Searches for Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state with 139 fb^{-1} of pp collision data with the ATLAS detector

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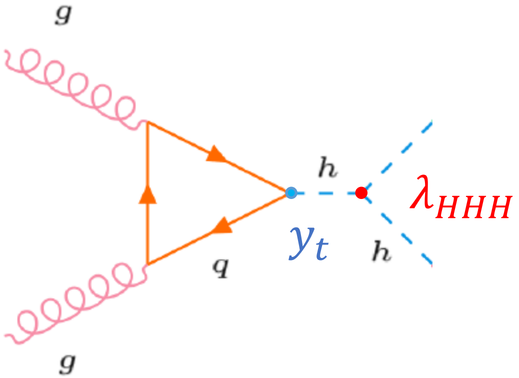
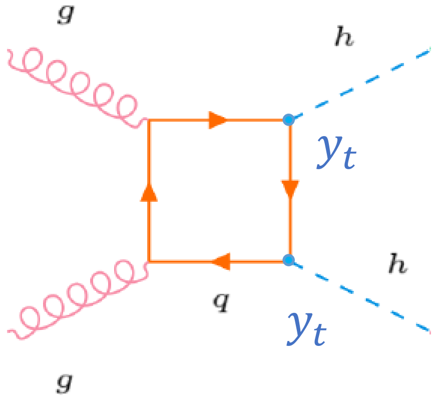
Motivation

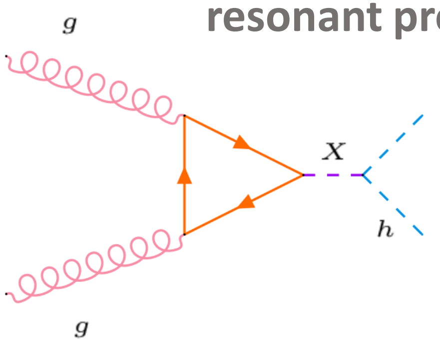
- Measuring the λ_{HHH} is a crucial test of electroweak symmetry breaking mechanism
- A direct probe of the λ_{HHH} is to measure the non-resonant di-Higgs production via the "triangle diagram"
- However, the "box diagram" interferes with the "triangle diagram" destructively, leading to a small cross section of 31.05 ± 1.90 fb (ggF)
- BSM scenarios can enhance the cross section too

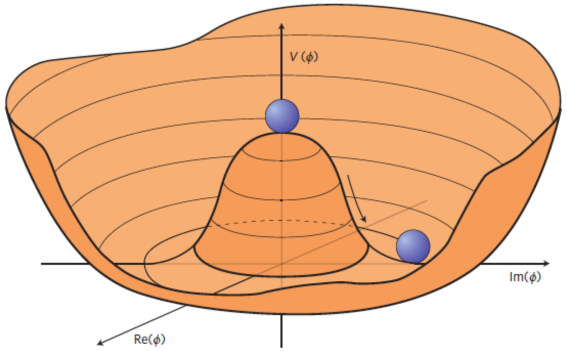
Non-resonant production





resonant production





Higgs potential: $$V(\phi) = \frac{1}{2}m_h^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4 = m_h^2 \frac{h^2}{2} + \lambda_{HHH} \frac{h^3}{3!} + \lambda_{HHHH} \frac{h^4}{4!}$$

Motivation

$bb\tau\tau$ final state:

- Relatively small background.
- Relatively high branching ratio.

$\tau^+\tau^-$ decay	Branching ratio
$b\bar{b}\tau_{had}\tau_{had}$	41%
$b\bar{b}e\tau_{had}$	23%
$b\bar{b}\mu\tau_{had}$	23%
$b\bar{b}\tau_{lep}\tau_{lep}$	12%

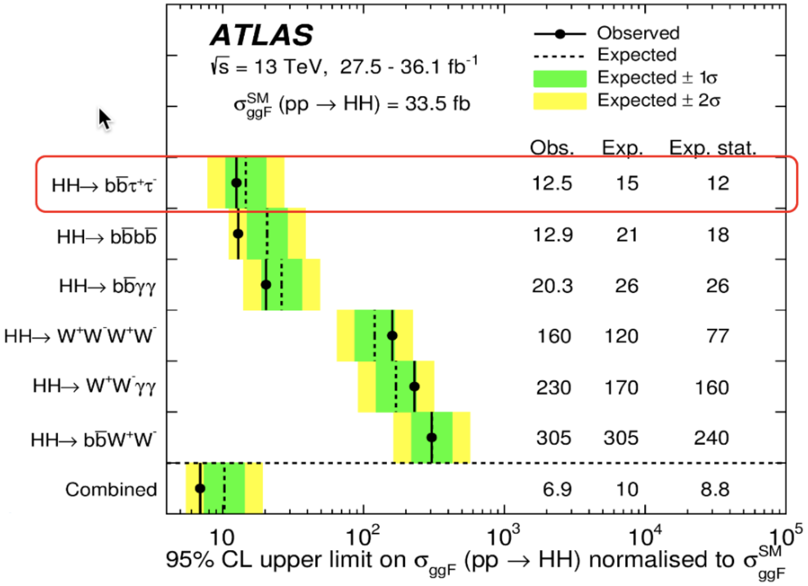
HadHad channel

LepHad channel

Analysis I am working on

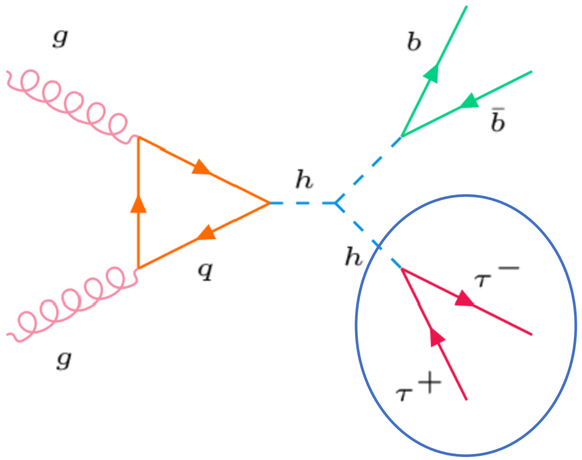
Branching ratio:

	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%



Lephad: high trigger efficiency (due to the lepton)

Hadhad: high purity (much less $t\bar{t}$ background)



$bb\tau\tau$ is the most sensitive decay channel with 36 fb^{-1} data![1]

1. Combination of searches for Higgs boson pairs in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, The ATLAS collaboration, *Physics Letters B*, doi:10.1016

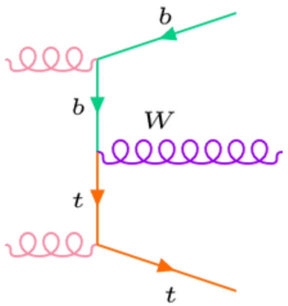
Selection: Yields

- Pre-selection:
  - Using Single lepton triggers and Lepton + τ_{had} triggers
  - $m_{\tau\tau}^{MMC}$ > 60 GeV
  - Exactly 2 b-tagged jets
  - Exactly 1 lepton and 1 τ_{had} with opposite sign
  - m_{bb} < 150 GeV

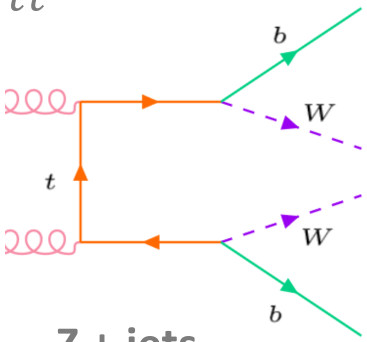
$L = 139\ fb^{-1}$

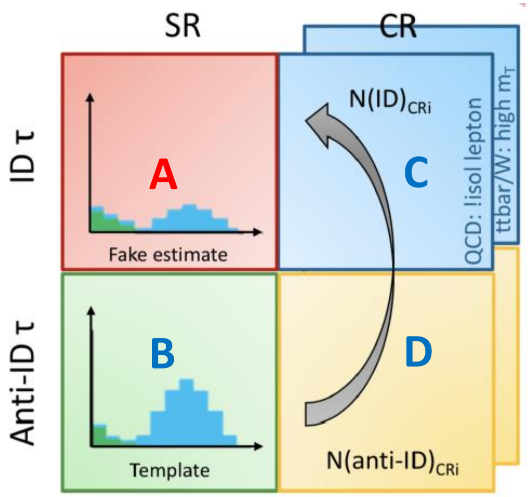
Process	Pre-fit Yield	Stat. Error
$t\bar{t}$	63140	120
Fake τ_{had}	32900	150
Single top	4180	50
Z+jets	2320	60
W+jets	84	11
Single Higgs	174	2
Di-boson	192	6
Non-res. HH	7.46	0.03

Single top

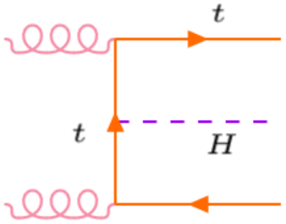


$t\bar{t}$

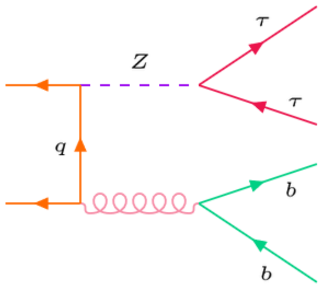




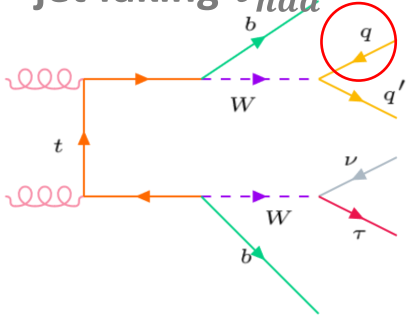
Single Higgs



Z + jets



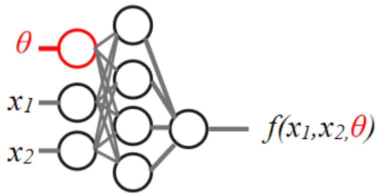
jet faking τ_{had}



- The background due to a jet faking the τ_{had} is estimated by a data driven fake factor method (ABCD method)
- Normalisation of $t\bar{t}$ and Z + jets are determined from the fit from low NN region and Z->ll control region
  - More details in backup

MVA classification

- Parametric Neural Network (PNN) is used for the resonant signal for both Lephad and Hadhad
  - Parametrised by resonant mass

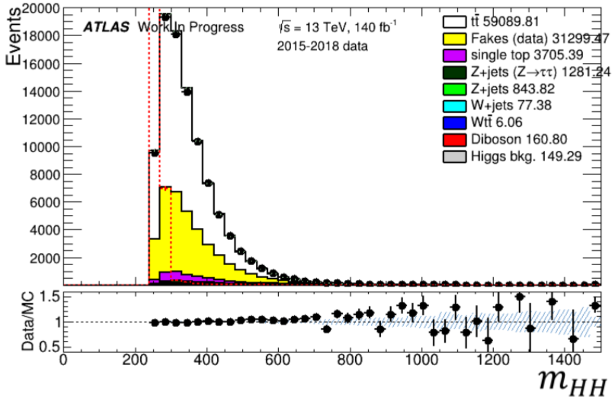


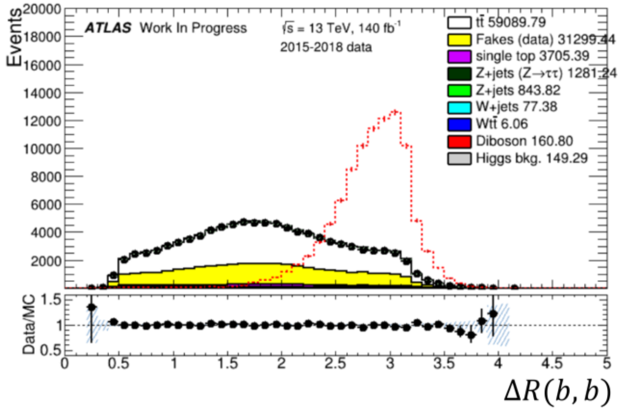
- NN(BDT) is used for Lephad (Hadhad) non-resonant

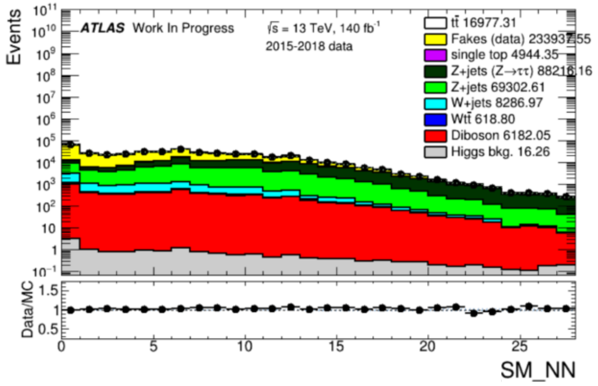
- Signal scale to integral of background

Variable	SLT	LTT
m_{bb}	✓	✓
$m_{\tau\tau}^{\mathrm{MMC}}$	✓	✓
m_{HH}	✓	✓
$\Delta R(\tau,\tau)$	✓	✓
$\Delta p_{\mathrm{T}}(\ell,\tau_{\mathrm{had-vis}})$	✓	✓
$\Delta R(b,b)$	✓	
$\Delta\phi(\tau^{\tau},bb)$	✓	
Sub-leading b-jet p_{T}	✓	
m_{T}^{W}	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$ ϕ Centrality	✓	
$\Delta\phi(\ell,E_{\mathrm{T}}^{\mathrm{miss}})$		✓
H_{T}		✓
$\Delta\phi(\tau\tau,E_{\mathrm{T}}^{\mathrm{miss}})$		✓

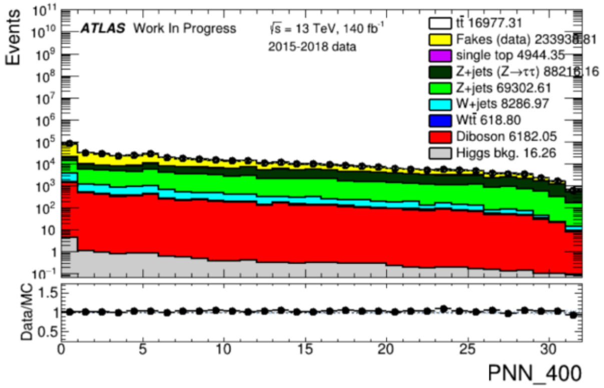
Lephad Input (SR preselection)



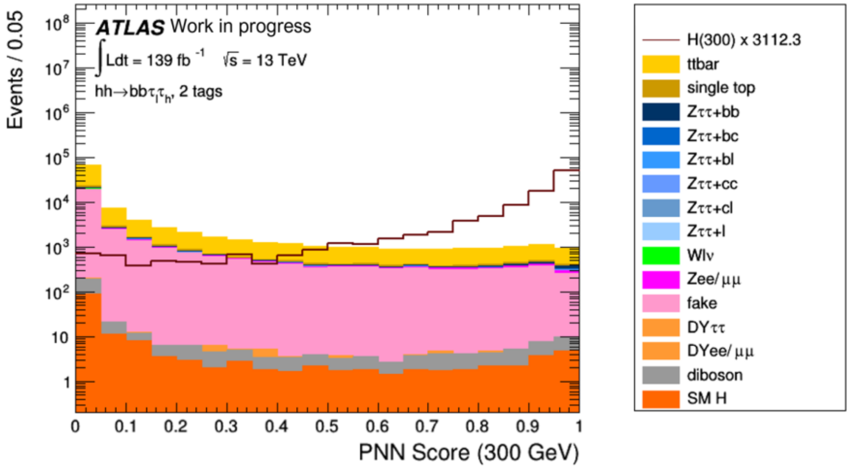


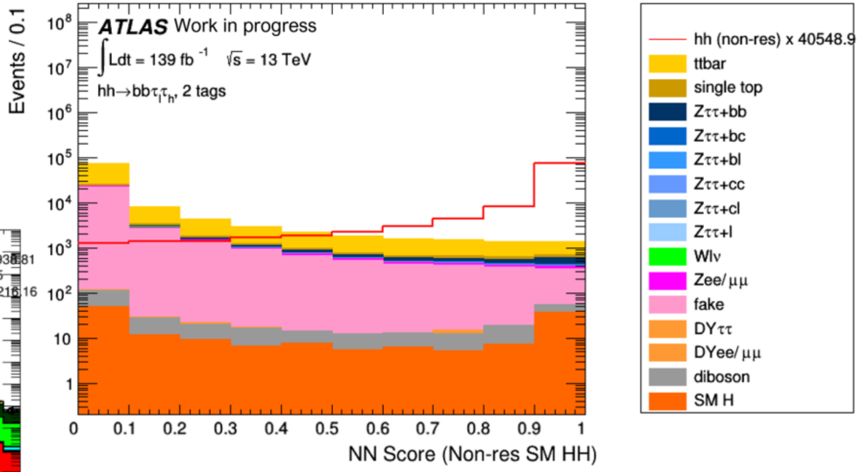


0-tag validation region



1-tag validation region





Uncertainties

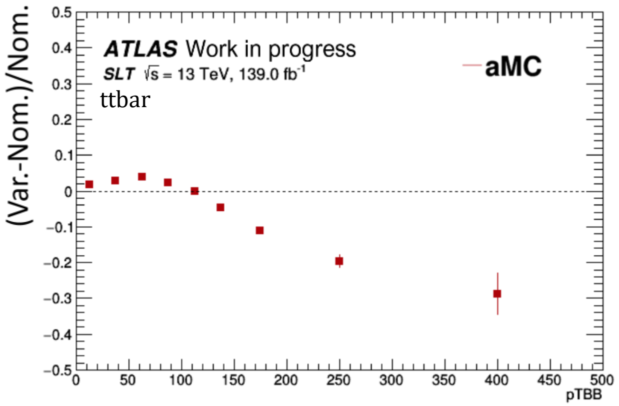
- Experimental uncertainties:
  - Uncertainties on efficiencies, resolution, scale etc. of physics objects. Check backup for more details

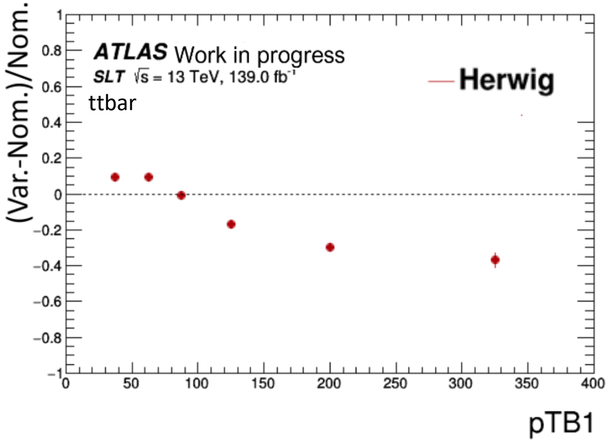
Modelling uncertainties for major background

General approach: split the normalisation and shape then parametrise the shape (which I have derived/studied most of them)

- $t\bar{t}$ & single top:
  - Matrix element, parton shower, initial/final state radiation(ISR/FSR), PDF + α_s
  - $t\bar{t}$: only consider shape as norm is freely floating in the limit
  - Single top: additional uncertainty due to interference

- Signal:
  - Resonant HH signal:
    - Scale variations, parton shower, PDF + α_s
  - Non-resonant HH signal:
    - Parton shower





Examples of systematics

- Z + Heavy flavour jets:
  - Scale variations, alternative PDF, matrix element matching and re-summation scale variation.
  - Only consider shape

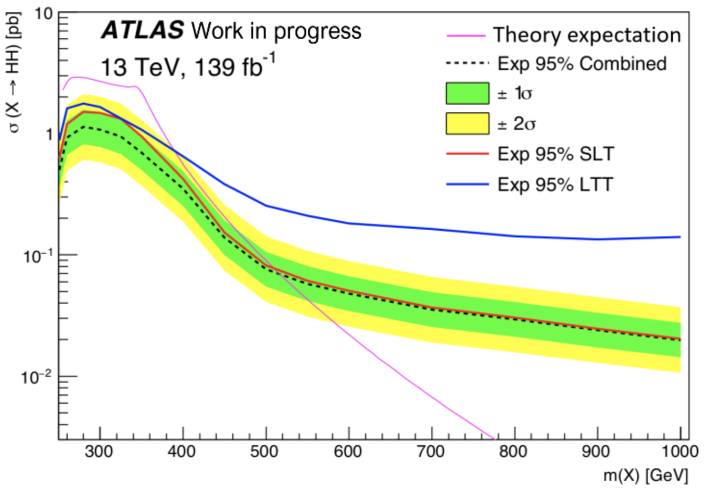
- Fake τ_{had} (Lephad):
  - Statistical uncertainty on FF and r_{QCD}
  - Non $t\bar{t}$ subtraction
  - $t\bar{t}$ modelling

Limit setting

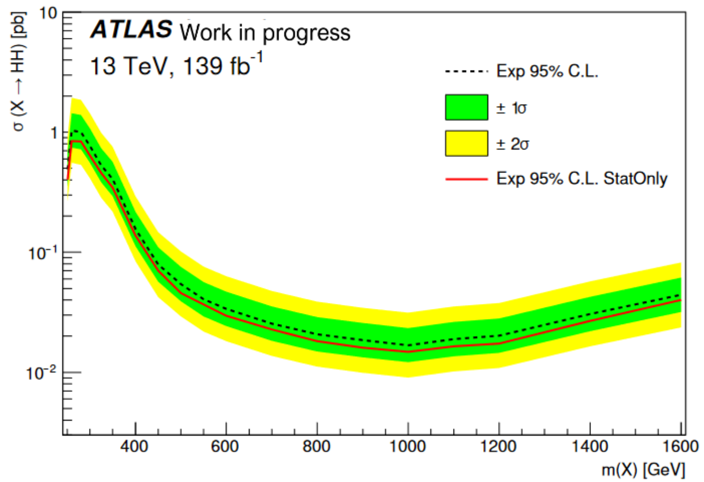
- Unfortunately, with the current dataset we are not expecting to see the SM non-resonant di-Higgs production
- We can still set limits on the upper limit on the cross section on the SM di-Higgs production (in bbtautau channel) and resonant signal mass
- Expected limits: **derived from simulation**
- Expected limit on Xs. with 36 fb^{-1} data in Lephad: 26.32 * Xs. (SM)
- Scale with luminosity (139 fb^{-1}), we expect the limit to be ~ 13 * Xs. (SM)
- The Lephad expected limit is 80% better!
- This is made possible by better b-tagging, tau-ID, tau-reconstruction, etc.

	Non resonant	-2σ	-1σ	Expected	1σ	2σ
Lephad Xs/Xs(SM)	Stat-Only	3.08	4.13	5.73	7.98	10.70
	Stat+Syst	3.90	5.24	7.27	10.12	13.57
Hadhad Xs/Xs(SM)	Stat-Only	2.01	2.70	3.75	5.22	7.00
	Stat+Syst	2.51	3.37	4.68	6.52	8.73

Limit for resonant Lephad



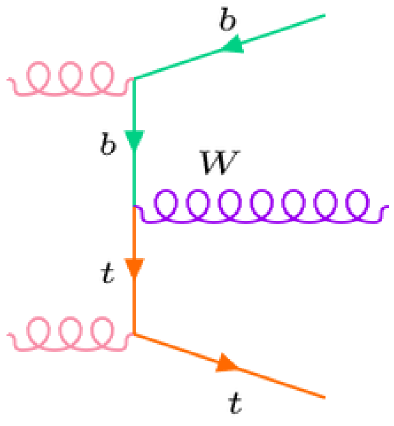
Limit for resonant Hadhad



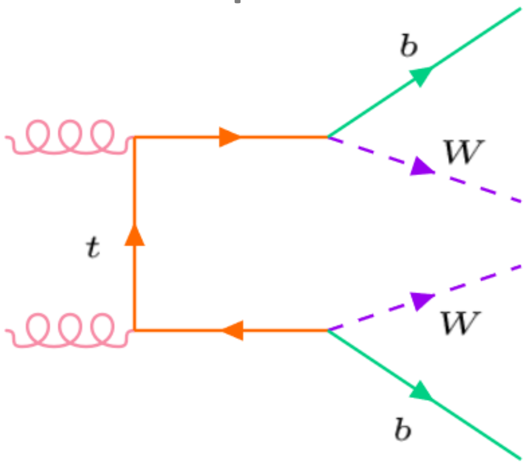
Backup: Signal and background

- Data:
  - Full run 2 data set with L = 139 fb^{-1}
- Signal:
  - Non-res HH (SM, ggF): Powheg + Pythia8 (NLO with NNLO cross-section)
  - 2HDM X->HH (ggF): Madgraph5 + Herwig7 (NLO), 19 m_X points from 251 GeV to 1.6 TeV
- MC Backgrounds
- In order of contribution:
  - $t\bar{t}$ and single top: Powheg + Pythia8, $t\bar{t}$ norm freely floating
  - V (W,Z) + jets: Sherpa 2.2.1, Z + HF jets norm freely floating as determined by the Z + HF CR (more details in backup)
  - Di-boson (semi-leptonic): Sherpa 2.2.1
  - Single SM Higgs: Powheg+Pythia8

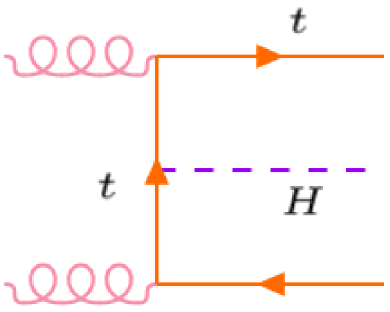
Single top process



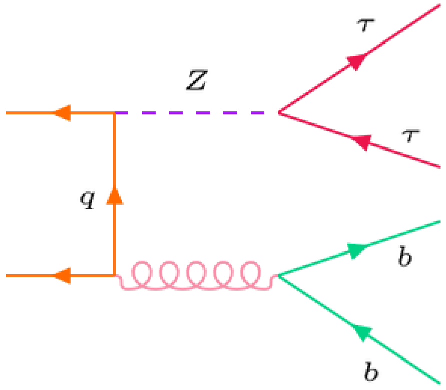
$t\bar{t}$ process



Single Higgs process



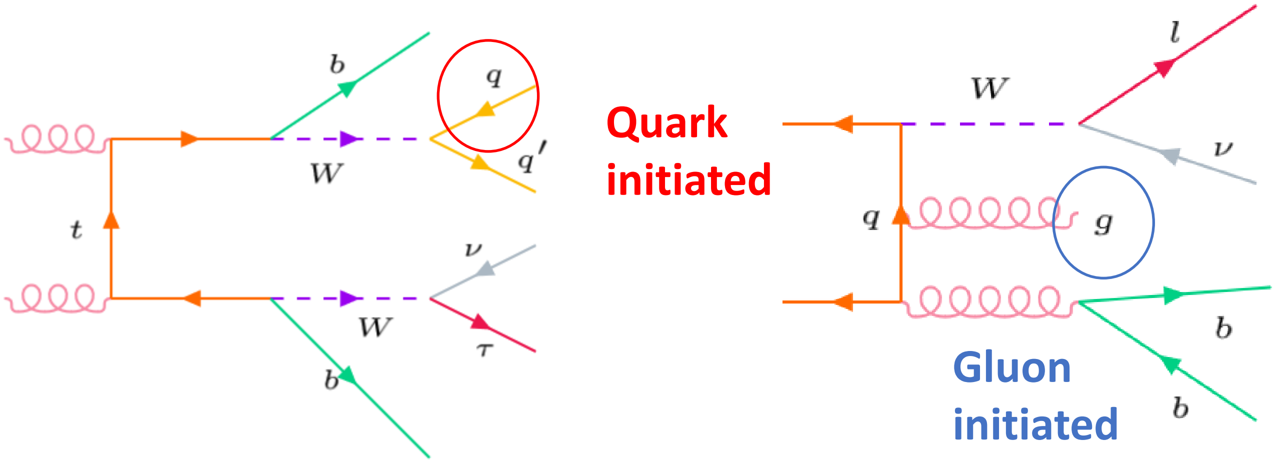
Z + jets process

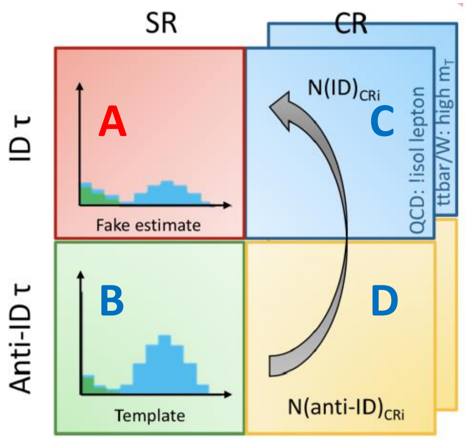


Backup: Background estimation: jet faking τ_{had}

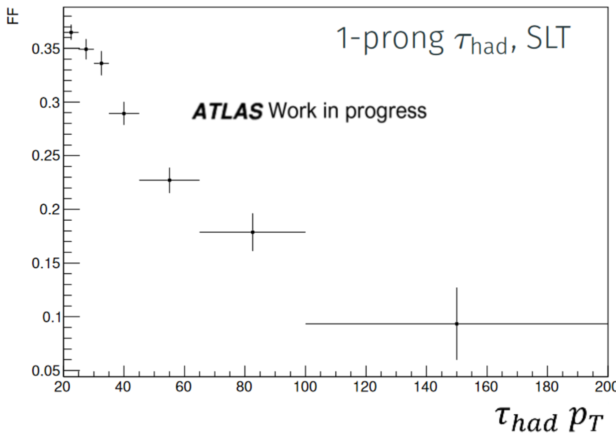
- The background due to a jet faking the τ_{had} is estimated by a data driven fake factor method (ABCD method)
- Anti-ID τ: reverting the Tau-ID to define a fake-τ enriched region
- Fake factor $\mathrm{FF} = \frac{N_C}{N_D}$, $\mathrm{N_A} = FF \times N_B$. FF is calculated for each CR, depends on channel/targeted process
- Lephad: a combined FF is calculated for combining the Gluon initiated and quark initiated (mostly $t\bar{t}$) FFs
  - $FF = FF_{QCD} \times r_{QCD} + \mathrm{FF}_{t\bar{t}} \times (1 - r_{QCD})$, where $r_{QCD} = \frac{N^{Fakes}_{QCD}}{N^{Fakes}_{all}}$.

jet faking τ_{had}





FF$_{t\bar{t}}$ measured in $t\bar{t}$ CR



Backup: object selection

Object selection

- Electrons:
  - Loose e-ID, loose isolation
  - p_T > 7 GeV, $|\eta|$ < 2.47 + crack veto
- Muons:
  - Loose muons with *PflowLoose_VarRadIso* isolation, p_T > 7 GeV, $|\eta|$ < 2.7
- Taus:
  - Loose RNN Tau-ID, loose electron-veto
  - p_T > 20GeV, $|\eta|$ < 2.5 + crack veto
  - 1- or 3-prong
- Anti-Taus
  - Fail loose RNN Tau-ID and RNN score > 0.01

- Jets:
  - Anti-k_t R=0.4 particle flow jets
  - Jet cleaning & tight JVT
  - pT>20GeV, $|\eta|$ <2.5
- b-tagging
  - DL1r with 77% WP
- MET
  - PFLow MET (TST)
- OLR
  - ASG OLR tool with dedicated jet- τ_{had} OLR:
  - τ_{had} > b-tagged jet > anti-τ_{had} > untagged-jet

Backup: Experimental uncertainties

- Jets:
  - JES (CategoryReduction) & JER (FullJER)
- Flavor tagging:
  - medium reduction
- Electrons:
  - scale, resolution, efficiencies (trigger, reco, ID, isolation)
- Muons:
  - momentum-calibration + efficiencies (reco, TTVA, iso)(muon trigger currently missing)
- Taus:
  - TES + efficiencies (eVeto,τhad-ID, trigger) SoftTrk
- MET:
  - Scale & Resolution

Backup: Selection for Hadhad channel

Triggers: Hadhad

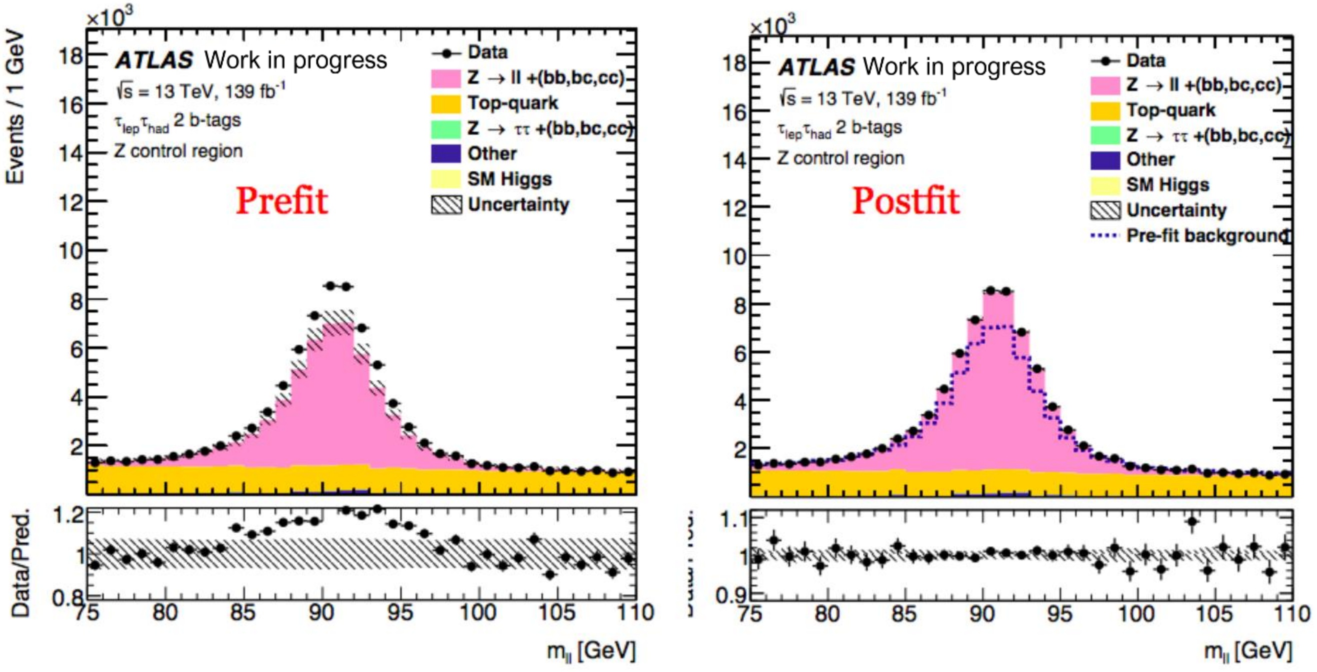
- Single τ_{had} triggers (STT)
  - HLT thresholds on τ_{had} p_T between 80 and 160 GeV, offline requirement p_T > HLT threshold + 20 GeV
  - Supplemented by non-isolated triggers
  - Apply before DTT. If failed STT, then pass the event through DTT

- Di-τ_{had} triggers (DTT)
  - Threshold on HLT τ_{had} p_T 35 (25) GeV for leading (sub-leading) τ_{had}, offline requirement p_T > HLT threshold + 5 GeV

Event selection

- All channels:
  - Pass triggers & matching of τ_{had}-legs
  - Offline trigger eff. plateau cuts on leptons, τ_{had}, and jets at L1
  - $m_{\tau\tau}^{MMC}$ > 60 GeV (Missing Mass Calculator used to reconstruct $\tau\tau$-system)
  - At least two central jets (one with p_T > 45 GeV)
- **Hadhad**
  - No e/μ
  - Exactly 2 loose τ_{had}
  - For L1Topo-triggered events: $\Delta R(\tau_{had}, \tau_{had}) < 2.5$

Backup: Z+HF CR



Pre-fit and post-fit m_{ll} distribution in the Z+HF CR

- The cross section of Z boson production in association with heavy flavour (b,c) jets is known to be not well predicted by the Sherpa MC and so these processes are normalised to data in a control region.
- Events selected with bbll trigger selection using single-lepton and di-lepton triggers
- Exactly two muons or two electrons with opposite-sign charges
- Exactly two b-tagged jets
- 75 GeV < m_{ll} < 110 GeV (select Z mass peak
- m_{bb} < 40 GeV or m_{bb} > 210 GeV (to veto Higgs mass peak and to ensure orthogonality to bbll signal region).
- This control region is included in the final fit as m_{ll} distribution shown in above figure.
- From a fit to data of this CR alone the normalisation of the Z+HF background is found to be 1.29 ± 0.019