State of the art Standard Model Higgs boson measurements

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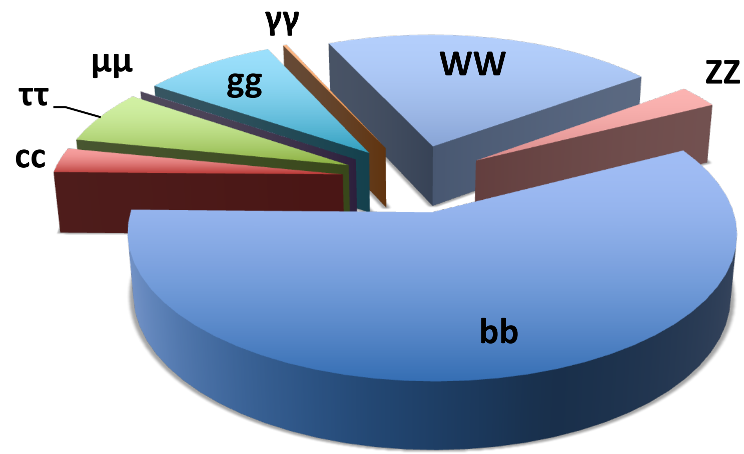
On behalf of the ATLAS and CMS Collaborations

Introduction

- Overview
  - Higgs over the past 10 years
  - Measurements
  - Overview
- Higgs measurements
  - H→bb
  - H→WW
  - H→ττ
  - H→γγ
  - Combinations
  - Higgs width
- Summary

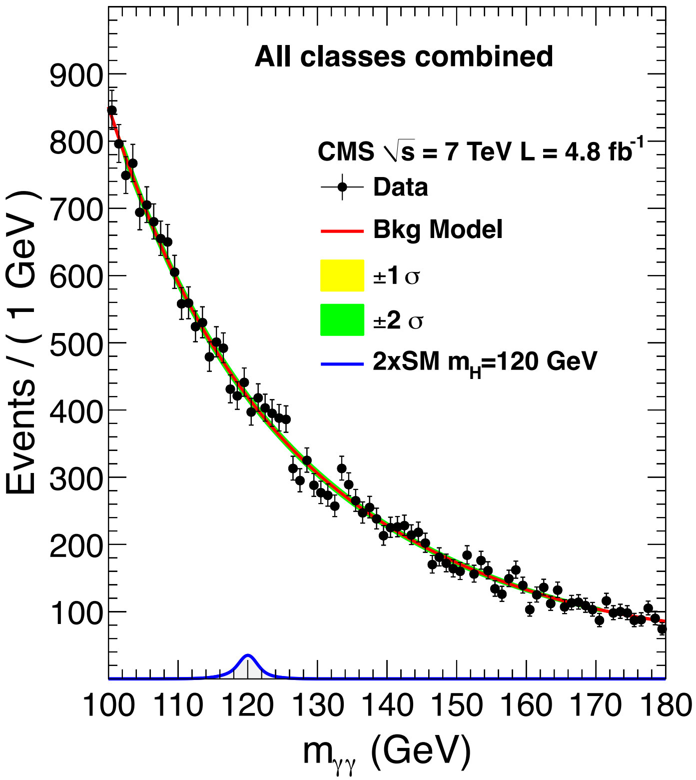


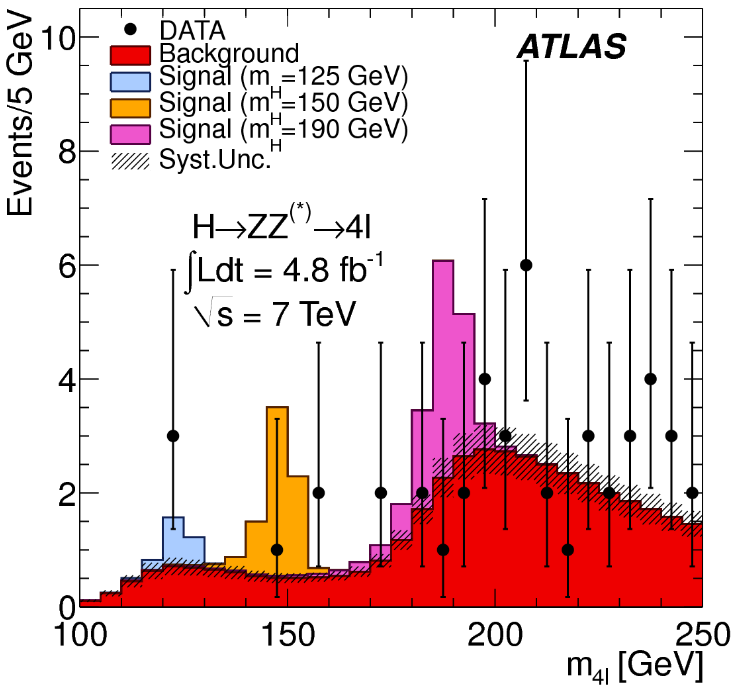
Higgs branching Ratios

CMS: arXiv:1202.1487
ATLAS: arXiv:1202.1415

Just over 10 years ago…

- There was some excitement about a smattering of events



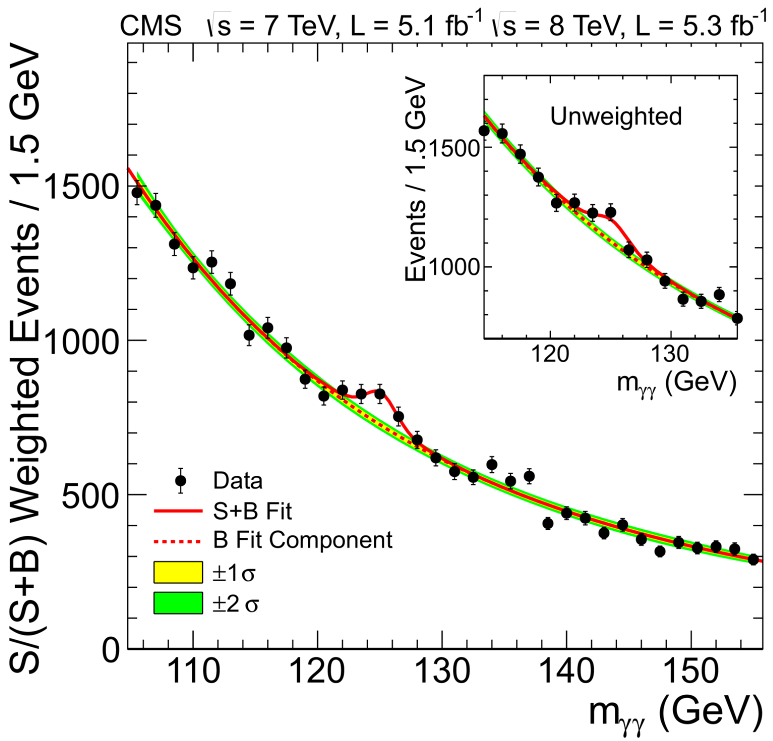


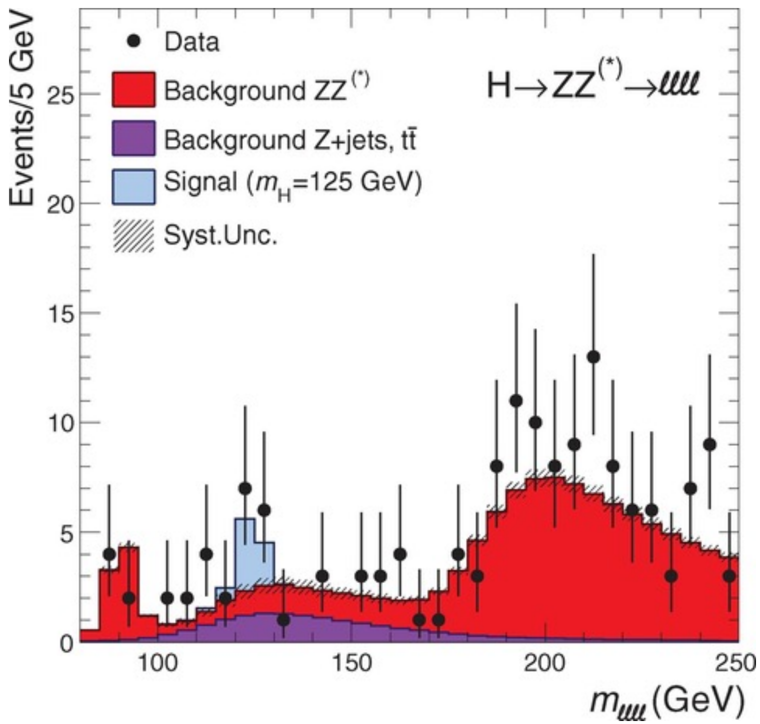
"More data are required to ascertain the origin of this excess."

"Once the look-elsewhere effect is considered, none of these excesses are significant."

[CMS arXiv:1207.7235](#)
[ATLAS arXiv:1207.7214](#)

…the discovery…





"An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle.

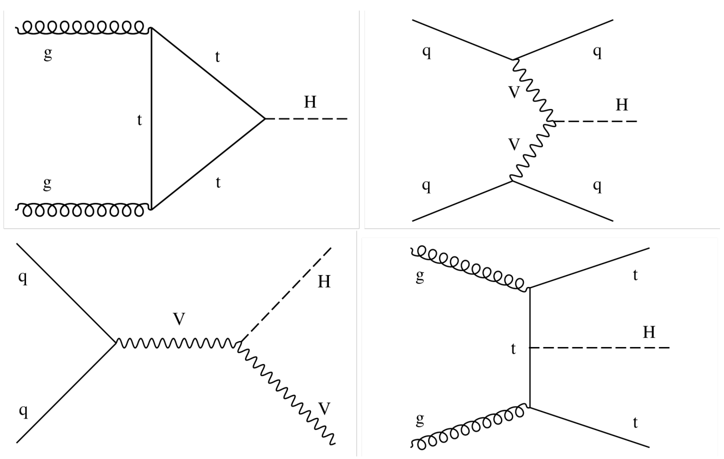
"Clear evidence for the production of a neutral boson with a measured mass of 126.0 +/- 0.4(stat) +/- 0.4(sys) GeV is presented."

...approximately 10 years (and 15M Higgs bosons) later

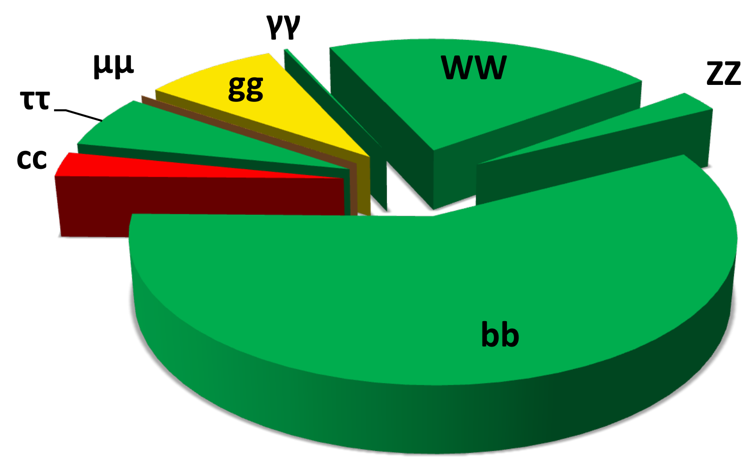
- A lot of amazing progress....

All main production modes observed to > 5 sigma

ggH VBF



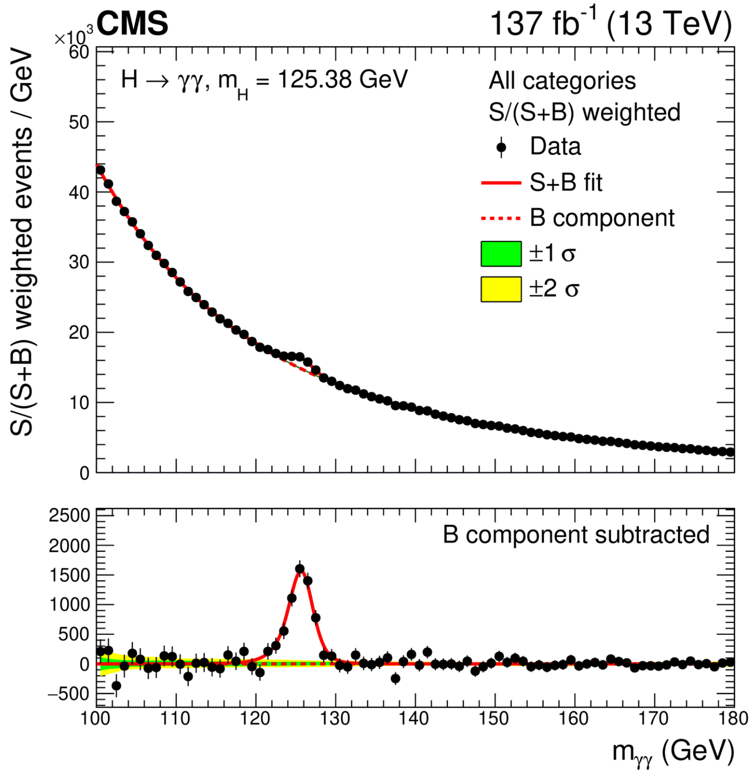
VH (V=W,Z) ttH

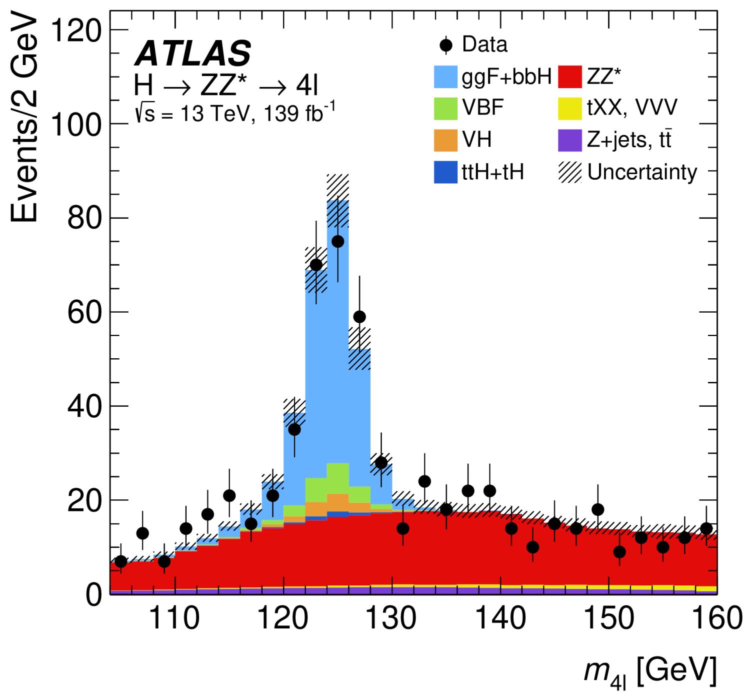


γγ, WW, ZZ, ττ, bb decays **observed** > 5σ
μμ decay **evidence** > 3σ

New era for Higgs physics

- Moving from the era of discovery to measurement

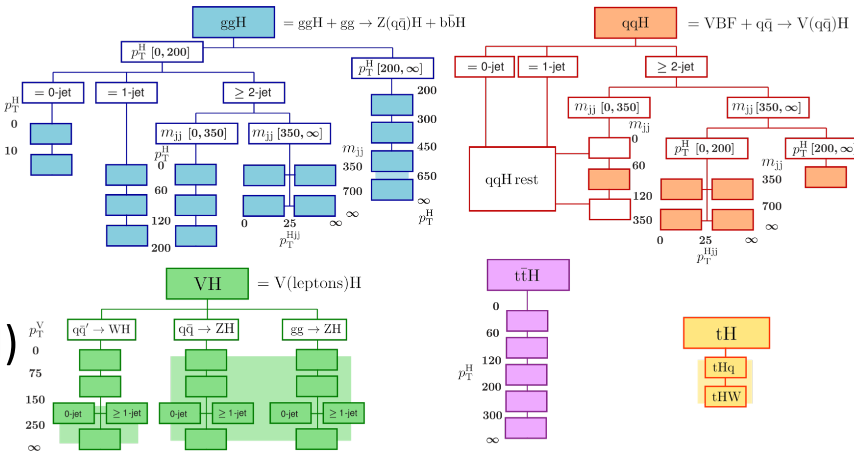




Measurements

- Inclusive (although also used broken down into production/decay modes)
  - Signal strength: μ = measurement/SM prediction
  - Coupling strength modifier: κ_X = alter strength(s) of coupling to X

- Simplified Template Cross Section (STXS)
  - Measure cross-sections in template bins
    - Minimise theoretical uncertainties
    - Maximise experimental sensitivity
    - Enhanced sensitivity beyond SM (BSM)



- Fiducial
  - Measure in restricted phase space that closely matches experimental selection
    - Less model dependence
    - Combinations more difficult
    - Difficult for complicated variables (multivariate outputs)
  - Differential: Measure in several bins

State-of-the-art

Channel	STXS	Fiducial
H→bb	ATLAS: ATLAS-CONF-2021-051 (09/21)	ATLAS: ATLAS-CONF-2022-015 (03/22) CMS: arXiv:2006.13251 (06/20)
H→WW	ATLAS: ATLAS-CONF-2021-014 (03/21) CMS: CMS-HIG-PAS-20-013 (03/22)	CMS: arXiv:2007.01984 (04/20)
H→ZZ	ATLAS: arXiv:2004.03447 (04/20) CMS: arXiv:2103.04956 (03/21)	ATLAS: arXiv:2004.03969 (04/20) CMS: arXiv:2103.04956 (03/21)
H→ττ	ATLAS: arXiv:2201.08269 (01/22) CMS: CMS-PAS-HIG-19-010 (07/20)	CMS: arXiv:2107.11486 (07/21)
H→yy	ATLAS: ATLAS-CONF-2020-026 (07/20) CMS: arXiv:2103.06956 (03/21)	ATLAS: arXiv:2202.00487 (02/22) CMS: CMS-PAS-HIG-19-016 (03/22)
Combinations	ATLAS: ATLAS-CONF-2021-053 (09/21) CMS: CMS-PAS-HIG-19-005 (01/20)	ATLAS: ATLAS-CONF-2022-002 (01/22)

Channel	State-of-the-art limits
H→cc	ATLAS: arXiv:2201.11428 (01/22), CMS: CMS-PAS-HIG-21-008 (02/22)

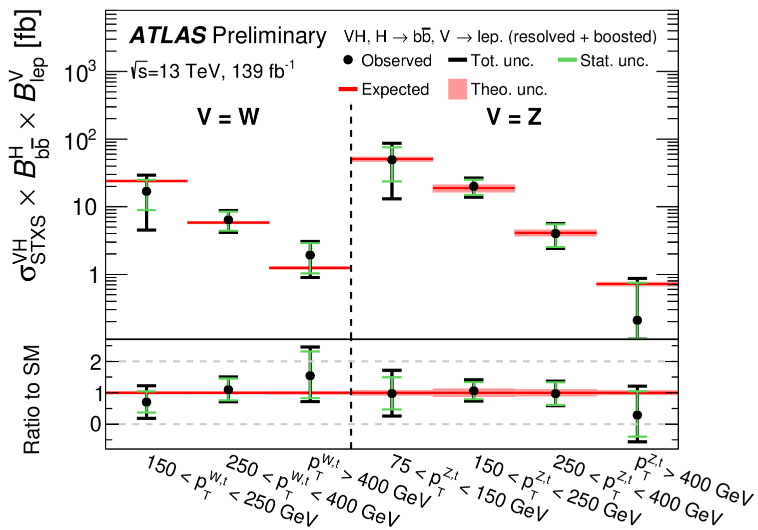
Property	State-of-the-art measurements
Mass	ATLAS: ATLAS-CONF-2020-005 (04/20), CMS: arXiv:2002.06398 (02/20)
Width	ATLAS: arXiv:1808.01191 (08/18), CMS: arXiv:2202.06923 (02/22)
CP	ATLAS: arXiv:2109.13808, arXiv:2004.04545 CMS: arXiv:2110.04836, arXiv:2003.10866

Newer results in **RED** discussed today
See talks on Thursday for latest H->cc and CP results

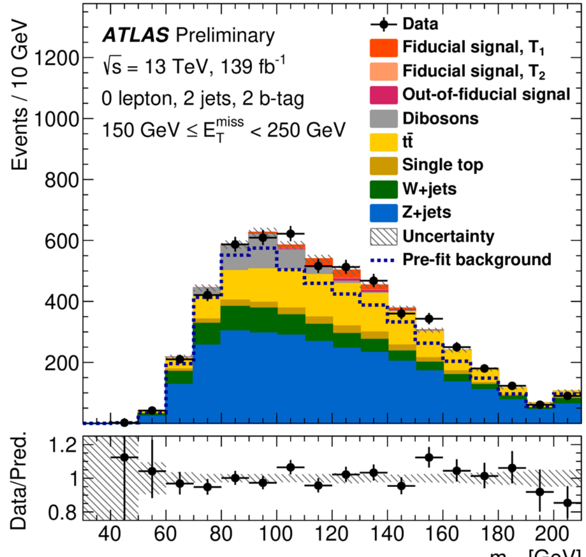
ATLAS-CONF-2021-051
ATLAS-CONF-2022-006

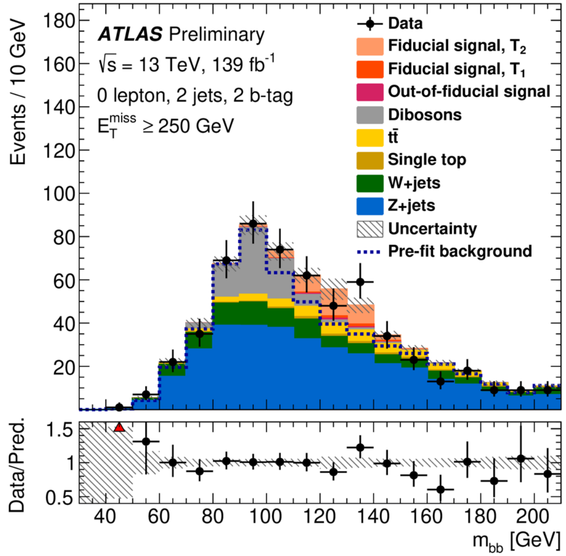
H→bb

- Two VH, H→bb results combined in new STXS measurement
  - Resolved: arXiv:2007.02873
  - Boosted: arXiv:2008.02508
  - Enhanced sensitivity to BSM



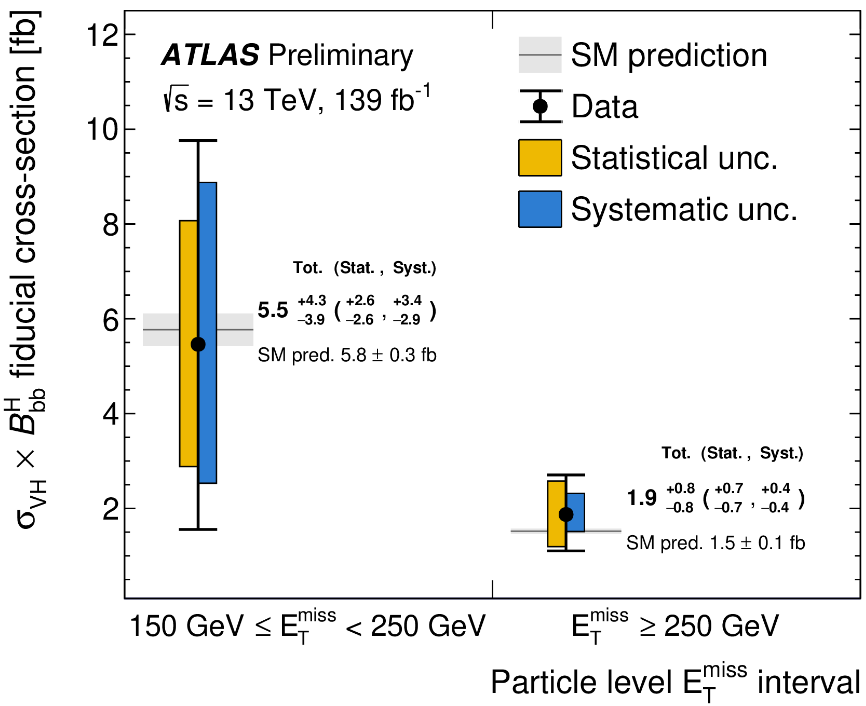
- Fiducial measurements*
  - Based upon resolved VH, H→bb STXS
  - Focuses only on H(bb) + MET final state





* See also X+H->bb measurements, ATLAS arXiv:2111.08340, CMS arXiv:2006.13251

H→bb Fiducial Measurement

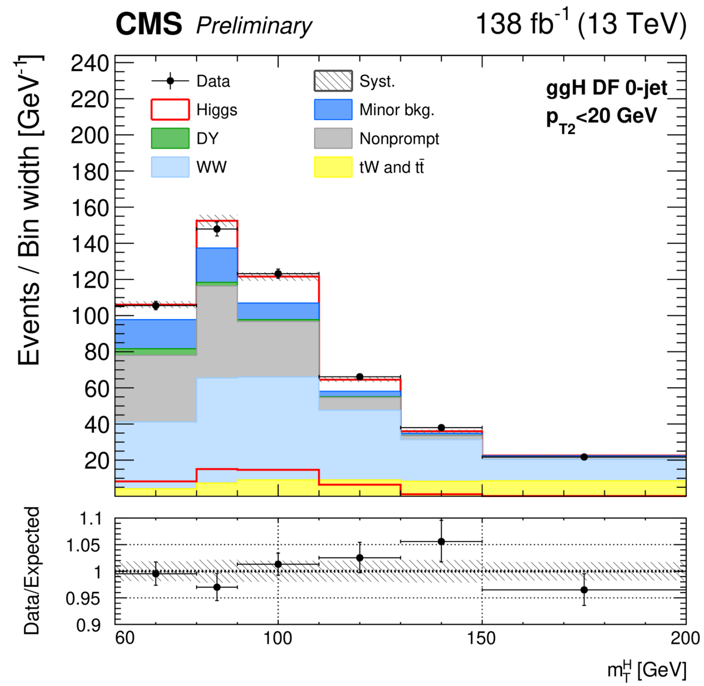


Source of uncertainty	σ_μ T_1	T_2
Total	0.71	0.53
Statistical	0.45	0.46
Systematic	0.55	0.26
Experimental	0.21	0.14
Jets	0.16	0.11
Missing transverse momentum	0.06	0.05
Flavour-tagging: b-jets	0.06	0.06
Flavour-tagging: c-jets	0.06	0.04
Flavour-tagging: light-flavour jets	0.03	0.01
Leptons	0.01	0.04
Pile-up	0.02	0.02
Luminosity	0.02	0.02
Background modelling	0.29	0.14
$t\bar{t}$	0.18	0.06
Dibosons	0.14	0.06
Z + jets	0.13	0.08
W + jets	0.10	0.03
Single top quark	0.07	0.04
Fiducial templates modelling	0.18	0.11
Unfolding uncertainty, T_1	0.17	< 0.01
PS model acceptance	0.01	0.09
Unfolding uncertainty, T_2	< 0.01	0.05
WH/ZH	0.01	0.03
NLO EW	0.01	0.02
QCD scale acceptance, $ggZH$	0.02	0.01
2/3 jets ratio	0.01	0.01
PS model m_{bb} shape	0.01	< 0.01
QCD scale acceptance	0.01	< 0.01
PDF acceptance	< 0.01	< 0.01
MC statistics	0.17	0.11
Floating normalizations	0.14	0.06

Limited by modelling of:
- Data statistical
- Jets
- Background modelling
- Unfolding uncertainty

H→WW

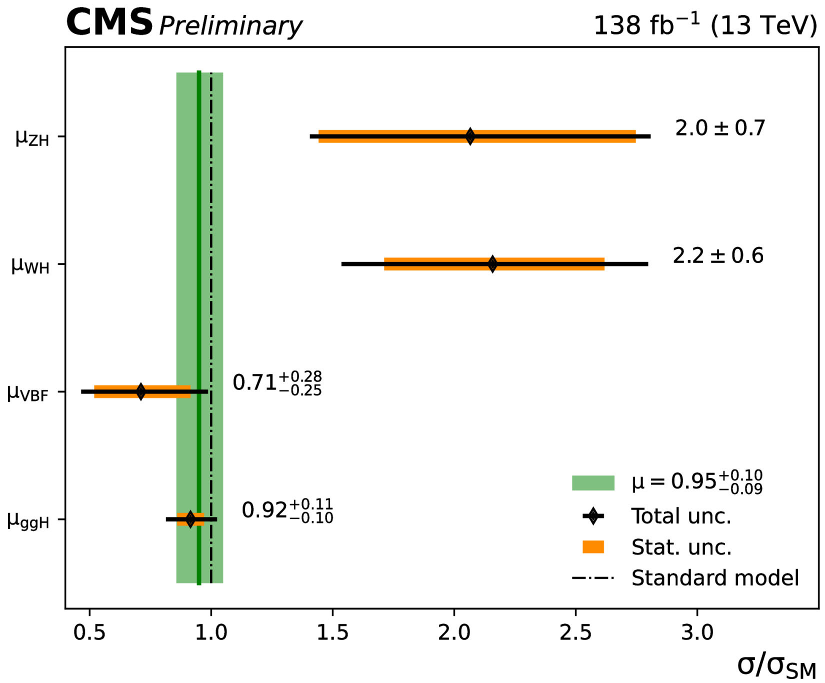
- Targets ggH, VBF, VH production modes
- Final states with at least two leptons
- Measurements
  - Combined cross section
    - μ=0.95 +0.10 -0.09
  - Production mode cross sections
  - 14 STXS bins

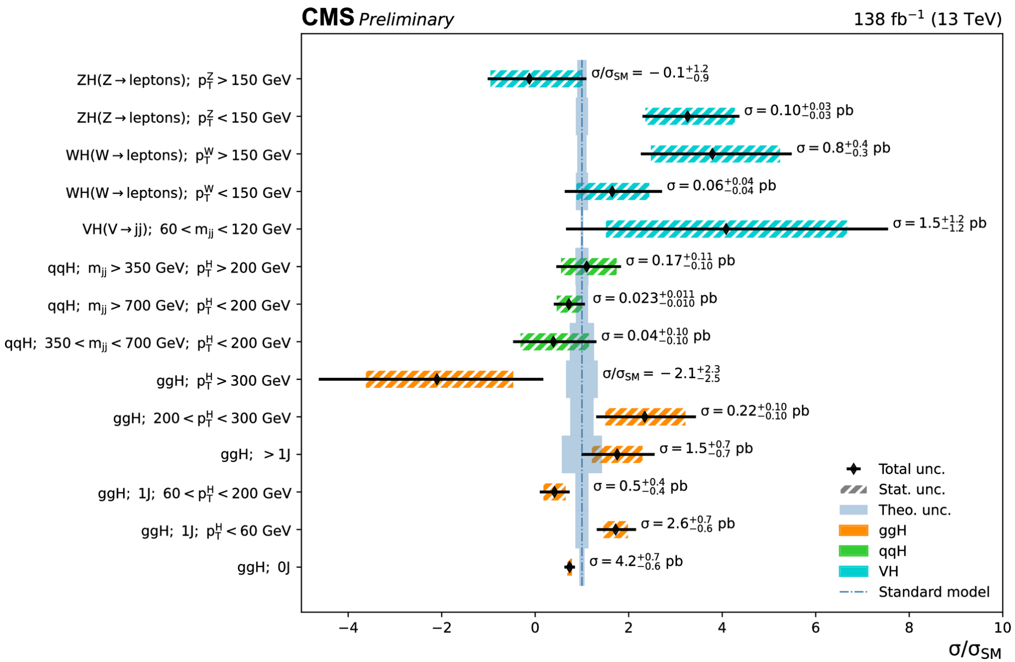


Category	Number of leptons	Number of jets	Sub-categorization
ggH	2	-	(DF, SF) × (0 jets, 1 jet, ≥ 2 jets)
VBF	2	≥ 2	(DF, SF)
VH2j	2	≥ 2	(DF, SF)
WHSS	2	≥ 1	(DF, SF) × (0 jets, 1 jet)
WH3ℓ	3	0	SF lepton pair with opposite or same sign
ZH3ℓ	3	≥ 1	(1 jet, 2 jets)
ZH4ℓ	4	-	(DF, SF)

NEW

H→WW



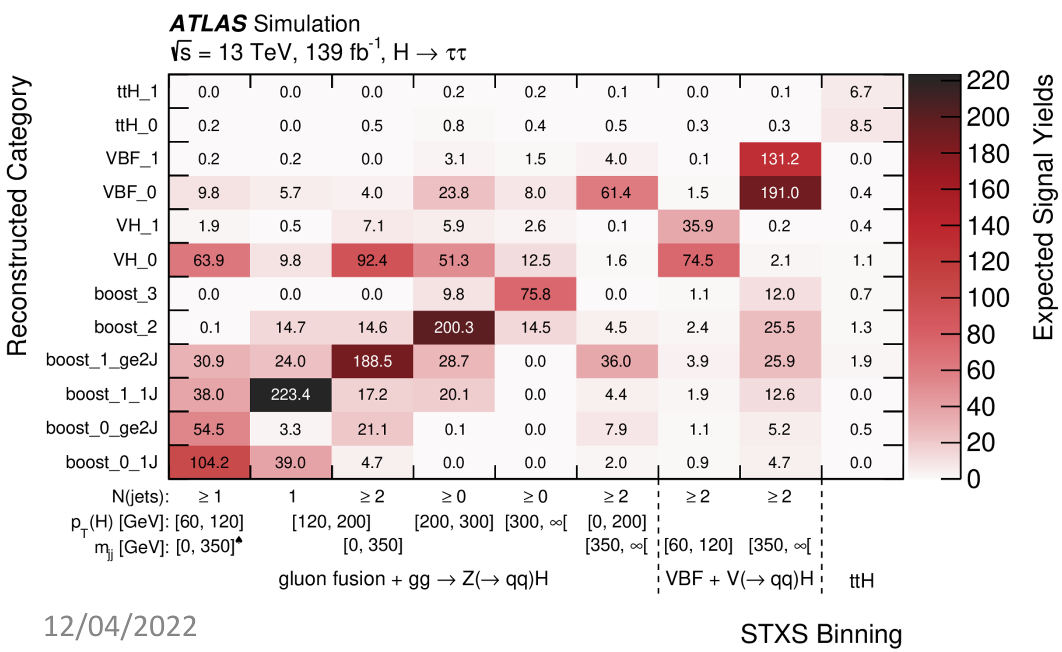


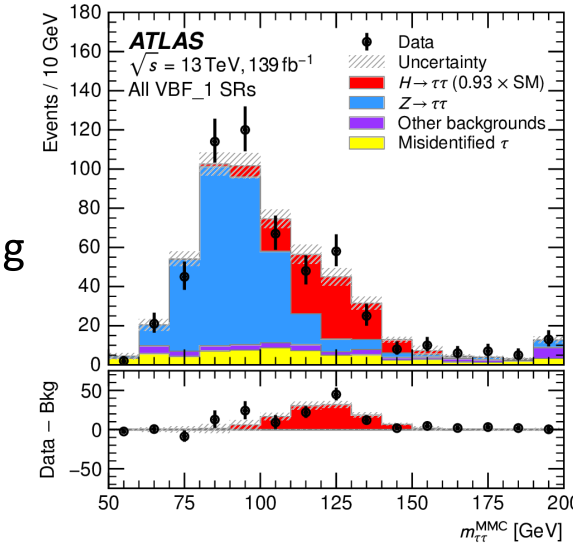
Uncertainty source	$\Delta\mu/\mu$	$\Delta\mu_{ggH}/\mu_{ggH}$	$\Delta\mu_{qqH}/\mu_{qqH}$	$\Delta\mu_{WH}/\mu_{WH}$	$\Delta\mu_{ZH}/\mu_{ZH}$
Theory (signal)	4%	5%	13%	2%	< 1%
Theory (background)	3%	3%	2%	4%	5%
Fake lepton rate	2%	2%	9%	15%	4%
Integrated luminosity	2%	2%	2%	2%	3%
B-tagging	2%	2%	3%	< 1%	2%
Lepton efficiency	3%	4%	2%	1%	4%
Jet energy scale	1%	< 1%	2%	< 1%	3%
Jet energy resolution	< 1%	1%	< 1%	< 1%	3%
p_T^{miss} scale	< 1%	1%	< 1%	2%	2%
PDF	1%	2%	< 1%	< 1%	2%
Parton shower	< 1%	2%	< 1%	1%	1%
Backg. norm.	3%	4%	6%	4%	6%
Stat. uncertainty	5%	6%	28%	21%	31%
Syst. uncertainty	9%	10%	23%	19%	11%
Total uncertainty	10%	11%	36%	29%	33%

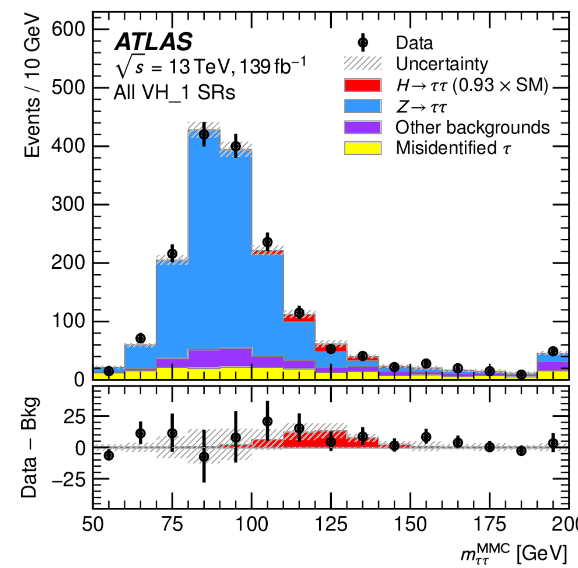
Limited by:
- Data statistical
- Signal uncertainties
- Lepton modelling

H→ττ

- Full Run 2 dataset STXS measurements
  - Targets ggH, VBF, VH, ttH production modes
  - Leptonic and hadronic τ final states
  - 12 reconstruction categories designed for STXS binning
- Measure
  - Inclusive and production mode cross sections
  - STXS cross section measurements in 9 bins

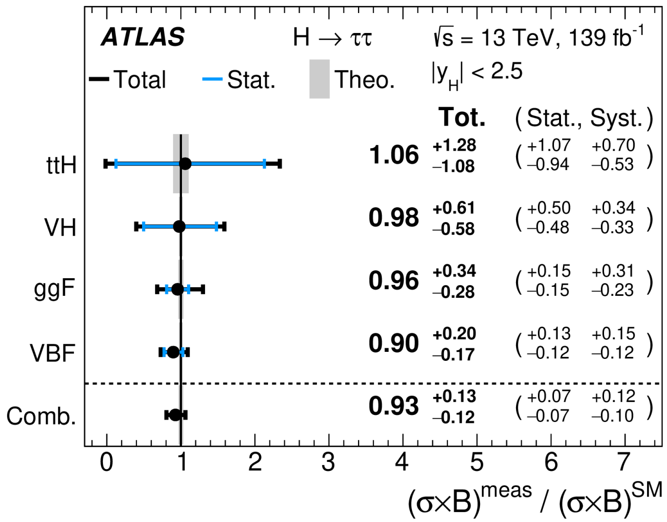






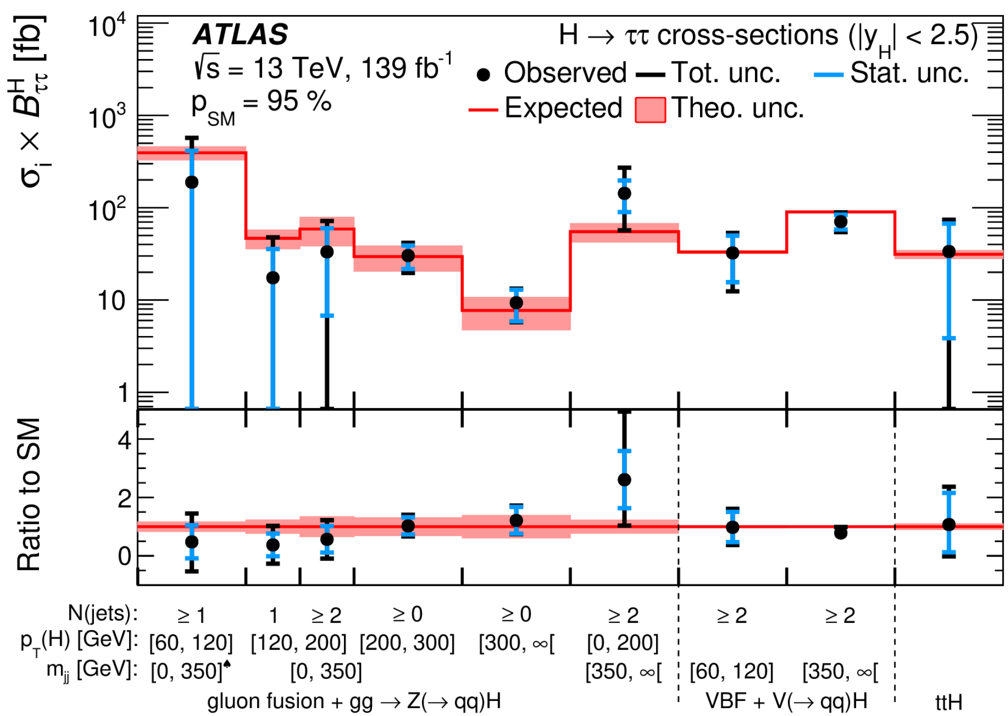
H→ττ

ATLAS arXiv2201.08269



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 E_T^{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

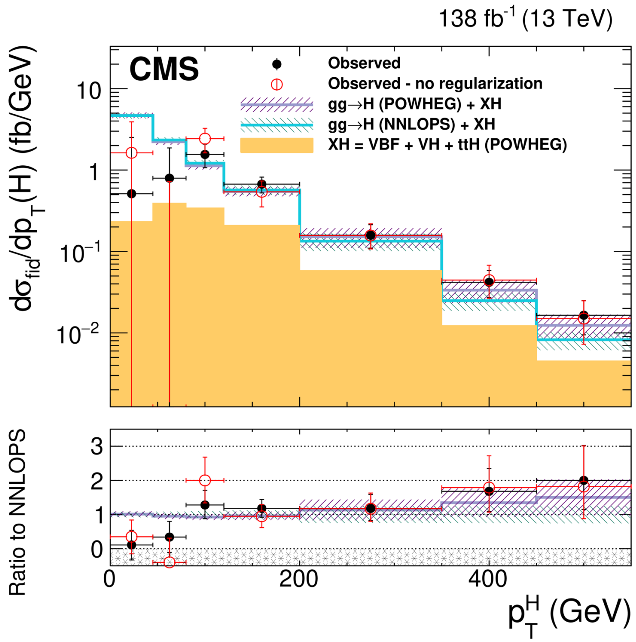
Limited by
- Data statistical
- Signal uncertainties
- Jet and missing transverse energy modelling
- Background sample size

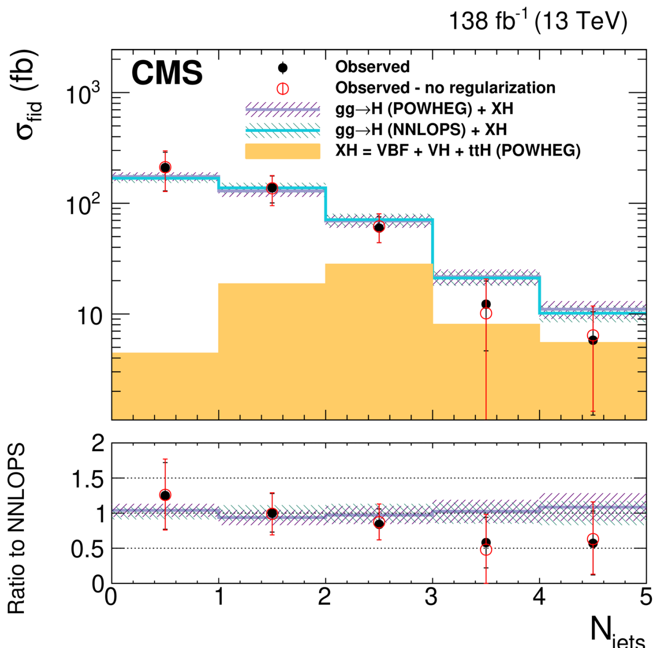


CMS arXiv:2107.11486

H→ττ

- Full Run 2 dataset results:
  - ➢ Fiducial inclusive cross section
    - 426±102 fb (expected 408 ± 27 fb)
  - ➢ Differential fiducial cross-sections
    - Number of jets, Higgs p_T and leading jet p_T

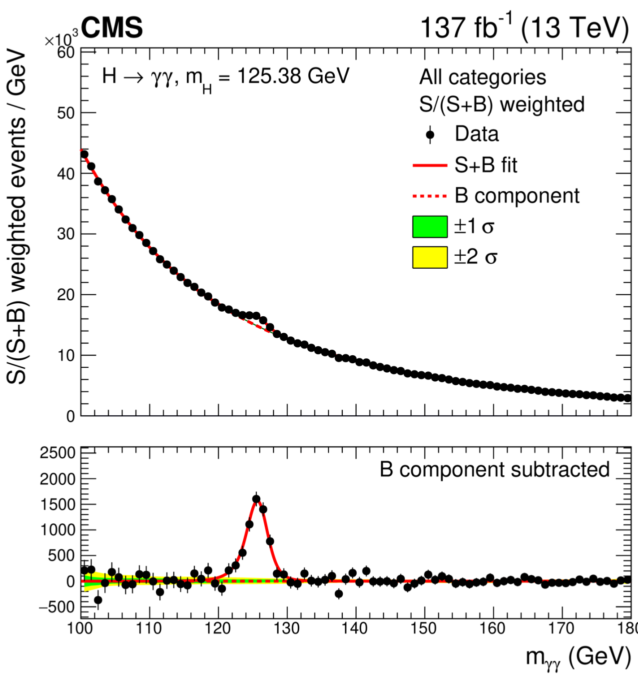


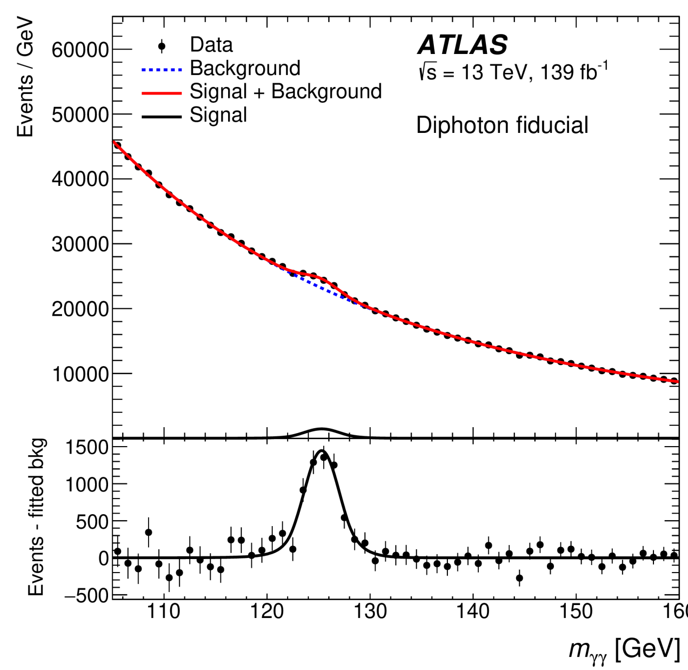


Limited by
- Data statistical
- Signal uncertainties
- Background modelling

$H \rightarrow \gamma\gamma$

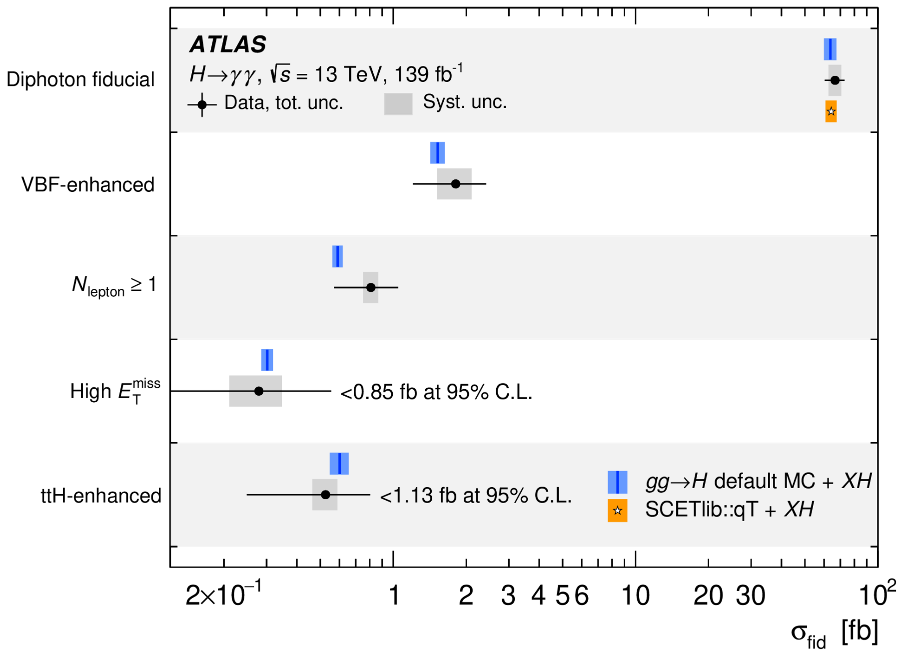
- Updated measurements with full Run 2 dataset
  - Both CMS and ATLAS provided fiducial cross-sections measurements:
    - Inclusive and differential
    - Targeting several production modes
    - As a function of multiple variables
    - Double differential measurements



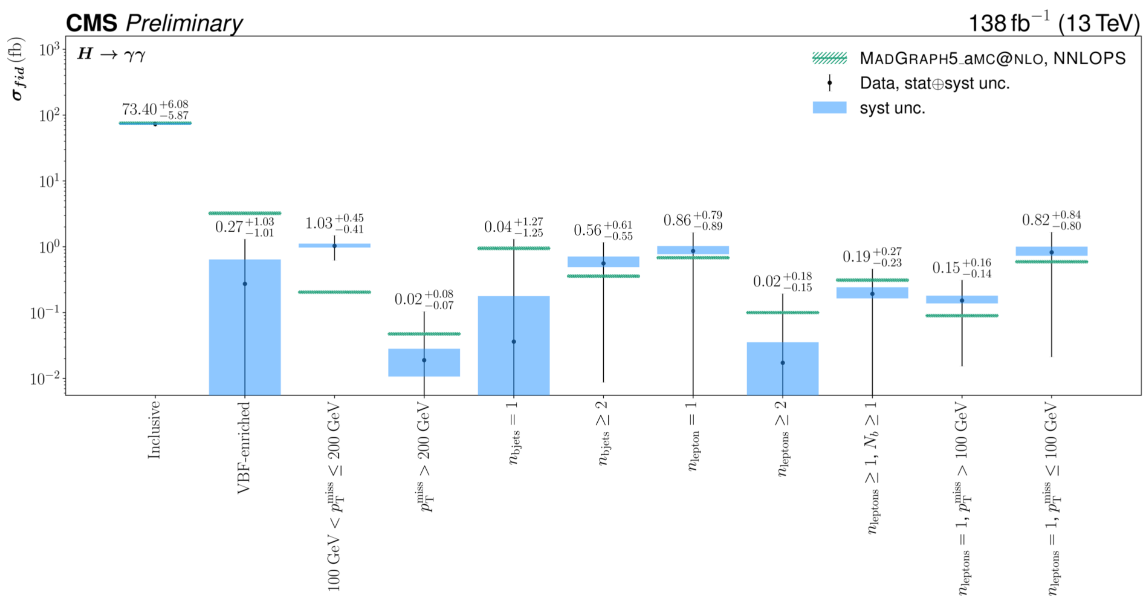


ATLAS arXiv:2202.00487
CMS-PAS-HIG-19-016

H→γγ



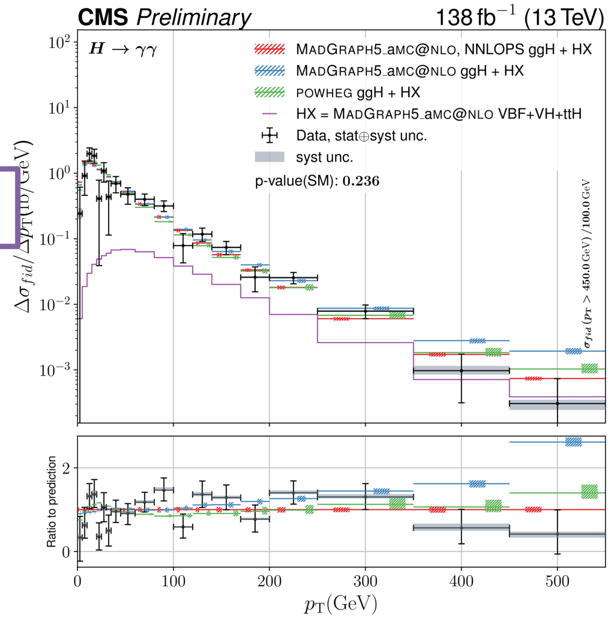
Both measurements primarily limited by data statistical uncertainty

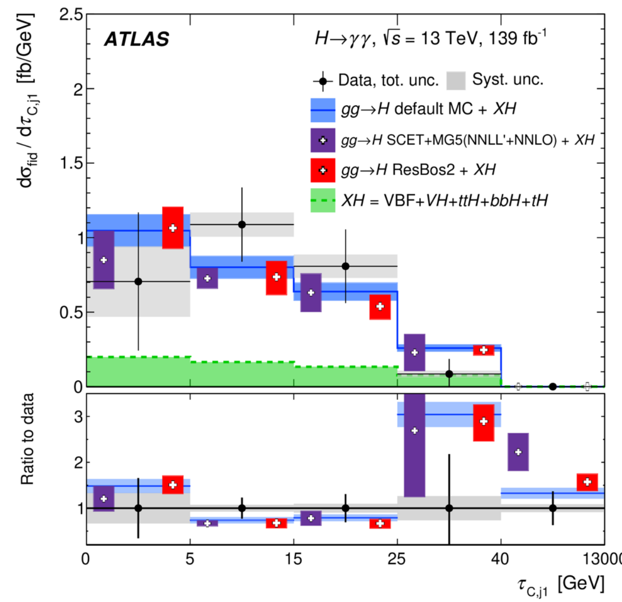


ATLAS arXiv:2202.00487
CMS-PAS-HIG-19-016

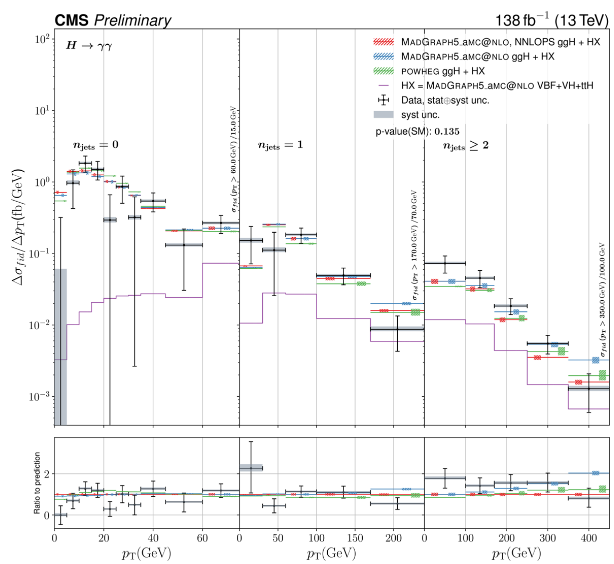
H→γγ

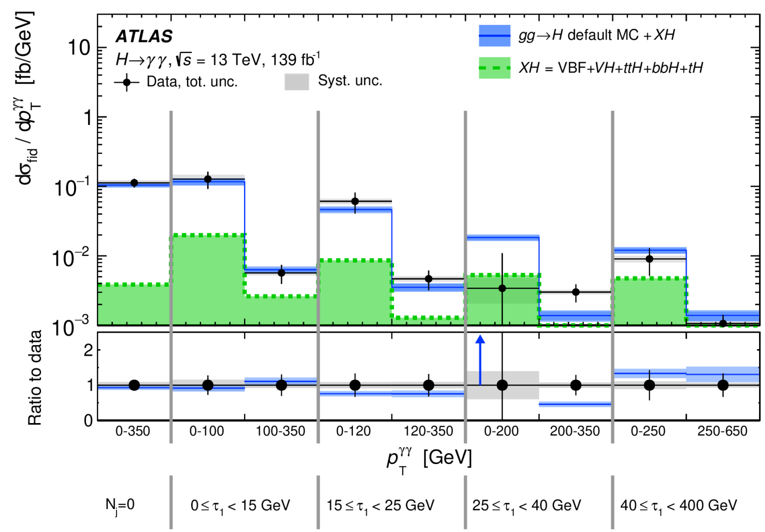
Differential





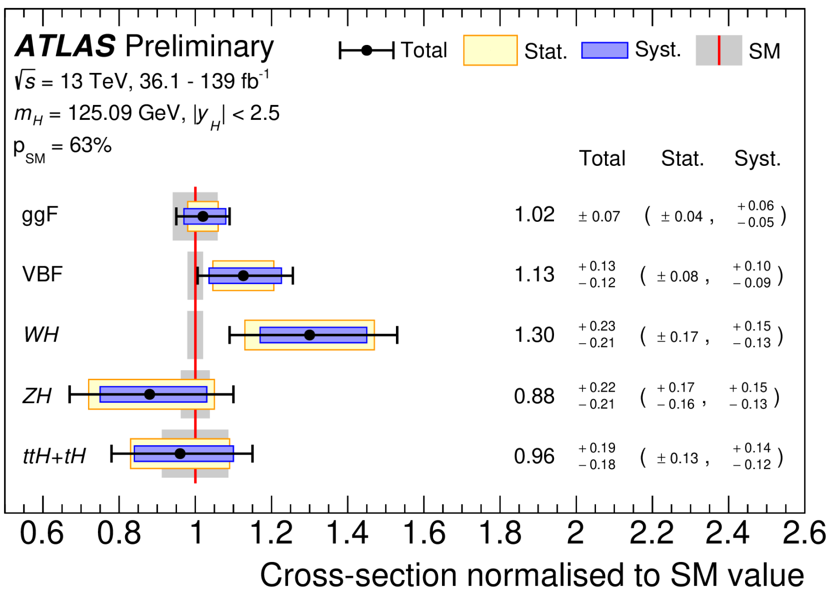
Double differential

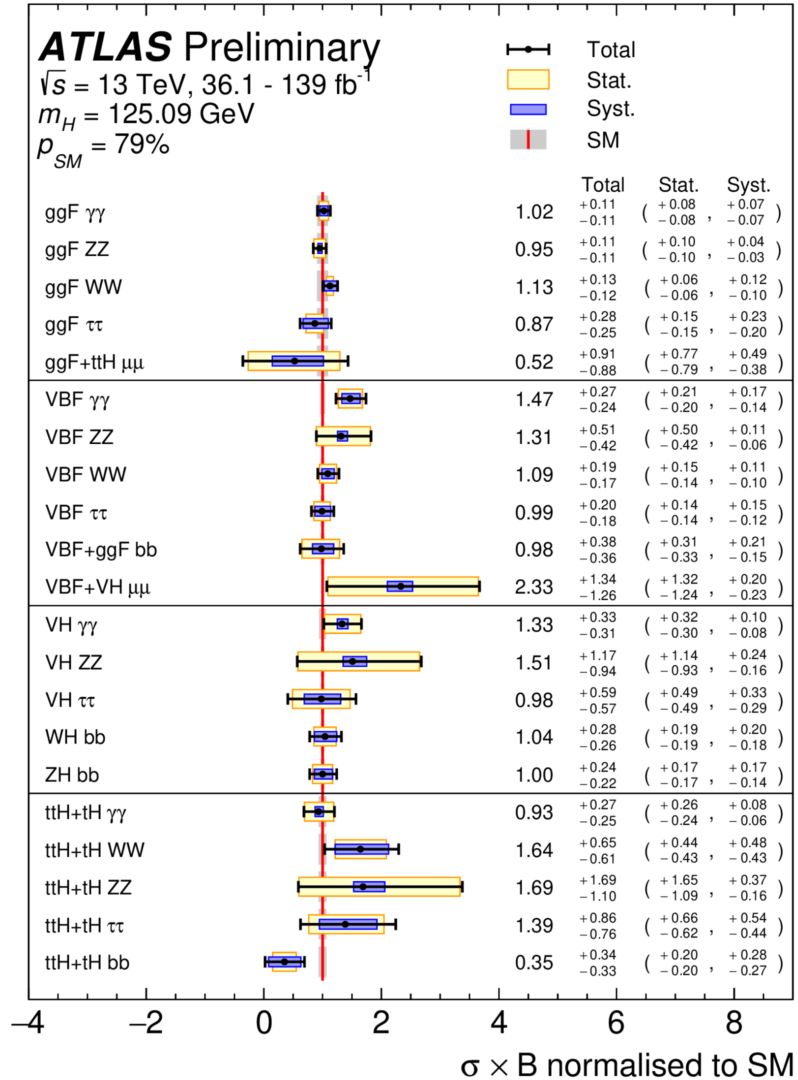




Combination

- Combination of latest results in
  - γγ, ZZ, WW, ττ, bb, μμ, Zγ
  - Many updated to full dataset
  - New channels included
- Global signal strength
  - 1.06 ±0.06



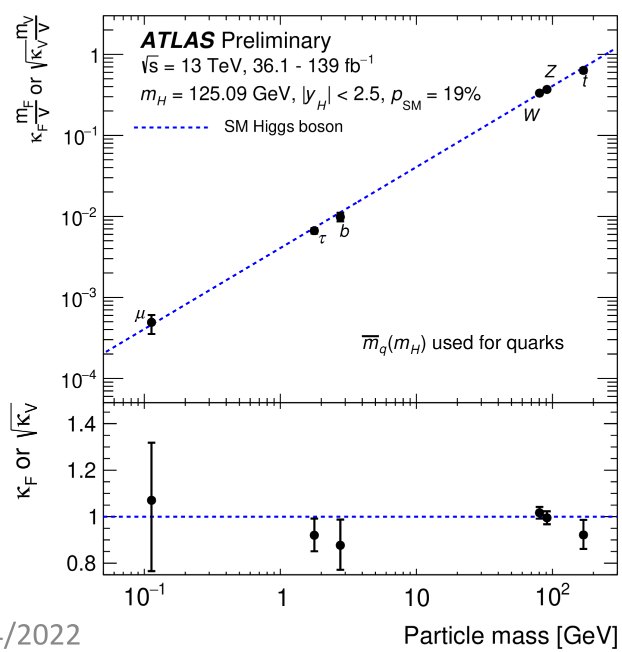


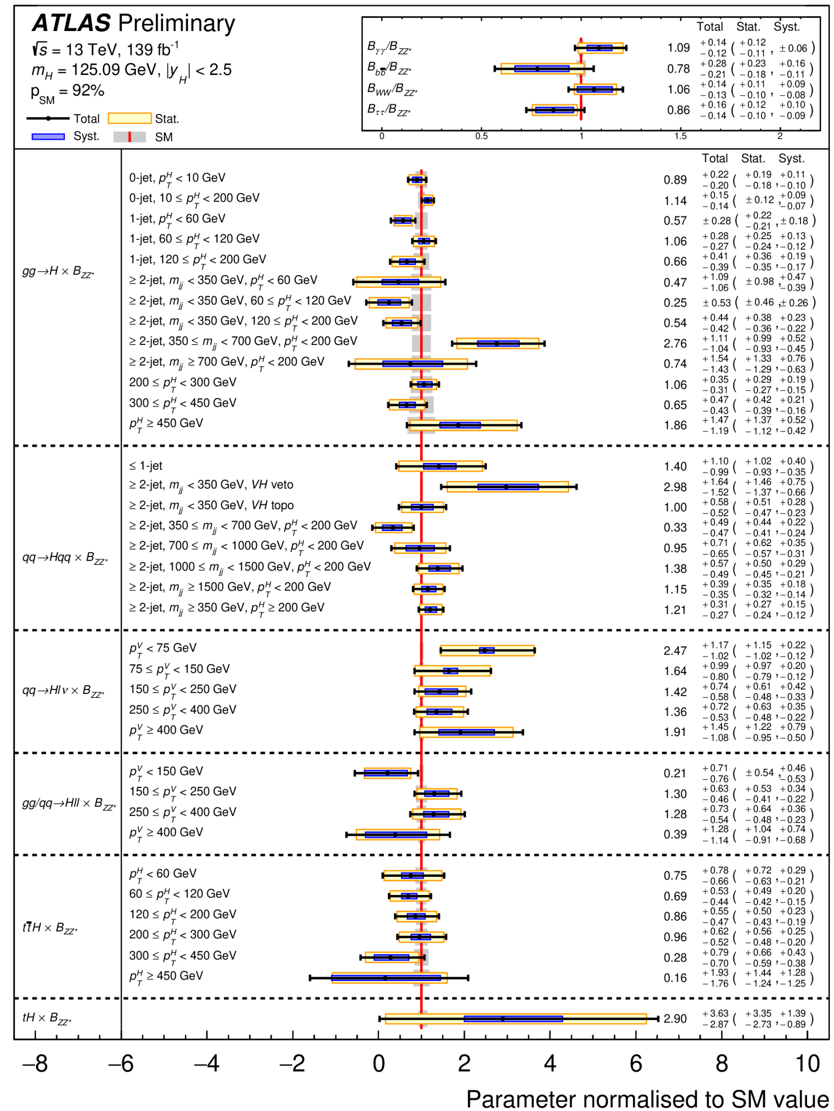
STXS Combination

- STXS combination performed
  - Covers 37 bins
- Measurements parameterized as:

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

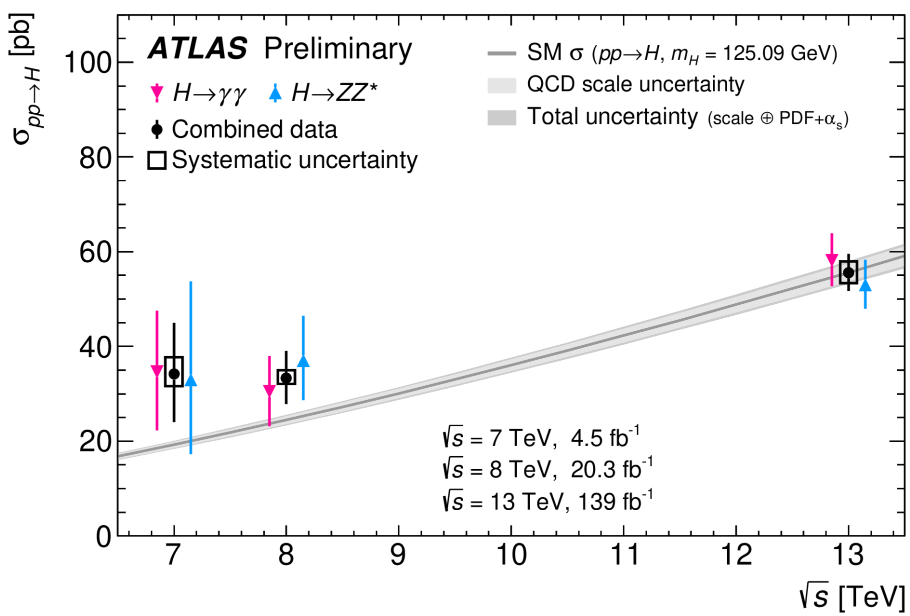
- All measured coupling strength parameters found to be consistent with the SM

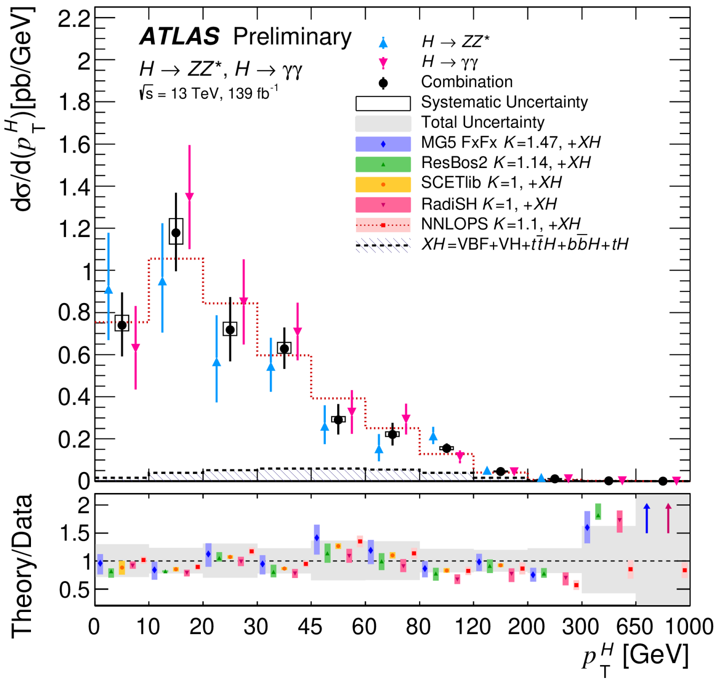




Fiducial Combination

- Combined measurement of H→ZZ and H→γγ
- Channels extrapolated to full phase space
  - ➢ Reduced total uncertainty
- Measurements as a function of:
  - ➢ Higgs transverse momentum, rapidity, number of jets, and leading jet transverse momentum

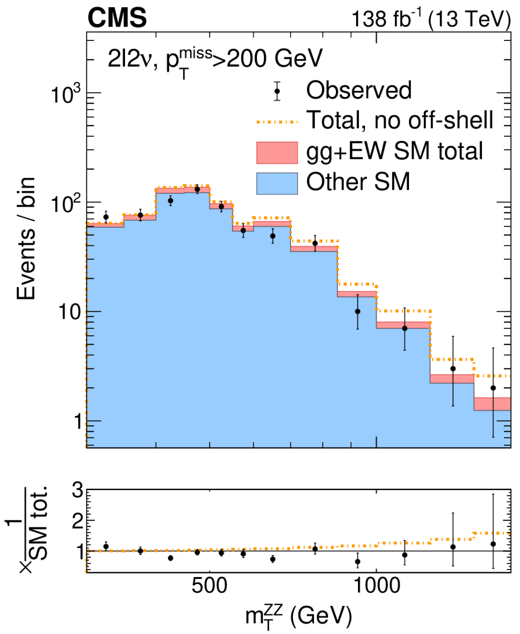


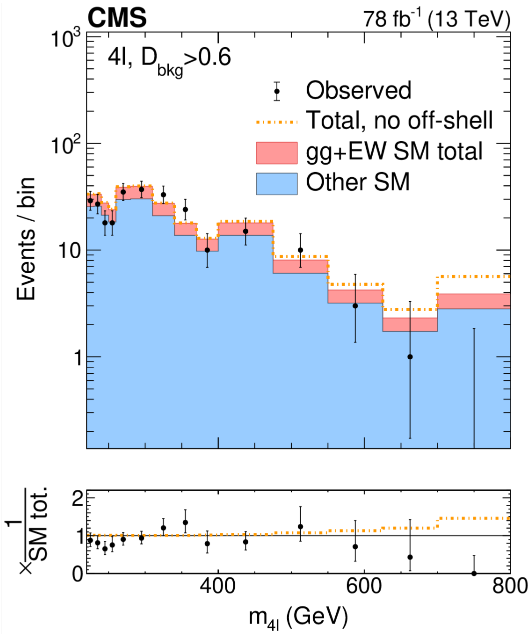


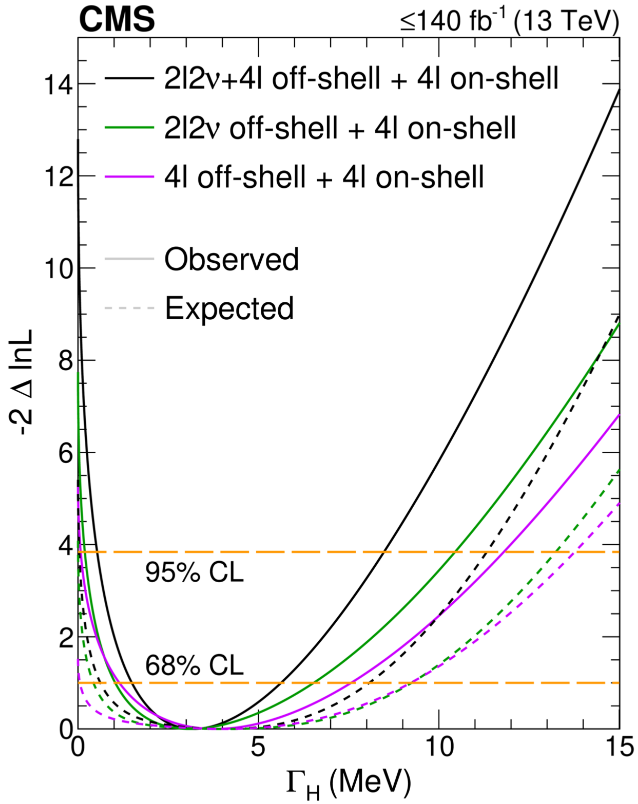
CMS arXiv:2202.06923

Higgs Width

- Up to full Run 2 dataset ZZ production
  - Four charged leptons or two charged leptons and MET
- First evidence for off-shell Higgs production
- Provides measurement of Higgs width
  - Γ_H= 3.2+2.4-1.7 MeV

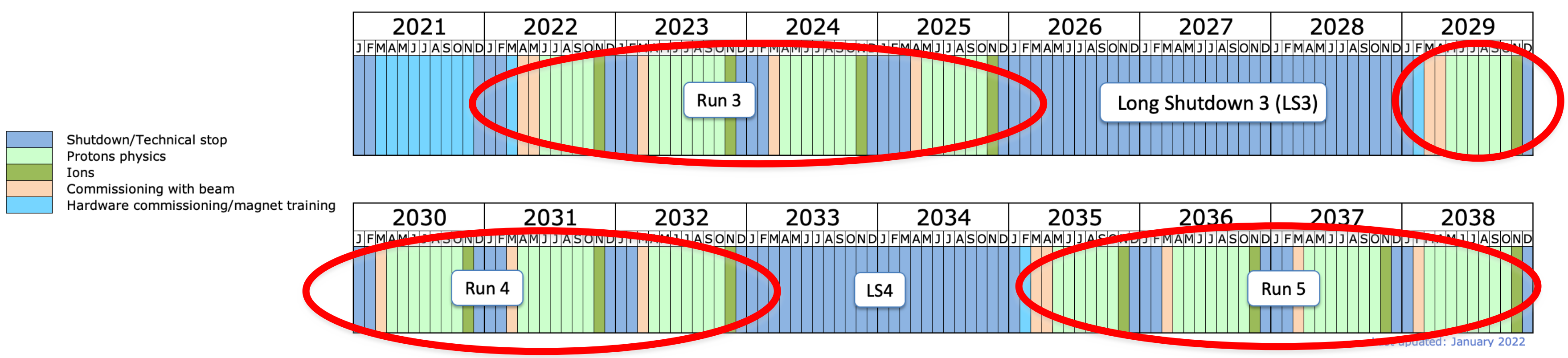






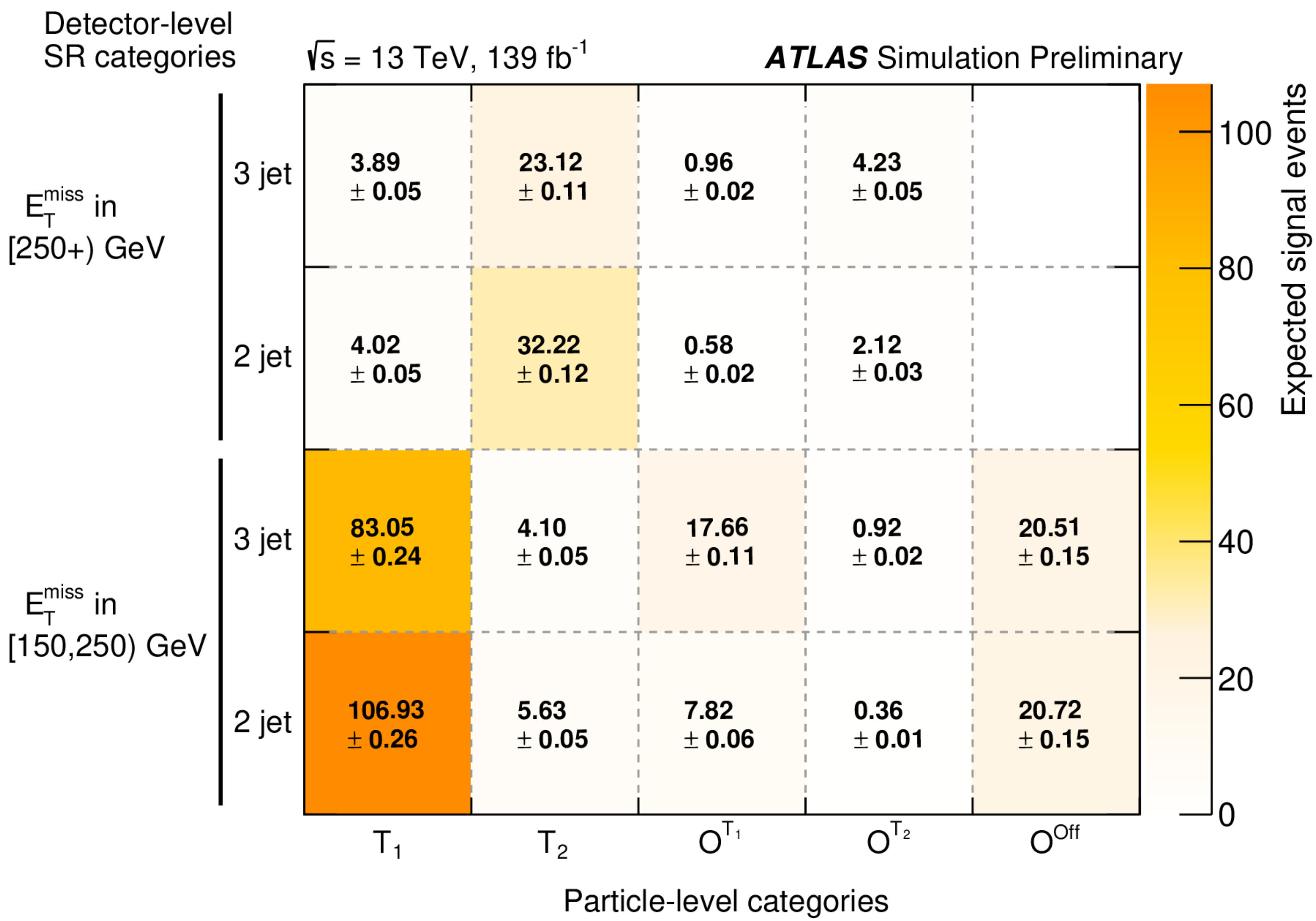
Summary

- An amazing amount of progress has been made since Higgs discovery in 2012
  - ➢ All main production channels and decays now observed
  - ➢ Significant progress on gaining sensitivity to rarer modes
- Higgs boson physics now into the age of measurements
  - ➢ Rapid and continual progress in making more precise measurements
  - ➢ Main limitations
    - Signal modelling uncertainties, object modelling and data statistics
- Still only at the very beginning of our exploration of the Higgs
  - ➢ A lot more data to analyse and improvements to be made
  - ➢ A lot more to learn and maybe some surprises….

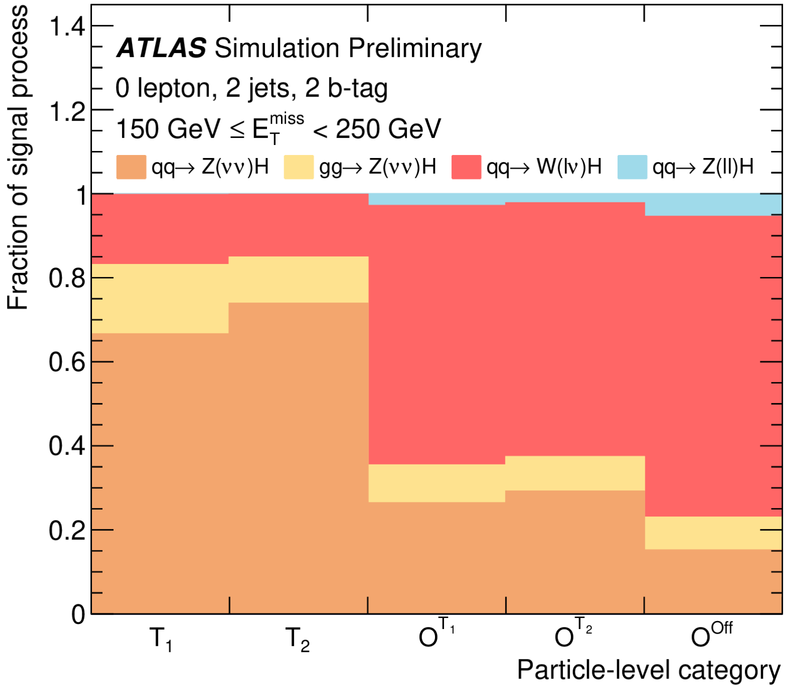


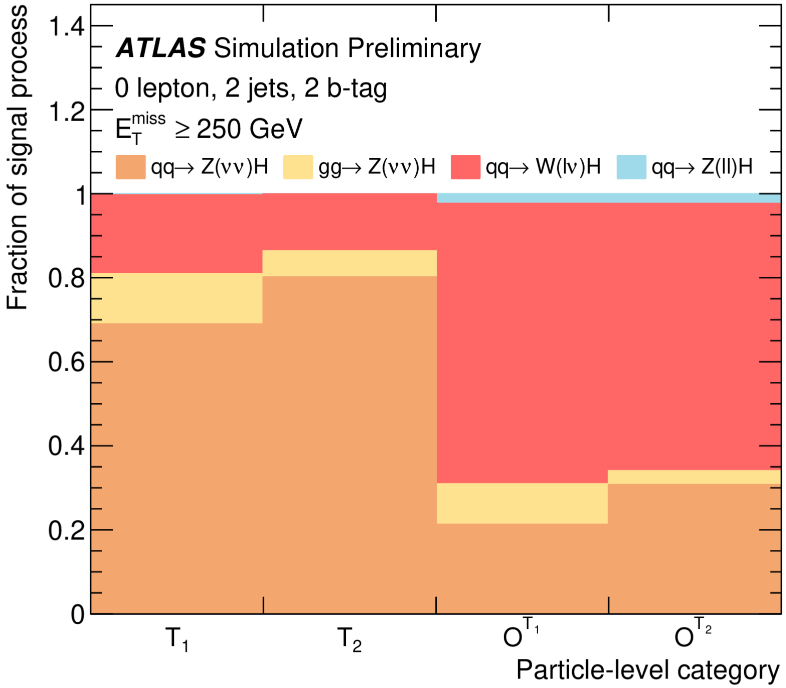
Backup Slides

H→bb: Signal Yields

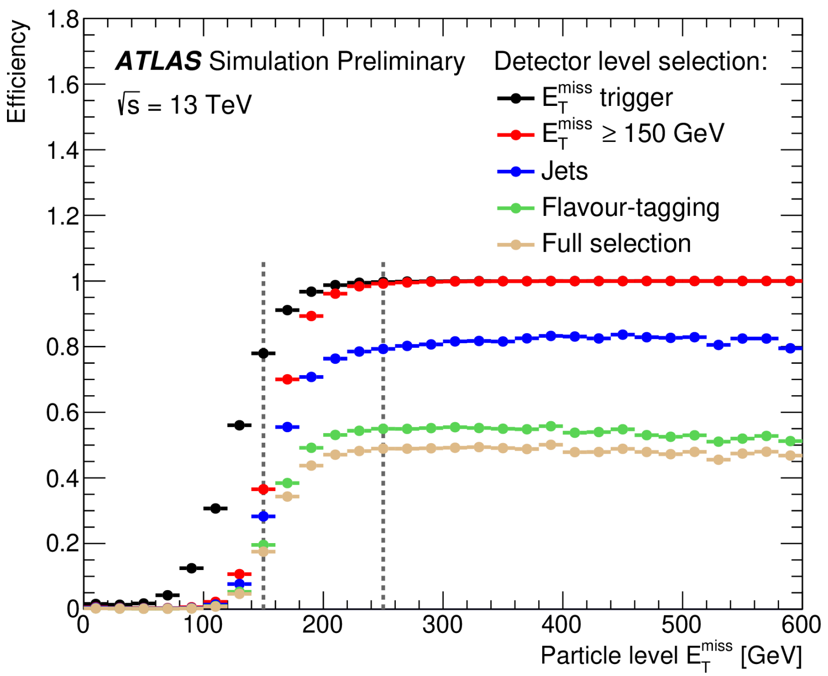


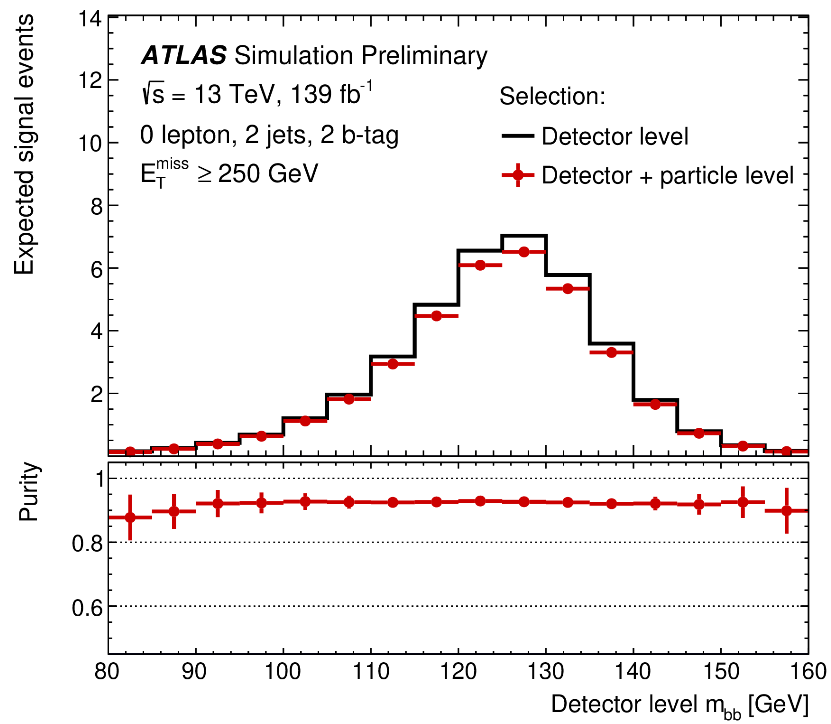
H→bb: Composition





H→bb: Efficiency/Purity





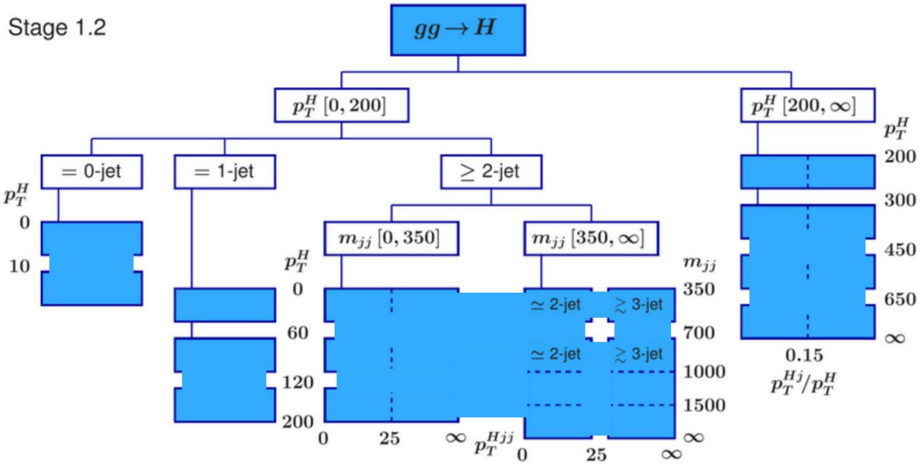
H→bb: Samples

Process	Generators	$\sigma \times B^{\mathrm{H}}_{\mathrm{bb}}$ [fb]
$qq \to ZH \to \nu\nu b\bar{b}$	Powheg MiNLO + GoSam + Pythia 8.212 (NNPDF3.0NLO)	153.05×0.582
$qq \to WH \to \ell^{+}\nu b\bar{b}$	Powheg MiNLO + GoSam + Pythia 8.212 (NNPDF3.0NLO)	282.78×0.582
$qq \to WH \to \ell^{-}\nu b\bar{b}$	Powheg MiNLO + GoSam + Pythia 8.212 (NNPDF3.0NLO)	179.49×0.582
$qq \to ZH \to \ell\ell b\bar{b}$	Powheg MiNLO + GoSam + Pythia 8.212 (NNPDF3.0NLO)	77.04×0.582
$gg \to ZH \to \nu\nu b\bar{b}$	Powheg + Pythia 8.212 (NNPDF3.0NLO)	24.57×0.582
$gg \to ZH \to \ell\ell b\bar{b}$	Powheg + Pythia 8.212 (NNPDF3.0NLO)	12.42×0.582

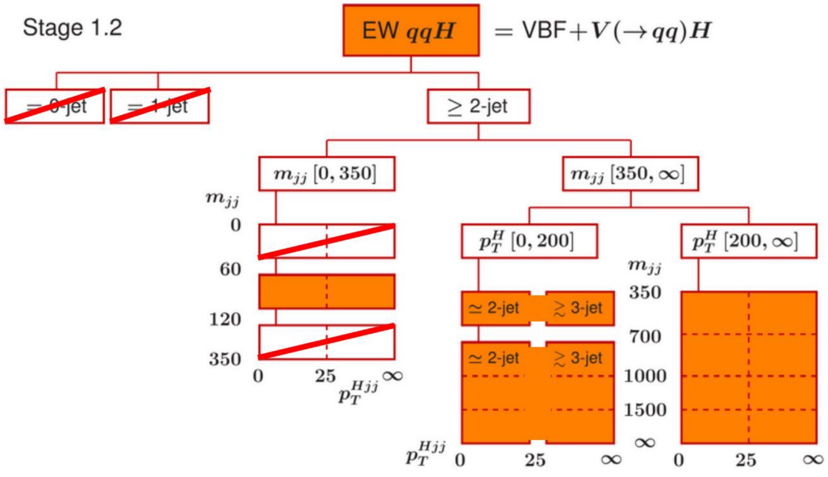
H→bb: Selection

Selection	Detector-level	Particle-level
Leptons	No electrons or muons $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ Electrons: $\lvert\eta\rvert < 2.47$, LooseLH, $\lvert d_0/\sigma_{d_0}\rvert < 5$, $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ Muons: $\lvert\eta\rvert < 2.7$, Loose, $\lvert d_0/\sigma_{d_0}\rvert < 3$, $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ Loose track-isolation	No electrons or muons $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ Electrons: $\lvert\eta\rvert < 2.47$ Muons: $\lvert\eta\rvert < 2.7$
Hadronic τ	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.5$ Medium	τ-labelled central jets
Anti-k_t $R = 0.4$ Jets	From topological clusters ≥ 2 central jets Central: $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$ Forward: $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $2.5 < \lvert\eta\rvert < 4.5$	From collider-stable particles ≥ 2 central jets Central: $p_{\mathrm{T}} > 20\,\mathrm{GeV}$, $\lvert\eta\rvert < 2.5$ Forward: $p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $2.5 < \lvert\eta\rvert < 4.5$
b-jets	2 b-tagged central jets, MV2 (70% efficiency) At least one b-jet with $p_{\mathrm{T}} > 45\,\mathrm{GeV}$	2 b-labelled central jets At least one b-labelled jet with $p_{\mathrm{T}} > 45\,\mathrm{GeV}$
Jet categories	Two, with exactly 2 and 3 jets	One, with 2 or 3 jets
Overlap removal	Between e, μ, τ and jets	Remove e/μ within $\Delta R = 0.4$ of a jet, remove τ-labelled jets
$E_{\mathrm{T}}^{\mathrm{miss}}$	Negative vectorial sum of p_{T} of jets, leptons, taus and photons plus a track-based soft term $> 150\,\mathrm{GeV}$	Negative vectorial sum of p_{T} of all stable interacting particles with $\lvert\eta\rvert < 5$, including muons with $p_{\mathrm{T}} > 6\,\mathrm{GeV}$ $> 150\,\mathrm{GeV}$
H_{T}	$> 120\,\mathrm{GeV}$ (2 jets), $> 150\,\mathrm{GeV}$ (3 jets)	$> 120\,\mathrm{GeV}$ (2 jets), $> 150\,\mathrm{GeV}$ (3 jets)
$\min \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{j})$	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)	$> 20^\circ$ (2 jets), $> 30^\circ$ (3 jets)
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{b}_1 + \vec{b}_2)$	$> 120^\circ$	$> 120^\circ$
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^\circ$	$< 140^\circ$
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	$< 90^\circ$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ regions	$150\,\mathrm{GeV} \leq E_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} \geq 250\,\mathrm{GeV}$	$150\,\mathrm{GeV} \leq E_{\mathrm{T}}^{\mathrm{miss}} < 250\,\mathrm{GeV}$ $E_{\mathrm{T}}^{\mathrm{miss}} \geq 250\,\mathrm{GeV}$

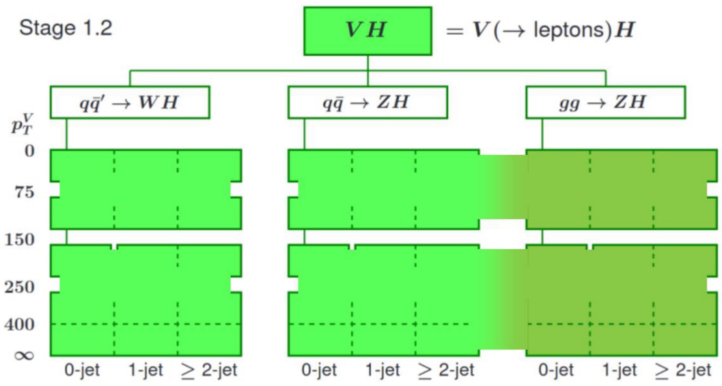
H→WW: STXS



Stage 1.2
$gg \to H$
p_T^H [0, 200]
p_T^H [200, ∞]
= 0-jet
= 1-jet
≥ 2-jet
m_{jj} [0, 350]
m_{jj} [350, ∞]
≃ 2-jet
≳ 3-jet
p_T^H
m_{jj}
p_T^{Hjj}
p_T^{Hj}/p_T^H
0.15

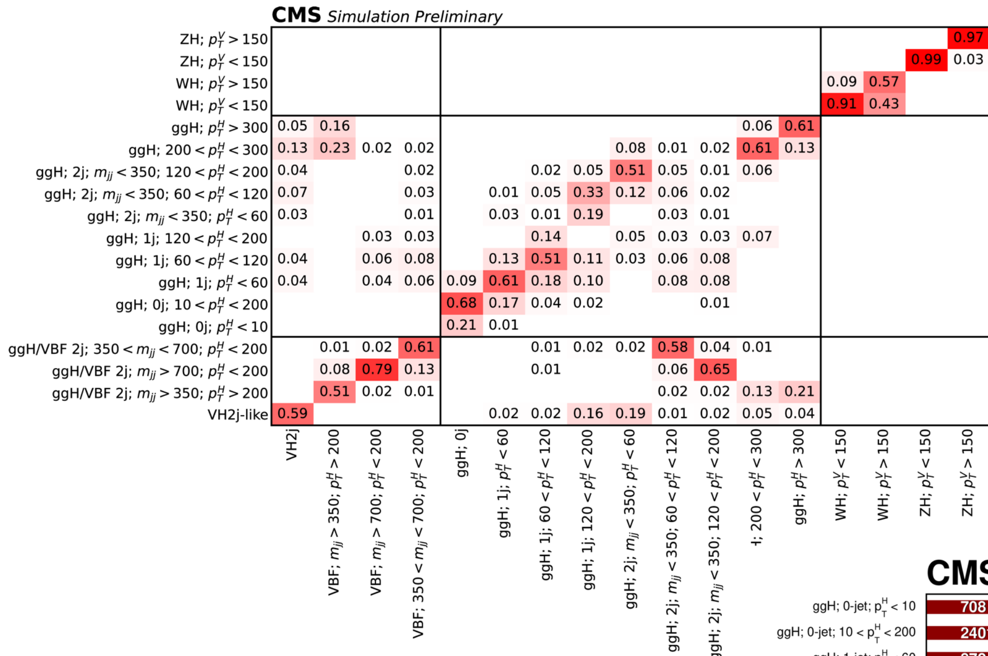


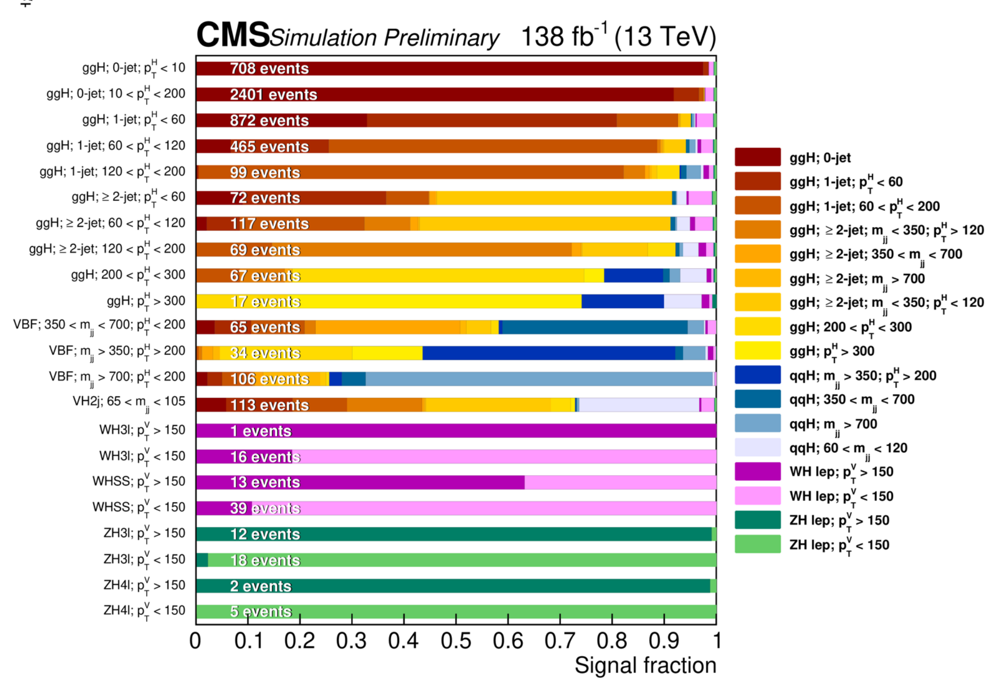
Stage 1.2
EW qqH
= VBF + $V(\to qq)H$
= 0-jet
= 1-jet
≥ 2-jet
m_{jj} [0, 350]
m_{jj} [350, ∞]
p_T^H [0, 200]
p_T^H [200, ∞]
≃ 2-jet
≳ 3-jet
m_{jj}
p_T^{Hjj}



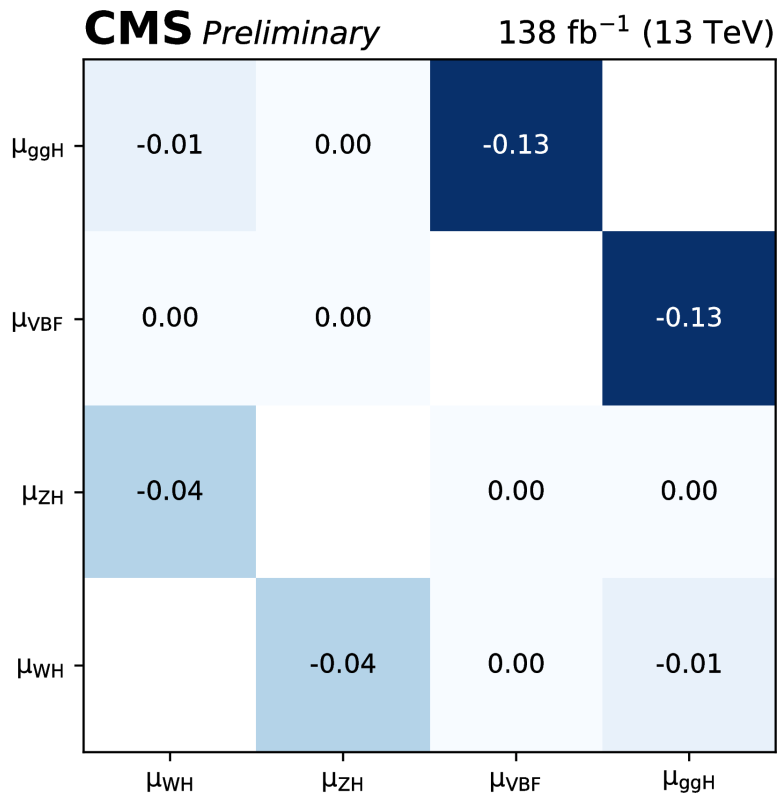
Stage 1.2
VH
= $V(\to$ leptons$)H$
$q\bar{q}' \to WH$
$q\bar{q} \to ZH$
$gg \to ZH$
p_T^V
0
75
150
250
400
∞
0-jet
1-jet
≥ 2-jet

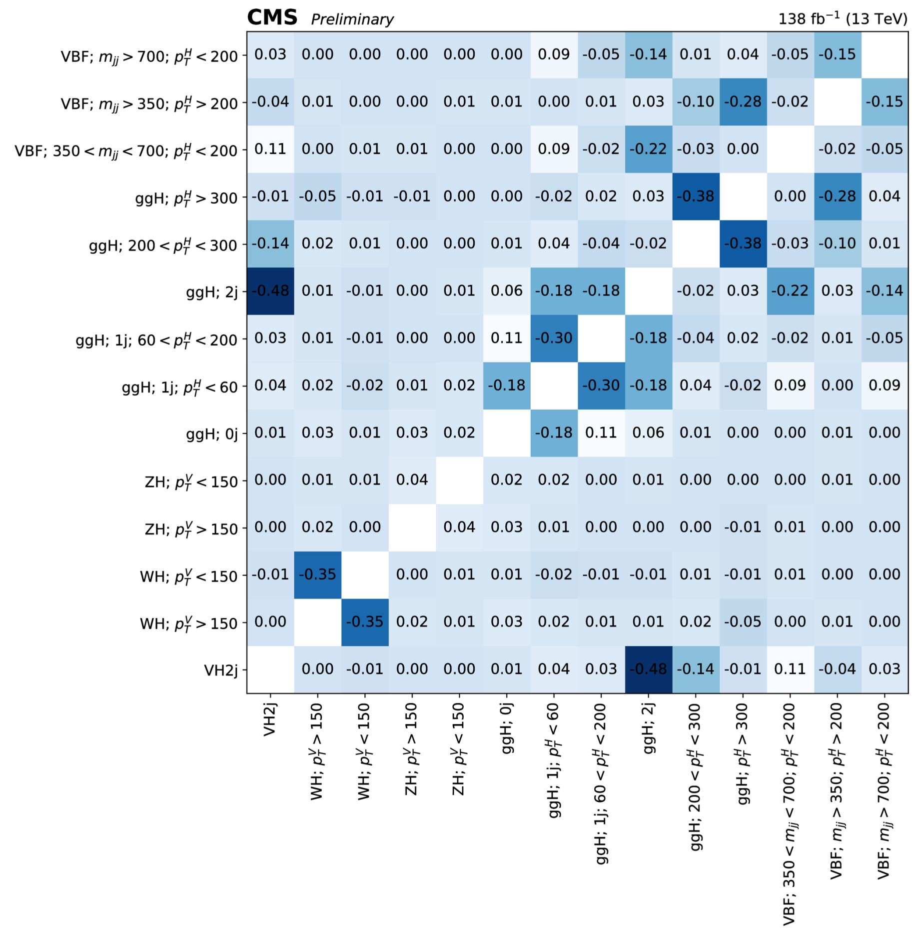
H→WW: Signal Composition



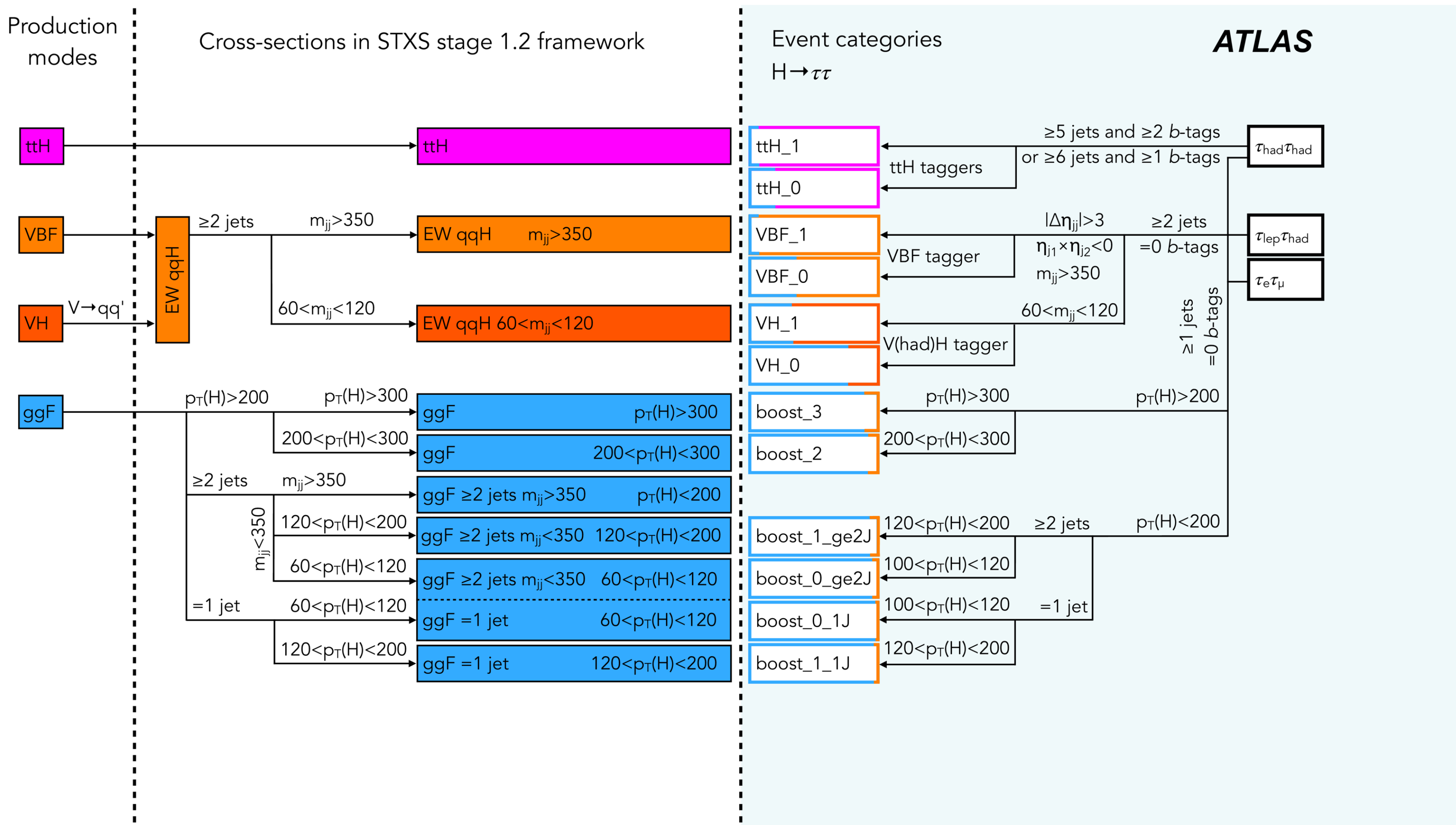


H→WW: Correlation



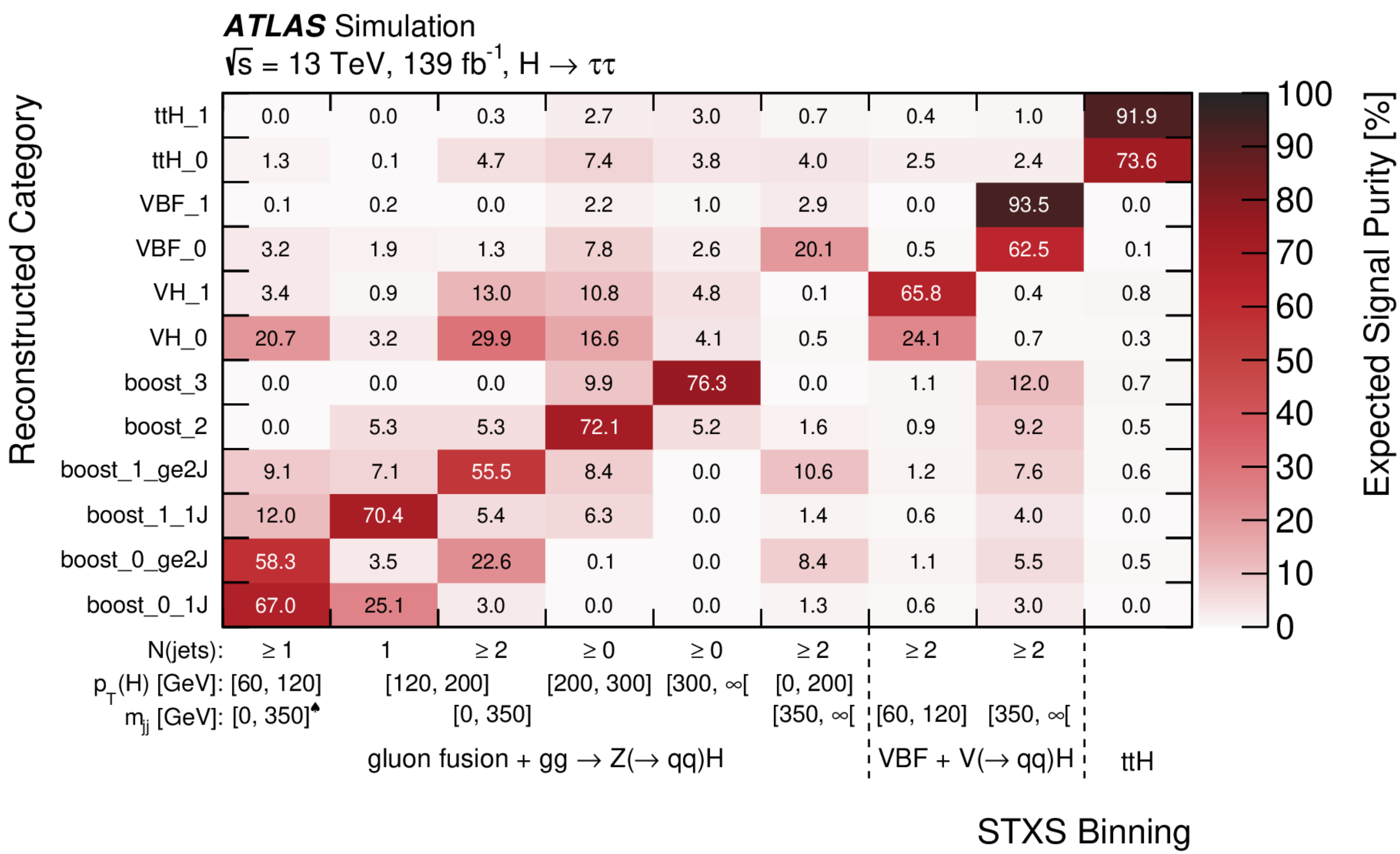


H→ττ: STXS

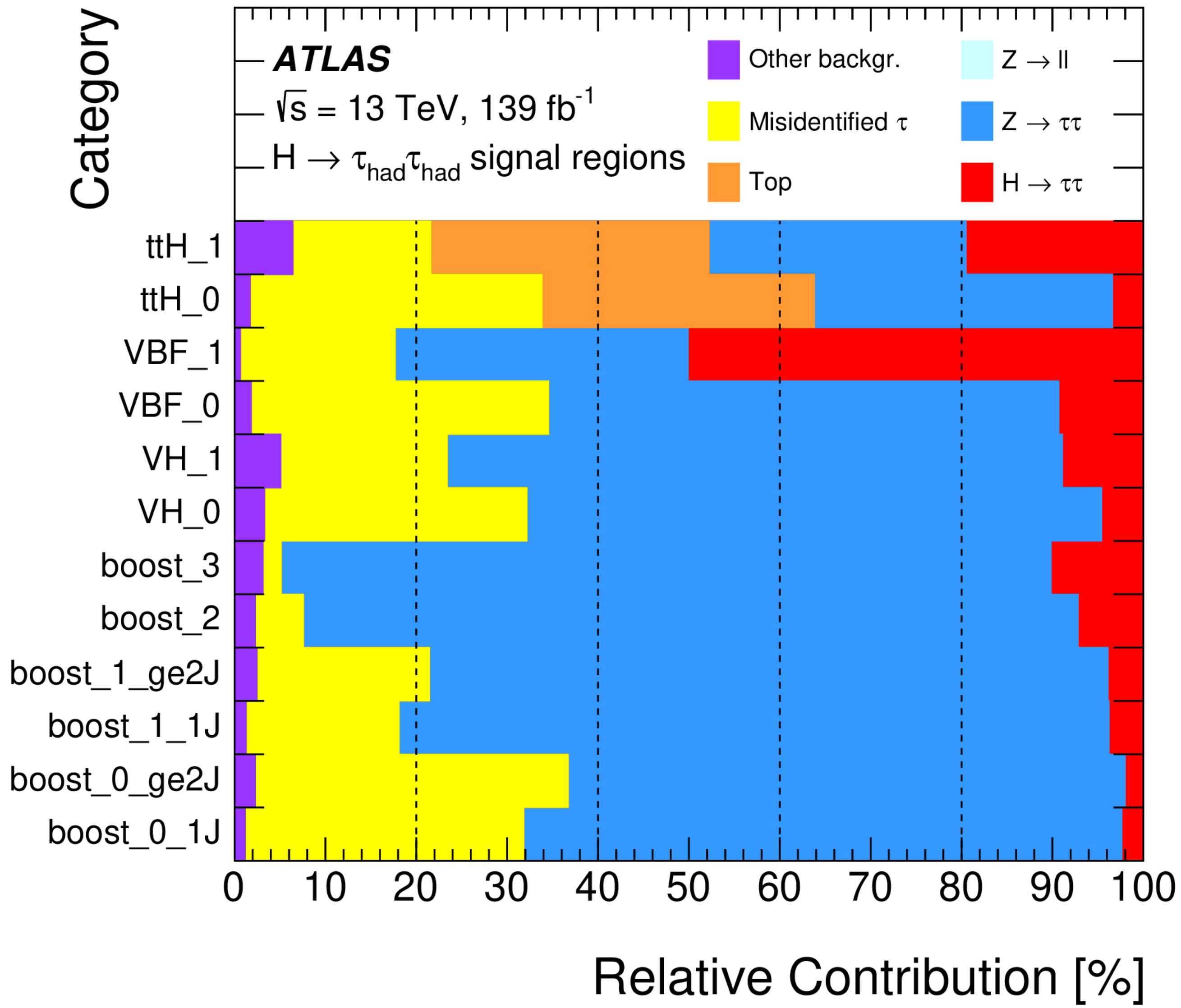


Production modes
Cross-sections in STXS stage 1.2 framework
Event categories
H→ττ
ATLAS
ttH
VBF
VH
ggF
V→qq'
EW qqH
≥2 jets
mjj>350
60<mjj<120
EW qqH mjj>350
EW qqH 60<mjj<120
pT(H)>200
pT(H)>300
200<pT(H)<300
mjj<350
120<pT(H)<200
60<pT(H)<120
=1 jet
ggF pT(H)>300
ggF 200<pT(H)<300
ggF ≥2 jets mjj>350 pT(H)<200
ggF ≥2 jets mjj<350 120<pT(H)<200
ggF ≥2 jets mjj<350 60<pT(H)<120
ggF =1 jet 60<pT(H)<120
ggF =1 jet 120<pT(H)<200
ttH_1
ttH_0
VBF_1
VBF_0
VH_1
VH_0
boost_3
boost_2
boost_1_ge2J
boost_0_ge2J
boost_0_1J
boost_1_1J
ttH taggers
≥5 jets and ≥2 b-tags
or ≥6 jets and ≥1 b-tags
VBF tagger
|Δηjj|>3
ηj1×ηj2<0
mjj>350
=0 b-tags
V(had)H tagger
≥1 jets
=0 b-tags
pT(H)<200
100<pT(H)<120
τhadτhad
τlepτhad
τeτμ

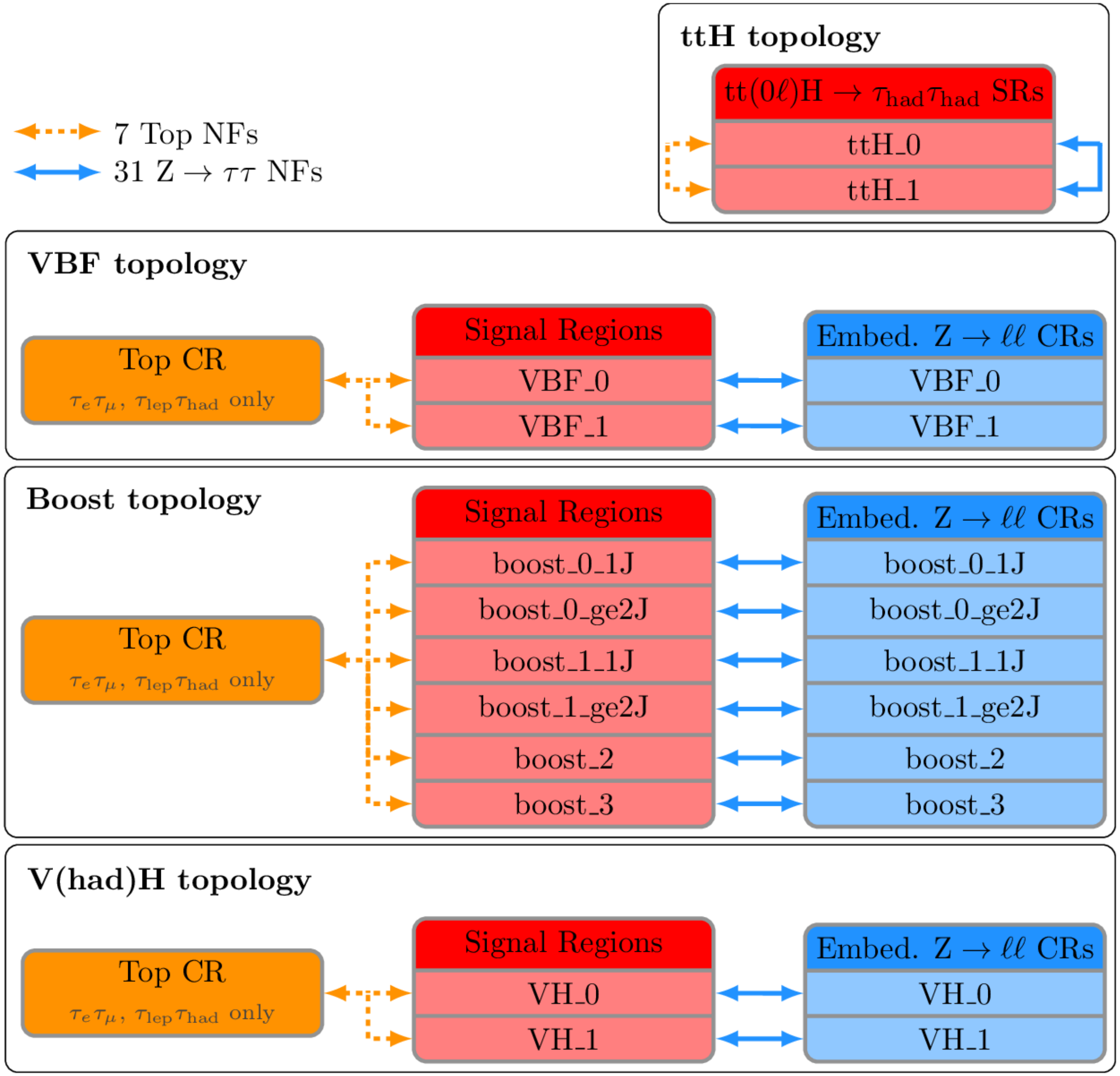
H→ττ: Composition



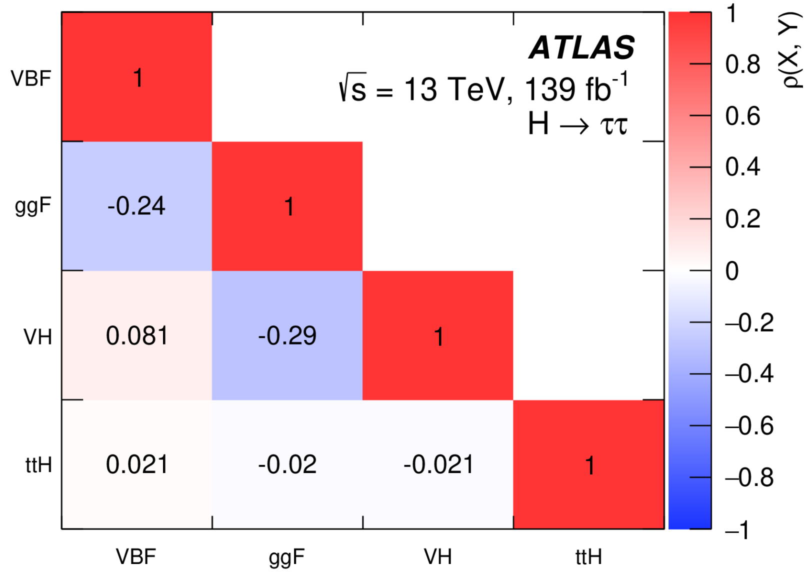
H→ττ: Contribution

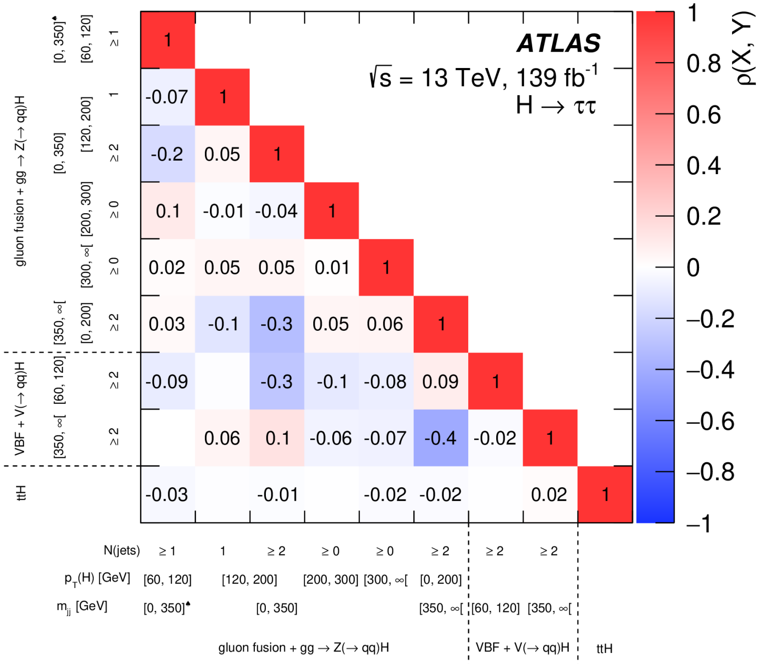


H→ττ: Fit


7 Top NFs
31 $Z \to \tau\tau$ NFs
ttH topology
$tt(0\ell)H \to \tau_{had}\tau_{had}$ SRs
ttH_0
ttH_1
VBF topology
Top CR
$\tau_e\tau_\mu$, $\tau_{lep}\tau_{had}$ only
Signal Regions
VBF_0
VBF_1
Embed. $Z \to \ell\ell$ CRs
VBF_0
VBF_1
Boost topology
Top CR
$\tau_e\tau_\mu$, $\tau_{lep}\tau_{had}$ only
Signal Regions
boost_0_1J
boost_0_ge2J
boost_1_1J
boost_1_ge2J
boost_2
boost_3
Embed. $Z \to \ell\ell$ CRs
boost_0_1J
boost_0_ge2J
boost_1_1J
boost_1_ge2J
boost_2
boost_3
V(had)H topology
Top CR
$\tau_e\tau_\mu$, $\tau_{lep}\tau_{had}$ only
Signal Regions
VH_0
VH_1
Embed. $Z \to \ell\ell$ CRs
VH_0
VH_1

H→ττ: Correlations

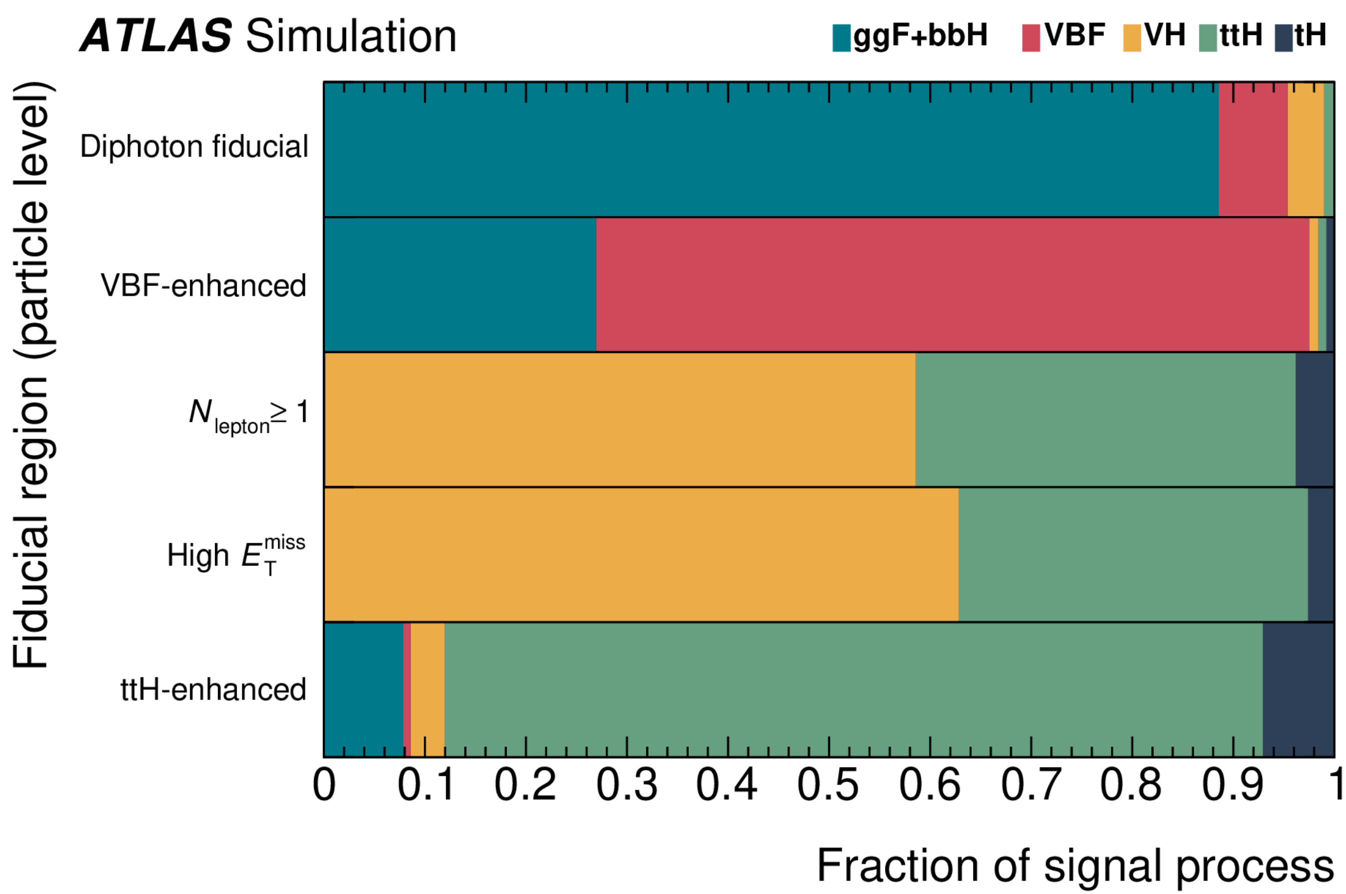




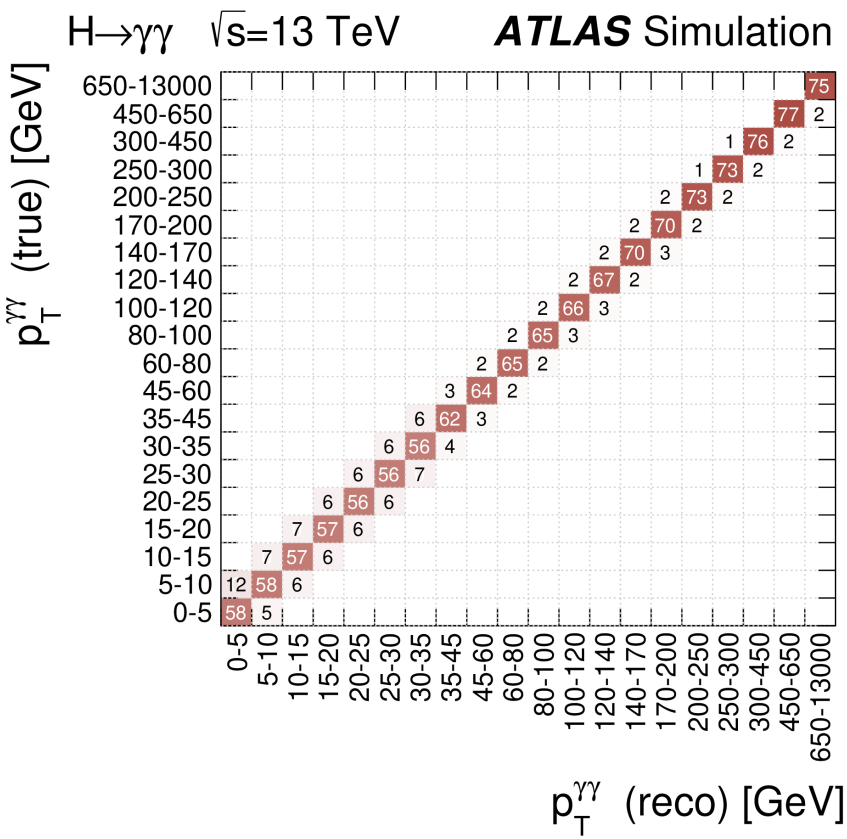
H→ττ: Samples

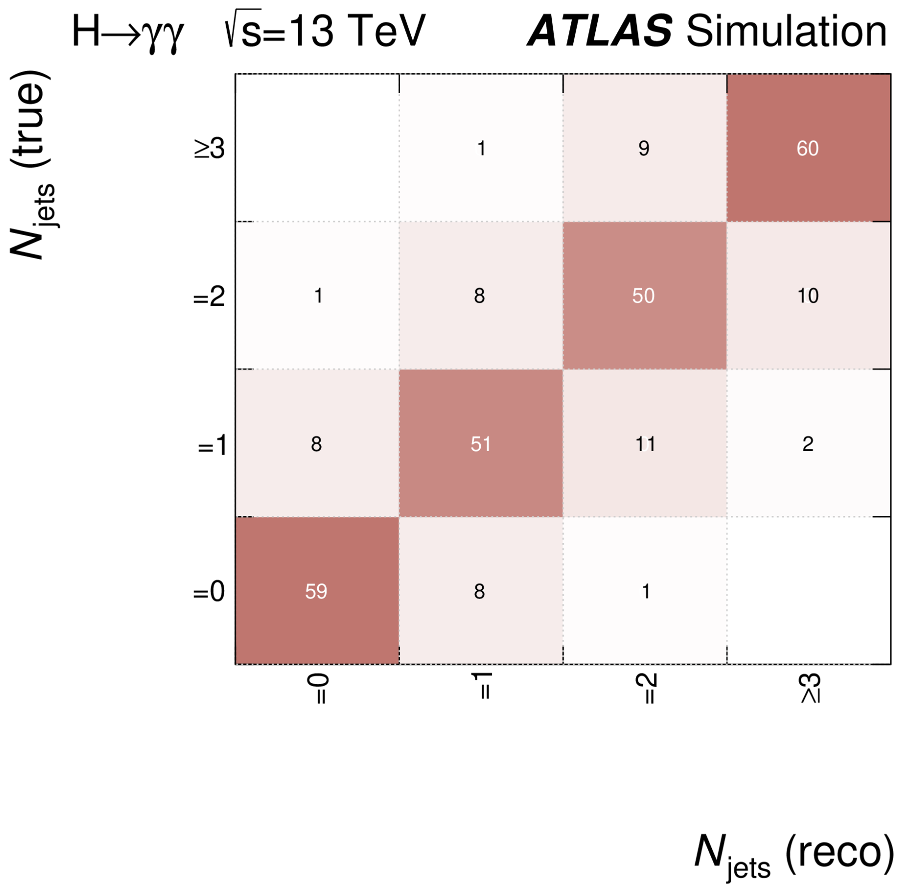
Process	Generator		PDF set		Tune	Normalisation
	ME	PS	ME	PS		
Higgs boson						
ggF	Powheg Box v2	Pythia 8	PDF4LHC15nnlo	CTEQ6L1	AZNLO	N^3LO QCD + NLO EW
VBF	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + NLO EW
VH	Powheg Box v2	Pythia 8	PDF4LHC15nlo	CTEQ6L1	AZNLO	NNLO QCD + NLO EW
$t\bar{t}H$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

H→ γγ : Sample Composition

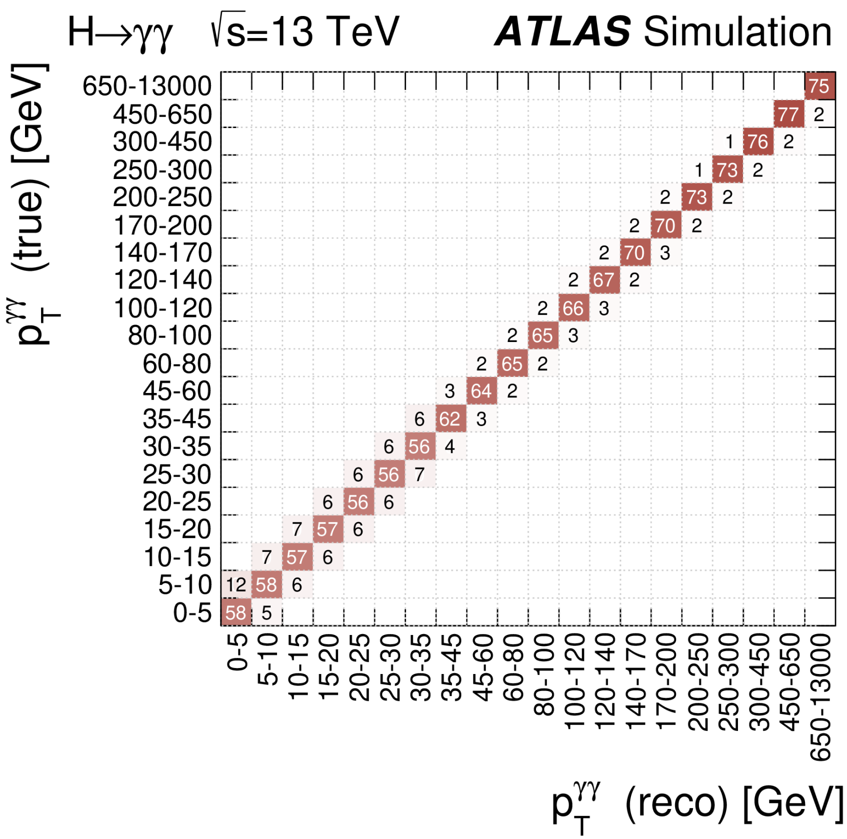


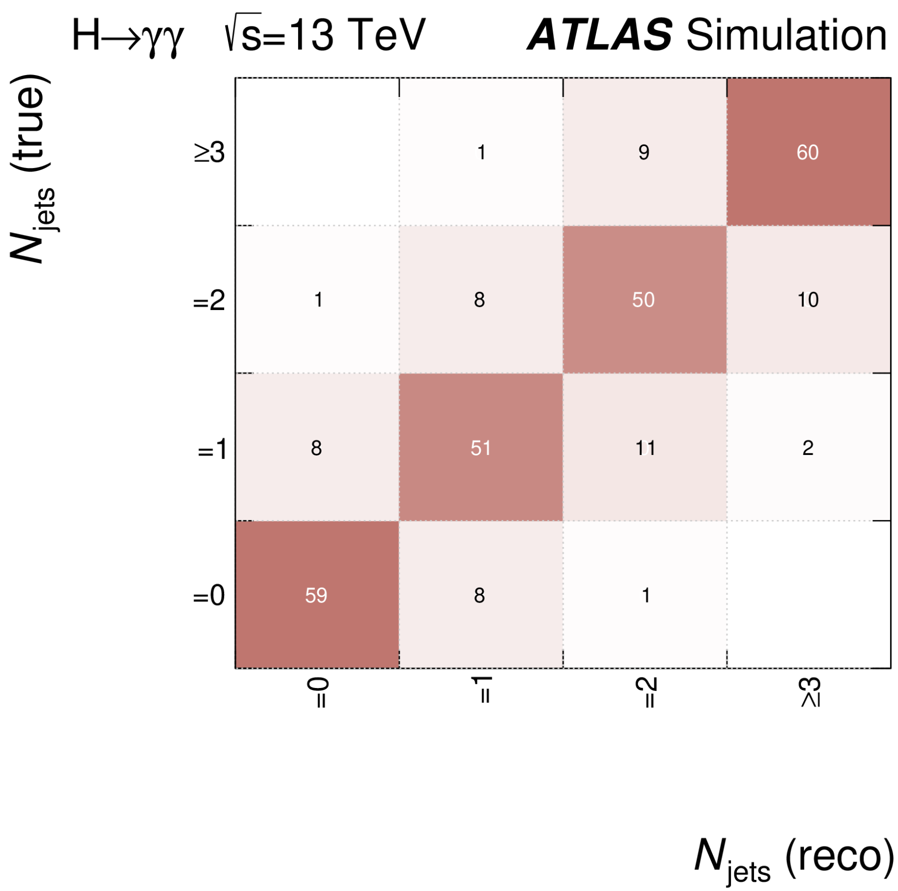
H→ γγ : Response Matrices





H→ γγ : Response Matrices



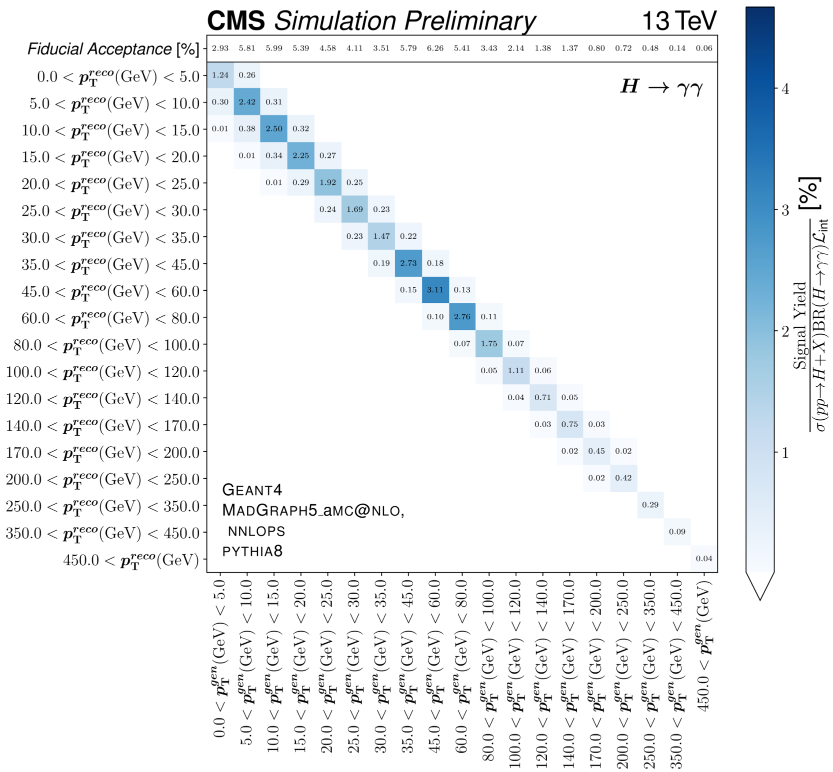


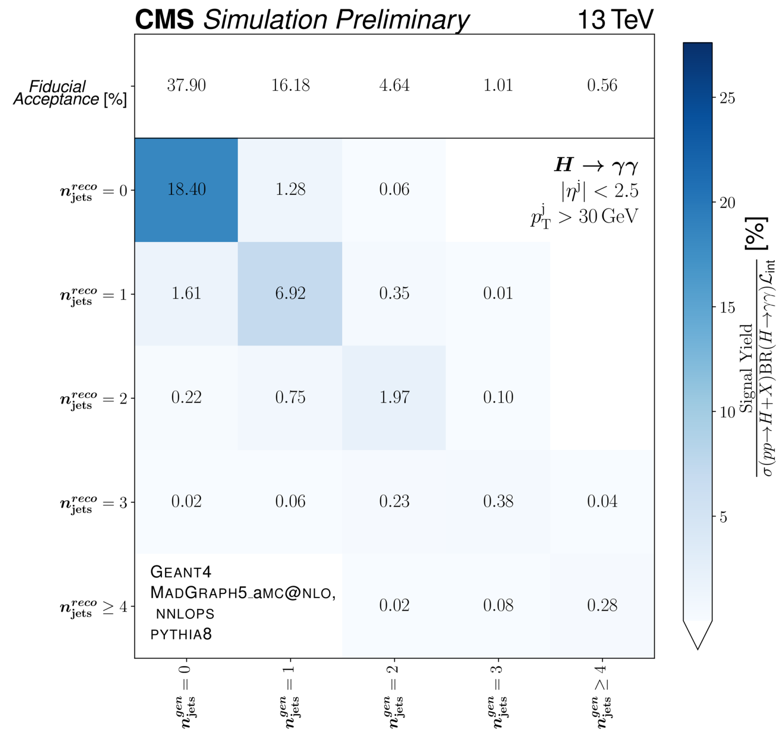
H→ γγ : Selections

Object	particle-level	detector-level
Photons	$E_T > 0.35/0.25 \times m_{\gamma\gamma}$	← same
	$\|\eta\| \in [0, 1.37] \cup [1.52, 2.37]$	← same
		tight identification (shower shapes)
	$E_T^{iso}(\Delta R < 0.2, p_T > 1\,\text{GeV, charged}) < 0.05 E_T$	$E_T^{iso, track}(\Delta R < 0.2, p_T > 1\,\text{GeV}) < 0.05 E_T$
		$E_T^{iso, calo}(\Delta R < 0.2) < 0.065 E_T$
Leptons	dressed with photons in $\Delta R < 0.1$	
		$\|z_0 \sin\theta\| < 0.5\,\text{mm} \wedge \|d_0/\sigma(d_0)\| < 5(e)/3(\mu)$
	$p_T > 15\,\text{GeV}$	← same
	e: $\|\eta\| \in [0, 1.37] \cup [1.52, 2.47]$	← same
	μ: $\|\eta\| \in [0, 2.7]$	← same
		medium identification requirements
		calorimeter and track-based isolation
Jets	anti-k_t $R = 0.4$ (excluding $\nu, \ell, X \leftarrow H$)	anti-k_t $R = 0.4$ particle-flow
	$p_T > 30\,\text{GeV}$	← same
	$\|y\| < 4.4$	← same
		tight-JVT for jets with $\|\eta\| < 2.5$ and $p_T < 60\,\text{GeV}$
b-jets	jets with $\|\eta\| < 2.5$ and b-hadron of $p_T > 5\,\text{GeV}$ within $\Delta R < 0.4$	jets passing the DL1r b-tagging at 70% efficiency
E_T^{miss}	$\sum p_T$ of neutrinos not from hadrons	$-\sum p_T$ of selected γ, ℓ, jets + soft tracks from primary vertex

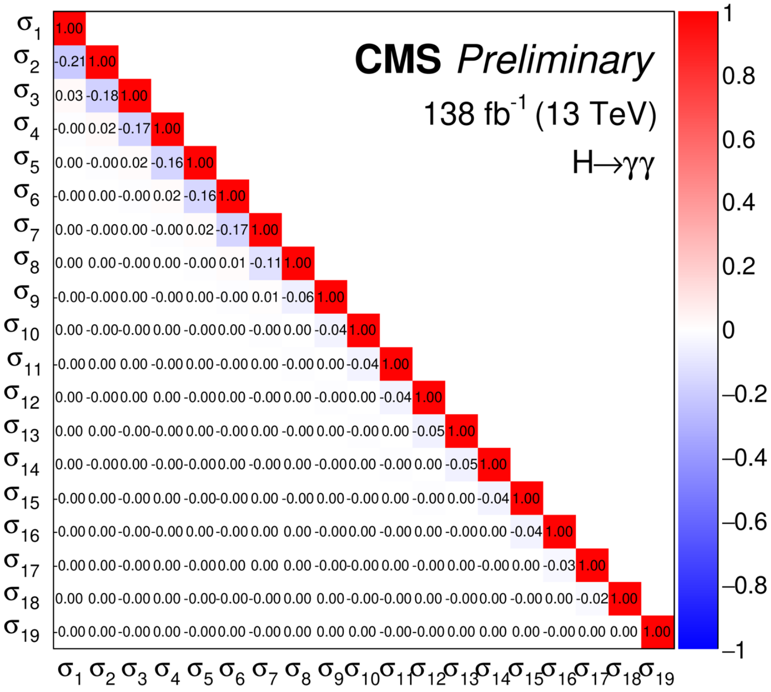
Region	definition
Diphoton	two selected photons
VBF-enhanced	at least two jets, $m_{jj} \geq 600\,\text{GeV}$, $\|\Delta y_{jj}\| \geq 3.5$
$N_{lepton} \geq 1$	electron or muon with $p_T^{\ell} > 15\,\text{GeV}$
High E_T^{miss}	$E_T^{miss} > 80\,\text{GeV}$, $p_T^{\gamma\gamma} > 80\,\text{GeV}$
$t\bar{t}H$-enhanced	at least one b-jet and $\left(N_\ell = 0 \text{ and } N_j \geq 4, \text{ or} N_\ell \geq 1 \text{ AND } N_j \geq 3\right)$

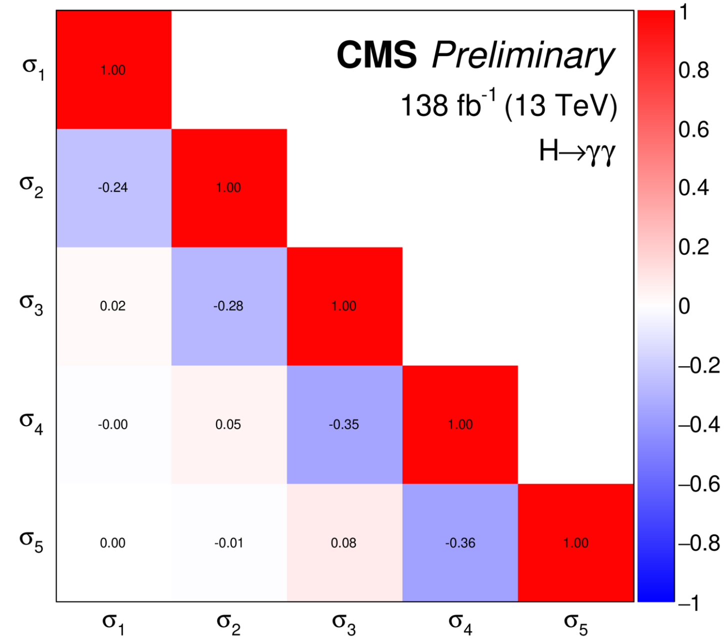
H→ γγ : Event Spread





H→ γγ : Correlation





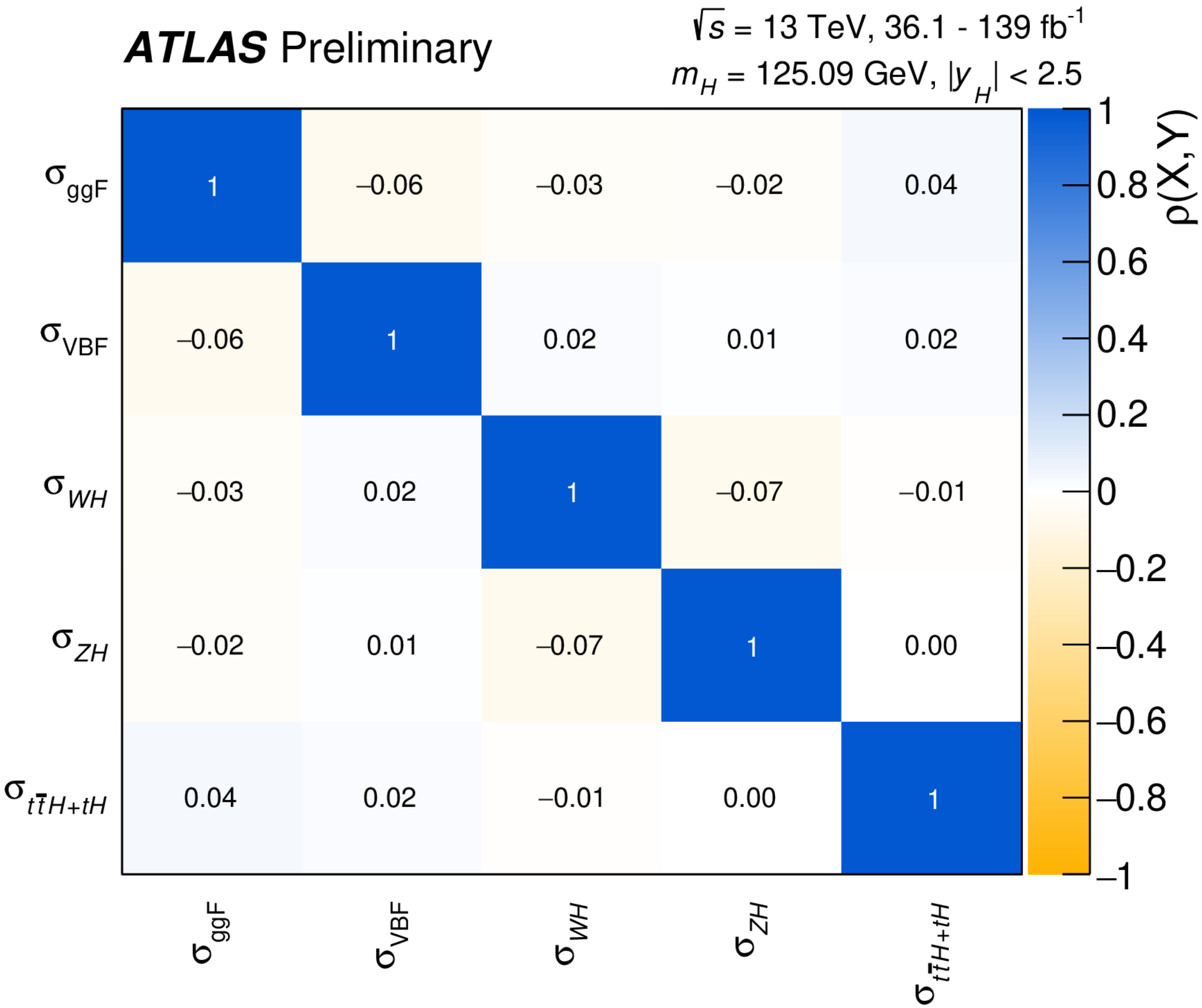
H→ γγ : tau_c

$$\tau_{C}^{j} = \max_{j}\left(\frac{\sqrt{E_{j}^{2} - p_{z,j}^{2}}}{2\cosh\left(Y_{j} - Y_{H}\right)}\right)$$

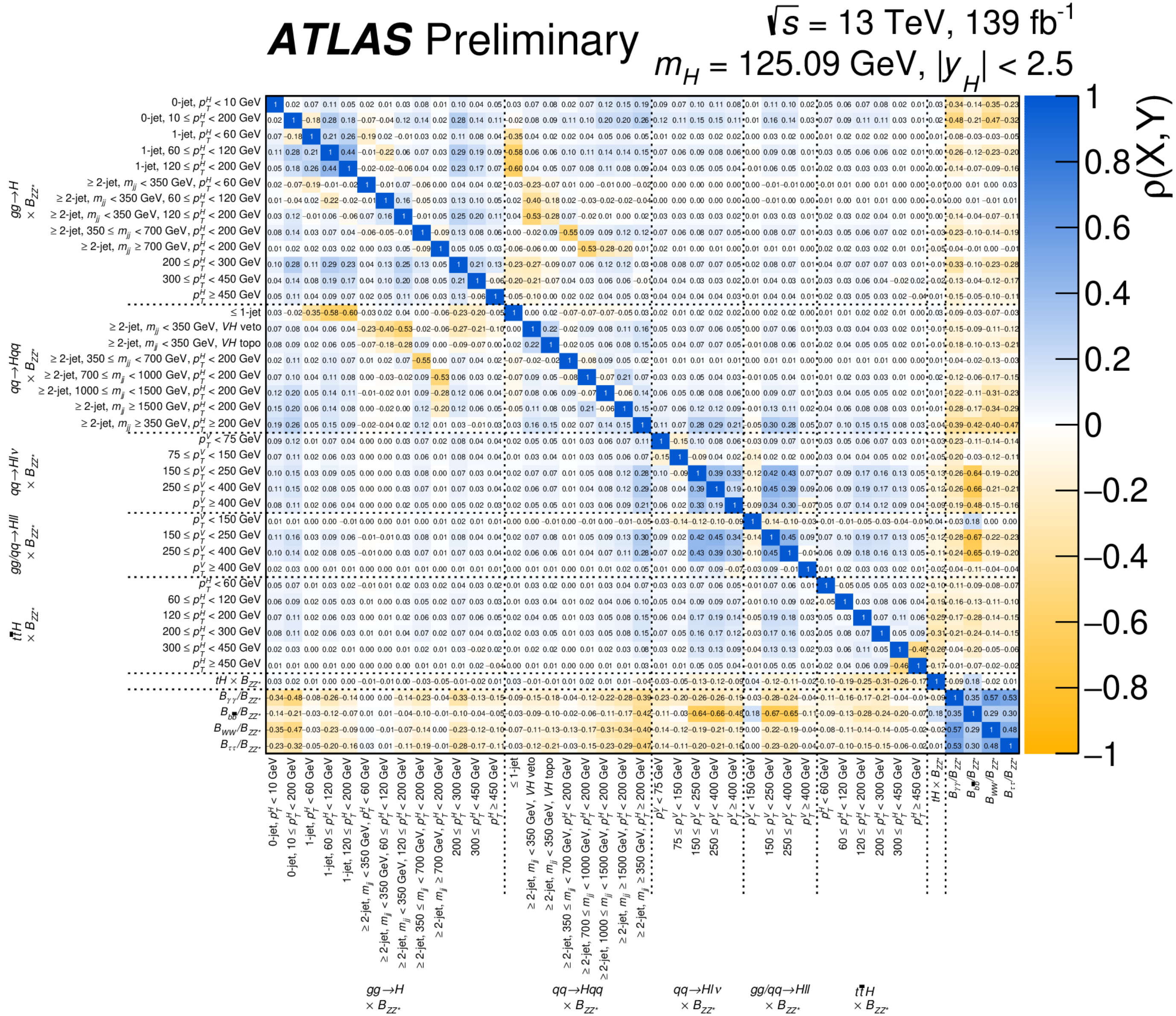
Combination

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Ref.	Used in combined measurement
$H \to \gamma\gamma$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H, tH$	139	[10]	Everywhere
$H \to ZZ^*$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H(4\ell)$	139	[11]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \to WW^*$	ggF, VBF	139	[12]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \to \tau\tau$	$\text{ggF}, \text{VBF}, WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	[13]	Everywhere
	$t\bar{t}H$	36.1	[19]	Everywhere but STXS and SMEFT
$H \to b\bar{b}$	WH, ZH	139	[14,15,16]	Everywhere
	VBF	126	[17]	Everywhere
	$t\bar{t}H$	139	[18]	Everywhere
$H \to \mu\mu$	$\text{ggF}, \text{VBF}, VH, t\bar{t}H$	139	[20]	Everywhere but STXS and SMEFT
$H \to Z\gamma$	$\text{ggF}, \text{VBF}, VH, t\bar{t}H$	139	[21]	Everywhere but STXS and SMEFT
$H \to inv$	VBF	139	[22]	Sec. 6.2 & 6.3

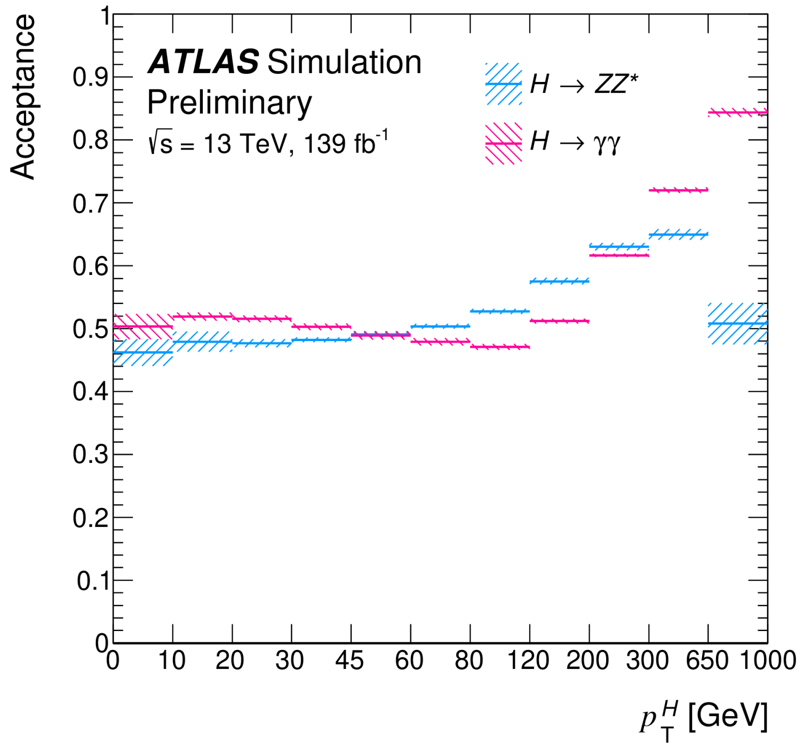
Combination: Correlations



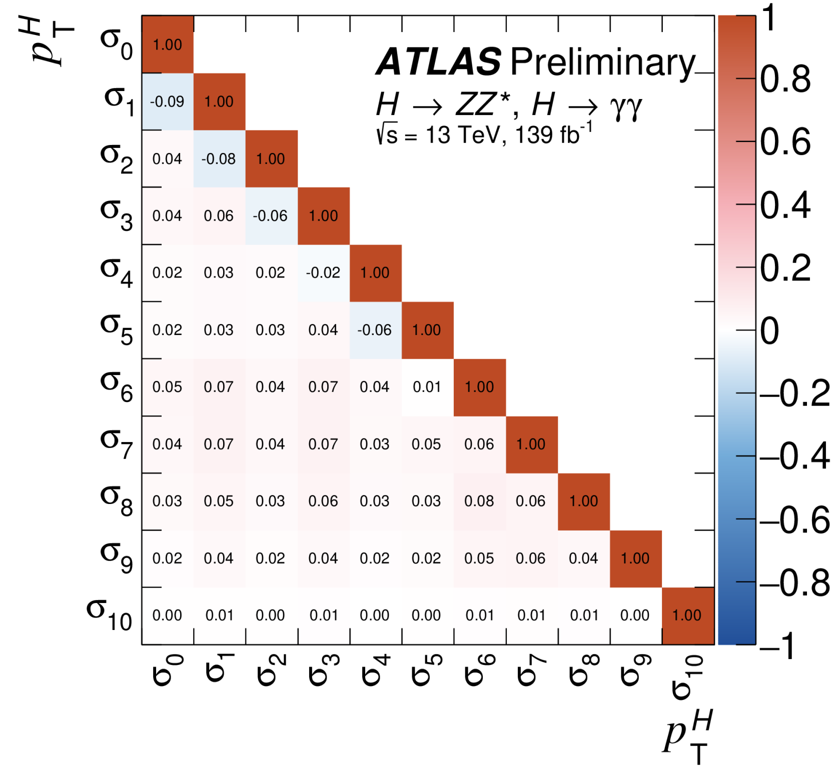
Combination: Correlations



Fiducial Combination



Acceptance



Correlation

Fiducial Combination

Diphoton

Photon and jet definitions	
Photons:	All photons except for those originating from hadron decay
	$p_{\mathrm{T}} > 15$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$
	$E_T^{\mathrm{iso}}(\Delta R < 0.2, p_{\mathrm{T}} > 1$ GeV, charged$) < 0.05\ E_{\mathrm{T}}$
Jets:	$p_T > 30$ GeV, $\|y\| < 4.4$
Event selection	
Diphoton fiducial:	$N_\gamma \geq 2$, $p_T^{\gamma_1} > 0.35 m_{\gamma\gamma}$, $p_T^{\gamma_2} > 0.25 m_{\gamma\gamma}$
Mass window:	105 GeV $< m_{\gamma\gamma} <$ 160 GeV

ZZ

Lepton and jet definitions	
Leptons	Dressed leptons not originating from hadrons or τ decay
	$p_{\mathrm{T}} > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_{\mathrm{T}} > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	p_{T} threshold for three leading leptons: $> 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$ as nominal.
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \mathrm{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra lepton with $p_{\mathrm{T}} > 12$ GeV	Quadruplet with largest ggF matrix element value