Recent Higgs results in the γγ and Zγ decay channels from the ATLAS and CMS collaborations

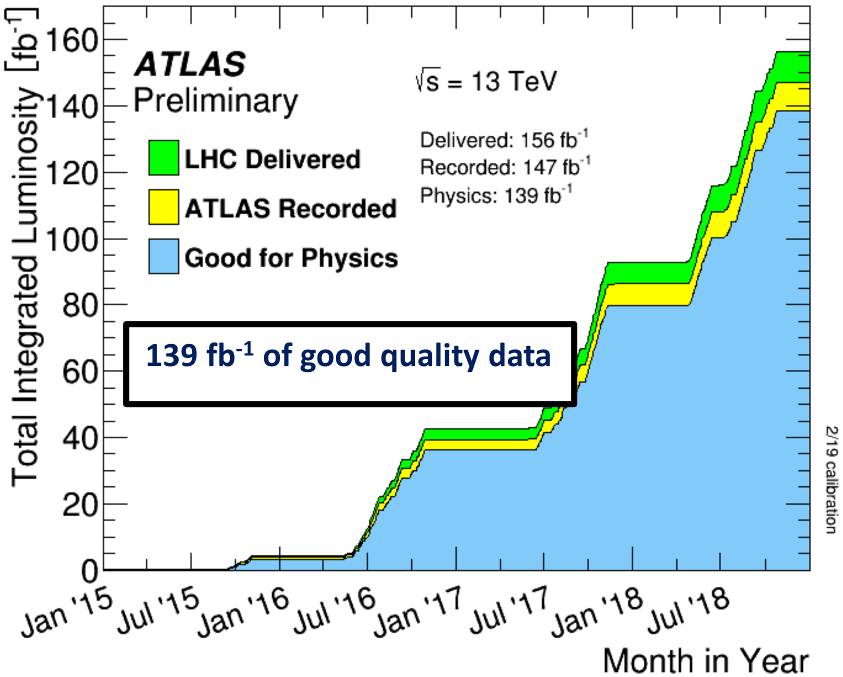
Rajdeep M Chatterjee (rchatter@umn.edu)**
On behalf of the ATLAS & CMS Collaborations

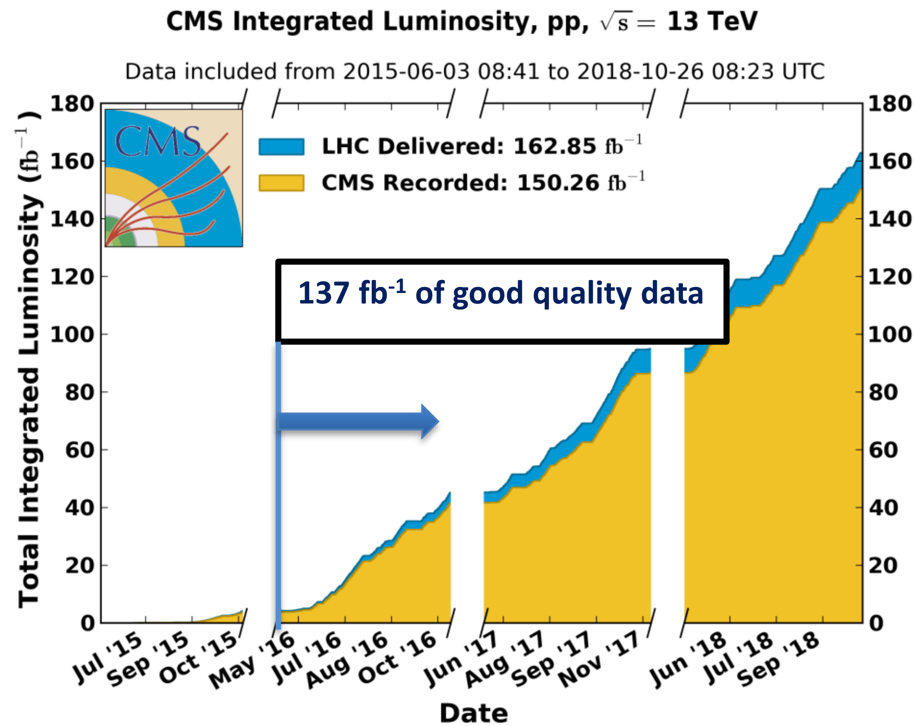
University of Minnesota

8th annual conference on Large Hadron Collider Physics (online)
25-30 May 2020

**A Zoom/Vidyo/Skype meeting can be setup on request

OUTLINE



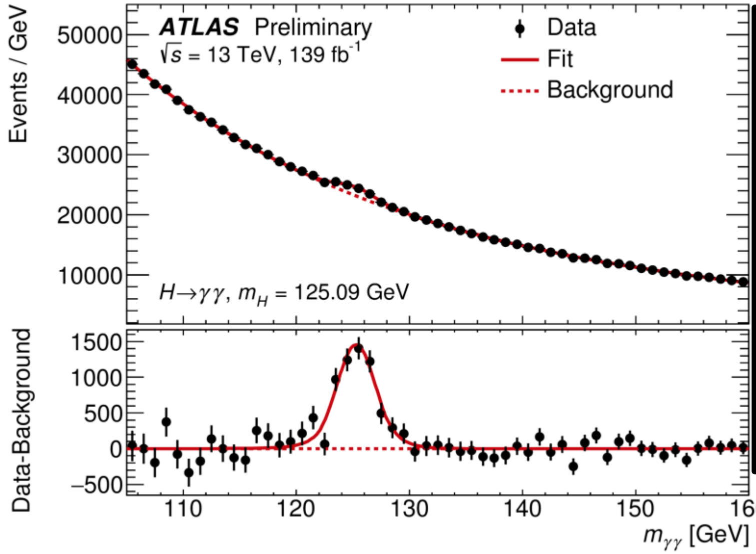


COLLABORATION	MEASUREMENT/SEARCH	DATASET
CMS	Higgs mass **	2016 (combined with Run 1)
ATLAS, CMS	**ttH+tH production and CP studies**	**FULL Run 2** ****NEW****
ATLAS	**Search for Higgs boson decays to Zγ**	**FULL Run 2** ****NEW****

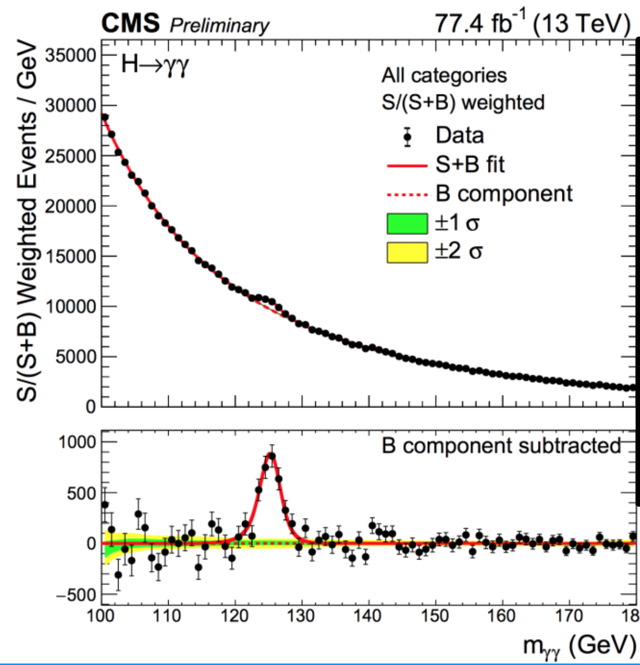
**Same measurement also performed by ATLAS earlier in Phys. Lett. B 784 (2018) 345

Overview of the H→γγ/Zγ channels

- **High resolution channels with a fully reconstructed final state** comprising of two photons/two leptons (e or μ) and a photon.
  - **B(H→γγ) ~ 0.23 %; B(H→Zγ) ~ 0.15 %**
- **Excellent $m_{\gamma\gamma}/m_{ll\gamma}$ resolution of ~ 1-2%** owing to the high precision with which leptons and photons are reconstructed**.
  - A signal appears/would appear as a bump in $m_{\gamma\gamma}/m_{ll\gamma}$ at around 125 GeV
- **The signal is modelled from simulation** parametrized as a function of m_H
  - Requires a precise understanding of the detector with corrections applied to simulated events to accurately represent data.
- **Data-driven estimate of the ~smoothly falling background** from continuum diphoton/Zγ production (+ fakes)



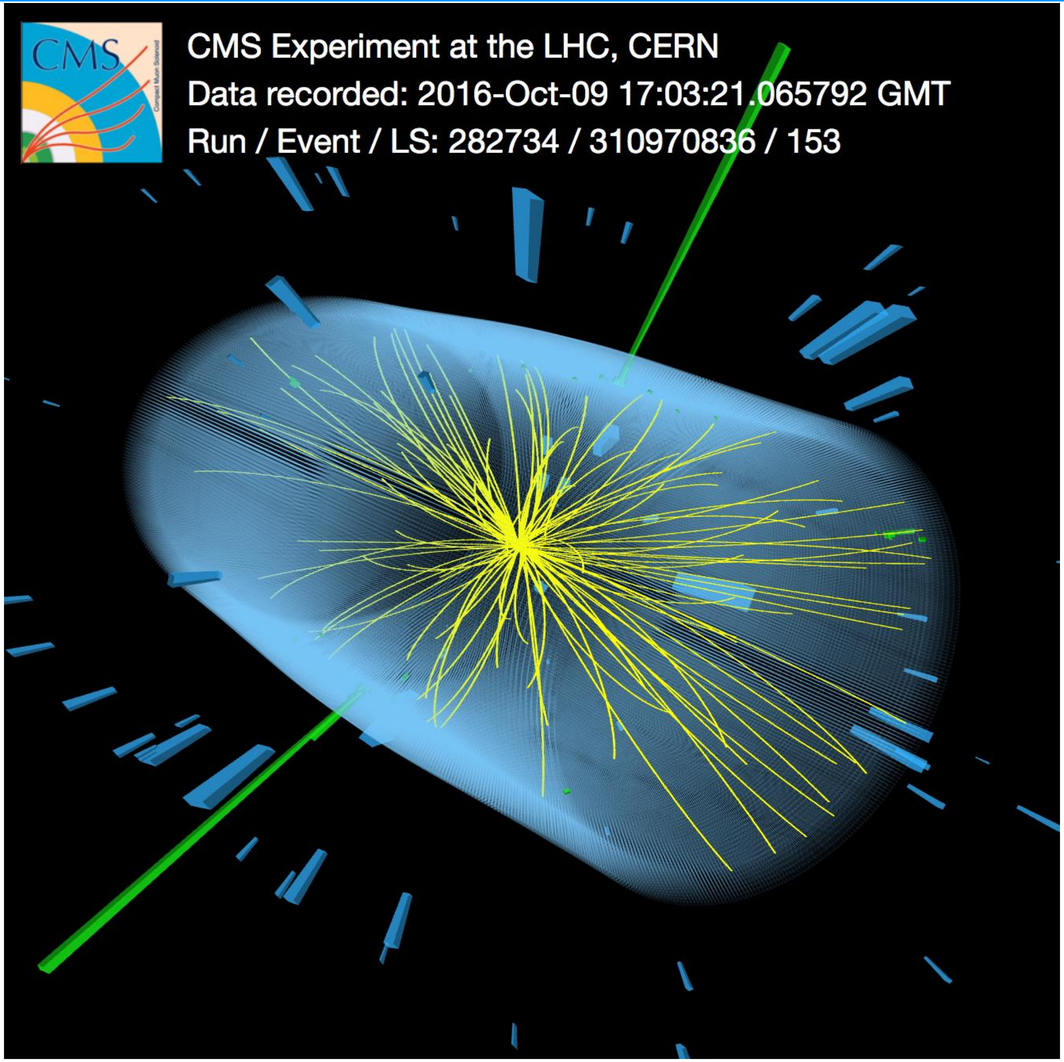
ATLAS-CONF-2019-029



CMS PAS-HIG-18-029

**See Shilpi's talk for lepton/photon performance in ATLAS and CMS

The Higgs Boson mass: H→γγ

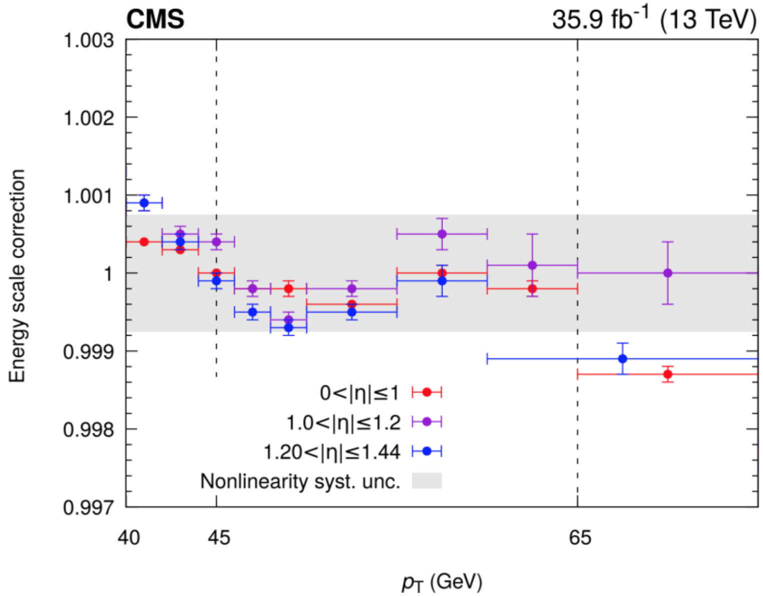


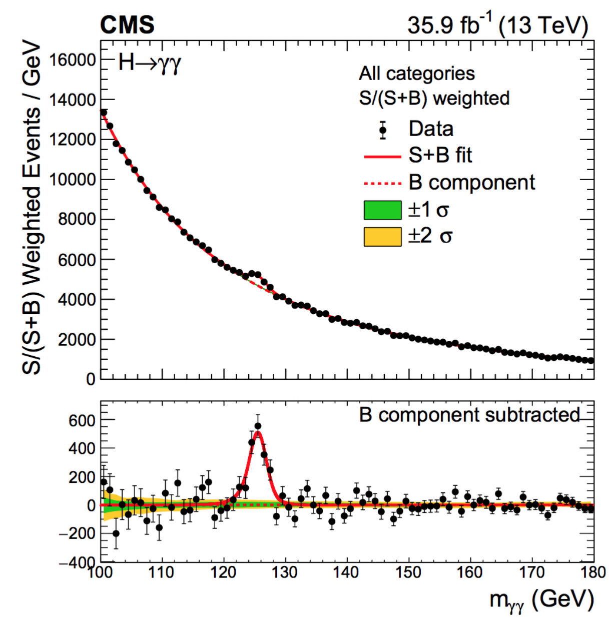
CMS: Phys. Lett. B 805 (2020) 135425

m_H in the diphoton channel with the 2016 dataset

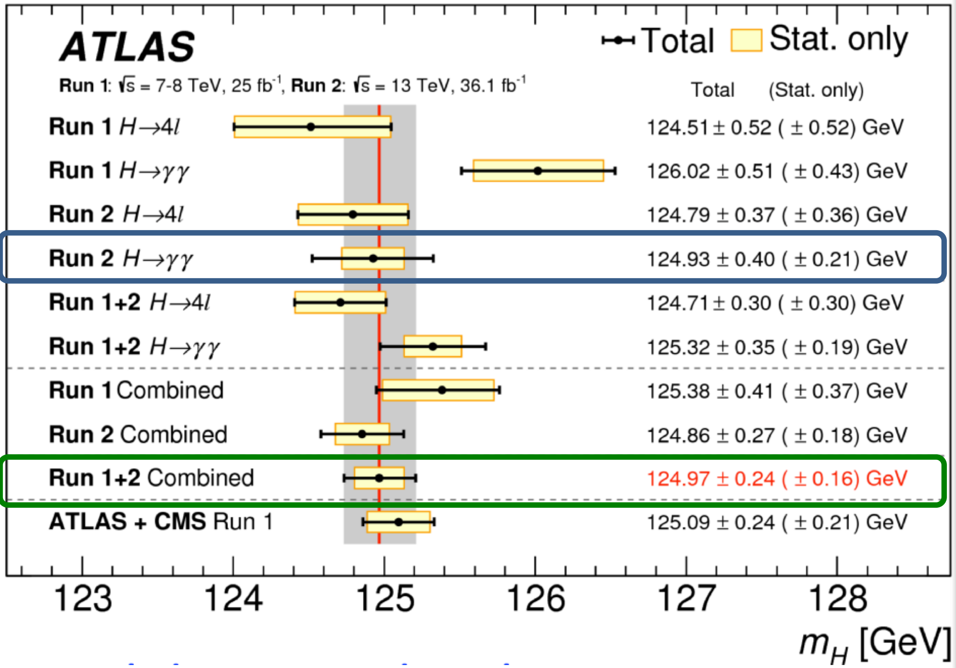
- Improved ECAL calibration leading to more stable response with time.
- Dedicated corrections for the photon energy scale using Z→ee events in data and simulation:
  - **Five times more granular.**
  - **Correct nonlinear discrepancies in the photon energy scale with p_T between data and simulation.**
  - **Precision of the electron energy scale at the level of 0.075%**
- **The $m_{\gamma\gamma}$ resolution in the most sensitive (weighted sum of all) category is 1.35 (1.68) GeV**

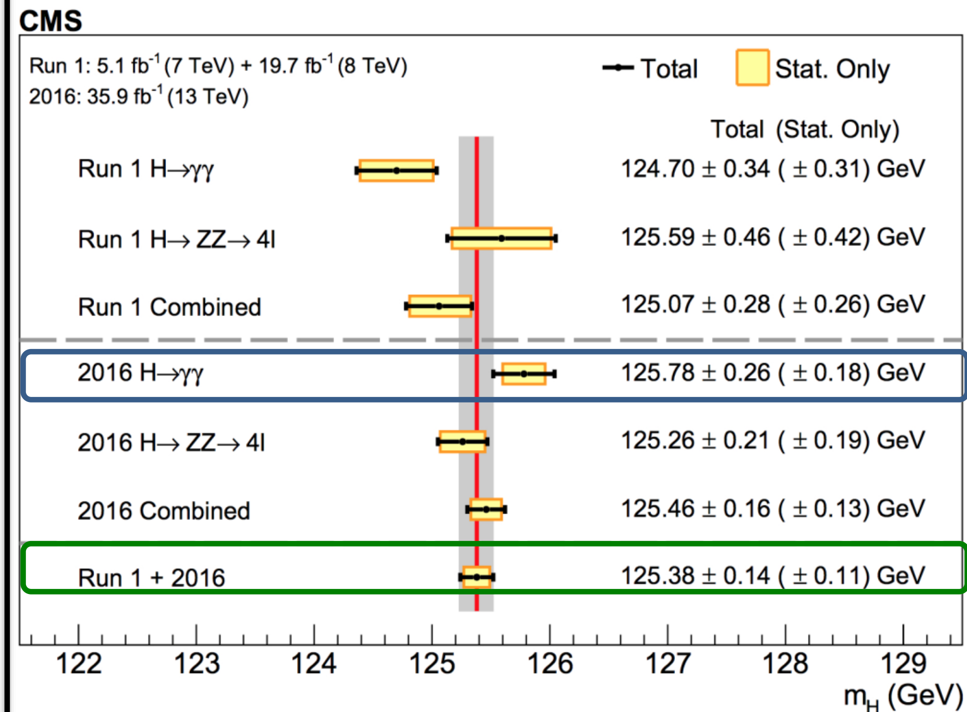
m_H = 125.78 ± 0.26 [0.18 (stat.) ± 0.18 (syst.)] GeV





Combined measurement of m_H





ATLAS

Run 1 + 2016 combined:

m_H = 124.97 ± 0.24 [0.16 (stat.) ± 0.18 (syst.)] GeV

See Will's talk for m_H measurements in the H→ZZ→4l channel (New ATLAS result with full Run 2).

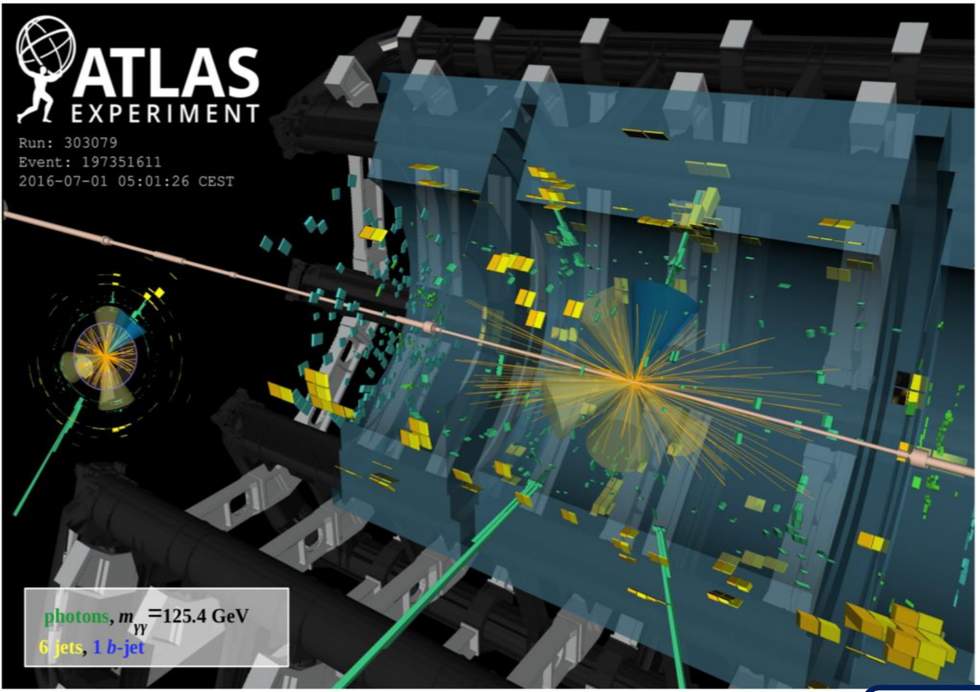
CMS

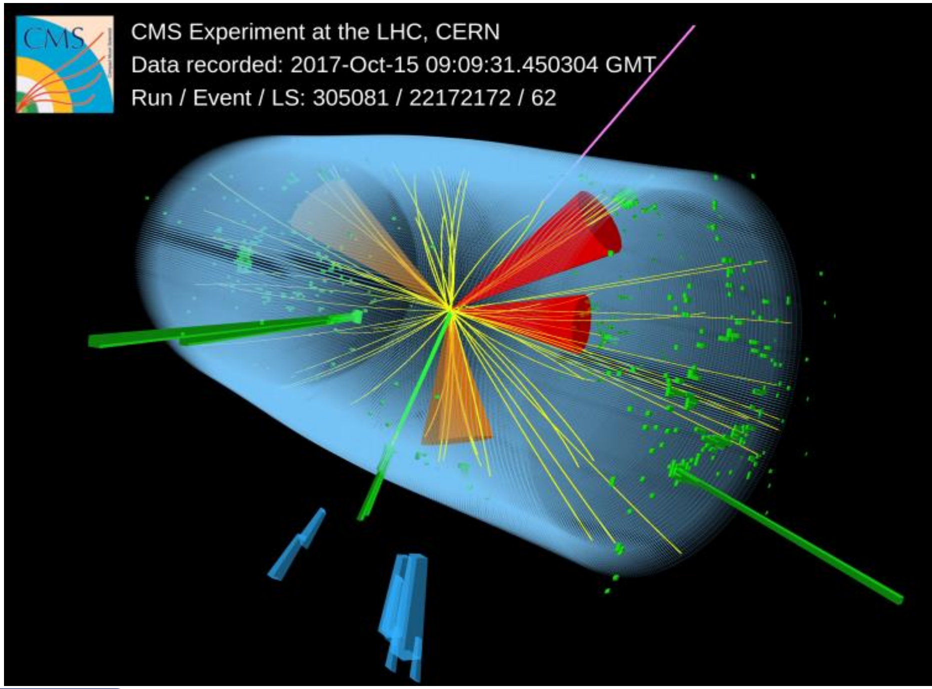
Run 1 + 2016 combined:

m_H = 125.38 ± 0.14 [0.11 (stat.) ± 0.08 (syst.)] GeV

Most precise measurement of m_H till date: ~0.1 %

ttH + tH production and CP properties of the Higgs boson





NEW

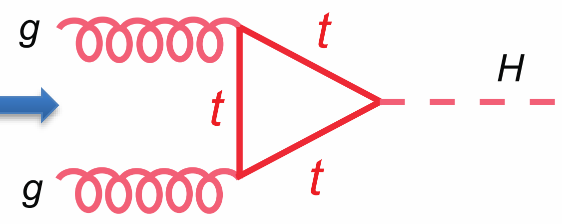
ATLAS: arxiv:2004.04545 CMS: arxiv:2003.10866

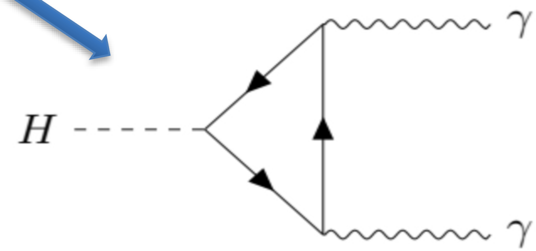
Both papers have been submitted to Phys. Rev. Lett.

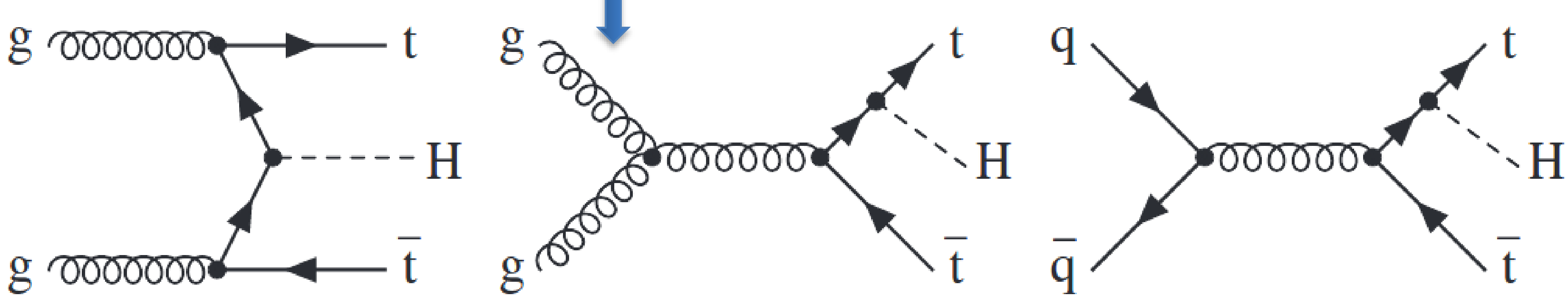
See Josh's talk for the current status of ttH measurements in CMS

The t-H coupling : Motivation

- Fermions couple to the Higgs boson via the Yukawa interaction.
  - The coupling is proportional to the fermion mass. Hence largest for the top quark.
- The t-H Yukawa coupling can be constrained indirectly in the production of the Higgs boson via gluon-gluon fusion and in the diphoton decay mode.
  - Requires assumptions on the contribution from BSM particles in the loops.
- ttH and tH production allows for a direct observation and measurement of the t-H Yukawa coupling







CP properties of the Higgs boson: Motivation

- The Higgs boson of the SM is **CP-even** with $J^{CP} = 0^{++}$
- All measurements to date of the CP properties of the Higgs boson via its interactions with gauge bosons are **compatible with the SM**.
- The CP properties of the Higgs boson via fermionic interactions have not been studied so far.
  - Higher sensitivity to the CP-odd contributions which "enter" at the same order as the CP-even terms (No $1/\Lambda^2$ suppression, where Λ is the scale for new physics).

Probe the CP structure of the t-H interaction

ATLAS

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + i\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

- Where κ_t is the top Yukawa coupling parameter and α is the CP mixing angle
  - **In the SM κ_t = 1 and $\alpha = 0^o$. For CP-odd $\alpha = 90^o$**
- Params. of interest: **κ_t and α**

CMS

$$\mathcal{A}(\mathrm{Htt}) = -\frac{m_\mathrm{t}}{v}\overline{\psi}_\mathrm{t}\left(\kappa_\mathrm{t} + \mathrm{i}\tilde{\kappa}_\mathrm{t}\gamma_5\right)\psi_\mathrm{t}$$

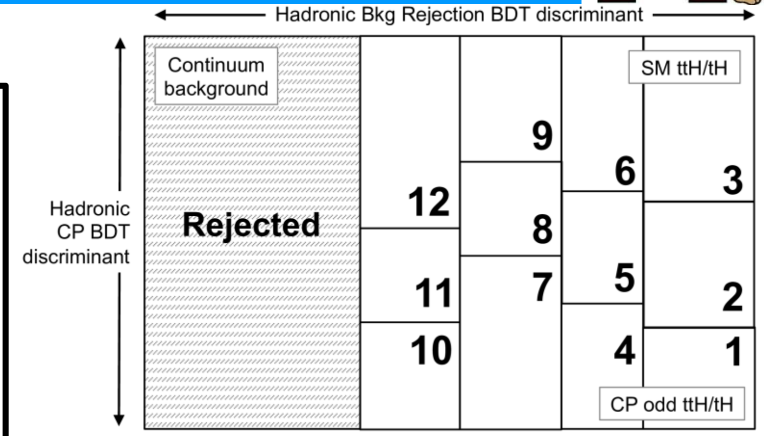
- Where κ_t and $\tilde{\kappa}_t$ are the CP-even and CP-odd Yukawa couplings. **In the SM κ_t =1 and $\tilde{\kappa}_t$ = 0**

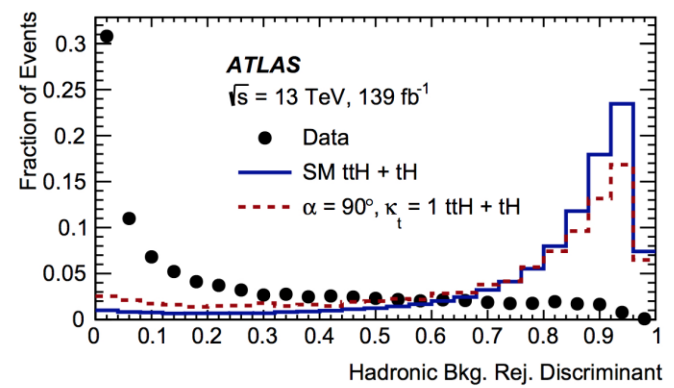
Param. of interest: $f_{\mathrm{CP}}^{\mathrm{Htt}} = \frac{|\tilde{\kappa}_\mathrm{t}|^2}{|\kappa_\mathrm{t}|^2 + |\tilde{\kappa}_\mathrm{t}|^2}\,\mathrm{sign}(\tilde{\kappa}_\mathrm{t}/\kappa_\mathrm{t})$

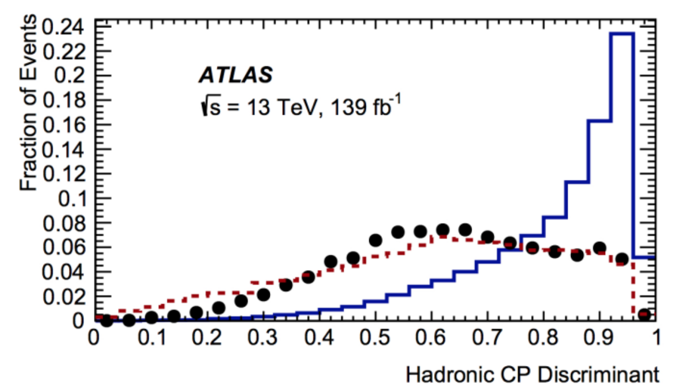
Analysis strategy : ATLAS

NEW

- Select events with 2 isolated photons and **≥ 1 b tagged jet**. Further divide events depending on the number of reconstructed leptons(e and μ).
  - Hadronic region : #jets ≥ 3 and #leptons = 0
  - Leptonic region : #leptons ≥ 1
- Events categorized into **12 (8) cats.** using a 2D-partition of 2 1D BDTs for the had. (lep.) regions.
  - "Bkg. rejection BDTs" used to separate the ttH process from other SM processes.
  - "CP BDTs" to separate the CP-even from the CP-odd couplings using the ttH and tH processes.
  - **The ttH and tH yields are parameterized in terms of k_t and α**
- A simultaneous fit is performed to the $m_{\gamma\gamma}$ distributions in all 20 categories for signal extraction.

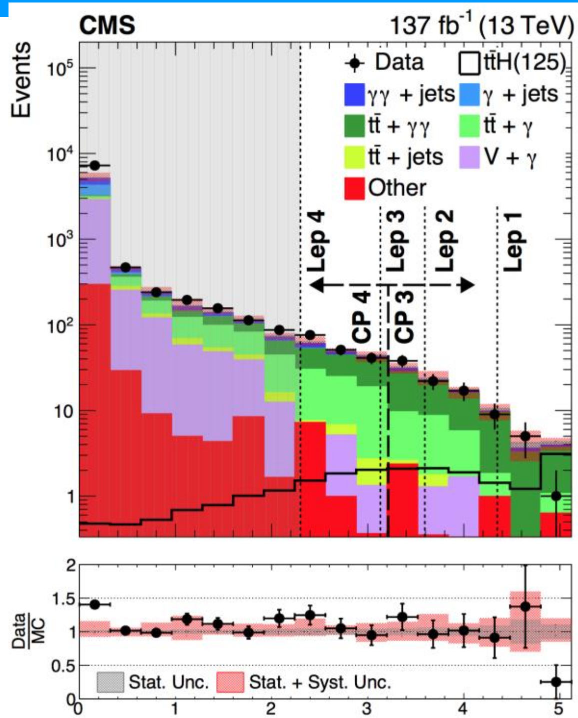




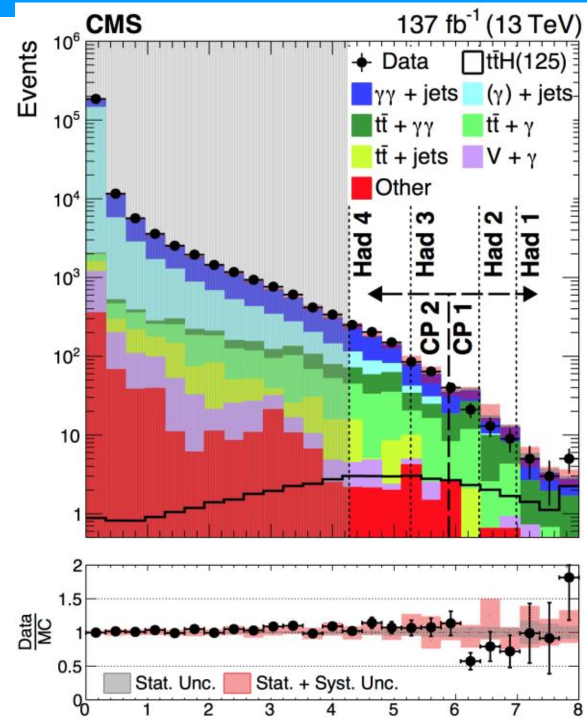


Analysis strategy : CMS

NEW



Lep Bkg. Rej. BDT

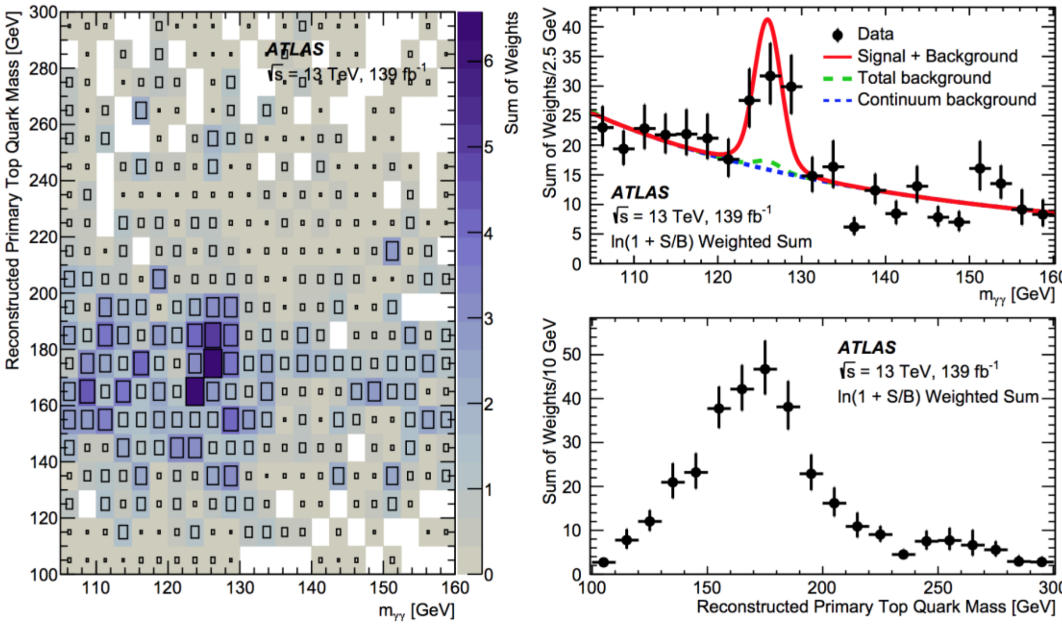


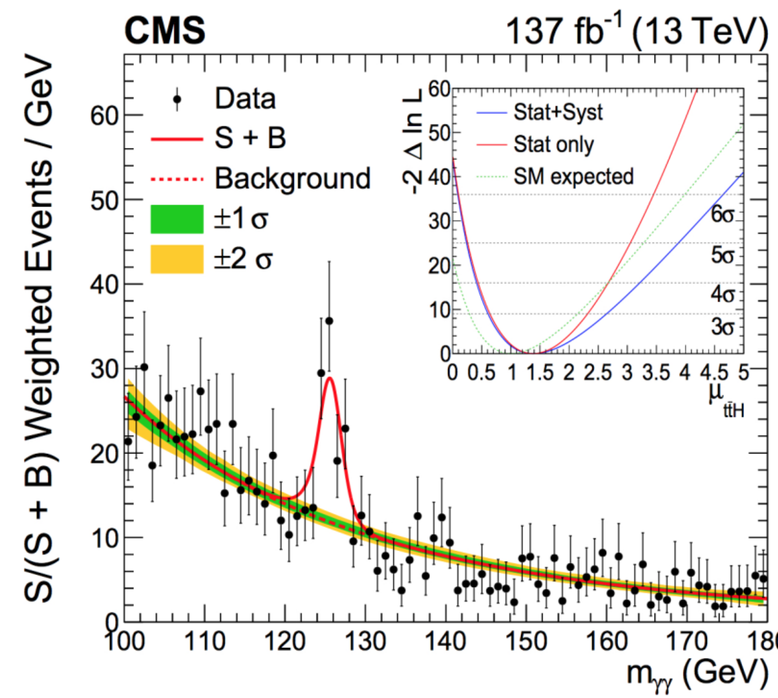
Had Bkg. Rej. BDT

- Select events with 2 isolated photons and **≥ 1 jet**.
  → Hadronic region : #jets ≥ 3 (1 b-jet) and #lep = 0 → Leptonic region : #lep ≥ 1
- **1D signal strength analysis :** "Bkg. Rej. BDTs" used to define 4*2 categories in the two regions.
- 2D CP analysis : "D_{0-} BDTs" used to define **12 categories : 3 D_{0-} * 2 Bkg. Rej. * 2 regions**
  - **The tH yield is parameterized in terms of $|f^{Htt}_{CP}|$ and μ_{ttH}**
- A simultaneous fit is performed to the $m_{\gamma\gamma}$ distributions in all categories for signal extraction.

Results: ttH + tH signal strength

NEW





- **μ_{ttH} = 1.4 ± 0.4 (stat.) ± 0.2 (syst.)**
  - Non ttH Higgs production modes constrained to SM prediction. Assume CP even coupling.
- **Obs. (Exp.) sig. = 5.2 σ (4.4 σ)**
- **tH rate: < 12 x SM** xsec at 95% CL

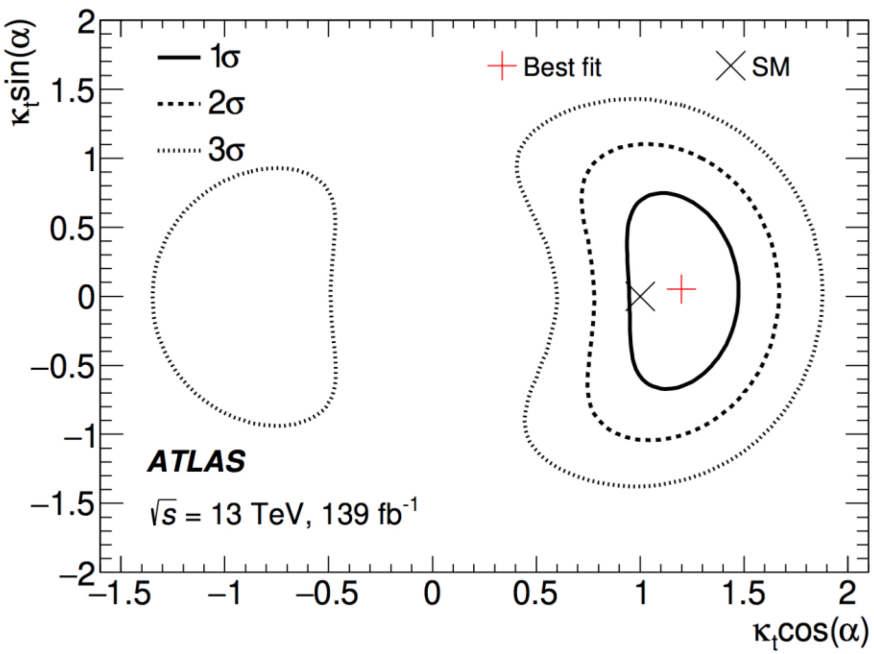
→ Non tH/ttH Higgs production modes constrained to the SM prediction.

ATLAS

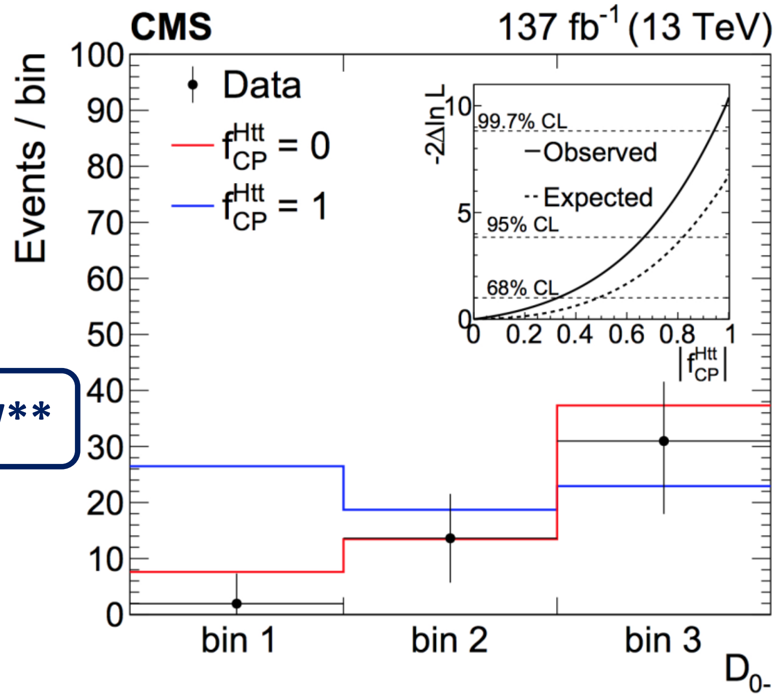
- **$\mu_{ttH} = 1.38 \pm^{0.29}_{0.27}$ (stat.) $\pm^{0.21}_{0.11}$ (syst.)**
  - Non ttH Higgs production modes constrained to SM prediction.
- **Obs. (Exp.) sig. = 6.6 σ (4.7 σ)**
- **$\sigma_{ttH}.B_{\gamma\gamma} = 1.56^{+0.34}_{-0.32}$ fb**

  $= 1.56 \pm^{0.33}_{0.30}$ (stat.) $\pm^{0.09}_{0.08}$ (syst.) fb
- SM prediction of $(\sigma_{ttH}.B_{\gamma\gamma})_{SM}$ **$= 1.13^{+0.08}_{-0.11}$ fb**

CMS



NEW



- → The Higgs boson coupling modifiers k_γ and k_g are constrained to the combination result .
- → κ_t is left free to float in the fit.

ATLAS

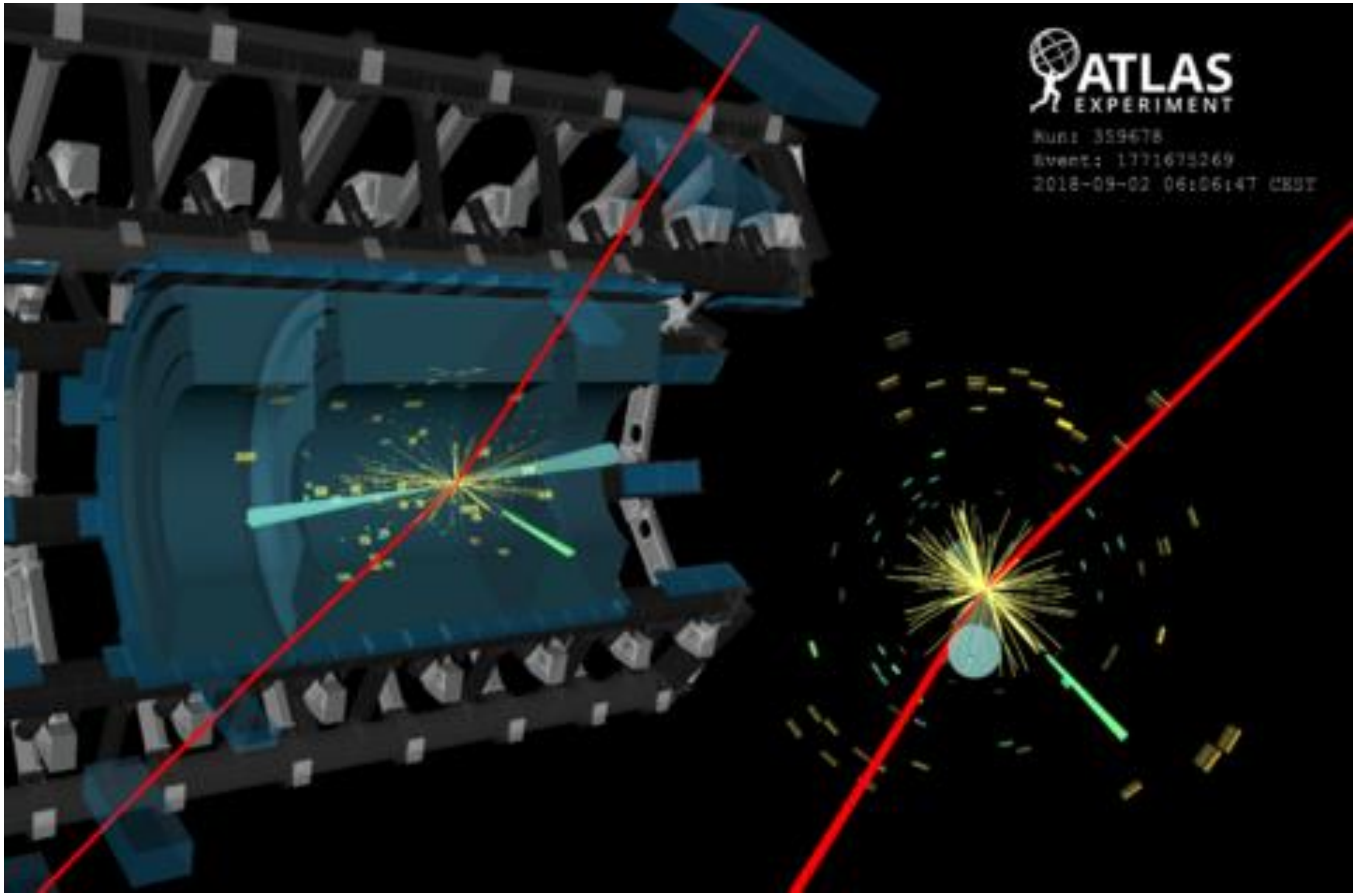
- **$|\alpha|$ > 43º (63º)** obs. (exp) exclusion at 95% CL
- Obs. (Exp.) pure CP-odd coupling excluded at **3.9 σ (2.5 σ)**

- → The Higgs boson couplings to other particles constrained to SM.
- → μ_{ttH} and $|f^{Htt}_{CP}|$ are free to float in the fit.

- **f^{Htt}_{CP} = 0.00 ± 0.33 at 68% CL**
- Limit at 95% CL : **$|f^{Htt}_{CP}|$ < 0.67**
- Obs. (Exp.) pure CP-odd coupling excluded at **3.2 σ (2.6 σ)**

CMS

A search for Higgs boson decays to Zγ



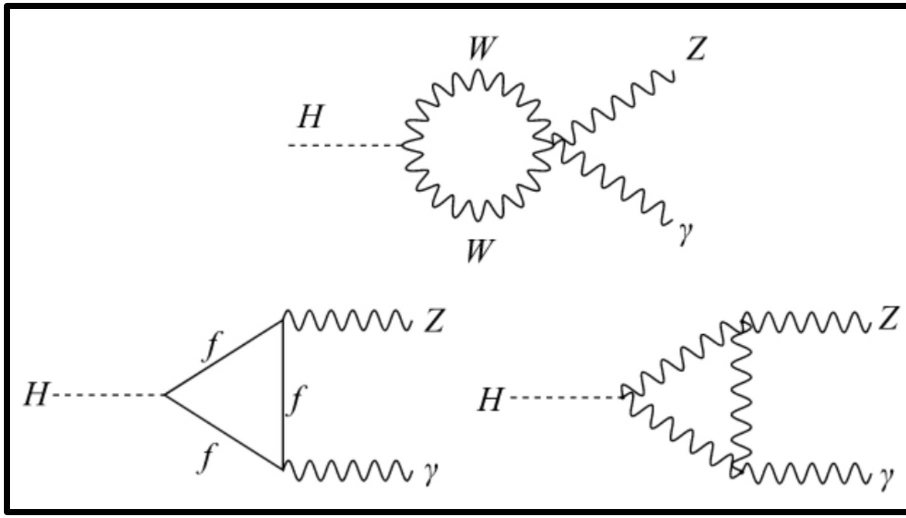
ATLAS: arxiv:2005.05382

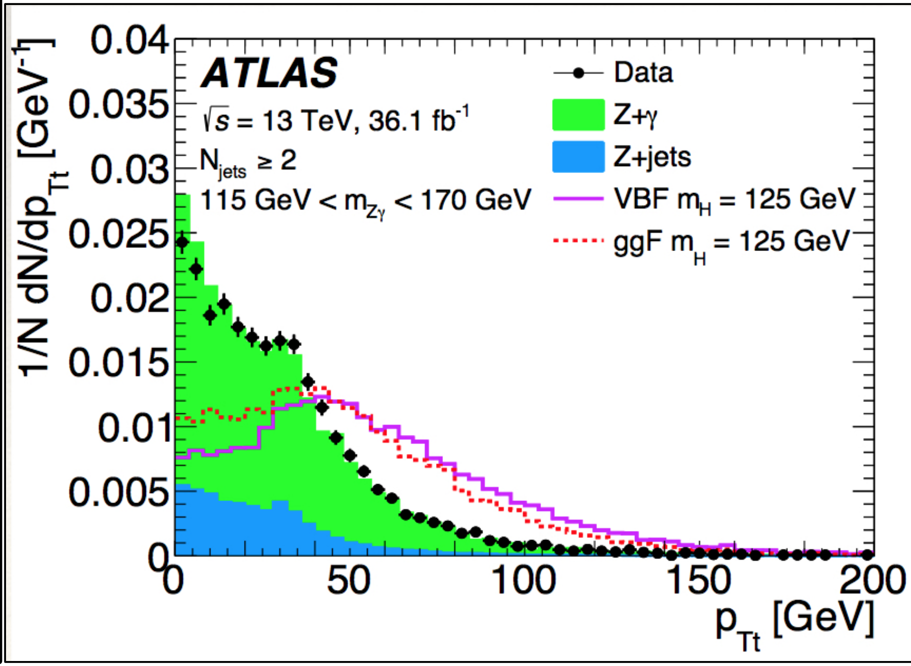
Submitted to Phys. Lett. B

NEW

Higgs boson decays to Zγ : Introduction

- The SM Higgs boson can decay into Zγ via loop diagrams with a branching ratio of ~0.15% @ m_H = 125.09 GeV.
  - **The branching ratio can differ from the above value in BSM scenarios where the Higgs is a neutral scalar of non-SM origin or for a composite Higgs.**
  - **The branching ratio can also differ if there exist additional non-SM particles that couple to the SM Higgs boson via loop corrections.**
- First result with the full 139 fb^{-1} Run 2 dataset.
- Search performed in Z(→ll) final states where l = e or μ.
  - **Z boson branching ratio ~ 7 % in these final states**
- One of the signal-bkg. discriminating variables $\mathbf{p_{Tt}}$ is used to suppress background an in categorization.
  - $p_{Tt} = (2 * p_{TZ} * p_{T\gamma} * \sin\Delta\Phi_{Z\gamma}) / p^{Z\gamma}_T$





Event selection and categorization

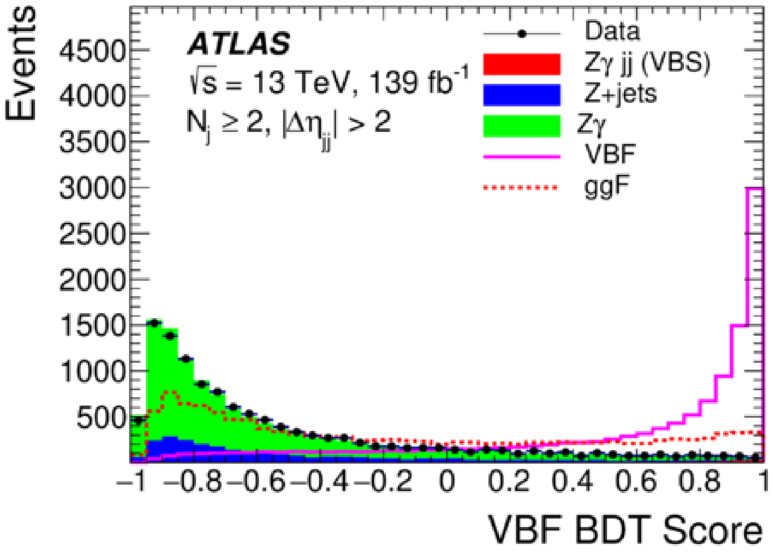
NEW

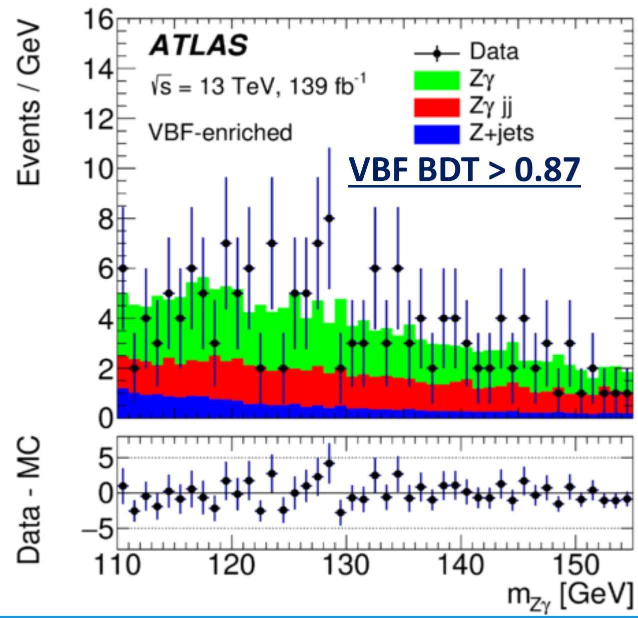
Event Selection :

- Select events with an opposite sign same flavour lepton pair (ee + μμ) and a photon
- Muon energy is corrected for FSR
  - **3% improvement $m_{Z\gamma}$ resolution**
- Constrained kinematic fit with the Z-boson lineshape is used to recompute the dilepton 4-vector
  - **14% improvement $m_{Z\gamma}$ resolution**
- m_{ll} within 10 GeV of nominal Z mass.

Event Categorization:

- **To optimize the S/B of the measurement events are picked up in one of six mutually exclusive categories :**
  - A VBF enriched category using a dedicated BDT
  - Remaining categories based on cut based selections on $p^{\gamma}_T/m_{Z\gamma}$ and p_{Tt} .



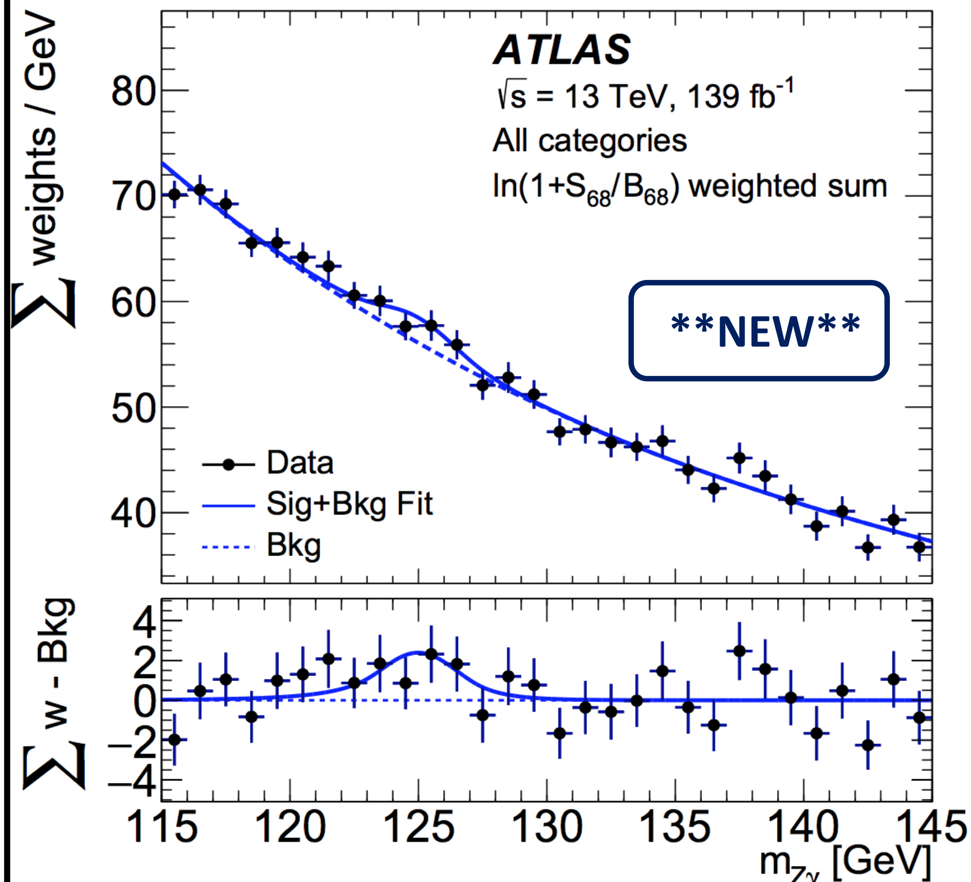


Results

- The observed data are **consistent with the background only hypothesis** with a **significance of 2.2 σ**
  - The expected significance is 1.2 σ under the hypothesis of the presence of a SM Higgs boson.
- The best fit signal strength $\mu_{Z\gamma}$:
  - **Observed $\mu_{Z\gamma} = 2.00^{+1.0}_{-0.9}$**

    $= 2.00 \pm 0.9(\text{stat})\ ^{+0.4}_{-0.3}\,(\text{syst})$

  with the signal yield normalized to the SM prediction.
- Observed 95% CL upper limit on **$\mu_{Z\gamma}$ = 3.6 x SM prediction**
  - Expected limit assuming no (SM) Higgs boson decay into Zγ is 1.7 (2.6) times the SM prediction.
- The observed upper limit on **$\sigma_{pp\rightarrow H}\cdot B_{H\rightarrow Z\gamma}$ is 305 fb** at 95% CL
- The upper limit at 95% CL on the **H→Zγ branching ratio is 0.55%** (assuming SM Higgs boson production cross-section).



Dominant uncertainty :

- Statistics
- The dominant systematic uncertainty, amounting to 28%, on $\mu_{Z\gamma}$ arises out of the "spurious-signal" uncertainties.

Summary

We have entered a precision era with LHC Run 2.

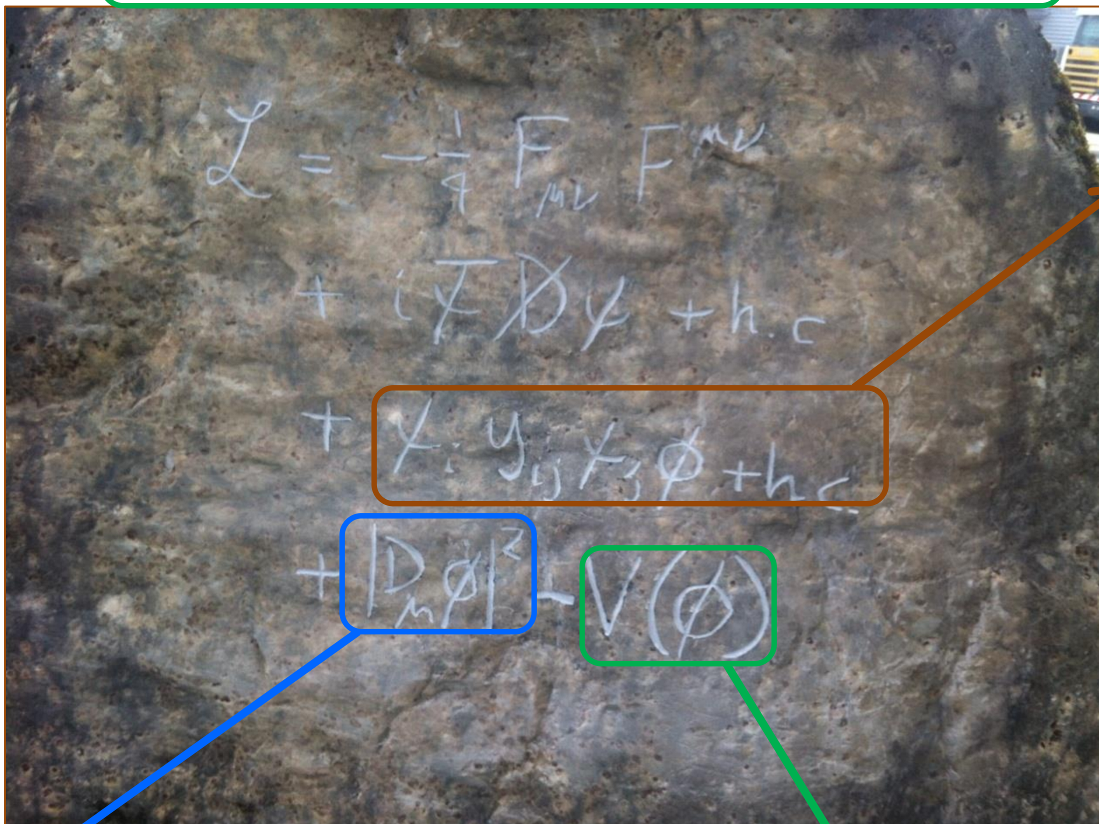
- **The m_H has been measured to a precision of 0.1 % by the CMS collaboration.**
  - The same measurement has also been performed by the ATLAS collaboration.
- **First single channel observation of Higgs boson production in association with a top quark pair by both experiments.**
  - **The CP structure of the H-t coupling has been studied for the first time with the pure CP-odd hypothesis excluded at > 3σ by both experiments.**
  - **Most stringent limit on tH production of < 12 times the SM xsec. at 95% CL from ATLAS**
- **The search for Higgs boson decays to Zγ has been updated with the full Run 2 dataset by the ATLAS collaboration.**
- **Exciting times are ahead with analyses being updated with the full Run 2 dataset.**
  - **From these individual measurements along with their combination a coherent global picture will emerge.**

No evidence available yet of any deviation from SM predictions

BACKUP

The Higgs boson : a particle like no other

The Higgs mass is a free parameter of the SM



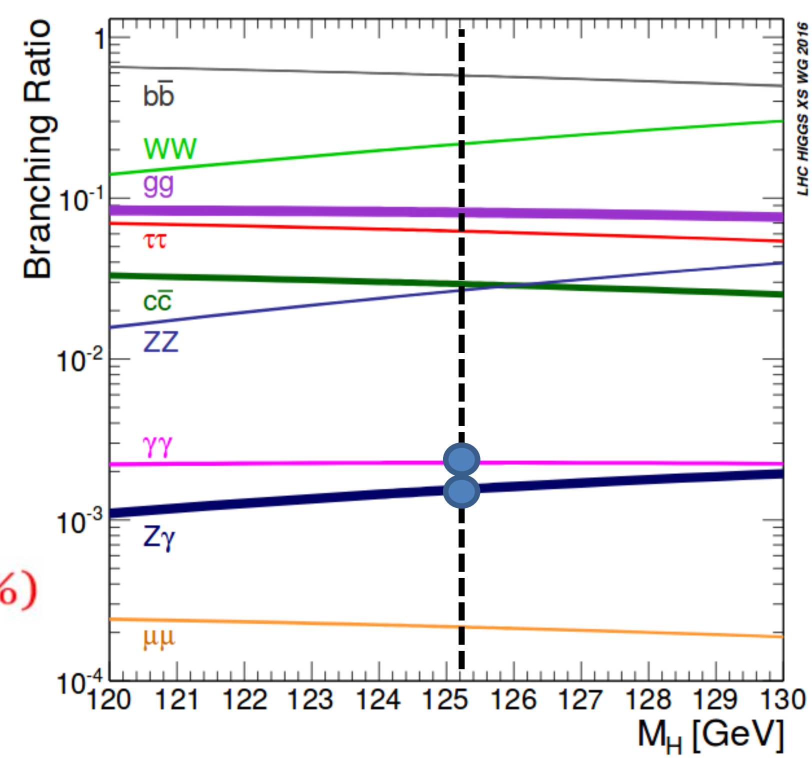
Yukawa interaction
→ Coupling to fermions

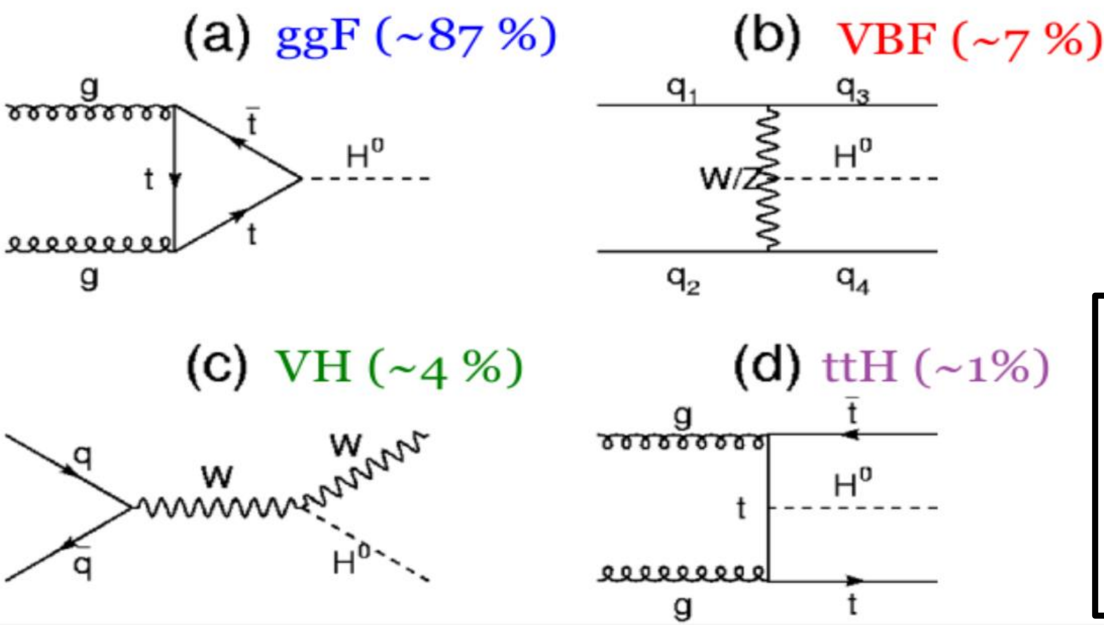
Gauge interaction
→ Coupling to bosons

$= \mu^2 . |\phi|^2 + 0.5 * \lambda . |\phi|^4$
→ Higgs self coupling

Higgs production at the LHC in Run 2

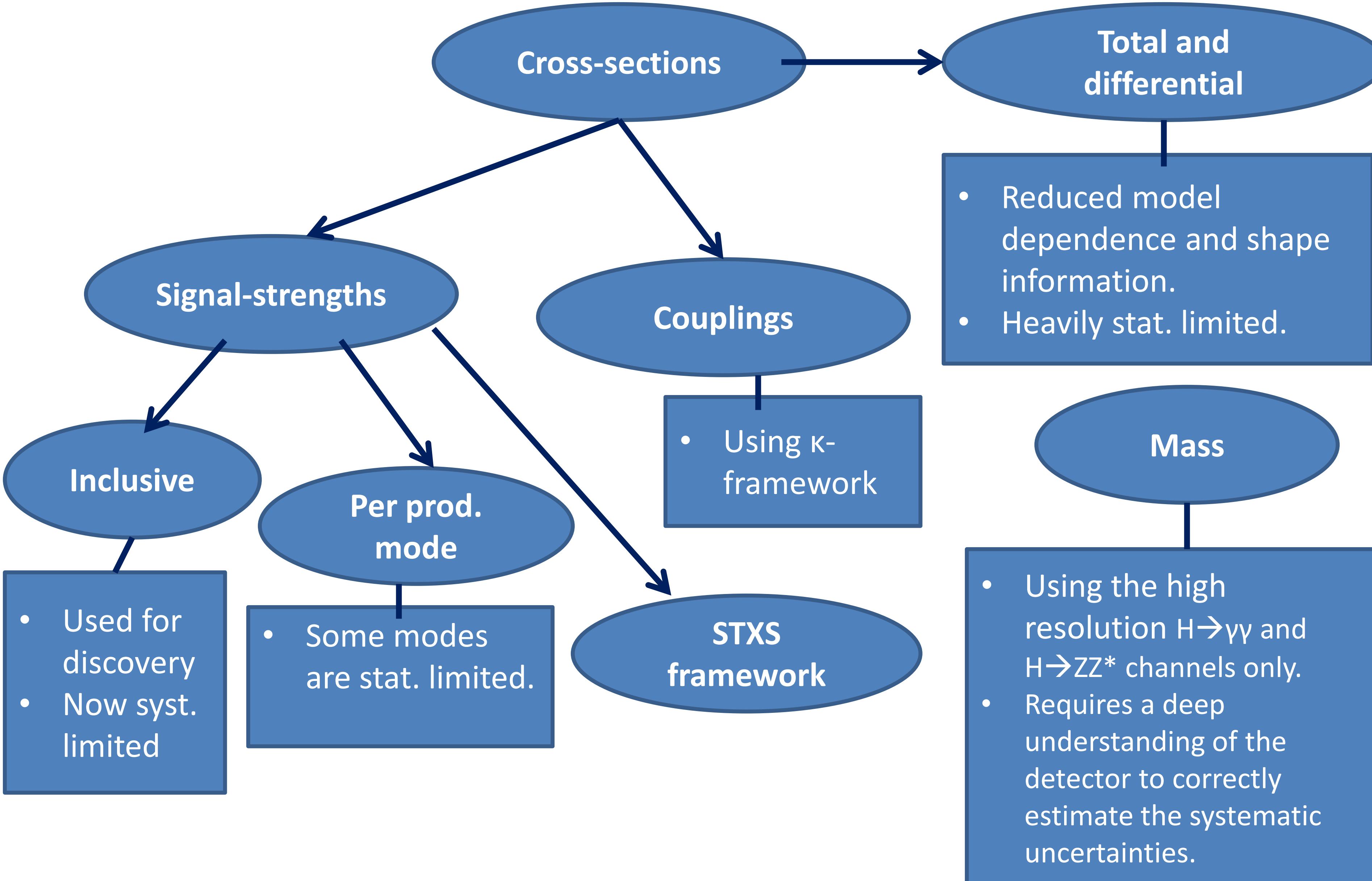
- **In Run 2 we have > 11 times increase in Higgs production w.r.t Run 1**
  - **Much higher sensitivity in the measurement of the properties of the Higgs boson.**
- **Gluon fusion is the dominant production mode.**
  - **Sensitivity to given production modes depend on the decay channel being considered.**





- **The decay modes presented today are γγ and Zγ**
  - **B(H→γγ) ~ 0.23 %**
  - **B(H→Zγ) ~ 0.15 %**

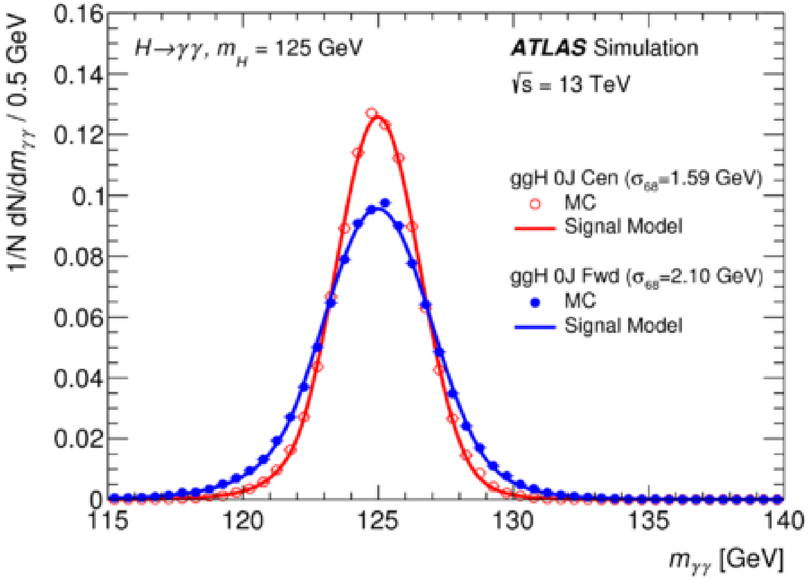
What do we wish to do with all this data



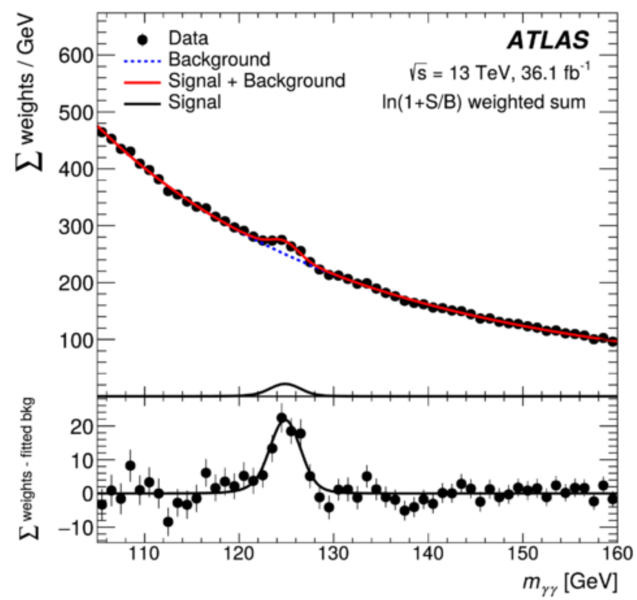
m_H in the diphoton channel with the 2016 dataset ATLAS

- Diphoton vertex selected using a dedicated DNN
- Events selected in a total of 31 exclusive cats. based on the photon kinematics and other objects.
- **The $M_{\gamma\gamma}$ resolution varies between 1.59 – 2.10 GeV**

m_H = 124.93 ± 0.40 [0.21 (stat.) ± 0.34 (syst.)] GeV

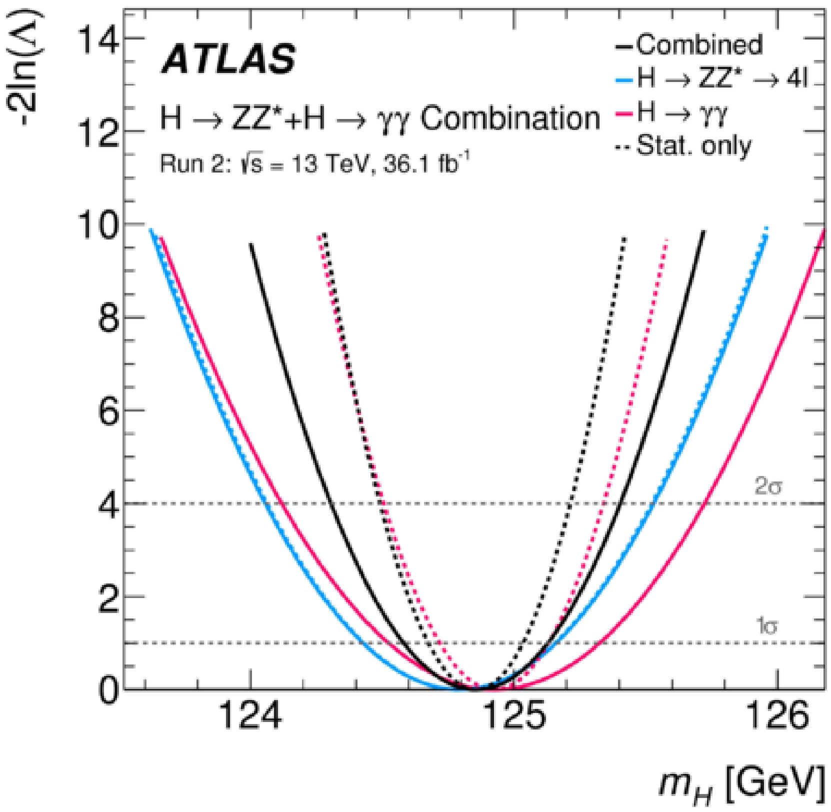


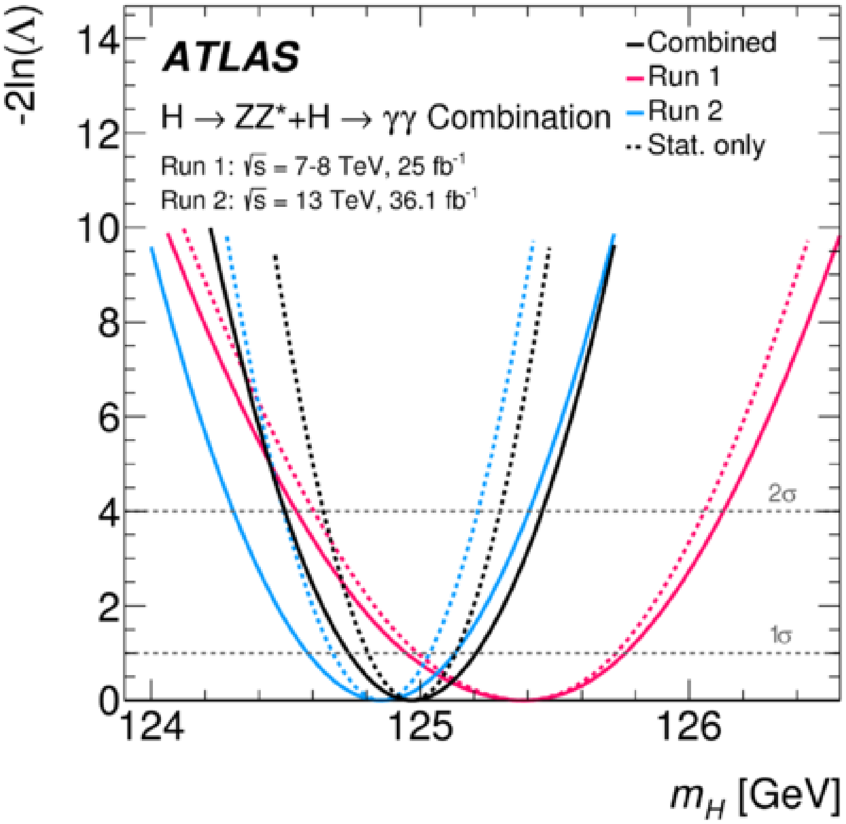
Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	±180
EM calorimeter layer calibration	±170
Non-ID material	±120
ID material	±110
Lateral shower shape	±110
$Z \to ee$ calibration	±80
Conversion reconstruction	±50
Background model	±50
Selection of the diphoton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



Phys. Lett. B 784 (2018) 345

Combined measurement of the Higgs mass ATLAS



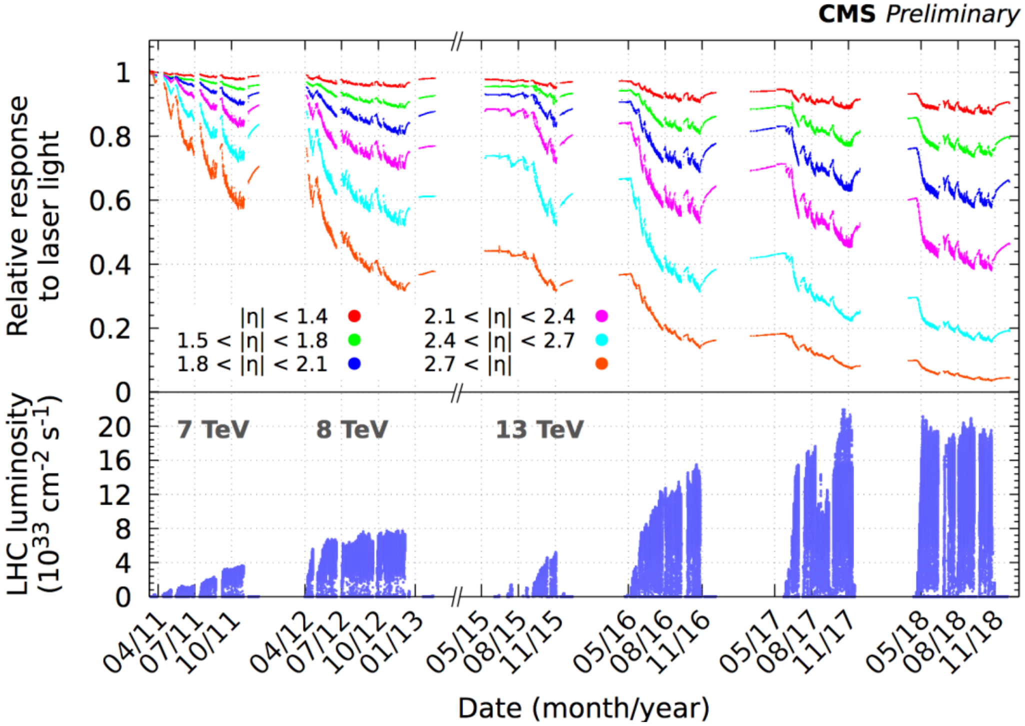


Phys. Lett. B 784 (2018) 345

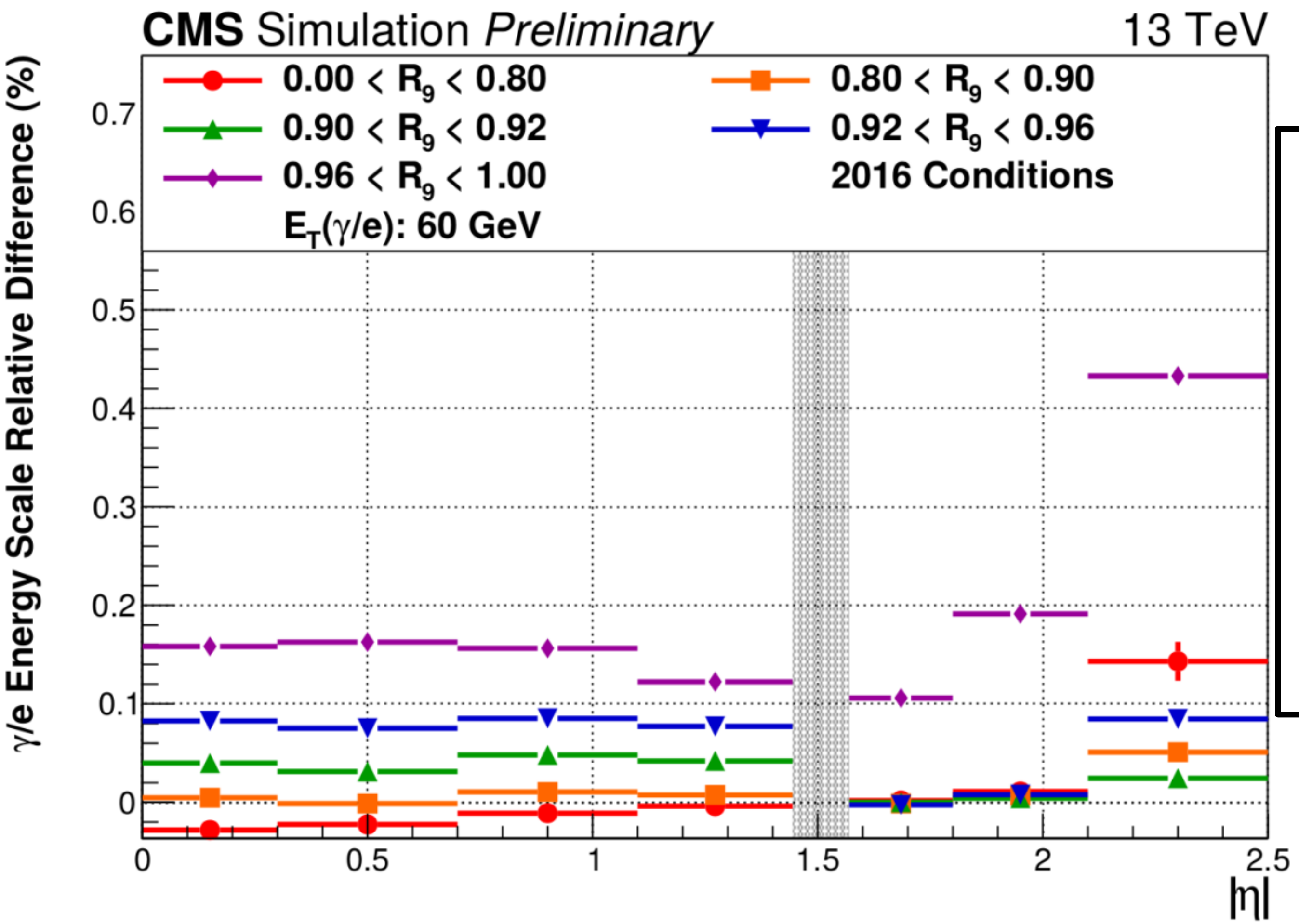
m_H in H→γγ : Systematic uncertainties CMS(1)

The main sources of uncertainty are those related to the photon energy scale :

- The electron energy scale uncertainties are propagated directly to the photon energy scale.
- Additional uncertainties on the photon energy scale account for the differences in between electron and photon interactions.
  - Modelling of upstream material
  - **Non-uniformity in light collection in ECAL crystals due to radiation damage**
    - **New light collection efficiency models that account for radiation damage.**

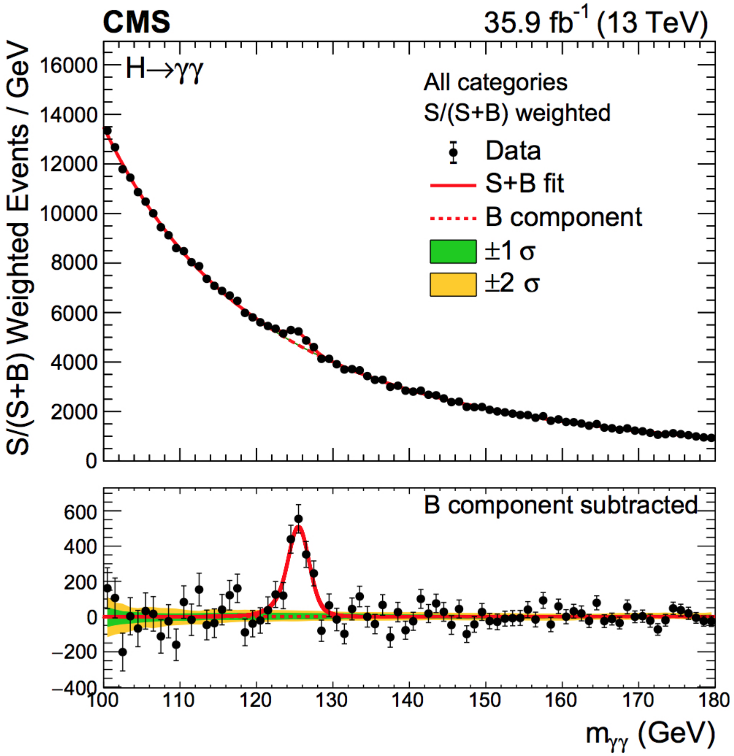


m_H in H→γγ : Systematic uncertainties CMS (2)



Phys. Lett. B 805 (2020) 135425

m_H in the diphoton decay channel with the 2016 dataset CMS

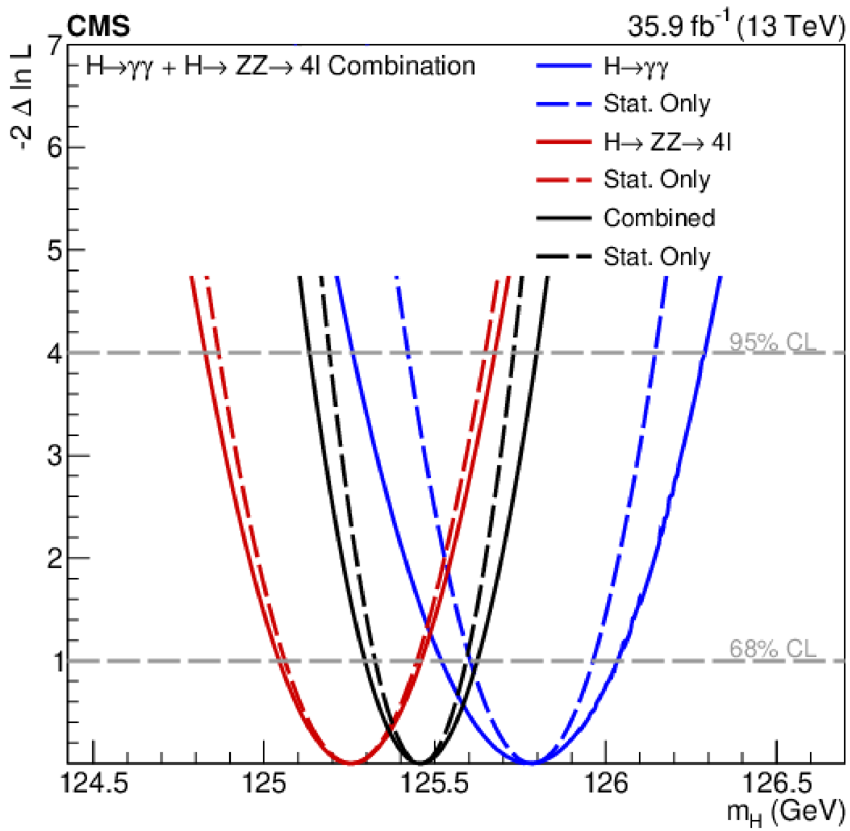


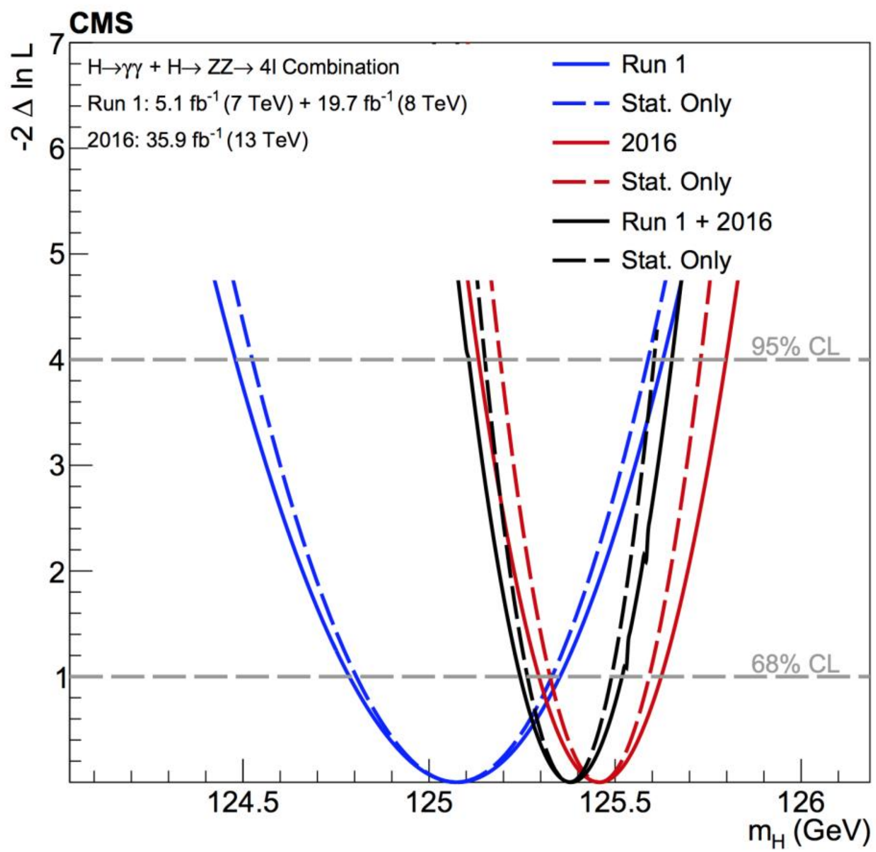
Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

Phys. Lett. B 805 (2020) 135425

- The signal model is obtained from simulation using a sum of up to 4 Gaussians.
- The background model is obtained directly from data using the discrete profiling method.
- Two signal strength parameters $\mu^{GGH+TTH}$, μ^{VBF+VH} are free to vary in the fit.
- Uncertainty on the photon energy scale arising out of the **Z→ee based energy energy scale corrections** are of the same order as those arising out of **differences in e-γ interaction**.

Combined measurement of the Higgs mass CMS

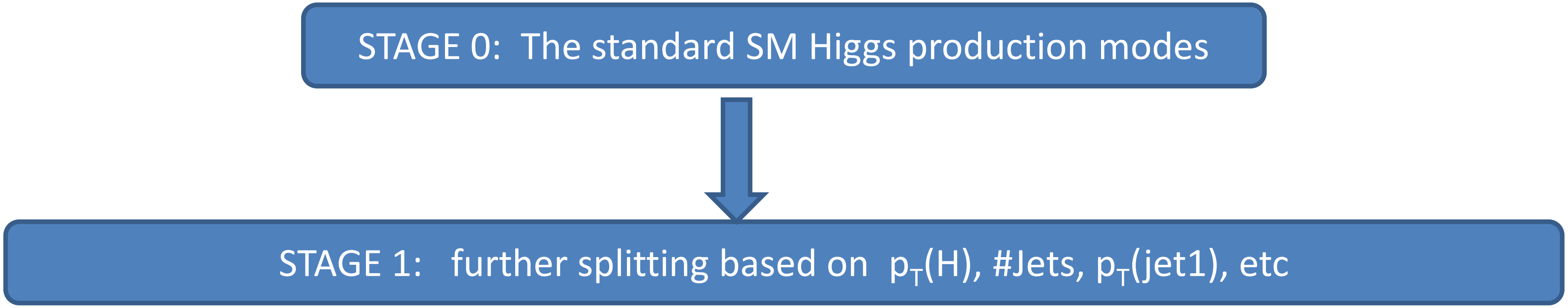




Phys. Lett. B 805 (2020) 135425

Simplified Template cross-sections (STXS)

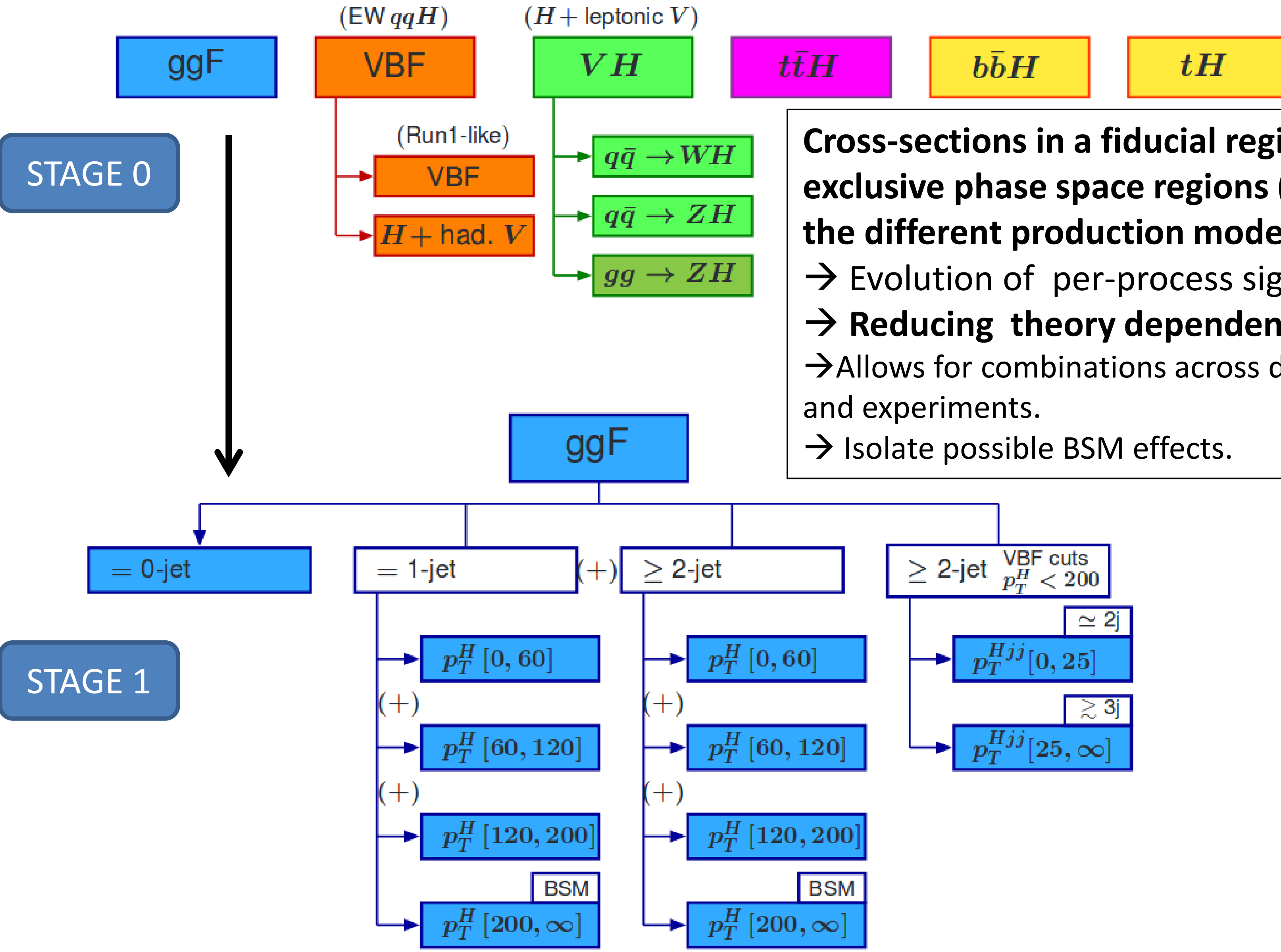
- The STXS framework, a logical evolution of the per process signal strength measurements, aims to maximize the sensitivity of measurements and minimize their theory dependence.
  - Developed collectively by ATLAS, CMS and theorists.
- Certain exclusive regions of phase space, “bins”, are defined specific to the different production modes in stages with increasing granularity:
  - minimizing the number of bins without loss of experimental sensitivity.
  - Allowing for combinations across decay channels and experiments.
  - Isolating possible BSM effects.



$H \rightarrow \gamma\gamma$ recast in STXS stage 1 bins

ATLAS : ATLAS-CONF-2018-028 CMS: PAS-HIG-18-029

Simplified Template cross-sections (STXS)



Cross-sections in a fiducial region, in exclusive phase space regions ("bins") for the different production modes

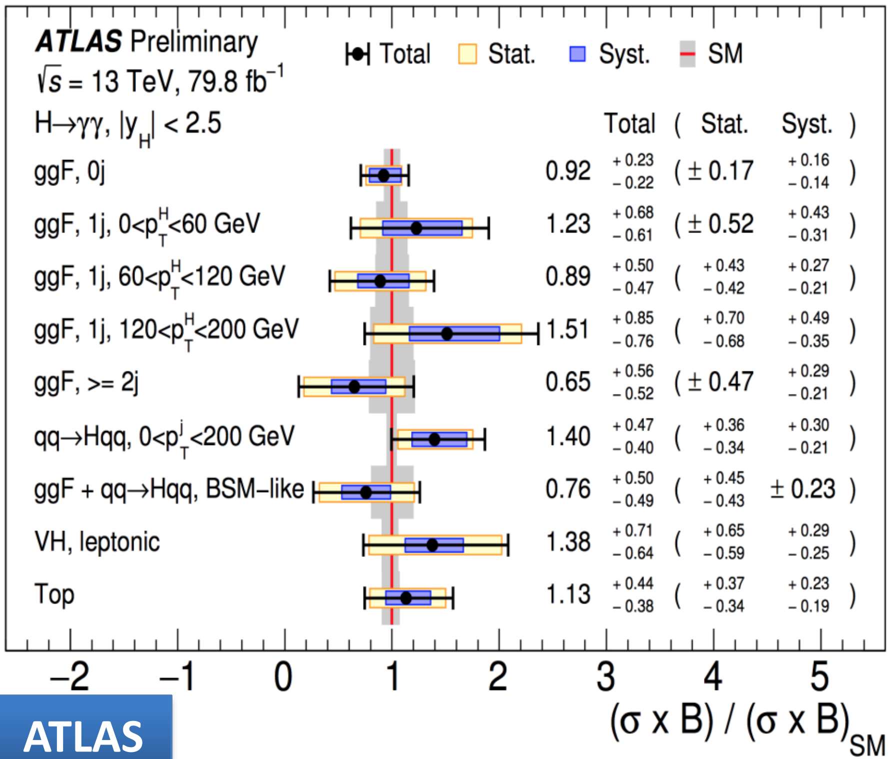
→ Evolution of per-process signal strengths.

→ **Reducing theory dependence.**

→ Allows for combinations across decay channels and experiments.

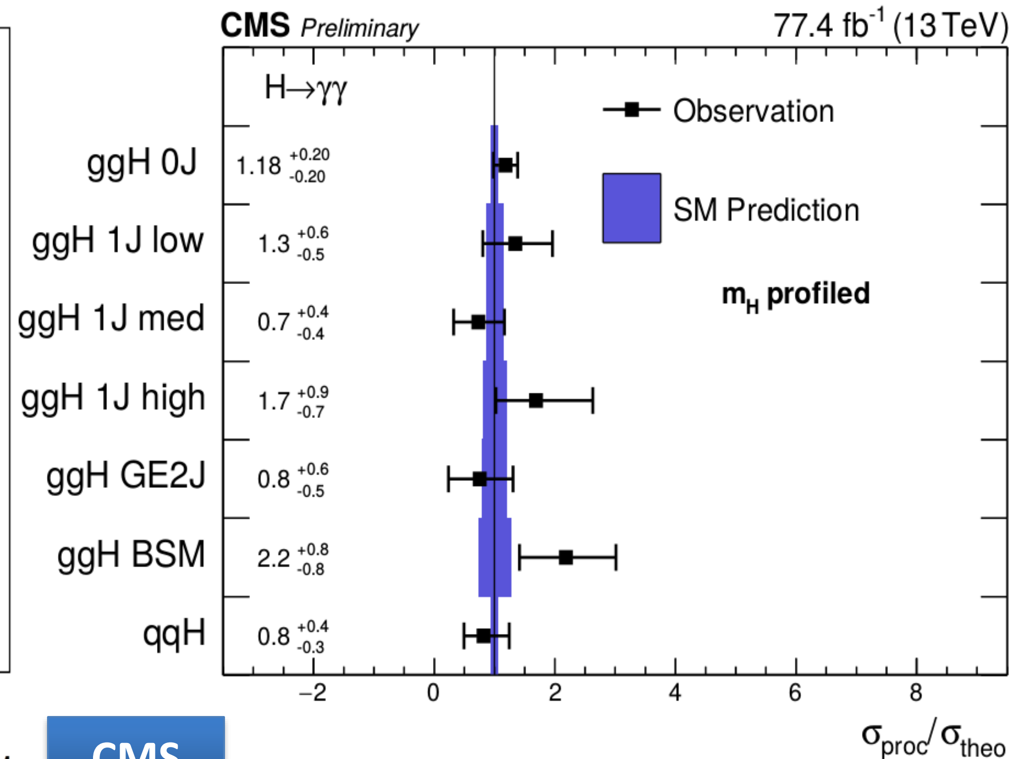
→ Isolate possible BSM effects.

H→γγ in STXS stage-1 bins : Grouping 1 results



ATLAS

- The stage-1 bins are defined using “cuts” on the corresponding “RECO” level quantities.
  - **9 STXS bins in all.**
  - Total of 27 categories in these bins with a mix of cut based and BDT selection

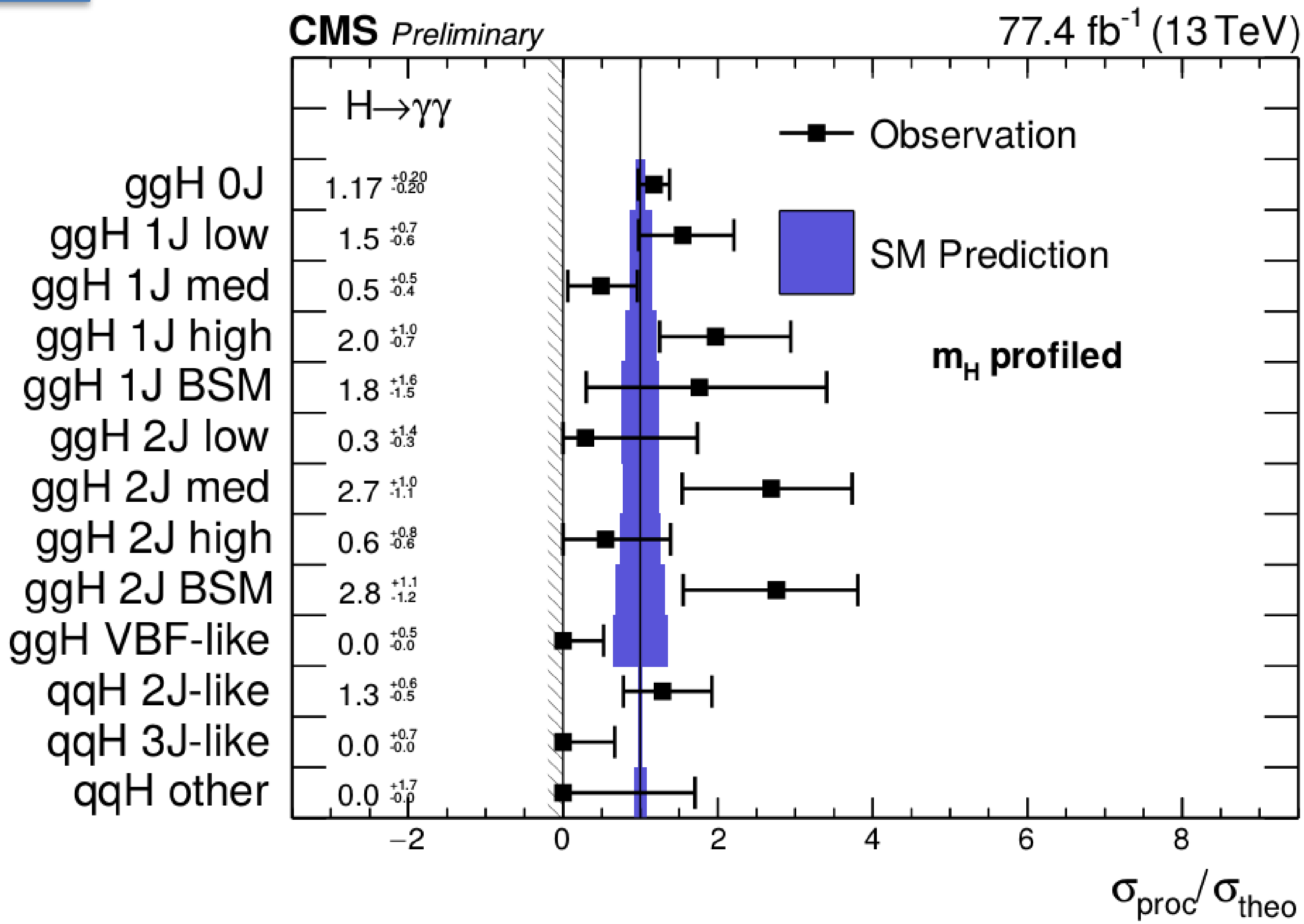


CMS

- **Analysis performed targeting the ggH and VBF bins.**
- The stage-1 bins are defined using “cuts” on the corresponding “RECO” level quantities.
  - Dedicated BDTs used to reject backgrounds.
  - **Two sets of results with 7 and 13 STXS bins respectively**

H→γγ in STXS stage-1 bins : Grouping 2 results

CMS



Maximum granularity achievable with 2016+2017.

ttH + tH production and CP properties of the Higgs boson

ATLAS: arxiv:2004.04545 CMS: arxiv:2003.10866

Both papers have been submitted to Phys. Rev. Lett.

BDT input features: ATLAS

ttH Bkg. Rejection BDT

- Leptonic channel input features :
  - Photons : $p^{\gamma}_T/m_{\gamma\gamma}$, η, Φ of each photon
  - Leptons : 4 vectors of up to 2 leading in p_T leptons
  - Jets : 4 vectors of up to 4 leading in p_T jets
  - MET : magnitude and Φ
- Hadronic channel input features
  - Photons : $p^{\gamma}_T/m_{\gamma\gamma}$, η, Φ of each photon
  - Jets : 4 vectors, b-tag of up to 6 leading in p_T jets
  - MET : magnitude

CP BDT

- Total of up to 20 input features :
  - Photons: p_T and η of the diphoton system
  - Top quarks: p_T, η, t-BDT scores of up to 2 reco. top quarks, $\Phi_{\gamma\gamma,t1}$, $\Phi_{\gamma\gamma,t2}$, $\Delta\eta_{t1t2}$, $\Delta\Phi_{t1t2}$, $m_{\gamma\gamma,t1}$, $m_{t1,t2}$
  - Jets and MET: #jets, #b-tagged jets, H_T, MET/sqrt(H_T), lowest and second lowest $\Delta\eta_{\gamma j}$

BDT input features: CMS

ttH Bkg. Rejection BDT

- Hadronic channel with up to 35 input features
  - Photons : $p^{\gamma}_T/m_{\gamma\gamma}$, η, PSV of each photon; Max and Min γ ID MVA
  - Diphoton system : $p^{\gamma\gamma}_T/m_{\gamma\gamma}$, $Y_{\gamma\gamma}$, $\Delta R_{\gamma\gamma}$, $\cos(\Delta\Phi)_{\gamma\gamma}$, |cos(Helicity angle)|
  - Jets and MET : 4 vectors, b-tag of up to 4 leading in p_T jets; Highest and 2nd Highest b-tag score; #jets, H_T, MET
  - Dedicated variables : DNN to suppress diphoton background, top-tagger BDT
- Leptonic channel with up to 32 input features :
  - Photons : Same
  - Diphoton system : Same
  - Leptons : #leptons, p_T, η of lead lepton
  - Jets and MET : Same [up to 3 lead jets]
  - Dedicated variables : DNN to suppress tt+γγ background

D_{0-} BDT to separate the CP-even and CP-odd couplings using the ttH/tH processes

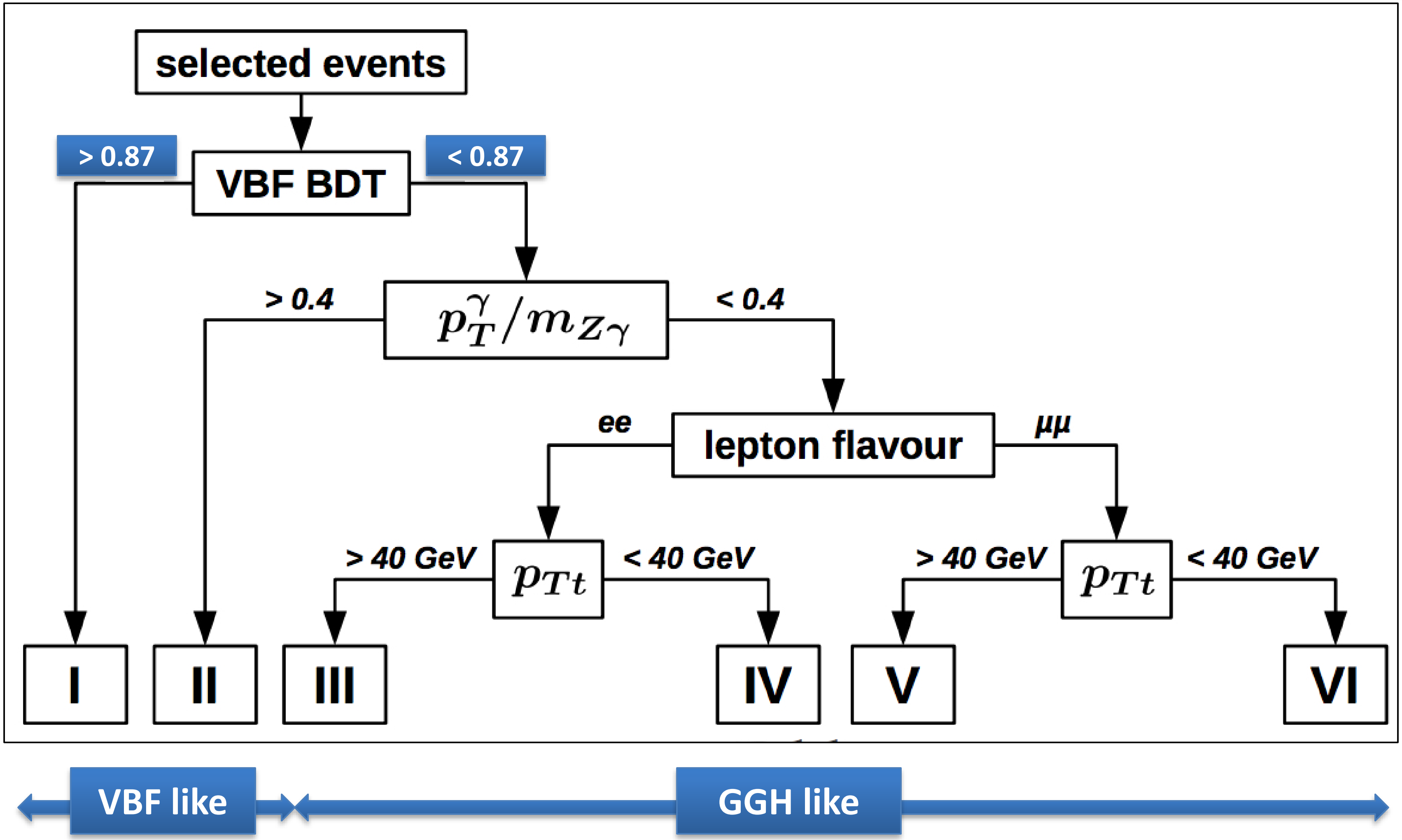
- input features :
  - Diphoton system: kinematic variables (not including $m_{\gamma\gamma}$)
  - Leptons (lepton channel only): #leptons, kinematic variables of the lead lepton
  - jets: kinematic variables, b-tag scores of up to 6 leading jets

A search for Higgs boson decays to Zγ (ATLAS)

arxiv:2005.05382

Event categorization

© D. Schaefer [CERN seminar]



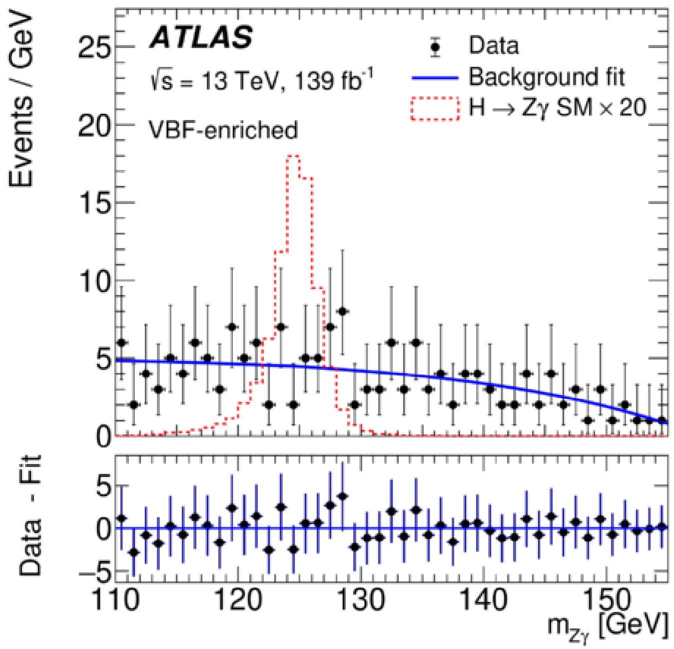
Signal and background modelling

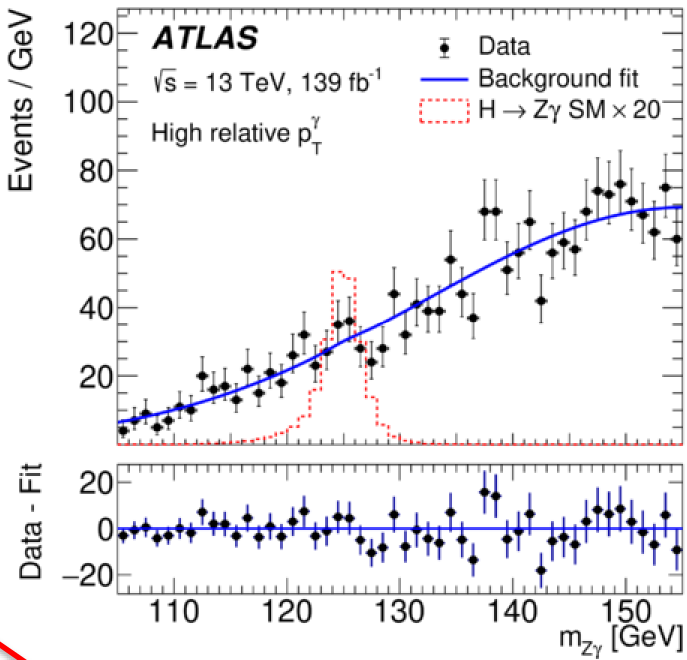
- A parametric signal model is obtained from fits to the $m_{Z\gamma}$ distributions in simulation for all 6 categories.
  - Used a double-sided crystal ball function.
- A parametric background model is used to describe the $m_{Z\gamma}$ distribution using a template of simulated Zγ and EW Zγjj events along with the Z+jets from data.
  - Family of functions : exponential, Bernstein and power law.
  - The choice of the analytical model of the background and the $m_{Z\gamma}$ fit range optimized in each category using the templates.
    - The "spurious signal" is require to be less than 50% of the exp. stat. unc. on the signal yield. A S+B fit to the $m_{Z\gamma}$ background-only distribution with m_H varied in the range 123-127 GeV : The max. number of signal events obtained from these fits constitute the spurious signal systematic unc.
    - The optimal fit range is by varying the bound of 105-115 GeV and 140-160 GeV in 5 GeV steps in order to achieve the highest signal significance.

Category	Function Type	Fit range [GeV]
VBF-enriched	Second-order power function	110–155
High relative p_T	Second-order exponential polynomial	105–155
ee high p_{Tt}	Second-order Bernstein polynomial	115–145
ee low p_{Tt}	Second-order exponential polynomial	115–160
$\mu\mu$ high p_{Tt}	Third-order Bernstein polynomial	115–160
$\mu\mu$ low p_{Tt}	Third-order Bernstein polynomial	115–160

S+B fits and significance

arxiv:2005.05382





Category	Events	S_{68}	B_{68}	w_{68} [GeV]	S_{68}/B_{68} $[10^{-2}]$	$S_{68}/\sqrt{S_{68}+B_{68}}$
VBF-enriched	194	2.7	18.7	3.7	14.3	0.58
High relative p_{T}	2276	7.6	112.8	3.7	6.7	0.69
High $p_{\mathrm{T}t}$ ee	5567	9.9	444.0	3.8	2.2	0.46
Low $p_{\mathrm{T}t}$ ee	76 679	34.5	6654.1	4.1	0.5	0.42
High $p_{\mathrm{T}t}$ $\mu\mu$	6979	12.0	610.8	3.9	2.0	0.48
Low $p_{\mathrm{T}t}$ $\mu\mu$	100 876	43.5	8861.5	4.0	0.5	0.46
Inclusive	192 571	110.2	16 701.9	4.0	0.7	0.85