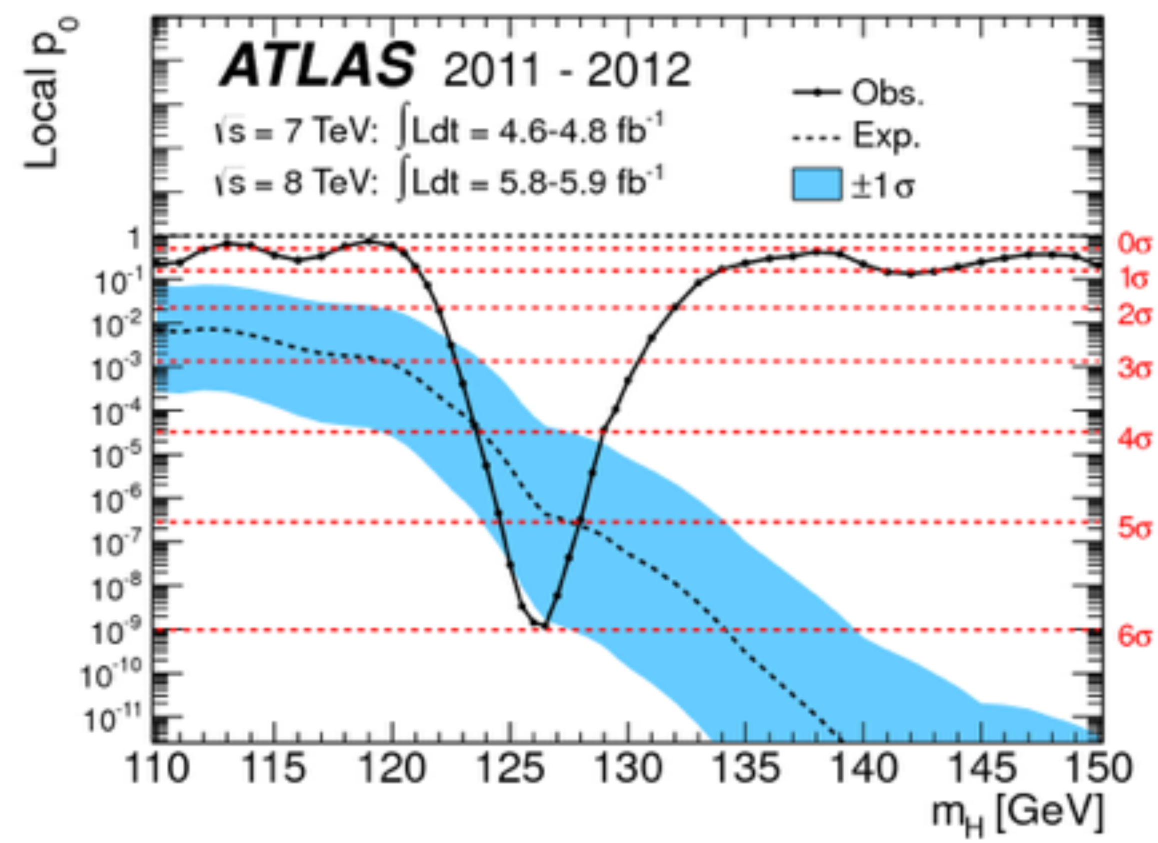
Latest Higgs physics results from the ATLAS experiment

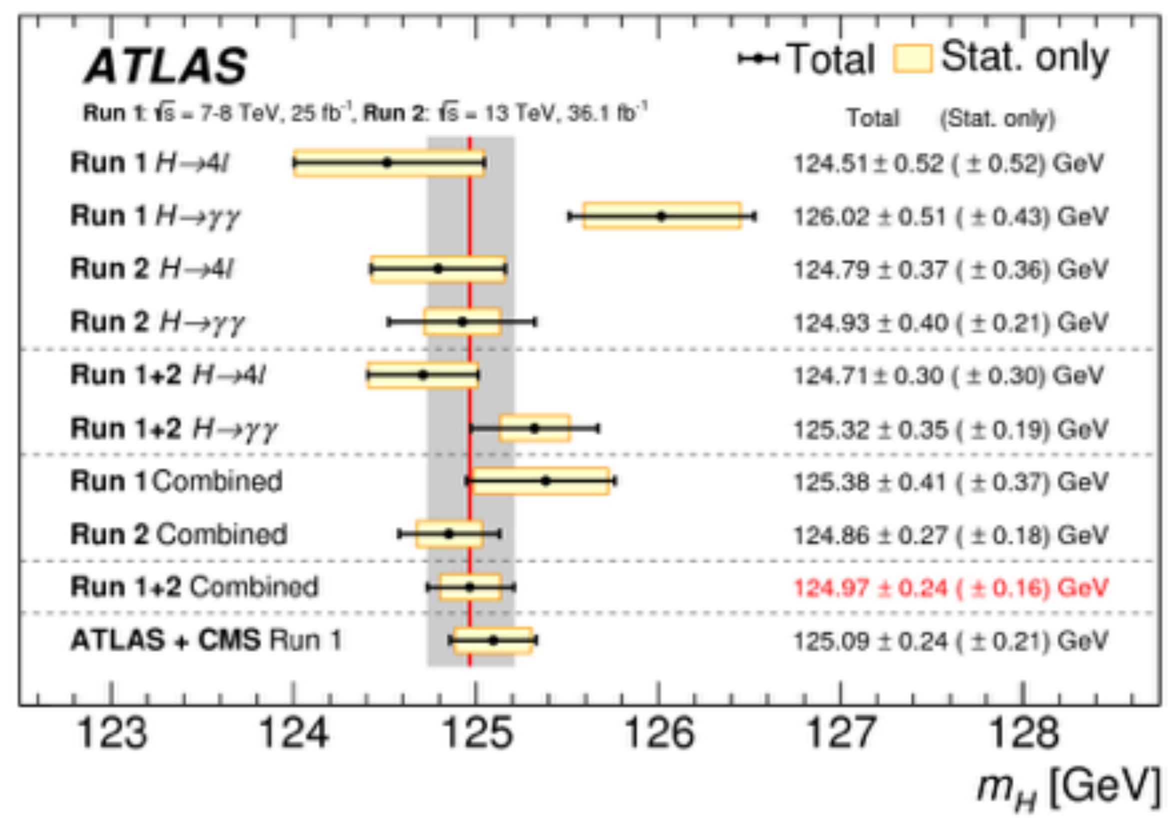
Chen Zhou (University of Wisconsin)
on behalf of the ATLAS Collaboration

CERN Seminar
June 26, 2018

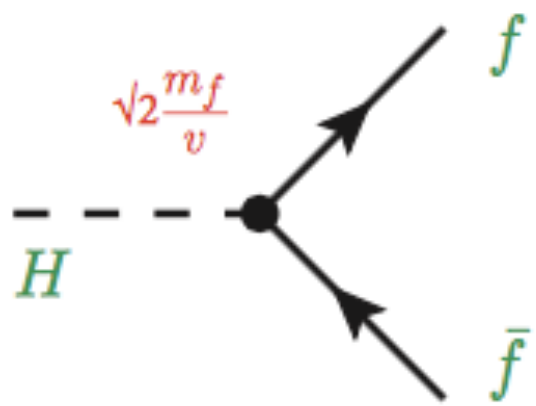
Higgs Physics @ ATLAS

- **The Higgs boson was discovered** by ATLAS and CMS in 2012
  - a major step for understanding the electroweak symmetry breaking
- Since then, many **Higgs property studies** (spin, parity, mass, couplings, cross sections, etc.) have been performed
  - no deviation from the Standard Model (SM) prediction was found
- Today: Higgs physics results with up to **80 fb^{-1}** of 13 TeV data
  - (selection from a larger set of new results)



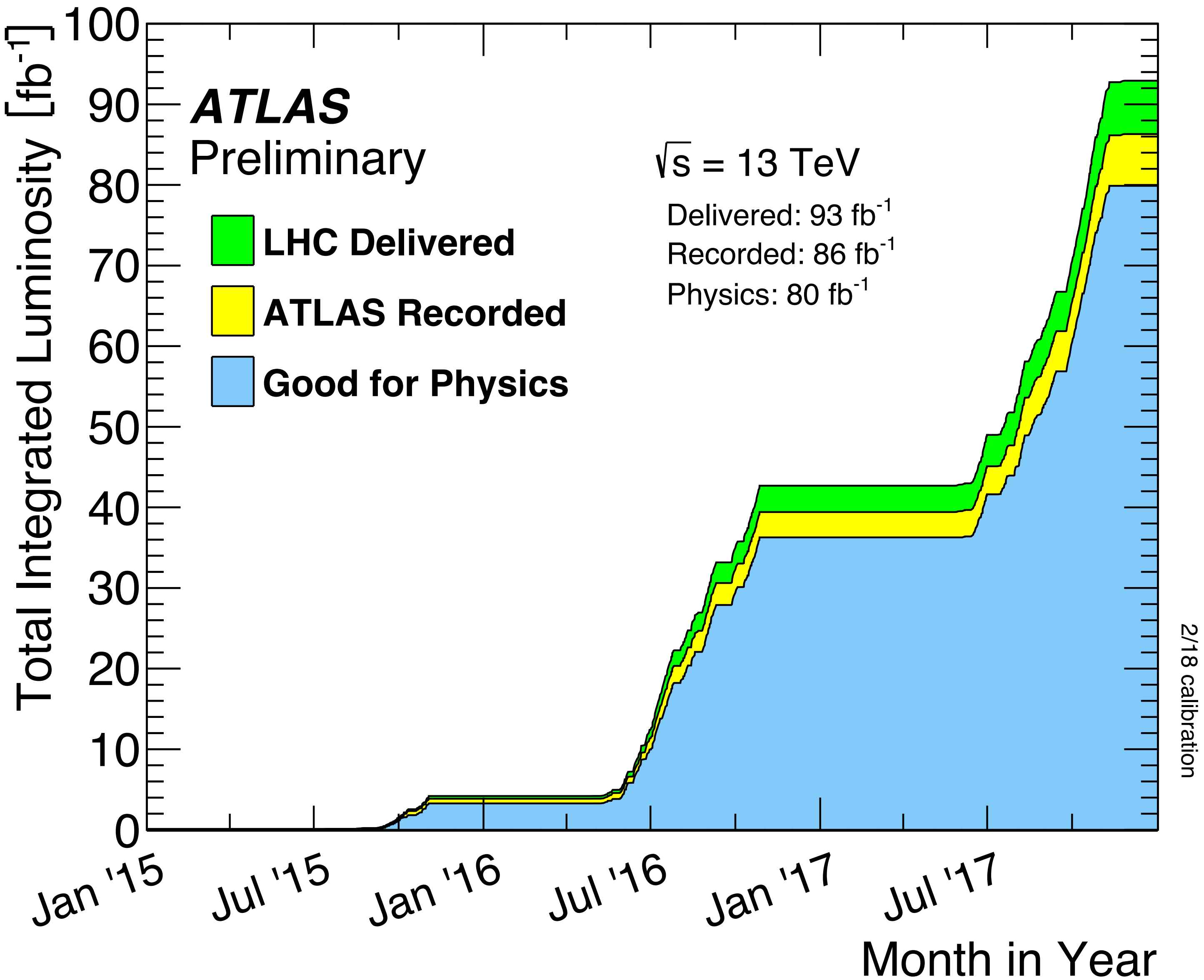


Yukawa couplings



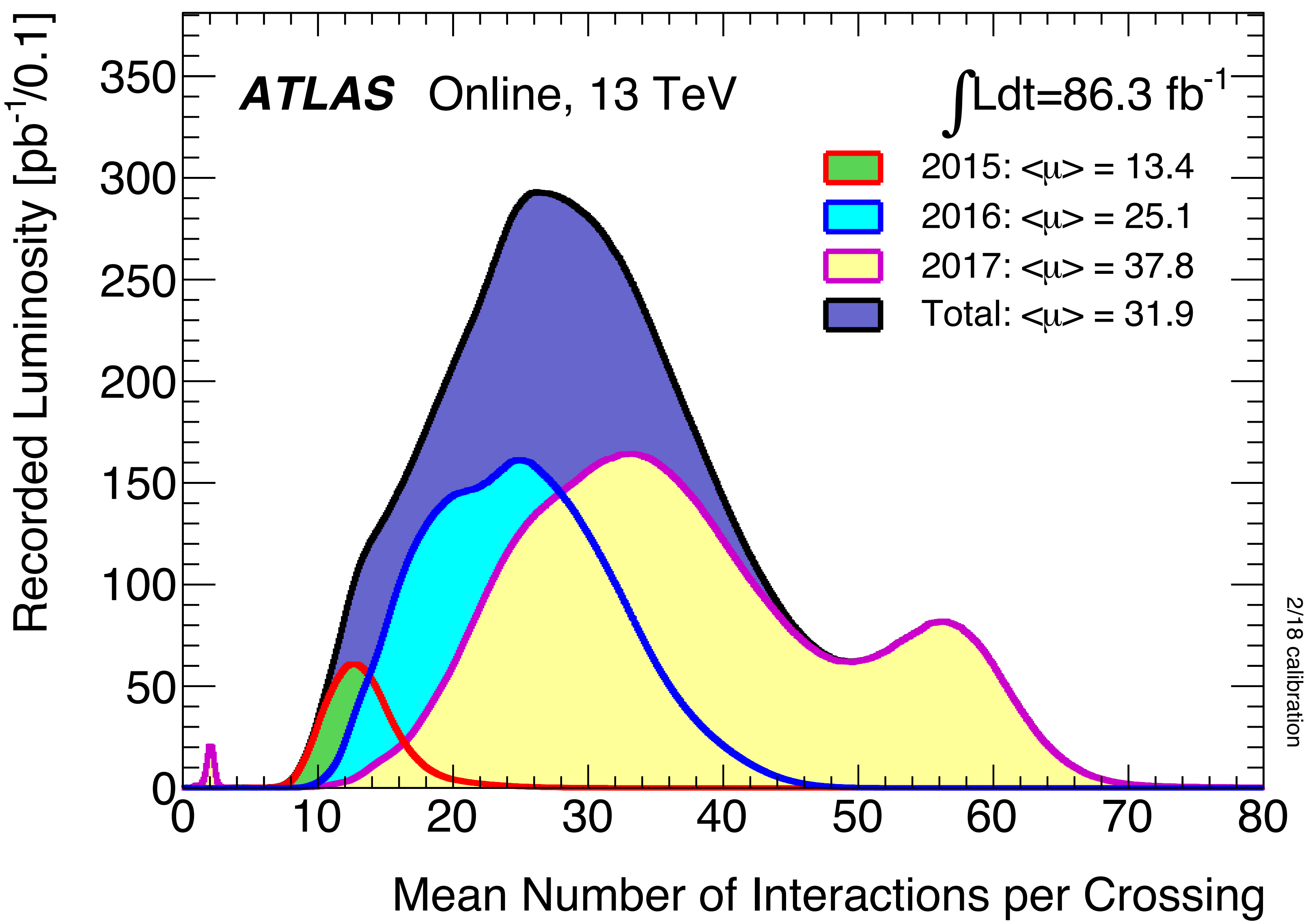
- In Standard Model, Higgs boson couple to fermions (quarks and leptons) through Yukawa interactions
  - **giving masses to quarks and leptons**
- Yukawa interactions are “a new kind of fundamental interaction” -Gavin Salam at LHCP theory summary talk
  - **important to study the Yukawa sector**
- Experimental signatures: **$t\bar{t}$H production** (today), **H→$\tau\tau$ decay** (today), etc.
  - Yukawa couplings are proportional to fermion masses

Data taking



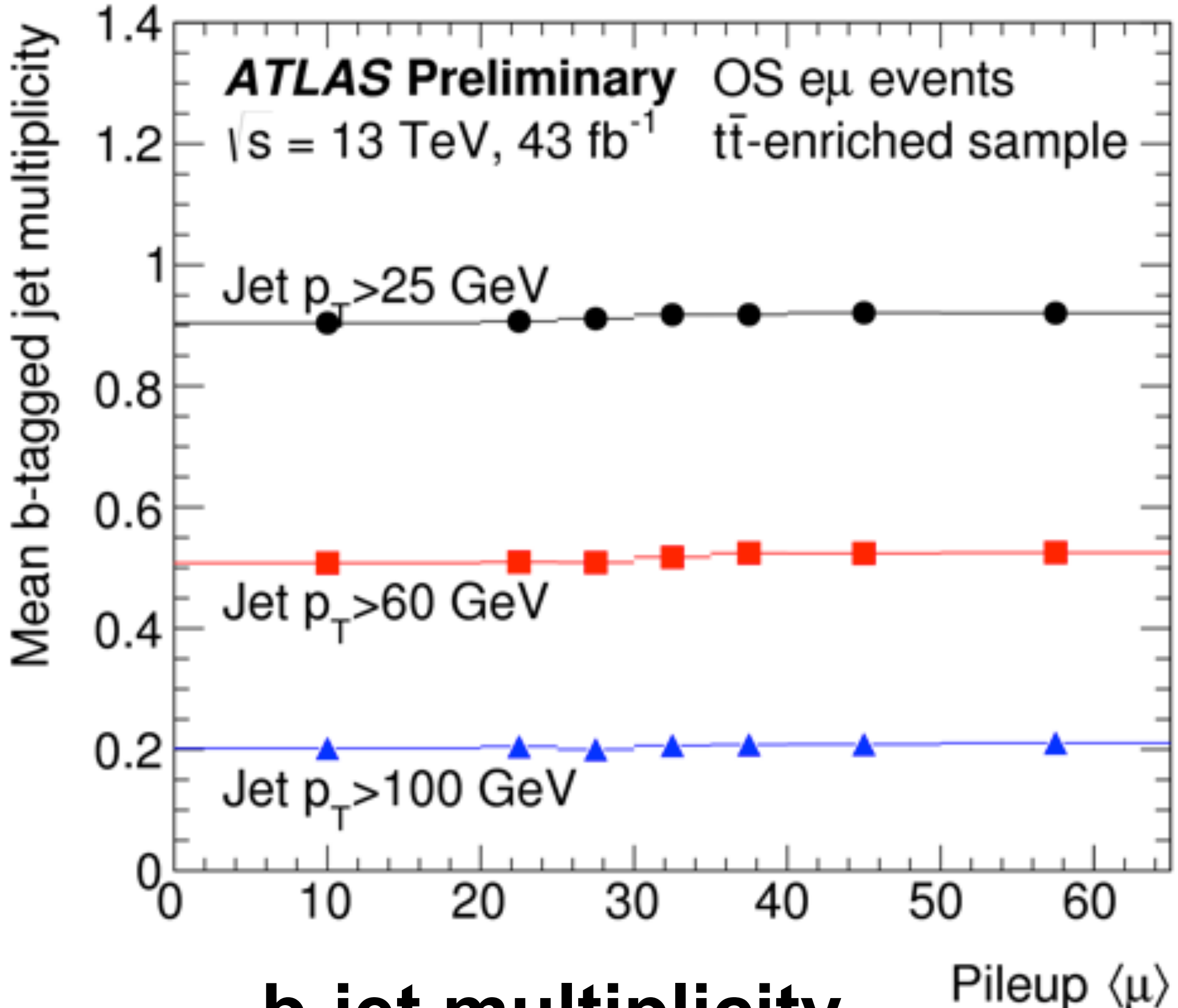
- 13 TeV proton-proton collision data recorded by ATLAS and after data quality requirement
  - 2015-2016: 36 fb^{-1}, 2017: 44 fb^{-1}
  - Thank CERN for the successful LHC operation!

Pileup

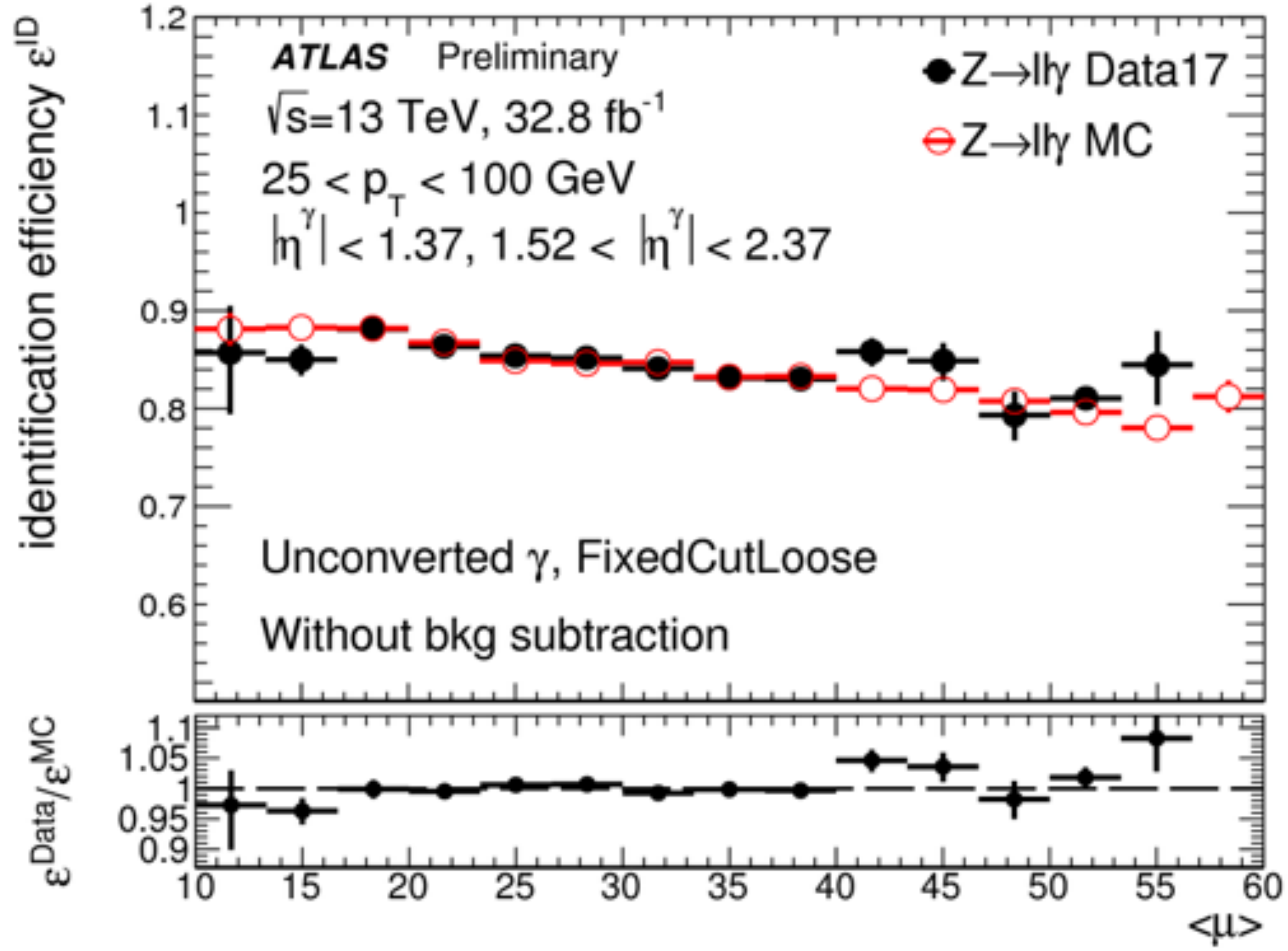


- Mean number of interactions per crossing (pileup):
    - <2015-2016>: ~24, <2017>: ~38
    - high pileup could be challenging for physics results

Performance vs pileup



b-jet multiplicity vs pileup



photon ID efficiency vs pileup

- Robust performance against high pileup
  - great effort in detector operation and particle reconstruction

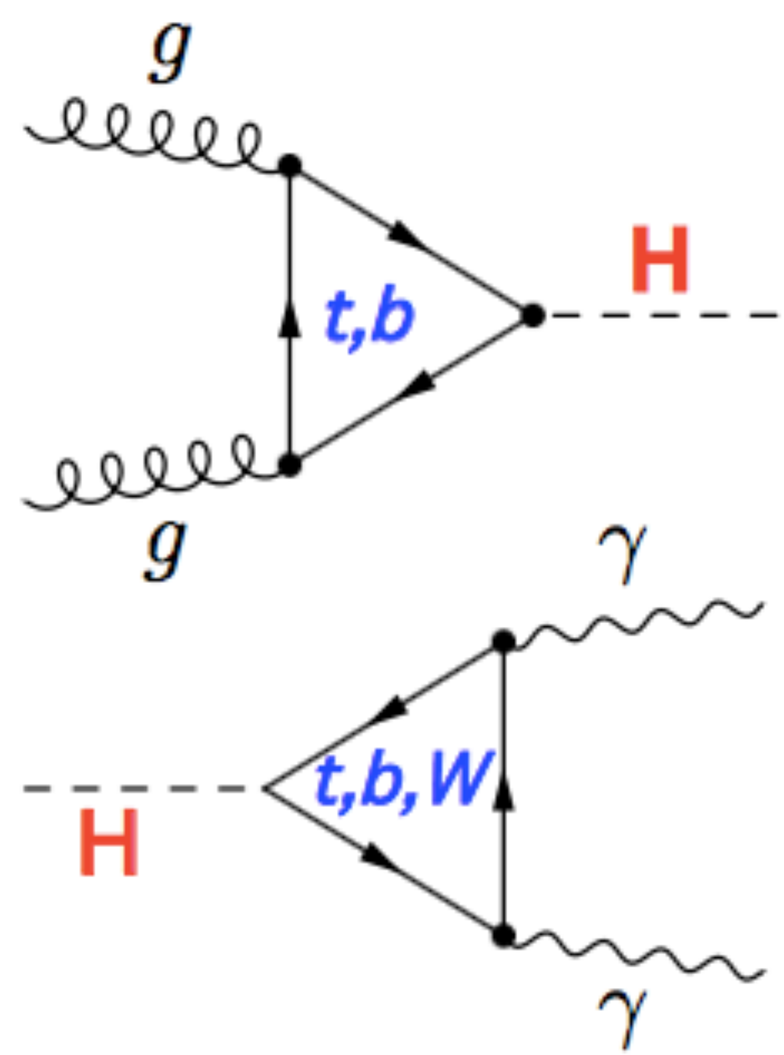
Contents of this talk

- Part 1: $t\bar{t}H$ observation
  - $t\bar{t}H$ ($H\to\gamma\gamma$)
  - $t\bar{t}H$ ($H\to ZZ^*\to$4-lepton)
  - $t\bar{t}H$ combination
- Part 2: $H\to\tau\tau$ cross section measurements
- Part 3: $H\to ZZ^*\to$4-lepton property measurements

Part 1: $t\bar{t}H$ observation

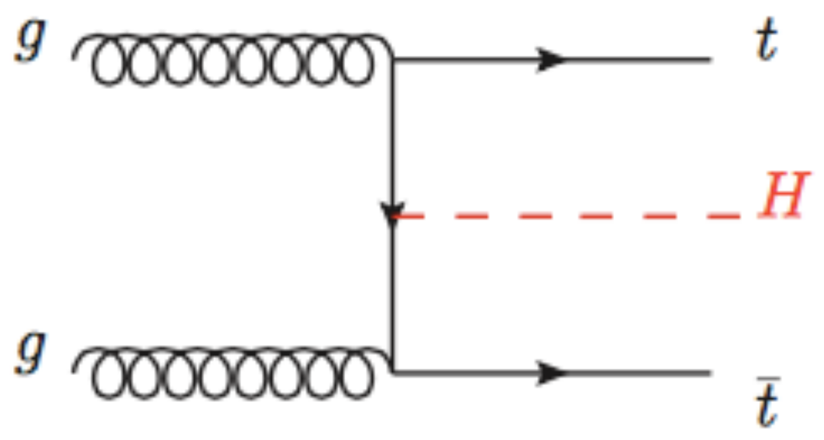
Higgs-top Yukawa coupling

- 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%); tree-level process
- Could get handles on BSM physics by comparison between loop-induced processes and direct $t\bar{t}$H production

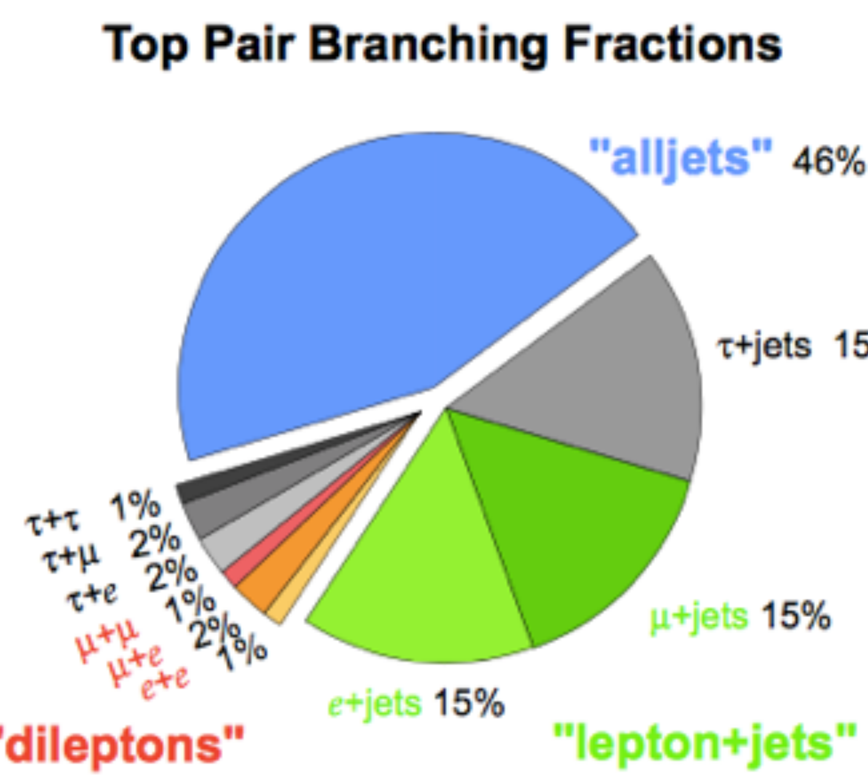


Study $t\bar{t}H$ production

- 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)
  - $t\bar{t}H$, $H\to b\bar{b}$

larger S/B

larger BF



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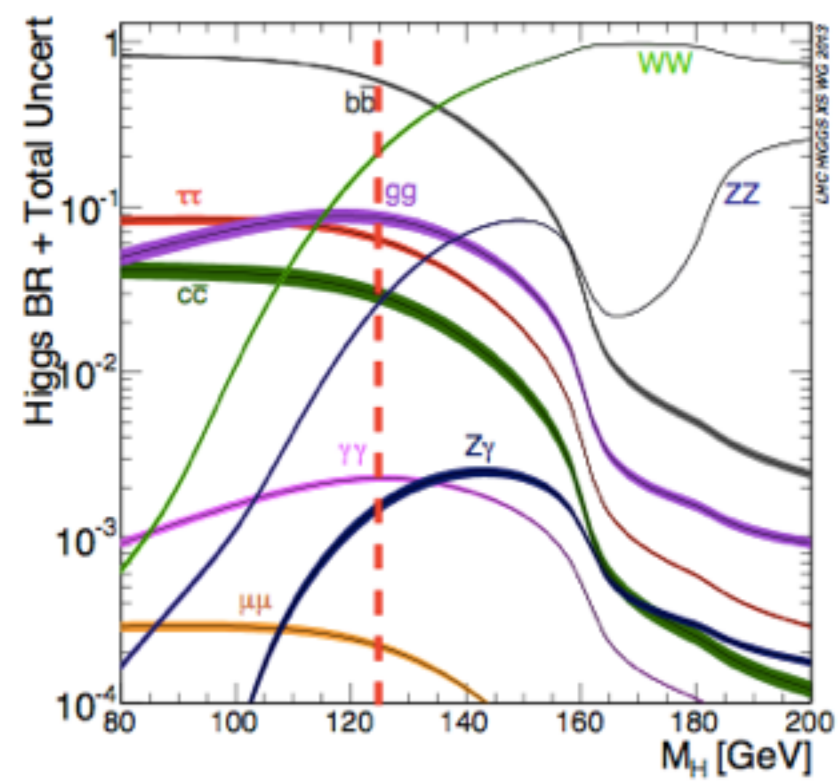


Study $t\bar{t}H$ production

- Previous ATLAS $t\bar{t}H$ results: combining 36.1 fb^{-1} of 13 TeV data, observed (expected) significance of **4.2 (3.8)** standard deviations
  - CERN seminar by Ximo Poveda (with a focus on $t\bar{t}H$ (multi-lepton) and $t\bar{t}H$ ($H \rightarrow b\bar{b}$))

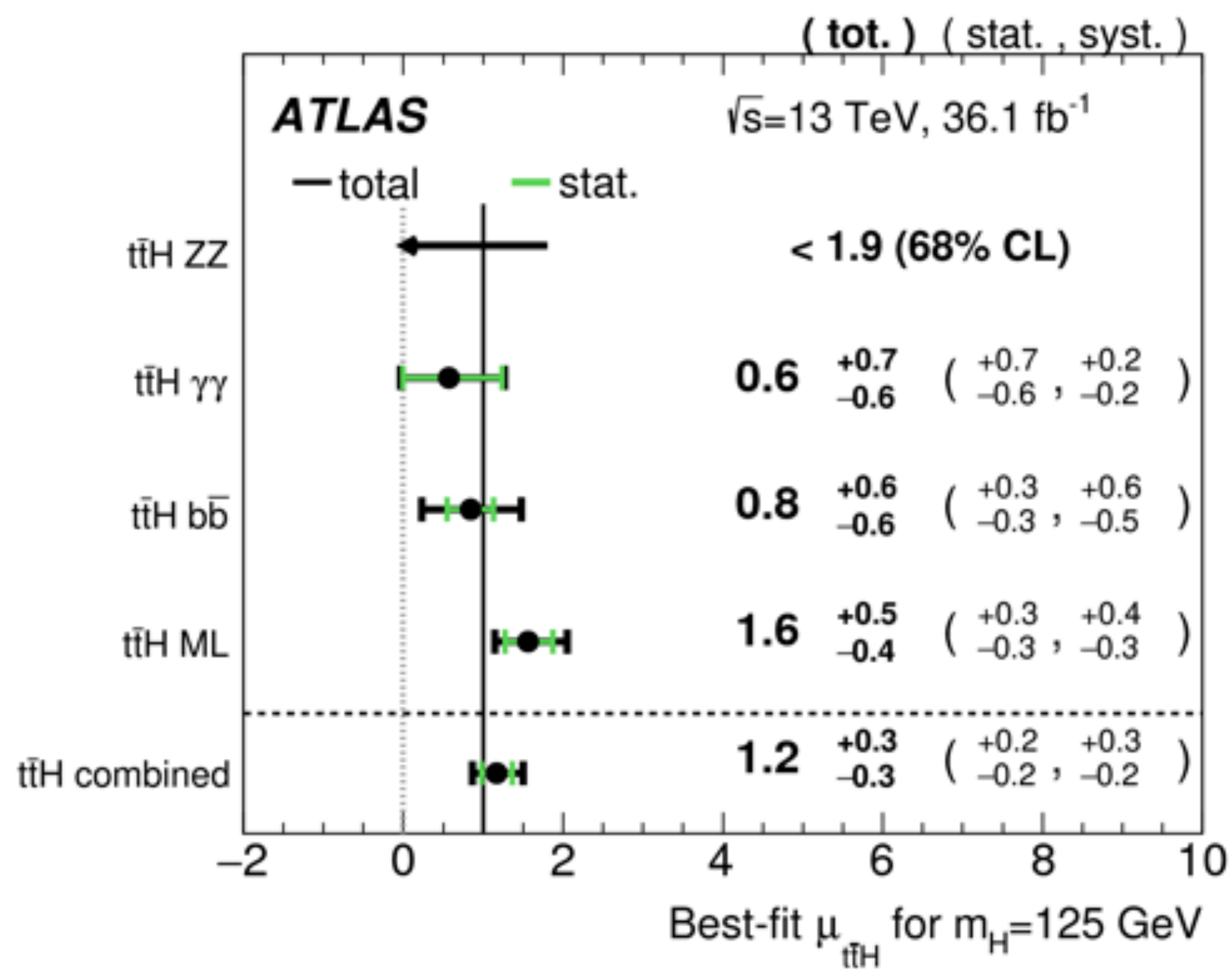
JHEP 03 (2018) 095

arxiv:1802.04146

PRD 97 (2018) 072016

PRD 97 (2018) 072003

PRD 97 (2018) 072003



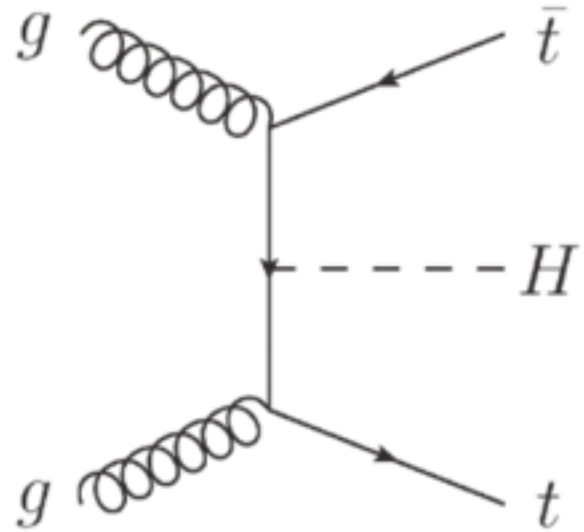
$\mu = \sigma / \sigma_{SM}$

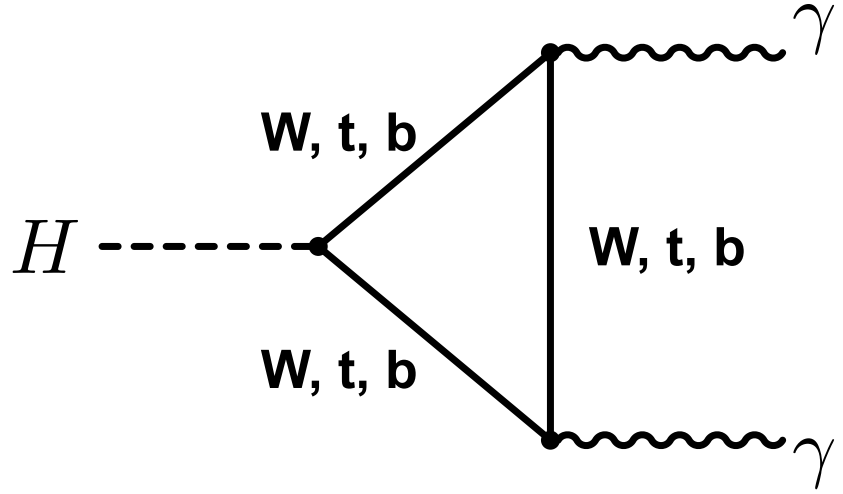
Study $t\bar{t}H$ production

- Latest CMS $t\bar{t}H$ results: combining data at 7, 8, and 13 TeV, observed (expected) significance of **5.2 (4.2)** standard deviations (PRL 120, 231801)
  - JHEP 11 (2017) 047 ($t\bar{t}H$, $H\rightarrow ZZ^*\rightarrow$4-lepton)
  - arxiv: 1804.02716 ($t\bar{t}H$, $H\rightarrow\gamma\gamma$)
  - arxiv: 1803.05485 ($t\bar{t}H$, multi-lepton)
  - arxiv: 1803.06986, arxiv: 1804.03682 ($t\bar{t}H$, $H\rightarrow b\bar{b}$)

- Now: ATLAS $t\bar{t}H$ ($H\rightarrow\gamma\gamma$) and $t\bar{t}H$ ($H\rightarrow ZZ^*\rightarrow$4-lepton) results are updated with **80 fb^{-1}** of 13 TeV data, and included in $t\bar{t}H$ combination (arxiv: 1806.00425)

$t\bar{t}H$ $(H\rightarrow\gamma\gamma)$ (80 fb^{-1})





arxiv: 1806.00425; June 2018

$t\bar{t}H$ ($H\rightarrow\gamma\gamma$) 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

- define **categories based on BDT output**

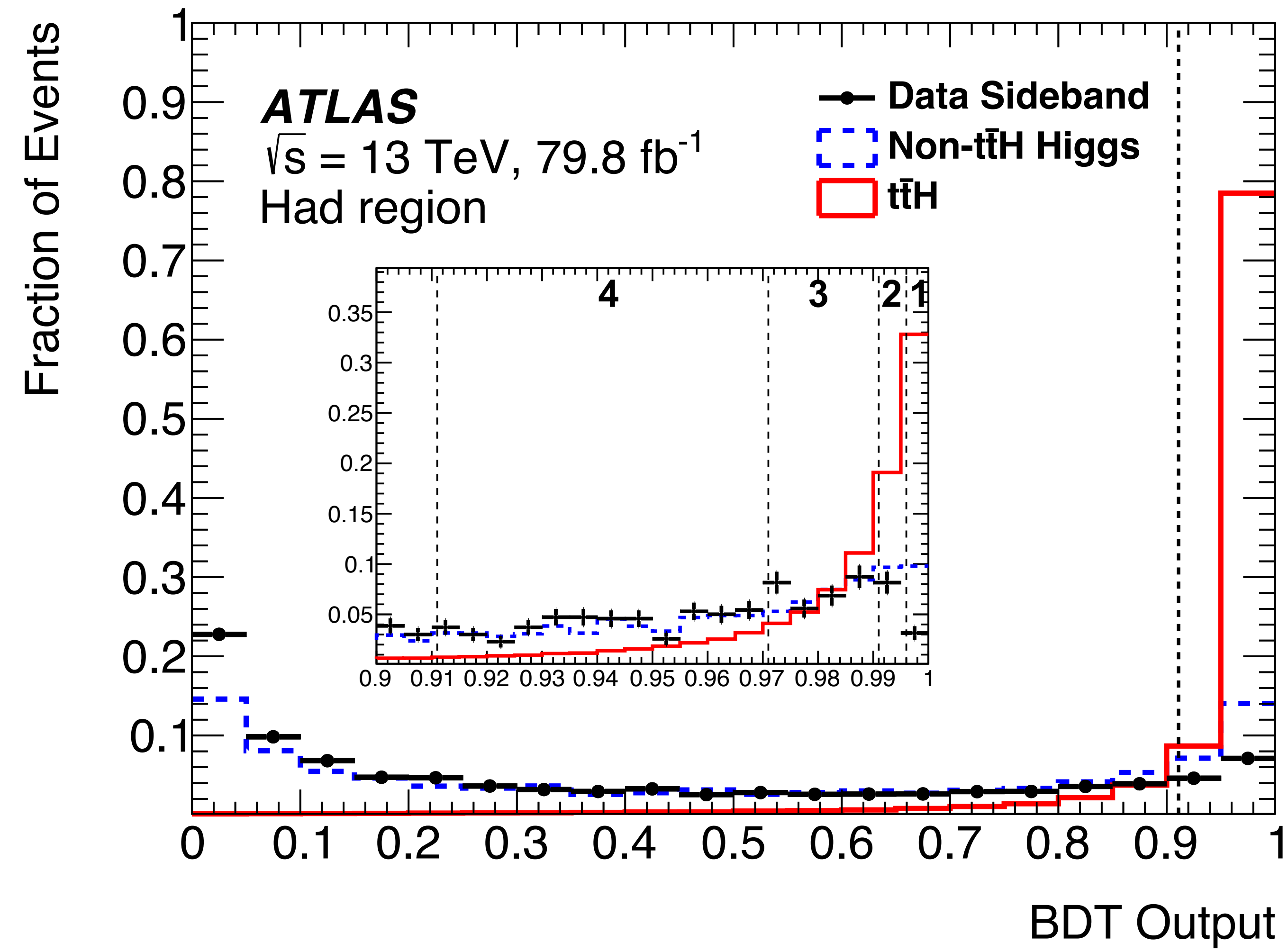
➔Fit **diphoton mass** over 7 categories

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

➔Measure $t\bar{t}H$ production cross section, etc.

Hadronic channel

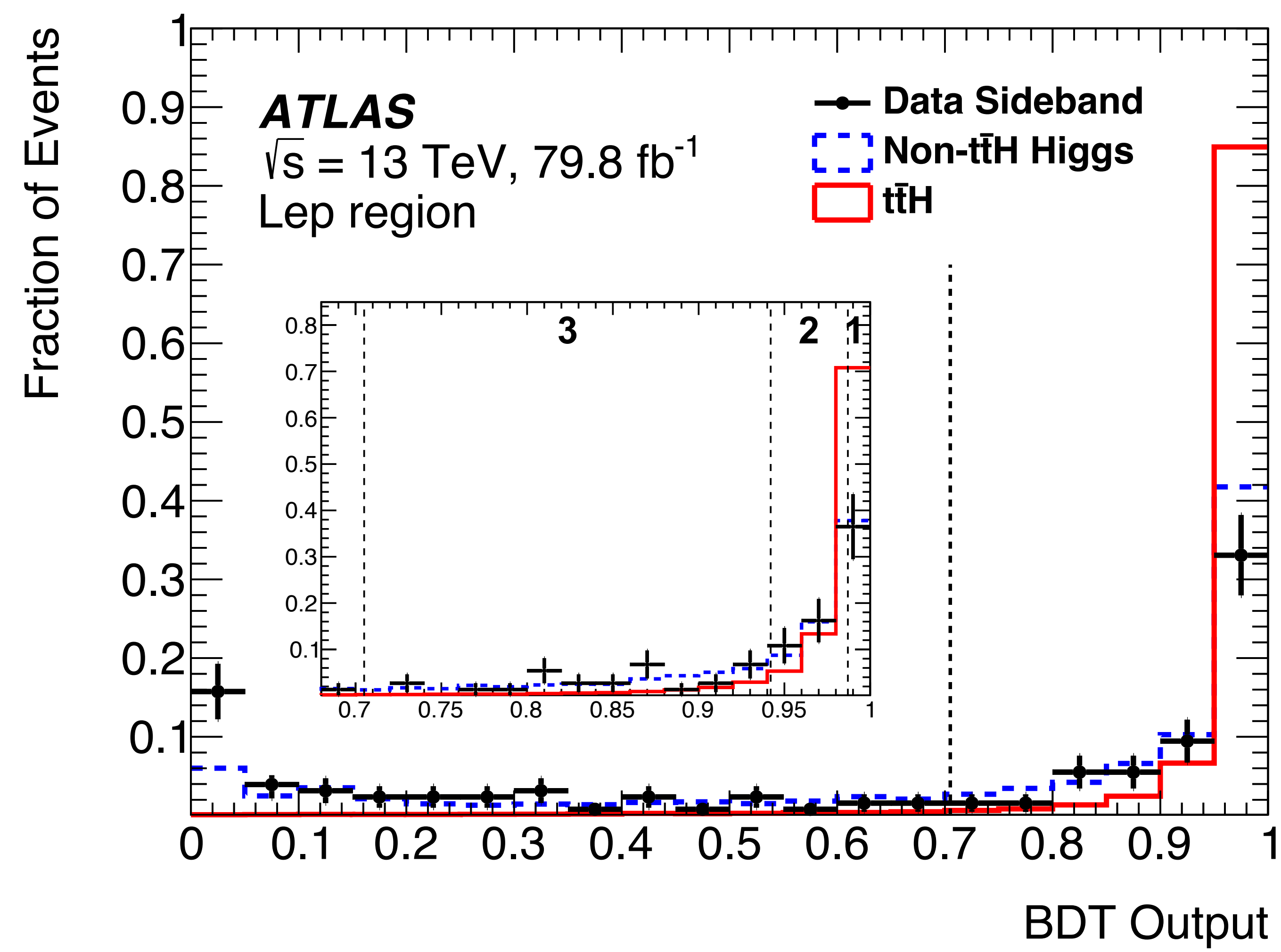
- Target: all-hadronic top-quark pair decays, or semi-leptonic top-quark pair decays with leptons not identified
- BDT trained with $t\bar{t}H$ simulation and data control region, using:
  - pT, η, ϕ, and b-tag status of first 6 jets (sorted by pT)
  - MET and ϕ(MET)
  - pT/mγγ, η, and ϕ of 2 photons



- Define 4 categories in hadronic channel based on BDT output, to exploit its good separation power

Leptonic channel

- Target: semi-leptonic top-quark pair decays
- BDT trained with $t\bar{t}H$ simulation and data control region, 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

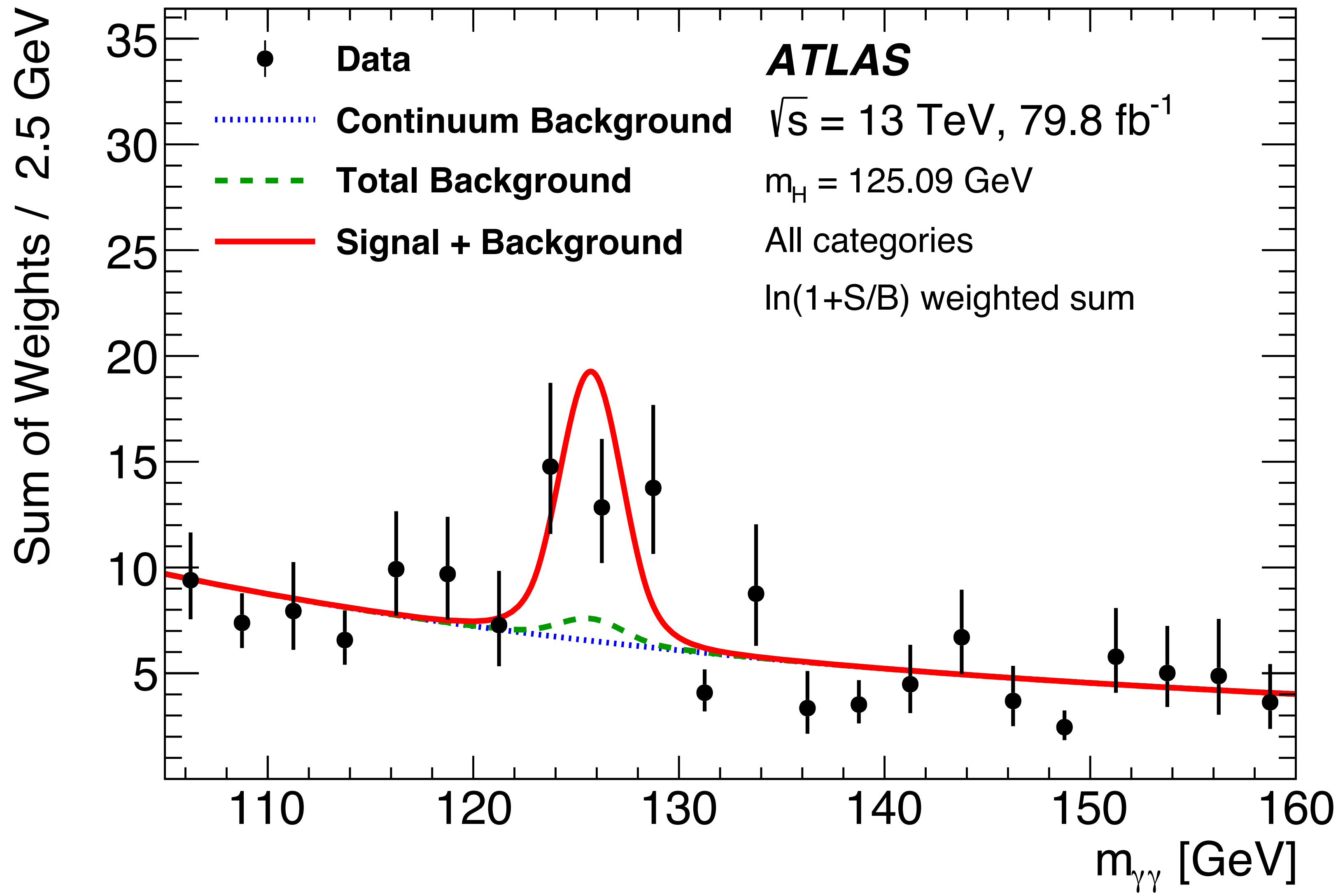


- Define 3 categories in leptonic channel based on BDT output, to exploit its good separation power

Signal and background modeling

- **Model of $t\bar{t}H$ signal and non-$t\bar{t}H$ Higgs background**
  - Yields from non-$t\bar{t}H$ production modes estimated from simulation
    - assign 100% uncertainties on ggF, VBF and VH separately, due to current understanding of heavy-flavor production
  - Mass shapes: parametrized from simulation with double-sided crystal ball functions in each category
- **Model of continuum background**:
  - Analytical functions fitted on (unbinned) data
  - From dedicated background-only samples
    - checked the BDTs do not induce a bump
    - studied functional forms and associated uncertainties

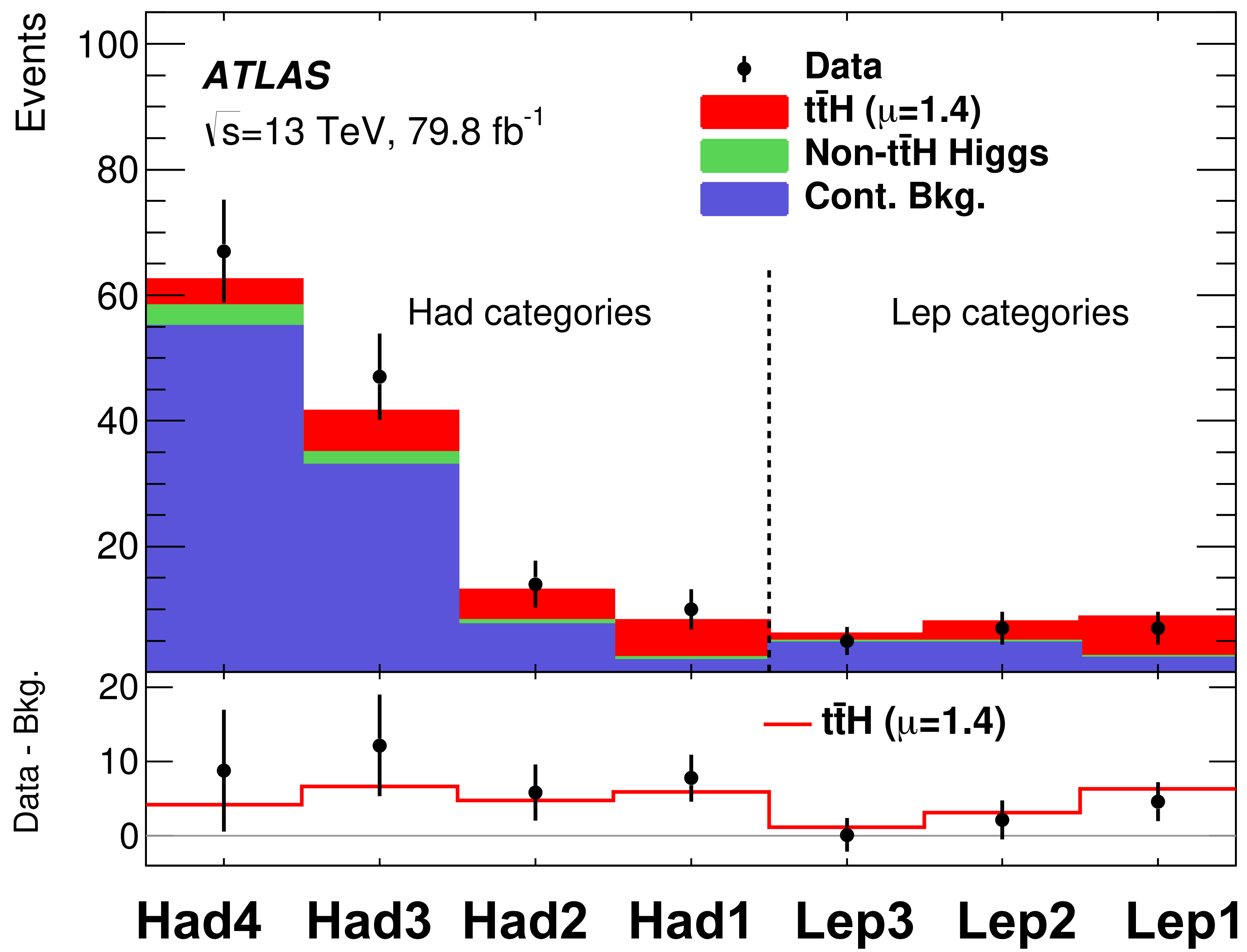
Diphoton mass: all categories



- Diphoton mass spectrum peaks at the Higgs mass around 125 GeV
- 36 $^{+12}_{-11}$ $t\bar{t}H$ ($H\rightarrow\gamma\gamma$) events fitted over 7 categories
  - ~90 $t\bar{t}H$ ($H\rightarrow\gamma\gamma$) events are expected to be produced at ATLAS during 2015-2017

Event yields: all categories

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



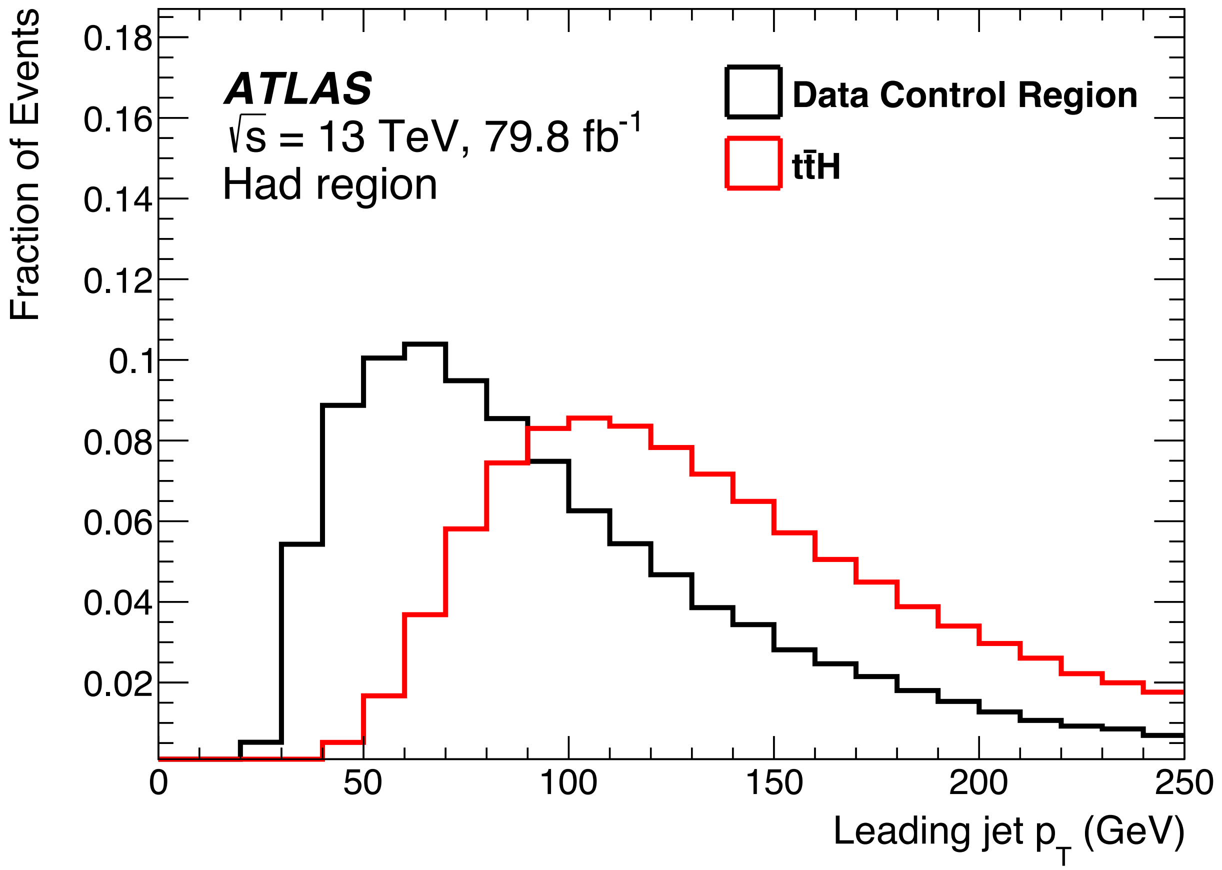
Expected S/B: 0.05 0.13 0.41 1.8 0.17 0.45 1.8

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

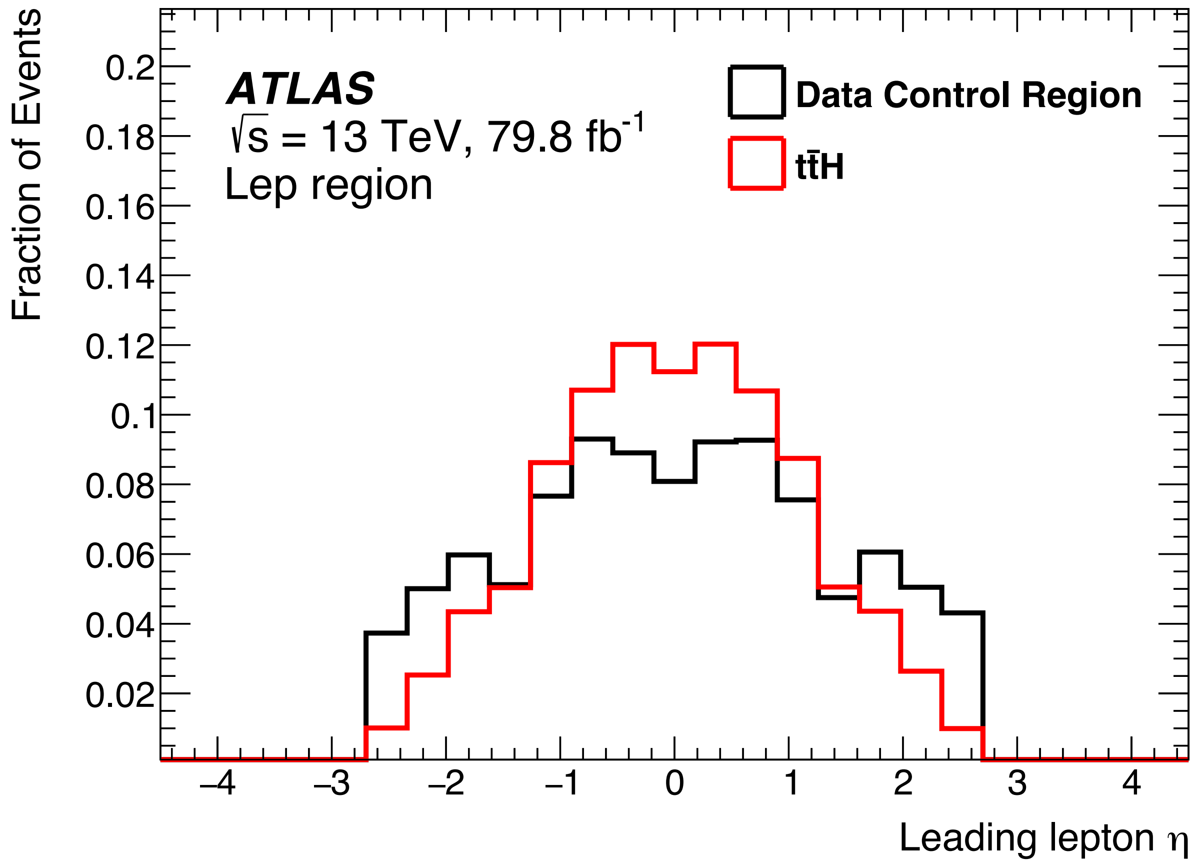
$t\bar{t}H$, $H \rightarrow \gamma\gamma$: 80 fb^{-1}	expected significance	observed significance
Had categories	2.7σ	3.8σ
Lep categories	2.5σ	1.9σ
Had+Lep categories	3.7σ	4.1σ

- The new $t\bar{t}H$ ($H \rightarrow \gamma\gamma$) analysis is **50% more sensitive** than the previous publication (arxiv:1802.04146), for the same luminosity
- The largest sensitivity improvement (about 30%) is achieved by using **object-level information of jets, leptons, photons and MET** as inputs to BDT

Some variables in BDT training



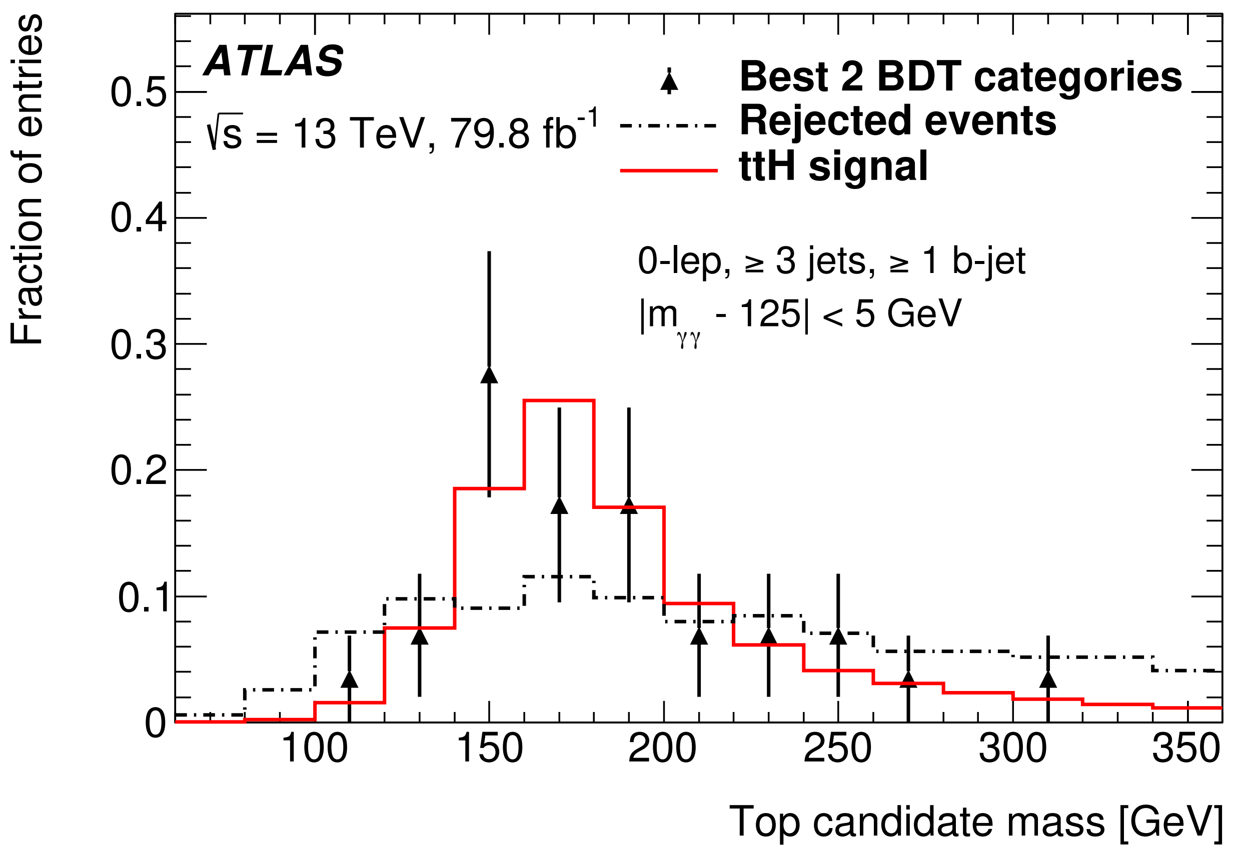
Hadronic channel leading jet pT

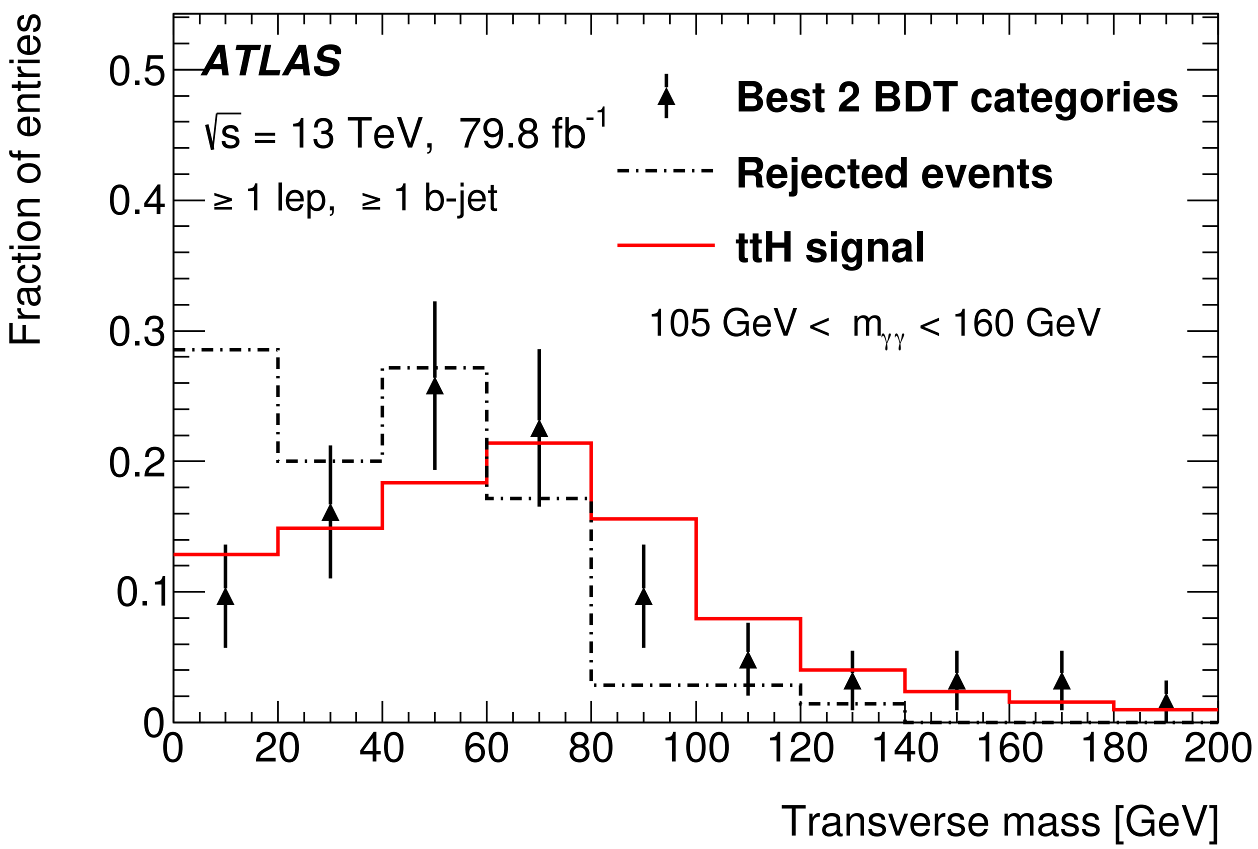


Leptonic channel leading lepton η

- Signal and background differ in object-level variables
- Cannot be shown in such figures: correlation between training variables

Some variables not in BDT training $t\bar{t}H$ (H→γγ)



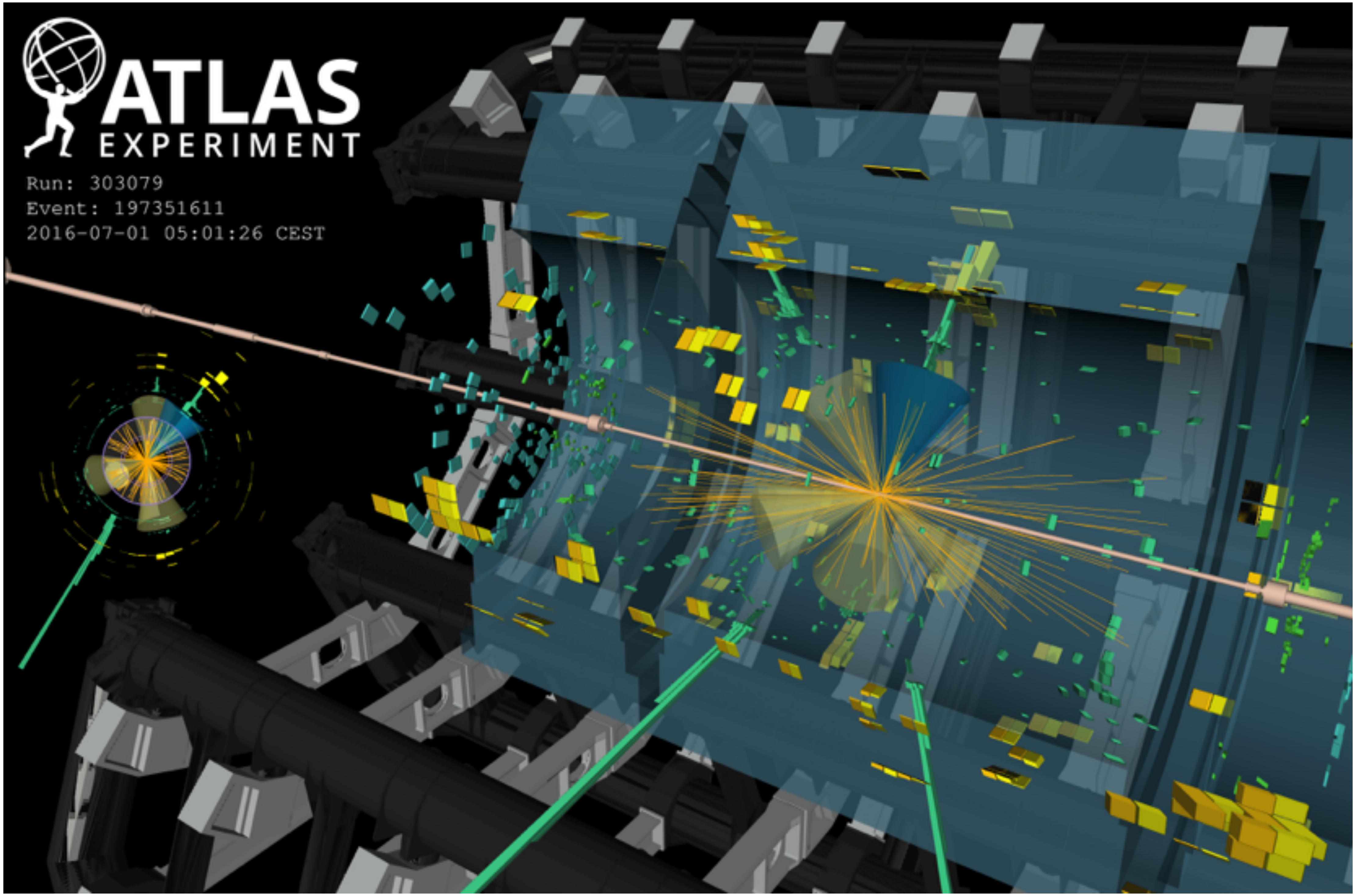


Hadronic channel
Top candidate mass
(based on top reconstruction)

Leptonic channel
Transverse mass

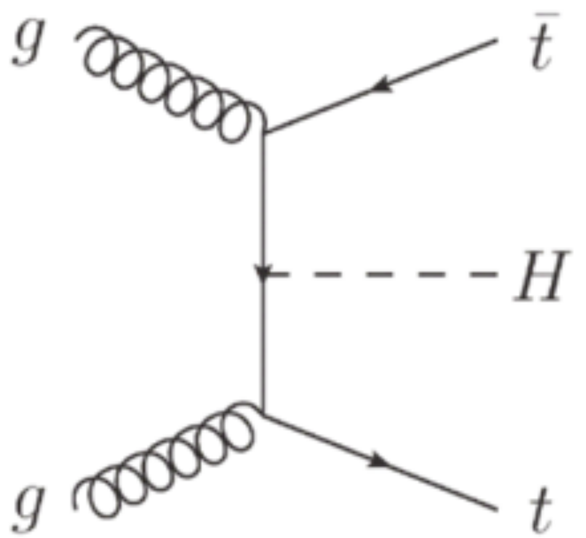
- The distributions of data in best BDT categories follow the distributions of $t\bar{t}H$ simulation
- These variables are for validation and not directly used in analysis

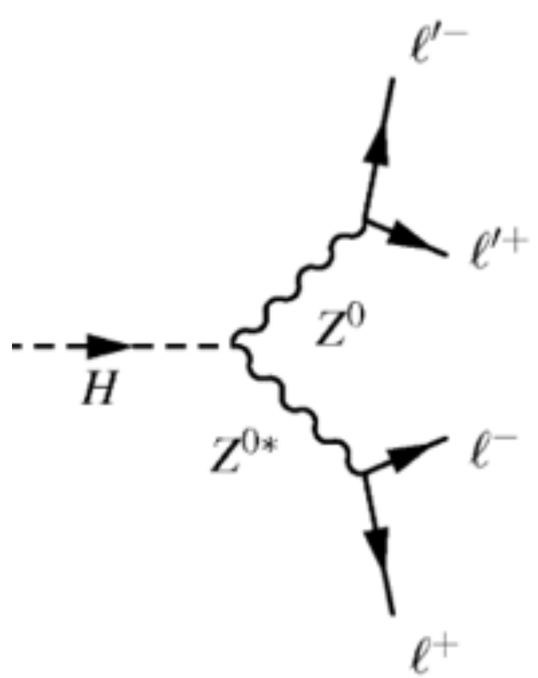
Display: $t\bar{t}H$ ($H \rightarrow \gamma\gamma$) Had1 candidate event



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

$t\bar{t}H$ ($H \rightarrow ZZ^* \rightarrow$4-lepton) (80 fb^{-1})



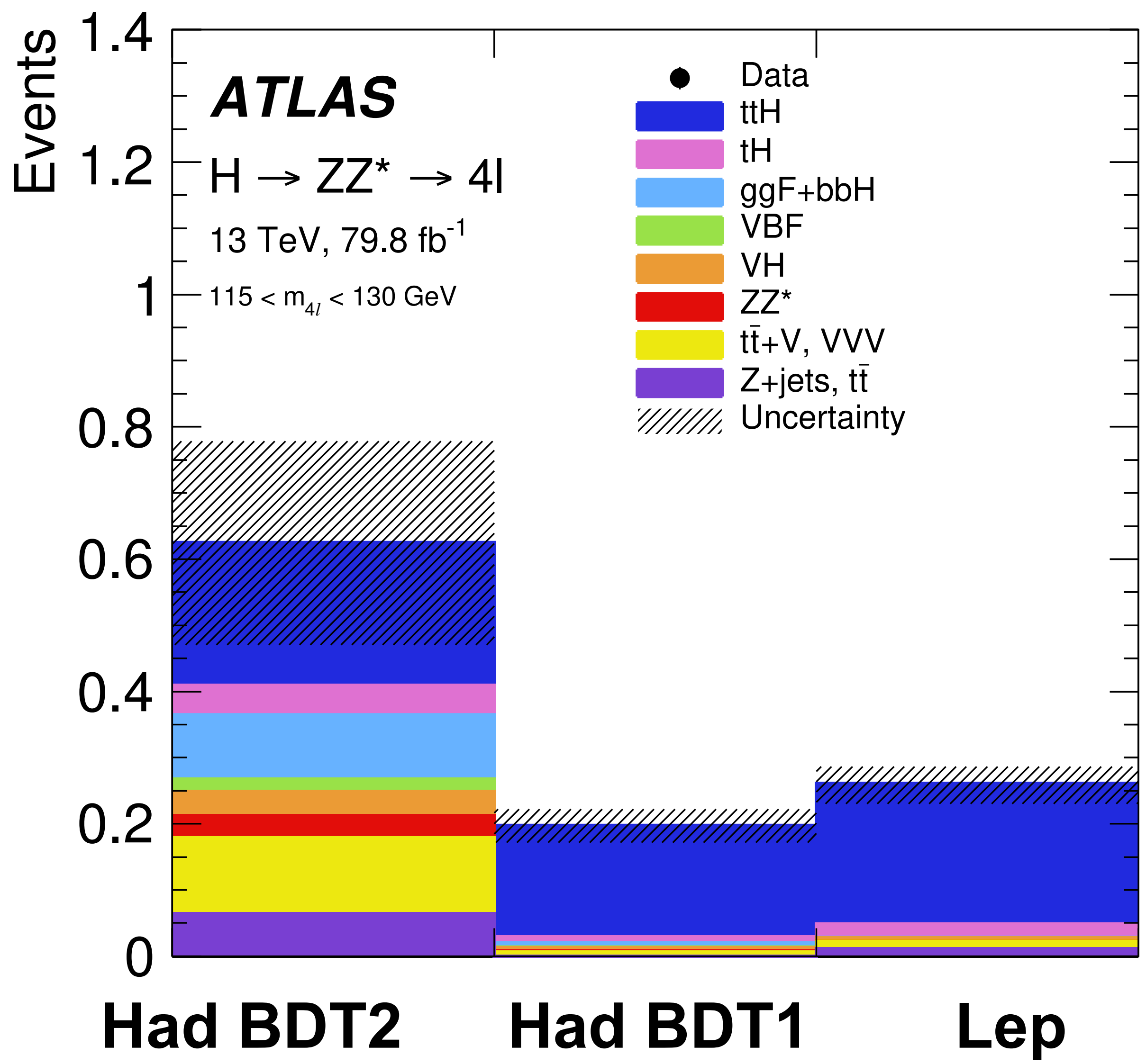


arxiv: 1806.00425; June 2018

Analysis strategy

- Select events with **four leptons** forming two same-flavor opposite-charge lepton pairs, and at least one b-jet
- Background: $t\bar{t}W$, $t\bar{t}Z$, and other Higgs production modes
- **Hadronic region** (no additional lepton):
  - targeting hadronic top-quark pair decay
  - train a BDT, further separate events into **2 BDT regions**
- **Leptonic region** (at least one additional lepton):
  - targeting semi-leptonic top-quark pair decay

Results



- Use event yields of the above regions as discriminant
  - expect ~0.6 signal events over small background, observe 0 event
- The observed (expected) signal significance is 0σ (1.2σ) in tt̄H (H→ZZ*→4-lepton) analysis

$t\bar{t}H$ combination and results

arxiv: 1806.00425; June 2018

$t\bar{t}H$ Combination

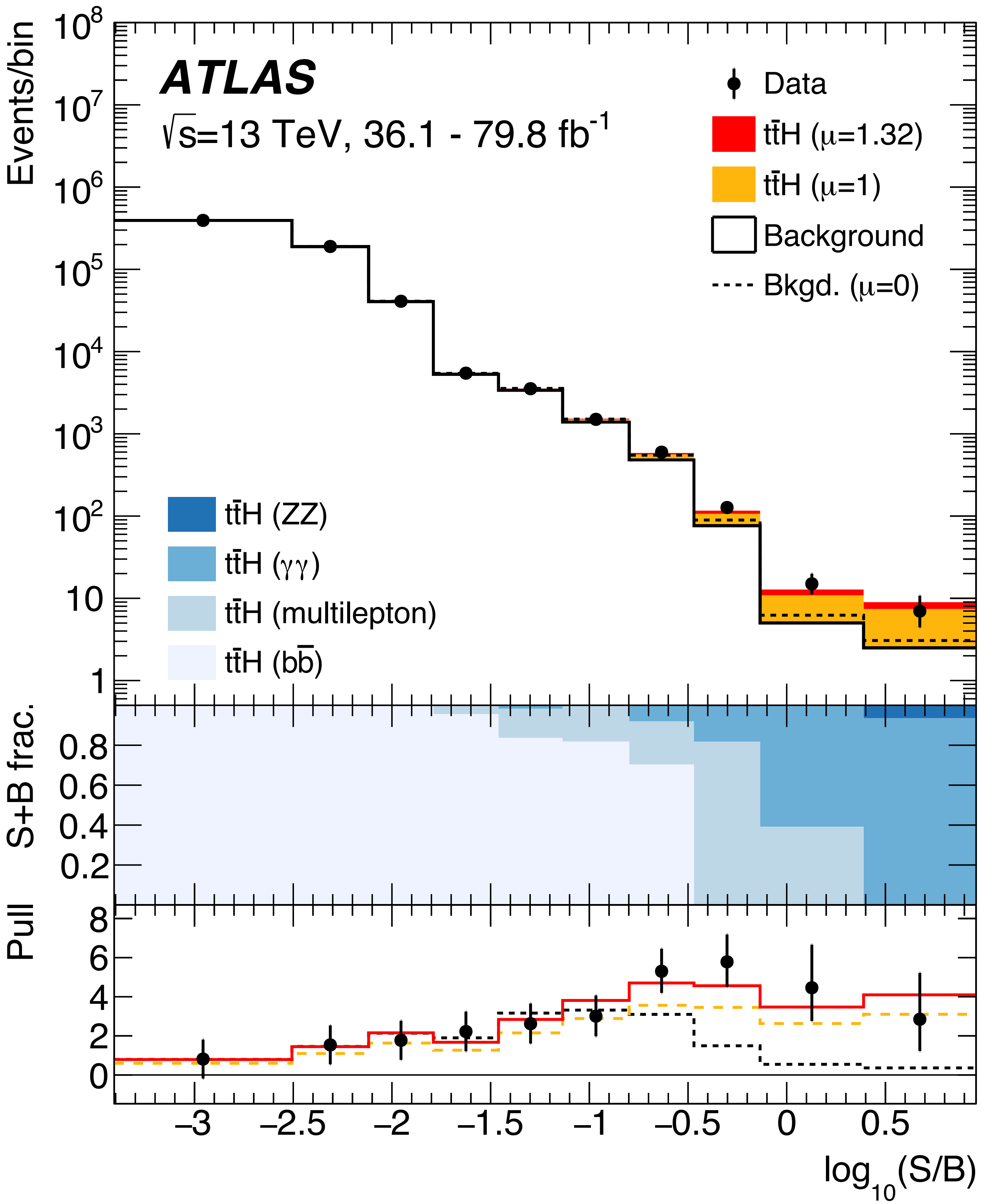
- **Combine four 13 TeV $t\bar{t}H$ analyses**
  - $\gamma\gamma$ (80 fb^{-1}): arxiv: 1806.00425, **NEW**
  - 4-lepton (80 fb^{-1}): arxiv: 1806.00425, **NEW**
  - multi-lepton (36 fb^{-1}): PRD 97 (2018) 072003
  - $b\bar{b}$ (36 fb^{-1}): PRD 97 (2018) 072016
- The relevant systematic uncertainties are correlated between the analyses
- Non-$t\bar{t}H$ production cross sections are fixed to the SM predictions
- Also **combine the 13 TeV analyses with the 7 TeV and 8 TeV analyses**

$t\bar{t}H$ significance

Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7σ	4.1σ
$H \to$ multilepton	36.1	2.8σ	4.1σ
$H \to b\bar{b}$	36.1	1.6σ	1.4σ
$H \to ZZ^* \to 4\ell$	79.8	1.2σ	0σ
Combined (13 TeV)	36.1–79.8	4.9σ	5.8σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	5.1σ	6.3σ

- The observed (expected) signal significance is **5.8σ (4.9σ)** in the Run 2 $t\bar{t}H$ combination
- The observed (expected) signal significance is **6.3σ (5.1σ)** in the Run 1 + Run 2 $t\bar{t}H$ combination
- Observation of $t\bar{t}H$ production at ATLAS!

Event yields in 13 TeV tt̄H analysis regions



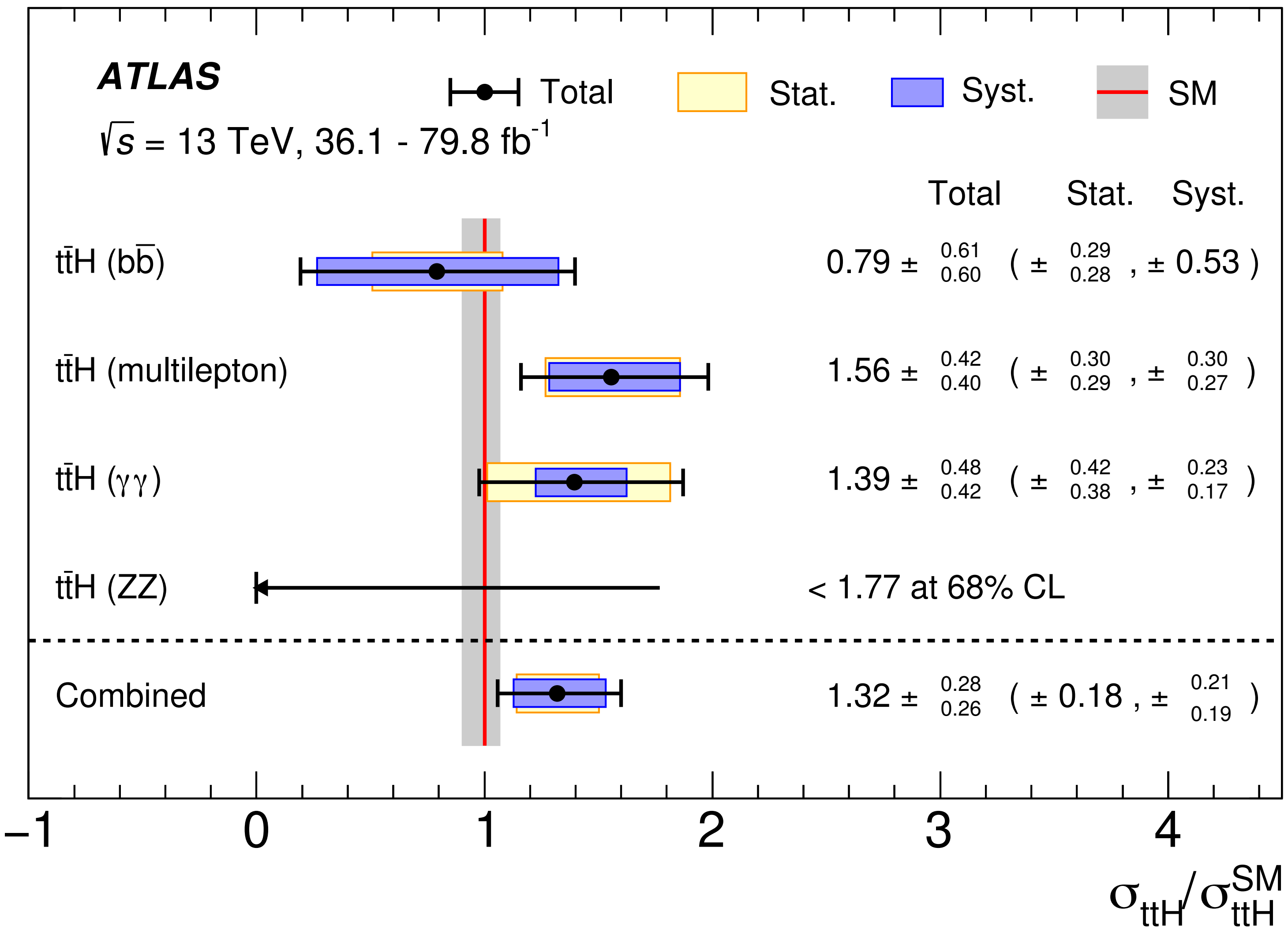
- Analysis regions are grouped by $\log_{10}(S/B)$
- A tt̄H signal-like excess is visible for high $\log_{10}(S/B)$
- Background-only model is not favored by data

Uncertainties

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties (excl. template statistics)	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

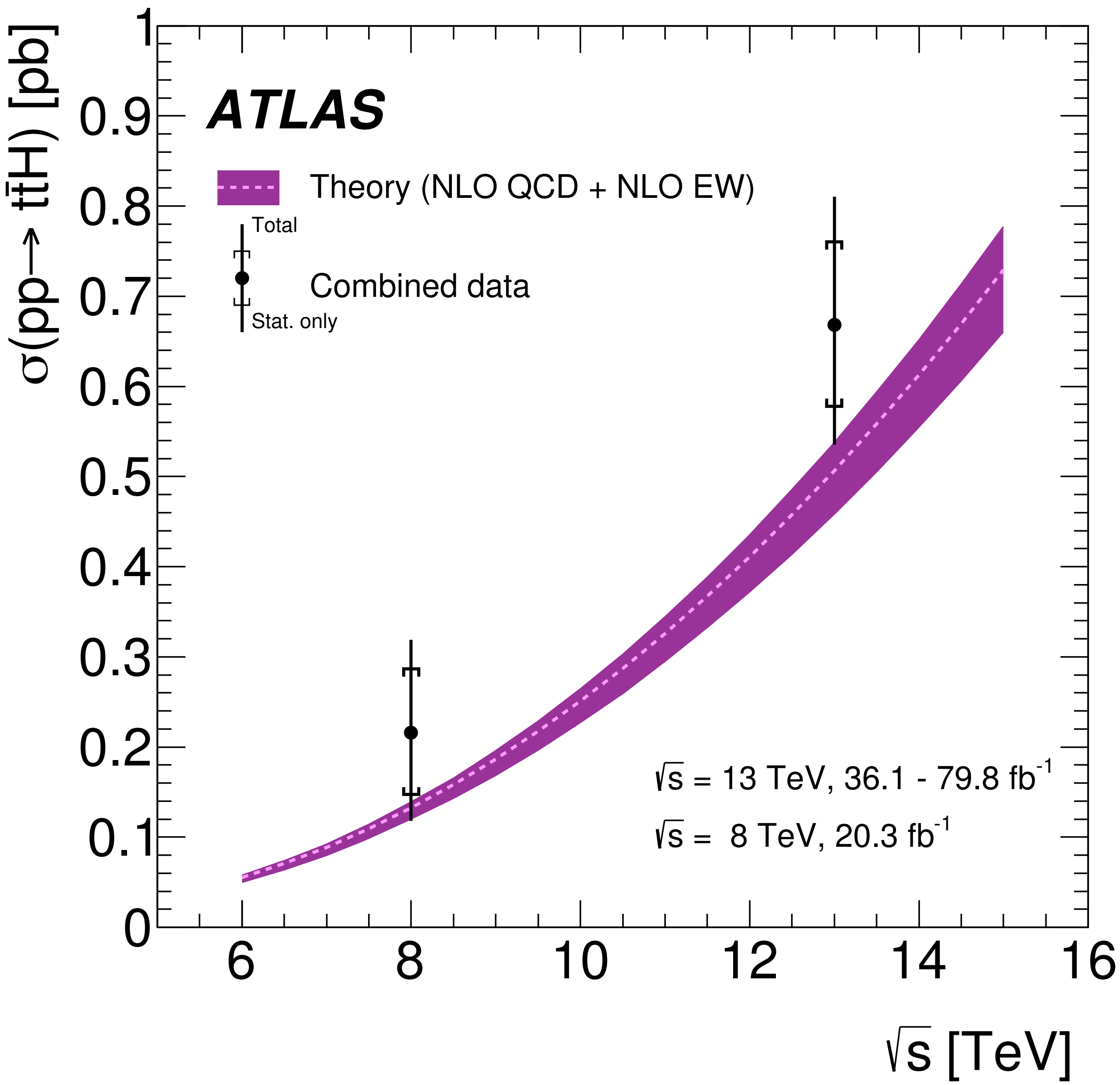
- The dominant systematics are $t\bar{t}$H, $t\bar{t}$+heavy flavor, and fake lepton modeling
- The impacts from systematic uncertainties and statistical uncertainties are about the same

13 TeV tt̄H cross section measurement



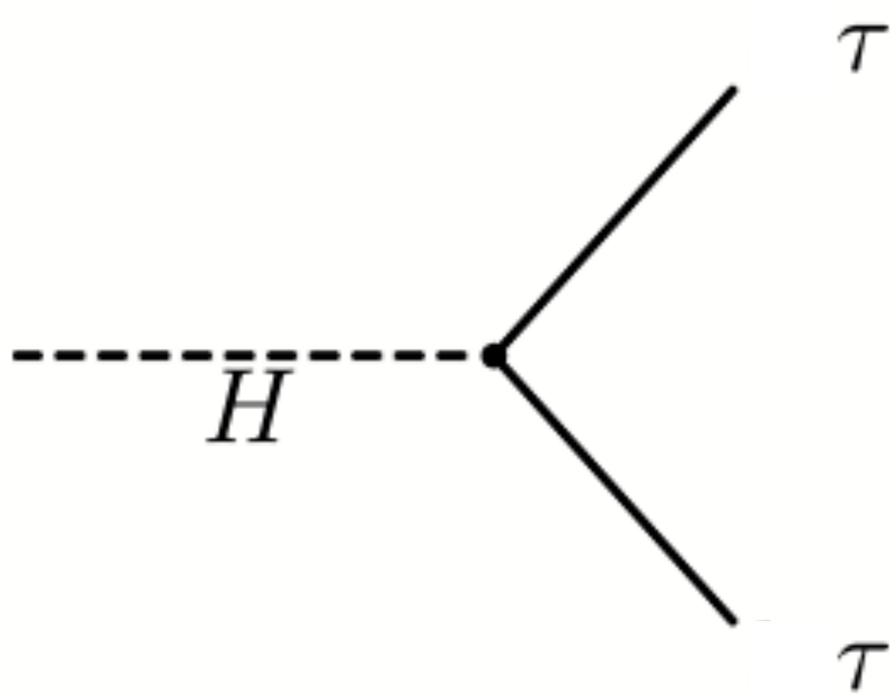
- The tt̄H production cross section at 13 TeV is measured to be 670 ± 90 (stat.) $^{+110}_{-100}$ (syst.) fb
  - ~20% total uncertainty (γγ, 4-lepton, and several multi-lepton channels are still strongly statistical limited)
- The SM prediction is 507 $^{+35}_{-50}$ fb

$t\bar{t}H$ cross section measurement: 8 TeV & 13 TeV



- The measured $t\bar{t}H$ cross sections are so far in agreement with the SM model prediction

Part 2: $H\rightarrow\tau\tau$ cross section measurements (36 fb^{-1})



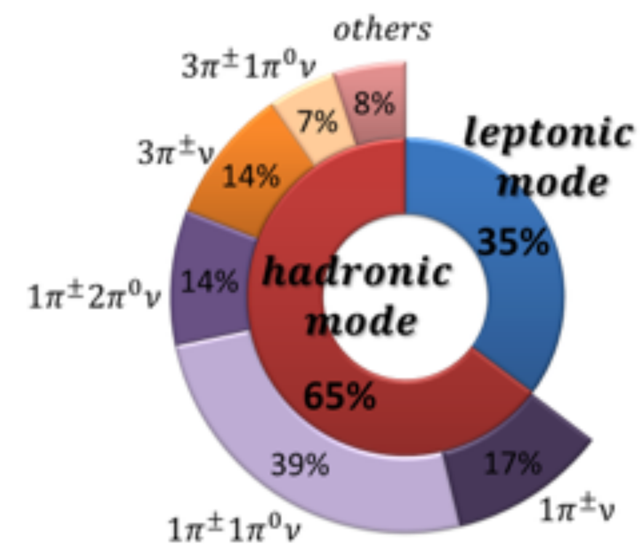
ATLAS-CONF-2018-021, June 2018

$H \to \tau\tau$ decay mode

- The first observation of the **$H \to \tau\tau$ decay mode** with 5.5σ was achieved from a combination of ATLAS and CMS Run 1 results
- A recent $H \to \tau\tau$ measurement by CMS reached 4.9σ using 35.9 fb^{-1} of Run 2 data and 5.9σ after combination with Run 1 data
- $H \to \tau\tau$ is currently the only **accessible leptonic decay mode** of the Higgs boson
  - could provide sensitivity to CP violation in the Higgs-fermion interactions

$H\rightarrow\tau\tau$ Analysis @ ATLAS

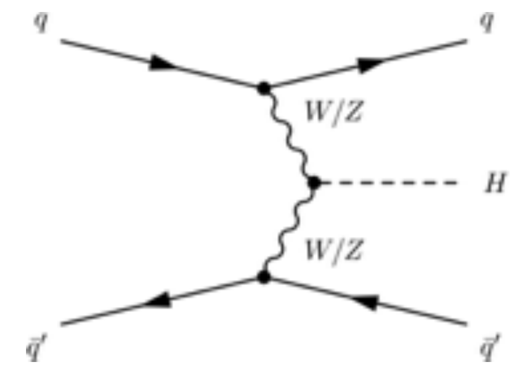
- Use 36.1 fb^{-1} of 13 TeV proton-proton collision data collected by ATLAS
- **3 analysis channels** to consider all combinations of the leptonic and hadronic tau decays:
  - $\tau_{lep}\tau_{lep}$ (~12%): N(lepton) = 2, N(hadronic tau) = 0
  - $\tau_{lep}\tau_{had}$ (~46%): N(lepton) = 1, N(hadronic tau) = 1
  - $\tau_{had}\tau_{had}$ (~42%): N(lepton) = 0, N(hadronic tau) = 2

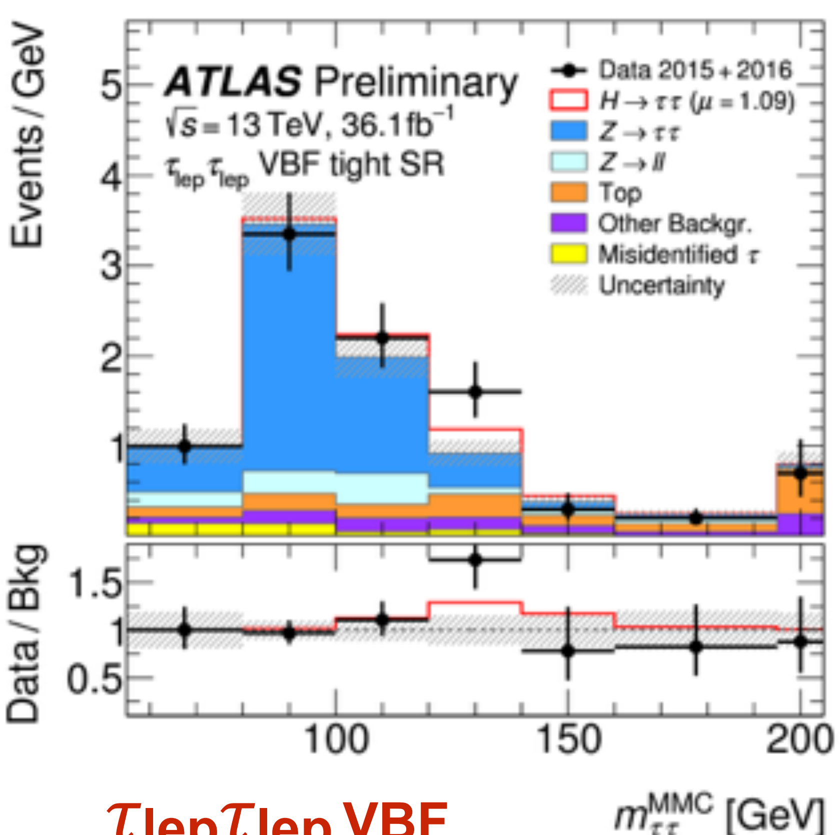


- Major background:
  - **$Z\rightarrow\tau\tau$ production** (discriminant shape estimated form simulation while normalization is determined from data sidebands)
  - misidentified hadronic tau (estimated using data-driven methods)

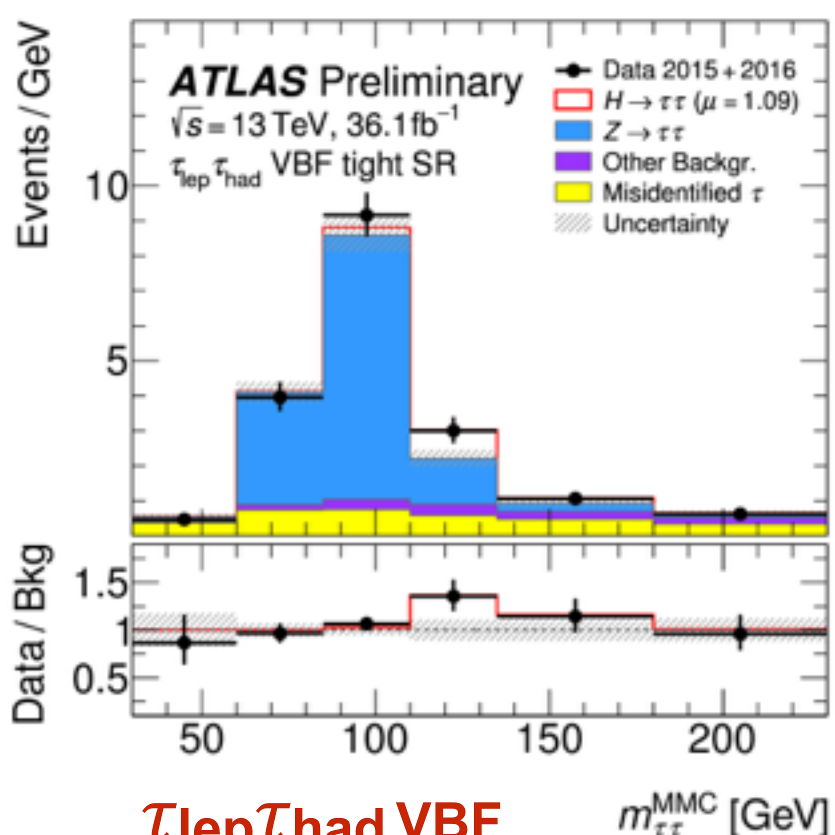
VBF regions

- In each channel, define “VBF” signal regions/ control regions (with at least 2 jets) to target VBF production mode of Higgs boson
- Reconstructed di-tau masses ($m_{\tau\tau}^{MMC}$) distributions in different VBF signal regions:

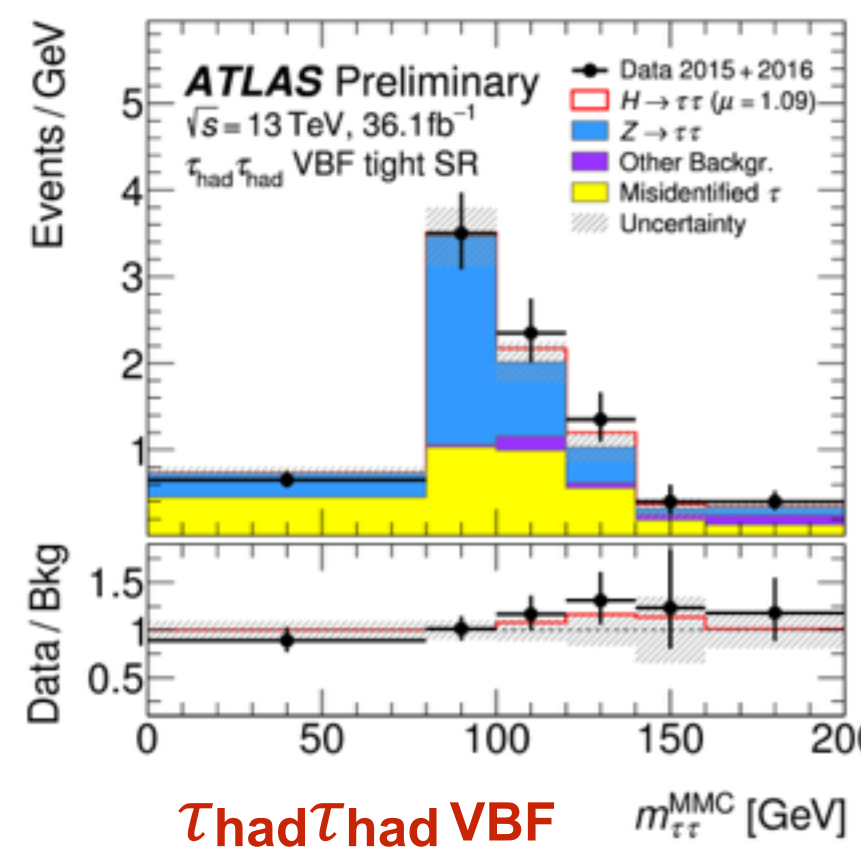




$\tau_{lep}\tau_{lep}$ VBF tight SR



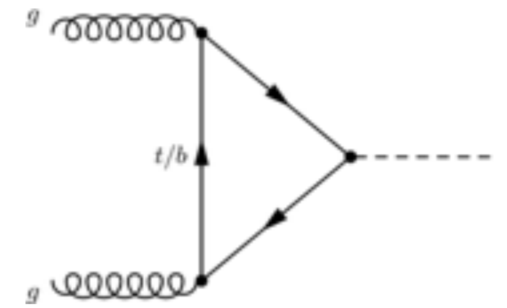
$\tau_{lep}\tau_{had}$ VBF tight SR



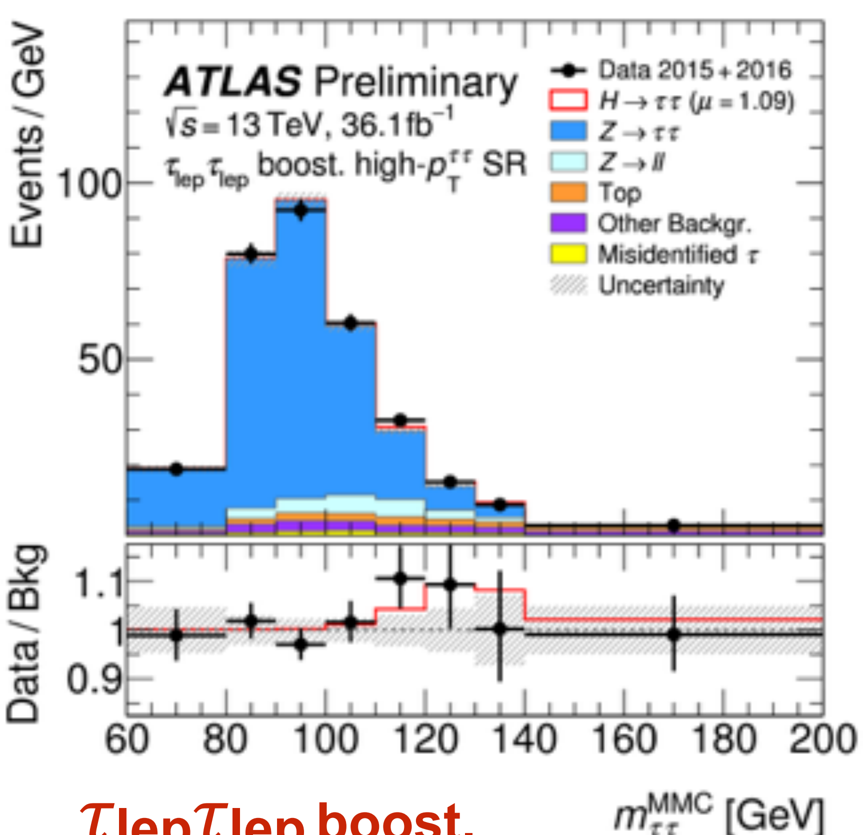
$\tau_{had}\tau_{had}$ VBF tight SR

Boosted regions

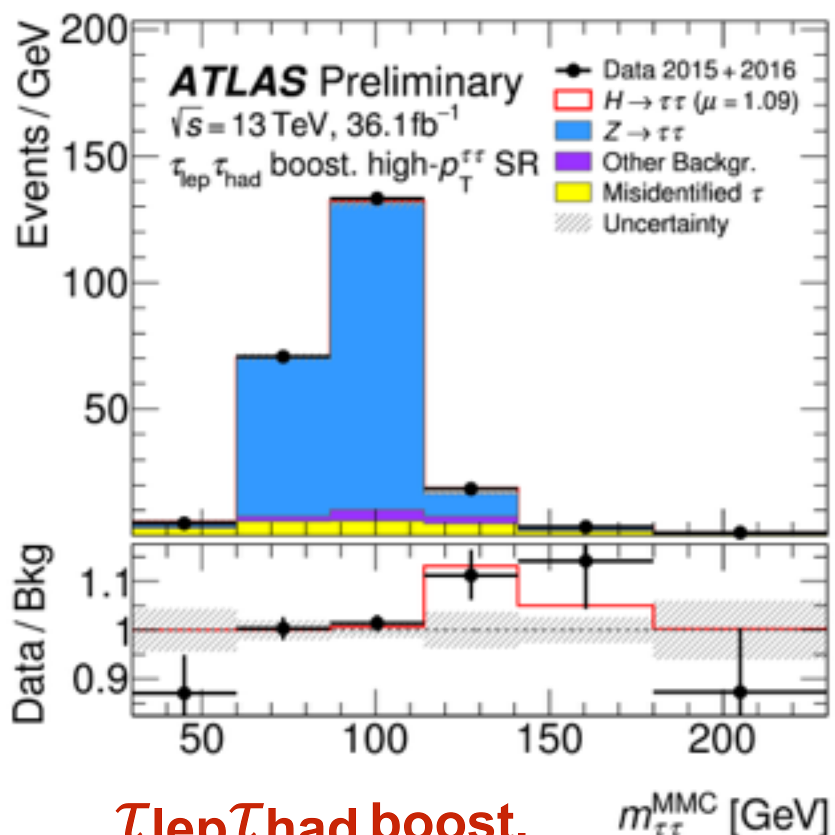
- In each channel, define "boosted" signal regions/control regions (orthogonal to VBF regions, $p_T^{\tau\tau} > 100$ GeV) to target ggF production mode of Higgs boson



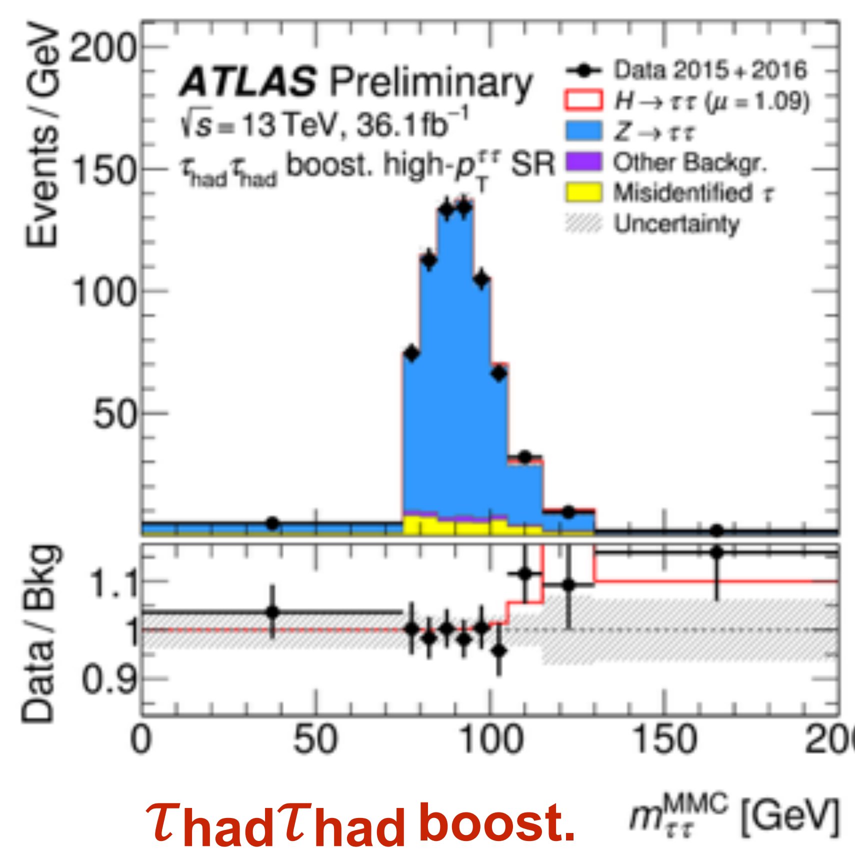
- Reconstructed di-tau masses ($m_{\tau\tau}^{MMC}$) distributions in different boosted signal regions:



$\tau_{lep}\tau_{lep}$ boost. high-$p_T^{\tau\tau}$ SR



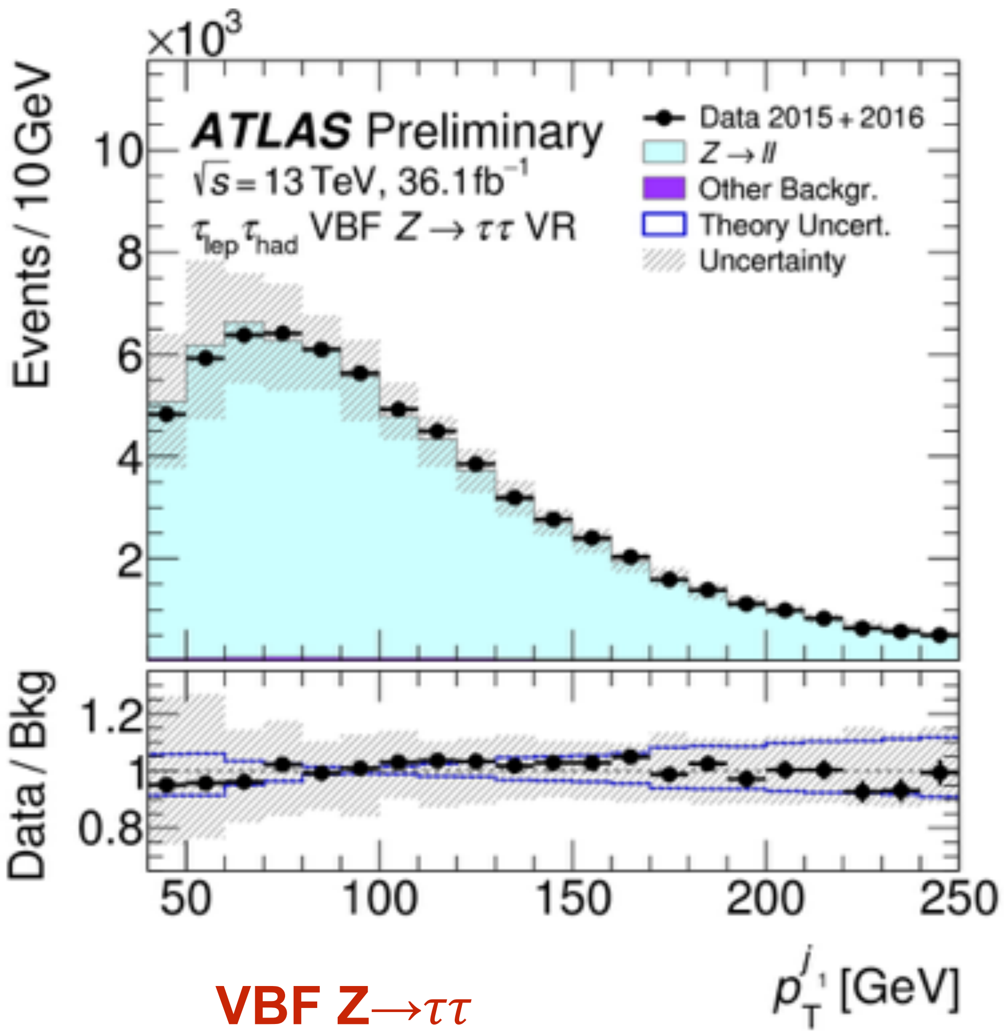
$\tau_{lep}\tau_{had}$ boost. high-$p_T^{\tau\tau}$ SR



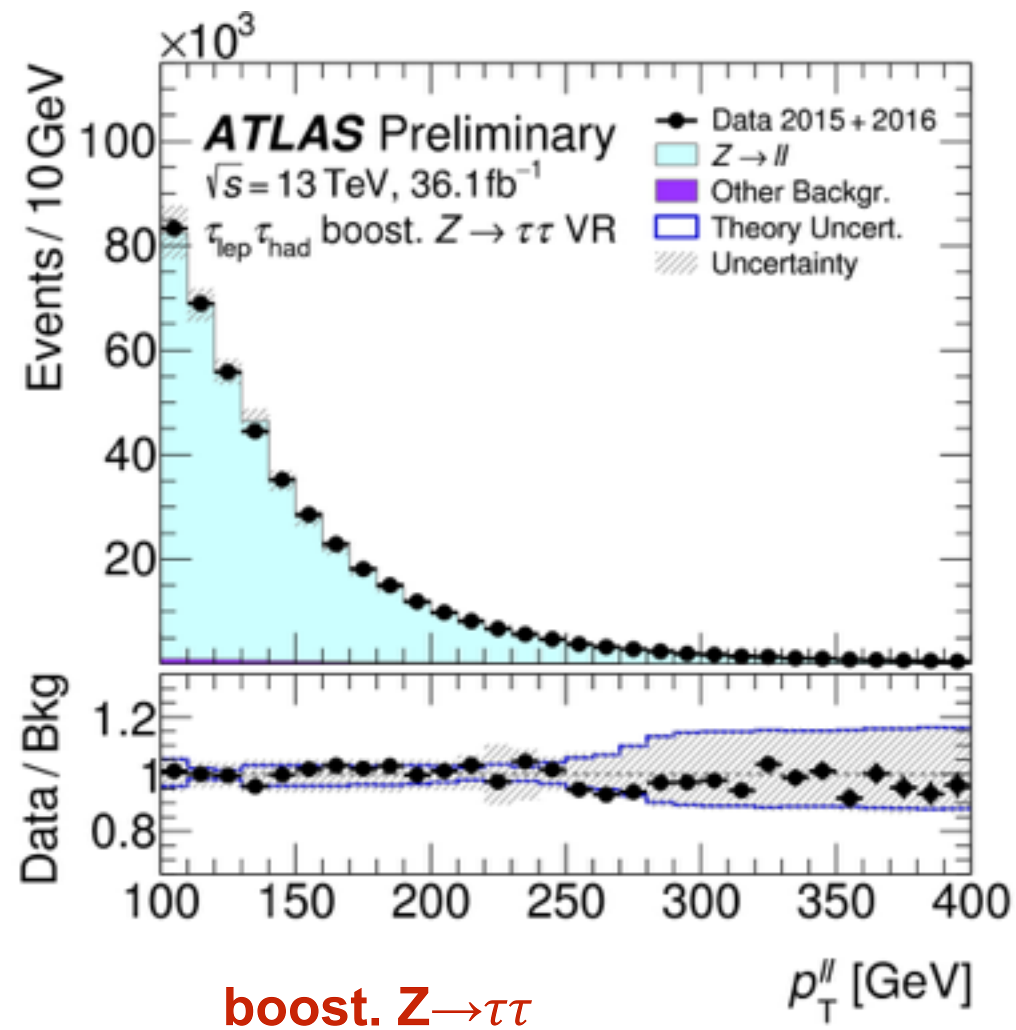
$\tau_{had}\tau_{had}$ boost. high-$p_T^{\tau\tau}$ SR

Z→ττ background validation

- Validation regions based on $Z \rightarrow ll$ events are studied to verify the $Z \rightarrow \tau\tau$ simulation
  - not included in the final fit
- Generally the simulation models well the $Z \rightarrow \tau\tau$ background in various topologies



VBF Z→ττ validation region



boost. Z→ττ validation region

Fit and Results

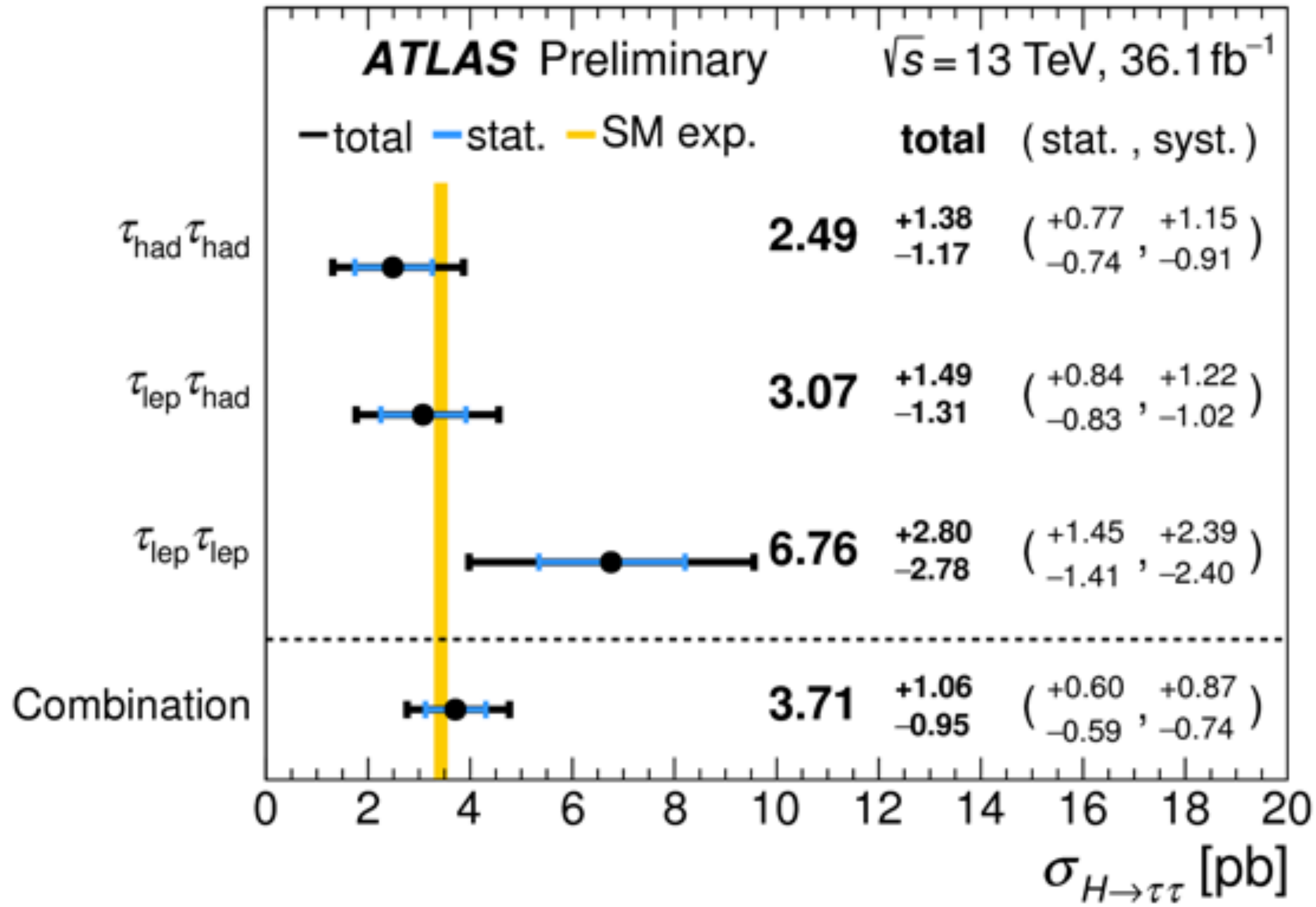
- Perform **simultaneous fits** using reconstructed di-tau masses ($m_{\tau\tau}^{MMC}$) in 13 signal regions and event yields in 6 control regions from 3 analysis channels
  - normalization of $Z \rightarrow \tau\tau$ is floated in the fits
  - minor background ($Z \rightarrow$ ll and top) are constrained by dedicated control regions
- The observed (expected) H$\rightarrow\tau\tau$ significance is **4.4σ (4.1σ)** in 13 TeV results
- The observed (expected) H$\rightarrow\tau\tau$ significance is **6.4σ (5.4σ)** combining 7, 8, and 13 TeV results

Results: uncertainties

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H\to\tau\tau}$ (%) Observed	Expected
Theoretical uncert. on signal	+13.5 / −8.7	+11.9 / −7.7
Background statistics	+11 / −10	+10.2 / −9.8
Jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	+11.5 / −9.3	+10.5 / −8.6
Background normalization	+6.8 / −4.8	+6.6 / −4.6
Misidentified τ	+4.5 / −4.2	+3.7 / −3.4
Theoretical uncert. on background	+4.6 / −3.6	+5.1 / −4.2
Hadronic taus	+4.7 / −3.0	+5.8 / −4.2
Flavour tagging	+3.3 / −2.4	+2.9 / −2.2
Luminosity	+3.3 / −2.3	+3.1 / −2.2
Electrons and muons	+1.2 / −1.0	+1.1 / −0.9
Total systematic uncert.	+24 / −20	+22 / −19
Data statistics	±16	±15
Total	+28 / −26	+27 / −25

- ~27% total uncertainty
  - dominated by systematic uncertainties (signal theoretical uncertainties, MC stats. for backgrounds, and Jet/MET uncertainties)

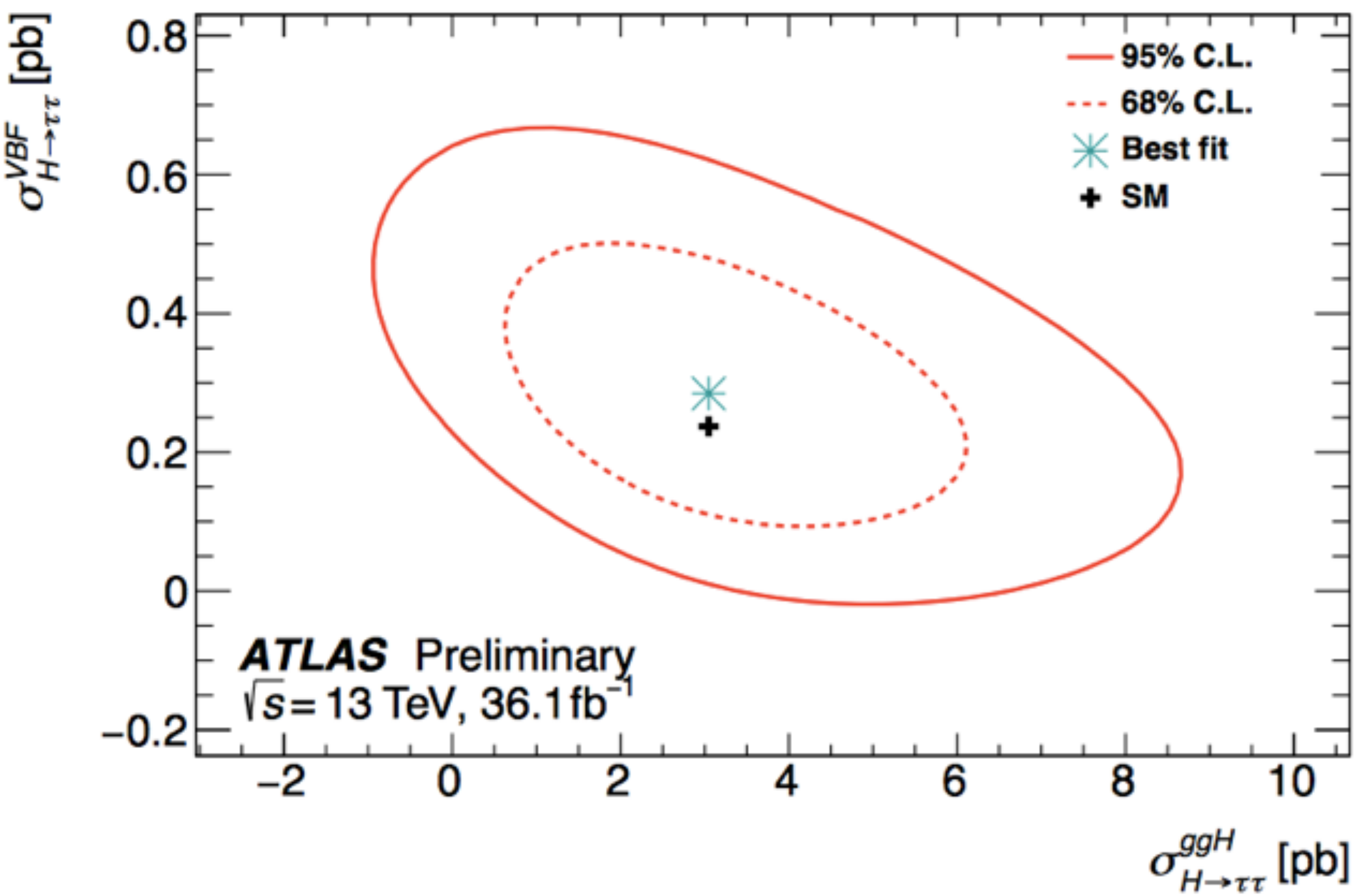
Results: cross sections



σ(H→ττ): combination & separate channels

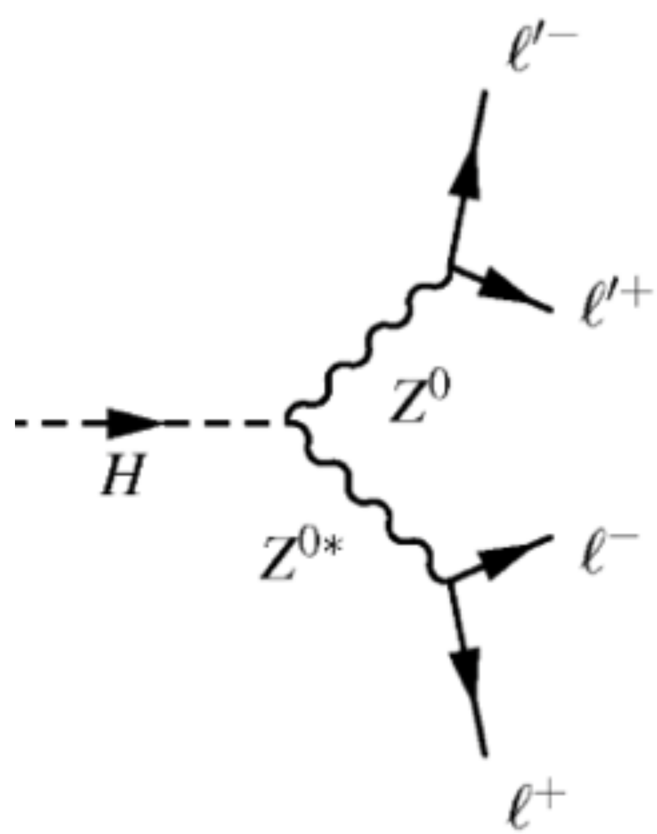
- The measured $H\to\tau\tau$ production cross section at 13 TeV is $3.71\ ^{+0.60}_{-0.59}$ (stat.) $^{+0.87}_{-0.74}$ (syst.) pb
- The SM prediction is 3.43 ± 0.18 pb

Results: cross sections



- Also measure ggF and VBF production cross sections simultaneously:
  - $\sigma(\text{VBF}, H\to\tau\tau) = 0.28 \pm 0.09\ (\text{stat.})\ ^{+0.11}_{-0.09}\ (\text{syst.})$ pb
  - $\sigma(\text{ggF}, H\to\tau\tau) = 3.0 \pm 1.0\ (\text{stat.})\ ^{+1.6}_{-1.2}\ (\text{syst.})$ pb
- All measurements are in agreement with the SM prediction

Part 3: $H \rightarrow ZZ^* \rightarrow$ 4-lepton property measurements (80 fb^{-1})



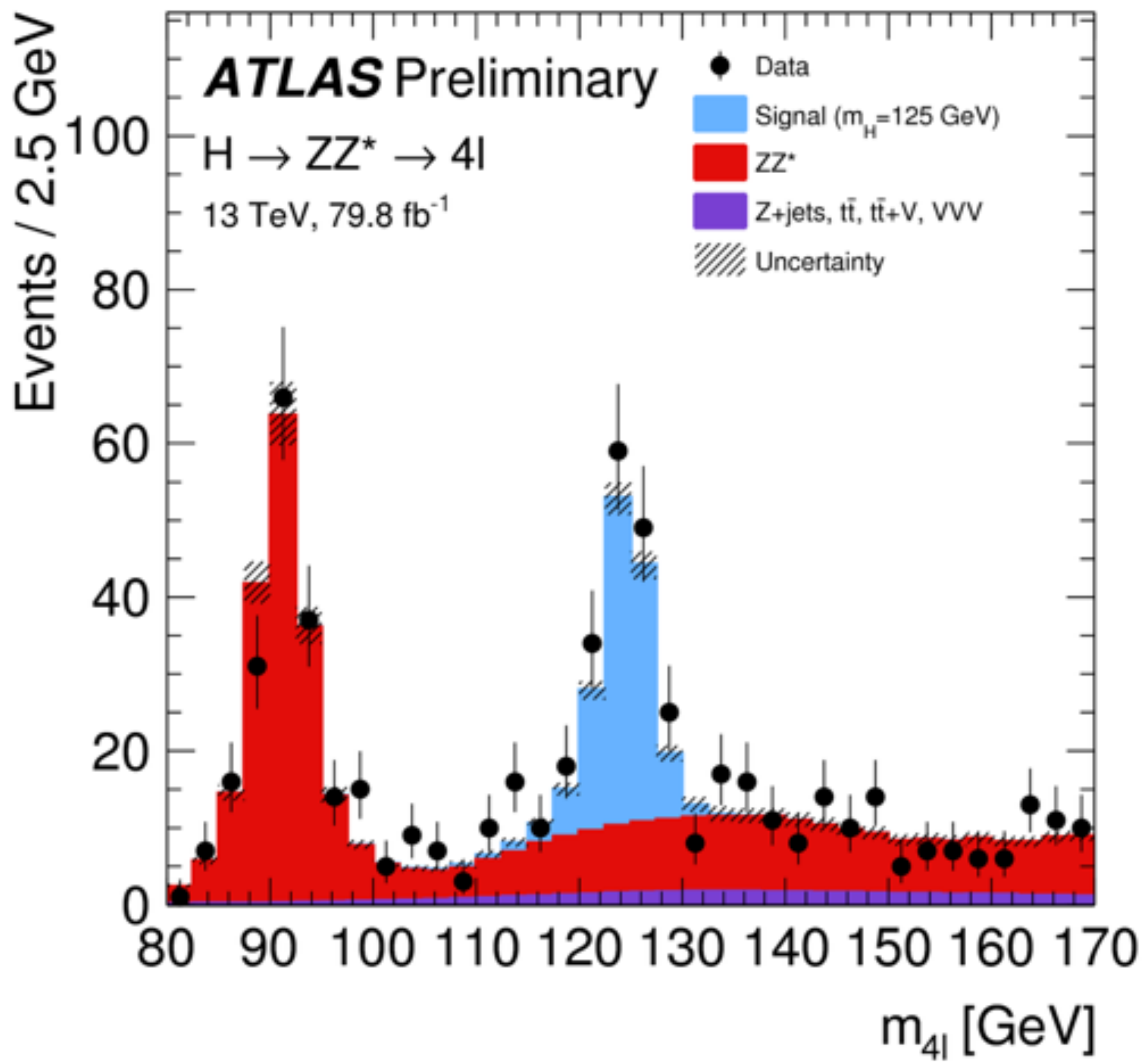
ATLAS-CONF-2018-018, June 2018

$H \rightarrow ZZ^* \rightarrow 4l$ analysis

- "Golden" Higgs decay channel with **high S/B ratio**
- Use 80 fb^{-1} of 13 TeV proton-proton collision data collected by ATLAS
- Select $H \rightarrow ZZ^* \rightarrow 4l$ candidates (next page)
- Measure Higgs properties with **granularity**:
  - fiducial and differential cross sections
  - production mode and simplified template cross sections

H→ZZ*→4l candidate selection

- Select events with **four leptons** forming two same-flavor opposite-charge lepton pairs:
  - ❖ leading lepton pair: closest to Z mass
  - ❖ four channels: 4e, 2e2μ, 2μ2e, 4μ
- **115 GeV < m_{4l} < 130 GeV** for statistical analysis (195 events observed)
- Major background: irreducible ZZ* production (modeled by simulation)

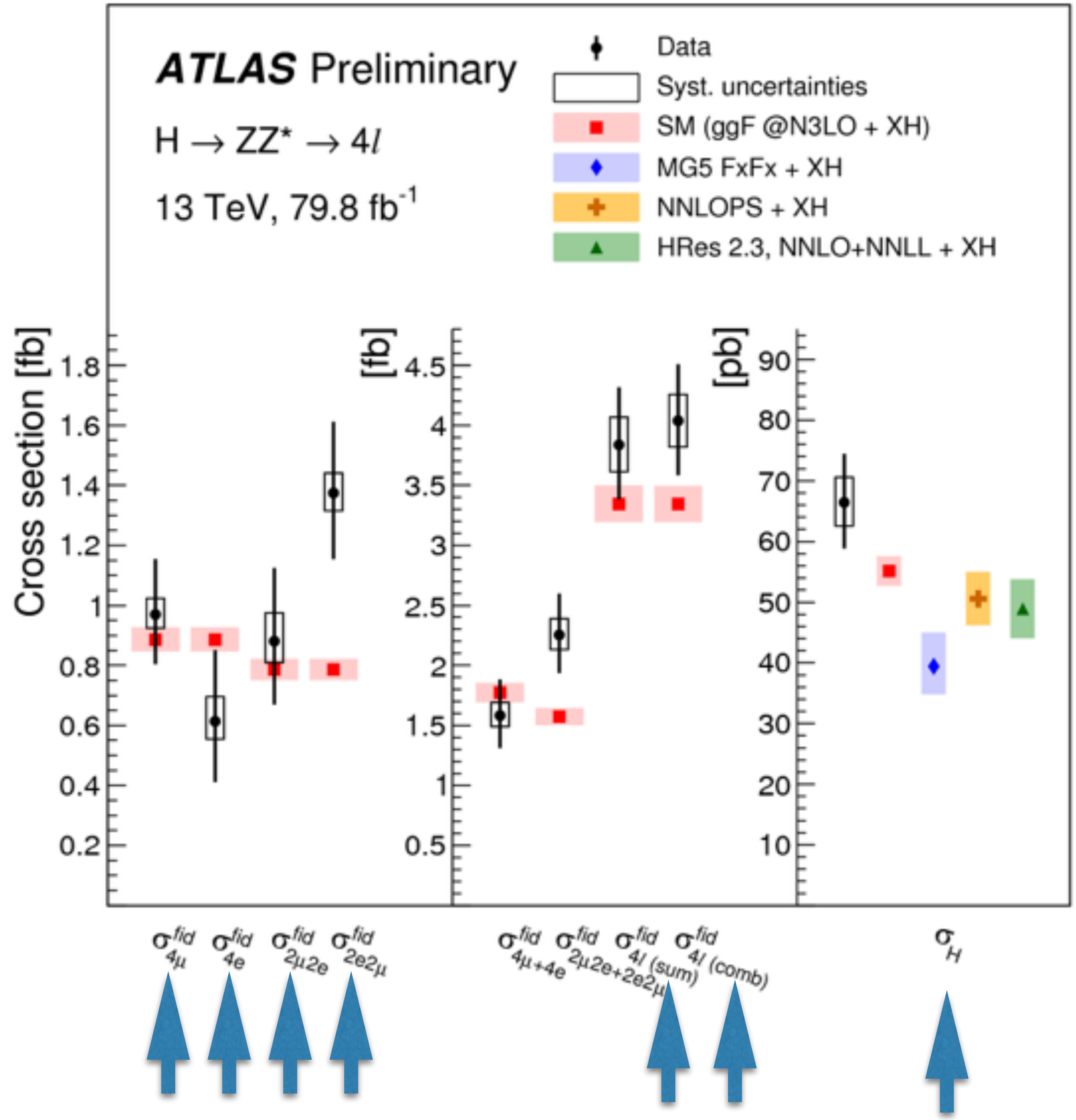


Fiducial and differential measurements $H \rightarrow ZZ^* \rightarrow 4l$

- Define **fiducial phase space** to closely match analysis selection
- To extract signal event yield in each decay channel or each differential bin, **m_{4l} distribution** is fitted
- Obtain cross sections using **correction factors** from simulation (and bin-by-bin unfolding)

Fiducial cross sections

- Fiducial cross section are measured **inclusively** and **separately** for decay channels
- Also extrapolate for total cross section



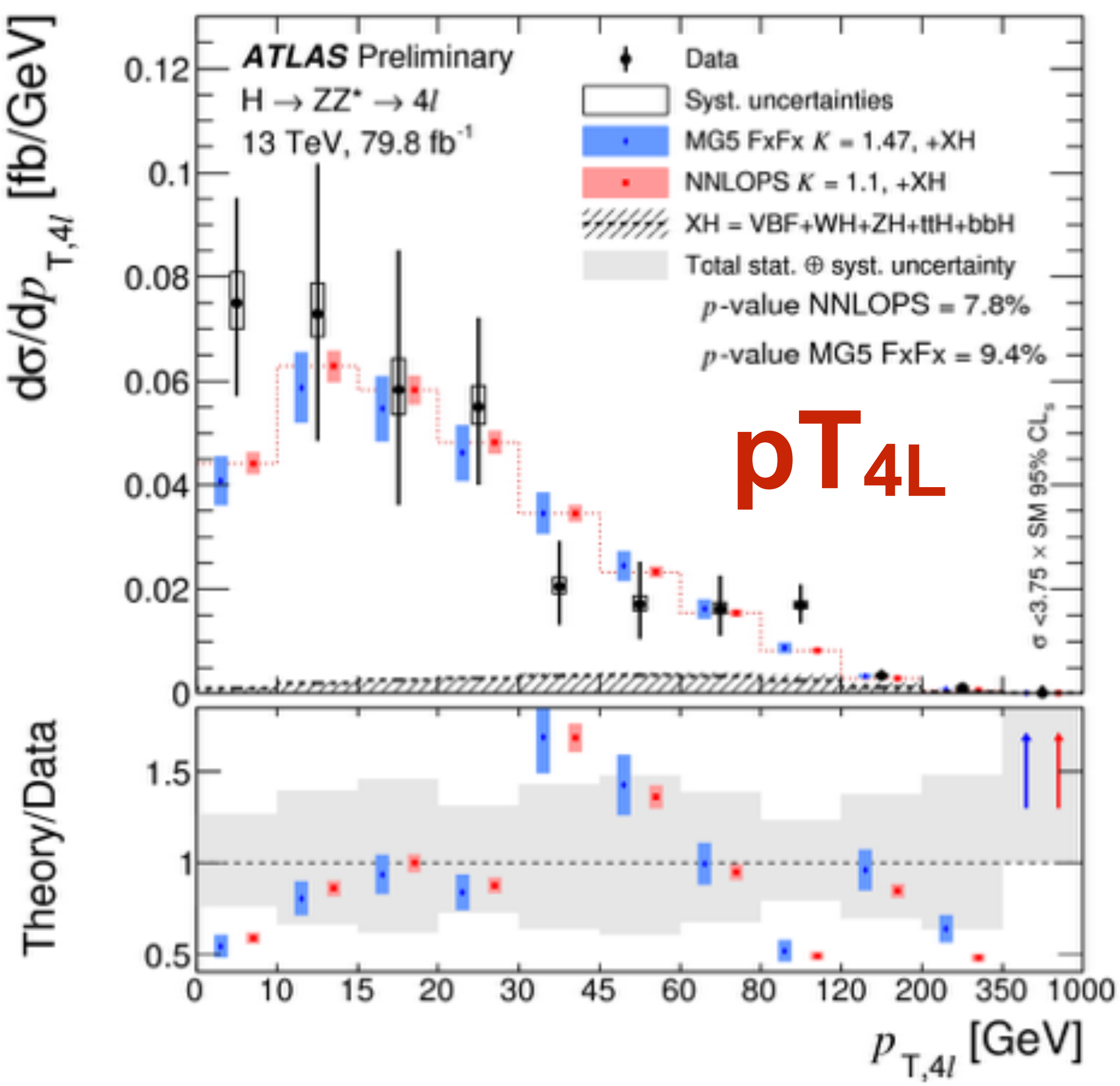
σ(fiducial, 4μ, 4e, 2μ2e or 2e2μ)

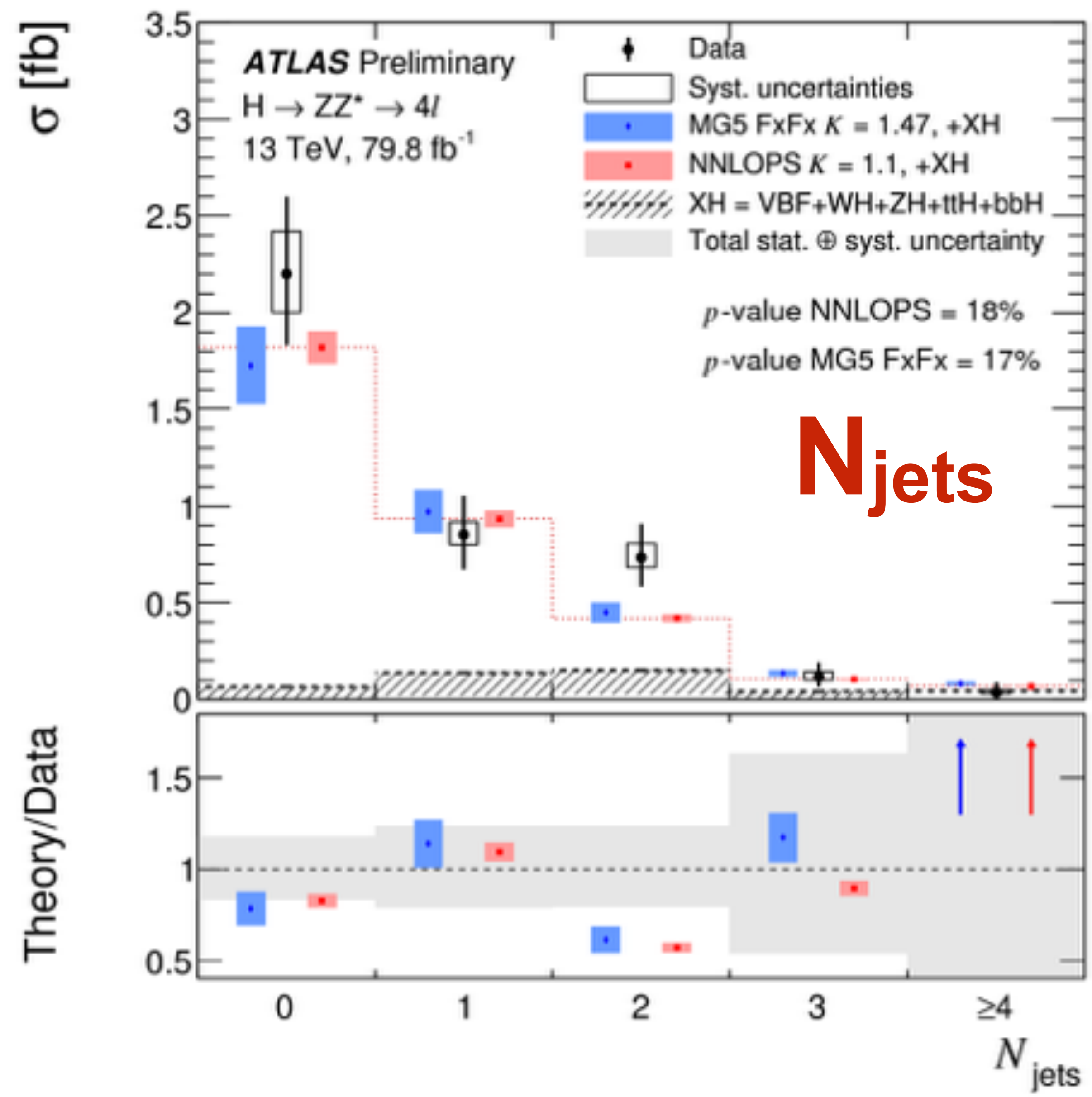
σ(fiducial, 4l)

σ(total)

Differential cross sections

- Differential cross sections are presented for
  - **pT_{4L}**: test QCD calculations and sensitive to BSM physics
  - **N_{jets}**: sensitive to modeling of gluon emission, fractions of different production modes and BSM physics





Production mode measurements

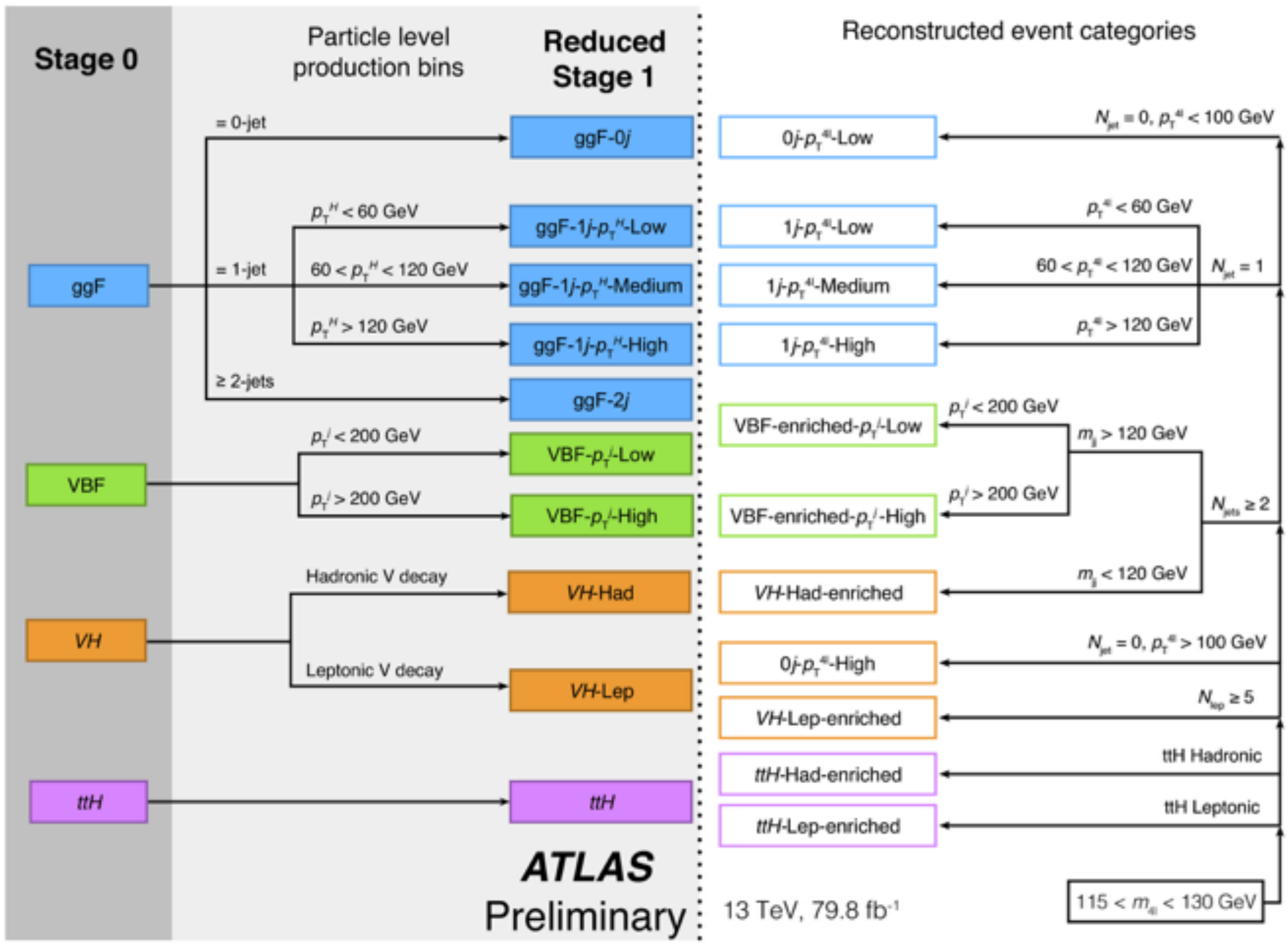
- **Simplified template cross sections**: separate production modes into kinematic regions
- Reconstructed events are categorized to **11 categories** to target different production modes and kinematic regions

ggF→

VBF→

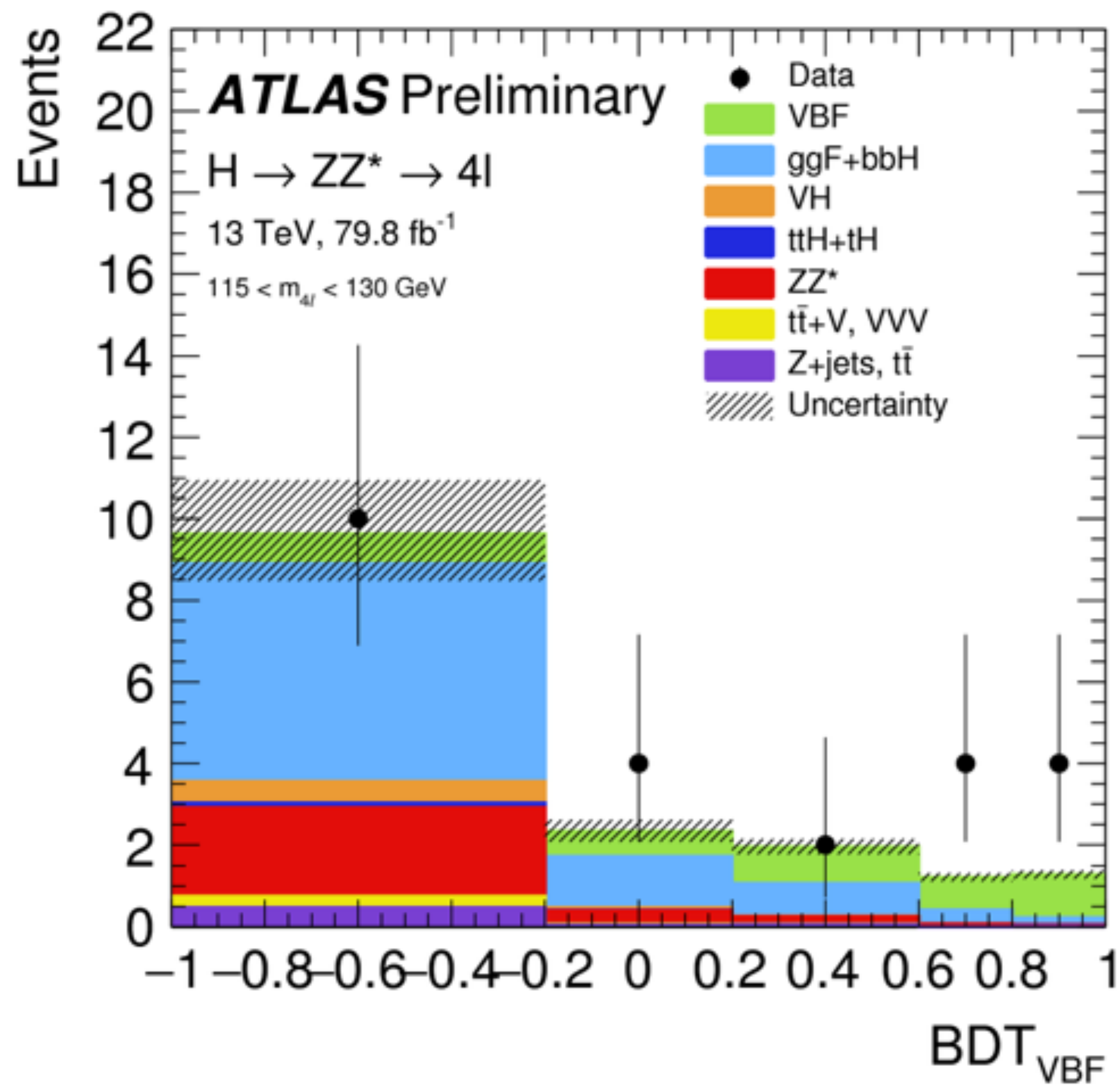
VH→

$t\bar{t}H$→



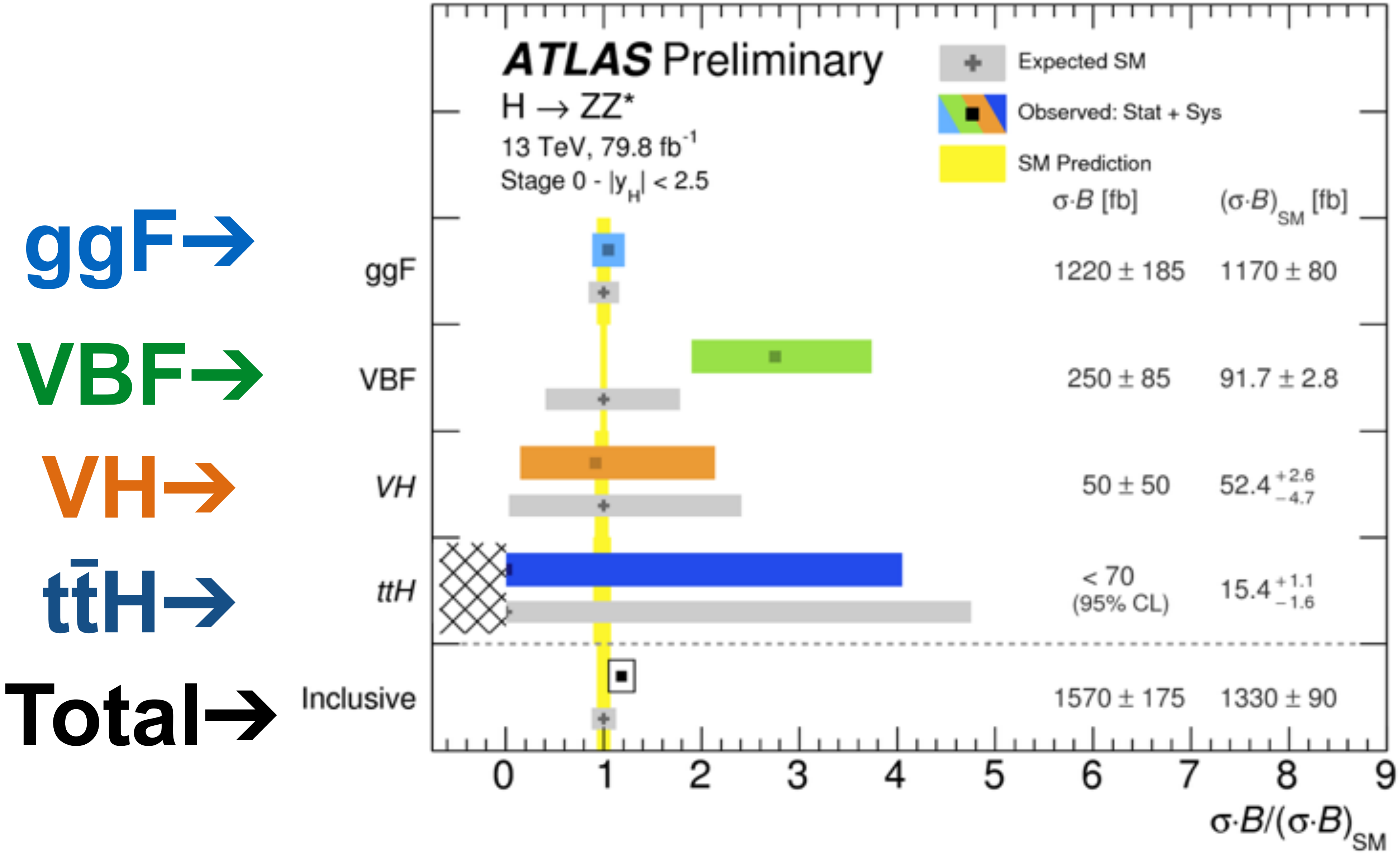
Production mode measurements

- In some categories, BDT are introduced to boost the sensitivity
- **Event yields** of BDT bins/categories are fitted to extract cross sections



Production mode cross sections

- Reported 4 production mode cross sections: ggF, VBF, VH, tt̄H
- Still dominated by statistical uncertainties



Simplified template cross sections

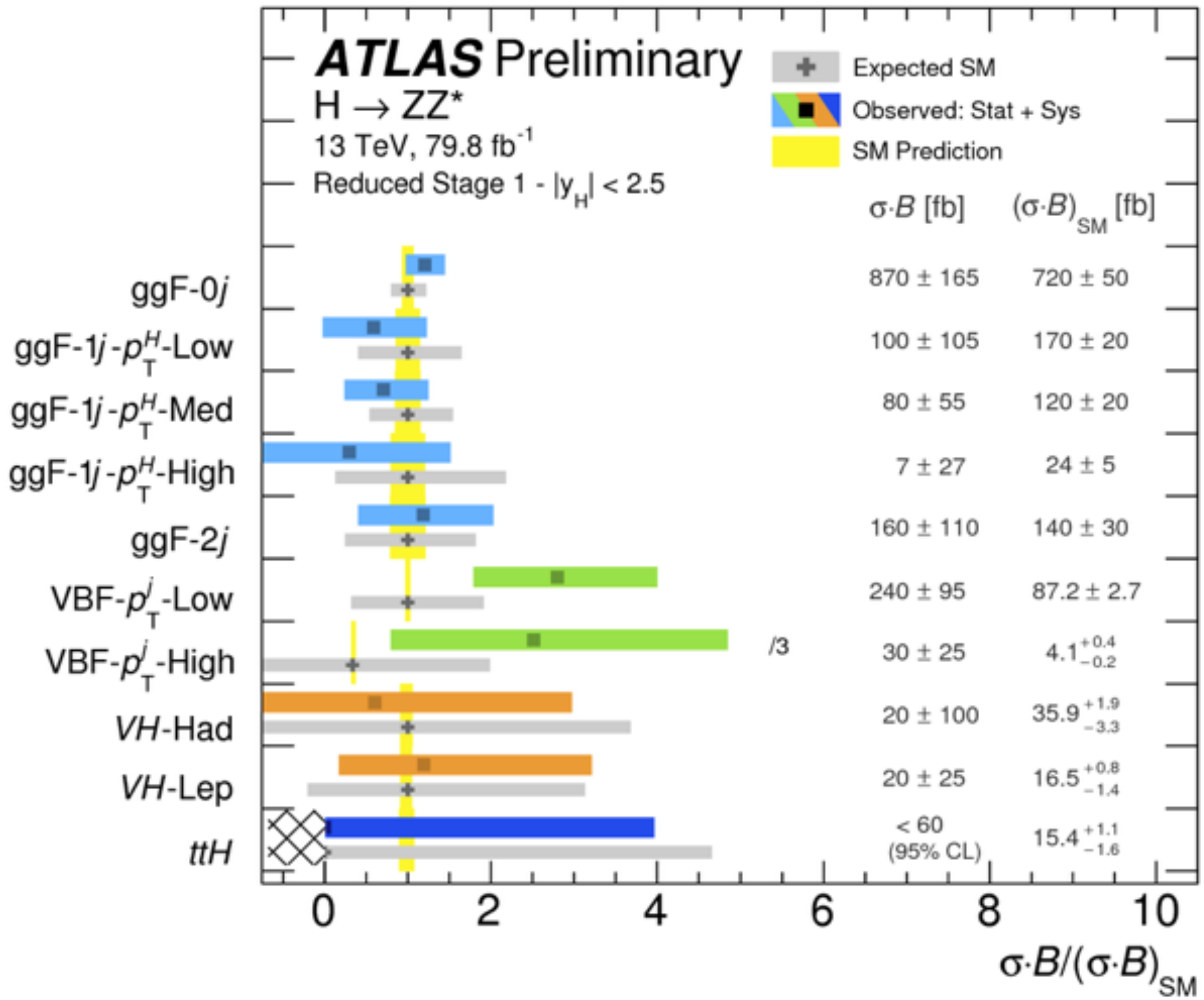
- Report simplified template cross sections (kinematic regions separated from production modes)
- All measurements are in agreement with SM

ggF→

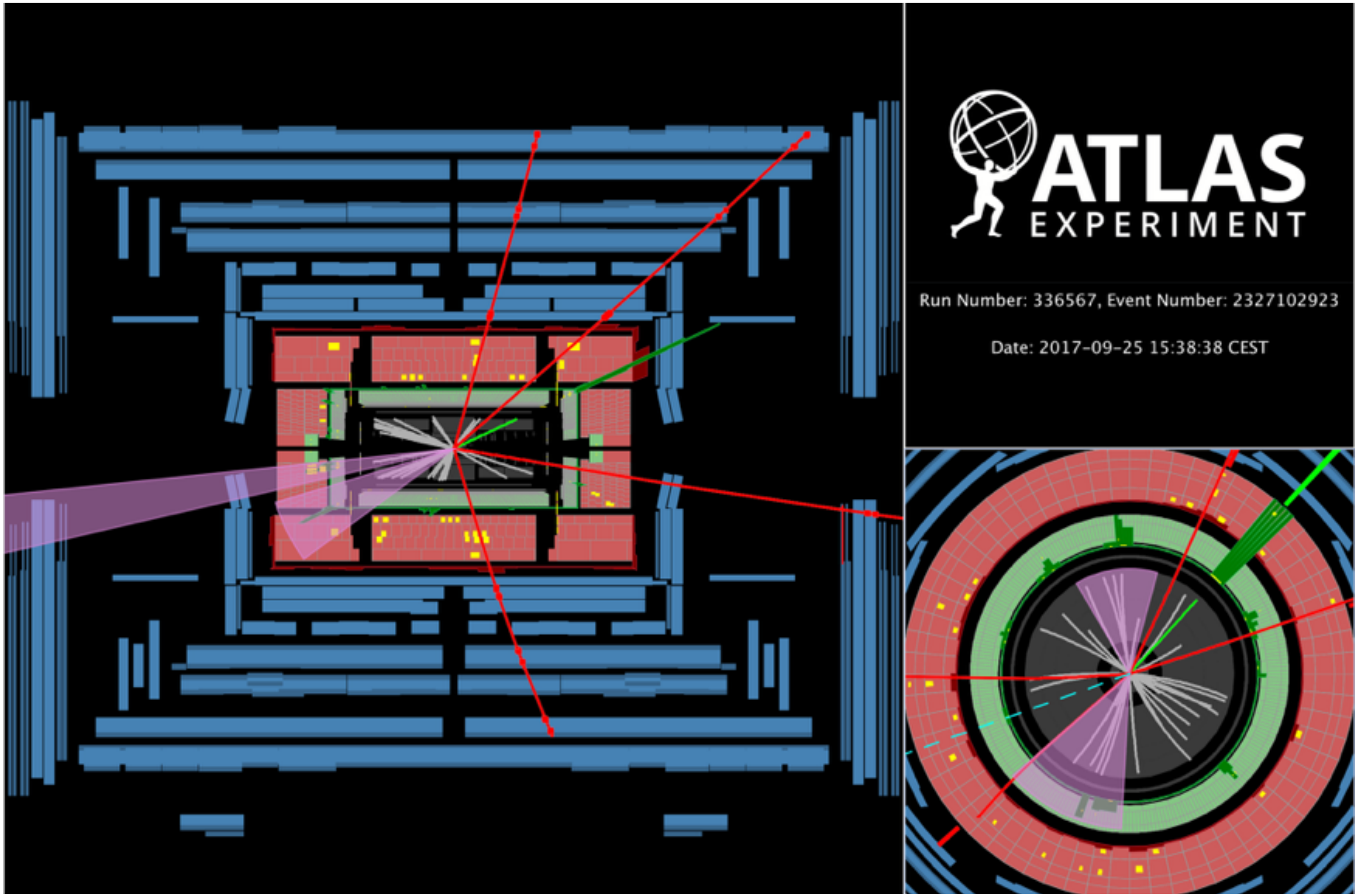
VBF→

VH→

$t\bar{t}$H→



Display: VH-Lep (H→ZZ*→4-lepton) candidate event



- 4μ VH-Lep candidate, with m_{4l} = 124.6 GeV, extra electron of pT = 79 GeV and MET = 49 GeV; **S(VH)/B ~ 2** where B is dominated by other Higgs production modes

Summary

- The ATLAS experiment reported on new Higgs physics results with up to **80 fb^{-1}**, including data from 2017
- The results include the **observation** of the **$t\bar{t}H$** production process (observed/expected 6.3σ/5.1σ) and the **$H \rightarrow \tau\tau$** decay mode (observed/expected 6.4σ/5.4σ) of the 125 GeV Higgs boson
  - These constitute an observation by the ATLAS experiment of **Yukawa interactions** in both quark and lepton sectors, consistent with SM
- Higgs property measurements in **$H \rightarrow ZZ^* \rightarrow 4l$** with 80 fb^{-1} are in agreement with the SM predictions