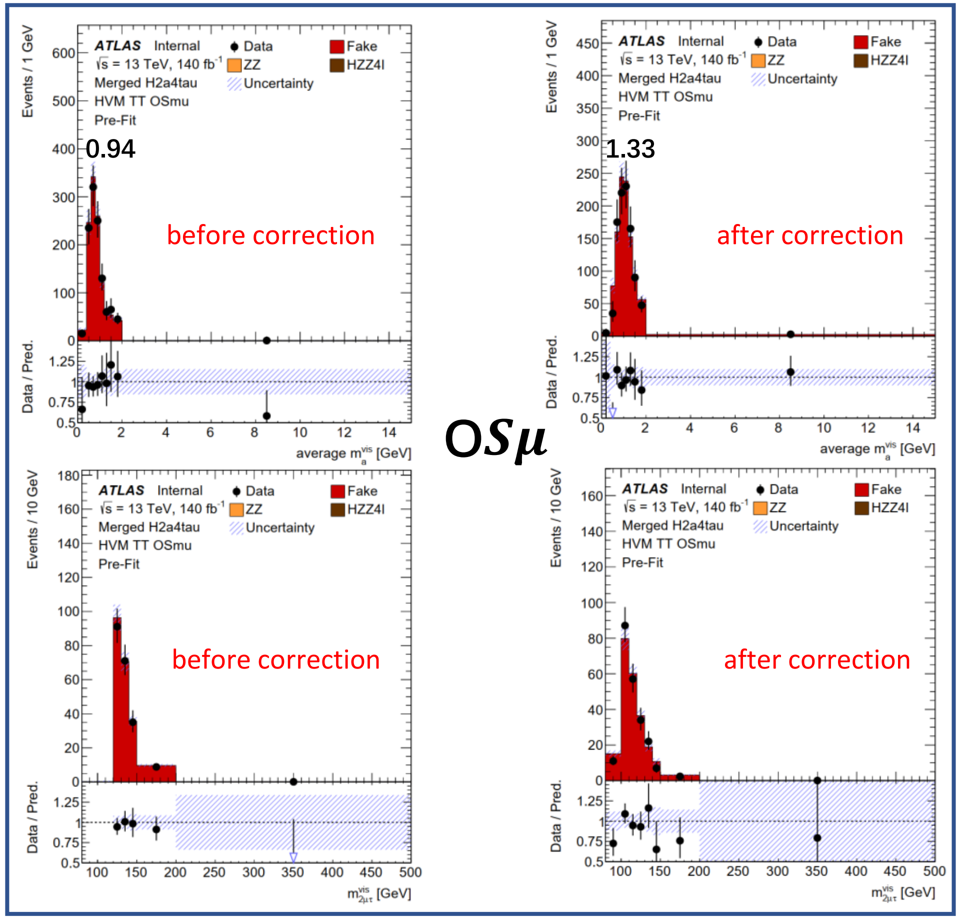




Correction check in validation region

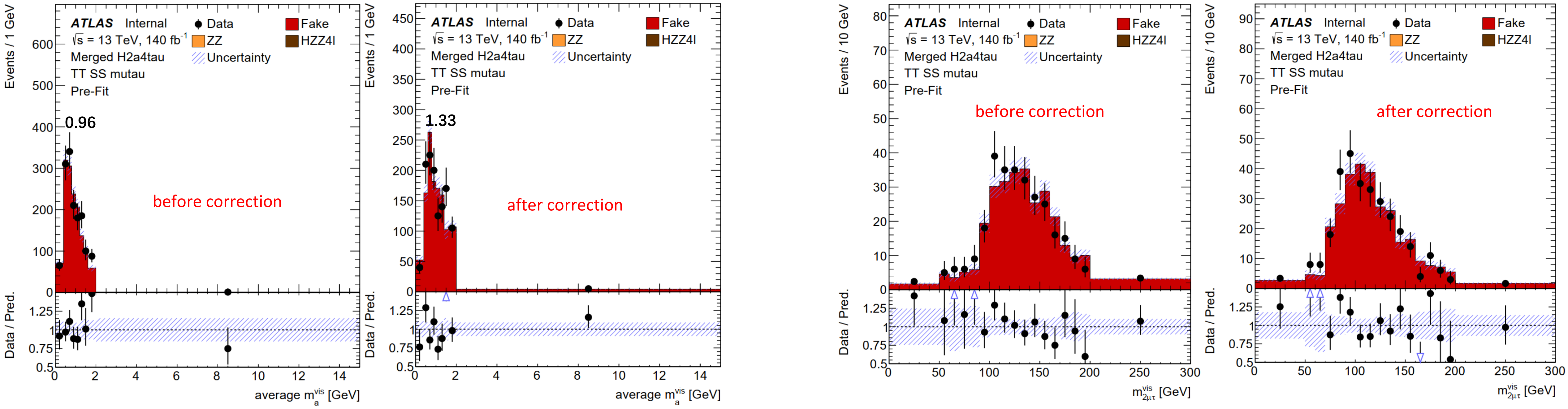
- The tau momentum correction is applied for both data and background in the VRs, then the relevant variables are re-calculated after tau momentum correction.
- The fake prediction still agrees with data after correction.





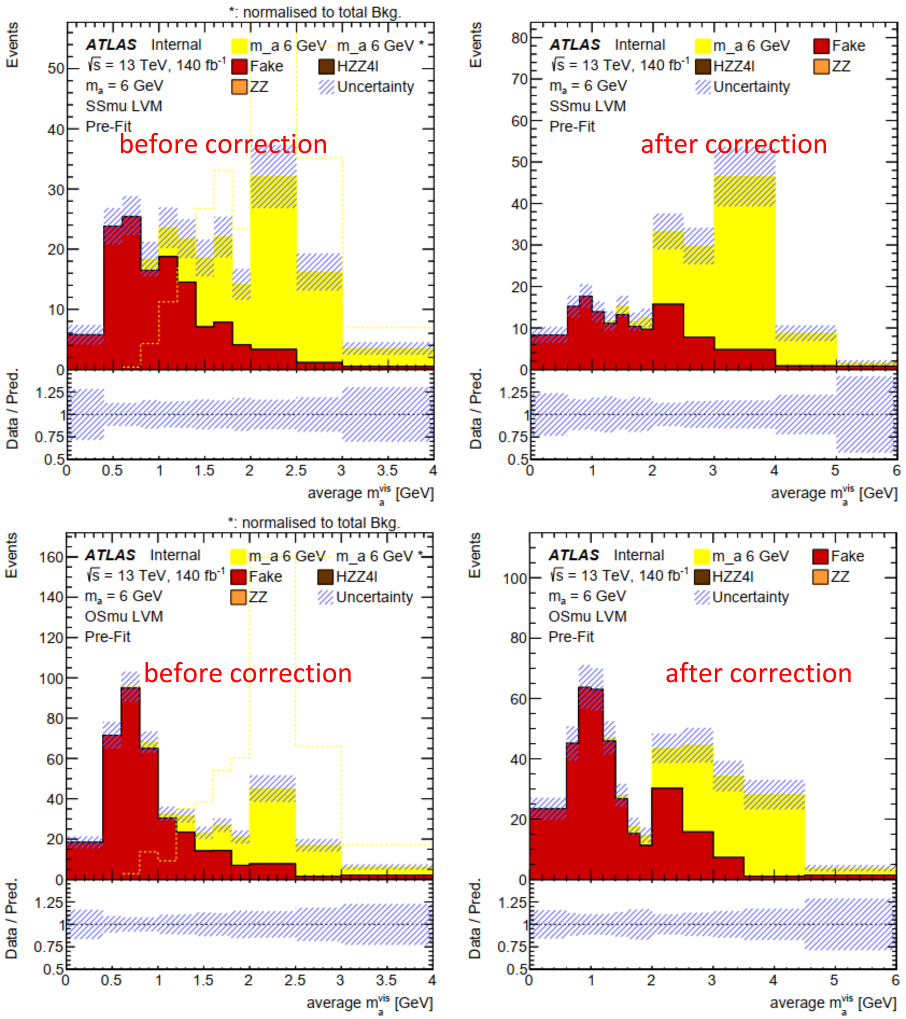
Correction check in cross-check region

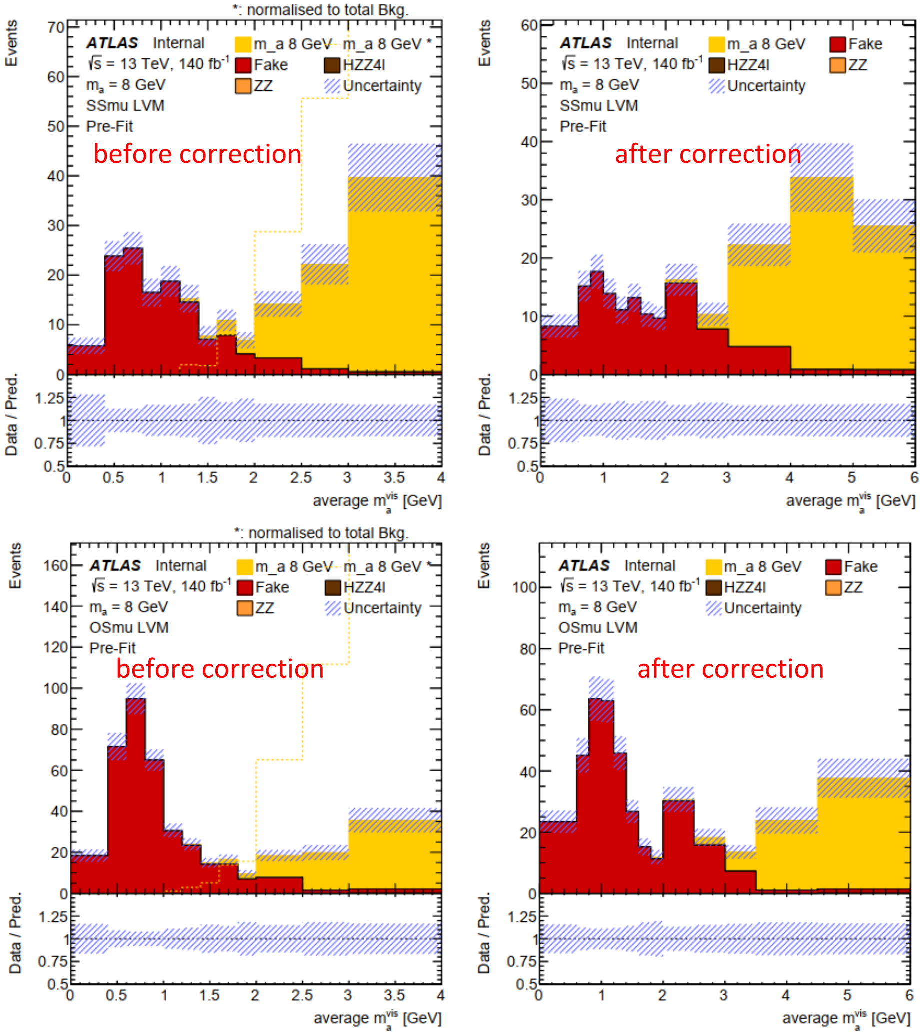
- The fake prediction still agrees with data in the cross-check region after correction.



Average $m_{\mu\tau}^{vis}$ ($m_a = 6, 8$ GeV)

- The same binning strategy is used for $m_a = 6{,}8$ GeV signal.





More cutflow table

cut name	4 GeV	6 GeV	8 GeV	10 GeV	12 GeV	14 GeV	15 GeV
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Preselection	5707.6	2773.7	2222.1	1955.2	1725.5	1561.7	1493.3
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N(baseline τ) $\geq$ 2	2441	1200	872	683	524	456	410
2 baseline $\mu\tau$	2332.6	1135.4	818	576	334	222	176
μ leadpt > 14 GeV	2319.6	1128.2	813	573	334	222	176
2 OS $\mu\tau$	2229	1092.7	784	556	323	215	168
2 mVis15 $\mu\tau$	2229	1092.7	784	556	323	215	168
Lead p_T^τ > 30 GeV	2047.7	1010.3	706	500	299	207	164
Sublead p_T^τ > 25 GeV	1678.8	845	581	417	260	184	149
2 signal $\mu\tau$	477	231	167	141	86	67	54
60 GeV < $m_{2\mu\tau}^{vis}$ < 120 GeV	420	206	150	128	77	60	49
2 OS μ	218	109	72	62	40	29	24
$m_{\mu\mu}$ < 50 GeV	214±9.1	107±5.0	69±4.0	60±3.3	39±2.6	27±2.2	24±2.0

Table 10: A summary of weighted cutflow of signal region in OSμ channle for m_a = 4, 6, 8, 10, 12, 14, 15 GeV (BR($H \to 2a \to 4\tau$) = 1.0 at 140 fb^{-1}), starting from the AOD generation level.

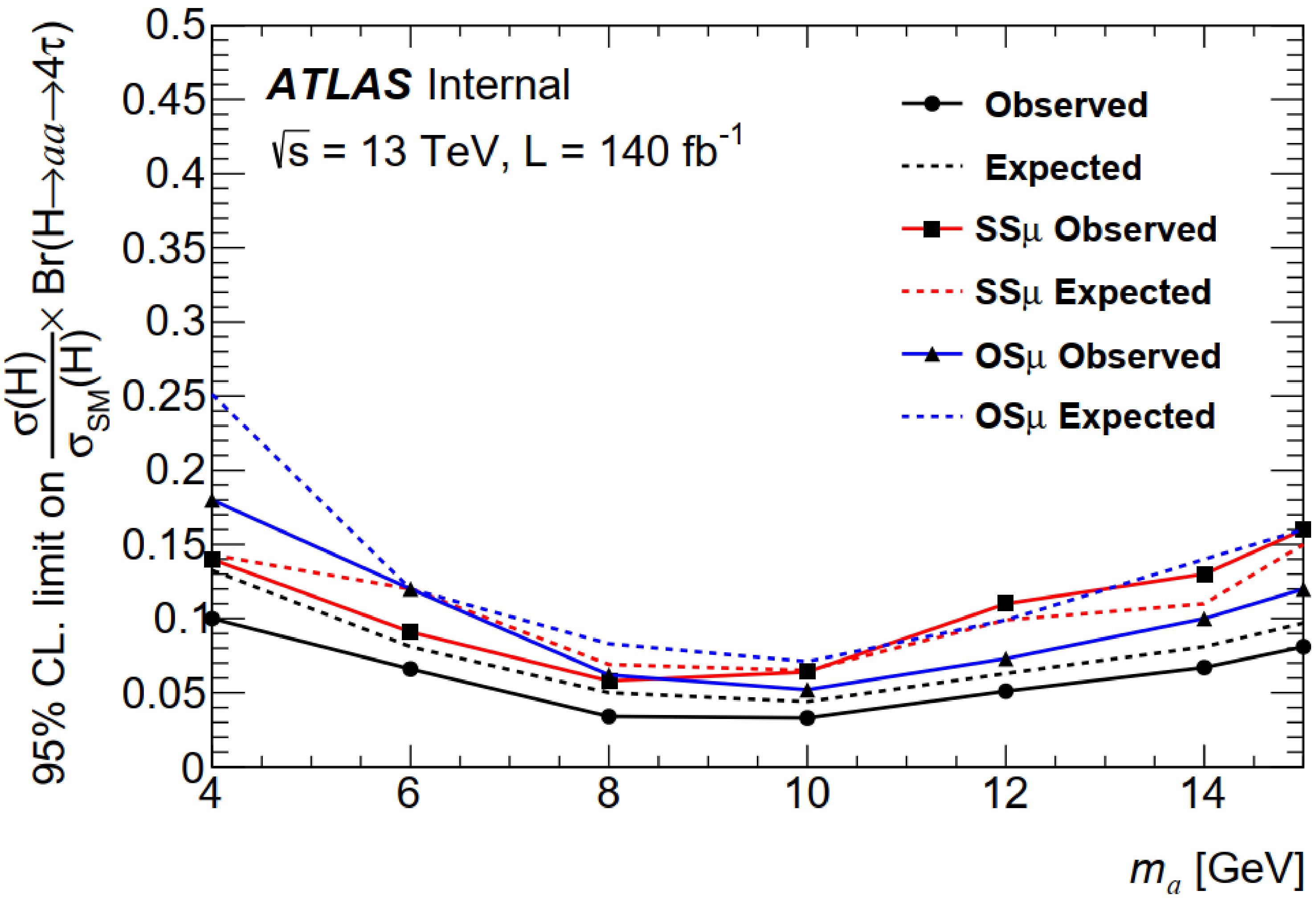
cut name	Events passed	Efficiency	Cumulative efficiency
AOD generation	5.5e+05	1	1
Preselection	5707.6	0.010459	0.010459
N(baseline μ) $\geq$ 2	5289.1	0.92668	0.0096917
N(baseline τ) $\geq$ 1	5276.2	0.99755	0.0096679
N(baseline τ) $\geq$ 2	2441	0.46264	0.0044728
2 baseline $\mu\tau$	2332.6	0.95562	0.0042743
μ leadpt > 14 GeV	2319.6	0.99441	0.0042504
2 OS $\mu\tau$	2229	0.96094	0.0040843
2 mVis15 $\mu\tau$	2229	1	0.0040843
Lead p_T^τ > 30 GeV	2047.7	0.91866	0.0037521
Sublead p_T^τ > 25 GeV	1678.8	0.81986	0.0030762
2 signal $\mu\tau$	477	0.28435	0.00087474
60 GeV < $m_{2\mu\tau}^{vis}$ < 120 GeV	420	0.88021	0.00076995
2 SS μ	202	0.48146	0.0003707

Table 7: Weighted cutflow of signal region in the SSμ channel for m_a = 4 GeV (BR($H \to 2a \to 4\tau$) = 1.0 at 140 fb^{-1}), starting from the AOD generation level.

cut name	Events passed	Efficiency	Cumulative efficiency
AOD generation	5.4574e+05	1	1
Preselection	5707.6	0.010459	0.010459
N(baseline μ) $\geq$ 2	5289.1	0.92668	0.0096917
N(baseline τ) $\geq$ 1	5276.2	0.99755	0.0096679
N(baseline τ) $\geq$ 2	2441	0.46264	0.0044728
2 baseline $\mu\tau$	2332.6	0.95562	0.0042743
μ leadpt > 14 GeV	2319.6	0.99441	0.0042504
2 OS $\mu\tau$	2229	0.96094	0.0040843
2 mVis15 $\mu\tau$	2229	1	0.0040843
Lead p_T^τ > 30 GeV	2047.7	0.91866	0.0037521
Sublead p_T^τ > 25 GeV	1678.8	0.81986	0.0030762
2 signal $\mu\tau$	477	0.28435	0.00087474
60 GeV < $m_{2\mu\tau}^{vis}$ < 120 GeV	420	0.88021	0.00076995
2 OS μ	218	0.51854	0.00039925
$m_{\mu\mu}$ < 50 GeV	214	0.98207	0.00039209

Table 9: Weighted cutflow of signal region in the OSμ channel for m_a = 4 GeV (BR($H \to 2a \to 4\tau$) = 1.0 at 140 fb^{-1}), starting from the AOD generation level.

Limits for *SSμ* and *OSμ*



CMS latest results

CMS PAS SUS-24-002

A search for a pair of light pseudoscalar bosons (a_1) produced from the decay of the 125 GeV Higgs boson (H) is presented. The analysis examines decay modes where one a_1 decays into a pair of tau leptons, and the other decays into either another pair of tau leptons or a pair of muons. The a_1 mass probed in this study ranges from 4 to 15 GeV. The data sample used was recorded by the CMS experiment in proton-proton collisions at a center-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 138 fb^{-1}. The study uses the $2\mu2\tau$ and 4τ channels in combination to constrain the product of the Higgs boson production cross section and the branching fraction to the 4τ final state, $\sigma(pp \to H + X)\mathcal{B}(H \to a_1a_1)\mathcal{B}^2(a_1 \to \tau\tau)$. This methodology takes advantage of the linear dependence of the fermionic coupling strength of pseudoscalar bosons on the fermion mass. Model-independent upper limits at 95% confidence level (CL) on $\sigma(pp \to H + X)\mathcal{B}(H \to a_1a_1)\mathcal{B}^2(a_1 \to \tau\tau)$, relative to the standard model Higgs boson production cross section σ_{SM}, are set. The observed (expected) upper limits range between 0.007 (0.011) and 0.079 (0.066) across the mass range considered. Exclusion limits at 95% on $\sigma(pp \to H + X)\mathcal{B}(H \to a_1a_1)$, relative to σ_{SM}, are derived for various Two Higgs Doublet Model + Singlet scenarios.