Higgs fiducial and differential measurements at ATLAS and CMS

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ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

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SEZIONE DI FIRENZE

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Motivation and outline

The challenges of differential measurements…

- High statistics required
- Measurement limited to a subset of phase space
- Detectors warp the distribution, need to be accounted for by unfolding
  - Statistically delicate operation, comes with many considerations

…and their strengths

- Sensitive probes for BSM effects and precision benchmarks for the SM
- Directly measure the spectrum of an observable
- No need to specify a signal hypothesis a priori
  - Directly re-interpretable by theorists

Covered in this talk

- $H \rightarrow \tau\tau$
  - CMS: HIG-20-015
- $H \rightarrow b\bar{b}$
  - ATLAS: ATLAS–CONF–2021–010
  - CMS: JHEP12(2020)085
- $H \rightarrow WW$
  - CMS: JHEP03(2021)003
- $H \rightarrow ZZ \rightarrow 4\ell$
  - ATLAS: Eur. Phys. J. C (2020) 942
  - CMS: arXiv:2103.04956 (submitted to EPJC)
- $H \rightarrow \gamma\gamma$
  - ATLAS: ATLAS-CONF-2019-029
  - CMS: JHEP01(2019)183

Measured observables

Wide range of observables giving sensitivity to several effects (including BSM)

- Higgs production-related quantities probe pQCD calculations, radiative corrections, choice of PDF, light quark couplings, CP-structure of the Higgs sector:
  - $\boldsymbol{p_T^H,\ \eta_H,\ N_{jets},\ m_{jj},\ |\Delta\eta_{jj}|,\ \Delta\phi_{jj}}$

- Jet-related quantities probe radiative QCD quark and gluon emission patterns, QCD resummation effects
  - $\boldsymbol{p_T^{j_1},\ p_T^{j_2},\ N_{jets},\ m_{jj}}$

- Channel specific decay-related observables probe EW corrections and Higgs spin-parity properties
  - $\boldsymbol{m_{\ell_1\ell_2},\ m_{\ell_3\ell_4},\ angular\ variables}$

Different channels have sensitivity to different variables

$H \rightarrow \tau\tau$

HIG-20-015

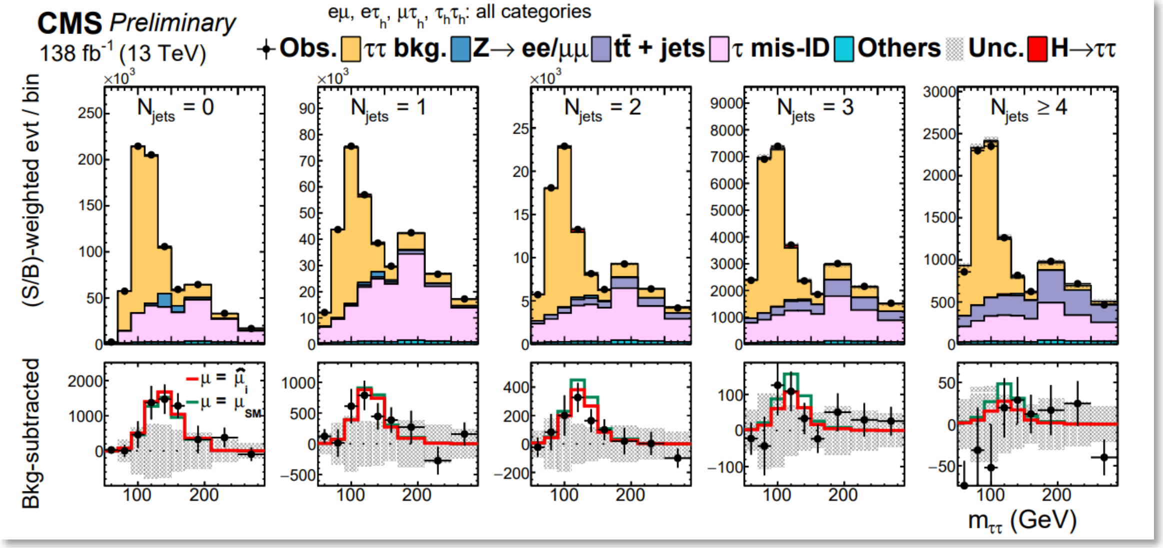
The H → $\tau\tau$ channel

NEW!

- The analysis measures p_T^H, N_{jets} and $p_T^{j_1}$ distributions
- Relatively large BR ($\sim 6\%$) makes this channel competitive, especially in the high p_T^H, N_{jets} regions
- All decay combinations of the $\tau\tau$ system considered, apart from $ee + 4\nu$ and $\mu\mu + 4\nu$
- **First differential measurement in this channel!**

Main backgrounds

- $Z \rightarrow \tau\tau, t\bar{t}$, di-boson production
  - Events with two τ leptons estimated with embedded samples
  - Di-muon events in data with muons replaced with simulated τ leptons
- Jets misidentified as τ_h
  - Misidentification probability estimated in data



The fit is done on the mass of the $\tau\tau$ system ($m_{\tau\tau}$), reconstructed with a simplified matrix-element algorithm

SM expectation

Fit result

Results

Results unfolded to particle level within likelihood fit

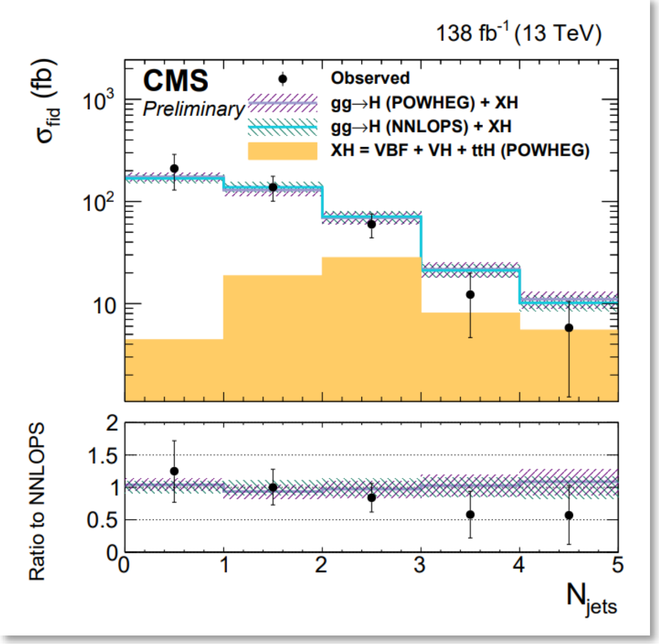
True for all analyses discussed except ALTAS $H \to \gamma\gamma$ (bin by bin corrections)

$$\mathcal{L} = \prod_i Poisson\left(n_i; \sum_j R_{ij}(\theta)\, \mu_j + b_i\right) \cdot \mathcal{C}(\theta) \cdot \mathcal{K}(\mu)$$

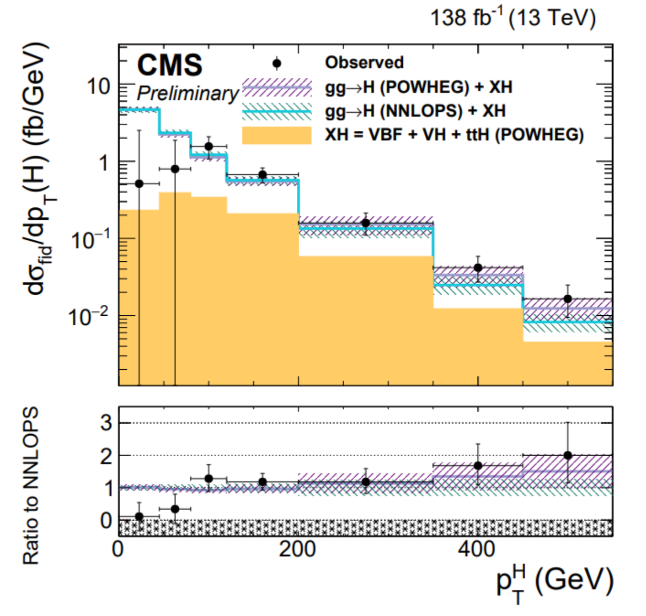
Migration matrix

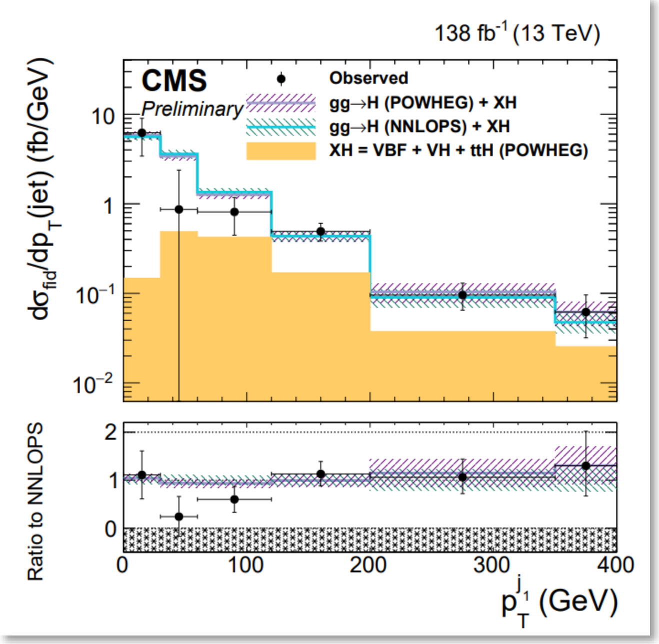
Particle level signal strength

Regularization term (optional), Tikhonov scheme in this analysis



- Measurement inclusive in production modes
- Prediction from POWHEGv2@NLO reweighted to NNLOPS
- Good agreement with expectation:
  - $p(p_T^H) = 17\%, p(N_{jets}) = 71\%, p\left(p_T^{j_1}\right) = 45\%$
- Fiducial cross section extracted from fit to N_{jets}:
  - $\sigma^{fid} = 426 \pm 102 \text{ fb} \left(\sigma_{SM}^{fid} = 408 \pm 27 \text{ fb}\right)$



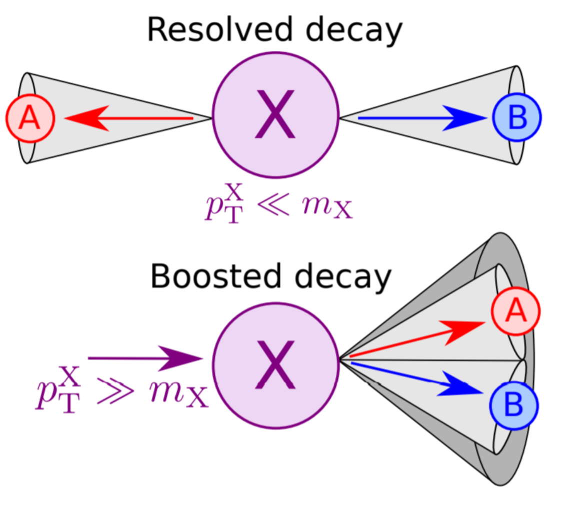


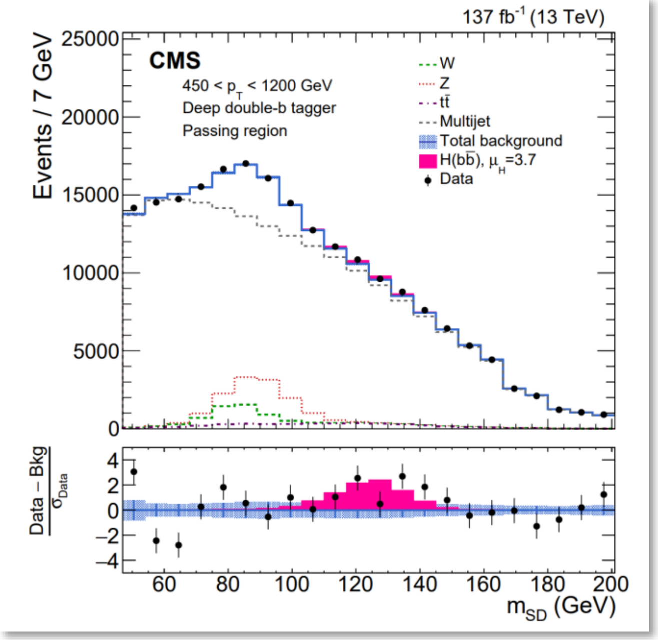
$H \to b\bar{b}$

ATLAS-CONF-2021-010 - JHEP12(2020)085

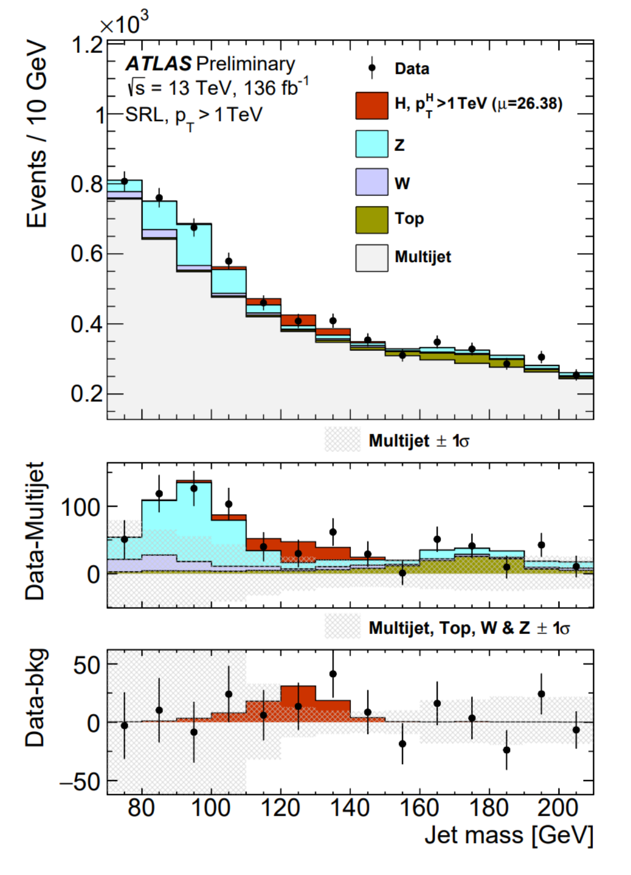
The H → $b\bar{b}$ channel

- Very high multijet (QCD) background
- $\mathrm{BR}(\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}) = 58\% \longrightarrow$ highest in the SM
- Mitigates natural cross section decrease at high p_T^H
- Both analyses target the boosted jet topology, i.e. a large radius jet with a 2 sub-jet structure





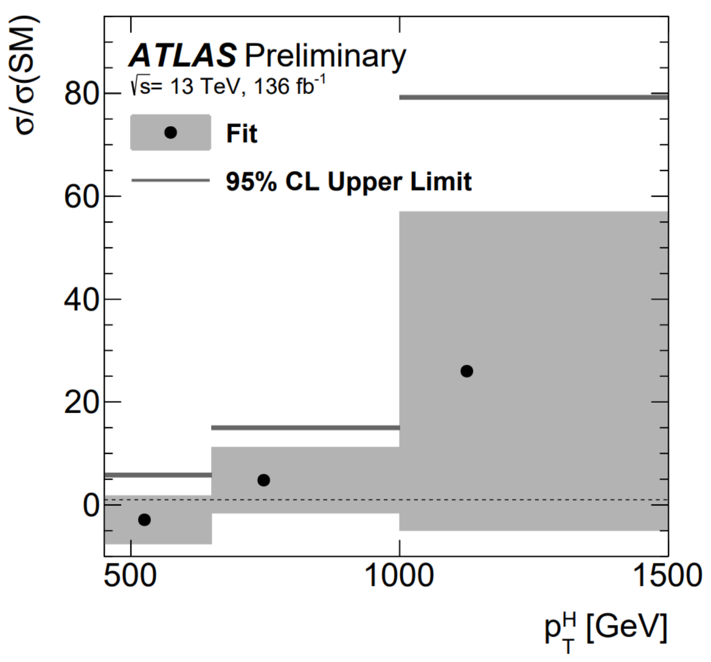
Signal extracted by fitting the jet mass distribution

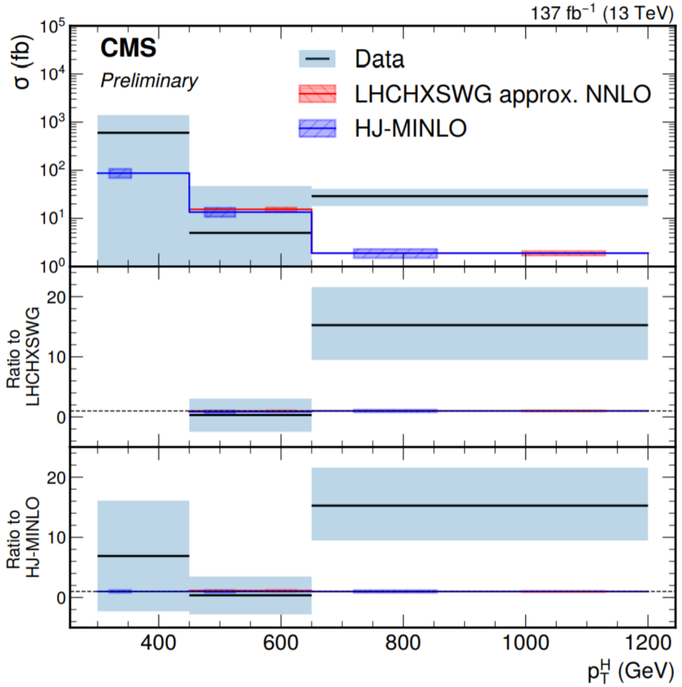


- ATLAS: $p_T^{j_1} > 450$ GeV, $p_T^{j_2} > 250$ GeV, one compatible with 2 sub-jets
- CMS: $p_T^{j_1} > 450$ GeV, dedicated MVA tagger

Results

- Different approach for the two analyses (differential results):
  - ATLAS: inclusive in production modes
  - CMS: targets gluon fusion, other modes treated as background





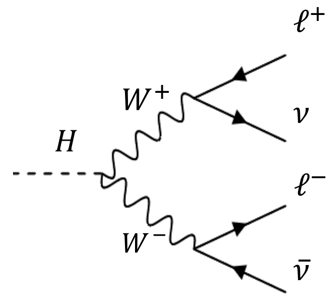
- ATLAS: good agreement with SM
  - Predictions from POWHEG+MINLO (ggH), POWHEG-BOX v2 (VBF, $gg \to VH$, $t\bar{t}H$) and POWHEG-BOX v2+MINLO ($qq \to VH$)
- CMS: 2.6σ excess in highest p_T^H bin, reduced to 1.8σ when considering all bins simultaneously
  - Prediction from HJ-MINLO
  - Also compared to NNLO calculation from LHCHXSWG

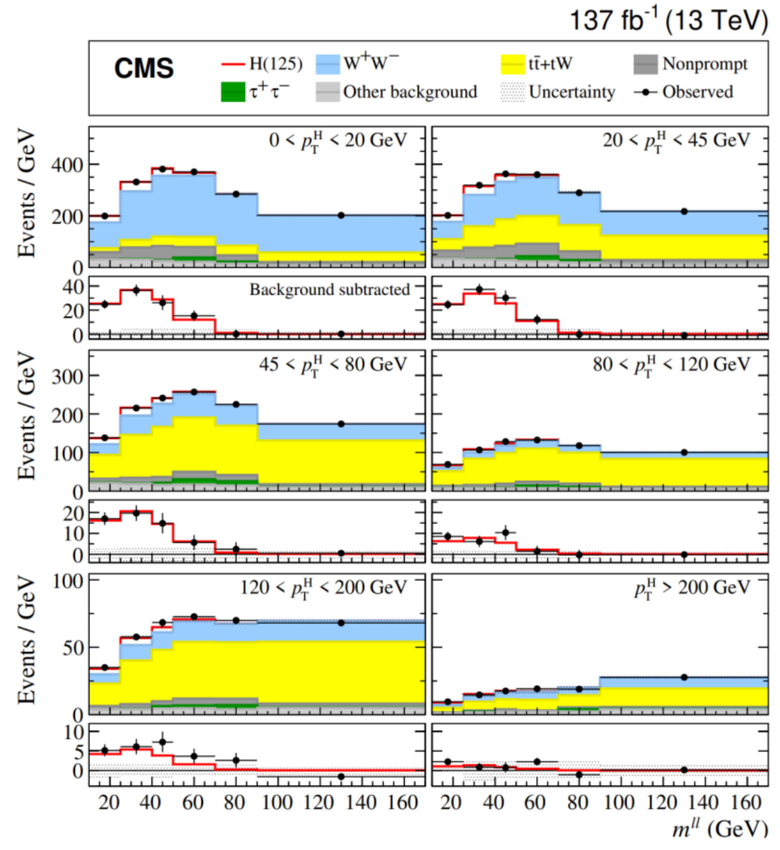
$H \rightarrow WW$

JHEP03(2021)003

The H → WW channel

- Bosonic channels give good sensitivity on a wide range
- Second highest total branching ratio, highest to a leptonic final state
- Final state with 2 leptons and 2 neutrinos provides best sensitivity
- **No access to full kinematics of the diboson system**
  - Neutrinos are undetected, resulting in missing transverse energy (MET)
  - The fit is done on the dilepton invariant mass and Higgs transverse mass





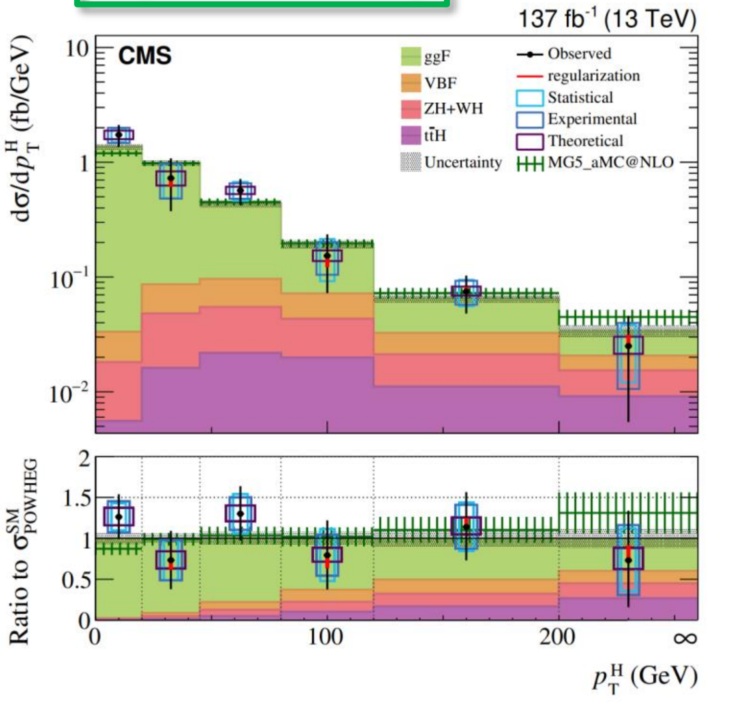
Main backgrounds

- **Non-resonant WW, $t\bar{t}$ (dominant):**
  - Normalization measured in data
- **Lepton misidentification, $DY \rightarrow \tau\tau$ (subdominant):**
  - DY normalization measured in control region, lepton misidentification probability estimated from data
- **Di-boson and tri-boson production (minor):**
  - Estimated via MC simulation

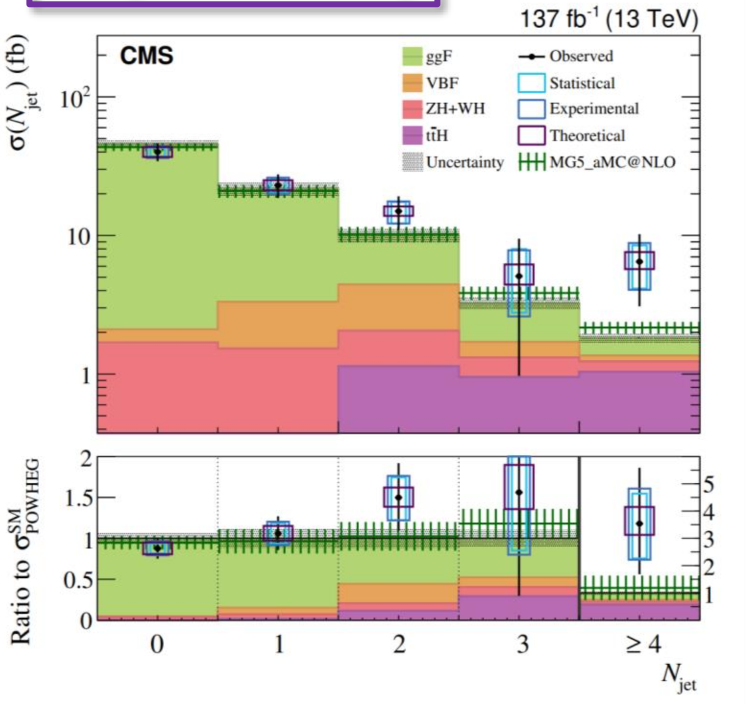
Results

- Fiducial and differential (p_T^H, N_{jets}) cross sections
- All production modes are considered
- Nominal prediction form POWHEGv2 at NLO, ggH reweighted to NNLOPS
- Results also compared to MG5@NLO
- Good agreement to SM, highest excess for $N_{jets} \geq 4$ at 1.4σ

Regularized unfolding



Unregularized unfolding



- Total fiducial cross section obtained from fit on p_T^H
- Good agreement with SM prediction obtained from POWHEGv2

$\sigma^{fid} = 86.5 \pm 9.5$ fb

$\sigma^{fid}_{SM} = 82.5 \pm 4.2$ fb

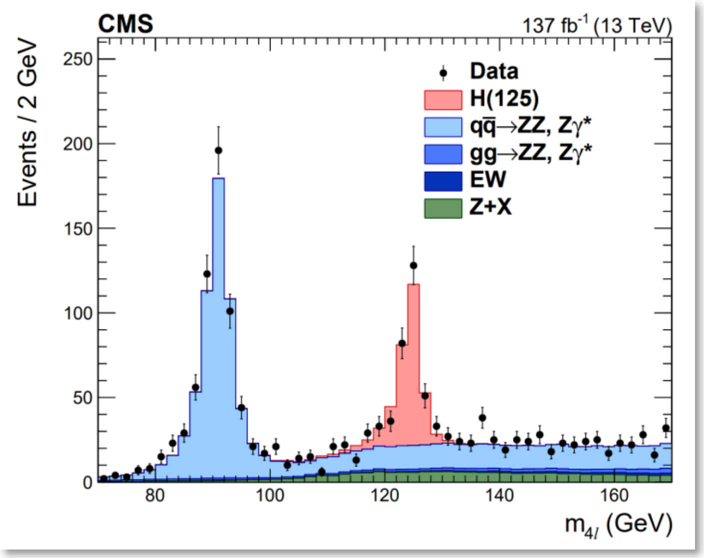
$\mu^{fid} = 1.03^{+0.12}_{-0.11}(\pm 0.05(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.03(\text{lumi.}) \pm 0.07(\text{exp.}))$

$\mathrm{H} \rightarrow \mathrm{ZZ} \rightarrow 4\ell$

EUR. PHYS. J. C (2020) 942 - ARXIV:2103.04956 (SUB. TO EPJC)

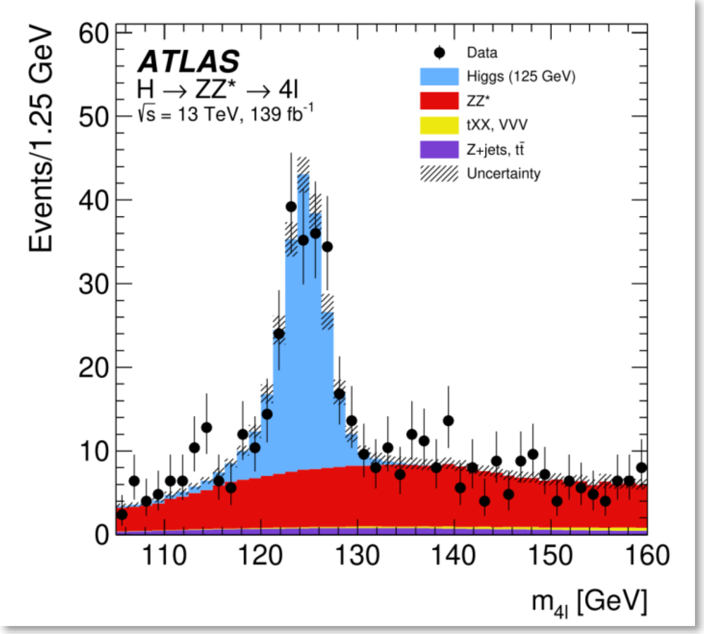
The H → ZZ → 4ℓ channel

- Relatively low BR compensated by very well reconstructed final state
- Selected events contain 4 leptons (e, μ), grouped into same-flavor opposite-charge (SFOC) pairs to form Z candidates
- **Access to the full kinematics of the Higgs system**

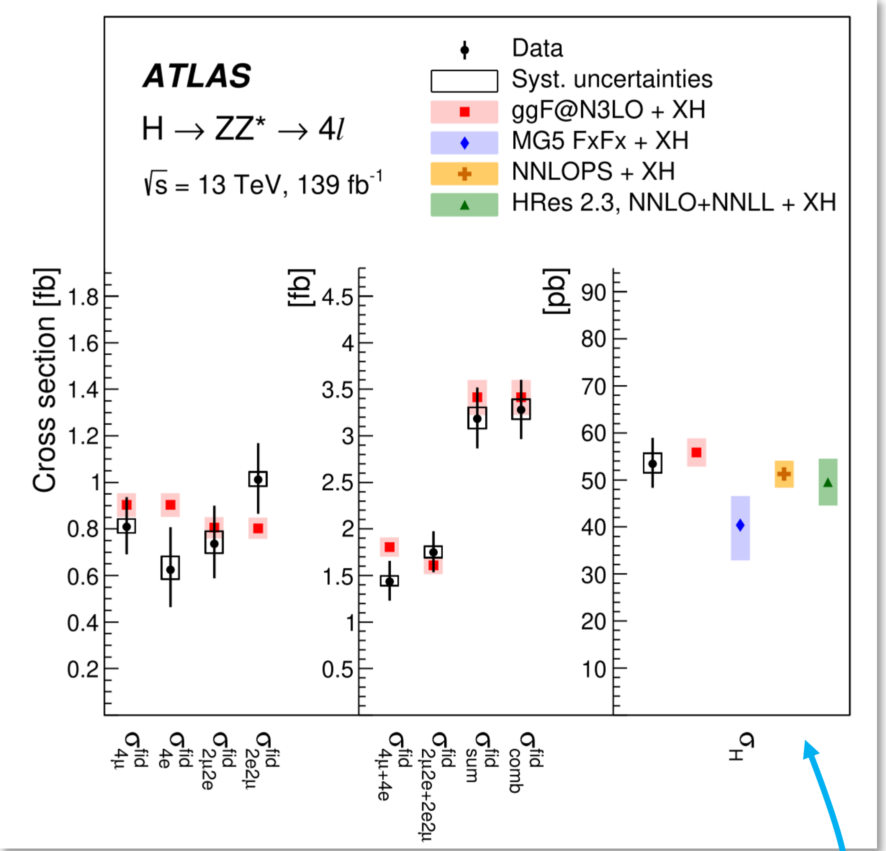


Main backgrounds

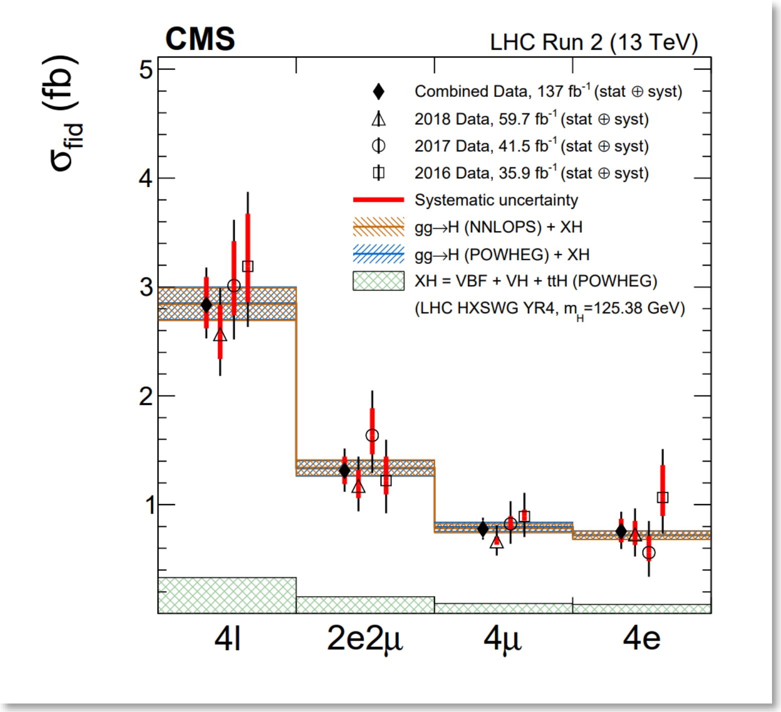
- **Non-resonant $ZZ/Z\gamma$ production (dominant):**
  - ATLAS: shape estimated from simulation and normalization measured in m_H sidebands
  - CMS: shape and normalization estimated from simulation
- $Z + jets, t\bar{t}, WZ$ **(subdominant):**
  - Estimated in dedicated control regions
- **Triboson, tVV and $t\bar{t}V$ (minor):**
  - Taken from simulation

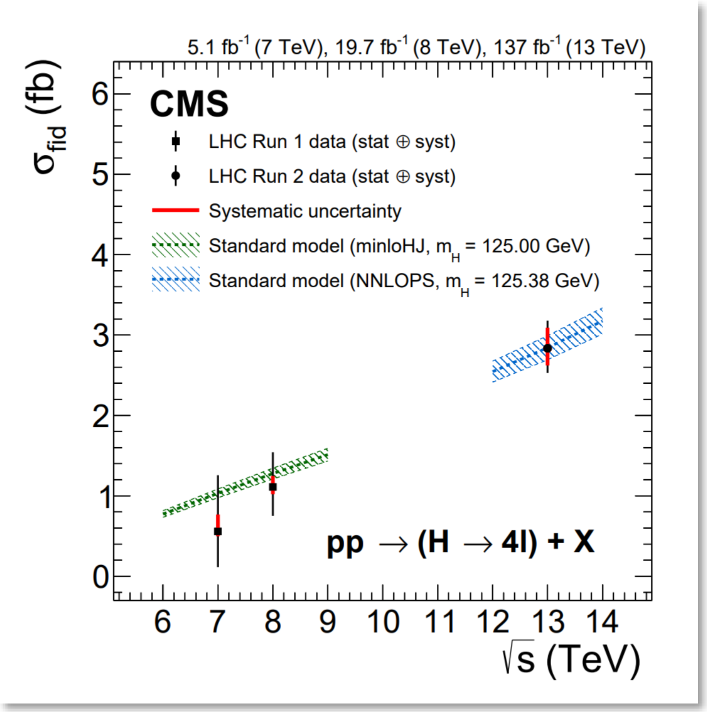


Results - fiducial cross sections



Total cross section extrapolated assuming SM acceptance and BRs





- Results compared to different MC predictions
- **Good compatibility with the SM expectation**

Results - differential cross sections

ATLAS+CMS

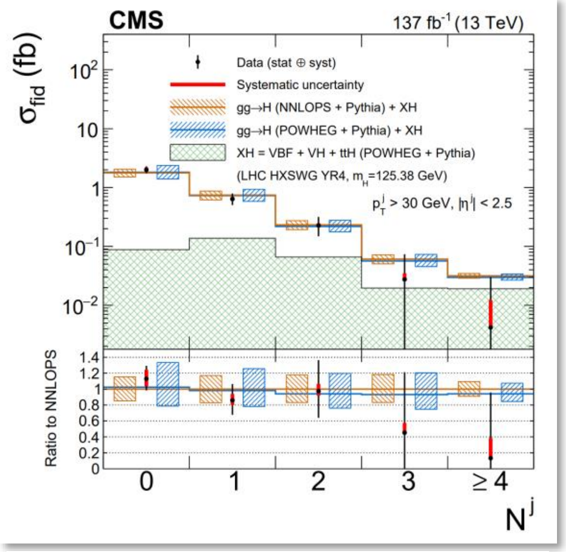
$p_T^H, |y_H|, N_{jets}, p_T^{j_1}$

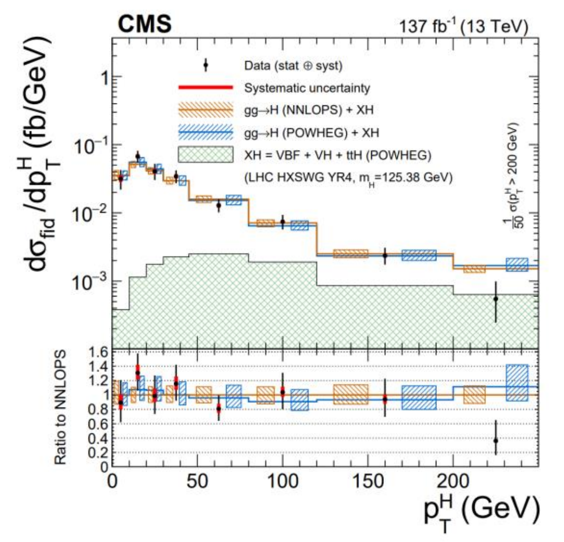
+

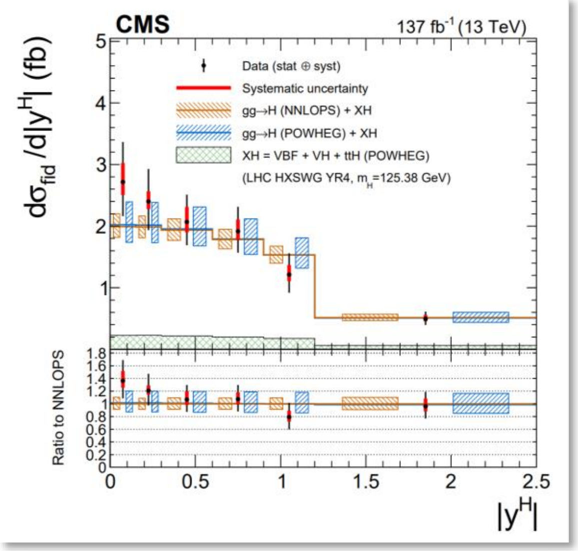
ATLAS

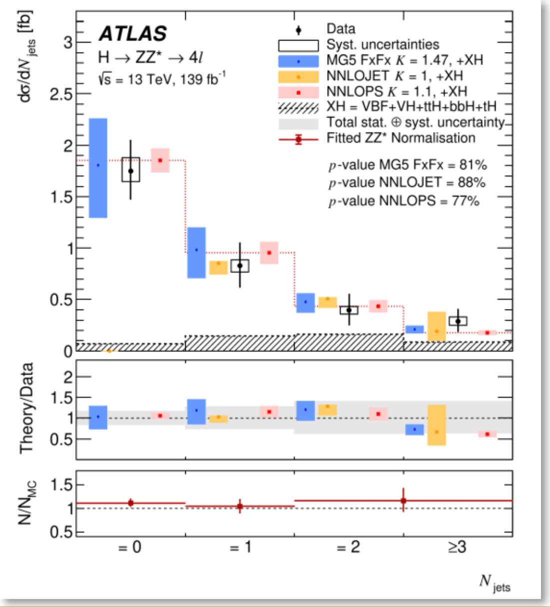
$m_{12}, m_{34}, |\cos\theta^*|$
$\cos\theta_1, \cos\theta_2, \phi, \phi_1$
$N_{b-jets}, p_T^{j_2}, m_{jj}$
$|\Delta\eta_{jj}|, \Delta\phi_{jj}$
$p_T^{Hj}, m_{4\ell j}, p_T^{Hjj}, m_{Hjj}$

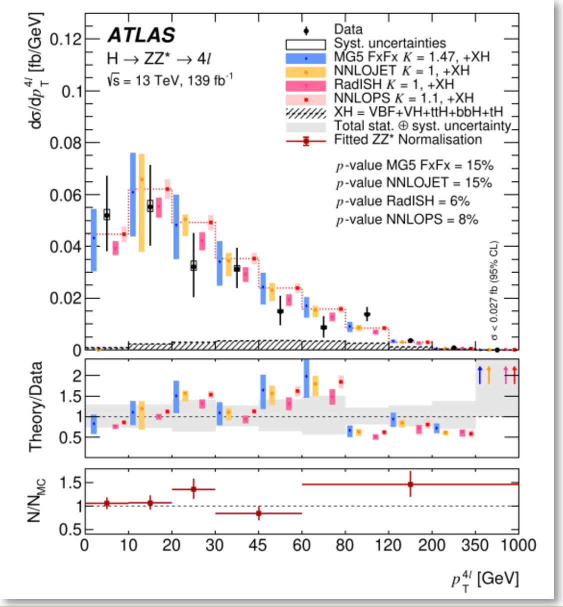
- Statistically dominated uncertainties
- Sensitive in the full range of many variables
- Good SM compatibility

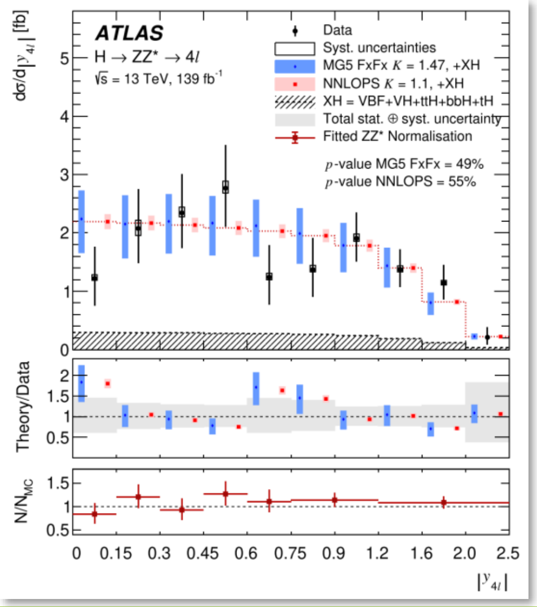












Results - double-differential cross sections

- ATLAS also measured a set of double-differential cross sections:

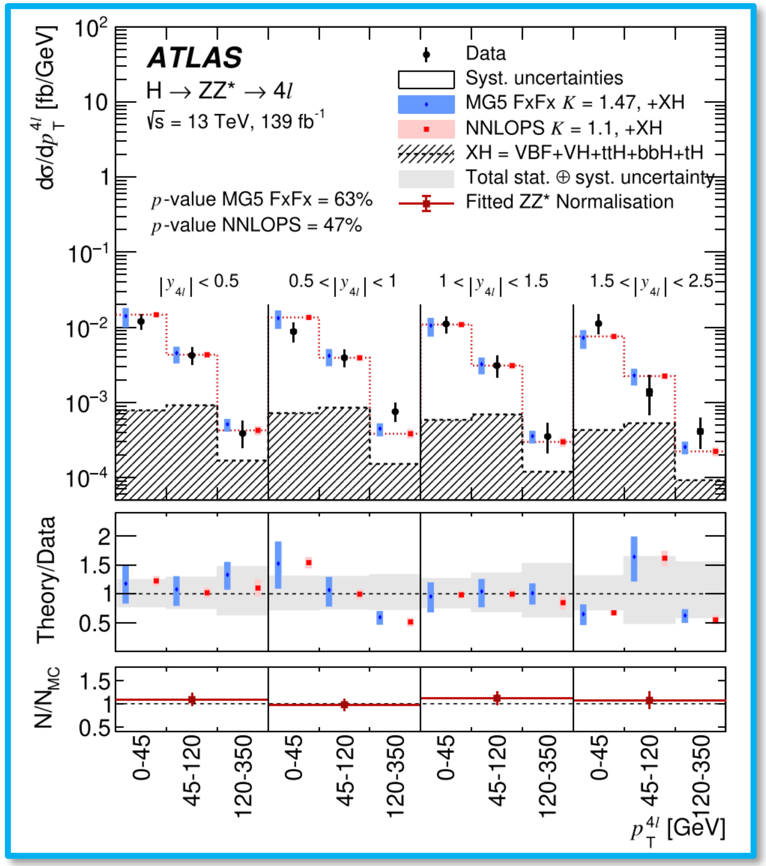
p_T^H VS $|y_H|$, p_T^H VS N_{jets}

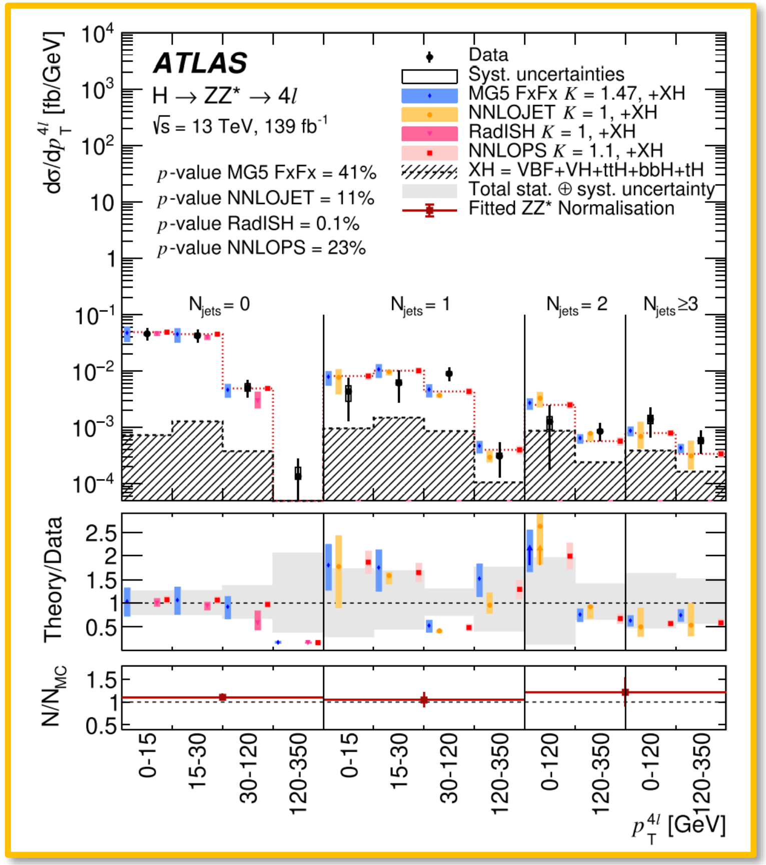
m_{12} VS m_{34}, p_T^H VS p_T^{Hj}

p_T^{Hj} VS m_{Hj}, p_T^H VS $p_T^{j_1}$

$p_T^{j_1}$ VS $|y_{j_1}|$, $p_T^{j_1}$ VS $p_T^{j_2}$

- 2D differential cross sections being made possible with Run II data
- Compared to NNLOPS and MG5@NLO-FxFx reweighted to N^3LO
- Jet-related distributions also compared to NNLOJET and RadISH



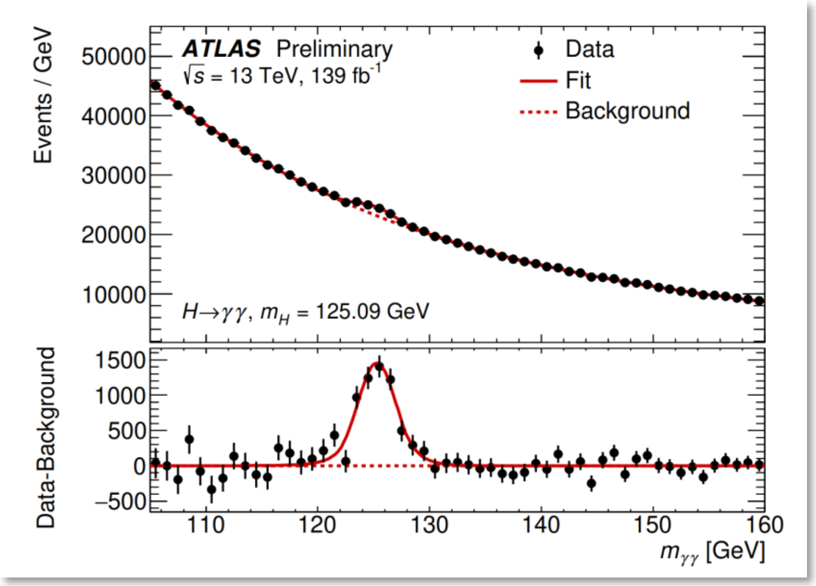


$H \rightarrow \gamma\gamma$

ATLAS-CONF-2019-029 - JHEP01(2019)183

The H → $\gamma\gamma$ channel

- Relatively small SM branching ratio (~0.2%) offset by very clean final state
- The full 4-momentum of the diphoton pair is accessible
- Excellent diphoton mass ($m_{\gamma\gamma}$) resolution of 1-2%
- Vertex assignment challenging (no tracker info)
  - Use of ML discriminants (BDT for CMS and NN for ATLAS)
- Main backgrounds: SM diphoton production (dominant), γ + jets, dijet (with misidentified jets)



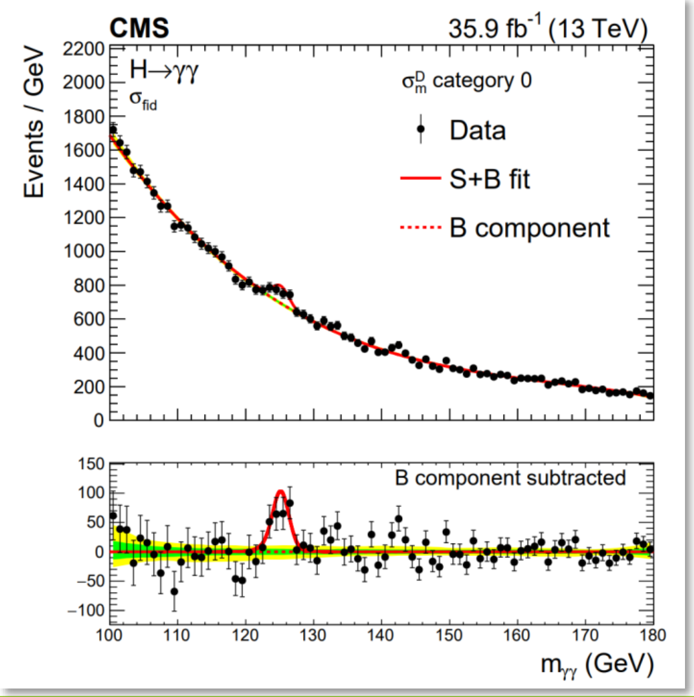
CMS (36 fb^{-1})

p_T^H, $|y_H|$, N_{jets}, $|\cos\theta^*|$, $p_T^{j_1}$, $p_T^{j_2}$, $|y_{j_1}|$, $|y_{j_2}|$, $|\Delta\phi_{Hj_1}|$, $|\Delta y_{Hj_2}|$, $|\Delta\phi_{jj}|$, $|\Delta\phi_{H,jj}|$, m_{jj}, $|\Delta\eta_{jj}|$, z

ATLAS (139 fb^{-1})

p_T^H, $|y_H|$, N_{jets}, $p_T^{j_1}$, m_{jj}, $\Delta\phi_{jj}$

Combinations with $H \to ZZ$ and $H \to bb$, see talk by Haider Abidi



Results

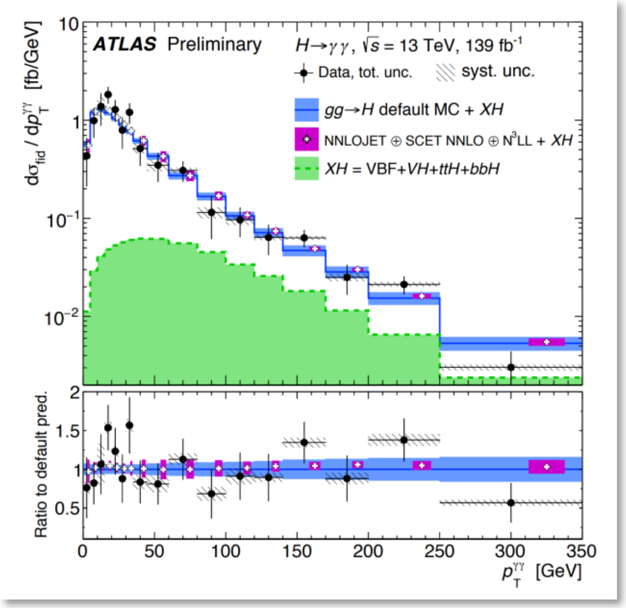
CMS (36 fb^{-1})

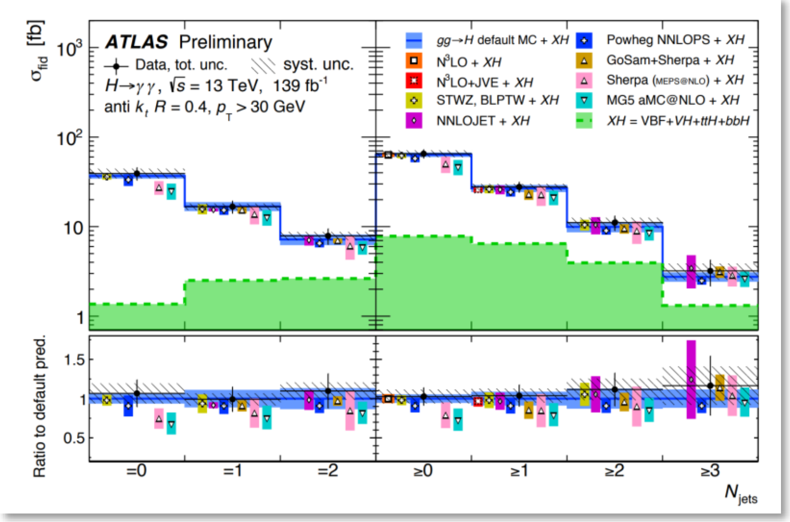
$$\sigma^{fid} = 84 \pm 11(\text{stat.}) \pm 7(\text{syst.})\ \text{fb}$$
$$\sigma^{fid}_{SM} = 73 \pm 4\ \text{fb}$$

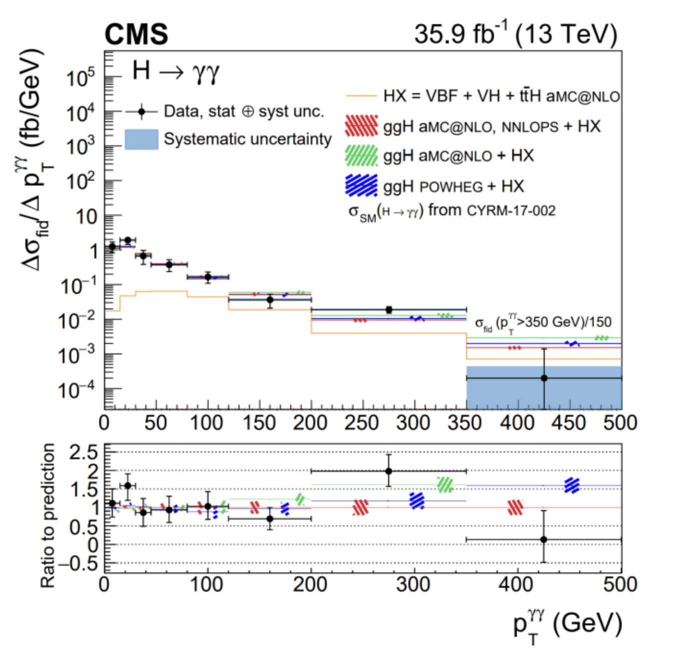
ATLAS (139 fb^{-1})

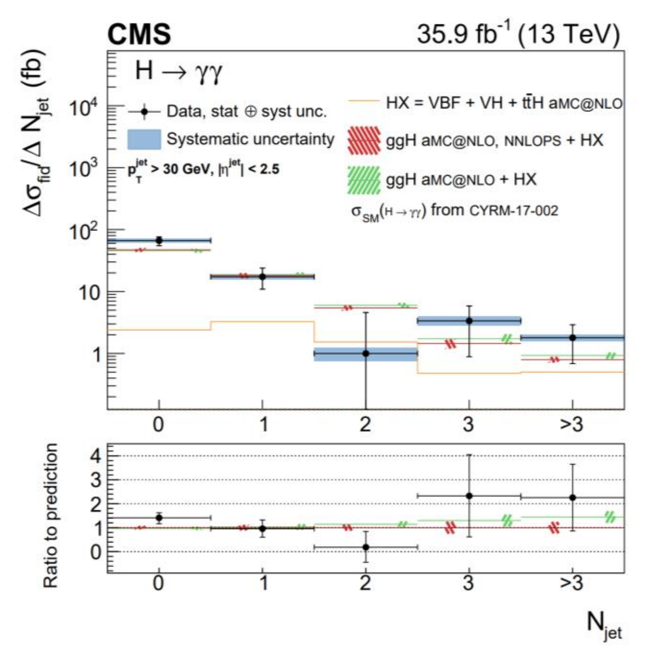
$$\sigma^{fid} = 65.2 \pm 4.5(\text{stat.}) \pm 5.6(\text{syst.})\ \text{fb}$$
$$\sigma^{fid}_{SM} = 63.6 \pm 3.3\ \text{fb}$$

- Good agreement with SM predictions
- ATLAS: default prediction from POWHEG@NNLOPS, compared with NNLOJET and others
- CMS: default prediction from MG5@NLO+FxFx reweighted to NNLOPS, compared to POWHEGv2









Conclusions

- I have presented the most recent fiducial and differential measurements in the Higgs sector from the ATLAS and CMS collaborations
- Wide range of production modes, decay channels and observables - first $H \rightarrow \tau\tau$ differential result!
- Results are unfolded to particle level, allowing direct comparison with theory
- Most measurements still statistically dominated, looking forward to Run III of the LHC and beyond!
- More Run II results still to come, stay tuned!

- **Thank you very much for your attention**

Backup

Combination

ATLAS-CONF-2019-032 - Physics Letters B 792 (2019)

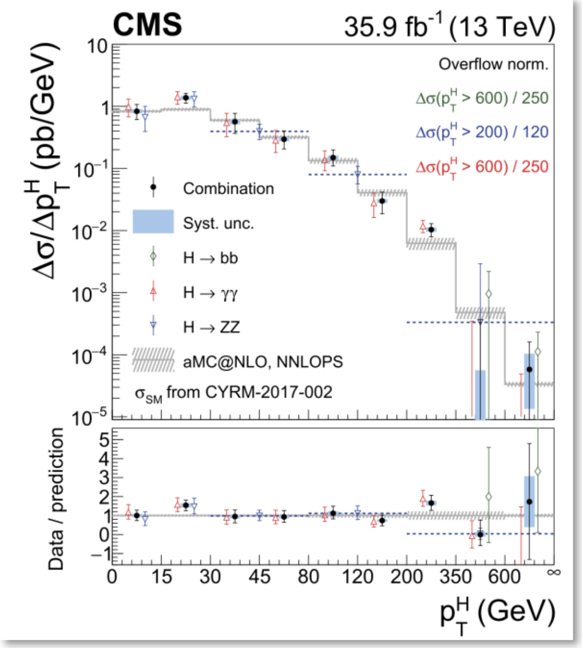
CMS (36 fb^{-1})

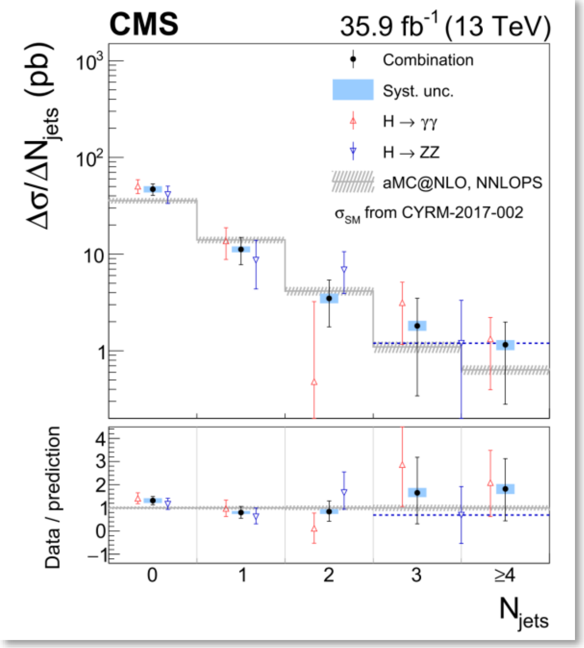
$H \rightarrow \gamma\gamma + H \rightarrow ZZ + H \rightarrow b\bar{b}$

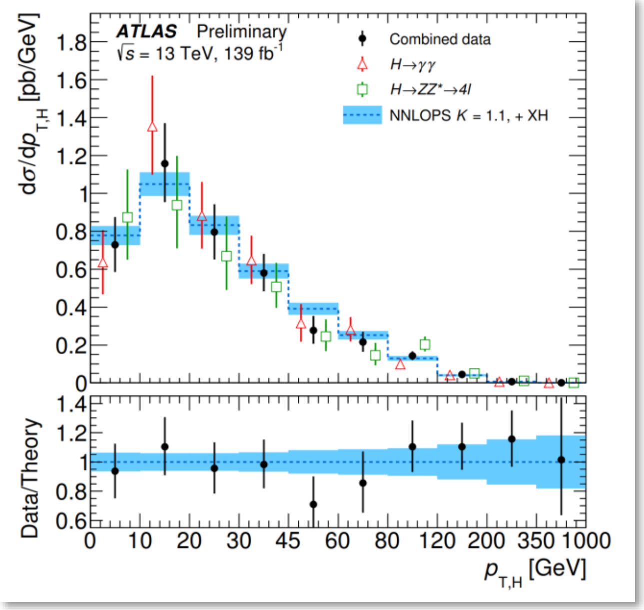
ATLAS (139 fb^{-1})

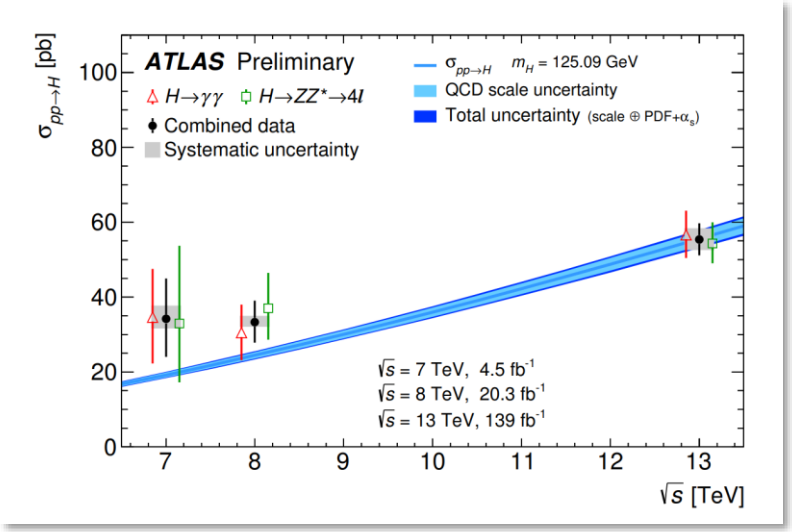
$H \rightarrow \gamma\gamma + H \rightarrow ZZ$

- Measurements must be extrapolated from the fiducial volume to the full phase space
- Done assuming SM acceptances
- **Good agreement with predictions**









Fiducial volume definitions - H → ττ

CMS

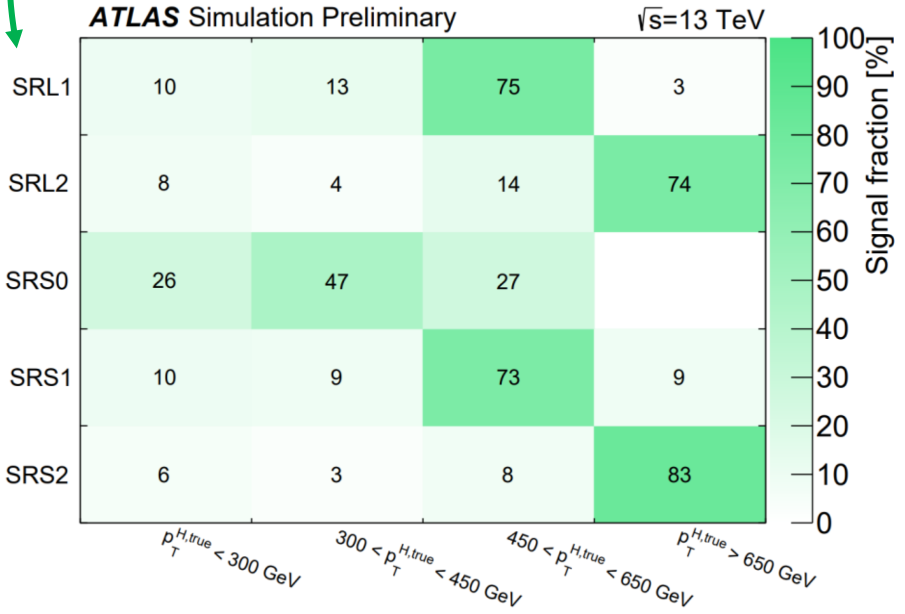
- $e\tau_h$ ($\mu\tau_h$):
  - Electron (muon) $p_T > 25(20)$ GeV and $|\eta| < 2.1$
  - Visible τ_h $p_T > 30$ GeV and $|\eta| < 2.3$
  - $m(e/\mu, \vec{p}_T^{miss}) < 50$ GeV
- $\tau_h\tau_h$:
  - Visible τ_h $p_T > 40$ GeV and $|\eta| < 2.1$
  - At least one jet with $p_T > 30$ GeV
- $e\mu$:
  - Leading (subleading) lepton $p_T > 24(15)$ GeV
  - Lepton $|\eta| < 2.4$
  - $m_T(e\mu, \vec{p}_T^{miss}) < 60$ GeV

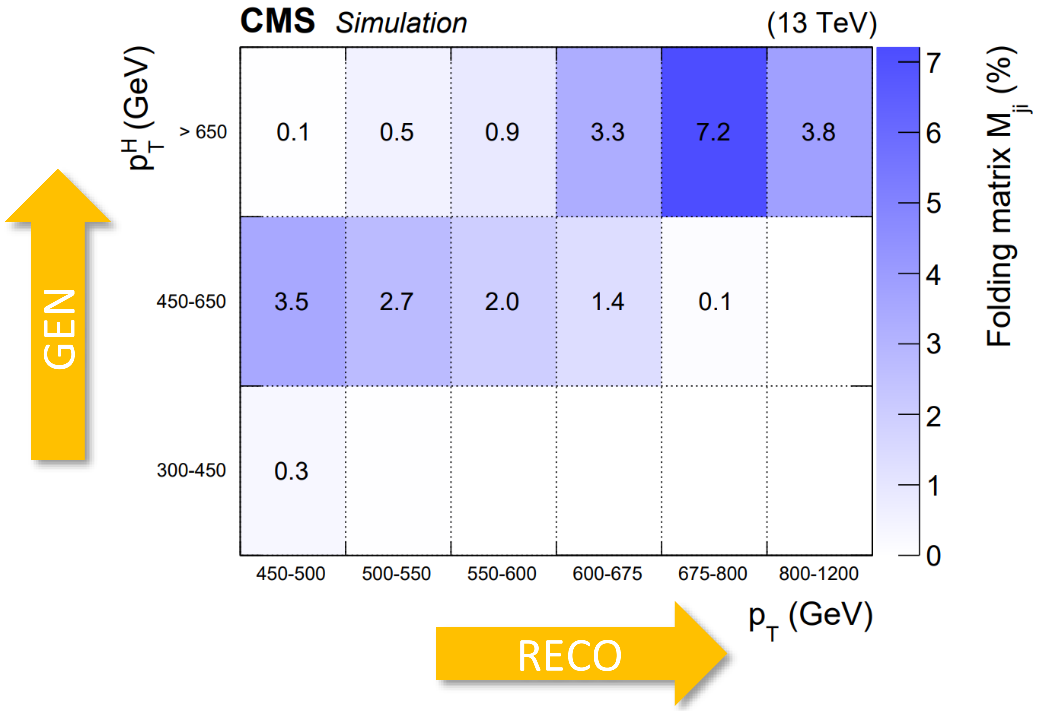
Momenta of photons radiated within $\Delta R = 0.1$ of a lepton are added to the lepton's momentum

Migration matrices - H → bb

SRL(S): leading (subleading) jet tagged

p_T^H [GeV] SRL	p_T^H [GeV] SRS	$\lvert\eta_H\rvert$ SRL/SRS
–	–	–
>450	>450	< 2
>1000	–	< 2
450–650, >650	300–450, 450–650, >650	< 2





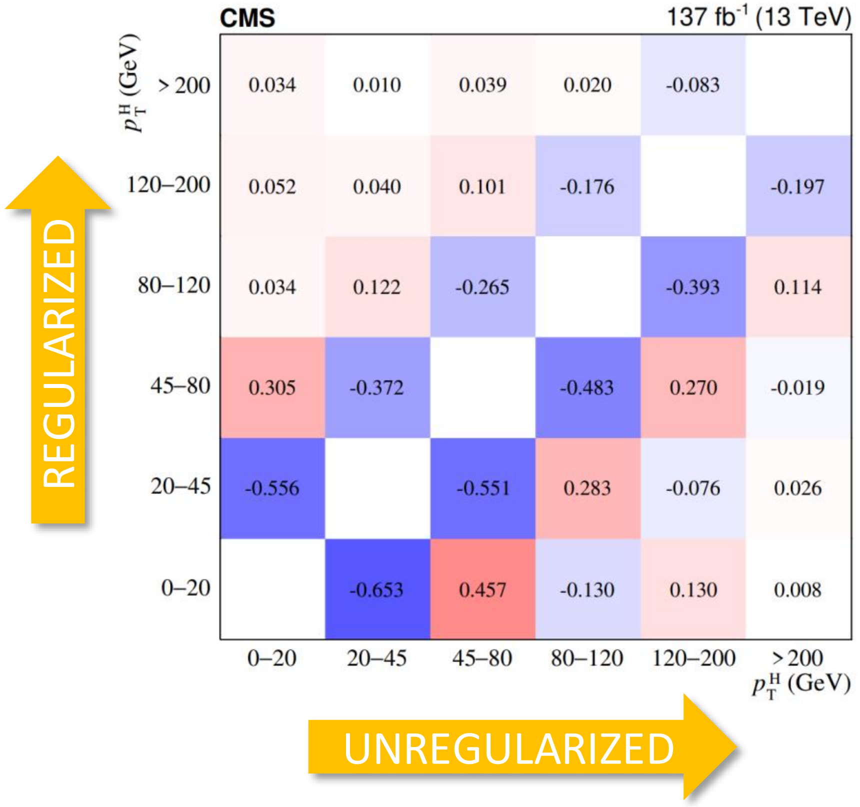
Fiducial volume definitions - $H \to WW$

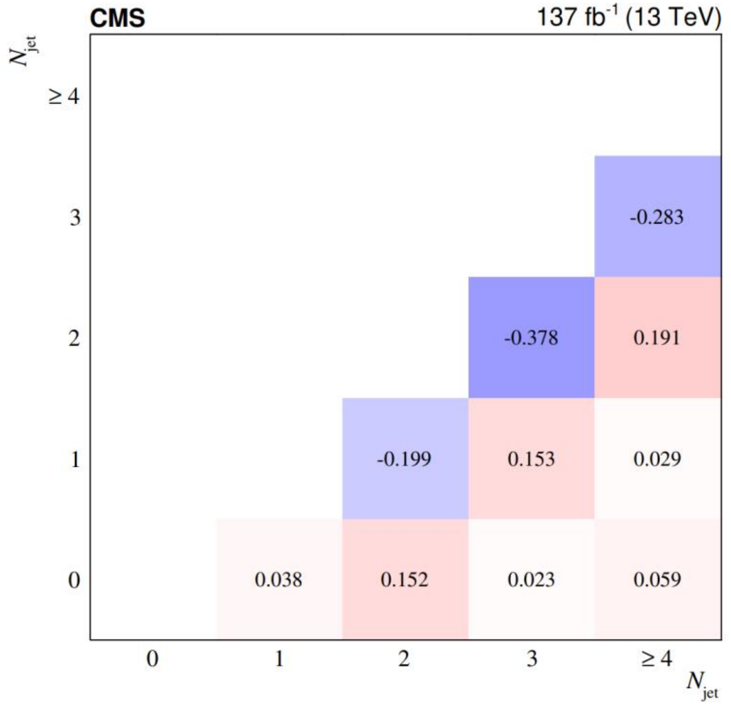
CMS

Observable	Condition
Lepton origin	Direct decay of $H \to W^+W^-$
Lepton flavors; lepton charge	e μ (not from τ decay); opposite
Leading lepton p_T	$p_T^{l_1} > 25$ GeV
Trailing lepton p_T	$p_T^{l_2} > 13$ GeV
$\|\eta\|$ of leptons	$\|\eta\| < 2.5$
Dilepton mass	$m^{ll} > 12$ GeV
p_T of the dilepton system	$p_T^{ll} > 30$ GeV
Transverse mass using trailing lepton	$m_T^{l_2} > 30$ GeV
Higgs boson transverse mass	$m_T^H > 60$ GeV

Momenta of photons radiated within $\Delta R = 0.1$ of a lepton are added to the lepton's momentum

Correlation matrices - H → WW





Correlations among the unfolded signal strength modifiers

Fiducial volume definitions - H → ZZ

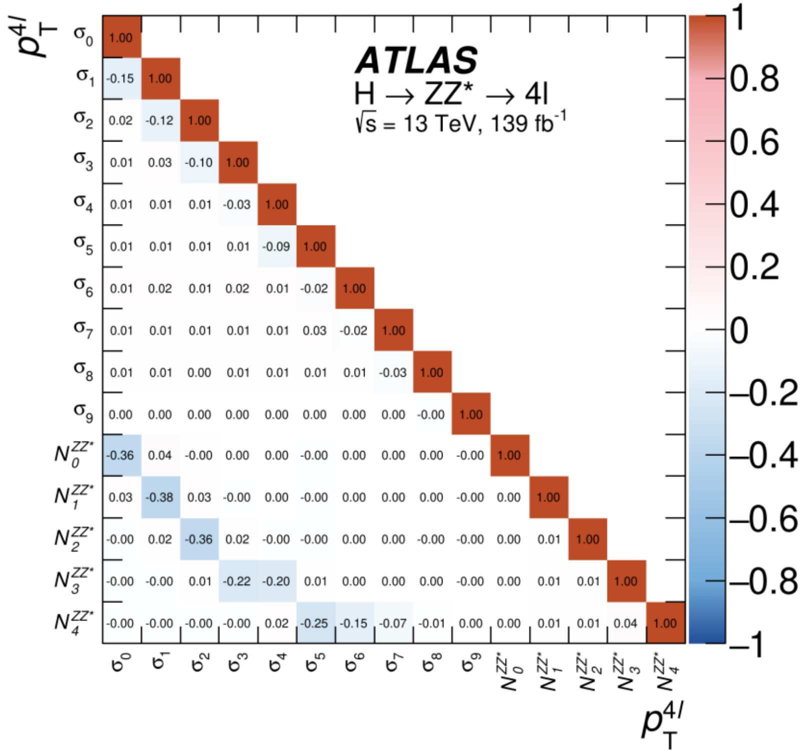
ATLAS

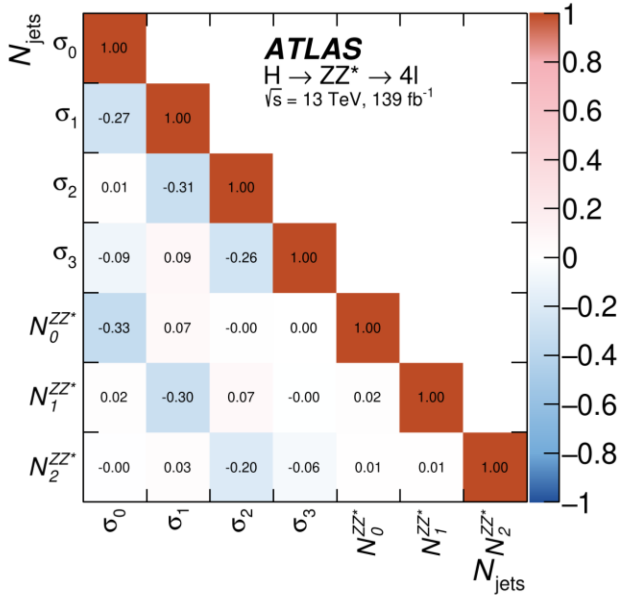
Leptons and jets	
Leptons	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
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	$\Delta R(\ell_i, \text{jet}) > 0.1$
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 $p_T > 12$ GeV	Quadruplet with largest matrix element value

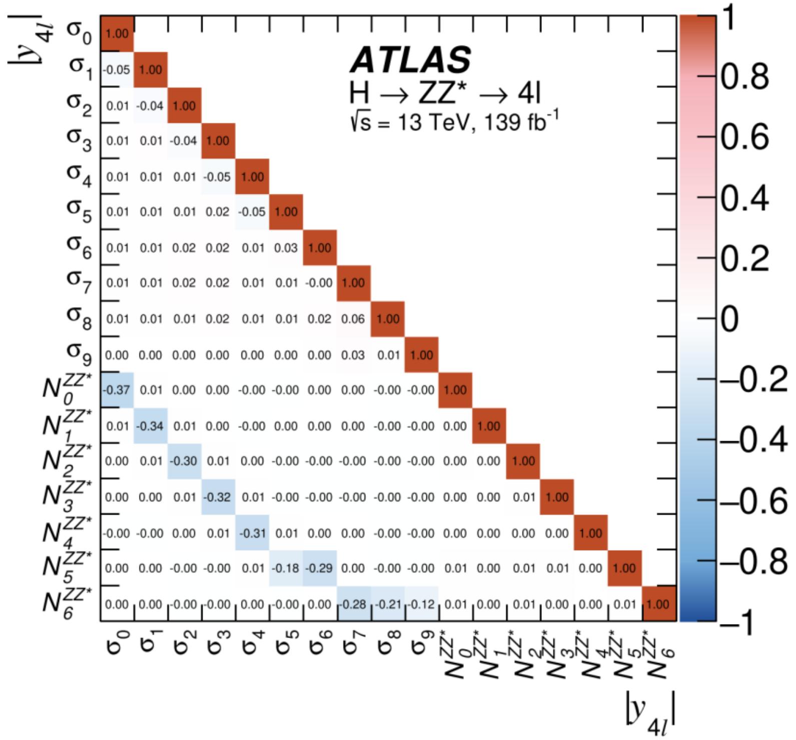
CMS

Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{Z_1} < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m_{Z_2} < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

Correlation matrices - H → ZZ







Fiducial volume definitions - H $\rightarrow \gamma\gamma$

ATLAS

Objects	Fiducial definition
Photons	$\lvert\eta\rvert < 2.37$ (excluding $1.37 < \lvert\eta\rvert < 1.52$), $\sum p_T^i / p_T^\gamma < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Diphoton	$N_\gamma \geq 2$, $105\,\text{GeV} < m_{\gamma\gamma} < 160\,\text{GeV}$, $p_T^{\gamma_1}/m_{\gamma\gamma} > 0.35$, $p_T^{\gamma_2}/m_{\gamma\gamma} > 0.25$

- The sum on p_T^i is extended to all charged particles within $\Delta R = 0.2$ of the photon

CMS

Phase space region	Observable	Bin boundaries								
	$p_T^{\gamma\gamma}$ (GeV)	0	15	30	45	80	120	200	350	∞
Baseline	N_{jet}	0	1	2	3	4	∞			
$p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$	$\lvert y^{\gamma\gamma}\rvert$	0	0.15	0.3	0.6	0.9	2.5			
$p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$	$\lvert\cos(\theta^*)\rvert$	0	0.1	0.25	0.35	0.55	1			
$\lvert\eta^\gamma\rvert < 2.5$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 0$	0	20	60	∞					
$\text{Iso}_{\text{gen}}^\gamma < 10\,\text{GeV}$	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} = 1$	0	60	120	∞					
	$p_T^{\gamma\gamma}$ (GeV), $N_{\text{jet}} > 1$	0	150	300	∞					
	$N_{\text{jet}}^{\text{b}}$	0	1	2	∞					
	N_{lepton}	0	1	2	∞					
	p_T^{miss} (GeV)	0	100	200	∞					
1-jet	$p_T^{j_1}$ (GeV)	0	45	70	110	200	∞			
Baseline + $\geq$1 jet	$\lvert y^{j_1}\rvert$	0	0.5	1.2	2	2.5				
$p_T^j > 30\,\text{GeV}$, $\lvert\eta^j\rvert < 2.5$	$\lvert\Delta\phi^{\gamma\gamma,j_1}\rvert$	0	2.6	2.9	3.03	π				
	$\lvert\Delta y^{\gamma\gamma,j_1}\rvert$	0	0.6	1.2	1.9	∞				
	$p_T^{j_2}$ (GeV)	0	45	90	∞					
2-jets	$\lvert y^{j_2}\rvert$	0	1.2	2.5	4.7					
Baseline + $\geq$2 jets	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
$p_T^j > 30\,\text{GeV}$, $\lvert\eta^j\rvert < 4.7$	$\lvert\Delta\phi^{\gamma\gamma,j_1 j_2}\rvert$	0	2.9	3.05	π					
	$\lvert\bar{\eta}_{j_1 j_2} - \eta_{\gamma\gamma}\rvert$	0	0.5	1.2	∞					
	$m^{j_1 j_2}$ (GeV)	0	100	150	450	1000	∞			
	$\lvert\Delta\eta^{j_1,j_2}\rvert$	0	1.6	4.3	∞					
VBF-enriched	$p_T^{j_2}$ (GeV)	0	45	90	∞					
2-jets + $\lvert\Delta\eta^{j_1,j_2}\rvert > 3.5$, $m^{j_1 j_2} > 200\,\text{GeV}$	$\lvert\Delta\phi^{j_1,j_2}\rvert$	0	0.9	1.8	π					
	$\lvert\Delta\phi^{\gamma\gamma,j_1 j_2}\rvert$	0	2.9	3.05	π					