上海交通大學
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ATLAS EXPERIMENT

Measurement of the associated production of a Higgs boson and a top-quark pair in multilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

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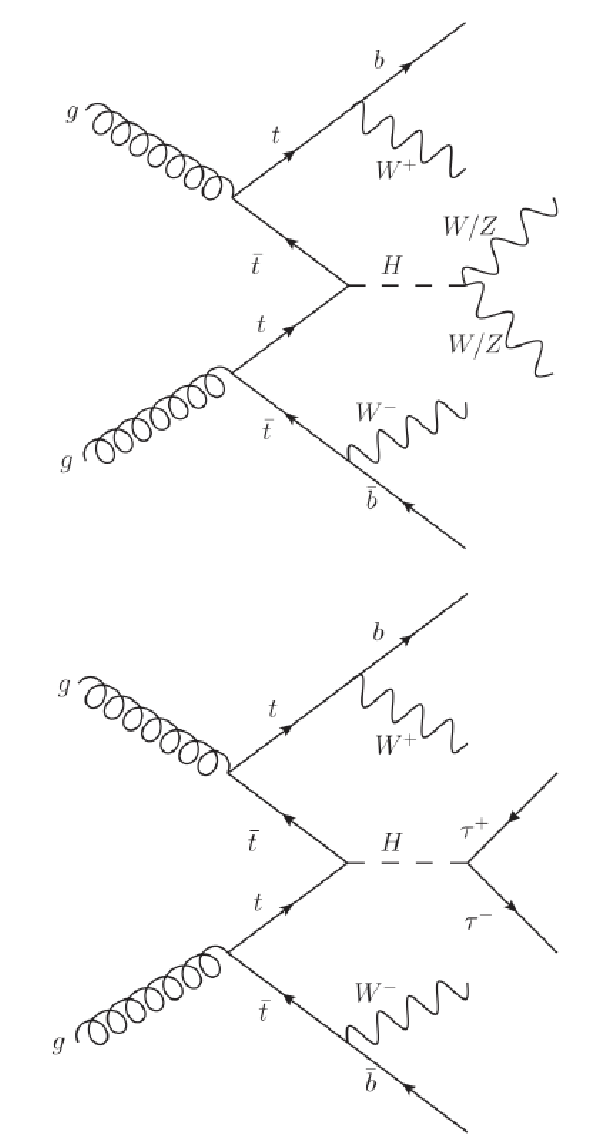


Motivation

- Probe **top-Higgs** yukawa coupling in direct way
  - potential window to BSM
- Sensitivity to Higgs self-coupling (strongest single Higgs sensitivity)

◆ Challenges:

- ttH cross-section at √s=13 TeV: 0.507 pb (~1% of Higgs produced at theLHC)
- Complexed final state (lots of jets coming both from the Higgs and from the tops)
- Cannot reconstruct the full process well with the neutrinos

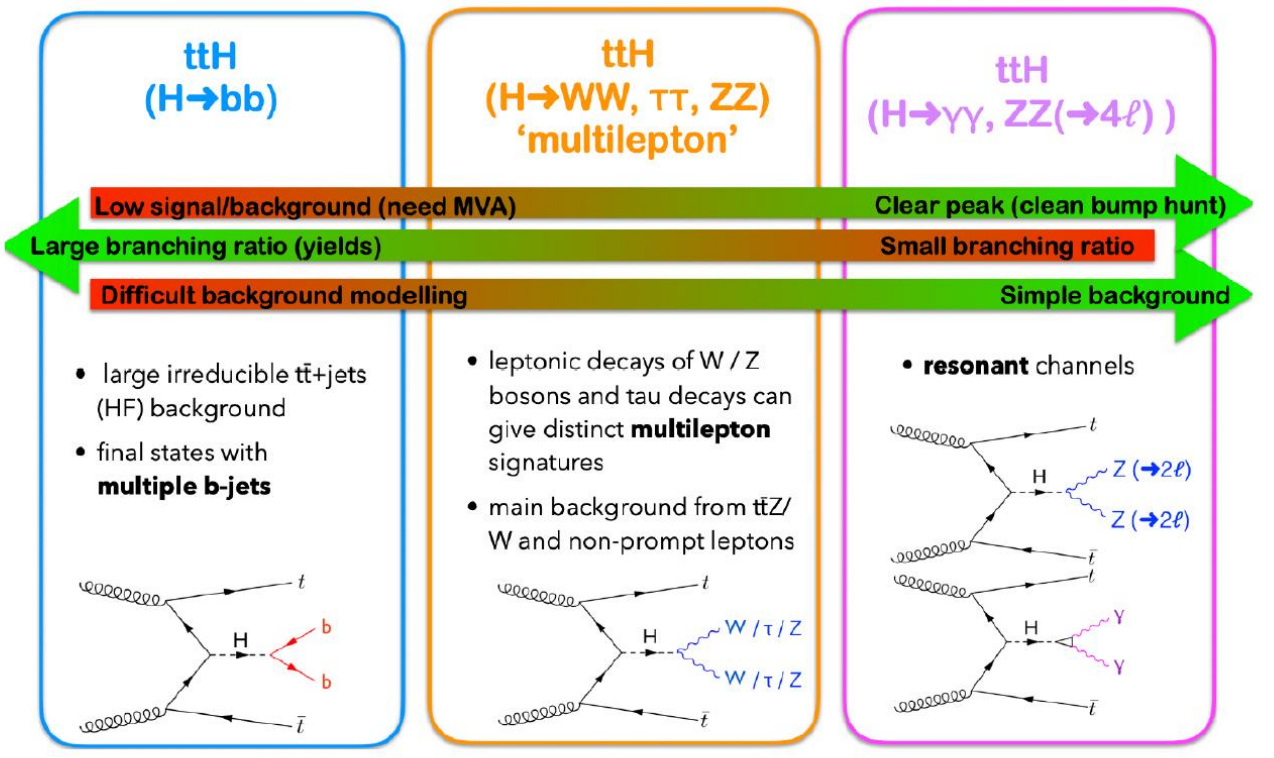
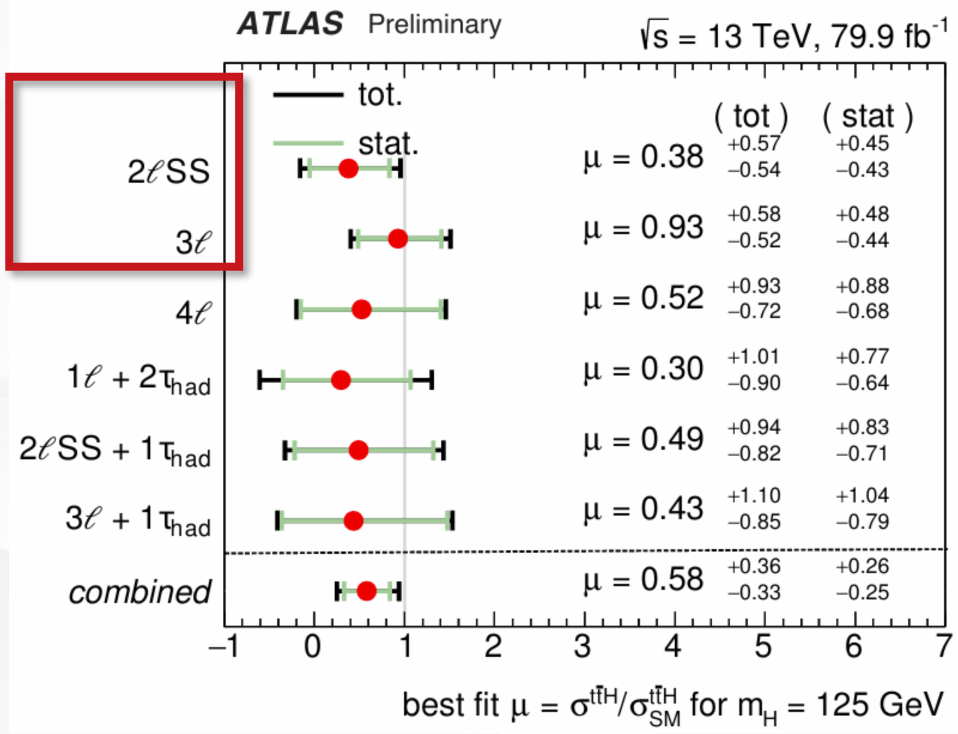


Figure from Tamara Vazquez Schroeder

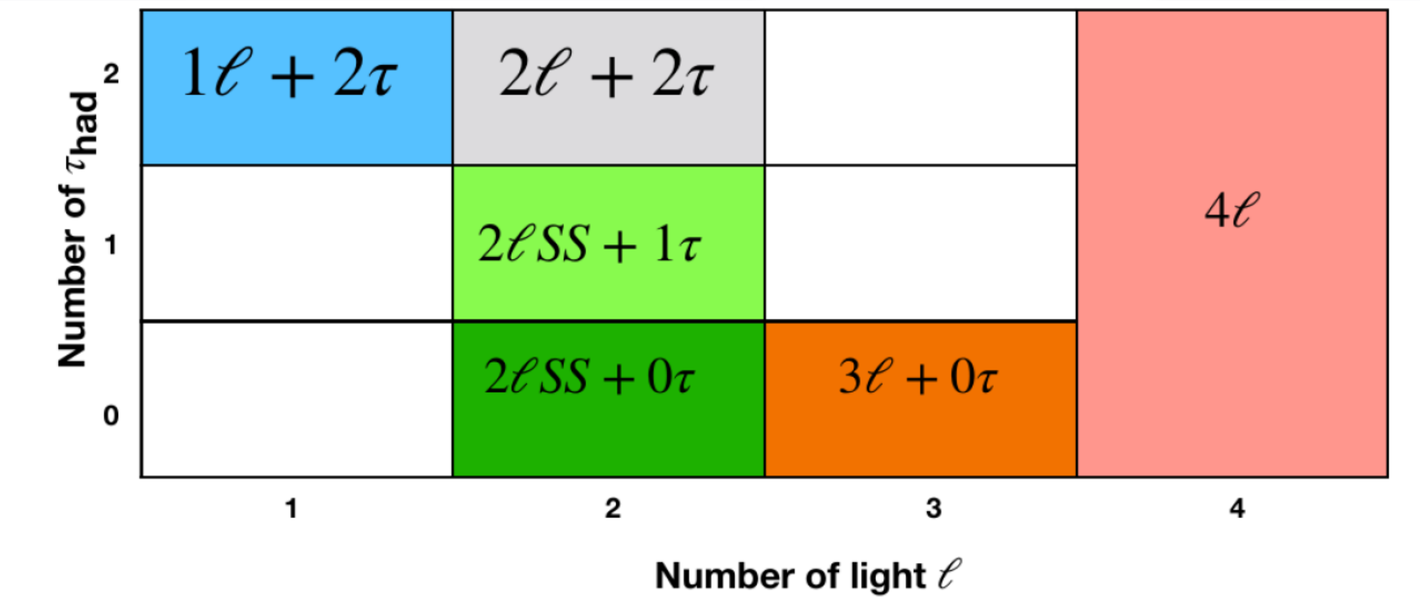
ttH Ml: previous measurement

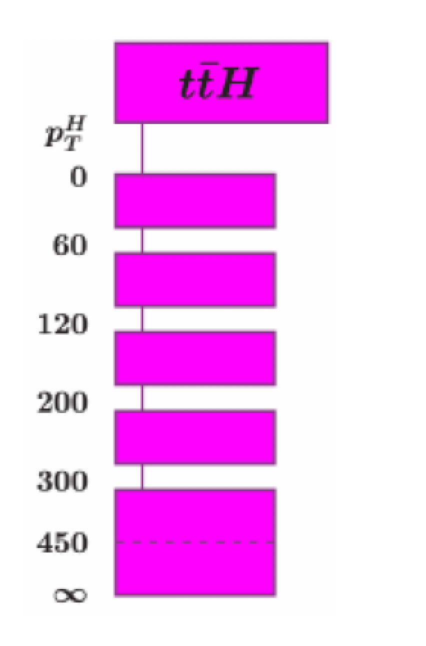
- Run 2 inclusive measurement with 80 fb^{-1} (ATLAS-CONF-2019-045)
- Signal strength: $0.58^{+0.36}_{-0.33}$
- Observed Significance: 1.8σ (3.1σ exp)
- Most sensitive channels: **2lSS, 3l**



Analysis Strategy

- Full run 2 dataset (140 fb^{-1})
- Split into 6 different channels using N_leptons,N_τhad , lepton charge
- **MVA** is used to define the signal regions and MVA-based control regions
- Template fit for fake lepton backgrounds
- Simplified Template Cross Sections (**STXS**) measurement(p_T^H)





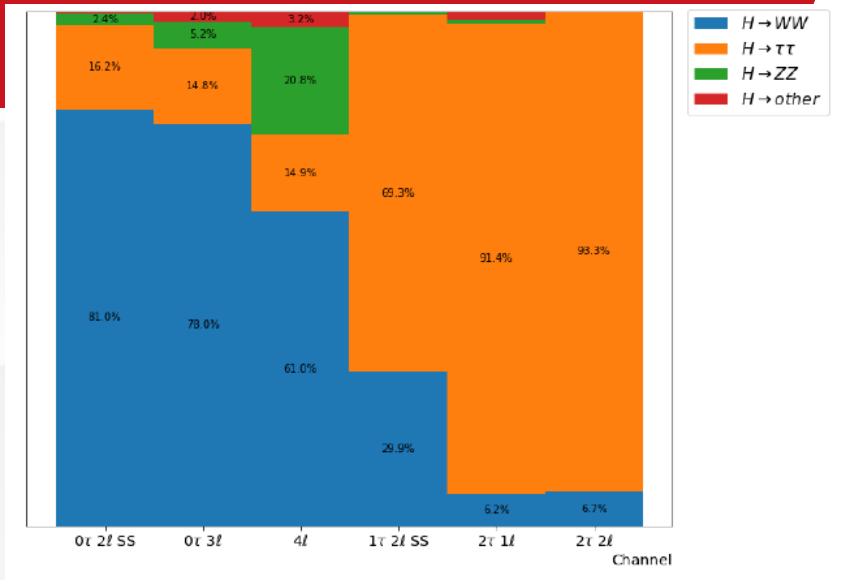
Channel Overview

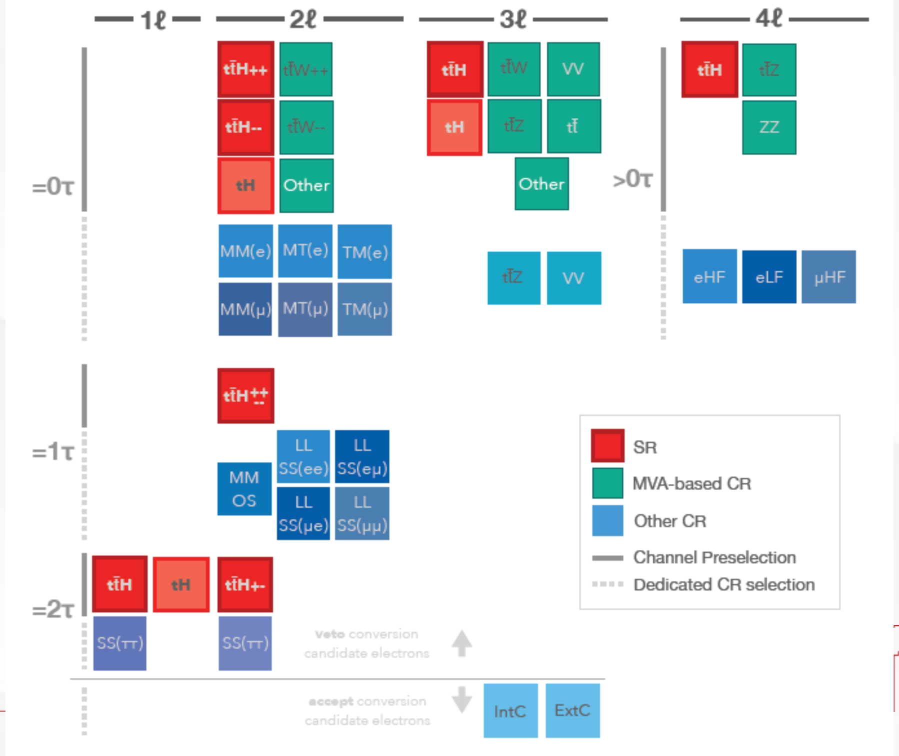
- 0τ 2 same-sign(light) leptons“2lSS”and 3(light) leptons “3l”

  ⇒ Most sensitive channels

- 4l channel
- 1τ 2lSS channel
- 2τ 1l and 2l channel

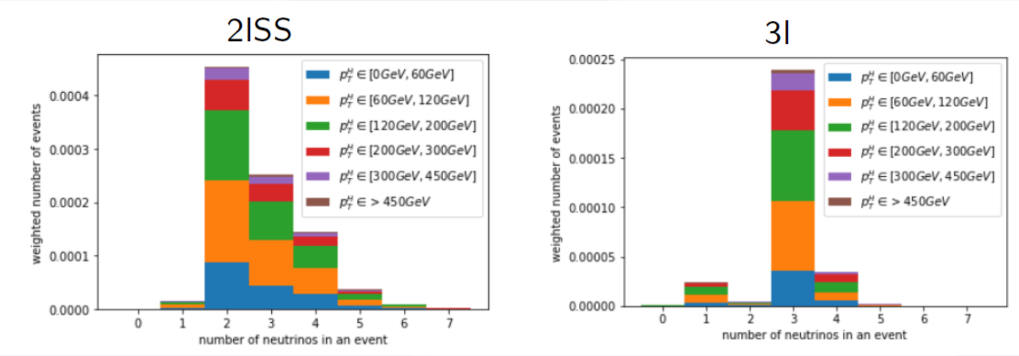
- ML+ 0τ: primary sensitive to H→WW/ZZ.
- ML+ ⩾1τ: primary sensitive to H→ττ.

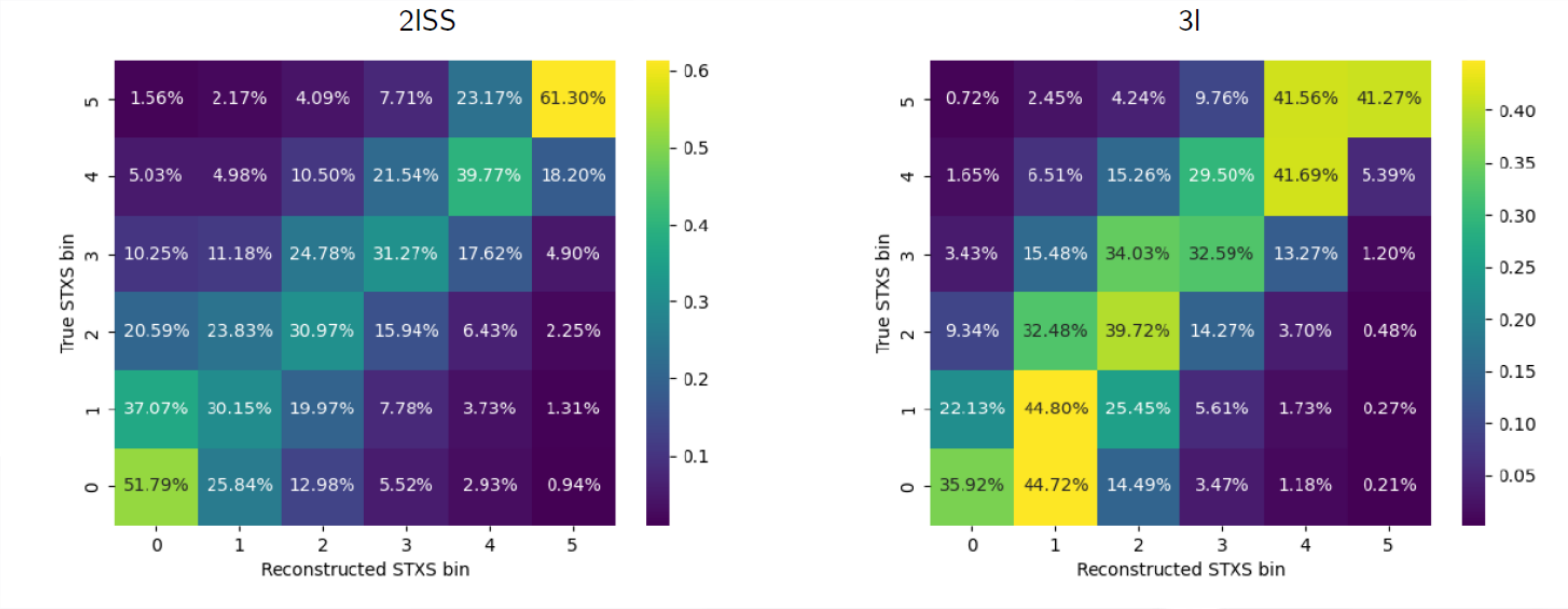




H_pT reconstruction in στ channel

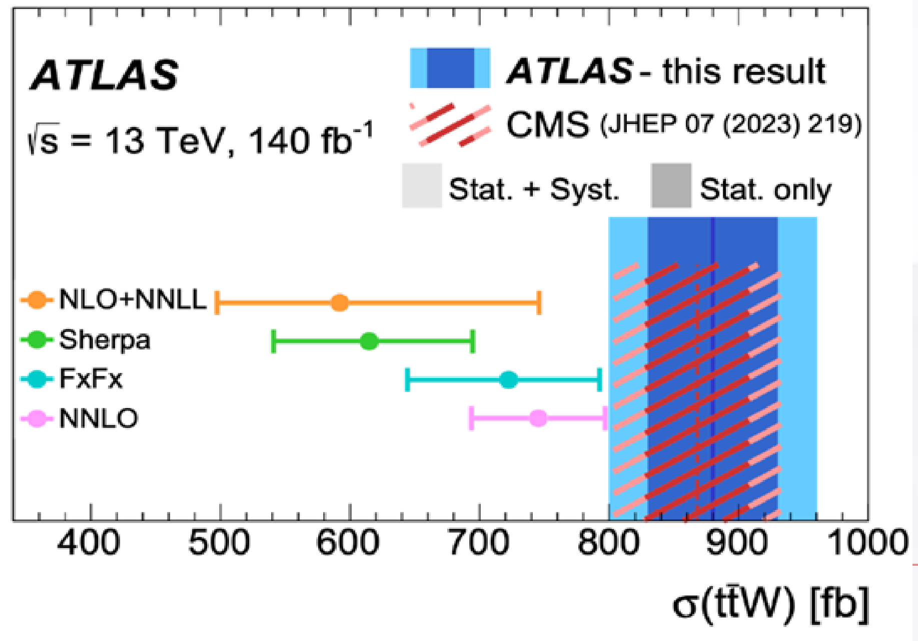
- Higgs pT is difficult to reconstruct (many neutrinos in H decay and not reconstructed soft particles)
- GNN is used to reconstructed H_pT in στ channel





Background Estimation

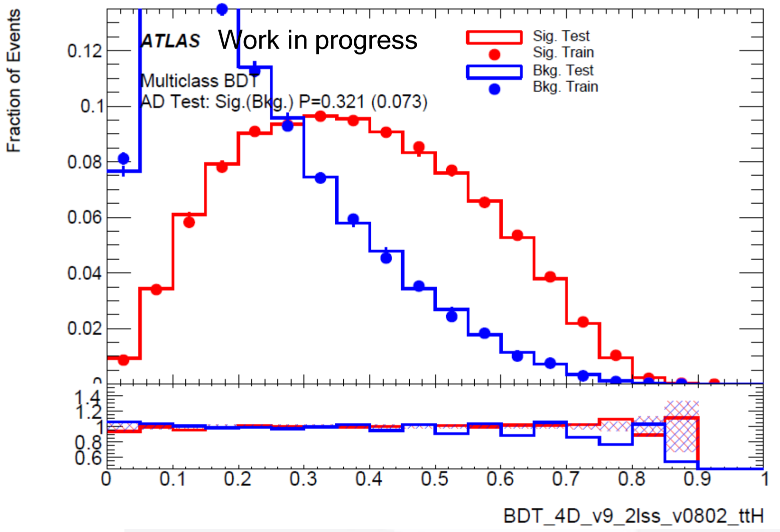
- The latest dedicated ttW background treatments are used for the $0_{\tau\text{had}}$ channel(JHEP05(2024)131)
- **Irreducible** backgrounds: ttW, ttZ, VV
  - Cut based and multiclass BDT
- **Reducible** backgrounds: fake or non-prompt leptons, Q mis-ID, fake τ_{had}
  - Fake factor and data-driven for non-prompt lepton
  - Template fit method inherited from ttWML

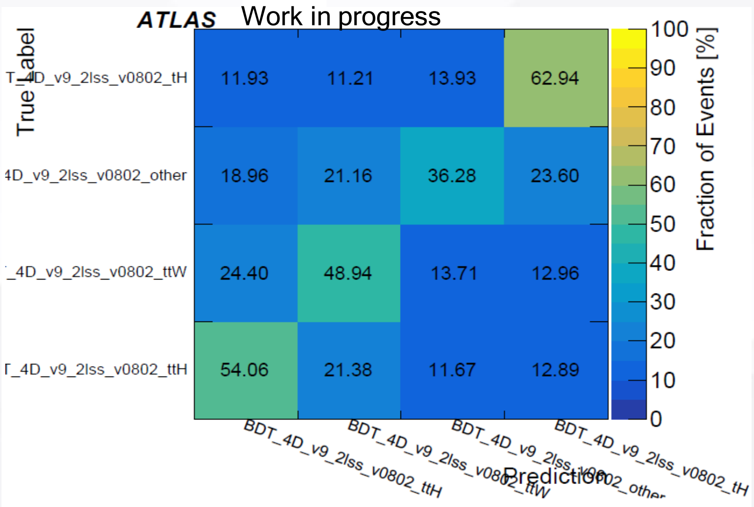


BDT discriminants(2lSS 0τ)

- 20 input variables
- k-folding is used: dataset divided into two subsets for training and testing
- Good prediction power for ttH and tHq, more difficult to distinguish ttH from ttW.

variable	description
N_{jets}	Number of central jets with $p_T > 25$ GeV
$\Delta R(\ell_0, \text{jet})$	Angular distance between leading lepton and its closest jet
$\Delta R(\ell_1, \text{jet})$	Angular distance between sub-leading lepton and its closest jet
$M(\ell_0, \ell_1)$	Invariant mass of leading lepton and sub-leading lepton
LD	Linear discriminant defined as: $0.6^* E_T^{miss} + 0.4^* H_T^{\text{jet}}$ 7
$p_T(\text{jet}_0)$	Transverse momentum of the leading jet
$p_T(\text{jet}_1)$	Transverse momentum of the sub-leading jet
$\Delta R^{\text{avg}}_{jets}$	Average ΔR between jets
$\text{Max}(\lvert\eta_l\rvert)$	Pseudo-rapidity difference between the leading and subleading leptons ($\lvert\eta_{\ell_0}\rvert$ and $\lvert\eta_{\ell_1}\rvert$)
$p_T(\ell_1)$	Transverse momentum of the subleading lepton
$\eta(\ell_0)$	Pseudo-rapidity of the leading lepton
M(lep, MET)	Invariant mass of leptons and missing transverse energy
$M_T^{(\ell 0, MET)}$	Transverse mass of the leading lepton and missing transverse energy
$M_T^{(\ell 1, MET)}$	Transverse mass of the sub-leading lepton and missing transverse energy
$\eta(\text{jet}_0)$	Pseudo-rapidity of the leading jet
$\eta(\text{jet}_1)$	Pseudo-rapidity of the sub-leading jet
H_T^{jet}	Scalar sum of the transverse momenta of the jets
$\Delta R(\ell_0, \ell_1)$	Angular distance between the two same-sign leptons
M_{b0}	Invariant mass of the leading b-jet
M_{b1}	Invariant mass of the sub-leading b-jet





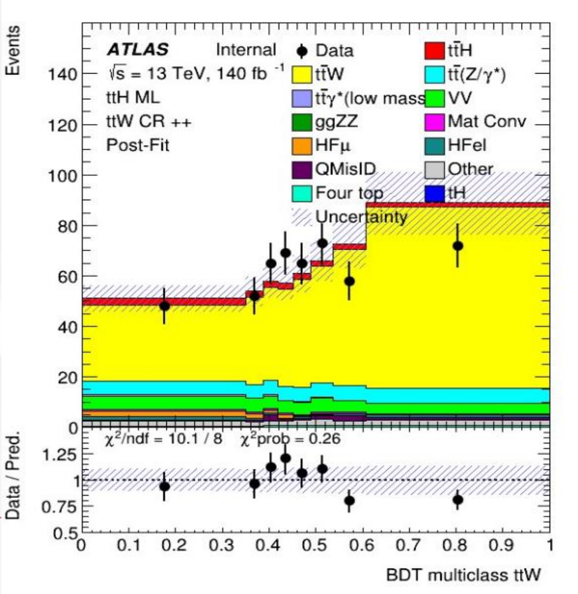
MVA-based CRs (2lSS 0tau)

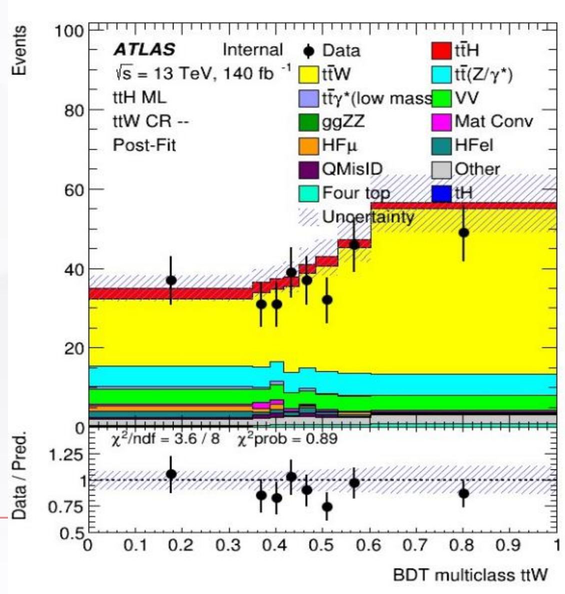
Pre-MVA selection:

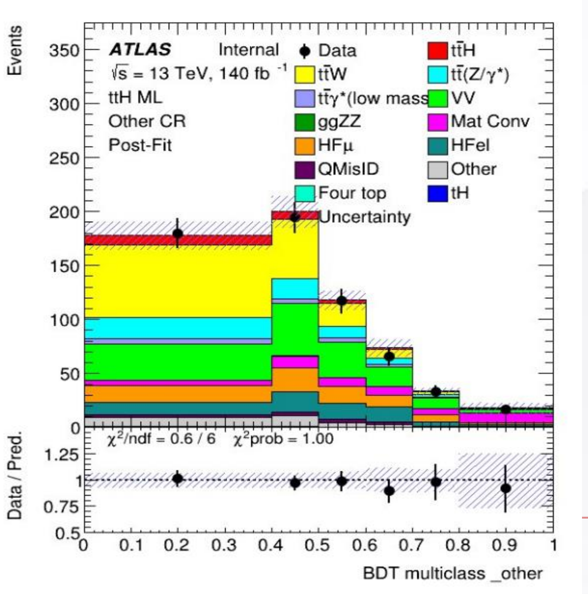
- ✓ SLT||DLT
- ✓ VeryTightPLIV
- ✓ ≥3j
- ✓ loose btag: ≥1b @85%
- ✓ Tau veto
- ✓ lep_pT> 15 GeV
- ✓ !(nJets_OR>=6 && nJets_OR_DL1r_77>=3)(4top veto)

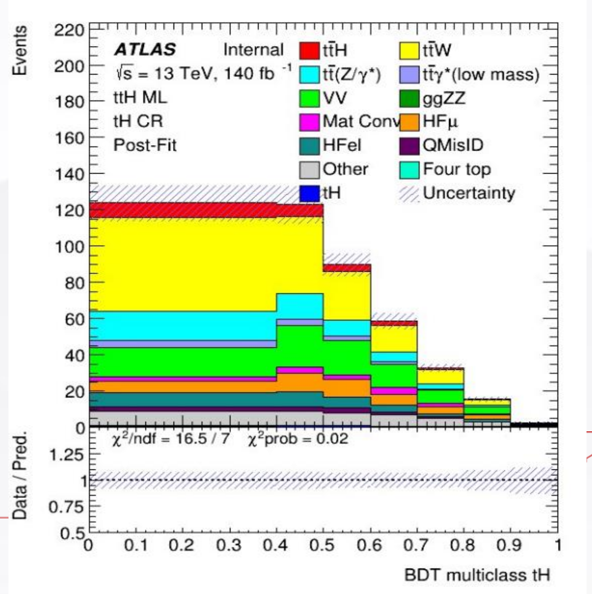
MVA selection:

Control Regions	
$t\bar{t}W$ ++	$2\ell SS + 0\tau_{had}$ pre-MVA selection total charge > 0 $\mathrm{Max}(BDT_{t\bar{t}H}, BDT_{tH}, BDT_{t\bar{t}W}, BDT_{Other}) = BDT_{t\bar{t}W}$
$t\bar{t}W$ −−	$2\ell SS + 0\tau_{had}$ pre-MVA selection total charge < 0 $\mathrm{Max}(BDT_{t\bar{t}H}, BDT_{tH}, BDT_{t\bar{t}W}, BDT_{Other}) = BDT_{t\bar{t}W}$
Other	$2\ell SS + 0\tau_{had}$ pre-MVA selection $\mathrm{Max}(BDT_{t\bar{t}H}, BDT_{tH}, BDT_{t\bar{t}W}, BDT_{Other}) = BDT_{Other}$



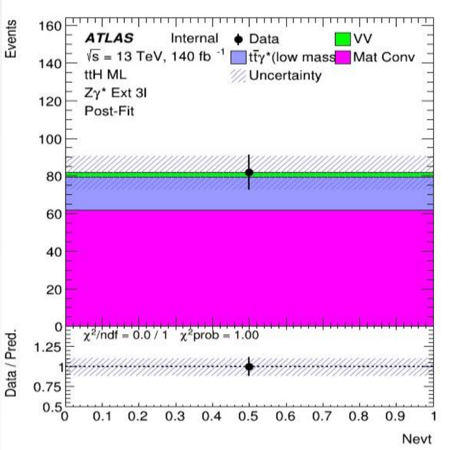


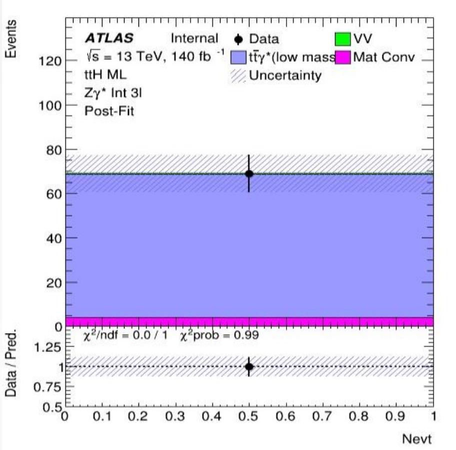


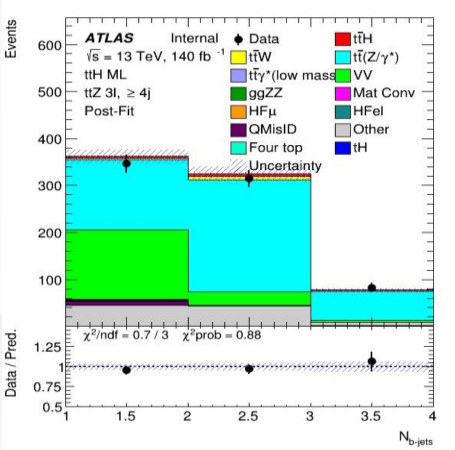


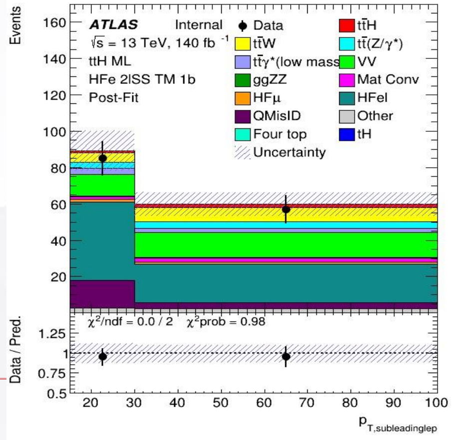
Cut-based CRs(inherited from ttWML)

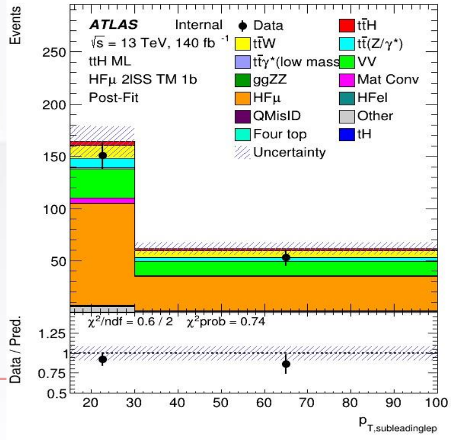
- **Prompt** background:
  - ➢ 3l VV and 3l $t\bar{t}Z$ CRs
  - ➢ Conversion: 3l Mat and 3l Int CRs
- **Non-prompt** background mainly from $t\bar{t}$: 6 Fake HF CRs

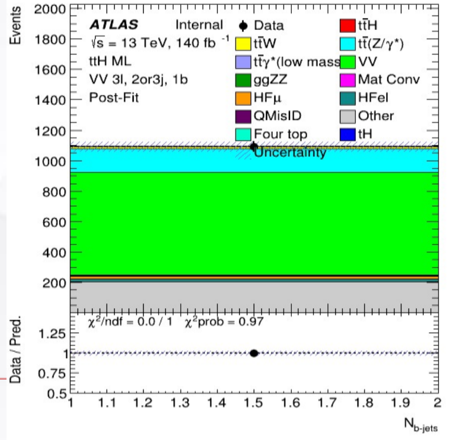










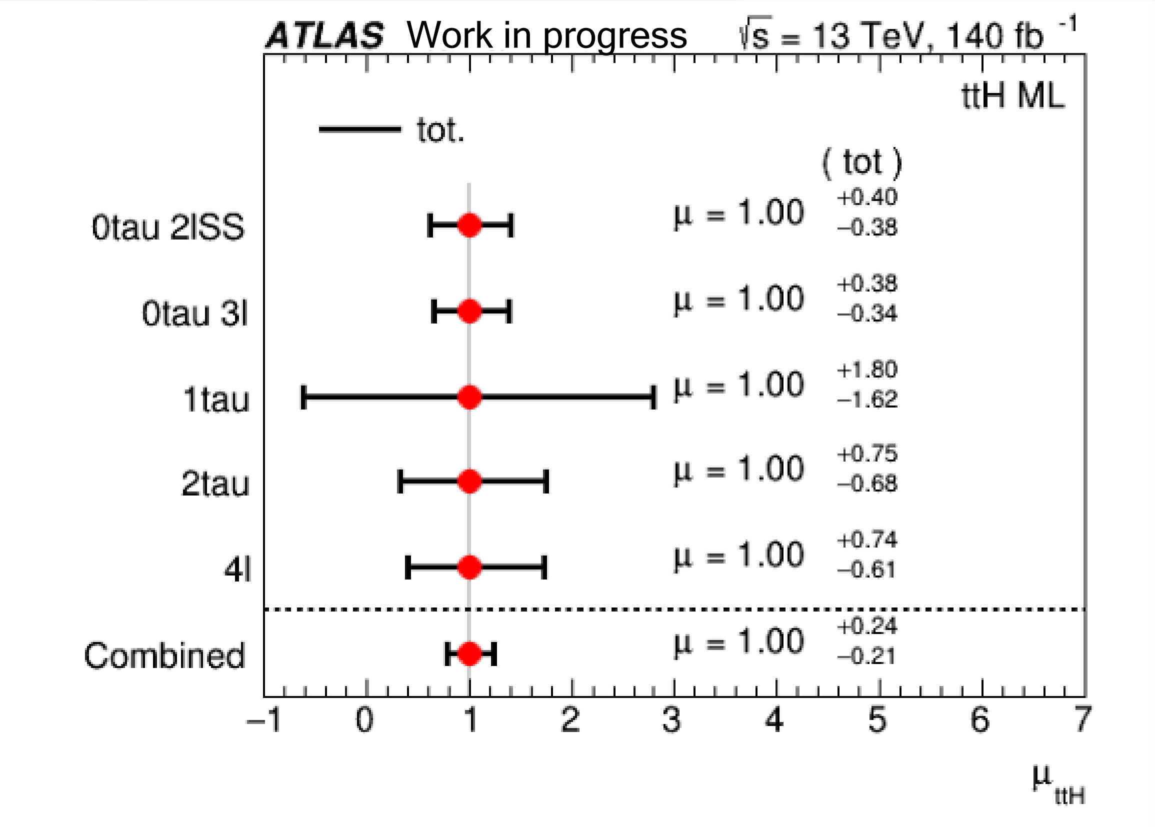


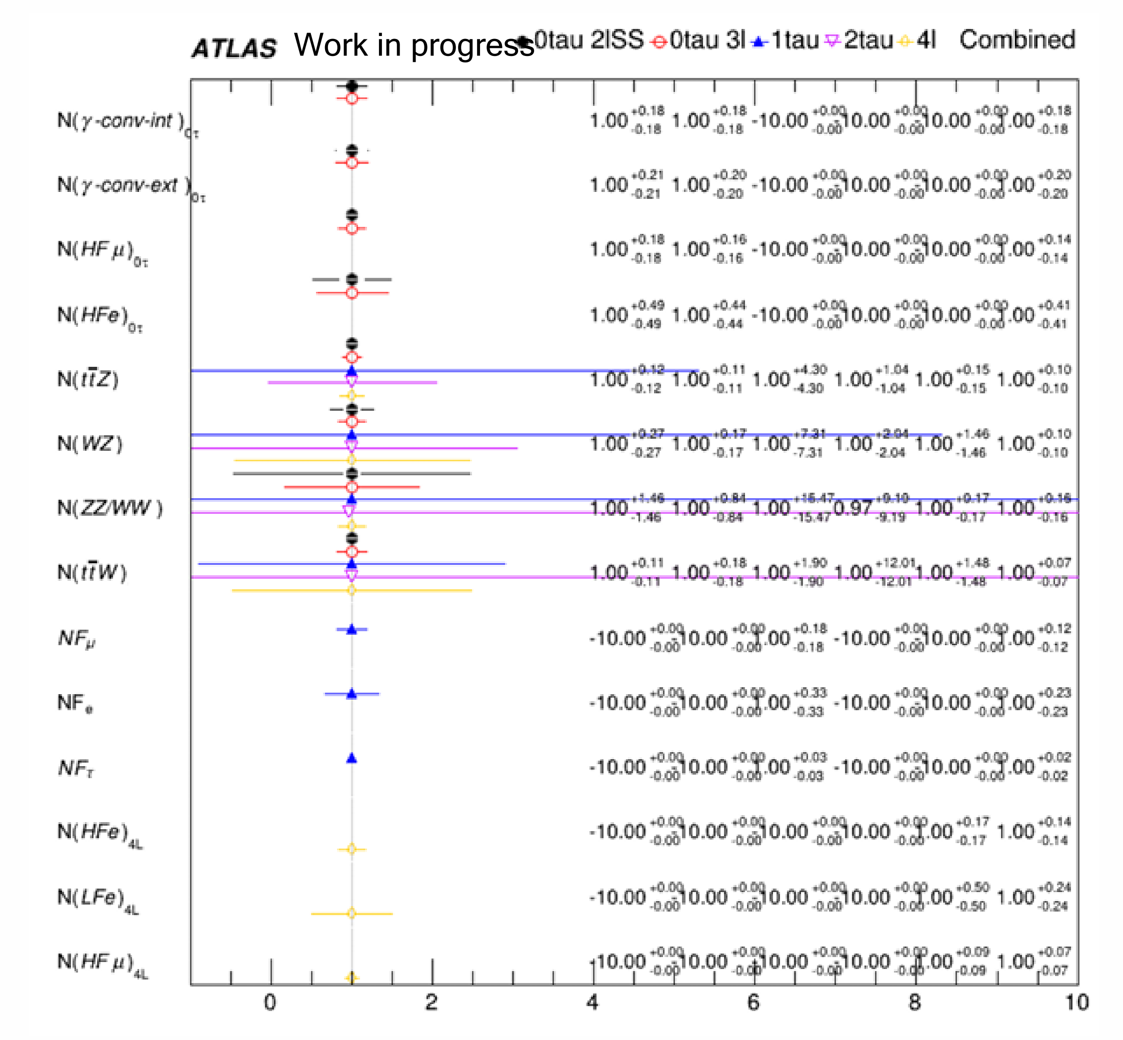
Regions definition

Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
N_{b-jets}	$1\ b^{85\%}$		$0\ b^{85\%}$	$1\ b^{85\%}$
Lepton requirement	3ℓ		$\mu\mu e^*$	$2\ell SS$
Lepton definition	(L, M, M)			$(T, M_{ex}) \Vert (M_{ex}, T) \Vert (M_{ex}, M_{ex})$
Lepton p_T [GeV]	(10, 15, 15)			(15, 15)
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	>10		< 10	–
$m_T(\ell_0, E^{miss}_T)$ [GeV]	–			< 250 for TM_{ex} and $M_{ex}T$ pairs
τ_{had} candidates (Medium)	0			0
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{ex}, M_{ex}T, M_{ex}M_{ex})$
Region naming	3ℓVV	3ℓttZ	3ℓIntC 3ℓMatC	$2\ell tt(e)_{TM_{ex}}, 2\ell tt(e)_{M_{ex}T}, 2\ell tt(e)_{M_{ex}M_{ex}}$ $2\ell tt(\mu)_{TM_{ex}}, 2\ell tt(\mu)_{M_{ex}T}, 2\ell tt(\mu)_{M_{ex}M_{ex}}$

Results: Combine fit(ASIMOV)

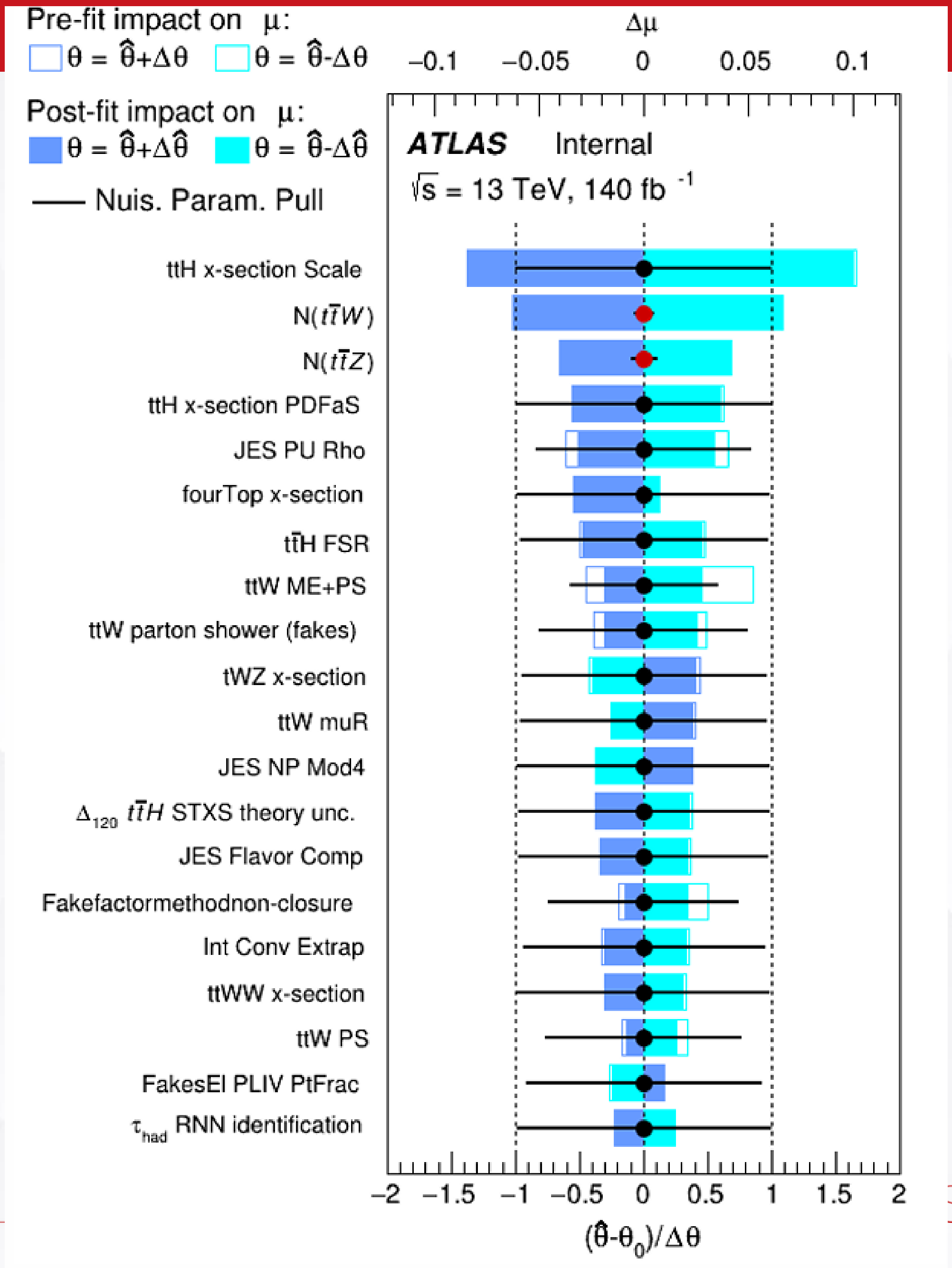
- Expected significance 5.5σ(3.1σ in previous 80 fb^{-1} analysis)
- Statistical and systematical uncertainties have similar impact (12% stat and 15% syst)





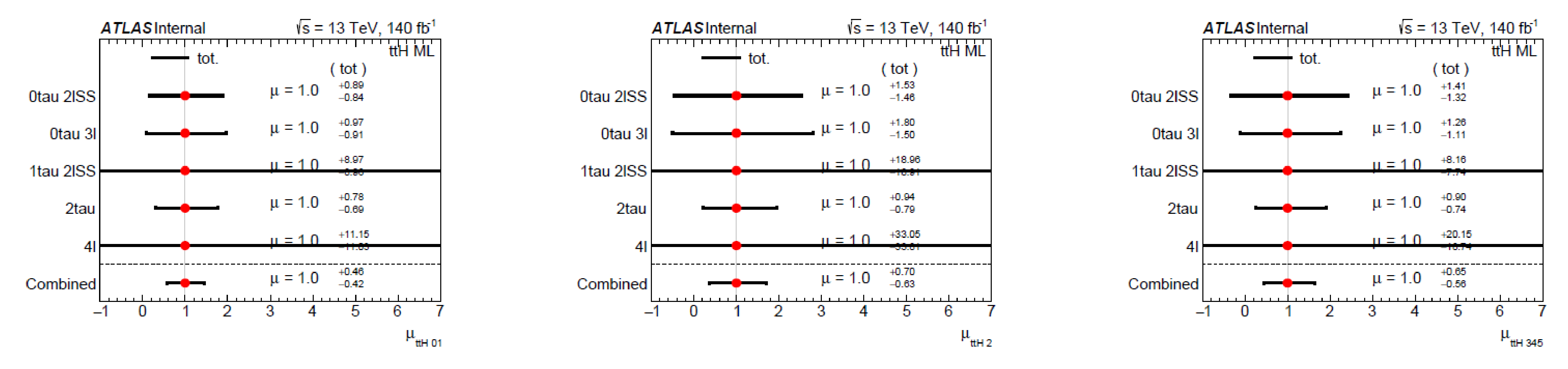
Results: Ranking

- Significant impact NPs:
  - ttH modeling, ttW and ttZ background
  - Jet relevant systematics



Result: STXS fit(ASIMOV)

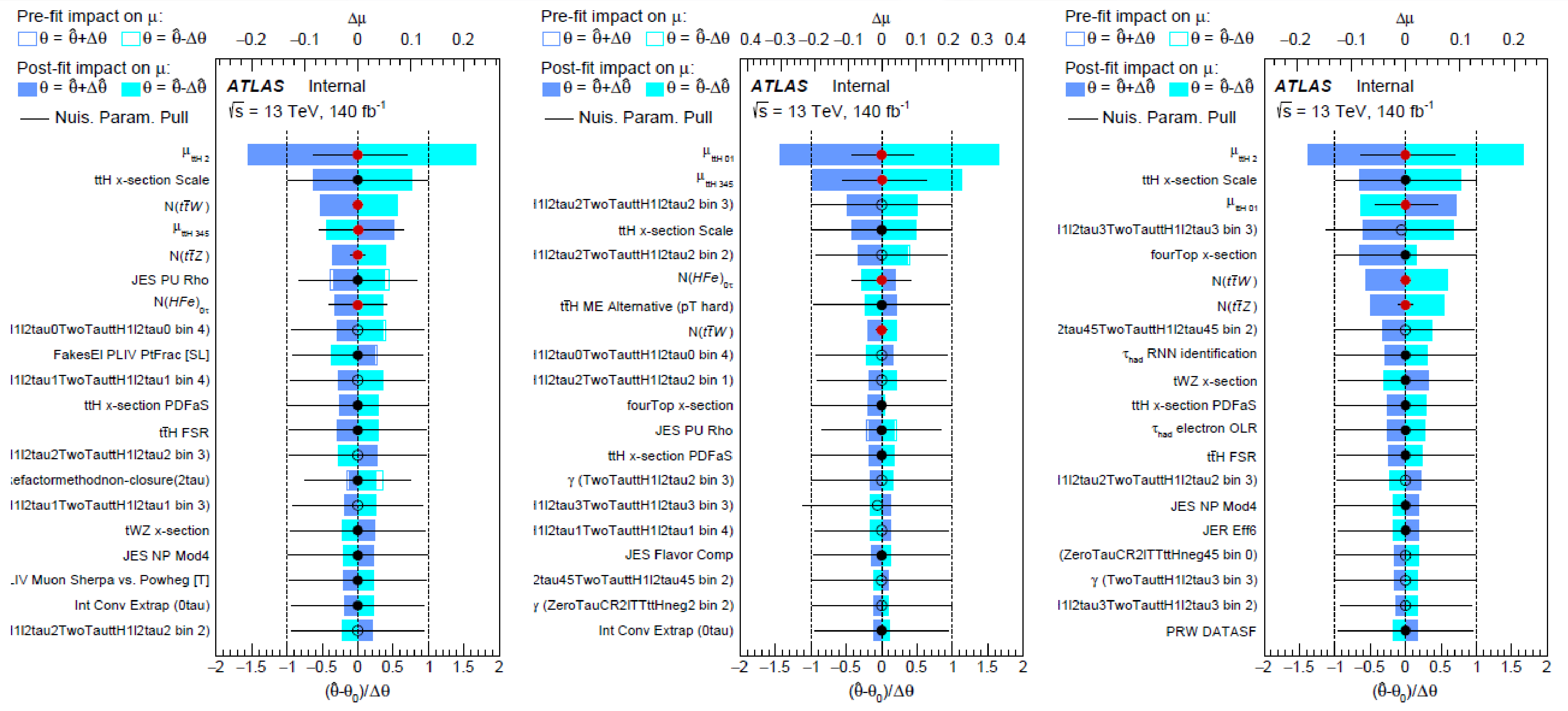
- The main STXS sensitivity is obtained in the $0\tau_{had}$ and $2\tau_{had}$ channels
- Measure 3 STXS μ_ttH bins due to lack of statistics



Exp(obs)	ATLAS-CONF-2019-045	This work
0 τ and 4l channels	2.89σ (2.12σ)	4.5σ
1 τ channel	1.06σ (0.48σ)	1.9σ
2 τ channels	1.02σ (0.32σ)	3.2σ
Combined	3.06σ (1.80σ)	**5.5σ**

Result: STXS fit(ASIMOV)

- ttH cross-section scale uncertainty , ttW and ttZ norm factors are the dominant uncertainties still.
- The heavy flavour electron fake normalisation appears higher compared to inclusive fit.



Summary

- **Challenging final states**:
  - rare cross section, large multiplicity of jets, presence of neutrinos
- Multiclass **BDT** to distinguish signal and backgrounds
- **GNN** to reconstruct the Higgs pT
- Measure the differential cross section as a function of:
  - 3 Higgs pT : [0,120), [120, 200), [200, inf) GeV
- Analysis provides inclusive and STXS cross-section measurement
- **Significant improvement** in sensitivity compared to partial run 2 analysis(3.1σ to 5.5σ exp)

Backup

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Higgs STXS template

- 6 bins in H pT in STXS framework for ttH
- Split ttH template in 6 STXS bins
- Additionally split ttH sample by Higgs decay mode (WW, ZZ, $\tau\tau$, other)
- Assume that ttH modelling uncertainties are independent on Higgs decay:

  derive uncertainties on Higgs decay inclusive template and apply to split templates

Triggers and object definition

- SL or DL trigger for the three channels

Channel	2ℓSS	3ℓ	4ℓ
Triggers	SL || DL	SL || DL	SL || DL

- PLIV selection on 2lSS and 3l channels
- Looser lepton definition on 4l channel

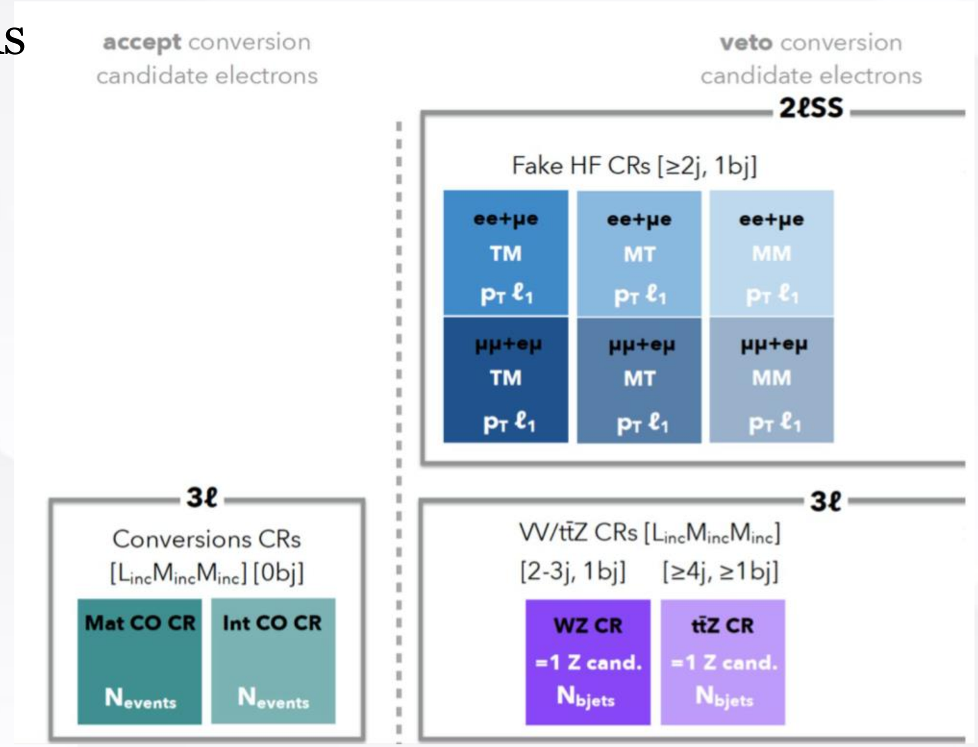
	2ℓSS+$0\tau_{\text{had}}$	3ℓ+$0\tau_{\text{had}}$	4ℓ
τ_{had} candidates	==0 M	==0 M	–
Leptons counting	==2 T: p_{T} >15 GeV	==3 (T,T,L): $p_{\text{T}} > 15, 15, 10$ GeV	==4 L: $p_{\text{T}} > 10$ GeV
Lepton details	SS	OS (to others): L $p_{\text{T}} > 10$ GeV SS pair: T p_{T} >15 GeV OS pair: $\lvert m(ll) - m_Z\rvert > 10$ GeV and $m(ll) > 12$ GeV	Sum charge = 0 OS pairs: $m(ll) > 12$ GeV $\lvert m(llll) - m_H\rvert > 5$ GeV
N_{jets}	≥ 3	≥ 2	≥ 2
$N_{b-\text{jets}}$ (@ 85% WP)	≥ 1	≥ 1	≥ 1

Background estimation II(cut-based ttWML)

- Prompt background:
  - 3l VV and 3l $t\bar{t}Z$ CRs
  - Conversion: 3l Mat and 3l Int CRs
- Non-prompt background mainly from $t\bar{t}$: 6 Fake HF CRs

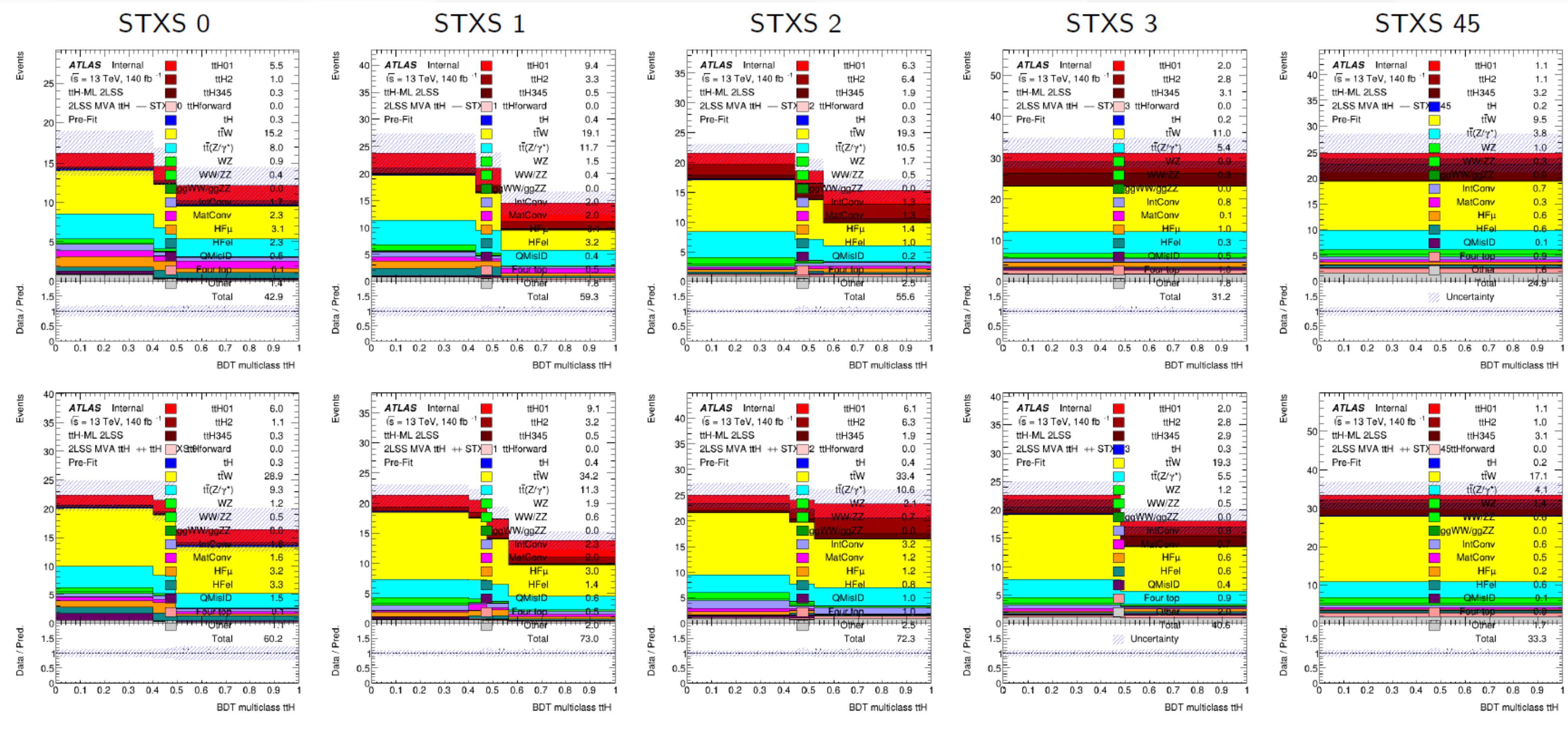
Regions definition

Control regions for:	Diboson	$t\bar{t}Z$	Conversions	HF non-prompt
N_{jets}	2 or 3	≥ 4	≥ 0	≥ 2
N_{b-jets}	1 $b^{85\%}$		0 $b^{85\%}$	1 $b^{85\%}$
Lepton requirement	3ℓ		$\mu\mu e^{*}$	2ℓSS
Lepton definition	(L, M, M)			(T, M_{ex}) || (M_{ex}, T) || (M_{ex}, M_{ex})
Lepton p_T [GeV]	(10, 15, 15)			(15, 15)
$\lvert m^{SF}_{\ell^+\ell^-} - m_Z \rvert$ [GeV]	< 10		> 10	–
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	>10		< 10	–
$m_T(\ell_0, E_T^{miss})$ [GeV]	–			< 250 for TM_{ex} and $M_{ex}T$ pairs
τ_{had} candidates (Medium)	0			0
Region split	–	–	internal / material	subleading $e/\mu \times (TM_{ex}, M_{ex}T, M_{ex}M_{ex})$
Region naming	$3\ell VV$	$3\ell ttZ$	3ℓIntC 3ℓMatC	$2\ell tt(e)_{TM_{ex}}$, $2\ell tt(e)_{M_{ex}T}$, $2\ell tt(e)_{M_{ex}M_{ex}}$ $2\ell tt(\mu)_{TM_{ex}}$, $2\ell tt(\mu)_{M_{ex}T}$, $2\ell tt(\mu)_{M_{ex}M_{ex}}$



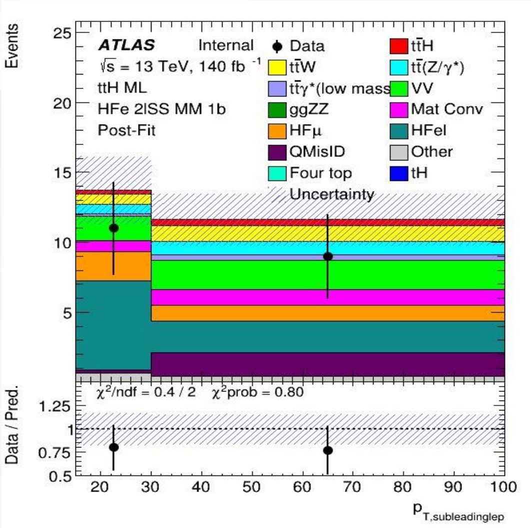
2lSS otau channel

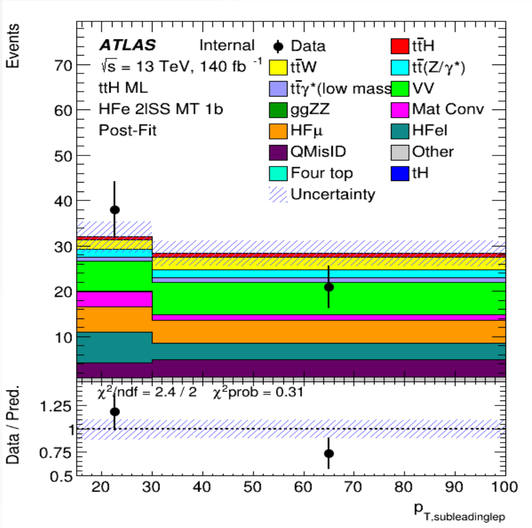
- ttH SRs of reconstructed Higgs pT

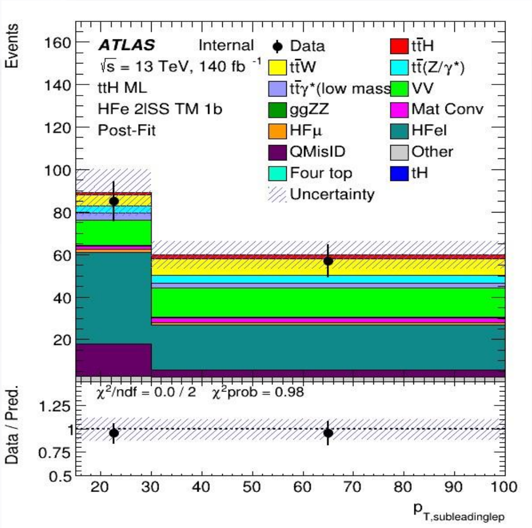


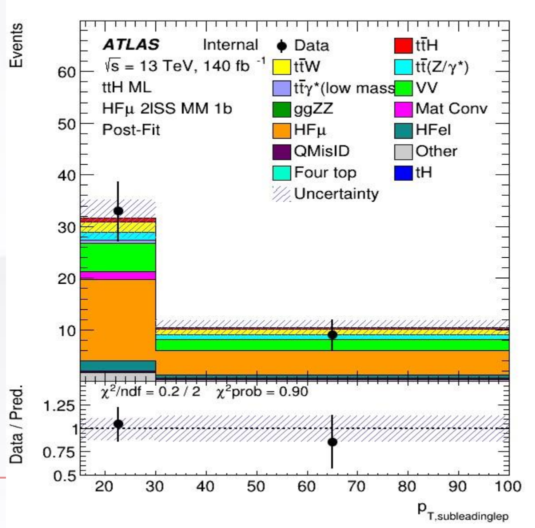
HF CRs

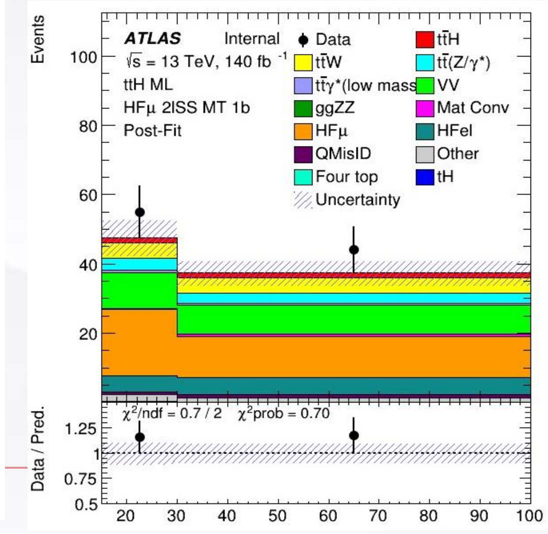
Post-fit

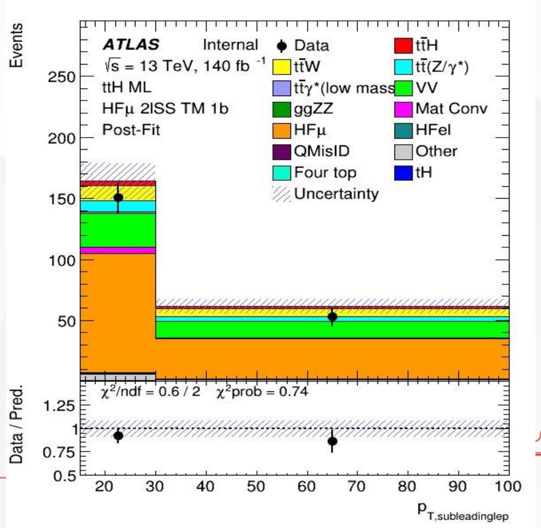












Experimental systematics

- Follows official recommendations.
- All channels are using harmonised systematics.

Experimental Systematics on Leptons

Type	Description	Systematics Name	Application	Analysis
Trigger				
Scale Factors	Ele./Muon Trigger Eff	custTrigSF_LooseID_FCLooseIso _SLTorDLT (one NP for electrons, two for muons)	Event Weight	all
	Electron PLIV Trigger Eff	PLIV_El_Trigger_*	Event Weight	-
Muons				
Efficiencies	Reconstruction and identification	MU_SF_ID_[STAT,SYST]	Event Weight	all
	Reconstruction and Identification (low p_T)	MU_SF_ID_[STAT,SYST]_LOWPT	Event Weight	all
	Isolation	MU_SF_Isol_[STAT,SYST]	Event Weight	all
	Track To Vertex Association	MU_SF_TTVA_[STAT,SYST]	Event Weight	all
p_T Scale	p_T Scale	MUONS_SCALE	p_T Correction	all
Resolution	Combined Momentum Resol.	MUONS_CB	p_T Correction	all
	Sagitta corr.	MUONS_SAGITTA_RESBIAS	p_T Correction	all
Isolation.	PLIV calibration	PLIV_Mu_*	Event weight	2ℓSS, 3ℓ, 1Tau
Electrons				
Efficiencies	Reconstruction	EL_SF_Reco	Event Weight	all
	Identification	EL_SF_ID	Event Weight	all
	Isolation	EL_SF_Isol	Event Weight	all
	PLIV calibration	PLIV_EL_*	Event Weight	2ℓSS, 3ℓ, 1Tau
Scale	Energy Scale	EG_SCALE_ALL	Energy Correction	all
Resolution	Energy Resolution	EG_RESOLUTION_ALL	Energy Correction	all
Hadronic Taus				
Efficiencies	Reconstruction	Tau_SF_Reco	Event Weight	1Tau, 2Tau
	Identification RNN	Tau_SF_RNNID_SYST	Event Weight	1Tau, 2Tau
	Identification (high p_T)	Tau_SF_RNNID_HighPt	Event Weight	1Tau, 2Tau
	Electron Veto BDT	Tau_SF_ELEOLR[TOTAL, STAT, SYST]	Event Weight	1Tau, 2Tau
	1-prong RNN identification	Tau_SF_RNNID_1PRONGPT[20,25,30,40+]	Event Weight	1Tau, 2Tau
	3-prong RNN identification	Tau_SF_RNNID_3PRONGPT[20,25,30,40+]	Event Weight	1Tau, 2Tau
Scale	Energy Scale	Tau_SME_TES_MODEL_CLOSURE	p_T correction	1Tau, 2Tau
	Energy Scale	Tau_SME_TES_DETECTOR	p_T correction	1Tau, 2Tau
	Energy Scale	Tau_SME_TES_INSITU[FIT, EXP]	p_T correction	1Tau, 2Tau
	Energy Scale	Tau_SME_TES_PHYSICSLIST	p_T correction	1Tau, 2Tau

Experimental Systematics on Jets and MET

Type	Origin	Systematics Name	Application	Analysis
Jets				
Jet Vertex Tagger		JVT	Event Weight	all
Energy Scale	Calibration Method	JET_EffectiveNP_Detector[1,2]	p_T Correction	all
		JET_EffectiveNP_Mixed[1,3]	p_T Correction	all
		JET_EffectiveNP_Modelling[1,4]	p_T Correction	all
		JET_EffectiveNP_Statistical[1,6]	p_T Correction	all
	η inter-calibration	JET_EtaIntercalibration_Modelling	p_T Correction	all
		JET_EtaIntercalibration_NonClosure (×4)	p_T Correction	all
		JET_EtaIntercalibration_TotalStat	p_T Correction	all
	High p_T jets	JET_SingleParticle_HighPt	p_T Correction	all
	Pile-Up	JET_Pileup_OffsetNPV	p_T Correction	all
		JET_Pileup_OffsetMu	p_T Correction	all
		JET_Pileup_PtTerm	p_T Correction	all
		JET_Pileup_RhoTopology	p_T Correction	all
	Non Closure	JET_PunchThrough_MC16	p_T Correction	all
	Flavour	JET_Flavor_Response	p_T Correction	all ($t\bar{t}W$)
		JET_BJES_Response	p_T Correction	all ($t\bar{t}W$)
		JET_Flavor_Composition	p_T Correction	all ($t\bar{t}W$)
		JET_Flavor_Composition_Prop	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavor_Response_Prop	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_GenShower	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_GenShower_HF	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_Shower	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_Shower_HF	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_Hadronization	p_T Correction	all (except $t\bar{t}W$)
		JET_Flavour_PerJet_Hadronization_HF	p_T Correction	all (except $t\bar{t}W$)
Resolution		JET_JER_EffectiveNP_[1,11]	p_T Correction	all
		JET_JER_EffectiveNP_12restTerm	p_T Correction	all
		JET_JER_DataVsMC_MC16	p_T Correction	all
		JET_JER_DataVsMC_AFII	p_T Correction	all
MET				
Soft Tracks Terms	Resolution	MET_SoftTrk_ResoPerp	p_T Correction	all
	Resolution	MET_SoftTrk_ResoPara	p_T Correction	all
	Scale	MET_SoftTrk_Scale	p_T Correction	all

Theory systematics

- Main backgrounds are left free floating: ttW, ttZ, WW/ZZ and WZ

Process	Generator+PS	Norm uncertainty	Alternative ME	Alternative PS	Scale variation
ttH	PhPy8		PhPy8 pThard1	PhH7	Scale, α_S, muR/muF, ISR/FSR, PDF, BR, STXS
ttW	Sherpa2.2.10	4l: $\pm$50%	MGPy8 FxFx (old)	PhPy8-PhH7	muR/muF,PDF, α_s
ttZ	MGPy8			MGH7	muR/muF, A14
tHjb	MGPy8				Scale, α_S
tWH	MGPy8				Scale, α_S
tt	PhPy8			PhH7	hdamp 4ℓ: muR/muF, ISR/FSR, 4FS, eHF pT modelling
tttt	MGPy8	+70% -15%	Sherpa2.2.11	MGH7	muR/muF
WW/ZZ	Sherpa2.2.2	0τ: $\pm$20%			muR/muF
WZ	Sherpa2.2.2	4l: $\pm$20%			muR/muF
VH	PhPy8	$\pm$30%			
VVV	Sherpa2.2.2	$\pm$30%			
ttt	MGPy8	$\pm$35%			
ttWW	MGPy8	$\pm$50%			
tZ	MGPy8	$\pm$5%			
tWZ	MGPy8	$\pm$50%			
QmisID	PhPy8	$\pm$20%			
Vgamma	Sherpa2.2.8	4l: $\pm$50%			

ttW Inclusive Cross-Section

- Simultaneous profile likelihood fit to data using event yields in **48 SRs** and **8 CRs**
- $\sigma(t\bar{t}W)$ =880±50$(stat)$ ±70$(syst)$ fb is consistent at 1.4 σ of the SM NNLO cross section

  745±50(scale)±13(2-loop approx.)± 19 (PDF, αs) fb