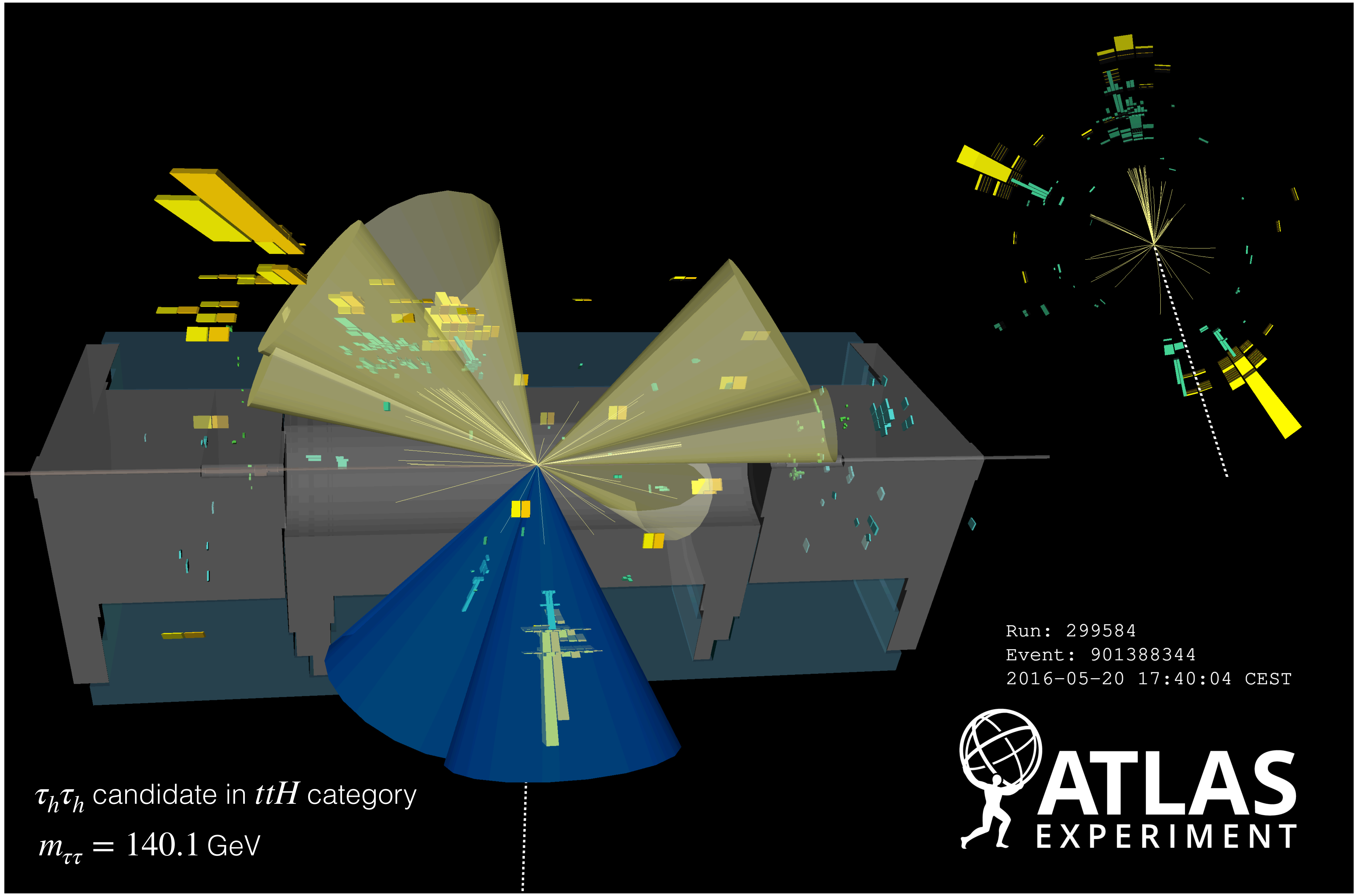
Measurement of $H \to \tau\tau$ Cross Sections at ATLAS

arXiv:2201.08269 (submitted to JHEP)



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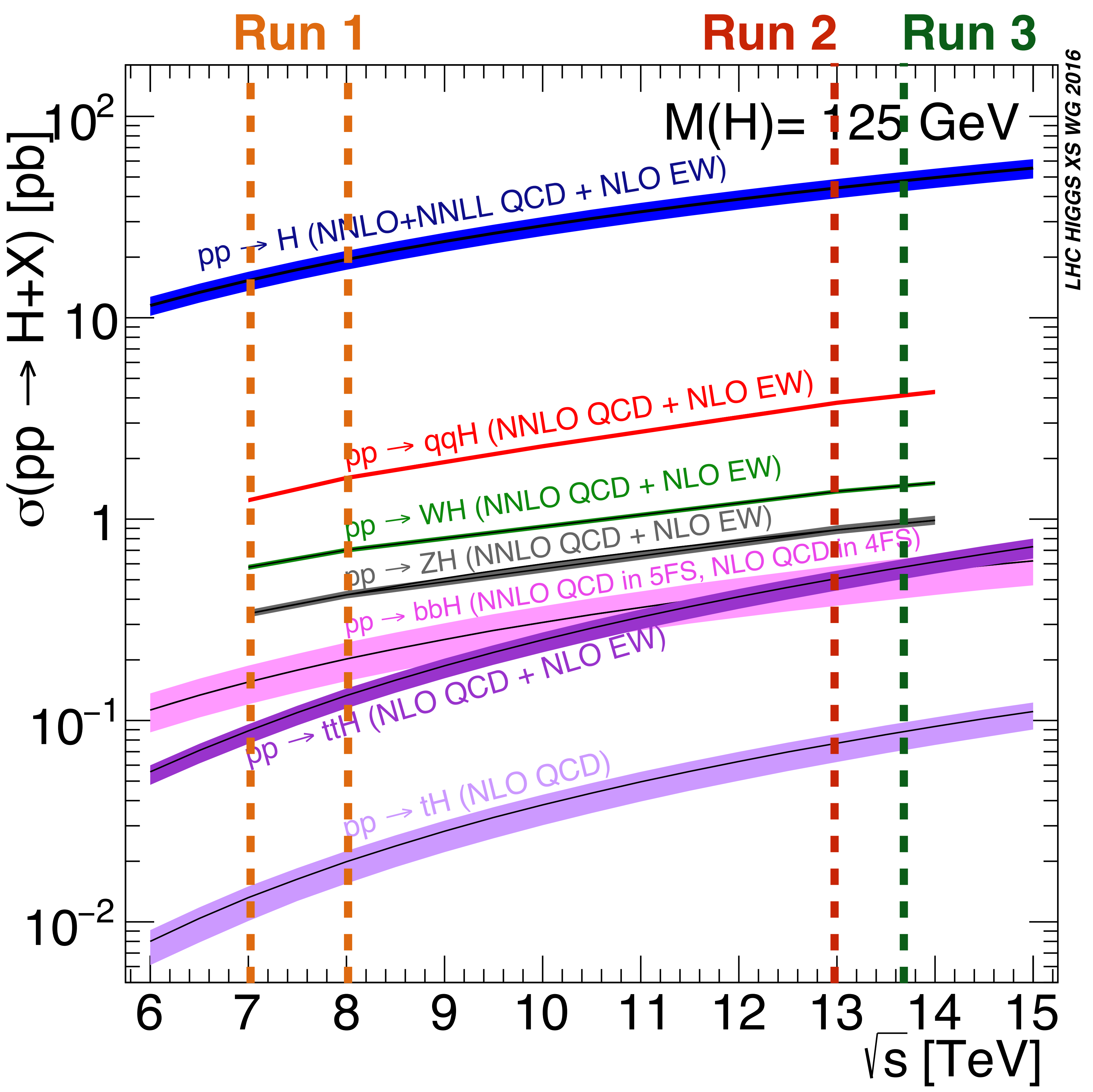
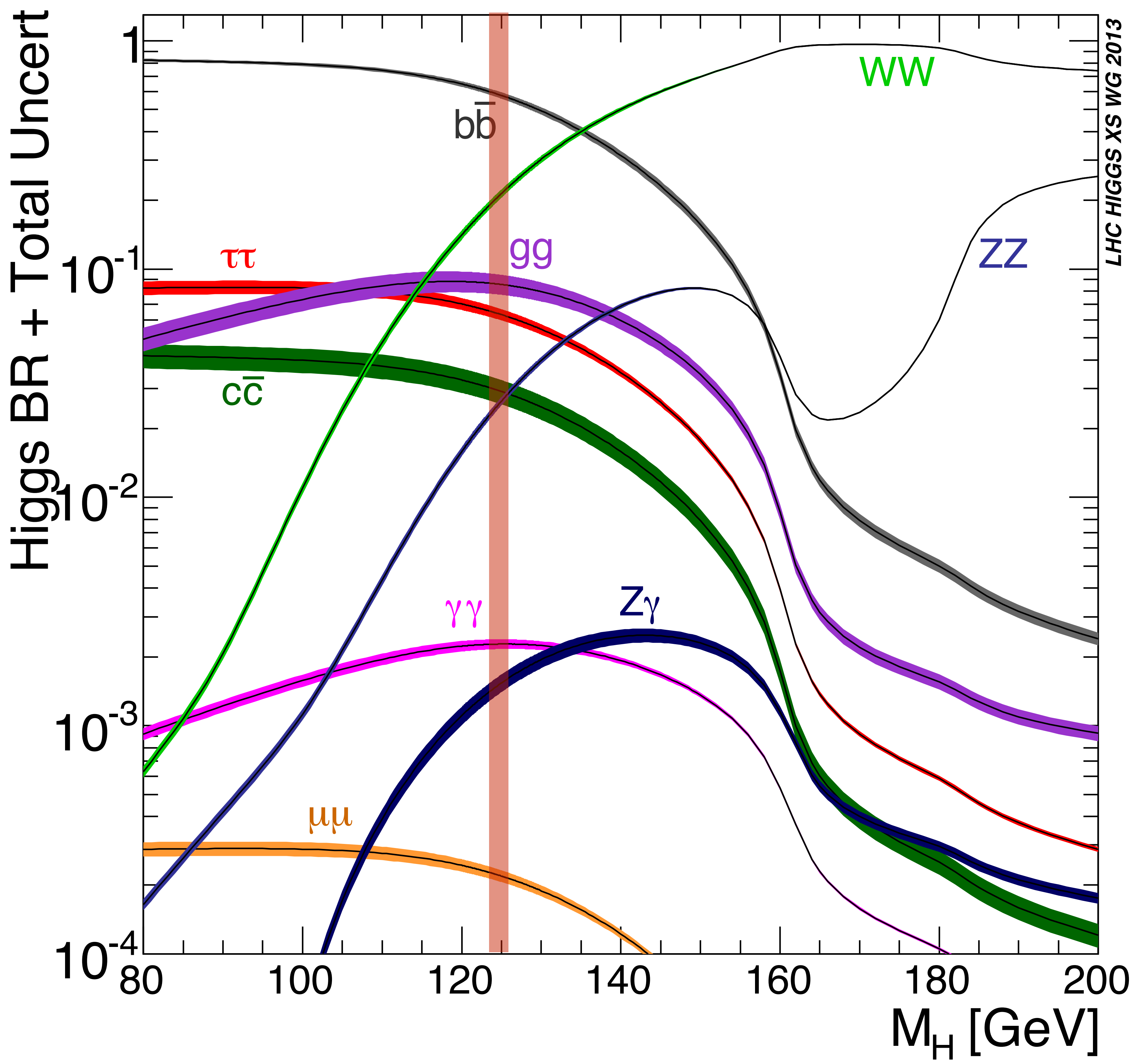
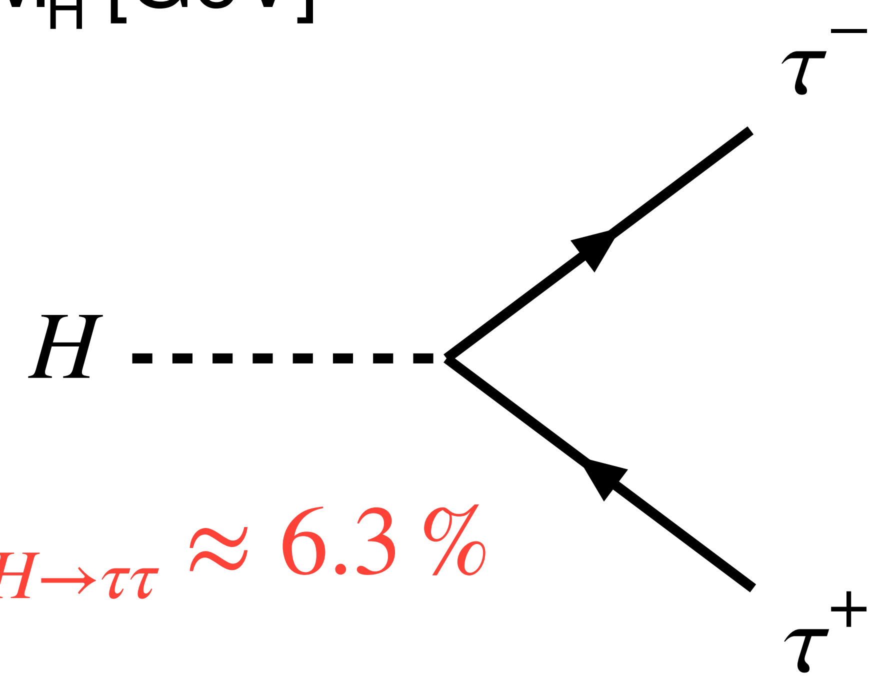
Higgs boson production at the LHC



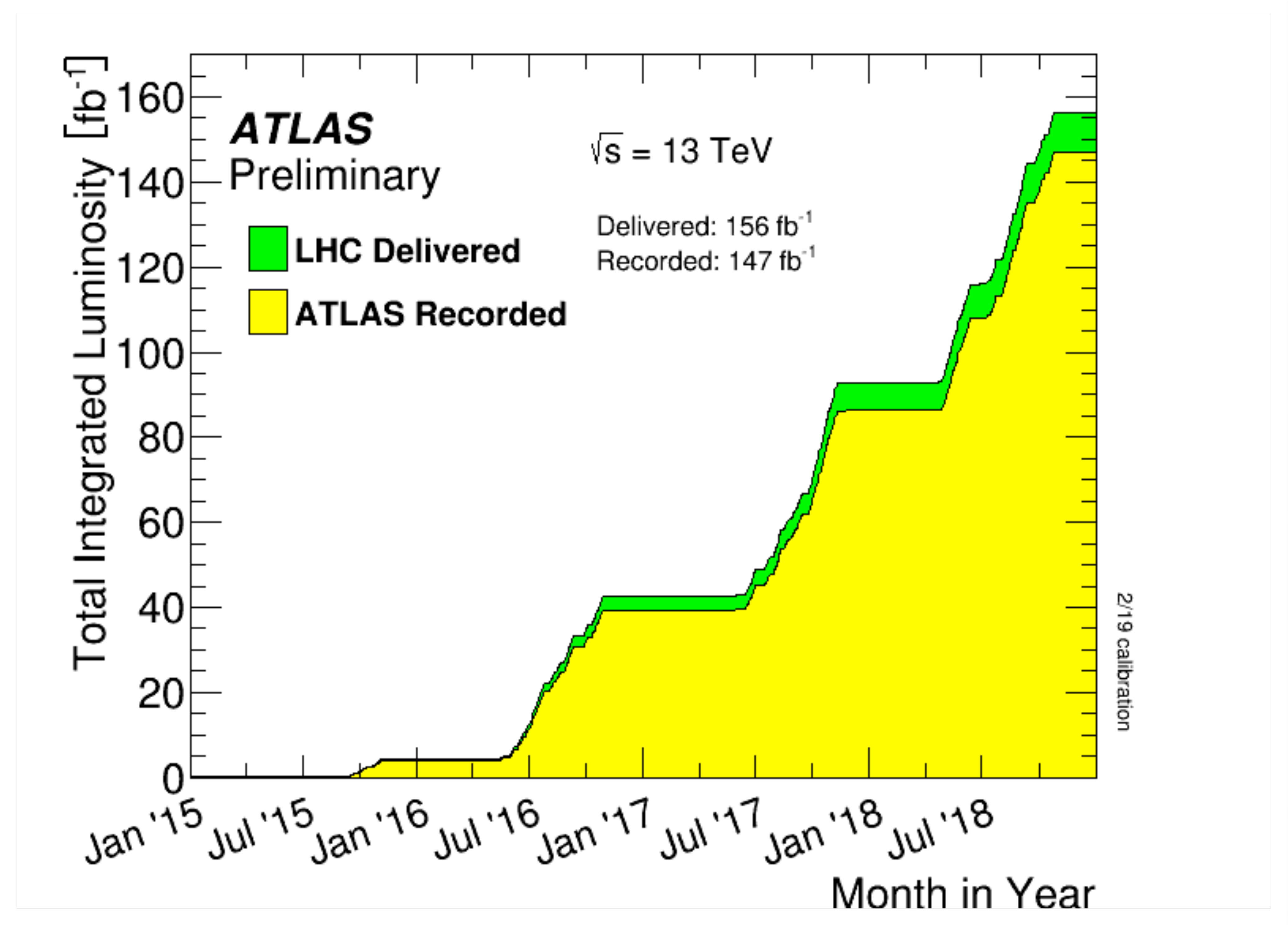


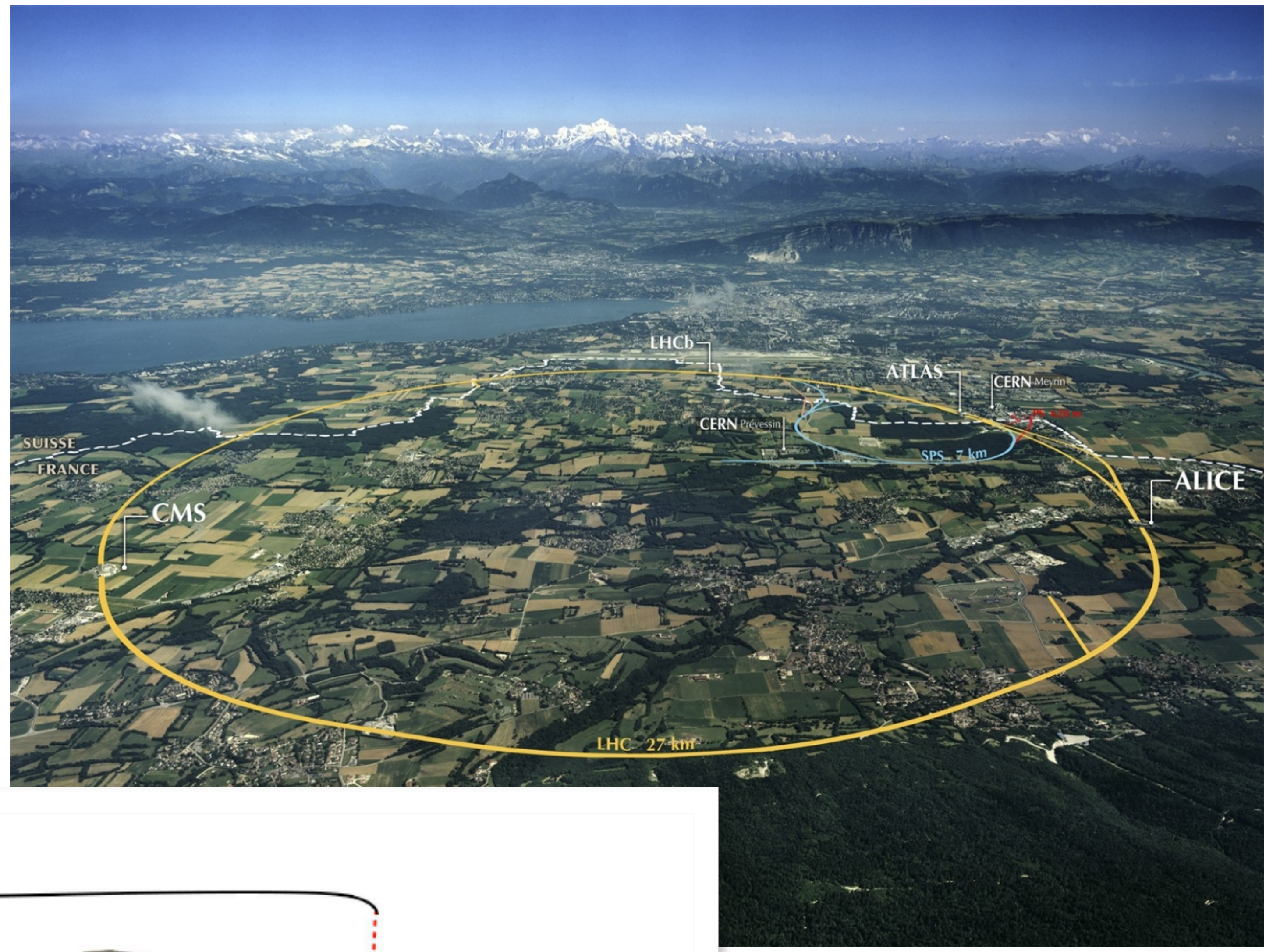
- Measure $\sigma \times BR_{H\to\tau\tau}$ for all relevant production modes: ggH, VBF, $V(\to qq)H$ and ttH

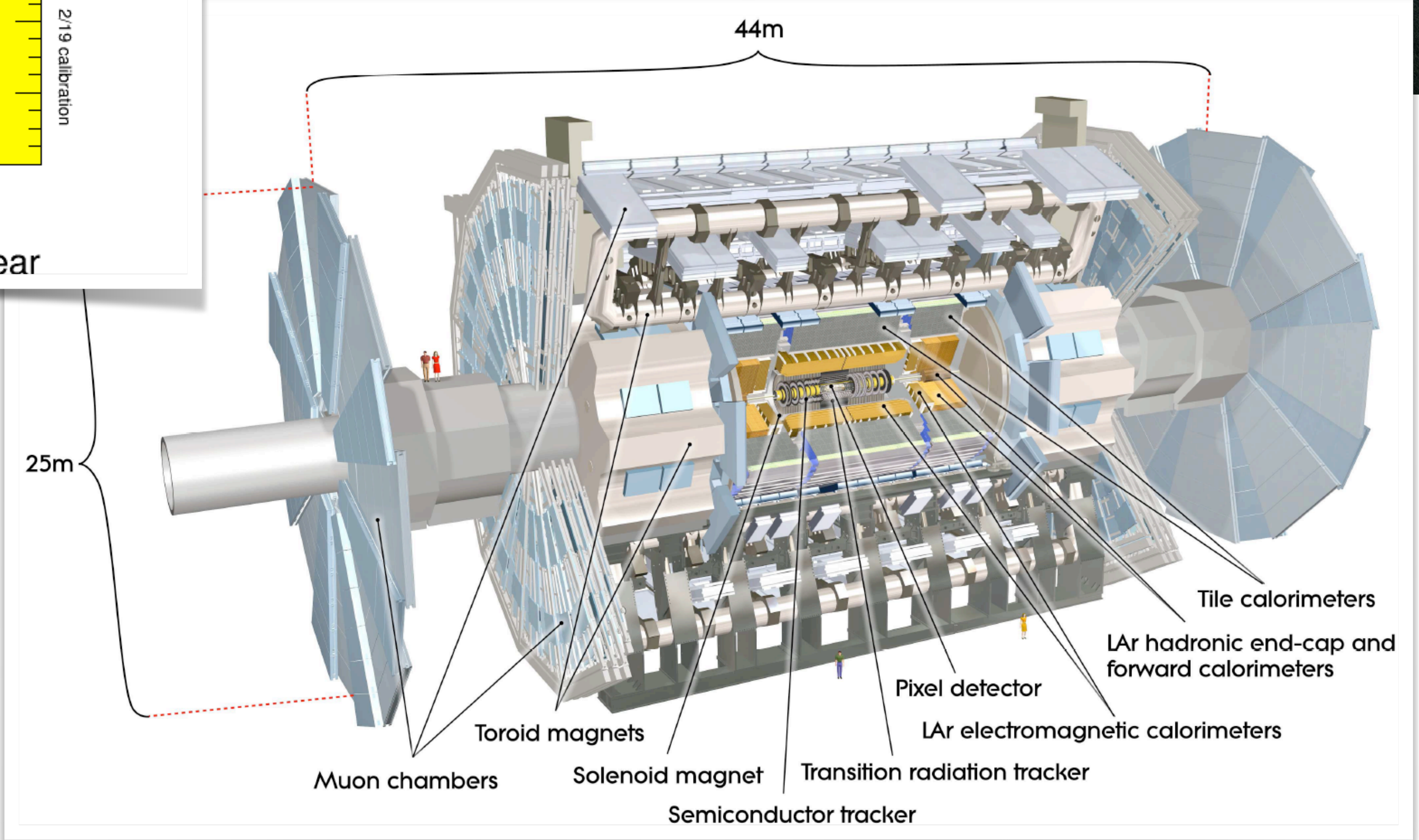


$BR_{H\to\tau\tau} \approx 6.3\,\%$

The ATLAS experiment at the LHC



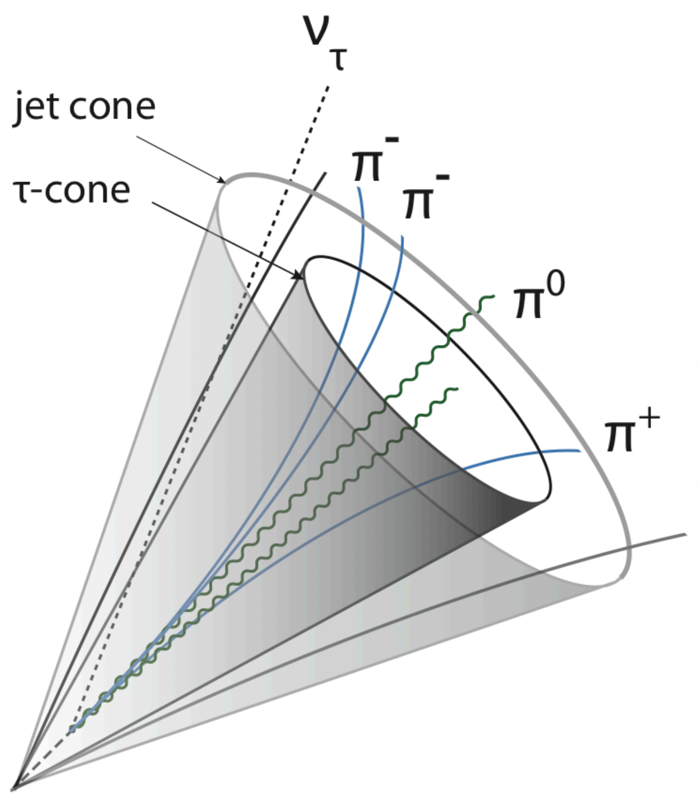


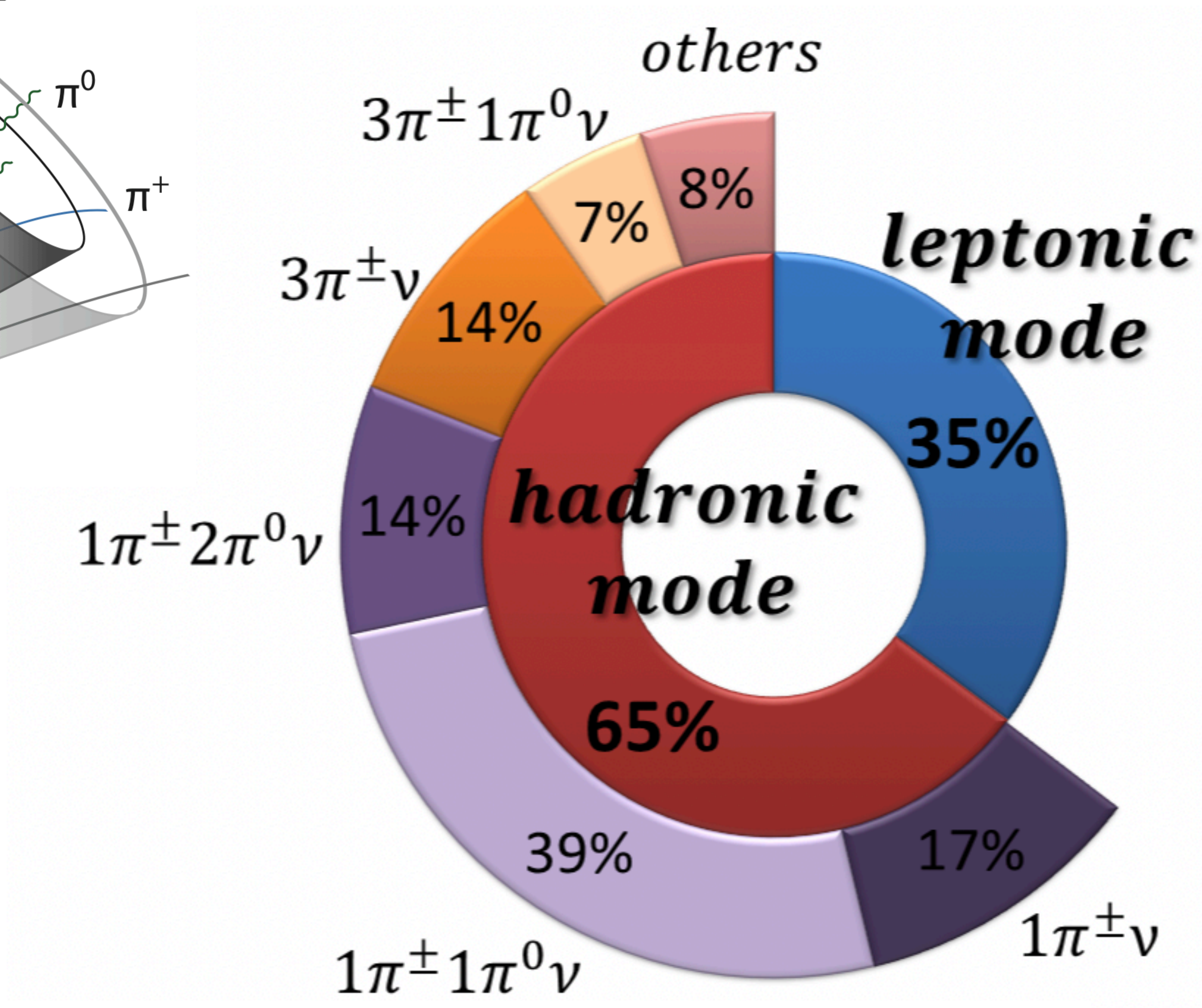


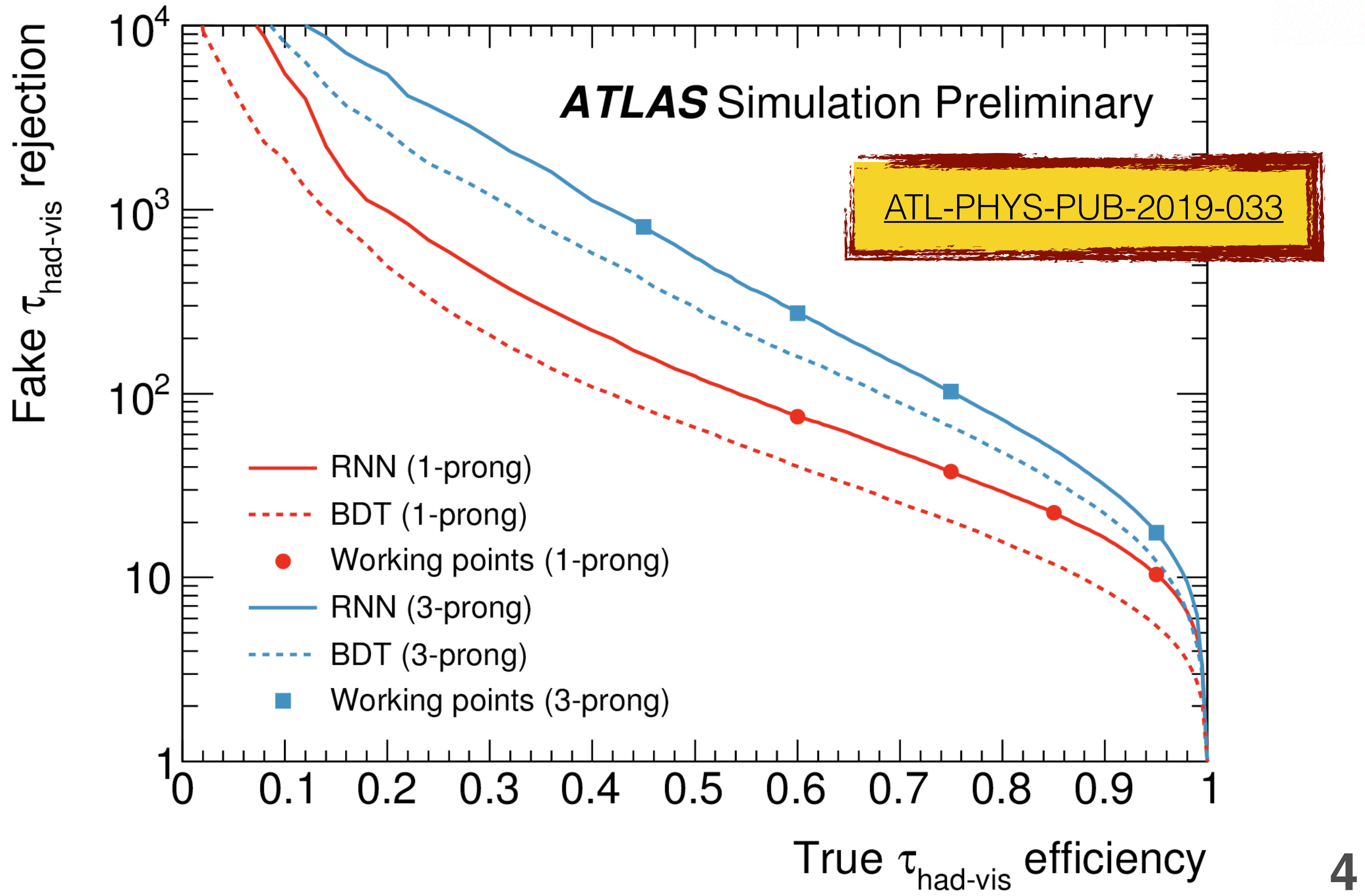
- Use full Run 2 dataset: $\mathscr{L}_{\text{int}} = 139\,\text{fb}^{-1}$ after data quality cuts

Reconstruction of τ-lepton decays

- Leptonic τ-lepton decays are reconstructed as electrons and muons (with relaxed d_0 cuts)
- Reconstruction of hadronic τ-lepton decays starts from anti-k_T jets with $R = 0.4$ as seeds
- Classify tracks within cone into tau, isolation, pile-up and conversion tracks using multiple BDTs - require exactly 1 or 3 tau-tracks
- Use RNN to identify hadronic tau decays and reject quark and gluonjets
- Use all relevant combinations of tau decay modes: $\tau_h\tau_h$, $\tau_\ell\tau_h$, $\tau_e\tau_\mu$ $(\ell = e, \mu)$
- No same flavour light leptons to avoid Z peak

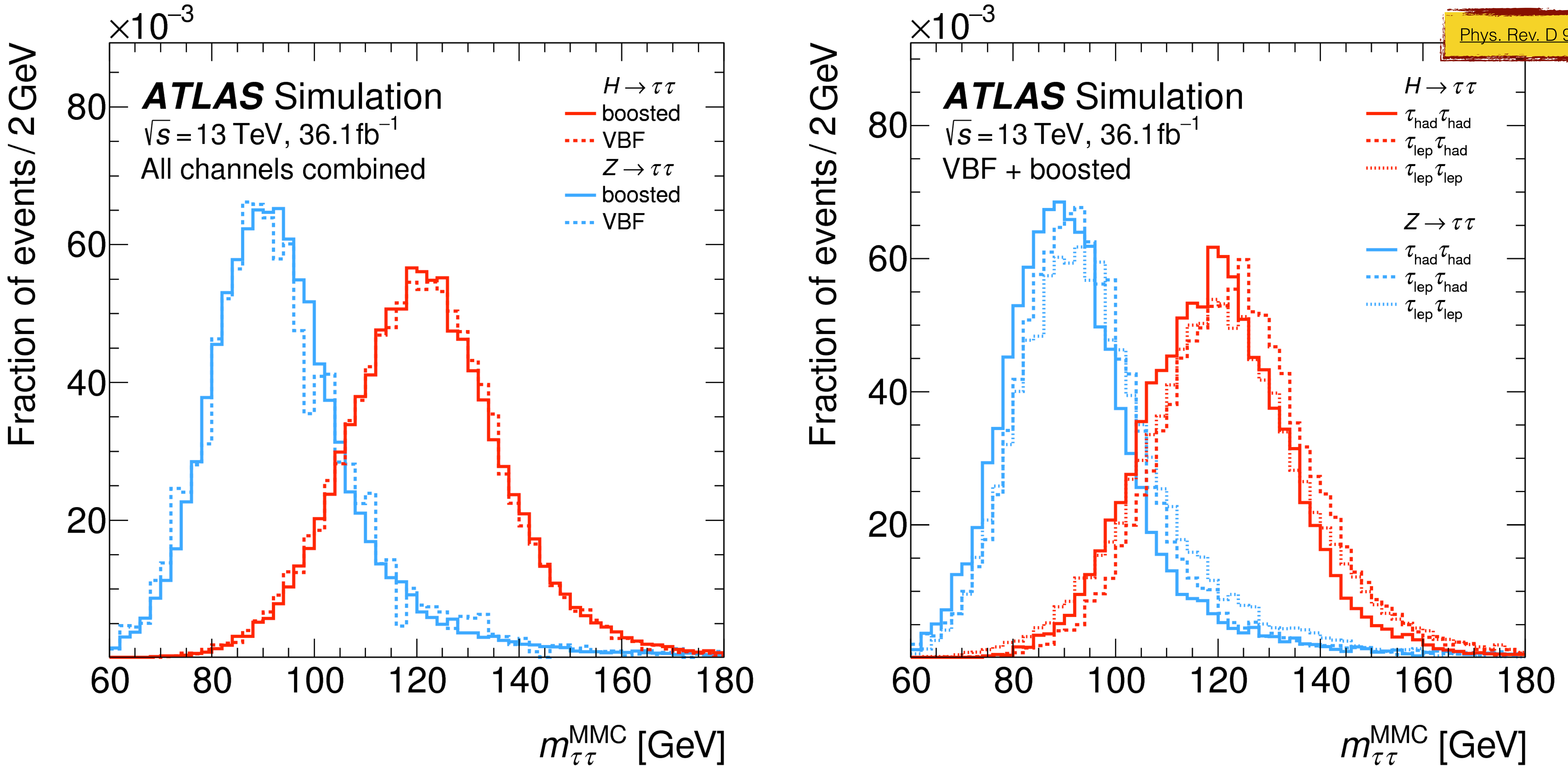






Di-tau mass reconstruction

Phys. Rev. D 99 (2019) 072001



- Use visible tau decay products and missing energy in missing mass calculator (MMC)
- Sample PDFs ad use Markov chain to find most likely solution to underconstrained problem

Preselection

Trigger signature	Data-taking period	p_T threshold [GeV] used in event selection
Single electron	2015 2016–2018	$p_T(e) > 25$ $p_T(e) > 27$
Single muon	2015 2016–2018	$p_T(\mu) > 21$ $p_T(\mu) > 27.3$
One electron, one muon	2015–2018	$p_T(e) > 18$, $p_T(\mu) > 14.7$
Two $\tau_{\text{had-vis}}$	2015–2018	$p_T(\text{leading } \tau_{\text{had-vis}}) > 40$ $p_T(\text{sub-leading } \tau_{\text{had-vis}}) > 30$

- Use single muon, single electron, muon+electron and $\tau_h\tau_h$(+jet) triggers
- Define exclusive categories of medium quality electrons, muons and hadronic tau decays to define analysis categories

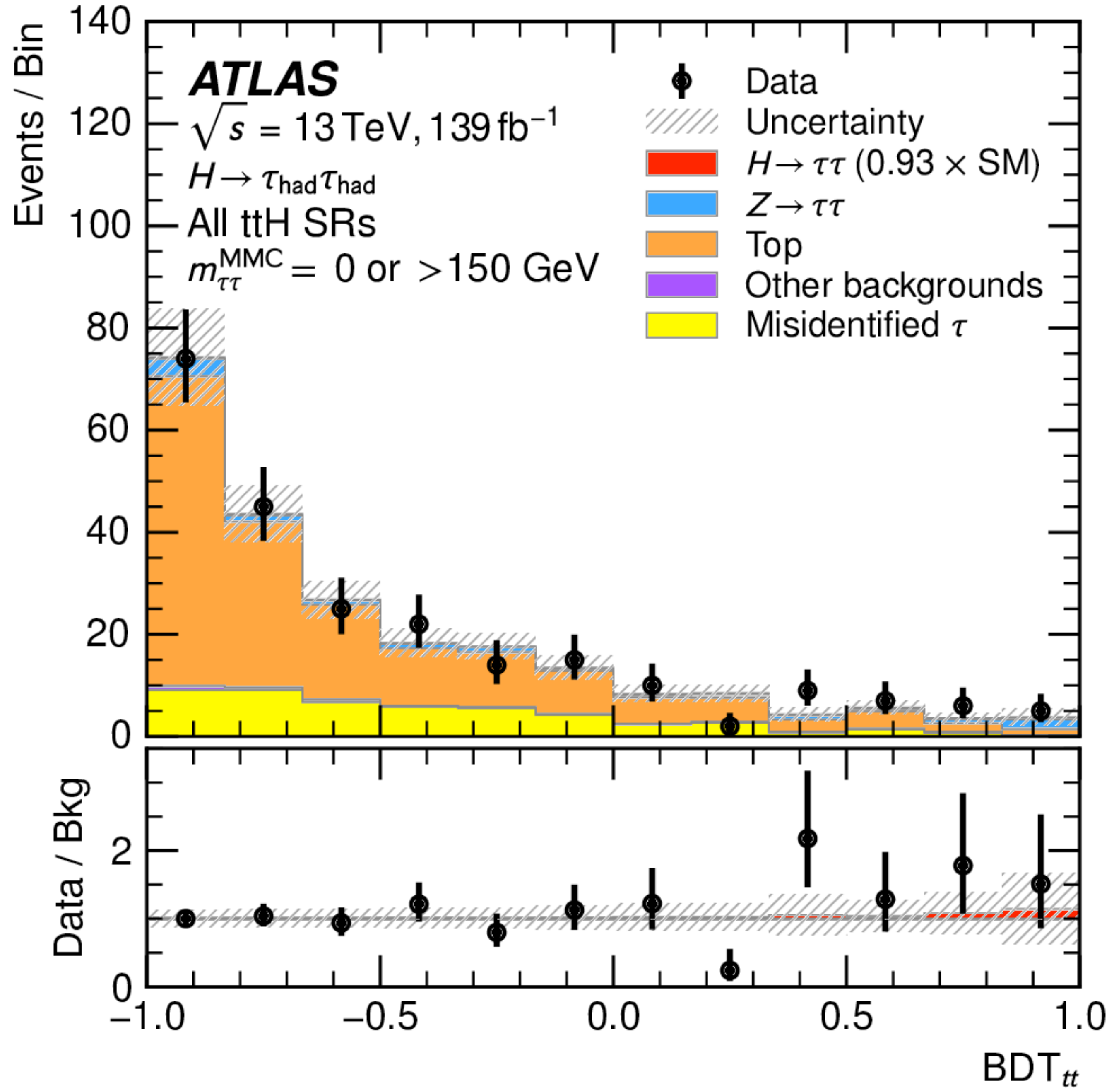
Criteria	$\tau_e\tau_\mu$	$\tau_{\text{lep}}\tau_{\text{had}}$		$\tau_{\text{had}}\tau_{\text{had}}$
		$\tau_e\tau_{\text{had}}$	$\tau_\mu\tau_{\text{had}}$	
$N(e)$	1	1	0	0
$N(\mu)$	1	0	1	0
$N(\tau_{\text{had-vis}})$	0	1	1	2
$N(b\text{-jets})$	0 (85% WP)	0 (85% WP)	0 (85% WP)	0 (70% WP) (≥ 1 or 2 in ttH categories)
$p_T(e)$ [GeV]	> 15 to 27	> 27		
$p_T(\mu)$ [GeV]	> 10 to 27.3		> 27.3	
$p_T(\tau_{\text{had-vis}})$ [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_T^{miss} [GeV]	> 20			
Kinematics	$m_{\tau\tau}^{\text{coll}} > m_Z - 25$ GeV 30 GeV $< m_{e\mu} <$ 100 GeV	$m_T < 70$ GeV		
Leading jet	$p_T > 40$ GeV			$p_T > 70$ 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	$0.1 < x_1 < 1.0$ $0.1 < x_2 < 1.0$	$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.2$		$0.1 < x_1 < 1.4$ $0.1 < x_2 < 1.4$

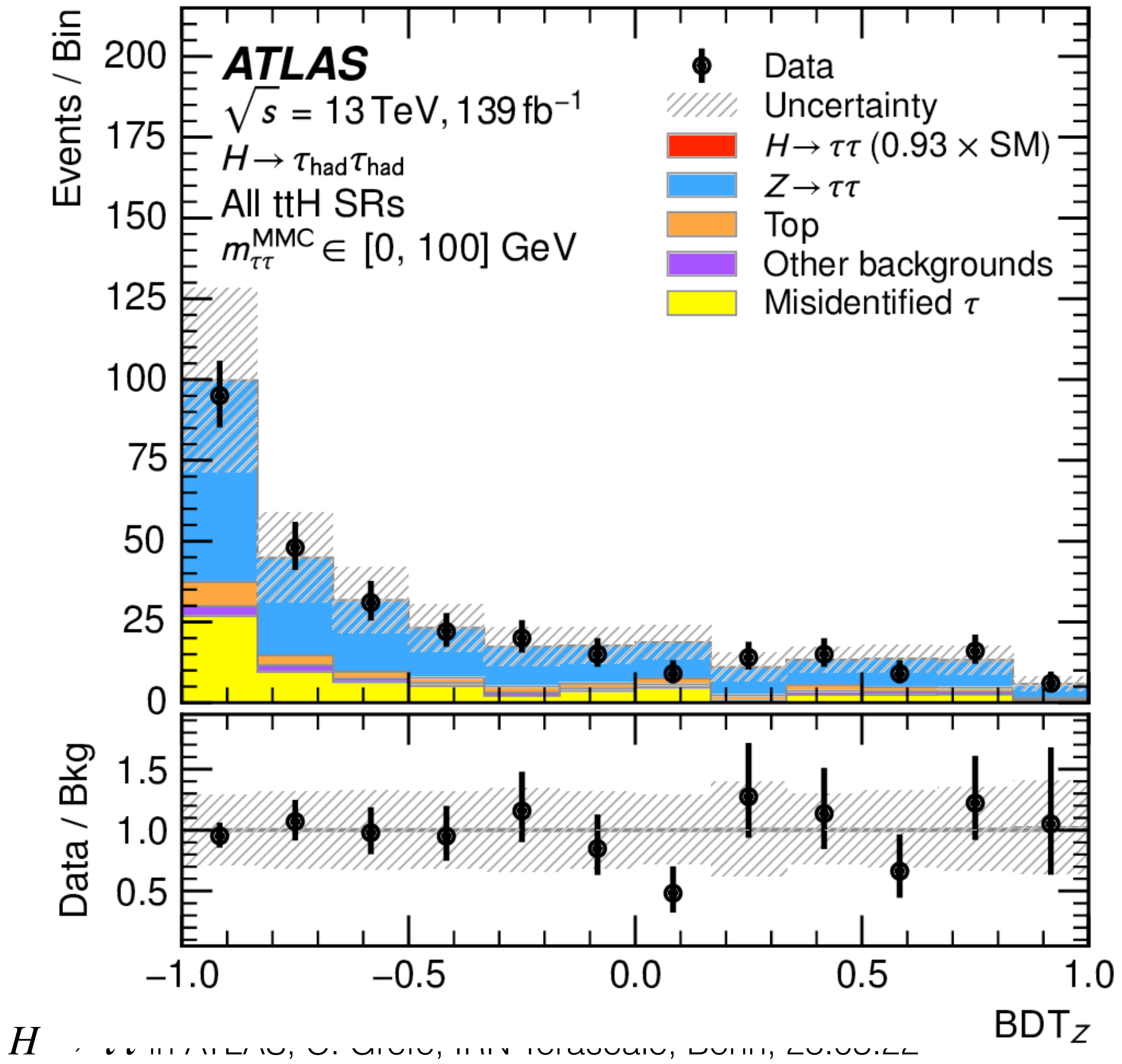
Event categories

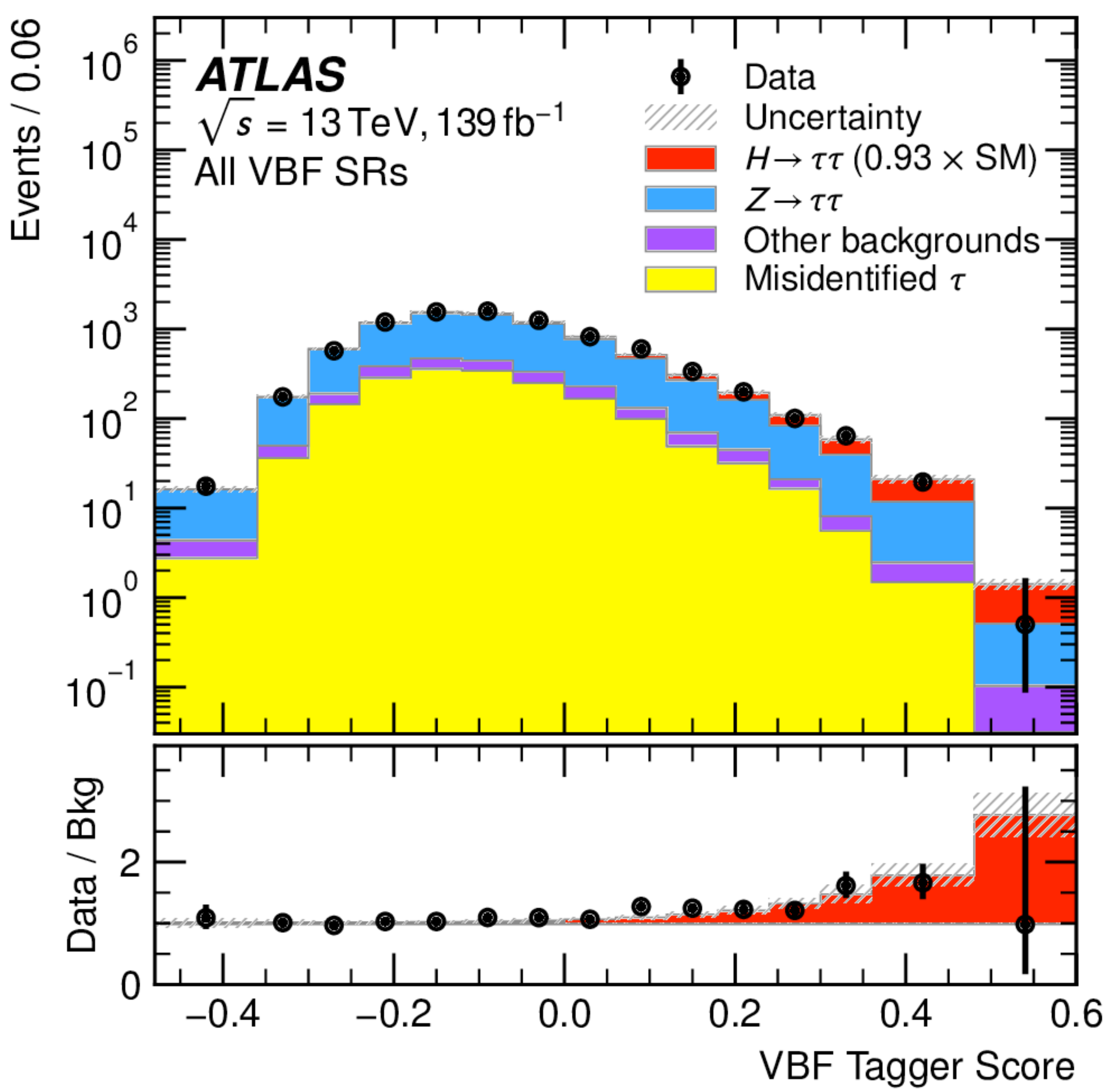
- Boosted (ggH): $p_T(H) > 100$ GeV
- *VBF*: $m_{jj} > 350$ GeV, $p_T^{j2} > 30$ GeV, $|\Delta\eta_{jj}| > 3$, jets in opposite hemispheres
- *VH*: $60 < m_{jj} < 120$ GeV, $p_T^{j2} > 30$ GeV
- *ttH*: 6 jets and at least 1 b-tag or 5 jets and at least 2 b-tags
- Additional BDT classifiers to purify *VBF*, *VH* and *ttH* categories

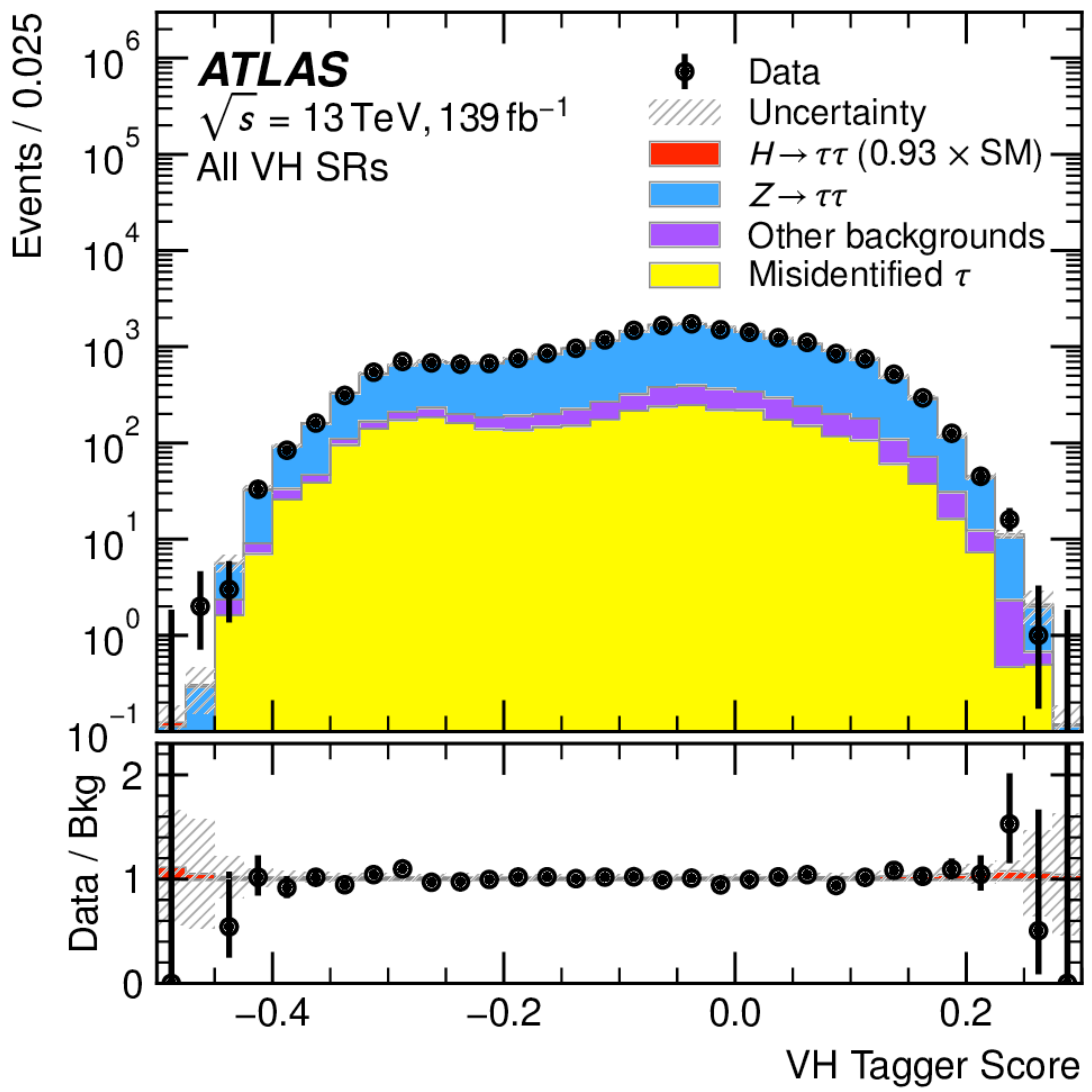
	Variable	VBF	V(had)H	ttH vs $t\bar{t}$	ttH vs $Z \to \tau\tau$
Jet properties	Invariant mass of the two leading jets	•	•		
	$p_{\mathrm{T}}(jj)$	•	•		
	Product of η of the two leading jets	•			
	Sub-leading jet p_{T}	•			
	Leading jet η				•
	Sub-leading jet η				•
	Scalar sum of all jets p_{T}			•	•
	Scalar sum of all b-tagged jets p_{T}				•
	Best W-candidate dijet invariant mass			•	•
	Best t-quark-candidate three-jet invariant mass			•	•
Angular distances	$\Delta\phi$ between the two leading jets	•			
	$\Delta\eta$ between the two leading jets	•	•		
	ΔR between the two leading jets		•		
	$\Delta R(\tau\tau, jj)$		•		
	$\Delta R(\tau, \tau)$		•	•	
	Smallest ΔR (any two jets)			•	
	$\|\Delta\eta(\tau,\tau)\|$			•	•
τ prop.	$p_{\mathrm{T}}(\tau\tau)$			•	
	Sub-leading τ p_{T}				•
	Sub-leading τ η				•
H cand.	$p_{\mathrm{T}}(Hjj)$	•	•		
	$p_{\mathrm{T}}(H)/p_{\mathrm{T}}(jj)$		•		
$\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$		•	•	•
	Smallest $\Delta\phi$ $(\tau, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$				•

Modelling in event categories









- VBF and VH are split into two regions to maximise sensitivity by cutting on BDT scores
- For ttH a rectangular cut is performed on both BDTs

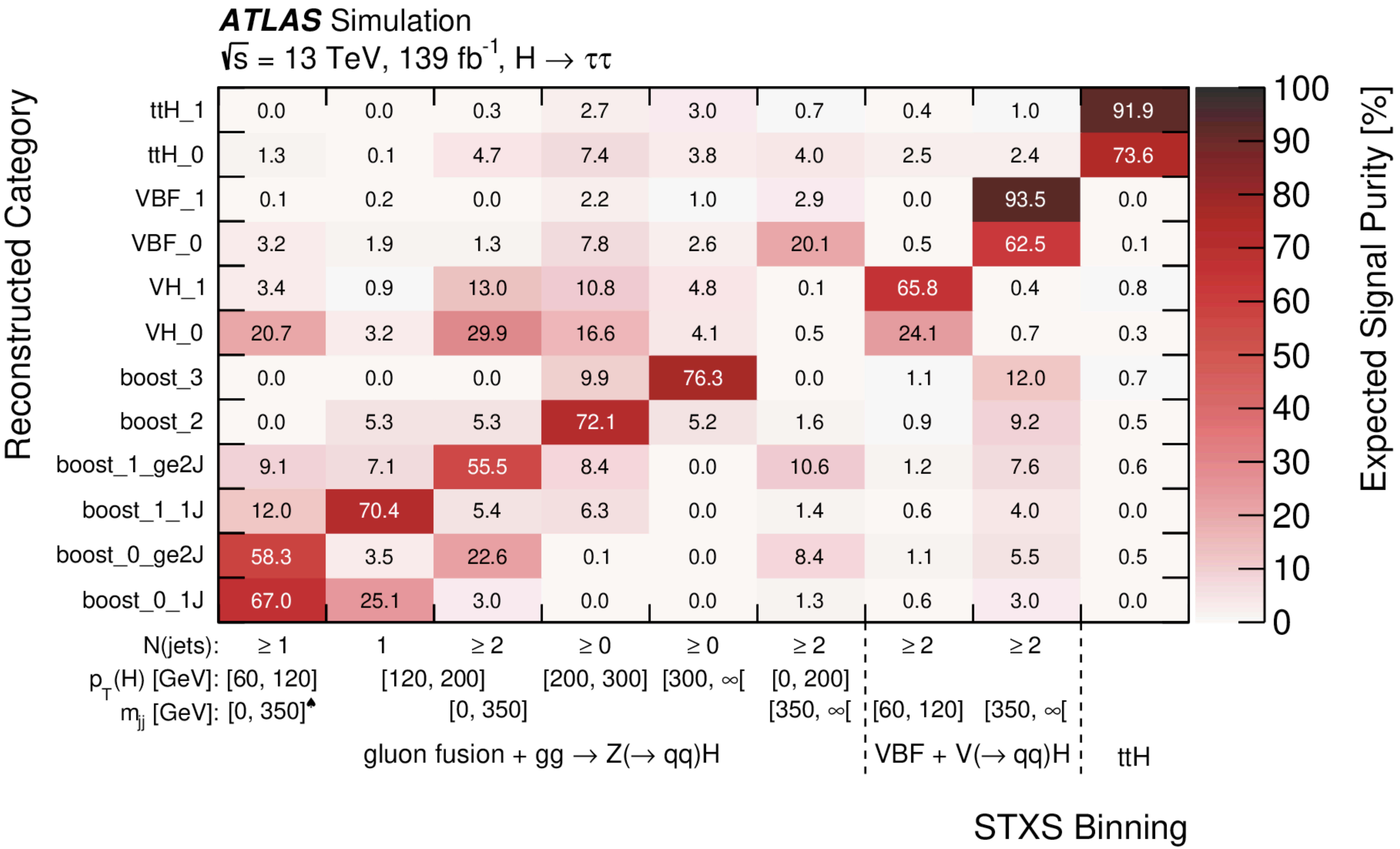
Simplified Template Cross Section Bins

Background Composition

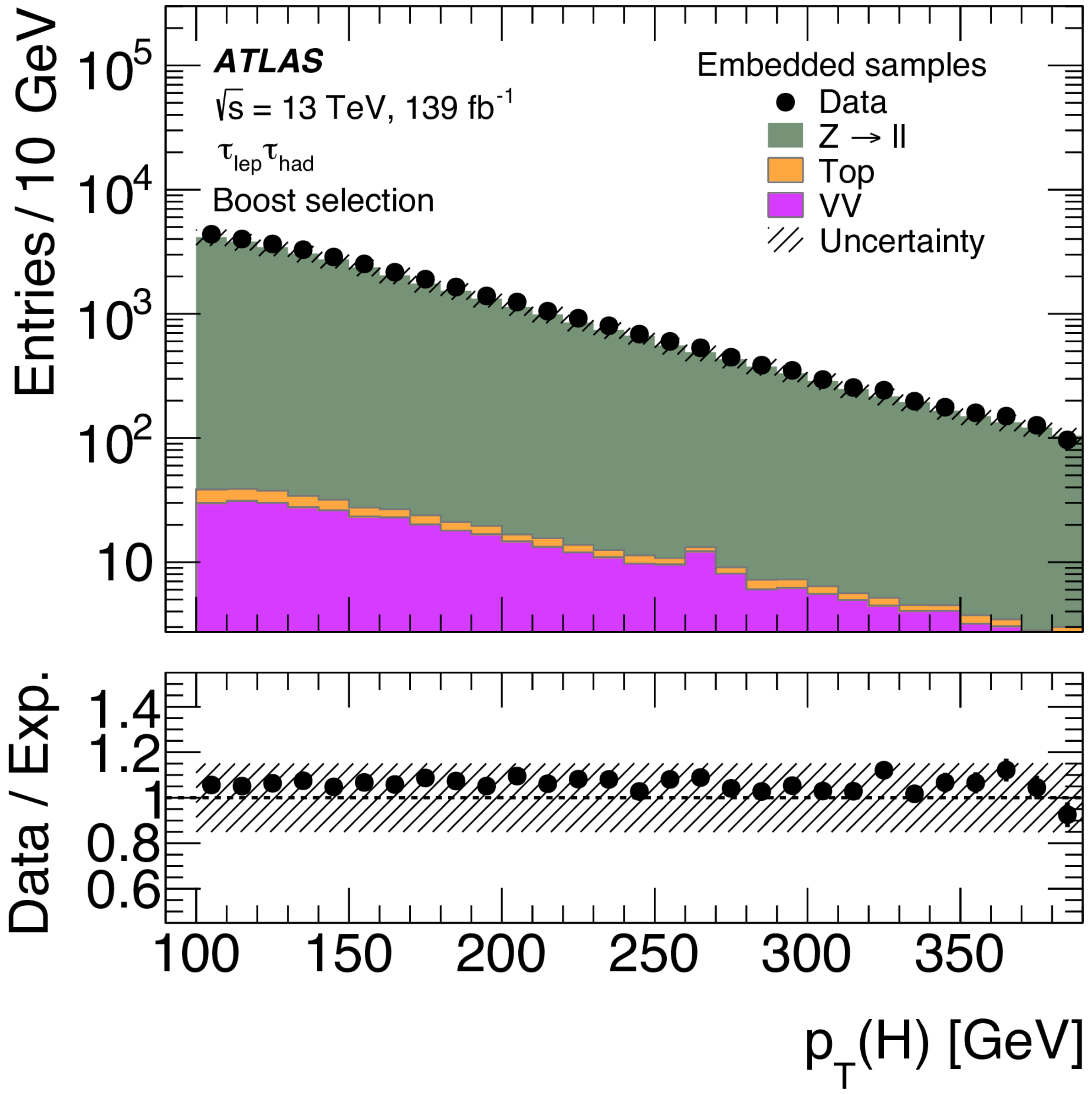
- Largest backgrounds from $Z \to \tau\tau$, misidentified τ-leptons and top quark processes

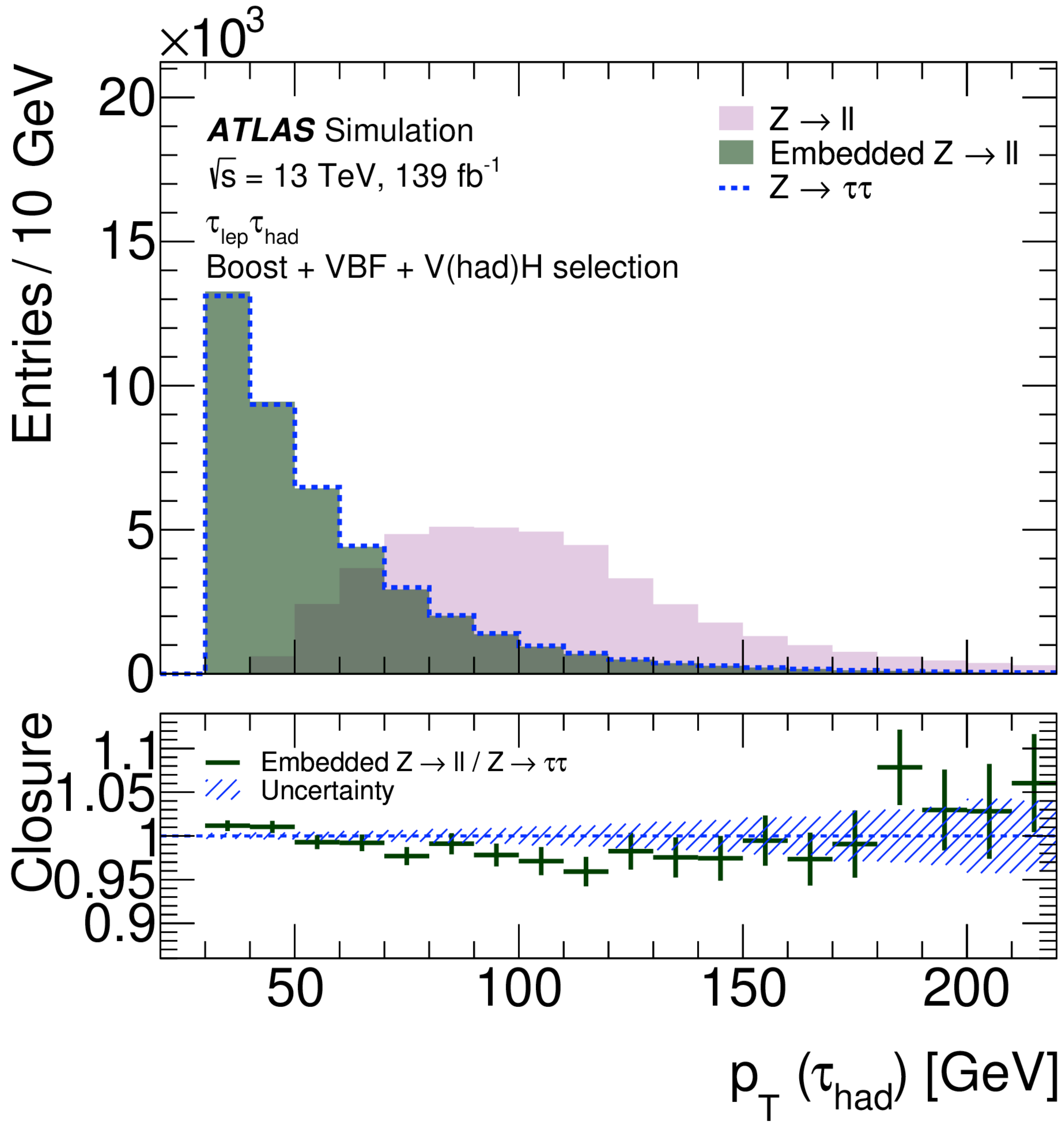
Process	Generator ME	Generator PS	PDF set ME	PDF set PS	Tune	Normalisation
Higgs boson						
ggF	Powheg Box v2	Pythia 8	PDF4LHC15nnlo	CTEQ6L1	AZNLO	N^3LO QCD + NLO EW
VBF	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + NLO EW
VH	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + 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

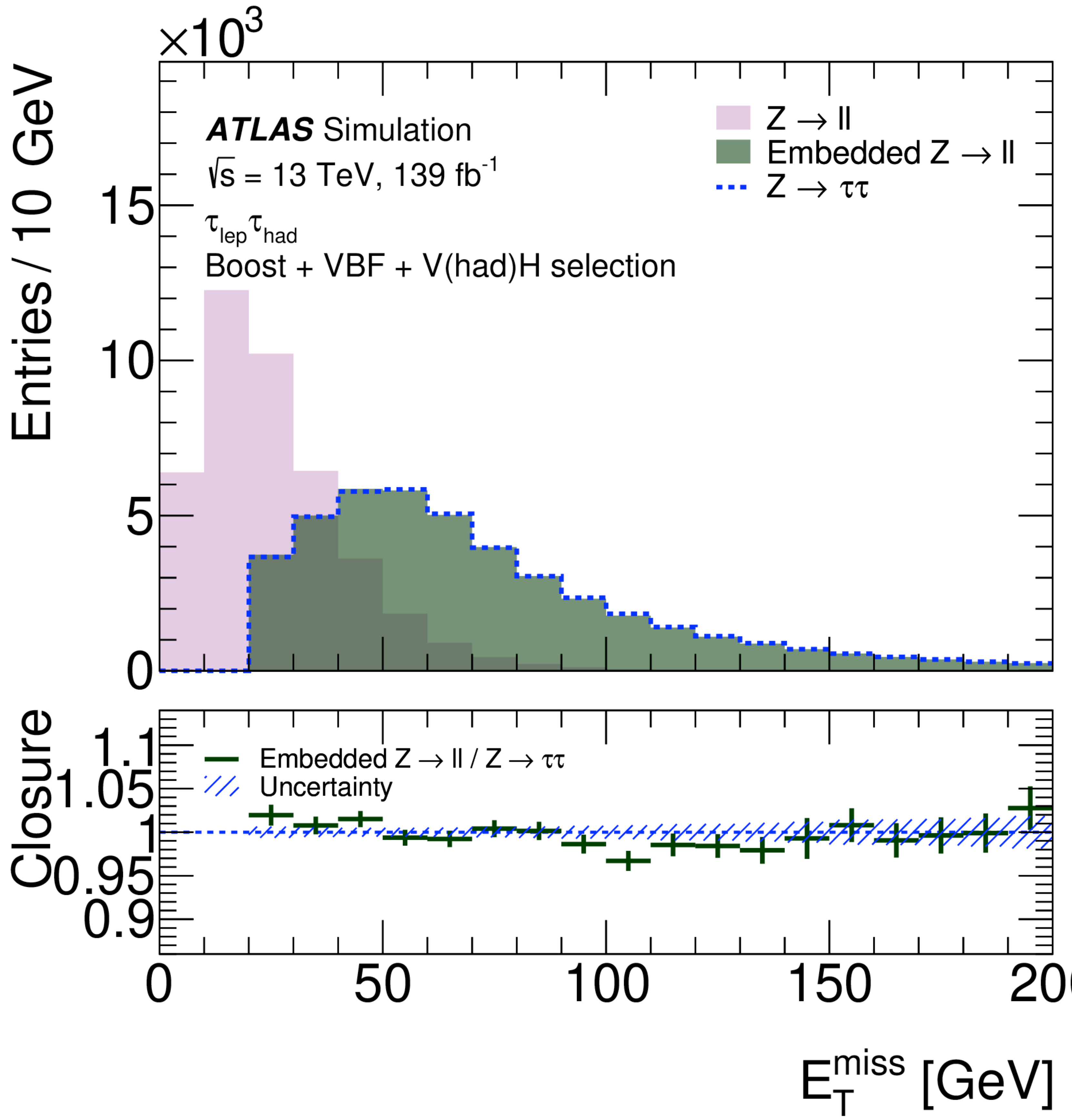
Signal purity in STXS bins



Modelling of $Z \to \tau\tau$ background







- "Simplified embedding": use $Z \to \ell\ell$ events, correct for e, μ and τ_h trigger and reconstruction efficiencies and scale visible p_T to correspond to hadronic τ-lepton decays - all event quantities are re-evaluated

- All detector uncertainties are propagated + non-closure uncertainties from comparison to $Z \to \tau\tau$ MC

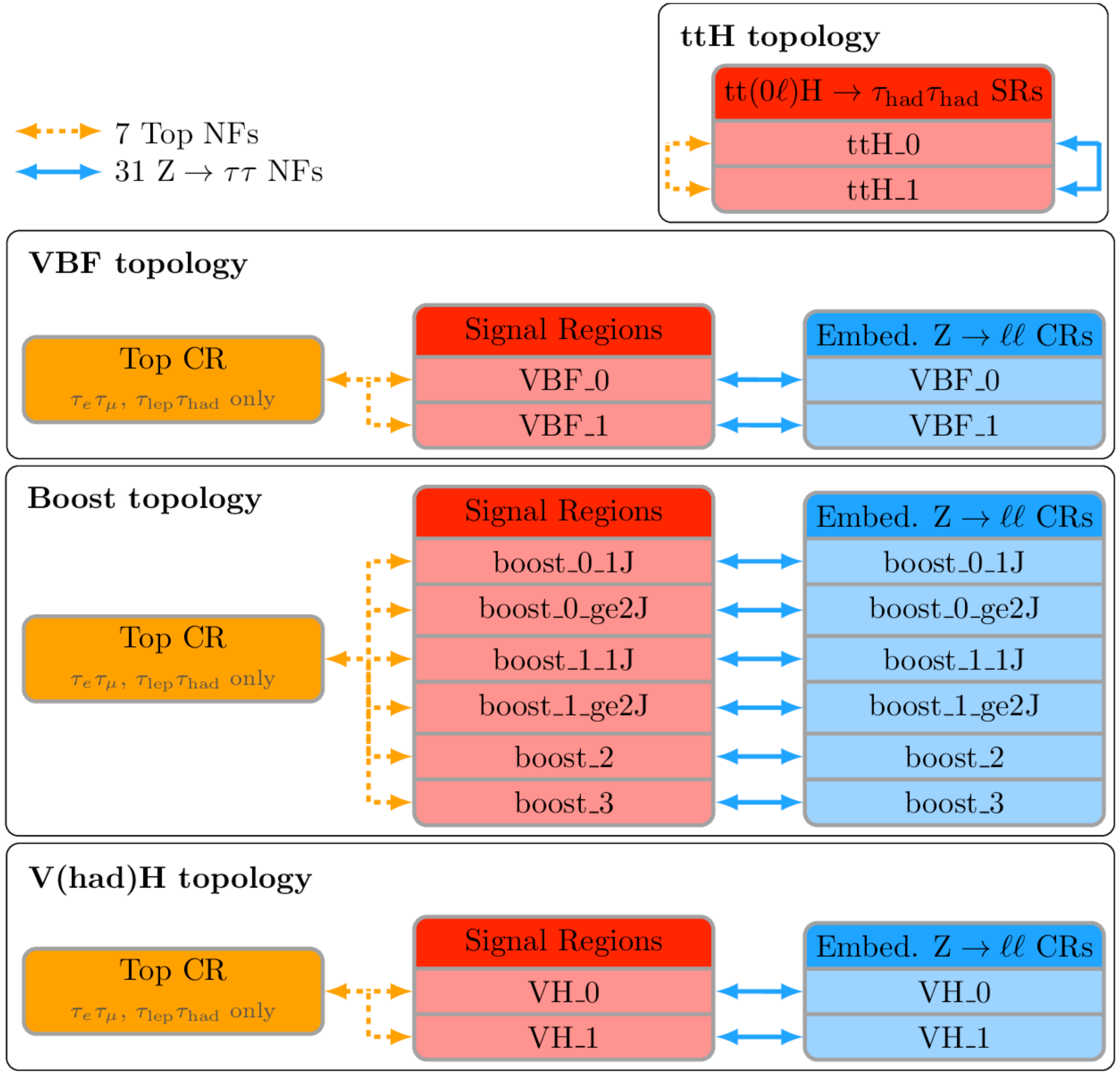
Misidentified τ-lepton background

- $\tau_h\tau_h$ and $\tau_\ell\tau_h$ use a fake factor approach to estimate hadronic tau fakes, light lepton fakes are negligible in $\tau_\ell\tau_h$
- $\tau_e\tau_\mu$ uses a matrix method to estimate light lepton fakes
- Check modelling in validation regions. Uncertainties are estimated from non-closure effects and statistics

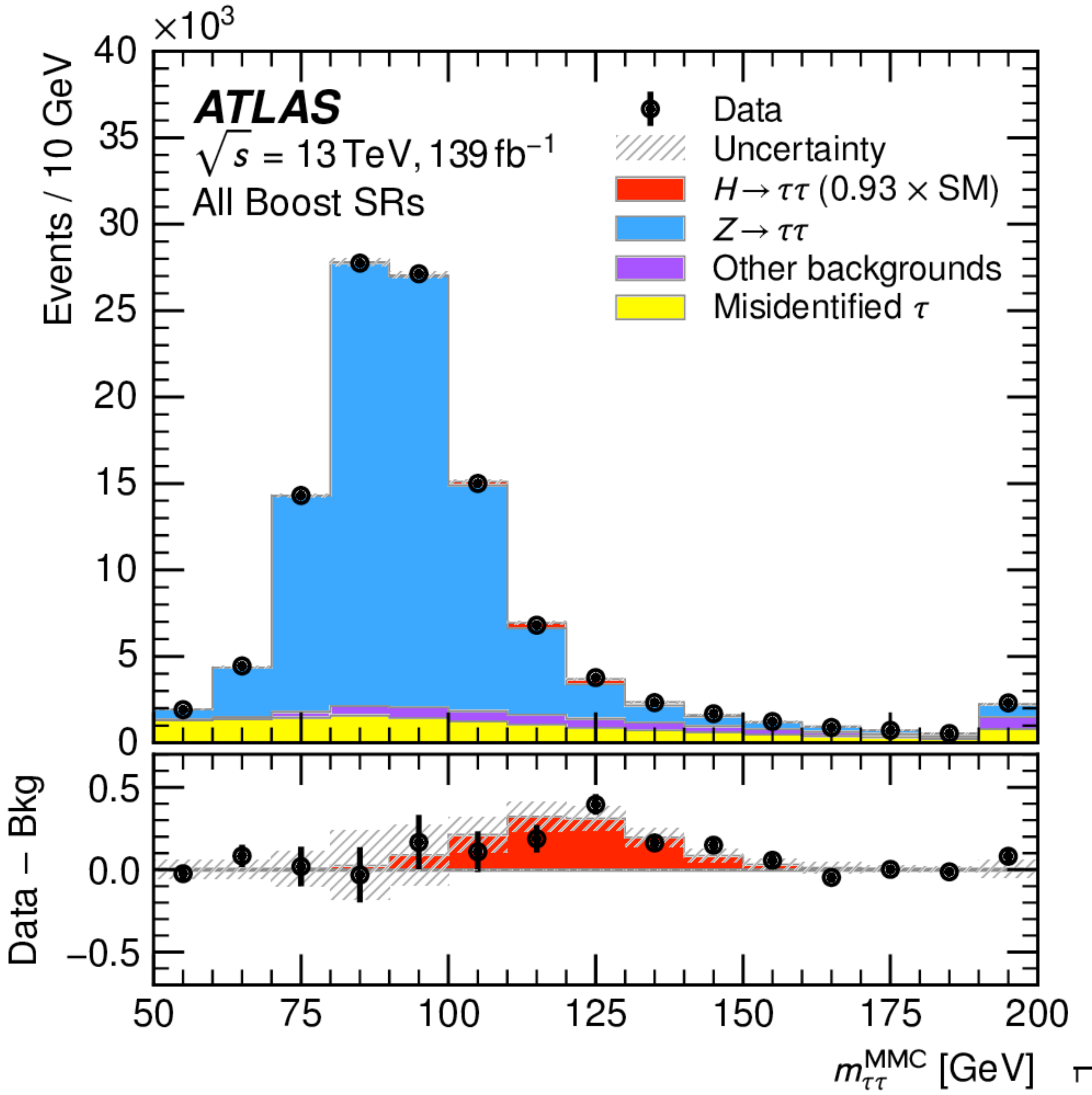
Fits and signal extraction

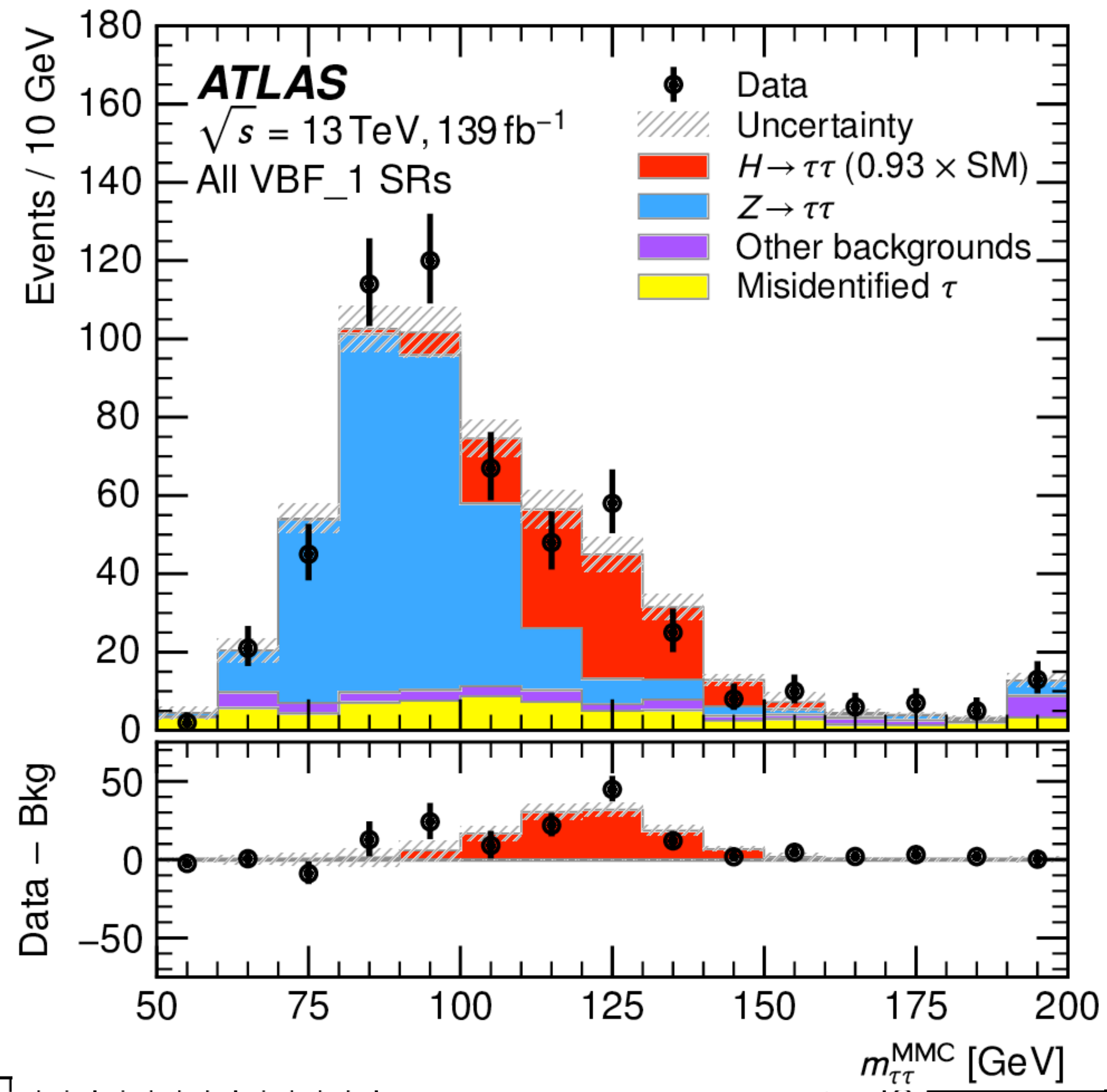
- Binned maximum likelihood fits in **32 signal regions** (10 boosted, VBF, VH bins x 3 decay modes + 2 ttH bins) + 6 top CRs ($\tau_\ell \tau_h$, $\tau_e \tau_\mu$) and 30 $Z \to \ell\ell$ regions to derive simplified embedding and $Z \to \tau\tau$ normalisation

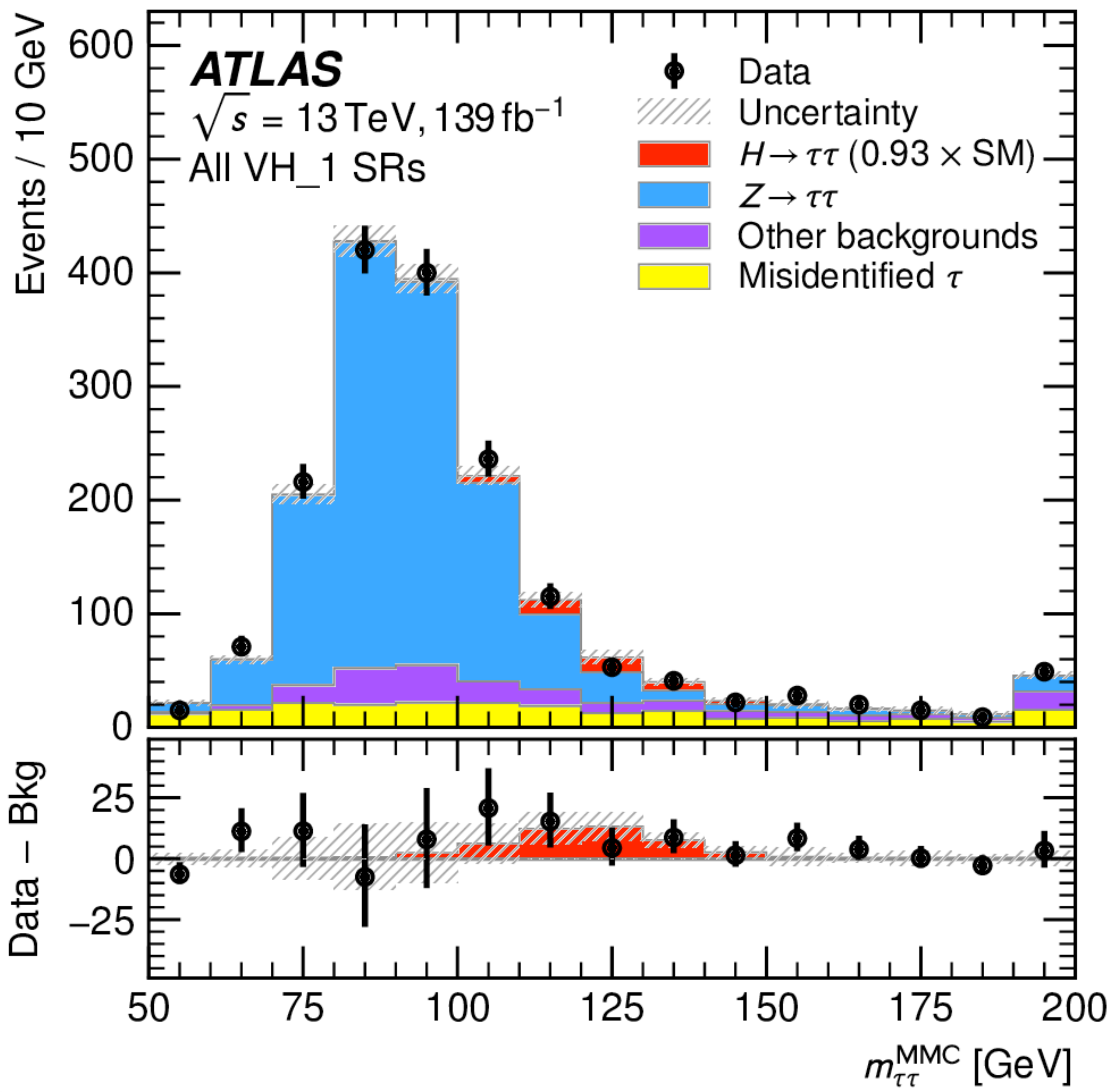
- Measure correlated signal combined over all regions (1 POI), per Higgs production mode (4 POIs), per STXS bin (9 POIs: VBF, VH, ttH + 6 boosted bins)

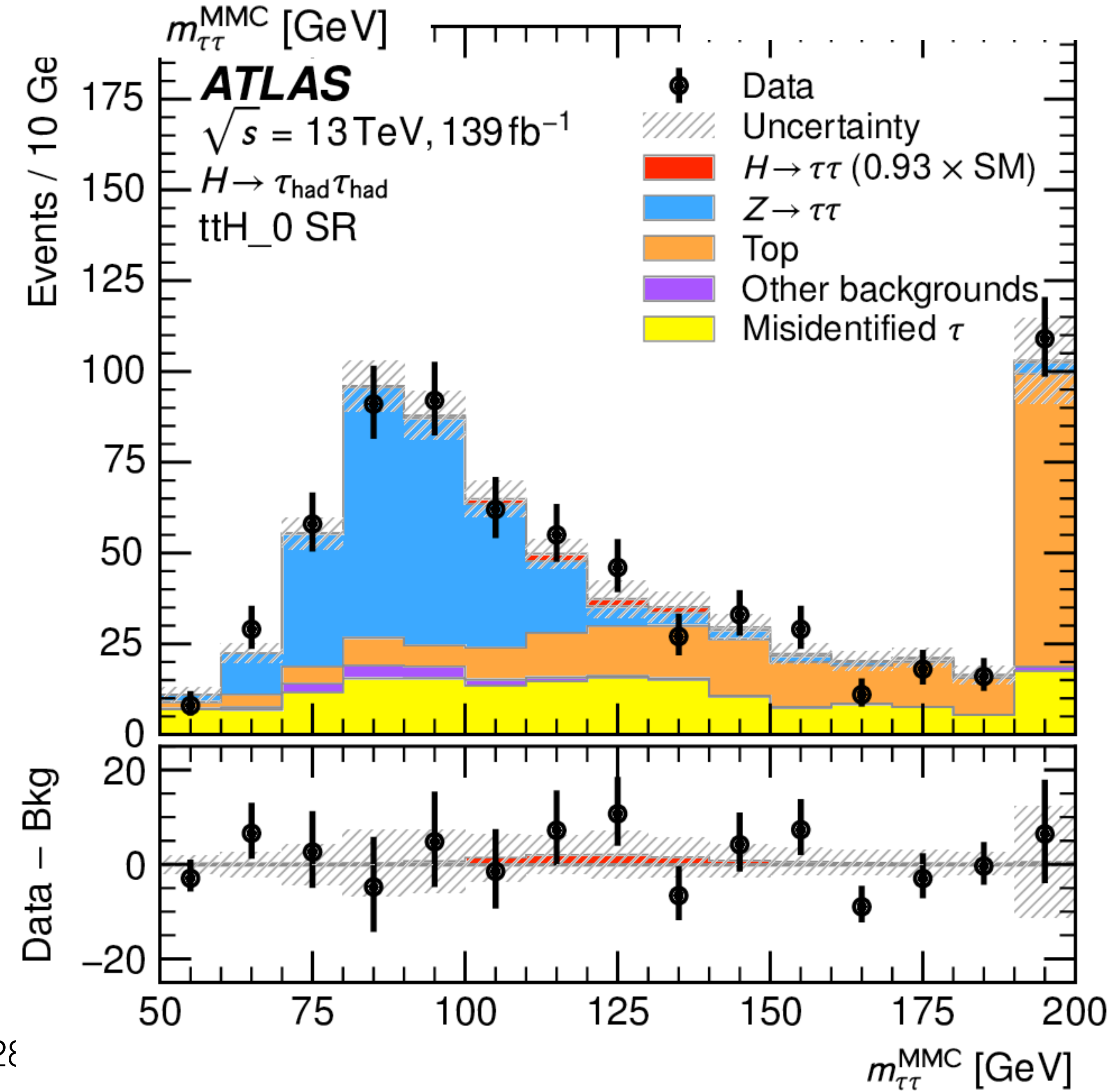


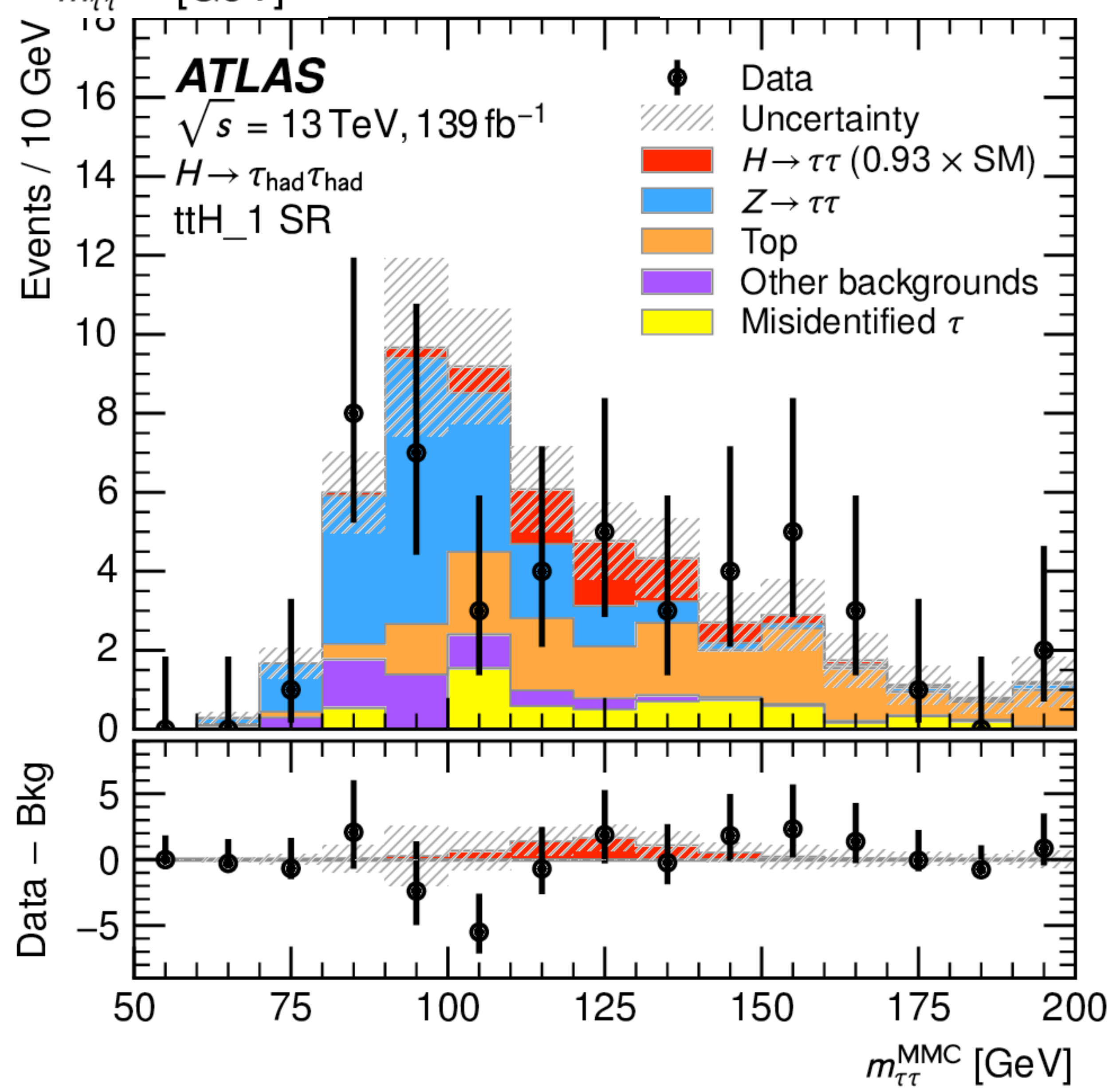
Post fit distributions



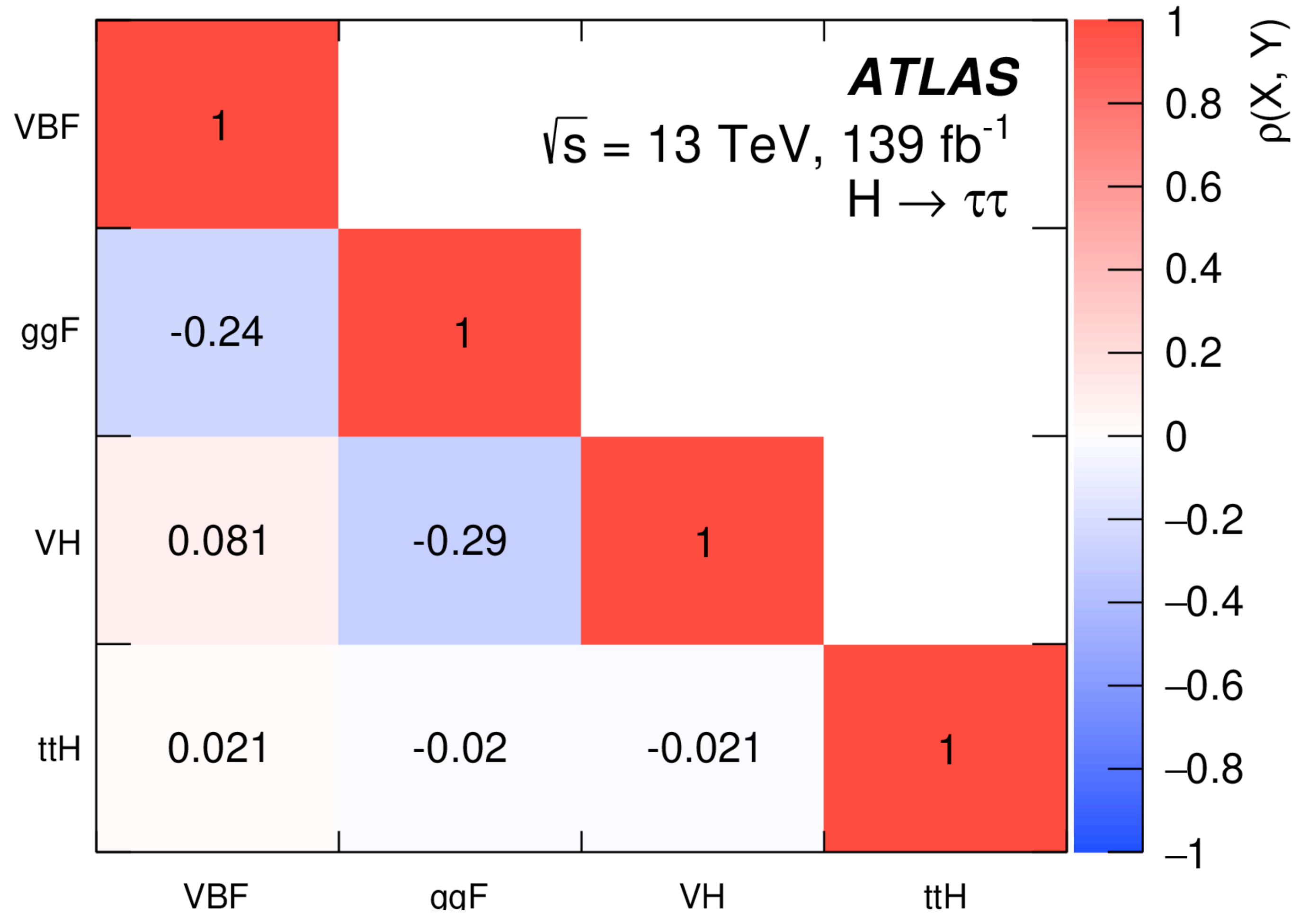




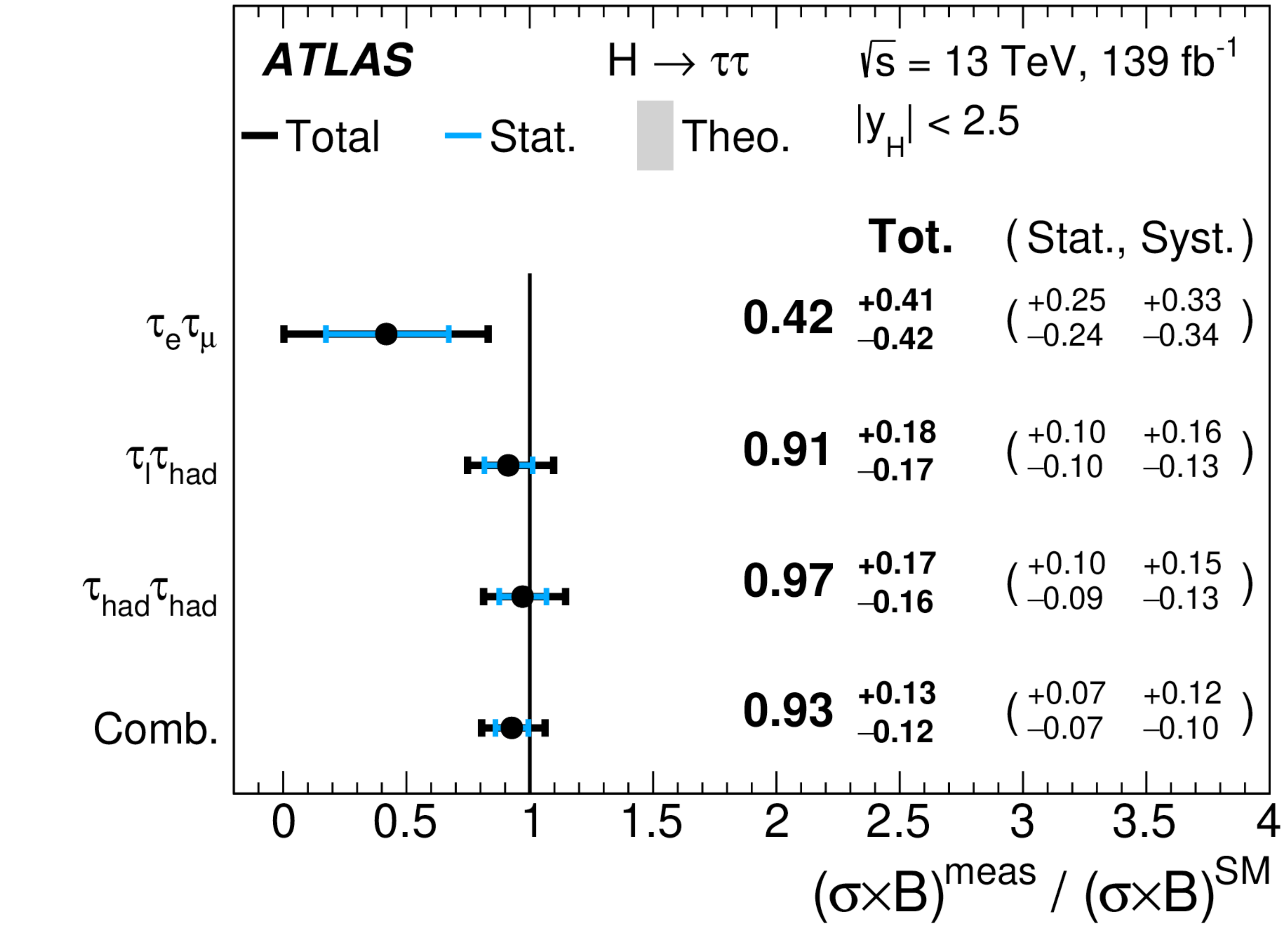


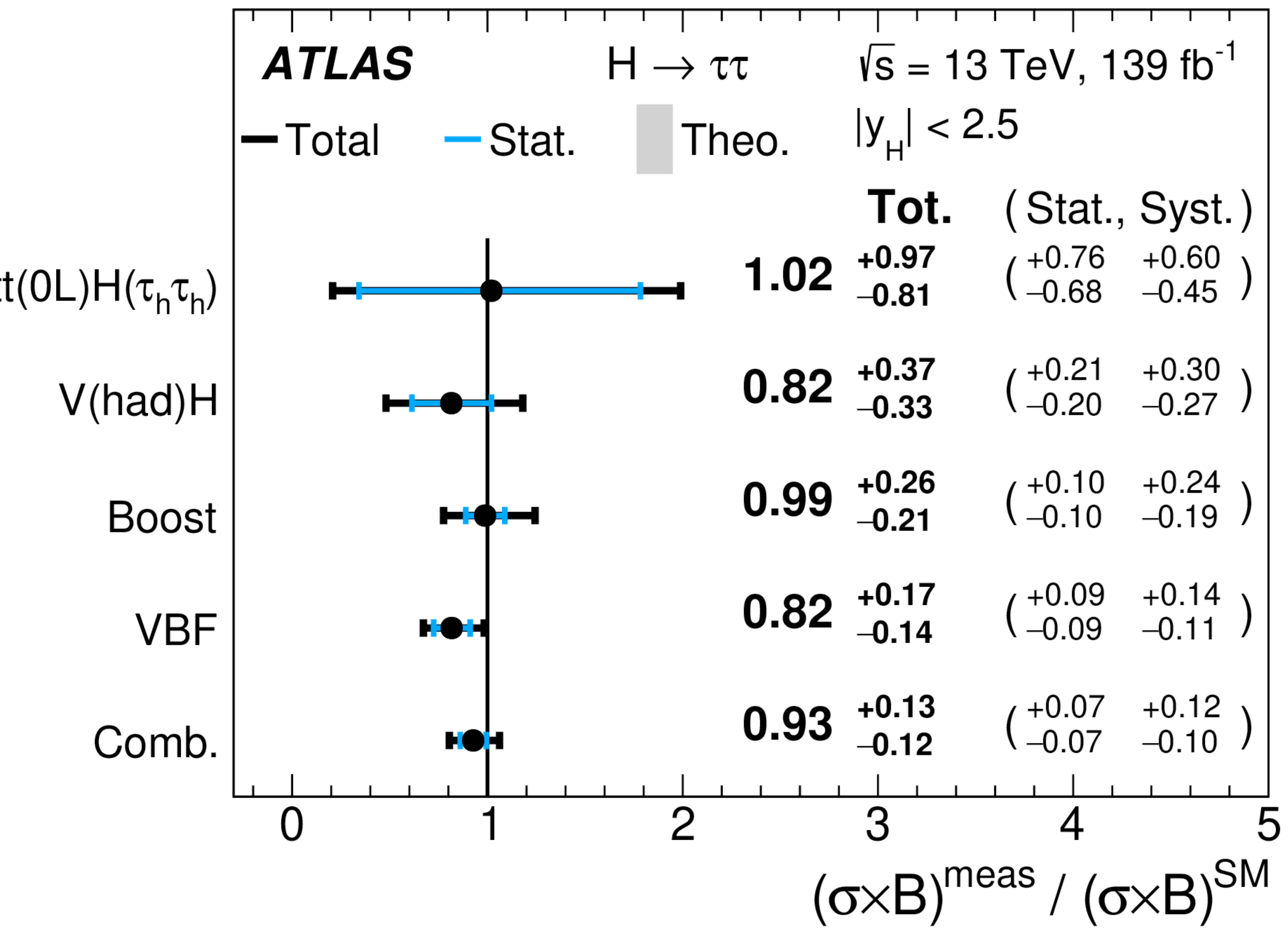


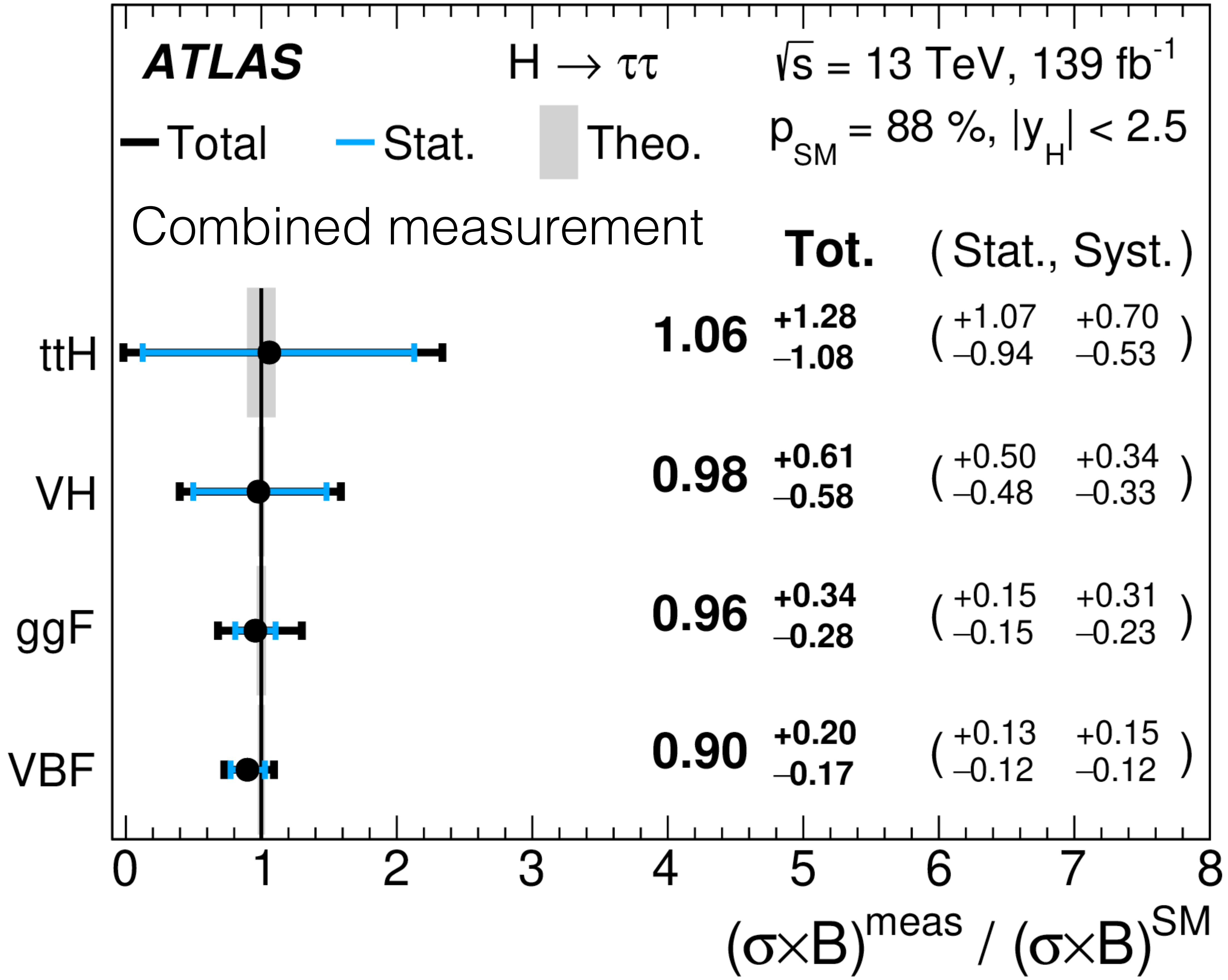
Fit results



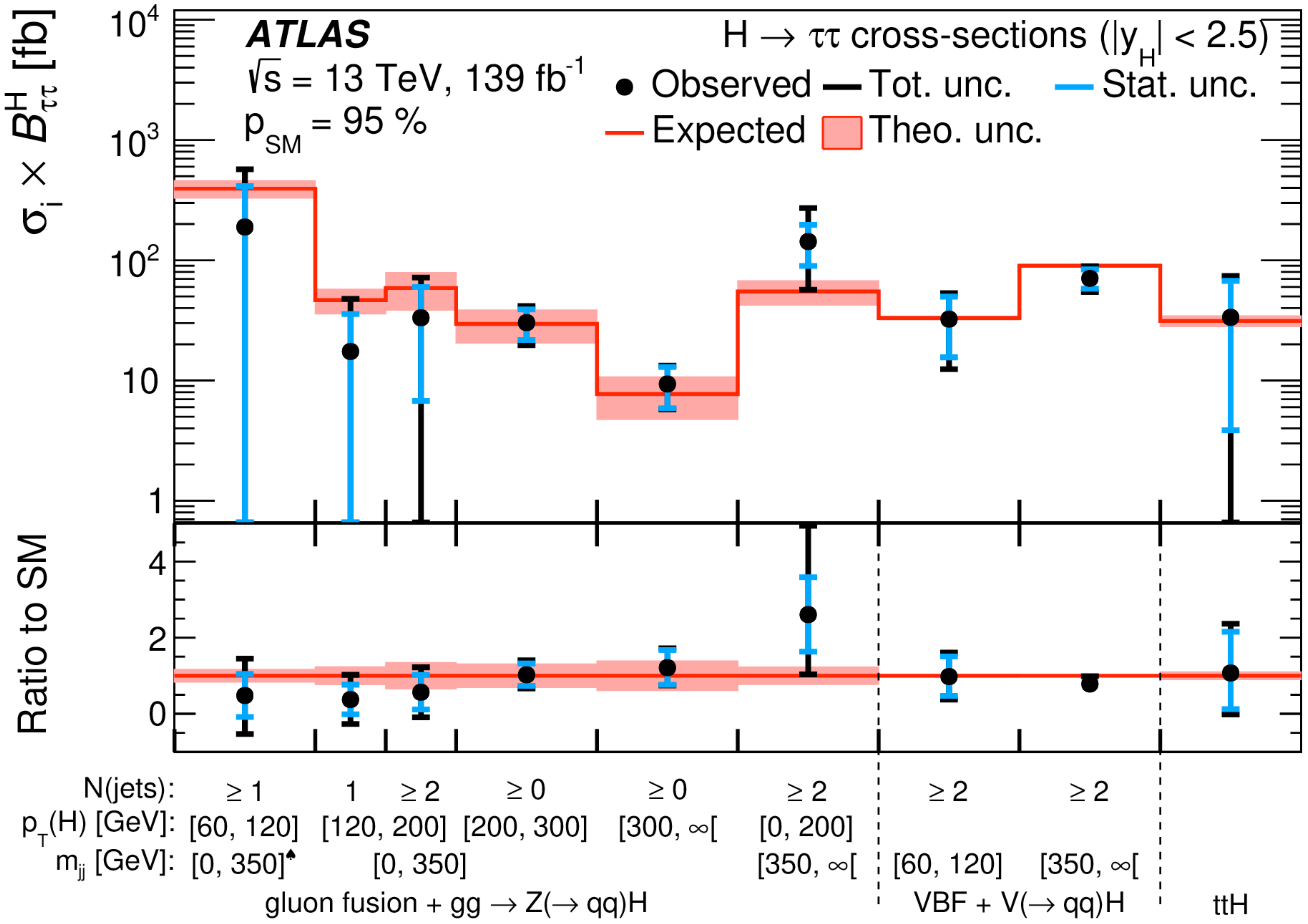
Exclusive measurements

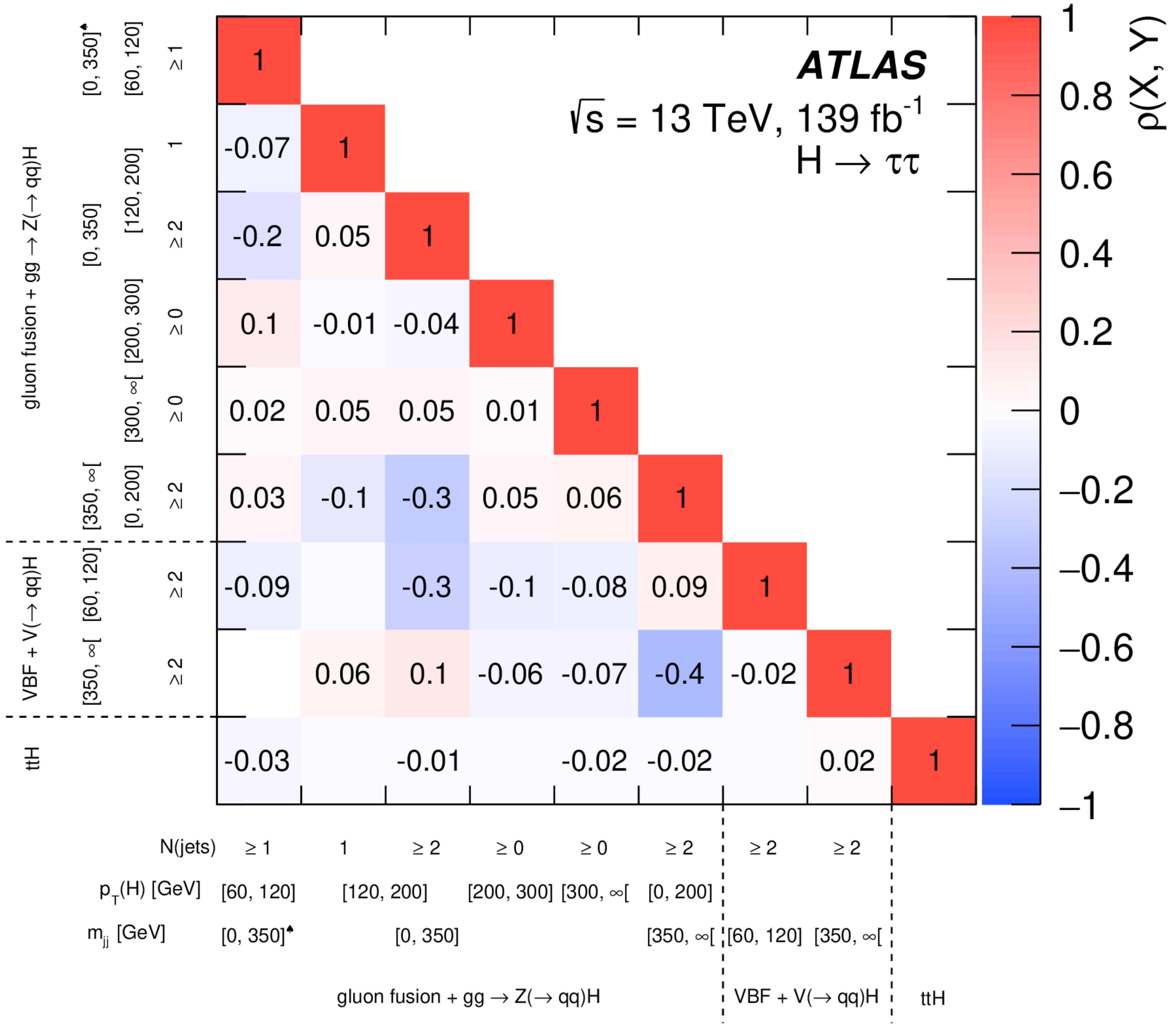






STXS fit results





Systematic uncertainties

Source of uncertainty	Impact on $\Delta\sigma / \sigma(pp \to H \to \tau\tau)$ [%] Observed	Expected
Theoretical uncertainty in signal	8.7	8.5
Jet and $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$	4.5	4.2
Background sample size	4.0	3.7
Hadronic τ decays	2.1	2.1
Misidentified τ	2.0	2.0
Luminosity	1.8	1.8
Theoretical uncertainty in Z + jets processes	1.7	1.2
Theoretical uncertainty in top processes	1.1	1.1
Flavour tagging	0.4	0.5
Electrons and muons	0.4	0.4
Total systematic uncertainty	12.0	11.4
Data sample size	7.2	6.7
Total	13.9	13.2

Summary and Outlook

- Measurement of $\sigma \times BR_{H\rightarrow\tau\tau}$ in 9 STXS bins using full Run 2 data
- First look at ttH with $H \rightarrow \tau_h\tau_h$, complementary to ttH multi-lepton analysis (Phys. Rev. D 97 (2018) 072003)
- Significant improvement over previous result (Phys. Rev. D 99 (2019) 072001): more data, improved tau ID and improved signal categorisation (especially VBF BDT)
- Still room for improvement: improved event reconstruction, better understanding of systematics, more STXS bins
- Looking forward to doubled statistics from Run 3 starting later this year!