ATLAS Measurement of ttH in the Diphoton Channel

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Top Physics at the Precision Frontier
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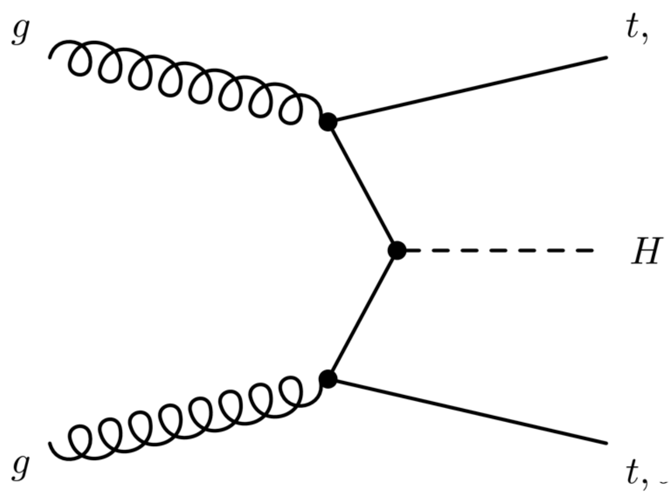
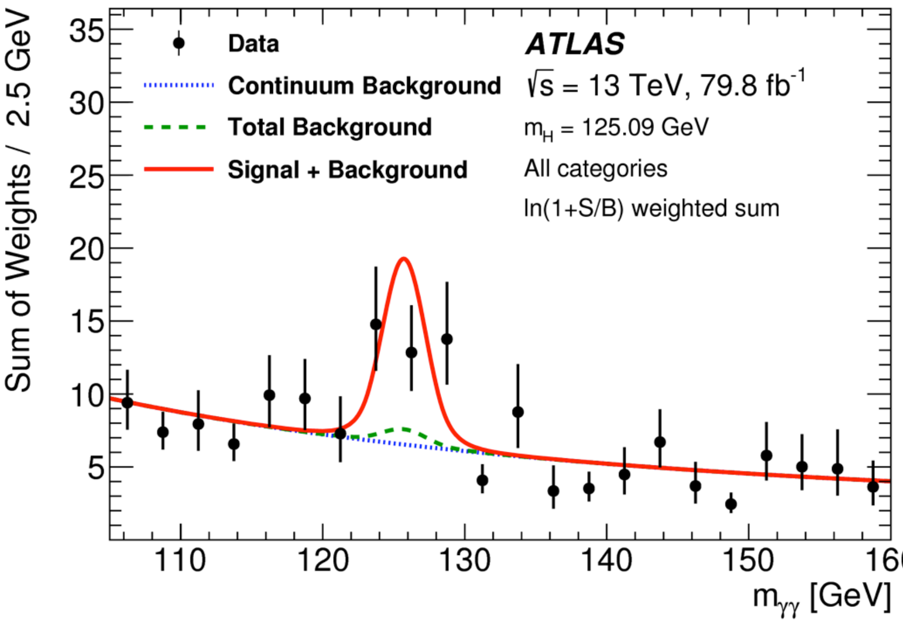
Overview

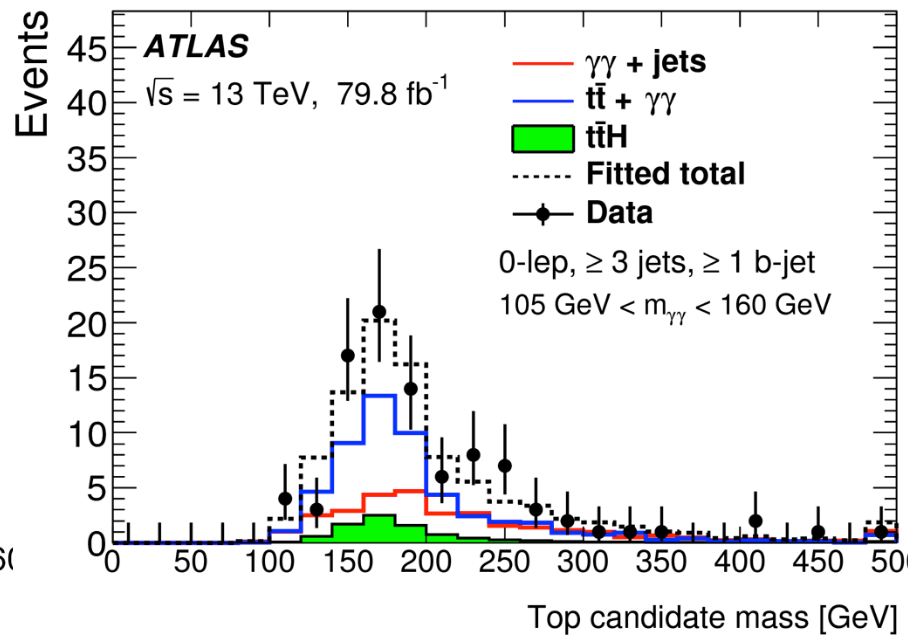
- The associated production of the Higgs boson with top quarks provides a direct access to the top-Higgs coupling



- The diphoton channel is one of the leading channels in the ttH measurements
  - The diphoton resonant decay is an unambiguous signature for the Higgs boson
  - Robust background estimation from diphoton mass sidebands

ttH→ γγ in the ATLAS ttH observation



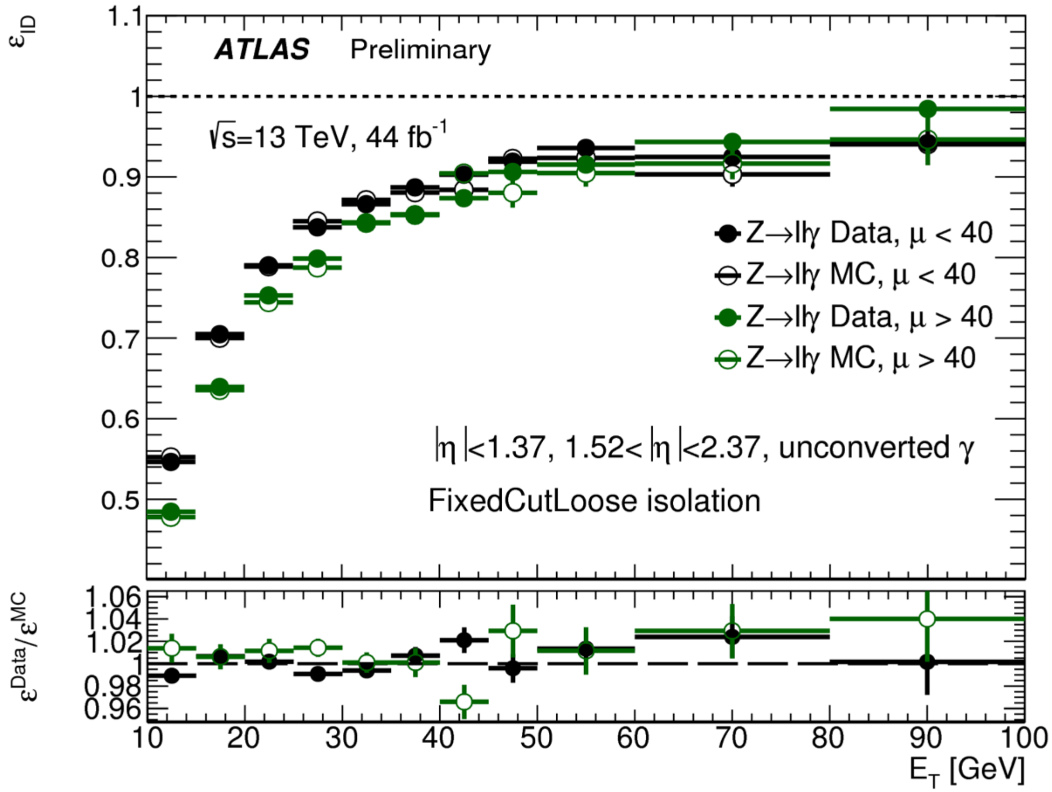


Convincing signals

We saw both Higgs peak and top peak in our sample!

Photon performance in ATLAS

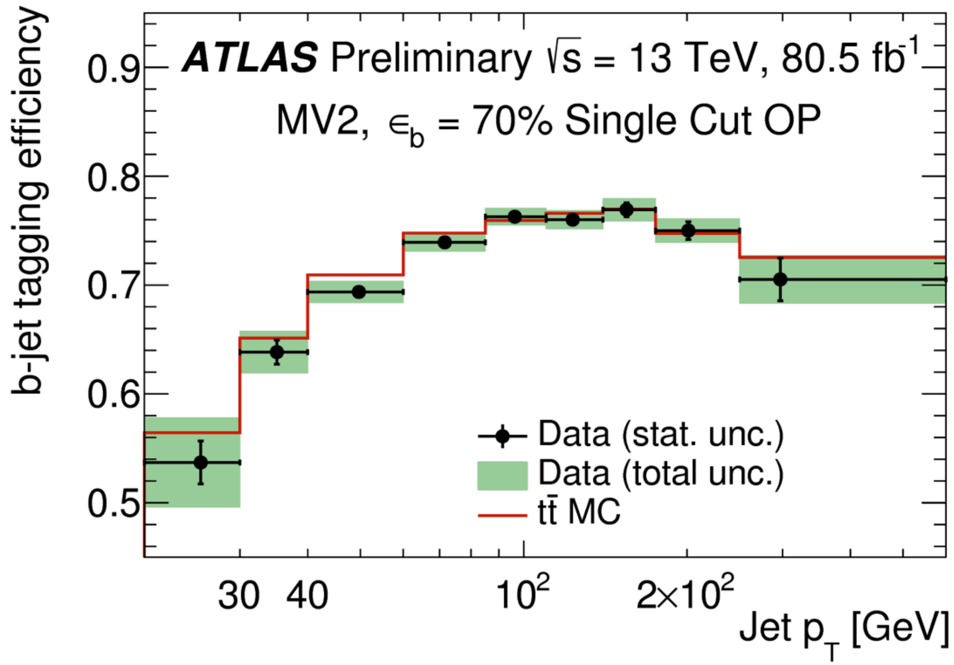
- Photons are selected using a multivariate discriminant based on shower shape variables in the EM calorimeter



- A “tight” identification, typically used in analysis, has an efficiency > 90% for high p_T photons, and a rejection at 10^3 - 10^4

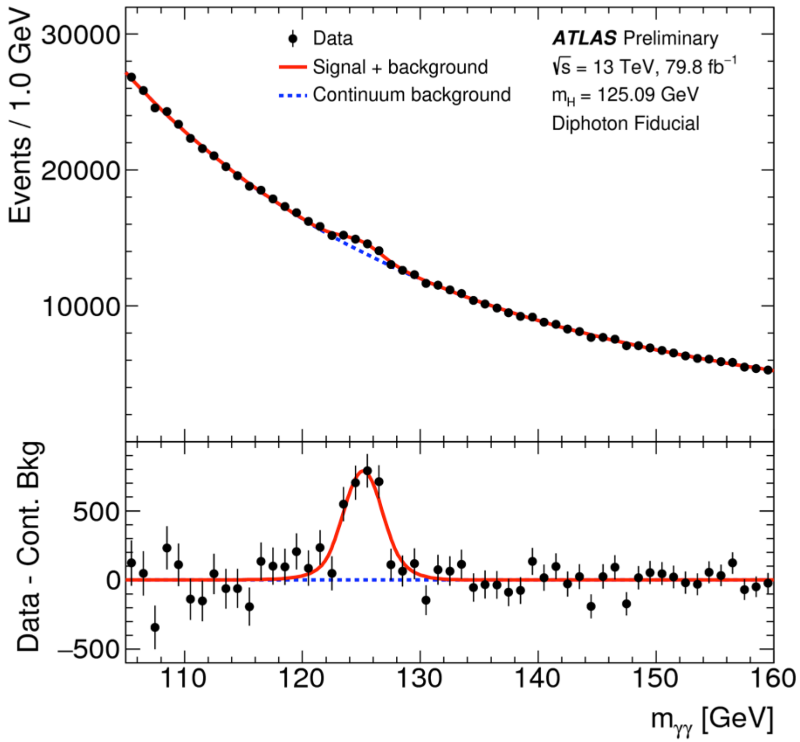
B-tagging performance in ATLAS

- B-jets are tagged using a multivariate discriminant combining tracking, secondary vertex and decay chain information



- The b-tagging is calibrated with a ttbar control sample
- In the ttH analysis, a b-tagger with a 77% efficiency is used, corresponding to a rejection of light jet at the level of a few hundreds

The diphoton sample in ATLAS



Select two energetic and well isolated photons

$P_{T\gamma 1}/m_{\gamma\gamma} > 0.35$, $P_{T\gamma 2}/m_{\gamma\gamma} > 0.25$

$|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$

Quality requirement - Isolation and identification criteria

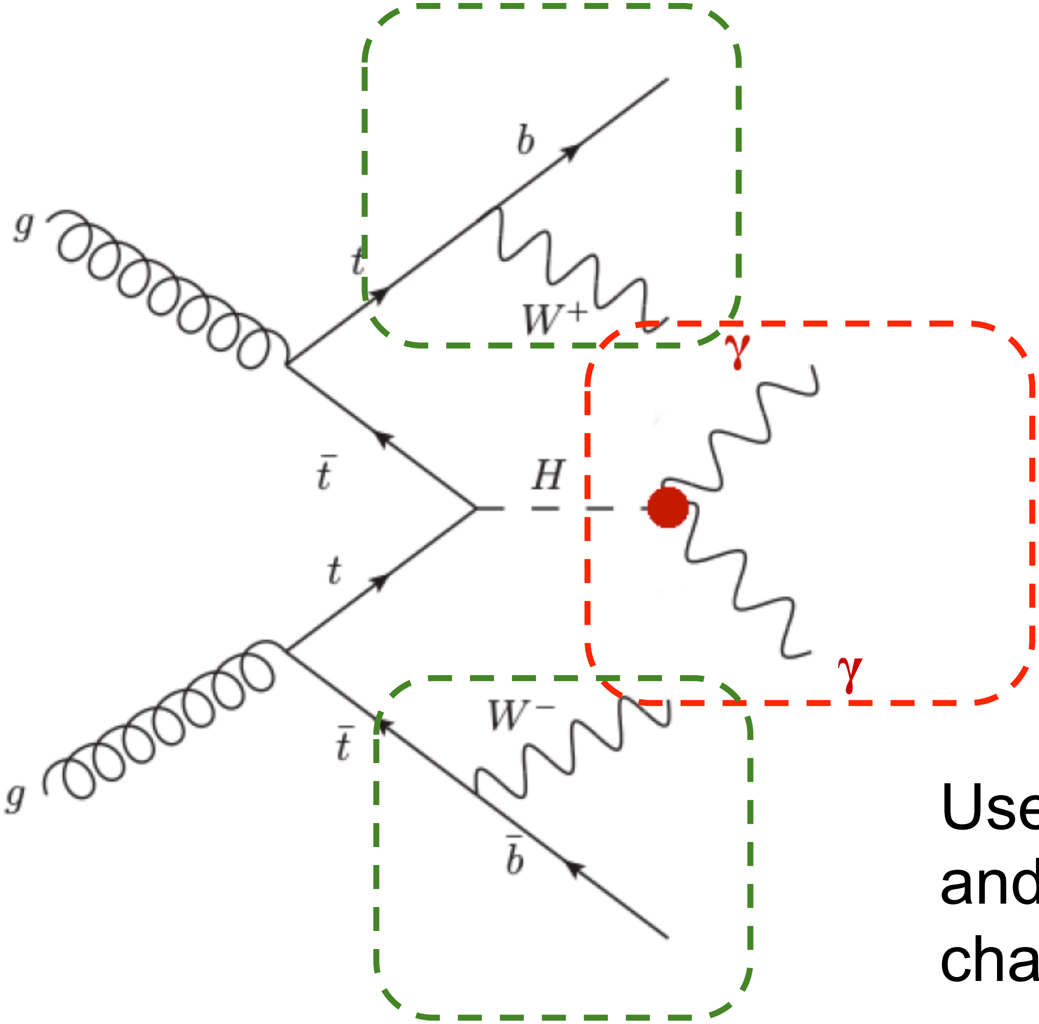
~ 1.5 million events with 105 GeV < $m_{\gamma\gamma}$ < 160 GeV at 139 fb^{-1}

Assume the theoretical prediction, at ***139 fb^{-1}***, the LHC should have produced

- ~ 7,000,000 Higgs bosons
- ~ 70,000 via ttH production
- ~ 160 in the ttHγγ channel

for the ATLAS experiment

Strategy



Use photons to tag the Higgs Boson

Use jets (b-jets), leptons, and E_T^{miss} to capture the characteristics of top quarks

Directly use properties of the objects in the event to train a multivariate discriminant

Multivariate Training

Training variables

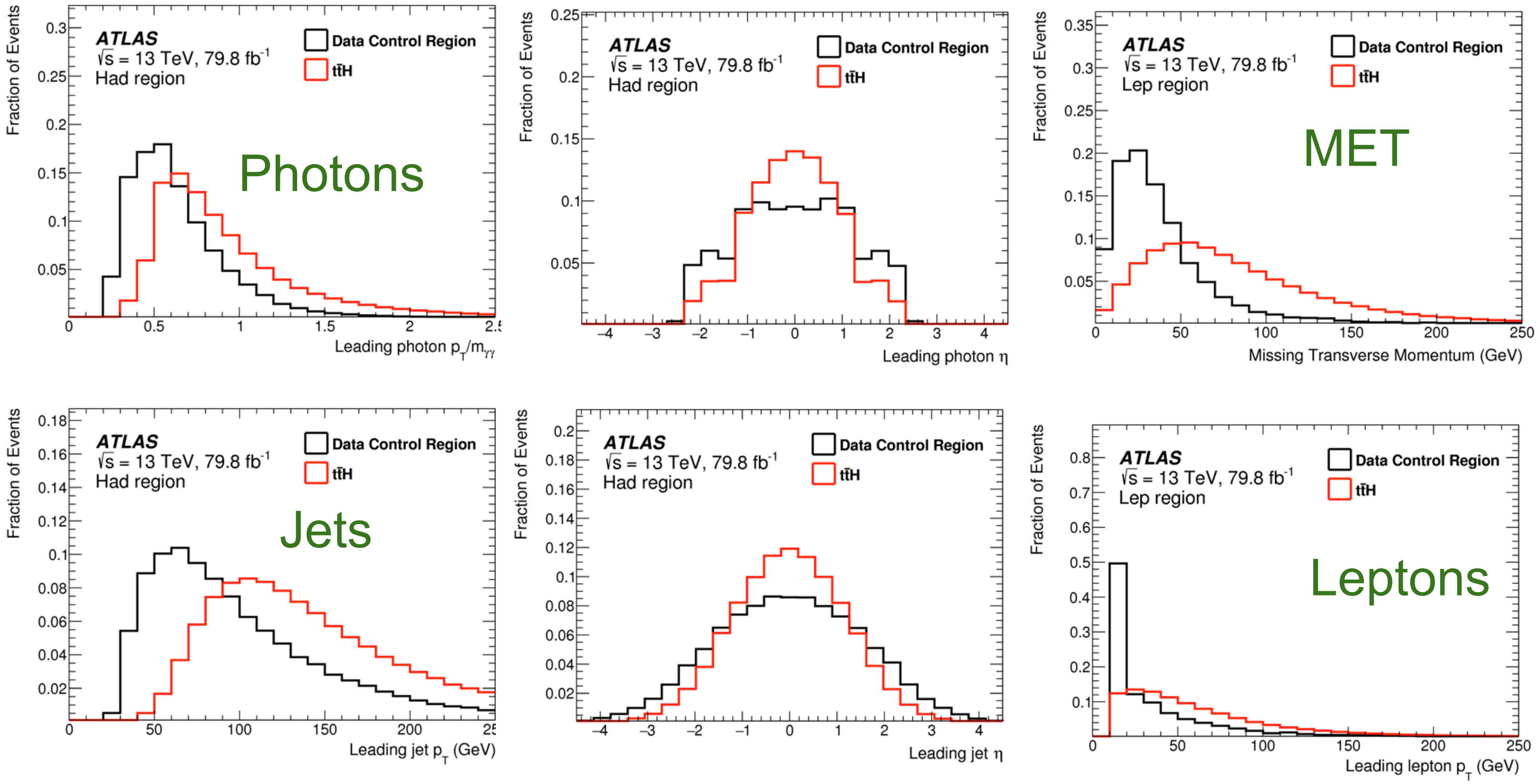
- 4-momenta of photons, jets, leptons
- Whether or not a jet is b-tagged
- Missing transverse energy and its φ direction

This discriminant is trained with

- ***Signal* - *Powheg*** Monte Carlo that models signal events
- ***Background* - *data control sample*** where the photon quality (isolation and/or identification) requirement is reversed
  - Mostly γγ + jets events, our main background before selection
  - ***See Jennet Dickinson's talk for our understanding of the background composition***

Training variables

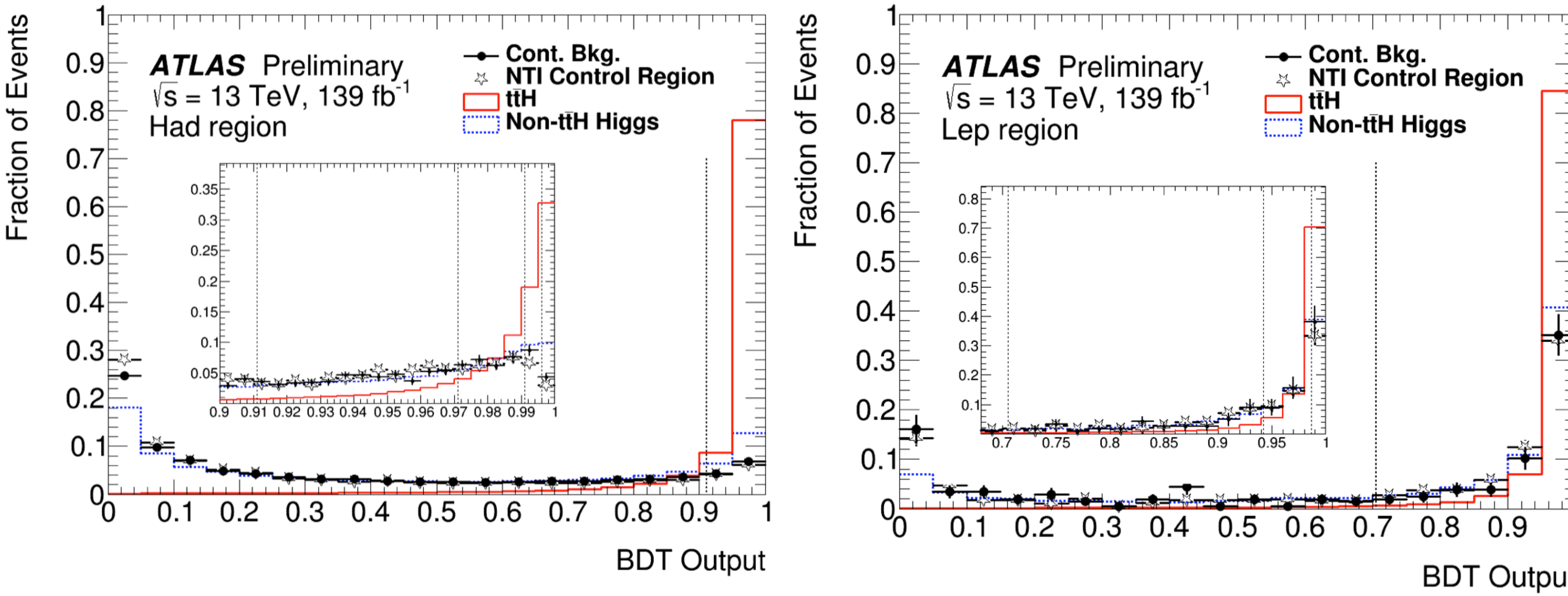
Some example training variables



The training algorithm is a ***Boosted Decision Tree (BDT)***

Multivariate ttH discriminant

The BDT is trained for events with a lepton (leptonic) and events without a lepton (hadronic), separately



Events with low BDT scores are removed

The remaining events are classified into multiple categories with different signal-to-background-ratios (S/Bs) based on the BDT scores, to maximize the sensitivity

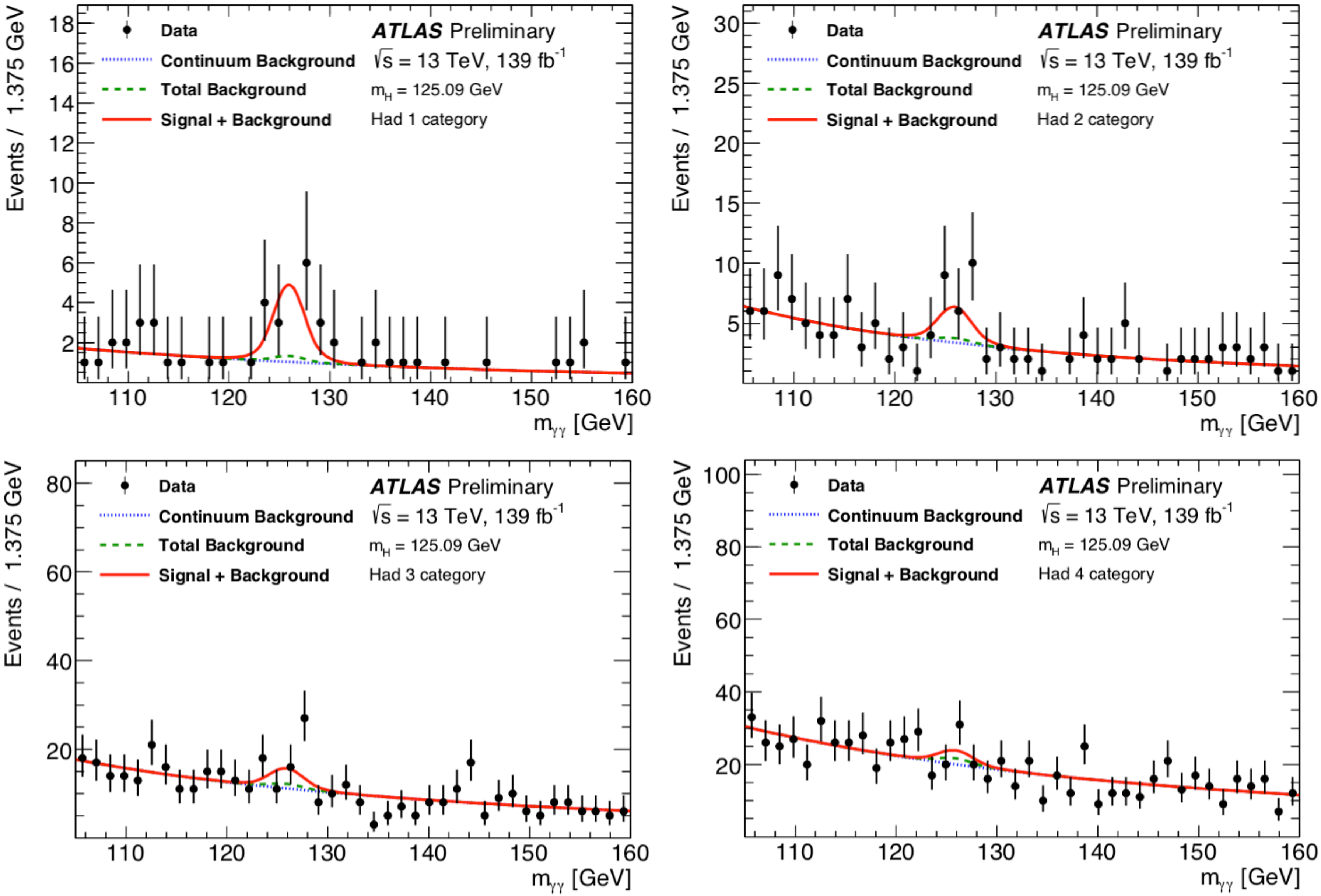
Performance of Categorization

Event yields in a narrow mass window around 125 GeV

Category	$t\bar{t}H$ Signal	non-$t\bar{t}H$ Higgs	Continuum Background	Total (Expected)	σ_{68} (GeV)	σ_{90} (GeV)
"Lep" Category 1	7.9 ± 1.5	0.42 ± 0.12	4.6 ± 0.9	12.9 ± 1.8	1.56	2.80
"Lep" Category 2	3.9 ± 0.6	0.43 ± 0.15	7.5 ± 1.2	11.8 ± 1.3	1.75	3.13
"Lep" Category 3	1.45 ± 0.24	0.49 ± 0.19	7.5 ± 1.2	9.5 ± 1.2	1.85	3.30
"Had" Category 1	6.9 ± 1.6	0.8 ± 0.5	4.5 ± 0.9	12.2 ± 1.9	1.39	2.48
"Had" Category 2	5.6 ± 1.0	1.1 ± 0.8	16.5 ± 1.7	23.2 ± 2.3	1.58	2.84
"Had" Category 3	7.7 ± 1.3	3.1 ± 2.2	56.0 ± 3.0	67 ± 4	1.65	2.96
"Had" Category 4	4.9 ± 0.8	5 ± 4	101 ± 4	111 ± 6	1.67	3.00

- The S/B goes beyond 1 in the best "hadronic" and "leptonic" categories
- Contamination of non-ttH Higgs signals are strongly suppressed; ttH purity reaches 90% level in the best categories
- Best categories also correspond to categories with best diphoton resolutions

Diphoton mass distributions (hadronic)



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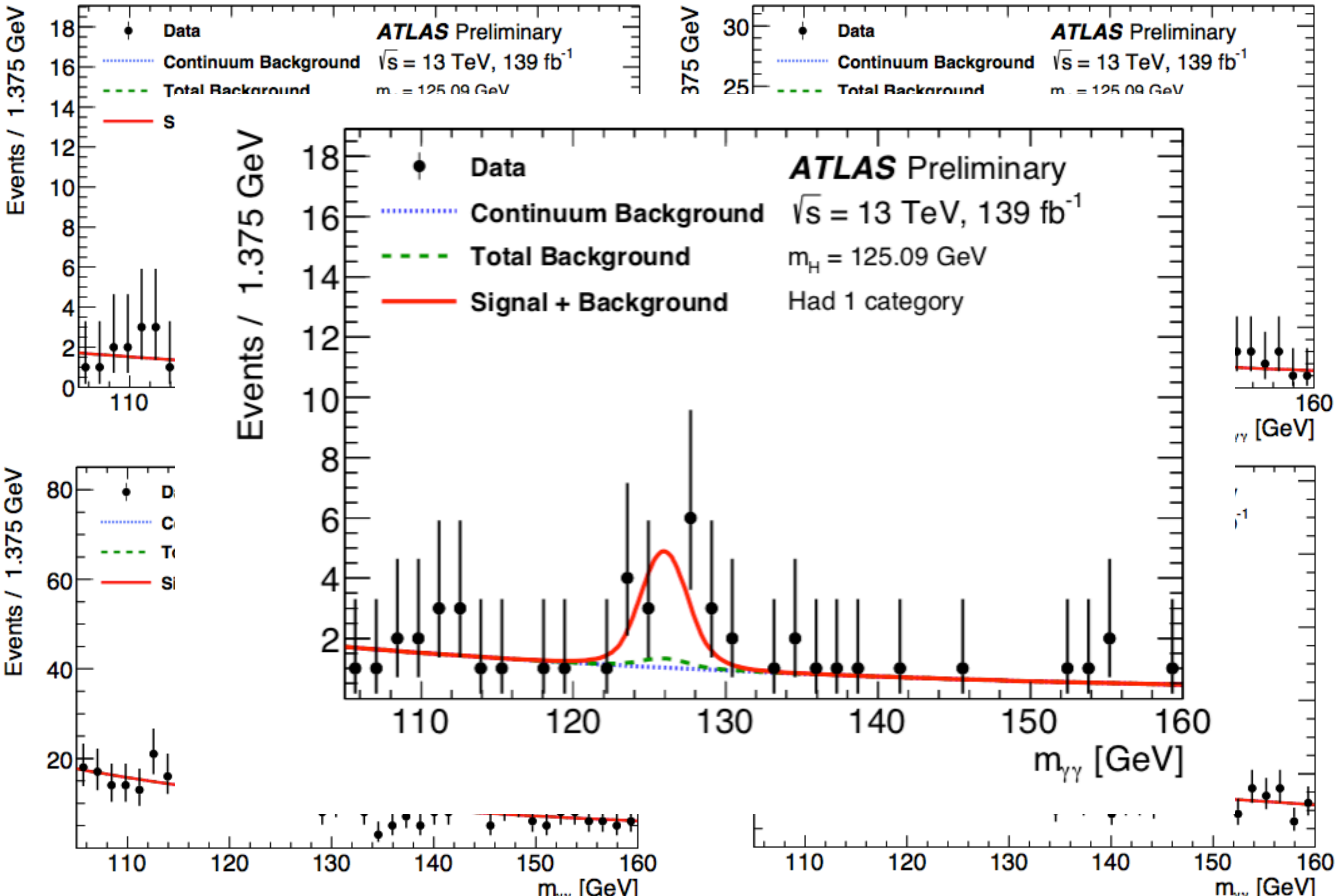

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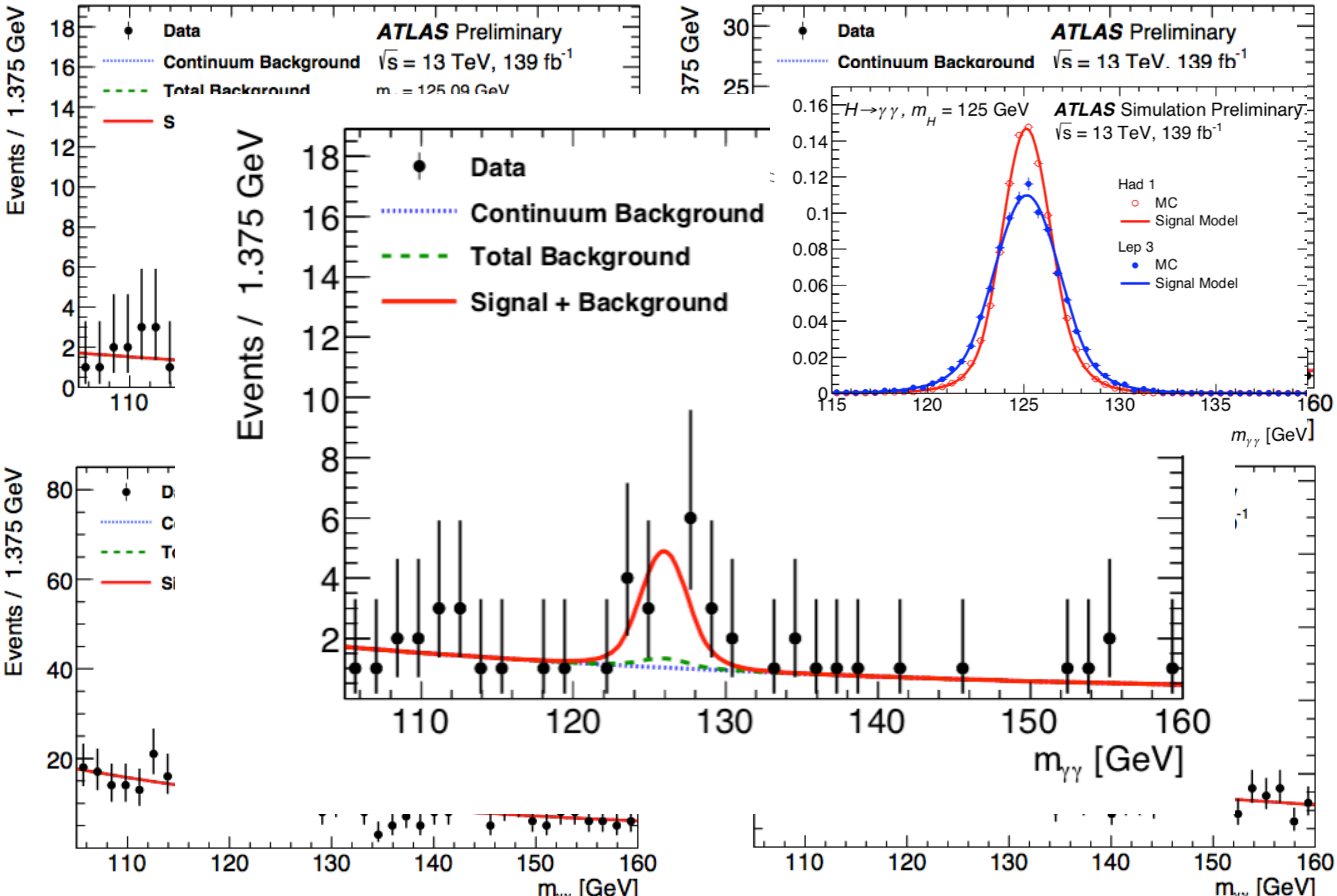
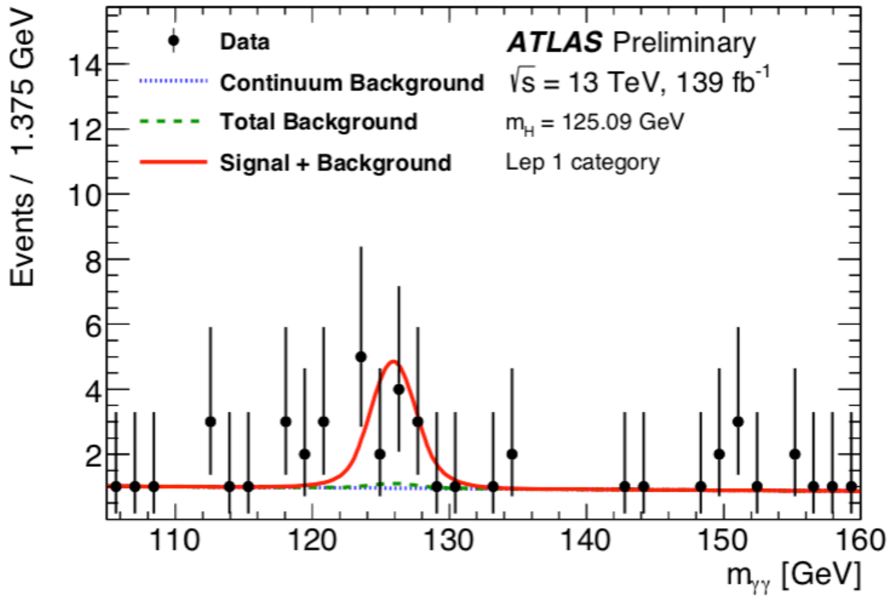
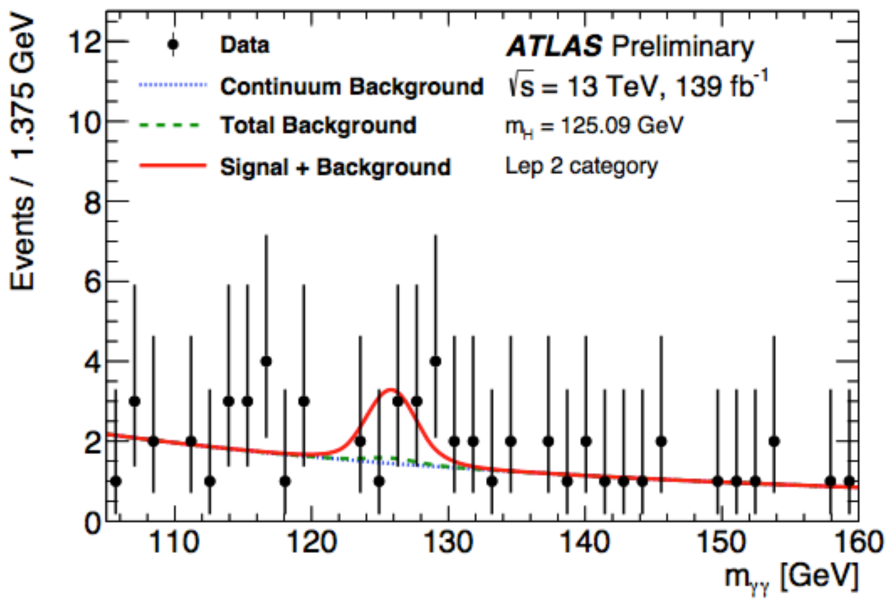
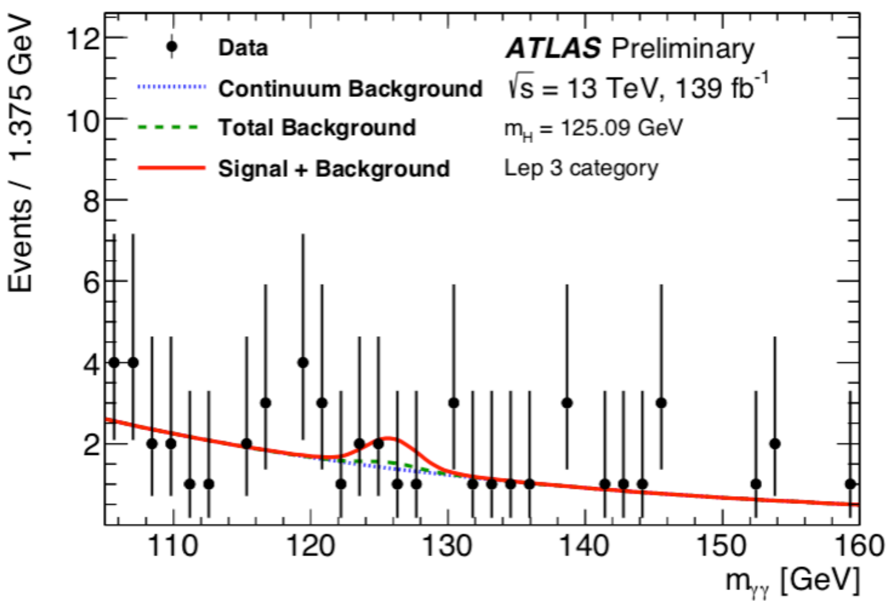


Diphoton mass distributions (leptonic)

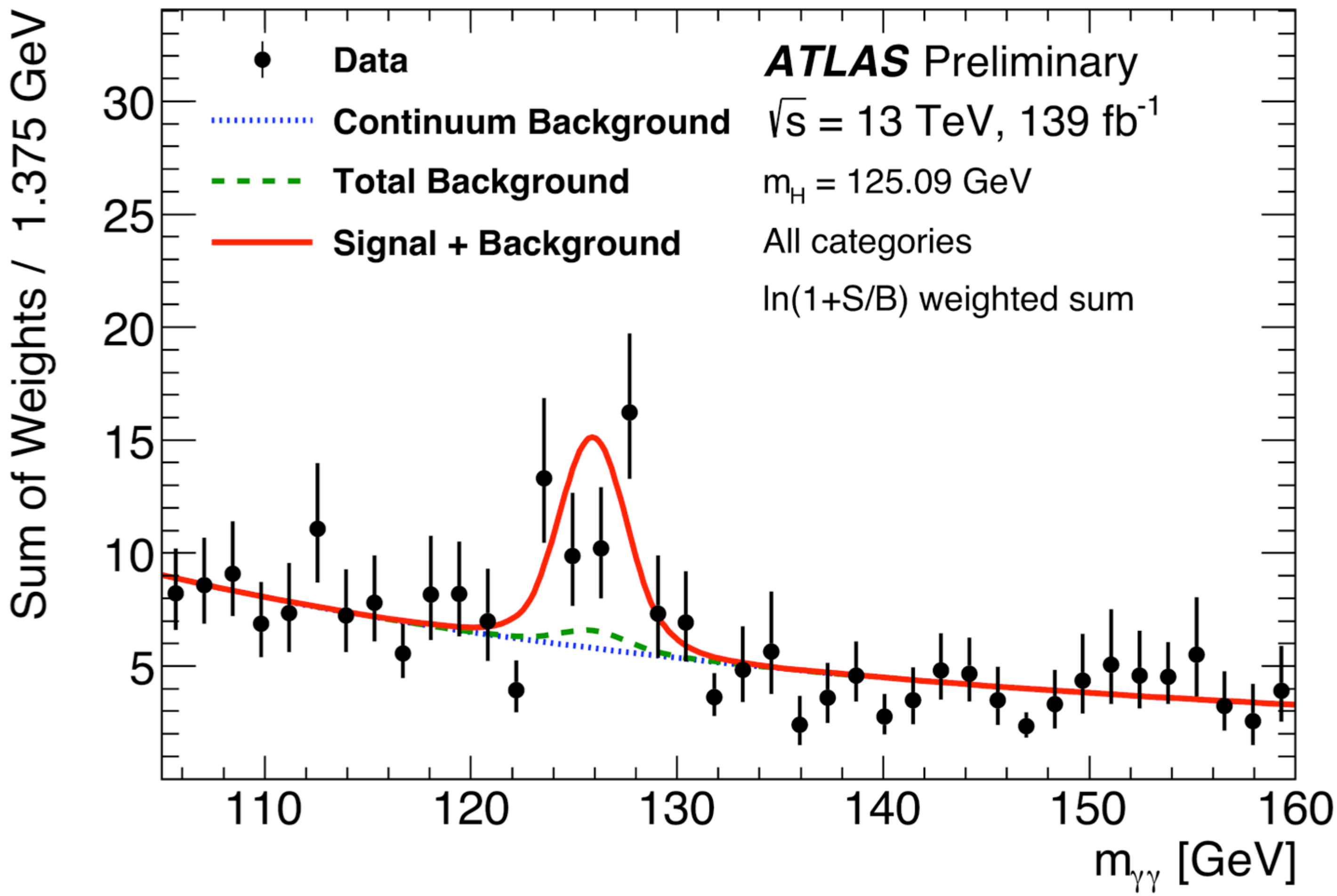




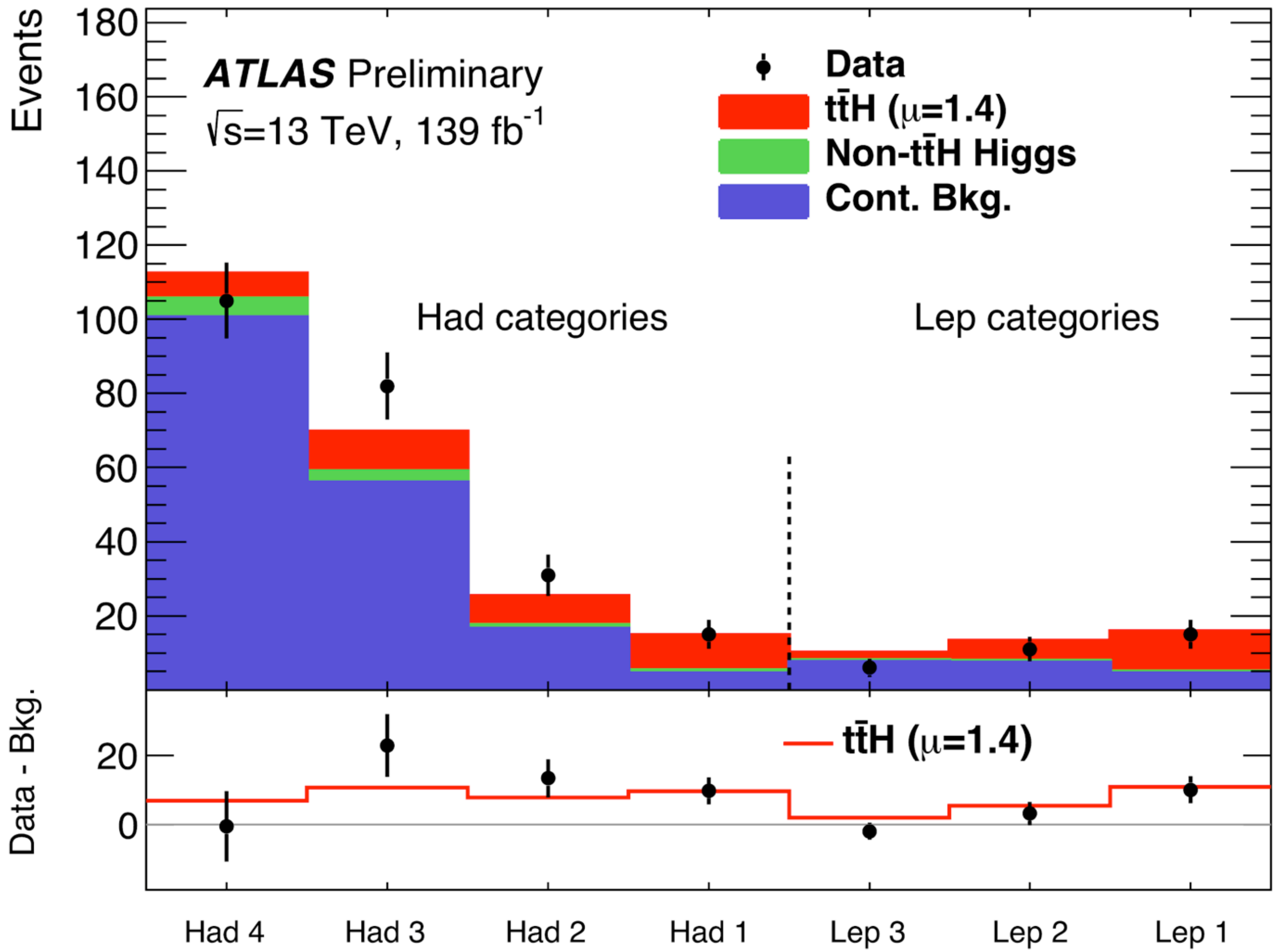


Weighted diphoton mass distribution

A nice way to visualize the power of categorization is to draw the S/B weighted mass distribution

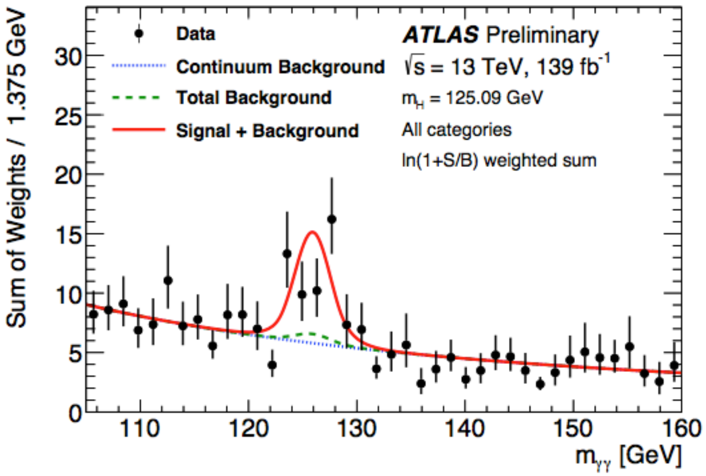


Summary of expected and observed event yields



All numbers calculated in a mass window containing 90% of the ttH signal events

Observed significance and rate



The expected significance of the ttH process is 4.2 σ, the observed is 4.9 σ

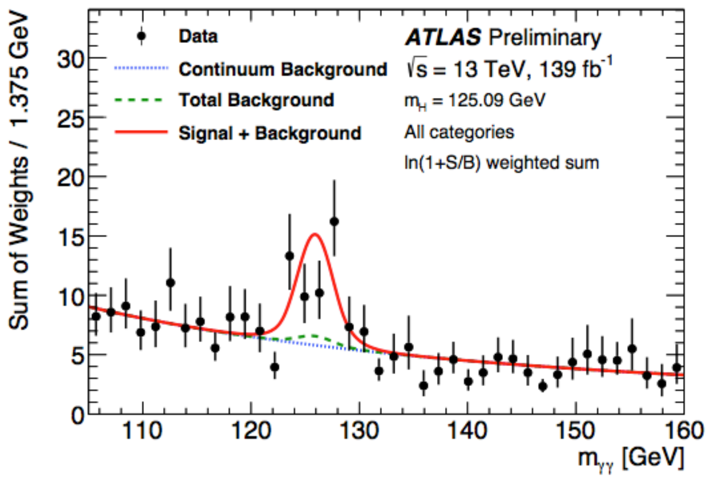
The measured ttH cross section times H→γγ branching ratio
:

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.59^{+0.43}_{-0.39}\ \text{fb} = 1.59^{+0.38}_{-0.36}\ (\text{stat.})\ ^{+0.15}_{-0.12}\ (\text{exp.})\ ^{+0.15}_{-0.11}\ (\text{theo.})\ \text{fb}$$

while the SM expectation is

$$\sigma_{t\bar{t}H} \times B_{\gamma\gamma} = 1.15^{+0.09}_{-0.12}\ \text{fb}$$

Observed significance and rate



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The signal strength (obs/SM) is measured to be

$$\mu_{t\bar{t}H} = 1.38\ ^{+0.41}_{-0.36} = 1.38\ ^{+0.33}_{-0.31}\ (\text{stat.})\ ^{+0.13}_{-0.11}\ (\text{exp.})\ ^{+0.22}_{-0.14}\ (\text{theo.})$$

Breakdown of systematic uncertainties

Uncertainty source	$\Delta\sigma_{\mathrm{low}}/\sigma$ [%]	$\Delta\sigma_{\mathrm{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution Function and α_S Scale (PDF+α_S)	0.3	0.5
Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)	0.4	0.3
Experimental uncertainties	7.8	9.1
Photon Energy Resolution (PER)	5.5	6.2
Photon Energy Scale (PES)	2.8	2.7
Jet/$E_{\mathrm{T}}^{\mathrm{miss}}$	2.3	2.7
Photon Efficiency	1.9	2.7
Background Modeling	2.1	2.0
Flavor Tagging	0.9	1.1
Leptons	0.4	0.6
Pileup	1.0	1.5
Luminosity and Trigger	1.6	2.3
Higgs Boson Mass	1.6	1.5

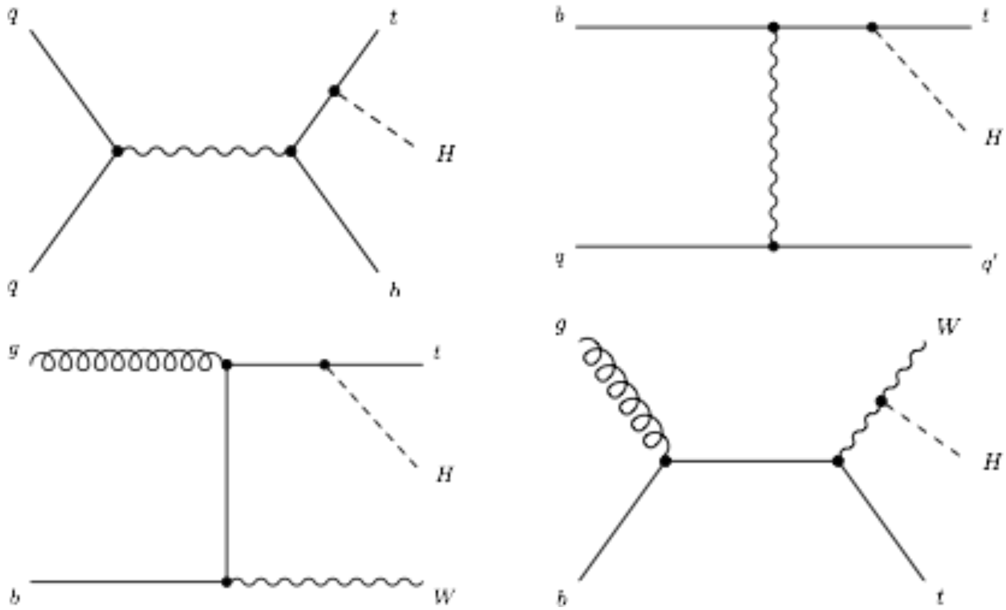
Observation of ttH → γγ

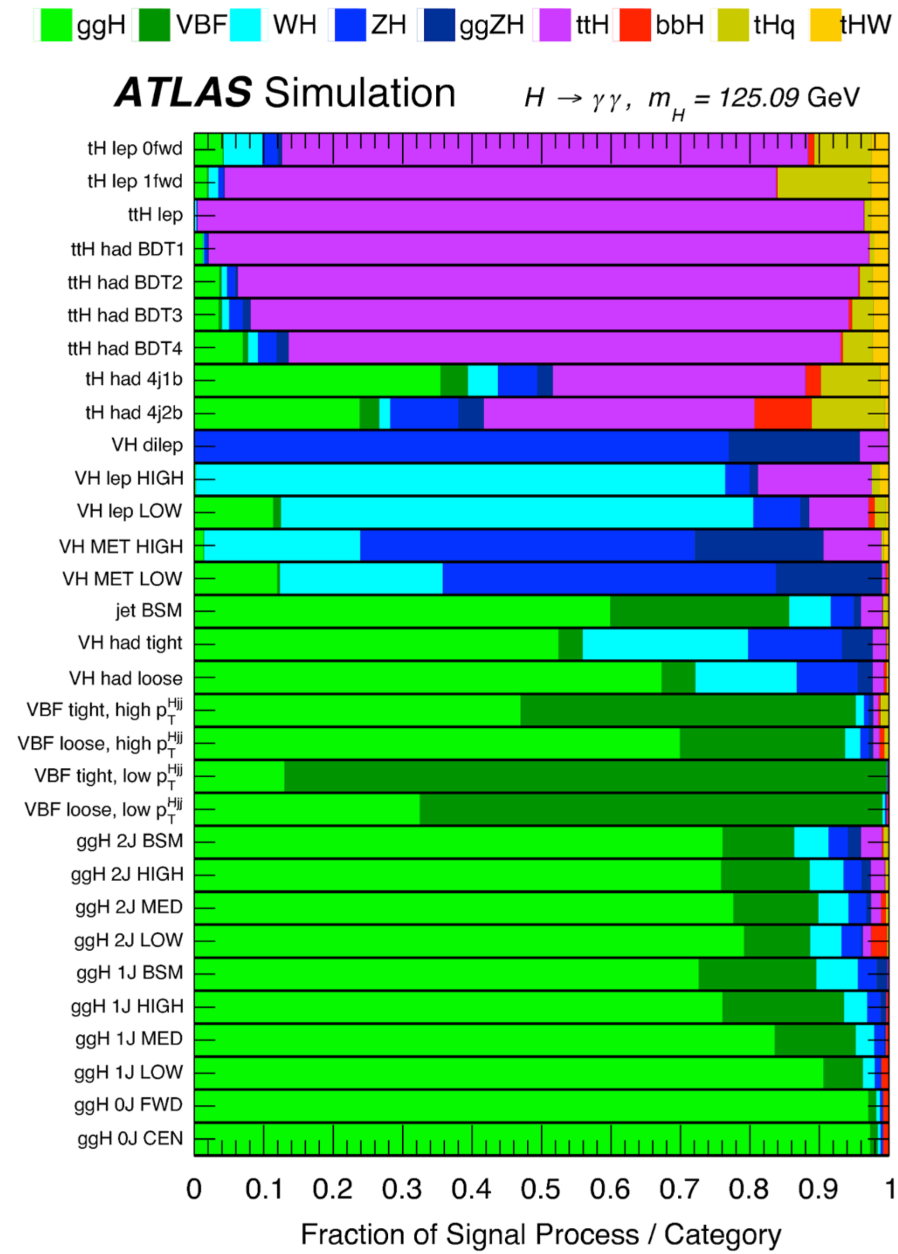
- ATLAS measurement of the ttH → γγ process from the full LHC Run-2 data set was reported
- **The ttH process is observed in the diphoton decay mode with a significance of 4.9 σ**
- The ttH cross section times H → γγ branching ratio is measured to be

$$1.59^{+0.43}_{-0.39}\ \mathrm{fb}$$

- **Details are available in [ATLAS-CONF-2019-004]**

Outlook - Single Top Higgs Production





Previous ATLAS publication included tH enriched categories, motivated to probe sign flip for kappa_top

Outlook - CP property of the top-Higgs coupling

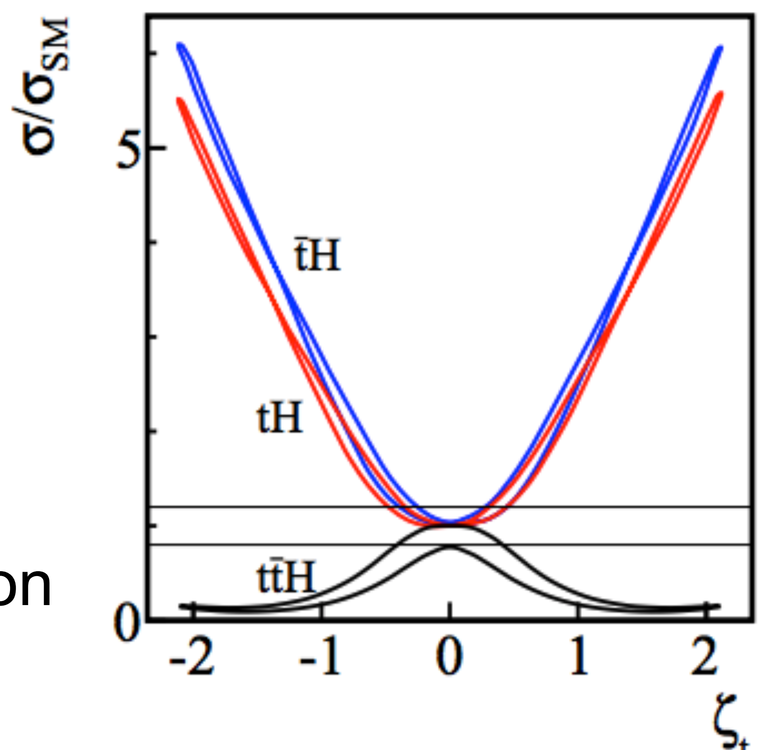
The presence of a CP-odd component in the top-Higgs interaction will affect the rate and kinematics of processes relevant to the top-Higgs interaction

$$\mathcal{L}_t = -\frac{m_t}{v}\left(\kappa_t \bar{t}t + i\tilde{\kappa}_t \bar{t}\gamma_5 t\right) H$$

Ellis et al.

- Gluon fusion
- Higgs to gamma gamma decay
- ttH
- Single top Higgs production

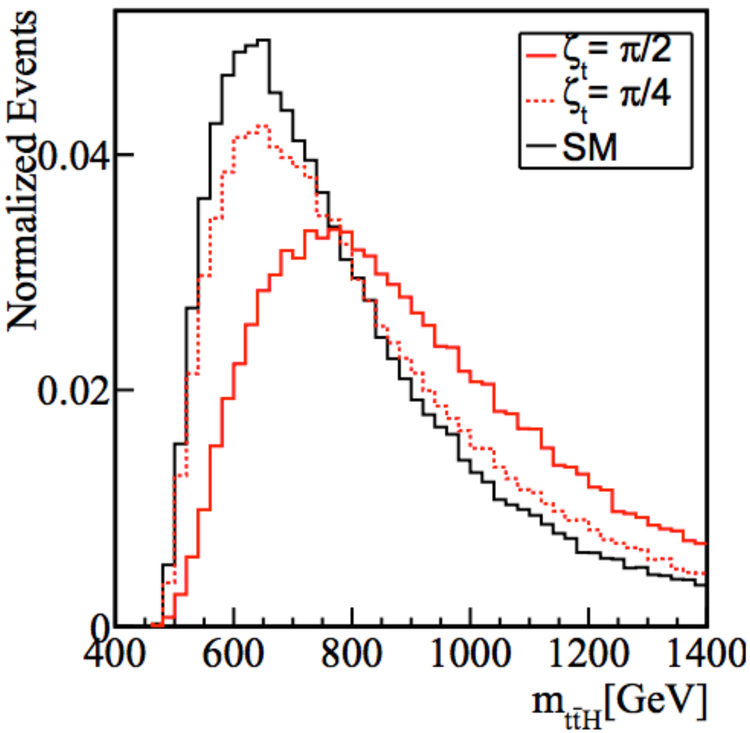
$$\begin{aligned} c_g^2 &= \mu_{gg} \simeq \kappa_t^2 + 2.6\tilde{\kappa}_t^2 + 0.11\kappa_t(\kappa_t - 1)\,, \\ c_\gamma^2 &= \mu_{\gamma\gamma} \simeq (1.28 - 0.28\kappa_t)^2 + (0.43\tilde{\kappa}_t)^2\,. \end{aligned}$$



Measurements can be done in ttH channel, or in the Higgs combination

Outlook - Differential Cross Sections

- ttH Differential cross sections can be sensitive to new physics:
  - $p_{T,H}$, m_{ttH}, m_{tH}, etc.



Two approaches

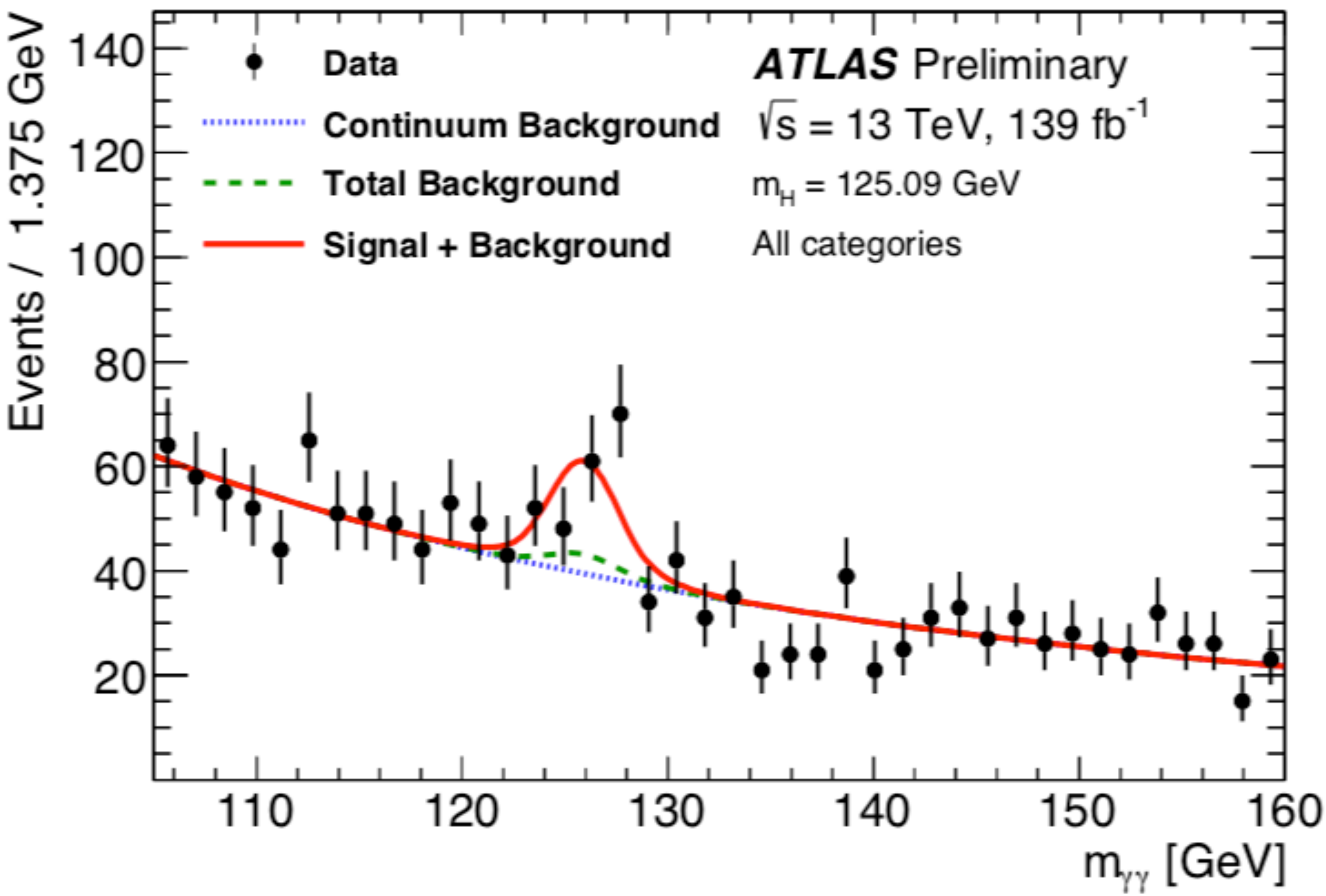
- Differential cross section measurements - reconstruct observables, extract signal yield in individual bins
- Simplified Template Cross Section (truth bin) - slice signal phase space at truth level, perform simultaneous fit to determine strengths of truth bins using reco level signal regions

Summary

- **ATLAS observed the ttH $\rightarrow$ γγ process in the full Run-2 data set**
- **More refined results will be submitted for publication**
- **There is a rich physics program in the ttH sector**

Back up

Unweighted diphoton mass distribution



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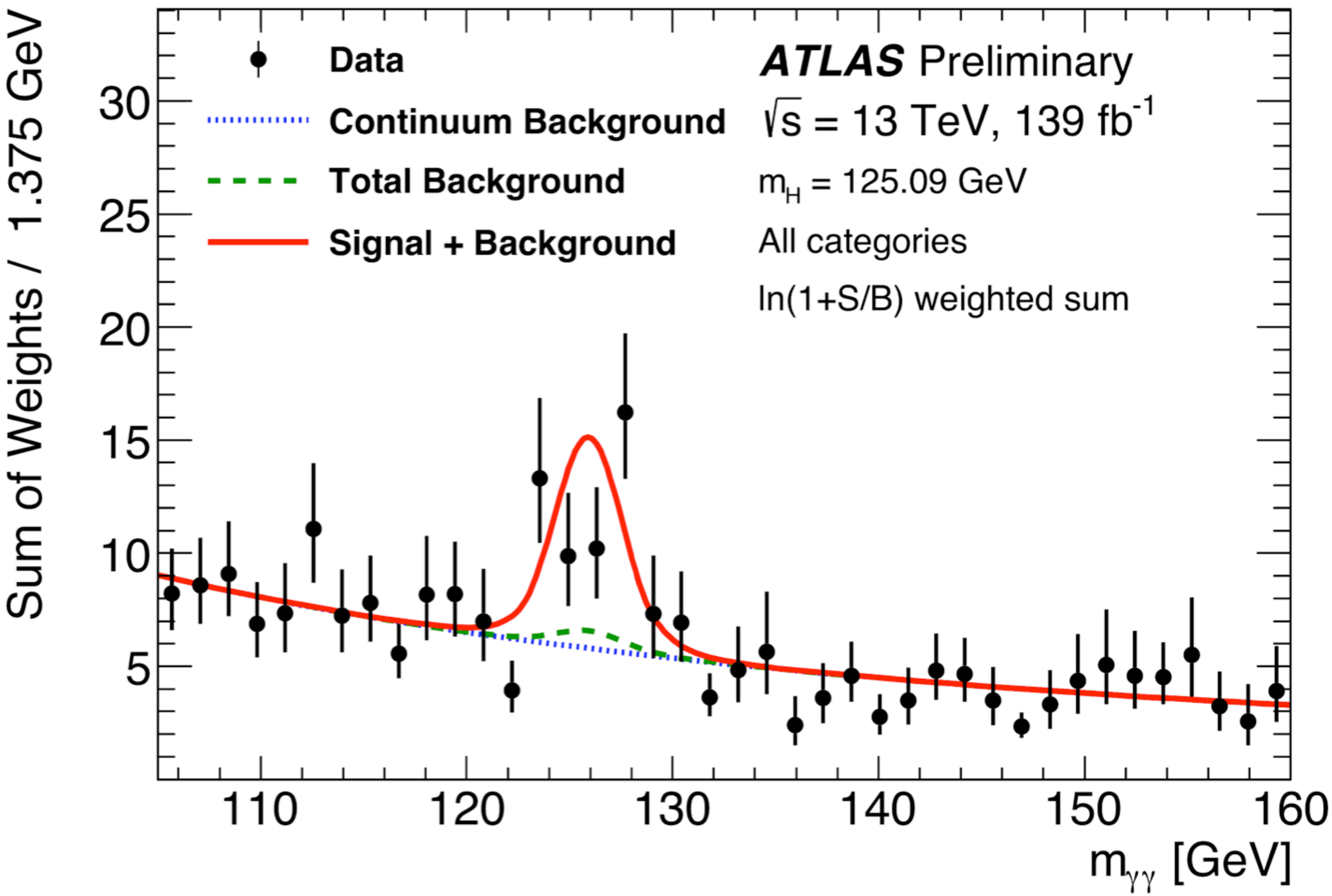

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