Measurement of Higgs decaying to tau leptons with ATLAS run-2 data

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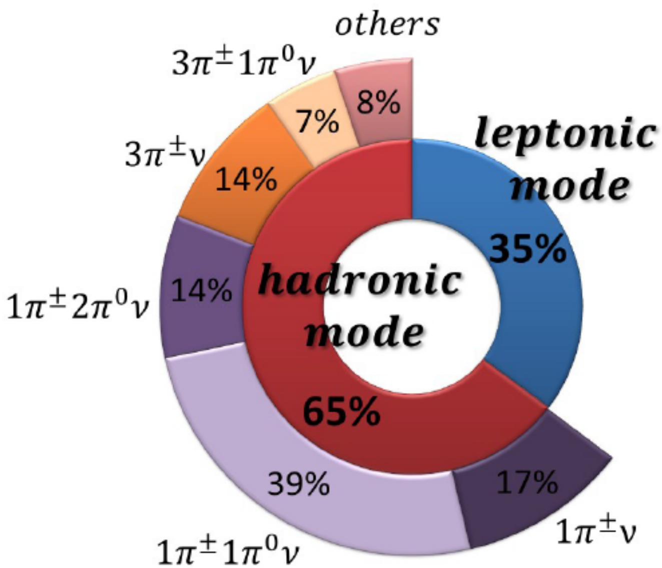
H→ττ from Run-1

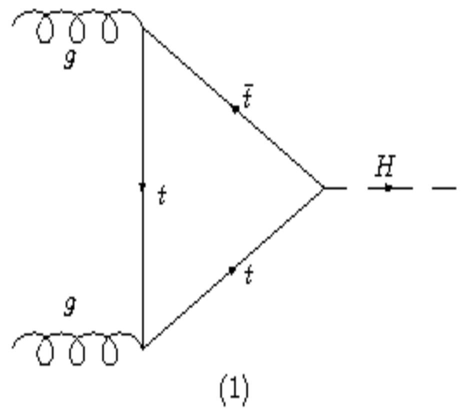
Higgs Yukawa coupling is a crucial part in the SM. Direct search for Hττ decay will confirm it is a SM Higgs



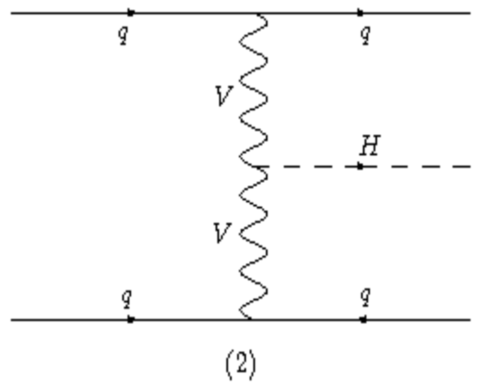
ee, eμ, μμ, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

$\tau_{lep}\tau_{lep}$ $\tau_{lep}\tau_{had}$ $\tau_{had}\tau_{had}$

Leptonic and hadronic decays of taus



Gluon-gluon Fusion



Vector-Boson Fusion

The combined fitted signal Strength:

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{sys.}) \pm 0.09(\text{theo. sys.})$$

This corresponds to 4.5σ for 125 GeV (3.4σ expected)

[JHEP 04 (2015) 117]

Run-2 event preselection

$\tau_{lep}\tau_{lep}$ $ee/\mu\mu$	$\tau_{lep}\tau_{lep}$ $e\mu$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
$N^{\text{loose}}_{e/\mu} = 2$, $N^{\text{loose}}_{\tau_{\text{had-vis}}} = 0$		$N^{\text{loose}}_{e/\mu} = 1$, $N^{\text{loose}}_{\tau_{\text{had-vis}}} = 1$	$N^{\text{loose}}_{e/\mu} = 0$, $N^{\text{loose}}_{\tau_{\text{had-vis}}} = 2$
e/μ : Medium, gradient iso.		e/μ : Medium, gradient iso.	
		$\tau_{\text{had-vis}}$: Medium	$\tau_{\text{had-vis}}$: Tight
Opposite charge		Opposite charge	Opposite charge
$m^{\text{coll}}_{\tau\tau} > m_Z - 25$ GeV		$m_T < 70$ GeV	
$30 < m_{\ell\ell} < 75$ GeV	$30 < m_{\ell\ell} < 100$ GeV		
$E^{\text{miss}}_T > 55$ GeV	$E^{\text{miss}}_T > 20$ GeV	$E^{\text{miss}}_T > 20$ GeV	$E^{\text{miss}}_T > 20$ GeV
$E^{\text{miss, HPTO}}_T > 55$ GeV			
$\Delta R_{\tau\tau} < 2.0$		$\Delta R_{\tau\tau} < 2.5$	$0.8 < \Delta R_{\tau\tau} < 2.5$
$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$		$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$	$\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$
$0.1 < x_1 < 1.0$		$0.1 < x_1 < 1.4$	$0.1 < x_1 < 1.4$
$0.1 < x_2 < 1.0$		$0.1 < x_2 < 1.2$	$0.1 < x_2 < 1.4$
$p^{j_1}_T > 40$ GeV		$p^{j_1}_T > 40$ GeV	$p^{j_1}_T > 70$ GeV, $\lvert\eta_{j_1}\rvert < 3.2$
$N_{b\text{-jets}} = 0$		$N_{b\text{-jets}} = 0$	

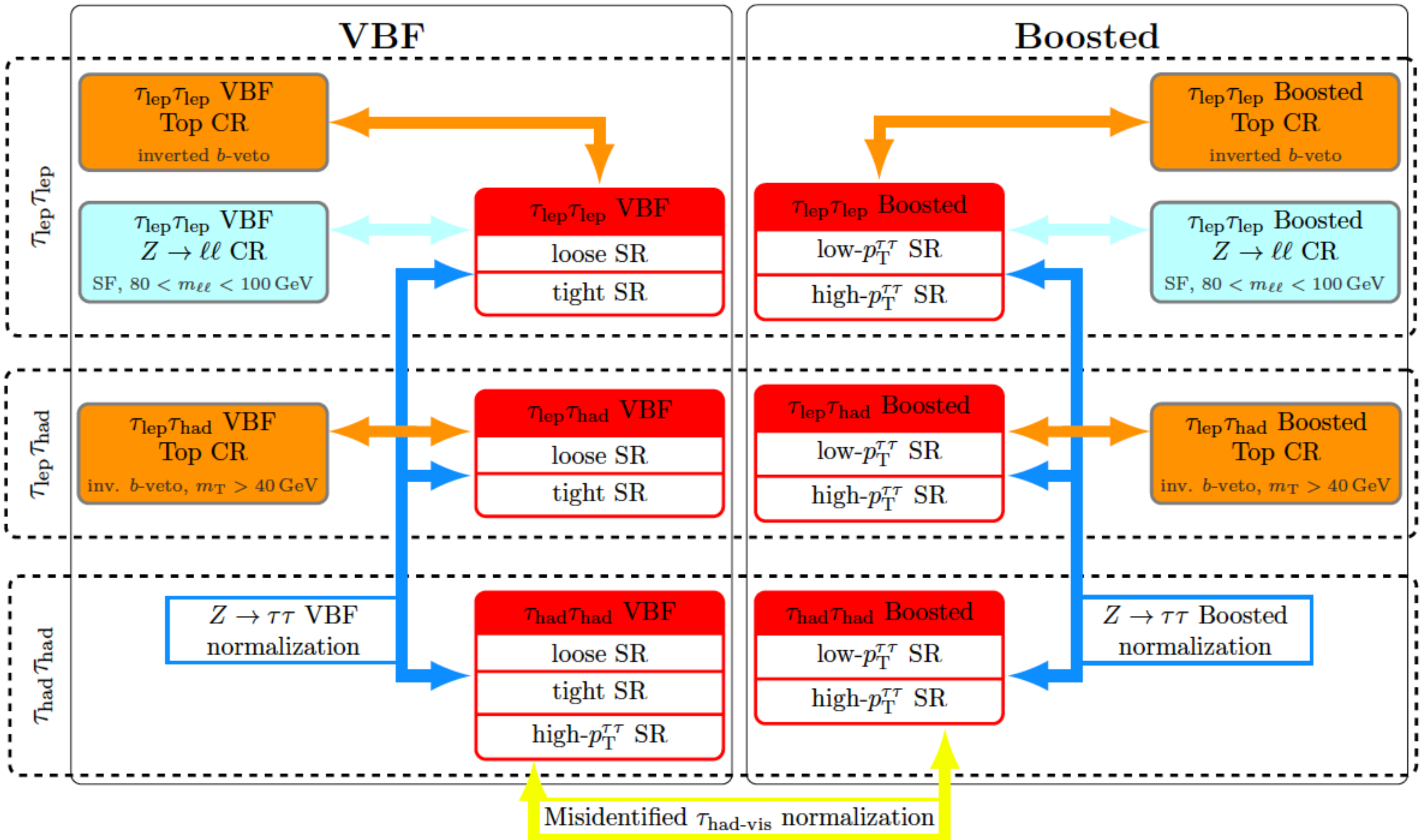
- Different numbers of light and tau_{had} leptons in each final state
- Harder MET cut in $\text{tau}_{\text{lep}}\text{tau}_{\text{lep}}$ to suppress $Z \to ll$ for same-flavor
- Jet pt cut: all three final states target at VBF and Boosted Higgs
- Increased jet pt cut for $\text{tau}_{\text{had}}\text{tau}_{\text{had}}$: 2016 trigger requirement
- B-veto: effective to remove top background for $\text{tau}_{\text{lep}}\text{tau}_{\text{lep}}$ and $\text{tau}_{\text{lep}}\text{tau}_{\text{had}}$

Signal regions

- Two categories are separately defined to probe different Higgs productions
  - VBF: two tagging jets from Vector-Boson-Fusion (VBF) in the forward region, but up to 30% from gluon-gluon-fusion (ggH)
  - Boosted: mainly high pt Higgs from ggH, but also 10-20% from VBF and VH

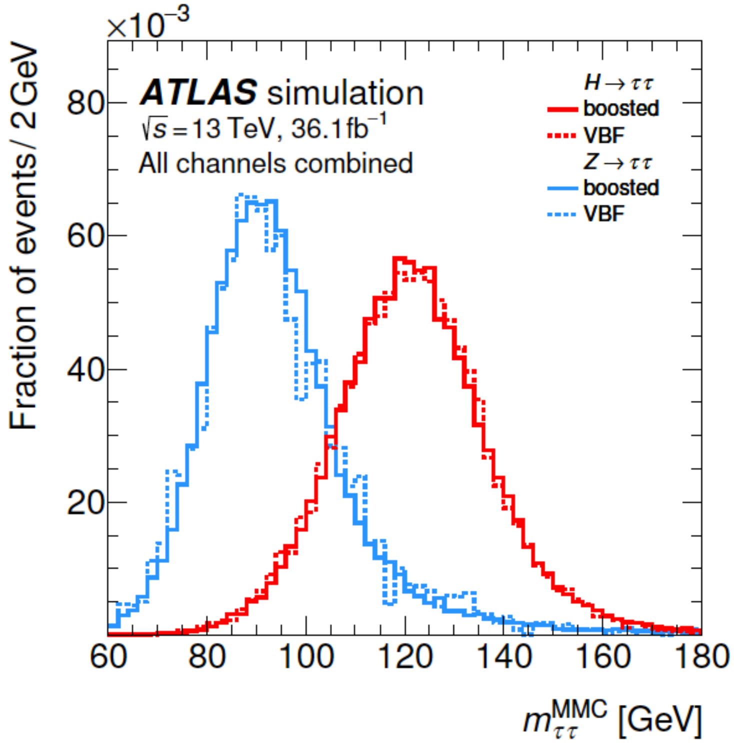
Signal Region		Inclusive	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
VBF	High-$p_{\mathrm{T}}^{\tau\tau}$	$p_{\mathrm{T}}^{j_2} > 30\,\mathrm{GeV}$ $\lvert\Delta\eta_{jj}\rvert > 3$ $m_{jj} > 400\,\mathrm{GeV}$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central leptons	—		$p_{\mathrm{T}}^{\tau\tau} > 140\,\mathrm{GeV}$ $\Delta R_{\tau\tau} < 1.5$
	Tight		$m_{jj} > 800\,\mathrm{GeV}$	$m_{jj} > 500\,\mathrm{GeV}$ $p_{\mathrm{T}}^{\tau\tau} > 100\,\mathrm{GeV}$	Not VBF high-p_{T} $m_{jj} > (1550 - 250 \cdot \Delta\eta_{jj})\,\mathrm{GeV}$
	Loose		Otherwise		
Boosted	high-$p_{\mathrm{T}}^{\tau\tau}$	Not VBF $p_{\mathrm{T}}^{\tau\tau} > 100\,\mathrm{GeV}$	$p_{\mathrm{T}}^{\tau\tau} > 140\,\mathrm{GeV}$ $\Delta R_{\tau\tau} < 1.5$		
	Low-$p_{\mathrm{T}}^{\tau\tau}$		Otherwise		

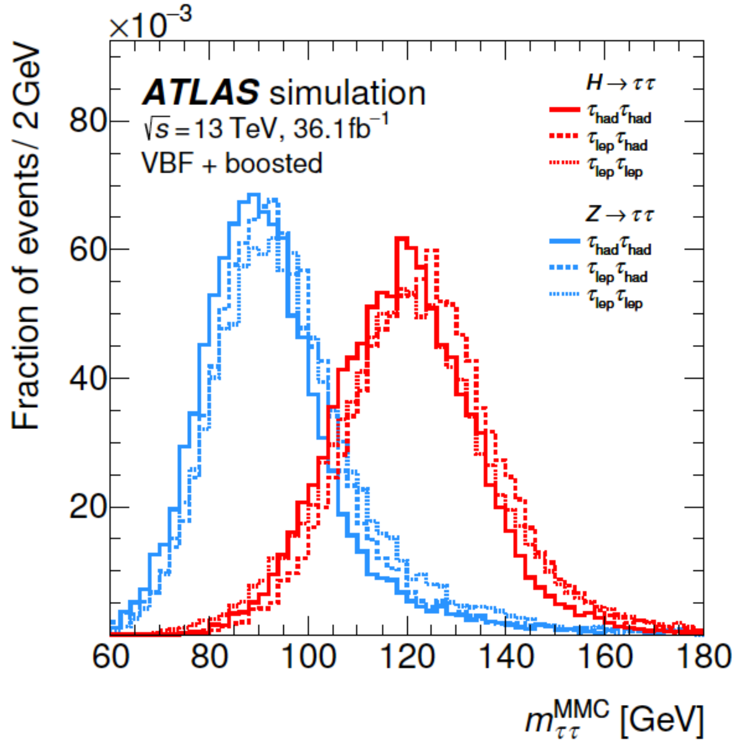
Signal regions and control regions

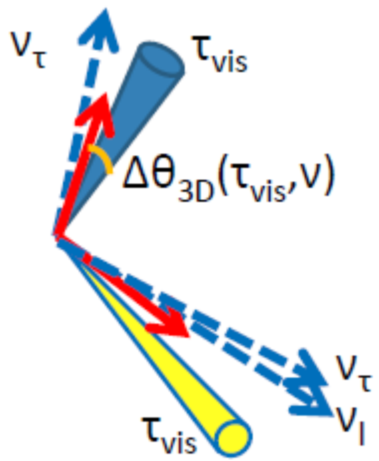


- Six CRs to constrain major backgrounds (top and $Z \to ll$) for $tau_{lep}tau_{lep}$ and $tau_{lep}tau_{had}$
- One $Z \to \tau\tau$ norm factor for VBF and Boosted each
- Fake norm in the two categories for $tau_{had}tau_{had}$ correlated

MMC mass

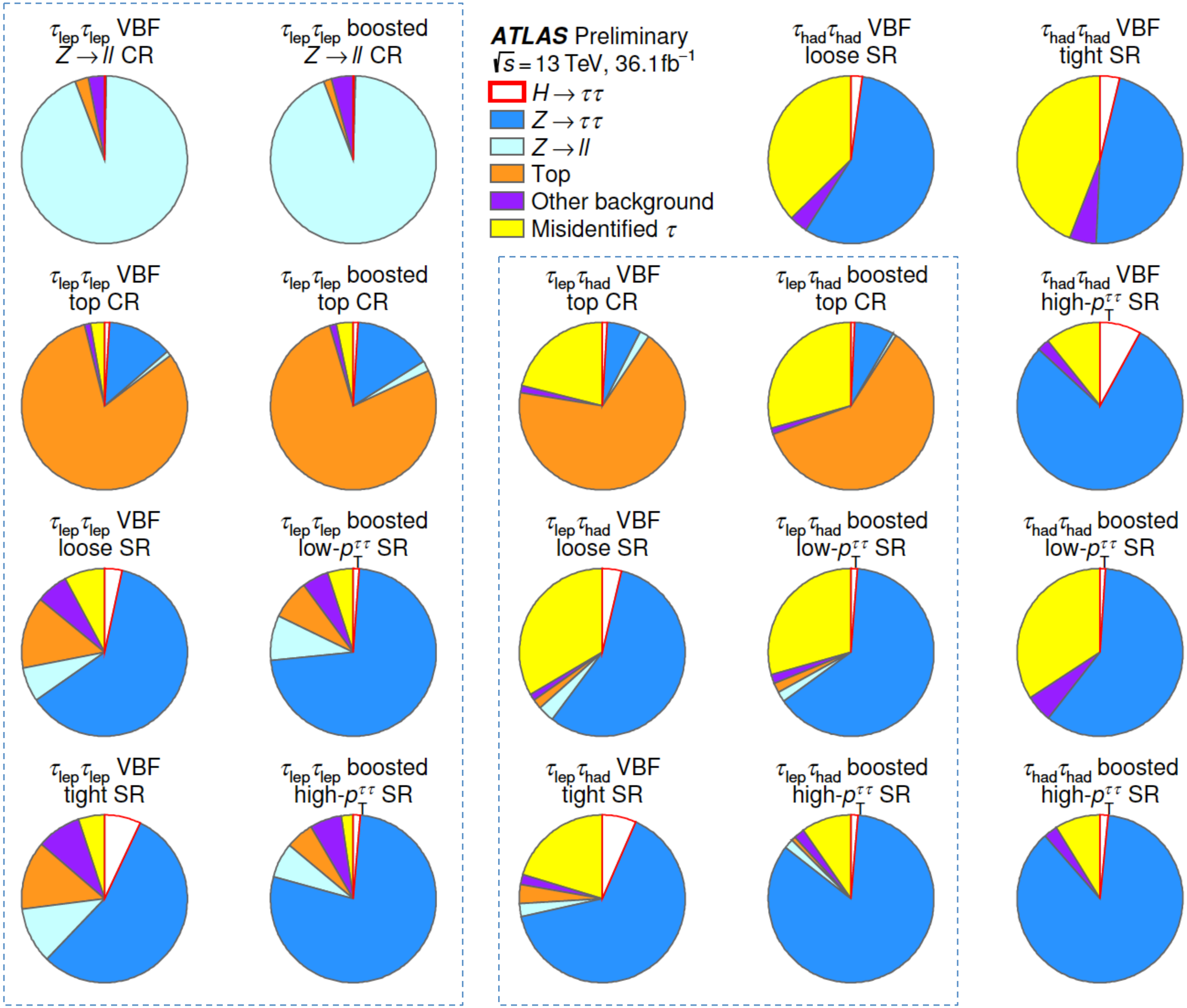






- Separate Z boson and Higgs peaks by MMC ditau mass
- MMC reconstruction: scan in the allowed phase space region (missing energy, angles...) for the most likely solutions that are consistent with the kinematics of tau decays
- Same variable as in Run 1 analysis, retuned for Run 2

Signal and background compositions

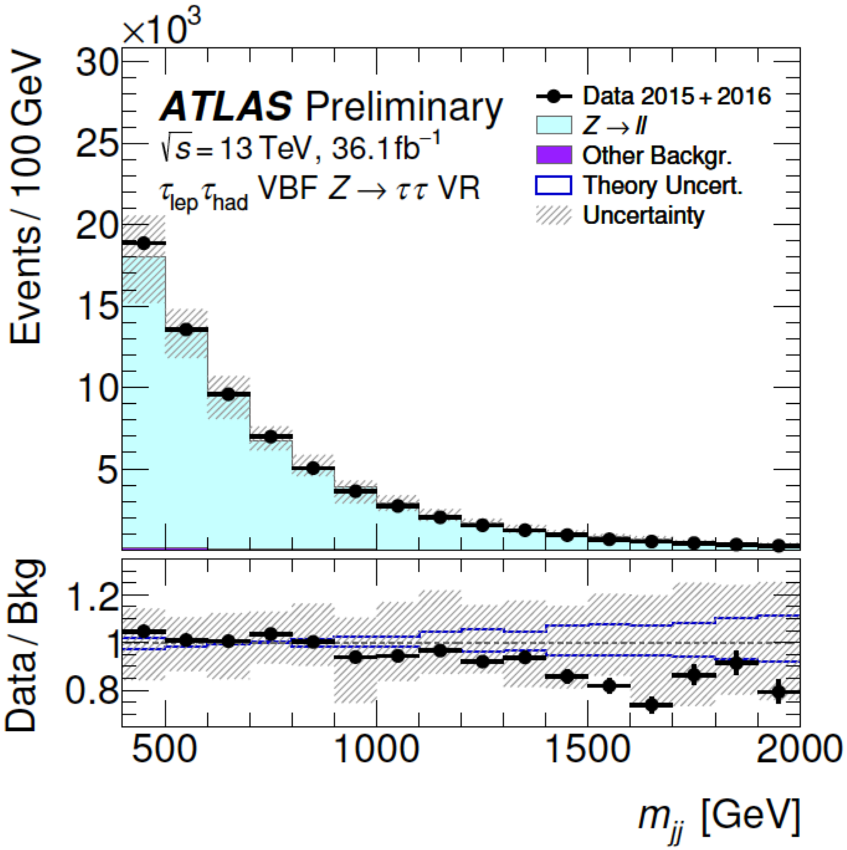


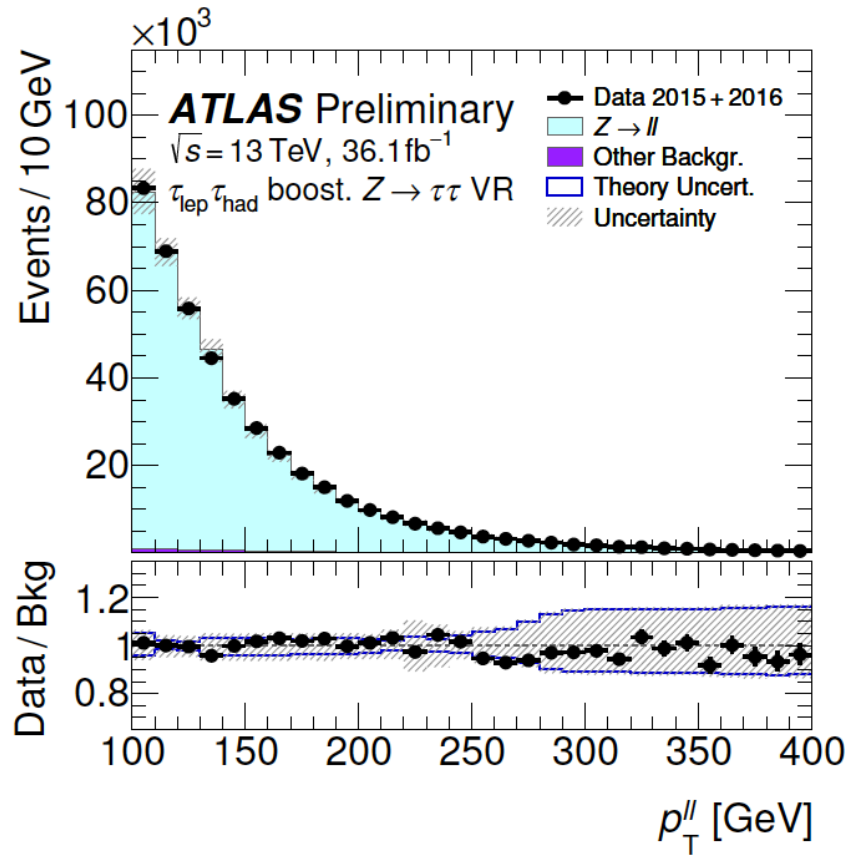
$tau_{had}tau_{had}$

$tau_{lep}tau_{lep}$

$tau_{lep}tau_{had}$

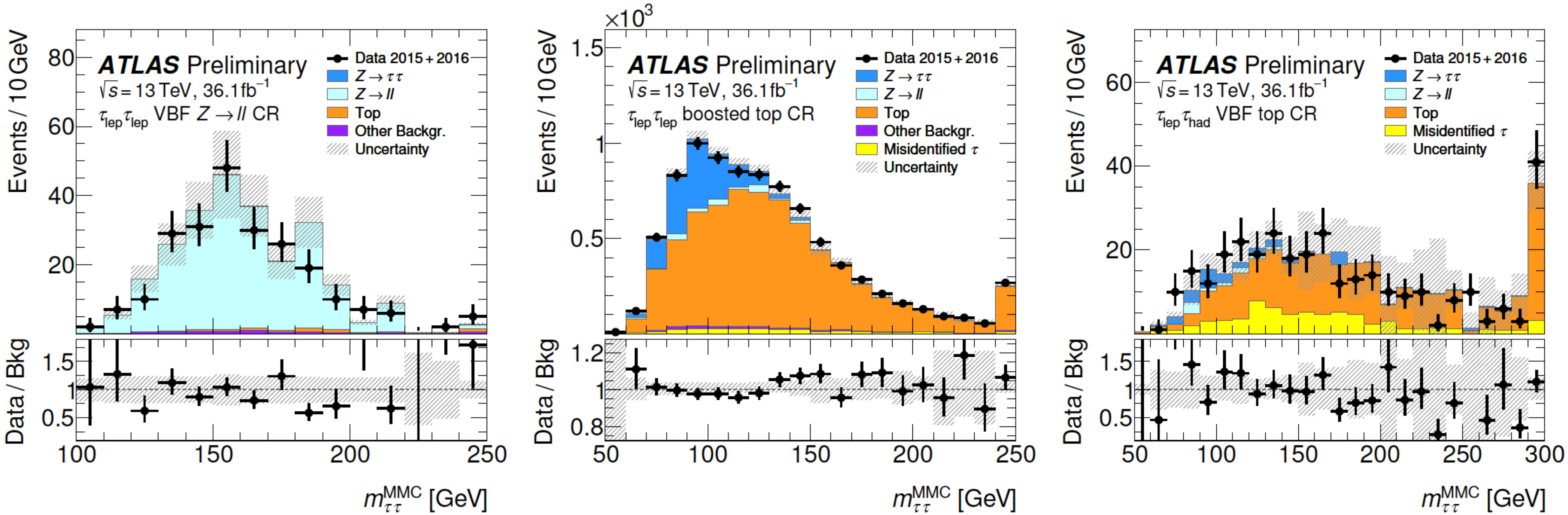
$Z\to\tau\tau$ validation





- Define validation regions with high purity in Z→ll events and similar kinematics as $Z\to\tau\tau$
- Based on SF $tau_{lep}tau_{lep}$ selection with dropped MET cuts and inverted m(ll) cuts
- Good modeling in variables that define the categories and signal regions

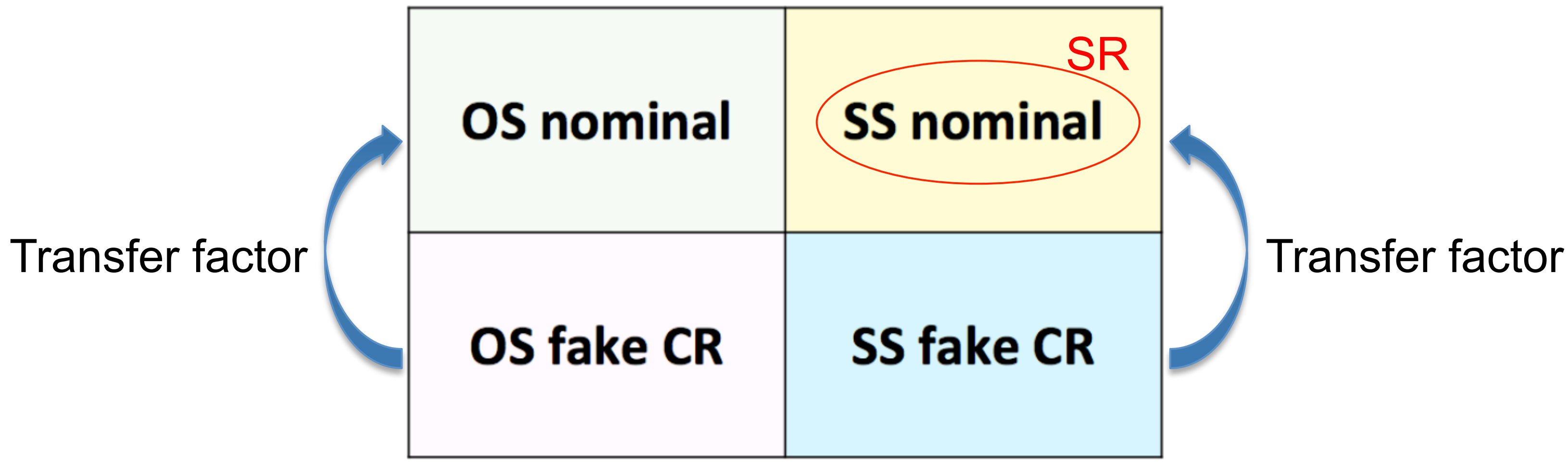
Top and Z→ll CRs



- Define control regions with high purity in Z→ll (invert m ll cut) and top (invert b-veto)
- check MMC shape modeling & constrain the normalization using data
- Observe good modeling (stat. and sys. errors indicated by hatched band)

Fake estimation for $tau_{lep}tau_{lep}$

Four different regions are defined for the fake estimation (**ABCD** method):



- OS/SS : same-sign/opposite-sign leptons
- Nominal: both leptons are isolated (Gradient) and pass Medium
- Fake CR: anti-isolation (harder for SF) for the subleading lepton, and also Loose ID in the case of electrons

- Fake lepton background is about 10% of the total background
- Get the fake transfer factor from SS and apply to OS, which are propagated down the cut flow and to all the SRs (**normalization**)
- Transfer factors are split in flavor, trigger and b-veto/b-tag bins
- SS is also used to derive the systematic uncertainties in SRs

Fake estimation for $tau_{lep}tau_{had}$ and $tau_{had}tau_{had}$

About 33% of total background
Using “Fake Factor” method:

$$N^{SR}_{fakes} = \left(N^{anti\text{-}\tau}_{Data} - N^{anti\text{-}\tau}_{MC,\,not\,j\to\tau}\right)\cdot\mathcal{F}$$

Estimate $F(N_{trk},p_T)$ in W+jets and QCD CRs

$$\mathcal{F} = R_W\mathcal{F}_W + R_{QCD}\mathcal{F}_{QCD}$$

- W+jets CR: invert m_T cut
- QCD CR: invert lepton isolation
- RQCD: estimated from data

Use SS for closure

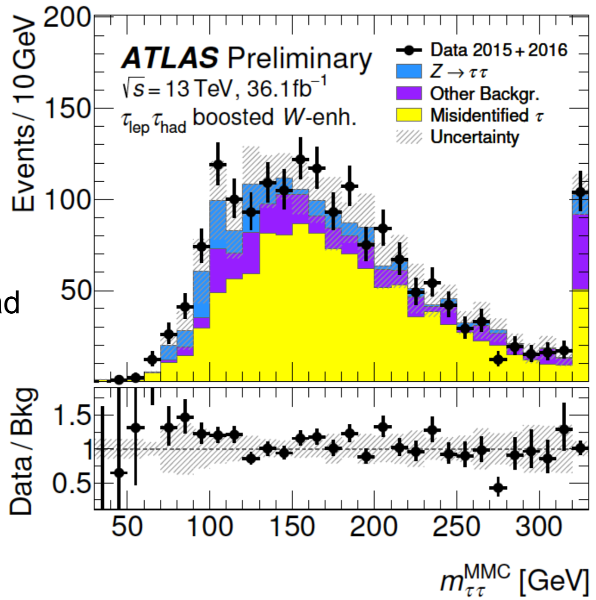
About 40% of total background

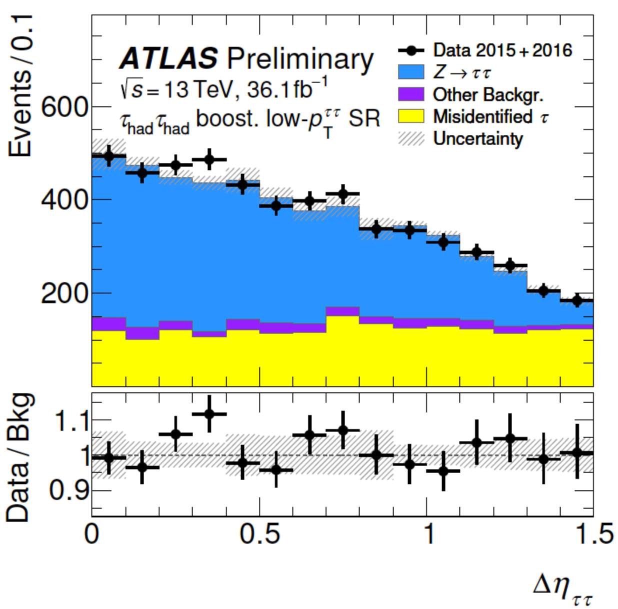
Get template events from SS, also include events with 2-track taus

Reweighted in $\Delta\phi(\tau,\tau)$ to improve MMC modeling at low mass

- Reweighting derived in events where subleading tau fails tight ID

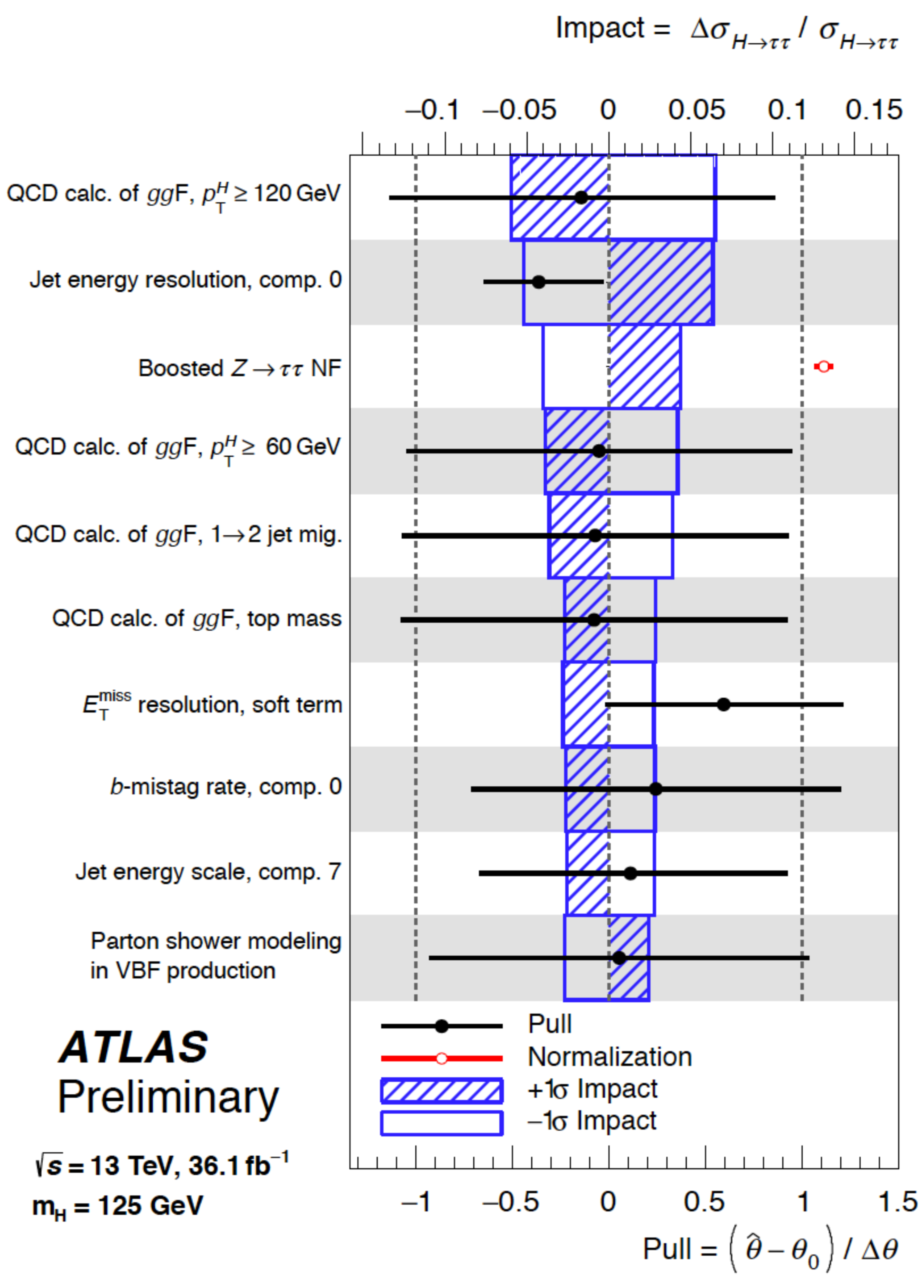
$tau_{lep}tau_{had}$





$tau_{had}tau_{had}$

Systematic Uncertainties



Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ (%)	
	Observed	Expected
Theoretical uncert. on signal	+13.5 / −8.7	+11.9 / −7.7
Background statistics	+11 / −10	+10.2 / −9.8
Jets and E_T^{miss}	+11.5 / −9.3	+10.5 / −8.6
Background normalization	+6.8 / −4.8	+6.6 / −4.6
Misidentified τ	+4.5 / −4.2	+3.7 / −3.4
Theoretical uncert. on background	+4.6 / −3.6	+5.1 / −4.2
Hadronic taus	+4.7 / −3.0	+5.8 / −4.2
Flavour tagging	+3.3 / −2.4	+2.9 / −2.2
Luminosity	+3.3 / −2.3	+3.1 / −2.2
Electrons and muons	+1.2 / −1.0	+1.1 / −0.9
Total systematic uncert.	+24 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −26	+27 / −25

- JER and MET soft shifted and constrained due to their correlation with the MMC reconstruction

- The constraints come from the $Z\to\tau\tau$ peak

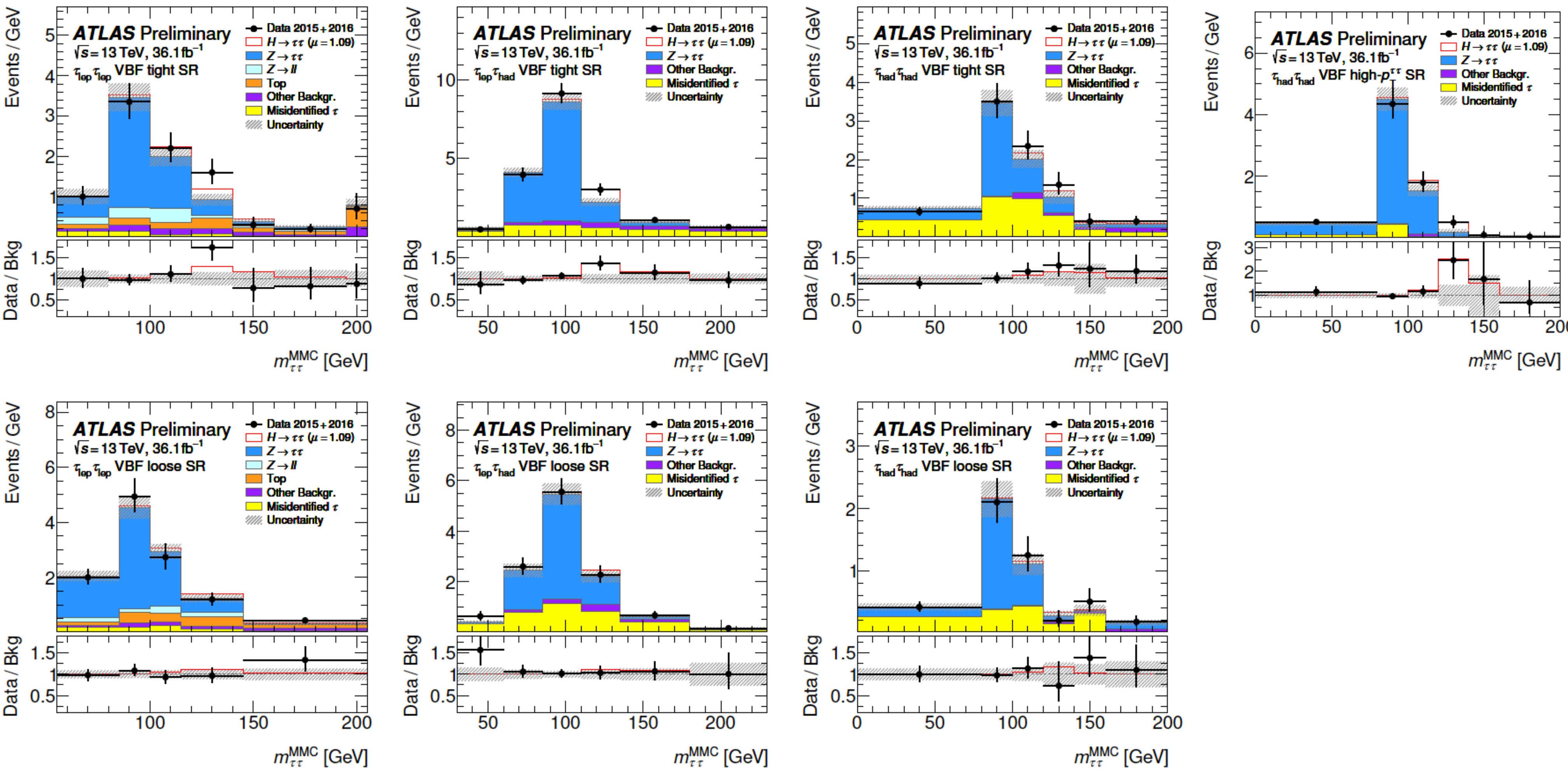
Postfit yeilds

tau$_{lep}$tau$_{lep}$	$\tau_{lep}\tau_{lep}$ VBF		$\tau_{lep}\tau_{lep}$ boosted	
	Loose	Tight	Low-$p_T^{\tau\tau}$	High-$p_T^{\tau\tau}$
Total background	231 ± 14	177 ± 12	4 089 ± 65	3 420 ± 57
Total signal	8.1 ± 2.3	13.5 ± 3.7	46 ± 12	47 ± 12
Data	237	188	4124	3444

tau$_{lep}$tau$_{had}$	$\tau_{lep}\tau_{had}$ VBF		$\tau_{lep}\tau_{had}$ boosted	
	Loose	Tight	Low-$p_T^{\tau\tau}$	High-$p_T^{\tau\tau}$
Total background	299 ± 18	459 ± 23	6 430 ± 88	6 230 ± 92
Total signal	11.7 ± 3.3	32.5 ± 8.4	80 ± 20	86 ± 24
Data	318	496	6556	6347

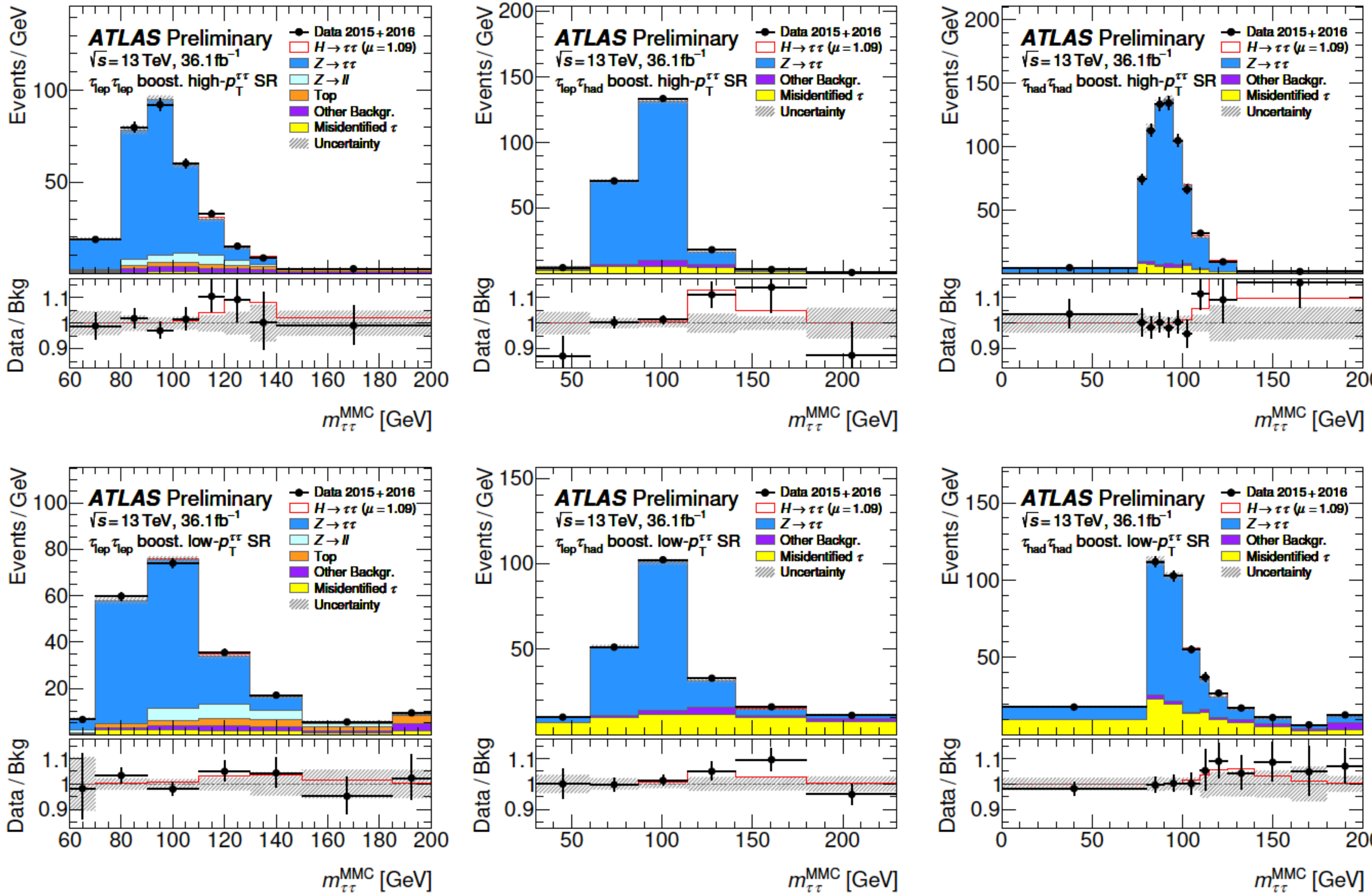
tau$_{had}$tau$_{had}$	$\tau_{had}\tau_{had}$ VBF			$\tau_{had}\tau_{had}$ boosted	
	Loose	Tight	High-$p_T^{\tau\tau}$	Low-$p_T^{\tau\tau}$	High-$p_T^{\tau\tau}$
Total background	119 ± 10	210 ± 13	168 ± 13	5 411 ± 80	4 068 ± 66
Total signal	2.6 ± 0.8	8.4 ± 2.4	14.6 ± 3.8	56 ± 15	67 ± 18
Data	121	220	179	5455	4103

SR distributions (VBF)



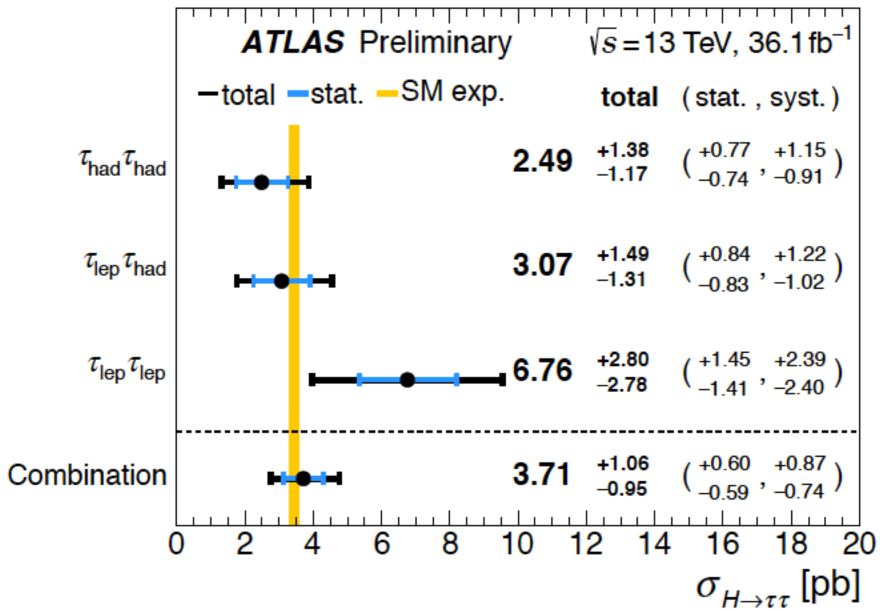
- MMC in the same binning as used in the fit
- Data well modeled by signal+background
- Signal scaled to observed cross section (1.08 of SM)

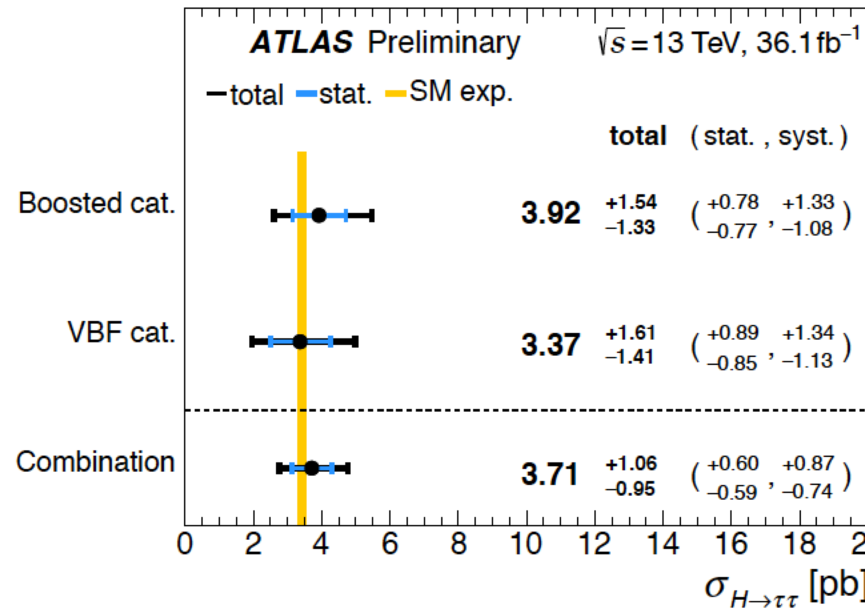
SR distributions (Boosted)

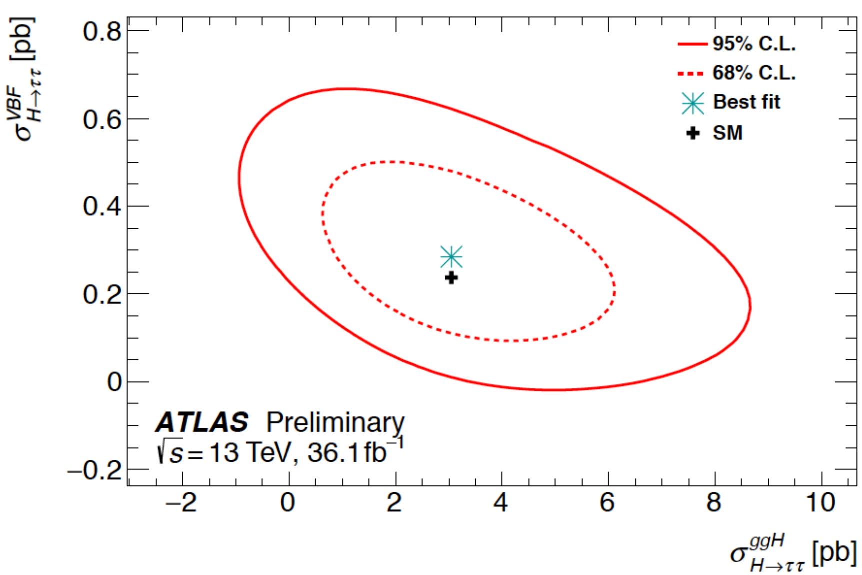


Boosted contributes roughly the same sensitivity as the VBF category

Fit results







Fitted: $\sigma_{ggH} = 3.0 \pm 1.0(\text{stat})^{+1.6}_{-1.2}(\text{sys})$ pb

$\sigma_{VBF} = 0.28 \pm 0.09(\text{stat})^{+0.11}_{-0.09}(\text{sys})$ pb

SM: $\sigma^{SM}_{ggH} = 3.05 \pm 0.13$ pb

$\sigma^{SM}_{VBF} = 0.237 \pm 0.006$ pb

Summary

Established $H \rightarrow \tau\tau$ events at 4.4σ (expected at 4.1σ) with Run-2.

When combined with Run-1, observed significance is 6.4σ (expected 5.4σ). First observation of SM $H \rightarrow \tau\tau$ in a single LHC experiment

Measured cross sections consistent with SM predictions

- Constraints on VBF coupling similar to Run 1
- Constraints on ggF coupling improved by factor ~2

Reference:

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2018-021