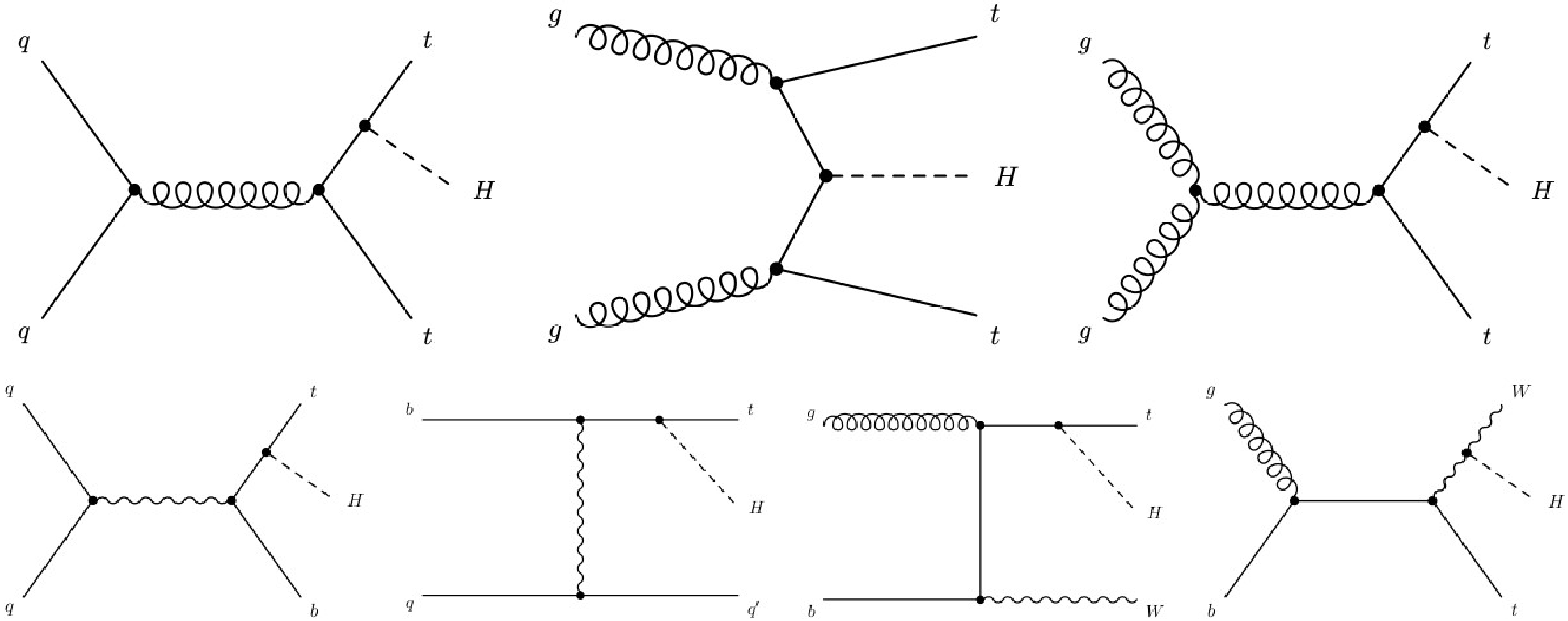
Recent ttH (tH) results from ATLAS



Henri Bachacou

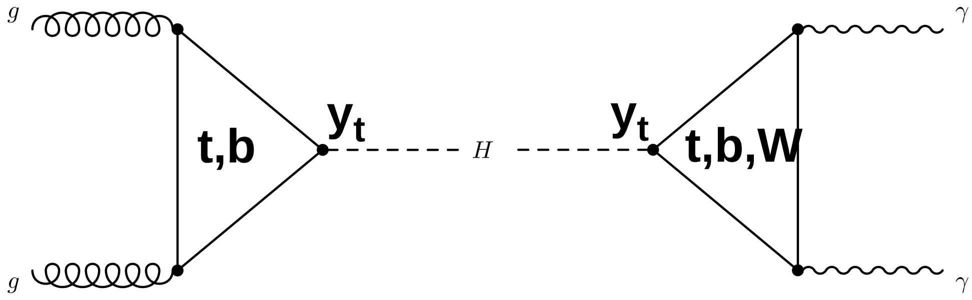
on behalf of the ATLAS collaboration

irfu
cea
saclay

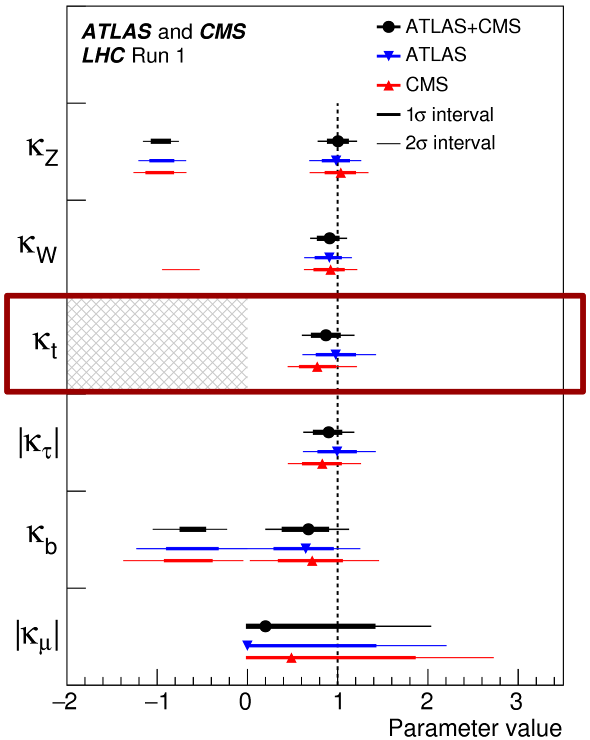
Why look for ttH (tH)?

- top Yukawa coupling in loops:
  - → Higgs gluon fusion production
  - → Higgs diphoton decay
- Can be extracted from fit of all production and decay modes
- Run 1 CMS-ATLAS result:

  $k_t = y_t/y_t(SM) = 0.87 \pm 0.15$
- top Yukawa coupling measured with <20% precision!



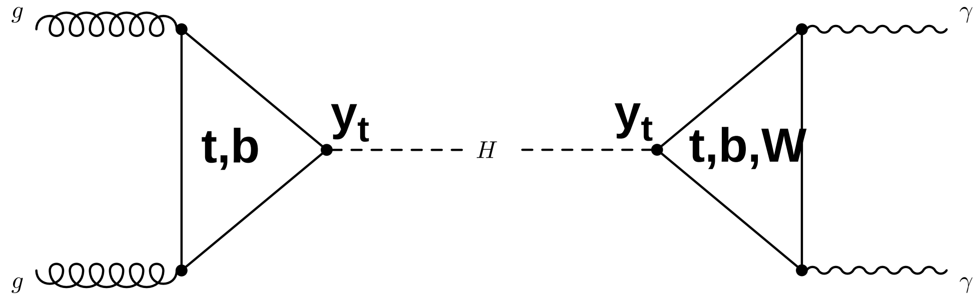
JHEP 08 (2016) 045

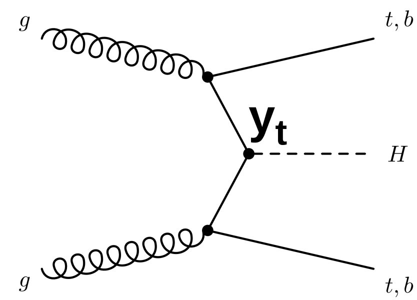


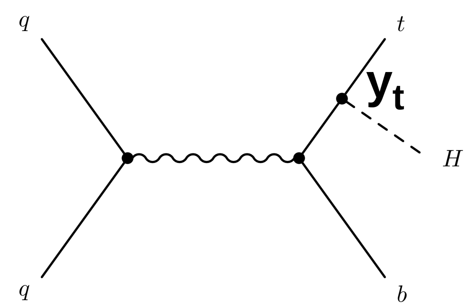
Why look for ttH (tH)?

- top Yukawa coupling in loops:
  - → Higgs gluon fusion production
  - → Higgs diphoton decay
- Can be extracted from fit of all production and decay modes
- Run 1 CMS-ATLAS result:

  $k_t = y_t/y_t(SM) = 0.87 \pm 0.15$
- But assumes no BSM contributions in loop, while ttH (tH) process allows for direct measurement of top Yukawa coupling







13 TeV

Process	Cross section [pb]
$t\bar{t}H$	0.51
$tHqb$	0.074
tHW	0.015

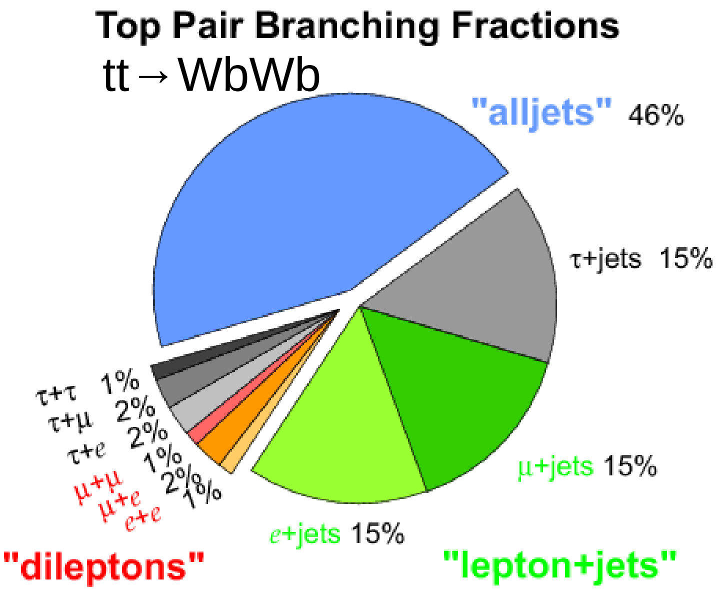
How to look for ttH?

- Signature depends on:
  - → ttbar system decay: 0, 1, or 2 leptons
  - → Higgs decay: bb, WW, ττ, ZZ*, γγ

<u>Four very different analyses:</u>

- ttH with H→bb (0, 1, or 2 e/μ)
- ttH to multilepton targets mostly H → WW and H → ττ
- ttH with H → γγ (0 or 1 e/μ)
- ttH with H → ZZ* → 4 leptons (e/μ)

(all based on 36 fb^{-1})



H→bb	58%
H→WW	21%
H→ττ	6%
H→ZZ*	2.6%
H→γγ	0.2%

$t\bar{t}H$, $H \rightarrow b\bar{b}$

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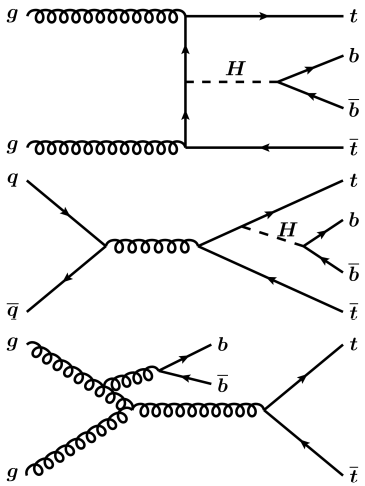
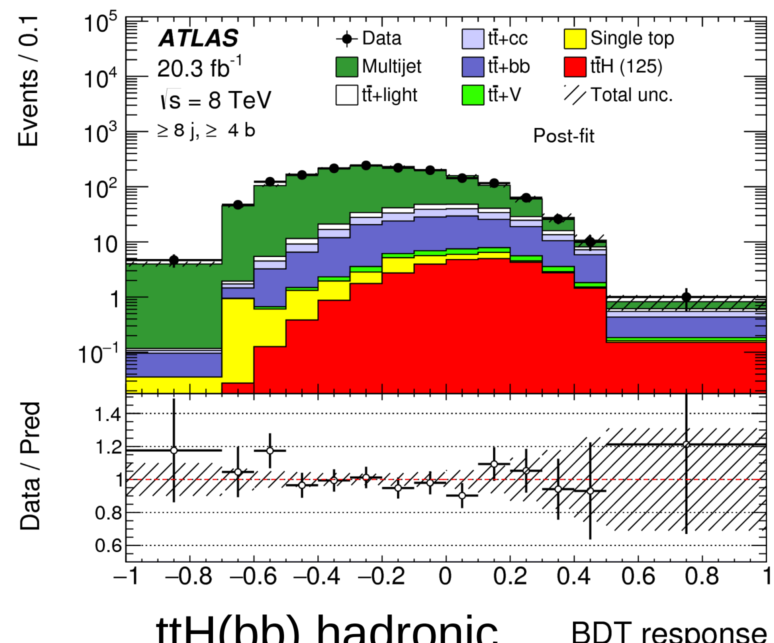
ttH, H → bb

- Largest Higgs BR, but:
  - → ttbb background large and difficult to model
  - → Complex final state with large jet and b-jet multiplicity → challenging object (b-tagging) and event reconstruction
- Signature:
  - → 1 (or 2) e/μ + 4 (2) jets from W's
  - → 4 b-jets (2 from ttbar, 2 from Higgs)
- All-hadronic channel also studied:
  - → Run 1 result: JHEP 05 (2016) 160
  - → Additional large multijet background

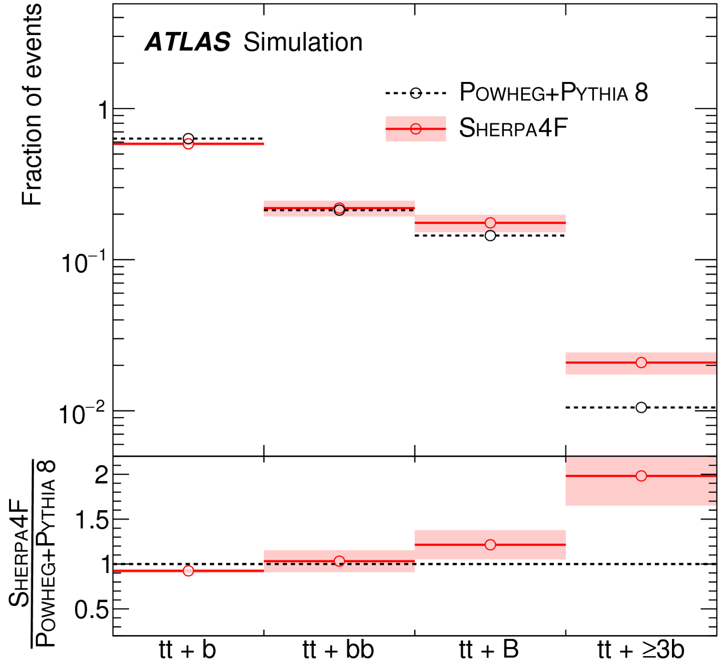


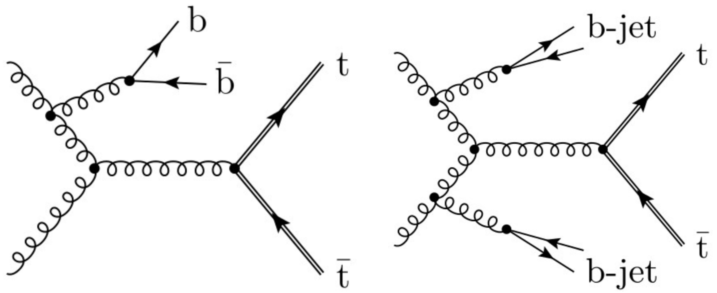


ttH(bb) hadronic

ttH, H→bb: ttbb modelling

- ttbar inclusive MC: Powheg+Pythia8 normalized to NNLO+NNLL cross-section
  - → tt+≥1b and tt+≥1c also from Powheg+Pythia8 but left free-floating in the fit
- Split into tt+HF categories depending on HF jets at particle level:
  - → tt+b : 1 additional b-jet
  - → tt+bb : 2 additional b-jet
  - → tt+B : only one b-jet containing 2 B hadrons
  - → tt+≥3b : other
  - → Rescale fractions of categories to Sherpa+OpenLoops 4F scheme (massive b-quarks, first g→bb from ME)





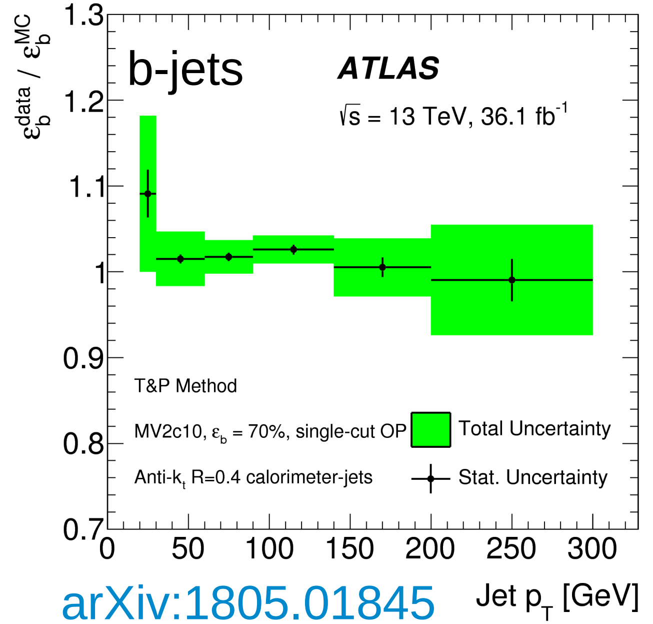
ttH, H→bb: strategy

- Preselection:
  - → Dilepton: two opposite sign e/μ, 3 jets, 2 medium b-tags
  - → Single Lepton: one e/μ, 5 jets, 2 very-tight or 3 medium b-tags
  - → Single Lepton Boosted: one e/μ, large-R jets from R=0.4 reclustered jets, Higgs candidate (pT>200 GeV) and top candidate (pT>250 GeV) (takes precedence over resolved channel)
  - → Single lepton trigger → leading lepton pT > 27 GeV
- Split into Signal and Control Regions based on jet and b-tag multiplicity/quality
- Multivariate analysis to separate tt+jets from ttH in each Signal Region
- Combined fit of all regions (fitting the MVA discriminant in the Signal Regions)

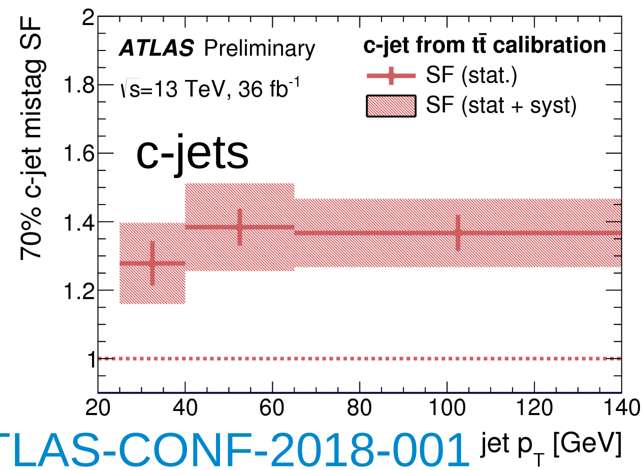
Semi-continuous b-tagging

- Four b-tagging working points calibrated on data:
  - → Loose – Medium – Tight – Very Tight corresponding to:

    85% - 77% - 70% - 60% eff. to tag a b-jet
  - → Assign a b-tagging score from 1 to 5 (from not-tagged to 60%)
- b-jets calibrated with ttbar events (2-10% uncertainty, dominated by ttbar modelling)
- c-jets calibrated with ttbar events (W→cs) and W+c events (5-20% uncertainty)
- light-jets calibrated with dijets events (10-50% uncertainty)



arXiv:1805.01845



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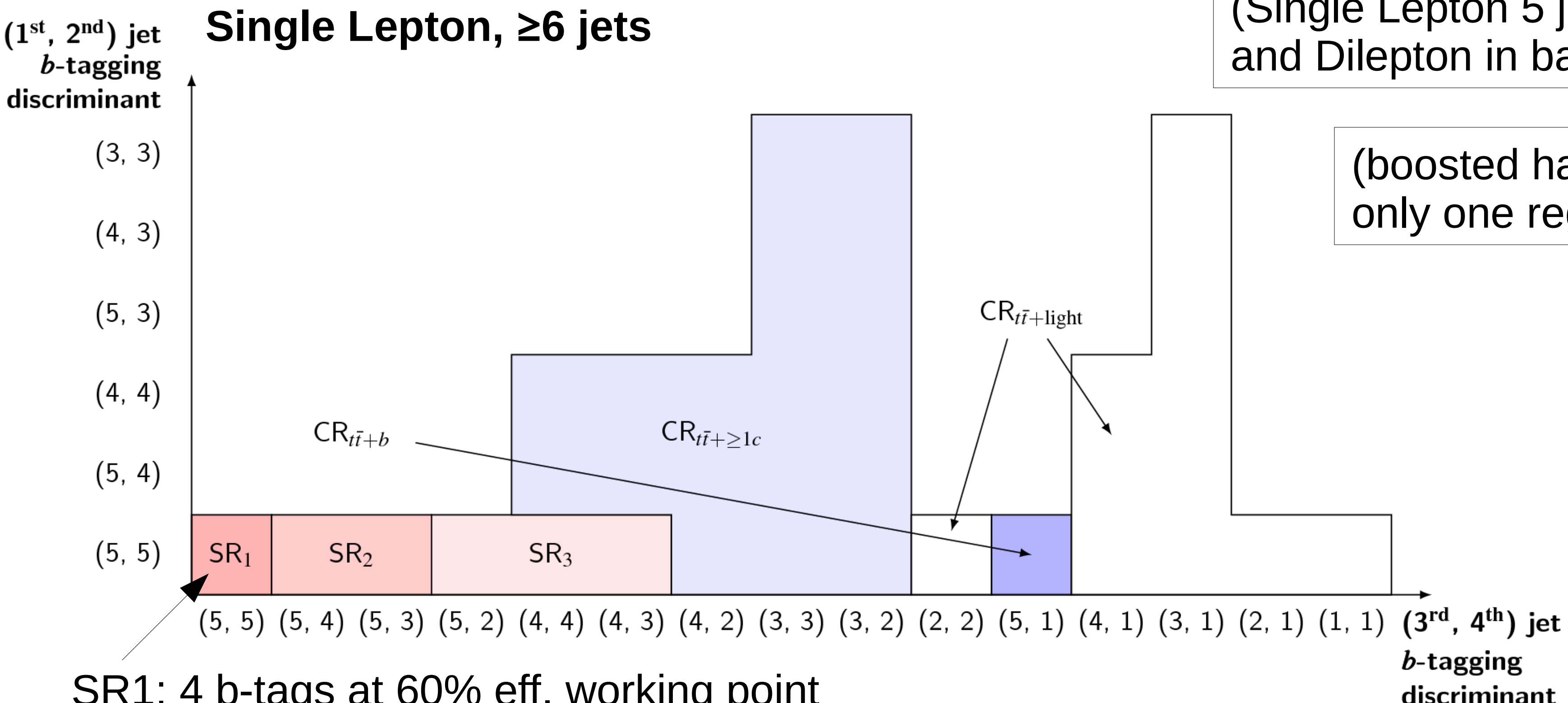
ttH, H→bb: Signal and Control Regions

- Split into jet and b-jet multiplicity/quality, merge regions with similar background content
  - → SR = Signal Region (“large” S/B); CR = Control Region (low S/B)

(Single Lepton 5 jets and Dilepton in backup)

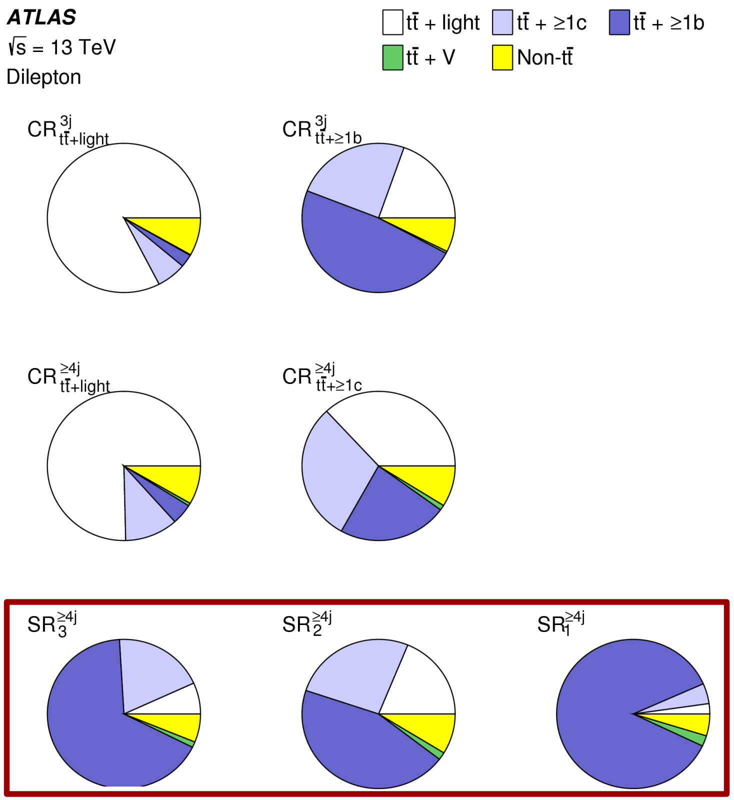
(boosted has only one region)

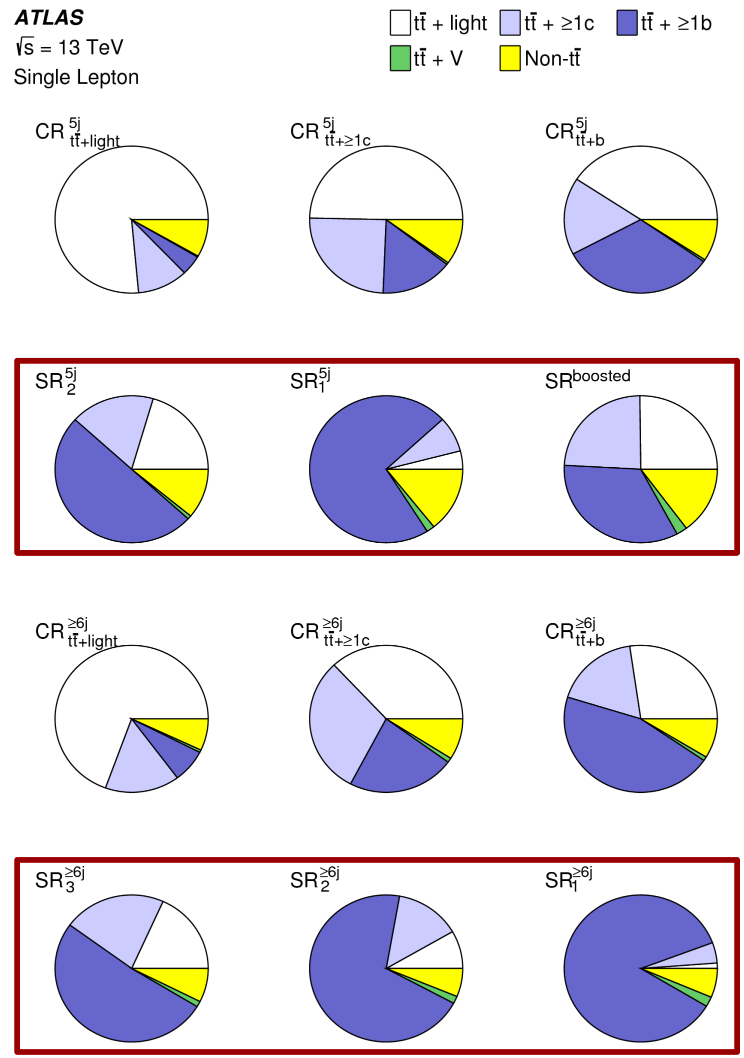


SR1: 4 b-tags at 60% eff. working point

ttH(bb) (1 and 2 leptons) Background composition

- 9 Signal Regions
- 10 Control Regions

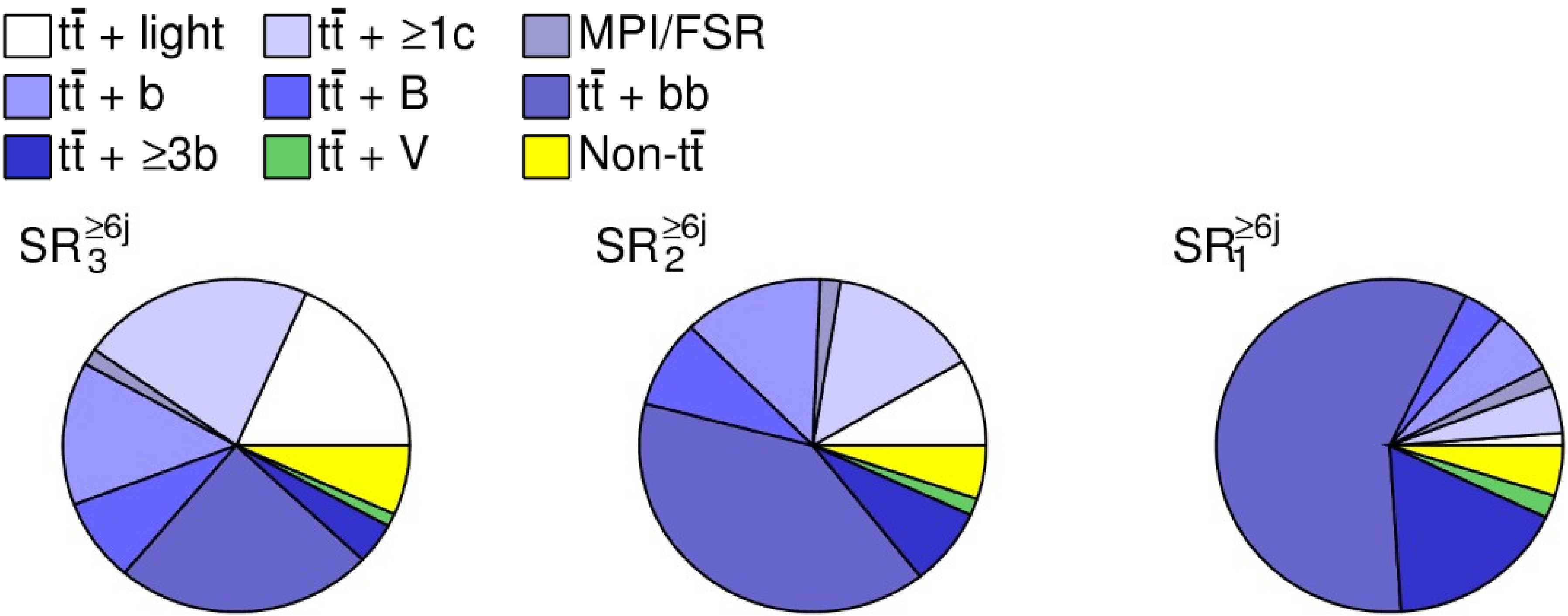




Dilepton **Single Lepton**

ttH(bb) (1 and 2 leptons) Background composition

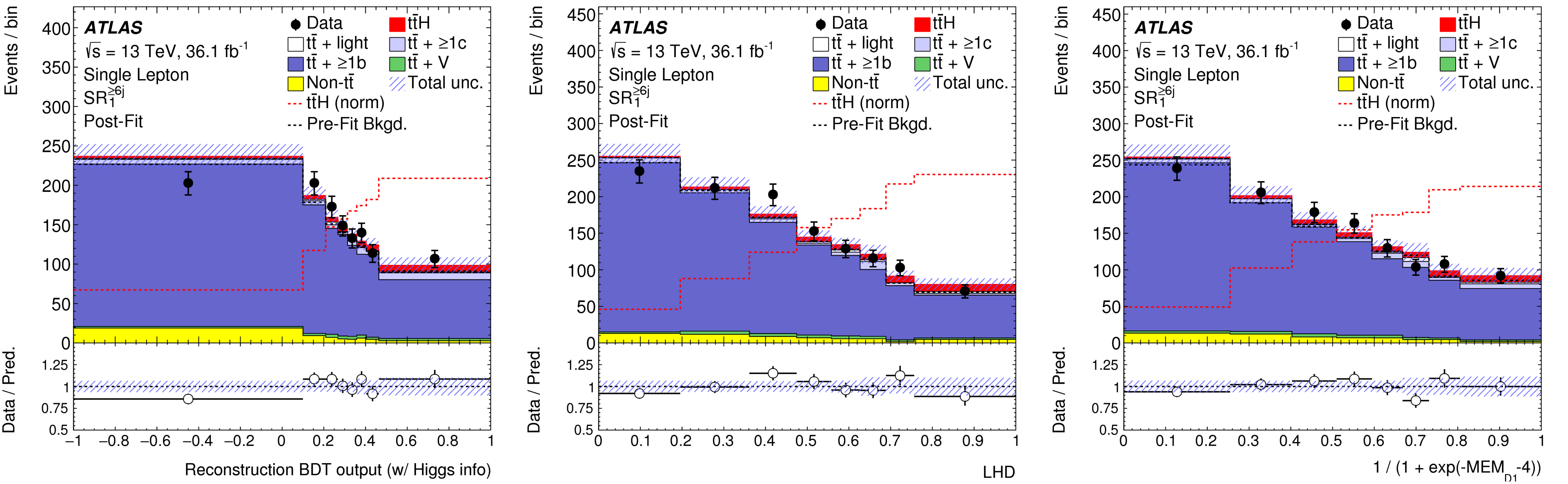
- Zooming in on most sensitive regions (Single Lepton 6 jets) and splitting ttb into categories:
  - → tt+≥1b ~ only relevant background in SR1 (four Very Tight b-tags)
  - → Within tt+≥1b: tt+bb dominant, tt+≥3b also important (two g→bb)



ttH(bb) Multi-Variate Analysis

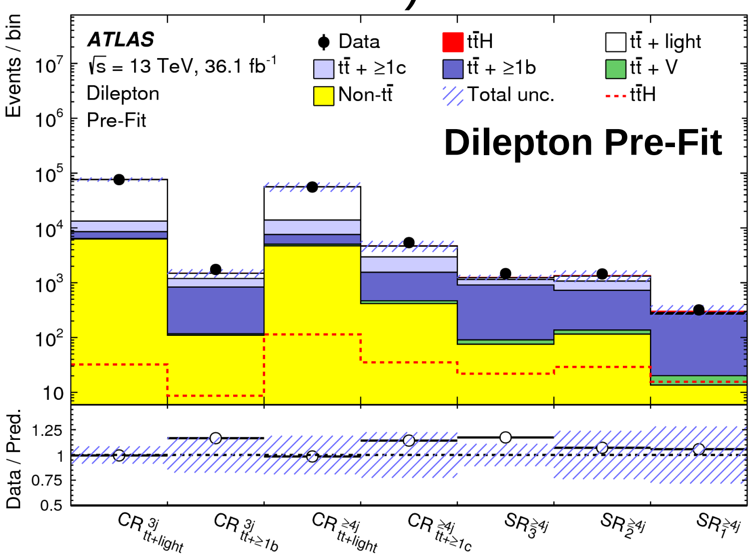
- Several MVA ingredients:
  - → Reconstruction BDT to attempt to reconstruct top quarks and H→bb
  - → Likelihood (LHD) for ttH signal vs tt+≥1b background using product of 1D pdf's of kinematic variables
  - → Matrix Element Method (MEM)

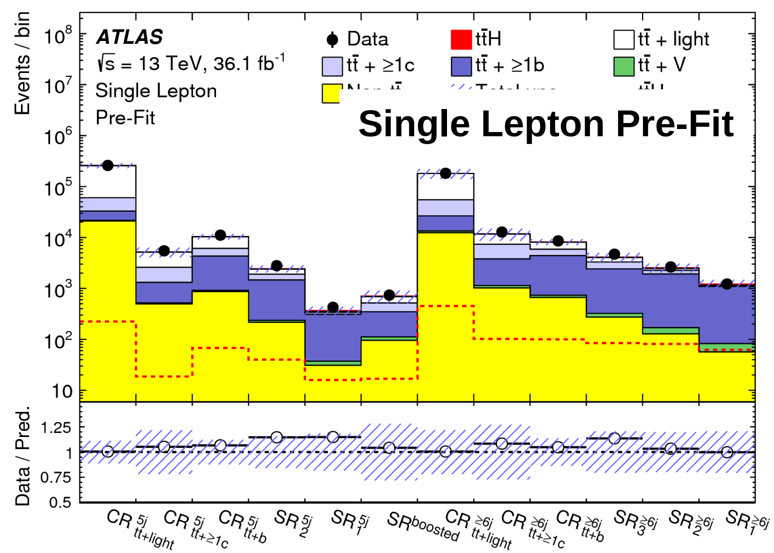
Single Lepton 6-jet SR1:



ttH(bb) Multi-Variate Analysis

- Final discriminant: classification BDT. Input variables:
  - → Reconstruction BDT, LHD, MEM
  - → Kinematic variables
- Combined fit of all 9 SRs and 10 CRs:
  - → Signal Regions: fit the classification BDT output
  - → Control Regions: fit the event yield (except in tt+≥1c 1l CRs: fit H_T to constrain tt+≥1c)





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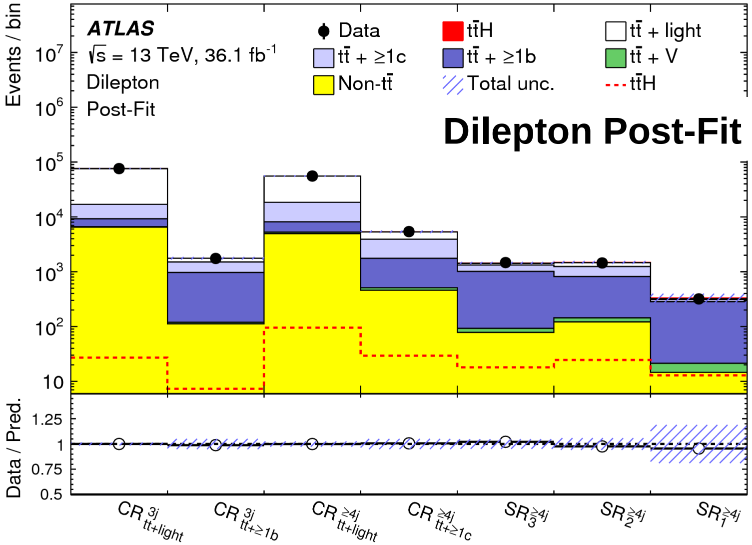
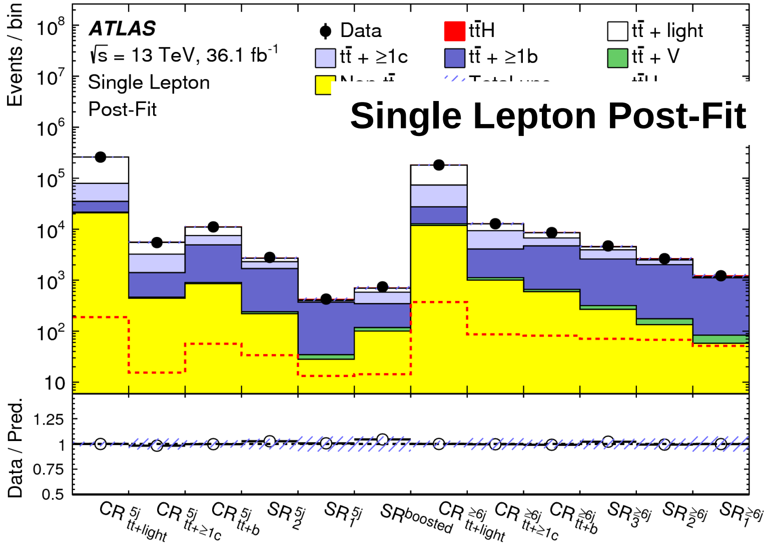
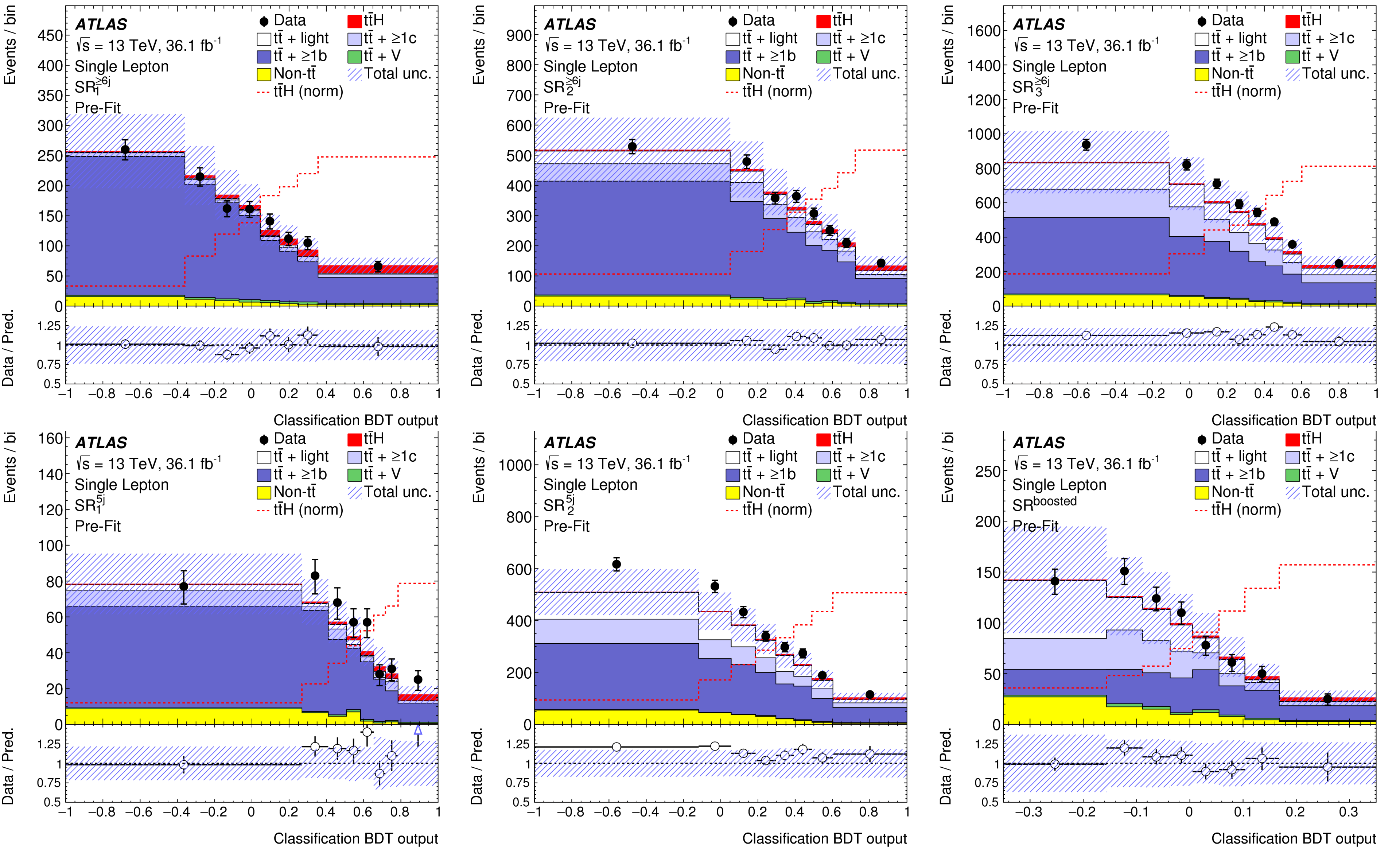
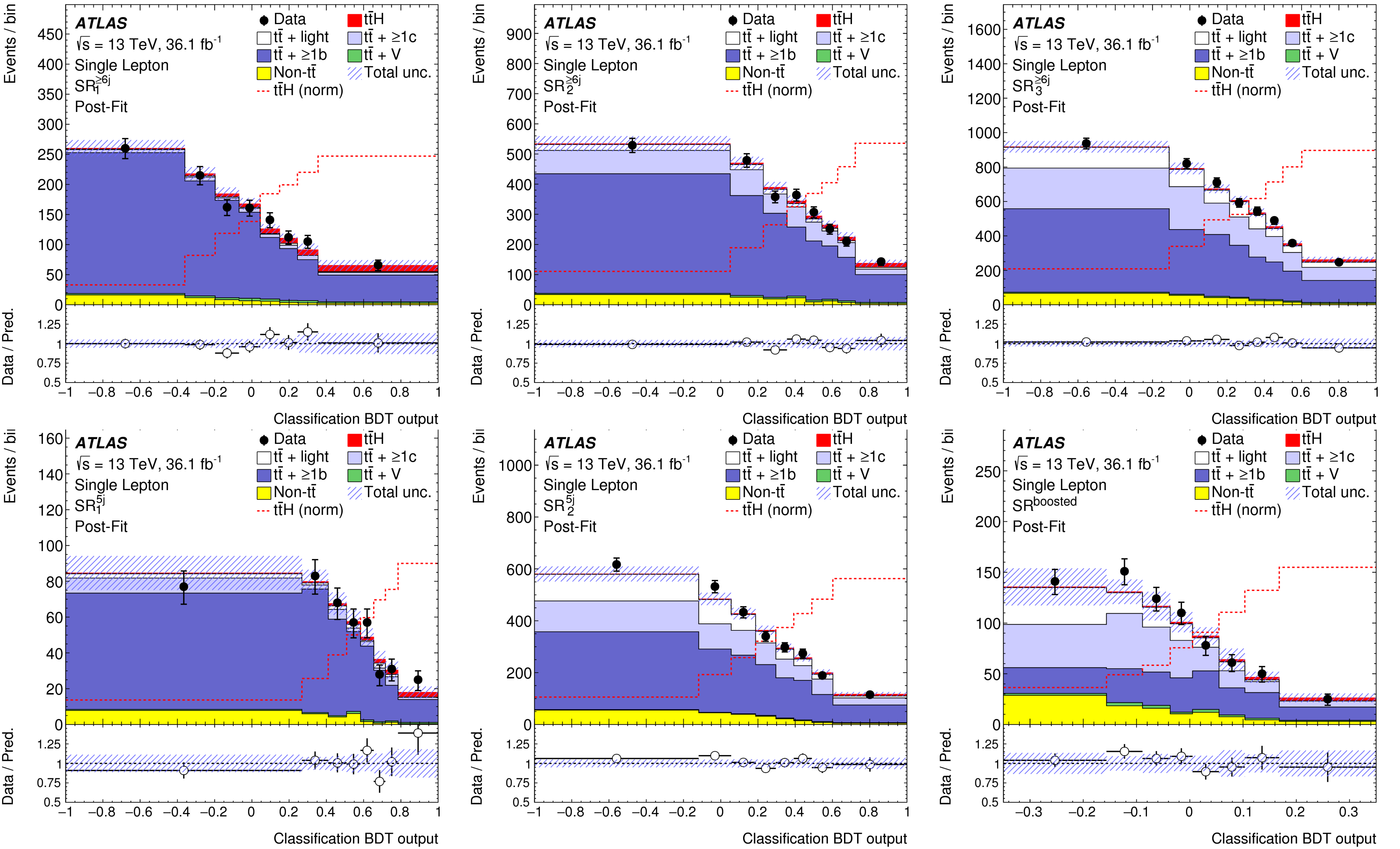




ttH(bb) Single Lepton Signal Regions: Pre-fit



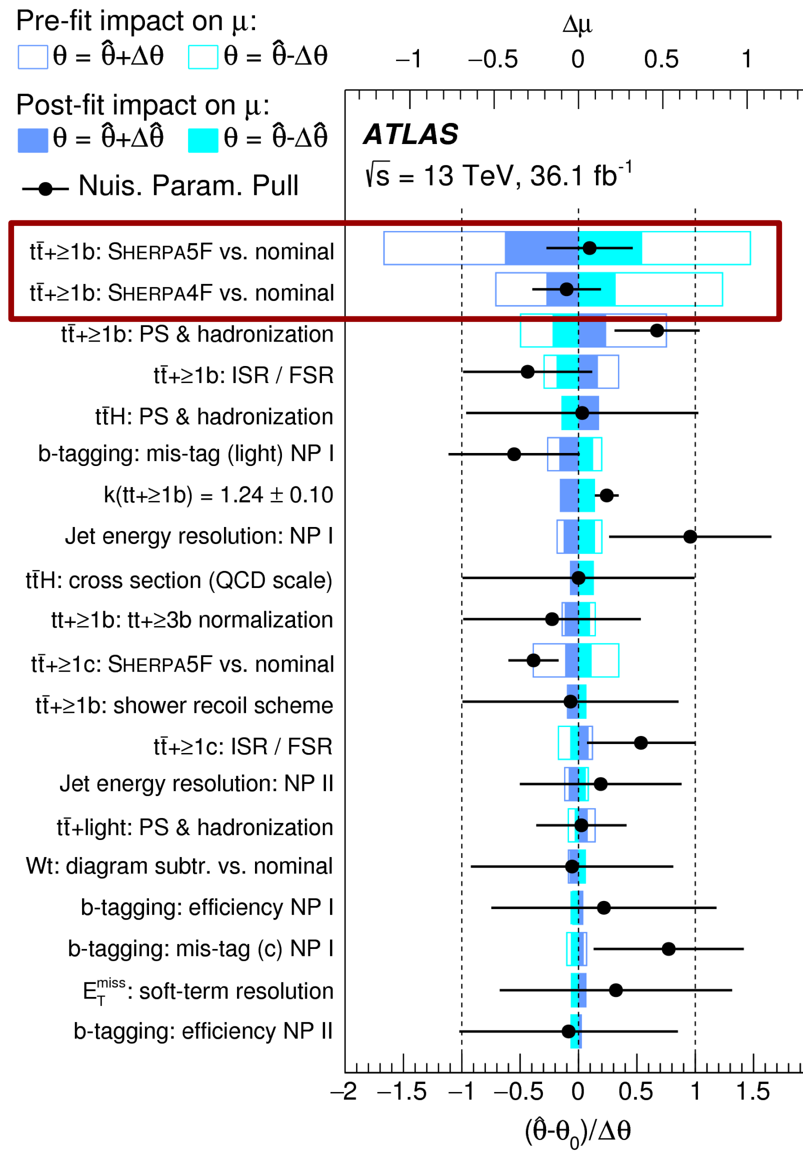
ttH(bb) Single Lepton Signal Regions: Post-fit



ttH(bb) systematics

- By far dominant: tt+≥1b modelling
  - → Esp. Sherpa vs PP8
- Also important: MC stat.

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	$+0.46$	-0.46
Background-model stat. unc.	$+0.29$	-0.31
b-tagging efficiency and mis-tag rates	$+0.16$	-0.16
Jet energy scale and resolution	$+0.14$	-0.14
$t\bar{t}H$ modeling	$+0.22$	-0.05
$t\bar{t}+\geq 1c$ modeling	$+0.09$	-0.11
JVT, pileup modeling	$+0.03$	-0.05
Other background modeling	$+0.08$	-0.08
$t\bar{t}+$light modeling	$+0.06$	-0.03
Luminosity	$+0.03$	-0.02
Light lepton (e,μ) id., isolation, trigger	$+0.03$	-0.04
Total systematic uncertainty	$+0.57$	-0.54
$t\bar{t}+\geq 1b$ normalization	$+0.09$	-0.10
$t\bar{t}+\geq 1c$ normalization	$+0.02$	-0.03
Intrinsic statistical uncertainty	$+0.21$	-0.20
Total statistical uncertainty	$+0.29$	-0.29
Total uncertainty	$+0.64$	-0.61

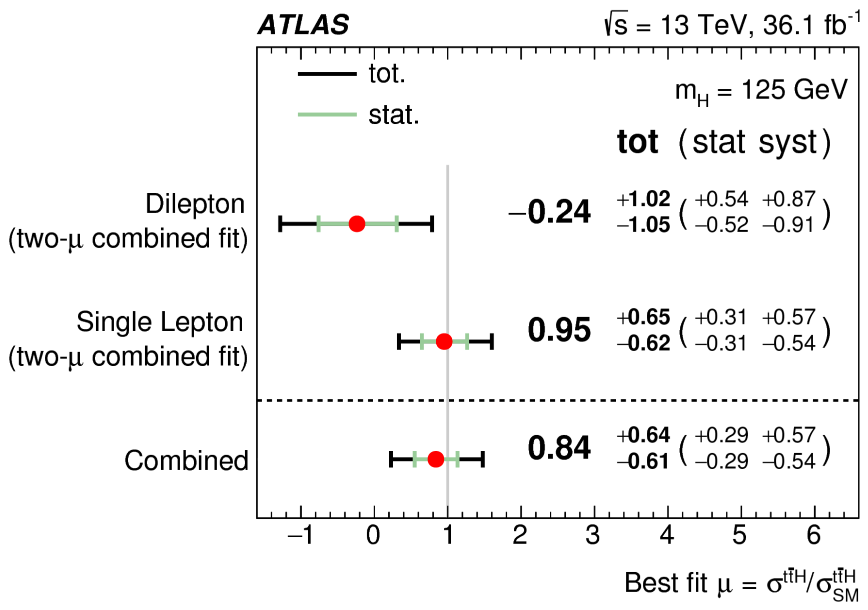


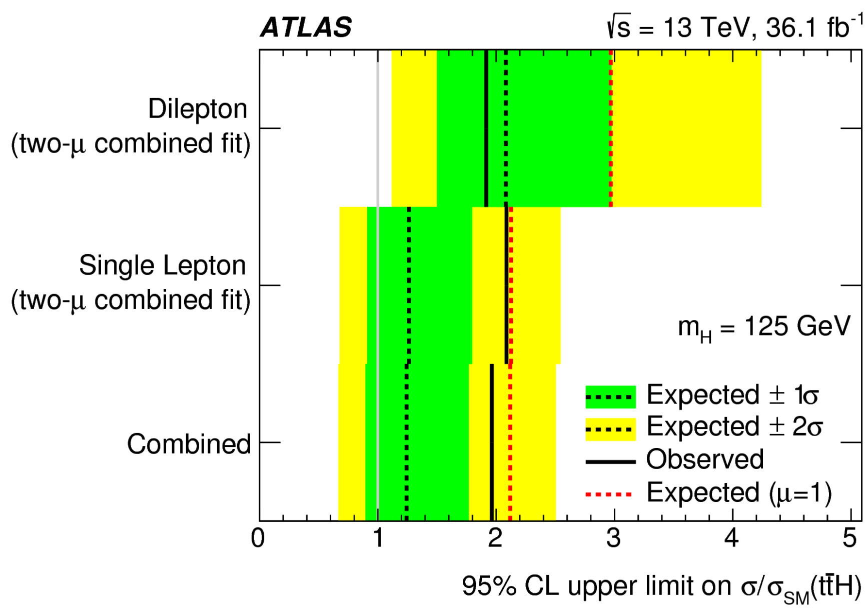
ttH, H→bb: result

- Significance wrt bgd-only hypothesis: 1.4σ (1.6σ expected)
- Signal strength $\mu = \sigma^{ttH}/\sigma^{ttH}(SM)$

  $\mu < 2.0$ at 95% CL

  $\mu = 0.84 +0.64 - 0.61$





ttH, multilepton

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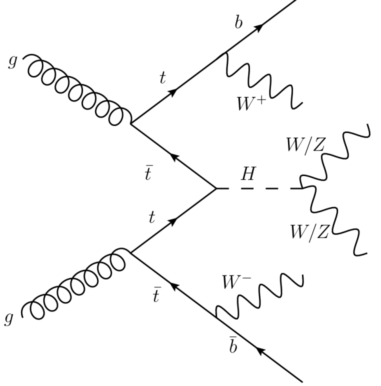
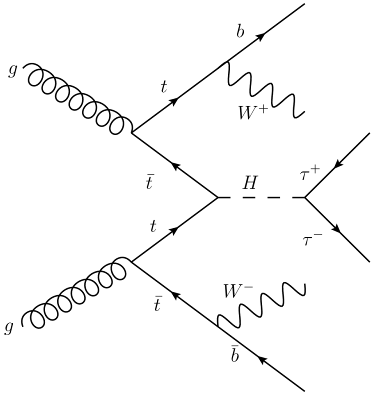
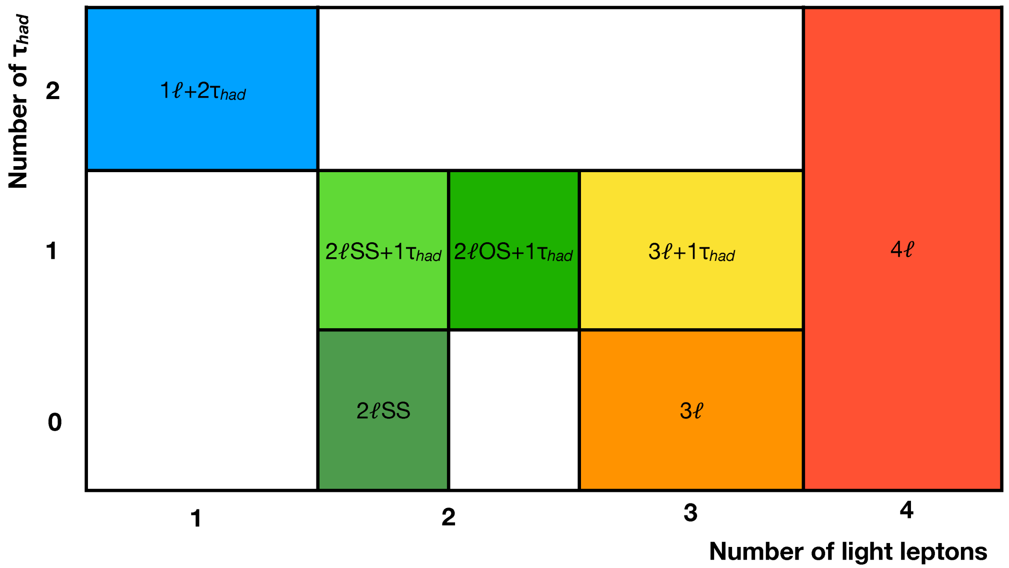
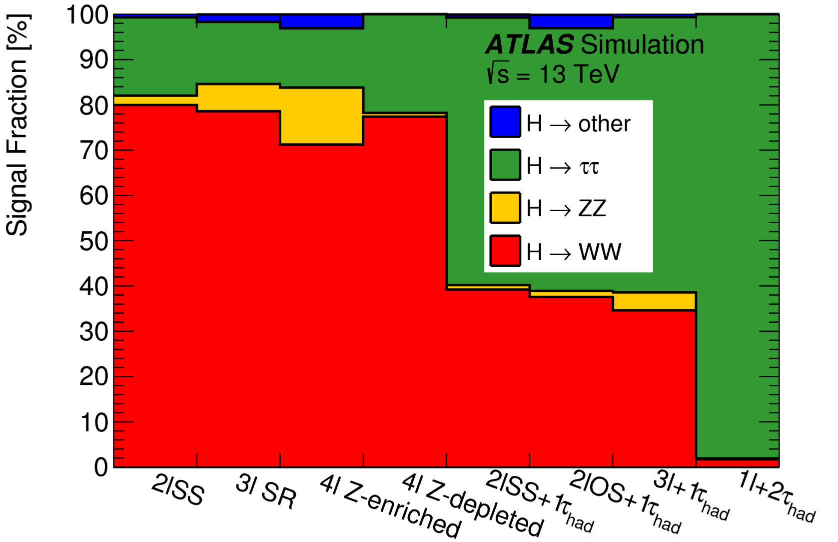
ttH multilepton



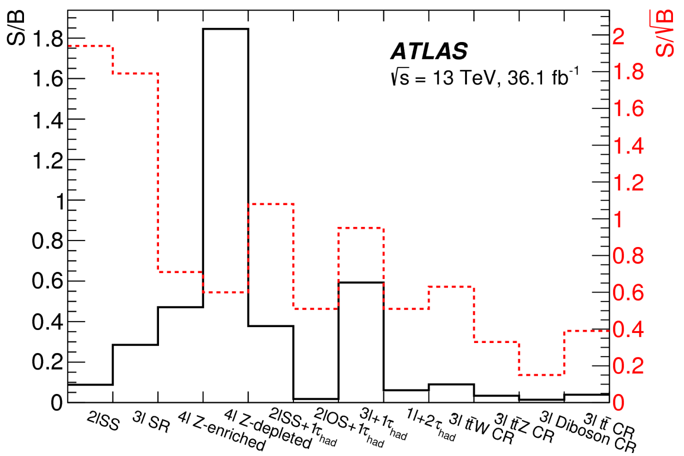
- Channels w/o hadronic-τ target H → WW (and H → ZZ*):
  - 2lSS = 2 light leptons (e or μ) of same sign
  - 3l = 3 light leptons
  - 4l = 4 light leptons (veto H → ZZ* → 4l, treated by dedicated analysis)
- Channels w/ 1 or 2 hadronic-τ target H → ττ and H → WW:
  - 2lSS+1τ, 2lOS+1τ, 3l+1τ, 1l+2τ







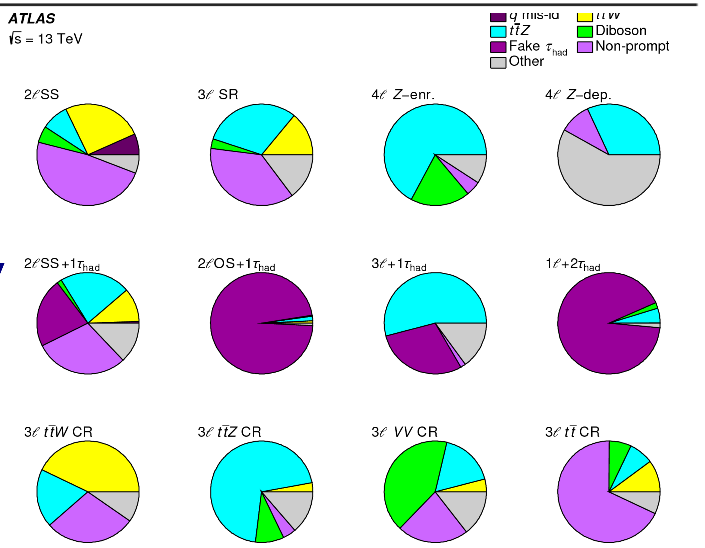
- Common preselection: 2 jets, 1 b-jet
- Further sel. of jet and leptons optimized for each channel
- Acceptance, S/B, bgd composition very different across channels



	2ℓSS	3ℓ	4ℓ	$1\ell{+}2\tau_{\rm had}$	2ℓSS$+1\tau_{\rm had}$	2ℓOS$+1\tau_{\rm had}$	$3\ell{+}1\tau_{\rm had}$	Total
$A\times\epsilon\ [10^{-4}]$	23	13	0.6+0.1	2.3	1.7	7.8	0.8	50

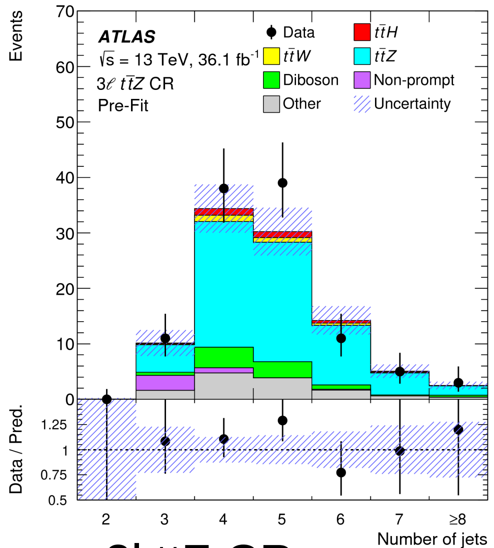
- MVA discriminant trained against main backgrounds:
  - → 2lSS: ttH vs tt and ttH vs ttV
  - → 3l: 5-dimensional multinomial BDT: ttH, ttW, ttZ, tt, VV
  - → 4l (Z-enriched): ttH vs ttZ
  - → Tau channels: ttH vs tt

(4l (Z-depleted) and 3l+1τ: cut-and-count)

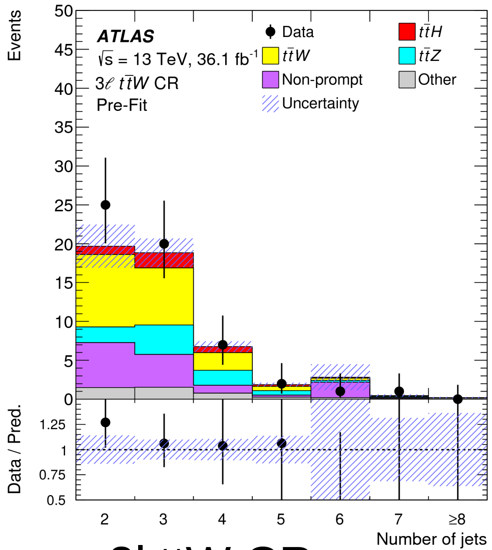


ttH multilepton: prompt lepton backgrounds

- Irreducible background from ttZ, ttW, diboson, from MC
- Also rare processes: tttt, ttt, tZ, tWZ, ttWW, ttγ*
- CRs for ttZ and ttW show good agreement with SM prediction:



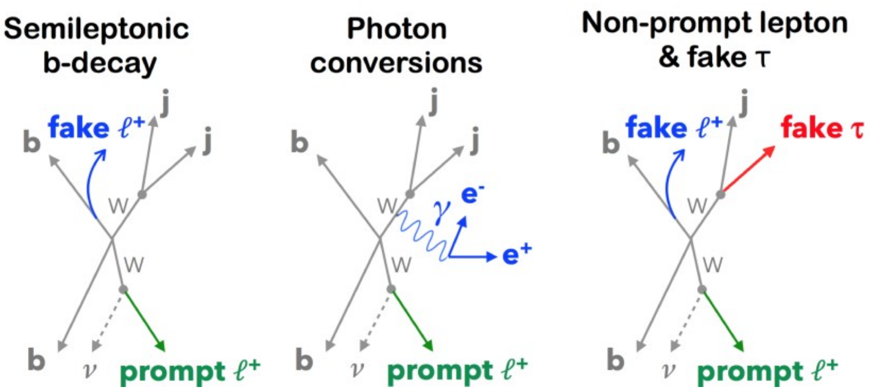
3l ttZ CR

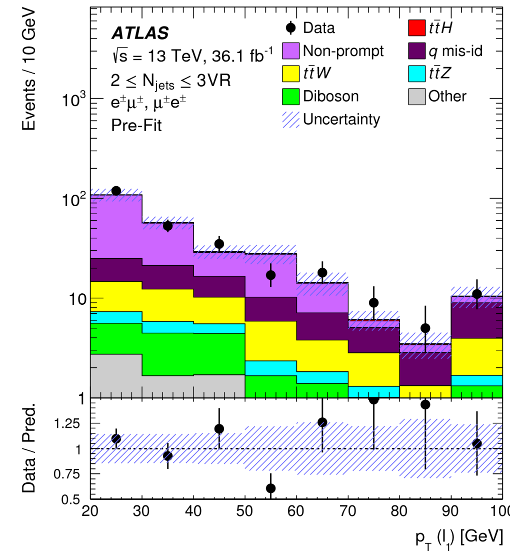


3l ttW CR

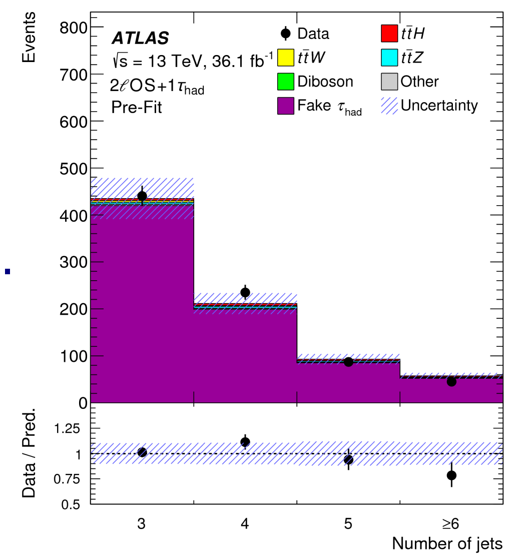
- Electron charge mis-ID (for 2lSS0τ and 2lSS1τ):
  → reduced by dedicated MVA
  → Data-driven estimate: rate from SS Z→ee applied to OS CRs

ttH multilepton: fake/non-prompt lepton backgrounds



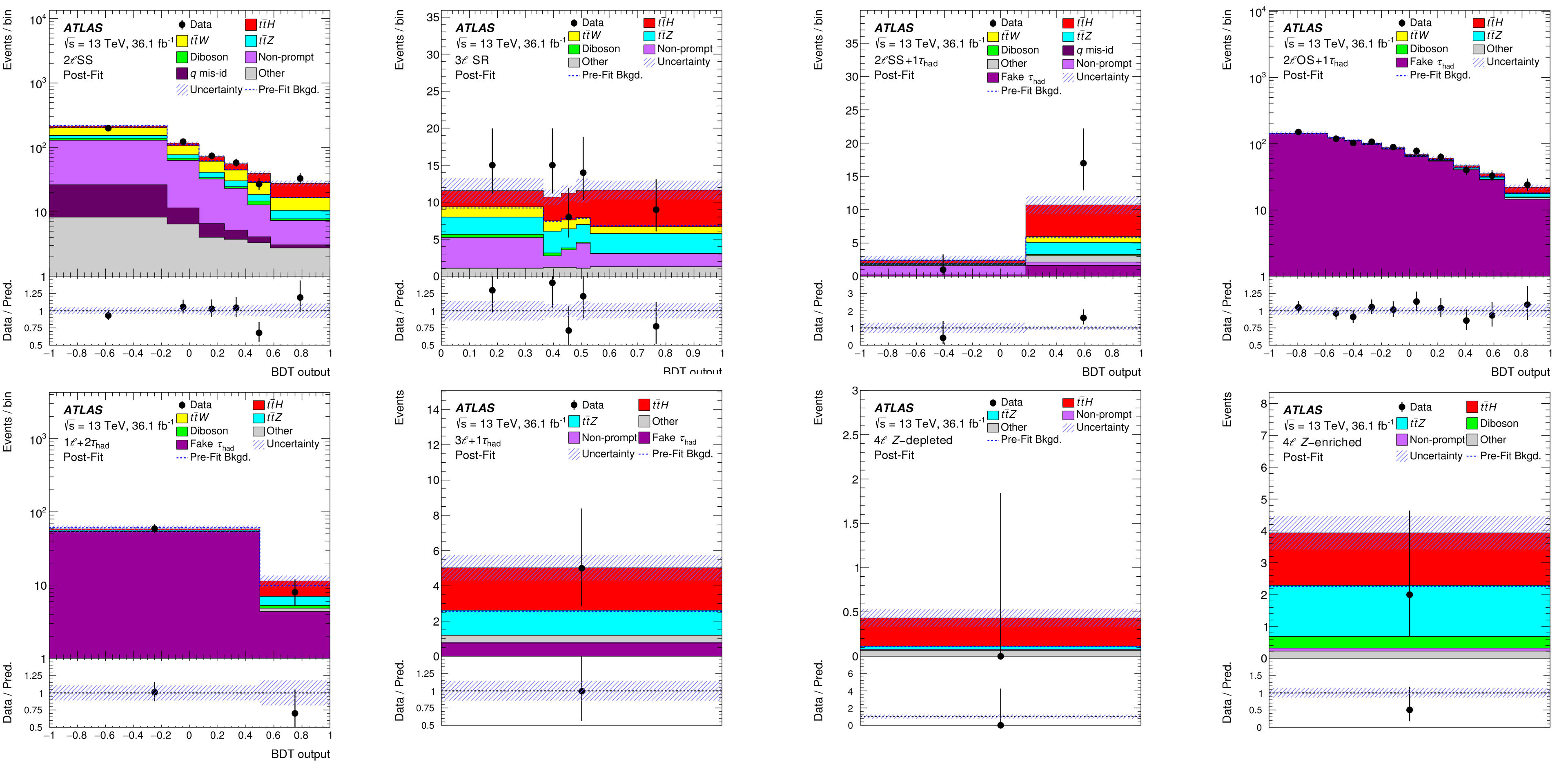


- BDT to reduce light lepton fake/non-prompt
  - → Isolation and b-tagging of track-jet near lepton
- Bgd estimate (mostly) data-driven
  - → 2lSS0τ/3l0τ: Matrix Method. Real and fake eff. from CRs, applied to loose-not-tight events
    - MC-based correction for HF vs conversion comp.
  - → Fake τ: fake SF from 2lOS1τ CR, applied to simulation in all τ channels
    - 2lSS1τ: must also consider fake light+fake τ



ttH multilepton: fit of eight channels

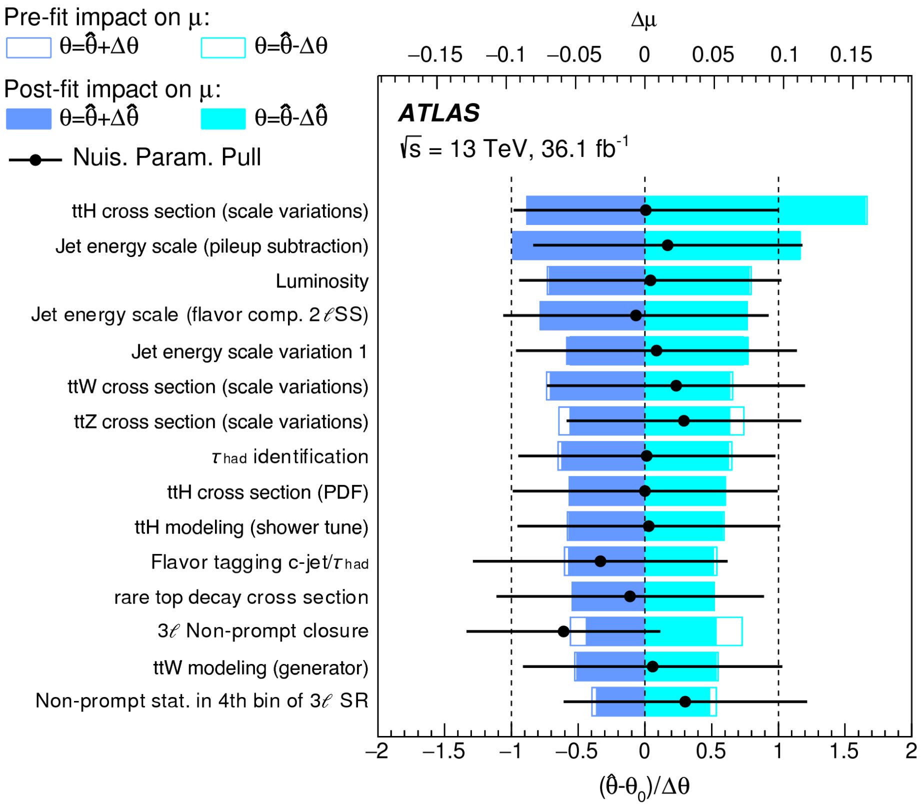
	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$	3ℓ+$1\tau_{\text{had}}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-



ttH multilepton: systematics

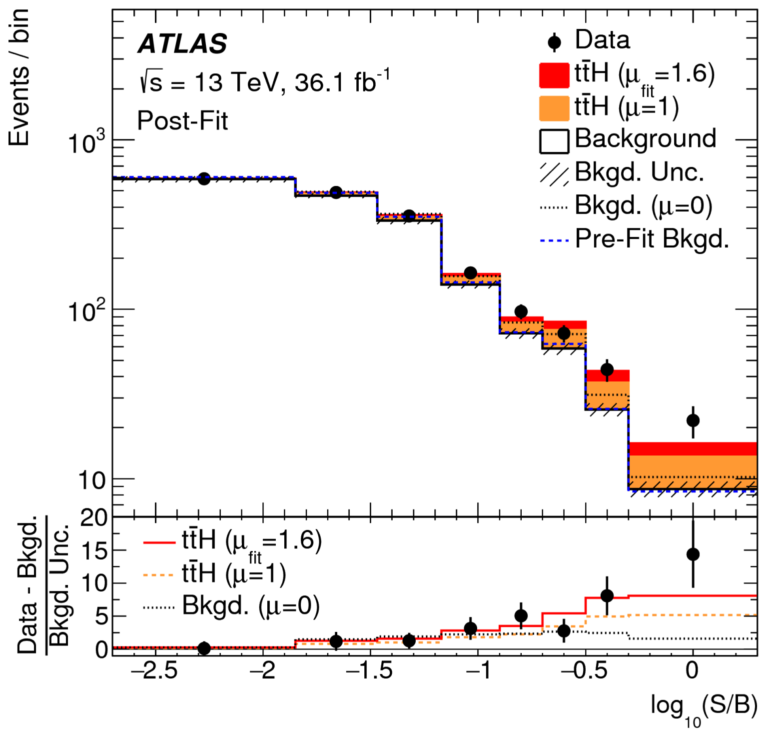
- Systematic uncertainties already important for some multilepton channels
- JES:
  - → Largest experimental uncertainty
  - → Flavor composition: can be improved by taking into account predicted flavor composition
- Fake estimates
- Can constrain ttW and ttZ backgrounds with more data

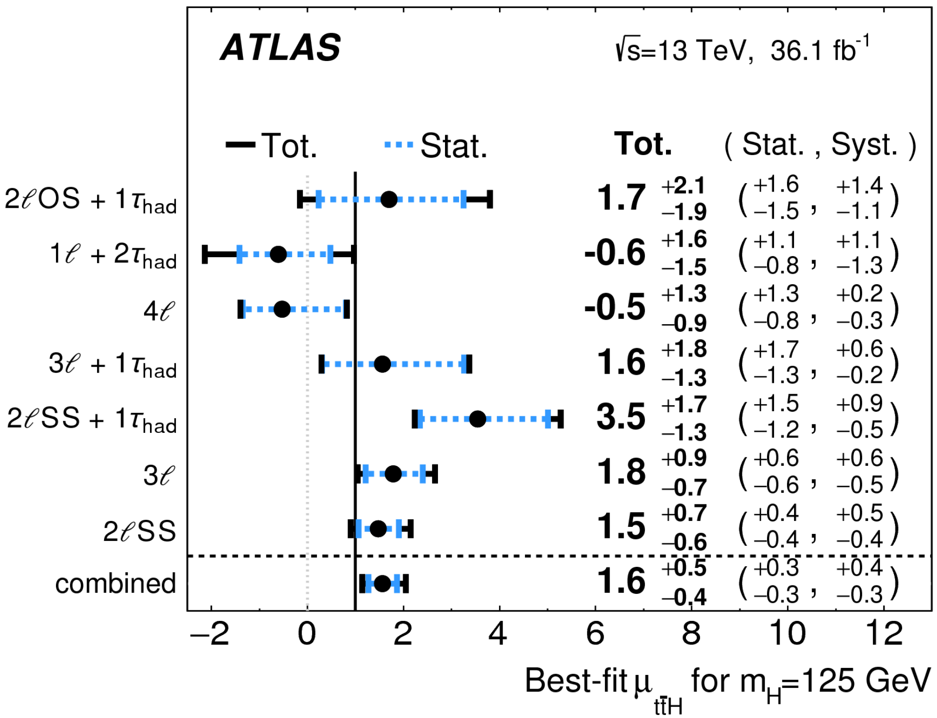
Uncertainty Source	$\Delta\mu$	
$t\bar{t}H$ modeling (cross section)	+0.20	−0.09
Jet energy scale and resolution	+0.18	−0.15
Non-prompt light-lepton estimates	+0.15	−0.13
Jet flavor tagging and τ_{had} identification	+0.11	−0.09
$t\bar{t}W$ modeling	+0.10	−0.09
$t\bar{t}Z$ modeling	+0.08	−0.07
Other background modeling	+0.08	−0.07
Luminosity	+0.08	−0.06
$t\bar{t}H$ modeling (acceptance)	+0.08	−0.04
Fake τ_{had} estimates	+0.07	−0.07
Other experimental uncertainties	+0.05	−0.04
Simulation sample size	+0.04	−0.04
Charge misassignment	+0.01	−0.01
Total systematic uncertainty	+0.39	−0.30



ttH multilepton result with 36 /fb

- Observed significance over background-only hypothesis: 4.1σ (exp. 2.8σ)
- Signal strength μ = 1.6 +-0.3 (stat) +0.4-0.3 (syst)



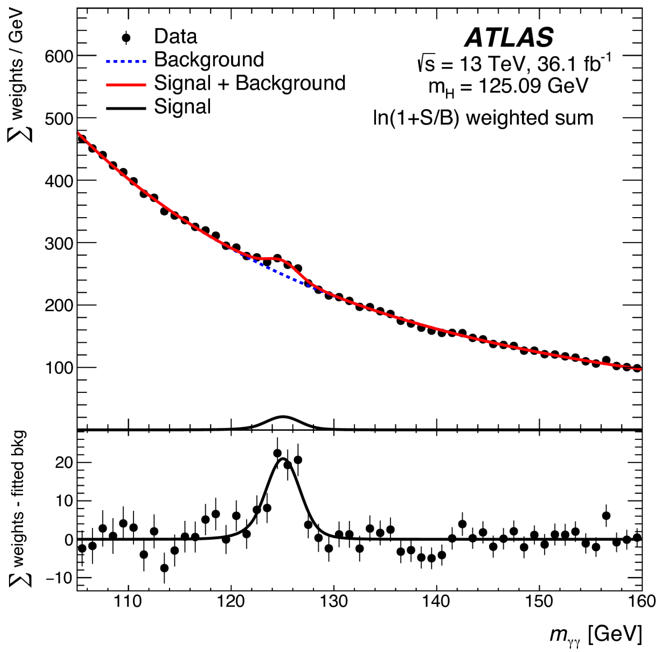


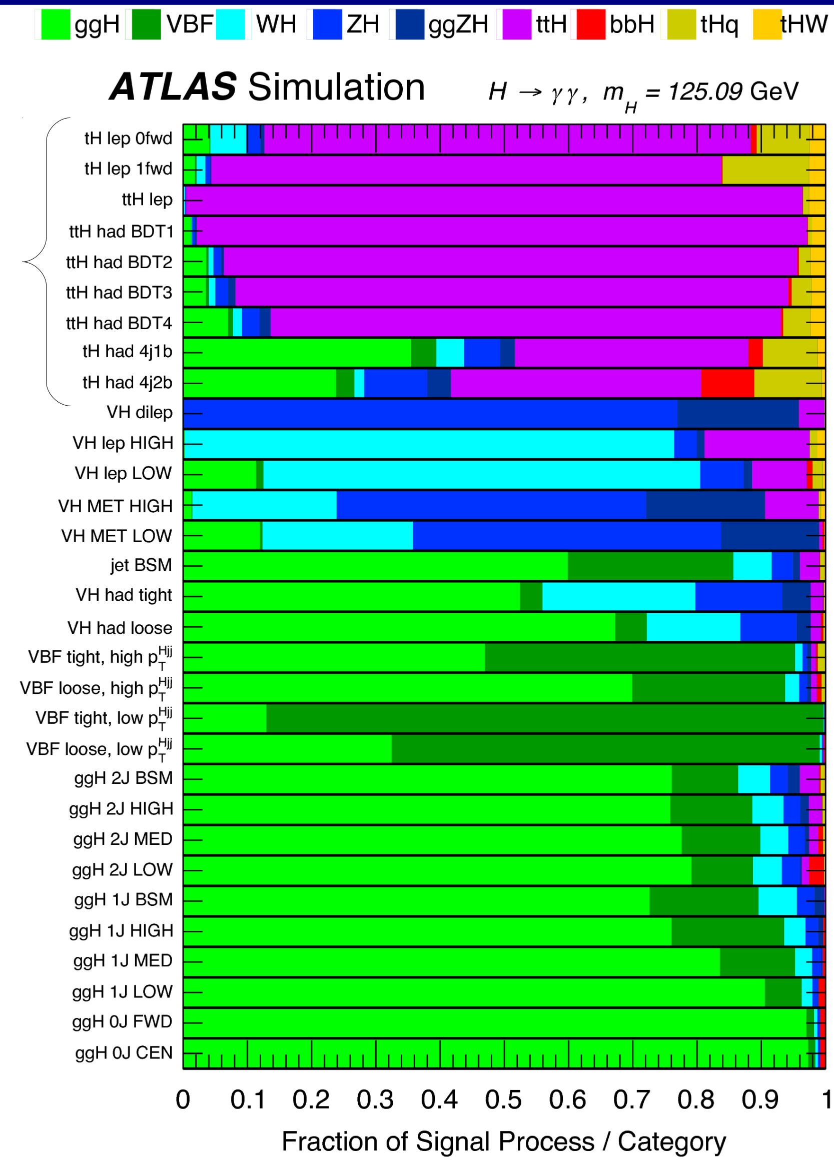
$t\bar{t}H$, $H \rightarrow \gamma\gamma$

arXiv:1802.04146 [hep-ex]

ttH, H→γγ

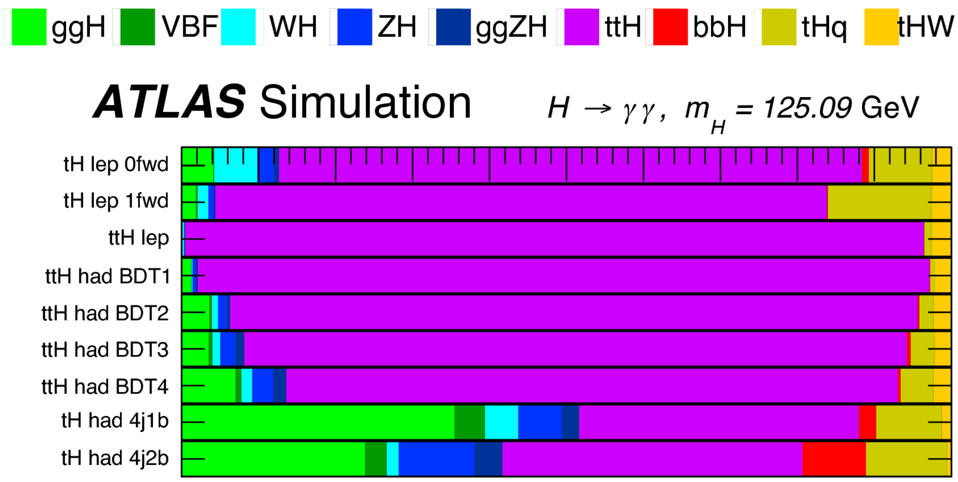
- H→γγ analysis defines 31 exclusive categories optimized to separate production processes and phase space regions

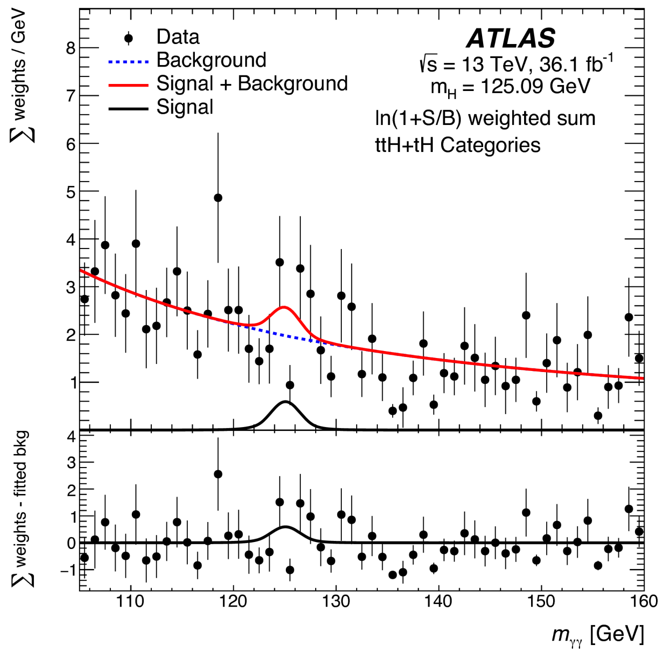




ttH, H → γγ

- One ttH leptonic category
- Four ttH hadronic category
  - → Four bins of BDT output
- Four tH categories (in fact dominated by ttH)





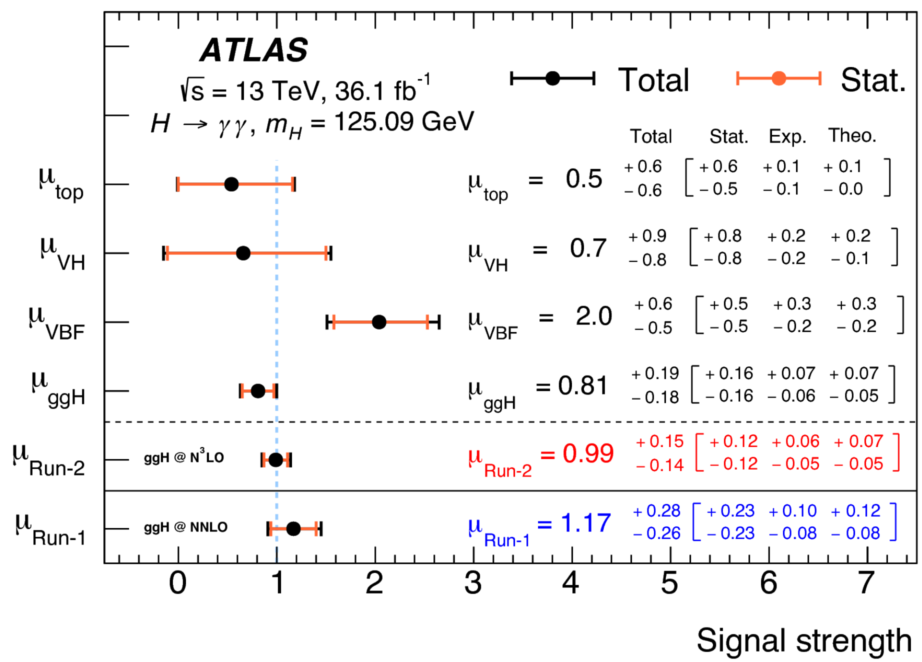
- ttH leptonic: 1 e/μ, 2 central jets, 1 b-jets
- ttH hadronic: 0 e/μ, 3 jets, 1 b-jet. BDT trained to separate ttH vs ggH+multijet
- Combined fit of each category m(γγ) distribution

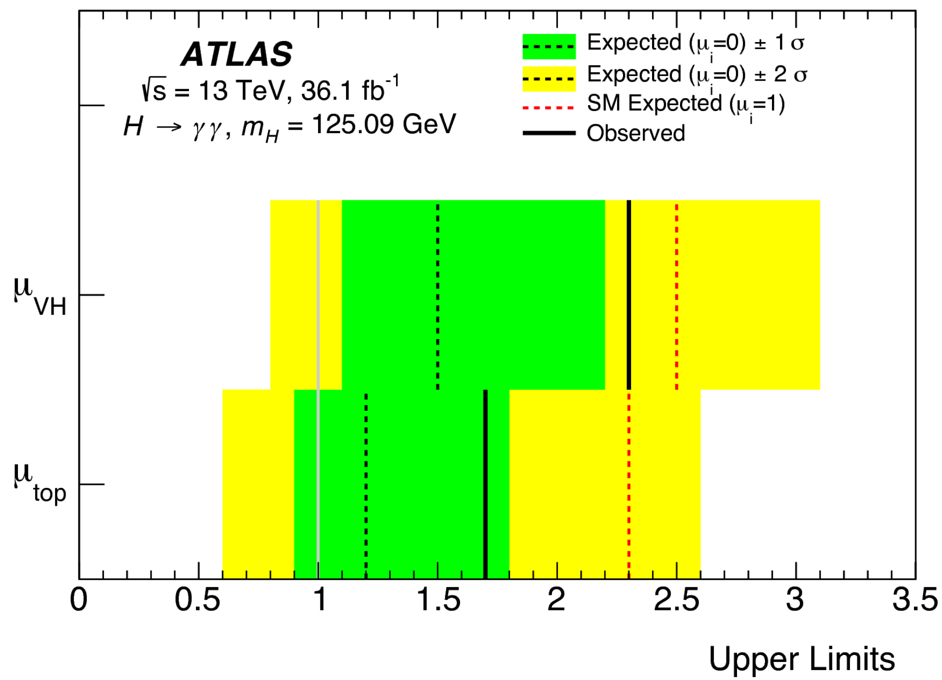
ttH, H→γγ: result

- Considers both ttH and tH categories, signal strength also applying to both ttH and tH processes:

$$\mu_{\text{top}} = 0.5\,^{+0.6}_{-0.6} = 0.5\,^{+0.6}_{-0.5}\,(\text{stat.})\,^{+0.1}_{-0.1}\,(\text{exp.})\,^{+0.1}_{-0.0}\,(\text{theo.})$$

- Completely stat-limited!





ttH, H → ZZ* → 4 light leptons

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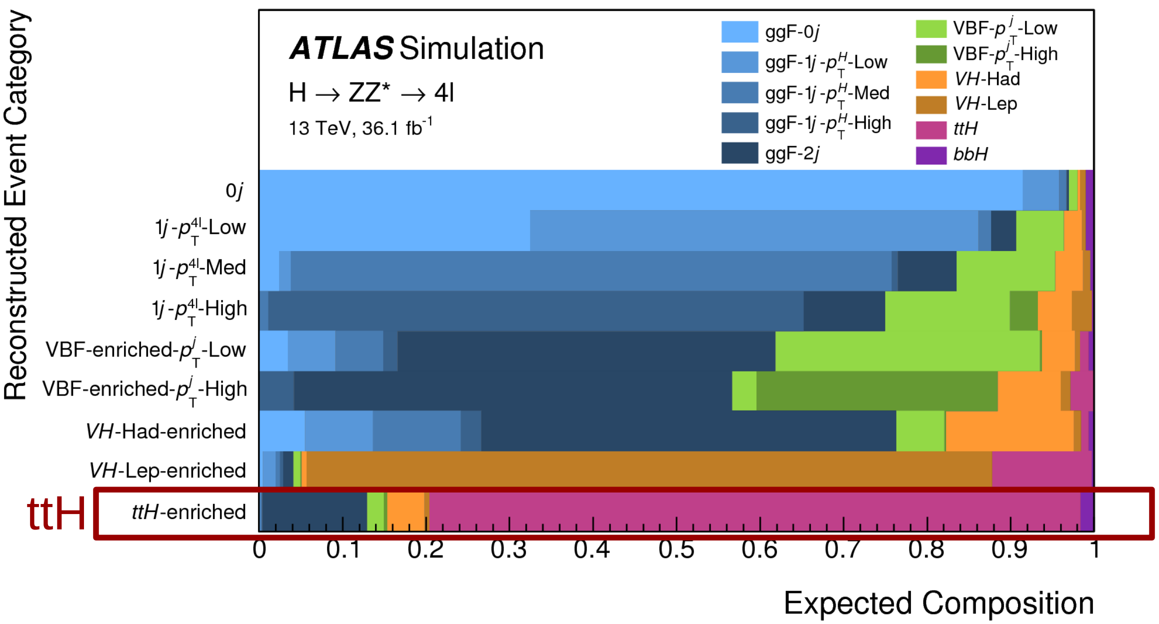
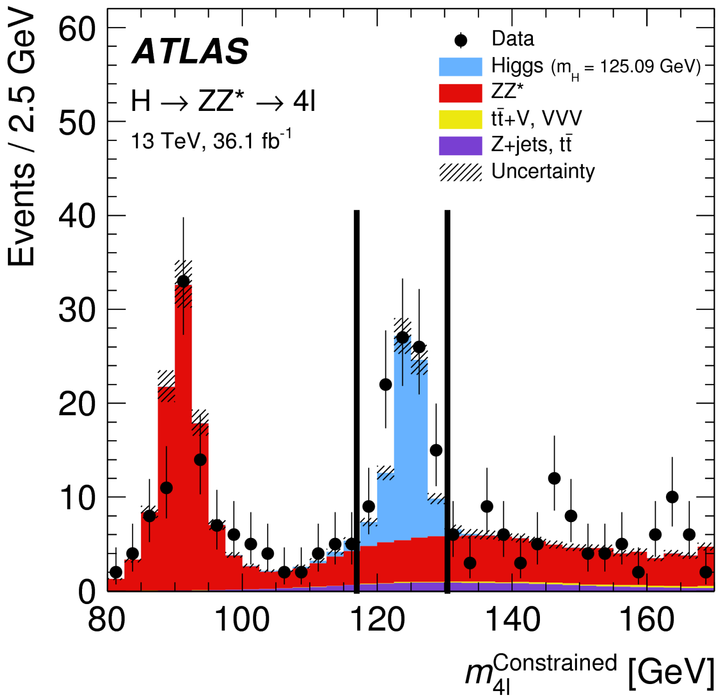
ttH, H → ZZ* → 4 light leptons

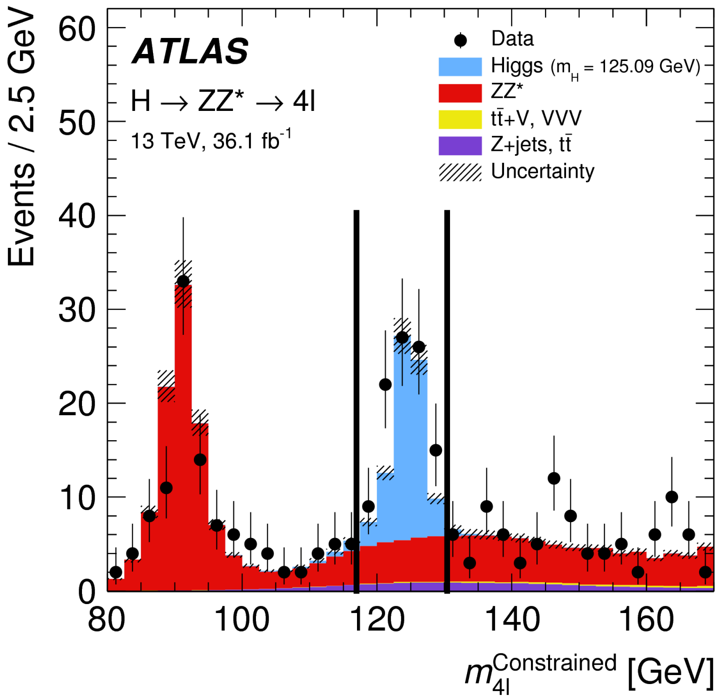
- Select Higgs candidates with mass 118 < m(4l) < 129 GeV
- Split into categories:





ttH, H→ZZ*→4 light leptons

- Select Higgs candidates with mass 118 < m(4l) < 129 GeV
- ttH-enriched category:
  - → ≥1 b-tagged jet
  - → ≥4 jets (hadronic ttbar) or
    1l+≥2 jets (semi-leptonic ttbar)
- Expect <0.1 background event!
- Observe zero event



Reconstructed category	Signal	ZZ^*	Other backgrounds	Total expected	Observed
ttH-enriched	0.39 ± 0.04	0.014 ± 0.006	0.07 ± 0.04	0.47 ± 0.05	0

ttH, combination of all channels

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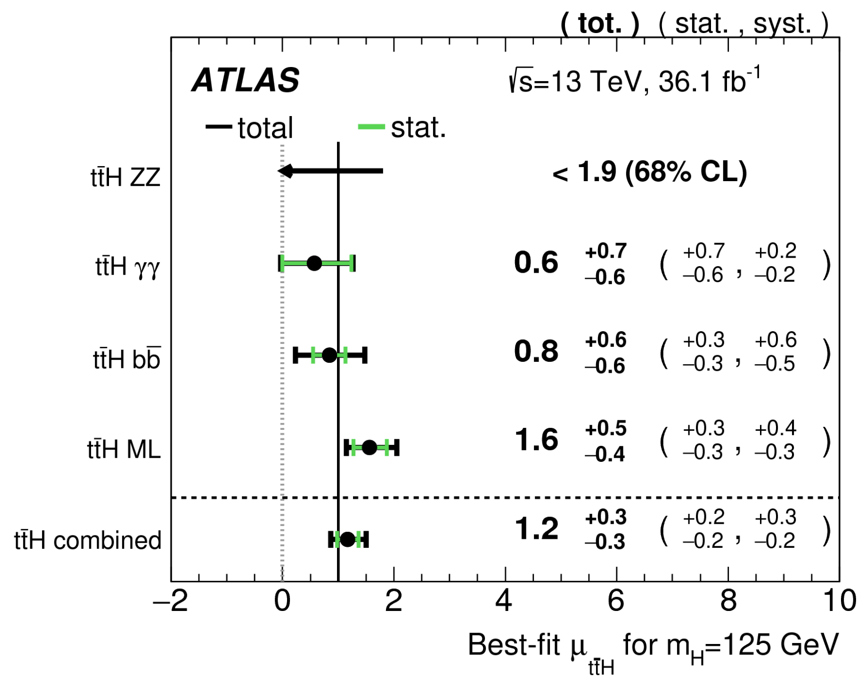
ttH, combination of all channels

- Combining:
  - → H→bb, multilepton
  - → H→γγ, H→ZZ*→4l, fitting only the ttH categories, fixing non-ttH Higgs processes (incl. tH) to SM prediction



Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ

ttH, combination of all channels

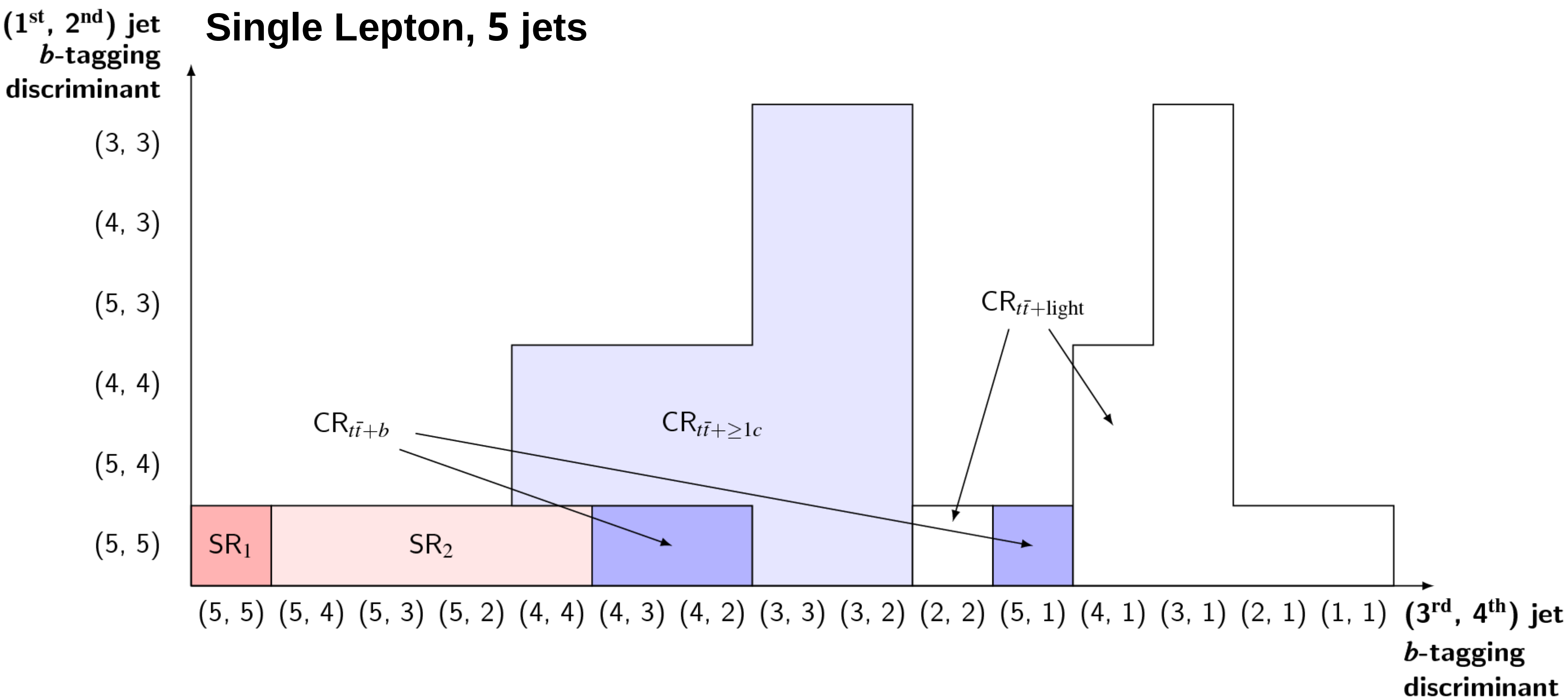
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to bb$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

Conclusion

- Latest ATLAS results using 36/fb recorded in '15-'16 show evidence for ttH with significance of 4.2σ (3.8σ expected):
  $$\mu = 1.17 \pm 0.19\,(\text{stat.})\,^{+0.27}_{-0.23}\,(\text{syst.})$$
- Cross-section measurement: $\sigma(t\bar{t}H) = 590^{+160}_{-150}$ fb
  in agreement with SM prediction: 507^{+35}_{-50} fb
- ttH(bb) already systematics-limited. Requires some breakthrough to make significant progress from here.
- ttH multilepton currently most sensitive analysis and still mostly stat-limited.
- With the additional data, ttH(yy) will become the single most sensitive channel.
- Already close to 100 fb^{-1} now on tape!

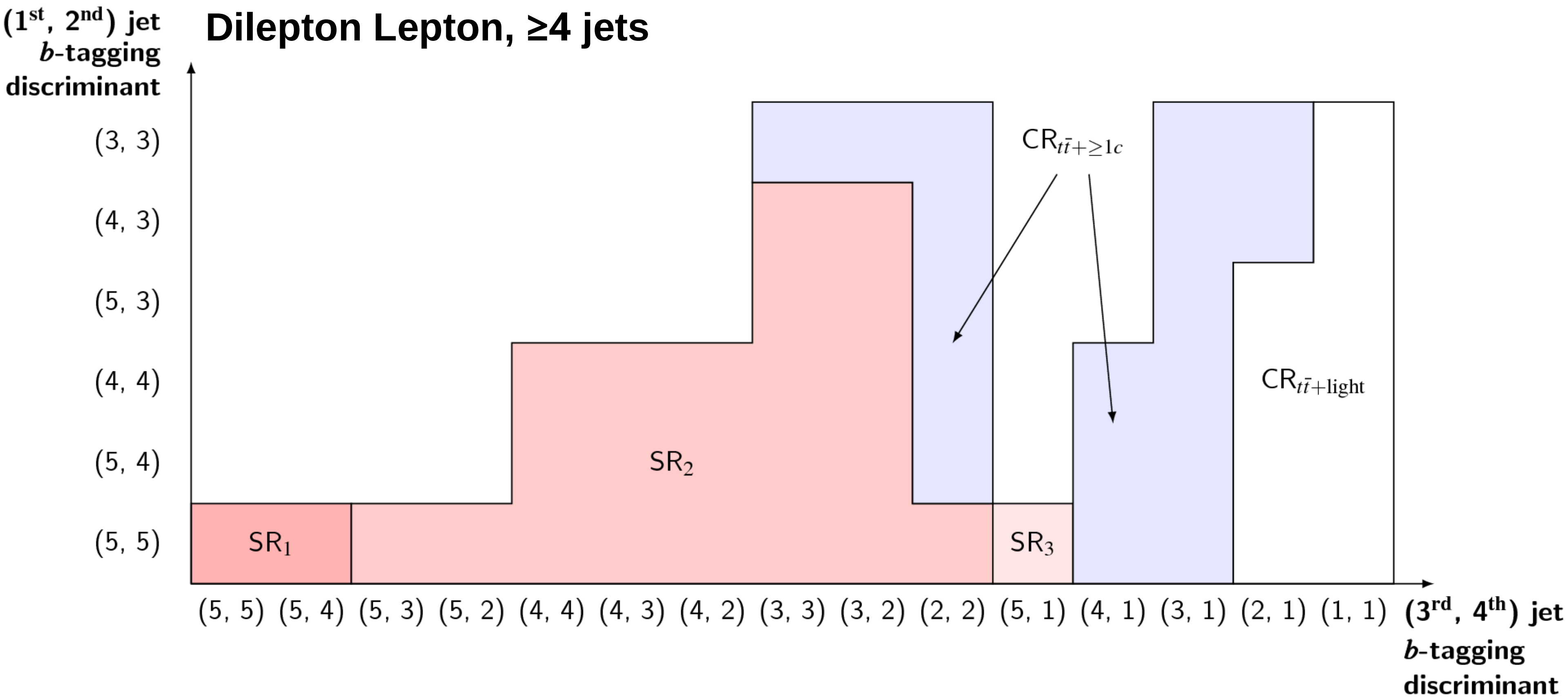
Backup

- Split into jet and b-jet multiplicity, merge regions with similar background content
  - → SR = Signal Region (“large” S/B); CR = Control Region (low S/B)



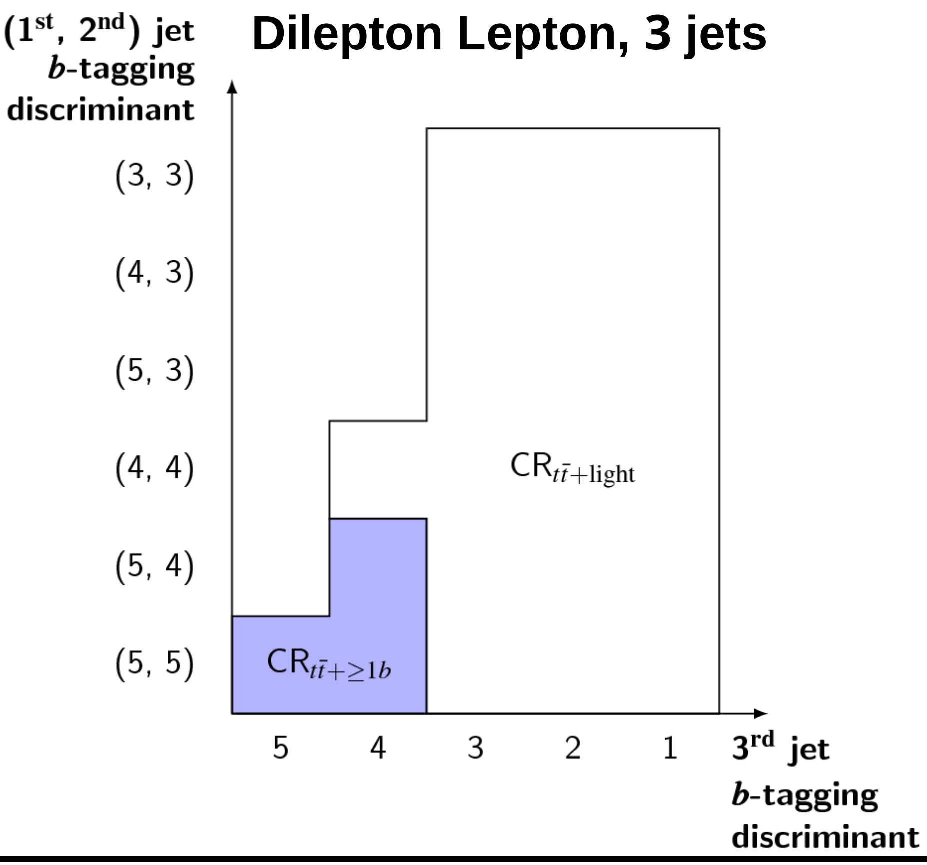
ttH(bb) (1 and 2 leptons)

- Split into jet and b-jet multiplicity, merge regions with similar background content
  - → SR = Signal Region ("large" S/B); CR = Control Region (low S/B)

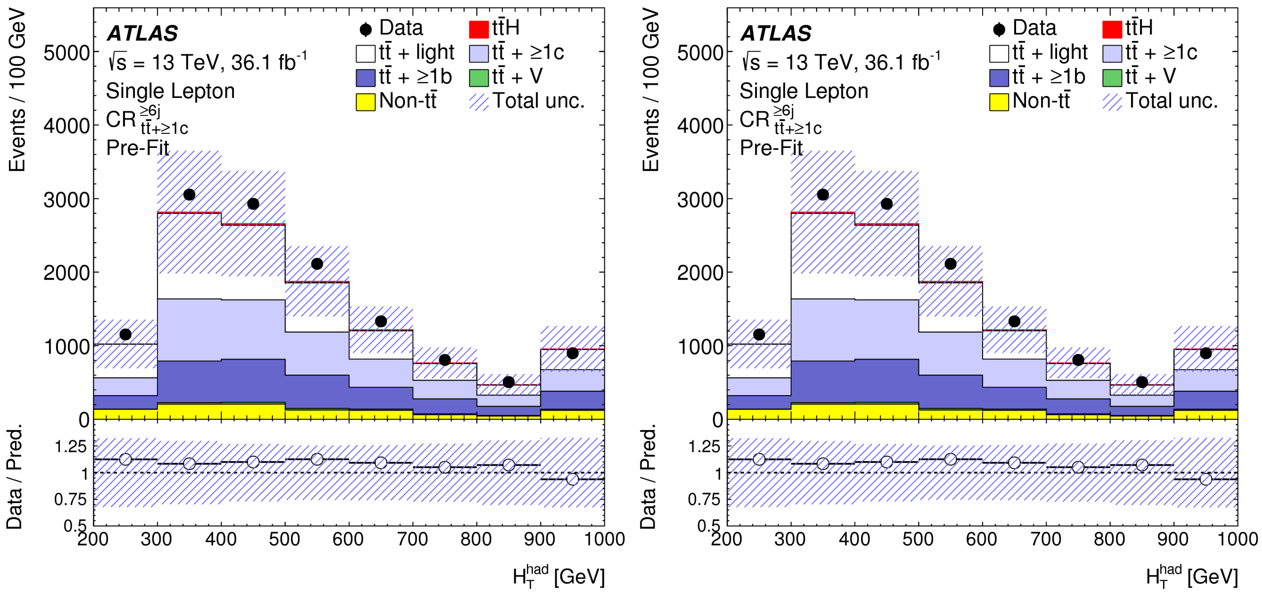


ttH(bb) (1 and 2 leptons)

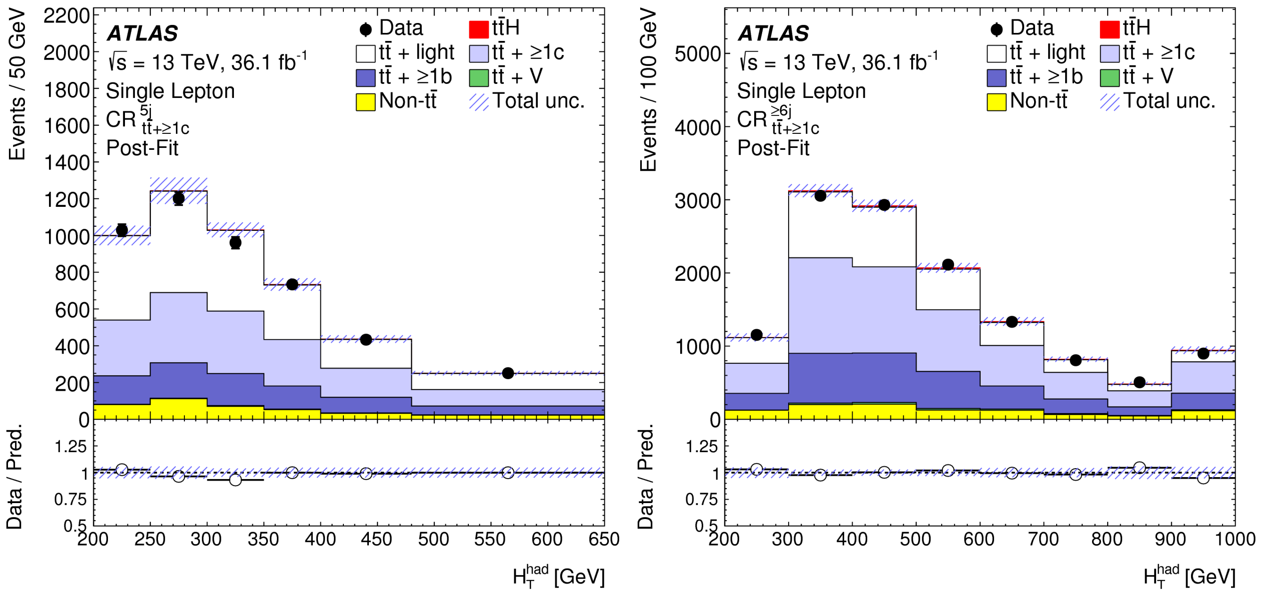
- Split into jet and b-jet multiplicity, merge regions with similar background content
  - → SR = Signal Region ("large" S/B); CR = Control Region (low S/B)



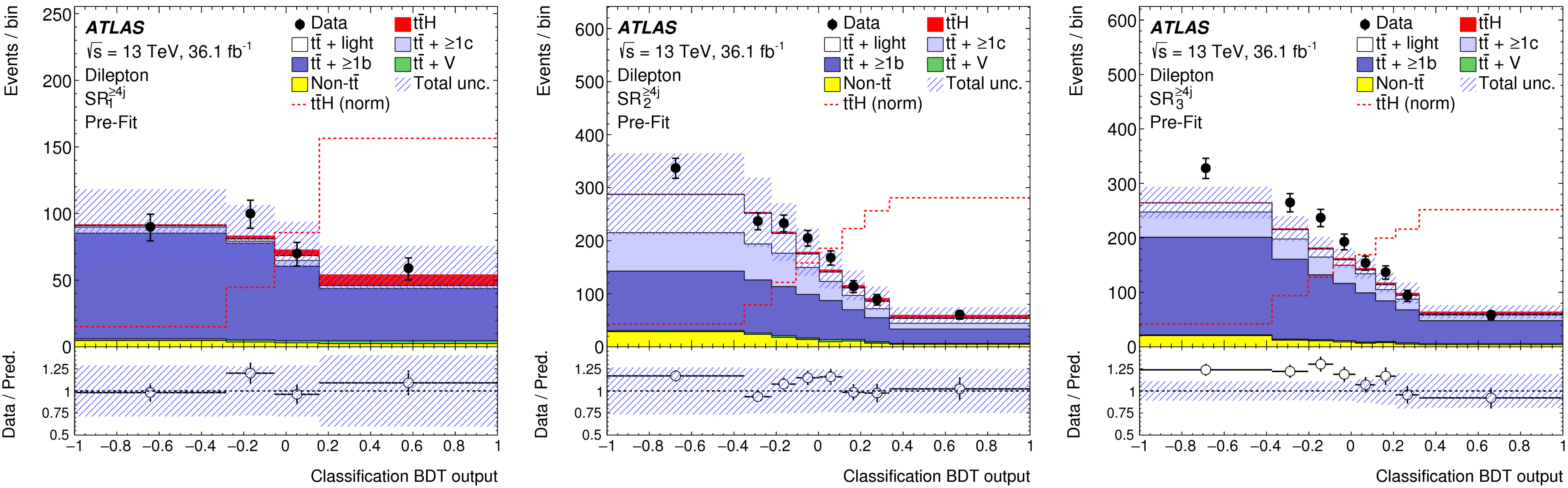
ttH(bb) Single Lepton Control Regions: Pre-fit



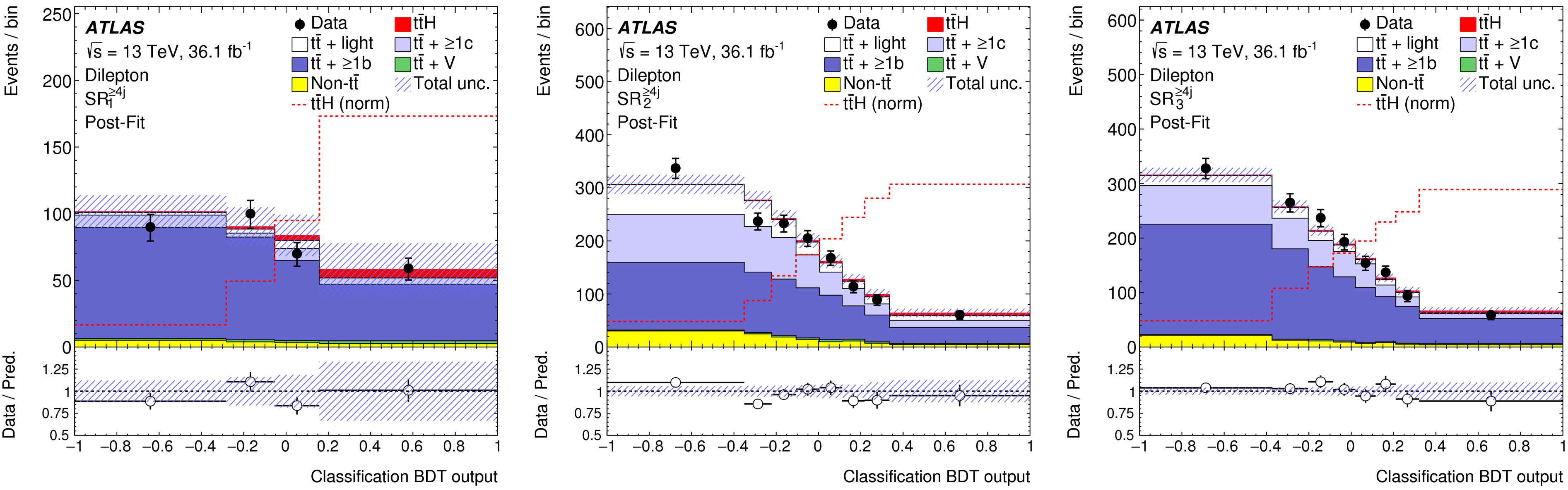
ttH(bb) Single Lepton Control Regions: Post-fit



ttH(bb) Dilepton Signal Regions: Pre-fit



ttH(bb) Dilepton Signal Regions: Post-fit



ttH(bb) systematics

Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t}+\geq 1c)$	Free-floating $t\bar{t}+\geq 1c$ normalization	$t\bar{t}+\geq 1c$
$k(t\bar{t}+\geq 1b)$	Free-floating $t\bar{t}+\geq 1b$ normalization	$t\bar{t}+\geq 1b$
SHERPA5F vs. nominal	Related to the choice of NLO event generator	All, uncorrelated
PS & hadronization	POWHEG+HERWIG 7 vs. POWHEG+PYTHIA 8	All, uncorrelated
ISR / FSR	Variations of μ_{R}, μ_{F}, h_{damp} and A14 Var3c parameters	All, uncorrelated
$t\bar{t}+\geq 1c$ ME vs. inclusive	MG5_aMC@NLO+HERWIG++: ME prediction (3F) vs. incl. (5F)	$t\bar{t}+\geq 1c$
$t\bar{t}+\geq 1b$ SHERPA4F vs. nominal	Comparison of $t\bar{t}+b\bar{b}$ NLO (4F) vs. POWHEG+PYTHIA 8 (5F)	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ renorm. scale	Up or down by a factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ resumm. scale	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ global scales	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ shower recoil scheme	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (MSTW)	MSTW vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ PDF (NNPDF)	NNPDF vs. CT10	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ UE	Alternative set of tuned parameters for the underlying event	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 1b$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+\geq 3b$ normalization	Up or down by 50%	$t\bar{t}+\geq 1b$

ttH, multilepton

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_T > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_T > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_T > 15$ GeV The opposite-charge lepton must be loose, isolated and pass the non-prompt BDT Zero medium τ_{had} candidates $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(3\ell) - 91.2\text{ GeV}\rvert > 10$ GeV
4ℓ	Four light leptons; sum of light-lepton charges 0 Third and fourth leading leptons must be tight $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for all SFOC pairs $\lvert m(4\ell) - 125\text{ GeV}\rvert > 5$ GeV Split 2 categories: Z-depleted (0 SFOC pairs) and Z-enriched (2 or 4 SFOC pairs)
$1\ell+2\tau_{\text{had}}$	One tight light lepton with $p_T > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
$2\ell\text{SS}+1\tau_{\text{had}}$	Two very tight light leptons with $p_T > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
$2\ell\text{OS}+1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_T > 25$, 15 GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
$3\ell+1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_T > 10$ GeV The opposite-charge light lepton must be loose and isolated

ttH, multilepton

Process	Cross section [pb]	QCD scale [%]	PDF+α_S [%]	Order
$t\bar{t}H$	0.51	$^{+5.8}_{-9.2}$	± 3.6	NLO QCD+EWK
$tHqb$	0.074	$^{+6.5}_{-15}$	± 3.7	NLO QCD
tHW	0.015	$^{+4.9}_{-6.7}$	± 6.3	NLO QCD
$t\bar{t}W$	0.60	$^{+13}_{-12}$	± 3.4	NLO QCD+EWK
$t\bar{t}(Z/\gamma^* \to ll)$	0.12	$^{+9.6}_{-11}$	± 4.0	NLO QCD+EWK
$t\bar{t}t\bar{t}$	0.0092	$^{+31}_{-26}$	$^{+5.5}_{-5.9}$	NLO QCD
$t\bar{t}W^+W^-$	0.0099	$^{+11}_{-12}$	± 2.1	NLO QCD
$t\bar{t}$	832	$^{+2.4}_{-3.5}$	± 4.2	NNLO QCD + NNLL
$t\bar{t}\gamma$	5.7	± 50		NLO QCD
tZ	0.61	± 50		LO QCD
tWZ	0.16	± 50		NLO QCD
Single t (s-channel)	10	± 4		NLO QCD
Single t (t-channel)	217	± 4		NLO QCD
Single t (Wt)	72	± 5		NLO QCD + NNLL
$VV(\to llXX)$	37	± 50		NLO QCD
$Z \to l^+l^-$	2070	± 5		NNLO QCD

ttH, multilepton

	Variable	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	2ℓSS$+1\tau_{\text{had}}$	2ℓOS$+1\tau_{\text{had}}$
Lepton properties	Leading lepton p_{T}		$\times$				
	Second leading lepton p_{T}	$\times$	$\times$			$\times$	
	Third lepton p_{T}		$\times$				
	Dilepton invariant mass (all combinations)	$\times$	$\times*$				$\times$
	Three-lepton invariant mass		$\times$				
	Four-lepton invariant mass			$\times$			
	Best Z-candidate dilepton invariant mass			$\times$			
	Other Z-candidate dilepton invariant mass			$\times$			
	Scalar sum of all leptons p_{T}			$\times$			$\times$
	Second leading lepton track isolation					$\times$	
	Maximum $\lvert\eta\rvert$ (lepton 0, lepton 1)	$\times$				$\times*$	
	Lepton flavor	$\times*$	$\times*$				
	Lepton charge		$\times$				
Jet properties	Number of jets	$\times*$	$\times*$		$\times$	$\times$	$\times$
	Number of b-tagged jets	$\times*$	$\times*$		$\times$	$\times$	$\times$
	Leading jet p_{T}						$\times$
	Second leading jet p_{T}		$\times$			$\times*$	
	Leading b-tagged jet p_{T}		$\times$				
	Scalar sum of all jets p_{T}		$\times$		$\times$	$\times$	$\times$
	Scalar sum of all b-tagged jets p_{T}						$\times$
	Has leading jet highest b-tagging weight?		$\times$				
	b-tagging weight of leading jet		$\times$				
	b-tagging weight of second leading jet		$\times$			$\times$	
	b-tagging weight of third leading jet					$\times$	
	Pseudorapidity of fourth leading jet					$\times$	
τ_{had}	Leading τ_{had} p_{T}				$\times$		$\times$
	Second leading τ_{had} p_{T}				$\times$		
	Di-τ_{had} invariant mass				$\times$		
	Invariant mass τ_{had}–furthest lepton					$\times$	
Angular distances	ΔR(lepton 0, lepton 1)		$\times$				
	ΔR(lepton 0, lepton 2)		$\times$				
	ΔR(lepton 0, closest jet)	$\times$	$\times$				
	ΔR(lepton 0, leading jet)		$\times$			$\times$	
	ΔR(lepton 0, closest b-jet)		$\times$				
	ΔR(lepton 1, closest jet)	$\times$	$\times$				
	ΔR(lepton 2, closest jet)		$\times$				
	Smallest ΔR(lepton, jet)		$\times$				$\times$
	Smallest ΔR(lepton, b-tagged jet)						$\times$
	Smallest ΔR(non-tagged jet, b-tagged jet)						$\times$
	ΔR(lepton 0, τ_{had})						$\times$
	ΔR(lepton 1, τ_{had})						$\times$
	Minimum ΔR between all jets				$\times$		
	ΔR between two leading jets					$\times$	
$\vec{p}_{\text{T}}^{\text{miss}}$	Missing transverse momentum $E_{\text{T}}^{\text{miss}}$	$\times$		$\times$			
	Azimuthal separation $\Delta\phi$(leading jet, $\vec{p}_{\text{T}}^{\text{miss}}$)		$\times$				
	Transverse mass leptons (H/Z decay) - $\vec{p}_{\text{T}}^{\text{miss}}$			$\times$			
	Pseudo-Matrix-Element			$\times$			

ttH, multilepton

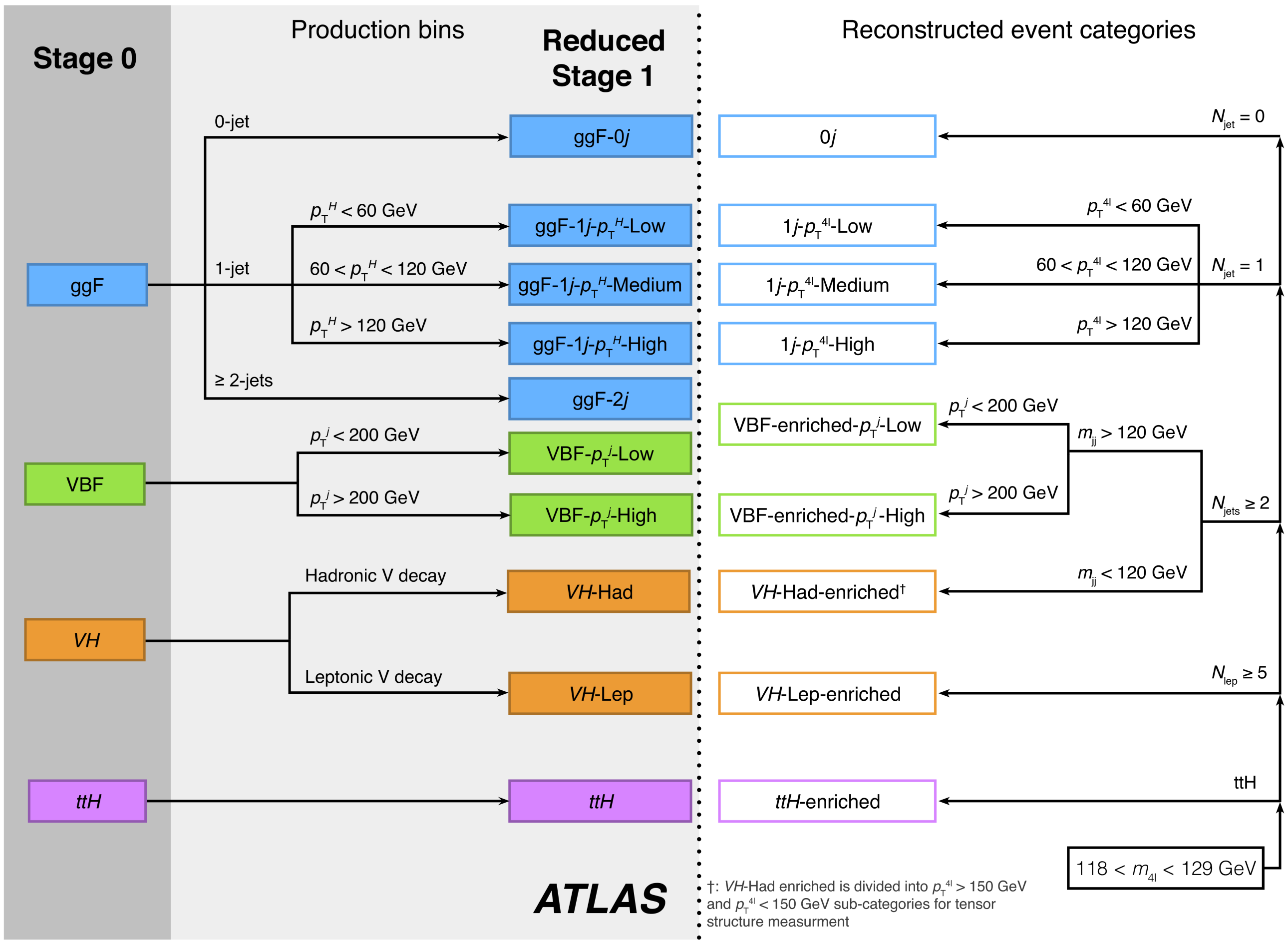
Systematic uncertainty	Type	Components
Luminosity	N	1
Pileup reweighting	SN	1
Physics Objects		
Electron	SN	6
Muon	SN	15
τ_{had}	SN	10
Jet energy scale and resolution	SN	28
Jet vertex fraction	SN	1
Jet flavor tagging	SN	126
$E_{\text{T}}^{\text{miss}}$	SN	3
Total (Experimental)	–	191
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	83
$t\bar{t}H$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Parton shower and hadronization model	SN	1
Higgs boson branching fraction	N	4
Shower tune	SN	1
$t\bar{t}W$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
$t\bar{t}Z$ **modeling**		
Cross section	N	2
Renormalization and factorization scales	S	3
Matrix-element MC event generator	SN	1
Shower tune	SN	1
Other background modeling		
Cross section	N	15
Shower tune	SN	1
Total (Signal and background modeling)	–	41
Total (Overall)	–	315

ttH, multilepton and combination

Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
2ℓOS+$1\tau_{\text{had}}$	$1.7\ ^{+1.6}_{-1.5}$ (stat.) $^{+1.4}_{-1.1}$ (syst.)	$1.0\ ^{+1.5}_{-1.4}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	0.9σ	0.5σ
1ℓ+$2\tau_{\text{had}}$	$-0.6\ ^{+1.1}_{-0.8}$ (stat.) $^{+1.1}_{-1.3}$ (syst.)	$1.0\ ^{+1.1}_{-0.9}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	–	0.6σ
4ℓ	$-0.5\ ^{+1.3}_{-0.8}$ (stat.) $^{+0.2}_{-0.3}$ (syst.)	$1.0\ ^{+1.7}_{-1.2}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	–	0.8σ
3ℓ+$1\tau_{\text{had}}$	$1.6\ ^{+1.7}_{-1.3}$ (stat.) $^{+0.6}_{-0.2}$ (syst.)	$1.0\ ^{+1.5}_{-1.1}$ (stat.) $^{+0.4}_{-0.2}$ (syst.)	1.3σ	0.9σ
2ℓSS+$1\tau_{\text{had}}$	$3.5\ ^{+1.5}_{-1.2}$ (stat.) $^{+0.9}_{-0.5}$ (syst.)	$1.0\ ^{+1.1}_{-0.8}$ (stat.) $^{+0.5}_{-0.3}$ (syst.)	3.4σ	1.1σ
3ℓ	$1.8\ ^{+0.6}_{-0.6}$ (stat.) $^{+0.6}_{-0.5}$ (syst.)	$1.0\ ^{+0.6}_{-0.5}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	2.4σ	1.5σ
2ℓSS	$1.5\ ^{+0.4}_{-0.4}$ (stat.) $^{+0.5}_{-0.4}$ (syst.)	$1.0\ ^{+0.4}_{-0.4}$ (stat.) $^{+0.4}_{-0.4}$ (syst.)	2.7σ	1.9σ
Combined	$1.6\ ^{+0.3}_{-0.3}$ (stat.) $^{+0.4}_{-0.3}$ (syst.)	$1.0\ ^{+0.3}_{-0.3}$ (stat.) $^{+0.3}_{-0.3}$ (syst.)	4.1σ	2.8σ

Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
Multilepton	$1.6\ ^{+0.5}_{-0.4}$	$1.0\ ^{+0.4}_{-0.4}$	4.1σ	2.8σ
$H \to b\bar{b}$	$0.8\ ^{+0.6}_{-0.6}$	$1.0\ ^{+0.6}_{-0.6}$	1.4σ	1.6σ
$H \to \gamma\gamma$	$0.6\ ^{+0.7}_{-0.6}$	$1.0\ ^{+0.8}_{-0.6}$	0.9σ	1.7σ
$H \to 4\ell$	< 1.9	$1.0\ ^{+3.2}_{-1.0}$	—	0.6σ
Combined	$1.2\ ^{+0.3}_{-0.3}$	$1.0\ ^{+0.3}_{-0.3}$	4.2σ	3.8σ

ttH, H→ZZ*→4 light leptons



ttH, combination of all channels