$t\bar{t}H$ measurement in multilepton final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

贾琛

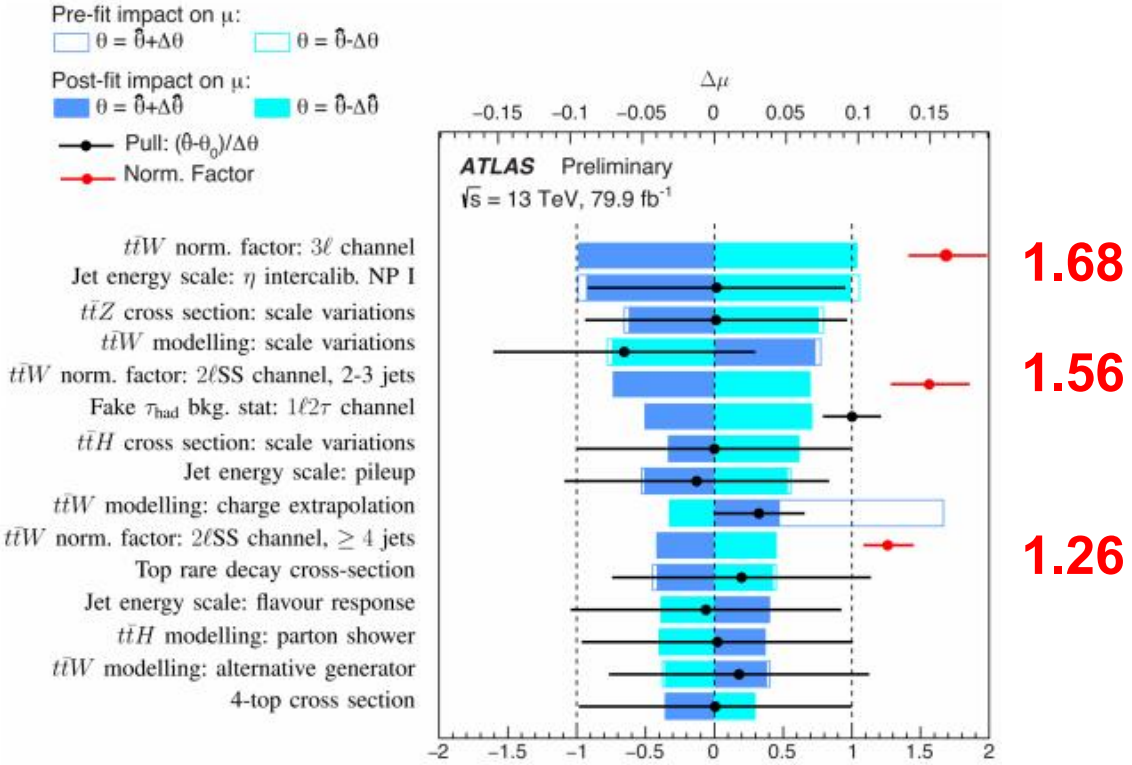
马连良教授
Shandong University

Outline

- **Overview of $t\bar{t}H$ multilepton ($t\bar{t}H$ML) results @80 fb^{-1}**
- **Overview of $t\bar{t}W$ML inclusive measurement @139 fb^{-1}**
- **Analysis of $t\bar{t}H$ML legacy paper**
  - ✓ MC samples
  - ✓ Objects selection
  - ✓ Main backgrouds estimation in 0tau channel
  - ✓ SRs/CRs definition in 2LSS0tau channel
  - ✓ Combined fit

ttHML@80 fb^{-1}

- **Previous Run2 result**
  - ✓ NF(ttW) very high -------- Predict σ(ttW)=600.8 fb
  - ✓ μ(ttH) quite low (0.58)
  - ✓ Observed significance: 1.8σ (expected 3.1σ)



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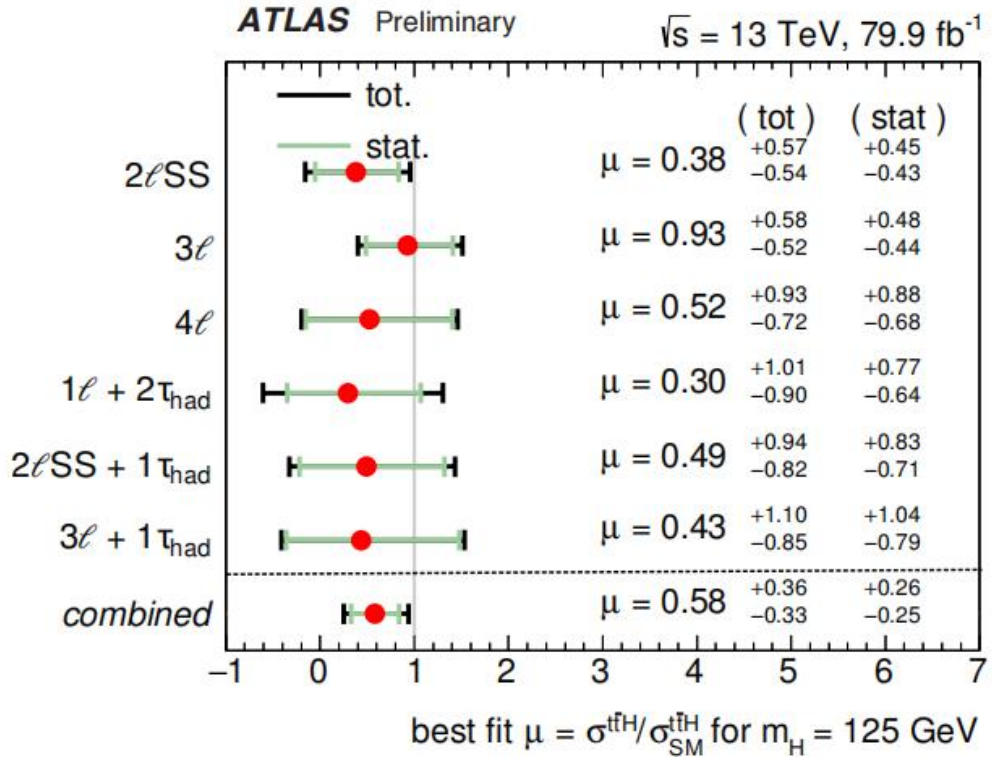

ttW inclusive (XS and charge ratio)

- **σ(ttW) = 890 ± 50 (stat) ± 70 (syst) fb (9% relative uncertainty)**
  - ✓ Predict σ(ttW)=615.78 fb, $\mu_{t\bar{t}W} = 1.44^{+0.14}_{-0.13}\ (tot.)$
- **σ(ttW+)/σ(ttW-) = 1.95 ± 0.21 (stat) ± 0.16 (syst) → consistent with SM**

Process	Generator (alternative)	Parton Shower (alternative)	PDF	Tune
$t\bar{t}W$	SHERPA-2.2.10 (MADGRAPH5_AMC@NLO)	SHERPA-2.2.10 (PYTHIA-8)	NNPDF 3.0 NNLO	SHERPA default
$t\bar{t}H$	POWHEG-BOX	PYTHIA 8	NNPDF 3.0 NLO / NNPDF 2.3 LO	A14

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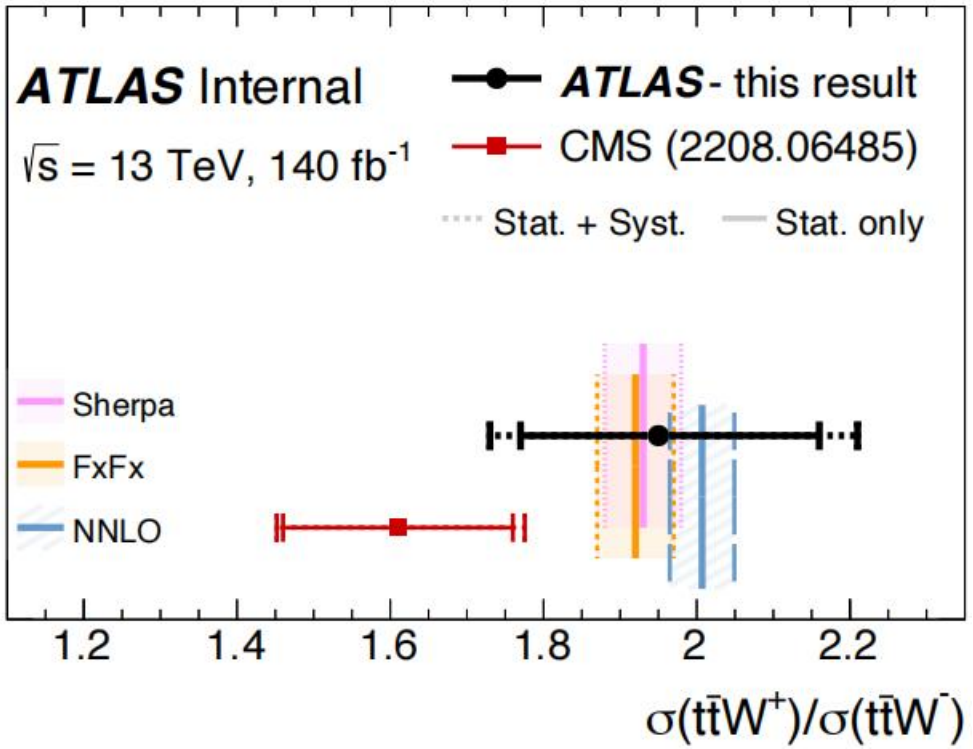
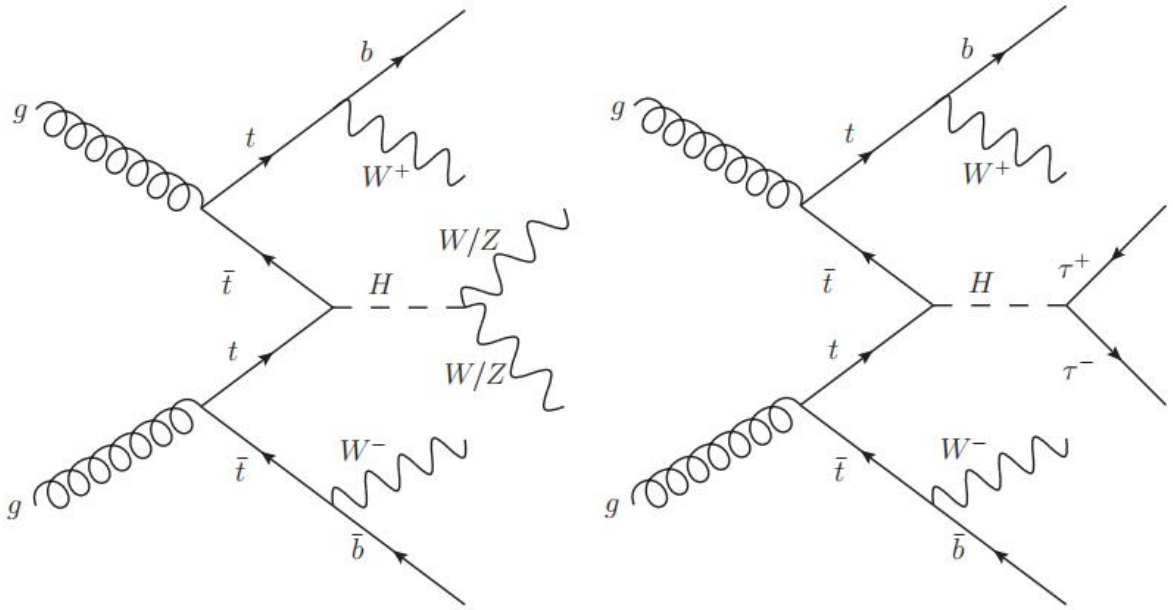


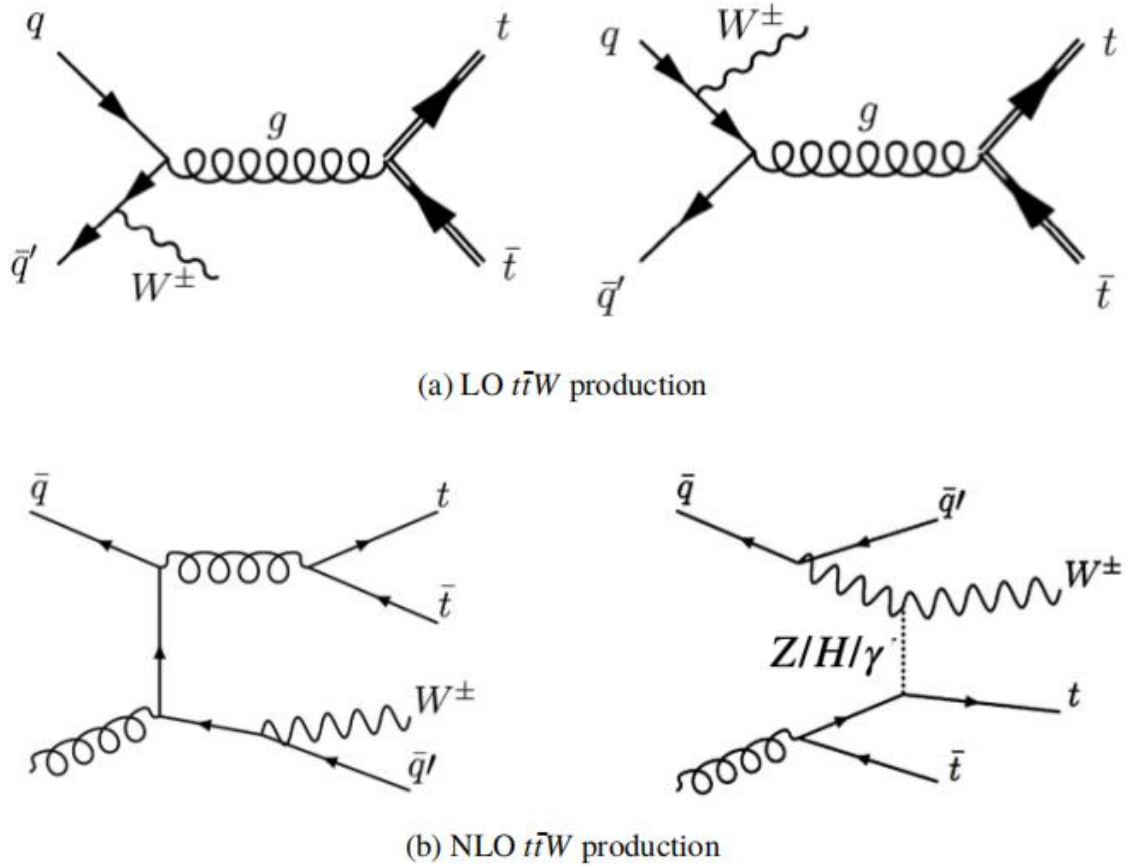
Legacy Run 2 ttHML Analysis strategy

- **Full Run 2!**
- **Build on ttW measurement for 0tau channels**
  - ✓ Make use of improved understanding of fakes and ttW modelling
  - ✓ Fake estimate similar but improved
- **Similar approach as 80 fb^{-1} analysis for tau channels**
  - ✓ Dedicated fake estimates
- **Combined inclusive fit result**
- **New interpretations**
  - ✓ Higgs reconstruction with GNN
  - ✓ Differential STXS measurement
  - ✓ Higgs CP measurement
    - ➢ Significant sensitivity coming from measuring tH
  - ✓ EFT and self-coupling sensitivity has been studied but would be left for combination rather than dedicated interpretation in this paper.

Feyman diagrams

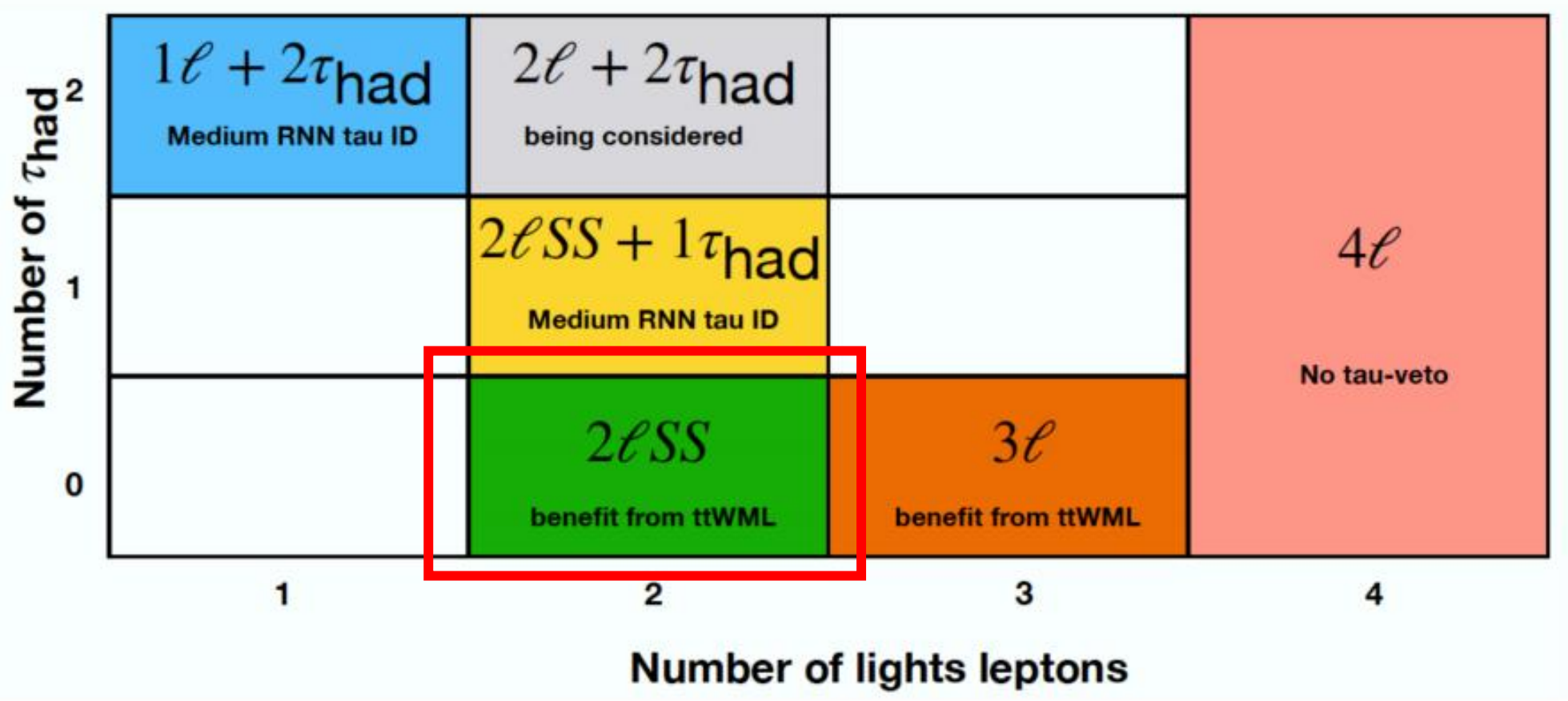


$t\bar{t}H$ process



$t\bar{t}W$ process

Legacy Run 2 ttHML



- **2LOS+1τ_{had} also shows good sensitivity (~1.5σ)**
  - ✓ More tests are still ongoing to determine whether adding this channel

MC sample

- **Latest samples used:**
  - ✓ Powheg+Py8 for ttH signal
  - ✓ Sherpa for ttW
  - ✓ aMC+Py8 for ttZ

- **Standard alternative samples used for systematics**

Process	Generator	ME order	Parton shower	PDF	Tune
$t\bar{t}H$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(POWHEG-BOX)	(NLO)	(HERWIG7.0.4)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(MG5_aMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
$t\bar{t}W$	SHERPA 2.2.10	MEPS@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(FxFx NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
	(POWHEG)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}W$ (EW)	SHERPA 2.2.10	LO	SHERPA	NNPDF3.0NNLO	SHERPA default
	(MG5_aMC)	(LO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14)
$t\bar{t}\ell\ell$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(MG5_aMC)	(NLO)	(HERWIG 7)	(NNPDF3.0NLO)	(H7-UE-MMHT)
	(MG5_aMC)	(NLO)	(PYTHIA 8)	(NNPDF3.0NLO)	(A14 VAR3C)
$t\bar{t} \to W^+bW^-\bar{b}\ell^+\ell^-$	MG5_aMC	LO	PYTHIA 8	NNPDF3.0LO	A14
$t\bar{t}t\bar{t}$	MG5_aMC	NLO	PYTHIA 8	NNPDF3.1NLO	A14
$t\bar{t}$	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
	(POWHEG-BOX)	NLO	(HERWIG7.1.3)	(NNPDF3.0NLO)	(H7-UE-MMHT)
$t\bar{t}t$	MG5_aMC	LO	PYTHIA 8	NNPDF2.3LO	A14
Single top (t-, Wt-, s-channel)	POWHEG-BOX	NLO	PYTHIA 8	NNPDF3.0NLO	A14
VV, $qqVV$, VVV	SHERPA 2.2.2(1)	MEPS@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z \to \ell^+\ell^-$	SHERPA 2.2.1	MEPS@NLO	SHERPA	NNPDF3.0NNLO	SHERPA default
$Z \to \ell^+\ell^-(\gamma \to e^+e^-)$	POWHEG-BOX	NLO	PYTHIA 8	CTEQ6L1NLO	A14
$Z \to \ell^+\ell^-(\gamma* \to e^+e^-)$	POWHEG-BOX	NLO	PYTHIA 8	CTEQ6L1NLO	A14

Objects selection

- **Triggers:**

Channel	2ℓSS	3ℓ	4ℓ	2ℓSS+$1\tau_{had}$	1ℓ+$2\tau_{had}$	2ℓ+$2\tau_{had}$
Triggers	SL || DL	SL || DL	DL only	DL only	SL only	DL only

- **Loose light leptons: used for channels association**
  - ✓ Loose (-LH) ID and FCLoose isolation for μ(e)
- **Jets: PFlow collection w/ anti-kt R=0.4**
- **Flavour-tagging: DL1r b-tagger**
- **Overlap removal procedure used**
- **Tighter light leptons required within channels (except 4L)**
  - ✓ Tighter ID and PLIV-based isolation
- **Additional cuts on electrons to reject those from conversion/QMisID**
- **Changes wrt ttW analysis**
  - ✓ Use a looser b-tagging WP from [==1b @60% || >=2b @77%] to [>=1b @85%]
  - ✓ Relaxing pT cut of the 2LSS leptons in 3L regions: from 20 GeV to 15 GeV

Leptons selection

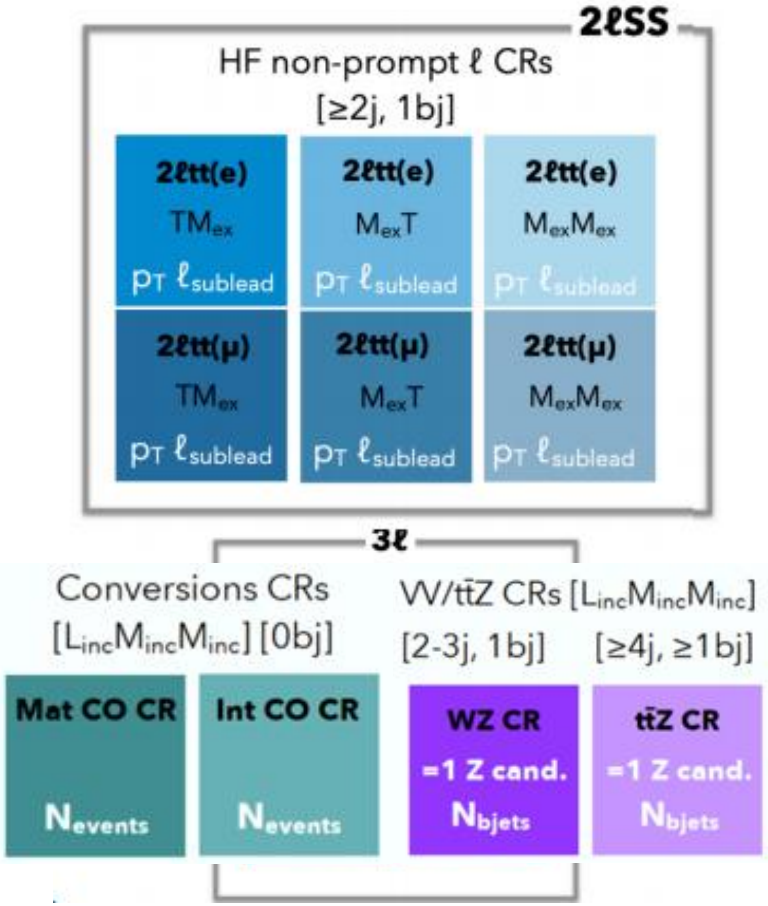
- **Pseudo-continuous Prompt Lepton Improved Veto (PLIV) WPs definition:**

	e				μ			
	L	M	M_{ex}	T	L	M	M_{ex}	T
LooseVar_Rad isolation	Yes				Yes			
Non-prompt lepton BDT (PLIV)	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*	No	*Tight*	*Tight-not-VeryTight*	*VeryTight*
Identification	Loose	Tight			Loose	Medium		
Charge mis-assignment veto (ECIDS)	No	Yes			N/A			
Conversion rejection	No	Yes			N/A			
Transverse impact parameter significance $\lvert d_0\rvert/\sigma_{d_0}$	< 5				< 3			
Longitudinal impact parameter $\lvert z_0 \sin\theta\rvert$	< 0.5 mm							

Table 5: Loose (L), Medium (M), Medium exclusive (M_{ex}), and Tight (T) light lepton definitions.

Main backgrounds estimation in 0tau

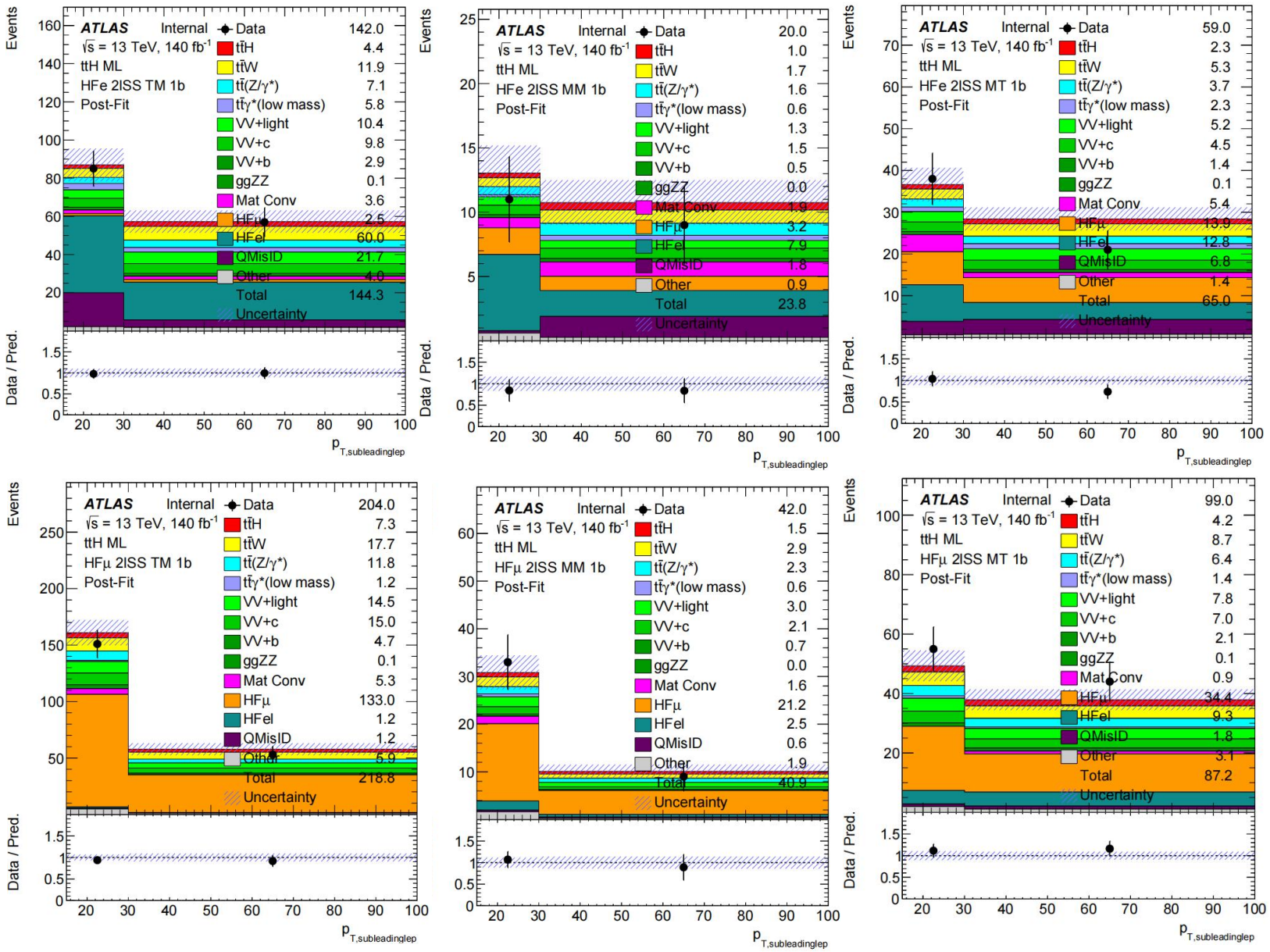
- **Background estimate through "Template fit"**



Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
$N_{b-\text{jets}}$	1 b@85	≥ 1 b@85	0 b@85	1 b@85
Lepton requirement		3ℓ	$\mu\mu e^{*}$	2ℓSS
Lepton definition		(L, M, M)		$(T, M_{\text{ex}}) \parallel (M_{\text{ex}}, T) \parallel (M_{\text{ex}}, M_{\text{ex}})$
Lepton p_{T} [GeV]		(10, 20, 20)		(20, 20)
$m^{\text{SF}}_{\ell^+\ell^-}$ [GeV]		> 12	> 12	–
$\lvert m^{\text{SF}}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]		< 10	> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]		–	< 10	–
$m_T(\ell_0, E_{\text{T}}^{\text{miss}})$ [GeV]		–		< 250 for TM_{ex} and $M_{\text{ex}}T$ pairs
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{\text{ex}}, M_{\text{ex}}T, M_{\text{ex}}M_{\text{ex}})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC	$2\ell\text{tt(e)}_{TM_{\text{ex}}}$, $2\ell\text{tt(e)}_{M_{\text{ex}}T}$, $2\ell\text{tt(e)}_{M_{\text{ex}}M_{\text{ex}}}$
			3ℓMatC	$2\ell\text{tt}(\mu)_{TM_{\text{ex}}}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}T}$, $2\ell\text{tt}(\mu)_{M_{\text{ex}}M_{\text{ex}}}$

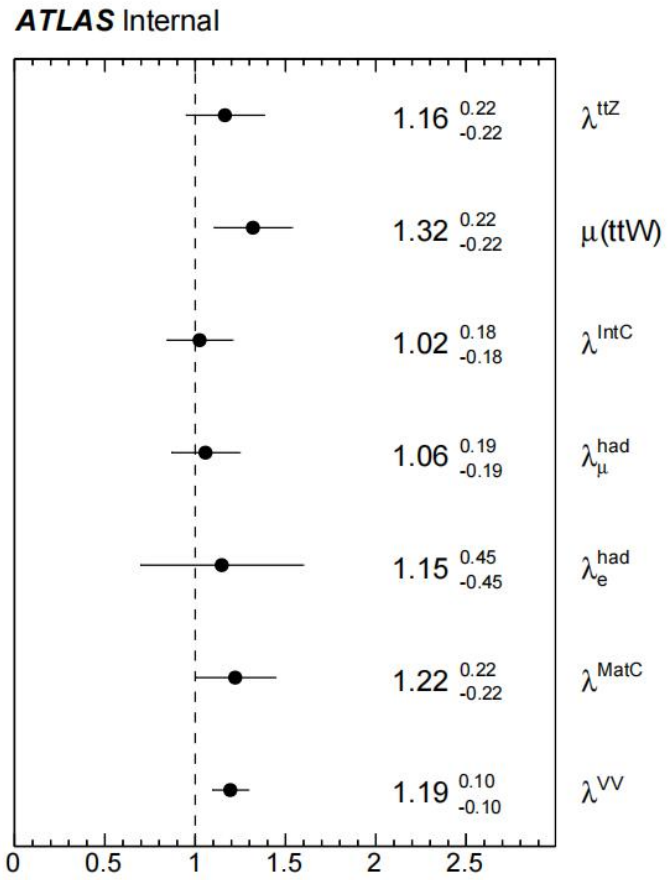
Main backgrounds estimation in 0tau

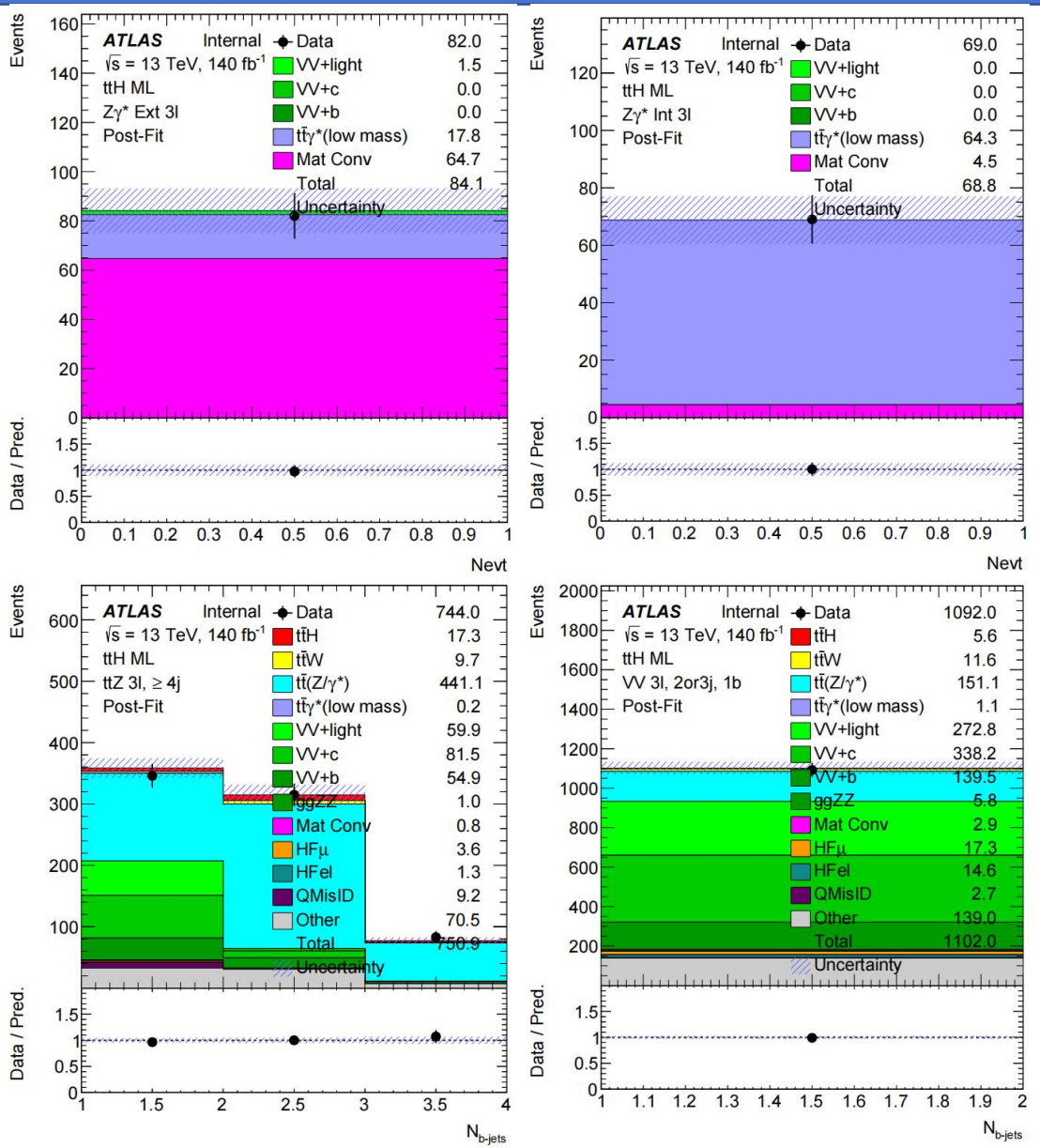
- **Fake lepton regions**
- **Good modelling using pseudo-continuos PLIV WPs**



Main backgrounds estimation in 0tau

- **Good modelling in conversions, diboson and ttZ CRs**
- **CR-only results are shown**





Signal region strategy

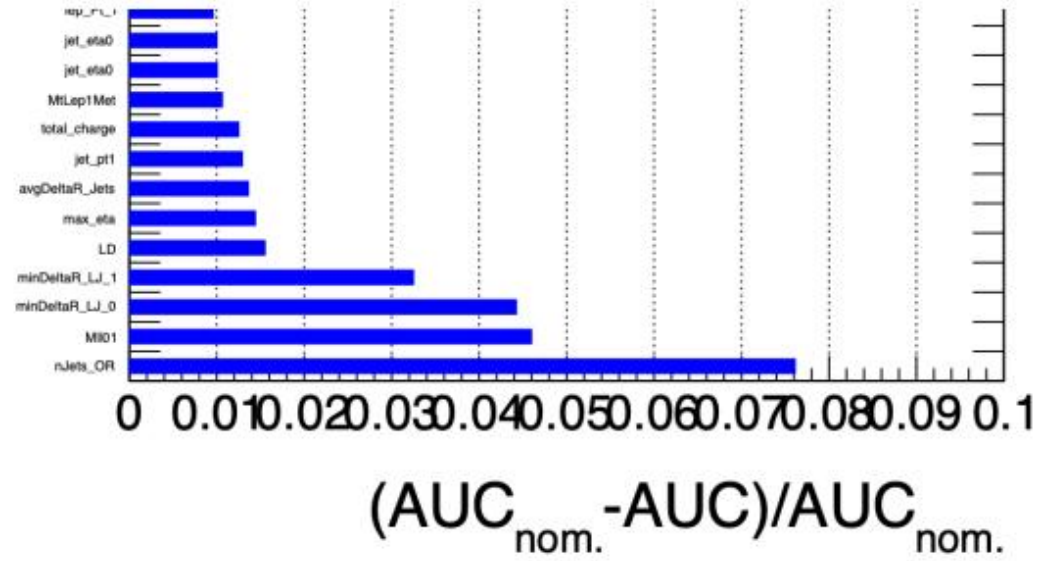
- **Define individual channel inclusive SRs**
  - ✓ Determine sensitivity and understand CRs and fit
  - ✓ Compare to results in 80 fb^{-1} analysis

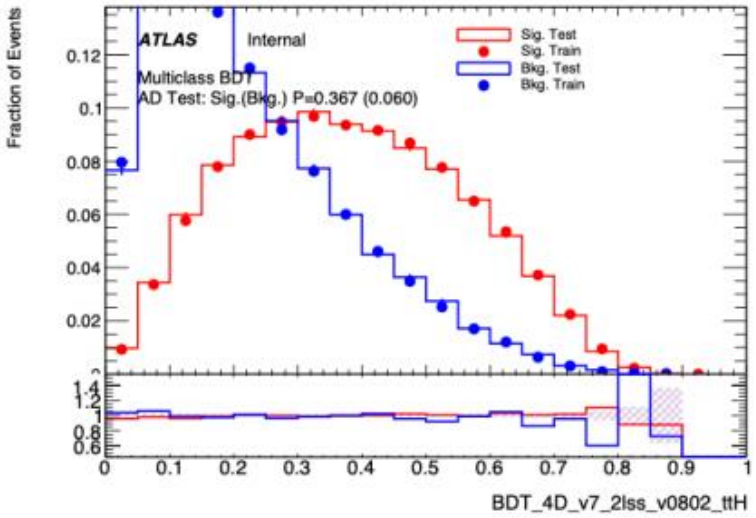
➢ **2LSS0tau pre-selection for MVA**
  - ✓ ==2 SS VeryTight PLIV leptons with pT>15 GeV
  - ✓ No τ(had) candidates in the event
  - ✓ ≥ 3 jets, of which ≥ 1 must be b-tagged with 85% WP

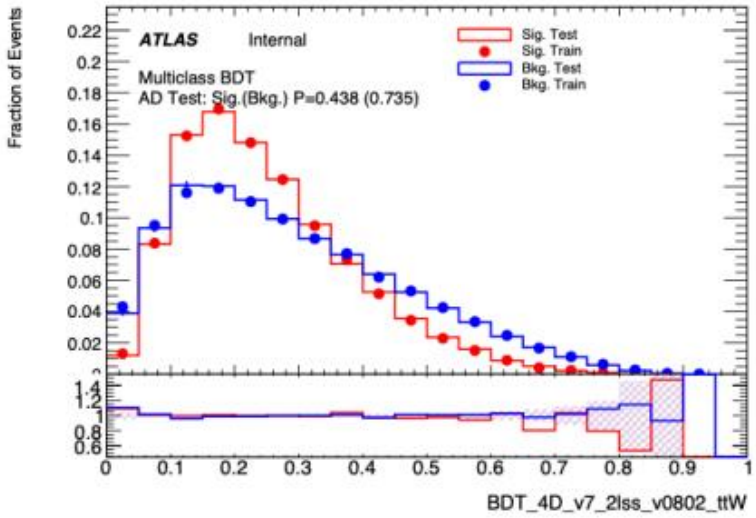
2LSS0tau MVA

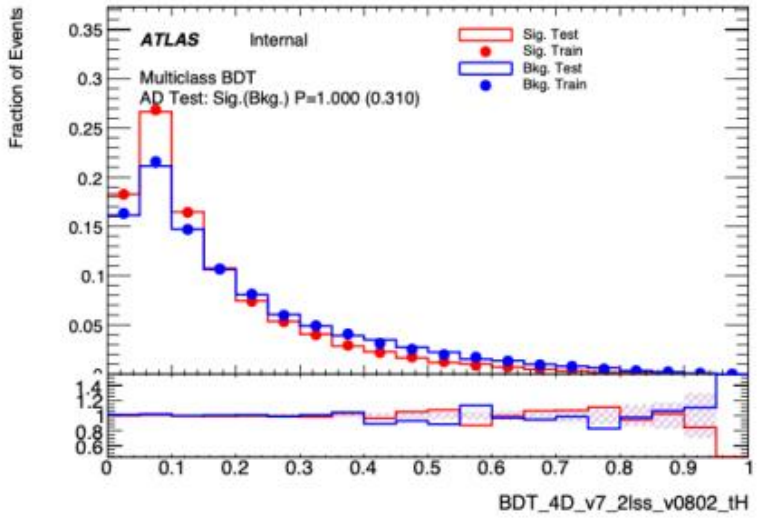
- **4D multiclass BDT is employed**
  - ✓ Trained using [mva-trainer]
  - ✓ 20 input variables
  - ✓ 4 output nodes: ttH, tH, ttW and Other

- **NJets, m(ll), and dR(l, jet) among most important inputs**



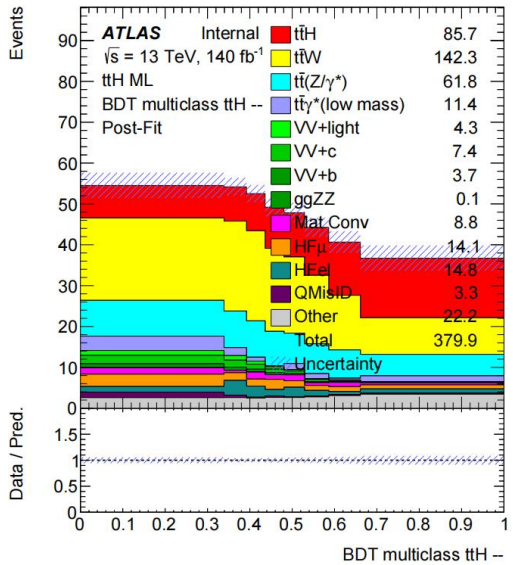


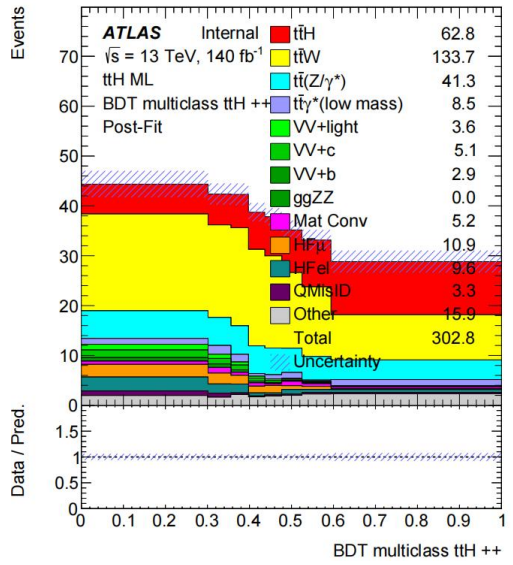


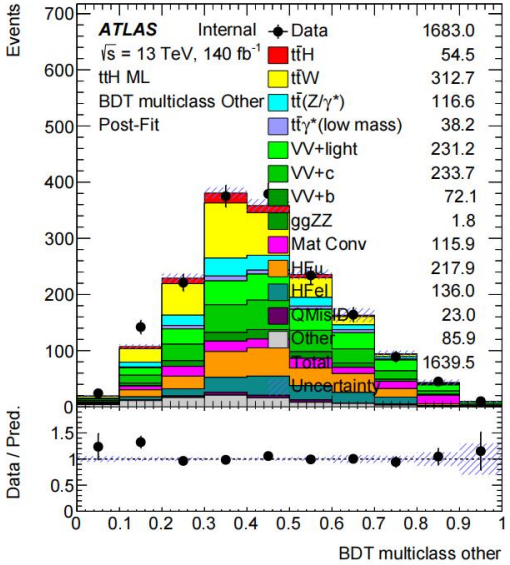


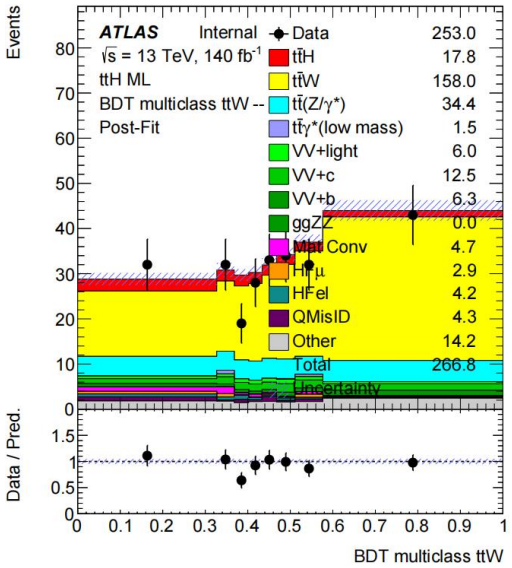
2LSS0tau SR/CR

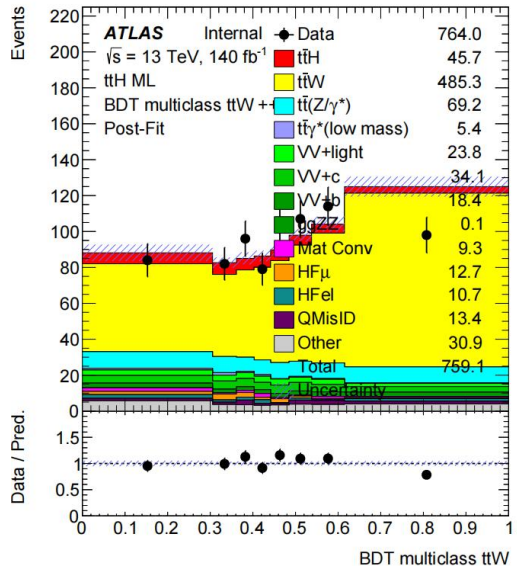
- **Standalone channel results**
- **Each event goes into which region depends on its largest BDT score**
  - ✓ tH node score is ignored
  - ✓ ttH SR: ttH>ttW && ttH>other
- **ttH and ttW regions split by charge**
- **Generally good modelling seen in CRs**
- **SRs blinded**









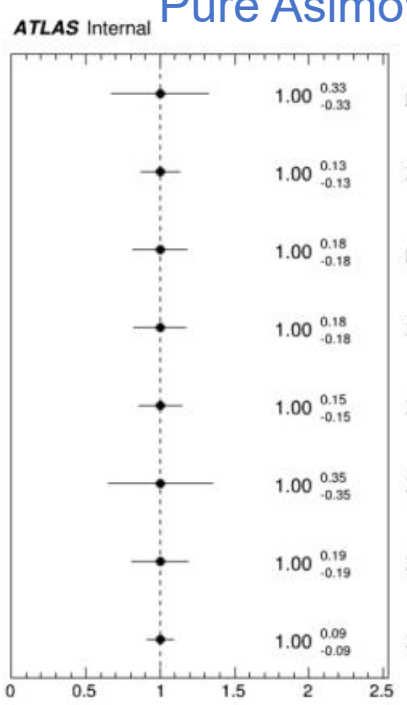


2LSS0tau Fit results

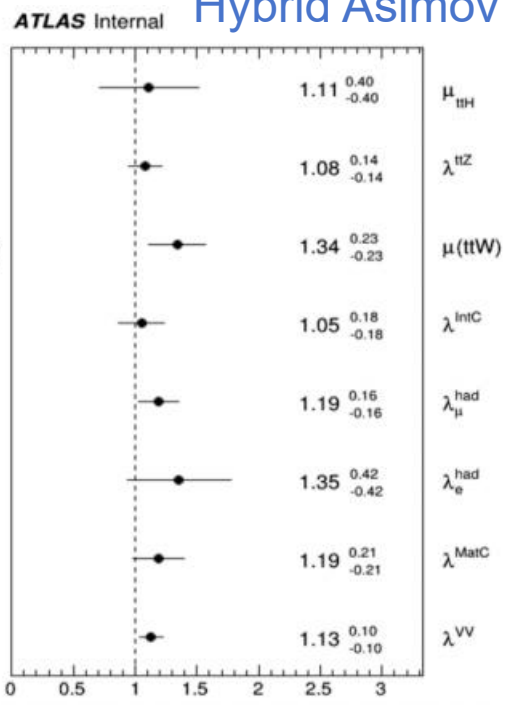
- **Standalone channel results**
- **Δμ(ttH)=0.33, 3.12σ significance**
  - ✓ 80 fb^{-1} = 2.3σ expected
- **NFs compatible with unity except NF(ttW) similar to previous measurements**
- **Highest ranked uncertainties**
  - ✓ ttW modelling
  - ✓ NF(ttW)
  - ✓ 4-tops XS (50%)

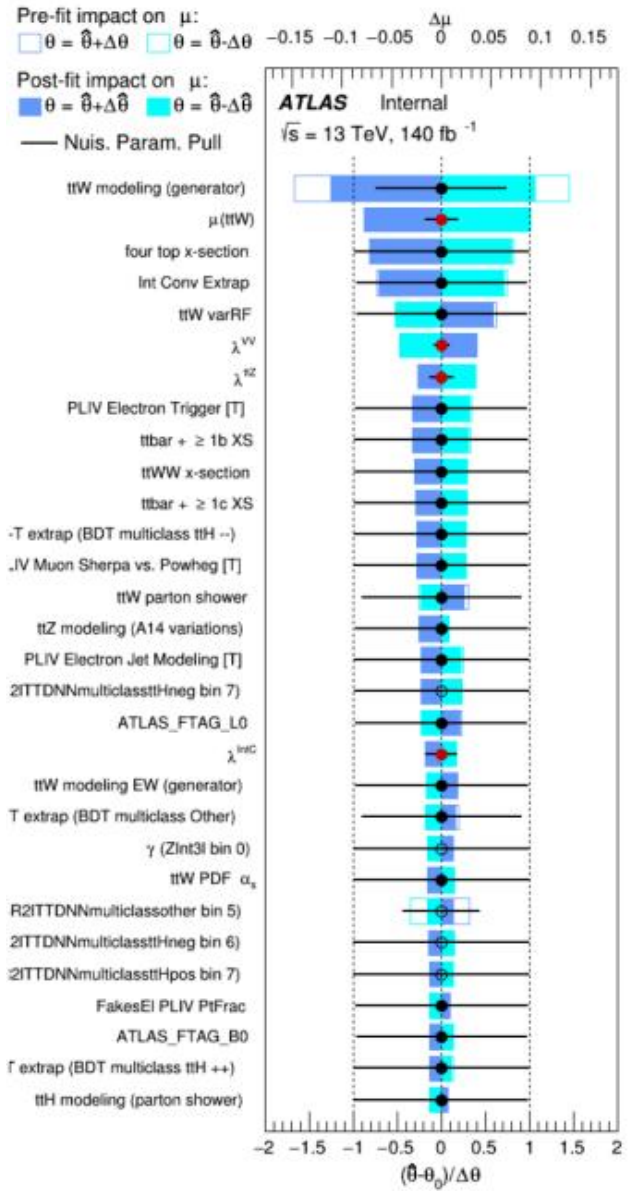
Hybrid Asimov: Real data in CRs and Asimov data in SRs

Pure Asimov



Hybrid Asimov



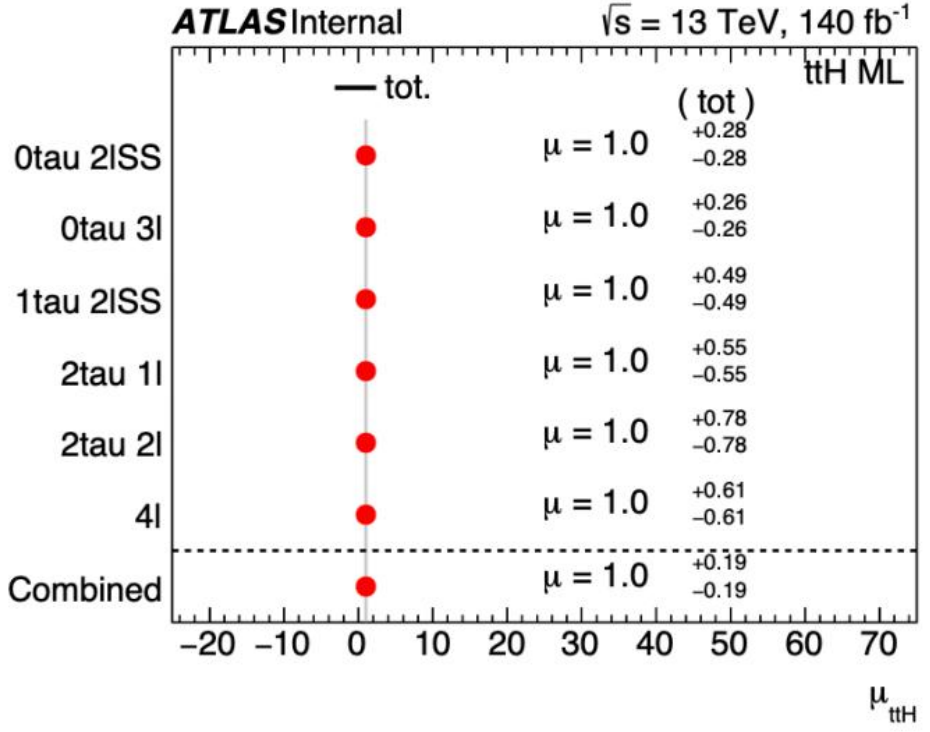


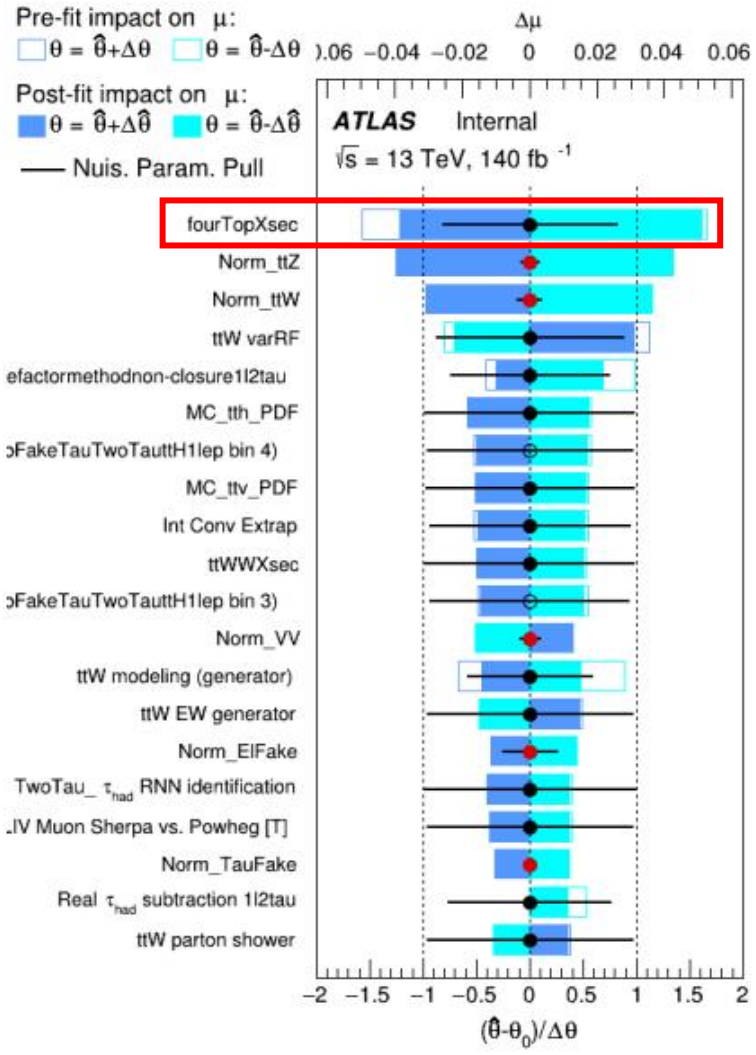
Combined fit

- **Combined fit correlations:**
  - μ_{ttH}: correlated through all channels
  - μ_{ttZ}: correlated in 0τ, 1τ and $4l$ channels
  - μ_{VV}: correlated in 0τ, 1τ and $4l$ channels
  - μ_{ttW}: correlated in 0τ, 1τ
  - Fake norm factors not correlated, as different fake estimation techniques and different fake lepton working points are used
- **Systematics**
  - ✓ All included where they exist for a given channel
  - ✓ Correlated when identical, otherwise uncorrelated

Combined fit

- **Δμ(ttH) = ±0.19 (significance is 5.7σ)**
  - ✓ 80 fb^{-1} = 3.1σ (expected)
- **Both statistics and systematics have a large impact on the uncertainty**
  - ✓ 12% statistics
  - ✓ 15% systematics
- **2LSS0tau and 3L0tau are most sensitive channels**
  - ✓ 1Tau channel helps reduce correlation with μ(ttW)
- **Preliminary ranking shows the largest uncertainties coming from σ(tttt), NF(ttZ) and NF(ttW)**





Summary

- **Significant sensitivity improvements since previous result**
- **Analysis strategy is frozen**
- **Some items still to be completed but these are well defined**
  - ✓ STXS measurement
  - ✓ Systematics correlaiton among all channels in the fit
  - ✓ CP measurement
  - ✓ ttH combination

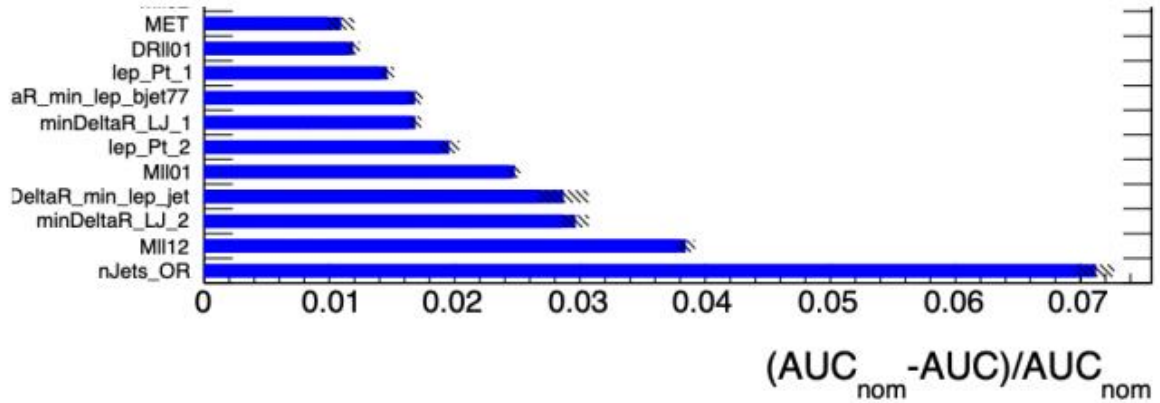
Thanks!

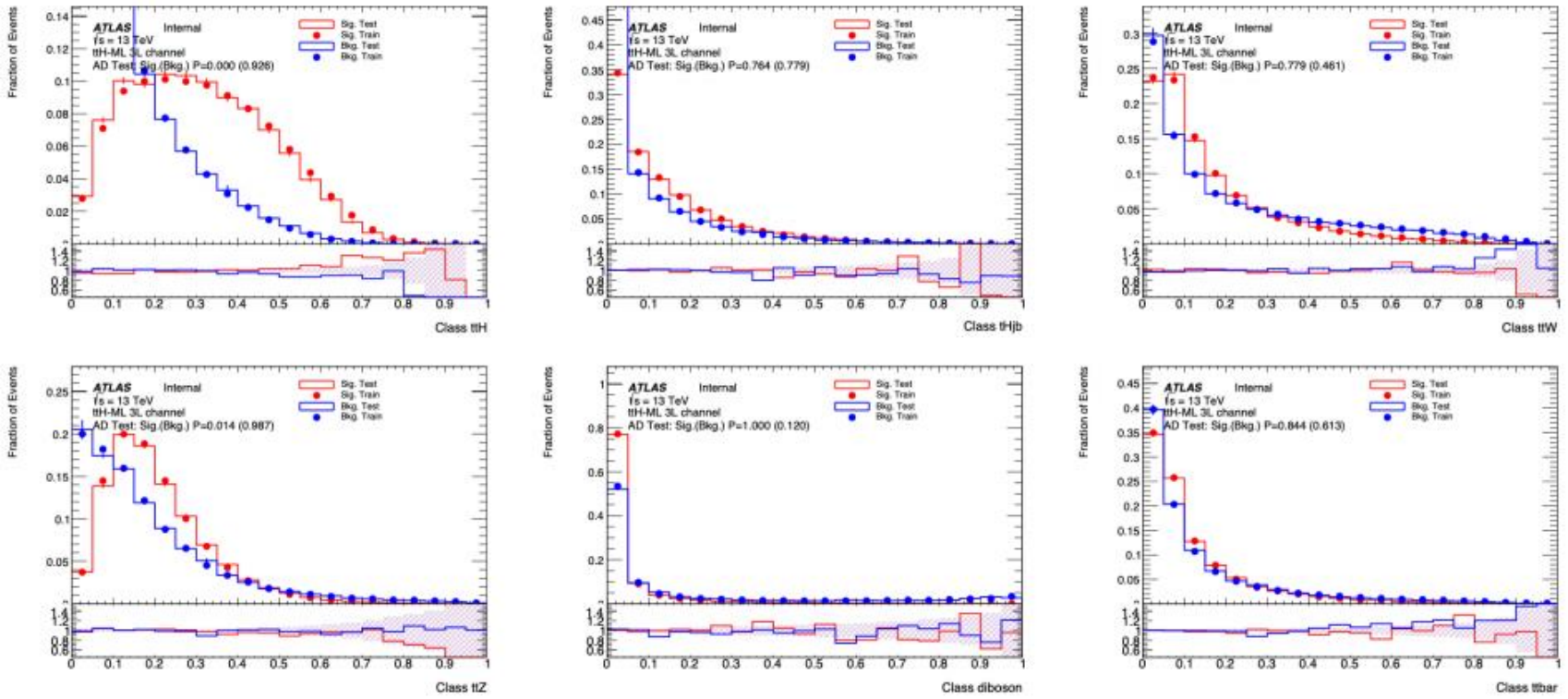
Back up

3L0tau MVA

- **6D multiclass BDT is employed**
  - ✓ Trained using mva-trainer
  - ✓ 16 input variables
  - ✓ 6 output nodes: ttH, tH, ttW, ttZ, VV & ttbar

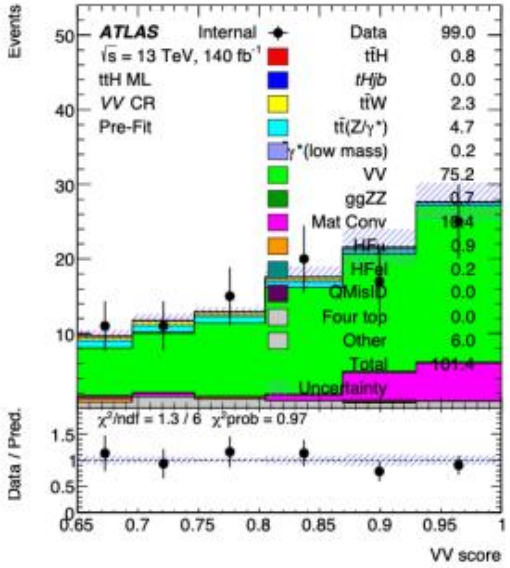
- **NJets, M(ll), dR(l, jet) among the most important variables**

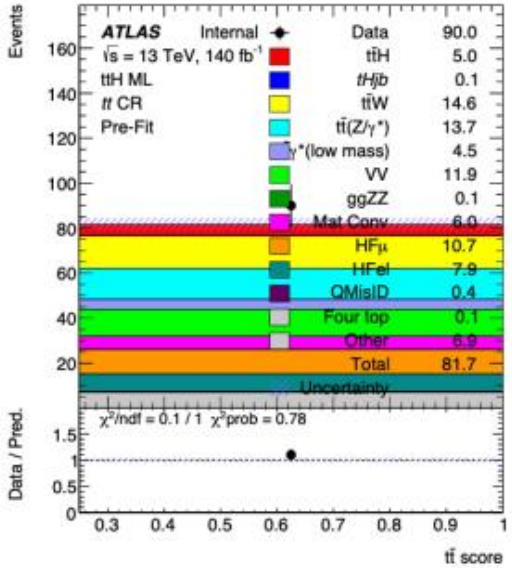


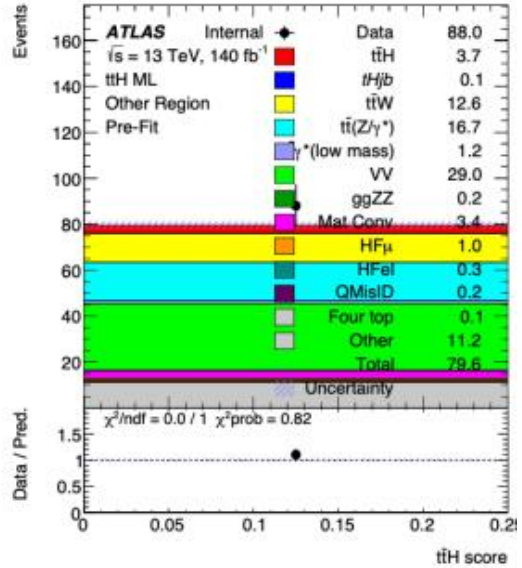


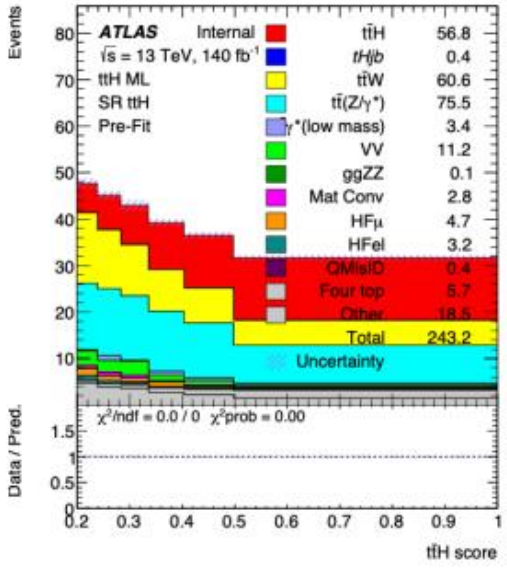
3L0tau SR/CR

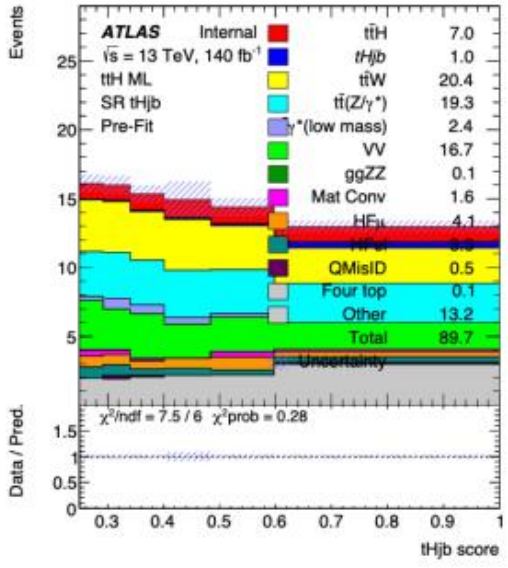
- **Pre-fit modelling generally good in CRs**
- **Uncertainty band does not yet systematics**

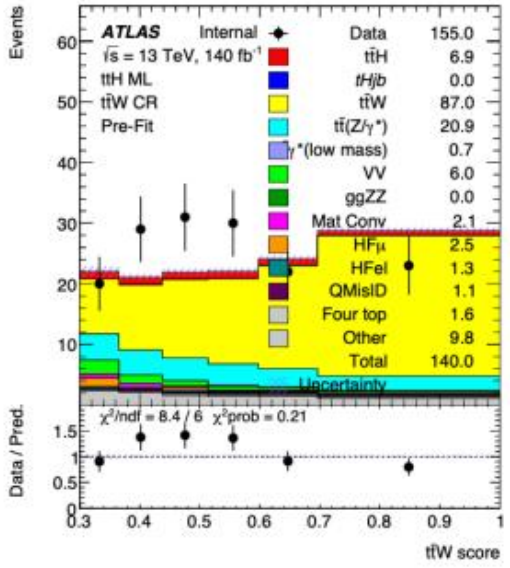


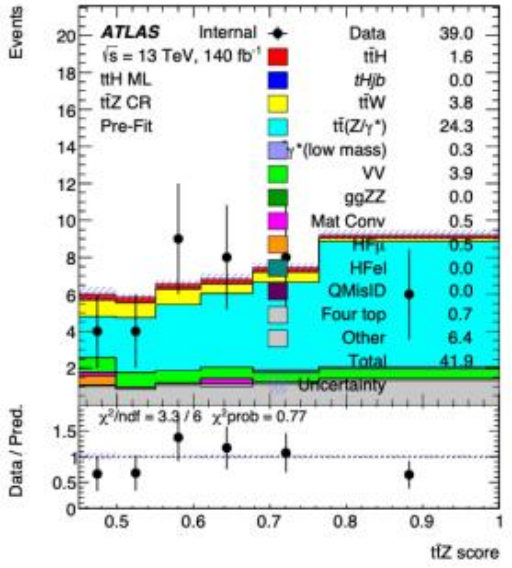






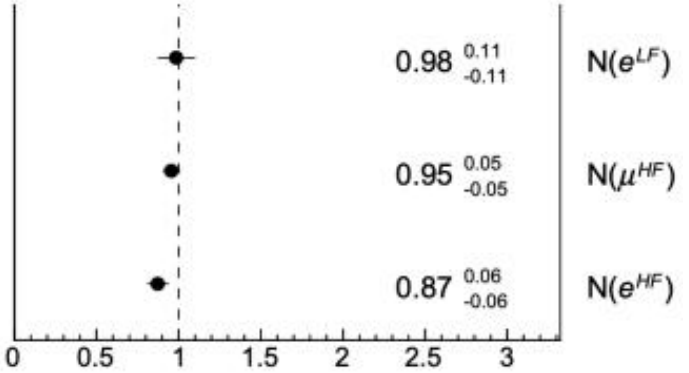


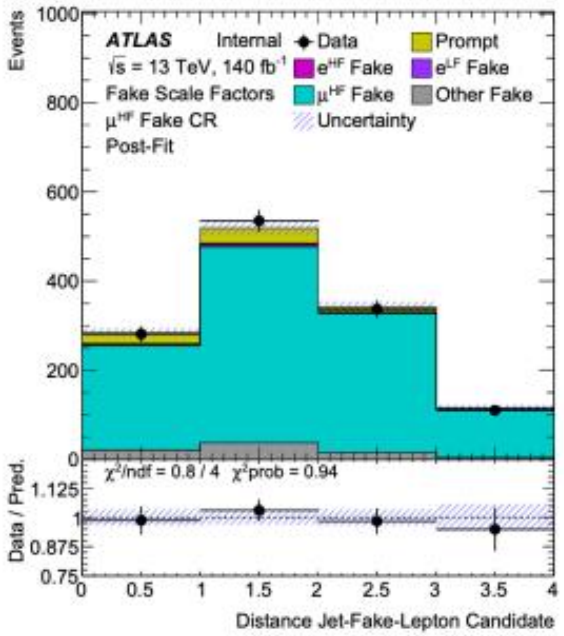


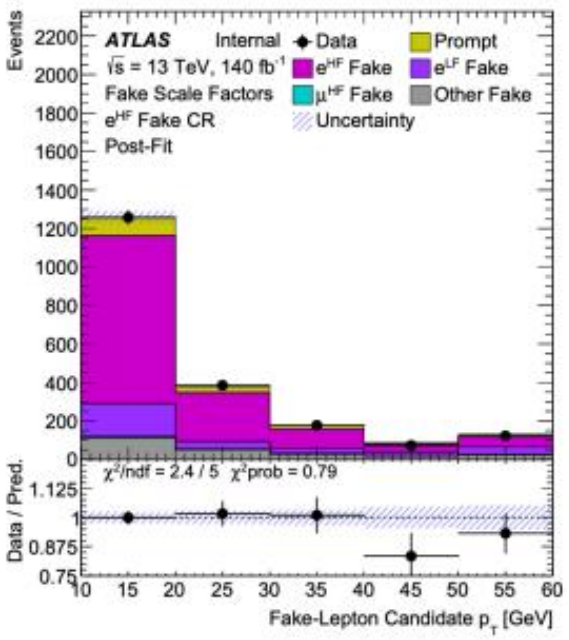


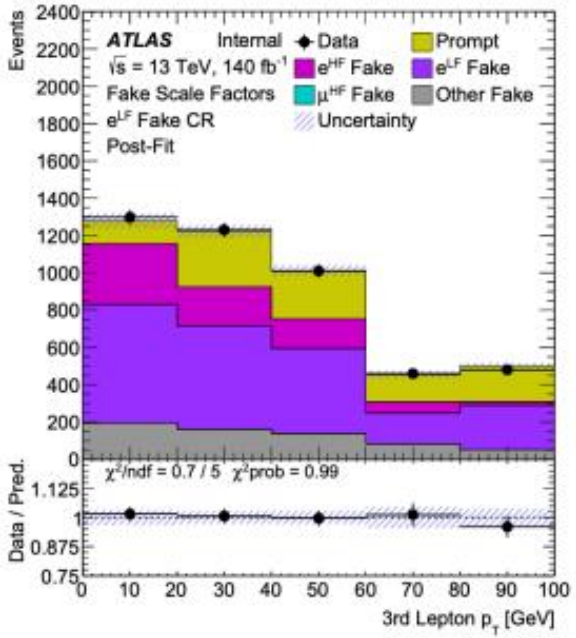
Extended template fit - 4L

- Identical philosophy to standard template fit
- But modified to looser lepton definitions and adding dedicated light flavour electron region
  - Classification by highest pT lepton in event





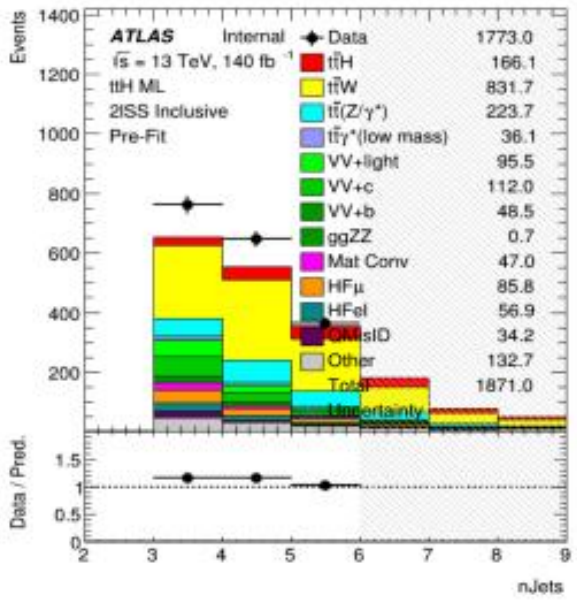


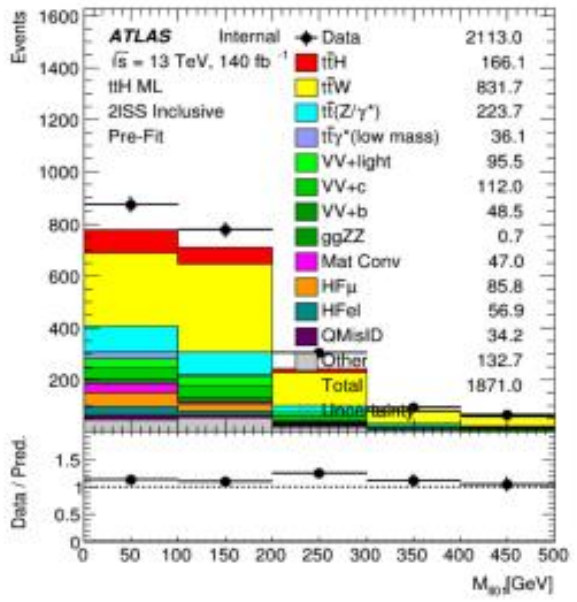


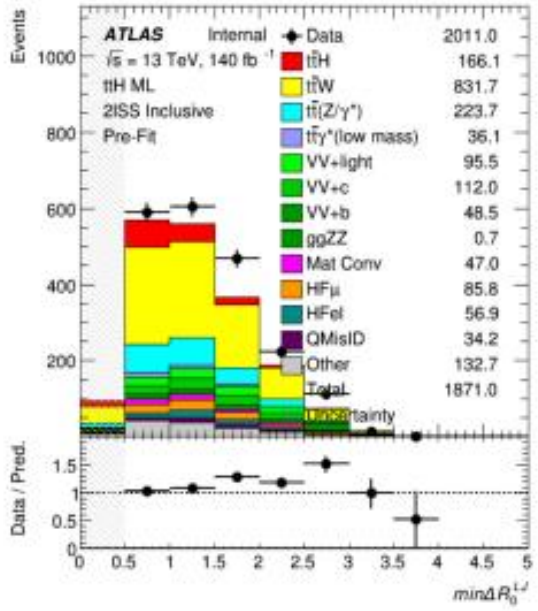
2LSS0tau

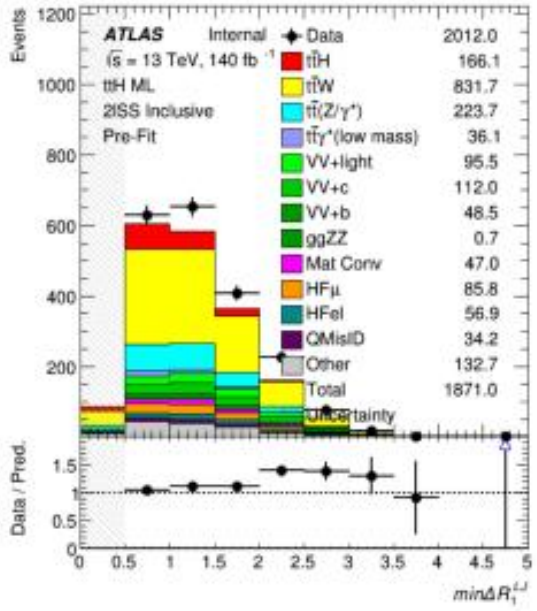
- **Modelling of input variables is checked**
  - ✓ Pre-fit normalisation off-set, this is expected to be fixed with ttW NF post-fit

- **Otherwise modelling is generally very good**



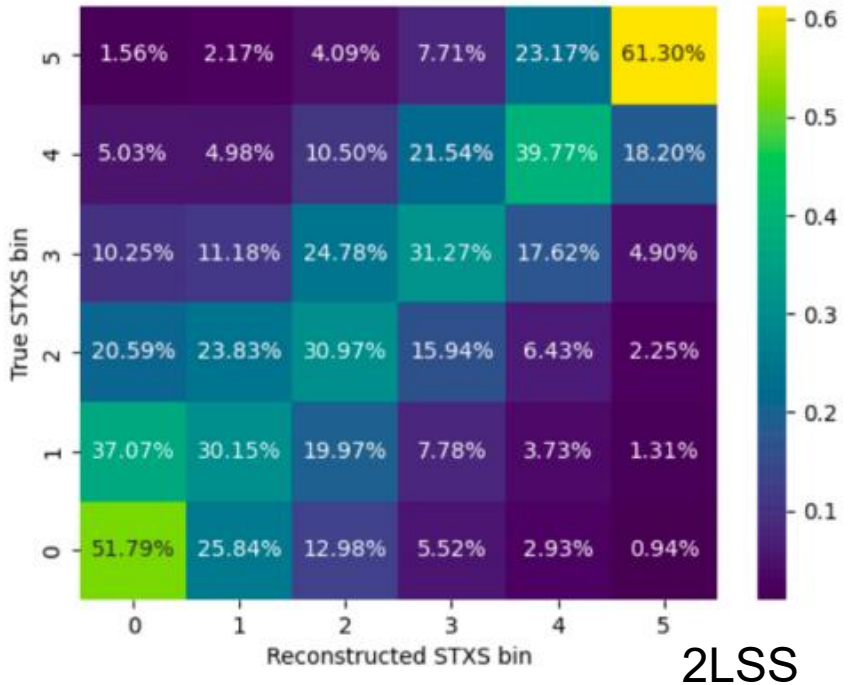




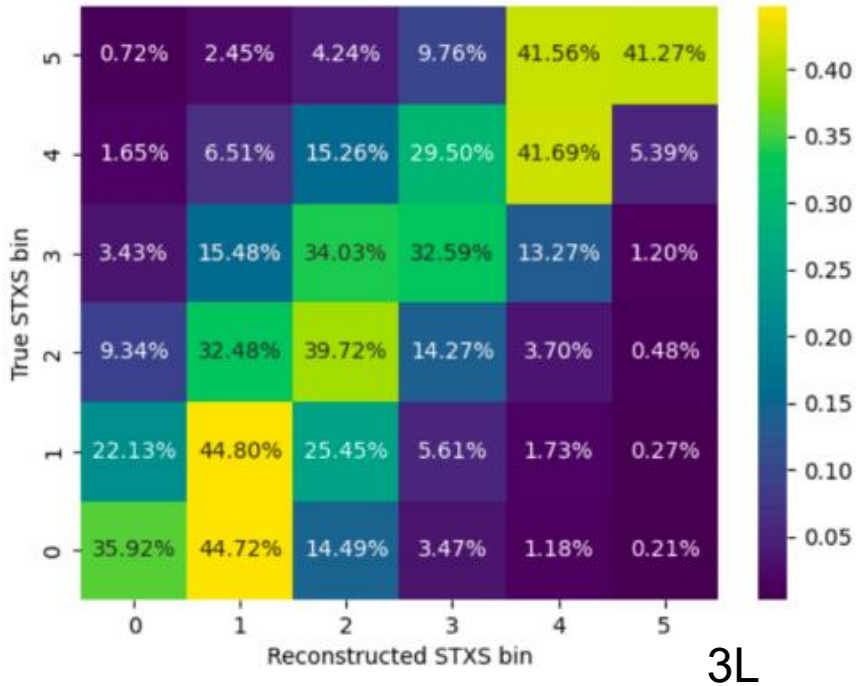


STXS | GNN

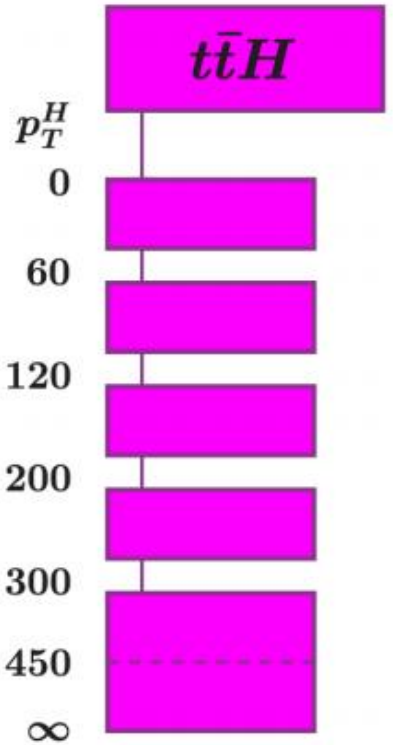
- **STXS interpretation is new for this round**
  - ✓ Used in 2LSS0tau and 3L0tau
- **Full Higgs reconstruction not possible in ML final state**
- **Using GNN for pT(H) reconstruction**
  - ✓ Trained for true STXS bin as a global attribute



2LSS



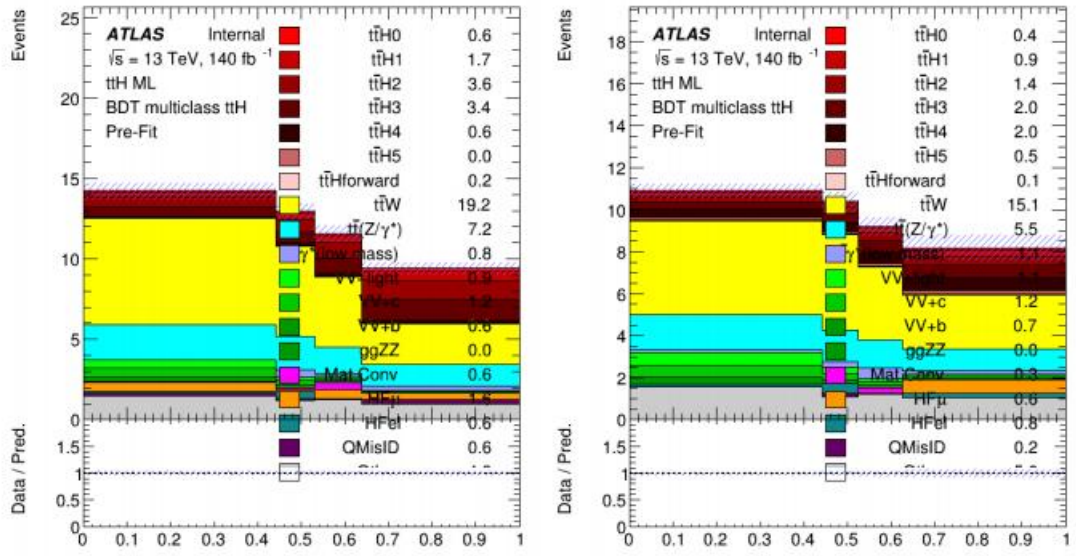
3L

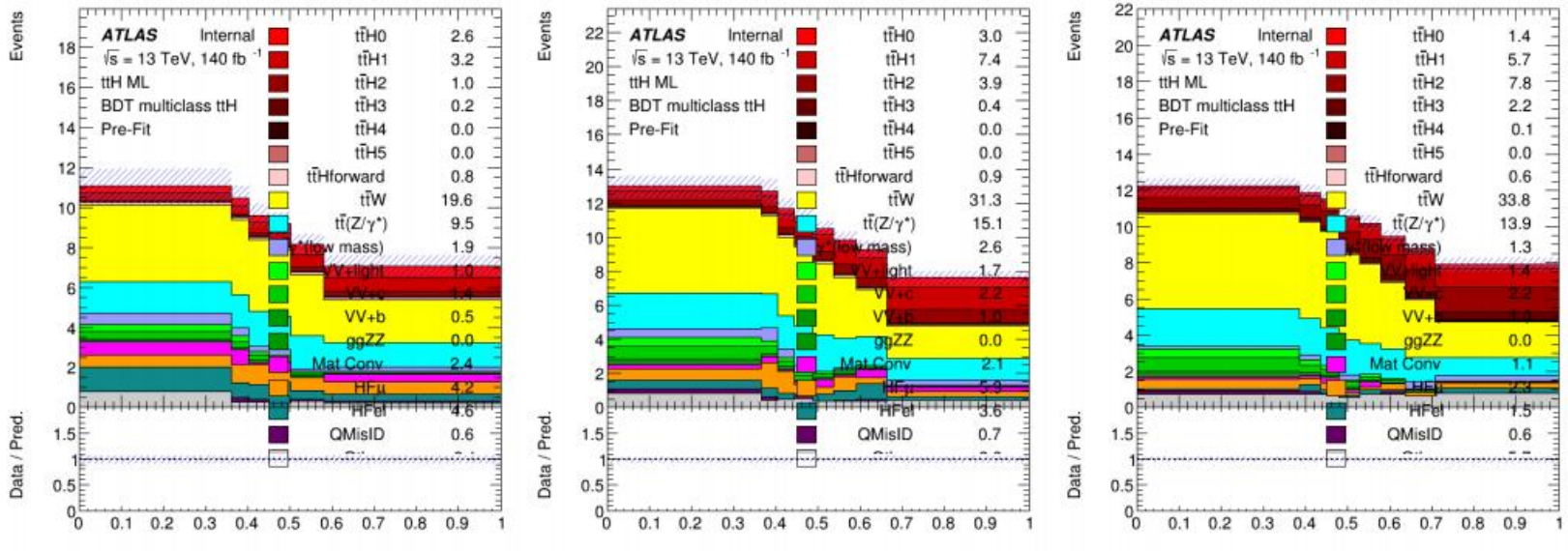


STXS | 2LSS0tau negtive SR

- **Several optimisations tried**
  - ✓ Conservative vs agressive binning
  - ✓ Different combinations of STXS bins

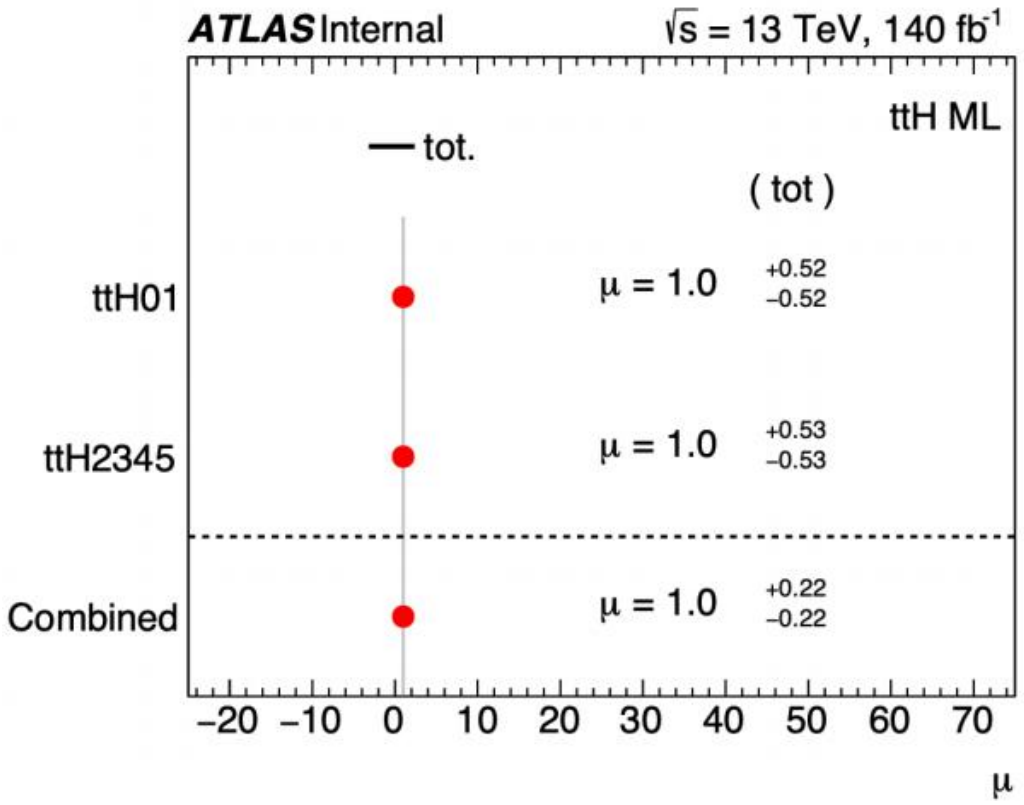
- **Decided to go with**
  - ✓ 5 reco bins (merging two highest bins)
  - ✓ More aggressive BDT binning
  - ✓ Fitting two STXS bins for ttHML alone
    - ➢ All 6 STXS bins in ttH combination





STXS | Results

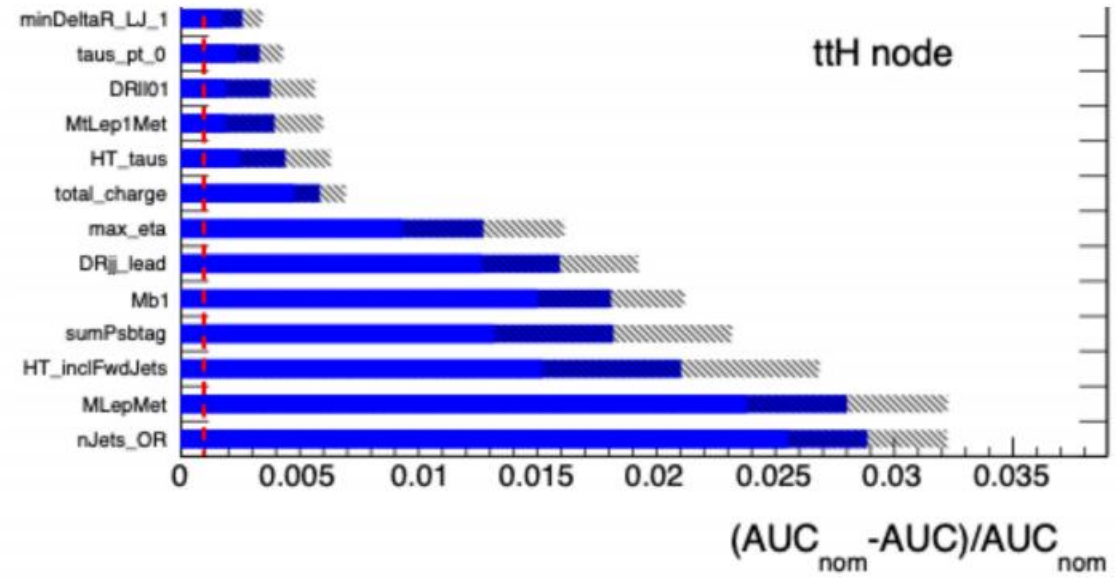
- **Results in ~50% uncertainty on combined bins**
- **~50% correlation between signal strengths**
- **Combined fit is compatible with previously shown inclusive fit**
  - ✓ Will use STXS binning for inclusive fit from now on.
- **Planning to also include 2tau channels in STXS fit**
  - ✓ Studies ongoing

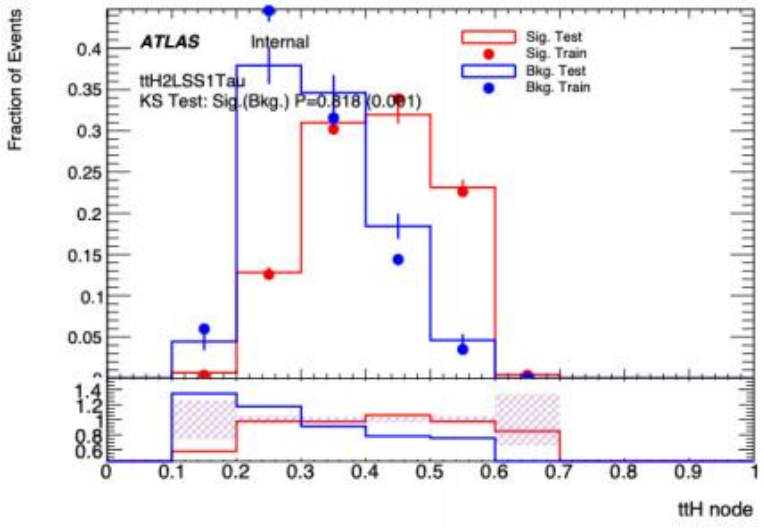


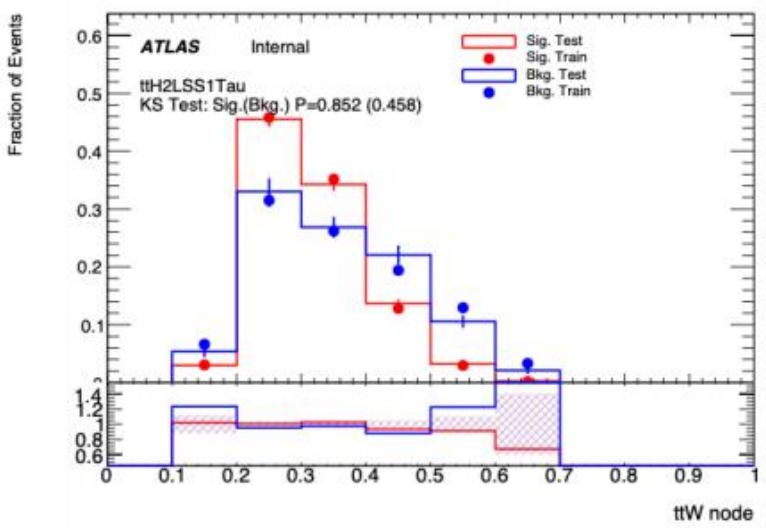
2LSS1tau MVA

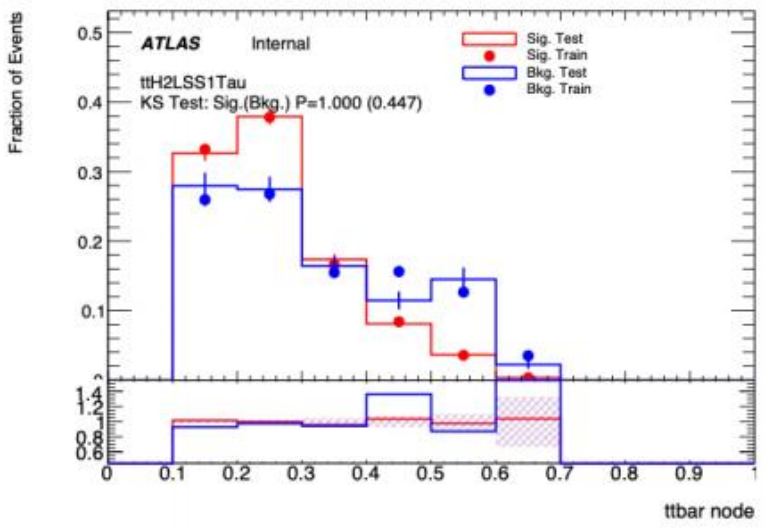
- **3D multiclass BDT is employed**
  - ✓ Trained using [mva-trainer]
  - ✓ 17 input variables
  - ✓ 3 output nodes: ttH, ttW and tt

- **nJets, MLepMet, HT**



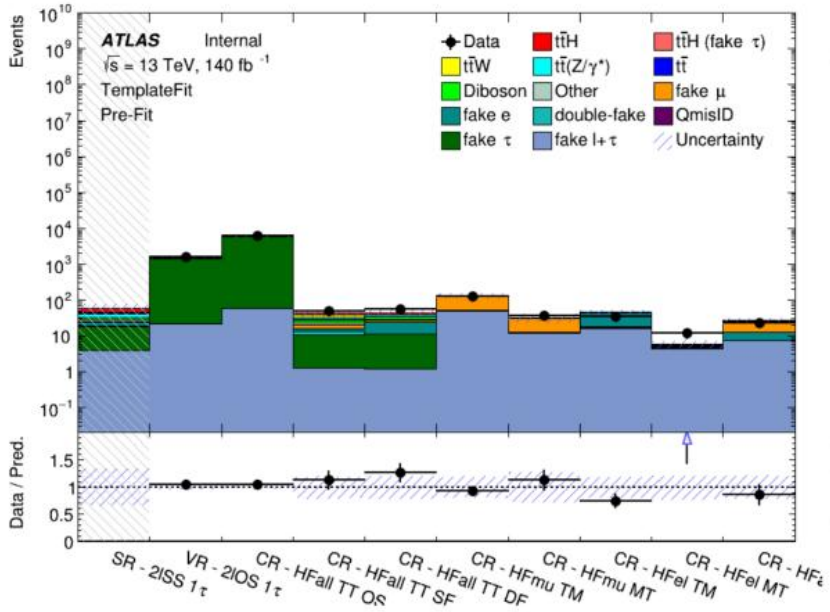


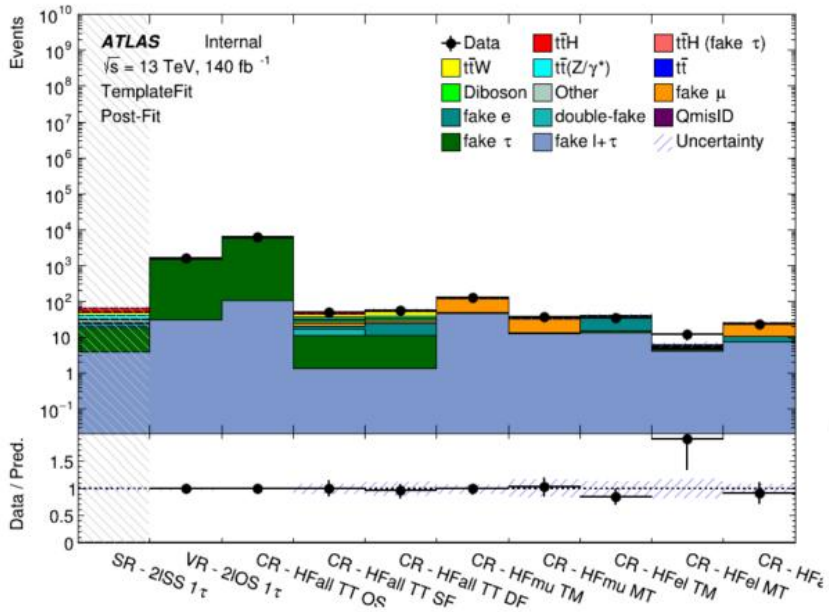


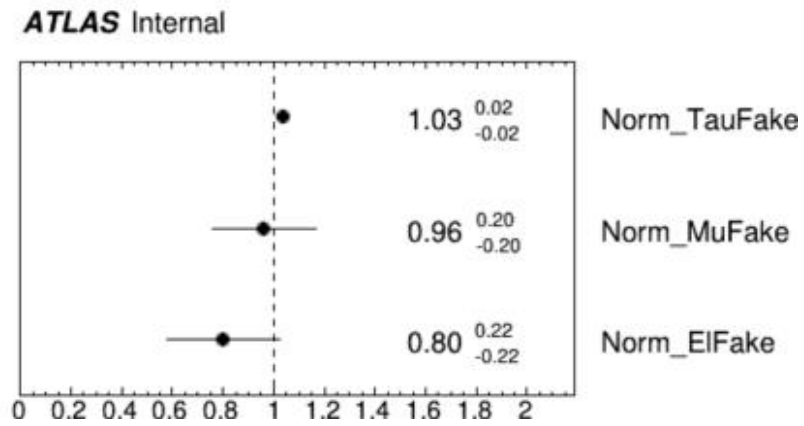


Extended template fit - 2LSS1tau

- **Template Fit method extended to include the fake-τ(had) scale factor**
  - ✓ 8 control regions with mixed e/μ definitions (TT, TM, MT, MM)
  - ✓ 8 templates with single and double fake leptons (e/μ/τ)
    - ➢ fake component selected using truth class information
    - ➢ no distinction between HF/LF/ɣ-conv
  - ✓ 3 scale factors: Ne, Nμ and Nτ
    - ➢ double-fake templates use multiple scale factors (e.g., fake e+τ is scaled by Ne*Nτ)

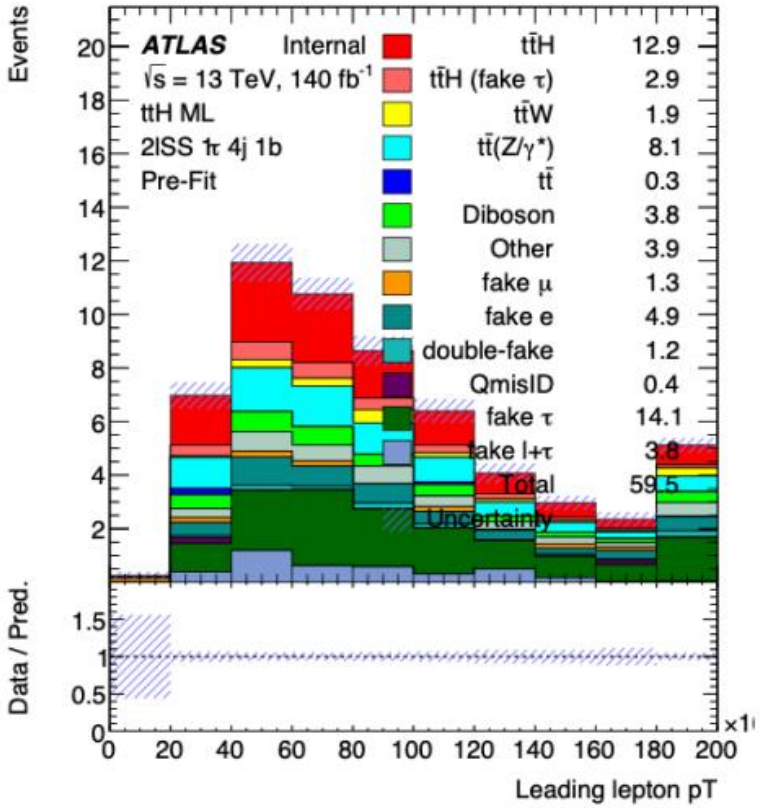


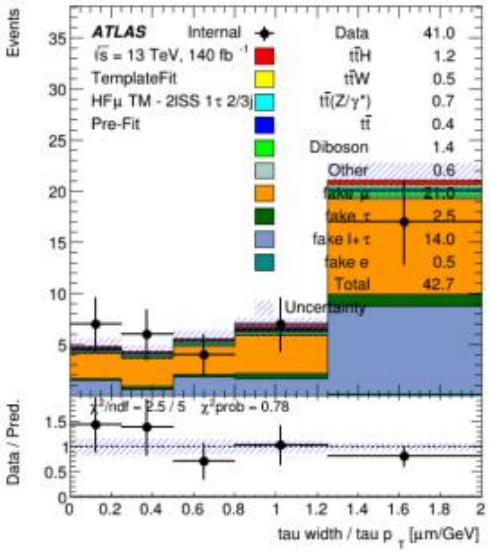


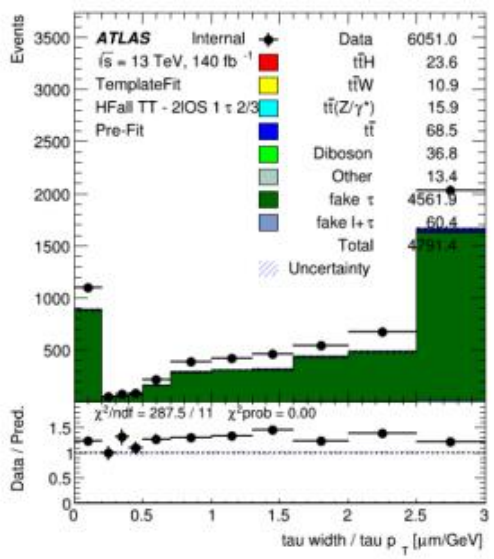


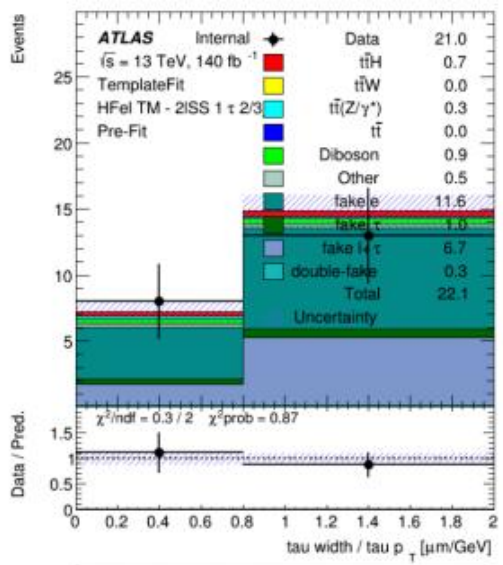
2LSS1tau SR/CR

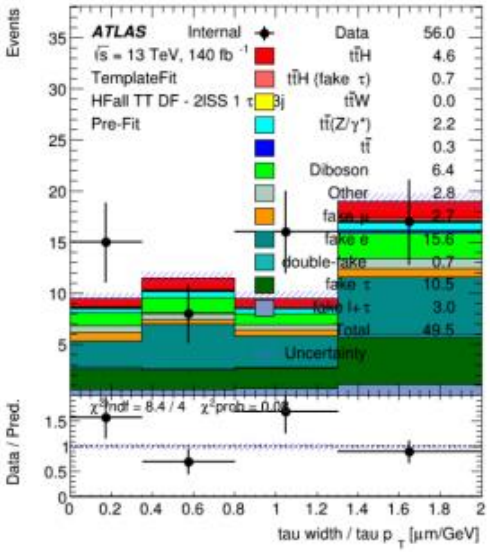
- **BDT still needs to be implemented in fit.**
- **Cut-based SR used for current fits**

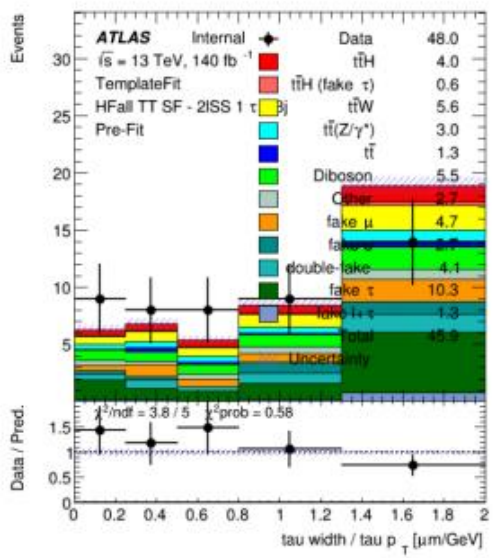


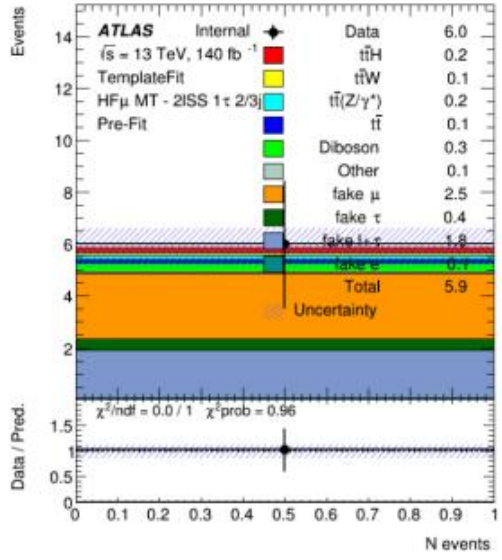








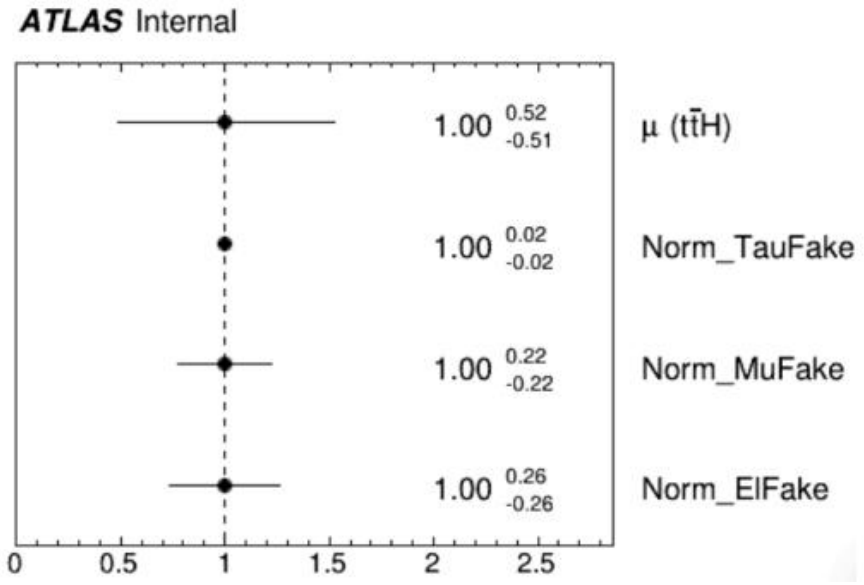


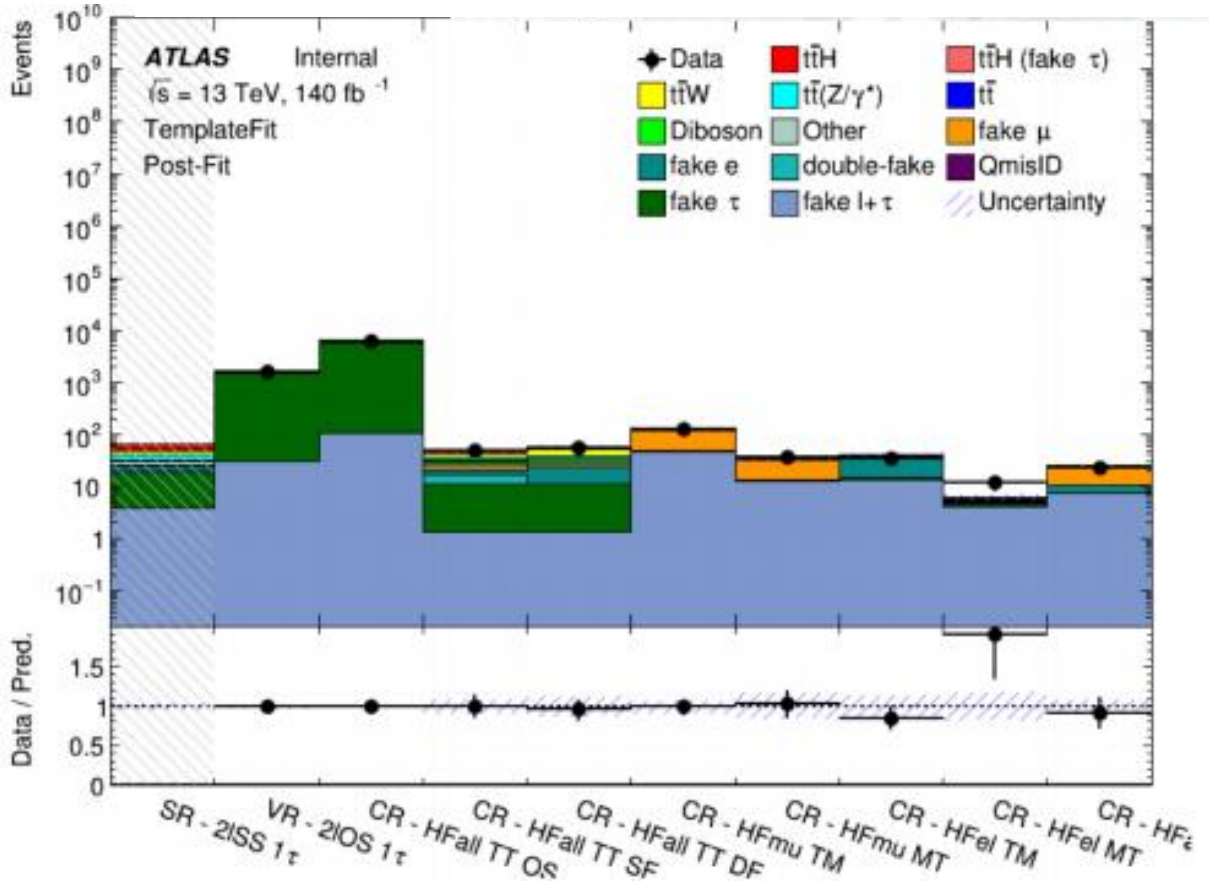


2LSS1tau Fit results

- **Standalone channel results**
  - ✓ total unc on μ(ttH) is 0.51
  - ✓ 80ifb = ~0.95 expected

- **Several systematics still missing**
  - ✓ JES/JER/FTag/ttH&ttbar modelling/…





Preselection regions

- **2LSS0tau**
  - ✓ ==2 SS VeryTight leptons with pT>15 GeV
  - ✓ No τ(had) candidates in the event
  - ✓ ≥ 2 jets, of which ≥ 1 must be b-tagged with 85% WP

- **3L0tau**
  - ✓ ==3 leptons with total charge equal to ±1
    - ➢ Opposite charge to others is loose with pT>10 GeV
    - ➢ SS di-lep pair is tight with pT>15 GeV
    - ➢ OS mll 10 GeV Z veto and mll>12 GeV
  - ✓ ≥ 2 jets, of which ≥ 1 must be b-tagged with 85% WP

- **4L**
  - ✓ ==4 loose light leptons
  - ✓ sum of lepton charges is zero
  - ✓ ≥2j ≥1 must be b-tagged with 85% WP
  - ✓ Mass cuts
    - ➢ Each OS mll>12 GeV, Higgs (->4l) 5 GeV veto

- **1L2tau**
  - ✓ ==1 light lepton pT>27
  - ✓ ==2 OS RNN Medium had. taus pT>20 GeV
  - ✓ ≥ 3 jets + 1 b-tag (77% WP)

- **2SSL1tau (cut-based SR)**
  - ✓ ==1 RNN Medium hadronic tau
  - ✓ ==2 SS PLIV tight light leptons pT>15 GeV
  - ✓ SF leptons m(ll) 10 GeV Z veto
  - ✓ ≥ 3 jets + 1 b-tag

- **2LOS2tau**
  - ✓ ==2 OS light lepton pT>10
    - ➢ OS mll 10 GeV Z veto and mll>12 GeV
  - ✓ ==2 OS RNN Medium had. taus pT>20 GeV
  - ✓ Nbjet > 0