$H \to \gamma\gamma$

Workshop on Photon Physics and Simulation at Hadron Colliders 2019

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on behalf of the ATLAS and CMS Collaboration

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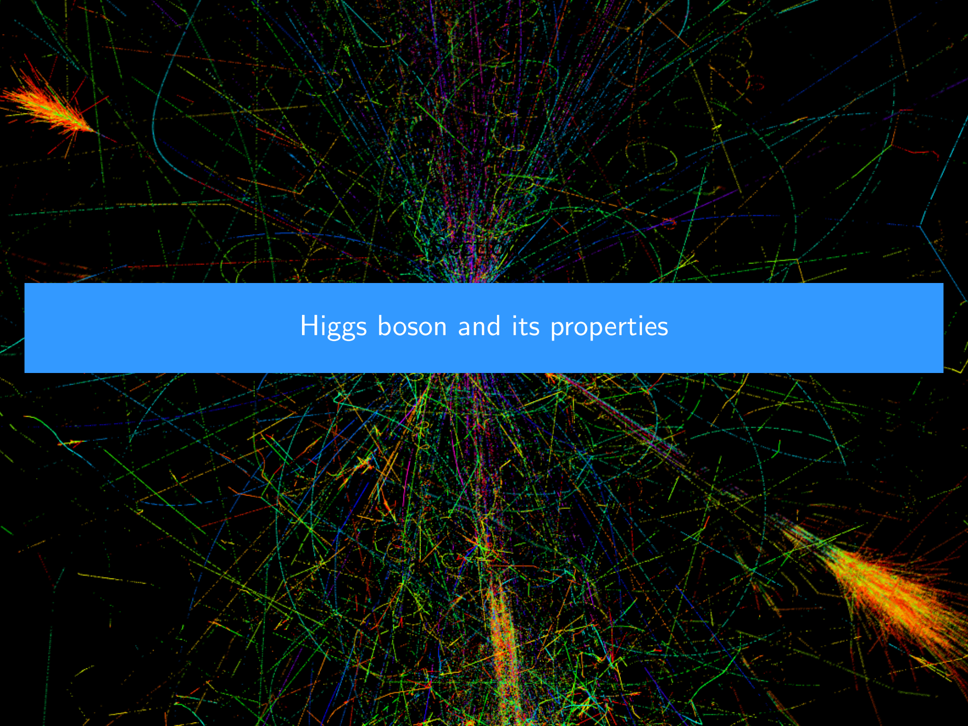
Recent $H \to \gamma\gamma$ analyses

Date[1]	Collaboration	Topic	Luminosity	link
2018/6	ATLAS	Mass	$36\,\text{fb}^{-1}$	*Phys. Lett. B 784 (2018) 345*
2017/11	ATLAS	EFT from STXS	$36\,\text{fb}^{-1}$	ATL-PHYS-PUB-2017-018
2018/2	ATLAS	STXS + fiducial/diff	$36\,\text{fb}^{-1}$	*Phys. Rev. D 98 (2018) 052005*
2018/7	ATLAS	STXS + fiducial/diff	$80\,\text{fb}^{-1}$	ATLAS-CONF-2018-028
2018/4	CMS	coupling	$36\,\text{fb}^{-1}$	*JHEP 11 (2018) 185*
2018/7	CMS	fiducial/diff	$36\,\text{fb}^{-1}$	*JHEP 01 (2019) 183*
2019/3	CMS	STXS (ggF and VBF)	$77\,\text{fb}^{-1}$	CMS-PAS-HIG-18-029
2019/4	ATLAS	ttH	$140\,\text{fb}^{-1}$	ATLAS-CONF-2019-004
2018/10	CMS	ttH	$77\,\text{fb}^{-1}$	CMS-PAS-HIG-18-018

[1] of the preprint



Section

Higgs boson and its properties

Higgs properties

Excess compatible with Higgs boson firmly established by ATLAS+CMS in 2012.

Measurements

- Mass: m_H known at 0.2% (single experiment)
- $\sigma \times Br$: inclusive, for each production-mode, fiducial region (STXS) (very optimized on the SM, acceptance extrapolations, model dependent)
- Fiducial cross sections or differential cross sections in fiducial regions (minimal model dependence)

Interpretations

- Spin and parity: 0^+, other models excluded in Run 1.
- Signal strengths: $\mu_i = \sigma_i / \sigma_i^{SM}$ (inclusive, per-production-mode, ...)
- Coupling modifiers to SM particles (k-framework)
- EFT interpretations, CP, ...

Higgs properties

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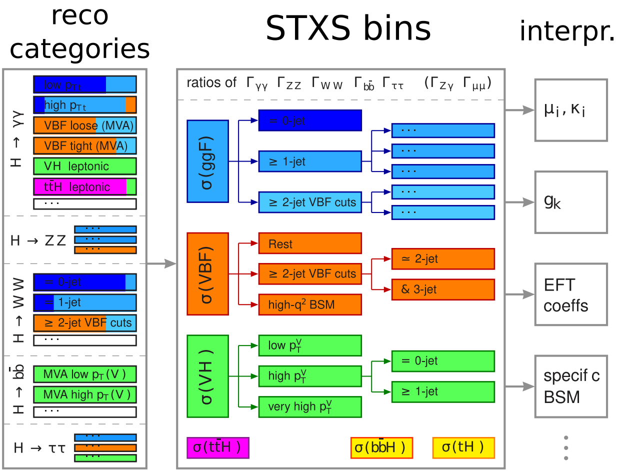
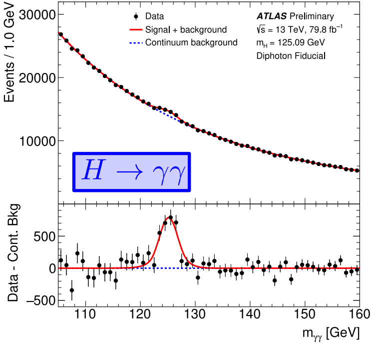
- Exclusive fiducial regions defined by production mode, p_T^H, N_j, VBF-topology, $p_T^{j_1}$, p_T^{Hjj}, p_T^V

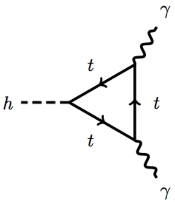


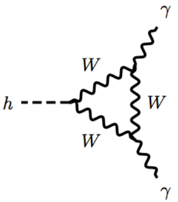
- Design measurement to split events according to STXS

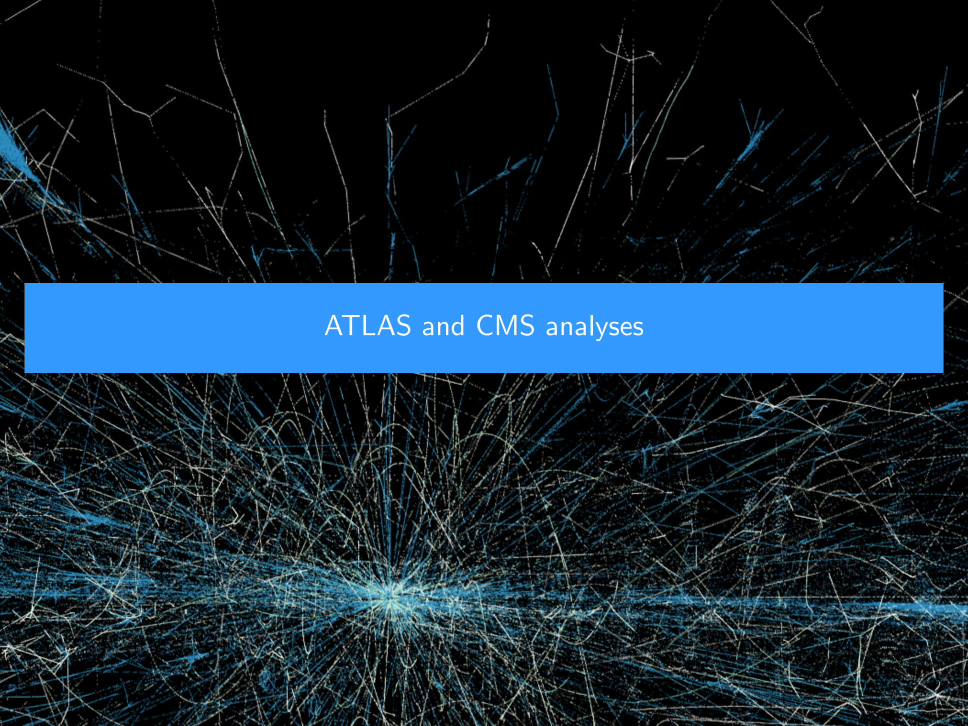
$H \to \gamma\gamma$

- Small Br: 2.27×10^{-3}
- Loop decay: sensitive to BSM
- Simple final state: good resolution (1.4–2.1 GeV), good efficiency ($\simeq 40\%$)
- Very large background $q\bar{q}/gg \to \gamma\gamma$ and fakes
- Falling background, can be modelled fitting data $m_{\gamma\gamma}$ sidebands









ATLAS and CMS analyses

Shape ($m_{\gamma\gamma}$) analysis in categories of selected events

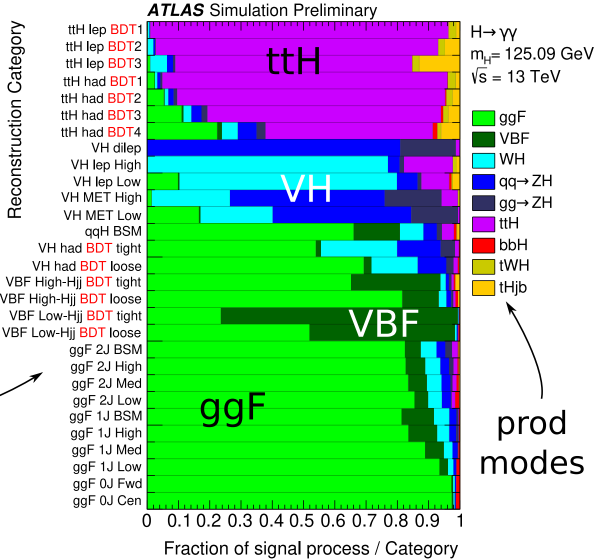
- Use fit to $m_{\gamma\gamma}$ to extract signal and bkg yields in selected sample
- Modeling background $m_{\gamma\gamma}$ distribution with analytical functions
- Signal shape from MC, as double sided Crystall Ball (ATLAS) or sum of Gaussians (CMS)
- Photons are selected using shower shapes and isolation:
  - ATLAS: rectangular cuts (tight selection)
  - CMS: BDT, usually used as a continous variable
- Extract signal in different categories pure of events under study (production mode, STXS, kinematic bin, . . .)
  - Categories defined from properies of selected objects (kinematic, identification, quality, . . .)
  - CMS has a predictor of the expected resolution

Coupling categorization in ATLAS (STXS)

ATLAS-CONF-2018-028

To measure many cross-sections with small correlation split events in pure categories

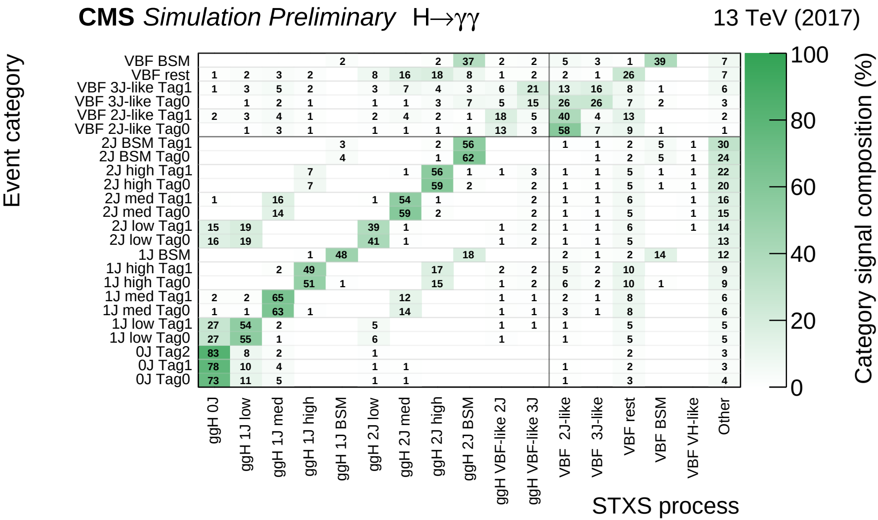
29 reco-categories inspired by STXS



prod modes

Categorization in CMS (ggF and VBF STXS)

- Diphoton-BDT using photon kinematic, BDT-id score, mass resolution, vertex probability
- VBF categorization:
  - dijet-BDT trained with signal: VBF, background: ggF+jets and non-Higgs (from control region inverting photon id score)
  - 6 categories using dijet $\otimes$ diphoton-BDT and p_T^{Hjj}, m_{jj}, $p_T^{j_1}$ mimic STXS (2J, 3J, BSM, rest)
- ggF categorization:
  - mimic STXS using $p_T^{\gamma\gamma}$ and number of jets. Split also by diphoton BDT ("Tag").
- All BDT validated on $Z \to ee$


CMS Simulation Preliminary H→γγ
13 TeV (2017)
Event category
VBF BSM
VBF rest
VBF 3J-like Tag1
VBF 3J-like Tag0
VBF 2J-like Tag1
VBF 2J-like Tag0
2J BSM Tag1
2J BSM Tag0
2J high Tag1
2J high Tag0
2J med Tag1
2J med Tag0
2J low Tag1
2J low Tag0
1J BSM
1J high Tag1
1J high Tag0
1J med Tag1
1J med Tag0
1J low Tag1
1J low Tag0
0J Tag2
0J Tag1
0J Tag0
ggH 0J
ggH 1J low
ggH 1J med
ggH 1J high
ggH 1J BSM
ggH 2J low
ggH 2J med
ggH 2J high
ggH 2J BSM
ggH VBF-like 2J
ggH VBF-like 3J
VBF 2J-like
VBF 3J-like
VBF rest
VBF BSM
VBF VH-like
Other
STXS process
Category signal composition (%)
100
80
60
40
20
0

ATLAS, great improvement using agressive optimization:

- Leptonic ($\geq 1\ell$, $\geq 1b$), hadronic ($\geq 1b$, $\geq 2j$, 0ℓ) regions
- Train two BDT with low-level variables: $p_T/m_{\gamma\gamma}, \eta, \phi$ of photons, p_μ of up to two leptons, p_μ of up to four/six jets (lep/had, p_T sorted), magnitude and ϕ of E_T-miss
- Categories defined from the BDT output
- Trained on MC ttH signal and control regions (non-tight non-isolated) for background

CMS:

- Leptonic ($\geq 1\ell$, $\geq 1b$), hadronic ($\geq 2j$, 0ℓ) regions
- Train two BDT with: $p_T/m_{\gamma\gamma}, \eta$, BDT-id of photons, $\Delta\phi_{\gamma\gamma}$ or ϕ, p_T and η of diphoton (had only), number of (b)-jets, p_T and η of the first three (four) jets (p_T ordering), $\sum_{\text{all jets}} p_T$ (had), b-discriminant, p_T and η of the lepton, E_T-miss
- Categories defined from the numbers of leptons (1/2) and BDT output
- Trained on MC ttH signal, bkg MC, ggF+VBF MC (only had)

ttH-categories

Main problem: theoretical systematic for ggF contamination (ggF+HF)

- ATLAS: 100% uncertainty on ggF, VBF, VH production (supported by $H \to 4\ell$, $ttbb$, Vb). Impact 3-4%
- CMS (only ggF): parton shower (from difference in jet multiplicity aMCNLO/data tt+j), gluon splitting (scaling the fraction of events from ggF+b in simulation by the measured difference data/simulation of $\sigma(ttbb)/\sigma(ttjj)$). Impact 2%.

Better recipe?

Background modeling in ATLAS

- Background $m_{\gamma\gamma}$ distributions are fitted directly on data with simple analytical functions both in ATLAS and CMS
- Different approach how the functional form (exponential, ...) are selected

- In ATLAS, for each category, one functional form is selected by dedicated studies on MC or control regions
- Due to the little s/b, small mismodeling on the shape can bias the signal yield
- Quantify bias using closure tests injecting 0 signal events: spurious signal
- Select functional form which pass criteria based on the spurious signal

Spurious signal (ATLAS)

- Build a background-only template, usually mixing $\gamma\gamma$ from Sherpa NLO and γj from control region
- Run a signal + background fit
- The spurious signal (the bias) is the number of fitted events (positive or negative)
- Assume the systematic on the signal yield to be the $\max_{m_H} |bias|$ changing m_H in a window

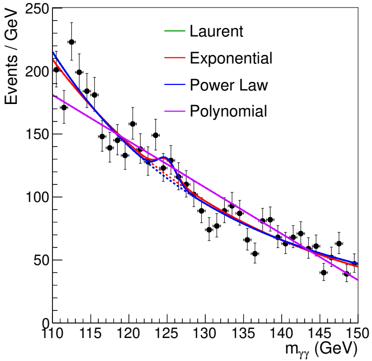
Problems:

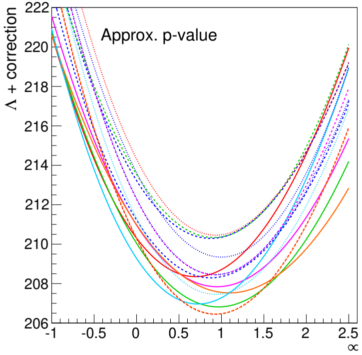
- MC is not data: need to try different variations (e.g. $\gamma\gamma$ purity)
- MC is limited: statistical fluctuation in the MC can increase the estimated spurious signal
- Limiting factor of the procedure: not scalable
  - Produce faster MC (e.g. smeared truth MC, LO generators): bilions of events
  - Use more flexible function (even not analytic) so that you expect better modeling (how to validate?)
  - Remove statistical fluctuation from your template

Background modeling in CMS (discrete profiling)

- Let the $s + b$ fit on data choose the best background function and profile
- Consider functions with different number of degrees of freedom from exponential, power-law, ... families:
  - select functions that can describe data with injection test and F-test
- Add penalty term to the likelihood to account for the number of free parameters N_B

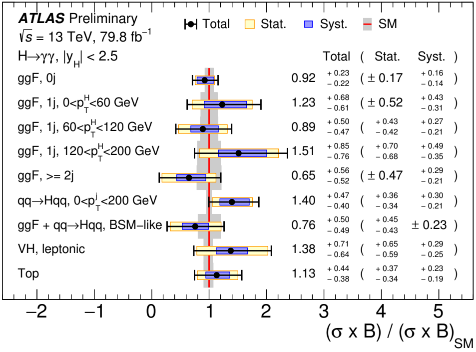
$$-2 \log \tilde{L} = -2 \log L + N_B$$

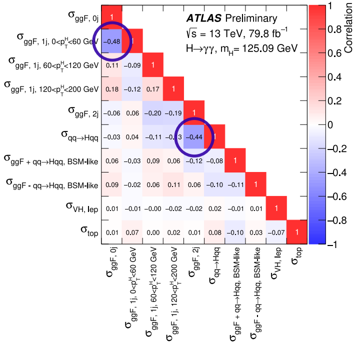




STXS results with 80 fb^{-1} (ATLAS)

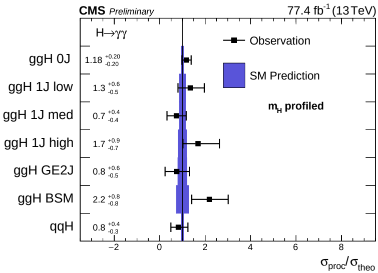
ATLAS-CONF-2018-028

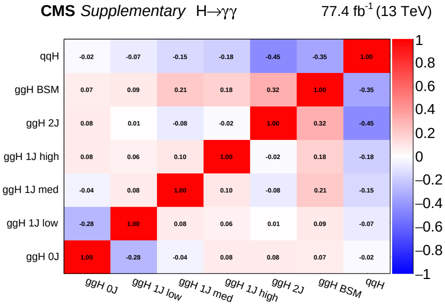




- Difficult to separate ggF 0j/ggF 1j $p_T < 60$ GeV and $qq \to Hqq$/ggF 2j
- Interpretation $\mu = 1.06 \pm 0.08(\text{stat})^{+0.08}_{-0.07}(\text{exp})^{+0.07}_{-0.06}(\text{theo})$
- Main theoretical uncertainty on μ: PS and UE (Pythia vs Herwig or AZNLO eigentunes variations for ggF); renormalization, factorization scales

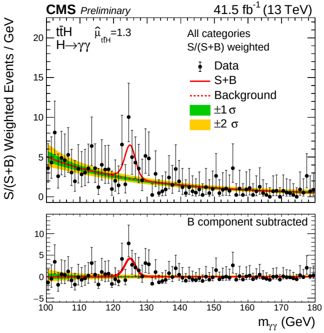
STXS (ggF,VBF) with 77 fb^{-1} (CMS)

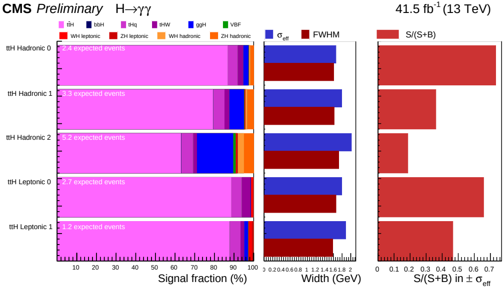




- Less correlation than ATLAS ggF 0j/ggF 1j $p_T < 60$ GeV (-28% vs -48%)
- ATLAS/CMS similar for $qq \to Hqq$/ggF 2j
- ATLAS decided to merge BSM STXS bins to avoid large correlations

ttH with $41.5\,\text{fb}^{-1}$ (CMS)



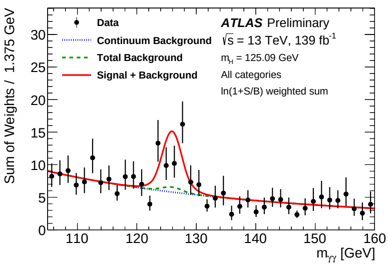


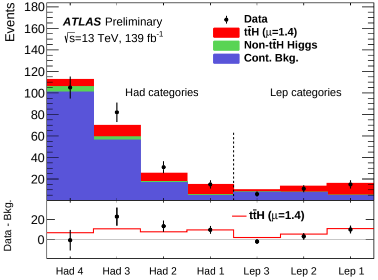
Very pure categories. Contamination from tH, ggF (hadronic categories), VH (leptonic categories)

In the best category: s/(s+b)=70%. ttH/all-Higgs = 89%. Resolution $\sigma_{68} = 1.66\,\text{GeV}$.

ttH with 140 fb^{-1} (ATLAS)

Phys. Lett. B 784 (2018) 173, ATLAS-CONF-2019-004, CMS-HIG-17-035





In the best category: s/(s+b)=60%. ttH/all-Higgs = 95%. Resolution $\sigma_{68} = 1.39$ GeV.

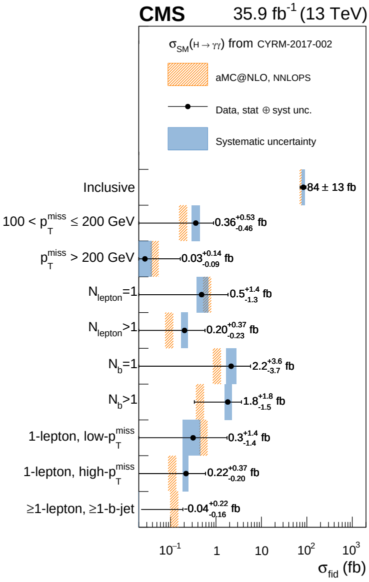
	Luminosity [fb^{-1}]	observed	expected
ATLAS $\gamma\gamma$	140	4.9σ	4.2σ
CMS $\gamma\gamma$	41.5	3.1σ	2.2σ
CMS $\gamma\gamma$	41.5+35.9	4.1σ	2.7σ
ATLAS combination	80	5.8σ	4.9σ
ATLAS combination	80 + Run1	6.3σ	5.1σ
CMS combination	36 + Run1	5.2σ	4.2σ

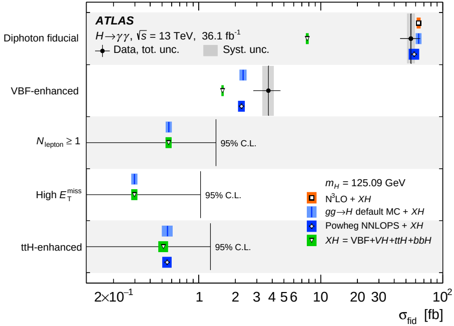
Strategy for fiducial and differential cross sections

- Define fiducial regions close to experimental analysis cuts
- Avoid selections that can distort observables
- For each reco-bin fit $m_{\gamma\gamma}$ distribution
- In addition CMS splits events by expected resolution
- CMS uses likelihood with matrix method (no regularization, since bins are large)
- ATLAS uses bin-by-bin unfolding (bias negligible)

Inclusive fiducial "diphoton" region	
ATLAS	CMS
$\lvert\eta^\gamma\rvert < 1.37$ or $1.52 < \lvert\eta^\gamma\rvert < 2.37$ $p_T^{\text{iso}}(R = 0.2)/p_T^\gamma < 0.05$ $p_T^{\gamma_1}/m_{\gamma\gamma} > 0.35$, $p_T^{\gamma_2}/m_{\gamma\gamma} > 0.25$	$\lvert\eta^\gamma\rvert < 2.5$ $p_T^{\text{iso}}(R = 0.3) < 10\,\text{GeV}$ $p_T^{\gamma_1}/m_{\gamma\gamma} > 1/3$, $p_T^{\gamma_2}/m_{\gamma\gamma} > 1/4$

Fiducial cross sections (ATLAS and CMS 36 fb^{-1})





- Define fiducial regions where some production are enhanced
- Don't try to split production modes with additional variables
- Would be good to harmonize on the most interesting regions (which ones?)

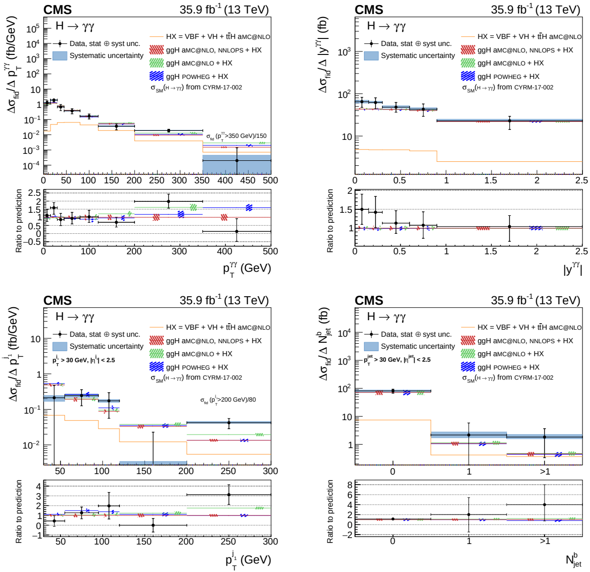
- Define fiducial regions only with kinematic cuts, close to the ones used in the analysis: small model dependency
- Many variables are investigated[2]: $p_T^{\gamma\gamma}$, $|y_{\gamma\gamma}|$, N_j, $p_T^{j_1}$, $p_T^{j_2}$, $|y_{j_1}|$, $|y_{j_2}|$, $|\cos(\theta^*)|$, $\Delta\phi_{jj}$, $|\Delta y_{jj}|$, $\Delta\phi_{\gamma\gamma,jj}$, $|\Delta\phi_{\gamma\gamma,j_1}|$, $|\Delta y_{\gamma\gamma,j_1}|$, m_{jj}, $|\overline{\eta}_{jj} - \eta_{jj}|$, $|\Delta\eta_{jj}|$, p_T^{miss}, $N_{b-\text{jets}}$, N_ℓ.
  Anything missing? Interesting to use different jet definitions (p_T, central/forward) ?
- Also double differential cross sections: $p_T^{\gamma\gamma} \times N_j$, $p_T^{\gamma\gamma} \times |\cos(\theta^*)|$. More?
- Already some variables are measured in specific phase space. Interesting to see differential distributions in specific phase space (e.g. $p_T^{\gamma\gamma}$, $\Delta\phi_{jj}$ within different fiducial regions)?

[2] ATLAS only, CMS only

CMS differential cross section (36 fb^{-1})

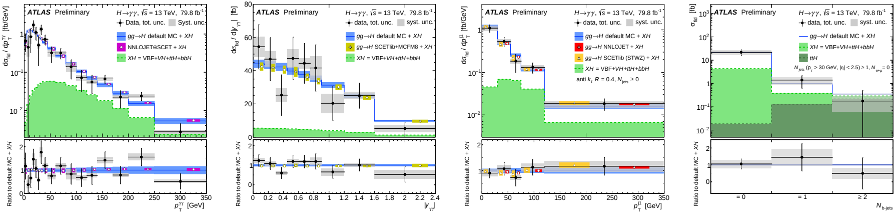
JHEP 01 (2019) 183

Unfolded (matrix method) distribution for $p_T^{\gamma\gamma}$, $y_{\gamma\gamma}$, $p_T^{j_1}$, N_{b-jets}



ATLAS differential cross sections (80 fb^{-1})

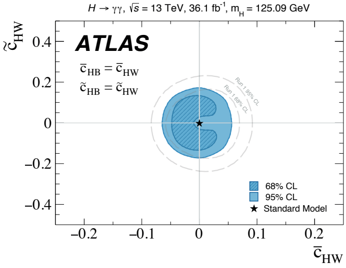
Unfolded (bin by bin) distribution for $p_T^{\gamma\gamma}$, $y_{\gamma\gamma}$, $p_T^{j_1}$, N_{b-jets} (lepton-veto)



p-value(χ^2) data/SM $> 30\%$

EFT interpretation:

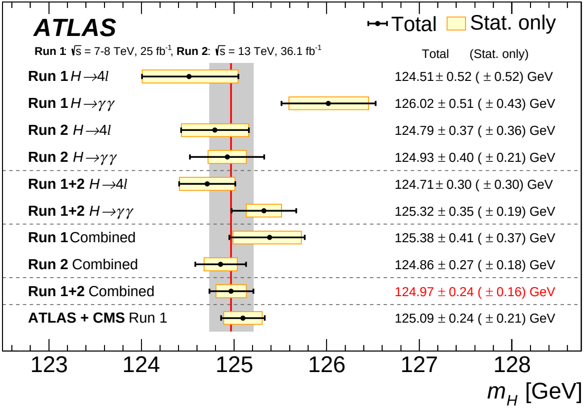
- introduce additional CP-even and CP-odd interactions in SILH framework
- inputs: $p_T^{\gamma\gamma}$, N_j, m_{jj}, $|\Delta\phi_{jj}|$, $p_T^{j_1}$ and their correlations



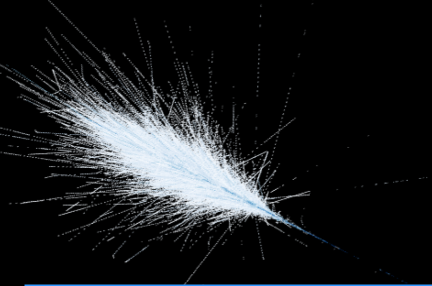
Mass measurement $\gamma\gamma + 4\ell$ with 36 fb^{-1} (ATLAS)

Phys. Lett. B 784 (2018) 345

- Hundreds of systematics on the energy/momentum scale
- Energy scale mostly from $Z \to \ell\ell$ ($\langle p_T^\ell \rangle \simeq 40$ GeV) comparing data/MC
  - $H \to \gamma\gamma$ ($\langle p_T^\gamma \rangle \simeq 60$ GeV) starts to be dominated by systematics



Any interest to improve $m_{H\to\gamma\gamma}$ with sys $\gtrsim$ 100 MeV?



Conclusions

Conclusions

Precision studies have been presented: no deviation from SM

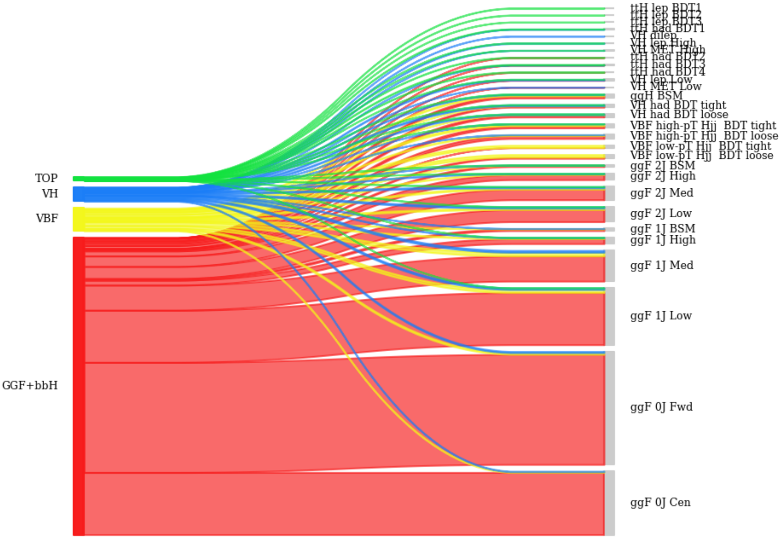
- Two complementary approaches: coupling/STXS (very optimized, model dependent) vs fiducial/differential cross sections
- How much differential we should be? As much as possible? Or not useful to quote results with very large errors and correlations?
- In STXS we have tens of cross sections. What do we want to optimize?
- How to share results? Just values and covariance?
- Main difficulty from the experimental point of view: modeling the shape of the background and its systematic
- Being more differential means more difficult to evaluate theoretical uncertainties (e.g. ggF+HF)

Now working on final Run2 papers with $140\,\mathrm{fb}^{-1}$. More complicated interpretations (EFT)

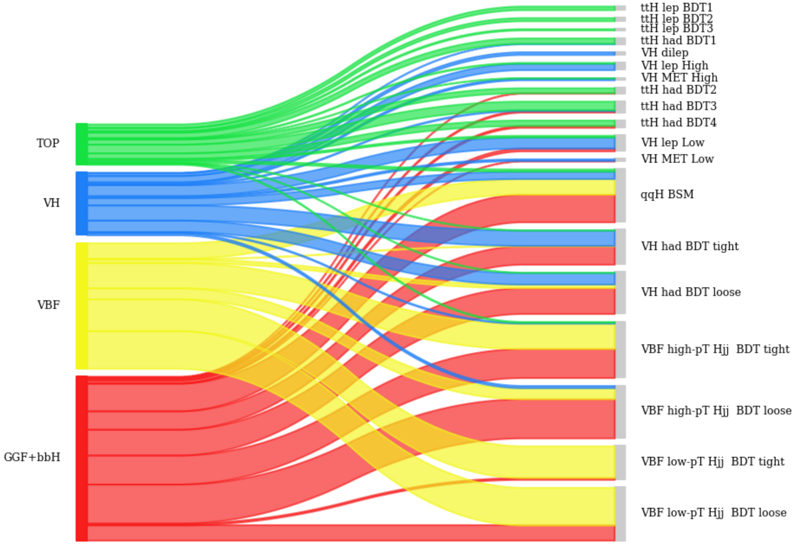

Thanks for your attention

Backup

Migrations ATLAS



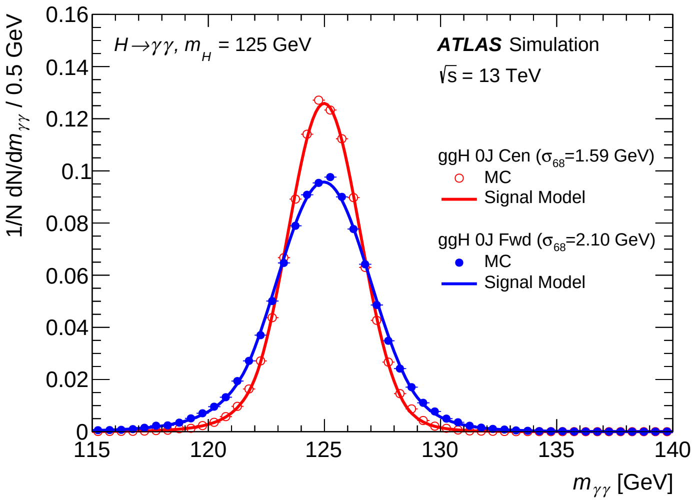
Migrations ATLAS (no ggF categories)



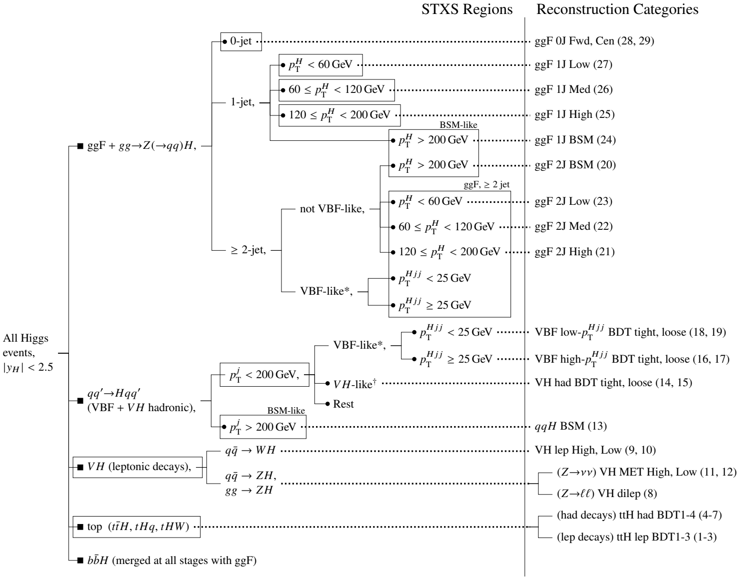
Systematic on m_H from $H \to \gamma\gamma$ (ATLAS)

Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	± 180
EM calorimeter layer calibration	± 170
Non-ID material	± 120
ID material	± 110
Lateral shower shape	± 110
$Z \to ee$ calibration	± 80
Conversion reconstruction	± 50
Background model	± 50
Selection of the diphoton production vertex	± 40
Resolution	± 20
Signal model	± 20

Signal shape (ATLAS)



STXS merged scheme (ATLAS)



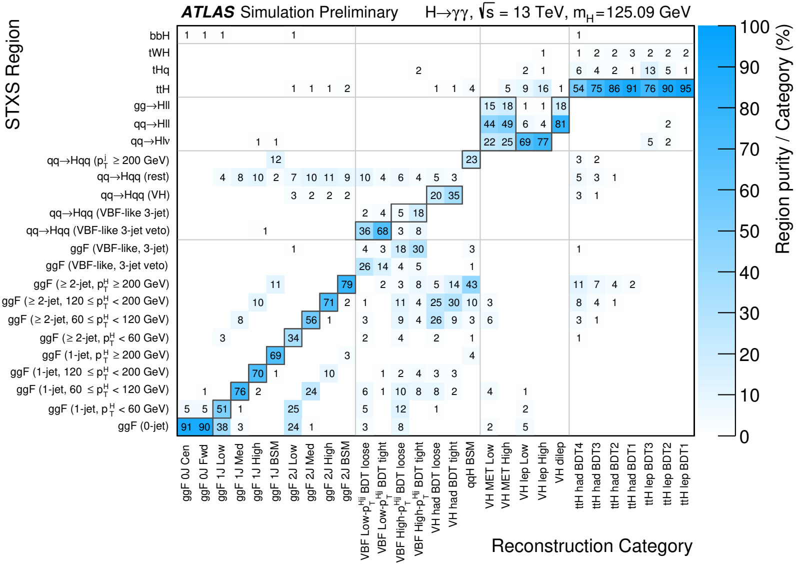
*VBF-like: $m_{jj} > 400$ GeV, $|\Delta y_{jj}| > 2.8$

† VH-like: $60 < m_{jj} < 120$ GeV

ATLAS STXS reco categories

Category label	Selection
ttH lep BDT1	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ {\rm BDT}_{\rm ttHlep} > 0.987$
ttH lep BDT2	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ 0.942 < {\rm BDT}_{\rm ttHlep} < 0.987$
ttH lep BDT3	$N_{\rm lep} \geq 1,\ N_{b-\rm jet} \geq 1,\ 0.705 < {\rm BDT}_{\rm ttHlep} < 0.942$
ttH had BDT1	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ {\rm BDT}_{\rm ttHhad} > 0.996$
ttH had BDT2	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.991 < {\rm BDT}_{\rm ttHhad} < 0.996$
ttH had BDT3	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.971 < {\rm BDT}_{\rm ttHhad} < 0.991$
ttH had BDT4	$N_{\rm lep} = 0,\ N_{\rm jets} \geq 3,\ N_{b-\rm jet} \geq 1,\ 0.911 < {\rm BDT}_{\rm ttHhad} < 0.971$
VH dilep	$N_{\rm lep} \geq 2,\ 70\,{\rm GeV} \leq m_{\ell\ell} \leq 110\,{\rm GeV}$
VH lep High	$N_{\rm lep} = 1,\ \lvert m_{e\gamma} - 89\,{\rm GeV}\rvert > 5\,{\rm GeV},\ p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}} > 150\,{\rm GeV}$
VH lep Low	$N_{\rm lep} = 1,\ \lvert m_{e\gamma} - 89\,{\rm GeV}\rvert > 5\,{\rm GeV},\ p_{\rm T}^{\ell+E_{\rm T}^{\rm miss}} < 150\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 1
VH MET High	$150\,{\rm GeV} < E_{\rm T}^{\rm miss} < 250\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 9 or $E_{\rm T}^{\rm miss} > 250\,{\rm GeV}$
VH MET Low	$80\,{\rm GeV} < E_{\rm T}^{\rm miss} < 150\,{\rm GeV},\ E_{\rm T}^{\rm miss}$ significance > 8
qqH BSM	$N_{\rm jets} \geq 2,\ p_{\rm T,j1} > 200\,{\rm GeV}$
VH had BDT tight	$60\,{\rm GeV} < m_{\rm jj} < 120\,{\rm GeV},\ {\rm BDT}_{\rm VH} > 0.78$
VH had BDT loose	$60\,{\rm GeV} < m_{\rm jj} < 120\,{\rm GeV},\ 0.35 < {\rm BDT}_{\rm VH} < 0.78$
VBF high-$p_{\rm T}^{Hjj}$ BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1}+\eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} > 25\,{\rm GeV},\ {\rm BDT}_{\rm VBF}^{\rm high} > 0.47$
VBF high-$p_{\rm T}^{Hjj}$ BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1}+\eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} > 25\,{\rm GeV},\ -0.32 < {\rm BDT}_{\rm VBF}^{\rm high} < 0.47$
VBF low-$p_{\rm T}^{Hjj}$ BDT tight	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1}+\eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} < 25\,{\rm GeV},\ {\rm BDT}_{\rm VBF}^{\rm low} > 0.87$
VBF low-$p_{\rm T}^{Hjj}$ BDT loose	$\lvert\Delta\eta_{jj}\rvert > 2,\ \lvert\eta_{\gamma\gamma} - 0.5(\eta_{\rm j1}+\eta_{\rm j2})\rvert < 5,\ p_{\rm T}^{Hjj} < 25\,{\rm GeV},\ 0.26 < {\rm BDT}_{\rm VBF}^{\rm low} < 0.87$
ggF 2J BSM	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \geq 200\,{\rm GeV}$
ggF 2J High	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [120, 200]$ GeV
ggF 2J Med	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [60, 120]$ GeV
ggF 2J Low	$N_{\rm jets} \geq 2,\ p_{\rm T}^{\gamma\gamma} \in [0, 60]$ GeV
ggF 1J BSM	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \geq 200\,{\rm GeV}$
ggF 1J High	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [120, 200]$ GeV
ggF 1J Med	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [60, 120]$ GeV
ggF 1J Low	$N_{\rm jets} = 1,\ p_{\rm T}^{\gamma\gamma} \in [0, 60]$ GeV
ggF 0J Fwd	$N_{\rm jets} = 0$, one photon with $\lvert\eta\rvert > 0.95$
ggF 0J Cen	$N_{\rm jets} = 0$, two photons with $\lvert\eta\rvert \leq 0.95$

ATLAS STXS efficiencies



ATLAS generators

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s} = 13$ TeV	Order of σ calculation
ggF	POWHEG NNLOPS	PYTHIA 8	PDF4LHC15	48.52	N^{3}LO(QCD)+NLO(EW)
VBF	POWHEG-BOX	PYTHIA 8	PDF4LHC15	3.78	approximate-NNLO(QCD)+NLO(EW)
WH	POWHEG-BOX	PYTHIA 8	PDF4LHC15	1.37	NNLO(QCD)+NLO(EW)
$q\bar{q}' \to ZH$	POWHEG-BOX	PYTHIA 8	PDF4LHC15	0.76	NNLO(QCD)+NLO(EW)
$gg \to ZH$	POWHEG-BOX	PYTHIA 8	PDF4LHC15	0.12	NNLO(QCD)+NLO(EW)
$t\bar{t}H$	POWHEG-BOX	PYTHIA 8	PDF4LHC15	0.51	NNLO(QCD)+NLO(EW)
$b\bar{b}H$	POWHEG-BOX	PYTHIA 8	PDF4LHC15	0.49	NNLO(QCD)+NLO(EW)
tHq	MG5_AMC@NLO	PYTHIA 8	CT10	0.07	4FS(LO)
tHW	MG5_AMC@NLO	Herwig++	CT10	0.02	5FS(NLO)
$\gamma\gamma$	SHERPA	SHERPA	CT10		
$V\gamma\gamma$	SHERPA	SHERPA	CT10		
$t\bar{t}\gamma\gamma$	MG5_AMC@NLO	PYTHIA 8	PDF4LHC15		

CMS STXS BDT validation