Searches for HH in the $b\bar{b}\tau^+\tau^-$ channel with ATLAS

2022/07/26

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Higgs Potential 2022

bbbb

γγbb

bbττ

bbℓℓ

bbVV

multi-lepton

ATLAS EXPERIMENT

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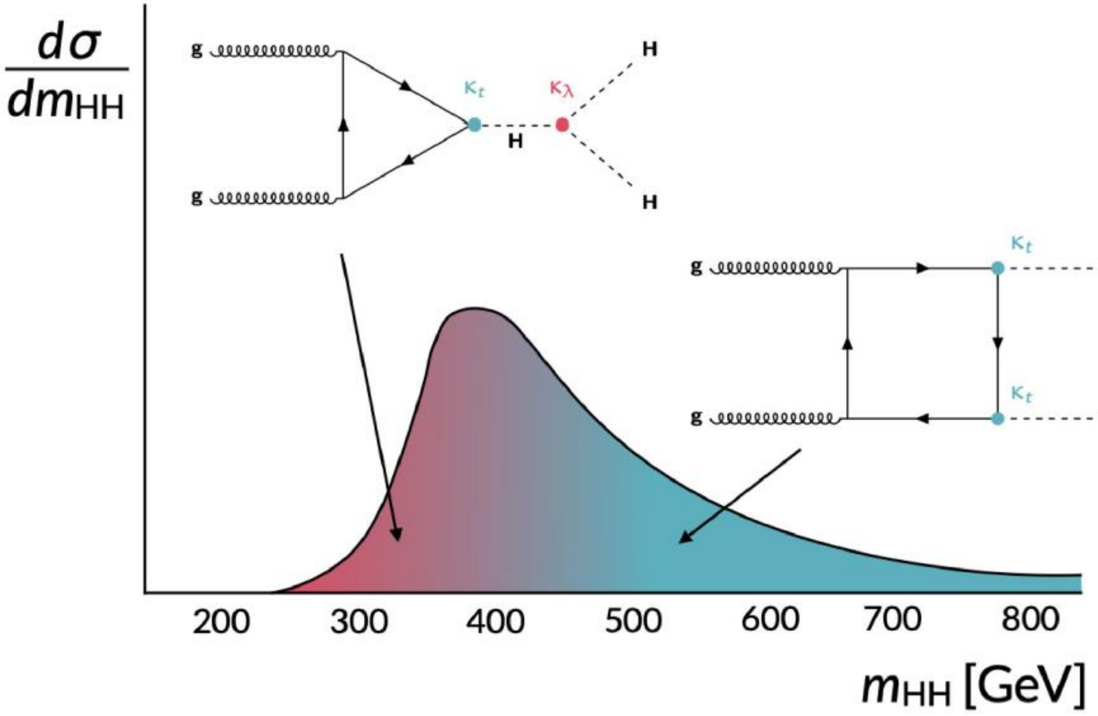
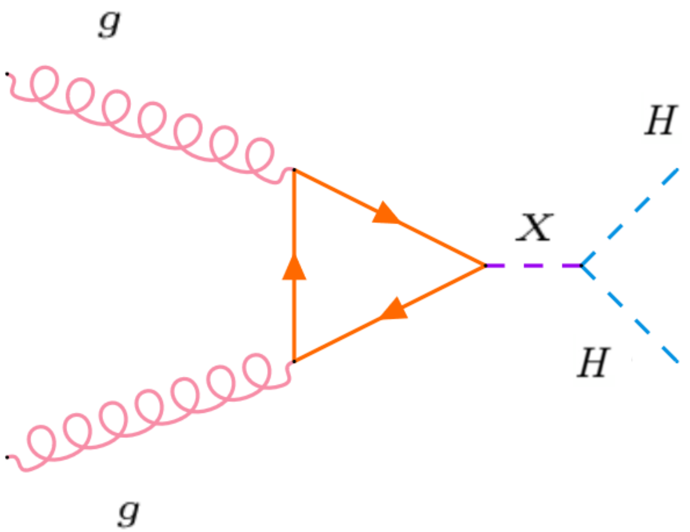
Motivation: DiHiggs searches

- Di-Higgs searches is of uttermost importance, however…
  - Cross-section is very small: $\sigma_{gg\to HH}$ = 31.05 fb at 13 TeV, due to:
    - Box diagram destructively interfere with triangle diagram
    - Small phase space

  - Though in many BSM…
    - modify the interaction strength (or add anomalous interaction),
    - or enhanced greatly via BSM resonances

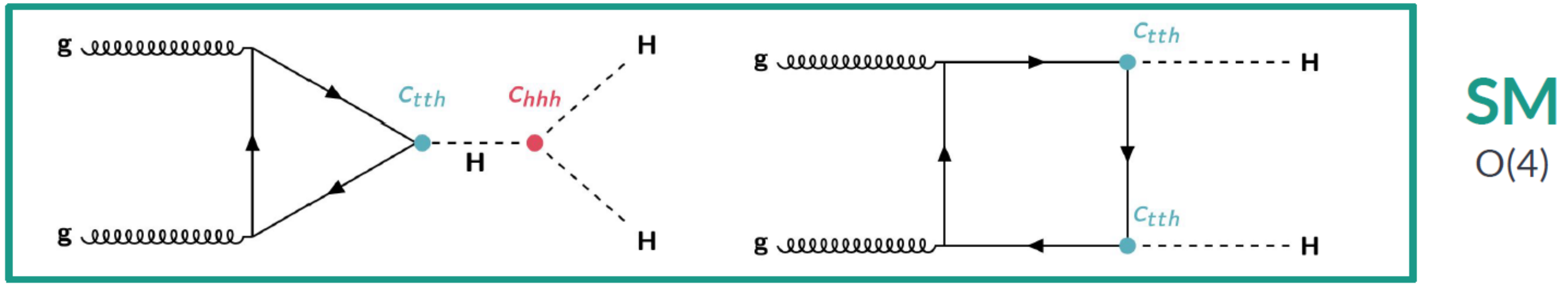


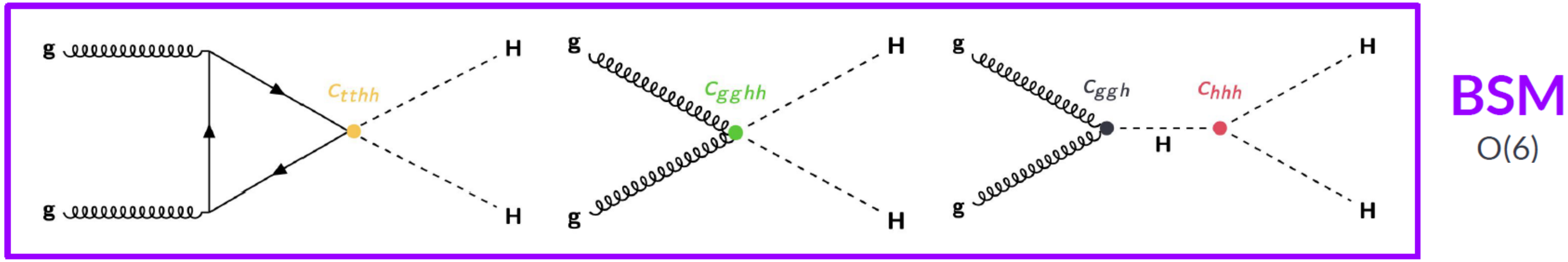
Non-resonant production



resonant production

EFT interpretation: Motivation





- Effective Field Theory (EFT) interpretation on di-Higgs searches

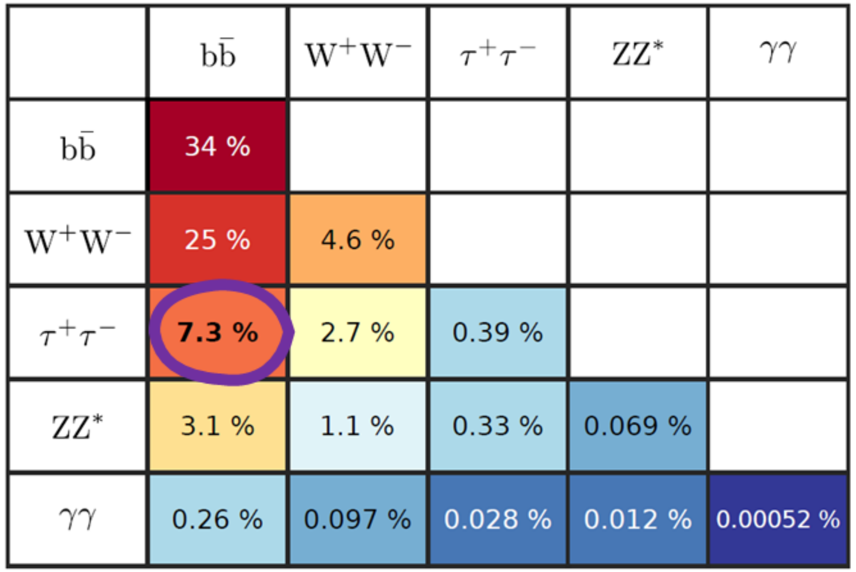
- Two EFT frameworks available:
  - SM EFT
  - Higgs EFT

SM: $c_{hhh} = c_{tth} = 1$ and $c_{ggh} = c_{tthh} = c_{gghh} = 0$.

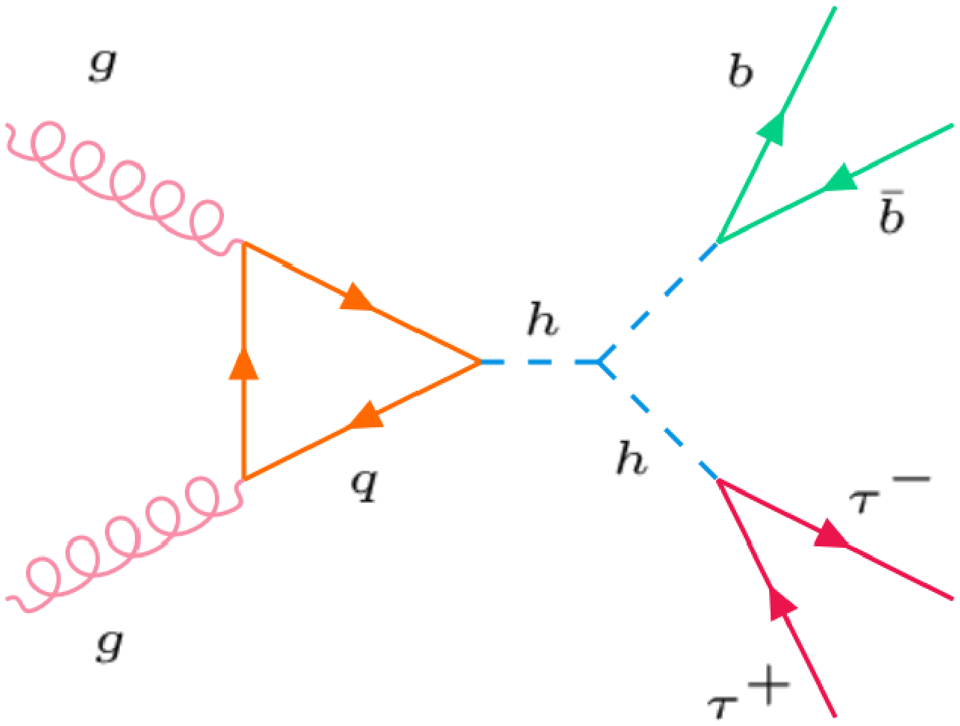
- HH searches present constraints on:
  - k_λ (c_{hhh}) or
  - c_{tthh}, c_{gghh}

Motivation: $bb\tau\tau$ channel

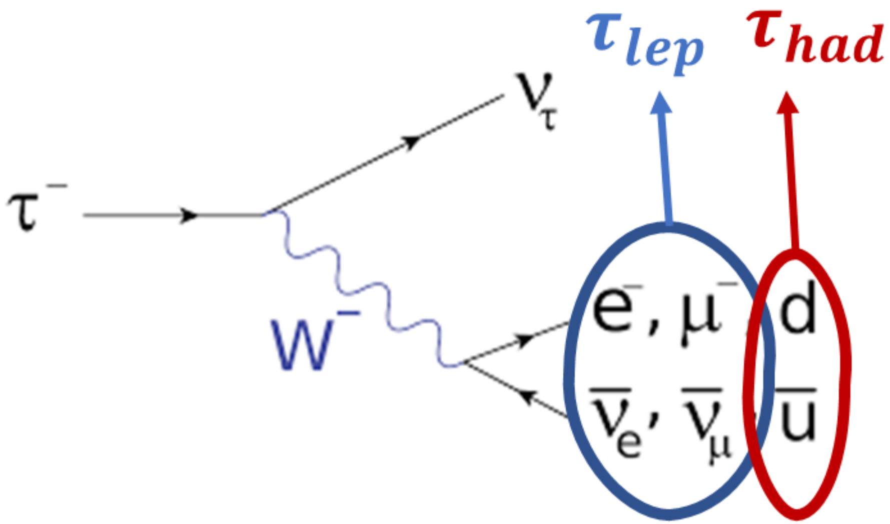
- Combines the advantages of high branching ratio and clean background
  - …relative to the bbyy and bbbb channels



	$b\bar{b}$	W^+W^-	$\tau^+\tau^-$	ZZ^*	$\gamma\gamma$
$b\bar{b}$	34 %				
W^+W^-	25 %	4.6 %			
$\tau^+\tau^-$	7.3 %	2.7 %	0.39 %		
ZZ^*	3.1 %	1.1 %	0.33 %	0.069 %	
$\gamma\gamma$	0.26 %	0.097 %	0.028 %	0.012 %	0.00052 %

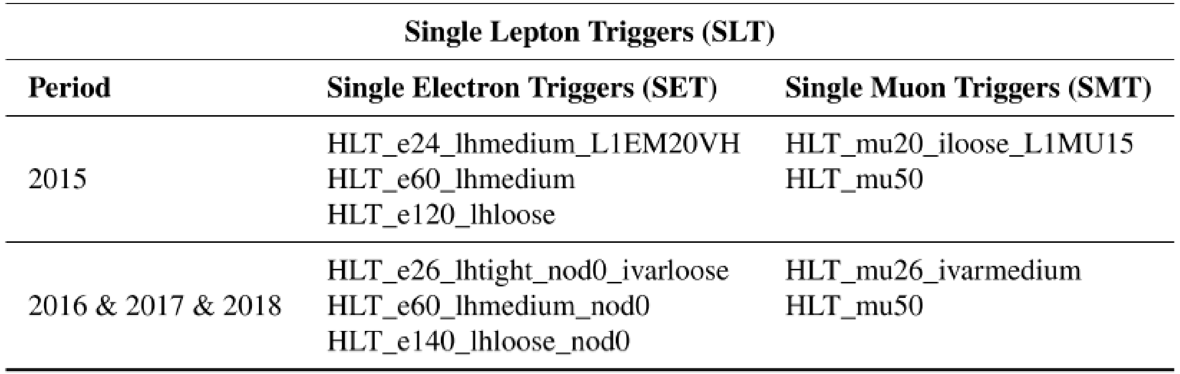


- Further divided into $\tau_{lep}\ \tau_{had}$ (Lephad) and $\tau_{had}\tau_{had}$ (Hadhad) channels
  - Based on the decay mode of the two τ-leptons



Analysis: Introduction

- Workflow:
  - Trigger selection
  - Reconstruction and event selection
  - Background and uncertainties estimation
  - Statistical analysis
  - Results!



Single Lepton Triggers (SLT)		
Period	**Single Electron Triggers (SET)**	**Single Muon Triggers (SMT)**
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_iloose_L1MU15 HLT_mu50
2016 & 2017 & 2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0	HLT_mu26_ivarmedium HLT_mu50

- Triggers:
  - A set of triggers is used, for...
    - Lephad: Single Lepton Triggers (SLT) + Lepton plus Tau Triggers (LTT)
    - Hadhad: Single Tau Triggers (STT) + Di-Tau Triggers (DTT)

Event selection

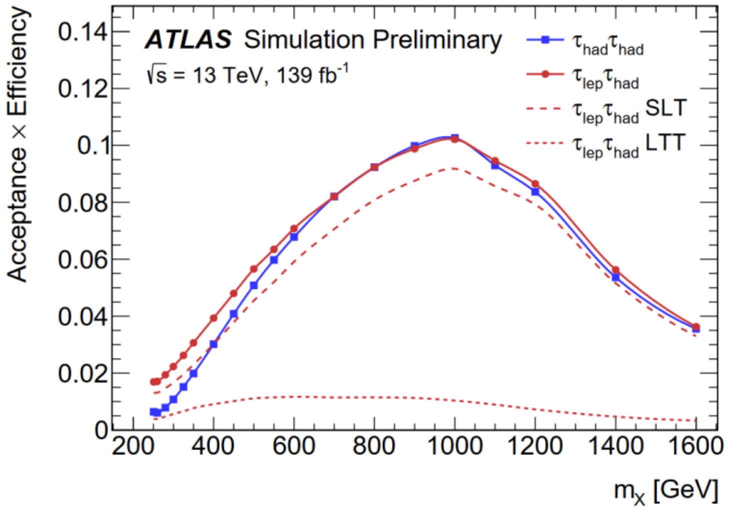
- Signal targeting:
  - SM ggF + VBF non-resonant, and
  - Generic narrow width scalar particle with mass 251 GeV ~ 1600 GeV

Hadhad	Lephad SLT	Lephad LTT
Single & di-τ_{had} triggers	single ℓ triggers	$\ell + \tau_{had}$ triggers
exactly two τ_{had}	exactly one τ_{had} & one e or μ	
lepton-veto	m_{bb} < 150 GeV	
trigger-dependent thresholds on $e/\mu/\tau_{had}$ and jets		
$m_{\tau\tau}^{MMC}$ > 60 GeV		
2 b-tagged jets		
OS el. charge of $\tau e/\tau\mu/\tau_{had}$ and τ_{had}		

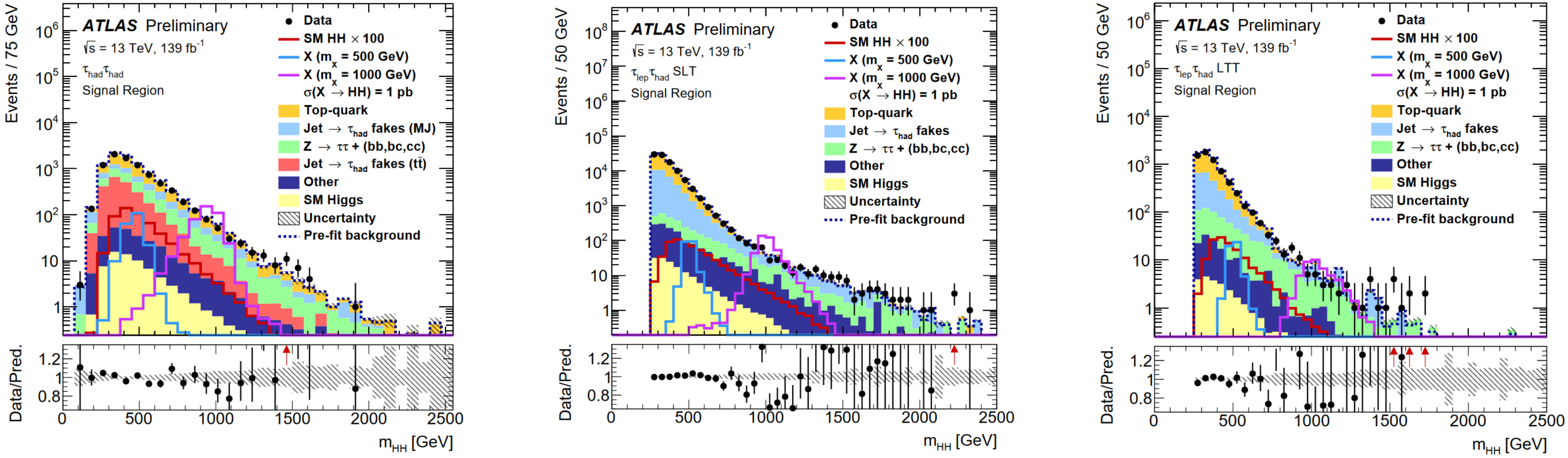
Non-resonant MC

Channel	$A \times \epsilon$
$\tau_{had}\tau_{had}$	4%
$\tau_{lep}\tau_{had}$ (SLT)	4%
$\tau_{lep}\tau_{had}$ (LTT)	1%

Resonant MC



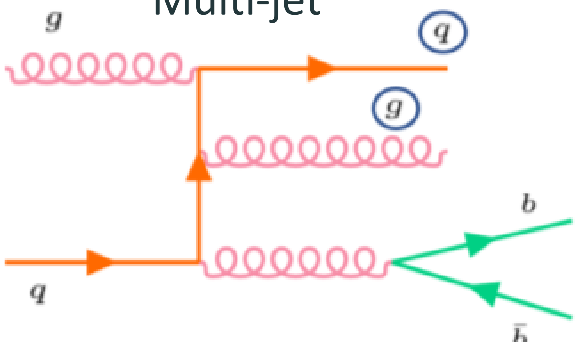
Background estimation



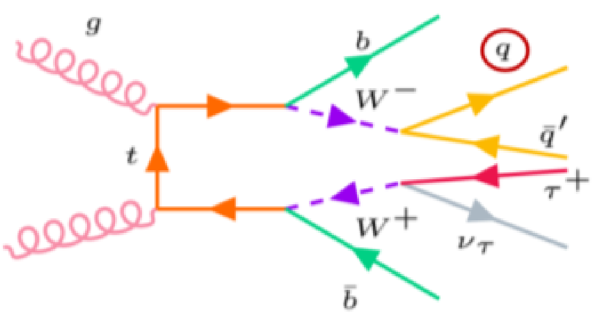
- Dominant background simulated:
  - $t\bar{t}$ and single top (normalised in fit)
  - V (W, Z) + jets (normalised in fit – dedicated CR)
  - Single SM Higgs/Other (simulation)
- Data-driven background:
  - Background due to a τ_{had} is fake by a jet (data-driven method)

Fake background estimation

Multi-jet

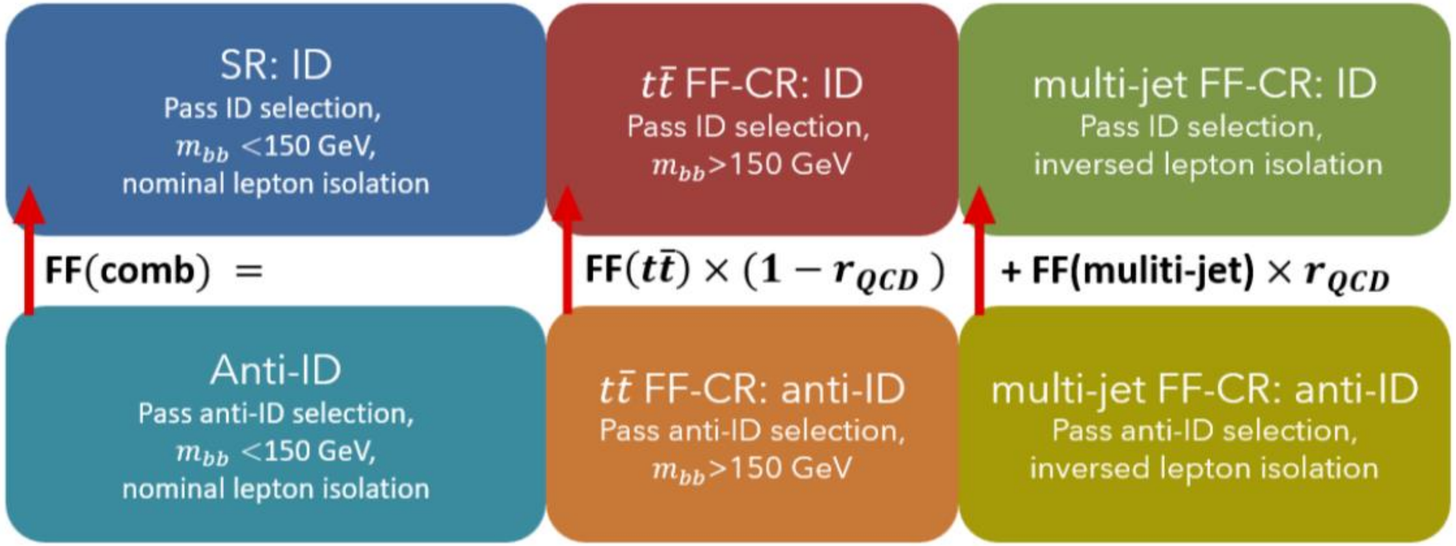


$t\bar{t}$



$$\mathrm{FF} = \frac{N(\text{ID selection})}{N(\text{anti-ID selection})},$$

$$N = N(\text{data}) - N(\text{true } \tau_{\text{had}}, \text{MC})$$



SR: ID
Pass ID selection,
m_{bb} <150 GeV,
nominal lepton isolation

$t\bar{t}$ FF-CR: ID
Pass ID selection,
m_{bb}>150 GeV

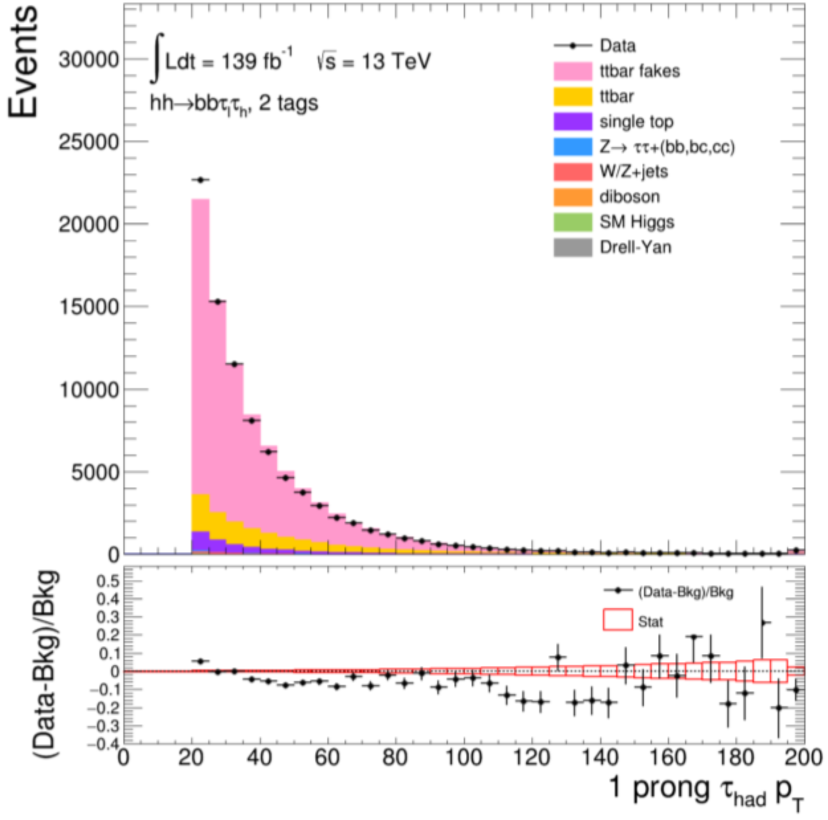
multi-jet FF-CR: ID
Pass ID selection,
inversed lepton isolation

$$\mathbf{FF(comb)} = \mathbf{FF}(t\bar{t}) \times (1 - r_{QCD}) + \mathbf{FF(muliti\text{-}jet)} \times r_{QCD}$$

Anti-ID
Pass anti-ID selection,
m_{bb} <150 GeV,
nominal lepton isolation

$t\bar{t}$ FF-CR: anti-ID
Pass anti-ID selection,
m_{bb}>150 GeV

multi-jet FF-CR: anti-ID
Pass anti-ID selection,
inversed lepton isolation

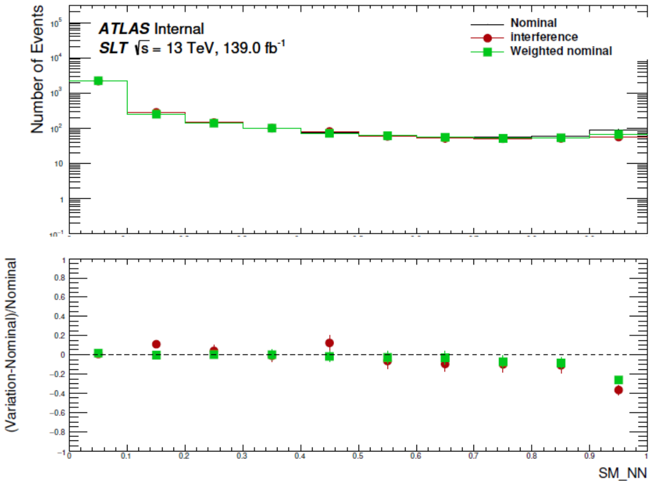


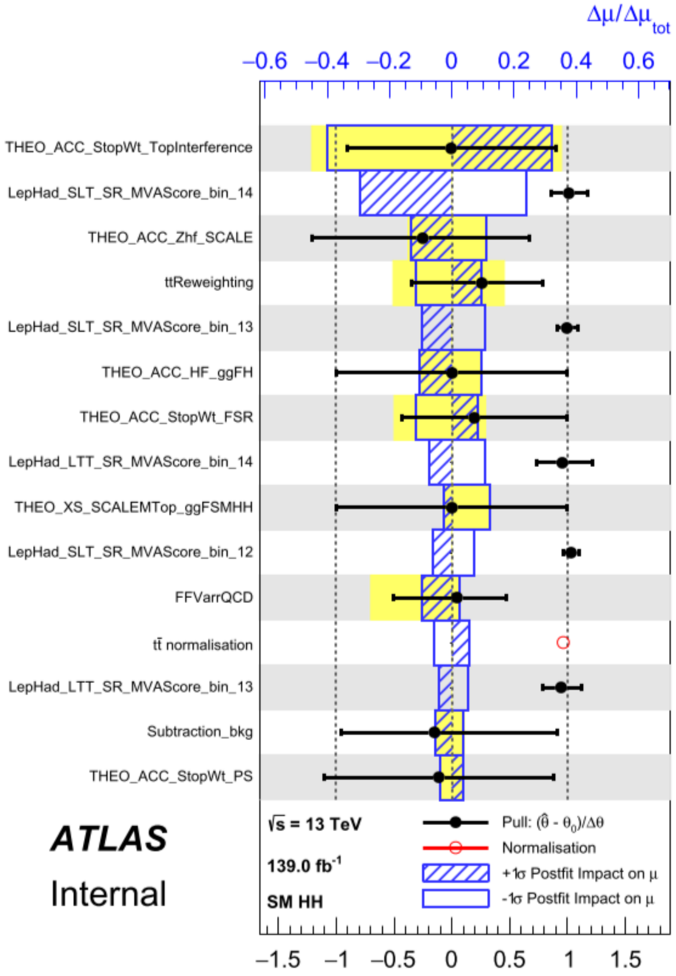
$t\bar{t}$ FF-CR, with fake background simulated by MC (not doing a good job!)

Systematics Uncertainties

- Experimental Systematics covering:
  - Luminosity, pileup reweighting
  - Physics objects reconstruction and identification: Tau, leptons, Jet, vertex…
  - b-tagging
  - And more on triggers, energy scale, resolution…
  - ~110 in total! Each are run independently for all samples

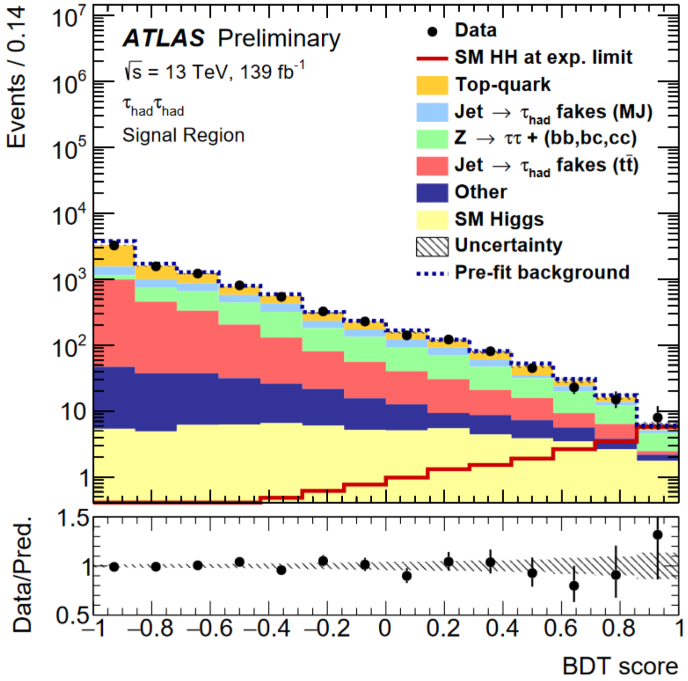
- Modelling Systematics:
  - Theory uncertainties on cross section
  - Uncertainties on acceptance:
    - Signal: Non-resonant + resonant
    - $t\bar{t}$, Single top
    - Z+jets
    - Single Higgs
    - + other minor background

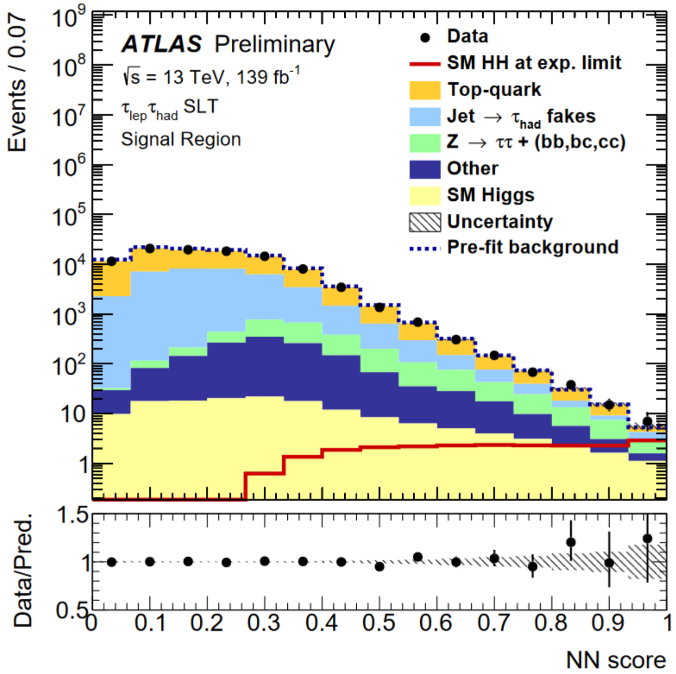


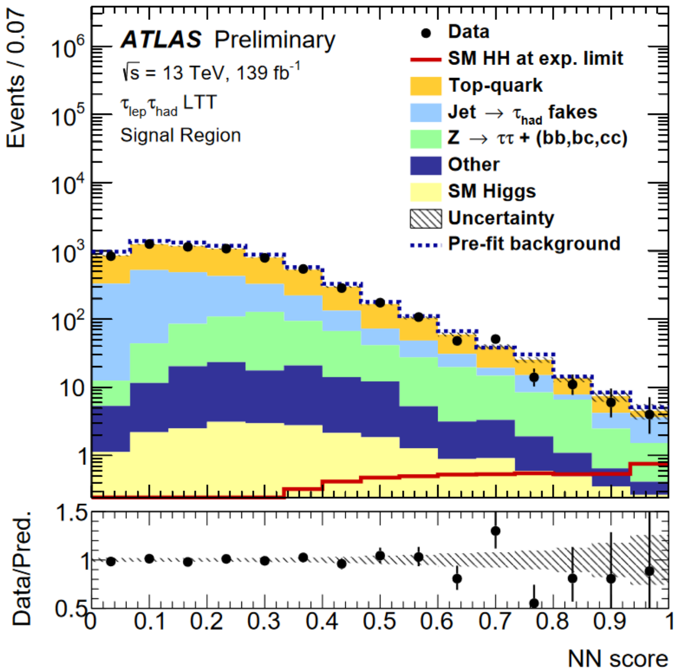


Single-top uncertainty due to the interference term

Statistical analysis: Non-resonant



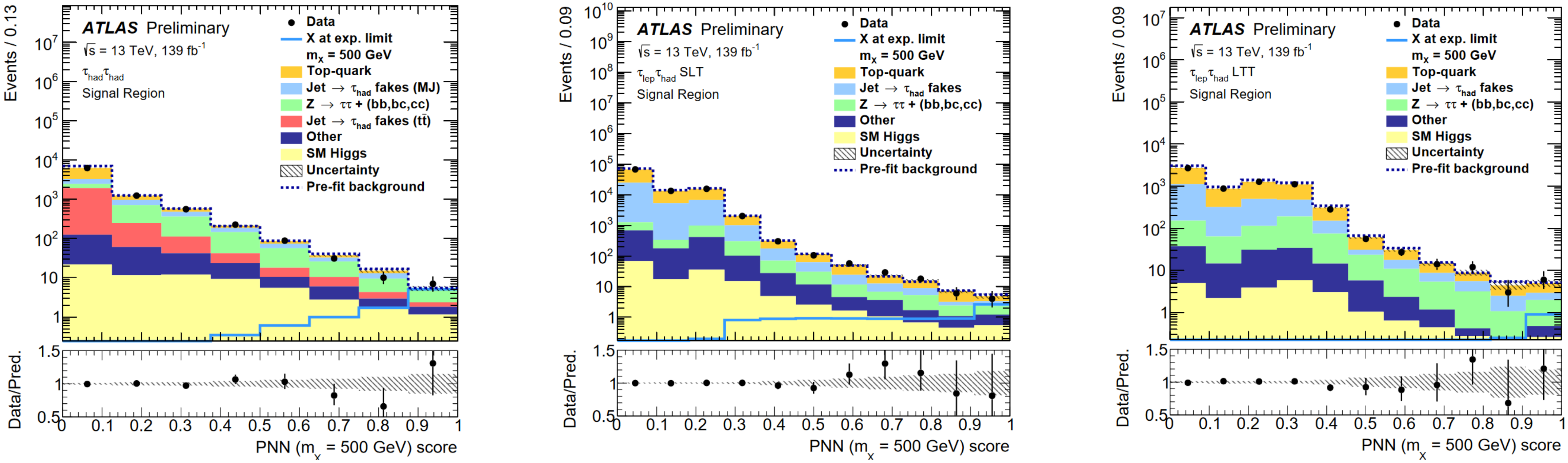




Non-resonant production

- Signal / background classifiers provide discriminant for likelihood fit
  - $\tau_{had}\tau_{had}$: Boosted Decision Trees
  - $\tau_{lep}\tau_{had}$: Neural Networks
- Trained on signal vs. all backgrounds using high-level variables:
  - E.g. m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, $\Delta R(\tau,\tau)$, more in backup

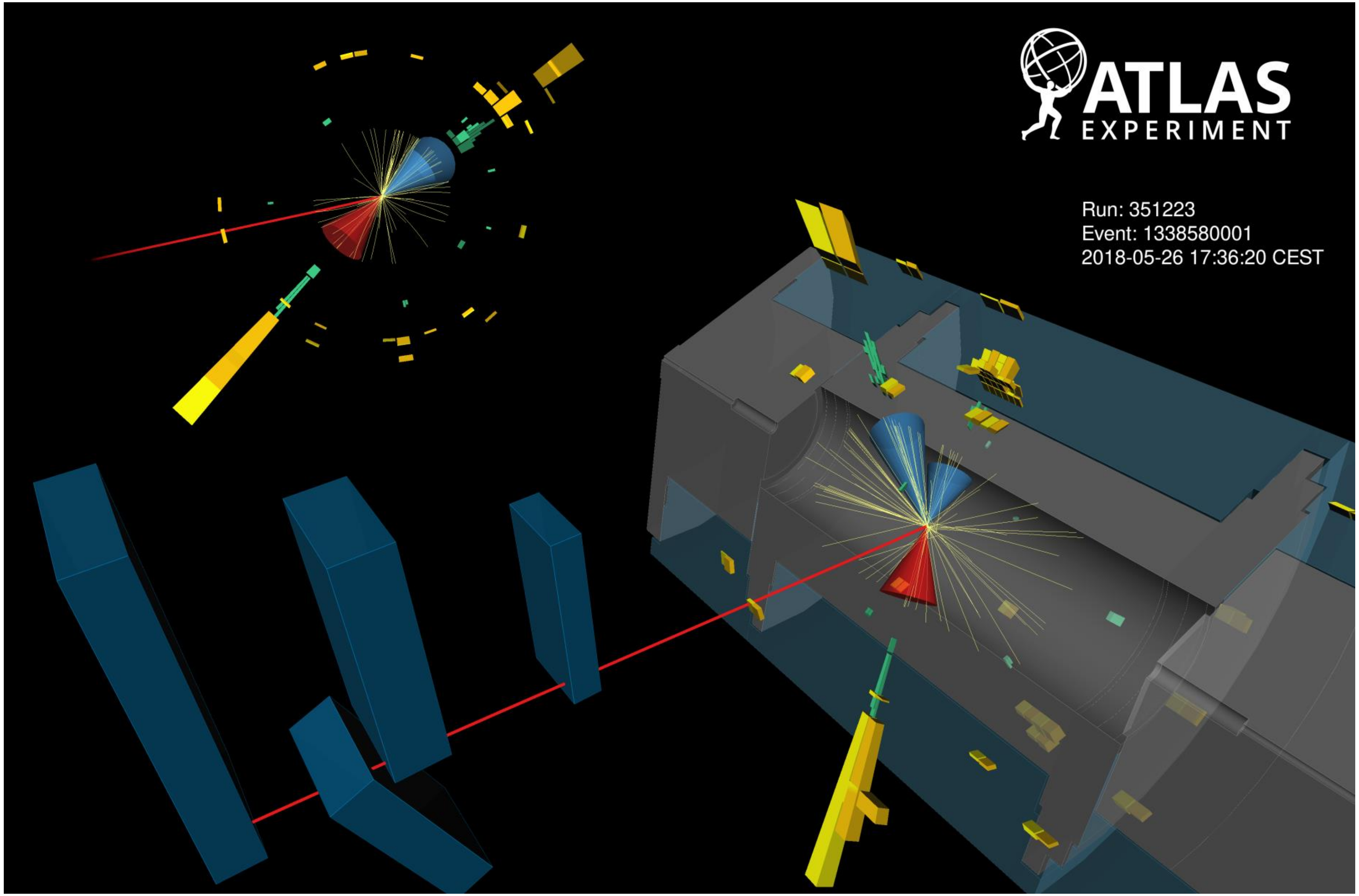
Statistical analysis: Resonant



Resonant production

- Parametrised neural networks (PNN) as discriminant
  - Same for Lephad and Hadhad
- Provide single classifier (per channel) for all considered m_X
  - Achieving high sensitivity for each mass points, and
  - also able to interpolate across them

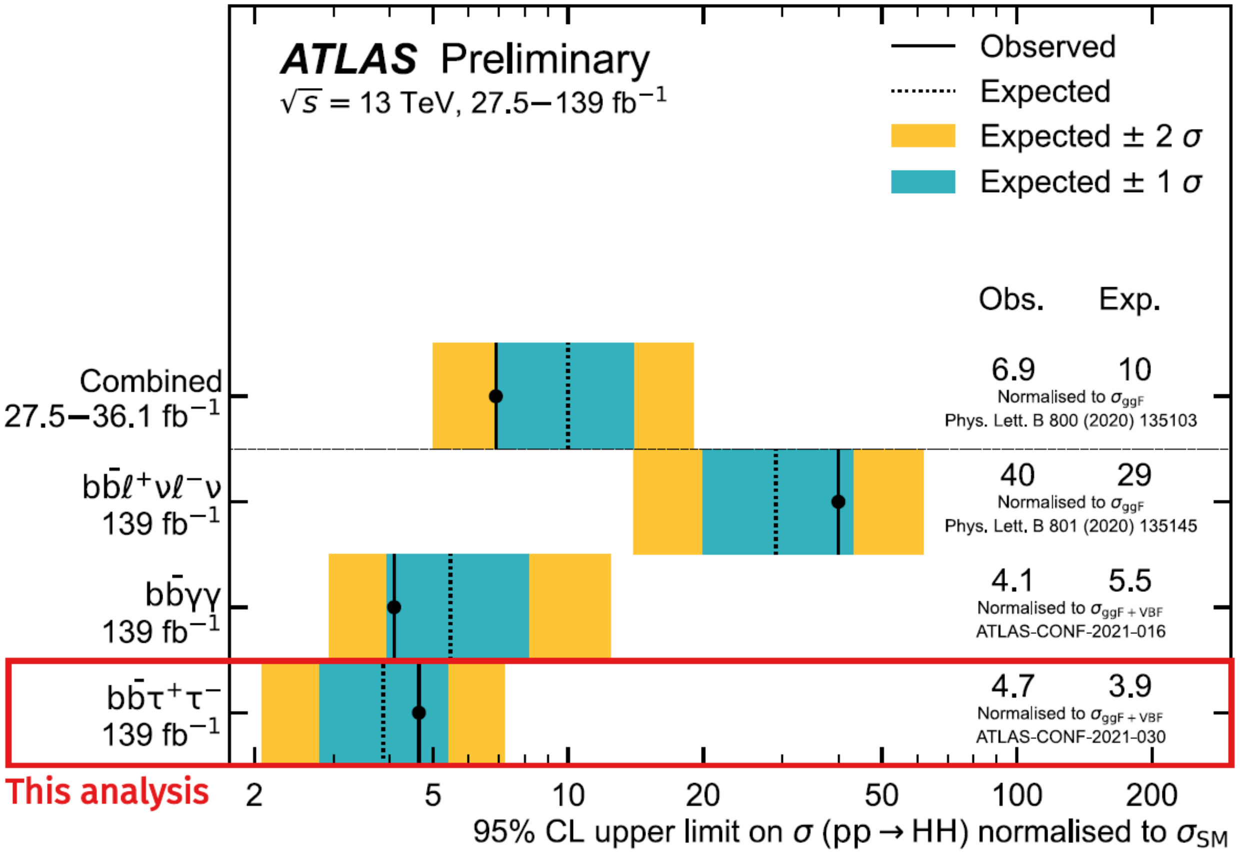
Motivation: $bb\tau\tau$ channel



Event display: $b\bar{b}\ \tau_{\mu}\tau_{had}$

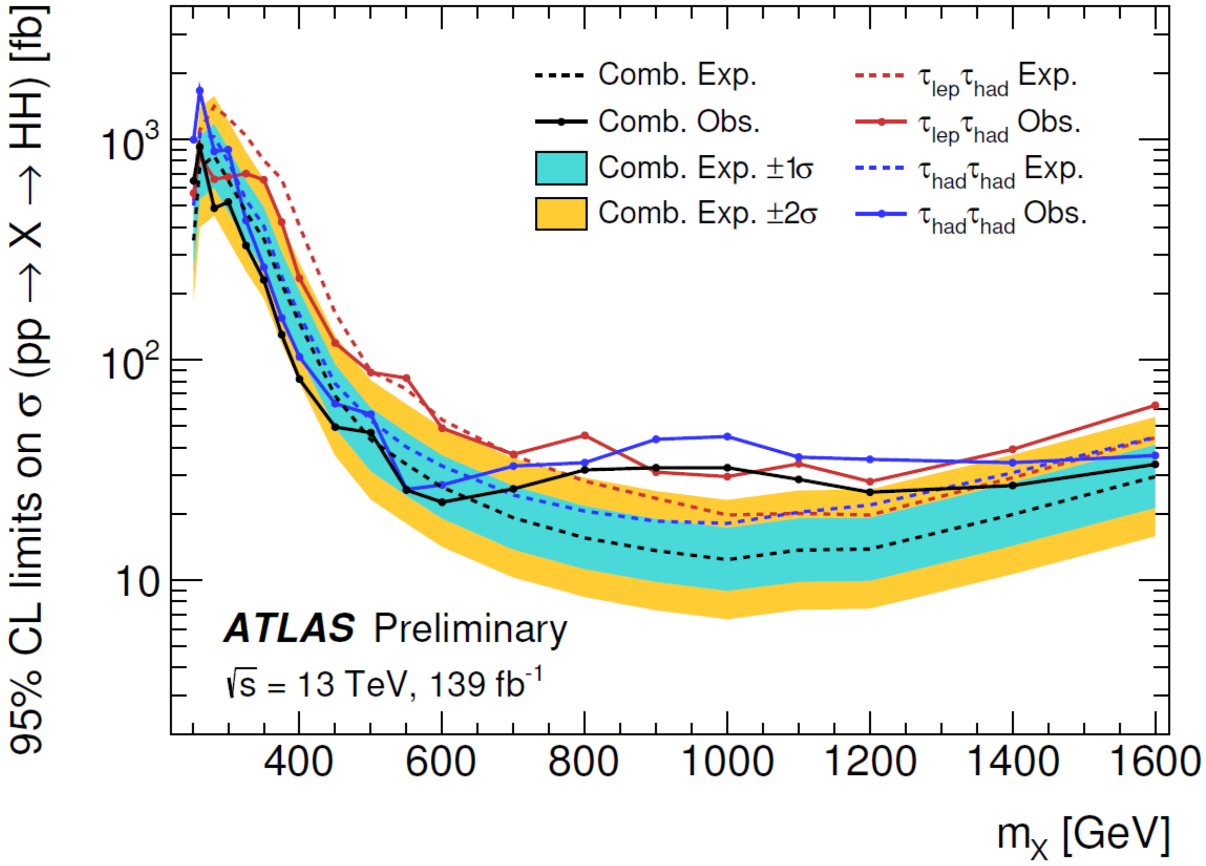
Results: Limits

ATL-PHYS-PUB-2021-031



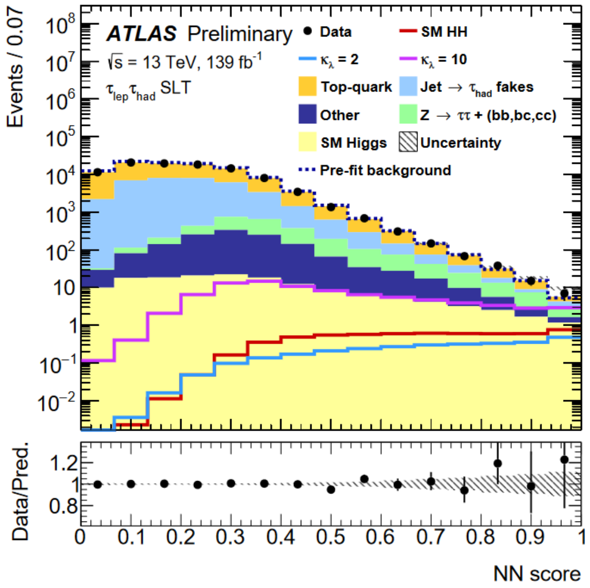
This analysis

ATLAS-CONF-2021-030



- Upper limit on $\sigma^{HH}_{ggF+VBF}$: obs. 4.7 × σ_{SM} (exp. 3.9 × σ_{SM})
  - Highest expected sensitivity to date
- Upper limits on σ_X → HH for narrow-width scalars ranging from approx. 20–10^3 fb
  - Largest excess at 1 TeV with local (global) significance of 3.0σ (2.0σ)

Results: $k_\lambda, c_{tthh}, c_{gghh}$ scan



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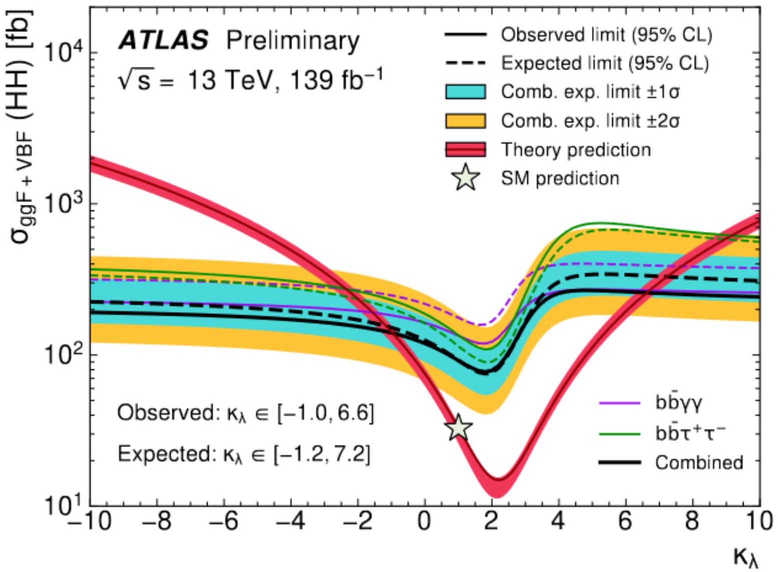

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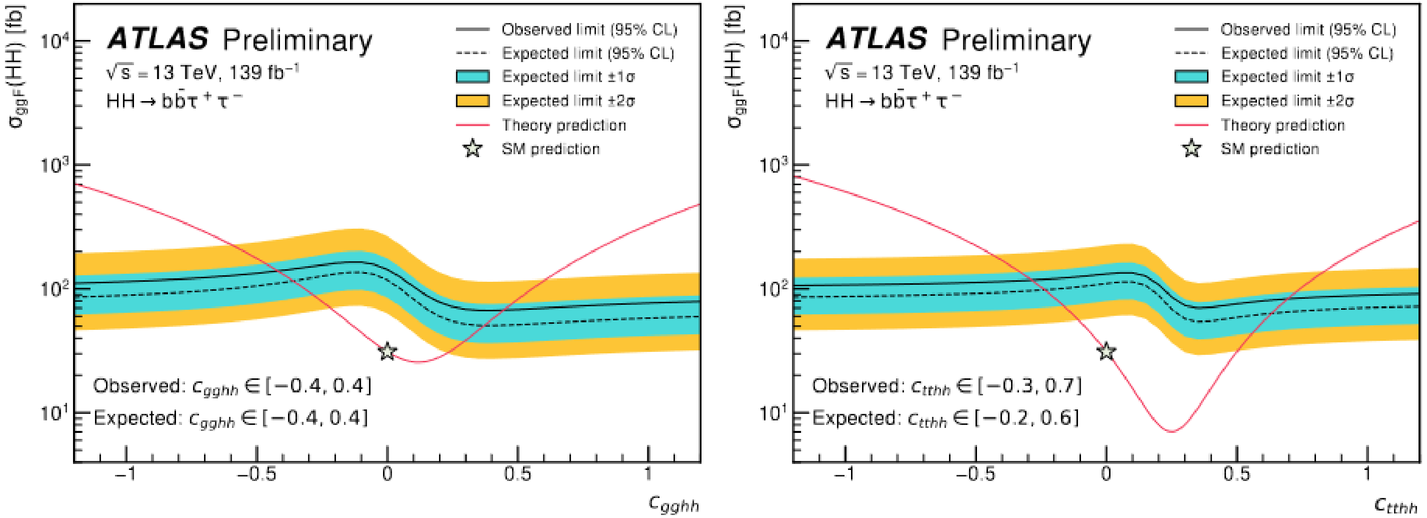
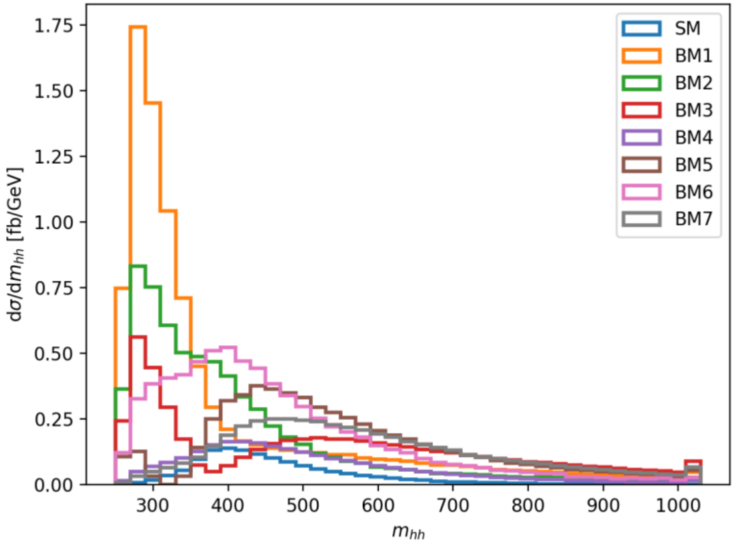


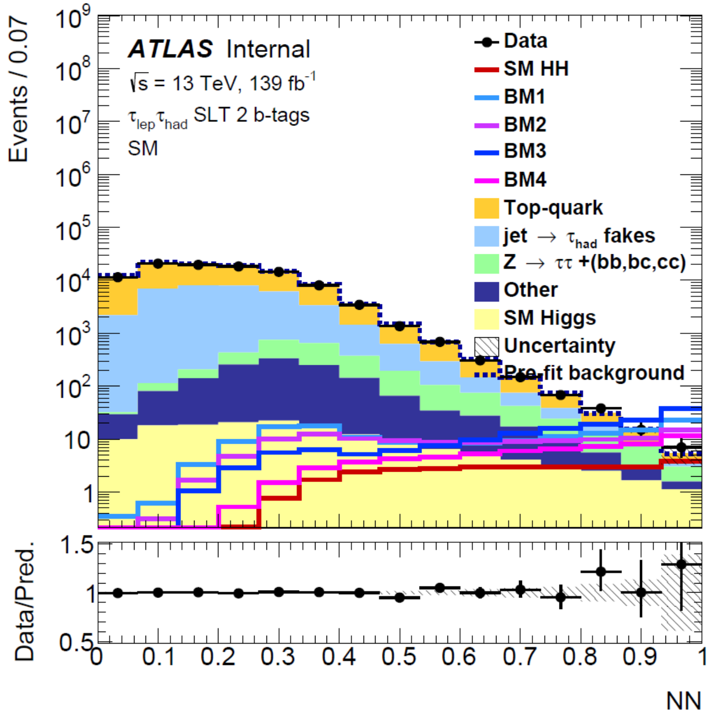
- **Scanning over a range of coupling modifier $k_\lambda, c_{tthh}, c_{gghh}$**
  - Using the same background and classifiers:
  - Perform m_{HH} reweighting using weights derived from truth samples

Results: HEFT Benchmarks

Benchmark	C_t	C_{hhh}	C_{tt}	C_{ggh}	C_{gghh}
SM	1	1	0	0	0
1	0.94	3.94	-0.333	0.5	0.333
2	0.61	6.84	0.333	0	-0.333
3	1.05	2.21	-0.333	0.5	0.5
4	0.61	2.79	0.333	-0.5	0.167
5	1.17	3.95	-0.333	0.167	-0.5
6	0.83	5.68	0.333	-0.5	0.333
7	0.94	-0.10	1	0.167	-0.167

- 7 benchmarks of HEFT framework
  - represent the different shapes of m_{HH}
  - Using a similar reweighting method used for 1-d scan





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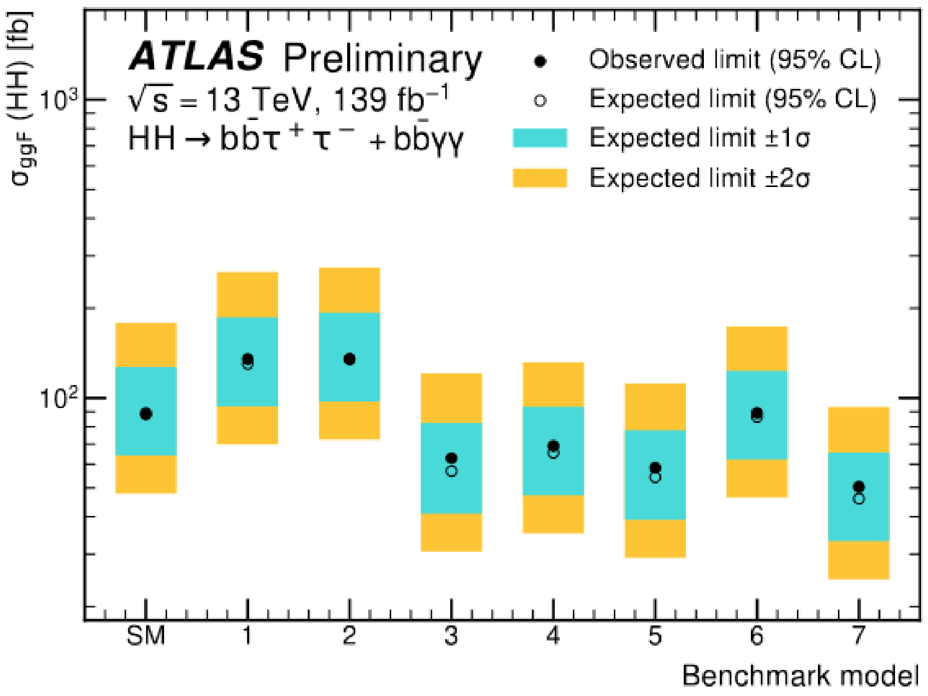


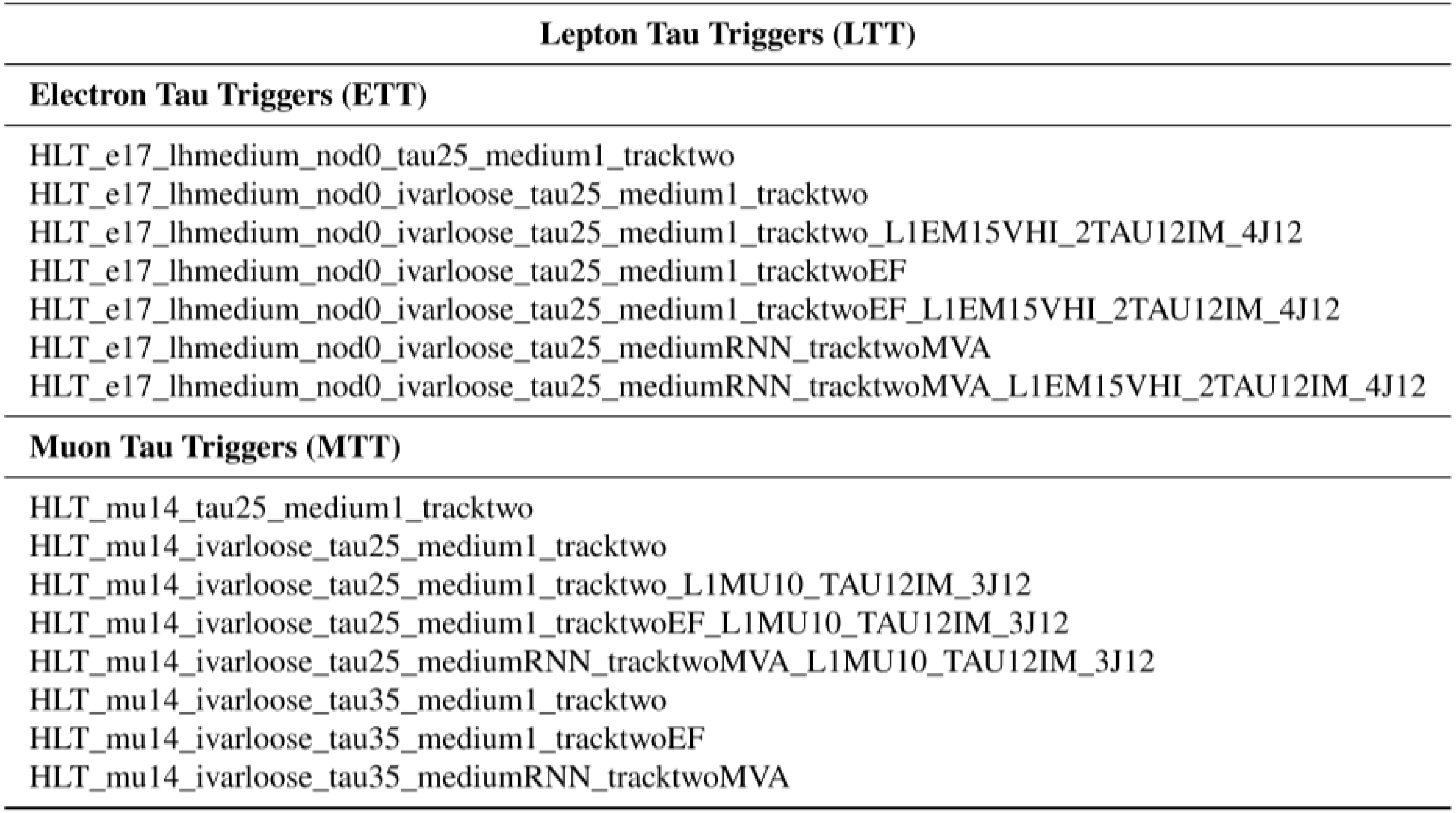
Summary

- **A short tour in the $\boldsymbol{bb\tau\tau}$ analysis…**

- **Fruitful results produced!**
  - Limits on di-Higgs production cross sections, k_λ, c_{tthh}, c_{gghh} and 7 HEFT benchmarks
    - World leading upper limit on non-resonant production
    - Excess around 1TeV resonance mass with 2σ global significance

- **Stay tuned in Run 3 for more exciting results!**

Backup: Lepton + Tau triggers menu



Lepton Tau Triggers (LTT)
Electron Tau Triggers (ETT)
HLT_e17_lhmedium_nod0_tau25_medium1_tracktwo
HLT_e17_lhmedium_nod0_ivarloose_tau25_medium1_tracktwo
HLT_e17_lhmedium_nod0_ivarloose_tau25_medium1_tracktwo_L1EM15VHI_2TAU12IM_4J12
HLT_e17_lhmedium_nod0_ivarloose_tau25_medium1_tracktwoEF
HLT_e17_lhmedium_nod0_ivarloose_tau25_medium1_tracktwoEF_L1EM15VHI_2TAU12IM_4J12
HLT_e17_lhmedium_nod0_ivarloose_tau25_mediumRNN_tracktwoMVA
HLT_e17_lhmedium_nod0_ivarloose_tau25_mediumRNN_tracktwoMVA_L1EM15VHI_2TAU12IM_4J12
Muon Tau Triggers (MTT)
HLT_mu14_tau25_medium1_tracktwo
HLT_mu14_ivarloose_tau25_medium1_tracktwo
HLT_mu14_ivarloose_tau25_medium1_tracktwo_L1MU10_TAU12IM_3J12
HLT_mu14_ivarloose_tau25_medium1_tracktwoEF_L1MU10_TAU12IM_3J12
HLT_mu14_ivarloose_tau25_mediumRNN_tracktwoMVA_L1MU10_TAU12IM_3J12
HLT_mu14_ivarloose_tau35_medium1_tracktwo
HLT_mu14_ivarloose_tau35_medium1_tracktwoEF
HLT_mu14_ivarloose_tau35_mediumRNN_tracktwoMVA

Backup: Object selection

Electrons:

Loose e-ID, loose isolation

$p_T > 7\,\text{GeV}$, $|\eta| < 2.47$ + crack veto

Muons:

Loose muons, `PflowLoose_VarRadIso` isolation

$p_T > 7\,\text{GeV}$, $|\eta| < 2.7$

Taus:

Loose RNN Tau-ID, loose electron-veto

$p_T > 20\,\text{GeV}$, $|\eta| < 2.5$ + crack veto

Anti-Taus:

Fail loose RNN Tau-ID & RNN score > 0.01

Jets:

Anti-k_t $R = 0.4$ PFlow

Jet cleaning & tight JVT

$p_T > 20\,\text{GeV}$, $|\eta| < 2.5$

b-tagging:

DL1r with 77% eff. WP

MET:

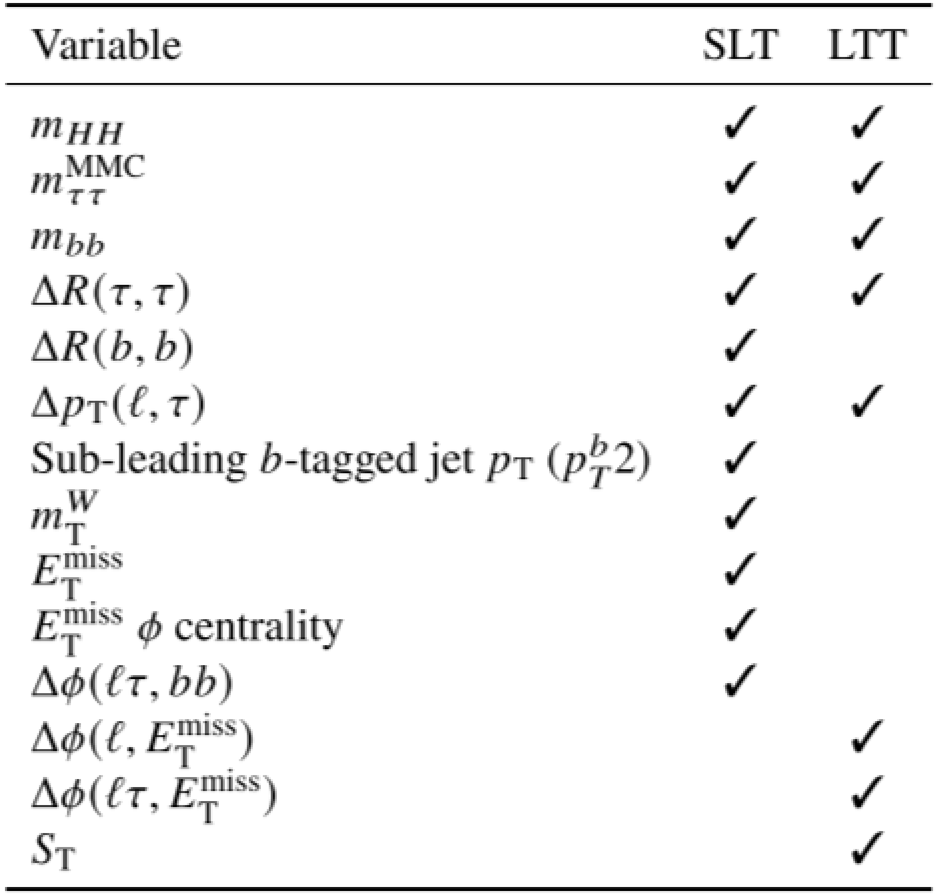
PFlow MET (TST)

OLR:

ASG OLR tool (Standard WP) with dedicated jet-τ_{had} OLR:

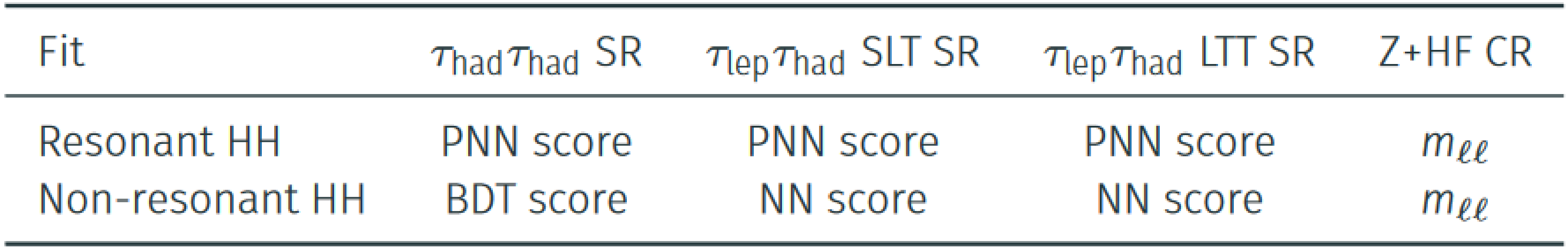
τ_{had} > b-tagged jet > anti-τ_{had} > un-tagged jet

Backup: Neural network inputs



Variable	SLT	LTT
m_{HH}	✓	✓
$m_{\tau\tau}^{\mathrm{MMC}}$	✓	✓
m_{bb}	✓	✓
$\Delta R(\tau,\tau)$	✓	✓
$\Delta R(b,b)$	✓	
$\Delta p_{\mathrm{T}}(\ell,\tau)$	✓	✓
Sub-leading b-tagged jet p_{T} (p_T^b2)	✓	
m_{T}^{W}	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	
$E_{\mathrm{T}}^{\mathrm{miss}}$ ϕ centrality	✓	
$\Delta\phi(\ell\tau,bb)$	✓	
$\Delta\phi(\ell,E_{\mathrm{T}}^{\mathrm{miss}})$		✓
$\Delta\phi(\ell\tau,E_{\mathrm{T}}^{\mathrm{miss}})$		✓
S_{T}		✓

Backup: Fit setup



Fit	$\tau_{\text{had}}\tau_{\text{had}}$ SR	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT SR	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT SR	Z+HF CR
Resonant HH	PNN score	PNN score	PNN score	$m_{\ell\ell}$
Non-resonant HH	BDT score	NN score	NN score	$m_{\ell\ell}$

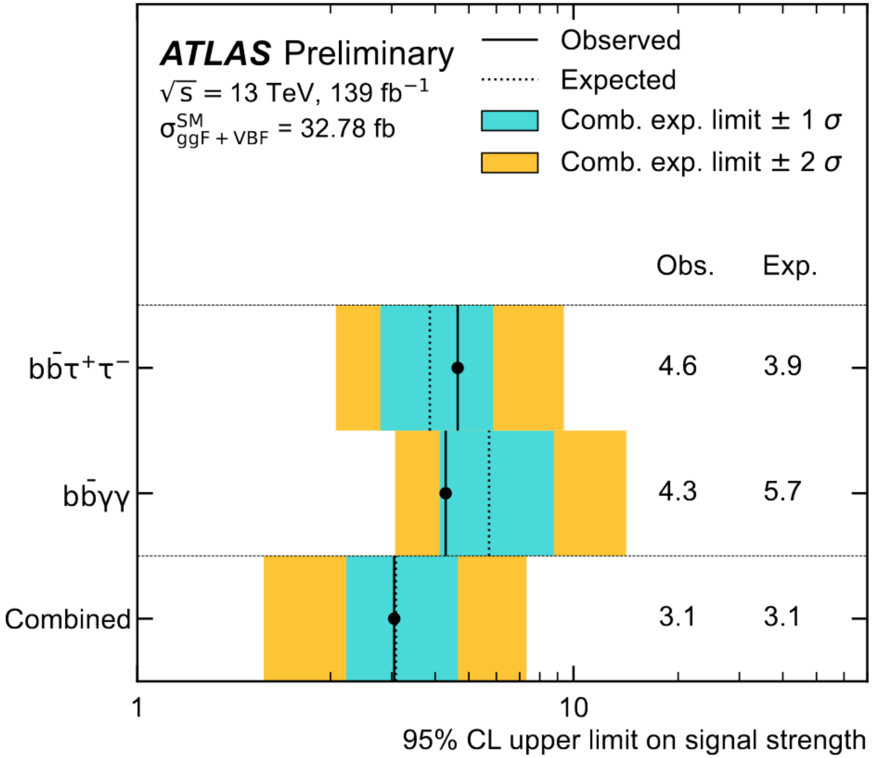
- MVA scores rebinned to optimize sensitivity while limiting background stat. uncertainty
- Fit to MVA score in three SRs with μ = σ/σ_{ref} as POI
    - Non-resonant HH (ggF+VBF): σref = $\sigma_{SM}^{ggF+VBF}$ (mH = 125 GeV)
- Resonant HH: σ_{ref} = 1 pb × BR
- $t\bar{t}$ and Z+HF normalisation determined from data

NP Correlation scheme:

- Experimental uncertainties (CP) are correlated between regions
- Cross section and acceptance uncertainties are correlated
- Rel. acceptance uncertainties originating from the same source are correlated between regions

Combination Results: Non-resonant and Resonant

	Obs.	$-2\,\sigma$	$-1\,\sigma$	Exp.	$1\,\sigma$	$2\,\sigma$
$b\bar{b}\gamma\gamma$	4.3	3.1	4.1	5.7	8.8	14.3
$b\bar{b}\tau^+\tau^-$	4.6	2.1	2.8	3.9	5.9	9.4
Combined	3.1	1.7	2.2	3.1	4.7	7.3



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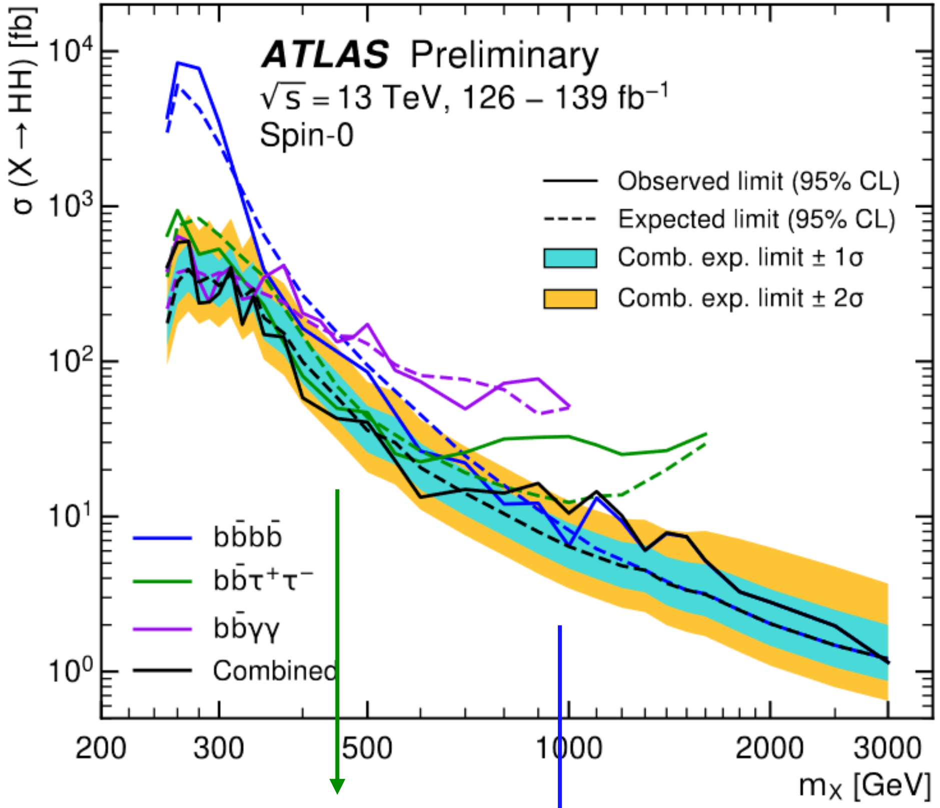

bbtautau dominates the sensitivity at medium m_X

4b dominates the sensitivity at high m_X