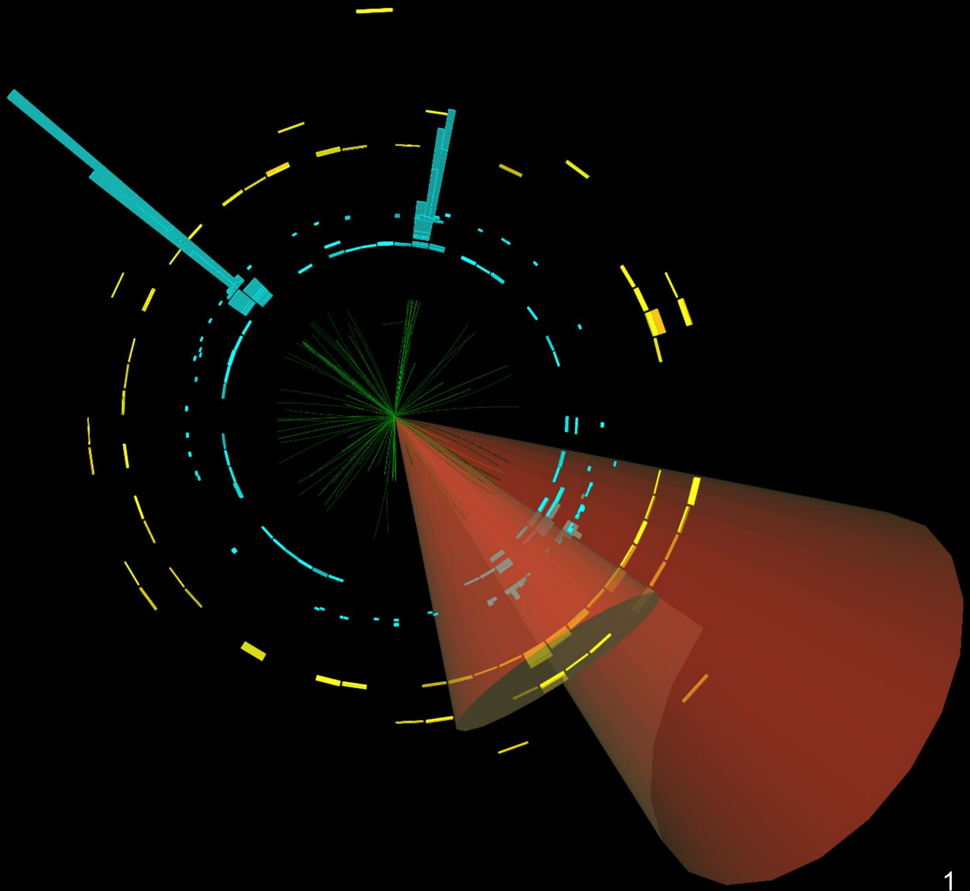
ATLAS and CMS non-resonant HH→$\gamma\gamma$bb



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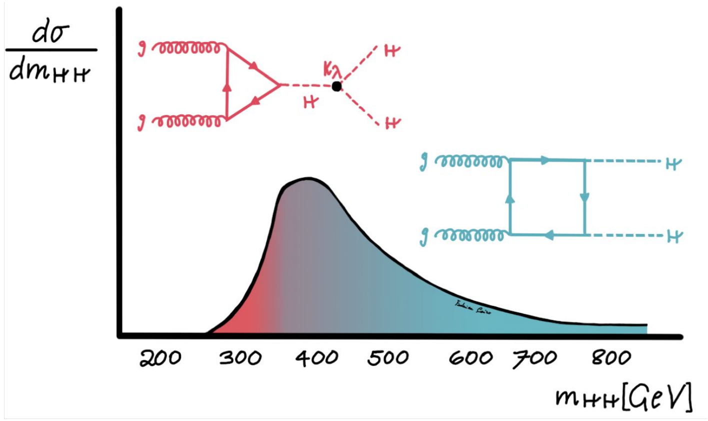
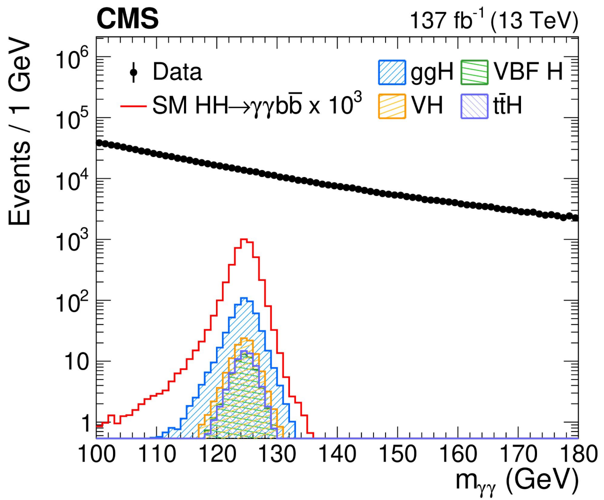
Motivation



- The ggF production results from the destructive interference between the triangle and box diagram.
- However, the **low m_{HH}** region is essential to constrain trilinear coupling.

The diphoton signature is a key channel for Higgs physics thanks to the efficient *photon reconstruction* and low *energy resolution* :
- low threshold for the object selection → good sensitivity to low m_{HH} ;
- simple background estimation and good S/B.



Publications

ATLAS:

https://arxiv.org/pdf/2112.11876.pdf

- Paper submitted in Dec. 2021, in review.

- Non-resonant ggHH and Resonant X→HH
- Non-resonant VBF HH just included as signal

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2018-34/

CMS:

https://arxiv.org/abs/2011.12373

- Paper submitted in Nov. 2020
  JHEP 03 (2021) 257

- Non-resonant ggHH analysis
- Non-resonant VBF HH included as contribution to the analysis

http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-19-018/index.html

Disclaimer: if a plot comes without a reference it means that it comes from one of the 2 papers above

Outline

1) Photons

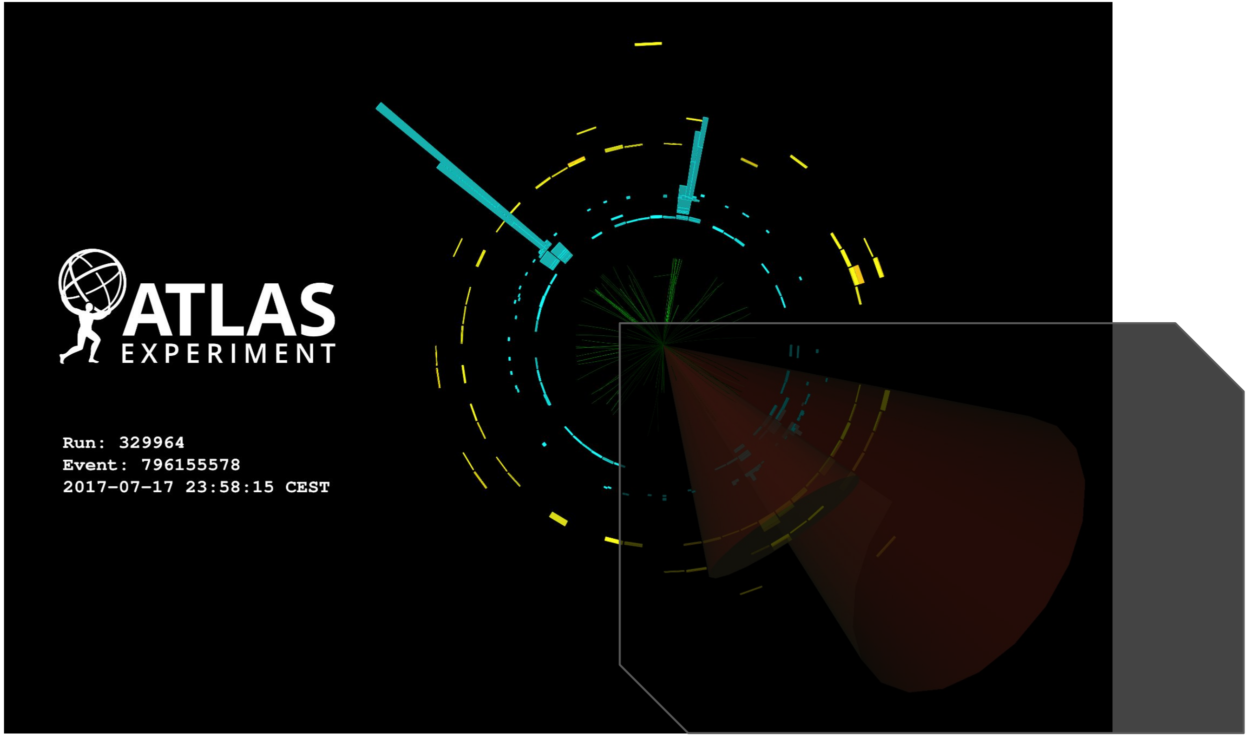
2) Jets

3) Background rejection

4) Signal extraction

5) Results

1) Photons

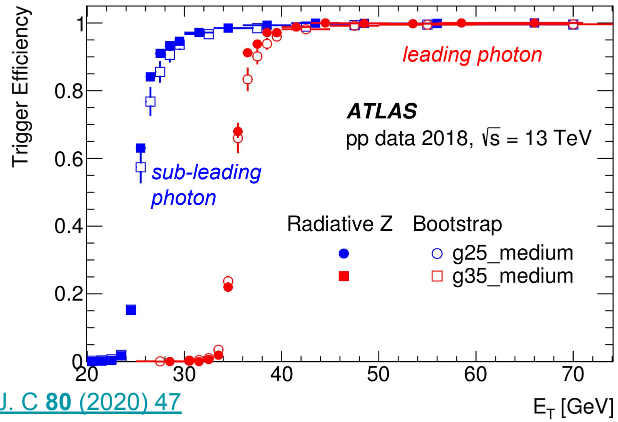

ATLAS
EXPERIMENT
Run: 329964
Event: 796155578
2017-07-17 23:58:15 CEST

1.1) Diphoton HLT Trigger

ATLAS:

- $p_{T,1}$ > 35 GeV; $p_{T,2}$ > 25 GeV
- identification criteria: raised from loose to medium for data period 2017-2018.

Efficiency: 83 % for non resonant and 70% for mx=300 GeV. When normalizing to the standard di-photon selection, these efficiencies are close to 100%



Eur. Phys. J. C **80** (2020) 47

CMS:

- $p_{T,1}$ > 30 GeV; $p_{T,2}$ > 18 (22) GeV
  2016 (2017-18)
- identification criteria: loose.

Efficiency: When normalizing to the standard di-photon selection, these efficiencies are close to 100%

1.2) Photons selection

ATLAS:

- Acceptance: electromagnetic clusters within $|\eta| < 2.37$, excluding the transition region $1.37 < |\eta| < 1.52$.
- Special vertexing: due to reduced track information, a NN is used to identify the PV instead of the usual highest $\sum p_T$ (Phys. Rev. D 90, 112015)
    - small difference between two definitions here.
    - The longitudinal showering in ATLAS ECAL allows to estimate the direction of the vertex
- Tight identification criteria: based on the lateral shape of the shower and hadronic leakage.
- Loose isolation: based on the transverse energy deposited in the EM-calorimeter and on the p_T of the tracks surrounding the photon candidate.

CMS:

- Acceptance: electromagnetic clusters within $|\eta| < 2.5$, excluding the transition region $1.44 < |\eta| < 1.57$.
- BDT vertexing including jets information: 99.9% efficient to find the right vertex.
- Loose Identification criteria: based on the lateral shape of the shower and hadronic leakage.
- Loose Isolation based photons and charged hadrons in a cone of dR = 0.3 around the photon.
- Jet Id and jets isolation used for classification BDT.

1.3) Diphoton selection

ATLAS:

- $p_{T,1} > 35$ GeV; $p_{T,2} > 25$ GeV (online)
- $p_{T,1} > 0.35 * m_{\gamma\gamma}$, $p_{T,2} > 0.25 * m_{\gamma\gamma}$
- $105 < m_{\gamma\gamma} < 160$ GeV

CMS:

- $p_{T,1} > 30$ GeV; $p_{T,2} > 18$ (22) GeV (online)
- $p_{T,1} > 0.33 * m_{\gamma\gamma}$, $p_{T,2} > 0.25 * m_{\gamma\gamma}$
- $100 < m_{\gamma\gamma} < 180$ GeV

DISCUSSION:

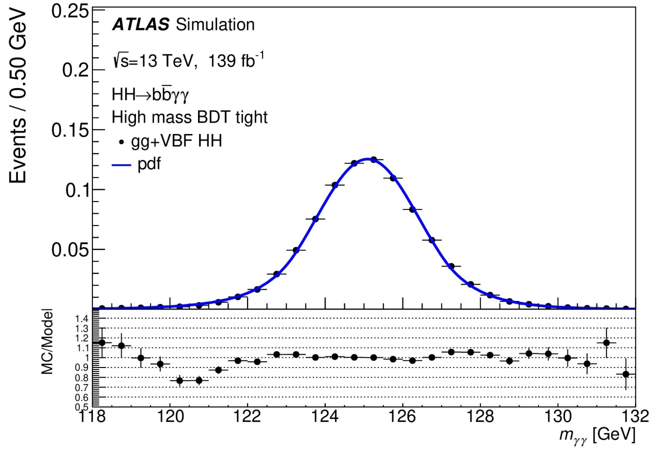
- Internal CMS a study if lowering $p_{T,2}/m_{\gamma\gamma} > 0.2$ would help to recover some events with very asymmetric decay: $p_{T,1} >> p_{T,2}$. Lowering $p_{T,1}/m_{\gamma\gamma}$ doesn't help.
- One need to be careful with fake photons that are more probable at low p_T.

- CMS have historically quite a large $m_{\gamma\gamma}$ region for non-resonant background fitting.
  → Reducing to 105-160 may help to reduce parametrization uncertainty.

1.4) Diphoton resolution

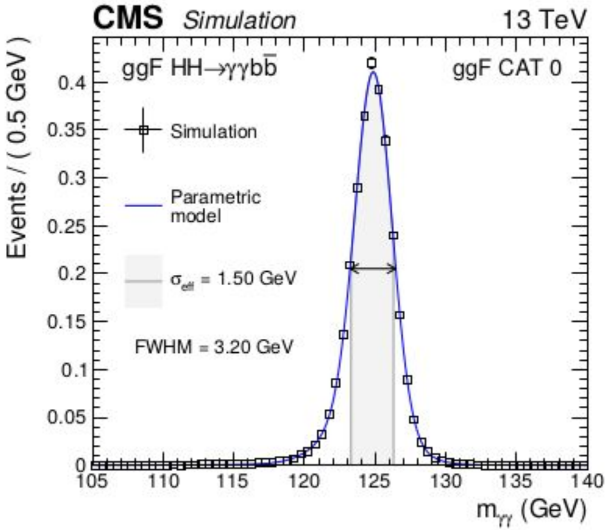
ATLAS:

- Double sided Crystal Ball resolution in $m_{\gamma\gamma}$
  $1.3 < \sigma < 1.7$ GeV



CMS:

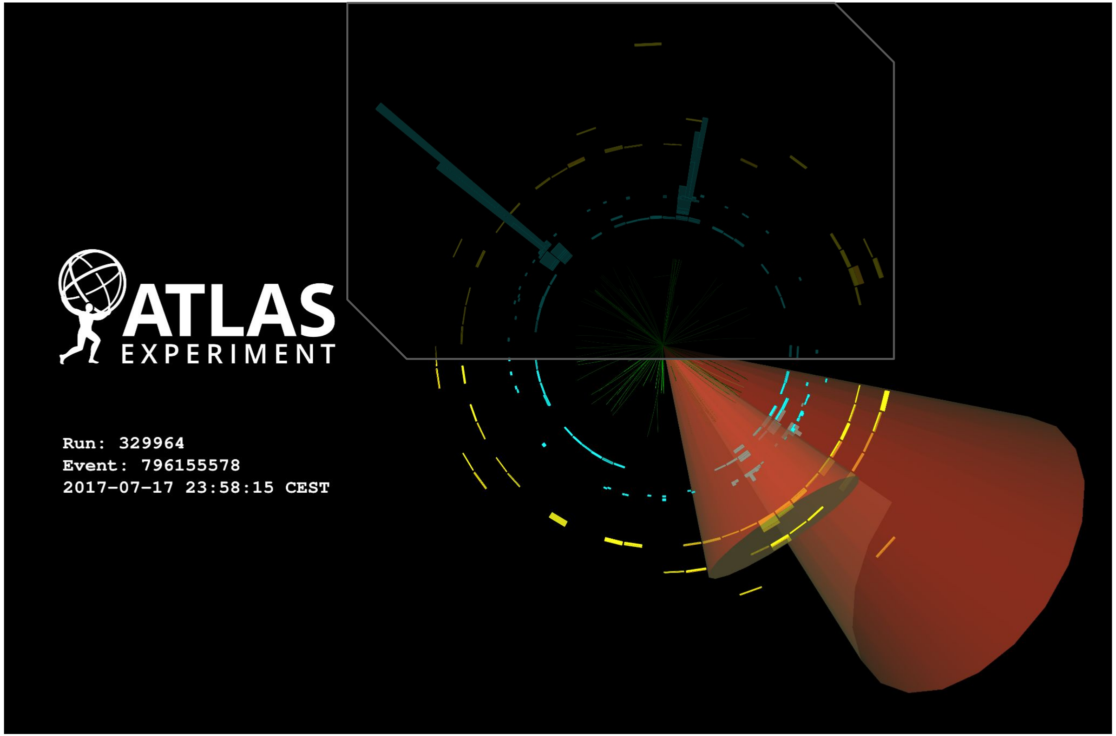
- σ_{eff}: 1.4 - 2 GeV. Depending on the purity and year.



DISCUSSION:

ATLAS and CMS resolutions are comparable even if ATLAS one is slightly better.

2) Jets selection



2.1) B-jets selection

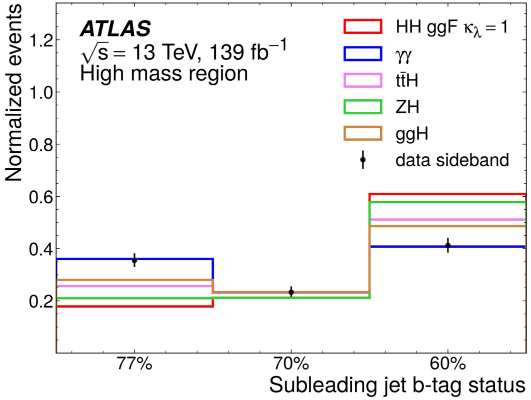
ATLAS:

Jets reconstruction:

- Input: Particle flow candidates.
- anti-kT R=0.4.
- p_T > 25 GeV; $|\eta|$ < 2.5; PU cleaning.

B-tagging:

- Based on DNN (see L. Gouskos talk)
- Exactly 2 jets identified with loose WP: 77% efficiency.
- B-tag quantile is part of BDT training.



CMS:

Jets reconstruction:

- Input: Particle flow candidates.
- anti-kT R=0.4.
- p_T > 25 GeV; $|\eta|$ < 2.5; PU cleaning.

B-tagging:

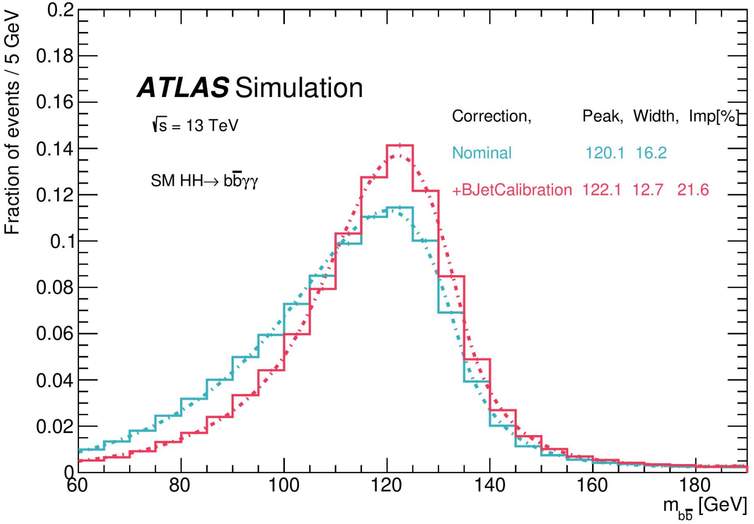
- Based on DNN (see L. Gouskos talk)
- 2 jets with largest b-tag sum are selected as candidates.
- B-tag score is part of BDT training.

2.2) Dijet mass resolution

ATLAS:

Corrections on the energy:

- Standard jet calibration
- Adding the nearby muon;
- SF to correct from the undetected neutrino obtained from tt MC samples based on jet p_T.

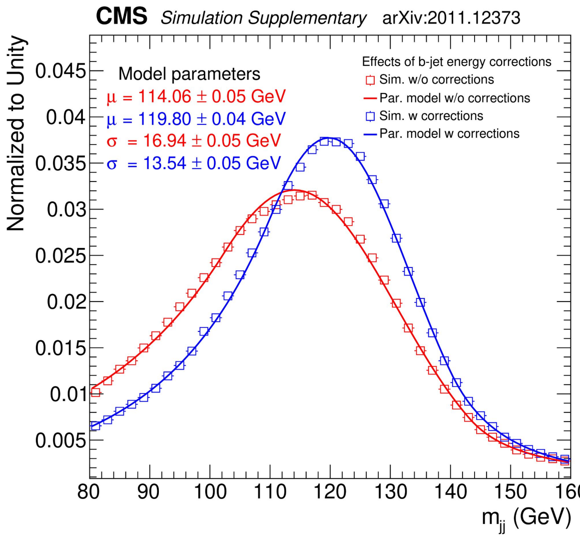


20% improvement on the resolution

CMS:

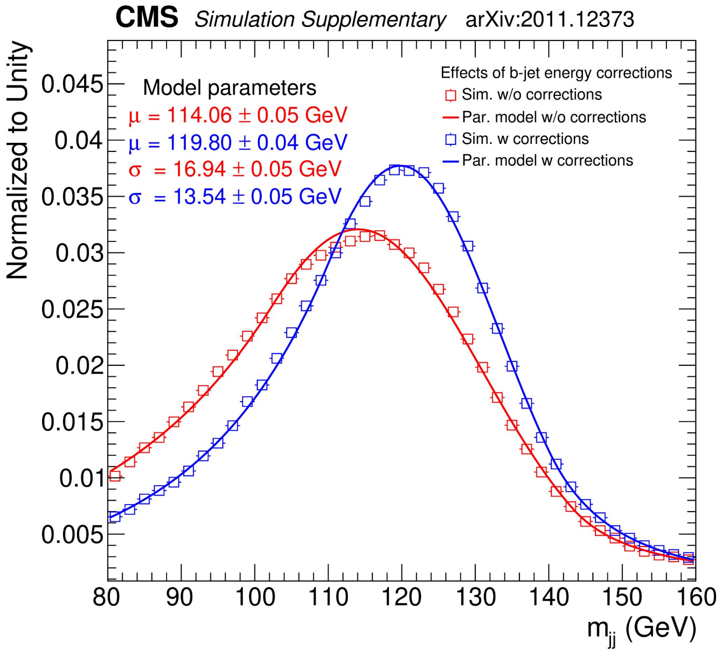
Corrections on the energy:

- Standard jet calibration
- L1 regression: Per jet DNN based correction looking on particle flow ;
- L2 regression: Per event Mjj oriented regression important for events with large MET.



2.3) Discussion

- The CMS and ATLAS di-jet resolution is similar despite a more staged and complex calibration system: this is an interesting result to be understood
- The m_{jj} distribution from ATLAS is obtained after b-tag selection while CMS distribution is shown before the BDT application.
  It improves once b-tagging is applied.

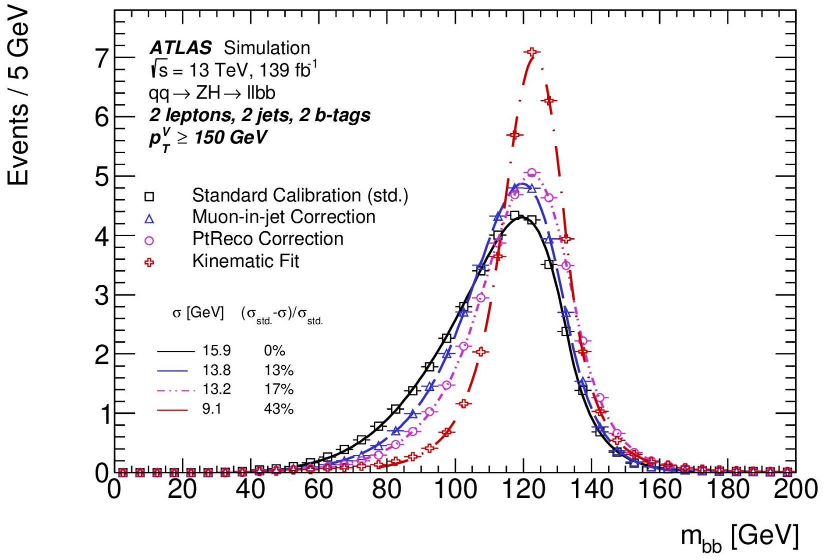


- On possible *idea for the future*: using an MVA to select the best 2 Higgs jets candidates, à la HH→4b.

2.4) Dijet mass resolution: going further

ATLAS:

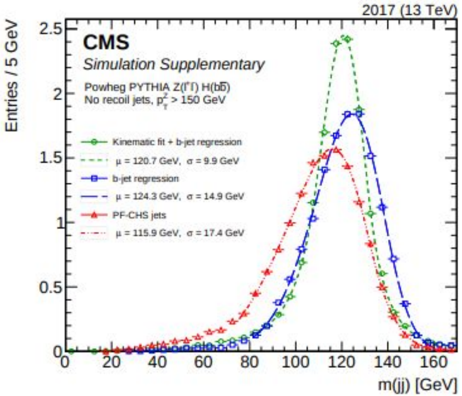
- Alternatives: NN regression or Kinematic fit procedure as done in VHbb.

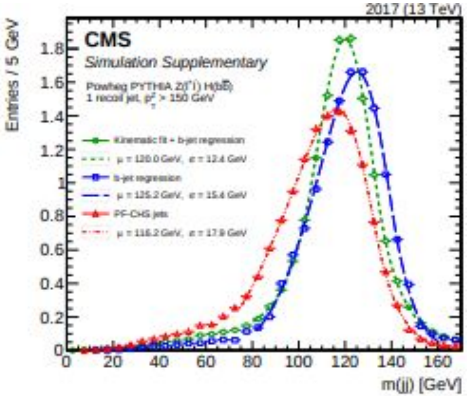


[Eur. Phys. J. C 81 (2021) 178]

CMS:

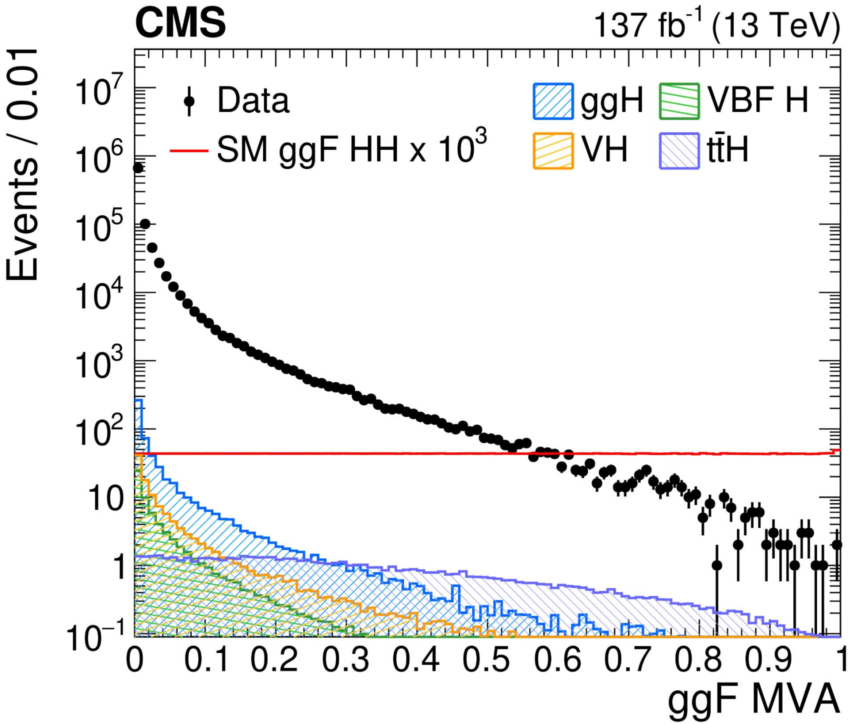
- Alternative: NN per jet regression + kinematic fit for ZHbb.
- Effect of kinematic-fit goes lower with extra-jets. For ggHH more extra jets than for VH.



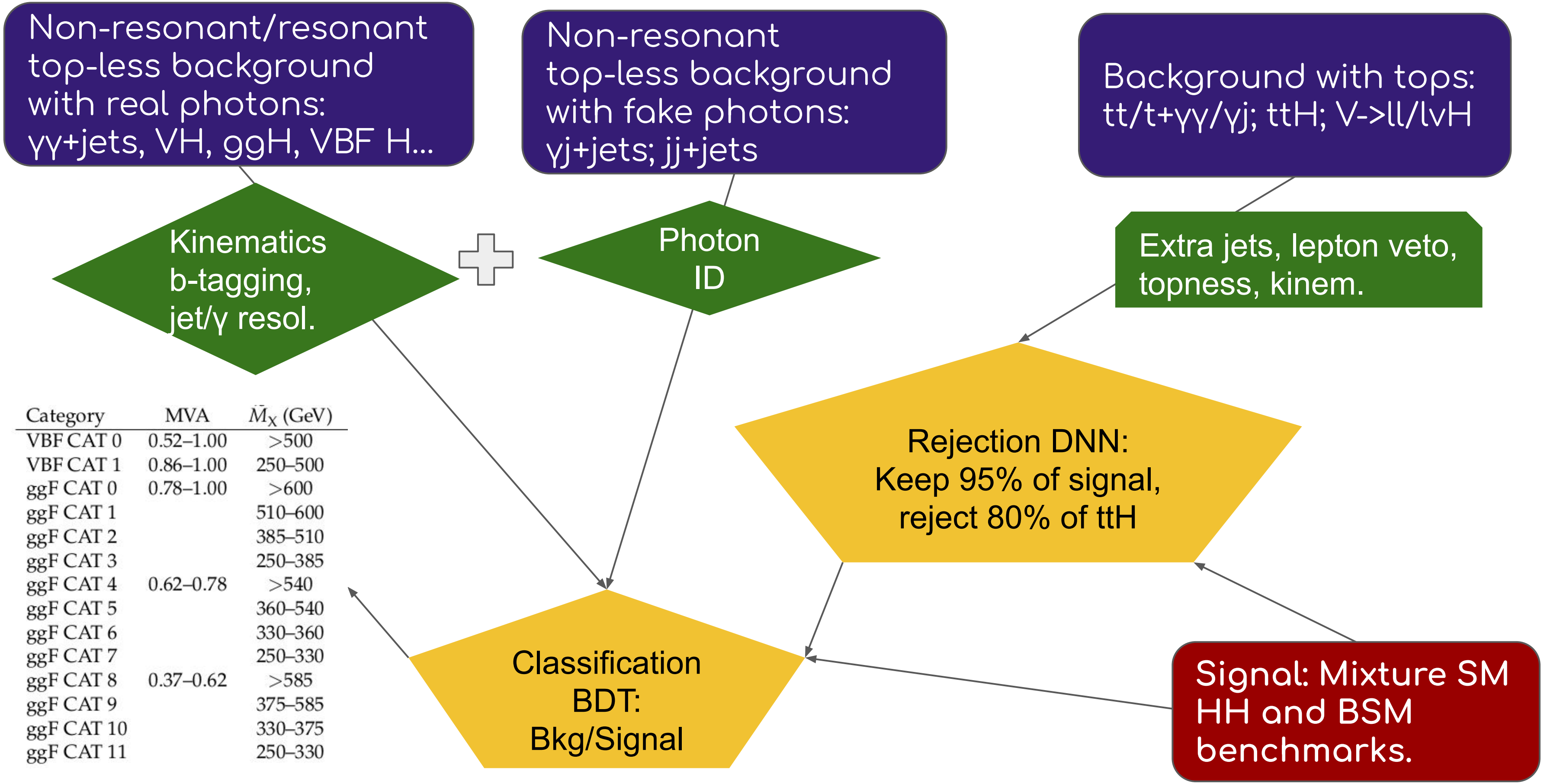


[Phys. Rev. Lett. 121 (2018) 121801]

3) Background rejection



3.1) Background strategy for CMS



Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500
ggF CAT 0	0.78–1.00	>600
ggF CAT 1		510–600
ggF CAT 2		385–510
ggF CAT 3		250–385
ggF CAT 4	0.62–0.78	>540
ggF CAT 5		360–540
ggF CAT 6		330–360
ggF CAT 7		250–330
ggF CAT 8	0.37–0.62	>585
ggF CAT 9		375–585
ggF CAT 10		330–375
ggF CAT 11		250–330

3.2) Background strategy for ATLAS

Fake jets backgrounds: γj+jets / jj+jets

γ Tight id cuts

γγ+jets, VH, ggH, VBF H, ttH

Kinematics
b-tagging,
jet/γ resol.

Extra jets, lepton veto,
topness

SIGNAL:
κ_λ = 1 for $m_{HH} \geq$ 350 GeV
κ_λ = 10 for $m_{HH} <$ 350 GeV

Classification
BDT:
Bkg/Signal

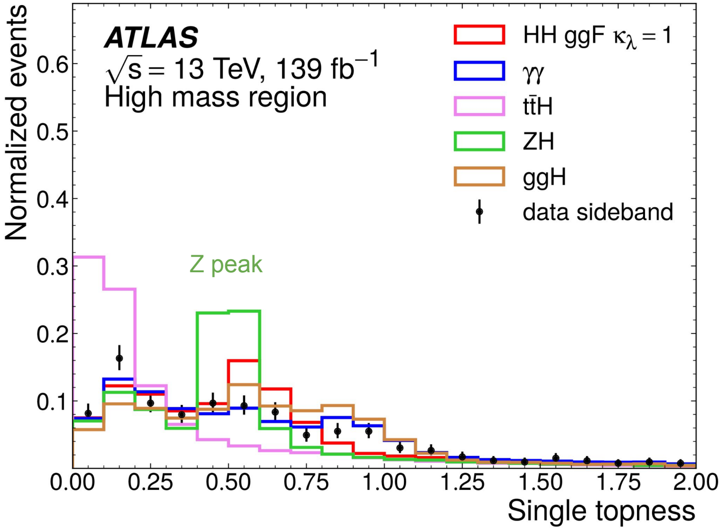
Category	Selection criteria
High mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} \geq$ 350 GeV, BDT score $\in$ [0.967, 1]
High mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} \geq$ 350 GeV, BDT score $\in$ [0.857, 0.967]
Low mass BDT tight	$m^*_{b\bar{b}\gamma\gamma} <$ 350 GeV, BDT score $\in$ [0.966, 1]
Low mass BDT loose	$m^*_{b\bar{b}\gamma\gamma} <$ 350 GeV, BDT score $\in$ [0.881, 0.966]

3.3) Discussion: variables

- Resolution variables (jets, photons, dijets, diphoton) helps a bit.
- Topness variable is very useful. It might be improved by taking into account the resolution correlation matrix between W→jj and t→Wbjjb

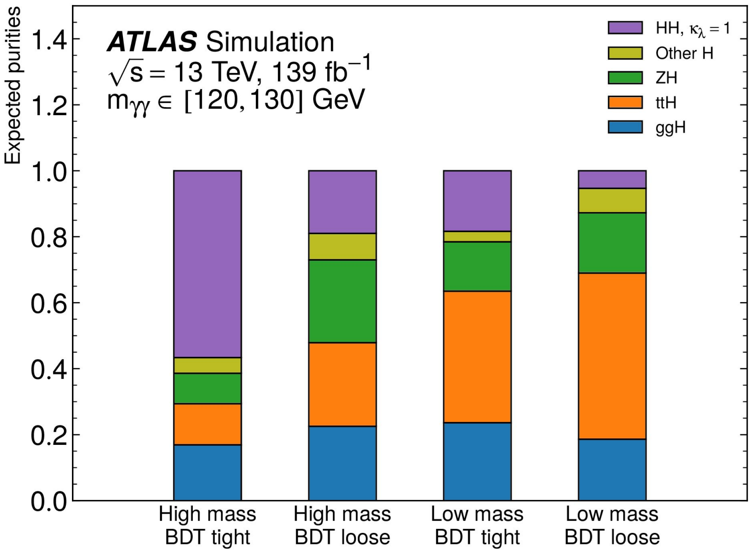
$$\chi_{Wt} = \min\sqrt{\left(\frac{m_{j_1 j_2} - m_W}{m_W}\right)^2 + \left(\frac{m_{j_1 j_2 j_3} - m_t}{m_t}\right)^2}$$

- This variable, as well as other anti-ttH variables helps against tt+$\gamma\gamma$ and t+$\gamma\gamma$.



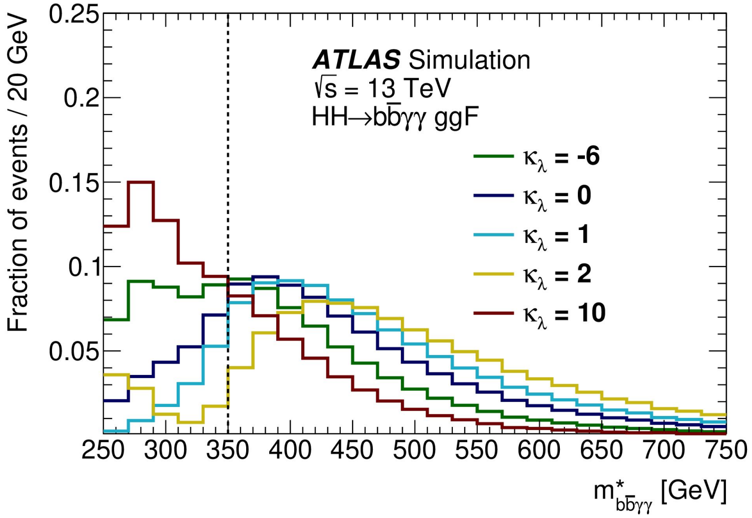
3.3) Discussion: variables

- Idea to separate top and non-top background into different BDT is motivated by rather orthogonal variables used in both cases. It is not easy to weight properly backgrounds with very different contributions.
- A dedicated effort is still clearly necessary if we want to tackle SM HH.
- For future: why not a DNN with multiple outputs.



3.4) Discussion: categories

- In CMS an optimisation is used to see how many categories gives best sensitivity: 12 cats is the most optimal solution since we have enough data.
- We train for SM HH + mixture of BSM Benchmarks.
- ATLAS trains on κ_λ = 10 for region below 350 GeV. This might in fact enhance the sensitivity particularly to self-coupling and explain why ATLAS and CMS κ_λ results are so similar (see next section).



3.5) VBF selection

ATLAS:

- No dedicated VBF selection.
- Tests were made based on the di-jet invariant mass to select the correct pair.
- Event shapes variables (Eur. Phys. J. C **72** (2012) 2211) that describes the patterns, correlations, and origins of the energy flow in an interaction, were found to have a good discrimination power.

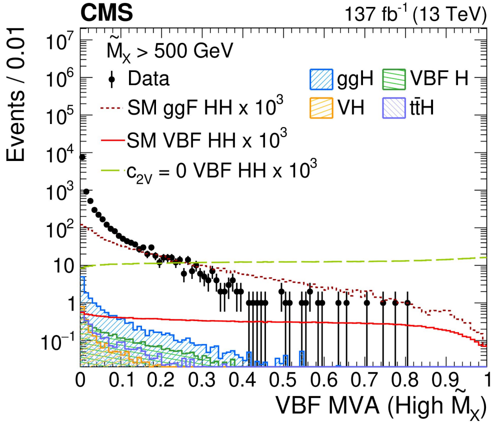
$$M_{xyz} = \sum_i \begin{pmatrix} p_{xi}^2 & p_{xi}p_{yi} & p_{xi}p_{zi} \\ p_{yi}p_{xi} & p_{yi}^2 & p_{yi}p_{zi} \\ p_{zi}p_{xi} & p_{zi}p_{yi} & p_{zi}^2 \end{pmatrix}$$

CMS:

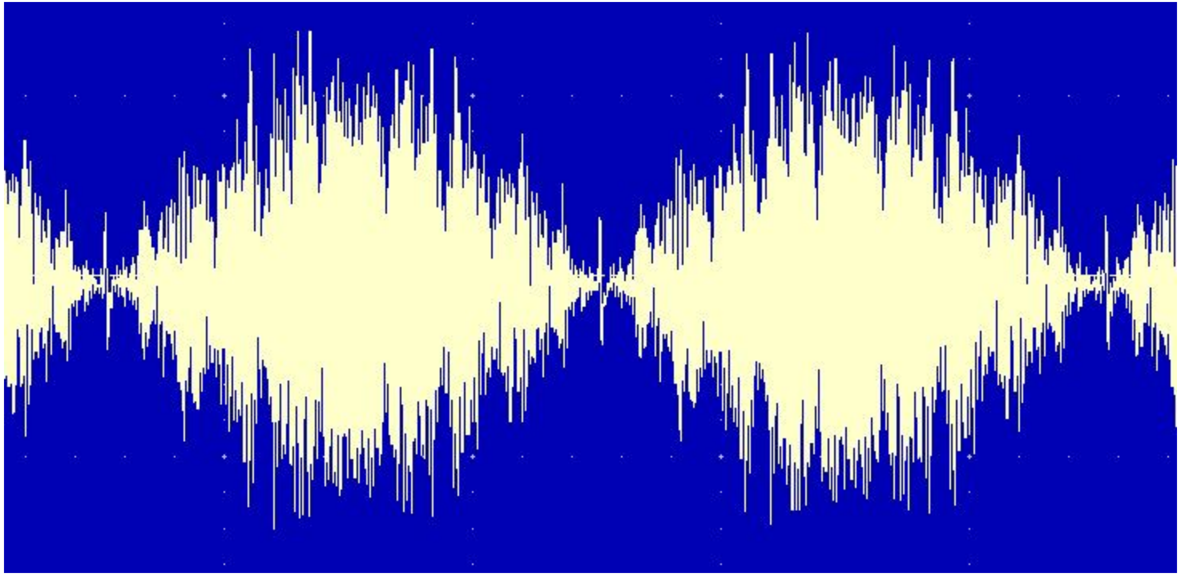
Category	MVA	$\tilde{M}_X$ (GeV)
VBF CAT 0	0.52–1.00	>500
VBF CAT 1	0.86–1.00	250–500

- 2 dedicated VBF categories:
  - Low m_{HH} sensitive to κ_λ ;
  - High m_{HH} sensitive to c_{2V} .

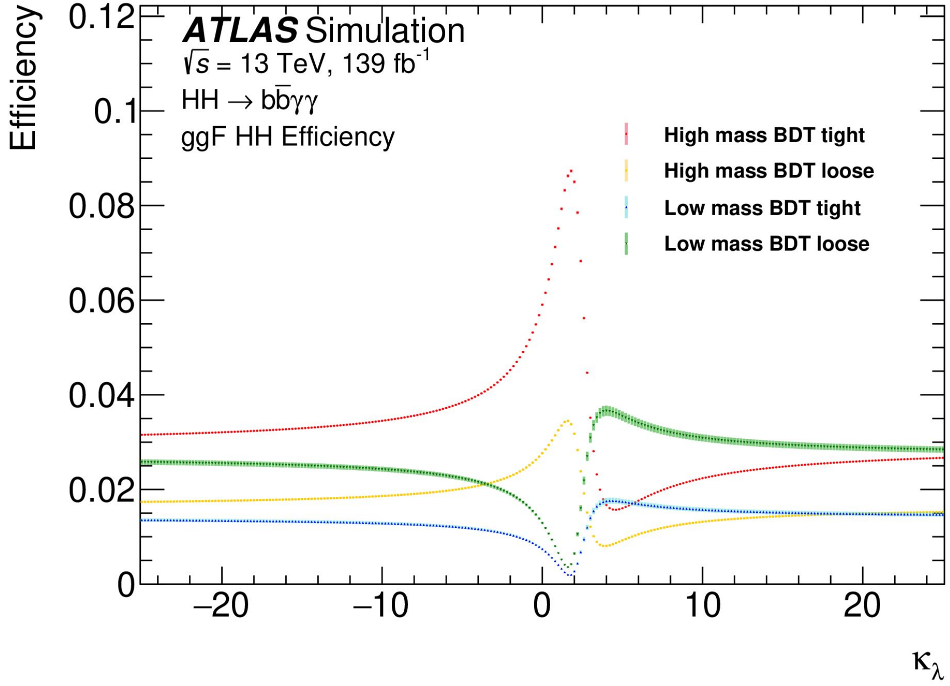
- multi-class BDT used to separate VBF HH from ggHH and γγ/γj+jets.
- VBF HH and ggHH are at the end considered simultaneously as signal.



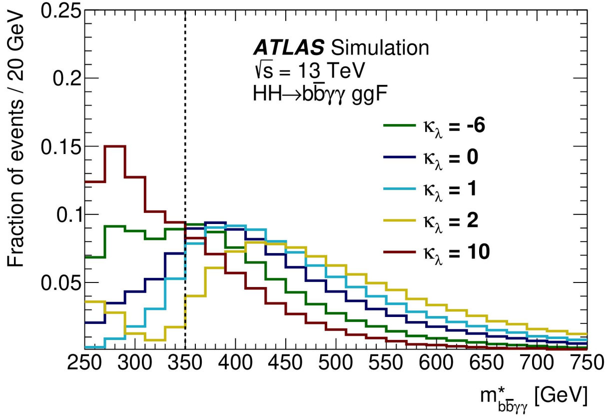
4) Signal extraction



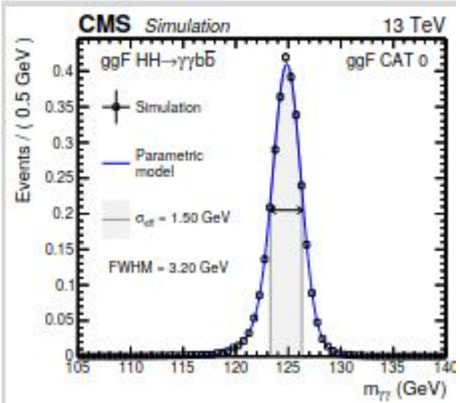
4.1) Efficiencies: example of ATLAS

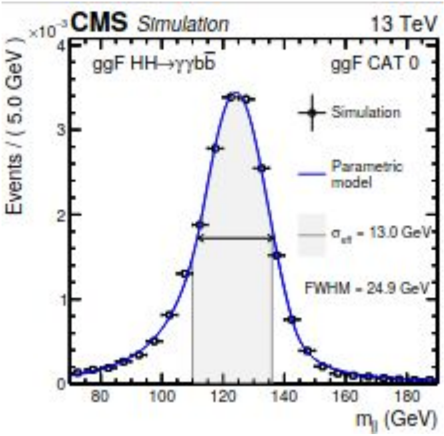


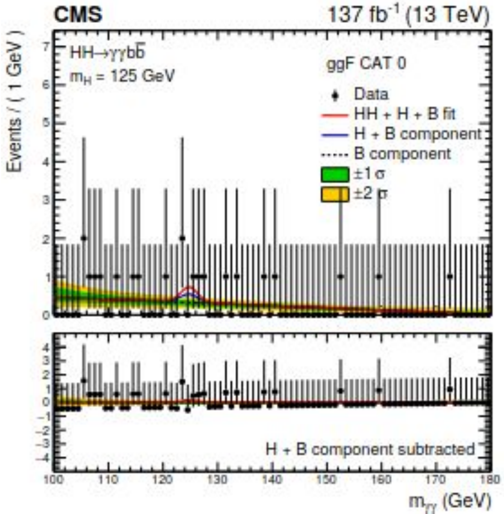
- Overall efficiency is around ~10%.
  - stringent photon cuts and the 2 b-jets requirement give the largest effect.
- Low mass categories catch signal for large $|\kappa_\lambda|$ value.
- High mass categories catch signal for maximum interference region around κ_λ = 1-3.

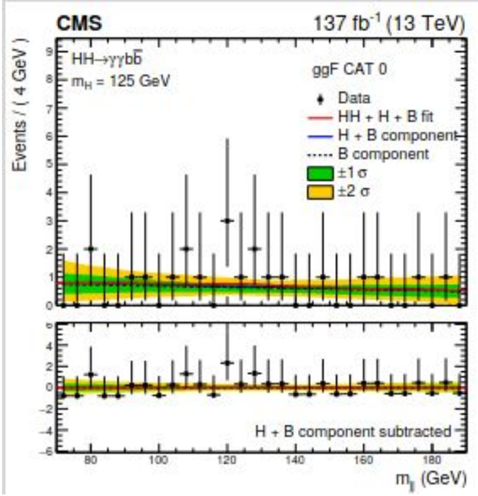


4.2) 2D likelihood in CMS: $m_{\gamma\gamma}$ x m_{jj}



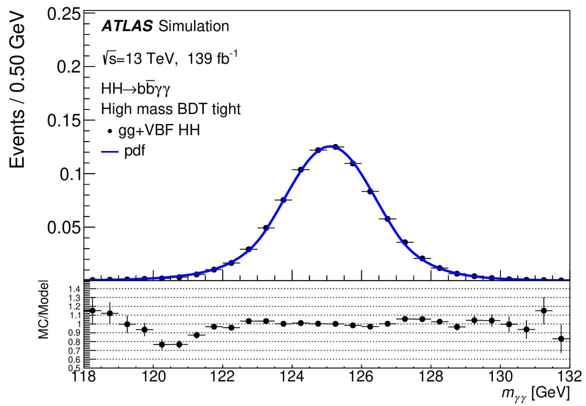


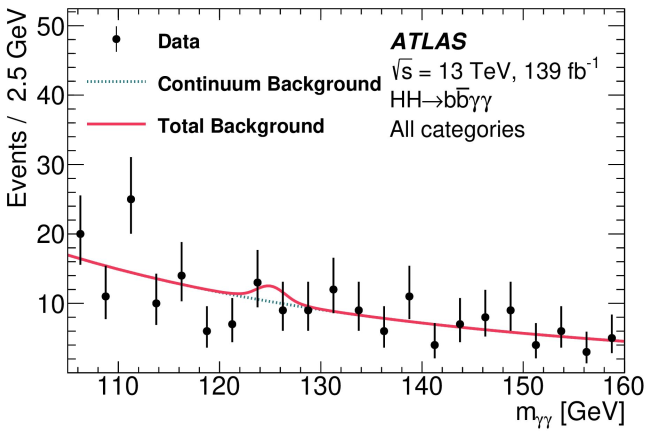




- 2D = 1D x 1D since both dimensions are uncorrelated (verified).
- VH, ttH, have similar shape in γγ but different in jj.
- Same background estimation technique for each dimension: envelop method.
- 2D improves ~ 5-10% over 1D.

4.3) 1D likelihood in ATLAS: $m_{\gamma\gamma}$





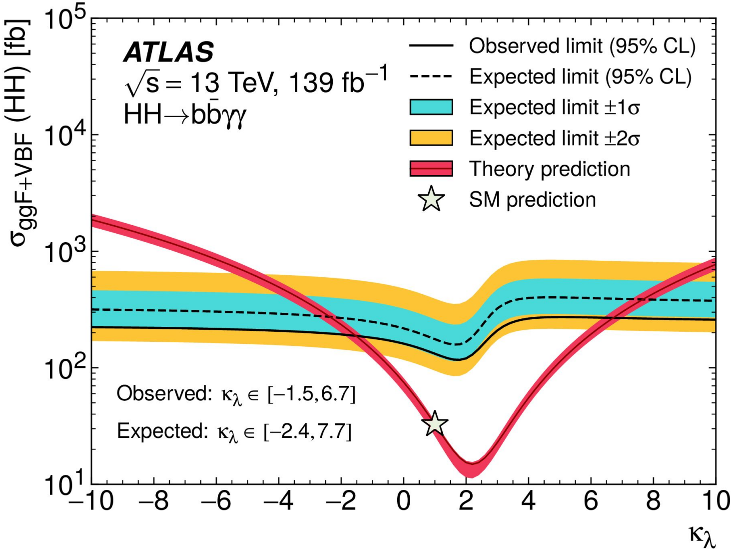
Signal shape:

- Using Double sided cristal ball:
  - Summing VBF HH and ggHH.
  - Summing single Higgs.
  - Considered κ_λ independant.

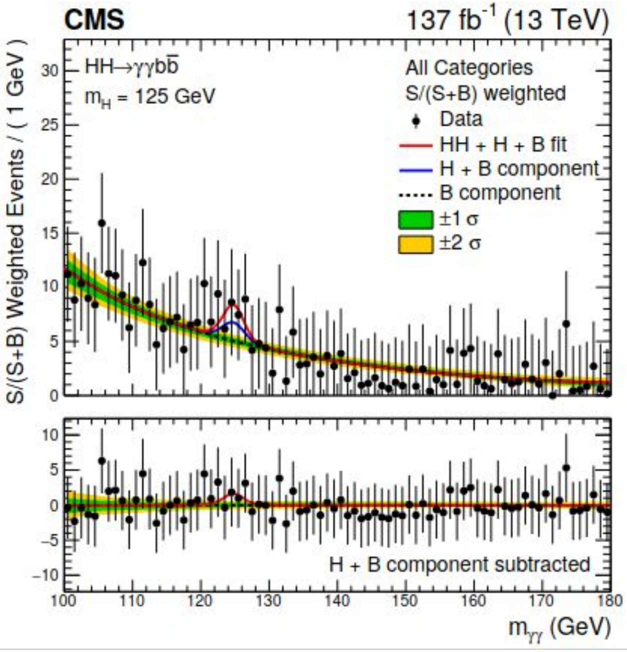
Background shape:

- Several functions are tried: criteria on the Spurious Signal and minimisation of number of d.o.f. (Wald test)
- Spurious signal is the potential signal bias made on a S+B fit made on simulated diphoton MC.
- This maximum bias found in the SR is used as NP.
- In all the categories, the exponential shape is chosen.

5) Results

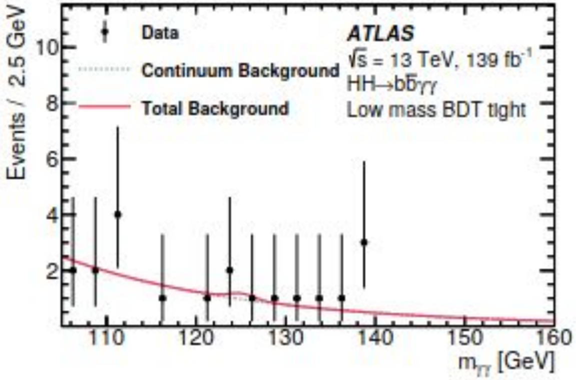


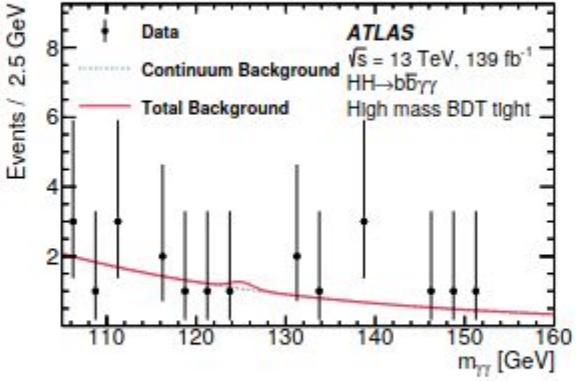
ATLAS
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
HH→$b\bar{b}\gamma\gamma$
Observed limit (95% CL)
Expected limit (95% CL)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
Observed: $\kappa_\lambda \in [-1.5, 6.7]$
Expected: $\kappa_\lambda \in [-2.4, 7.7]$
$\sigma_{ggF+VBF}$ (HH) [fb]
κ_λ



CMS
137 fb^{-1} (13 TeV)
HH→$\gamma\gamma b\bar{b}$
m_H = 125 GeV
All Categories
S/(S+B) weighted
Data
HH + H + B fit
H + B component
B component
±1 σ
±2 σ
S/(S+B) Weighted Events / (1 GeV)
H + B component subtracted
$m_{\gamma\gamma}$ (GeV)

5.1) SM HH

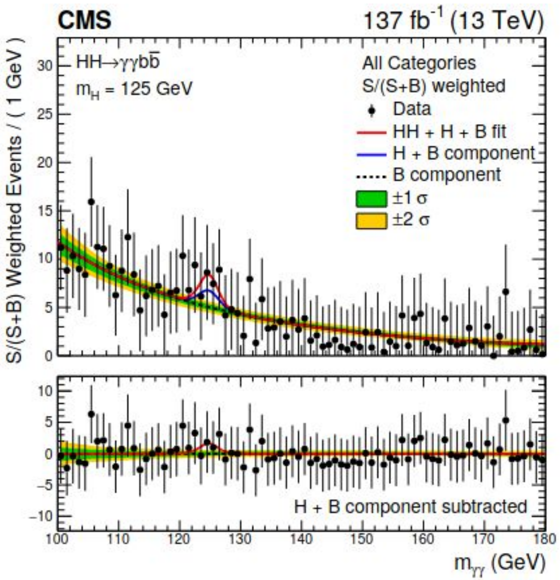




- Both experiments uses NLO prediction for signal: impacts limits at 5-10% compared to LO.

- CMS with a more complex analysis compensates worst b-tag and is more sensitive by 10%.

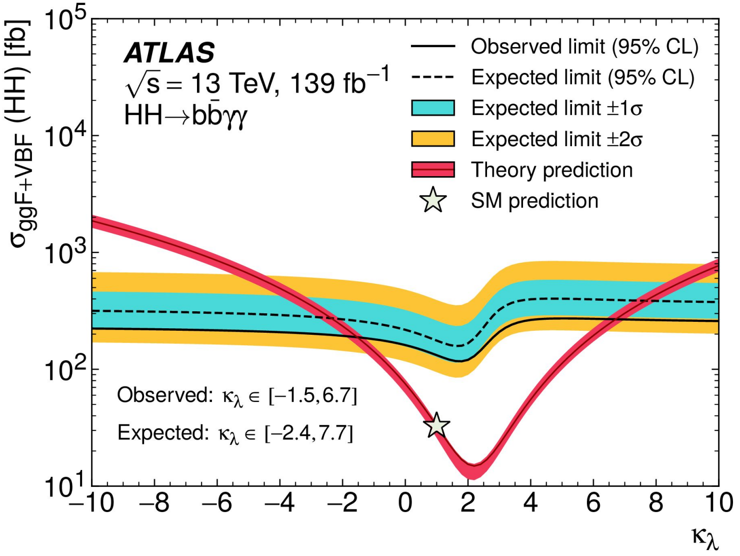
- ½ of the difference ATLAS/CMS comes from top mass scheme uncertainty (Recommendation came after CMS publication)

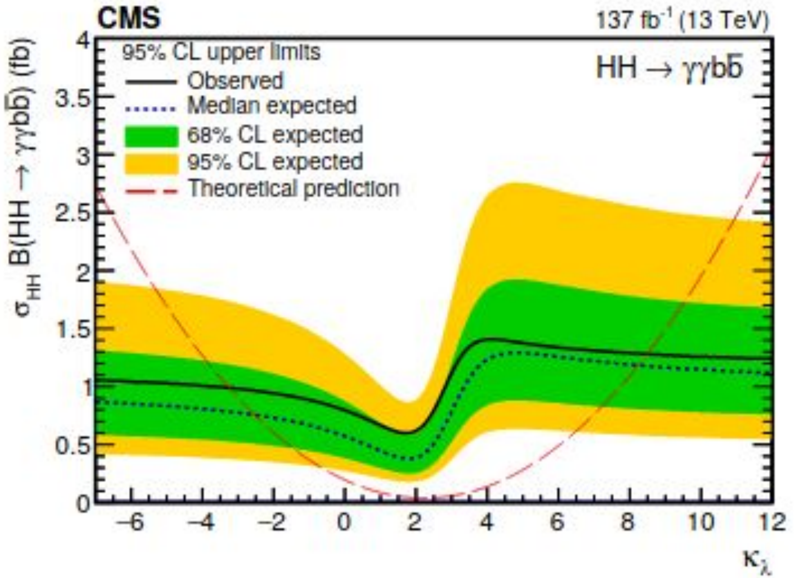


In units of SM	ATLAS*	CMS
Expected	5.7	5.2
Observed	4.2	7.7

- Asymptotic CLS is used. ATLAS checked that full CLS increases limits by 8% since stats is low..

5.2) κ_λ scan: limits

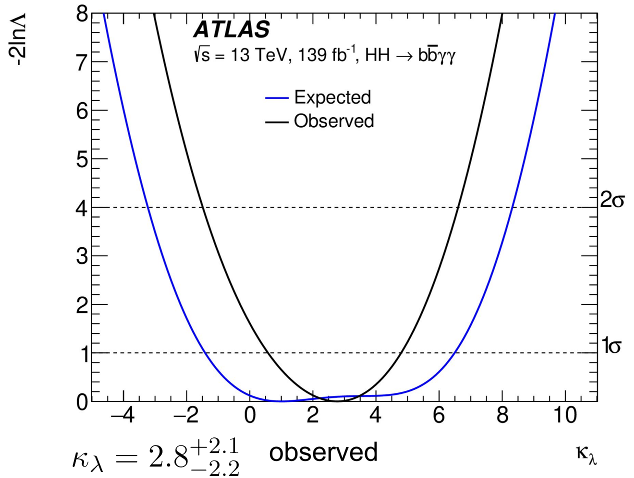




- Impact of VBF on the κ_λ contraint: ~ 5%.
- Expected similar between 2 experiences: probably dedicated training at low mass in ATLS with $|\boldsymbol{\kappa_\lambda}|$= 10 helps there.

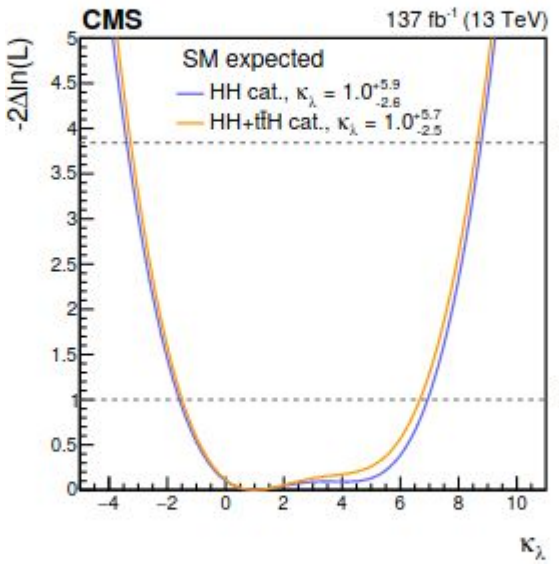
Limits on κ_λ	ATLAS*	CMS
Expected	[−2.4, 7.7]	[− 2.5, 8.2]
Observed	[−1.5, 6.7]	[− 3.3, 8.5]

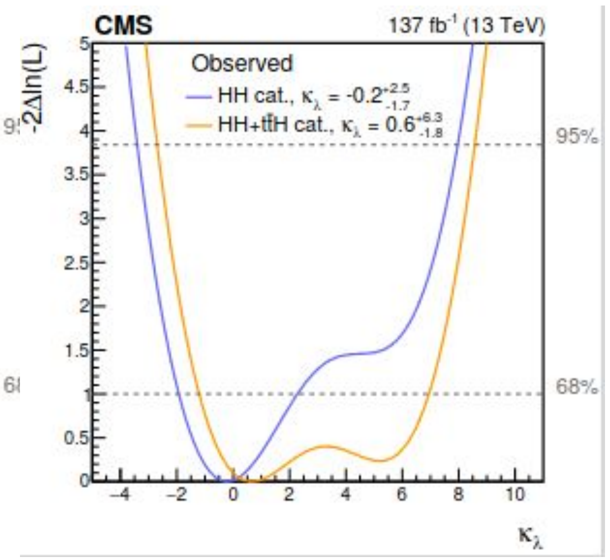
5.2) κ_λ scan: likelihood



$\kappa_\lambda = 2.8^{+2.1}_{-2.2}$ observed

$\kappa_\lambda = 1.0^{+5.5}_{-2.4}$ expected

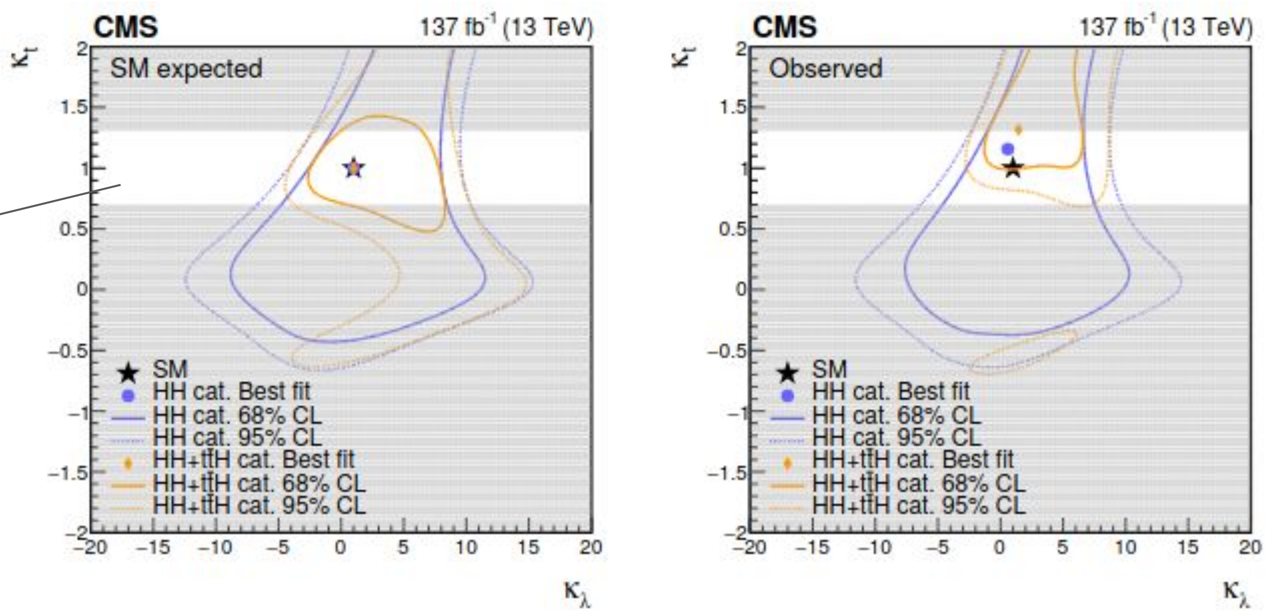




- Since we are slowly moving toward a measurement both collaborations made public likelihood scans.
- CMS collaboration added data categories enriched in ttH events. This helps to constrain ttH contribution and add small constraint to κ_λ trough EW corrections to single H prod.
- Observed likelihood shape can be different from expected as function of the best-fit value.

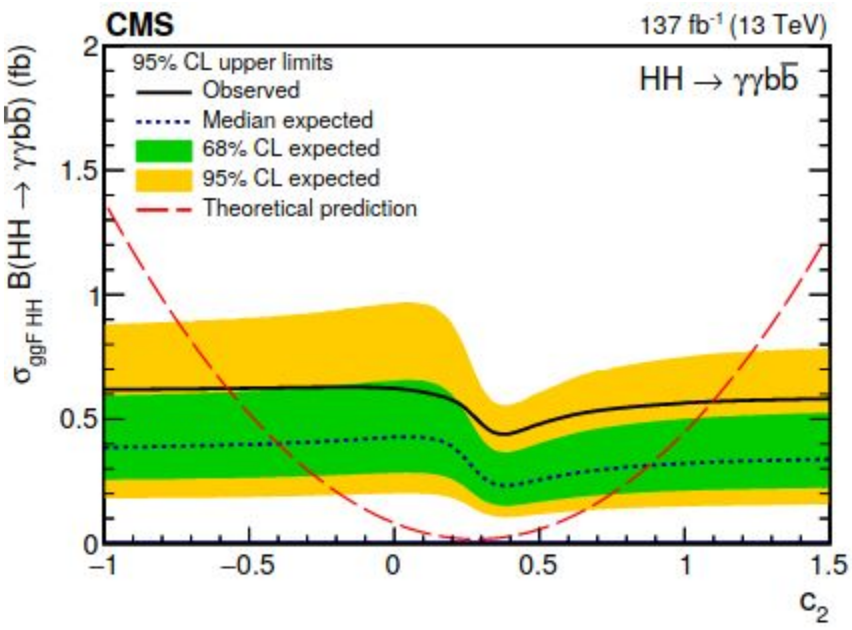
5.3) κ_λ x κ_t constraints: CMS

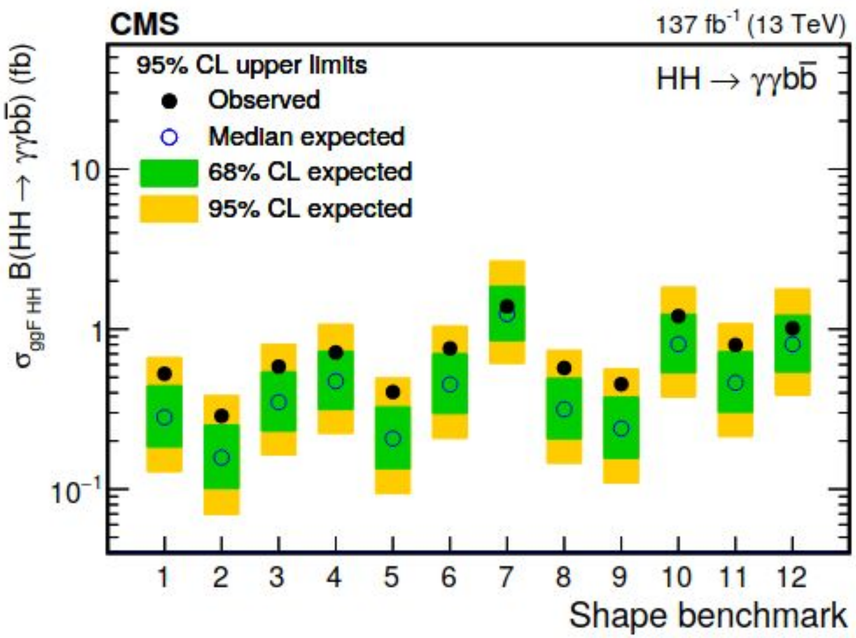
Validity region of κt dependence (LO) of single H production used in this analysis



- Simultaneous fit with ttH categories clearly constraints k_T(=1.3 +-0.2) without degrading k_λ sensitivity.

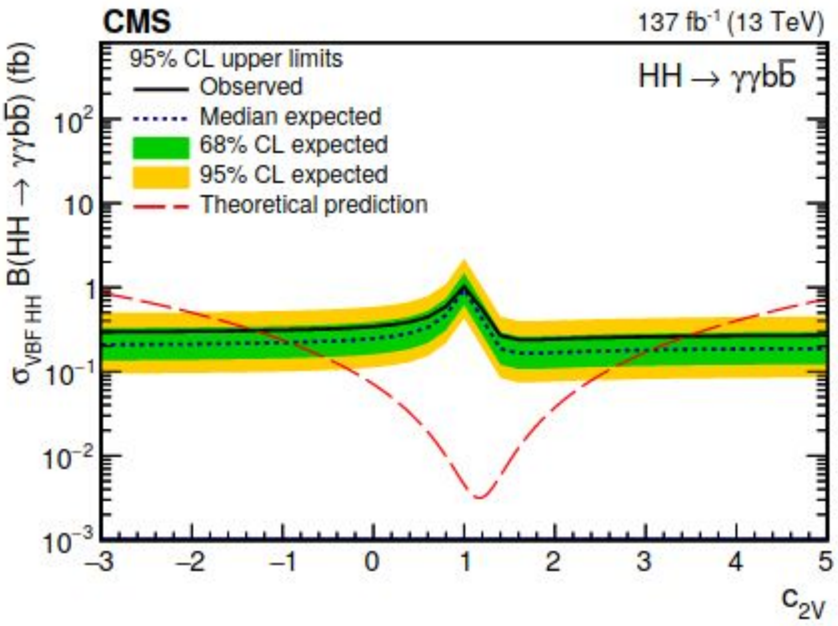
5.4) C_2 and benchmarks: CMS

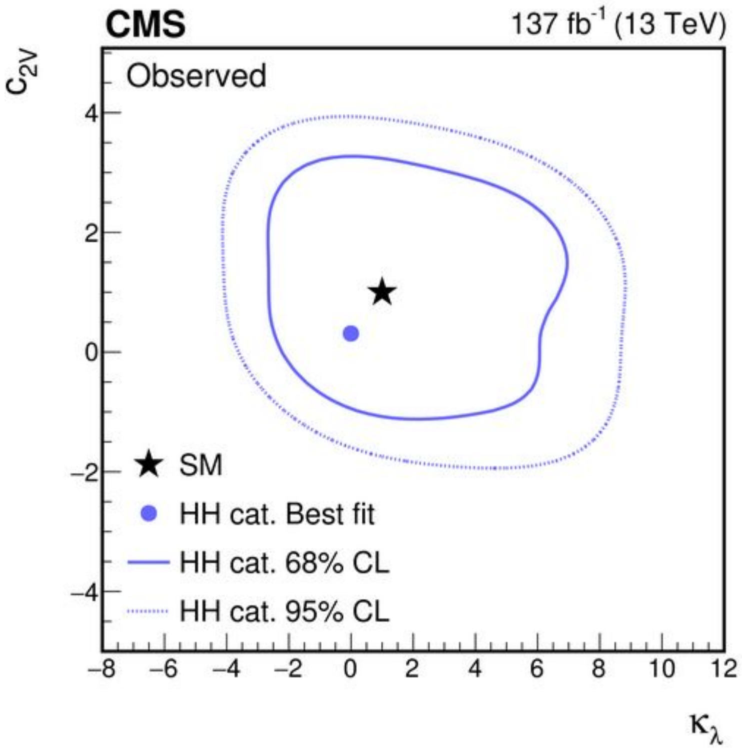




- The $c_2 > 1.1$ and $c_2 < -0.6$ is excluded (SM prediction for this operator: 0).
- Benchmark limits are setup: no visible excess observed anywhere.
- Level of excess changes for different benchmarks: the technique shows to be useful to be sure we didn't miss any important corner of the phase-space,

5.5) VBF HH and C_{2V}: CMS





- VBF limit is very weak: 225 times SM.
- VBF categories provide strong limits on C_{2V}. However, C_{2V} = 0 is not excluded by this channel.

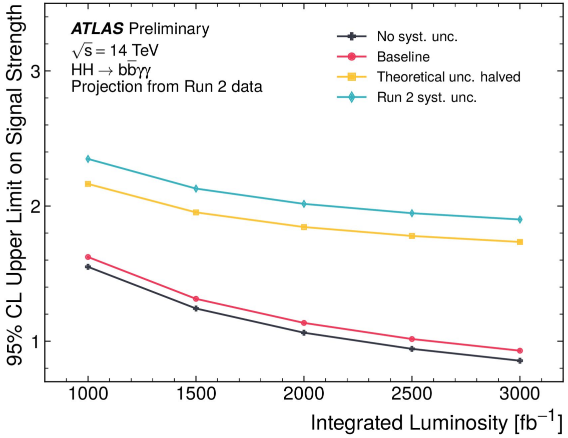
CONCLUSION

- Both CMS and ATLAS analyses in this channel are finished for Run II.
- Results are comparables:
  - CMS have slightly better results for SM HH
  - ATLAS and CMS have same level of limits on kL.
  - CMS shows extra results on VBF HH (to come for ATLAS) and BSM interpretations.
- Run 3 improvements:
  - B-jets selection and calibration
  - Single Higgs background rejection

BACKUP

Future: ATLAS

ATLAS released a projection of the full Run-2 limits for the snowmass studies: [ATL-PHYS-PUB-2022-001]

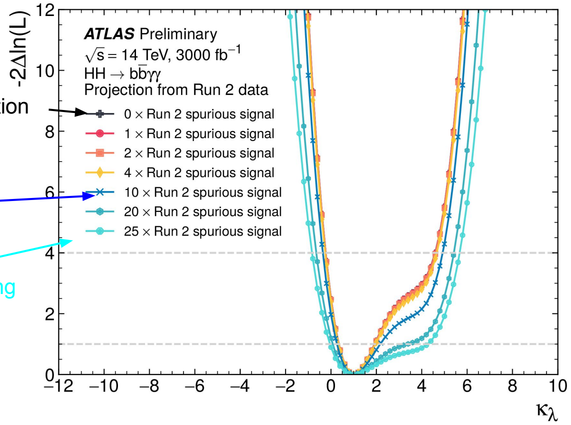


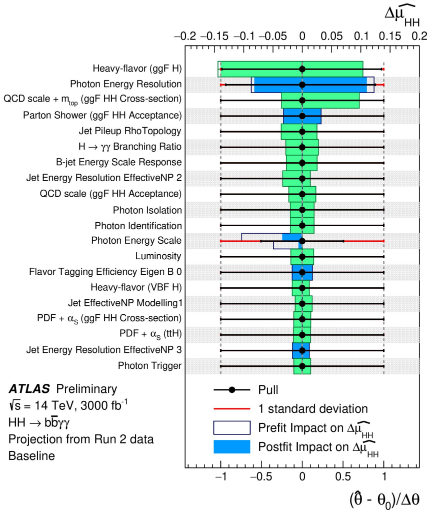
4 scenarios:
- no systematics
- Baseline: no spurious signal, theory syst halved, experimental systematic follow theory syst ing dedicated pattern
- theory syst. halved: Run-2 syst, except theory syst that are halved
- Run-2 like configuration: spurious signal is scaled with luminosity

Possible different bgd modelisation

With mitigation procedures like GPR

If we don't do anything





The heavy flavour modelisation and QCD scale of the ggF $H \to \gamma\gamma$ are also impacting highly the signal strength measurement.
↳ challenges for the theoretical community.

Reweighting and couplings

- Only the VBF samples are generated at LO and the XS is rescaled to the NLO prediction.
- For the κ_λ parameterization, the signal yields are parametrized in each category with 2nd order polynomial based on two basis:
    - ggF: only 2 couplings are available (1 and 10). A reweighting method is performed to get a continuous description, based on the truth m_{HH} obtained from a linear combination of LO samples.
    - VBF: the signal yield is parametrized based on a basis of 4 samples (0, 1, 2 and 10).
- Other couplings are set to their SM values.

ATLAS BDT Strategy

- Only one step is used to train the BDT for event selection:
  - signal: ggF HH
  - background: $\gamma\gamma$, ttH, ggH, and ZH
- From the score three regions are defined to maximise the number counting significance : tight, loose and rejected events.
- Regions must guarantee at least 9 $\gamma\gamma$ events in the data sideband ($105 < m_{\gamma\gamma} < 120$ or $130 < m_{\gamma\gamma} < 160$ GeV).
- photon's p_T are rescaled to $m_{\gamma\gamma}$ to avoid correlation with fitting variable.

Variable	Definition
Photon-related kinematic variables	
$p_T/m_{\gamma\gamma}$	Transverse momentum of each of the two photons divided by the diphoton invariant mass $m_{\gamma\gamma}$
η and ϕ	Pseudorapidity and azimuthal angle of the leading and subleading photon
Jet-related kinematic variables	
b-tag status	Tightest fixed b-tag working point (60%, 70%, or 77%) that the jet passes
p_T, η and ϕ	Transverse momentum, pseudorapidity and azimuthal angle of the two jets with the highest b-tagging score
$p_T^{b\bar{b}}$, $\eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudorapidity and azimuthal angle of the b-tagged jets system
$m_{b\bar{b}}$	Invariant mass of the two jets with the highest b-tagging score
H_T	Scalar sum of the p_T of the jets in the event
Single topness	For the definition, see Eq. (**??**)
Missing transverse momentum variables	
E_T^{miss} and ϕ^{miss}	Missing transverse momentum and its azimuthal angle