Preliminary

ttH Coupling Measurements

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Outline

- Introduction
- Signal and Background
- Multi-lepton Final States
- Two Same-sign Light Leptons and Hadronic Tau Decay
- Tau-Lepton Purity
- Specific Analysis Results
- Combination with other Multi-lepton Channels
- Combination with other ATLAS ttH Channels
- Combination of ATLAS and CMS ttH Results
- Conclusions and Outlook

>>> LHC Higgs Boson Physics <<<

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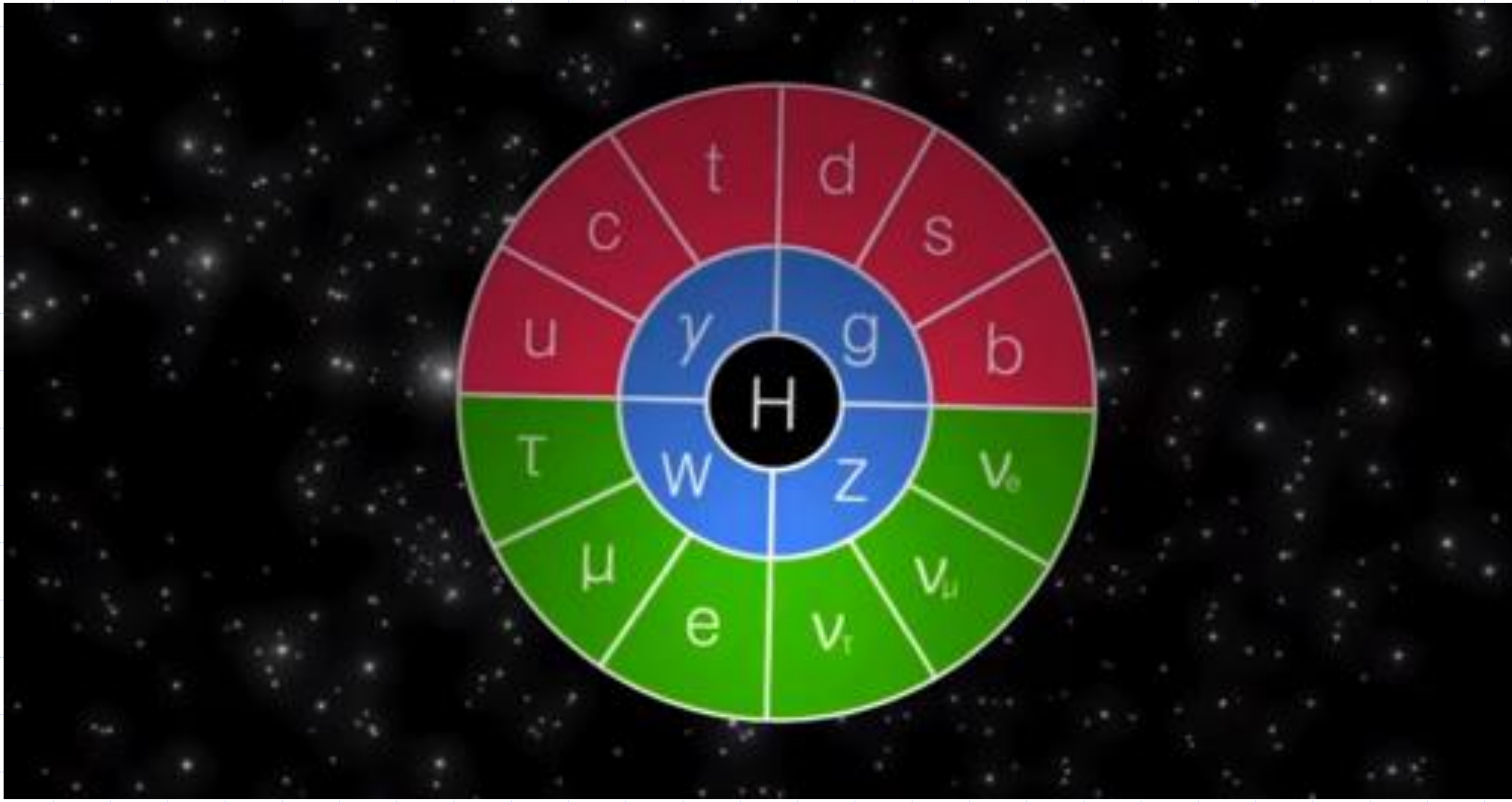

Focus on Higgs Boson Production in Association with a Top-Quark Pair

- "An important motivation of the ttH research is the fact that at present the only quantity which can help us to get an idea about the scale of New Physics is the top Yukawa coupling."
  Fedor Bezrukov, Mikhail Shaposhnikov
  ZhETF, 2015, Vol. 147, No. 3, p. 389[arXiv:1411.1923]

Recall:

- Yukawa coupling g(ffH) ~ m_f
- $m_{top}/m_{bottom} = 173/5 \approx 35$

Run-1 ttH Summary State of the Art

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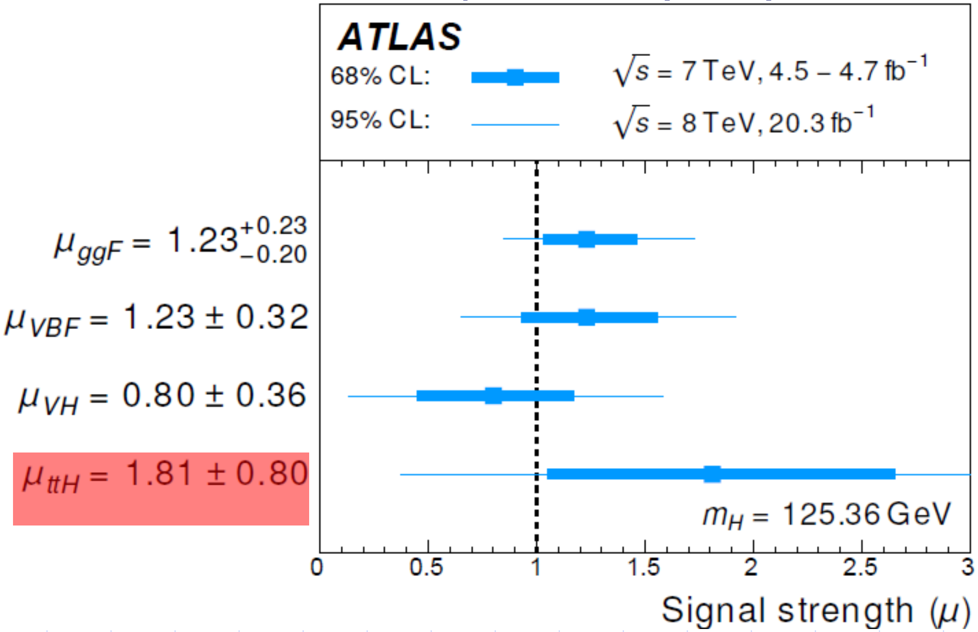
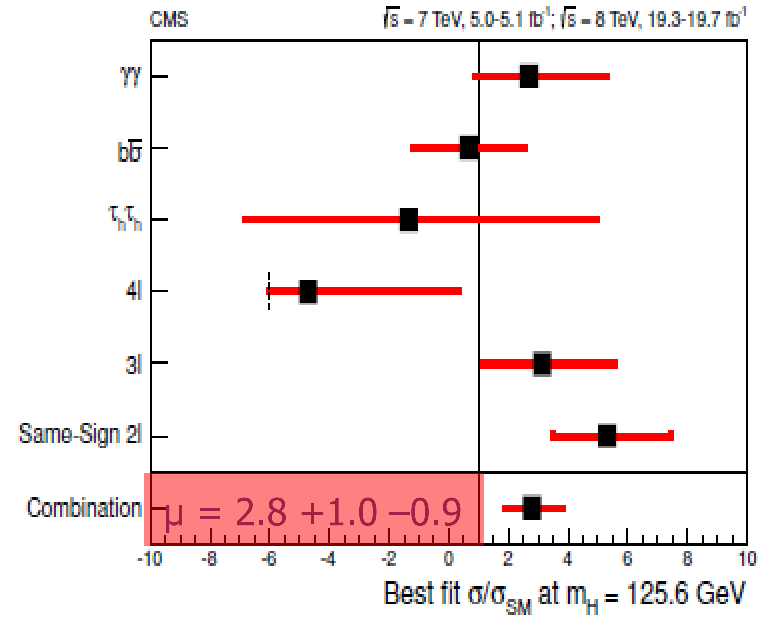
Eur. Phys. J. C76 (2016) 6



CMS: JHEP 09 (2014) 087



LHC Run-2: recorded 35.9 fb^{-1} and Analysis of 13.2 fb^{-1} Presented Here

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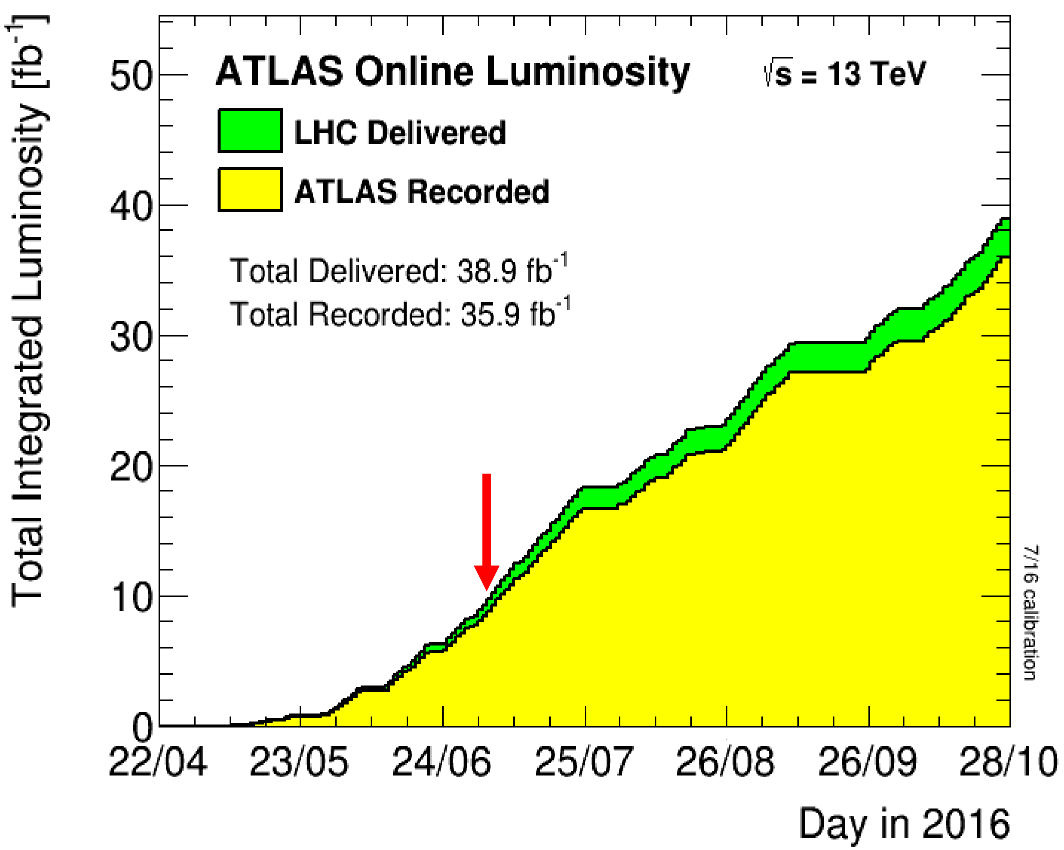

Experimental Challenge:

- ttH Signal 510 fb (6300 events)
- Background 80 mb = $80 \cdot 10^{12}$ fb ($1.04 \cdot 10^{15}$ events)
- Thus, finding one ttH event in 165 billion background events.

ATLAS: 10.0 (2016) + 3.2 (2015) = 13.2/fb

Indirect (loop) & Direct (Tree-level) g(ttH) Measurement

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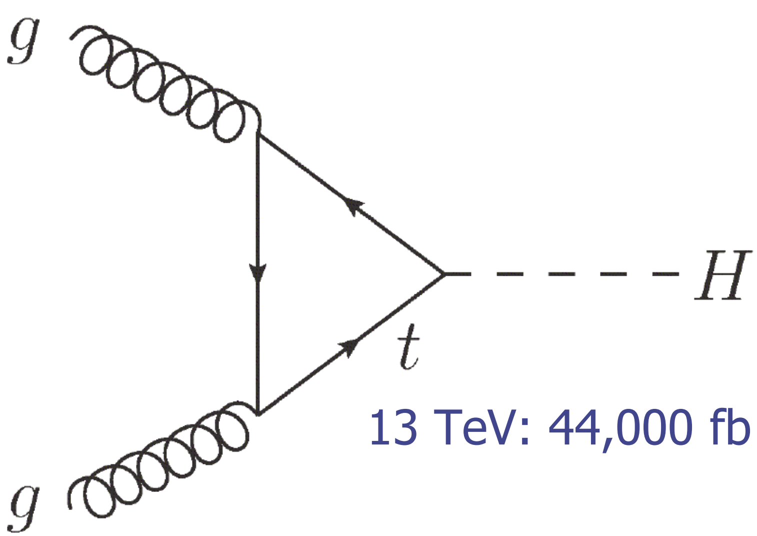
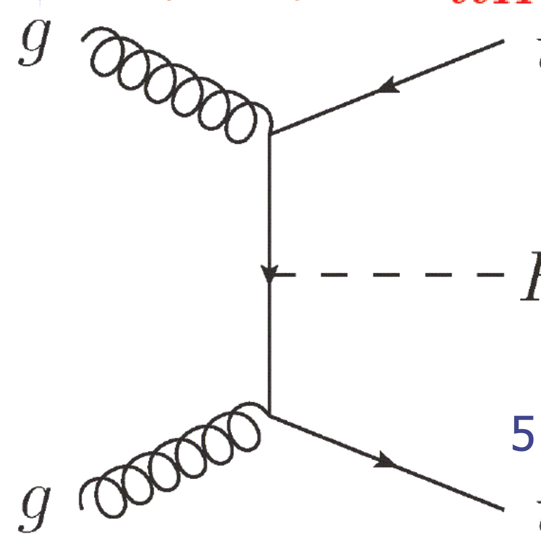
- Highest rate gg→H though loop, however, effects of ttH coupling not distinguishable from new physics contribution.
- Tree-level direct measurement: pp→ttH, very sensitive to physics beyond the Standard Model.

$$\sigma(t\bar{t}H) \propto g^2_{t\bar{t}H}$$



13 TeV: 44,000 fb



510 fb

- NLO accuracy in QCD using MG5_aMC with the NNPDF2.3 PDF with NLO electroweak corrections
- interfaced to Pythia8 to provide parton showering, hadronisation and multiple parton interactions, using the A14 parameter set.

ttH
Higgs and Top-Pair Decay Modes

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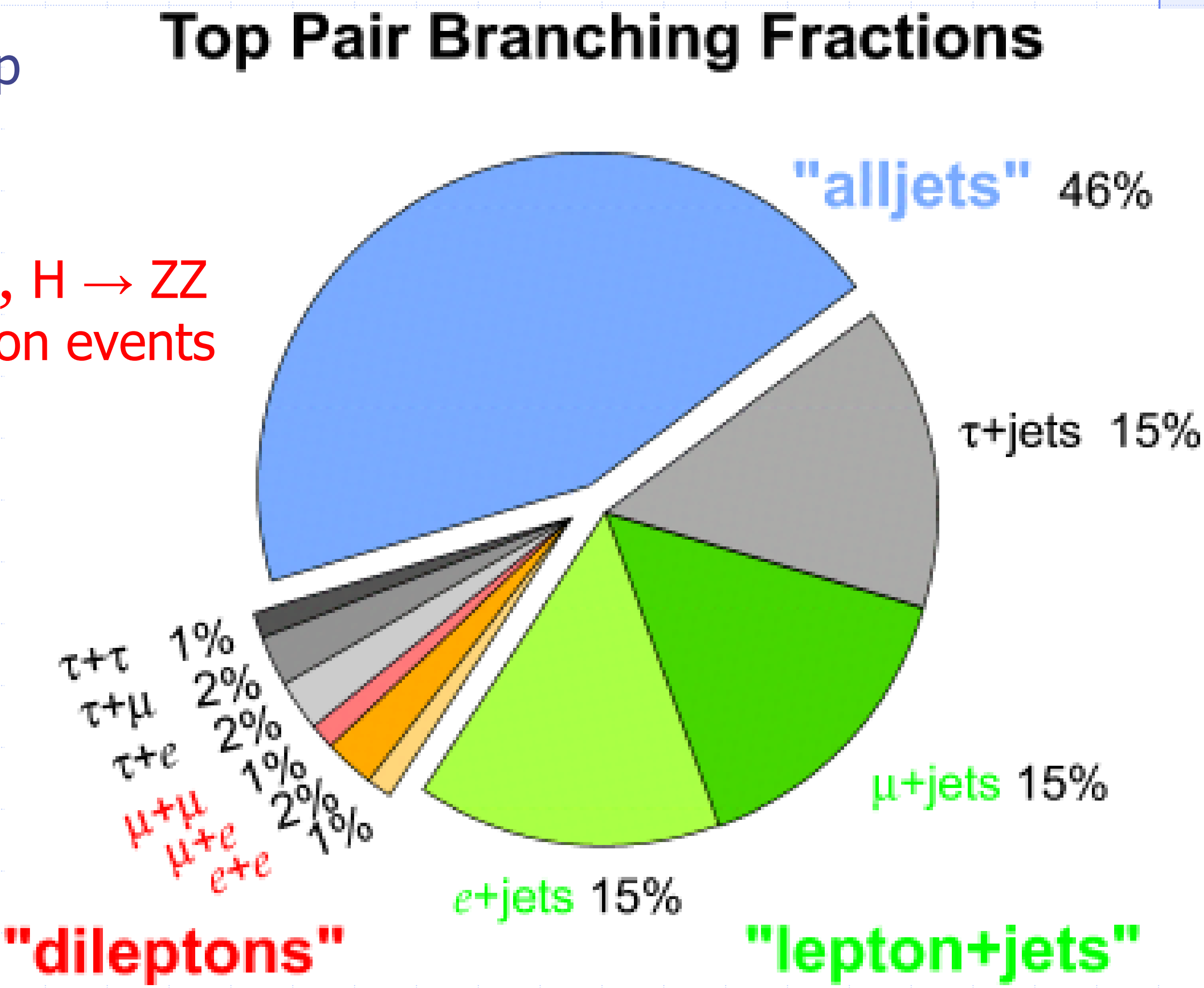
- $H \to \gamma\gamma$
  has a narrow bump
- $H \to bb$
  has a large rate
- $H \to WW$, $H \to \tau\tau$, $H \to ZZ$
  produce multi-lepton events
- $H \to ZZ \to 4\ell$
  has too low a rate



ATLAS ttH (Multi-leptons) Agreement in Validation Regions

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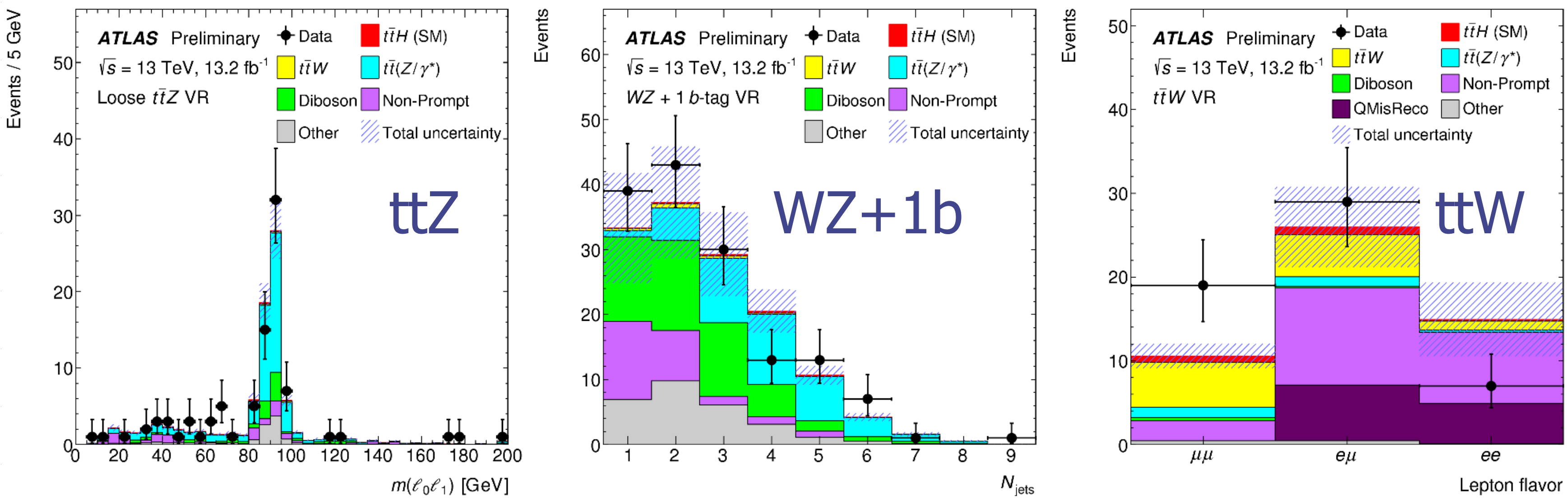
ATLAS-CONF-2016-058



VR	Purity	Expected	Data
Tight $t\bar{t}Z$	68%	32 ± 4	28
Loose $t\bar{t}Z$	58%	91 ± 12	89
$WZ + 1$ b-tag	33%	137 ± 27	147
$t\bar{t}W$	22%	51 ± 10	55

Four ATLAS ttH Multi-leptons Channels

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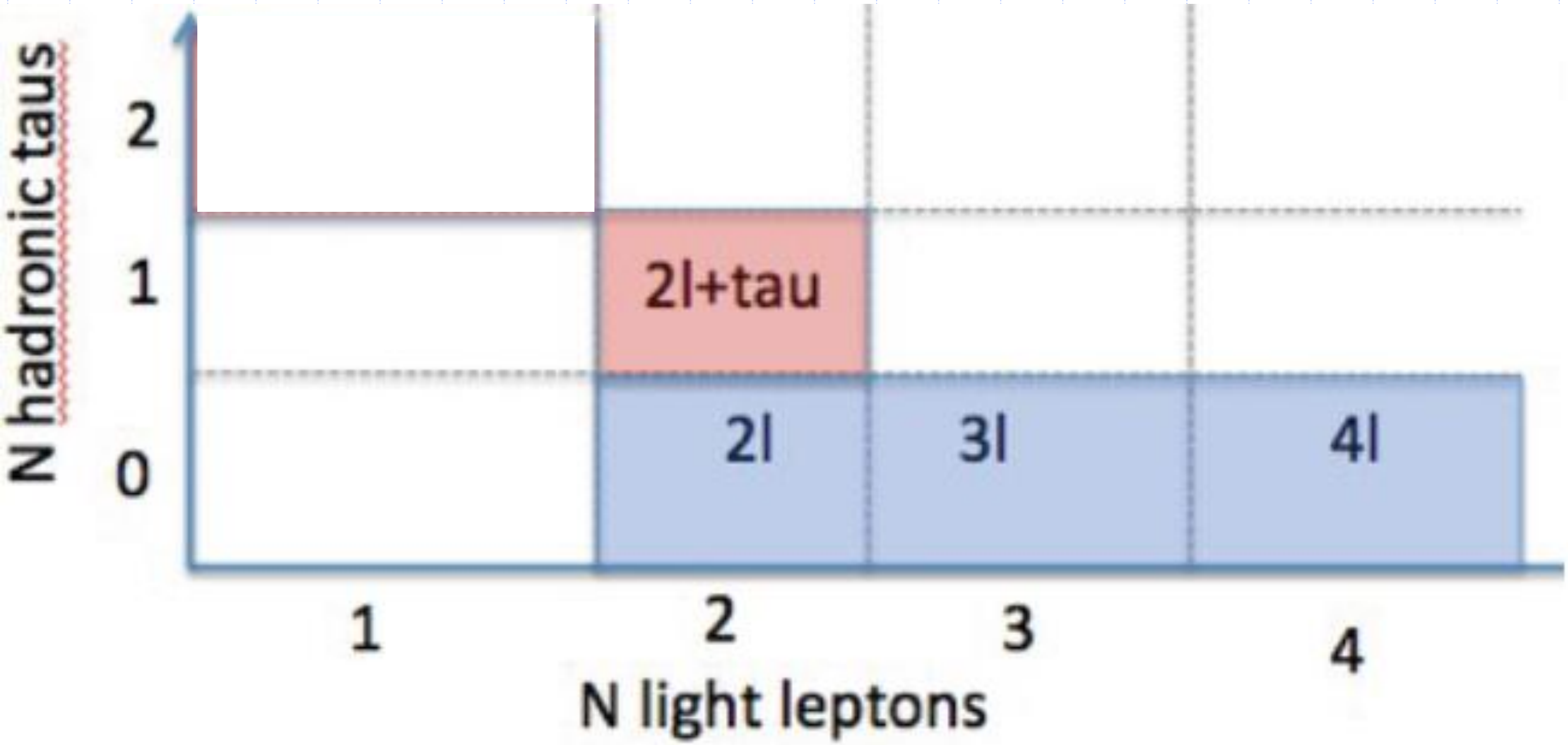
- Characterization by number of light leptons (electrons or muons) and number of hadronically decaying tau leptons



Four ATLAS ttH Multi-leptons Channels

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- Monte Carlo truth study shows enhanced $H \rightarrow \tau\tau$ selection in the two same-sign light leptons and one hadronically decaying tau final state

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\mathrm{had}}$	77%	17%	3%	3%
$2\ell 1\tau_{\mathrm{had}}$	46%	51%	2%	1%
3ℓ	74%	20%	4%	2%
4ℓ	72%	18%	9%	2%

Two Same-sign Leptons and One Hadronic Tau Final State

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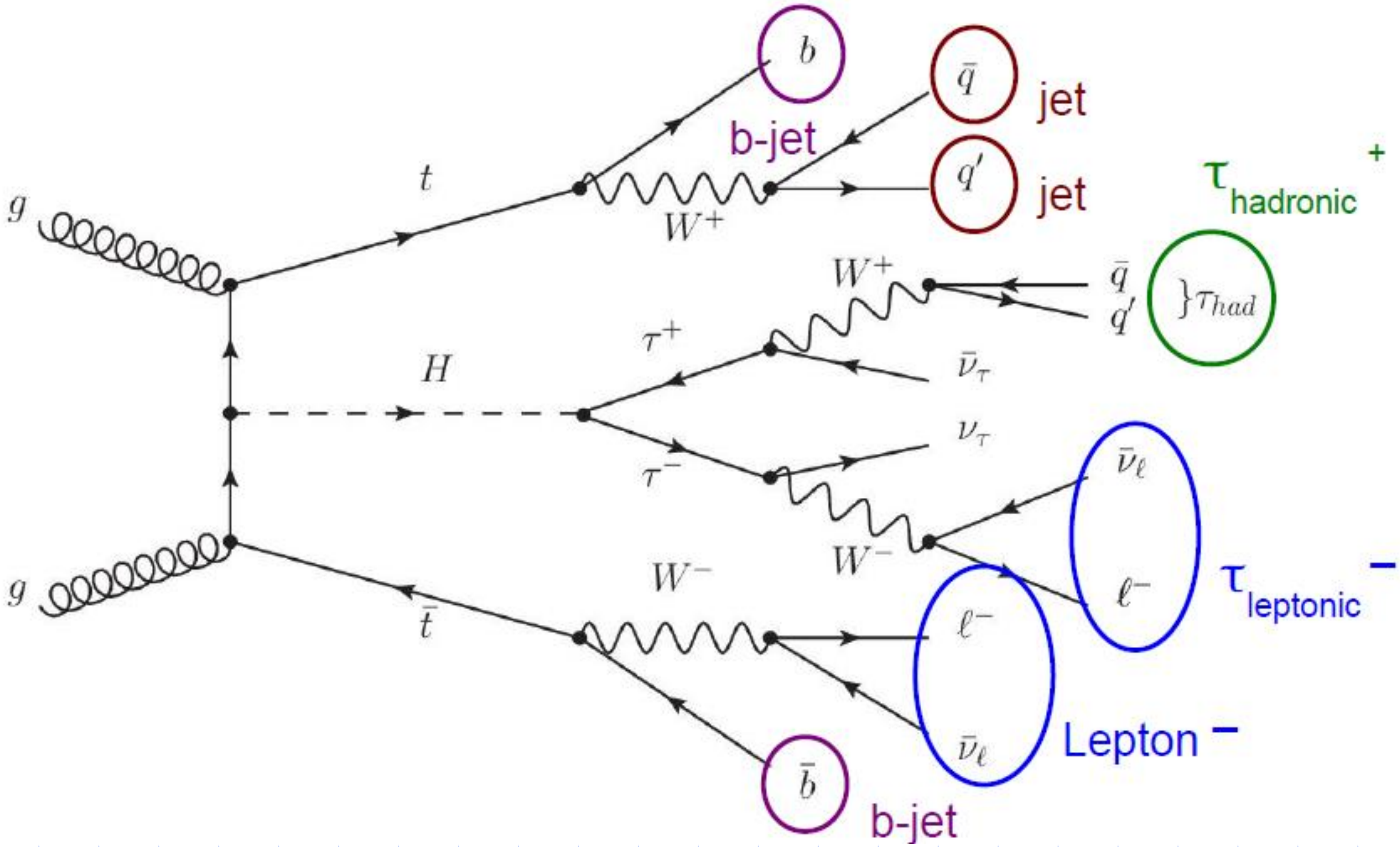

Main background: ttbar
Fake background estimate determined from data

ttH Candidate (Multi-leptons) Same-sign e and μ and Tau-jet

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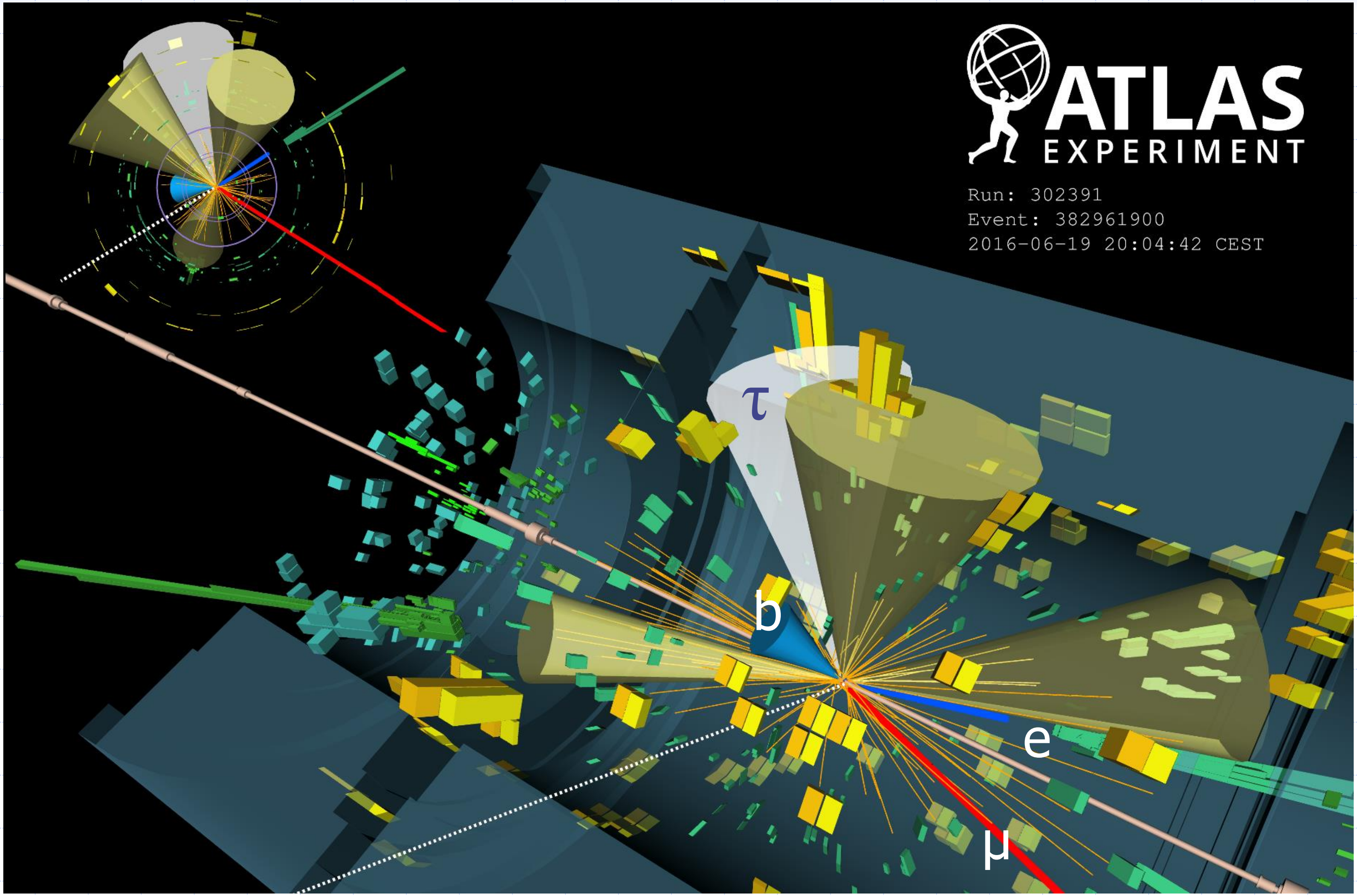

ATLAS ttH (Multi-leptons) Background Composition

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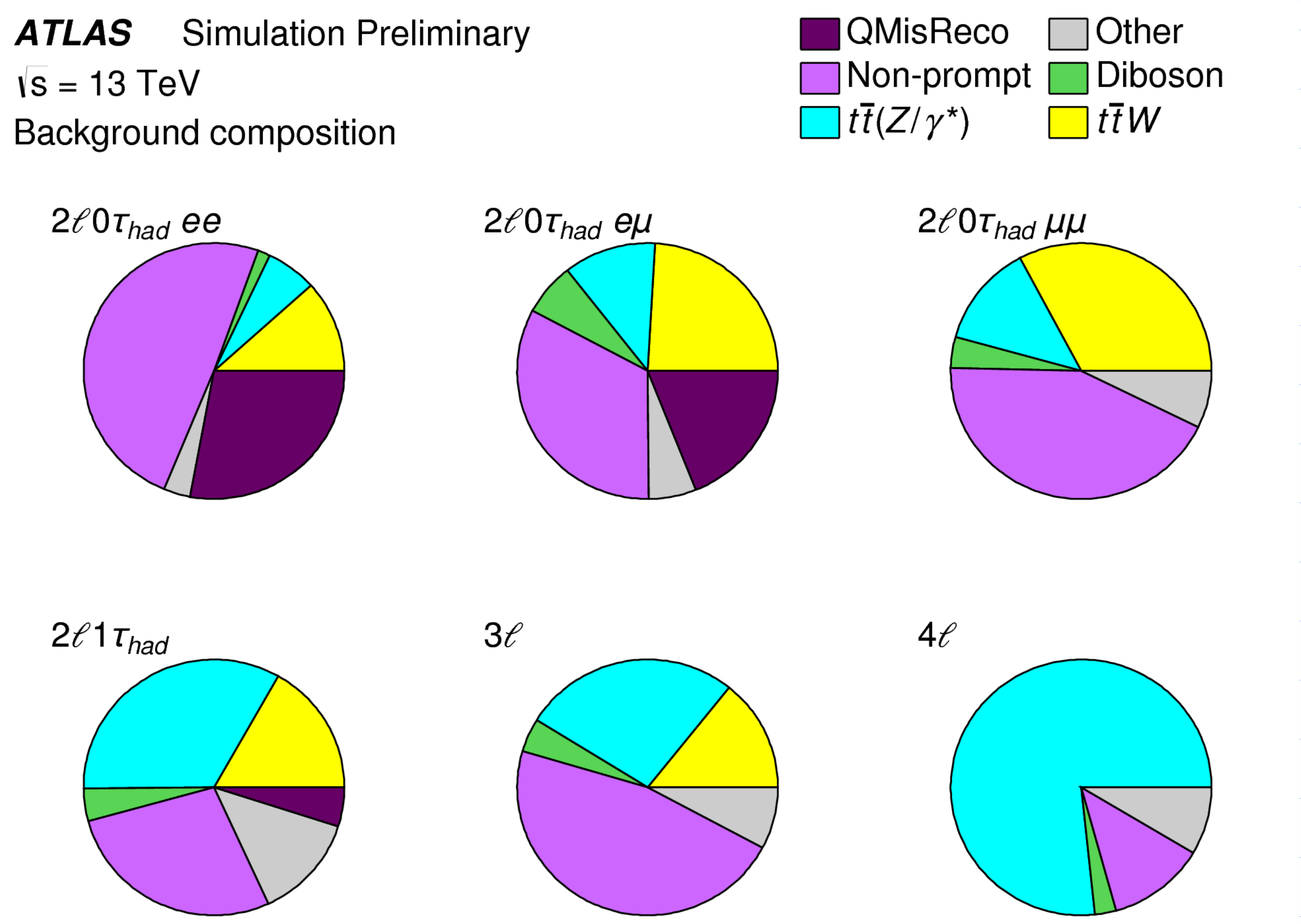

ATLAS ttH (Multi-leptons)

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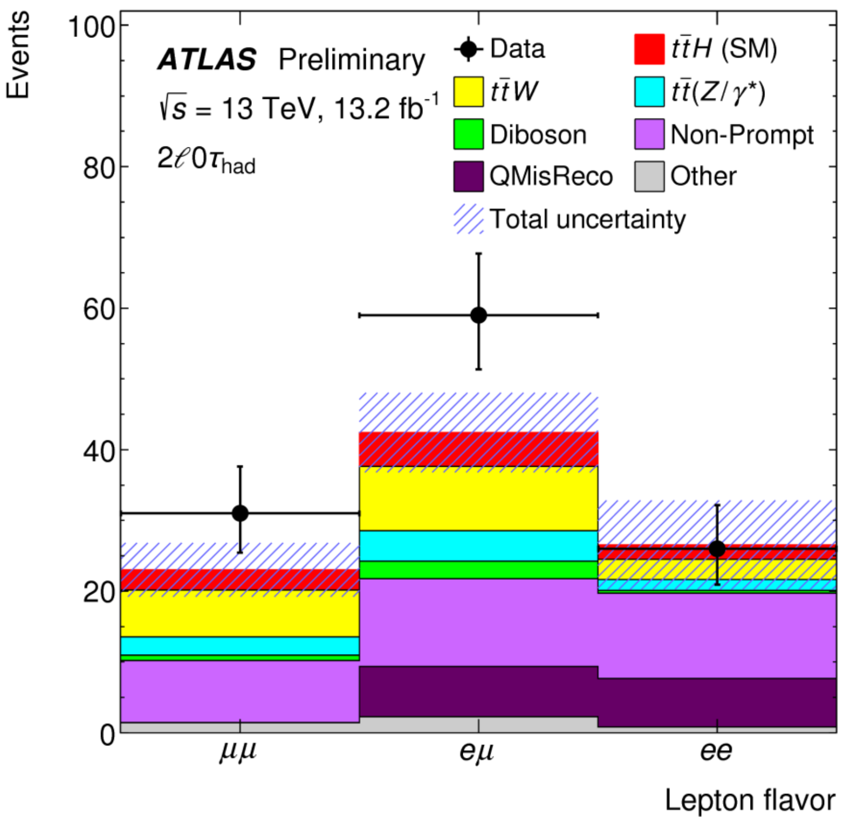
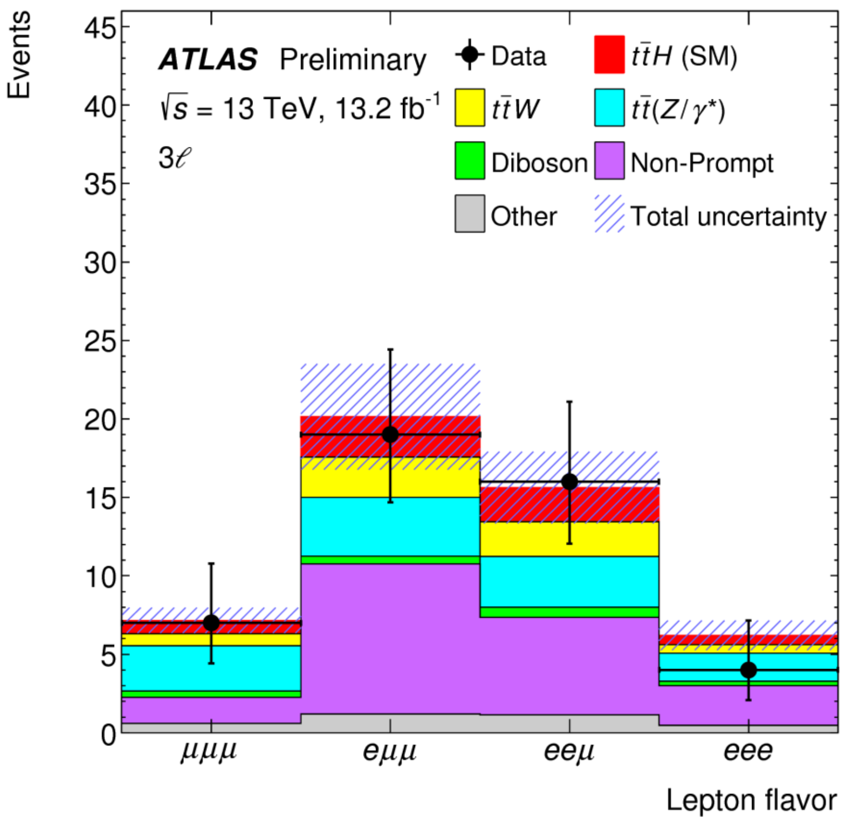
2 light leptons without tau



3 light leptons



ATLAS ttH (Multi-leptons) Candidates

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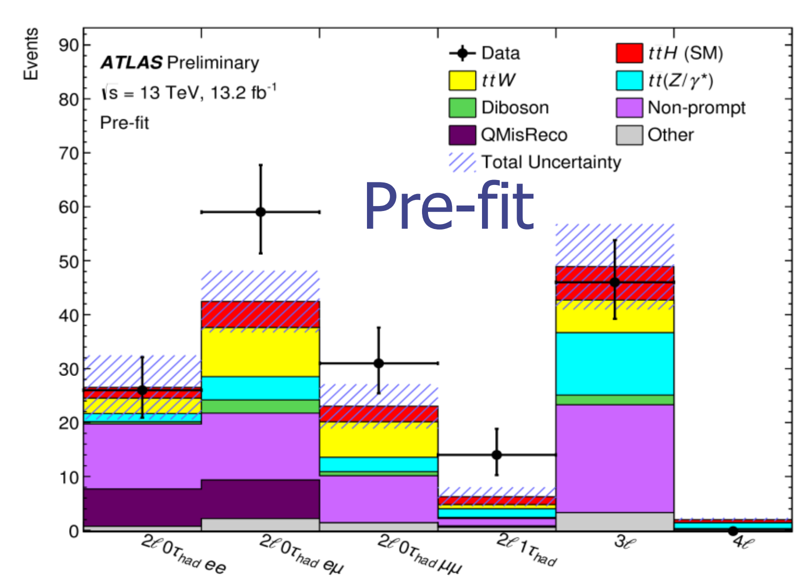

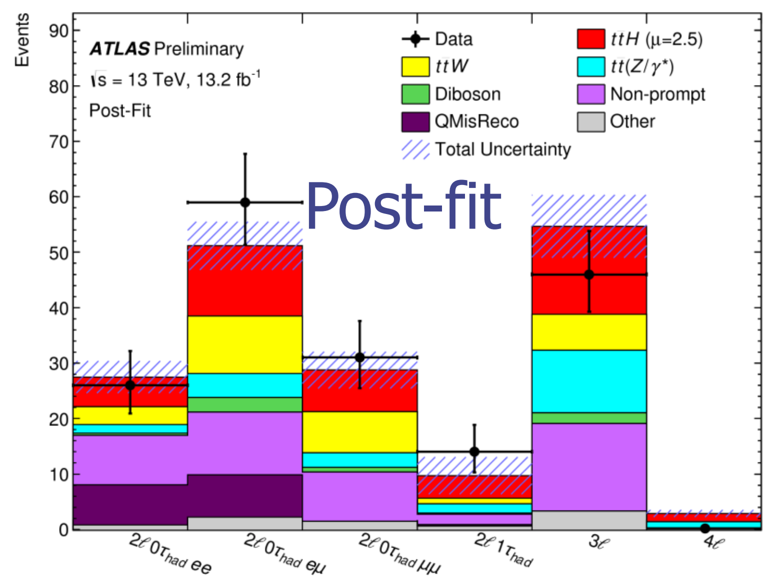

	$2\ell 0\tau_{\rm had}$ ee	$2\ell 0\tau_{\rm had}$ $e\mu$	$2\ell 0\tau_{\rm had}$ $\mu\mu$	$2\ell 1\tau_{\rm had}$	3ℓ	4ℓ
$t\bar{t}W$	3.2 ± 0.9	10.4 ± 2.9	7.4 ± 1.8	1.0 ± 0.5	6.5 ± 1.5	—
$t\bar{t}(Z/\gamma^*)$	1.53 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.7 ± 0.4	11.3 ± 1.9	1.08 ± 0.20
Diboson	0.40 ± 0.26	2.6 ± 1.5	0.8 ± 0.5	0.21 ± 0.15	1.9 ± 1.0	0.04 ± 0.04
Non-prompt leptons	9 ± 4	11 ± 4	8.9 ± 3.3	1.9 ± 1.6	15 ± 4	0.17 ± 0.10
Charge misreconstruction	7.2 ± 1.4	7.6 ± 1.8	—	0.25 ± 0.03	—	—
Other	0.83 ± 0.16	2.3 ± 0.6	1.5 ± 0.4	0.66 ± 0.16	3.4 ± 0.8	0.12 ± 0.05
Total background	22.2 ± 3.4	39 ± 5	21 ± 4	5.7 ± 1.7	39 ± 5	1.42 ± 0.24
$t\bar{t}H$ (2.5 × SM)	5.3 ± 1.8	13 ± 4	7.6 ± 2.5	4.0 ± 1.2	16 ± 5	1.5 ± 0.5
Data	26	59	31	14	46	0

ATLAS ttH (Multi-leptons) Simultaneous Fit Results $\mu=2.5^{+1.3}_{-1.1}$

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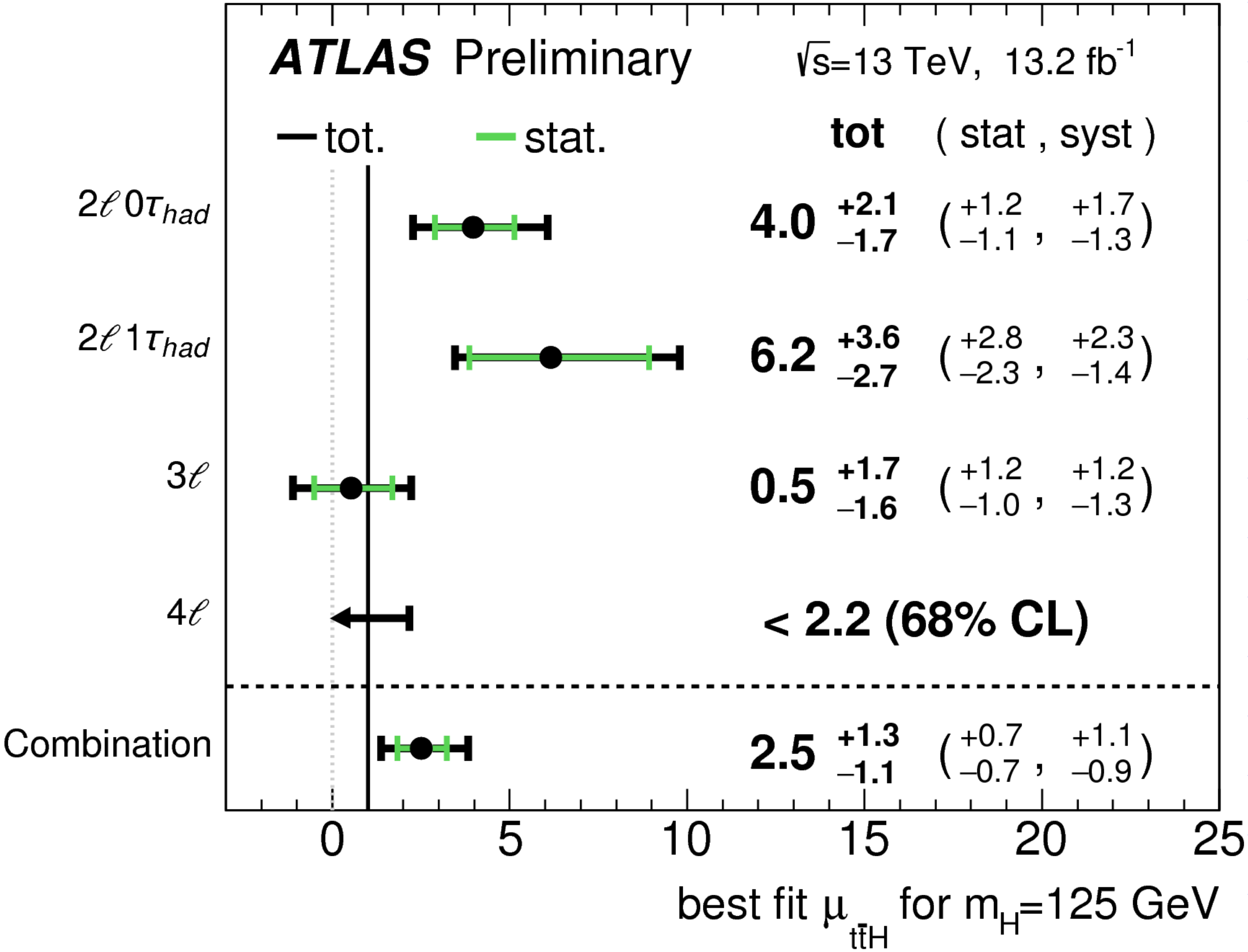
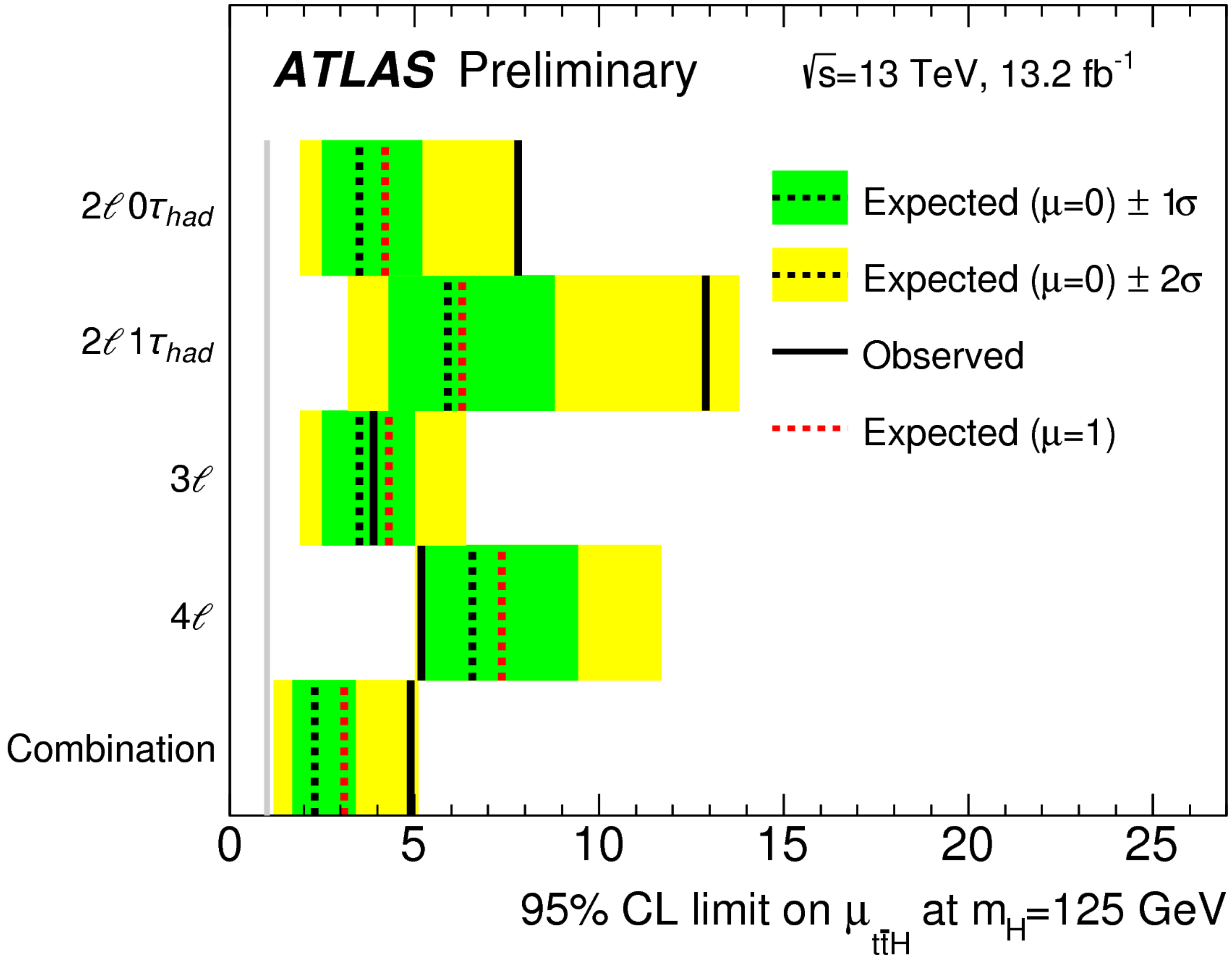


ATLAS ttH (Multi-leptons)
95% CL Limit μ<4.9 (2.3 Expected)



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Other ttH Final States

ATLAS ttH (H→γγ) Run-1 Data

Phys.Rev.D90, 112015 (2014)

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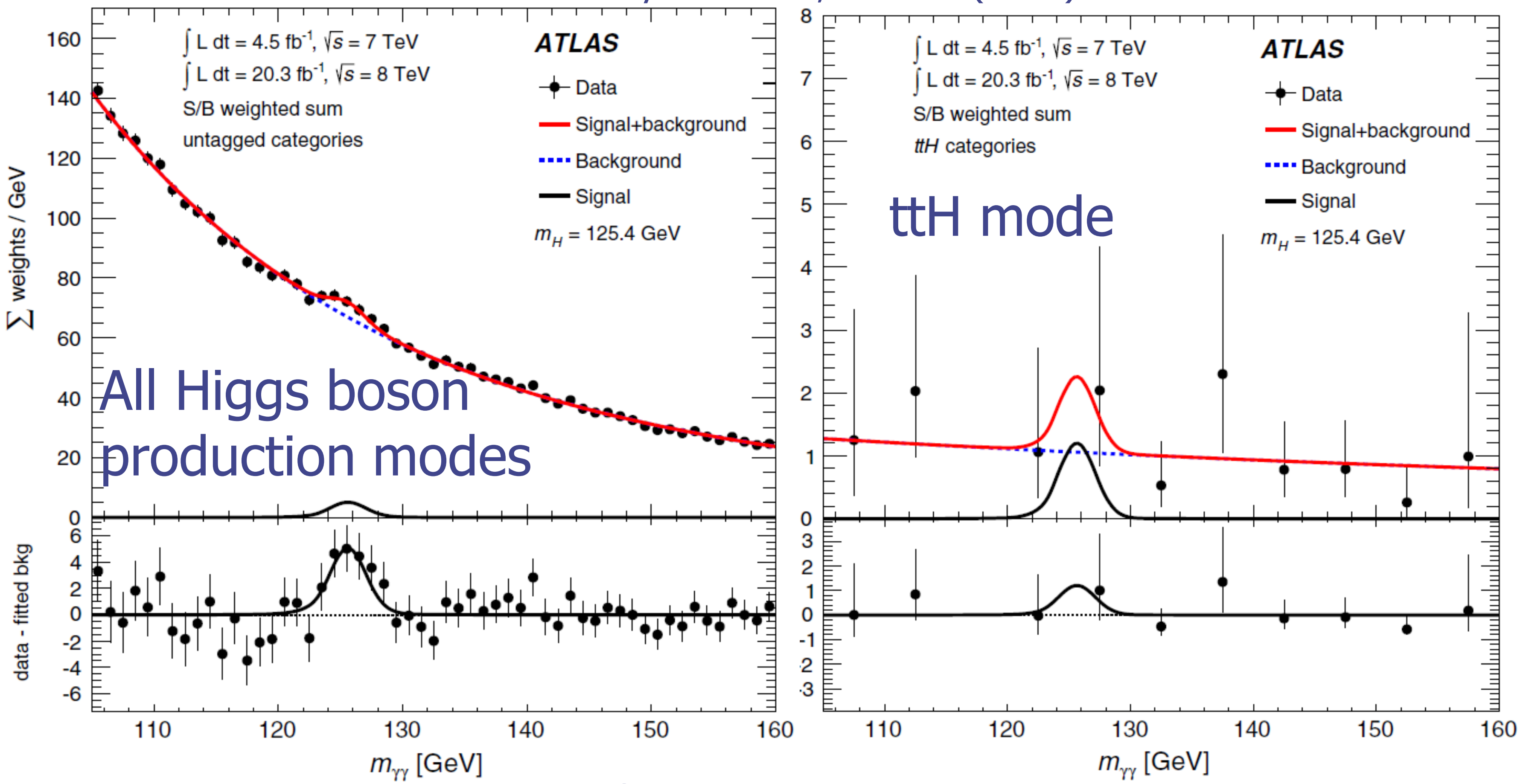
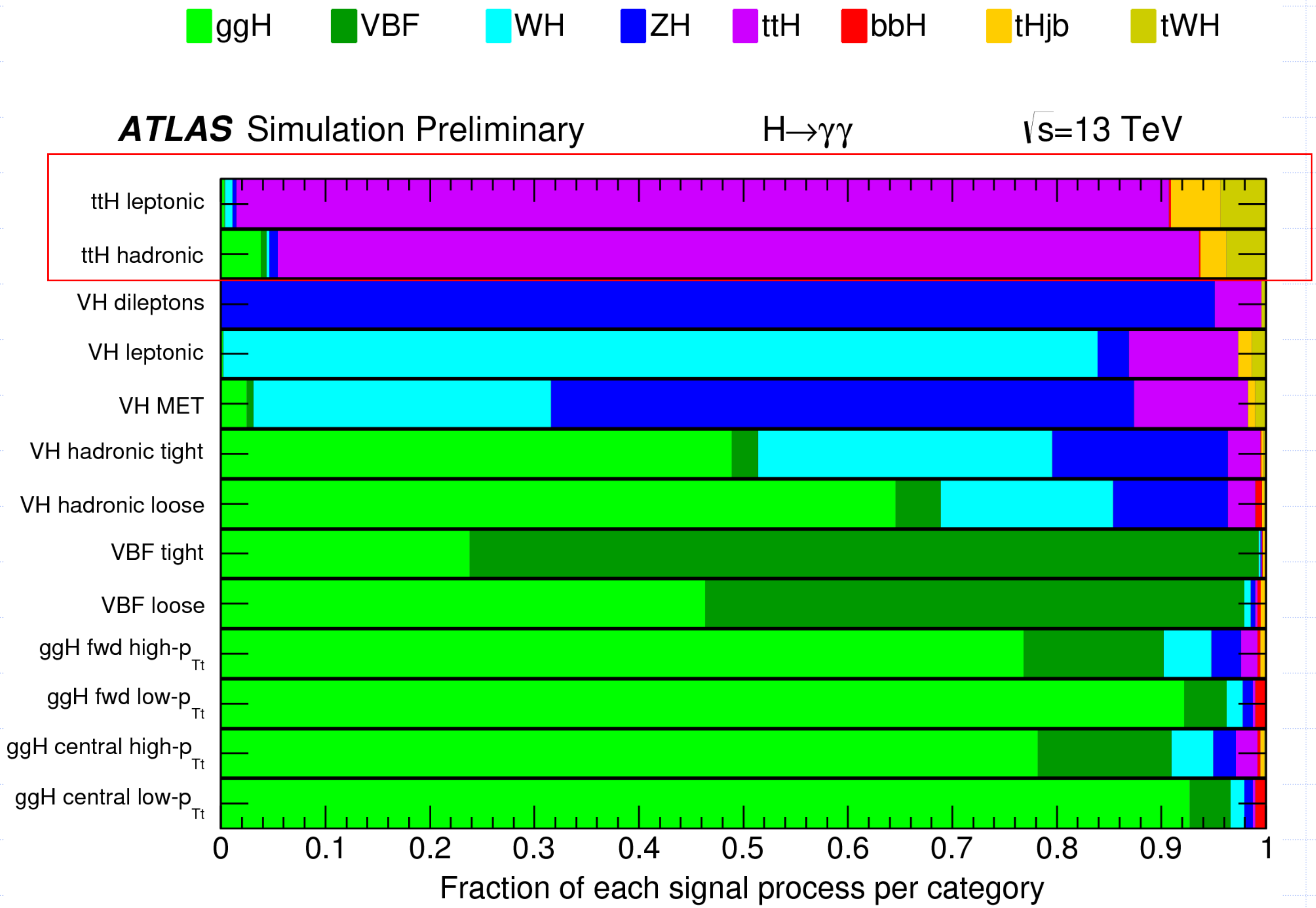


Challenge to separate ttH from other Higgs production modes (a peak in the γγ invariant mass spectrum at 125 GeV is surely from the Higgs boson).

ATLAS ttH (H→γγ) Run-2 data

ATLAS-CONF-2016-067



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ATLAS ttH (H→γγ) Run-2 data

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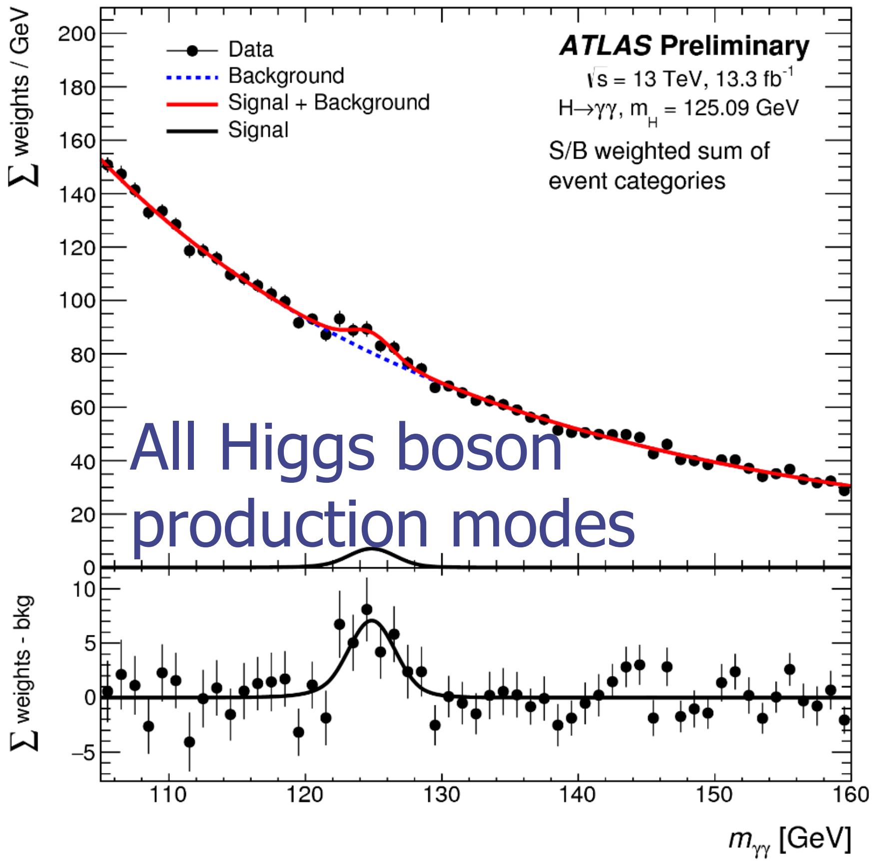
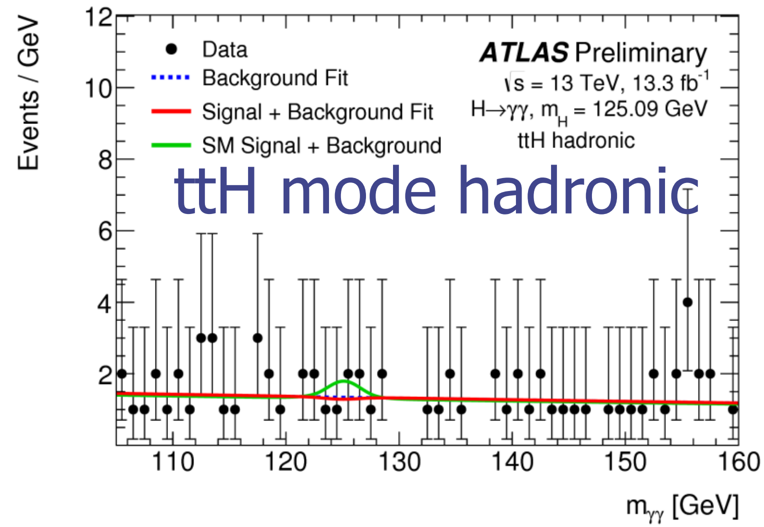
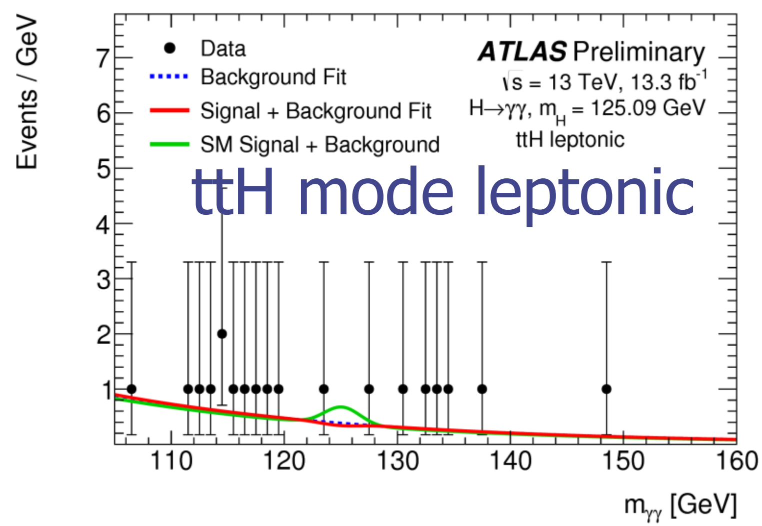
ATLAS-CONF-2016-067



All Higgs boson production modes



ttH mode hadronic



ttH mode leptonic

Loose di-photon selection sensitive to tH and anomalous couplings.

ATLAS Results
ttH (H→γγ)

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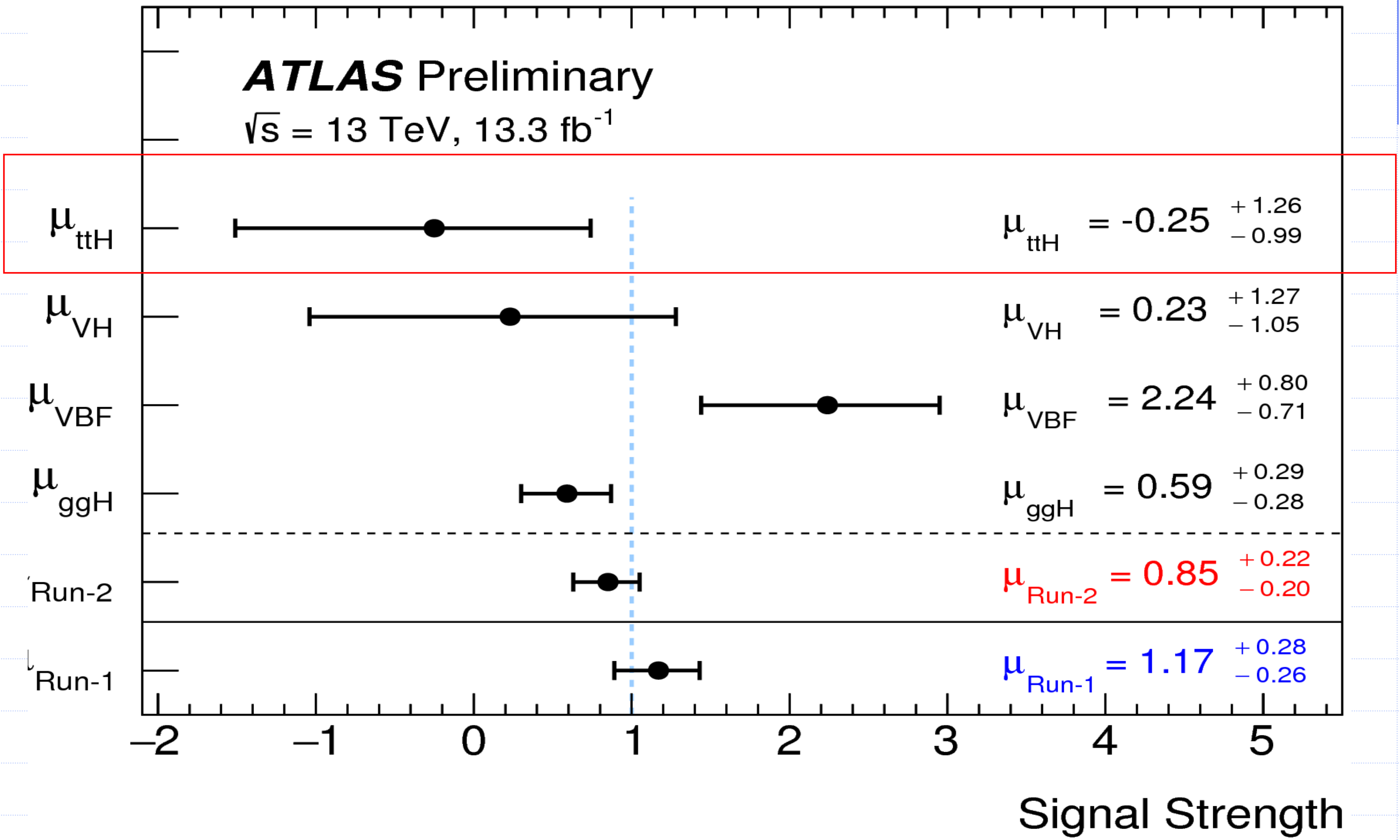
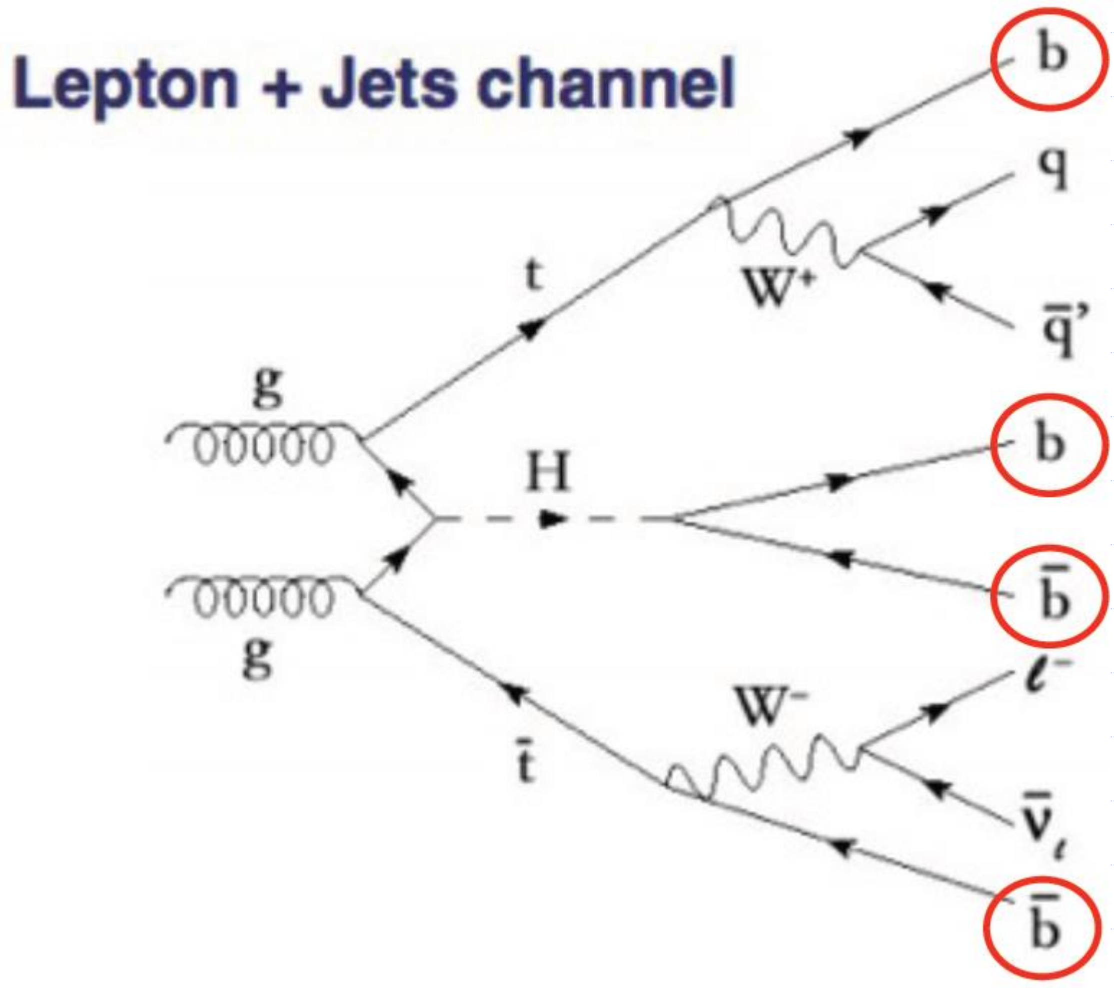


ttH (H→bb)



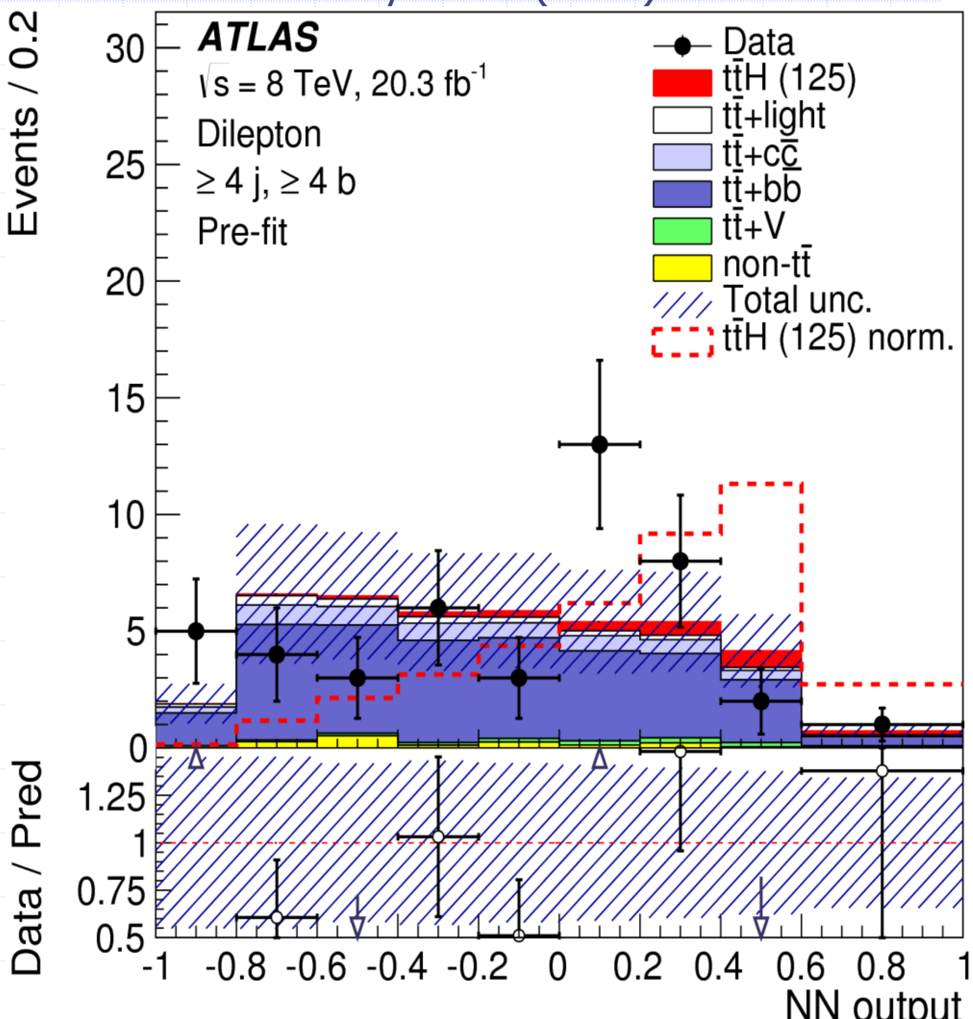
BR(H →bb)=58% for m_H=125 GeV

Categorize events by jet and b-jet multiplicity

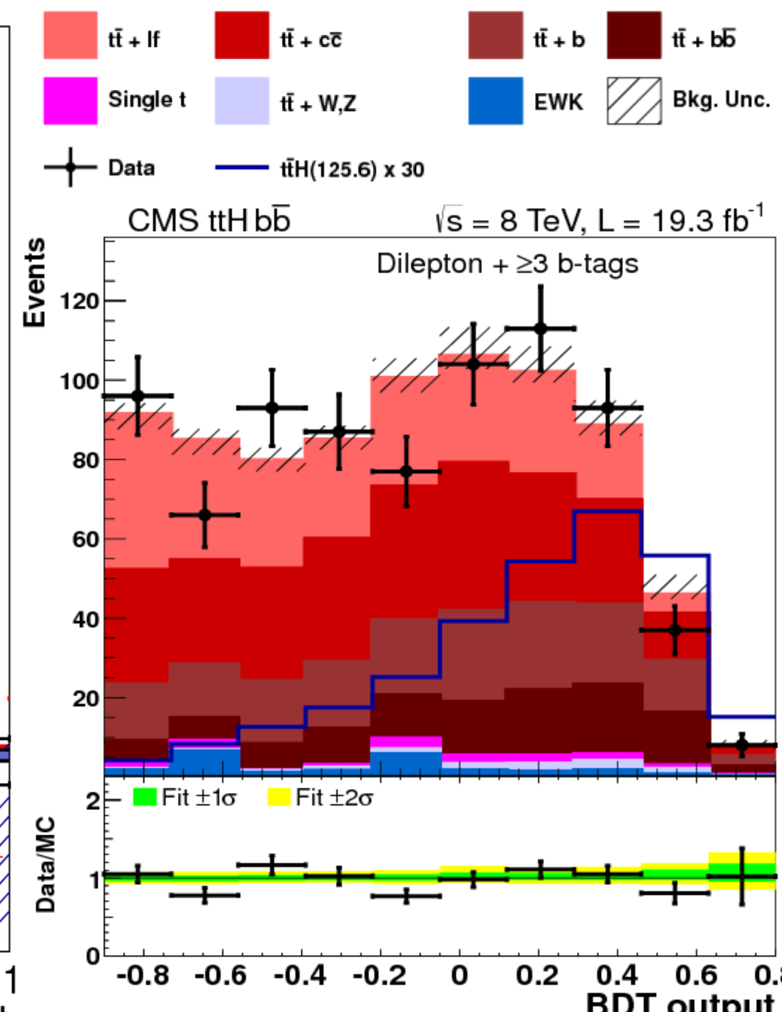
Multivariant discriminant analysis

ttH (H→bb) Run-1

Eur. Phys. J. C (2015) 75



JHEP 09 (2014) 087



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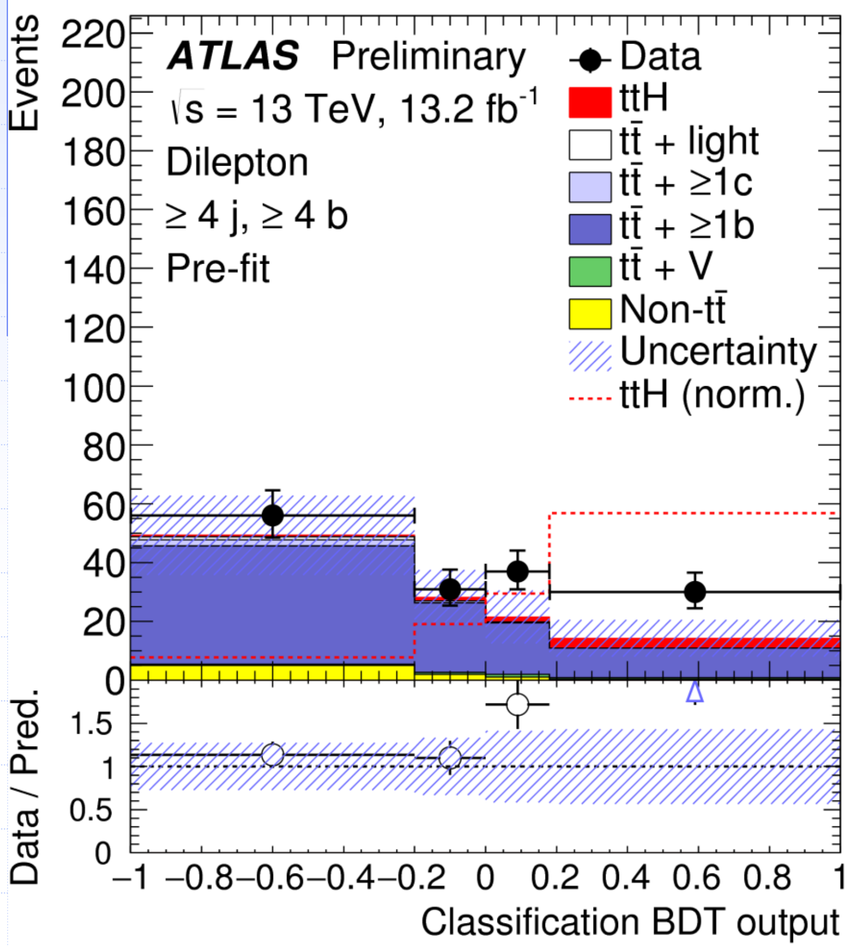
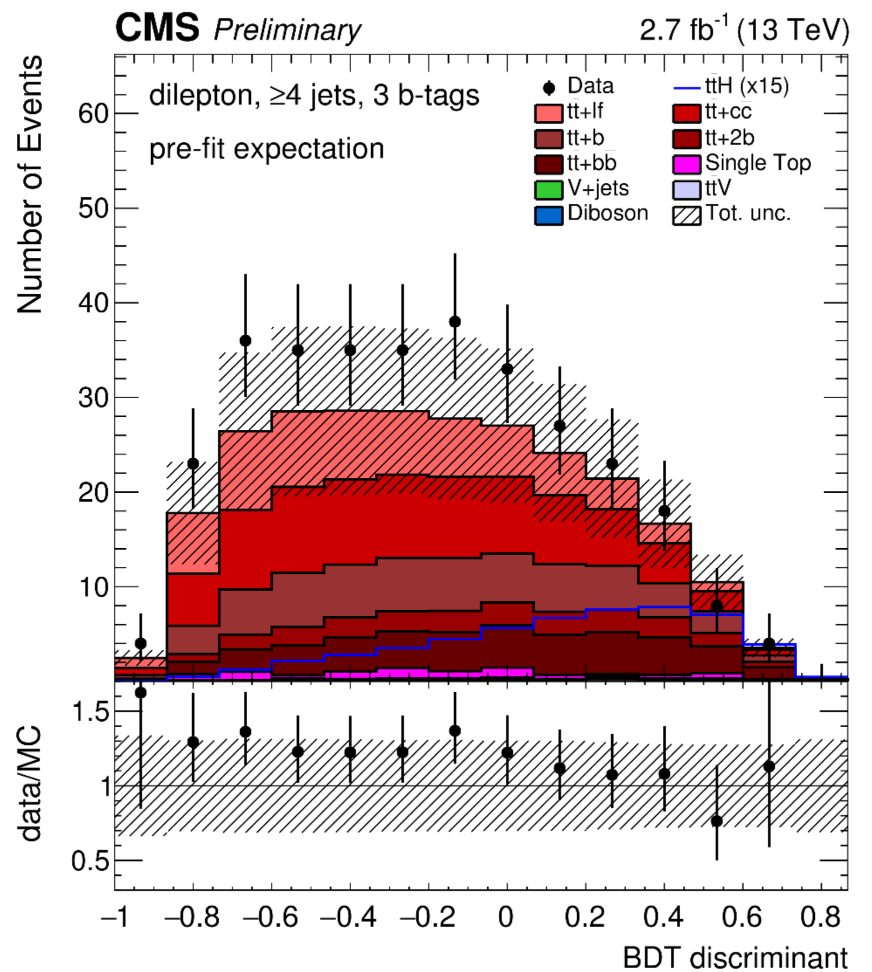
ttH (H→bb) Run-2

ATLAS-CONF-2016-080



CMS-PAS-HIG-16-004



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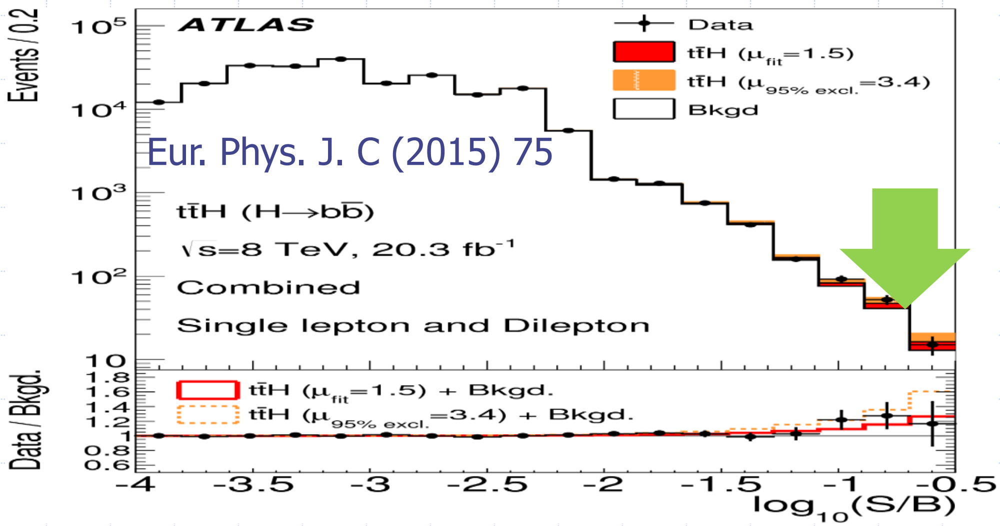
ttH (H→bb) Run-1 and Run-2



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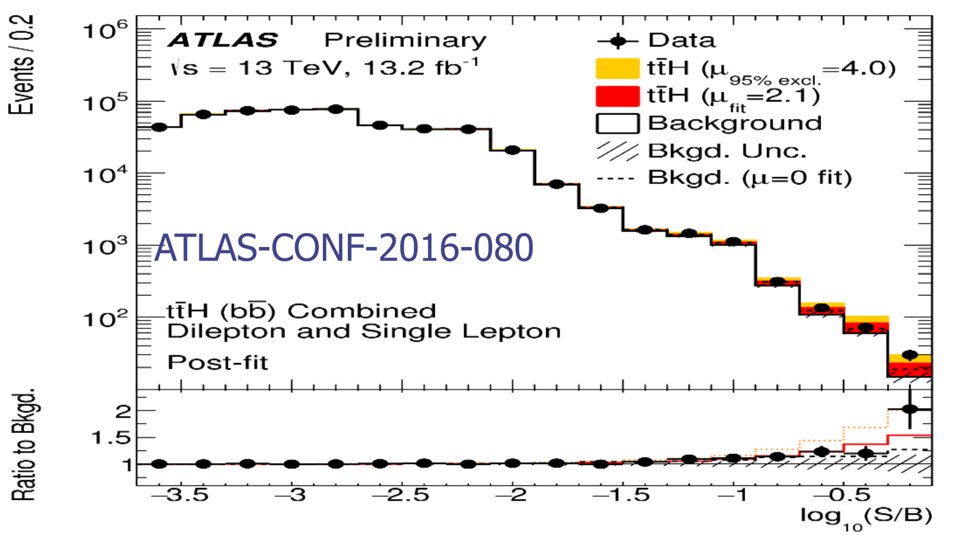
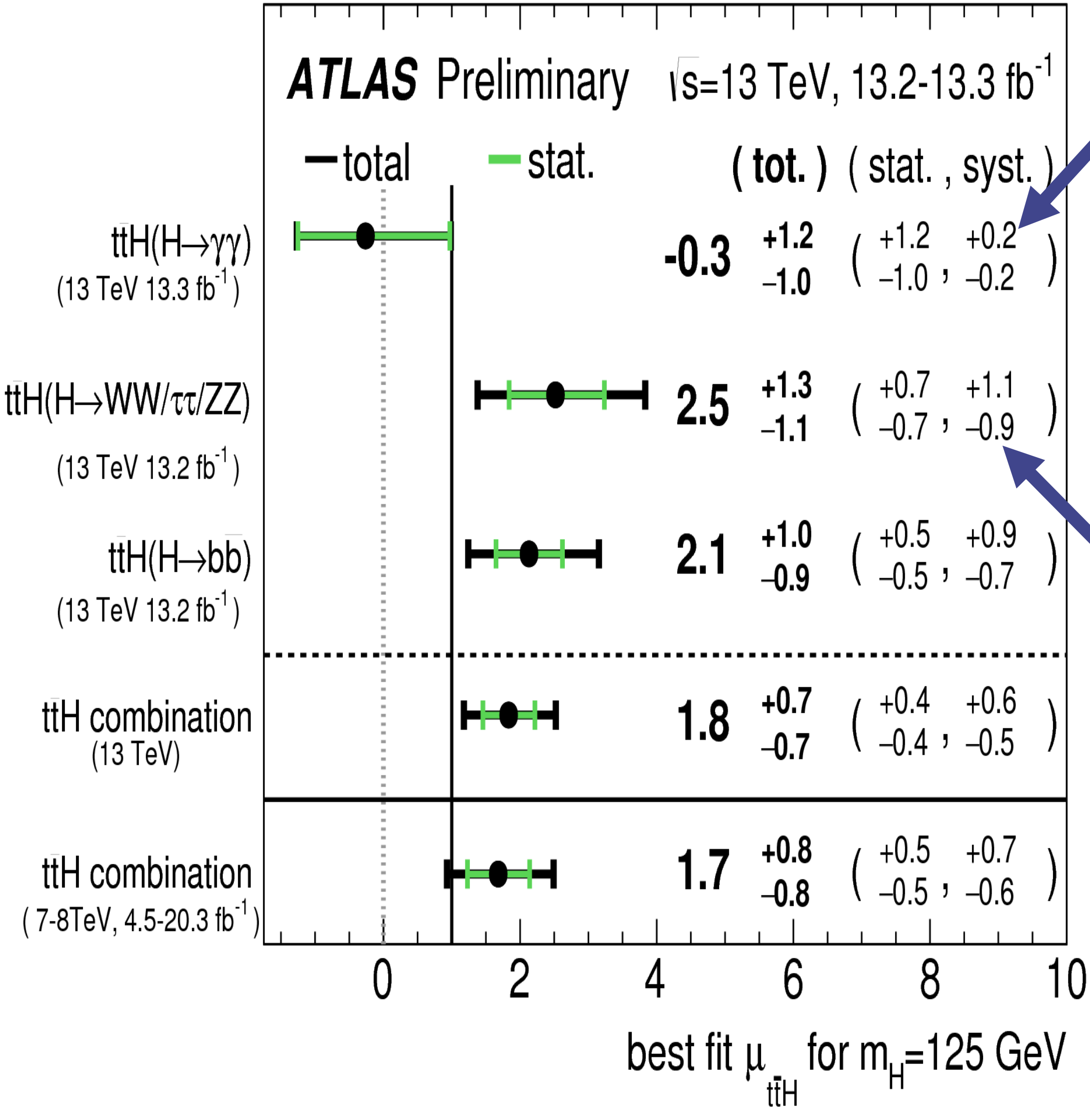


ATLAS-CONF-2016-080

Observed (expected) μ limits at 95% CL

	ATLAS	CMS
Run-1	3.4 (2.2)	4.1 (3.5)
Run-2	4.0 (1.9)	2.6 (3.6)

ATLAS ttH (Multi-lepton, γγ, bb) Results



Analytic functions and fit to the data sidebands to estimate continuum background.

Non-prompt background (heavy-flavour). Mis-reconstruction of el. charge. Irreducible bckg (diboson, ttW, ttZ simulation).

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Run-1 ttH multi-lepton final state: number of events (CMS)

JHEP 09 (2014) 087

	ee	$e\mu$	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}H$, $H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H$, $H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H$, $H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

Run-2 ttH multi-lepton final state: number of events (CMS)

CMS-PAS-HIG-16-022

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	$\mu\mu$	ee	$e\mu$	3ℓ
$t\bar{t}W$	18.3 ± 0.9	6.8 ± 0.6	24.5 ± 1.1	12.2 ± 0.7
$t\bar{t}Z/\gamma^*$	5.8 ± 0.6	7.4 ± 0.6	15.3 ± 1.3	22.6 ± 1.0
Di-boson	1.4 ± 0.2	1.1 ± 0.2	2.6 ± 0.3	5.7 ± 0.4
tttt	0.8 ± 0.2	0.4 ± 0.1	1.5 ± 0.2	1.2 ± 0.1
tqZ	0.2 ± 0.3	0.4 ± 0.4	0.6 ± 0.6	2.7 ± 0.8
Rare SM bkg.	1.6 ± 0.3	0.5 ± 0.1	1.8 ± 0.1	0.3 ± 0.1
Charge mis-meas.		6.7 ± 0.1	10.0 ± 0.1	
Non-prompt leptons	33.4 ± 1.2	23.1 ± 1.1	61.9 ± 1.7	51.0 ± 1.8
All backgrounds	61.5 ± 1.7	46.4 ± 1.5	118.0 ± 2.5	95.7 ± 2.3
$t\bar{t}H$ ($H \to WW^*$)	6.3 ± 0.2	2.6 ± 0.1	8.5 ± 0.2	8.0 ± 0.2
$t\bar{t}H$ ($H \to \tau\tau$)	1.6 ± 0.1	0.7 ± 0.1	2.5 ± 0.1	2.1 ± 0.1
$t\bar{t}H$ ($H \to ZZ^*$)	0.2 ± 0.0	0.1 ± 0.0	0.3 ± 0.0	0.5 ± 0.0
Data	74	45	154	105

Category	Obs. limit	Exp. limit $\pm 1\sigma$	Best fit μ $\pm 1\sigma$
Same-sign dileptons	4.6	$1.7^{+0.9}_{-0.5}$	$2.7^{+1.1}_{-1.0}$
Trileptons	3.7	$2.3^{+1.2}_{-0.7}$	$1.3^{+1.2}_{-1.0}$
Combined categories	3.9	$1.4^{+0.7}_{-0.4}$	$2.3^{+0.9}_{-0.8}$
Combined with 2015 data	3.4	$1.3^{+0.6}_{-0.4}$	$2.0^{+0.8}_{-0.7}$

Run-2 CMS: up to August 2016 data

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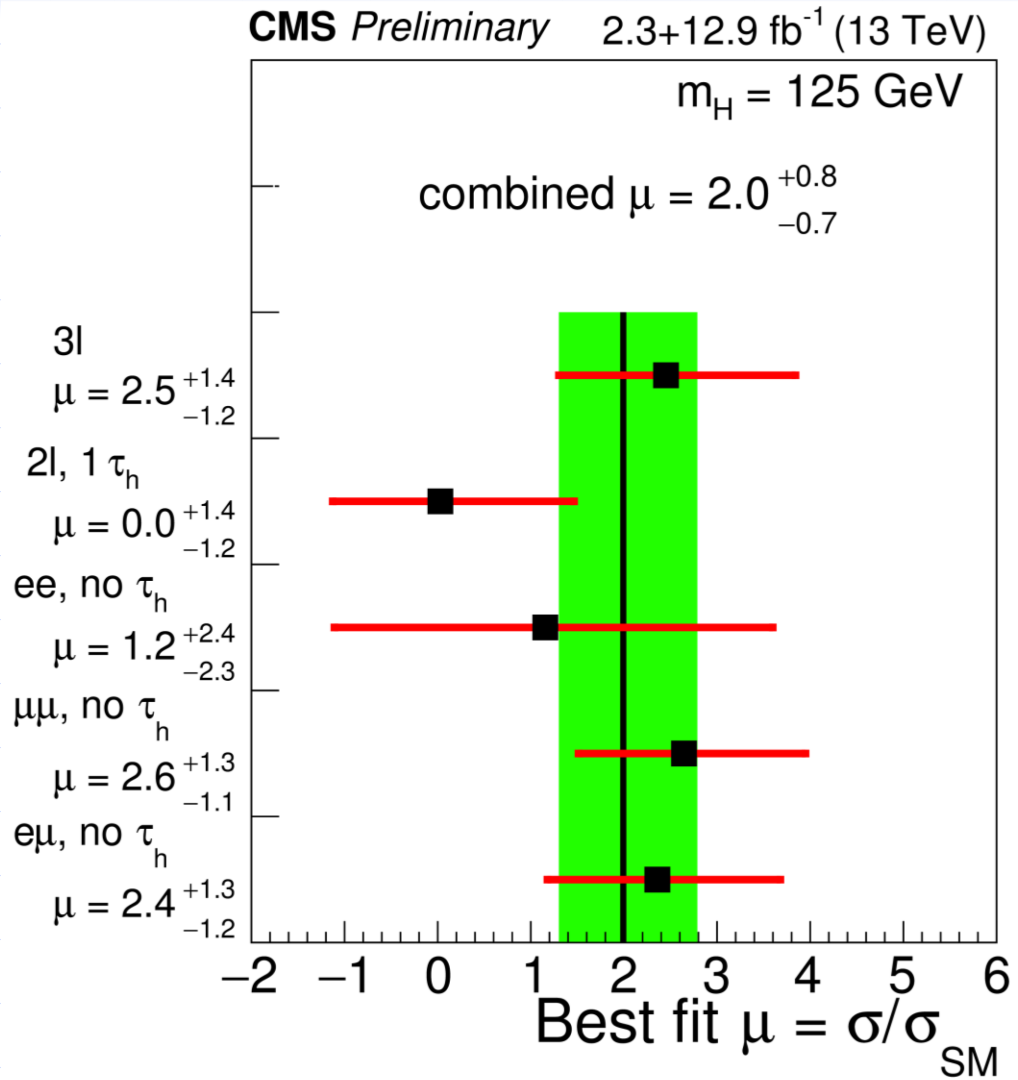

ttH, H→multilepton

$$\mu(ttH) = 2.0^{+0.8}_{-0.7}$$

ttH, H→γγ

$$\mu(ttH) = 1.9^{+1.5}_{-1.2}$$

Combined ATLAS and CMS ttH Results

Recall Run-1: The ATLAS and CMS Collaborations, JHEP 08 (2016) 045

Run-2: work in progress

LHC Run-1 Status: ttH Coupling 2.3σ Above SM Expectation

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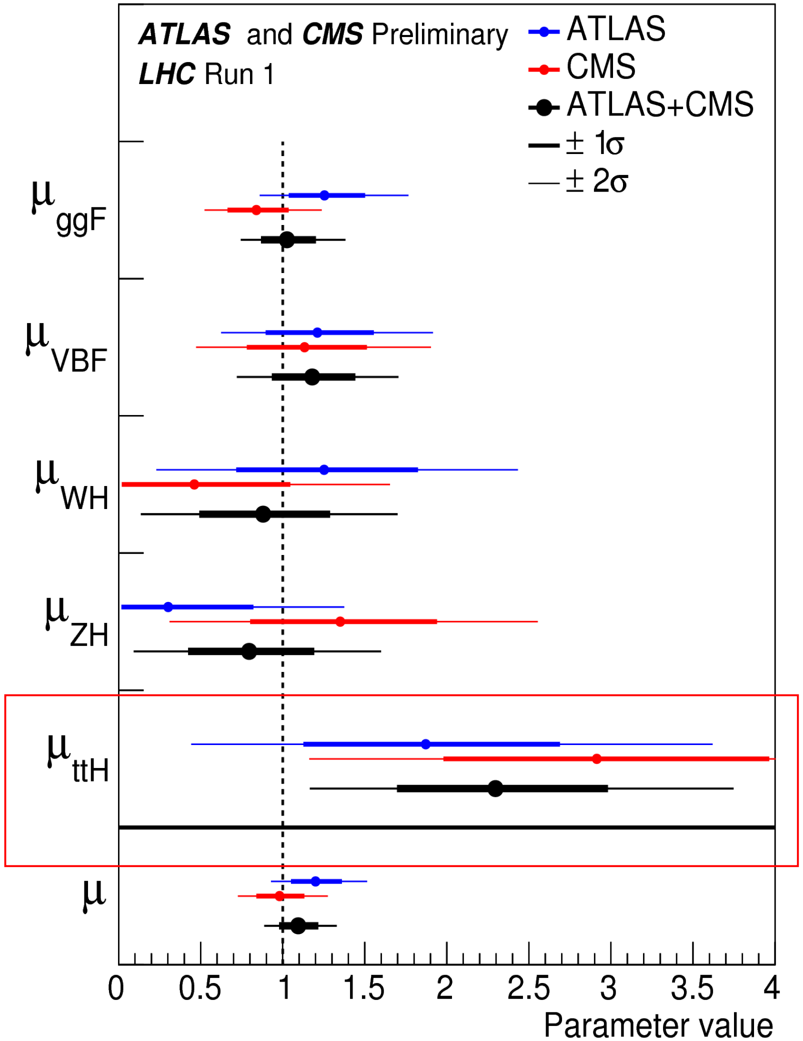
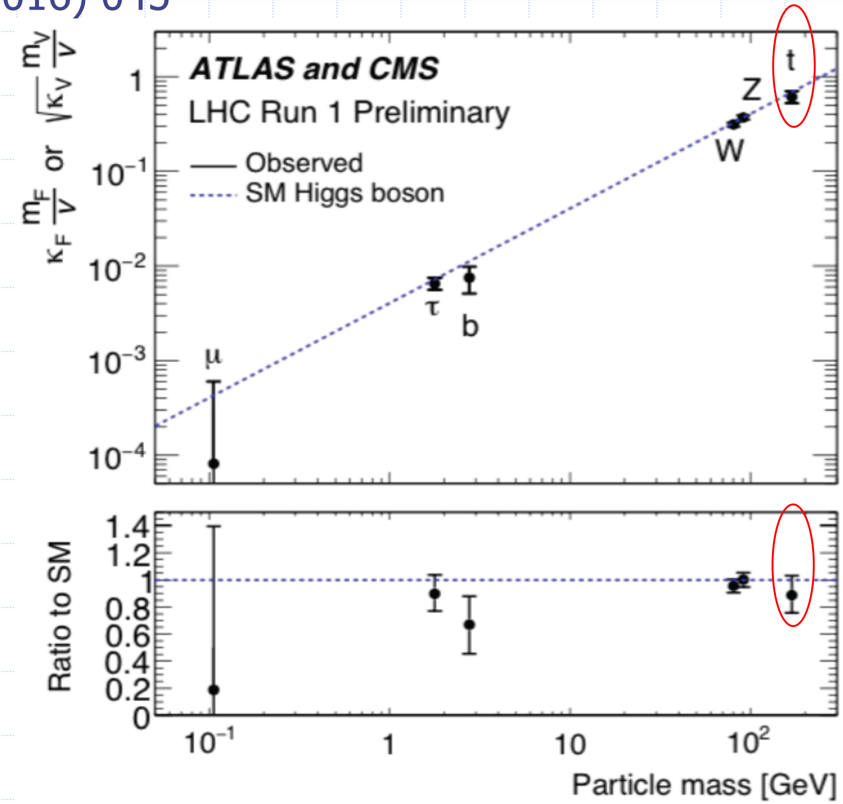
JHEP 08 (2016) 045





$$\mu(ttH) = 2.3^{+0.7}_{-0.6}$$

Run-1&2 Summary of ttH Coupling Measurements

μ(ttH)	Run-1	Run-2
ATLAS	$2.3^{+0.7}_{-0.6}$	$1.8^{+0.7}_{-0.7}$
CMS		$2.0^{+0.8}_{-0.7}$

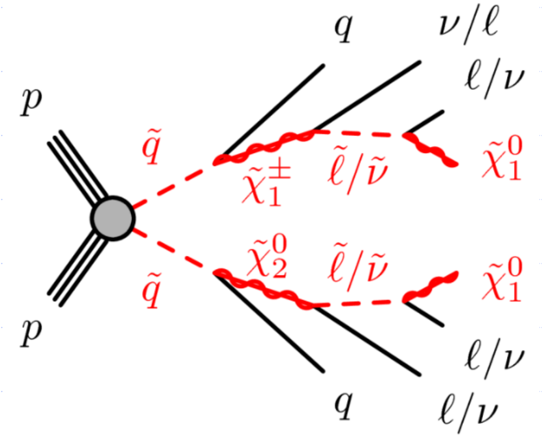
Simple combination $\mu(ttH) = 2.03^{+0.42}_{-0.38}$

Deviation from 1: 2.7σ

Deviation from 0: 5.3σ

Interpretation pMSSM

- Idea: testing pMSSM scenarios for overlapping signature with ttH analyses (example ttH multileptons)
- G. Aad et al. [ATLAS Collaboration], "Summary of the ATLAS experiments sensitivity to supersymmetry after LHC Run 1 interpreted in the phenomenological MSSM," JHEP 1510 (2015) 134.)



- Two pMSSM scenarios identified (same-charge dilepton and tau) which could mimic ttH events. Significant efficiencies.
- One scenario similar to the one described in P. Huang, A. Ismail, I. Low and C. E. M. Wagner, "Same-Sign Dilepton Excesses and Light Top Squarks," Phys. Rev. D **92** (2015) 7, 075035.

Conclusions and Outlook

- ttH direct measurement is the key reaction to determine top Yukawa coupling independent of new physics in the gluon-Higgs sector.
- Multiple analysis channels contribute sensitivity.
- Excellent LHC Run-2 operation and ATLAS data recording.
- About 36 fb^{-1} recorded and 13 fb^{-1} analysed at 13 TeV.
- Increased sensitivity with initial Run-2 data compared to Run-1 results. Focus on systematics and new techniques.
- $\mu = 2.0 \pm 0.4$ (simple comb.) Run-1 and 13 fb^{-1} Run-2 data

Outlook:

- Excellent prospects for establishing ttH signal.
- Strong exclusion of models predicting non-SM ttH rates or observing new physics.
- Interest in experimental/theory collaboration for ttH.

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Supplements

ttH (Multi-leptons) Tight and Loose Light Lepton Definitions

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	Loose		Tight	
	e	μ	e	μ
Track isolation	99% eff.	99% eff.	$< 0.06 \times p_{\mathrm{T}}$ (*)	$< 0.06 \times p_{\mathrm{T}}$ (*)
Calorimeter isolation	99% eff.	99% eff.	$< 0.06 \times p_{\mathrm{T}}$ (*)	99% eff. (*)
Identification working point	Loose	Loose	Tight	Loose
Transverse impact parameter $\|d_0\|/\sigma_{d_0}$	< 5	< 3	< 5	< 3
z impact parameter $\|\Delta z_0 \sin\theta_\ell\|$	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm

- Selections for tight leptons are applied on top of the selections for loose leptons

ttH (Multi-leptons) Selection Signal (SR) and Validation Regions (VR)

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SR/VR	Channel	Selection criteria
SR	$2\ell 0\tau_{\mathrm{had}}$	Two tight light leptons with $p_{\mathrm{T}} > 25$, 25 GeV Sum of light lepton charges ± 2 Any electrons must have $\lvert\eta_e\rvert < 1.37$ Zero τ_{had} candidates $N_{\mathrm{jets}} \geq 5$ and $N_{b-\mathrm{jets}} \geq 1$
SR	$2\ell 1\tau_{\mathrm{had}}$	Two tight light leptons, with $p_{\mathrm{T}} > 25$, 15 GeV Sum of light lepton charges ± 2 Exactly one τ_{had} candidate, of opposite charge to the light leptons $\lvert m(ee) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for ee events $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$
SR	3ℓ	Three light leptons; sum of light lepton charges ± 1 Two same-charge leptons must be tight and have $p_{\mathrm{T}} > 20$ GeV $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$, or $N_{\mathrm{jets}} = 3$ and $N_{b-\mathrm{jets}} \geq 2$
SR	4ℓ	Four light leptons; sum of light lepton charges 0 All leptons pass "gradient" isolation selection $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert > 10$ GeV for all SFOC pairs 100 GeV $< m(4\ell) <$ 350 GeV and $\lvert m(4\ell) - 125\ \mathrm{GeV}\rvert > 5$ GeV $N_{\mathrm{jets}} \geq 2$ and $N_{b-\mathrm{jets}} \geq 1$
VR	Tight $t\bar{t}Z$	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 2$
VR	Loose $t\bar{t}Z$	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 4$ and $N_{b-\mathrm{jets}} \geq 1$, or $N_{\mathrm{jets}} = 3$ and $N_{b-\mathrm{jets}} \geq 2$
VR	WZ + 1 b-tag	3ℓ lepton selection %and trigger selection At least one $\ell^+\ell^-$ pair with $\lvert m(\ell^+\ell^-) - 91.2\ \mathrm{GeV}\rvert < 10$ GeV $N_{\mathrm{jets}} \geq 1$ and $N_{b-\mathrm{jets}} = 1$
VR	$t\bar{t}W$	$2\ell 0\tau_{\mathrm{had}}$ lepton selection %and trigger selection $2 \leq N_{\mathrm{jets}} \leq 4$ and $N_{b-\mathrm{jets}} \geq 2$ $H_{\mathrm{T,jets}} > 220$ GeV for ee and $e\mu$ events $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and ($m(ee) < 75$ or $m(ee) > 105$ GeV) for ee events

ttH (Multi-leptons) Signal and Main Background Pre-fit

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	$2\ell 0\tau_{\rm had}$ ee	$2\ell 0\tau_{\rm had}$ $e\mu$	$2\ell 0\tau_{\rm had}$ $\mu\mu$	$2\ell 1\tau_{\rm had}$	3ℓ	4ℓ
$t\bar{t}W$	2.9 ± 0.7	9.1 ± 2.5	6.6 ± 1.6	0.8 ± 0.4	6.1 ± 1.3	—
$t\bar{t}(Z/\gamma^*)$	1.55 ± 0.29	4.3 ± 0.9	2.6 ± 0.6	1.6 ± 0.4	11.5 ± 2.0	1.12 ± 0.20
Diboson	0.38 ± 0.25	2.5 ± 1.4	0.8 ± 0.5	0.20 ± 0.15	1.8 ± 1.0	0.04 ± 0.04
Non-prompt leptons	12 ± 6	12 ± 5	8.7 ± 3.4	1.3 ± 1.2	20 ± 6	0.18 ± 0.10
Charge misreconstruction	6.9 ± 1.3	7.1 ± 1.7	—	0.24 ± 0.03	—	—
Other	0.81 ± 0.22	2.2 ± 0.6	1.4 ± 0.4	0.63 ± 0.15	3.3 ± 0.8	0.12 ± 0.05
Total background	25 ± 6	38 ± 6	20 ± 4	4.8 ± 1.4	43 ± 7	1.46 ± 0.25
$t\bar{t}H$ (SM)	2.0 ± 0.5	4.8 ± 1.0	2.9 ± 0.6	1.43 ± 0.31	6.2 ± 1.1	0.59 ± 0.10
Data	26	59	31	14	46	0

- ``Other" backgrounds include tZ, tWZ, tHqb, tHW, tttt, ttWW, and triboson production

ttH (Multi-leptons) Effects of Systematic Uncertainties on μ

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Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	$+0.56$	-0.64
Jet-vertex association, pileup modeling	$+0.48$	-0.36
$t\bar{t}W$ modeling	$+0.29$	-0.31
$t\bar{t}H$ modeling	$+0.31$	-0.15
Jet energy scale and resolution	$+0.22$	-0.18
$t\bar{t}Z$ modeling	$+0.19$	-0.19
Luminosity	$+0.19$	-0.15
Diboson modeling	$+0.15$	-0.14
Jet flavor tagging	$+0.15$	-0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	$+0.12$	-0.10
Other background modeling	$+0.11$	-0.11
Total systematic uncertainty	$+1.1$	-0.9

- Due to correlations between the different sources of uncertainties, the total systematic uncertainty can be different from the sum in quadrature of the individual sources.

pMSSM scenarios-1 (dilepton+tau channel)

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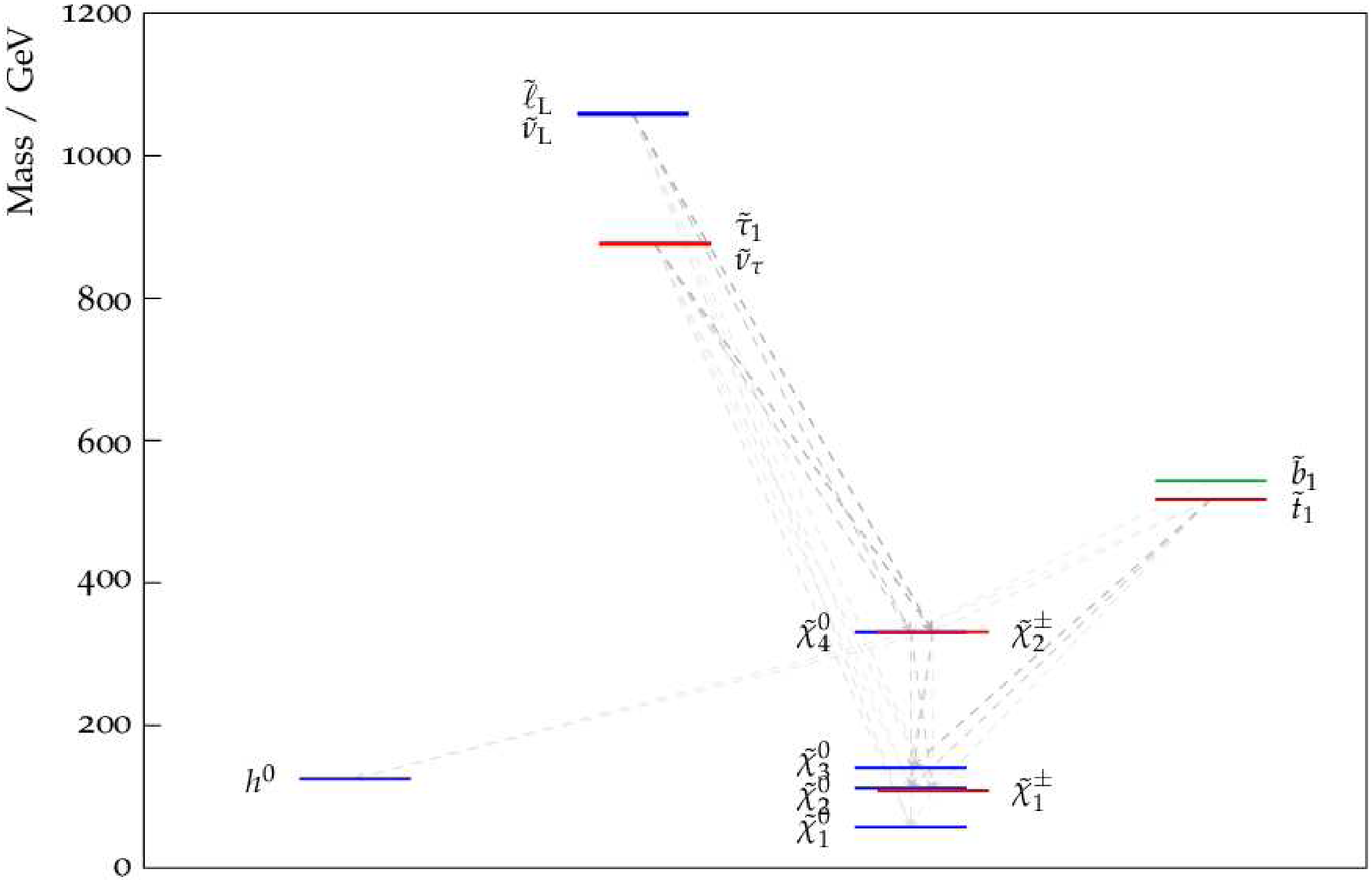
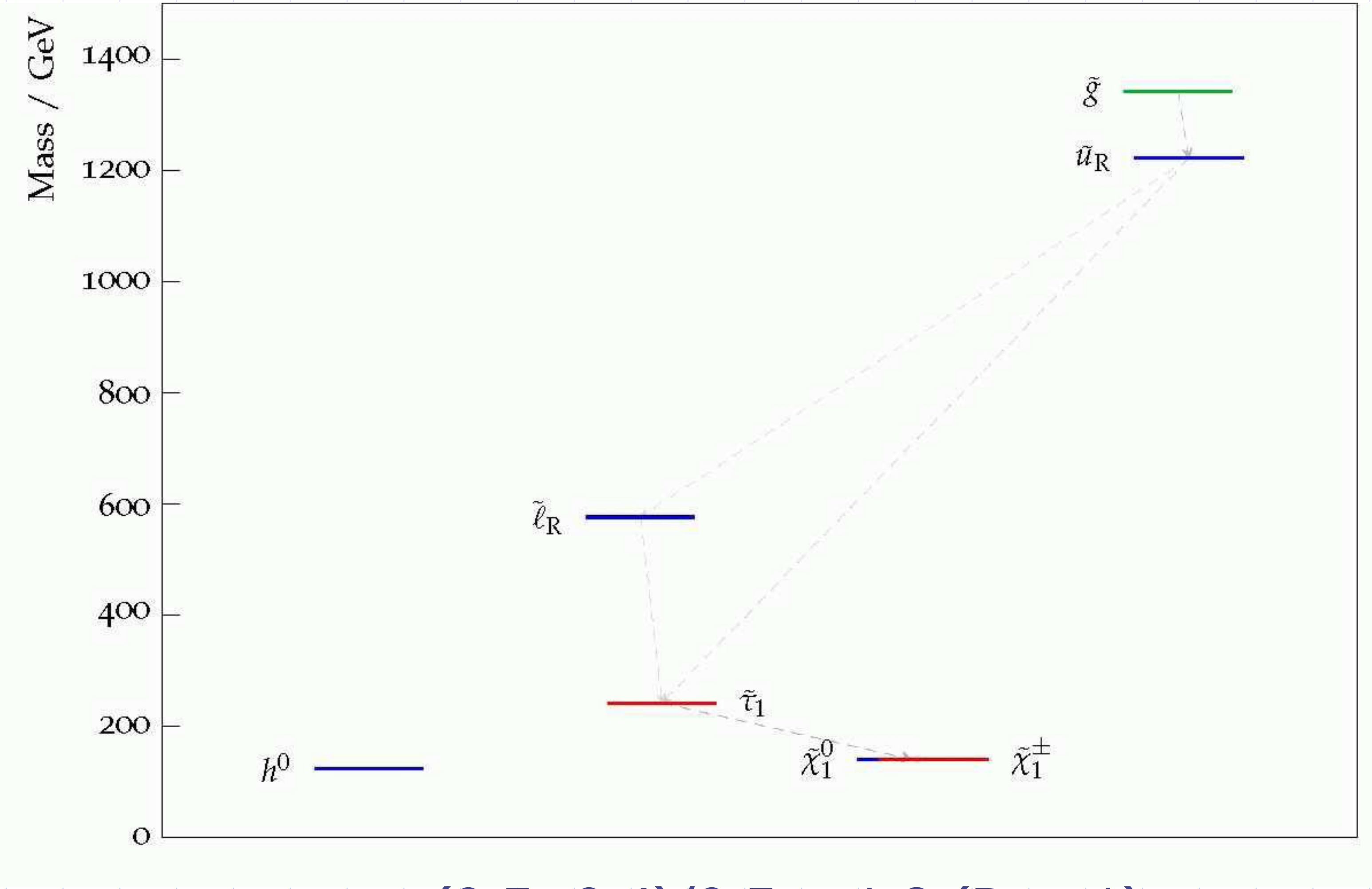


$\mu = (0.5+1.3)/0.5 = 3.6$ (Run-1)

pMSSM scenarios-2 (dilepton+tau channel)



μ = (0.5+0.4)/0.5 = 1.8 (Run-1)