Measurement of Higgs boson production in association with two top quarks ($t\bar{t}H$) in the $H\rightarrow\gamma\gamma$ channel using 139 fb^{-1} of data collected with the ATLAS detector

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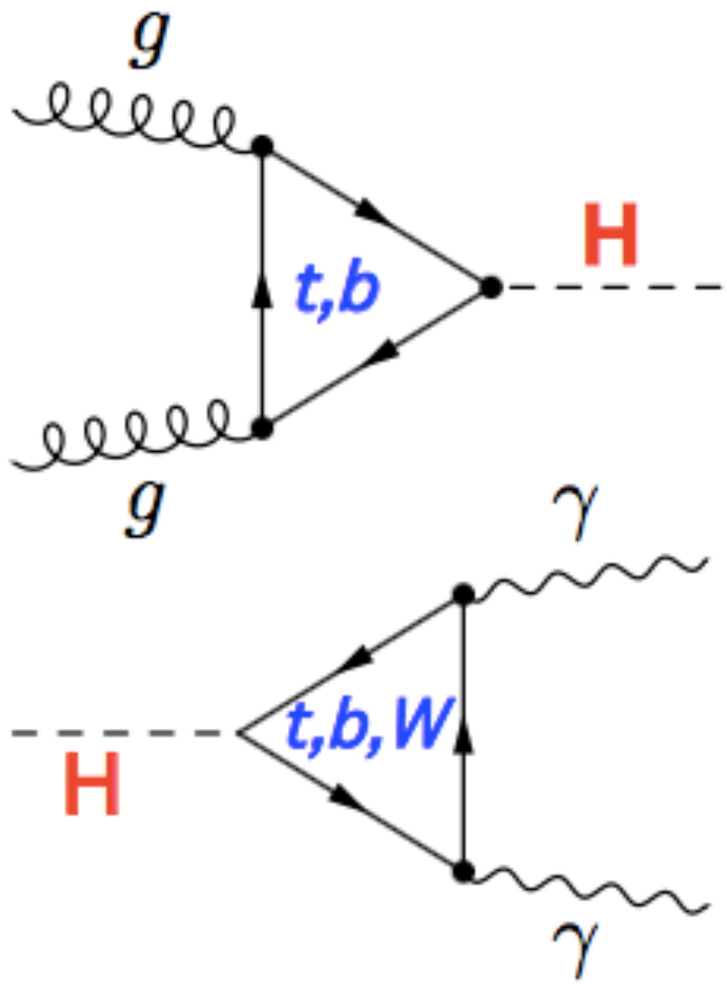
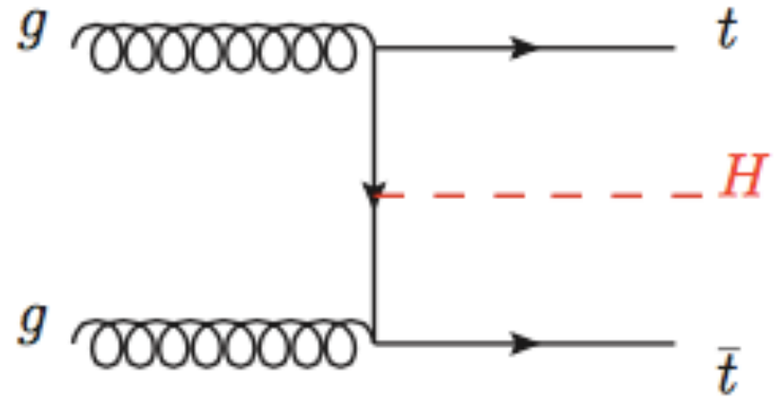
Higgs-top Yukawa coupling

- A probe of fundamental interest: the Yukawa coupling between the Higgs boson and the top quark, the heaviest particle in SM
- Higgs-top Yukawa coupling can be **indirectly probed** via the gluon-fusion production cross section and H→γγ decay branch ratio (loop-level processes)
- BSM particles could be present in the loop



$t\bar{t}H$ production mode

- A **more direct test** of this coupling can be performed through the production of the Higgs boson in association with a top quark pair ($t\bar{t}H$)
- A very rare Higgs production mode (~1%; 507 fb at 13 TeV); mainly a tree-level process
- Could get handles on BSM physics by comparison between loop-induced processes and direct $t\bar{t}H$ production



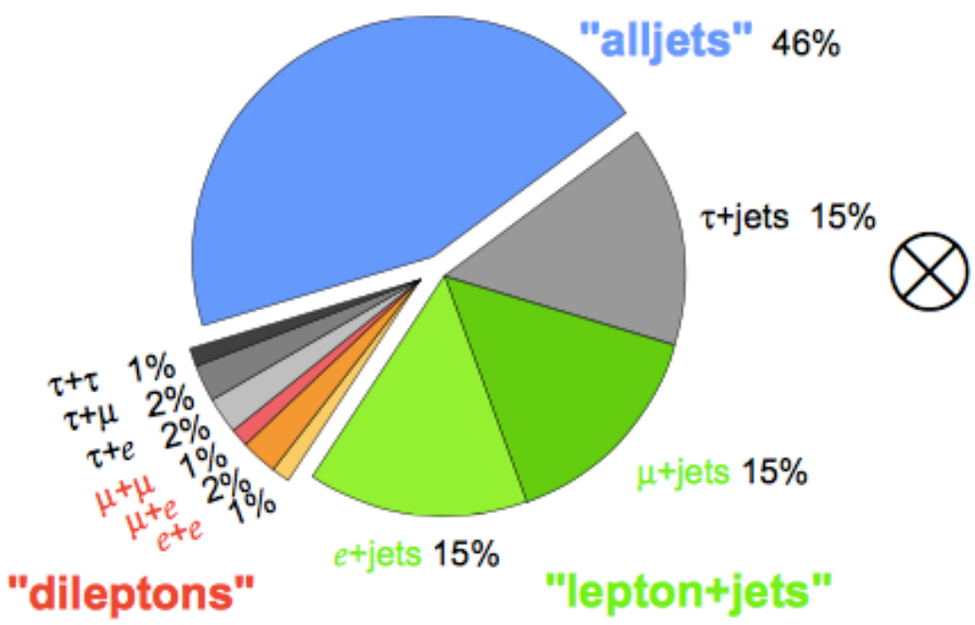
Study $t\bar{t}H$ production

- Need to consider different Higgs boson decay channels for such a rare production mode!
  - $t\bar{t}H$, $H \to ZZ^* \to$ 4-lepton
  - $t\bar{t}H$, $H \to \gamma\gamma$
  - $t\bar{t}H$, multi-lepton ($H \to WW^*$, $\tau\tau$, ZZ^*, excluding $ZZ^* \to$ 4-lepton, see Rohin's talk later)
  - $t\bar{t}H$, $H \to b\bar{b}$

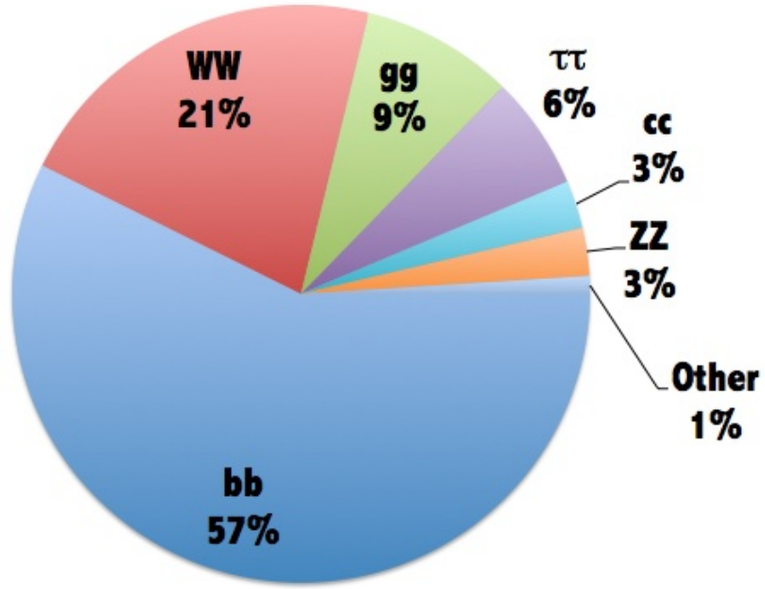
larger S/B

larger BF

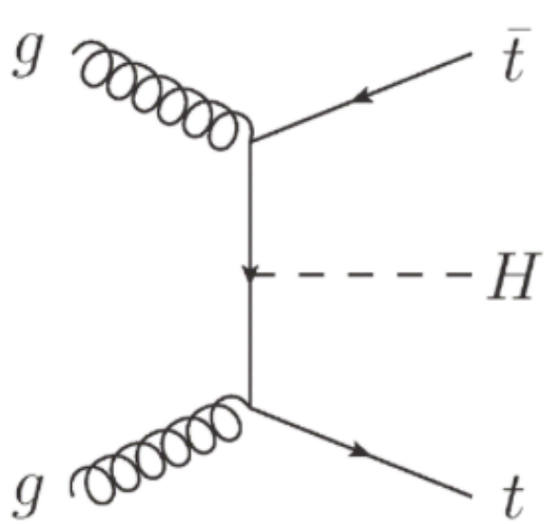
Top Pair Branch Fractions

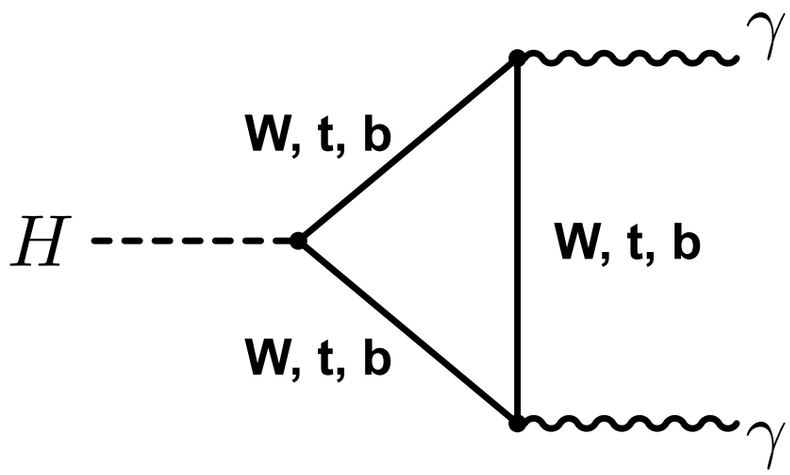


Higgs Branch Fractions



This talk:
$t\bar{t}H$ ($H\to\gamma\gamma$) (139 fb^{-1})





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$t\bar{t}H$ ($H \to \gamma\gamma$) analysis strategy

Select events with **two photons** and at least one b-jet

➔Separate to **hadronic channel** ($n_{lep} = 0$) and **leptonic channel** ($n_{lep} >= 1$)

- Background: continuum bkg. ($\gamma\gamma$, $t\bar{t}\gamma\gamma$, etc.) and resonant bkg. from other Higgs production modes (ggH, tH, etc.)

➔In each channel, train a Boost Decision Tree (BDT) with XGBoost package to separate $t\bar{t}H$ signal from backgrounds

- define **event categories based on BDT output**

➔Fit **diphoton mass** over all categories

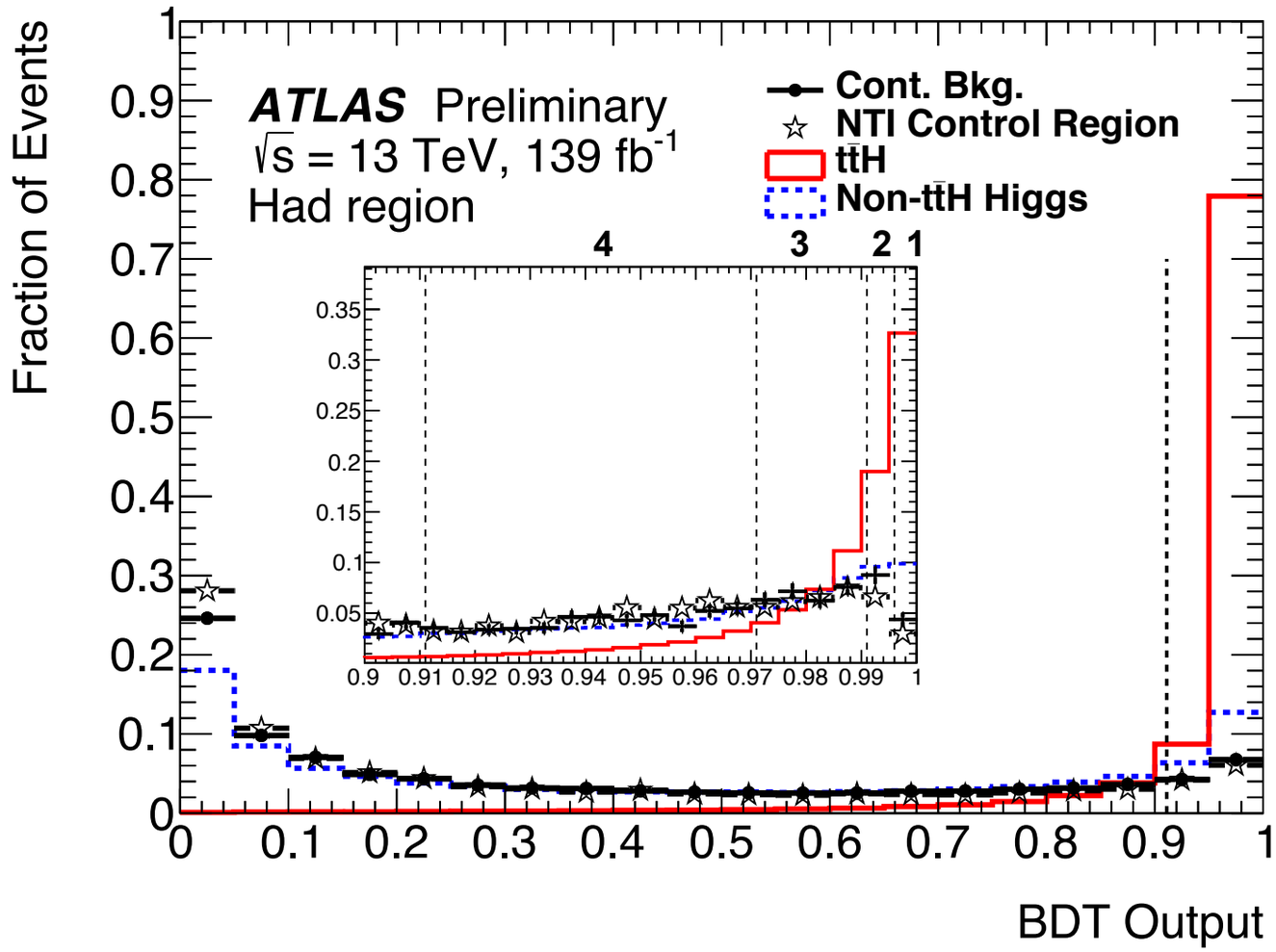
- robust continuum background estimation from data sidebands; narrow signal peaks around Higgs boson mass

➔Measure $t\bar{t}H$ production signal strength, etc.

Hadronic channel

- Target: all-hadronic top-quark pair decays, or semi-leptonic top-quark pair decays with leptons not identified
- BDT trained with $t\bar{t}H$ simulation and data control region having photons failing identification, using:
  - pT, η, ϕ, and b-tag status of first 6 jets (sorted by pT)
  - MET and ϕ(MET)
  - pT/mγγ, η, and ϕ of 2 photons

(Each distribution is normalized to unity)



- Events with low BDT score are vetoed
- Define 4 categories in hadronic channel based on BDT output, to exploit its good separation power

Leptonic channel

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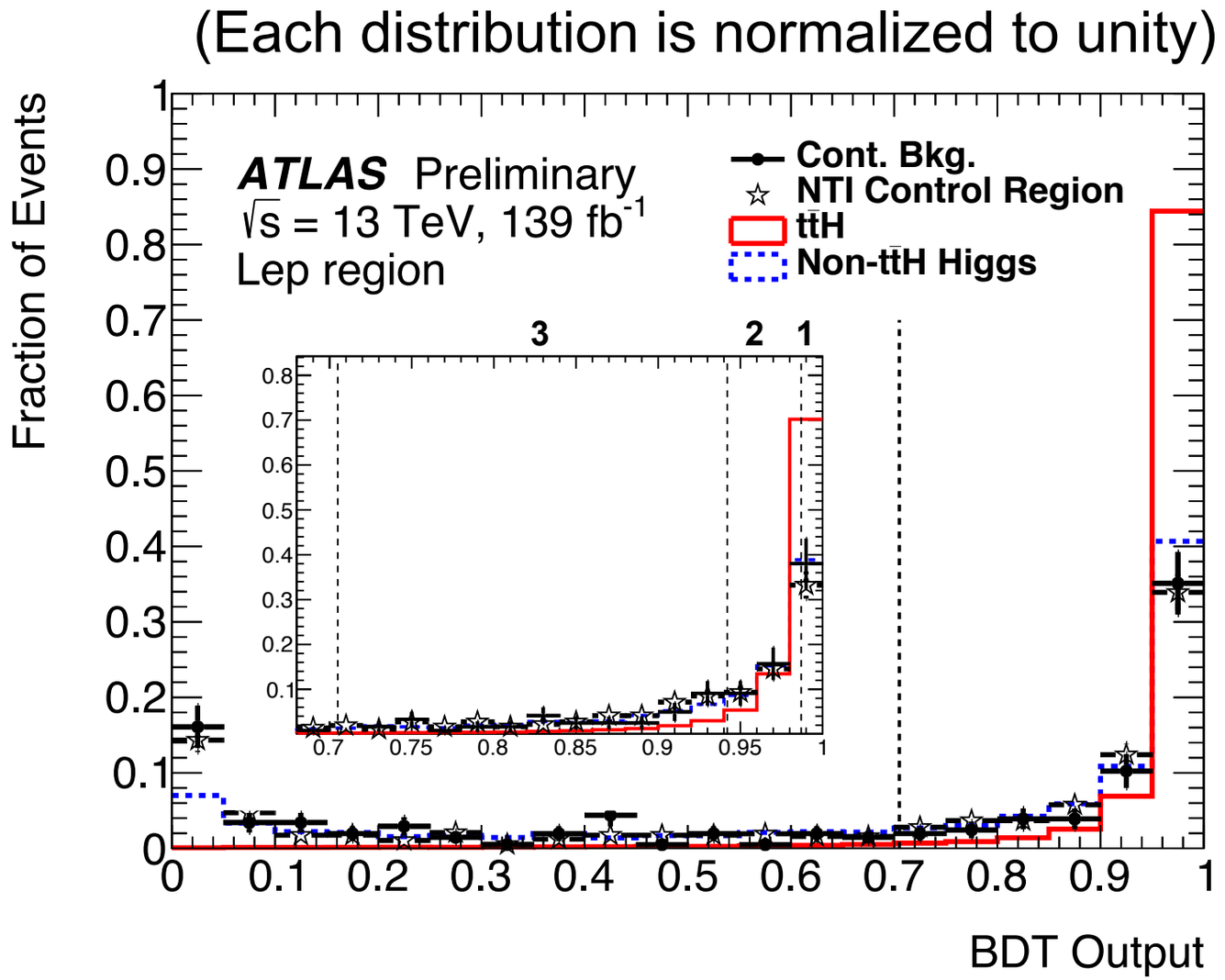
- Target: semi-leptonic top-quark pair decays
- BDT trained with $t\bar{t}H$ simulation and data control region having photons failing identification, using:
  - pT, η, ϕ of first 4 jets, first 2 leptons (sorted by pT)
  - MET and ϕ(MET)
  - pT/mγγ, η, and ϕ of 2 photons

(Each distribution is normalized to unity)



- Events with low BDT score are vetoed
- Define 3 categories in leptonic channel based on BDT output, to exploit its good separation power

Signal and background modeling

- **For each event category, need to model diphoton mass distributions of signal and backgrounds**
- **Model of $t\bar{t}H$ signal and non-$t\bar{t}H$ Higgs background**
  - Expected yields from $t\bar{t}H$ and non-$t\bar{t}H$ production modes estimated from simulation
  - Mass shapes: parametrized from simulation with double-sided crystal ball functions
- **Model of continuum background**:
  - Analytical functions fitted on (unbinned) data
  - Using dedicated background-only samples
    - checked the BDTs do not induce a bump
    - studied functional forms and associated uncertainties

Diphoton mass: individual category

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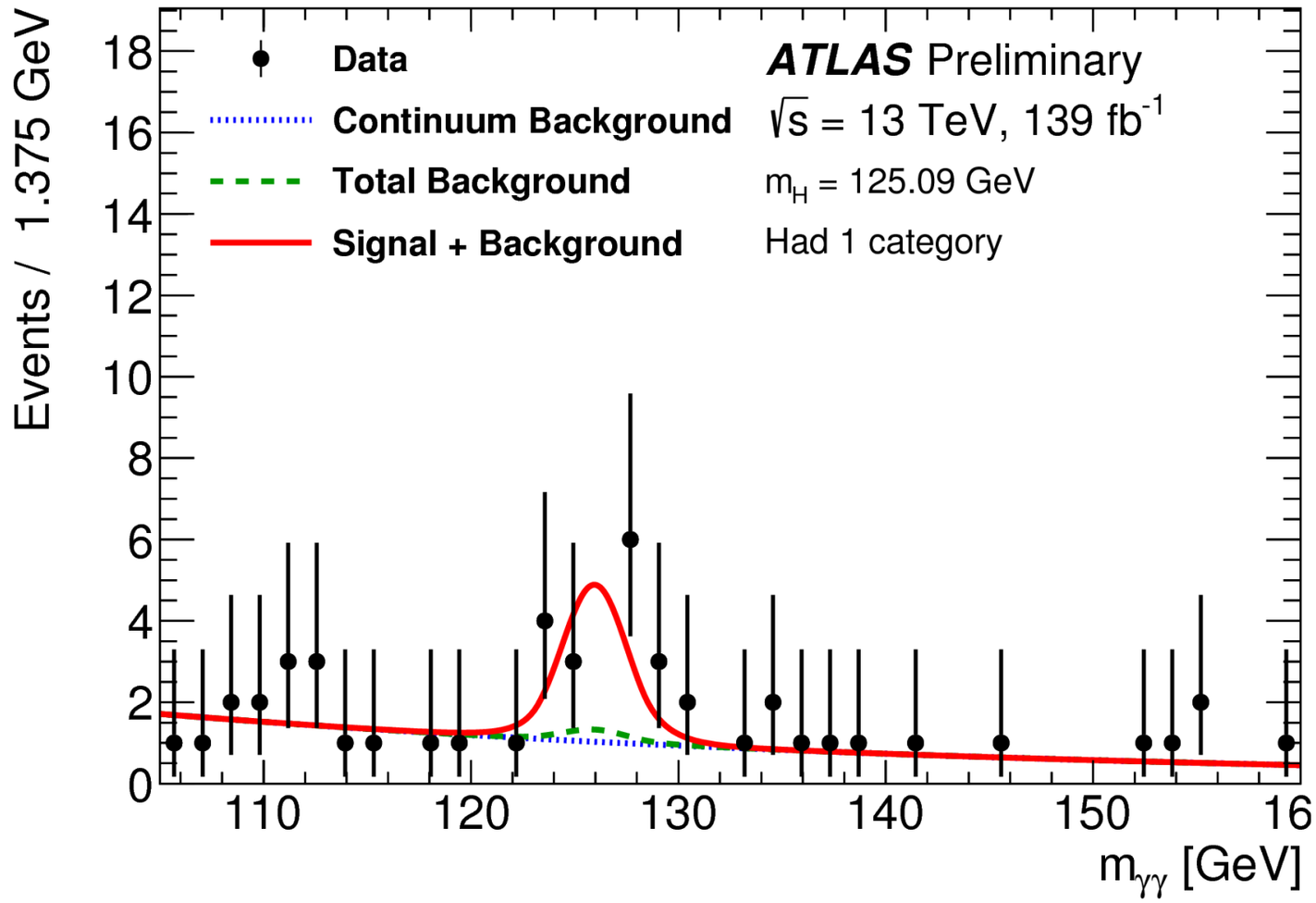

Had BDT1

- Had BDT1 (category with highest S/B in hadronic channel):
  - expect 6.9 $t\bar{t}H$ events, 5.3 background events, observe 15 events, in the mass window containing 90% of the signals

Diphoton mass: individual category

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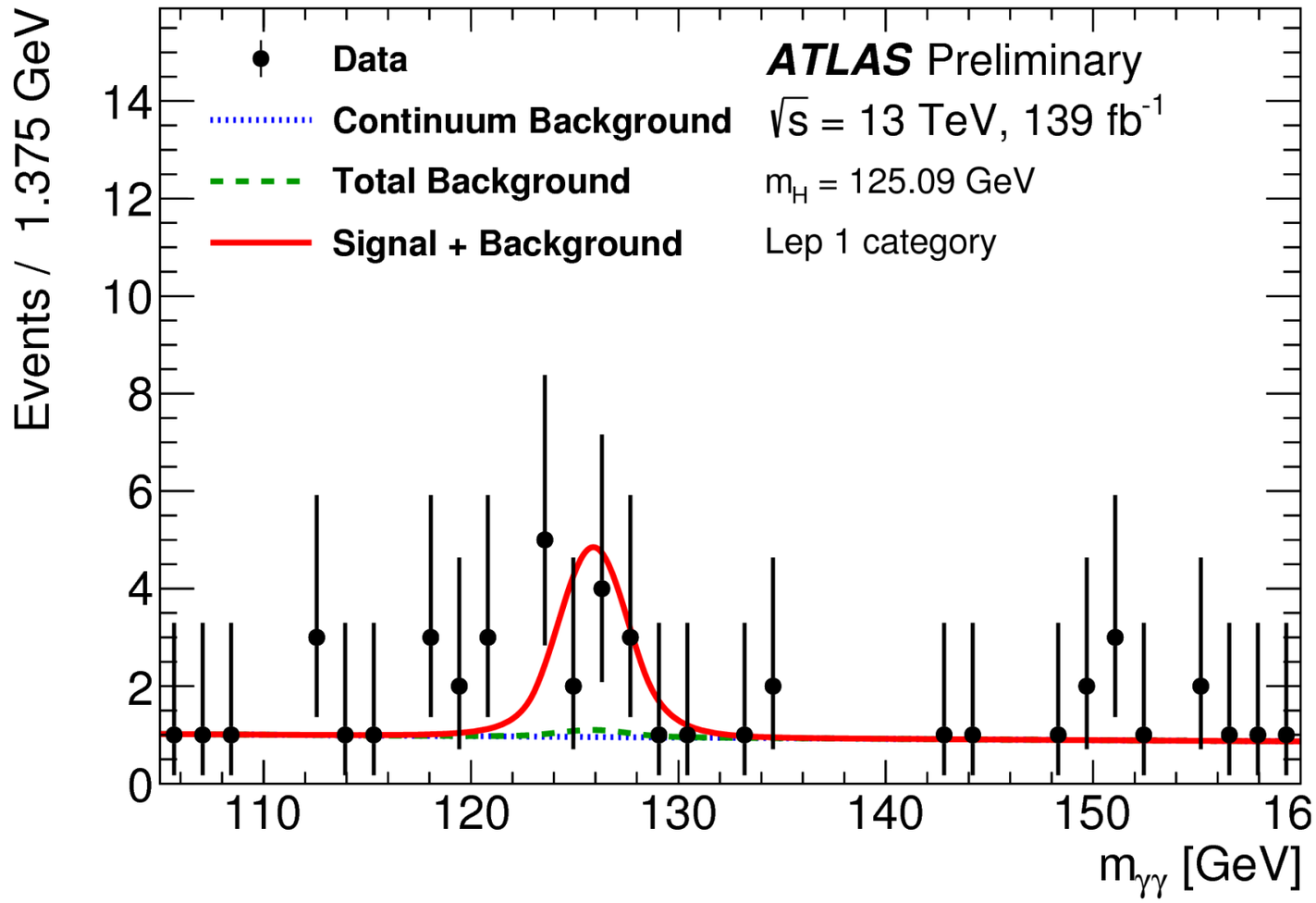
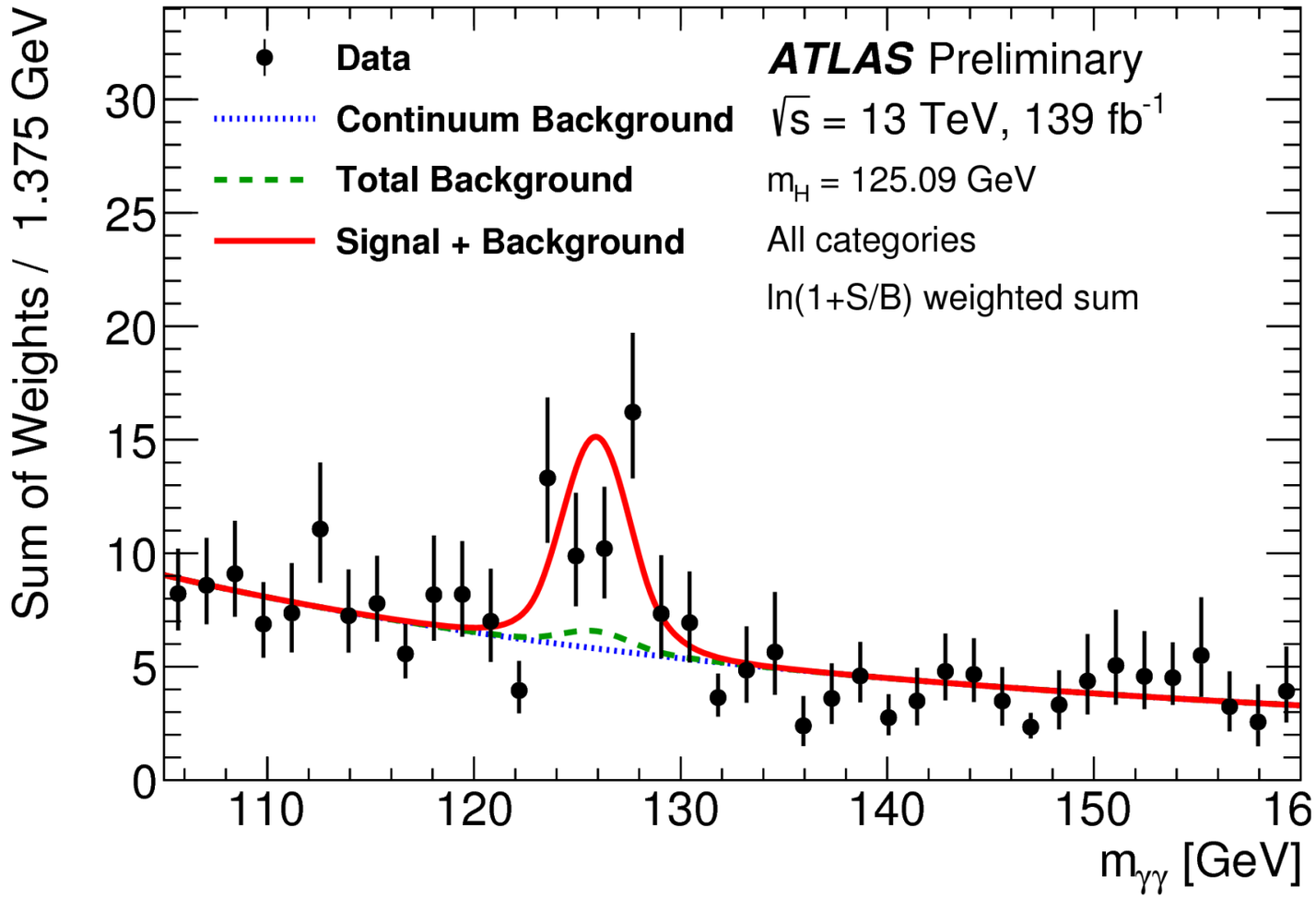


Lep BDT1

- Lep BDT1 (category with highest S/B in leptonic channel):
  - expect 7.9 $t\bar{t}H$ events, 5.0 background events, observe 15 events, in the mass window containing 90% of the signals

Diphoton mass: all categories ATLAS-CONF-2019-004



- Diphoton mass spectrum peaks at the Higgs mass around 125 GeV
- ~53 $t\bar{t}H$ ($H\rightarrow\gamma\gamma$) events fitted over 7 categories, in the mass window containing 90% of the signals

Event yields: all categories

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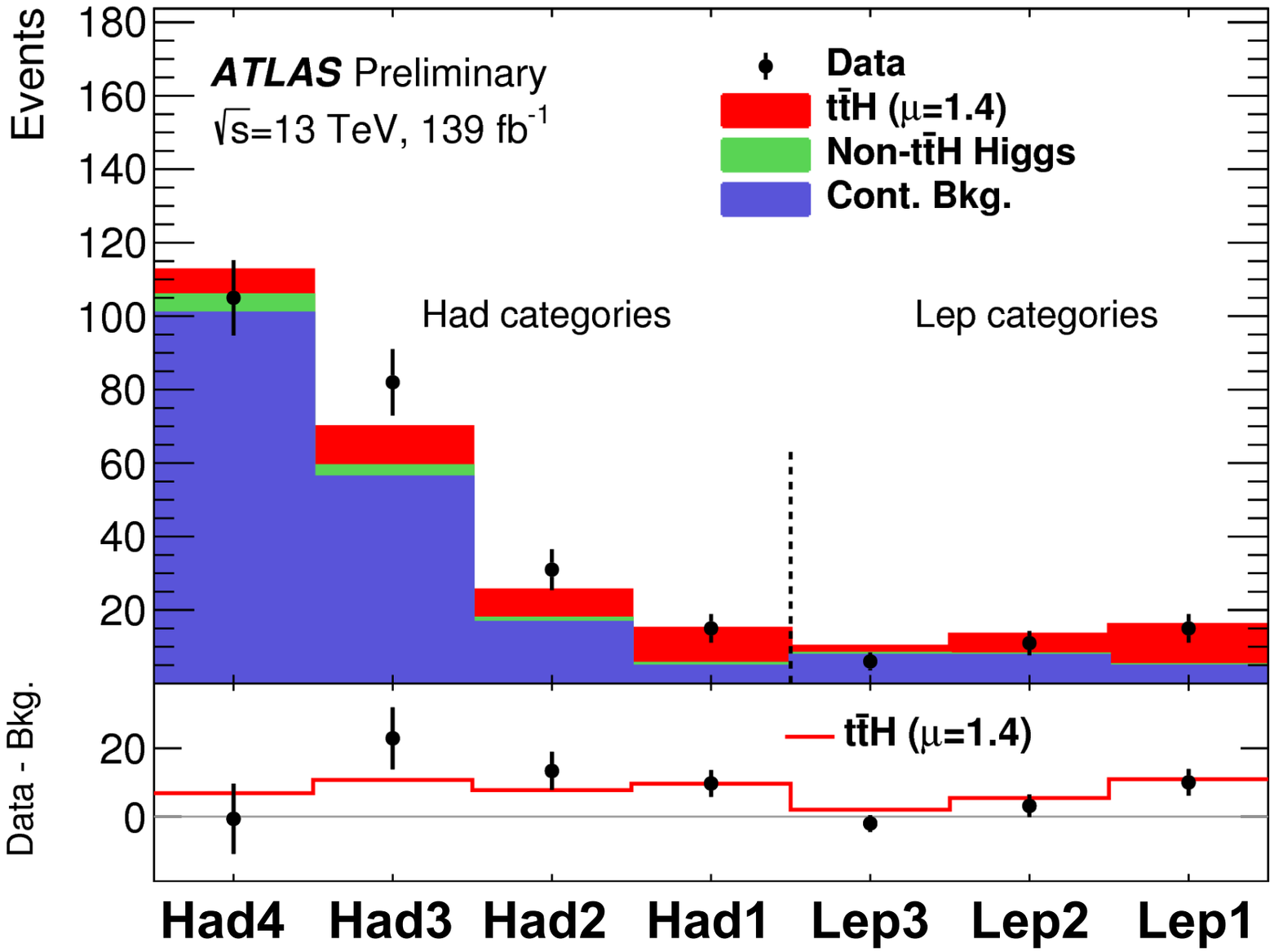
- Number of events in each category, in the mass window containing 90% of the signal events



Expected S/B: 0.05 0.13 0.32 1.6 0.18 0.49 1.6

$t\bar{t}H$ ($H\to\gamma\gamma$) results: significance

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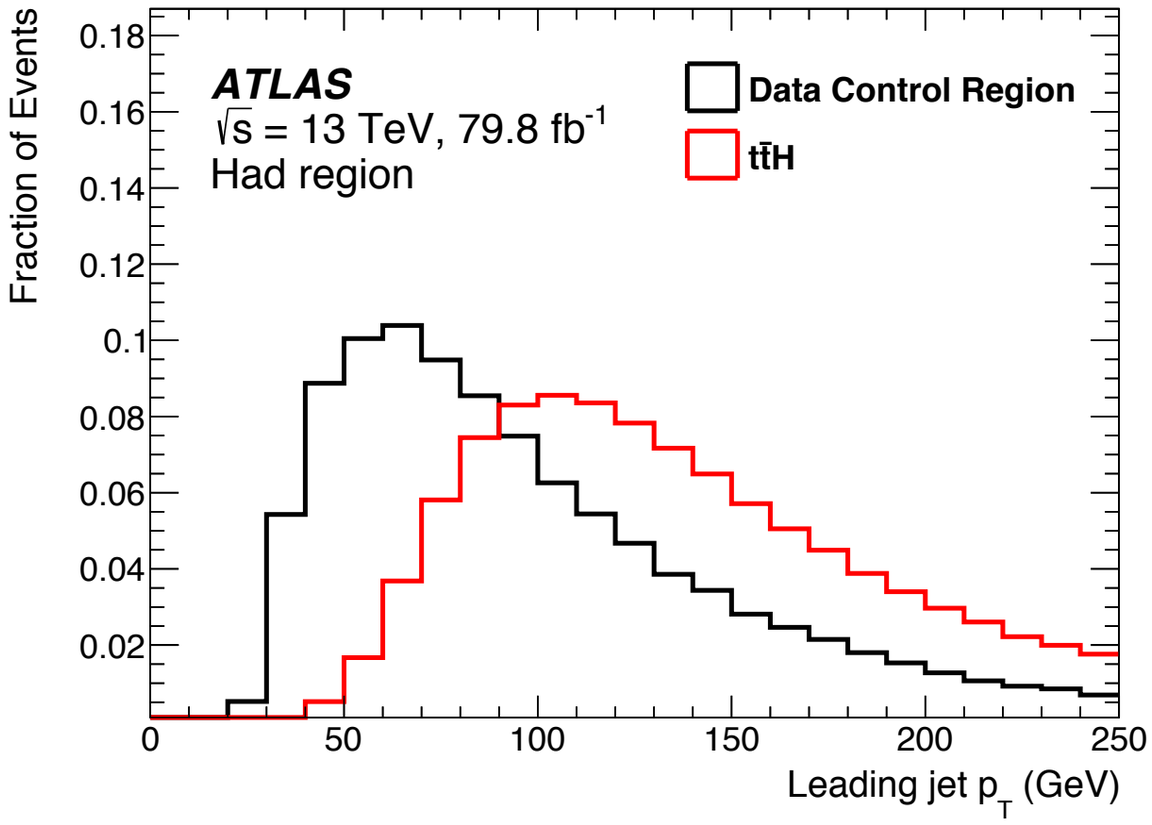
$t\bar{t}H$, $H\to\gamma\gamma$	expected significance	observed significance
36 fb^{-1} results PRD 98 (2018) 052005	1.7σ	0.9σ
139 fb^{-1} result ATLAS-CONF-2019-004	4.2σ	4.9σ

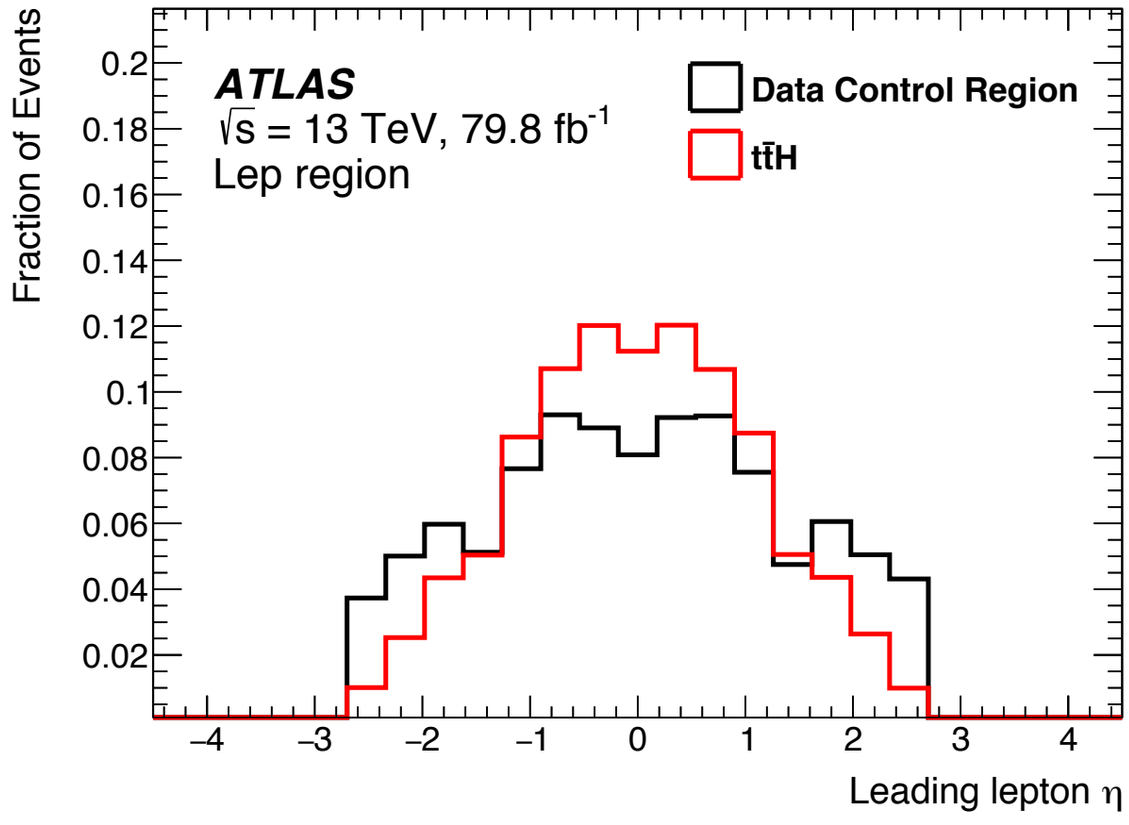
- The new $t\bar{t}H$ ($H\to\gamma\gamma$) analysis has **better sensitivity** than the 36 fb^{-1} publication (PRD 98 (2018) 052005), for the same luminosity
- The largest sensitivity improvement is achieved by using **kinematic information of jets, leptons, photons and MET** as inputs to BDT

Example variables in BDT training

Phys. Lett. B
784 (2018) 173



Hadronic channel
leading jet pT

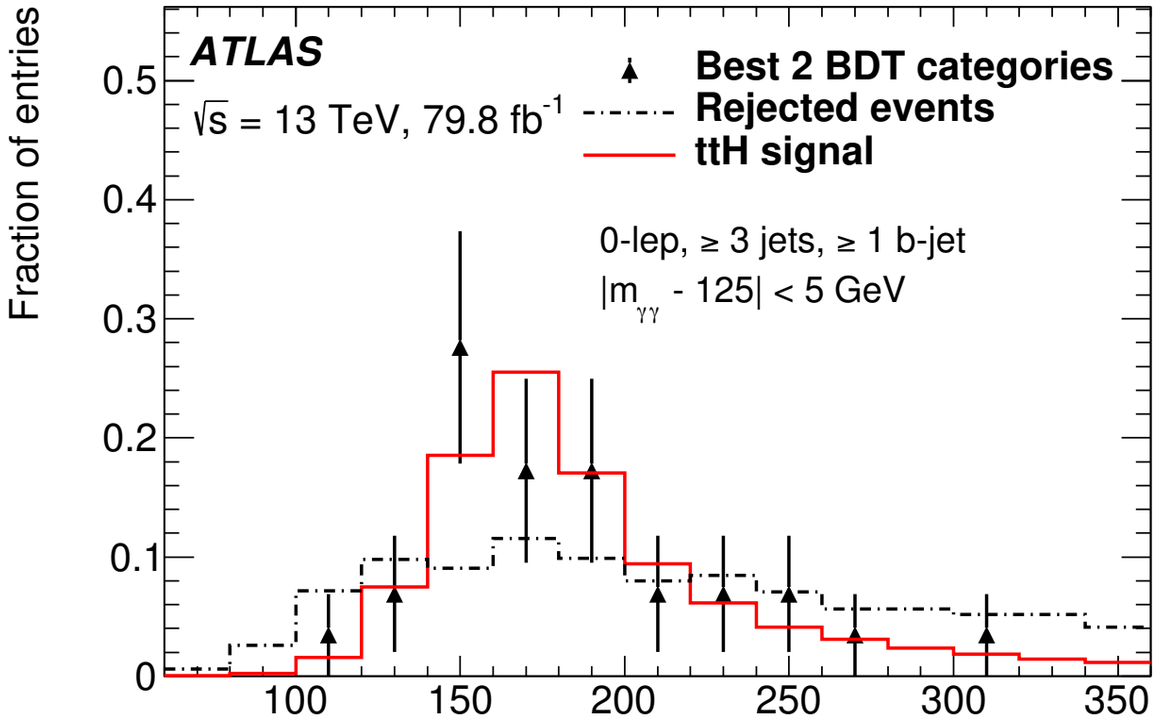


Leptonic channel
leading lepton η

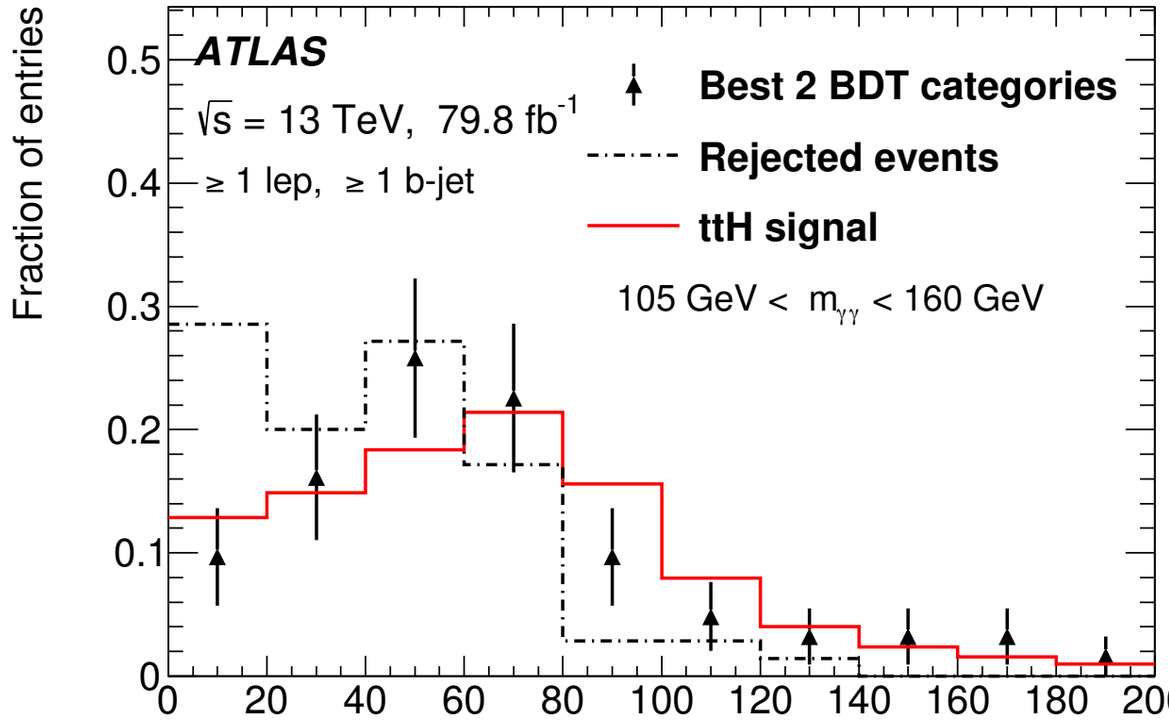
- Signal and background differ in kinematic variables of jets, leptons, photons and MET
- BDT can also utilize correlation between training variables

Example variables for BDT validation

Phys. Lett. B
784 (2018) 173



Hadronic channel
Top candidate mass
(based on top reconstruction)



Leptonic channel
Transverse mass

- The distributions of data in best BDT categories follow the distributions of $t\bar{t}H$ simulation
- These variables are for validation and not directly used in analysis

$t\bar{t}H$ signal strength measurement ATLAS-CONF-2019-004

- The $t\bar{t}H$ signal strength is measured to be
  - $1.38^{+0.41}_{-0.36} = 1.38^{+0.33}_{-0.31}(\text{stat.})^{+0.13}_{-0.11}(\text{exp.})^{+0.22}_{-0.14}(\text{theo.})$
- The $t\bar{t}H$ total cross section times the $H\to\gamma\gamma$ branch ratio is measured to be
  - $1.59^{+0.43}_{-0.39}$ fb $= 1.59^{+0.38}_{-0.36}(\text{stat.})^{+0.15}_{-0.12}(\text{exp.})^{+0.15}_{-0.11}(\text{theo.})$ fb
  - ~25% precision
  - in agreement with the NLO SM prediction of $1.15^{+0.09}_{-0.12}$ fb

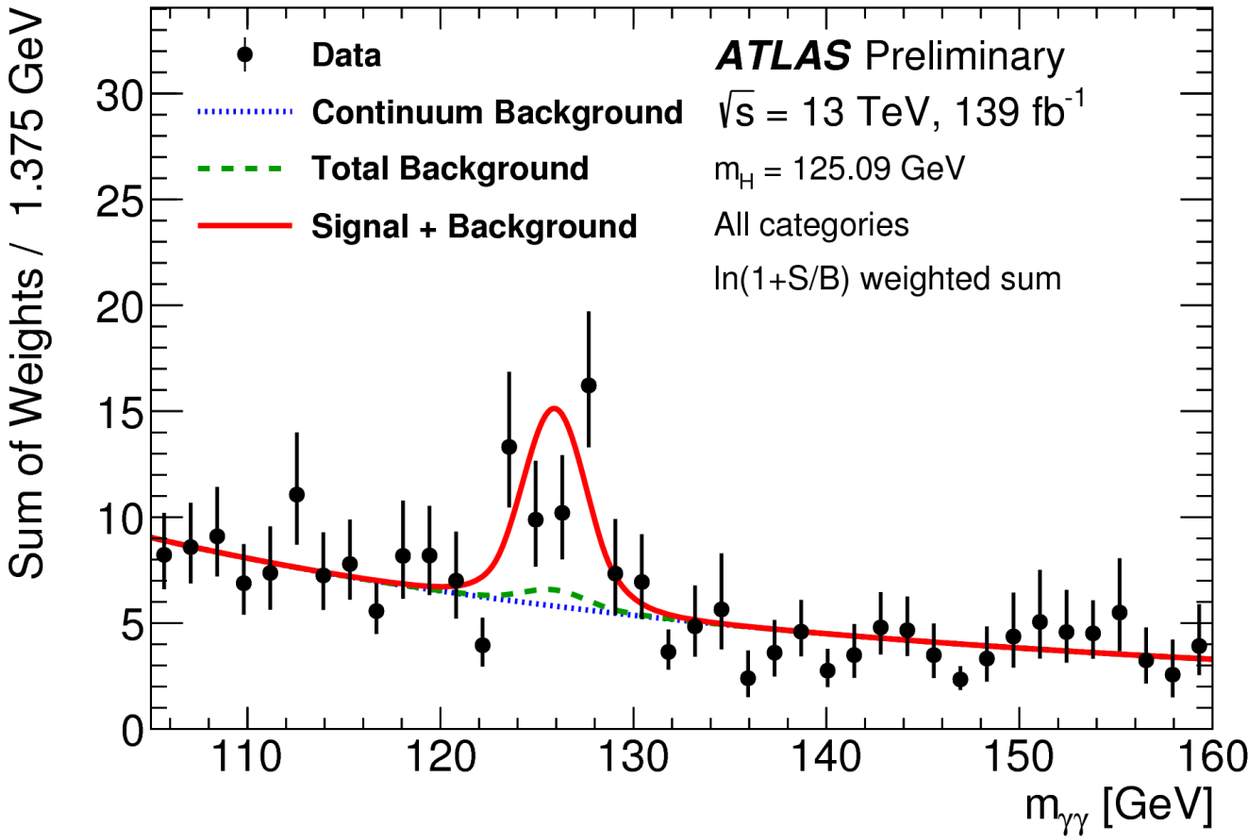
Breakdown of systematic uncertainties ATLAS-CONF-2019-004

- This channel is still **statistically limited**
  - Parton showering and photon energy resolution systematics are the highest ranked ones

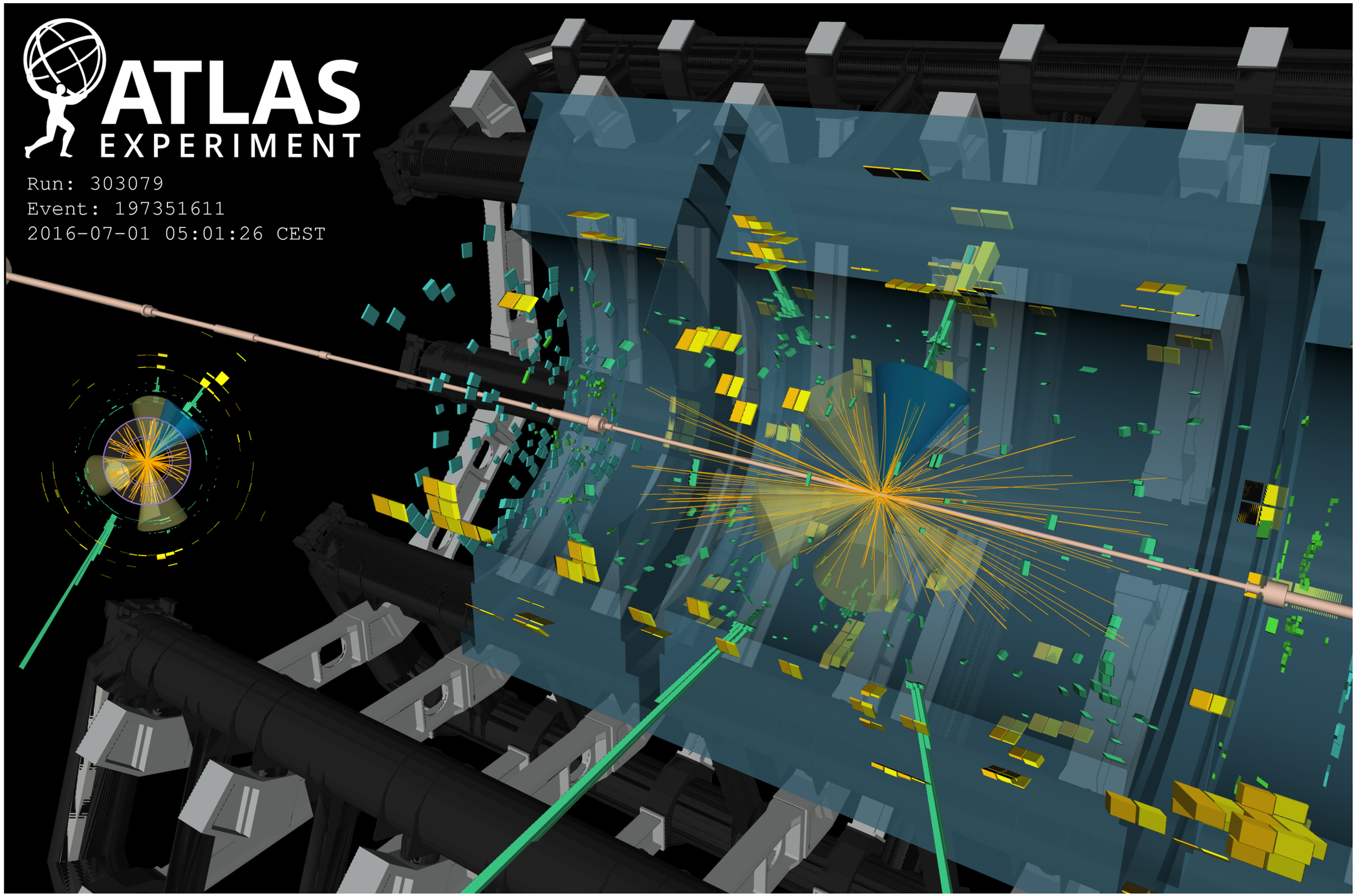
Uncertainty source	$\Delta\sigma_{\text{low}}/\sigma$ [%]	$\Delta\sigma_{\text{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution 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/$E_{\text{T}}^{\text{miss}}$	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

Summary

- ATLAS measured the $t\bar{t}H$ ($H\to\gamma\gamma$) process using the **full Run-2 data set**
- We use kinematic information of jets, leptons, photons and MET with advanced **machine learning** algorithm XGBoost BDT, to improve the sensitivity of this analysis
- The $t\bar{t}H$ production is observed in the $H\to\gamma\gamma$ decay mode with a **4.9σ observed significance**
- The signal strength and the $t\bar{t}H$ cross section times $H\to\gamma\gamma$ branch ratio measurements are in agreement with the SM predictions



Display: $t\bar{t}H$ ($H \to \gamma\gamma$) Had1 candidate event



- $t\bar{t}H$ ($H \to \gamma\gamma$) Had1 candidate, with $m_{\gamma\gamma}$ = 125.4 GeV and six jets; **S/B (Had1) ~ 2**