ATLAS EXPERIMENT

Run: 302391
Event: 382961900
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Search for the 125 GeV Higgs Boson produced in association with top quarks

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Motivation

- After the Higgs discovery, it's important to precisely measure the Higgs properties.
- Yukawa coupling measurement is one of the main topics.
  - ✓ **Top Yukawa coupling (Y_t)** is the largest in SM ($Y_t \sim 1$).

Y_t Measurements

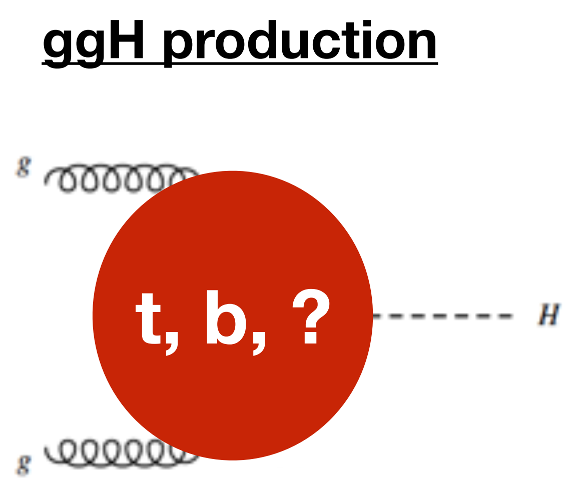
Indirectly measure the Y_t in ggH production and $H \rightarrow \gamma\gamma$ decays.

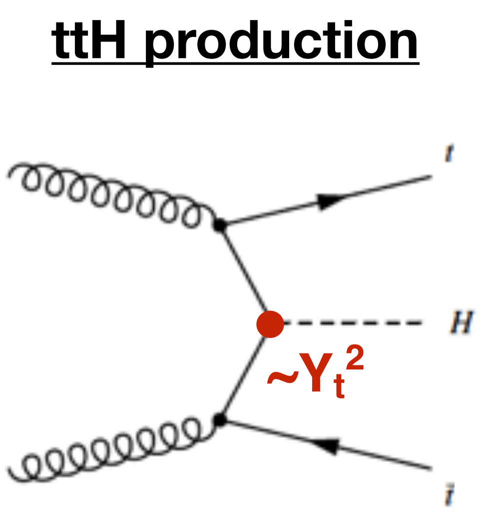
✓ Top quark is main contribution in the loop.

✓ But also sensitive to the presence of BSM particles in the loop.

Directly measure the Y_t in **ttH production.**

✓ Deviation from 1 is a hint of the BSM physics.





Both approaches to measure Top Yukawa coupling are important to understand the SM and search for the BSM physics.

Run 1 Results & Run 2 Expectation

- ttH signal strength (μ_{ttH}) has been measured in LHC Run 1.

$$\mu_{ttH} : 2.3^{+0.7}_{-0.6} \text{ (ATLAS+CMS)}$$

...SM consistent **within large uncertainty.**

- At Run 2, ttH cross section increase more than this main backgrounds.

Process	ttH	ttZ	ttW	tt
$\sigma_{13TeV}/\sigma_{8TeV}$	3.9	3.7	2.4	3.3

- Plan to collect ~100fb^{-1} of data at Run 2.

Larger sensitivity of search for ttH production would be expected at Run 2.

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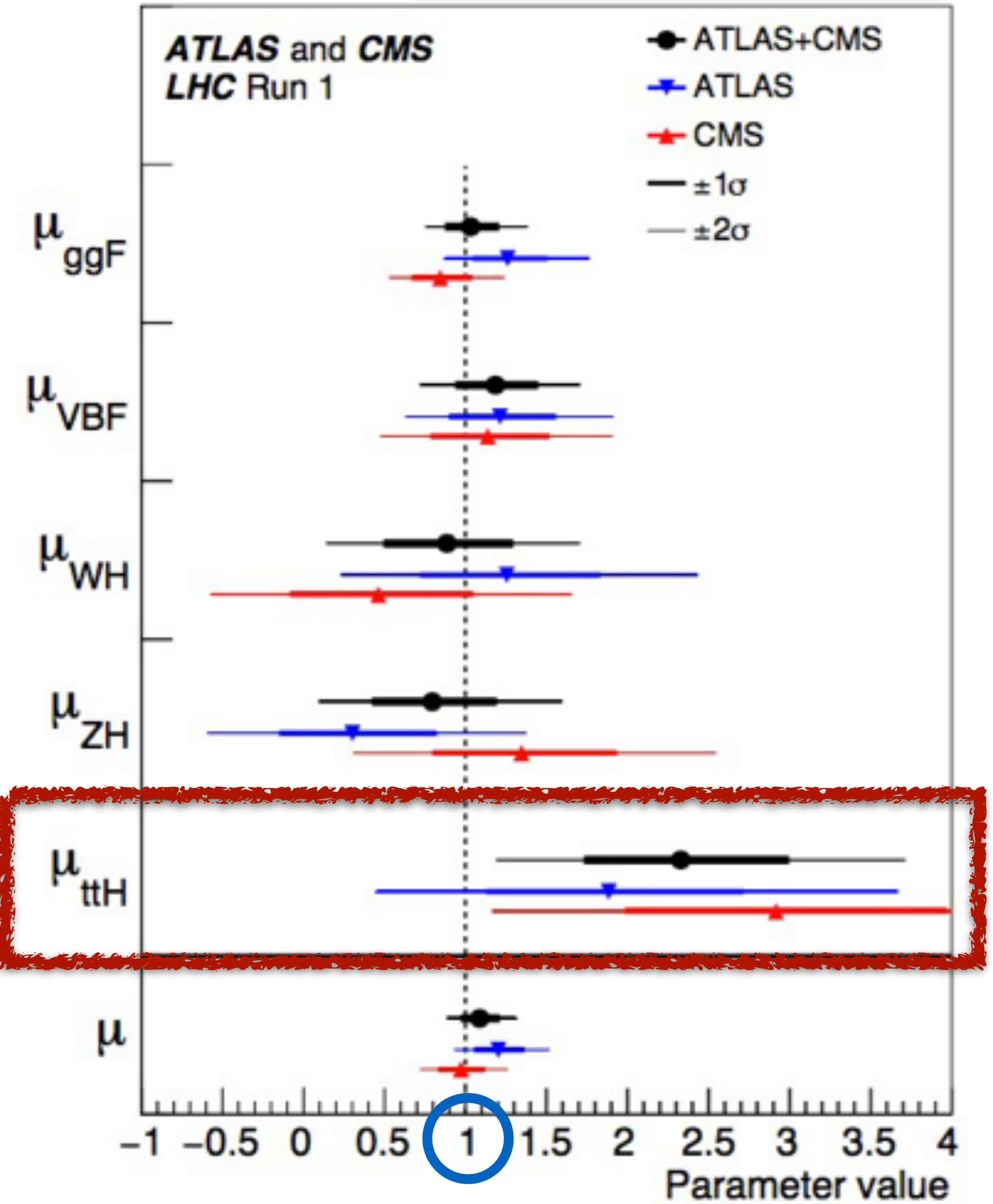
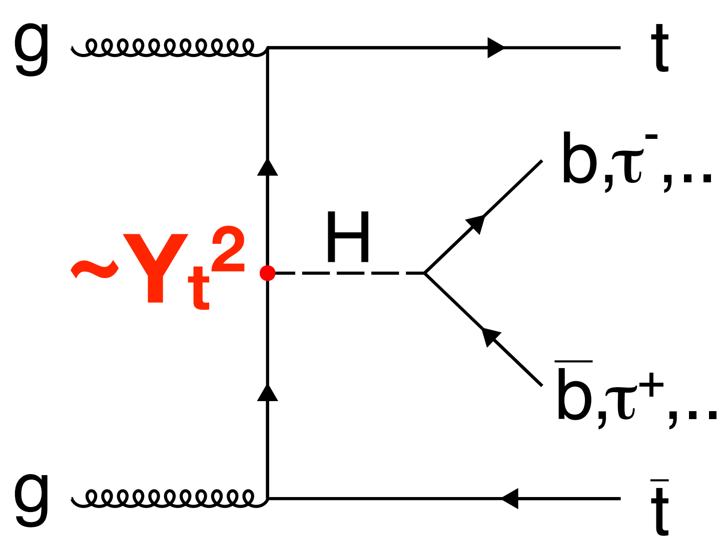


$\mu=\sigma/\sigma_{SM}$ = 1
...SM consistent.

ATLAS Run 2 Search for ttH production

- ATLAS searches for the ttH production in many Higgs decay modes.

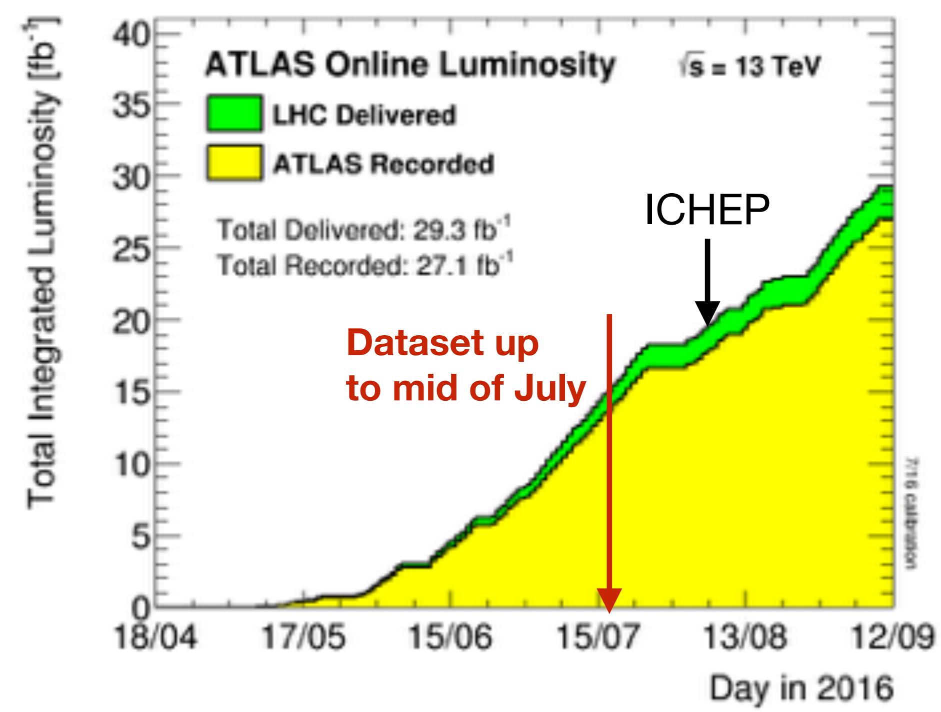


	Branching Ratio (m_H = 125GeV)
H→bb	0.58
H→WW	0.21
H→ττ	0.063
H→ZZ	0.026
H→γγ	0.0023

Analysis Channels:

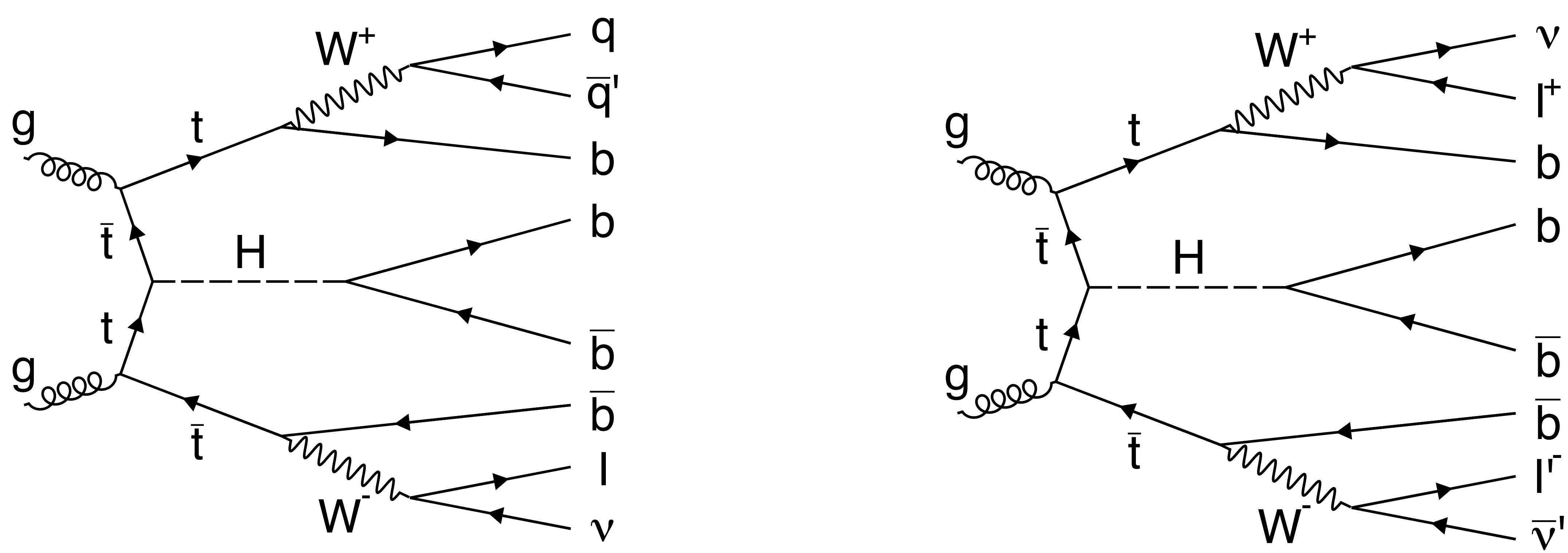
- ✓ **H→bb:** Large BR. But large backgrounds.
- ✓ **multi-lepton:** Targets H→WW, ττ, ZZ. S/B > 0.1.
- ✓ **H→γγ:** Tiny BR. But clean mass resonance.

This presentation shows the first ATLAS Run 2 results with total luminosity of 13.2 - 13.3 fb^{-1}.



ttH(bb): Event Selection

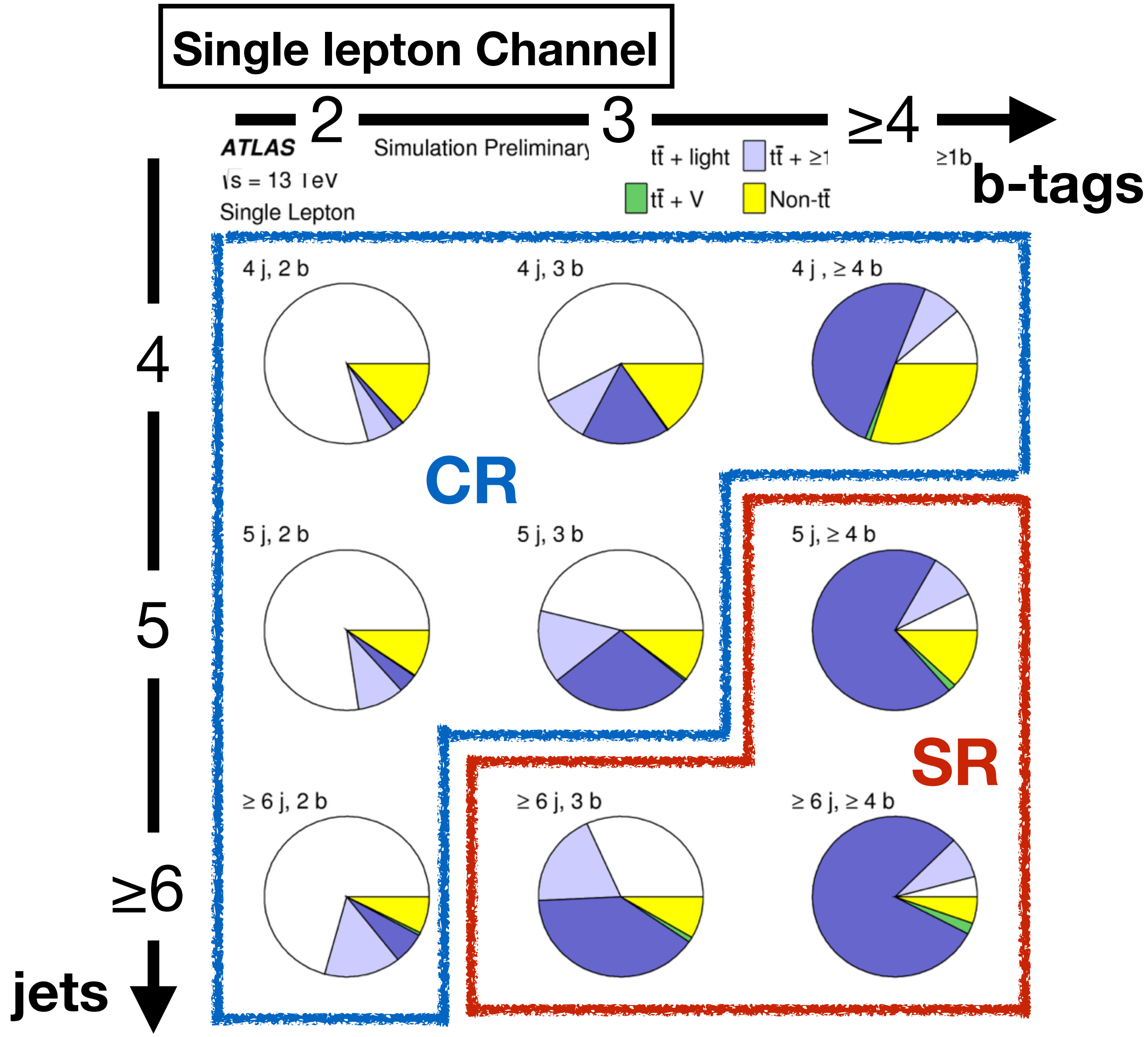
- Events are collected by single lepton trigger (24 (20) GeV in 2016 (2015)).

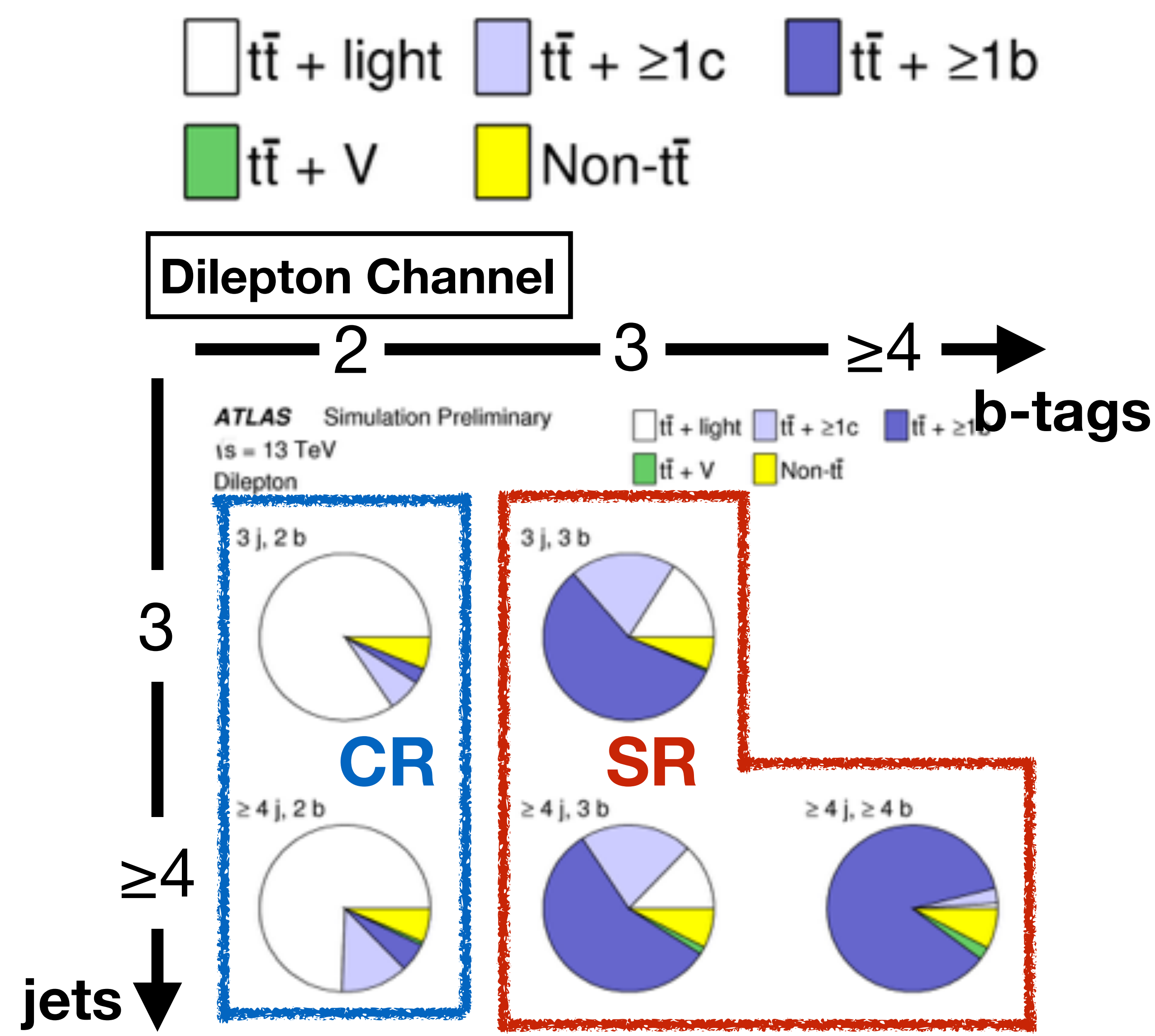


Single Lepton Channel
- 1 light lepton (e,μ)
- At least 4 jets
- At least 2 b-tagged jets

Dilepton Channel
- 2 opposite charge light leptons (e,μ)
- At least 3 jets
- At least 2 b-tagged jets
- Z mass veto

ttH(bb): Event Categorization





- Events are categorized by number of jets and b-tags.
- **Signal Region (SR)** : Enriched in signal.
- **Control Region (CR)** : Use to constraint backgrounds.

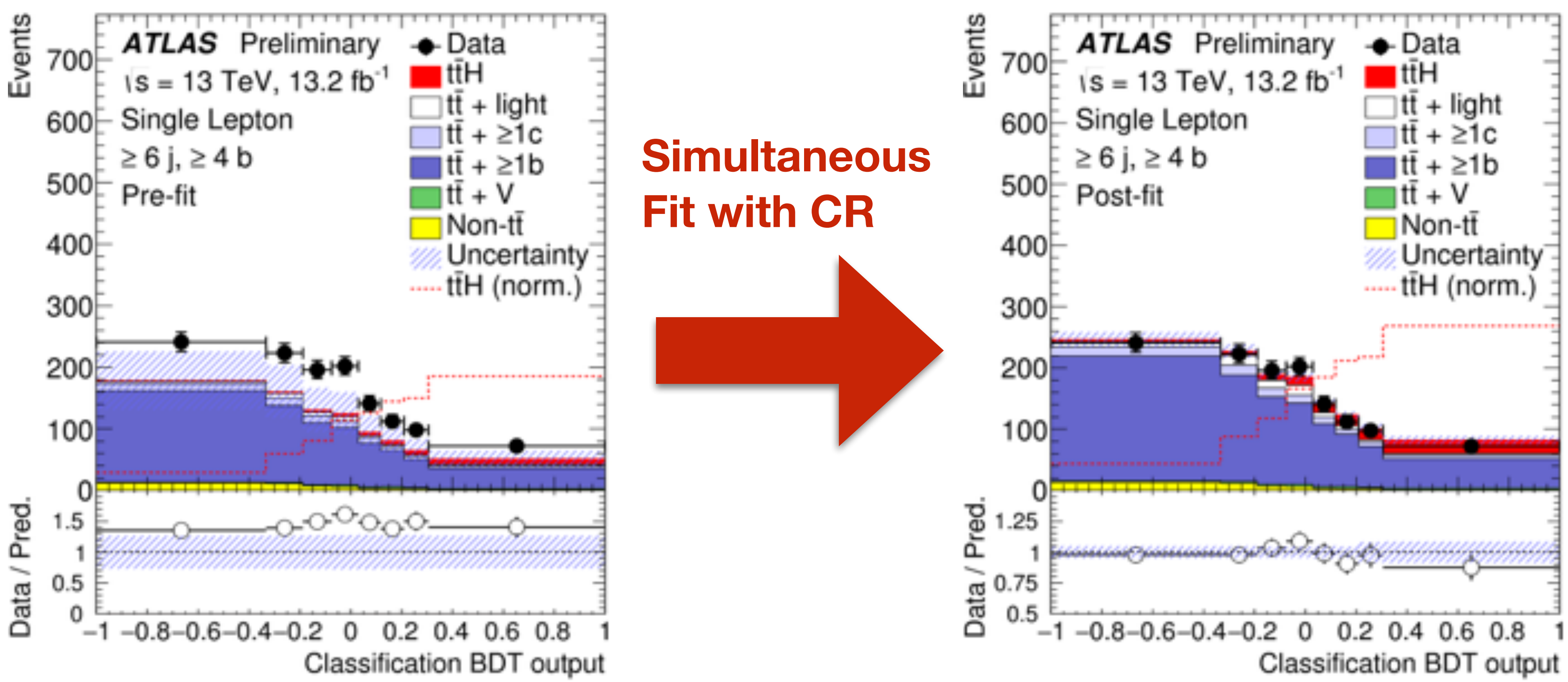
} **Simultaneous Fit**

- The main and irreducible backgrounds are tt + ≥1b, other (tt + ≥1c and tt + light) are reducible and much smaller.

ttH(bb): Discriminating Variables

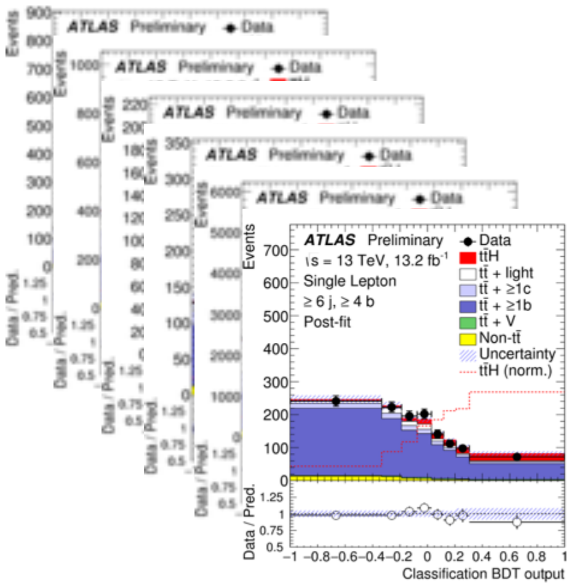
- Use the sequence of multivariate techniques;
  - ✓ **“reconstruction BDT”:** Match observed jets to Higgs and Top Quarks.
  - ✓ **“classification BDT”:** Use event kinematics and outputs from “reconstruction BDT” for training to separate signal from backgrounds.
- In SR, “Classification BDT” is used to extract signal in simultaneous fit with CR.
- In CR, scalar sum of p_T of jets, H_T^{had} (and leptons, H_T) are used in single lepton (dilepton) channel to constraint tt + ≥1b, tt + ≥ 1c normalizations and their uncertainties in simultaneous fit with SR.

NOTE: Normalization for tt + ≥1b and tt + ≥ 1c are allowed to float feely in the fit.

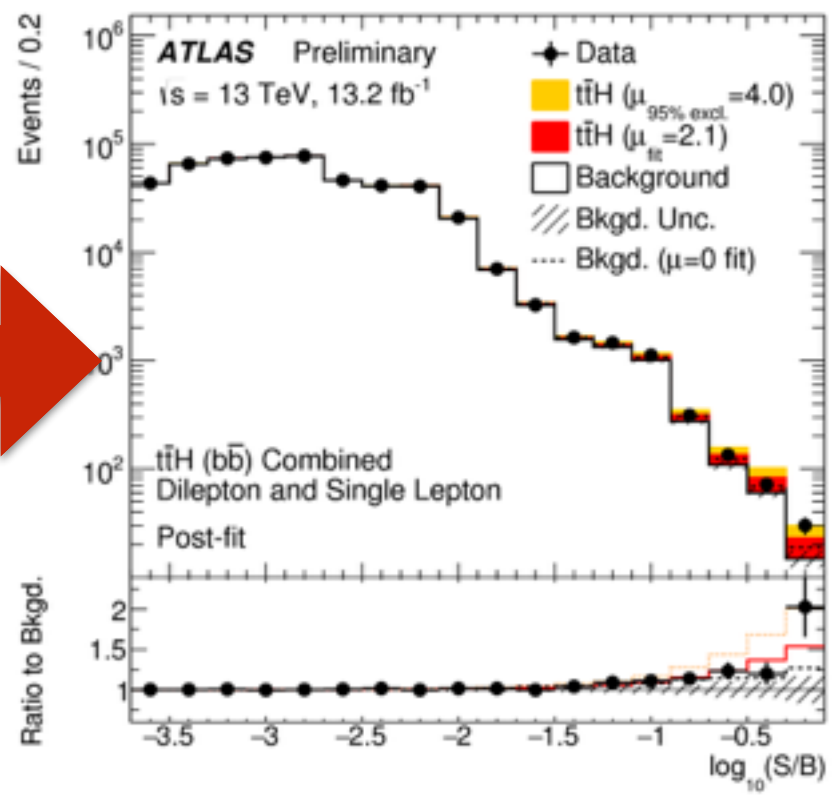


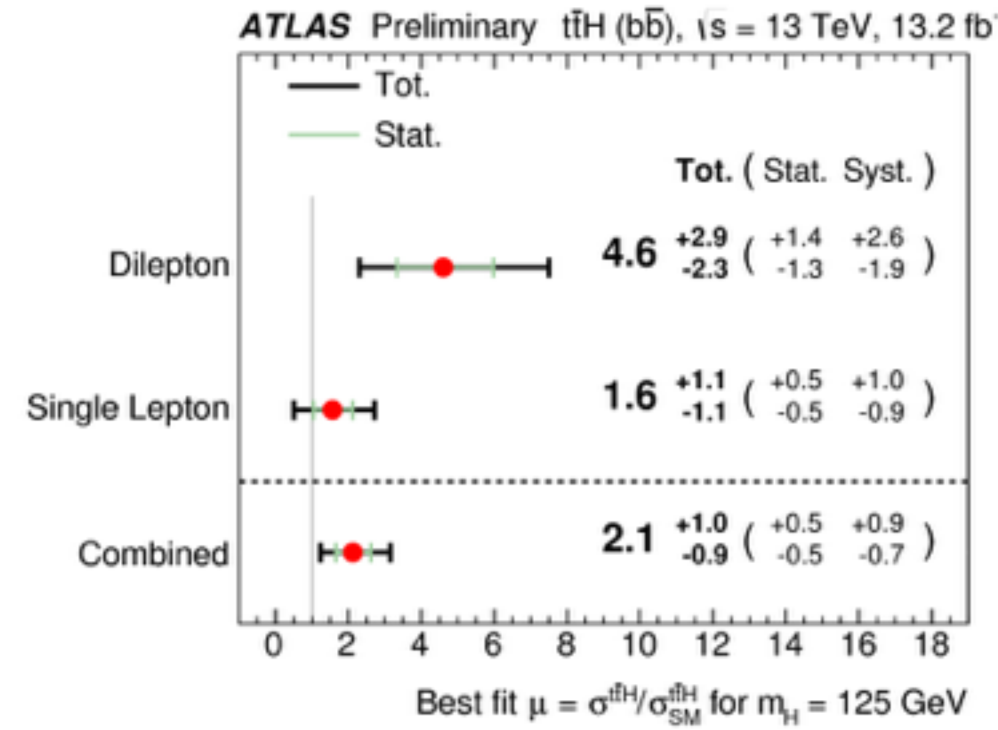
ttH(bb): Results

classification BDT in SRs.



…Extract S/B in each bin.



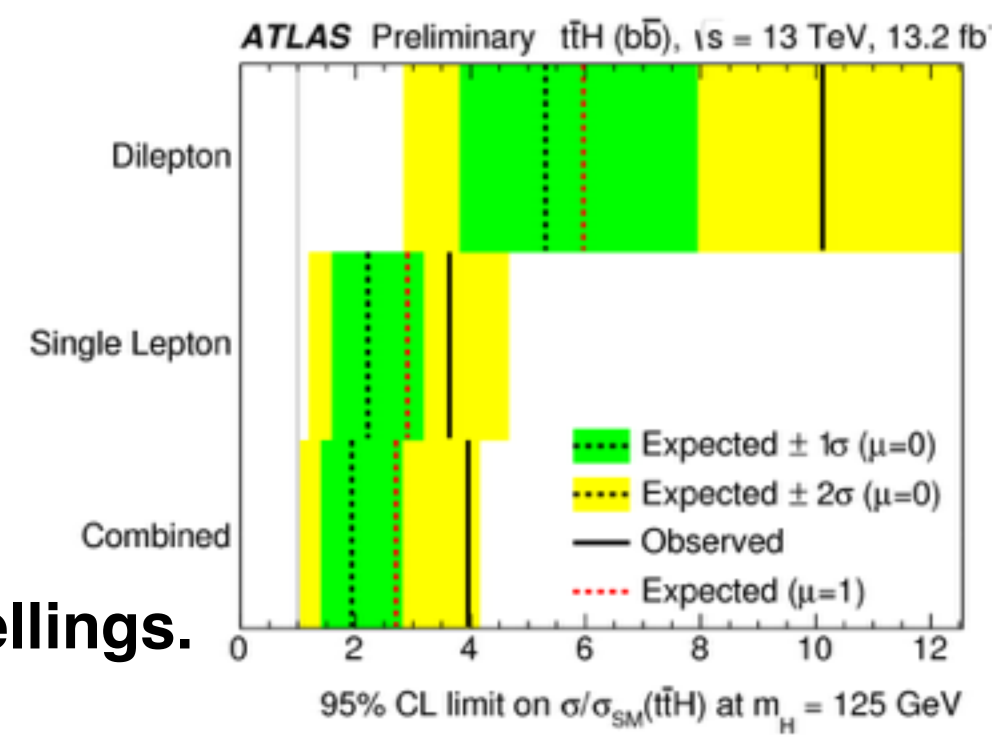


- Observed signal strength μ:

$$\mu = 2.1 \pm 0.5(stat.)\ ^{+0.9}_{-0.7}(syst.)$$

- Observed (and expected) 95% CL upper limit:

$$4.0\ (1.9\ ^{+0.9}_{-0.5}\ [\mu = 0])$$

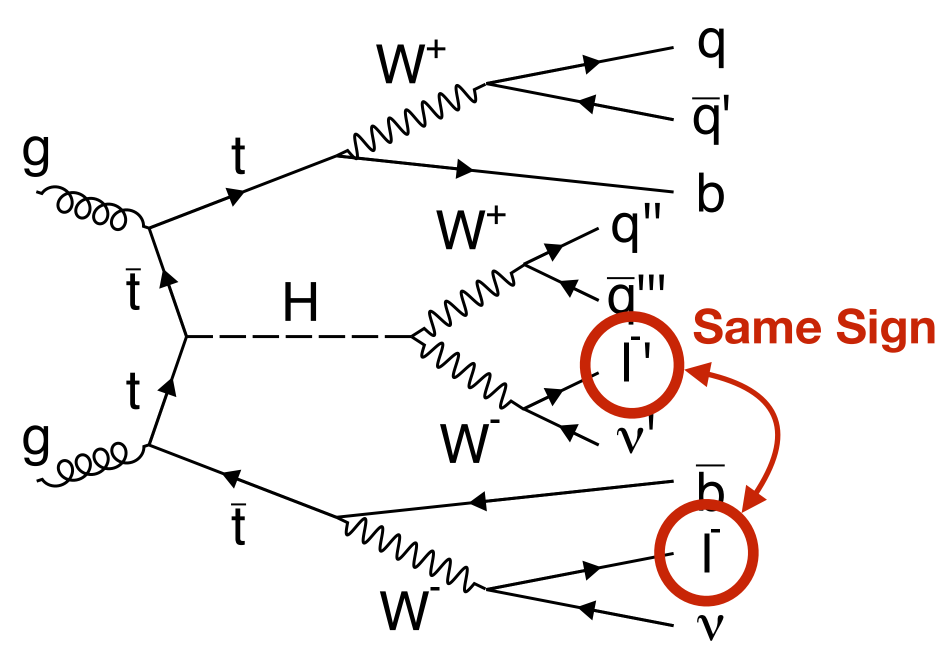


…Systematic uncertainty is dominated by tt+≥1b modellings.

ttH(multi-lepton): Event Selection

- Events are categorized by number of leptons and flavors.
  - ✓ **$2l0\tau_{had}$**: 2 same-charge light leptons + no τ_{had}
    $N_{jets} \geq 5$ and $N_{b\text{-}tags} \geq 1$
  - ✓ **$2l1\tau_{had}$**: 2 same-charge light leptons + 1 τ_{had}
    $N_{jets} \geq 4$ and $N_{b\text{-}tags} \geq 1$
  - ✓ **3l**: 3 light leptons w/ sum of charges = ± 1
    ($N_{jets} \geq 4$ and $N_{b\text{-}tags} \geq 1$) or ($N_{jets} \geq 3$ and $N_{b\text{-}tags} \geq 2$)
  - ✓ **4l**: 4 light leptons w/ sum of charges = 0
    $N_{jets} \geq 2$ and $N_{b\text{-}tags} \geq 1$

ex) $2l0\tau_{had}$, $H\rightarrow WW^*$



- A lot of background events (tt, Z+jets) are effectively rejected by lepton charge requirements and number of jets and b-tags.
- The fraction of higgs decay modes in each category.

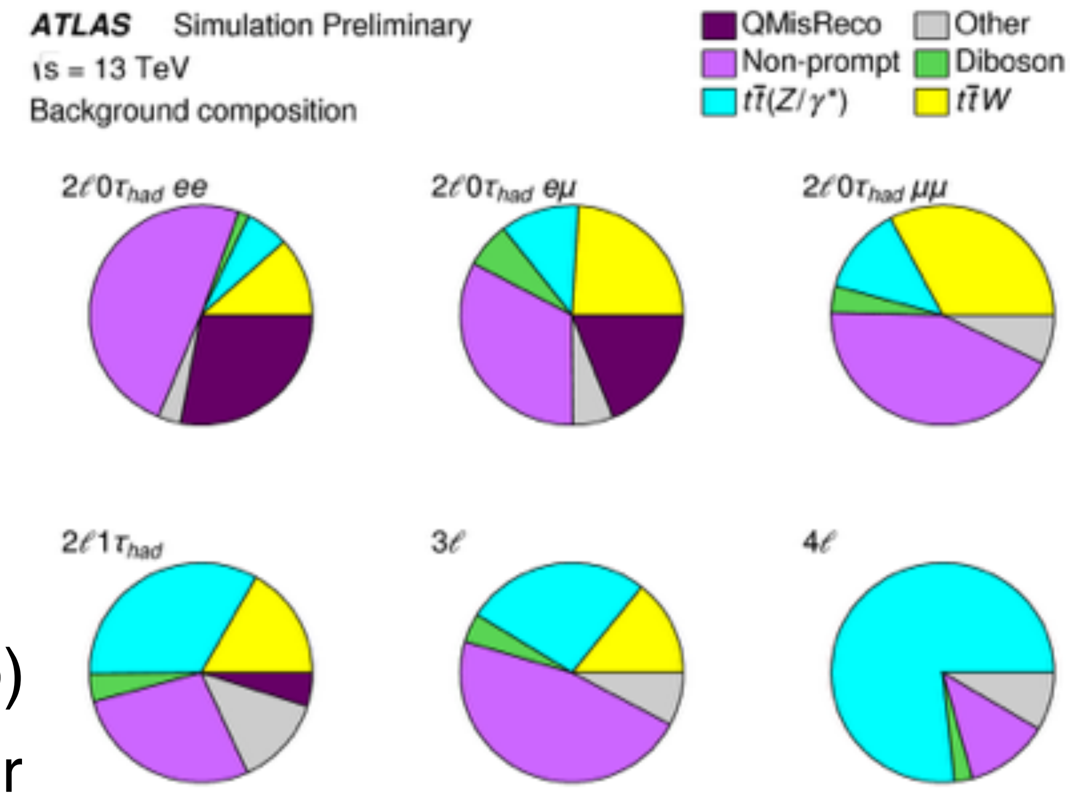
	Higgs boson decay mode				$A \times \epsilon$
Category	WW^*	$\tau\tau$	ZZ^*	Other	$(\times 10^{-4})$
$2\ell 0\tau_{\text{had}}$	77%	17%	3%	3%	14
$2\ell 1\tau_{\text{had}}$	46%	51%	2%	1%	2.2
3ℓ	74%	20%	4%	2%	9.2
4ℓ	72%	18%	9%	2%	0.88

…$H\rightarrow WW^*$, $\tau\tau$ and ZZ^* are inclusively searched in ttH (multi-lepton) channel.

ttH(multi-lepton): Backgrounds Estimation

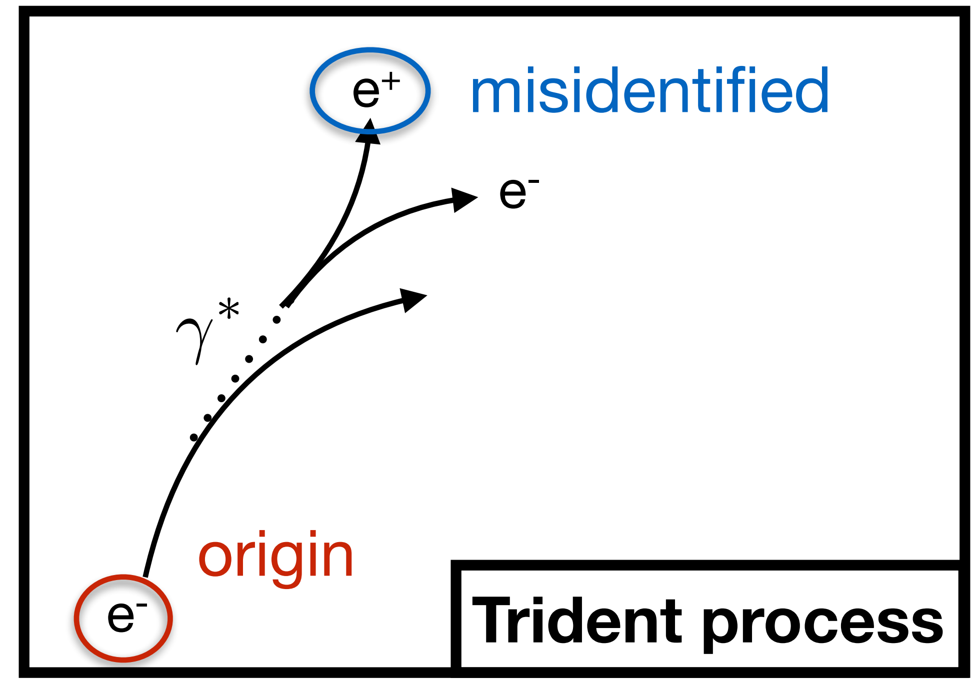
Reducible backgrounds

- Non-prompt lepton events
  - ✓ Heavy flavor hadrons decaying to leptons.
  - ✓ Estimated with data in control region with loose lepton identification requirements and low jet multiplicity.
- Mis-Reconstruction of Electron Charge (QMisReco)
  - ✓ Charge of electrons is mis-reconstructed by detector interactions and slightly curved track at high p_T.
  - ✓ Estimated from data in $Z \rightarrow ee$ control regions.

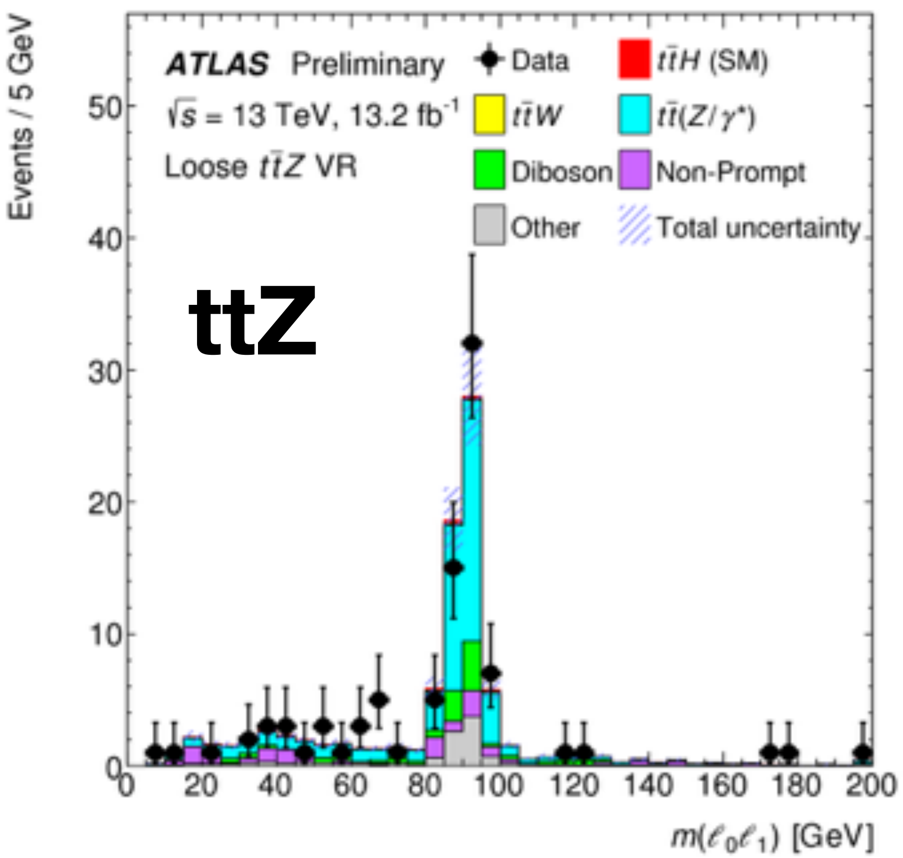


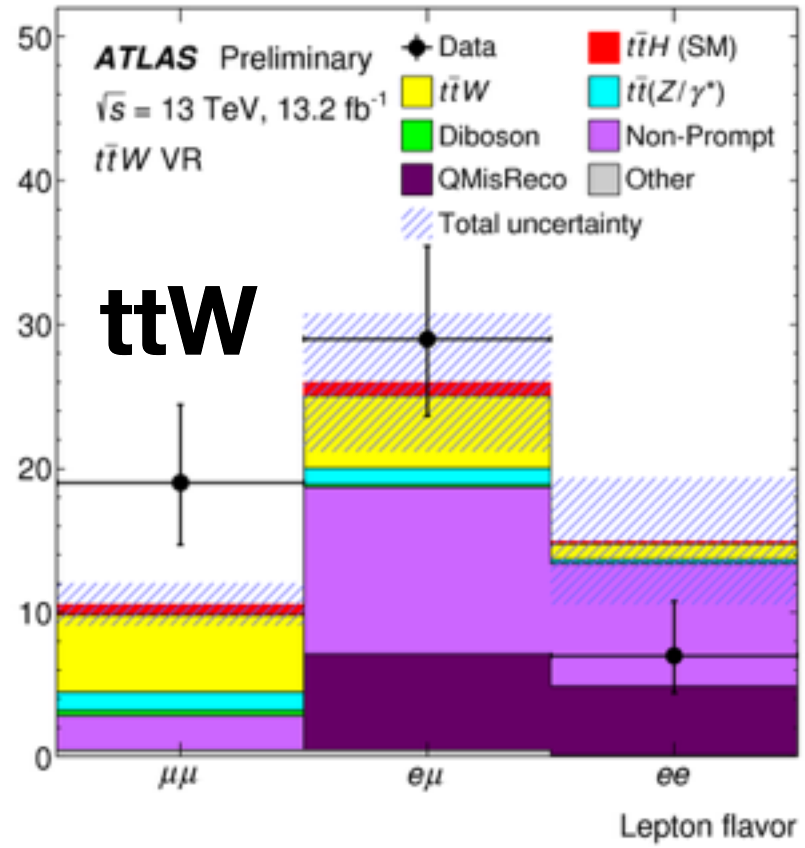
Irreducible backgrounds

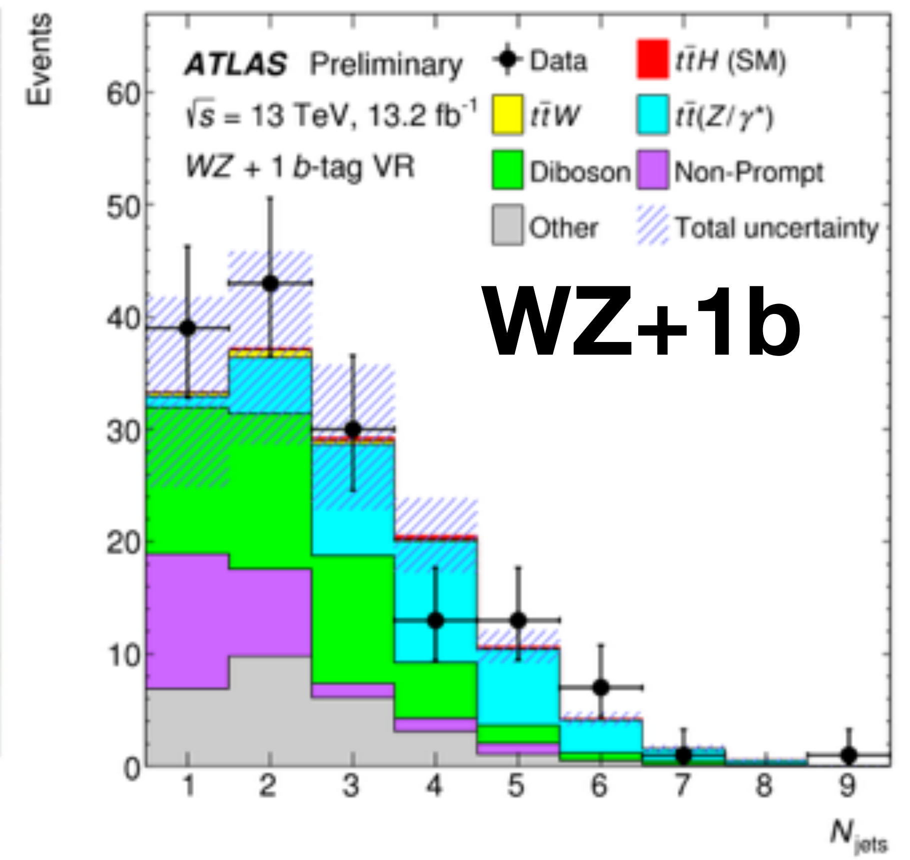
- Diboson, ttZ and ttW events.
  - ✓ Estimated with MC simulation.
  - ✓ Cross-check in dedicated validation region.



ttH(multi-lepton): Validation Region





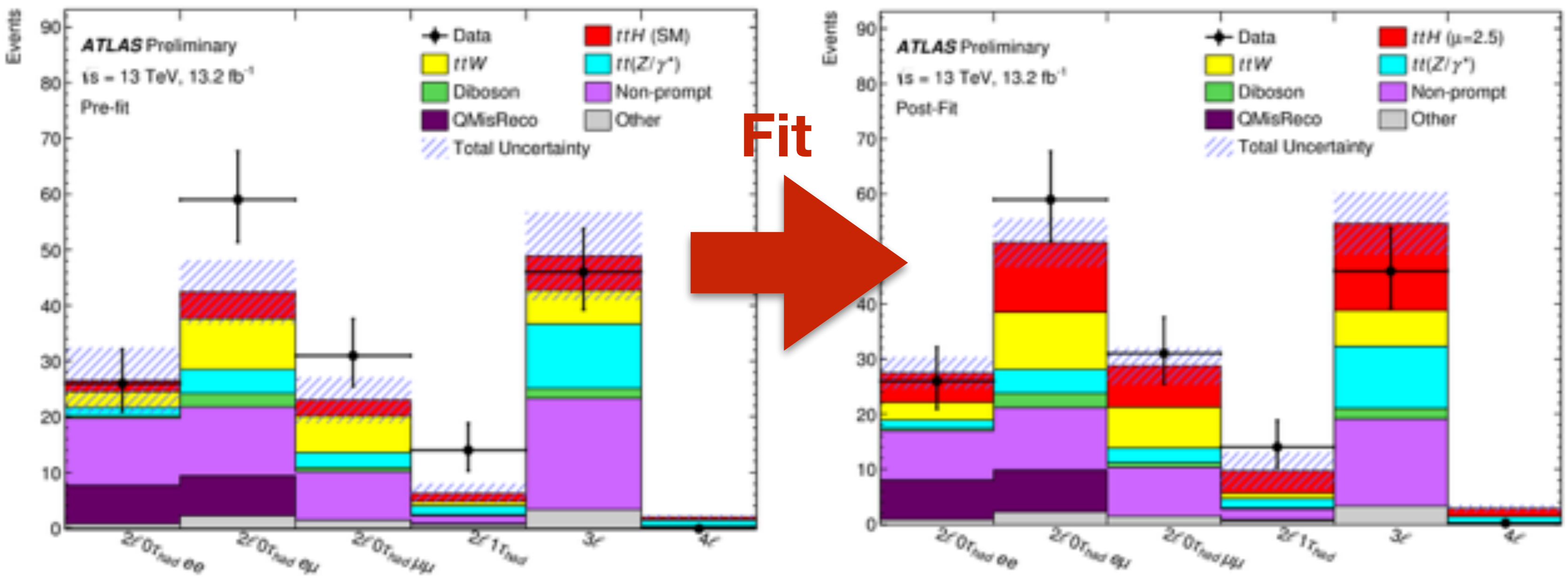


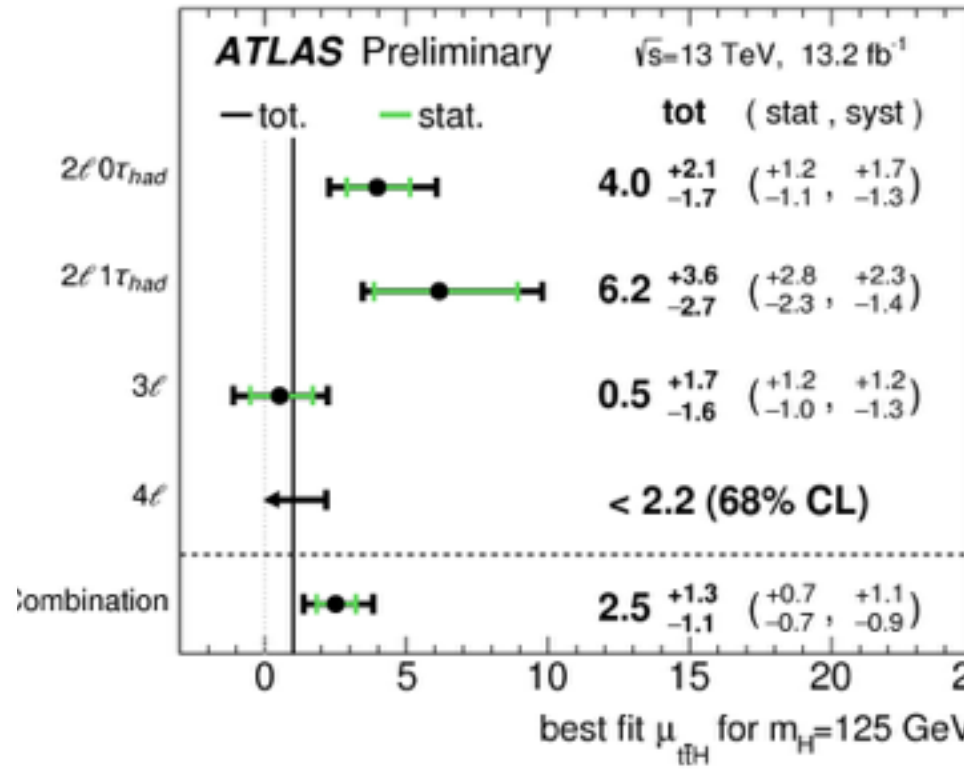
VR	Purity	Expected	Data
Tight $t\bar{t}Z$	68%	32 ± 4	28
Loose $t\bar{t}Z$	58%	91 ± 12	89
$WZ + 1$ b-tag	33%	137 ± 27	147
$t\bar{t}W$	22%	51 ± 10	55

Good agreement between data and MC simulation in these validation regions.

ttH(multi-lepton): Results

Prediction and observed data





…Cut and counting experiments are done in each category.

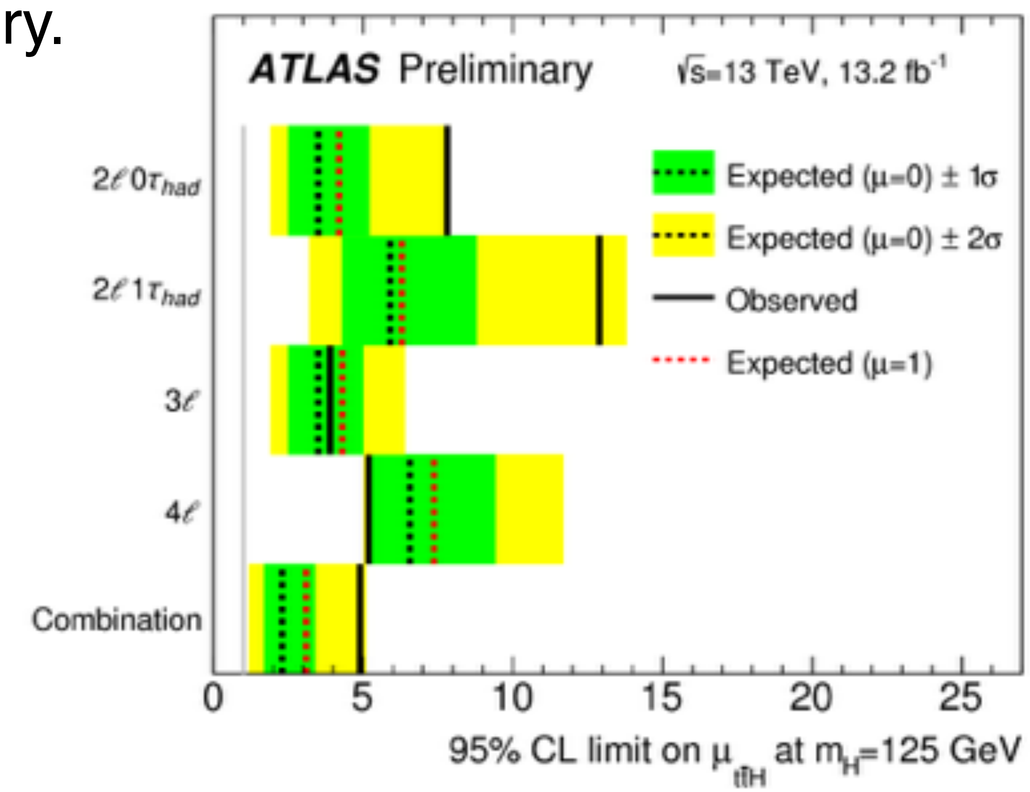
- Observed signal strength μ:

$$\mu = 2.5 \pm 0.7(stat.)\ ^{+1.1}_{-0.9}(syst.)$$

- Observed (and expected) 95% CL upper limit:

$$4.9\ (2.3\ ^{+1.1}_{-0.6}\ [\mu = 0])$$

… Systematic uncertainty is dominated by non-prompt lepton estimation.



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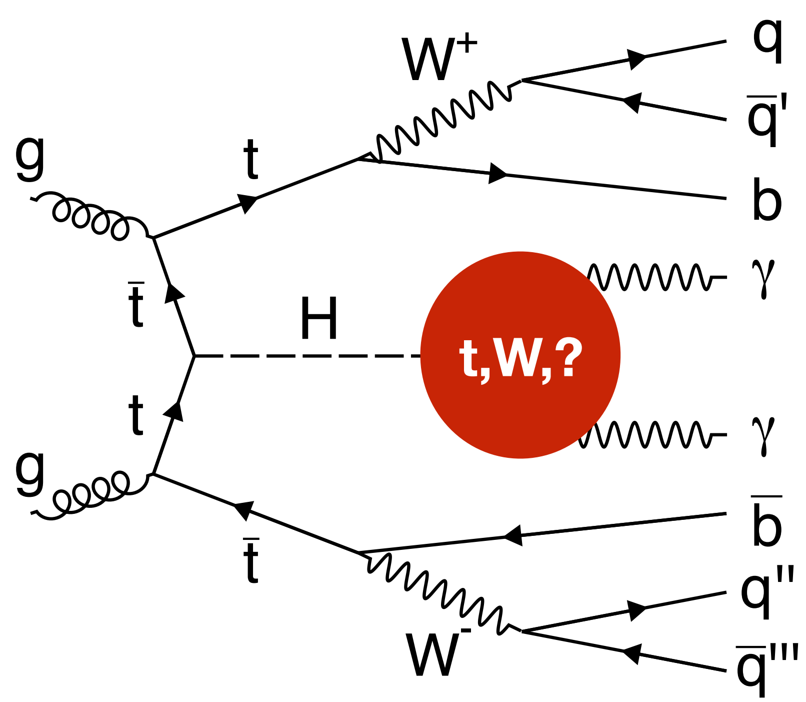
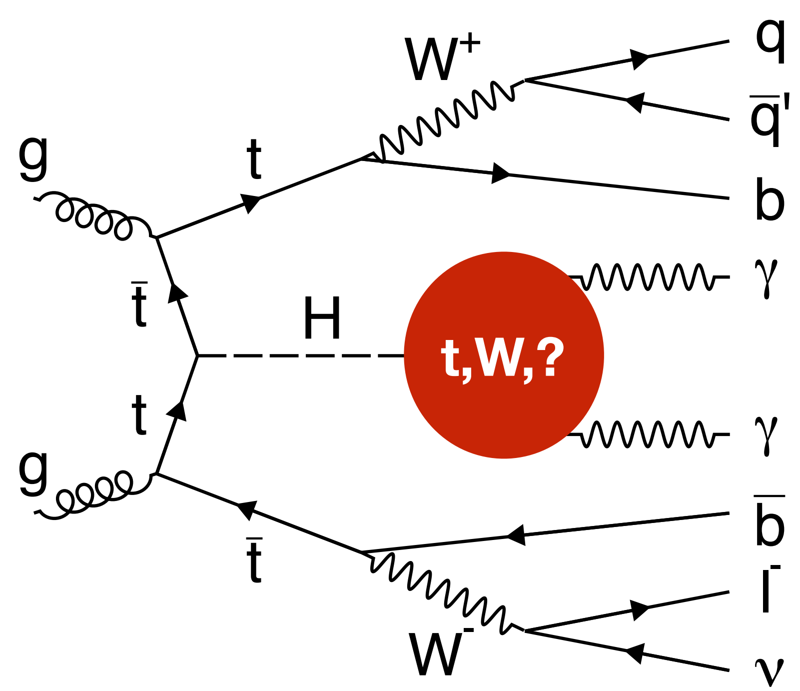
ttH(γγ): Event Selection

- Events are collected by diphoton trigger. Thresholds: 35 & 25 GeV.
- Events must have two tight and isolated photons.





Hadronic Channel

- No light lepton (e,μ)
- At least 5 jets
- At least 1 b-tagged jets

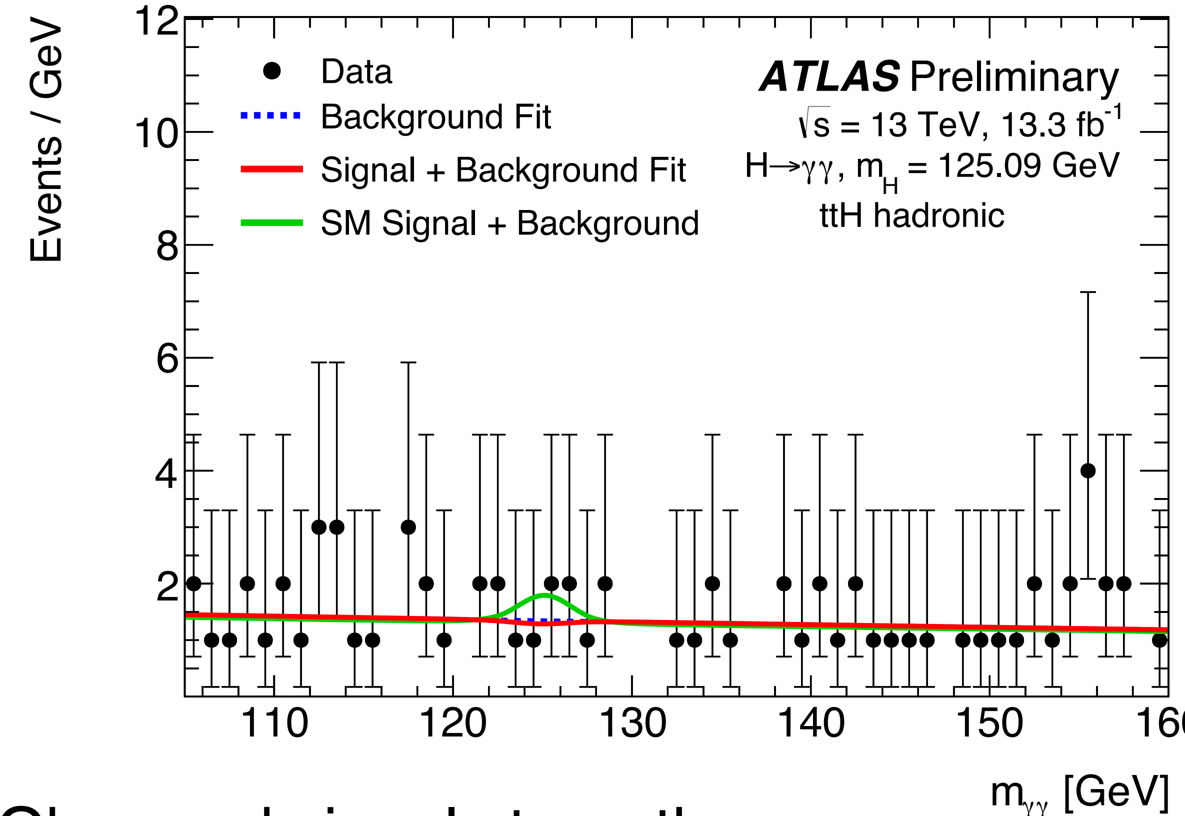
Leptonic Channel

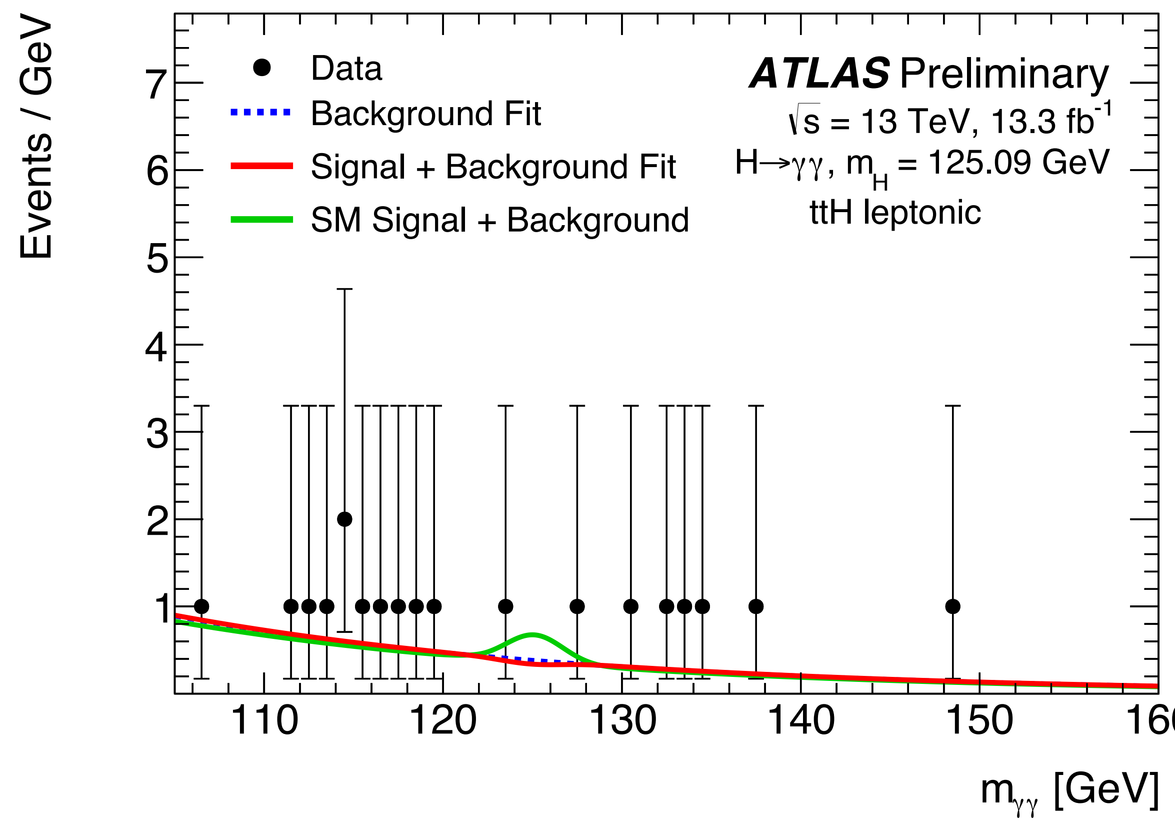
- At least 1 light lepton (e,μ)
- At least 2 jets
- At least 1 b-tagged jet
- E_T^{miss} > 20 GeV (1 b-tag)
- Z veto (m_{ll} and $m_{e\gamma}$)

- In both channels, the purity in ttH process in H→γγ is quite high (~90%).

ttH(H→γγ): Results

- The dominant continuum backgrounds are estimated by exponential function extracted from side band region.
- Signal modelling: Double-sided crystal ball function.





- Observed signal strength μ:

$$\mu = -0.3\ ^{+1.2}_{-1.0}(stat.) \pm 0.2(syst.)$$

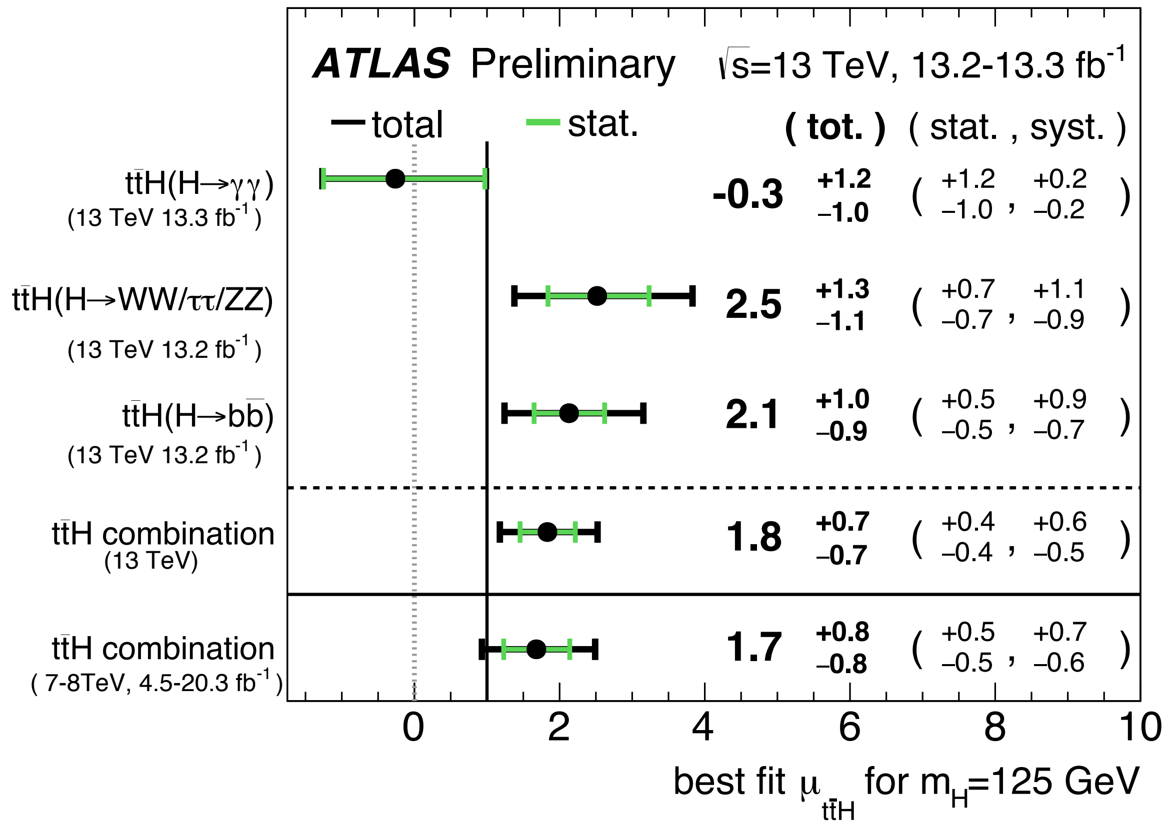
- Observed (and expected) 95% CL upper limit:

$$2.6\ (2.7\ ^{+1.3}_{-0.8}\ [\mu = 0])$$

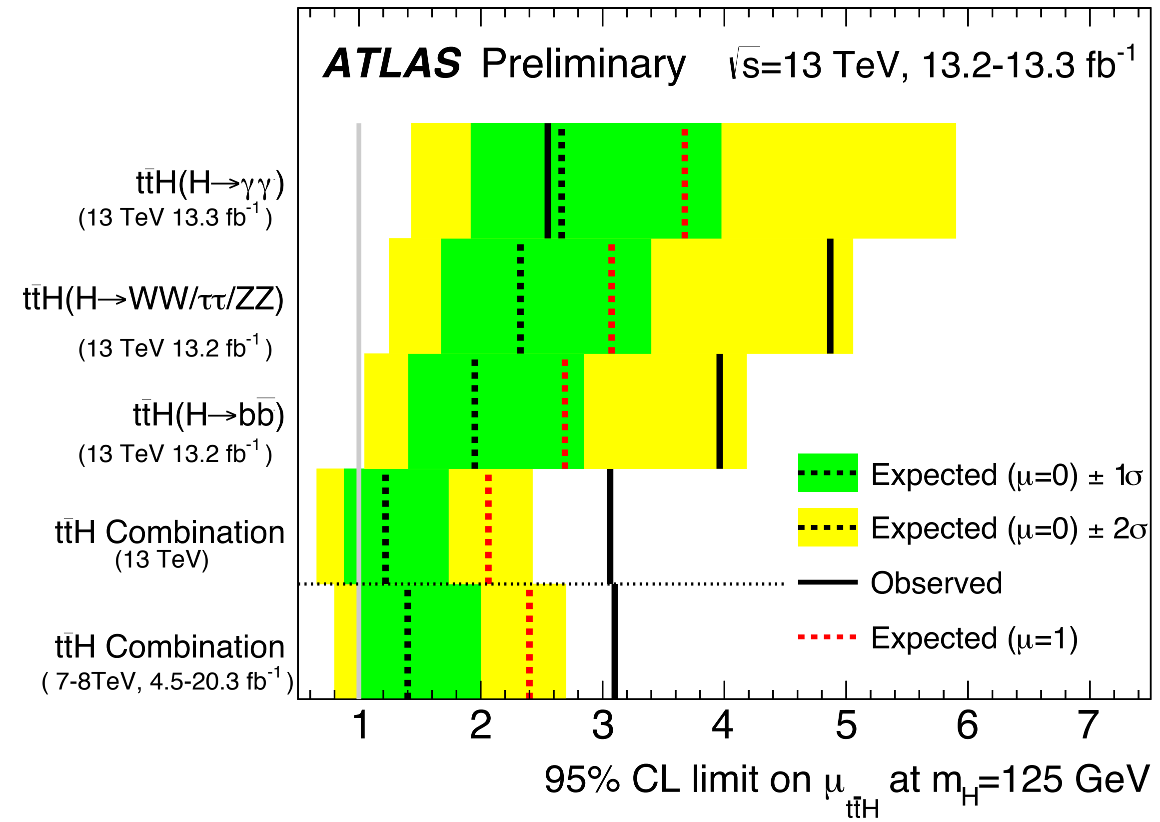
… The total uncertainty is dominated by data statistics.

Combination of ttH Results

ttH Signal Strength



95% CL Upper Limit



- Observed signal strength μ:

$$\mu = 1.8 \pm 0.4(stat.)\ ^{+0.6}_{-0.5}(syst.)$$

- Observed (and expected) 95% CL upper limit:

$$3.0\ (1.2\ ^{+0.5}_{-0.3}\ [\mu = 0])$$

Significance w.r.t background only hypothesis

Channel	Significance Observed $[\sigma]$	Significance Expected $[\sigma]$
$t\bar{t}H,\ H \to \gamma\gamma$	-0.2	0.9
$t\bar{t}H,\ H \to (WW, \tau\tau, ZZ)$	2.2	1.0
$t\bar{t}H,\ H \to b\bar{b}$	2.4	1.2
$t\bar{t}H$ combination	2.8	1.8

Summary

- We have presented the first ATLAS Run 2 results of the search for ttH production with total luminosity of 13.2 - 13.3 fb^{-1}.

- Signal strength μ_{ttH}:
  - H→bb: $\mu = 2.1 \pm 0.5(stat.) ^{+0.9}_{-0.7}(syst.)$
  - multi-lepton: $\mu = 2.5 \pm 0.7(stat.) ^{+1.1}_{-0.9}(syst.)$
  - H→γγ: $\mu = -0.3 ^{+1.2}_{-1.0}(stat.) \pm 0.2(syst.)$
  - ttH Combination:

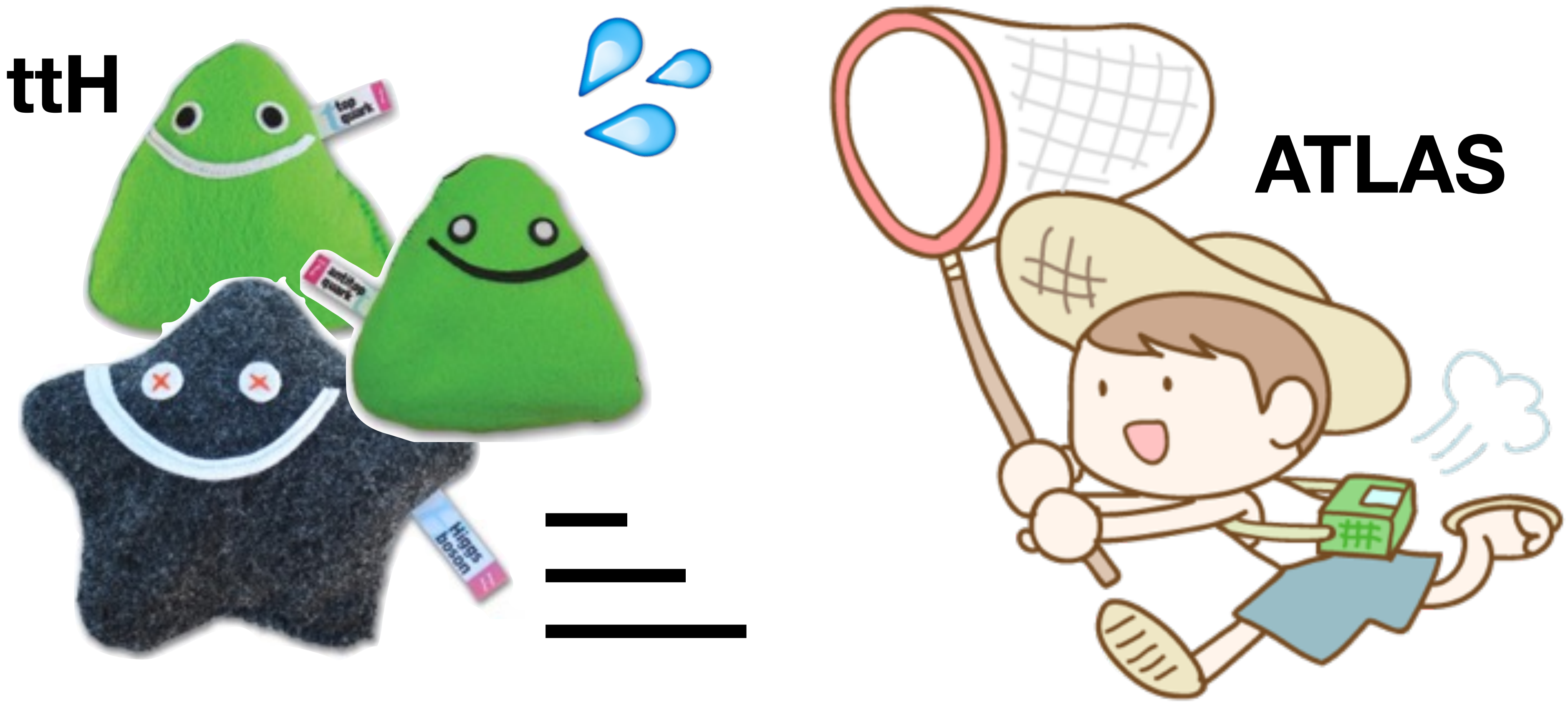
$$\mu = 1.8 \pm 0.4(stat.) ^{+0.6}_{-0.5}(syst.)$$

Exceeded Run 1 sensitivity !

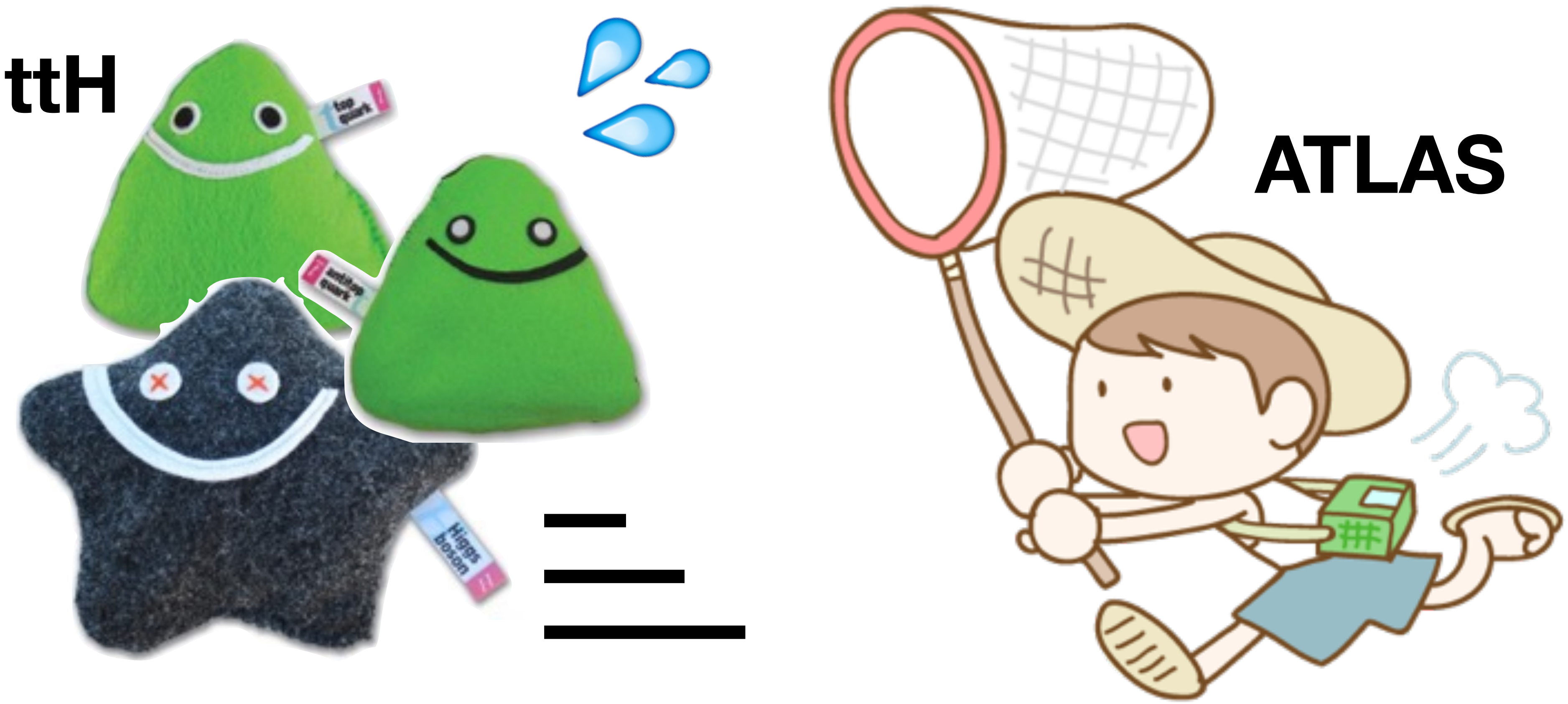
- The total luminosity in 2016 run expected to be ~ 35fb^{-1}.
- Update all analysis and plan to publish the results with full 2015-2016 dataset.

Don't miss it !

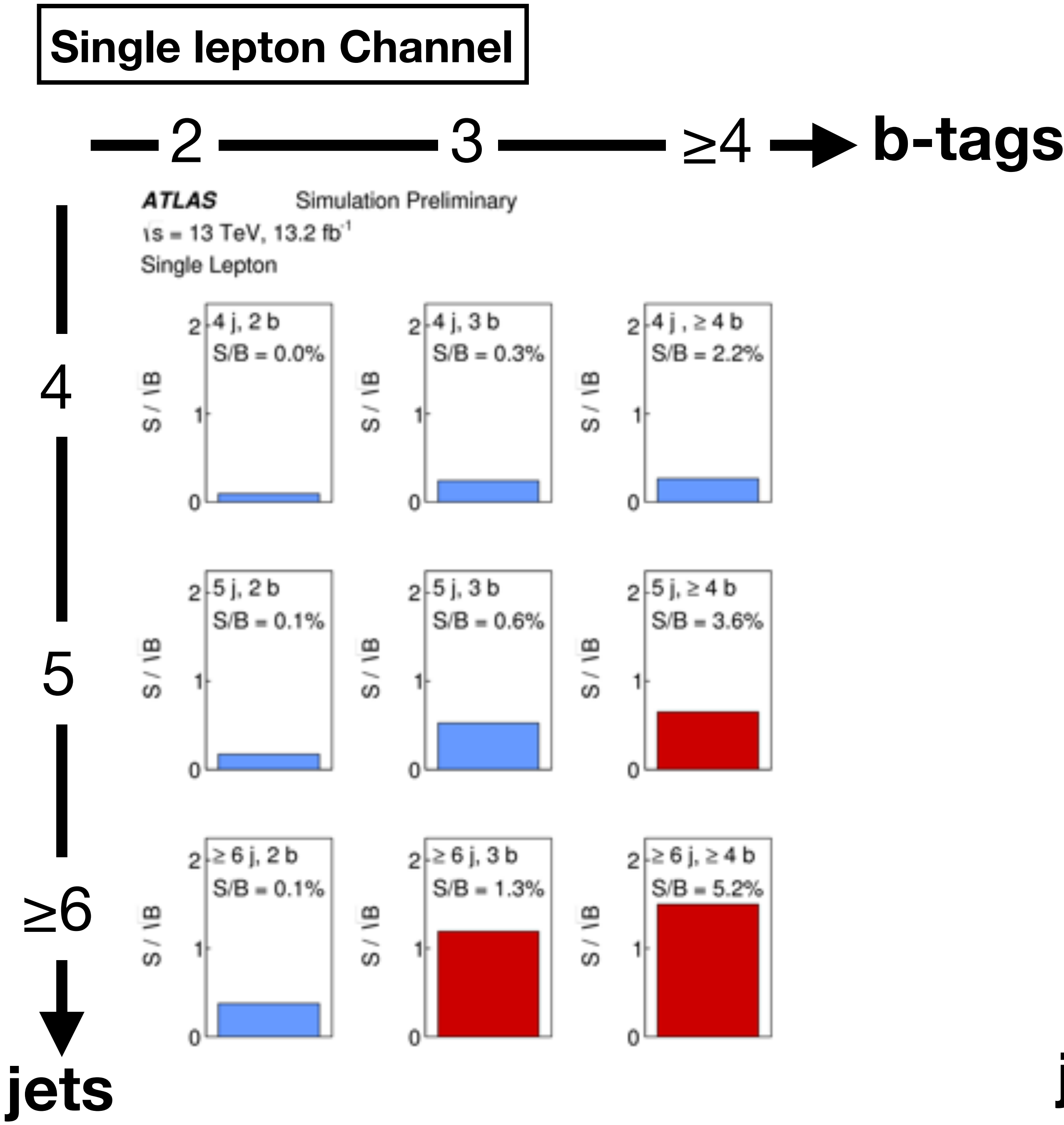
Thanks for your attention!

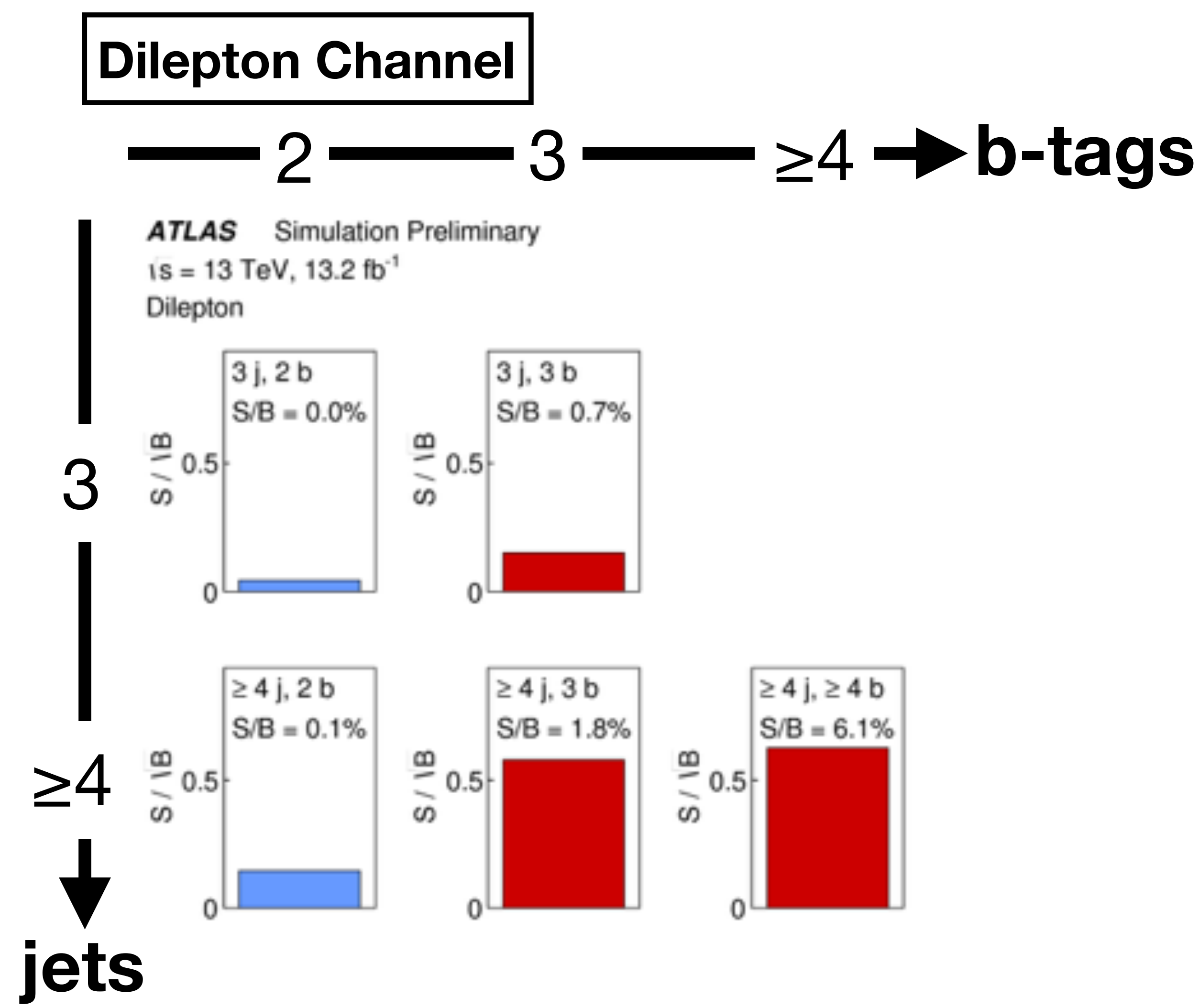


Backup

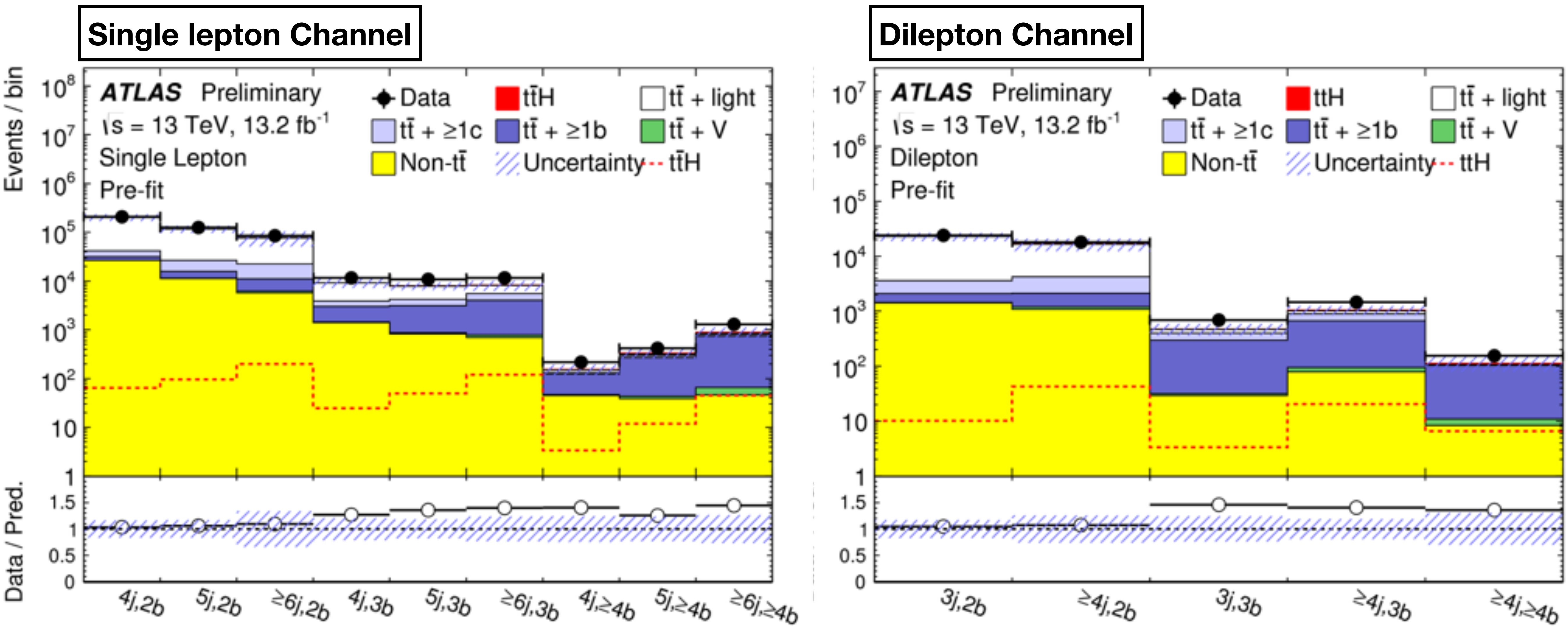


ttH(bb): Event Categorization



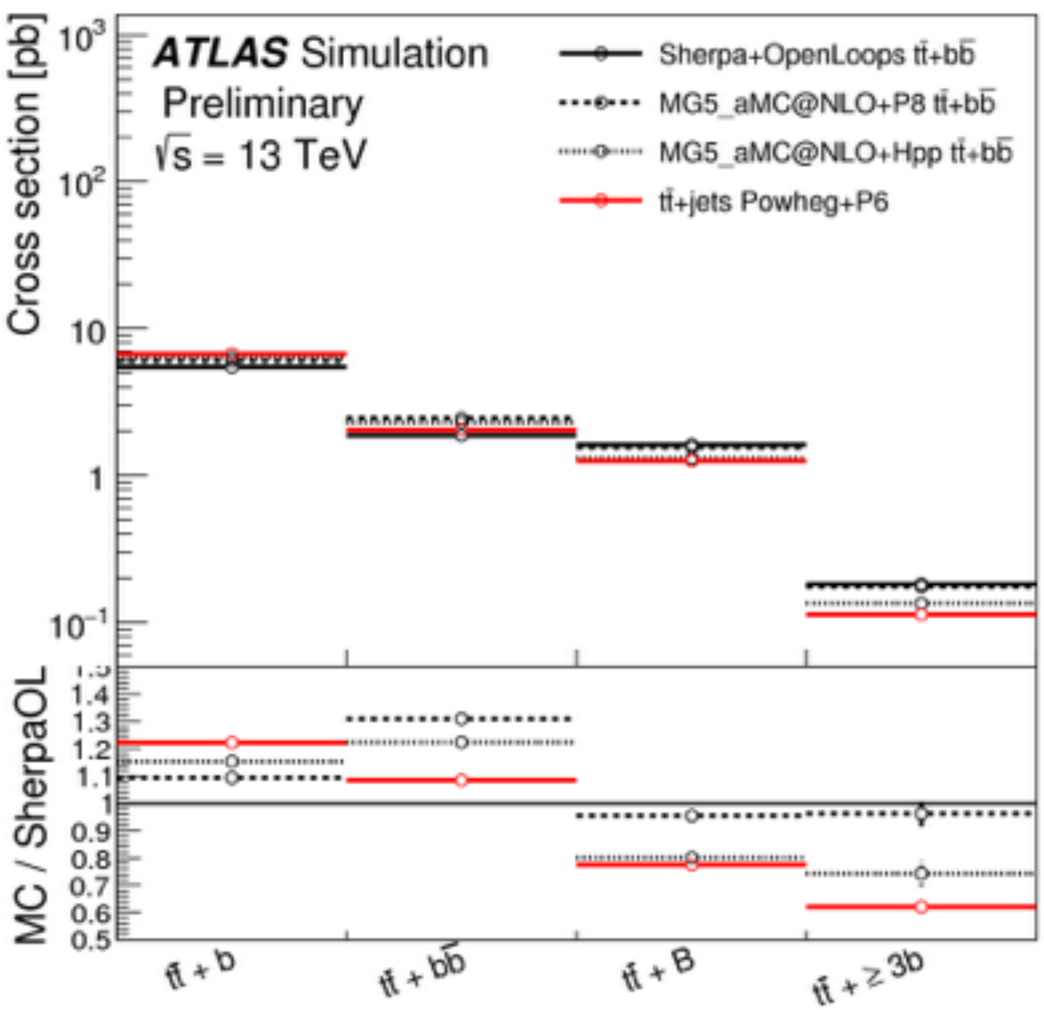


ttH(bb): Event Yields in Each Category



- Comparison of predicted and observed event yields in each category before fitting to data.
- The data overshoot the predictions in the regions with large tt + ≥1b and tt + ≥ 1c background components.

ttH(bb): tt + ≥1b modelling



Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	±6%	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_R, μ_F, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_T	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_Q from $H_T/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_Q, μ_R, and μ_F to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

- tt+ light: Powheg+Pythia 6 NLO simulation with top and tt p_T corrected to NNLO calculation.
- tt+ ≥1b: Corrected to 4-flavour scheme NLO tt+bb calculation with Sherpa+OpenLoops.
- A lot of uncertainties are considered for tt + ≥1b, tt + ≥1c and tt + light modelling: generator differences, parton shower and hadonization modelling, PDF, and initial and final state radiation.

ttH(bb): Inputs for "reconstruction BDT"

Single lepton Channel

Variable	≥6j, ≥4b	≥6j, =3b	=5j, ≥4b
Topological information from $t\bar{t}$:			
t_{lep} mass	✓	✓	✓
t_{had} mass	✓	✓	–
Incomplete t_{had} mass	–	–	✓
W_{had} mass	✓	✓	–
Mass of W_{had} and b from t_{lep}	✓	✓	–
Mass of q from W_{had} and b from t_{lep}	–	–	✓
Mass of W_{lep} and b from t_{had}	✓	✓	✓
$\Delta R(W_{\mathrm{had}}, b$ from $t_{\mathrm{had}})$	✓	✓	–
$\Delta R(q$ from W_{had}, b from $t_{\mathrm{had}})$	–	–	✓
$\Delta R(W_{\mathrm{had}}, b$ from $t_{\mathrm{lep}})$	✓	✓	–
$\Delta R(q$ from W_{had}, b from $t_{\mathrm{lep}})$	–	–	✓
$\Delta R(\mathrm{lep}, b$ from $t_{\mathrm{lep}})$	✓	✓	✓
$\Delta R(\mathrm{lep}, b$ from $t_{\mathrm{had}})$	✓	✓	✓
$\Delta R(b$ from t_{lep}, b from $t_{\mathrm{had}})$	✓	✓	✓
$\Delta R(q_1$ from W_{had}, q_2 from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(b$ from t_{had}, q_1 from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(b$ from t_{had}, q_2 from $W_{\mathrm{had}})$	✓	✓	–
min. $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(\mathrm{lep}, b$ from $t_{\mathrm{lep}})$ - min. $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	✓	✓	–
$\Delta R(\mathrm{lep}, b$ from $t_{\mathrm{lep}})$ - $\Delta R(b$ from t_{had}, q from $W_{\mathrm{had}})$	–	–	✓
Topological information from Higgs :			
Higgs mass	✓	✓	✓
Mass of Higgs and q_1 from W_{had}	✓	✓	✓
$\Delta R(b_1$ from Higgs, b_2 from Higgs$)$	✓	✓	✓
$\Delta R(b_1$ from Higgs, lep$)$	✓	✓	✓
$\Delta R(b_1$ from Higgs, b from $t_{\mathrm{lep}})$	–	✓	✓
$\Delta R(b_1$ from Higgs, b from $t_{\mathrm{had}})$	–	✓	✓

Dilepton Channel

Variable
Topological information from $t\bar{t}$:
$\Delta R(b$ from t, lep from $t)$
$\Delta R(b$ from $\bar{t}$, lep from $\bar{t})$
Mass of b from t and lep from t
Mass of b from $\bar{t}$ and lep from $\bar{t}$
$p_{\mathrm{T}}(b$ from t, lep from $t)$
$p_{\mathrm{T}}(b$ from $\bar{t}$, lep from $\bar{t})$
$\Delta R(b$ from t, b from $\bar{t})$
$\lvert\Delta R(b$ from t, lep from $t)$ - $\Delta R(b$ from $\bar{t}$, lep from $\bar{t})\rvert$
Min. $\Delta R(b$ from $t\bar{t}$, lep$)$
Max. $\Delta R(b$ from $t\bar{t}$, lep$)$
Topological information from Higgs :
Higgs Mass
$\Delta R(b_1$ from Higgs, b_2 from Higgs$)$
$\Delta R(\mathrm{Higgs}, t\bar{t})$
$\lvert\Delta R(b_1$ from Higgs, b_2 from Higgs$)$ - $\Delta R(b$ from t, b from $\bar{t})\rvert$
Min. $\Delta R(\mathrm{Higgs}, \mathrm{lep})$
Max. $\Delta R(\mathrm{Higgs}, \mathrm{lep})$
Min. $\Delta R(\mathrm{Higgs}, b$ from $t\bar{t})$
Max. $\Delta R(\mathrm{Higgs}, b$ from $t\bar{t})$

tt information (green)

Higgs information (red)

ttH(bb): Inputs for “classification BDT” (Single lepton)

Variable	Definition	Region $\geq$ 6j, $\geq$ 4b	Region $\geq$ 6j, 3b	Region 5j, $\geq$ 4b
General kinematic variables				
$\Delta R_{\rm bb}^{\rm avg}$	Average ΔR for all b-tagged jet pairs	✓	✓	✓
$\Delta R_{bb}^{\max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum $p_{\rm T}$	✓	–	–
$\Delta\eta_{\rm jj}^{\max}$	Maximum $\Delta\eta$ between any two jets	✓	✓	✓
$m_{\rm bb}^{\min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	–
$m_{\rm jj}^{\min\ \Delta R}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m_{\rm bj}^{\max\ p_T}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum $p_{\rm T}$	–	✓	–
$p_{\rm T}^{\rm jet5}$	$p_{\rm T}$ of the fifth leading jet	✓	✓	✓
$\rm N_{bb}^{Higgs\ 30}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\rm N_{40}^{jet}$	Number of jets with $p_{\rm T} \geq 40 GeV$	–	✓	–
$H_{\rm T}^{\rm had}$	Scalar sum of jet $p_{\rm T}$	–	✓	✓
$\Delta R_{\rm lep-bb}^{\min\ \Delta R}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	–	–	✓
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Scalar sum of the $p_{\rm T}$ divided by sum of the E for all jets and the lepton	✓	✓	✓
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	✓*
$m_{\rm H}$	Higgs boson mass	✓	✓	✓
$m_{{\rm H},b_{\rm lep\ top}}$	Mass of Higgs boson and b-jet from leptonic top	✓	–	–
$\Delta R_{\rm Higgs\ bb}$	ΔR between b-jets from the Higgs boson	✓	✓	✓
$\Delta R_{{\rm H},t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{\rm H,lep\ top}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{{\rm H},b_{\rm had\ top}}$	ΔR between Higgs boson and b-jet from hadronic top	–	✓*	✓*

Event Kinematics

Outputs from “reconstruction BDT”

ttH(bb): Inputs for “classification BDT” (Dilepton)

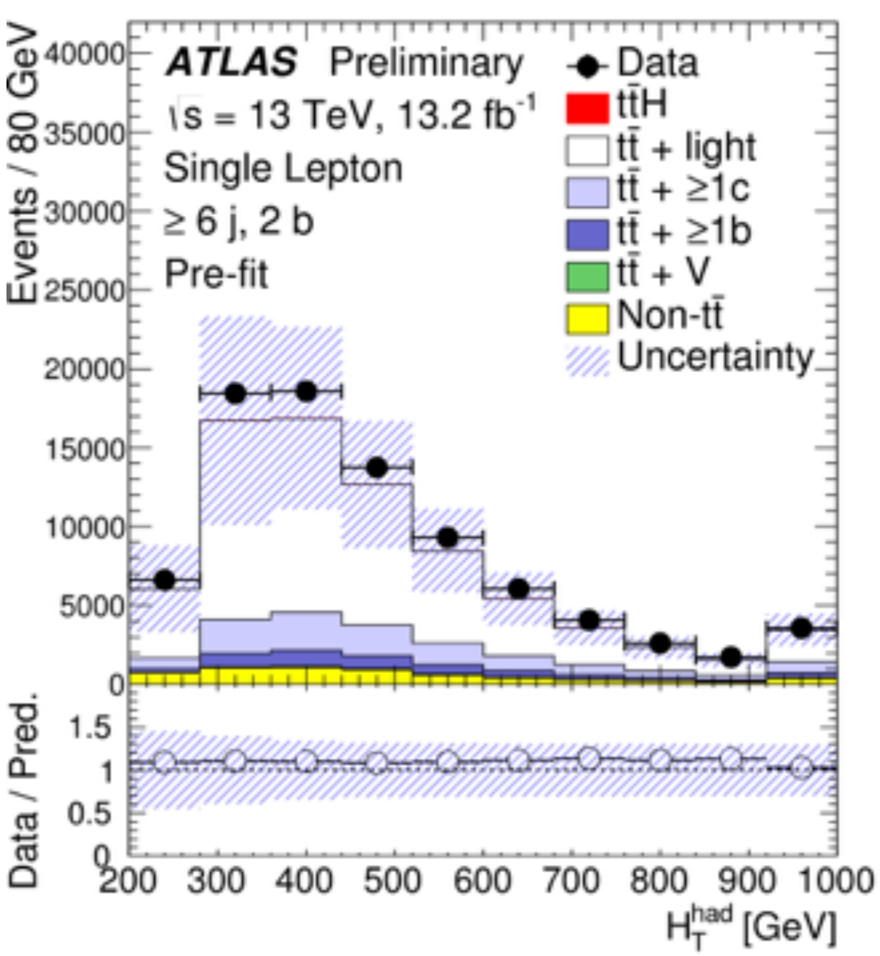
Variable	Definition	Region		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
General kinematic variables				
$\Delta\eta_{bb}^{\text{avg}}$	Average $\lvert\Delta\eta\rvert$ among pairs of b-jets	✓	–	–
$\Delta\eta_{\text{bb}}^{\text{max}}$	Maximum $\Delta\eta$ between any two b-jets	–	✓	✓
$\Delta\eta_{\text{jj}}^{\text{avg}}$	Average $\Delta\eta$ among jet pairs	–	✓	–
$\Delta R_{bb}^{\text{max } p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	✓	✓
$\Delta R_{\text{bb}}^{\text{Higgs}}$	ΔR between the two b-tagged jets with mass closest to the Higgs boson mass	✓	–	–
$\Delta R_{\text{bb}}^{\text{max m}}$	ΔR between the two b-jets with the largest invariant mass	✓	✓	✓
$m_{\text{bb}}^{\text{max } p_T}$	Mass of the two b-tagged jets with the largest vector sum p_{T}	–	–	✓
$m_{\text{bb}}^{\text{Higgs}}$	Mass of the two b-tagged jets closest to the Higgs boson mass	✓	✓	✓
$m_{\text{bb}}^{\text{min}}$	Minimum mass of two b-tagged jets	–	–	✓
$m_{\text{bb}}^{\text{min } \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	✓
$p_{\text{T},b}^{\text{min}}$	Minimum b-tagged jet p_{T}	–	–	✓
$H_{\text{T}}^{\text{all}}$	Scalar p_{T} sum of all leptons and jets	–	✓	✓
$\text{N}_{\text{bb}}^{\text{Higgs 30}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\text{N}_{\text{jj}}^{\text{Higgs 30}}$	Number of jet pairs with invariant mass within 30 GeV of the Higgs boson mass	–	✓	–
Aplanarity	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [42] built with all jets	✓	✓	✓
Centrality	Sum of the p_{T} divided by sum of the E for all jets and both leptons	✓	–	✓
$H2_{\text{jets}}$	Third Fox–Wolfram moment computed using all jets	–	✓	–
$H4_{\text{all}}$	Fifth Fox–Wolfram moment computed using all jets and leptons	–	–	✓
Variables from reconstruction BDT output				
BDT output		✓*	✓*	–
m_{H}	Higgs boson mass	✓(*)	✓(*)	–
$\Delta\eta_{\text{H},l}^{\text{min}}$	Minimum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{\text{H},l}^{\text{max}}$	Maximum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta_{\text{H,b}}^{\text{min}}$	Minimum $\Delta\eta$ between the Higgs boson and a b-jet	✓*	–	–

Event Kinematics

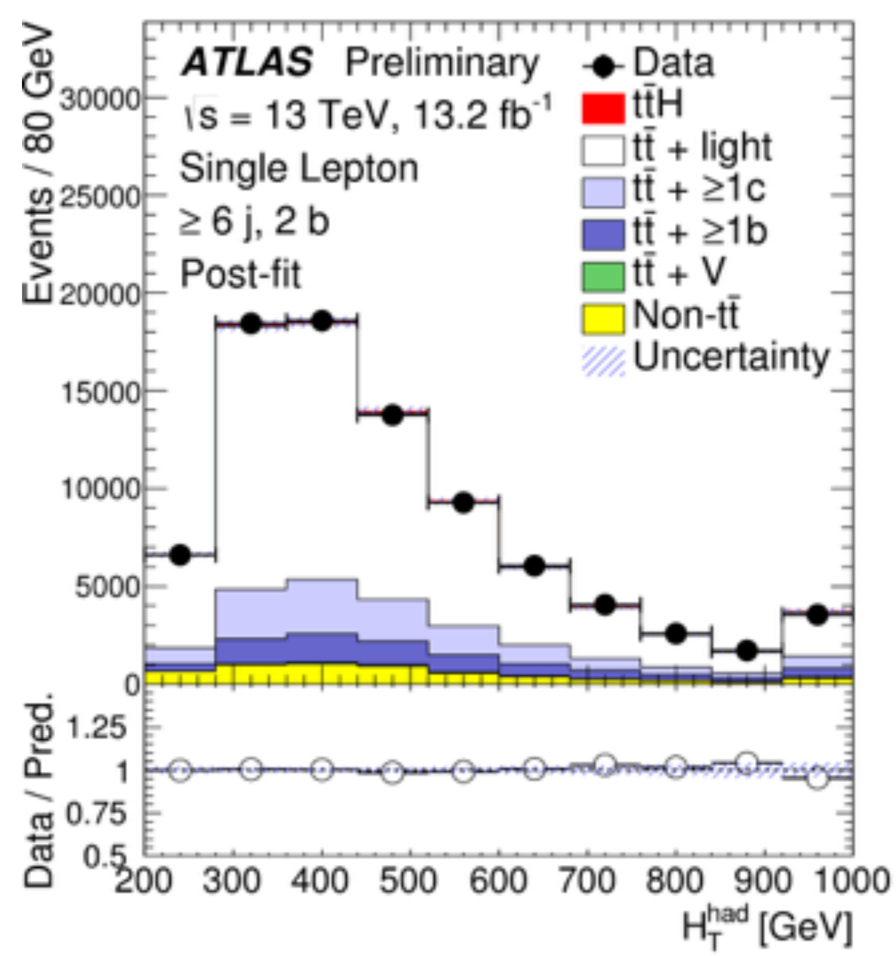
Outputs from “reconstruction BDT”

ttH(bb): Discriminating Variables in CR

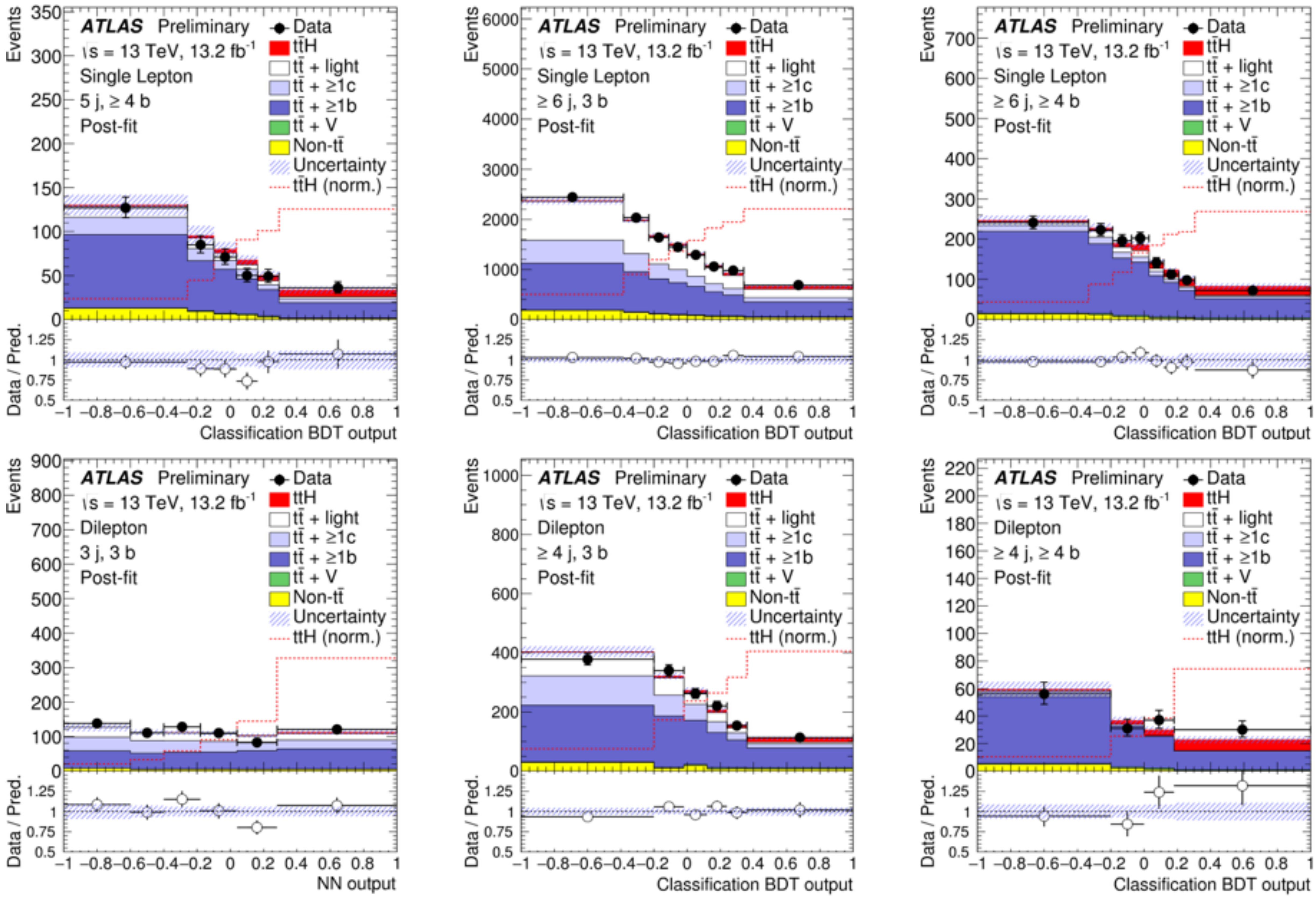
- Scalar sum of p_T of jets, H_T^{had} (and leptons, H_T) in control regions is used to constraint tt normalization and its uncertainties in simultaneous fit with signal region.
- Normalization for tt + ≥1b and tt + ≥ 1c are allowed to float feely in the fit.



Simultaneous Fit with SR



ttH(bb): Post-Fit “classification BDT”



ttH(bb): Uncertainty Source

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.53$	-0.53
Jet flavour tagging	$+0.26$	-0.26
$t\bar{t}H$ modelling	$+0.32$	-0.20
Background model statistics	$+0.25$	-0.25
$t\bar{t}+\geq 1c$ modelling	$+0.24$	-0.23
Jet energy scale and resolution	$+0.19$	-0.19
$t\bar{t}$+light modelling	$+0.19$	-0.18
Other background modelling	$+0.18$	-0.18
Jet-vertex association, pileup modelling	$+0.12$	-0.12
Luminosity	$+0.12$	-0.12
$t\bar{t}Z$ modelling	$+0.06$	-0.06
Light lepton (e,μ) ID, isolation, trigger	$+0.05$	-0.05
Total systematic uncertainty	$+0.90$	-0.75
$t\bar{t}+\geq 1b$ normalisation	$+0.34$	-0.34
$t\bar{t}+\geq 1c$ normalisation	$+0.14$	-0.14
Statistical uncertainty	$+0.49$	-0.49
Total uncertainty	$+1.02$	-0.89

Highest systematic uncertainty

Total systematic uncertainty

Statistical uncertainty

Total uncertainty

- All experimental, modelling (theory) uncertainties are considered.
- Check these impacts on ttH signal strength μ.
- Systematic uncertainty is dominated by tt + ≥1b modelling.

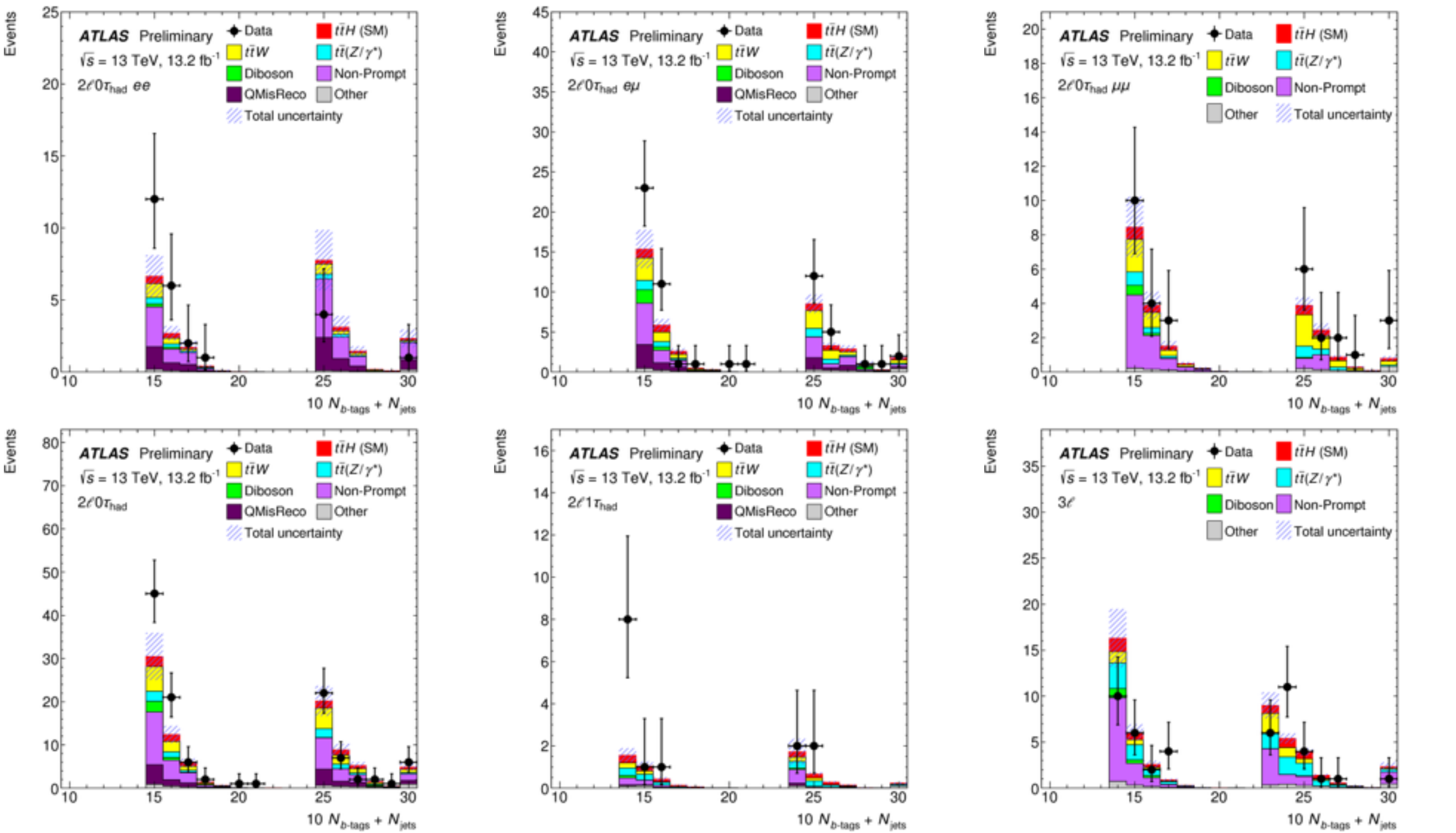
ttH(multi-lepton): SR & CR Definition

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

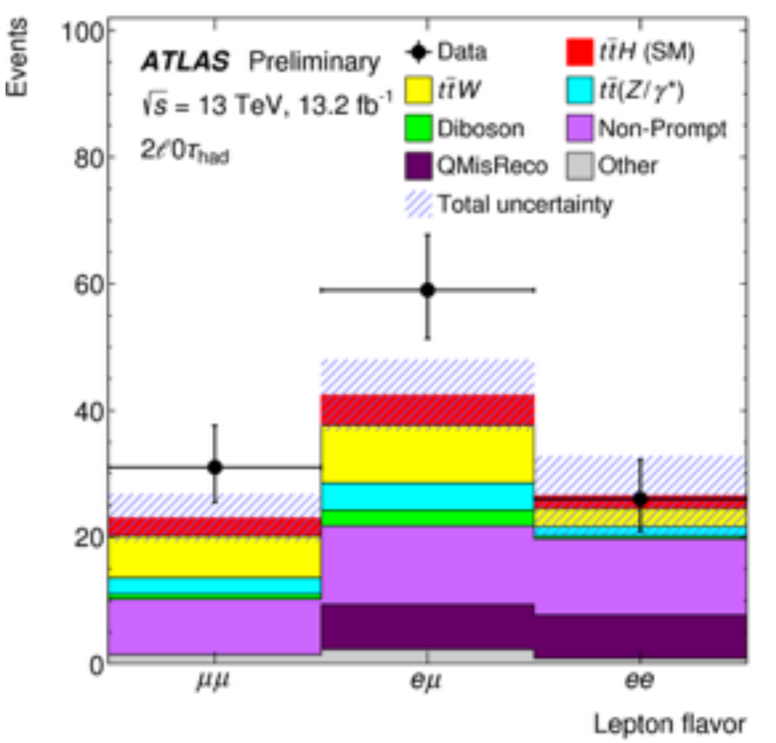
Signal Region

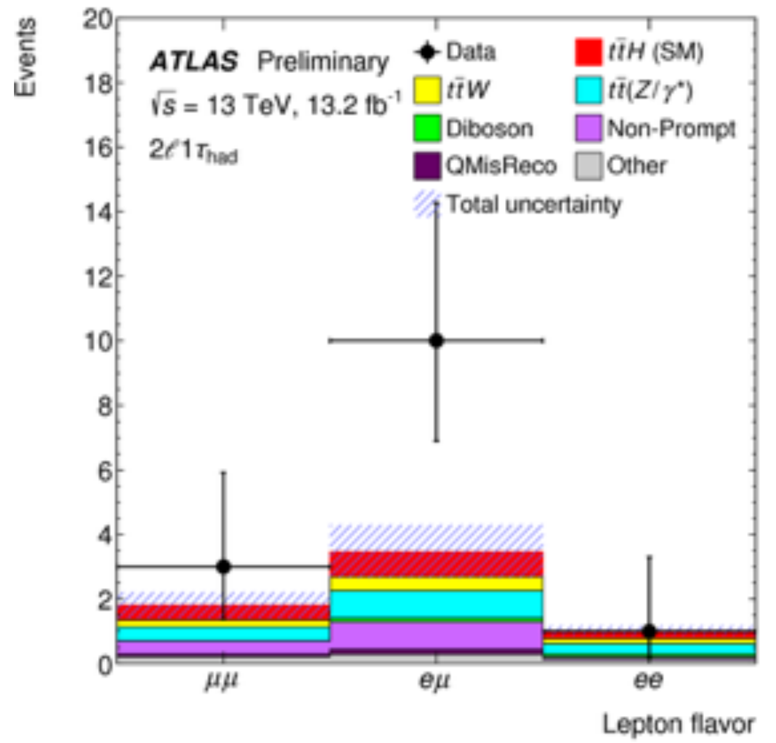
Control Region

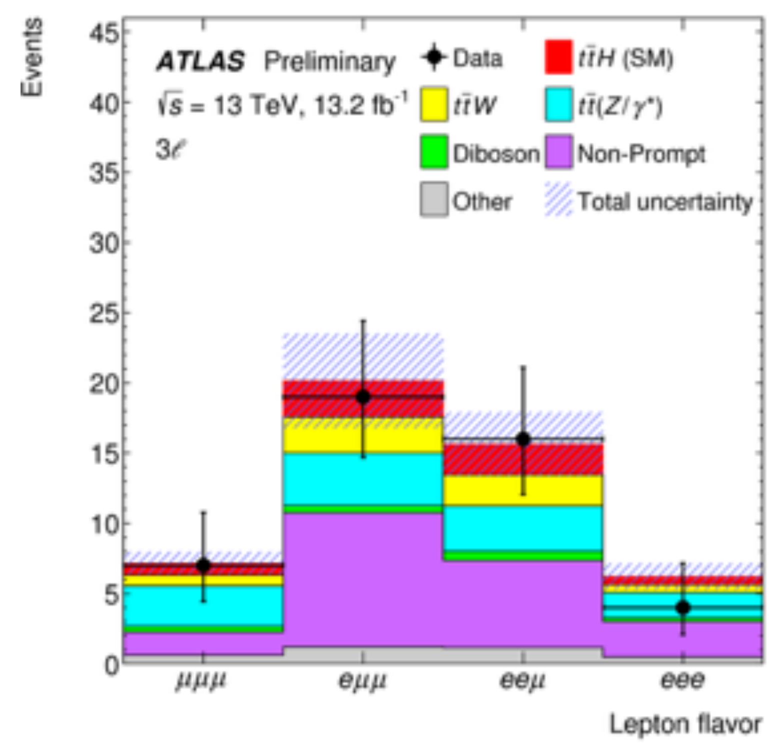
ttH(multi-lepton): N_{jets} & $N_{b\text{-}tags}$ in SR



ttH(multi-lepton): Lepton Flavour in SR







- There are a little bit data excesses in μμ and eμ channel in both $2l0\tau_{had}$ and $2l1\tau_{had}$ signal regions.
- Good agreement between data and expectation in 3l signal region.

ttH(multi-lepton): Systematic Uncertainty

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

Highest uncertainty

Total systematic uncertainty

- All uncertainties related to theory, experiment and fake estimation are considered.
- Check these impacts on ttH signal strength μ.
- Systematic uncertainty is dominated by non-prompt leptons and charge mis-reconstruction estimation.
- Uncertainty from efficiency of the jet-to-vertex association method is the most important detector-related systematic one; ~2.5 % per jet, which becomes important in high-jet-multiplicity final states.