Measurements of Higgs boson properties in decays to two tau leptons with the ATLAS detector

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Higgs 2022 Conference

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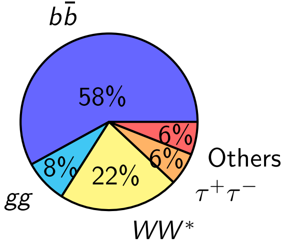
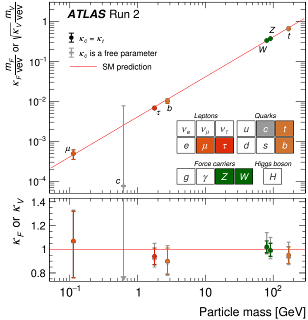
ATLAS EXPERIMENT

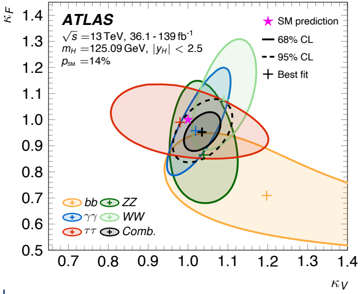
The $H \to \tau\tau$ Decay Channel

Nature 607, pages 52–59 (2022)

- $H \to \tau\tau$ BR: 6% $\Rightarrow$ 480000 events in Run 2
- Most precisely measured Yukawa coupling
- Best channel to study lepton couplings
- This talk: Measurement of cross-sections from and test of CP violation in $\tau\tau$ decays







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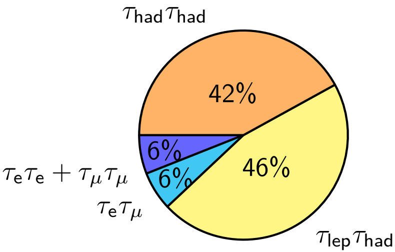
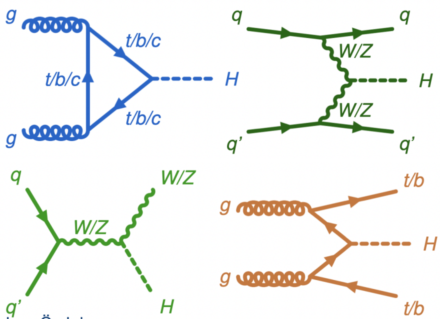


- Split $\tau\tau$ decays into four final states
- Not considering $\tau_e\tau_e + \tau_\mu\tau_\mu$, large and difficult to model $Z \to \ell\ell$ bkg
- Main backgrounds: $Z \to \tau\tau$, multi-jet production

- 4 Higgs boson production modes
- Target each one with dedicated event selection



ggF Categorisation

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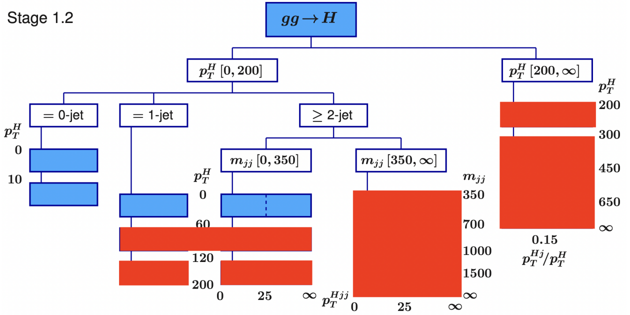
- Focus on boosted ggF events, baseline cut $p_T(H) > 100$ GeV
- For STXS: region split in $p_T(H)$ and N_{jets} (1J, $\geq$ 2J)

Region	boost_0	boost_1	boost_2	boost_3
$p_T(H)$ [GeV]	$[100, 120]$	$[120, 200]$	$[200, 300]$	> 300

Measuring 6 STXS bins total:



VBF, VH and ttH Selections

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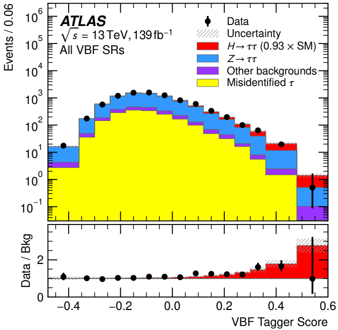
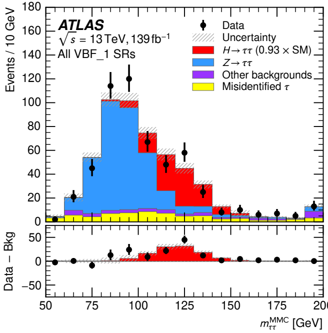
Main features of dedicated regions:

- VBF: $m_{jj} > 350$ GeV, $\eta(j_0) \times \eta(j_1) < 0$
- V($\rightarrow qq$)H: 60 GeV $< m_{jj} <$ 120 GeV
- ttH (only in $\tau_{\text{had}}\tau_{\text{had}}$): Presence of additional jets, including b-tagged ones
- Train taggers to define signal-enriched selection
- Events passing tagger score cuts → region "_1", rest "_0"
- In all regions, using likelihood-based mass estimate $m_{\tau\tau}^{\text{MMC}}$ in template fit





Fit Model

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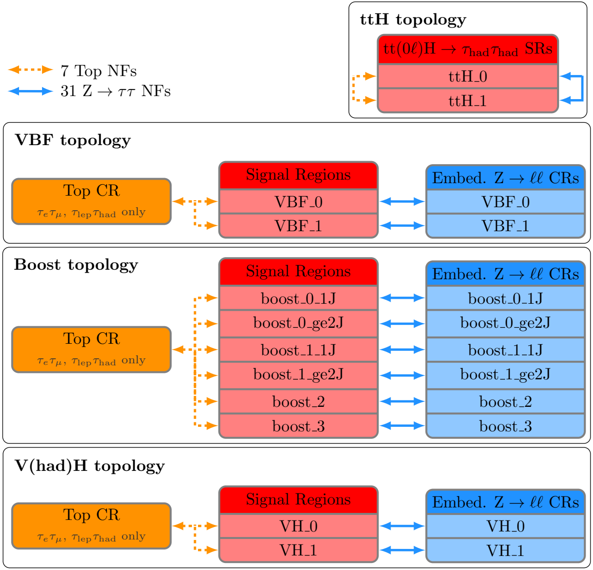
- $Z \to \ell\ell$-enriched selections to constrain $Z \to \tau\tau$ background
- Kinematic embedding procedure to ensure compatible phase-space
- In $\tau_{\rm lep}\tau_{\rm lep}$ and $\tau_{\rm lep}\tau_{\rm had}$, dedicated Top regions and NFs



Measured Cross-Sections

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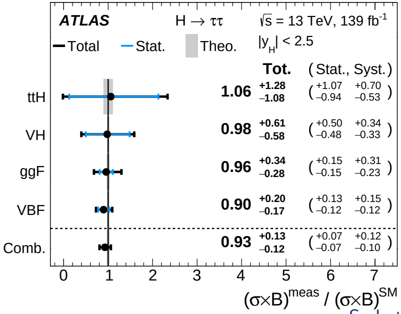
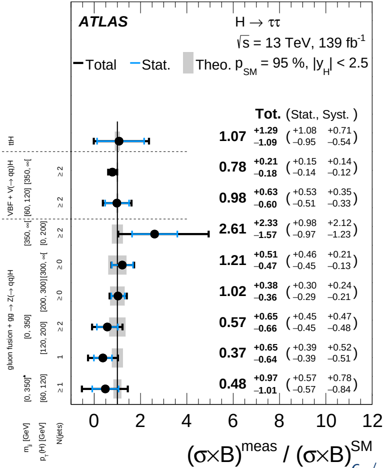
- Cross-sections measured inclusively, per production mode and in STXS
- Inclusively, well beyond 5σ
- Highest precision on VBF
- ggF precision better at high $p_T(H)$
- SM compatibility p-value: 95%



- Similar stat./syst. unc impact
- Leading syst.: Signal modelling



Strengths of the $H \to \tau\tau$ Channel

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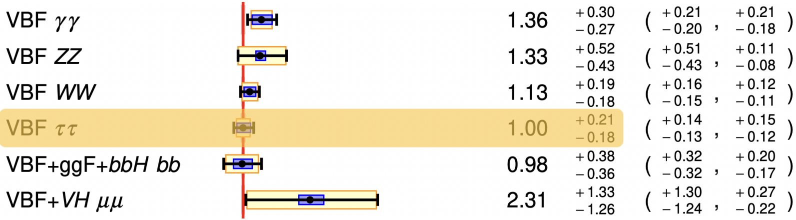
- Sensitivity to VBF among the highest
- Very sensitive to high-p_T ggF STXS bins



ggF STXS Bin	$H \to \tau\tau$ standalone	Combination of final states
$p_T(H)/\text{GeV} \in [200, 300]$	$1.02^{+0.38}_{-0.36}$	$1.43^{+0.35}_{-0.33}$
$p_T(H) > 300$ GeV ($\in [300, 450]$ in comb.)	$1.21^{+0.51}_{-0.47}$	$0.71^{+0.47}_{-0.45}$

CP Violation in Higgs Couplings

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- Origin of baryon asymmetry in the Universe still unknown
- CP-violating processes outside of the SM needed
- Higgs boson couplings could contribute, not yet experimentally excluded

Effective Lagrangian:

$$\mathscr{L}_{H\tau\tau} = -\frac{m_{\tau\tau}}{v}\kappa_\tau \left(\underbrace{\cos(\phi_\tau)\bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\sin(\phi_\tau)\bar{\tau}i\gamma_5\tau}_{\text{CP-odd}}\right) H$$

- ϕ_τ: CP mixing angle between even and odd components
- SM: $\phi_\tau = 0$, pure CP-odd: $\phi_\tau = 90^\circ$, else: CP violation

$\Rightarrow$ CP-odd contribution at tree-level possible!

CP-Sensitive Observable
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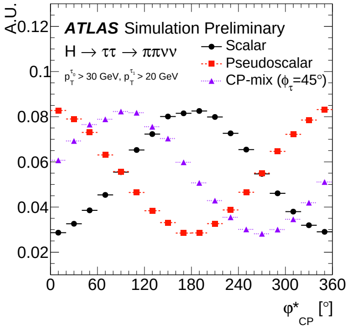
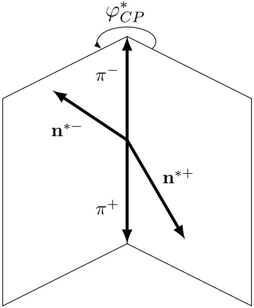
- Need an observable that gives insights on ϕ_τ
- Acoplanarity angle φ^*_{CP}, angle between tau decay planes in rest frame

$$d\Gamma_{H\to\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

- b: Spectral function, quantifies spin analysing power (depends on τ decay)
- $E_\pm$: Energy of charged τ decay products





- φ^*_{CP} reconstruction method for $\tau\tau \to \pi\pi\nu\nu$ decays
- $n^{*\pm}$: Directional impact parameter of $\pi^\pm$ track

Decay Mode Classification

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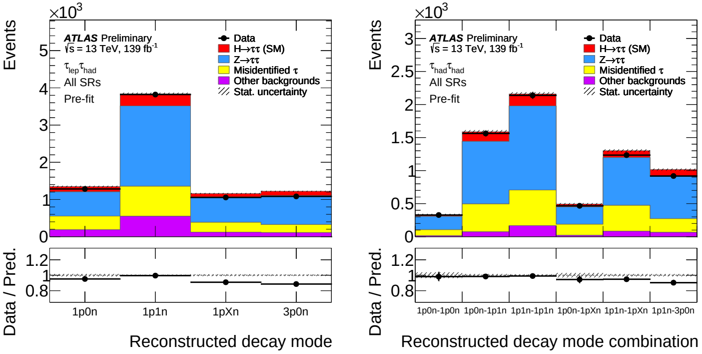
- Definition of φ^*_{CP} depends on τ decay mode
- Considering leptonic decays and 4 τ_{had} decay modes



- Simplest case: 1p0n decay, highest ϕ_τ sensitivity
- Can only define φ^*_{CP} approximately in some modes, reduced ϕ_τ sensitivity
- Leptonic decays involve 2 neutrinos, less clear

$\Rightarrow$ Not considering $\tau_{\text{lep}}\tau_{\text{lep}}$ and some $\tau_{\text{had}}\tau_{\text{had}}$ decays

Event Categorisation

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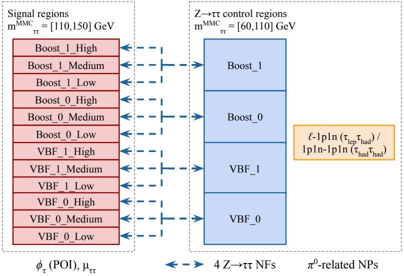
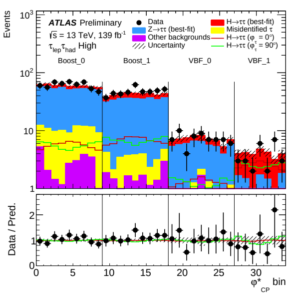
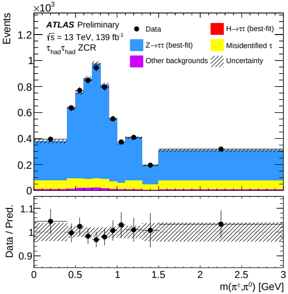
- "Boost" split: $p_T(H) > 140$ GeV, $\Delta R(\tau,\tau) < 1.4 \Rightarrow$ "Boost_1"
- Decay modes grouped into Loose, Medium, Tight categories based on sensitivity $\Rightarrow$ 12 SRs
- Experimental challenge to identify and reconstruct neutral τ decay components $\Rightarrow$ Dedicated CRs







Test of CP Violation

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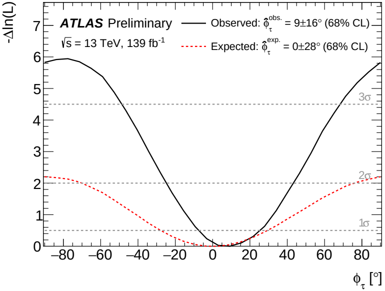
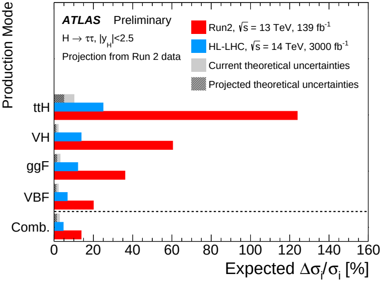
- Change in total $H \rightarrow \tau\tau$ normalisation can come from other BSM sources than CP-odd coupling component
- But want to test only CP violation without being sensitive to this
  $\Rightarrow$ Signal normalisation unconstrained in fit
- Only basing conclusion on the shape of signal, less model-dependent

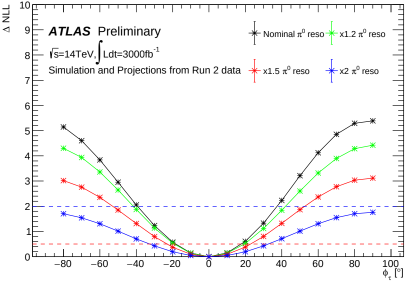


- Observed ϕ_τ consistent with SM prediction of 0
  $\Rightarrow$ No sign of CP violation found in τ Yukawa coupling
- Pure CP-odd hypothesis excluded at 3.4σ

HL-LHC Prospects

- HL-LHC projections performed for cross-sections and ϕ_τ
- Scale expected distributions to 3000 fb^{-1} and 14 TeV for each process
- Uncertainties adapted to HL-LHC environment





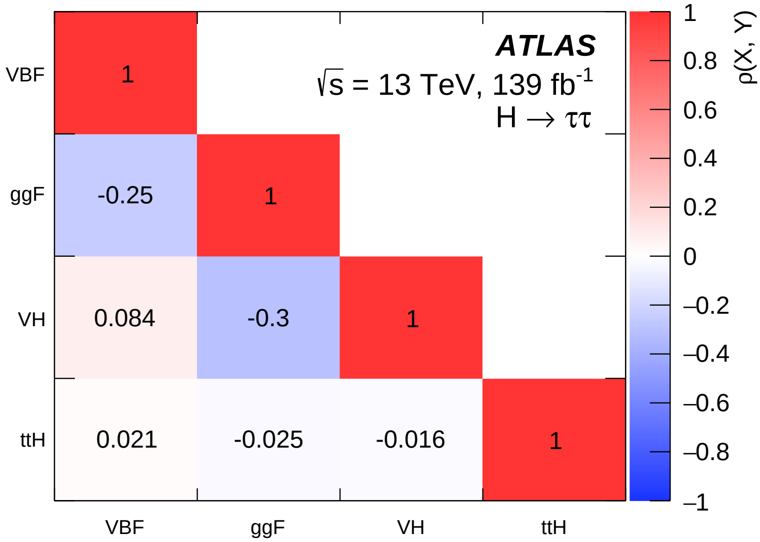
- Uncertainty on inclusive xsec measurement projected to be $\approx 5\%$
- Each production mode measured at least twice as precisely
- CP projection from 2019, based on 36.1 fb^{-1} study
- HL-LHC projection looks very similar to Run 2 result

Conclusion

- Much to learn from studying $H \to \tau\tau$ decays
- Great sensitivity to VBF and high-p_T ggF
- Basis for further interpretations of the data
- Lepton-flavour violation: See Kieran's talk tomorrow
- First ATLAS constraints on CP-odd contribution to $H\tau\tau$ coupling
- Consistent with SM prediction of no CPV, CP-odd hypothesis disfavoured

Additional Material

Correlation Between Signal Cross-Sections



Ranking on ggF Cross-Section

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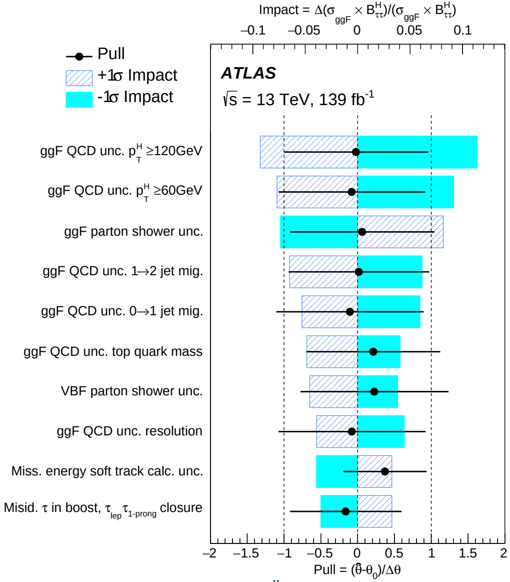
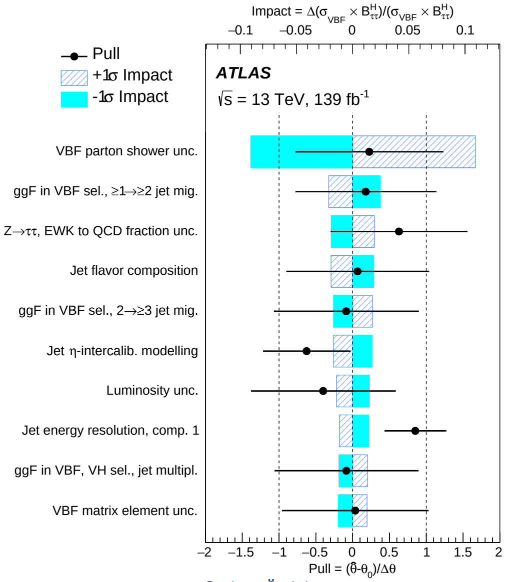


Ranking on VBF Cross-Section



Ranking on *VH* Cross-Section

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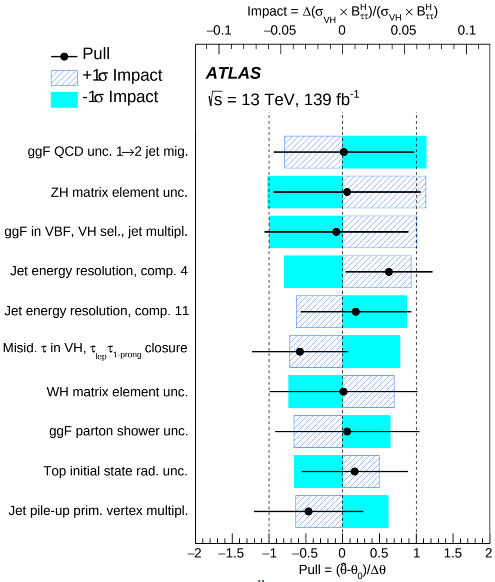
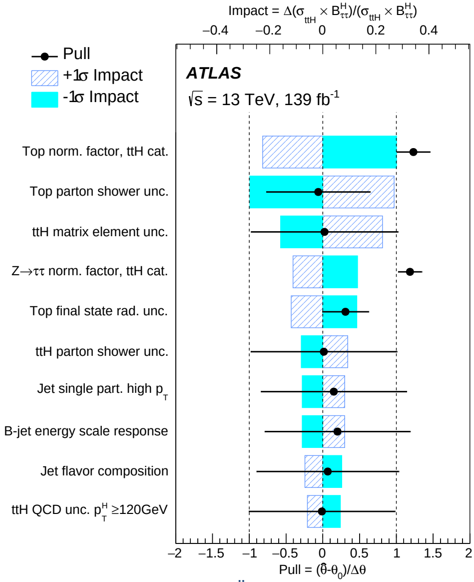


Ranking on *ttH* Cross-Section



Event Selection STXS Measurement

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Criteria	$\tau_e\tau_\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$
		$\tau_e\tau_{\text{had}}$	$\tau_\mu\tau_{\text{had}}$	
$N(e)$	1	1	0	0
$N(\mu)$	1	0	1	0
$N(\tau_{\text{had-vis}})$	0	1	1	2
$N(b\text{-jets})$	0 (85% WP)	0 (85% WP)	0 (85% WP)	0 (70% WP) (≥ 1 or 2 in ttH categories)
$p_{\text{T}}(e)$ [GeV]	> 15 to 27	> 27		
$p_{\text{T}}(\mu)$ [GeV]	> 10 to 27.3		> 27.3	
$p_{\text{T}}(\tau_{\text{had-vis}})$ [GeV]		> 30		> 40, 30
Identification	e/μ: Medium	$e/\mu/\tau_{\text{had-vis}}$: Medium		$\tau_{\text{had-vis}}$: Medium
Isolation	e: Loose, μ: Tight	e: Loose	μ: Tight	
Charge	Opposite charge			
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 20			
Kinematics	$m_{\tau\tau}^{\text{coll}} > m_Z - 25\,\text{GeV}$ $30\,\text{GeV} < m_{e\mu} < 100\,\text{GeV}$	$m_{\text{T}} < 70\,\text{GeV}$		
Leading jet	$p_{\text{T}} > 40\,\text{GeV}$			$p_{\text{T}} > 70\,\text{GeV}$, $\lvert\eta\rvert < 3.2$
Angular	$\Delta R_{e\mu} < 2.0$ $\lvert\Delta\eta_{e\mu}\rvert < 1.5$	$\Delta R_{\ell\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\ell\tau_{\text{had-vis}}}\rvert < 1.5$		$0.6 < \Delta R_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}} < 2.5$ $\lvert\Delta\eta_{\tau_{\text{had-vis}}\tau_{\text{had-vis}}}\rvert < 1.5$
Coll. app. x_1/x_2	$0.1 < x_1 < 1.0$ $0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.2$		$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.4$

Combination Result - Production And Decay

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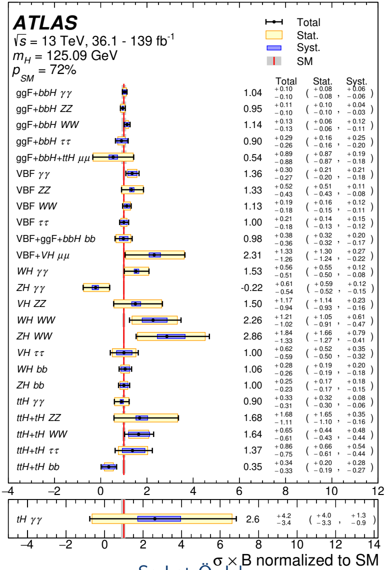

Combination Result- STXS

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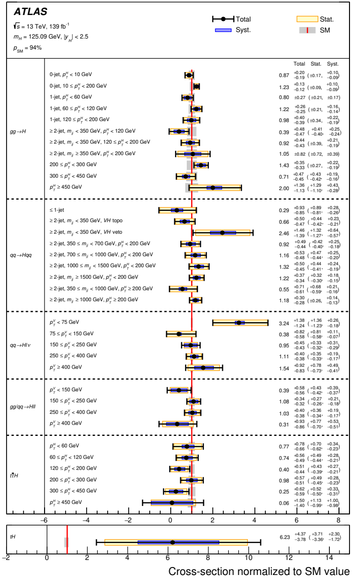

Generator Information

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Process	Generator ME	Generator PS	PDF set ME	PDF set PS	Tune	Normalisation
Higgs boson						
ggF	Powheg Box v2	Pythia 8	PDF4LHC15nnlo	CTEQ6L1	AZNLO	N^3LO QCD + NLO EW
VBF	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + NLO EW
VH	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + NLO EW
$t\bar{t}H$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO QCD + NLO EW
tH	MadGraph5_aMC@NLO	Pythia 8	CT10	NNPDF2.3lo	A14	NLO
$b\bar{b}H$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO
Background						
V + jets (QCD/EW)	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NNLO for QCD, LO for EW
$t\bar{t}$	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NNLO + NNLL
Single top	Powheg Box v2	Pythia 8	NNPDF3.0nnlo	NNPDF2.3lo	A14	NLO
Diboson	Sherpa 2.2.1		NNPDF3.0nnlo		Sherpa	NLO