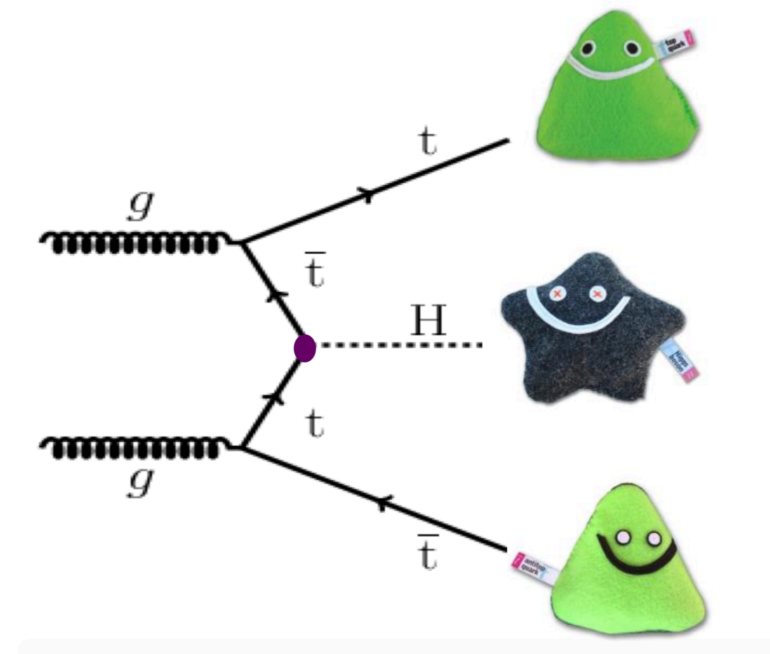


ttH Combination in ATLAS

Merve Nazlim Agaras

Top LHC France

25 April, 2019

$$m_{top} = y_t\, v/\sqrt{2} \approx 174\ \text{GeV} \Rightarrow y_t \approx 1$$

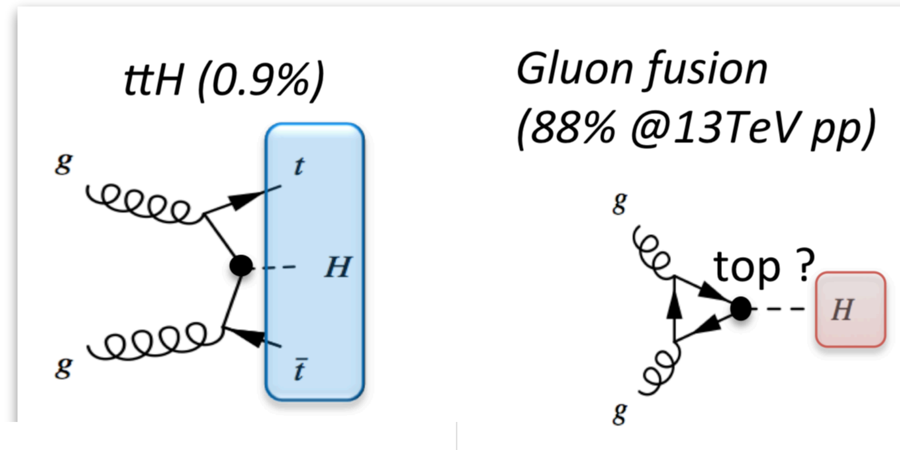
Top Yukawa Coupling at LHC

- In the SM is the only quark with a "natural mass"

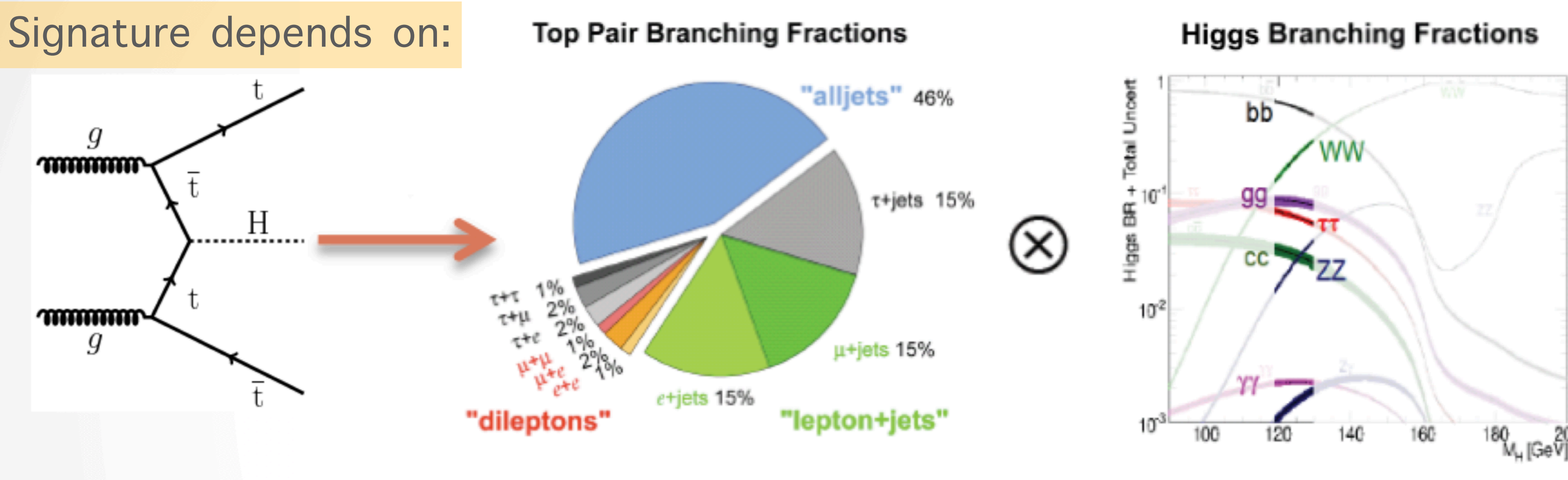
Motivation

- Impact on theory:
  - destabilizes the weak scale (m_H^2 corrections)
  - destabilizes our vacuum (λ corrections)
  - controls the birth ($gg \to h$) and the death ($h \to \gamma\gamma$) of the Higgs

- Can be determined:
  - Indirect Higgs gluon fusion production & Higgs diphoton decay
  - Direct measurement possible through ttH production



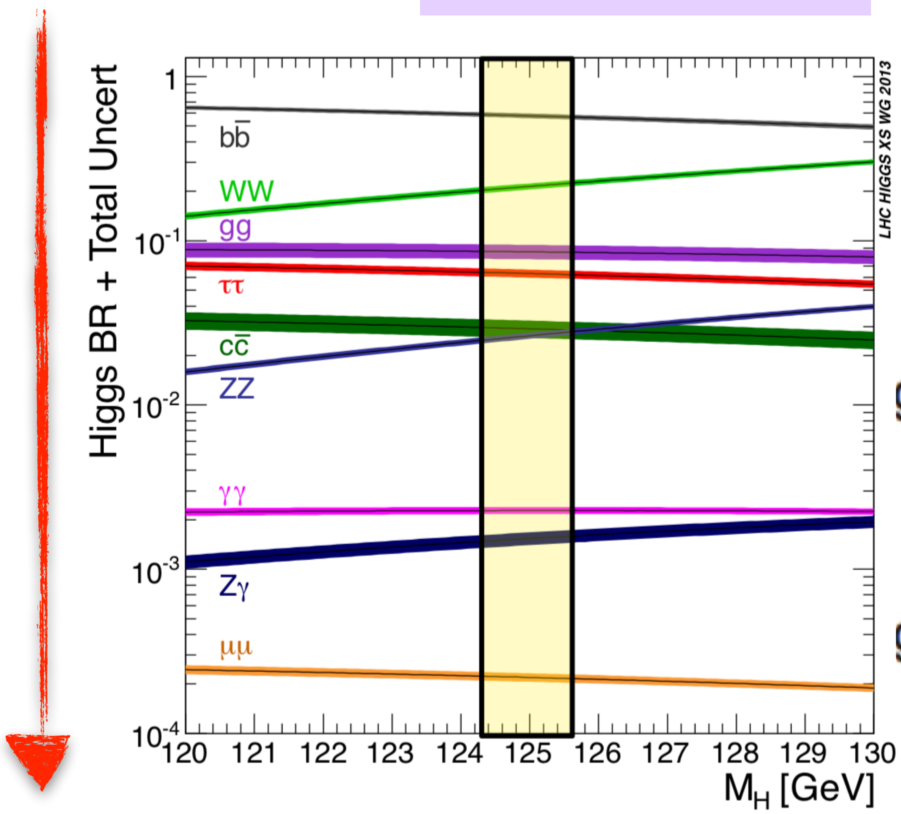
Signature depends on:



ttH in ATLAS

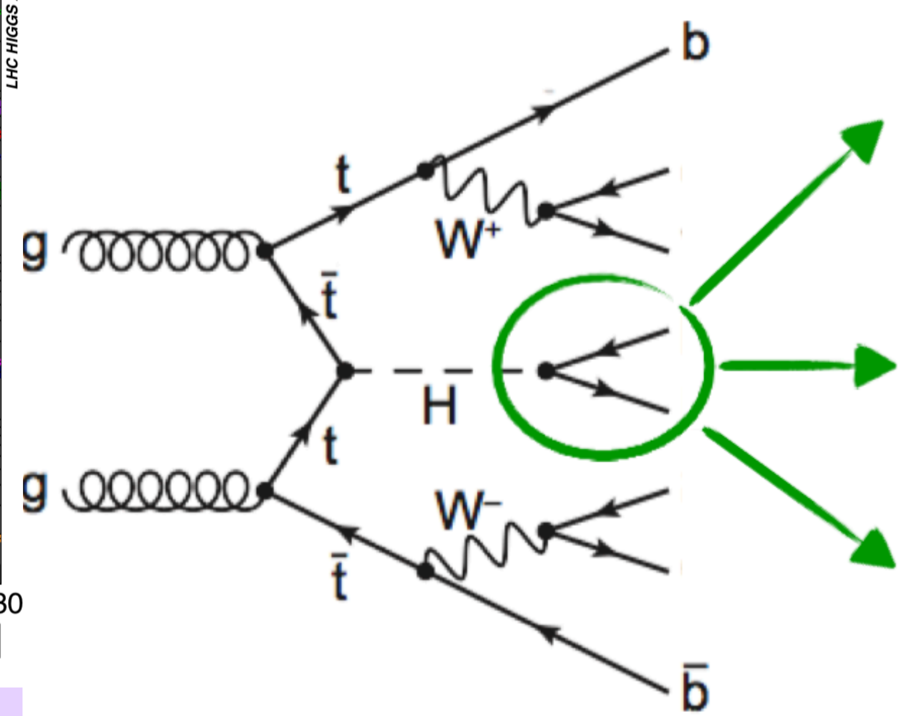
Large BR

Large background



Small BR

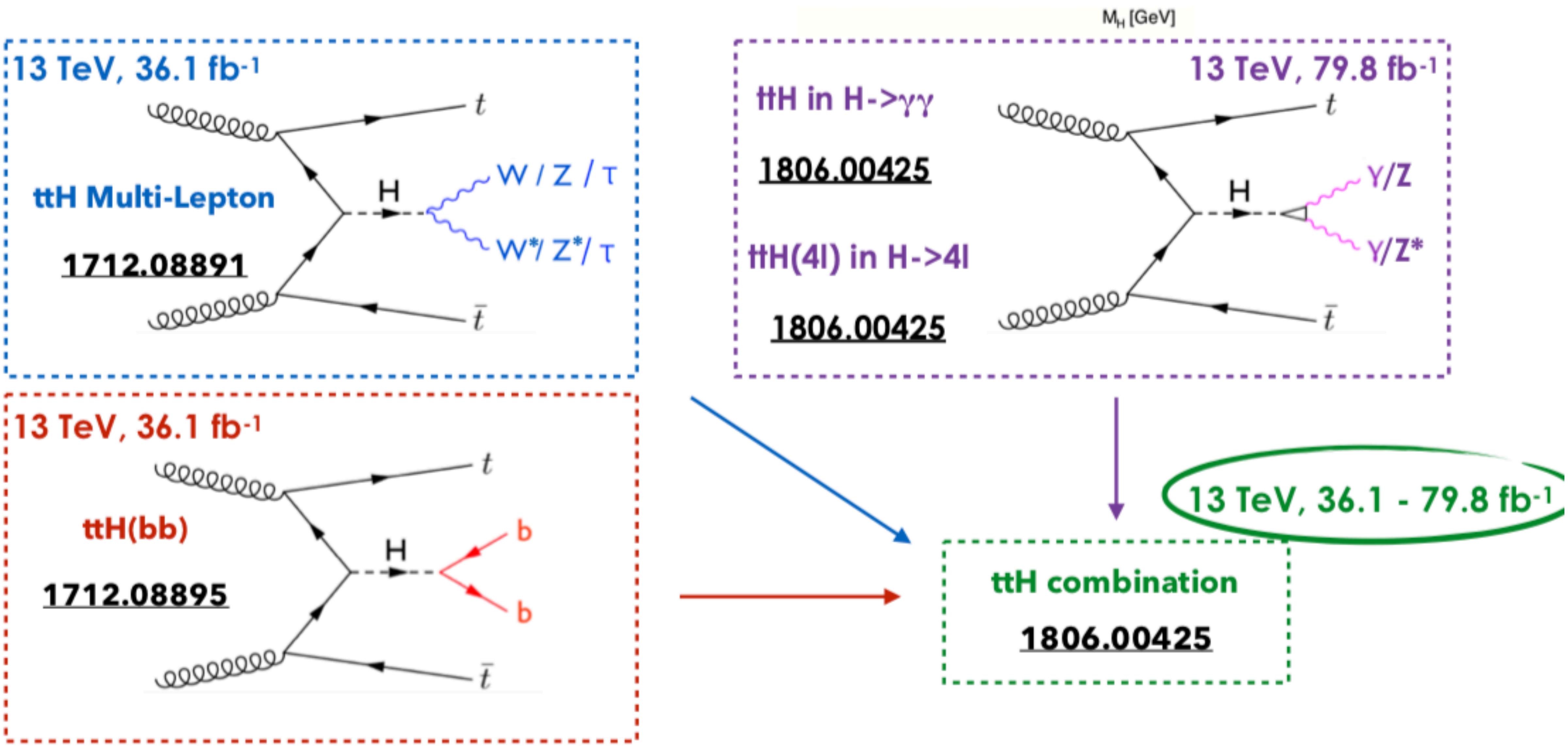
Purity and precision



Search channel	benefits/ challenges
H->bb	Large rate/ large combinatorics
Multilep (H->WW,ZZ,TT)	Lower rate/ challenge fakes
H->gamgam, ZZ(4l)	Very clean/ small rate

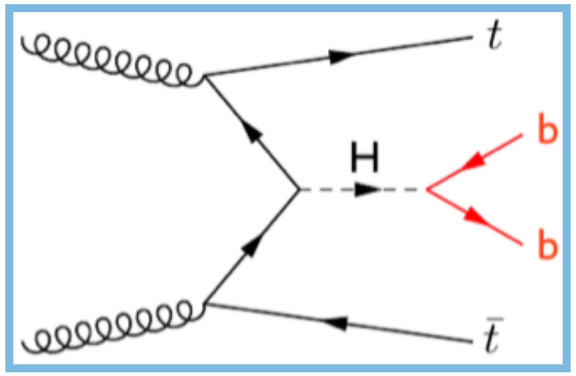
Overview of the input channels & combination

in this presentation…



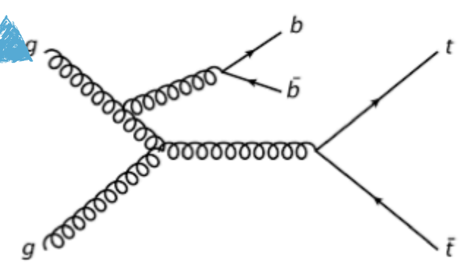
H->bb Analysis Strategy

Details in NIHAL's talk



- Largest Higgs BR, but:
  - Complex final state with large jet and b-jet multiplicity → challenging object (b- tagging) and event reconstruction
  - ttbb background large and difficult to model with associated theory uncertainty

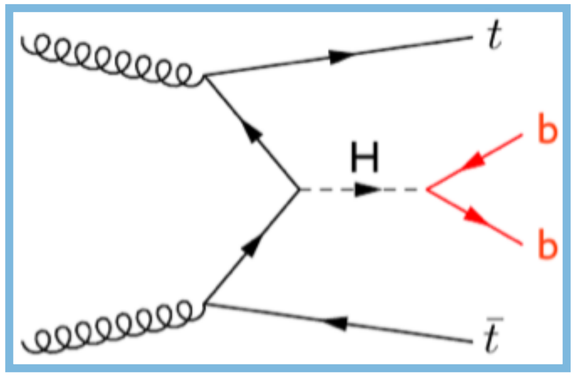
Biggest challenge: good and precise modelling of the $\mathbf{t\bar{t}}$**+HF** (≥**1b**, ≥**1c**) background



- Nominal sample: 5-flavour scheme;
- Relative contribution of $t\bar{t}$+≥1b subcomponents reweighted to $t\bar{t}$+$b\bar{b}$ predictions by Sherpa+OpenLoops (4-flavour scheme);

H->bb Analysis Strategy

Details in NIHAL's talk



- Largest Higgs BR, but:
  - Complex final state with large jet and b-jet multiplicity → challenging object (b- tagging) and event reconstruction
  - ttbb background large and difficult to model with associated theory uncertainty

Categorisation

- Split into jet and b-jet multiplicity/quality, merge regions with similar background content

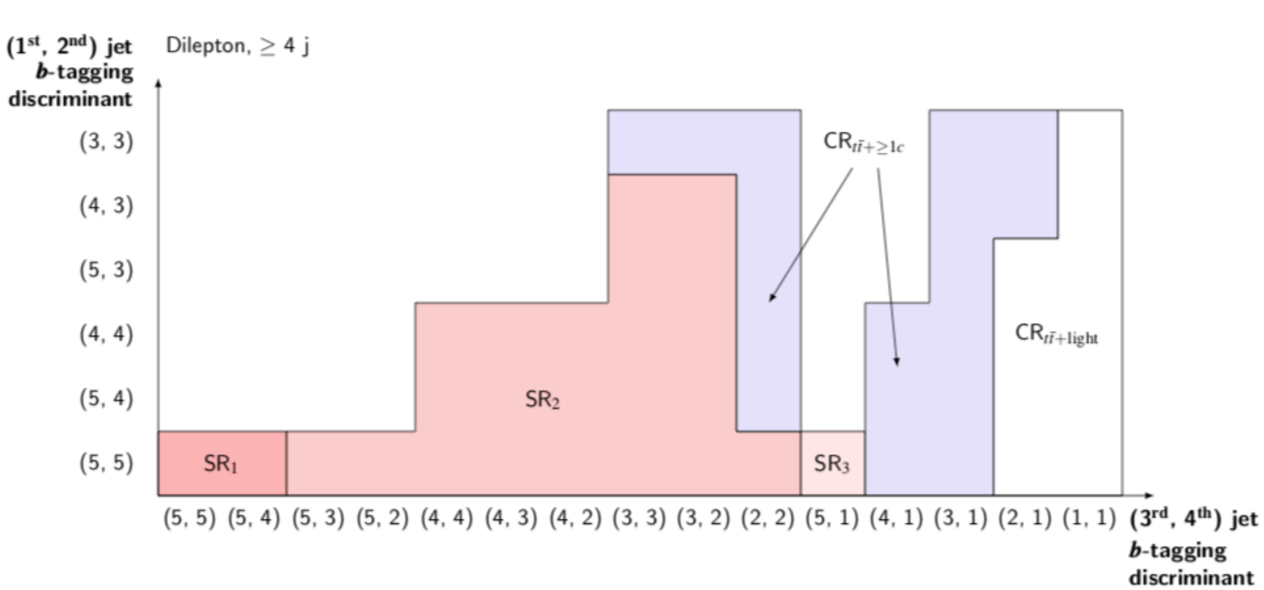
  (1ℓ & 2ℓ , # of jets, b-tag score)

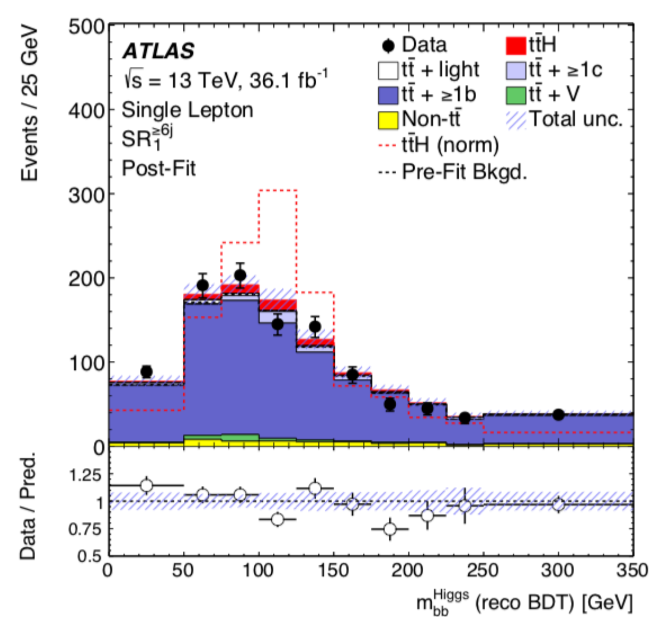
Reconstruction

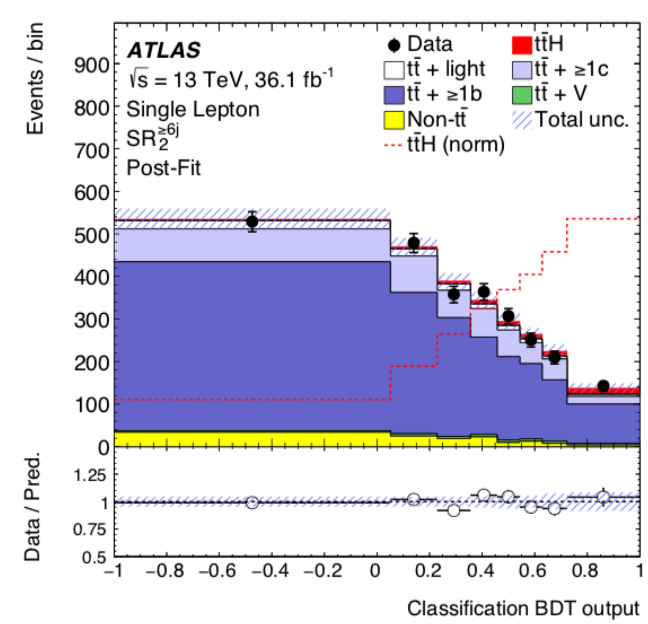
- To reconstruct Higgs and top candidates from high combinatorics of (b-)jets (RecoBDT, LHD, MEM)

ClassificationBDT

- Fit performed on classification BDT output
- inputs: reconstruction MVA, kinematics, b-tagging info

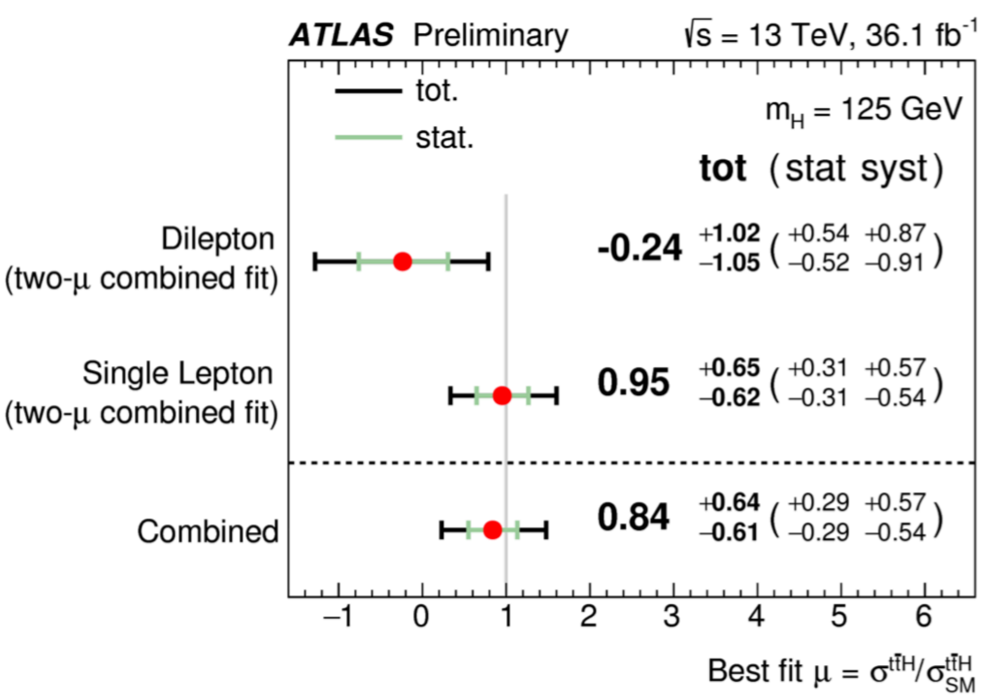




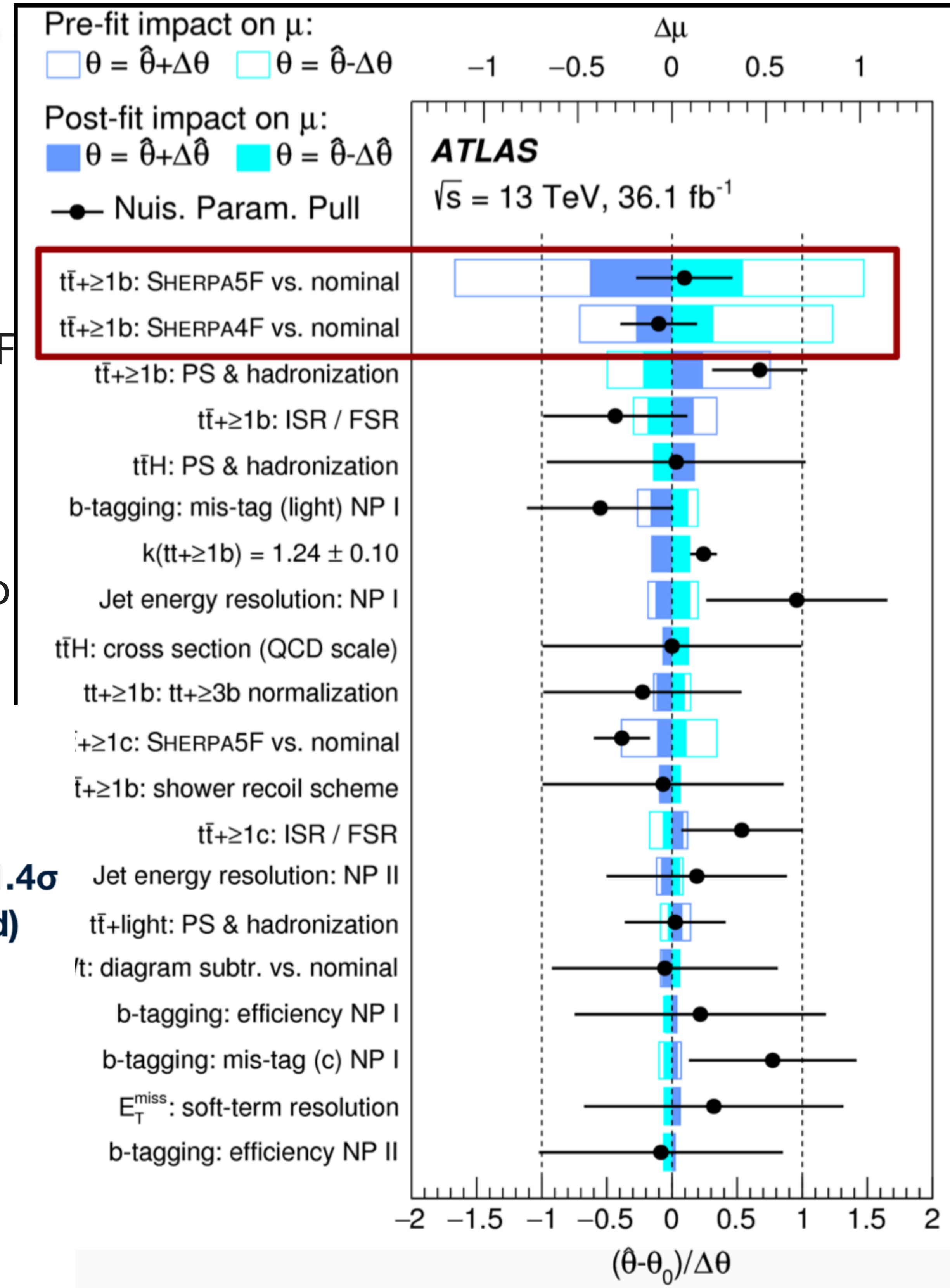


H->bb Results

- Signal extraction: Combined binned profile likelihood fit of classification BDT output in SRs(9) and CRs(10)
  - Signal strength: $\mu = \sigma/\sigma_{SM}$
- Free-floating normalisation factors for tt+HF
  - tt+≥1b: 1.24±0.10
  - tt+≥1c: 1.63±0.23
- systematic uncertainty on tt+≥1b simulatio (Esp.SherpavsPP8) and limited MC stat.

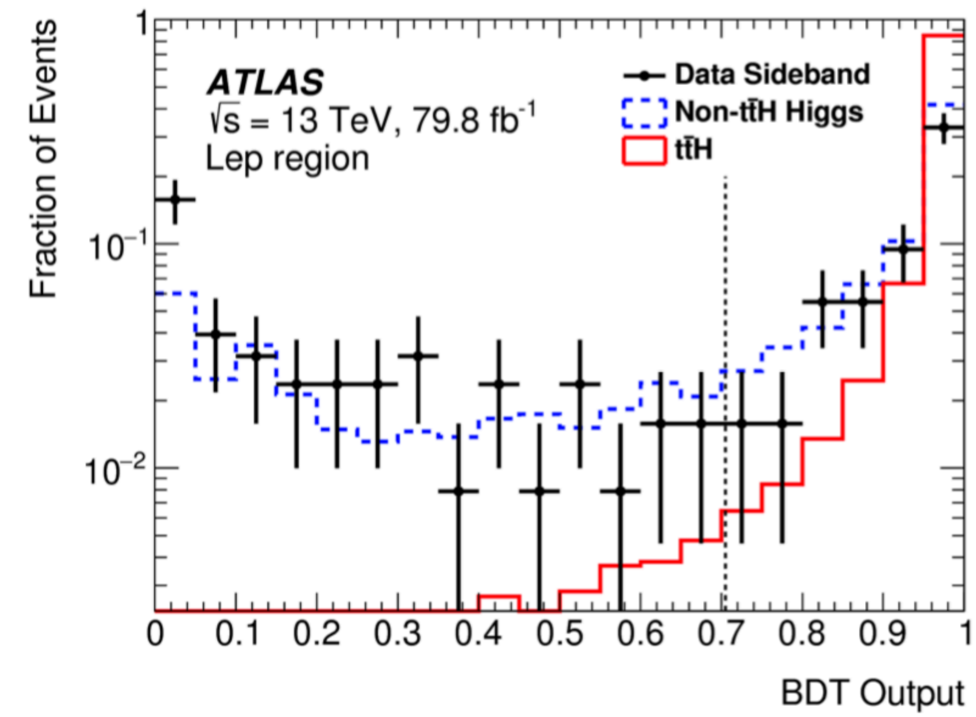


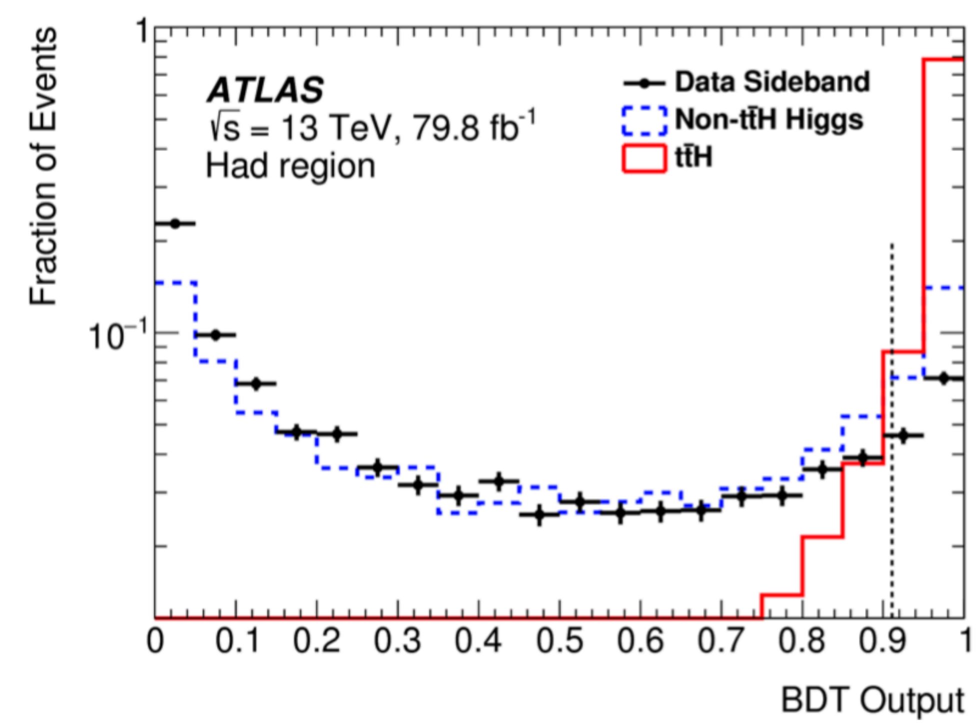
significance: 1.4σ (1.6σ expected)



H->γγ Analysis Strategy

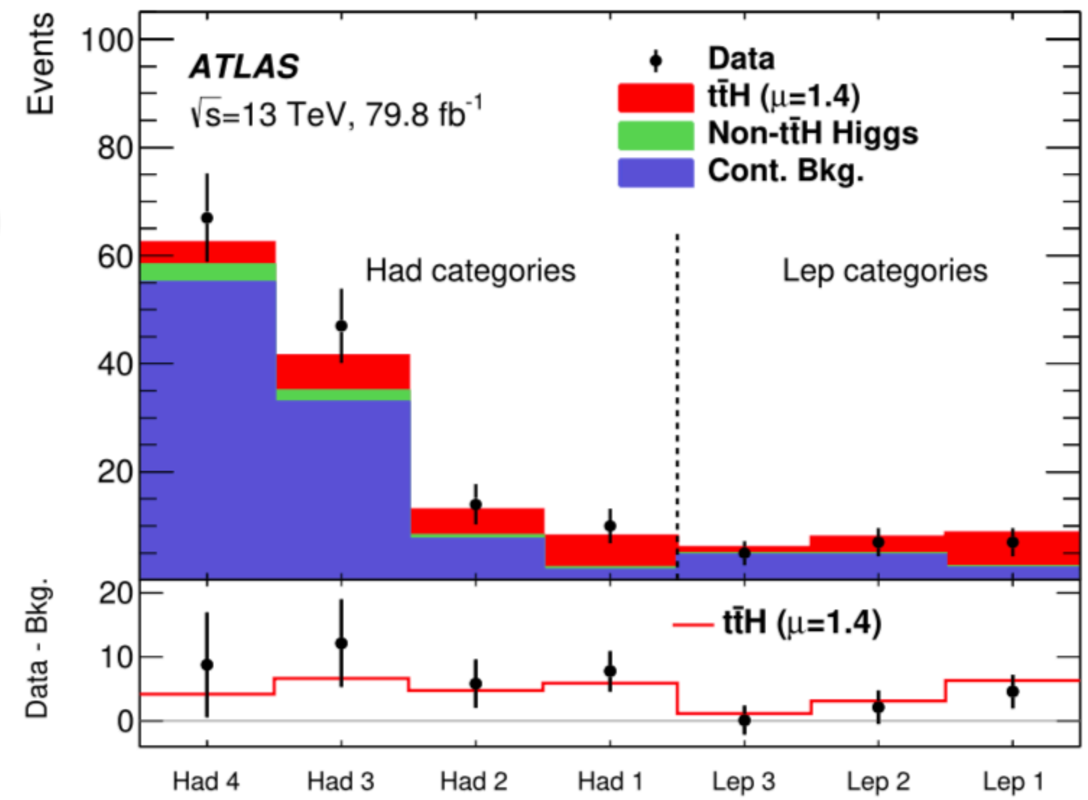
- Events are selected requiring two isolated photons (pt>25GeV,35GeV), and split into two regions, hadronic and leptonic, based on the decay of the top quark.
- 2 signal regions targeting ttH production:
  - Leptonic: ≥1l, bjet (semi-leptonic top-quark decay) (3)
  - Hadronic: ≥3jets, ≥1bjet 0 isolated leptons (hadronic top decay) (4)
- 2 BDTs trained to discriminate the ttH signal from the main background (XGBoost)
  - γγ, tt+γγ (data in control regions)
  - non-ttH production (from simulation)
  - Input vars: 4-vector information of photons (p_T/m_{yy}), jets, E_T^{miss} (both cat), lepton(s) (lep cat), and b-tag (had cat);
  - Cut on BDT output to veto backgrounds





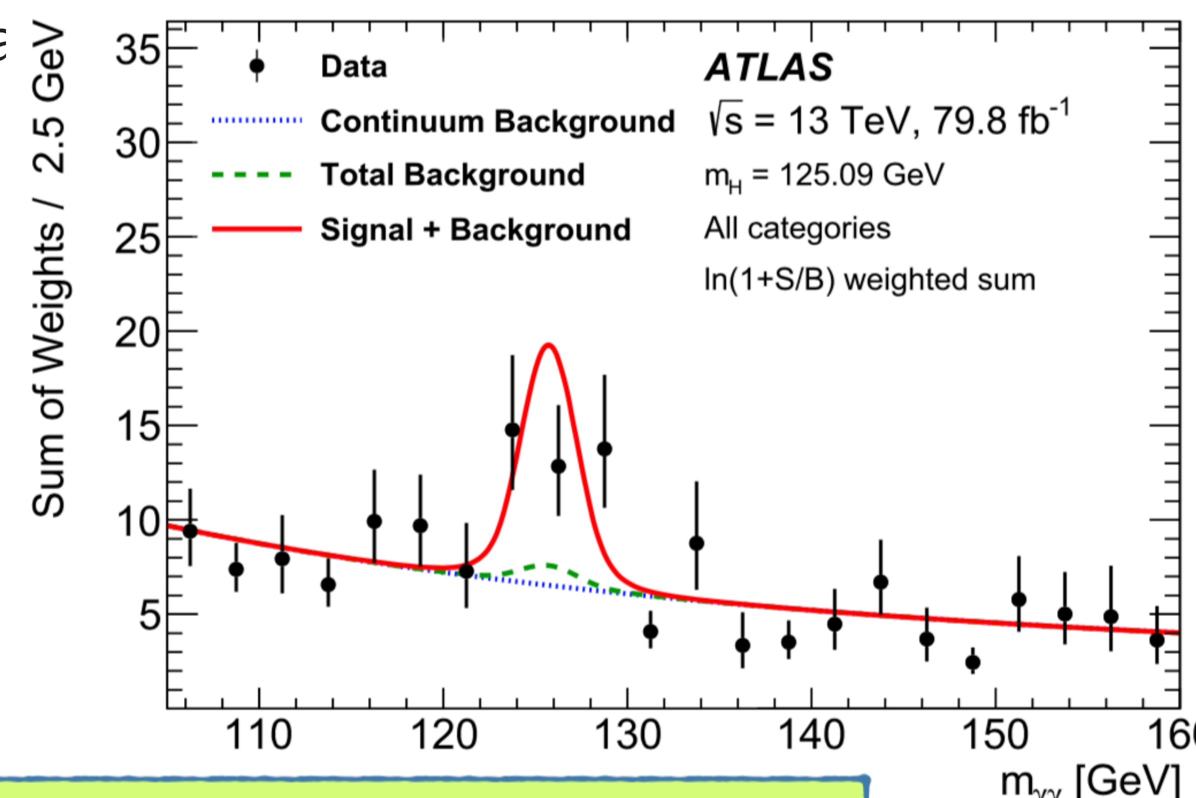
H -> γγ Results

- Background estimation and signal extraction performed by simultaneous ML unbinned fit of $m_{\gamma\gamma}$ (105-160 GeV) in all 7 categories
  - The shape of the signal and background $m_{\gamma\gamma}$ distributions is described with analitical functions
  - Signal (DSCB): A Gaussian core (model signal peak) and power-law curves (model outer tails of signal)
  - Background (one par. func.) background from simulation (Lep) and a dedicated data control region (Had);



Dominant uncertainties

- Statistical (~29%);
- tt̄H parton shower model (8%);
- photon isolation, energy resolution & scale (8%);
- Jet energy scale & resolution (6%);

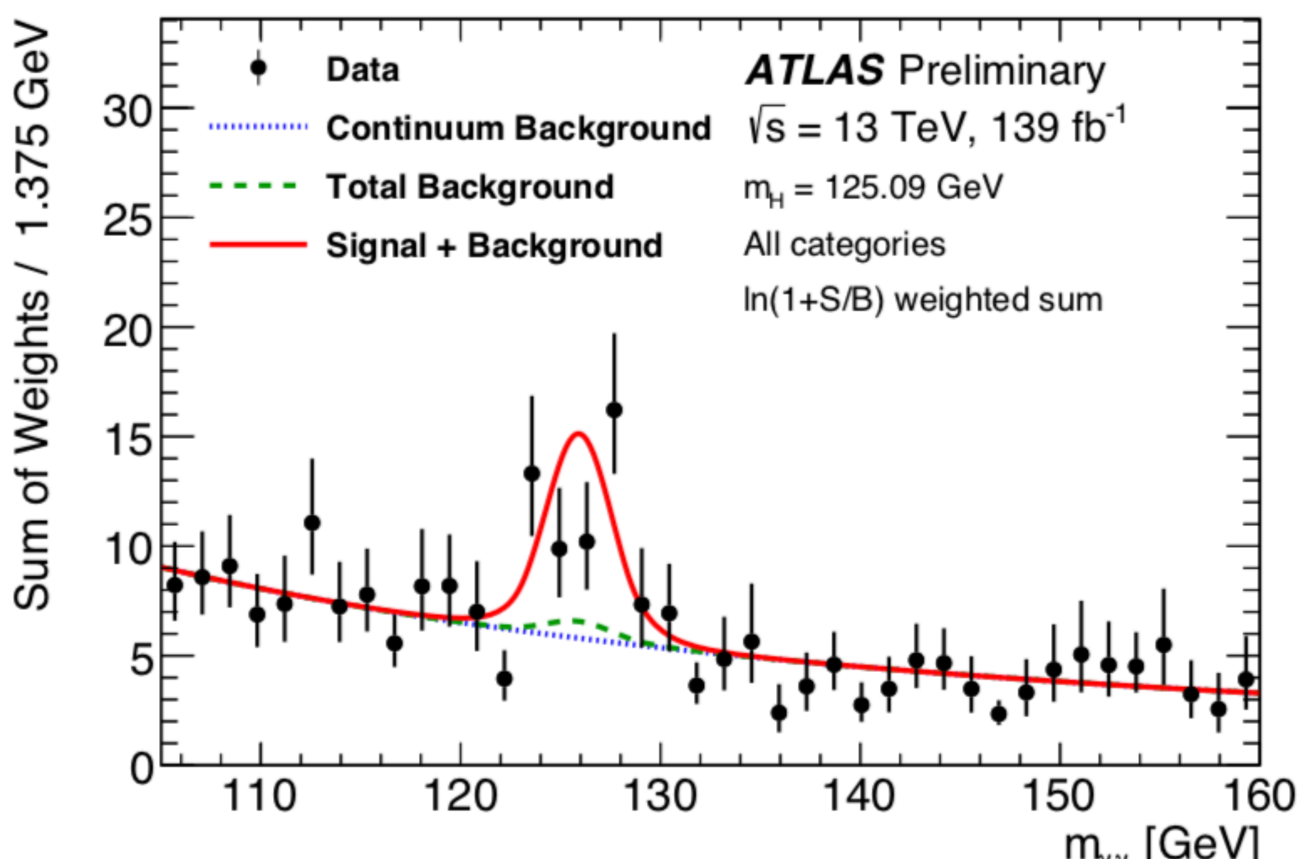


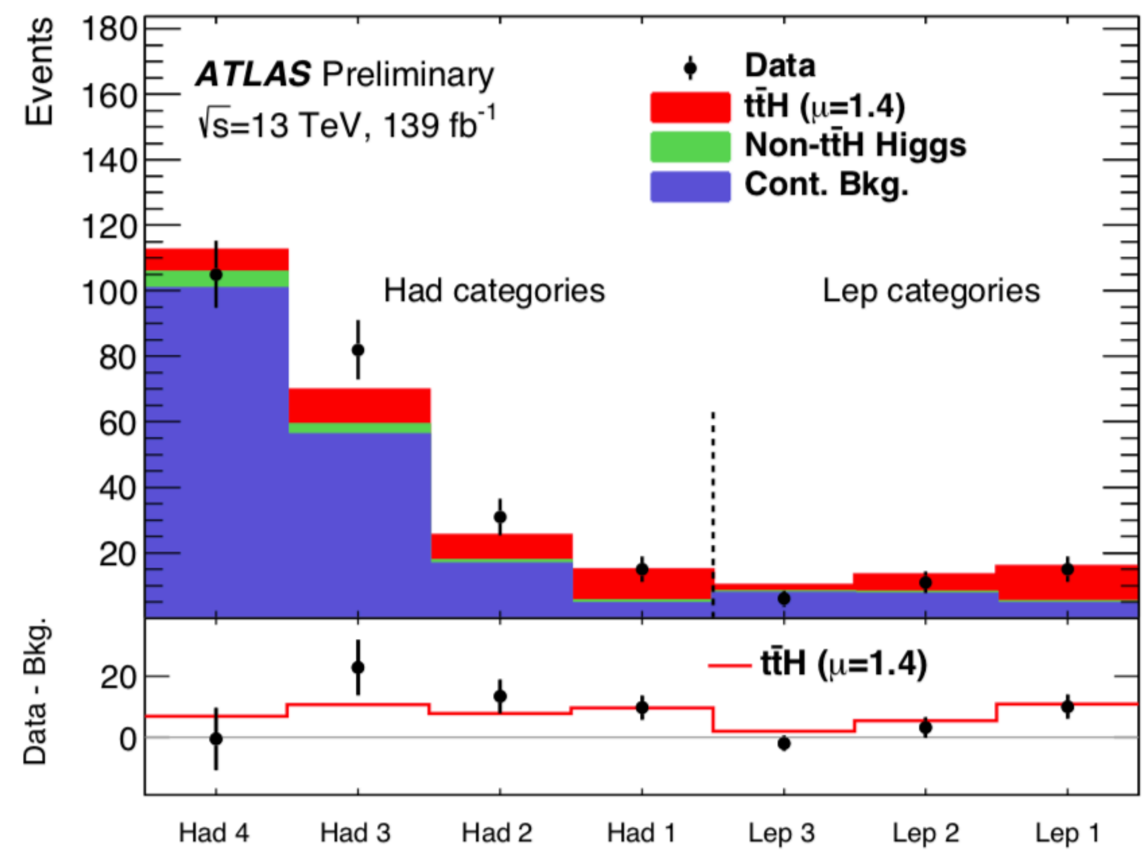
Significance: 4.1 σ (expected 3.7 σ)

H -> γγ Update

ATLAS-CONF-2019-004

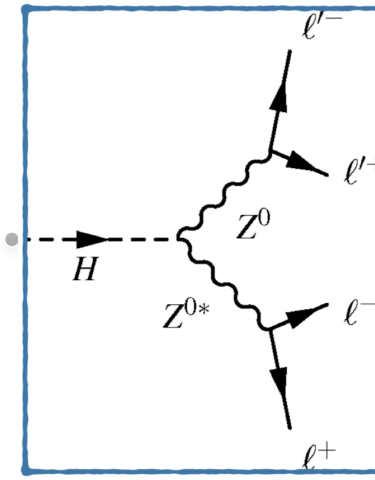
- Update on 2019 Moriond at 139 fb^{-1}
  - The analysis utilizes the same event selection and categorization
  - The photon identification and efficiency measurements, as well as energy calibration, have been updated



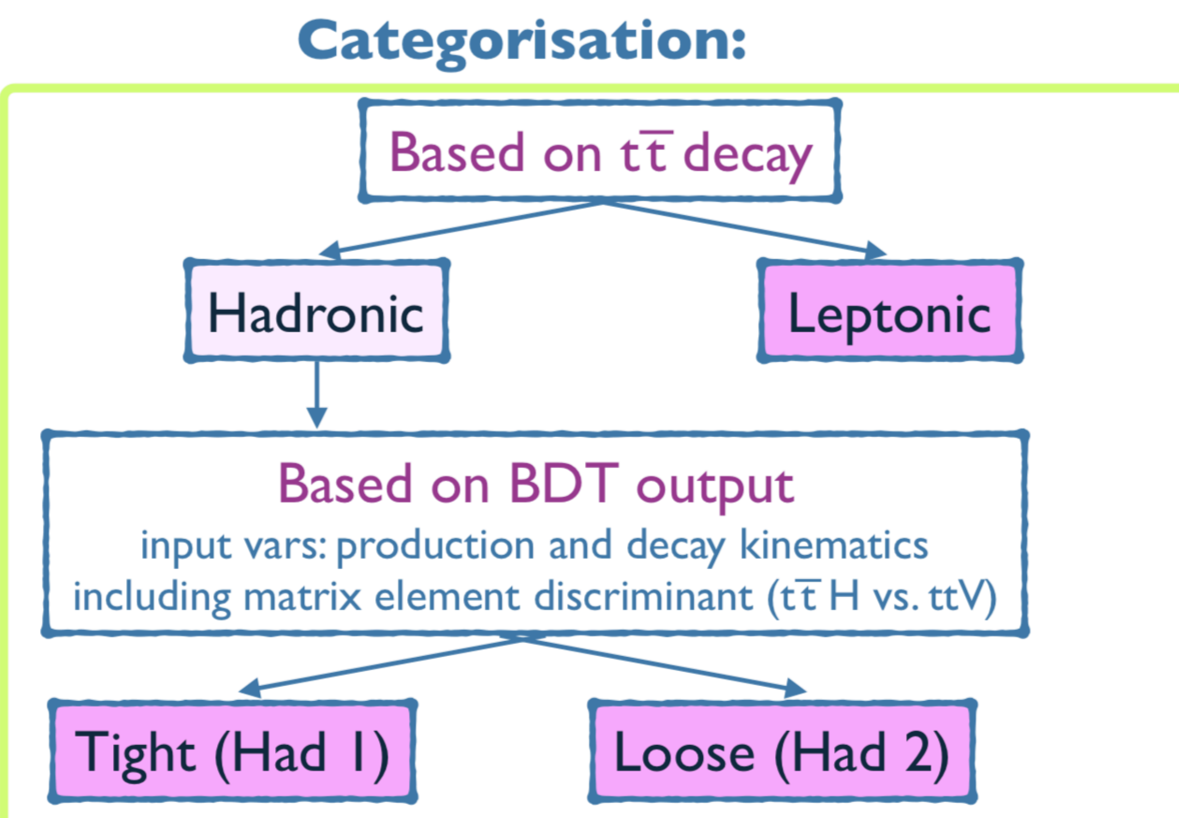


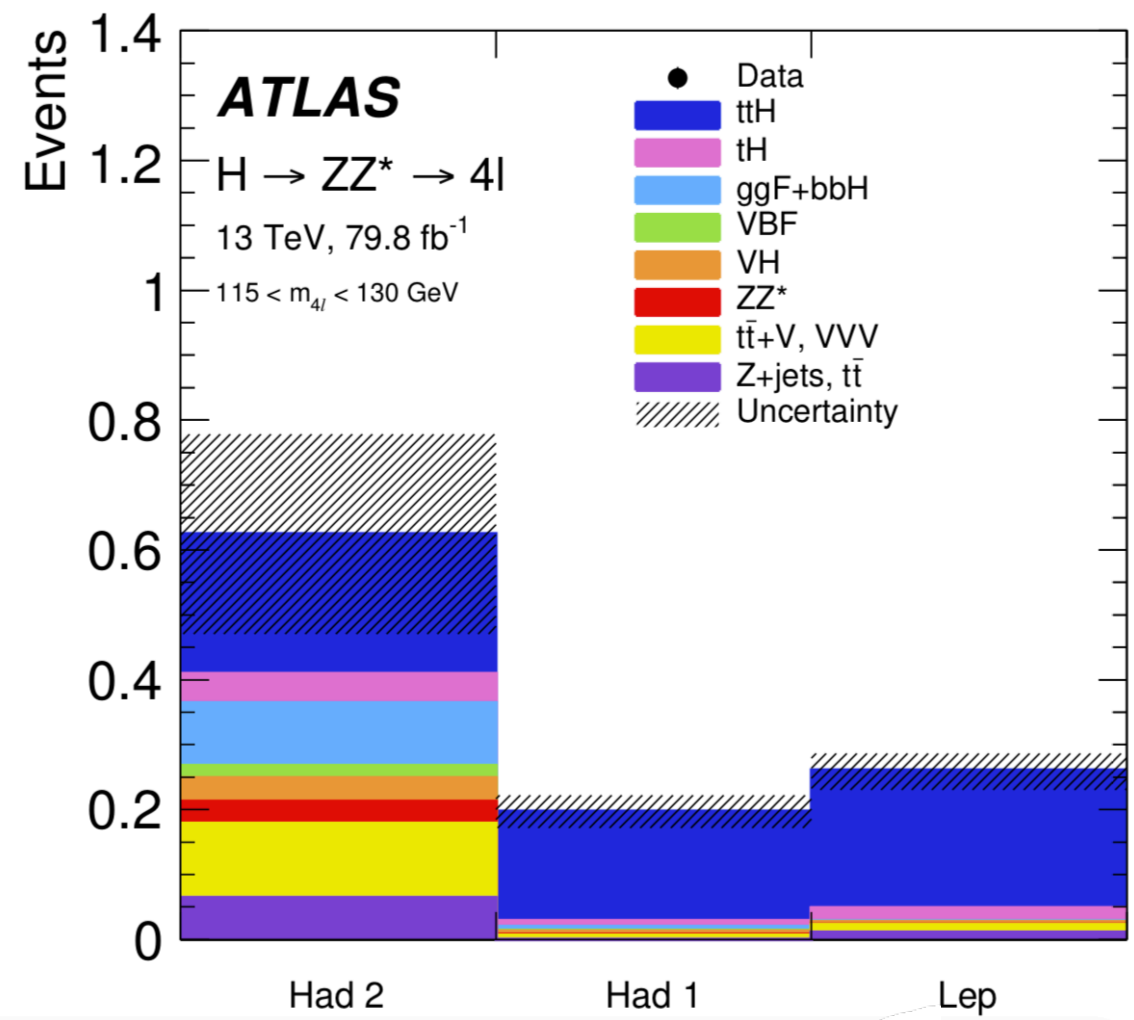
The ttH process is observed in the diphoton decay mode with a significance of 4.9 σ

ZZ -> 4l



- Extremely low rate, Clean final state w/ high S/B
- 3 Analysis regions
  - 115 GeV < m4l < 130 GeV





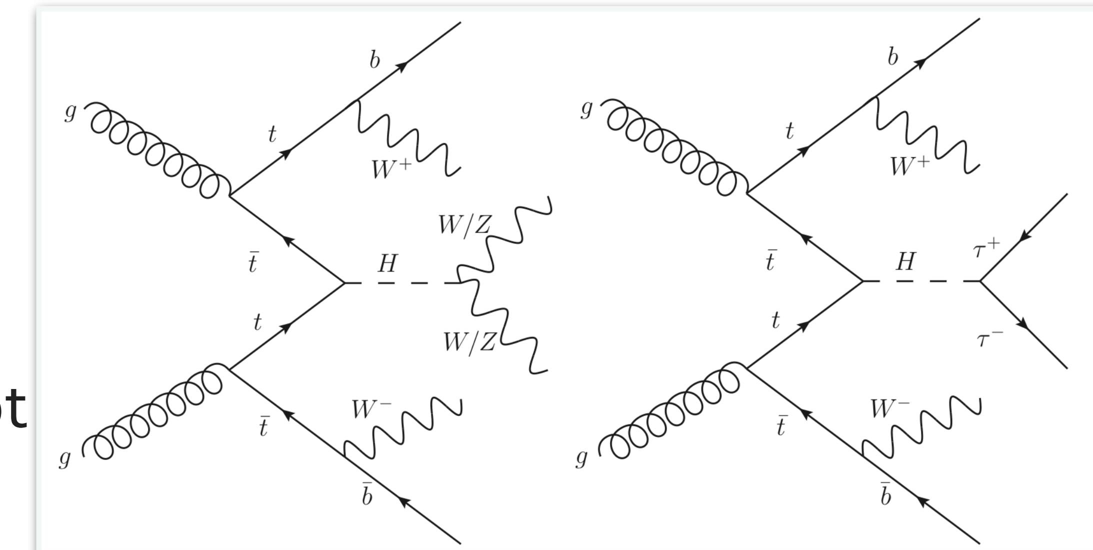
Extremely statistically limited:

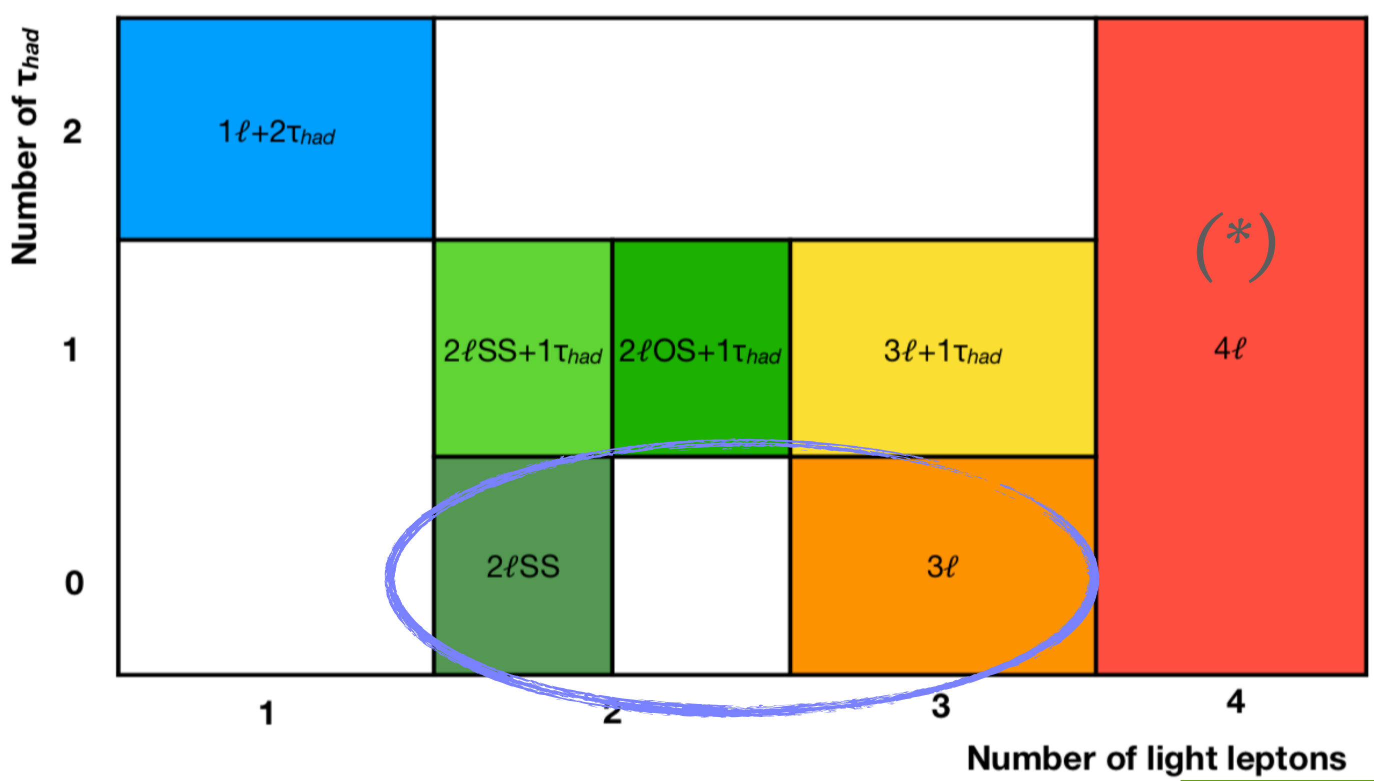
- no events observed in signal region
- 1.1 events expected (0.6 ttH)
- Expected sensitivity: 1.2σ

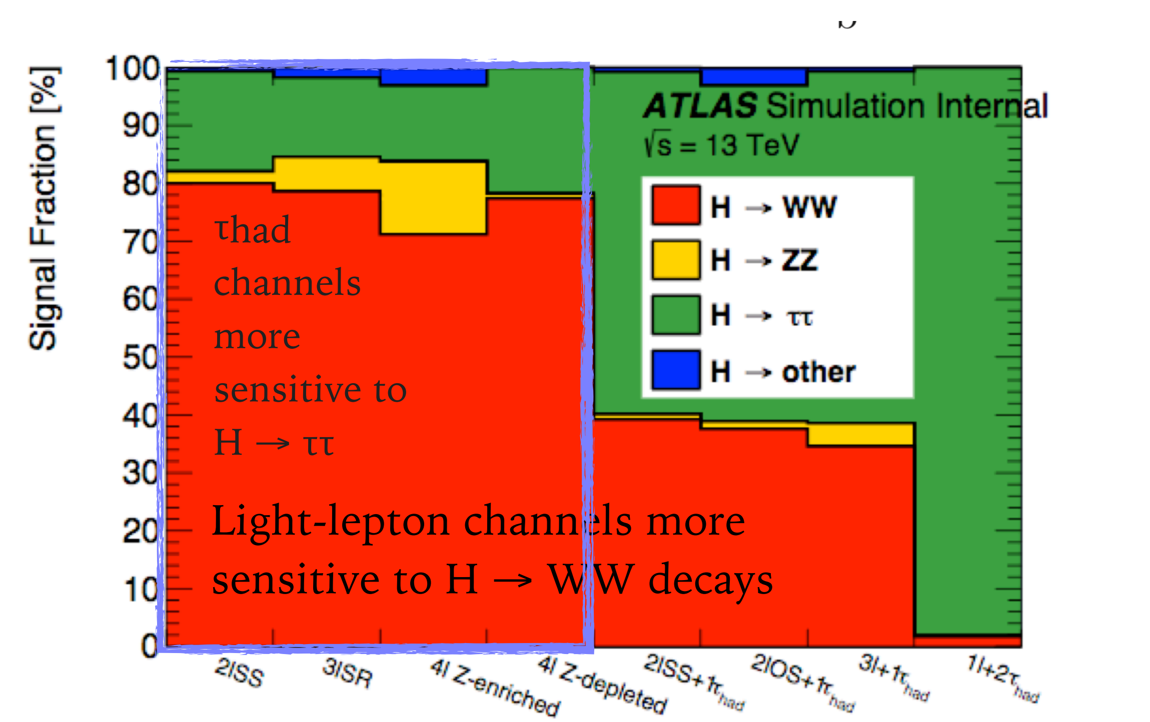
	Expected				Observed
Bin	$t\bar{t}H$ (signal)	Non-$t\bar{t}H$ Higgs	Non-Higgs	Total	Total
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

Multilepton Analysis Strategy

- Targets Higgs decays to WW, ZZ and $\tau\tau$ with ≥ 2 (1light) lepton in their final state
- Analysis channels are defined wrt light leptons (l) and hadronic taus (τ_{had}) multiplicity (7 orthogonal channels)
- MVA in lepton definitions to reject fakes/non-prompt lepton
- Event classified in the different regions using MVA







(*)for m(4l) != Higgs mass window

Multilepton Background Composition

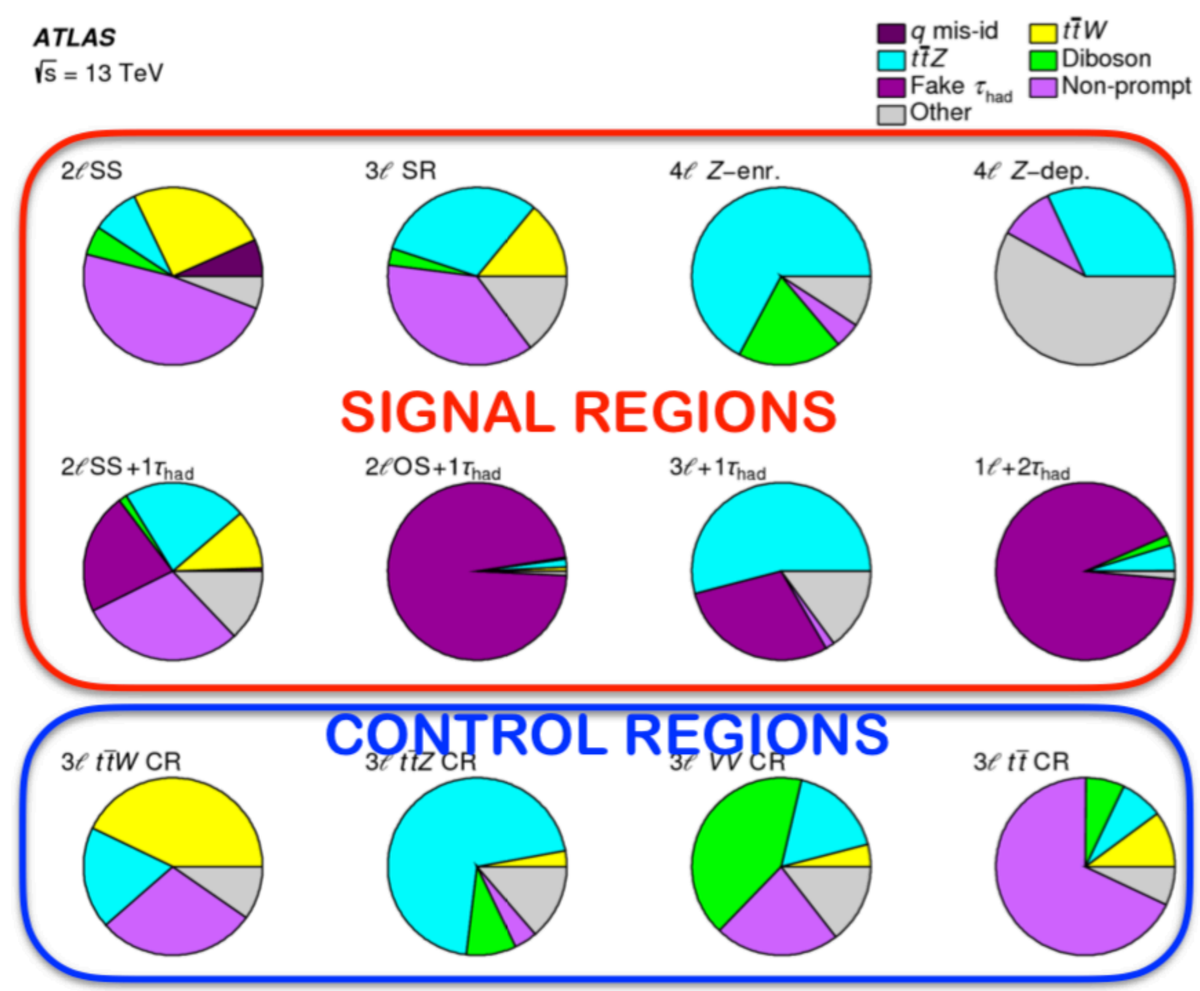
- Non-prompt lepton in mainly $t\bar{t}$
  - semileptonic b-decay
  - γ conversions
- Fake τ from light/b-jets

DATA-DRIVEN (DD):
MATRIX METHOD (MM), FAKE FACTOR (FF)

FF ~ matrix method except prompt background is taken from MC

- Misidentified charge lepton
  - trident electrons (Bremsstrahlung) and track curvature
  - using 3D likelihood method [pT, η, Tight/Loose]

DATA-DRIVEN (DD):
LIKELIHOOD FIT



- Irreducible backgrounds with prompt-leptons ($t\bar{t}Z$, $t\bar{t}W$, VV)

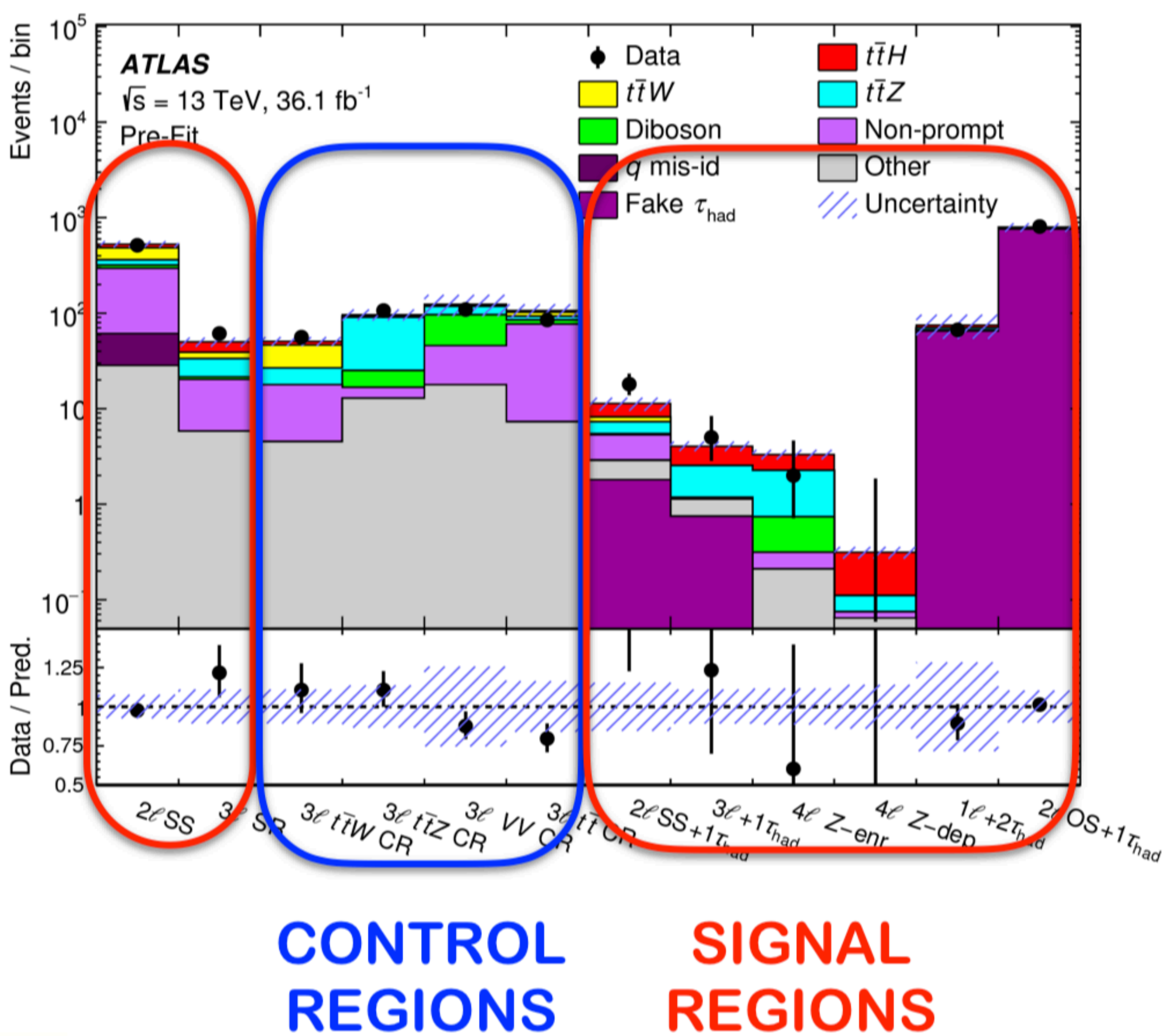
Multilepton Analysis Strategy

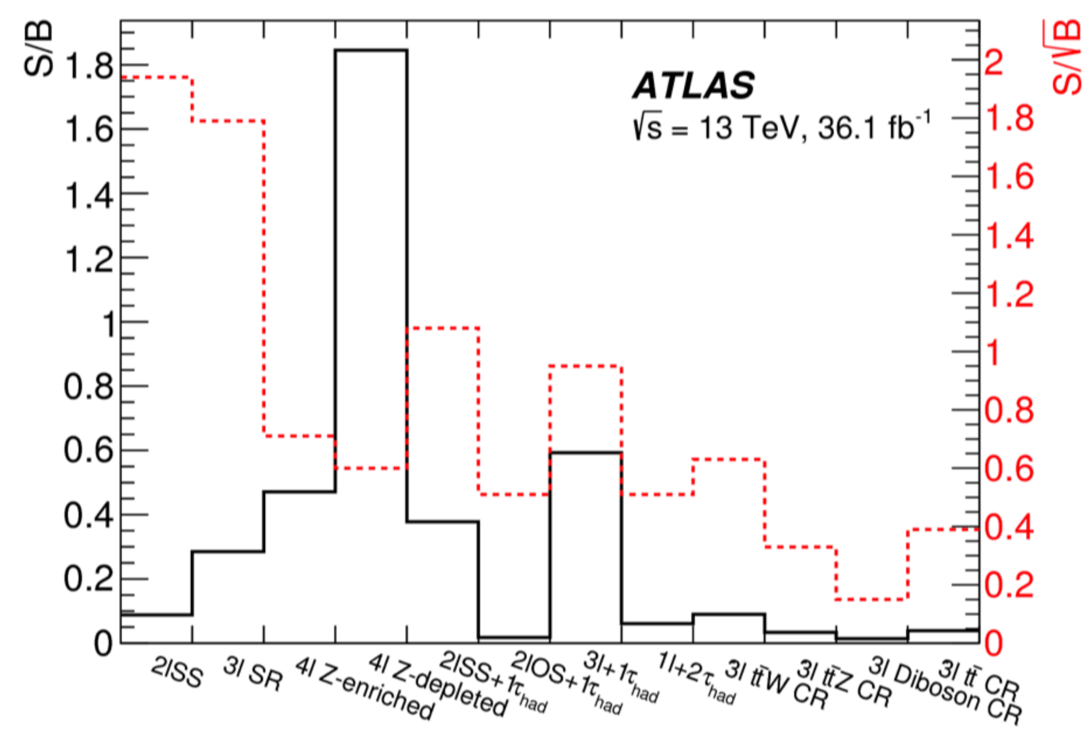
- Challange: which type of method we should use for reducible background and which type of fakes will be most dominant
  - Object definition
    - Lepton MVA-based isolation (PromptLeptonIso) to reject non-prompt l from semileptonic b-decay (track jets properties, lepton track/calorimeter isolation variables)
    - Lepton MVA to reduce charge misidentification background (QMisID)
  - Analysis strategy
    - Event MVA discriminant used in the final fit for the most sensitive channels
    - Need a data-driven method that provides a correct modelling of the shape of the fakes contribution
- With more data
  - Smaller statistical unc.
  - Flaws of assumptions / simplifications in the DD methods become a problem

	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	-	-	-	-	-

0-tau Channels

- Signal extraction: fit or cut on BDTs (boosted decision tree)
- Input variables: system reconstruction, pseudo-continuous b-tagging, kinematics… (Backup)
- 2lSS0τ: combination of two BDTs (ttH vs. ttbar; ttH vs. ttV)
- 3l0τ: 5-dimensional multinominal BDTs mapped to 5 categories (ttH, ttW, ttZ, ttbar, VV)
- 4l (Z-enriched): ttH vs. ttZ





Most statistically sensitive to ttH: 2lSS+0τ and 3l+0τ

Purest but lowest statistics: 4l

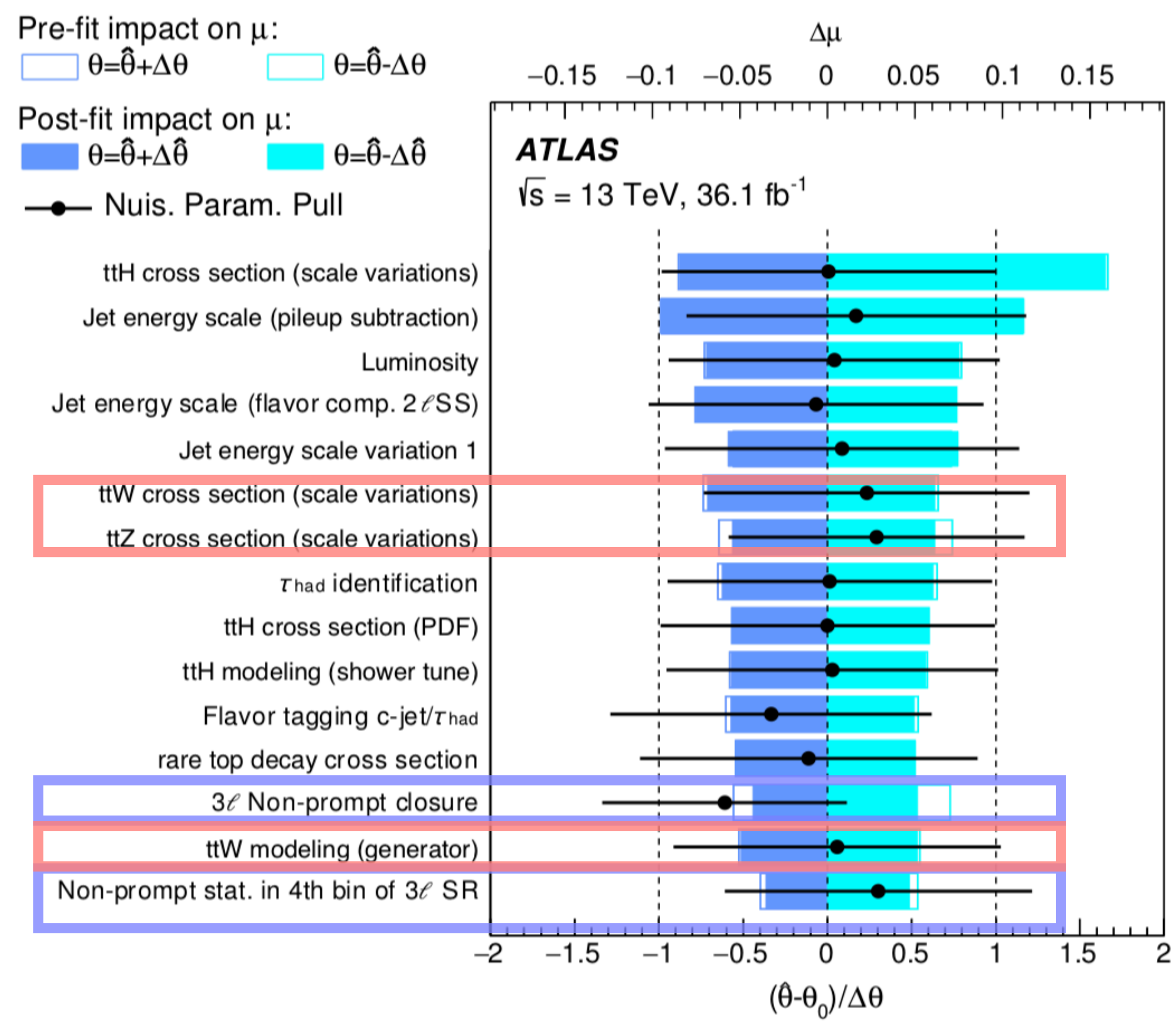
M.Nazlim Agaras

Multilepton Results

Observed significance over background-only hypothesis: 4.1σ (exp. 2.8σ)

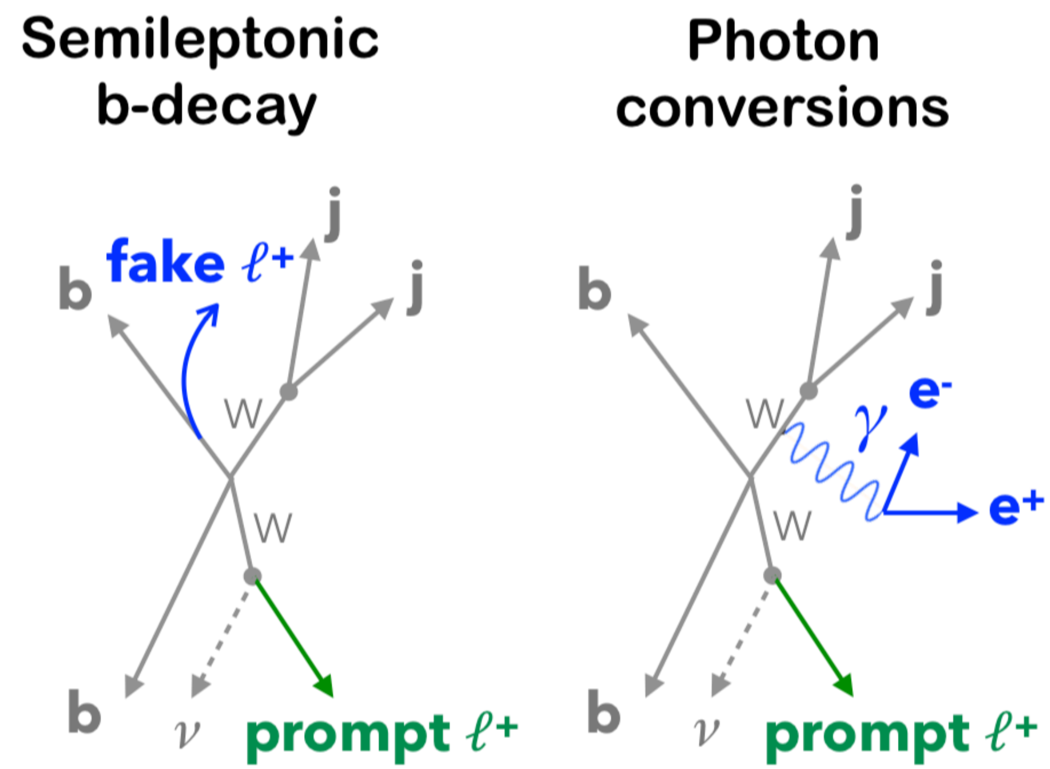
- Systematic uncertainties already important for some multilepton channels
- JES
  - Largest experimental uncertainty
  - Flavour composition: can be improved by taking into account predicted flavor composition
- Non-prompt light lepton estimates uncertainties ranked as 3rd group of systematics with the largest impact on the signal strength measurement

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



Multilepton at 79.9 fb^{-1}

- Soon to be public
- Many improvements/changes
  - Light lepton fake estimates
  - SR/CR & lepton definitions



- Further improvements
  - Matrix Element Method (MEM)
    - Assign probability density value based on theory

MEM weight

Integration

Matrix Element at LO

$$w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha}\int d\Phi_\alpha \cdot \delta^4\left(p_1^\mu + p_2^\mu - \sum_{k\geq 2} p_k^\mu\right)\cdot \frac{f(x_1,\mu_F)f(x_2,\mu_F)}{x_1 x_2 s}\cdot\left|\mathcal{M}_\alpha(p_k^\mu)\right|^2\cdot W(\Phi'|\Phi_\alpha)$$

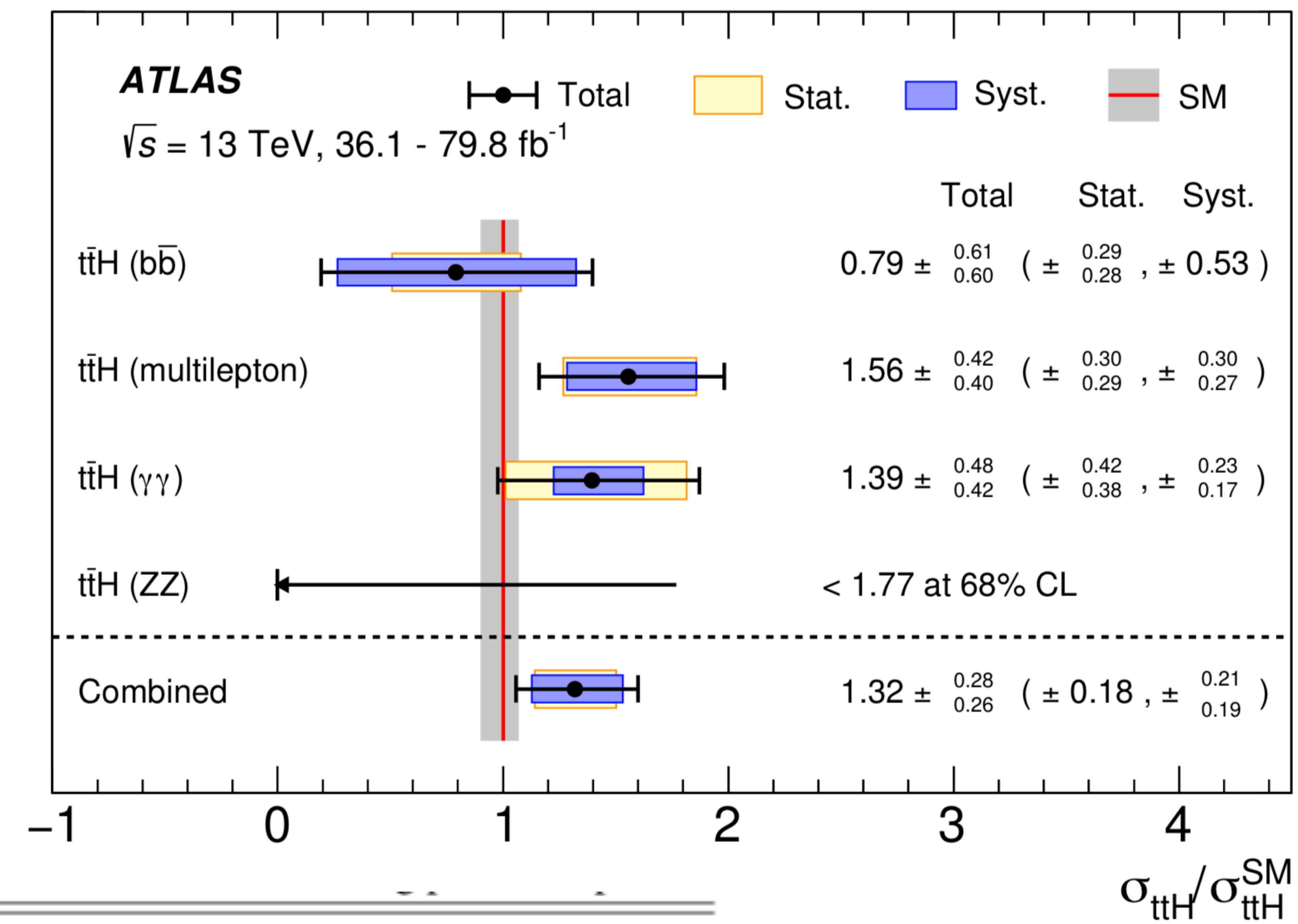
Phase-space enforcing 4-momentum conservation

Parton distribution function

Transfer functions relating pardon-level to reconstructed quantities

Combination

- Combination of ttH searches in $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ (79.8 fb^{-1}) with $H \rightarrow bb$ and $H \rightarrow$ multi lepton (36.1 fb^{-1})
- Profile likelihood method, based on simultaneous fits to the signal regions and control regions of the individual analyses
- The overlap between the selected events in the different analyses is found to be negligible



Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \rightarrow \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \rightarrow$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \rightarrow ZZ^* \rightarrow 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

Run 2 data alone: Observation of ttH!

Combination

- ttH(γγ) and ttH(4l) statistically limited;
- ttH(bb) and ttH(ML) limited by systematic uncertainties, mostly theoretical uncertainties
- Difference between two releases are studied
- Correlation scheme studied in detail
  - Theory uncertainties (QCD scale, BR uncertainties, PDF uncertainty) correlated
  - Experimental uncertainties largely uncorrelated (Due to changes in object reconstruction and systematic calc. in releases)
  - Other Higgs production modes fixed to SM

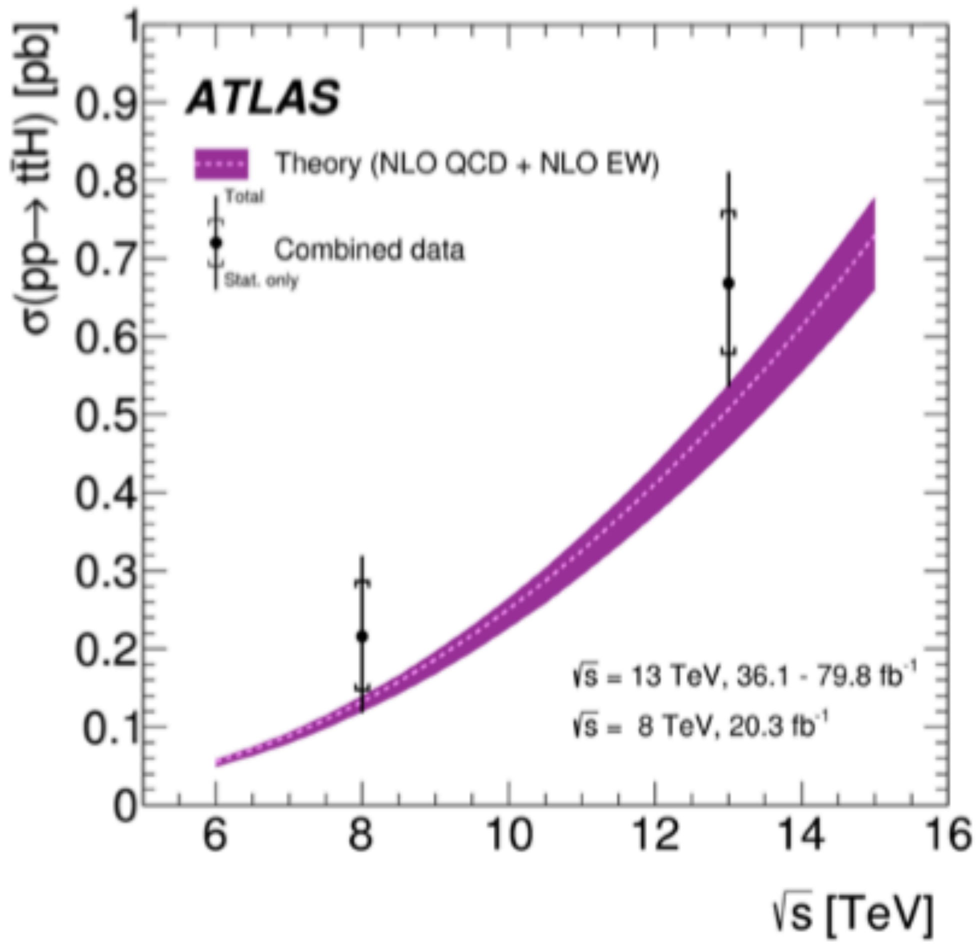
Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, $E_{\mathrm{T}}^{\mathrm{miss}}$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

Combination

Combination with measurements @7TeV (4.5 fb^{-1}) and @8TeV (20.3 fb^{-1})*:

6.3σ (exp 5.1σ)

* Eur. Phys. J. C 76 (2016) 6



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$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4 σ	1.6 σ
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Combined (13 TeV)	36.1–79.8	670 $\pm$ 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3 σ	5.1 σ

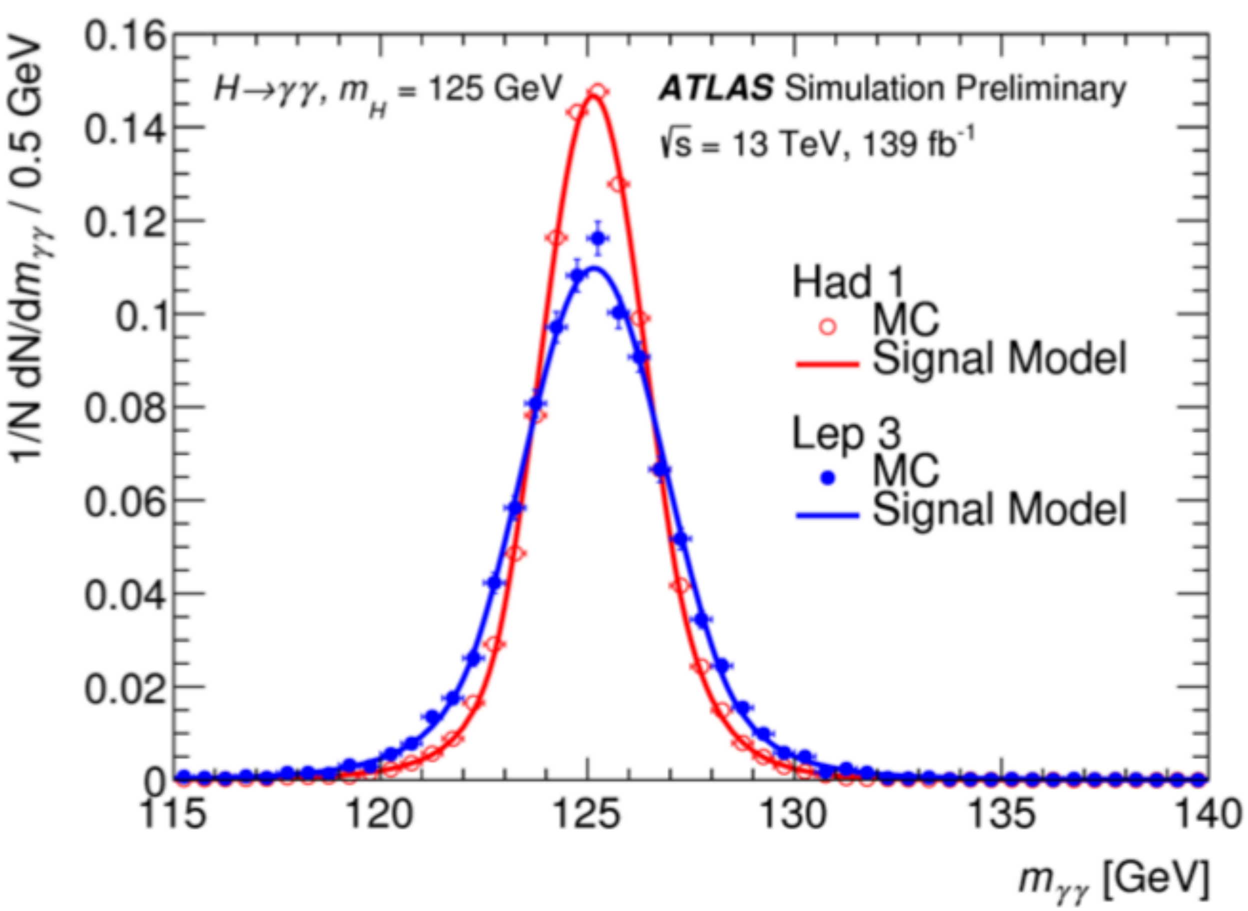
Conclusion

- Search for ttH production performed in ATLAS with 36.1 - 79.8 fb^{-1} of data at 13 TeV
- Challenging analyses:
  - very low cross section and high combinatorics of final state particles
  - heavy use of MVA techniques to efficiently discriminate signal from large backgrounds
  - large systematics uncertainties on modelling of signal and irreducible backgrounds ttbb and ttV
- First ATLAS observation of ttH production at 6.3σ (expected 5.1σ) → direct observation of Higgs to top Yukawa coupling
  - ttH(bb) already systematics-limited. Requires some breakthrough to make significant progress from here.
  - ttH multilepton currently most sensitive analysis and mostly stat-limited
  - With the additional data, ttH(yy) become the single most sensitive channel.

Backup

Backup

$$f_{\rm DCB}(m_{\gamma\gamma}) = N \times \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{low} \leq t \leq \alpha_{high} \\ \dfrac{e^{-\frac{1}{2}\alpha_{low}^2}}{\left[\frac{1}{R_{low}}(R_{low}-\alpha_{low}-t)\right]^{n_{low}}} & \text{if } t < -\alpha_{low} \\ \dfrac{e^{-\frac{1}{2}\alpha_{high}^2}}{\left[\frac{1}{R_{high}}(R_{high}-\alpha_{high}+t)\right]^{n_{high}}} & \text{if } t > \alpha_{high} \end{cases}$$



Category	σ_{68} (GeV)	σ_{90} (GeV)
"Had" Category 1	1.39	2.48
"Had" Category 2	1.58	2.84
"Had" Category 3	1.65	2.96
"Had" Category 4	1.67	3.00
"Lep" Category 1	1.56	2.80
"Lep" Category 2	1.75	3.13
"Lep" Category 3	1.85	3.30

68 (90) means the smallest window containing 68 (90)% of signal events

Backup

- Di-photon trigger requirement
  - 2015+2016: 2 photons passing loose ID, leading $E_T \geq 35$ GeV, sub-leading $E_T \geq 25$ GeV
  - 2017+2018: 2 photons passing medium ID, leading $E_T \geq 35$ GeV, sub-leading $E_T \geq 25$ GeV
- Both photons passing tight ID and isolated with $|\eta| < 2.37$ (excluding $1.37 < |\eta| < 1.52$)
- Leading (sub-leading) photon $p_T/m_{\gamma\gamma} > 0.35$ (0.25)
- $m_{\gamma\gamma}$ is required to be within (105, 160) GeV

- Events passing pre-selection are sorted into two ttH-enriched regions: hadronic region (≥1 b-jet, ≥3 jets, 0 leptons) and leptonic region (targetting leptonic/semi-lep. top decays; ≥1 b-jet, ≥1 leptons)
  - Jets: $p_T > 25$ GeV, $|\eta| < 4.4$
  - b-jet: MV2c10 tagger, 77% working point
  - Leptons: $p_T > 10$ GeV, isolated
- Afterwards events in these two regions are further categorized based on XGBoost BDT discriminant

Backup

- Training samples:
  - ➢ Signal: ttH signal simulated with Powheg+Pythia8
  - ➢ Background: data events in NTI region
    - ❖NTI: one or both photons fail tight ID or isolation requirement

- Major continuum background in ttH categories coming from γγ+jets and ttγγ contributions
- For bkg. model, only one-parameter functions considered due to the low statistics in data spectra
  - ➢ Exponential function: $f(m_{\gamma\gamma}) = e^{c \cdot m_{\gamma\gamma}}$
  - ➢ Power Law function: $f(m_{\gamma\gamma}) = m_{\gamma\gamma}^{c}$
- Choices are made based on the spurious signal test (using S+B pdf to fit the pure bkg. templates)
  - ➢ Hadronic templates: NTI data events without b-jet cut
  - ➢ Leptonic templates: ttγγ MC events (Madgraph) without photon ID and isolation requirements

Backup

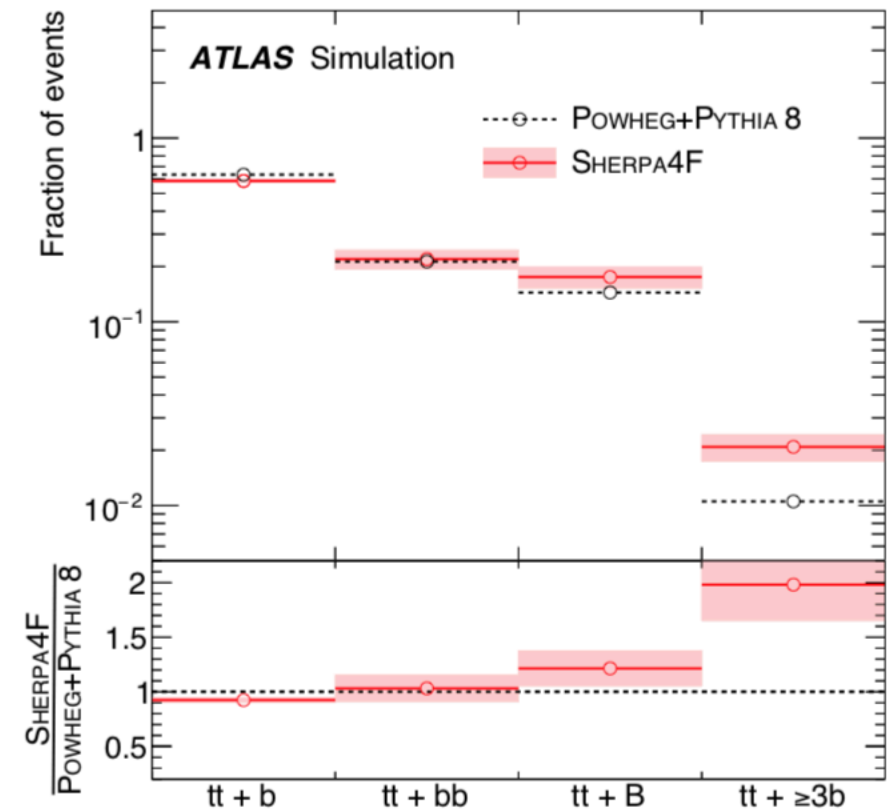
Uncertainty source	$\Delta\sigma_{\text{low}}/\sigma$ [%]	$\Delta\sigma_{\text{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution Function and α_S Scale (PDF+α_S)	0.3	0.5
Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)	0.4	0.3
Experimental uncertainties	7.8	9.1
Photon Energy Resolution (PER)	5.5	6.2
Photon Energy Scale (PES)	2.8	2.7
Jet/$E_{\text{T}}^{\text{miss}}$	2.3	2.7
Photon Efficiency	1.9	2.7
Background Modeling	2.1	2.0
Flavor Tagging	0.9	1.1
Leptons	0.4	0.6
Pileup	1.0	1.5
Luminosity and Trigger	1.6	2.3
Higgs Boson Mass	1.6	1.5

- Relative contributions of sys. unc. to total error on $(\sigma \times Br)_{obs}$
- This channel is still stat. unc. dominated for now

Backup

Modelling of $t\bar{t}$ is crucial to the analysis, $t\bar{t}+\mathrm{HF}$ has large theory uncertainty

- Split into $t\bar{t}+\mathrm{light}$, $t\bar{t}{+}{\geq}1c$, $t\bar{t}{+}{\geq}1b$
  - Further split $t\bar{t}{+}{\geq}1b$ by number of additional b-hadrons in jets
- Nominal $t\bar{t}$ sample uses 5FS prediction
  - Use dedicated Sherpa 4FS $t\bar{t}+b\bar{b}$ prediction to improve modelling
    - Both additional b-quarks to NLO precision in QCD
    - Takes b-quark mass into account
  - Reweight relative $t\bar{t}{+}{\geq}1b$ subcomponents to 4FS values



$t\bar{t}$ modelling is dominant contribution to total systematic uncertainty

- Compare nominal prediction of Powheg+Pythia8 to alternate MC predictions for each of $t\bar{t}+\mathrm{light}$, $t\bar{t}{+}{\geq}1c$ $t\bar{t}{+}{\geq}1b$

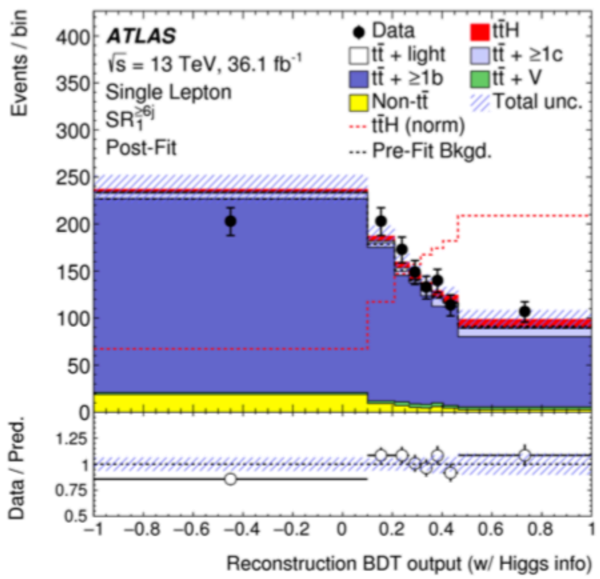
Systematic	Comparison	$t\bar{t}$ component
ME generator	Powheg+Pythia8 vs Sherpa (5FS)	all
Parton Shower	Powheg+Pythia8 vs Powheg+Herwig7	all
Additional radiation	Comparison of Powheg+Pythia8 tunings	all
4FS vs 5FS	Powheg+Pythia8 vs Sherpa+OpenLoops (4FS)	$t\bar{t}{+}{\geq}1b$

Backup

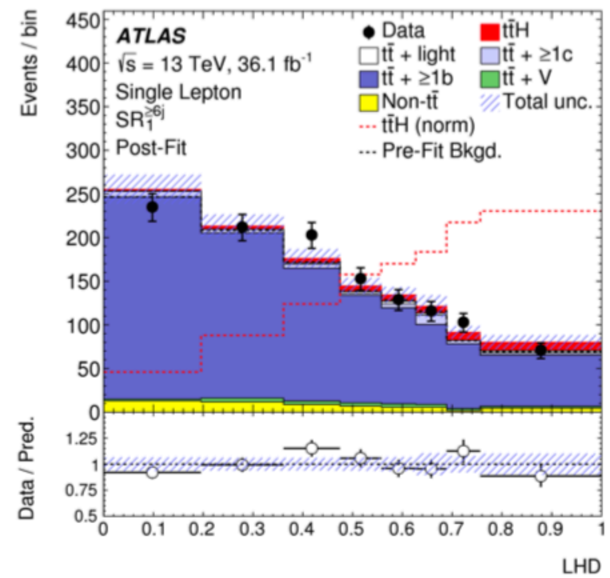
Systematic source	Description	$t\bar{t}$ categories
$t\bar{t}$ cross-section	Up or down by 6%	All, correlated
$k(t\bar{t} + \geq 1c)$	Free-floating $t\bar{t} + \geq 1c$ normalization	$t\bar{t} + \geq 1c$
$k(t\bar{t} + \geq 1b)$	Free-floating $t\bar{t} + \geq 1b$ normalization	$t\bar{t} + \geq 1b$
SHERPA5F 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 $H_T/2$ 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%	$t\bar{t} + \geq 1b$

Backup

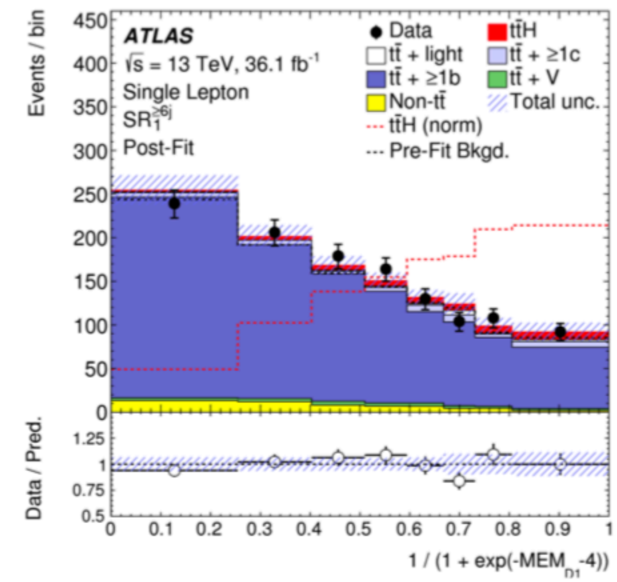
Reco BDT



LHD



MEM



Reco BDT BDT trained to solve jet-parton assignment for $t\bar{t}H$ hypothesis. Invariant masses, angular separation of jets/leptons, score per combination

LHD Sig and bkg probabili … mplates of reconstructed variables, combines all permutations

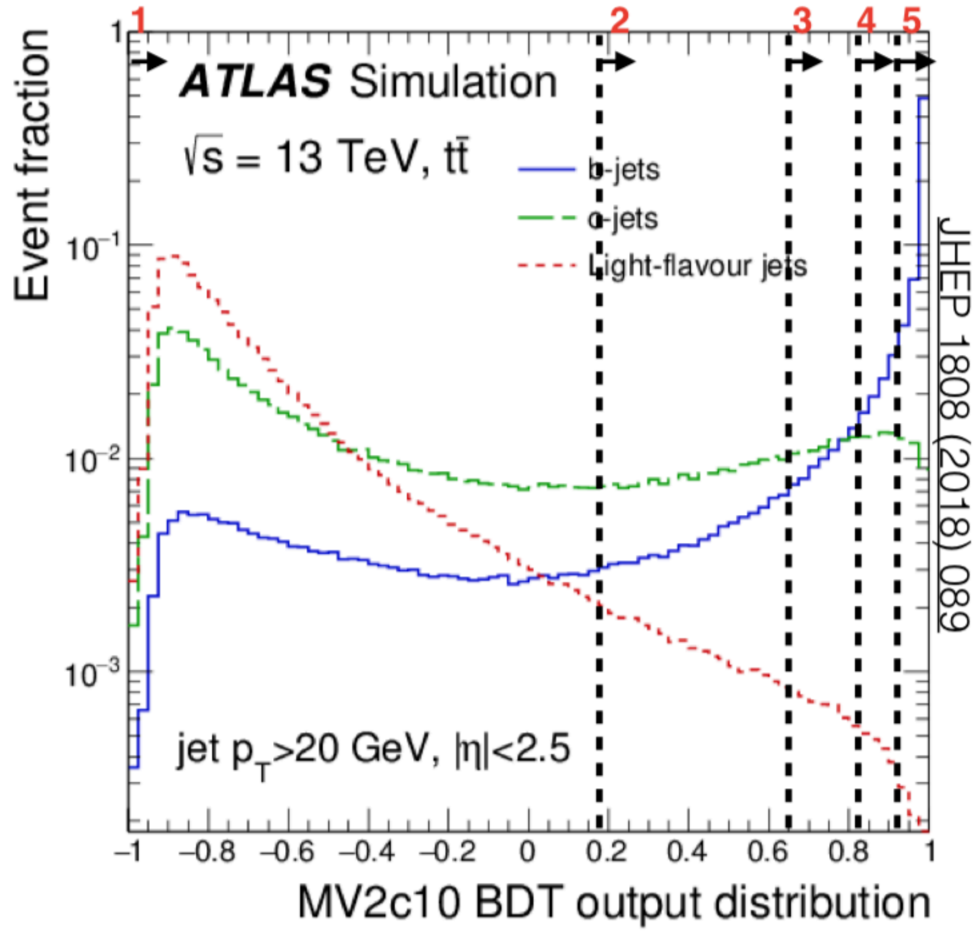
https://indico.cern.ch/event/727396/contributions/3014588/attachments/1657104/2653199/28052018_HiggsTop_DDATLAS_TVS.pdf

MEM Sig and bkg probabilities calculated at particle level. Transfer functions map detector level quantities to parton level

Variable	Definition	$SR_1^{\geq 4j}$	$SR_2^{\geq 4j}$	$SR_3^{\geq 4j}$
General kinematic variables				
m_{bb}^{min}	Minimum invariant mass of a b-tagged jet pair	✓	✓	-
m_{bb}^{max}	Maximum invariant mass of a b-tagged jet pair	-	-	✓
$m_{bb}^{\text{min}\ \Delta R}$	Invariant mass of the b-tagged jet pair with minimum ΔR	✓	-	✓
$m_{\text{jj}}^{\text{max}\ p_{\text{T}}}$	Invariant mass of the jet pair with maximum p_{T}	✓	-	-
$m_{bb}^{\text{max}\ p_{\text{T}}}$	Invariant mass of the b-tagged jet pair with maximum p_{T}	✓	-	✓
$\Delta\eta_{bb}^{\text{avg}}$	Average $\Delta\eta$ for all b-tagged jet pairs	✓	✓	✓
$\Delta\eta_{\ell,\text{j}}^{\text{max}}$	Maximum $\Delta\eta$ between a jet and a lepton	-	✓	✓
$\Delta R_{bb}^{\text{max}\ p_{\text{T}}}$	ΔR between the b-tagged jet pair with maximum p_{T}	-	✓	✓
$N_{bb}^{\text{Higgs}\ 30}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓	-
$n_{\text{jets}}^{p_{\text{T}}>40}$	Number of jets with $p_{\text{T}} > 40$ GeV	-	✓	✓
$\text{Aplanarity}_{b\text{-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor [100] built with all b-tagged jets	-	✓	-
$H_{\text{T}}^{\text{all}}$	Scalar sum of p_{T} of all jets and leptons	-	-	✓
Variables from reconstruction BDT				
BDT output	Output of the reconstruction BDT	✓**	✓**	✓
m_{bb}^{Higgs}	Higgs candidate mass	✓	-	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	-	-
$\Delta R_{H,\ell}^{\text{min}}$	Minimum ΔR between Higgs candidate and lepton	✓	✓	✓
$\Delta R_{H,b}^{\text{min}}$	Minimum ΔR between Higgs candidate and b-jet from top	✓	✓	-
$\Delta R_{H,b}^{\text{max}}$	Maximum ΔR between Higgs candidate and b-jet from top	-	✓	-
$\Delta R_{bb}^{\text{Higgs}}$	ΔR between the two jets matched to the Higgs candidate	-	✓	-
Variables from b-tagging				
$w_{b\text{-tag}}^{\text{Higgs}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	-	✓	-

Variable	Definition	$\mathrm{SR}^{\geq 6j}_{1,2,3}$	$\mathrm{SR}^{5j}_{1,2}$
General kinematic variables			
ΔR^{avg}_{bb}	Average ΔR for all b-tagged jet pairs	✓	✓
$\Delta R^{\max p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_T	✓	–
$\Delta\eta^{\max}_{jj}$	Maximum $\Delta\eta$ between any two jets	✓	✓
$m^{\min \Delta R}_{bb}$	Mass of the combination of two b-tagged jets with the smallest ΔR	✓	–
$m^{\min \Delta R}_{jj}$	Mass of the combination of any two jets with the smallest ΔR	–	✓
$N^{\mathrm{Higgs}\ 30}_{bb}$	Number of b-tagged jet pairs with invariant mass within 30 GeV of the Higgs-boson mass	✓	✓
H^{had}_{T}	Scalar sum of jet p_T	–	✓
$\Delta R^{\min}_{\ell,bb}$	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 [100] built with all jets	✓	✓
H_1	Second Fox–Wolfram moment computed using all jets and the lepton	✓	✓
Variables from reconstruction BDT			
BDT output	Output of the reconstruction BDT	✓*	✓*
m^{Higgs}_{bb}	Higgs candidate mass	✓	✓
$m_{H,b_{\mathrm{lep\ top}}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	✓	–
$\Delta R^{\mathrm{Higgs}}_{bb}$	ΔR between b-jets from the Higgs candidate	✓	✓
$\Delta R_{H,t\bar{t}}$	ΔR between Higgs candidate and $t\bar{t}$ candidate system	✓*	✓*
$\Delta R_{H,\mathrm{lep\ top}}$	ΔR between Higgs candidate and leptonic top candidate	✓	–
$\Delta R_{H,b_{\mathrm{had\ top}}}$	ΔR between Higgs candidate and b-jet from hadronic top candidate	–	✓*
Variables from likelihood and matrix element method calculations			
LHD	Likelihood discriminant	✓	✓
MEM_{D1}	Matrix element discriminant (in $\mathrm{SR}^{\geq 6j}_{1}$ only)	✓	–
Variables from b-tagging (not in $\mathrm{SR}^{\geq 6j}_{1}$)			
$w^{\mathrm{Higgs}}_{b\text{-tag}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	✓	✓
B^{3}_{jet}	3rd largest jet b-tagging discriminant	✓	✓
B^{4}_{jet}	4th largest jet b-tagging discriminant	✓	✓
B^{5}_{jet}	5th largest jet b-tagging discriminant	✓	✓

Backup



	none	*loose*	*medium*	*tight*	*very-tight*
Efficiency	-	85%	77%	70%	60%
Discriminant value	1	2	3	4	5

- Regions built using 5 b-tagging working points and Njets

Backup

Process	Event generator	ME order	Parton Shower	PDF	Tune
$t\bar{t}H$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO [70]	A14
	(MG5_aMC)	(NLO)	(Herwig++)	(CT10 [71])	(UE-EE-5)
$tHqb$	MG5_aMC	LO	Pythia 8	CT10	A14
tHW	MG5_aMC	NLO	Herwig++	CT10	UE-EE-5
$t\bar{t}W$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
$t\bar{t}(Z/\gamma^* \to ll)$	MG5_aMC	NLO	Pythia 8	NNPDF 3.0 NLO	A14
	(Sherpa 2.1.1)	(LO multileg)	(Sherpa)	(NNPDF 3.0 NLO)	(Sherpa default)
tZ	MG5_aMC	LO	Pythia 6	CTEQ6L1	Perugia2012
tWZ	MG5_aMC	NLO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}t$, $t\bar{t}t\bar{t}$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}W^+W^-$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
$t\bar{t}$	Powheg-BOX v2 [72]	NLO	Pythia 8	NNPDF 3.0 NLO	A14
$t\bar{t}\gamma$	MG5_aMC	LO	Pythia 8	NNPDF 2.3 LO	A14
s-, t-channel, Wt single top	Powheg-BOX v1 [73–75]	NLO	Pythia 6	CT10	Perugia2012
$VV(\to llXX)$, $qqVV$, VVV	Sherpa 2.1.1	MEPS NLO	Sherpa	CT10	Sherpa default
$Z \to l^+l^-$	Sherpa 2.2.1	MEPS NLO	Sherpa	NNPDF 3.0 NLO	Sherpa default

Backup

	e					μ		
	L	L†	L*	T	T*	L	L†	L*/T/T*
Isolation	No	Yes				No	Yes	
Non-prompt lepton BDT	No		Yes			No		Yes
Identification	Loose			Tight		Loose		
Charge misassignment veto BDT	No				Yes	No		
Transverse impact parameter significance, $\|d_0\|/\sigma_{d_0}$	< 5					< 3		
Longitudinal impact parameter, $\|z_0 \sin\theta\|$	< 0.5 mm							

	2ℓSS	3ℓ	4ℓ	1ℓ+$2\tau_{\text{had}}$	2ℓSS+$1\tau_{\text{had}}$	2ℓOS+$1\tau_{\text{had}}$	3ℓ+$1\tau_{\text{had}}$
Light lepton	2T*	1L*, 2T*	2L, 2T	1T	2T*	2L†	1L†, 2T
τ_{had}	0M	0M	–	1T, 1M	1M	1M	1M
N_{jets}, $N_{b\text{-jets}}$	$\geq 4, = 1, 2$	$\geq 2, \geq 1$	$\geq 2, \geq 1$	$\geq 3, \geq 1$	$\geq 4, \geq 1$	$\geq 3, \geq 1$	$\geq 2, \geq 1$

Channel	Selection criteria
Common	$N_{jets} \geq 2$ and $N_{b\text{-jets}} \geq 1$
$2\ell SS$	Two very tight light leptons with $p_T > 20$ GeV
	Same-charge light leptons
	Zero medium τ_{had} candidates
	$N_{jets} \geq 4$ 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)
$1\ell + 2\tau_{had}$	One tight light lepton with $p_T > 27$ GeV
	Two medium τ_{had} candidates of opposite charge, at least one being tight
	$N_{jets} \geq 3$
$2\ell SS + 1\tau_{had}$	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
	$N_{jets} \geq 4$
	$\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
$2\ell OS + 1\tau_{had}$	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
	$N_{jets} \geq 3$
$3\ell + 1\tau_{had}$	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

Backup

	Variable	$2\ell SS$	3ℓ	4ℓ
Lepton properties	Leading lepton p_T		×	
	Second leading lepton p_T	×	×	
	Third lepton p_T		×	
	Dilepton invariant mass (all combinations)		×∗	
	Three-lepton invariant mass		×	
	Four-lepton invariant mass			×
	Best Z-candidate dilepton invariant mass			×
	Other Z-candidate dilepton invariant mass			×
	Scalar sum of all leptons p_T			×
	$\|\eta\|$ of the more forward leptons	×		
	Lepton flavour	×∗	×∗	
	Lepton charge		×	
Jet properties	Number of jets	×∗	×∗	
	Number of b-tagged jets	×∗	×∗	
	Second leading jet p_T		×	
	Leading b-tagged jet p_T		×	
	Scalar sum of all jets p_T		×	
τ_{had}	Leading τ_{had} p_T			
	Second leading τ_{had} p_T			
	Di-tau invariant mass			
Angular distances	ΔR lepton 0–lepton 1	×	×	
	ΔR lepton 0–lepton 2		×	
	ΔR lepton 0–closest jet (any)	×	×	
	ΔR lepton 0–leading jet (any)		×	
	ΔR lepton 0–closest b-jet		×	
	ΔR lepton 1–closest jet (any)	×	×	
	ΔR lepton 1–closest b-jet		×	
	ΔR lepton 2–closest jet (any)		×	
	ΔR lepton 2–closest b-jet		×	
	ΔR lepton–closest light jet		×	
	Minimum ΔR between all jets			
$\vec{p}_T^{miss}$	Missing transverse energy E_T^{miss}	×		×
	Azimuthal separation leading jet-$\vec{p}_T^{miss}$		×	
	Transverse mass leptons (H/Z decay) - $\vec{p}_T^{miss}$			×
	Pseudo-Matrix-Element			×

Backup

Channel	Region	Selection criteria
2ℓSS		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b\text{-jets}} \geq 1$
(3ℓ)		One very tight, one loose light lepton with $p_{\text{T}} > 20$ (15) GeV
		Zero τ_{had} candidates
	ϵ_{real}	Opposite charge; opposite flavor
	ϵ_{fake}	Same charge; opposite flavor or $\mu\mu$
4ℓ		$1 \leq N_{\text{jets}} \leq 2$
		Three loose light leptons; sum of light lepton charges ±1
		Subleading same-charge lepton must be tight
		Veto on 3ℓ selection
	Either	One SFOC pair with $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert < 10$ GeV
		$E_{\text{T}}^{\text{miss}} < 50$ GeV, $m_{\text{T}} < 50$ GeV
	or	No SFOC pair
		Subleading jet $p_{\text{T}} > 30$ GeV
2ℓSS+$1\tau_{\text{had}}$		$2 \leq N_{\text{jets}} \leq 3$ and $N_{b\text{-jets}} \geq 1$
		One very tight, one loose light lepton with $p_{\text{T}} > 15$ GeV
		A SFSC pair
		$\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV
		Zero or one medium τ_{had} candidate, opposite in charge to the light leptons
1ℓ+$2\tau_{\text{had}}$		$N_{\text{jets}} \geq 3$ and $N_{b\text{-jets}} \geq 1$
		One tight light lepton, with $p_{\text{T}} > 27$ GeV
		Two τ_{had} candidates of same charge
		At least one τ_{had} candidate has to satisfy tight identification criteria
2ℓOS+$1\tau_{\text{had}}$		Two loose and isolated light leptons, with $p_{\text{T}} > 25, 15$ GeV
		One loose τ_{had} candidate
		$\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV and $m(\ell^+\ell^-) > 12$ GeV
		$N_{\text{jets}} \geq 3$ and $N_{b\text{-jets}} = 0$

Backup

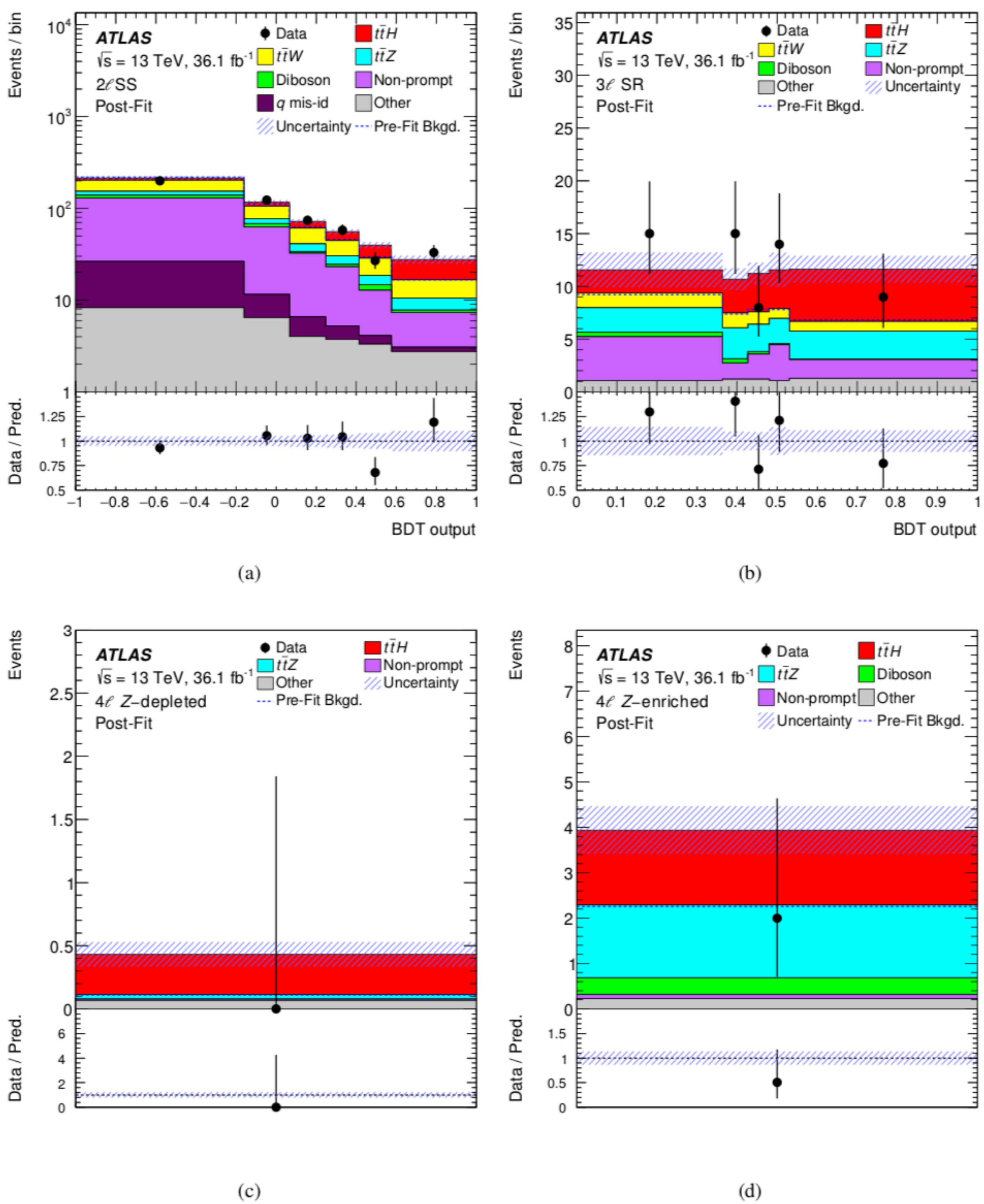
Data-driven non-prompt/fake leptons and charge misassignment		
Control region statistics	SN	38
Light-lepton efficiencies	SN	22
Non-prompt light-lepton estimates: non-closure	N	5
γ-conversion fraction	N	5
Fake τ_{had} estimates	N/SN	12
Electron charge misassignment	SN	1
Total (Data-driven reducible background)	–	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

Backup

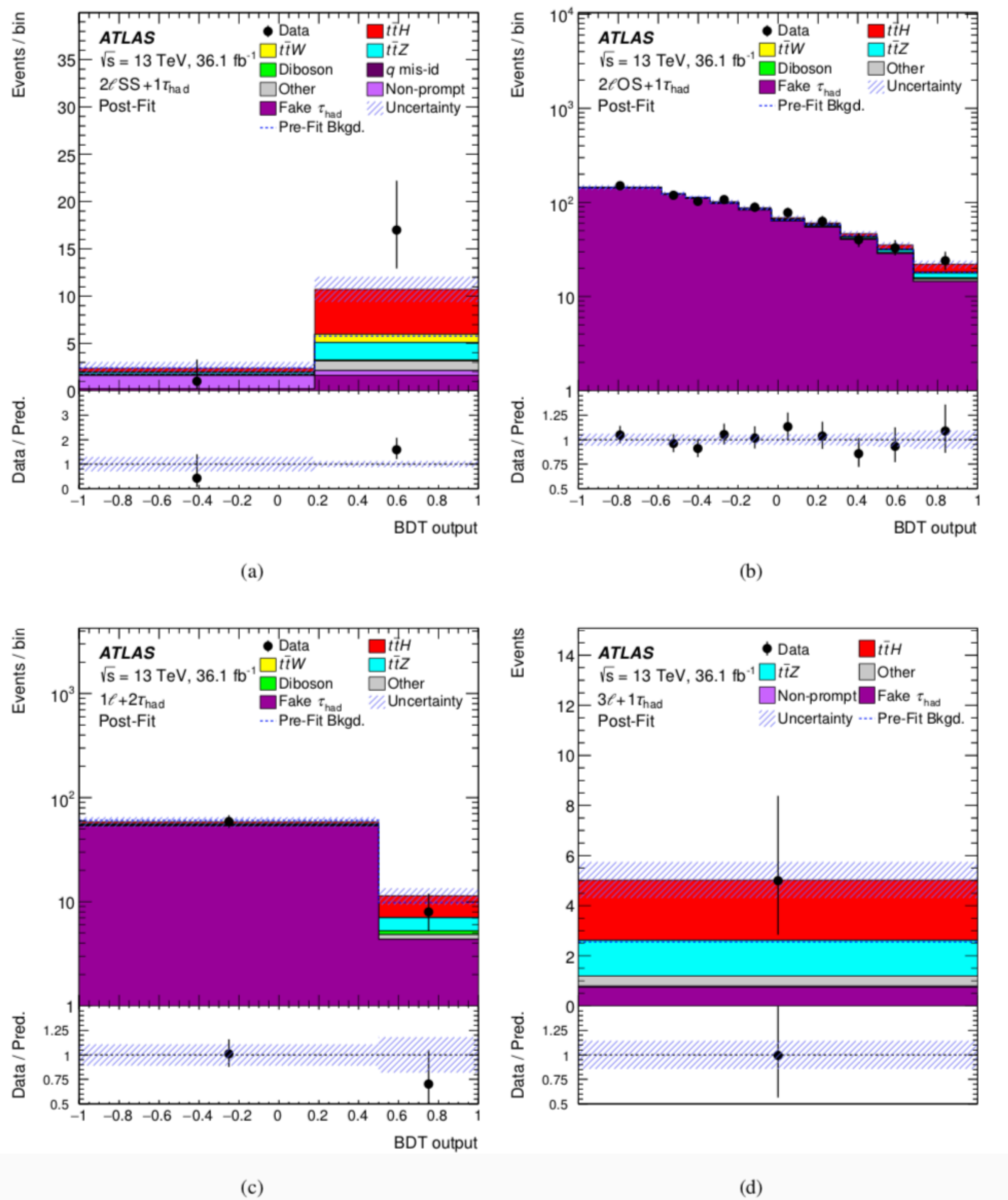
Channel	Best-fit μ Observed	Best-fit μ Expected	Significance Observed	Significance Expected
2ℓOS+1τ_{had}	$1.7\ ^{+1.6}_{-1.5}$ (stat.) $^{+1.4}_{-1.1}$ (syst.)	$1.0\ ^{+1.5}_{-1.4}$ (stat.) $^{+1.2}_{-1.1}$ (syst.)	0.9σ	0.5σ
1ℓ+2τ_{had}	$-0.6\ ^{+1.1}_{-0.8}$ (stat.) $^{+1.1}_{-1.3}$ (syst.)	$1.0\ ^{+1.1}_{-0.9}$ (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+1τ_{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+1τ_{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

Backup



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
2ℓSS
Post-Fit
Data
tt̄H
tt̄W
tt̄Z
Diboson
Non-prompt
q mis-id
Other
Uncertainty
Pre-Fit Bkgd.
Events / bin
Data / Pred.
BDT output
(a)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
3ℓ SR
Post-Fit
Data
tt̄H
tt̄W
tt̄Z
Diboson
Non-prompt
Other
Uncertainty
Pre-Fit Bkgd.
Events / bin
Data / Pred.
BDT output
(b)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
4ℓ Z-depleted
Post-Fit
Data
tt̄H
tt̄Z
Non-prompt
Other
Uncertainty
Pre-Fit Bkgd.
Events
Data / Pred.
(c)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
4ℓ Z-enriched
Post-Fit
Data
tt̄H
tt̄Z
Diboson
Non-prompt
Other
Uncertainty
Pre-Fit Bkgd.
Events
Data / Pred.
(d)

Backup



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
2ℓSS+1τhad
Post-Fit
Data
ttW
Diboson
Other
Fake τhad
Pre-Fit Bkgd.
ttH
ttZ
q mis-id
Non-prompt
Uncertainty
Events / bin
Data / Pred.
BDT output
(a)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
2ℓOS+1τhad
Post-Fit
Data
ttW
Diboson
Fake τhad
Pre-Fit Bkgd.
ttH
ttZ
Other
Uncertainty
Events / bin
Data / Pred.
BDT output
(b)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
1ℓ+2τhad
Post-Fit
Data
ttW
Diboson
Fake τhad
Pre-Fit Bkgd.
ttH
ttZ
Other
Uncertainty
Events / bin
Data / Pred.
BDT output
(c)
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
3ℓ+1τhad
Post-Fit
Data
ttZ
Non-prompt
Uncertainty
ttH
Other
Fake τhad
Pre-Fit Bkgd.
Events
Data / Pred.
(d)

Backup

2ℓSS/3ℓ+0τ: Matrix Method

$$N^{f}_{TT} = w_{TT}N^{TT} + w_{T\not T}N^{T\not T} + w_{\not T T}N^{\not T T} + w_{\not T\not T}N^{\not T\not T}$$

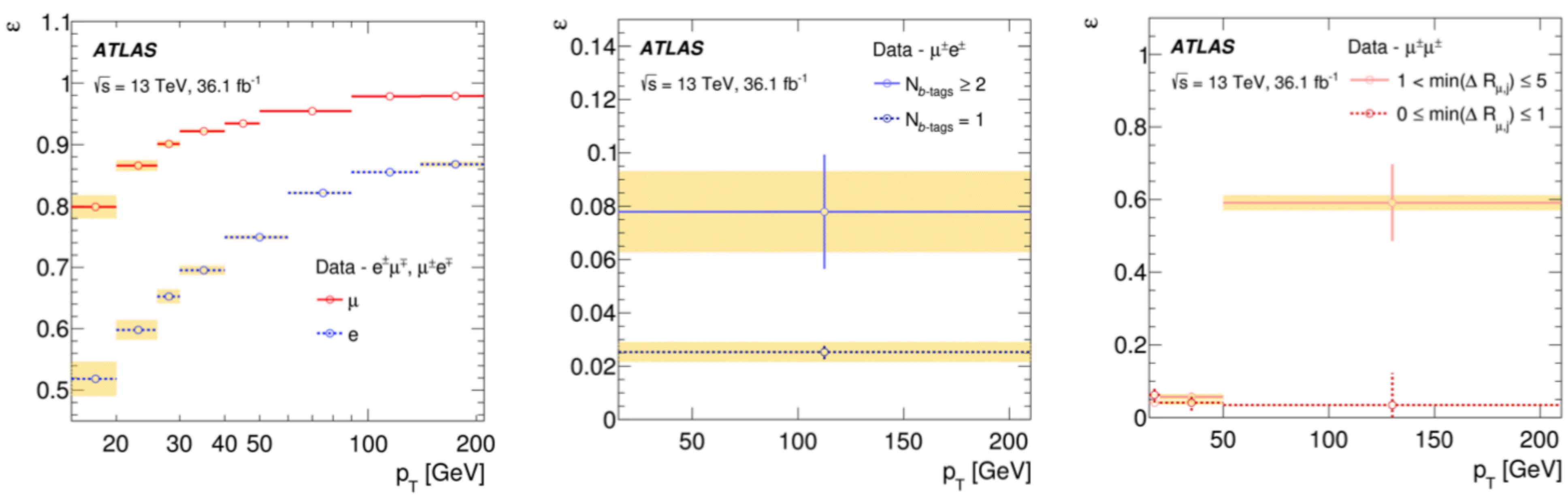
events in pre-MVA signal region with SS **loose** leptons
(in 3ℓ, lep_0 (OS to SS pair) is prompt in 98% of the times)

f(ε_r, ε_f)
via tag&probe method in $t\bar{t}$ events

Channel	Region	Selection criteria
2ℓSS		$2 \le N_{\text{jets}} \le 3$ and $N_{b\text{-jets}} \ge 1$
(3ℓ)		One very tight, one loose light lepton with $p_T > 20$ (15) GeV
		Zero τ_{had} candidates
	ϵ_{real}	Opposite charge; opposite flavour
	ϵ_{fake}	Same charge; opposite flavour or $\mu\mu$

- **electrons and muons ε_r**: 1D (p_T) parametrisation

- **electrons ε_f**: 2D ($N_{b\text{-tags}}$, p_T) parametrisation
- **muons ε_f**: 2D (minΔR(μ,j), p_T) parametrisation



Backup

EXPERIMENT

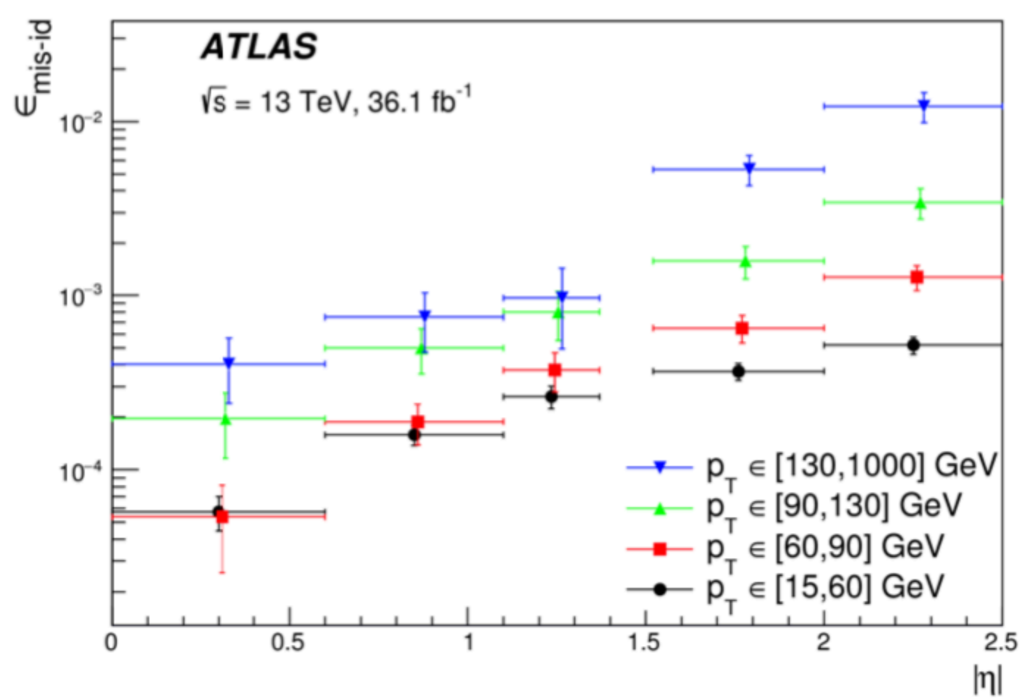
- Estimate QMisID background from data using SS electrons under Z-peak
- Using **3D likelihood method** [p_T, η, **Tight/Anti-tight**]

high p_T ➜ straighter track ➜ higher chance of QMisID

high η ➜ more material ➜ more trident electrons

needed to provide input to Matrix Method (QMisID subtraction) + increase statistics (consider tight+antitight events)

- Obtain QMisID rates $\boldsymbol{\varepsilon}_{\text{mis-id}}$ by minimising a global likelihood function in a sample of Z➜ee events reconstructed as SS or OS pairs
  - The background is subtracted using a sideband method
- Scale OS data events by this rate
- Total systematic uncertainty **~30 %**
  - Dominated by closure test uncertainty at low p_T and by statistical uncertainties at high p_T



Backup

Treatment of conversions

- $\varepsilon_{f,\gamma}$ significantly higher than $\varepsilon_{f,hf}$
- Account for the change of photon conversion fraction between the CR and SR from simulation
- Use to correct ε_f

- **Systematic uncertainties: 40%**
  - 15% from modelling of conversions in MC
  - 20% from measurement of $t\bar{t}\gamma$
  - 50% from modelling of semileptonic b-decays

Non-closure

- Apply Matrix Method on $t\bar{t}$ MC, compare to $t\bar{t}$ MC prediction
- (11 ± 8)% and (9 ± 18)% non-closure in 2ℓSS and 3ℓ, respectively
- Include non-closure as systematic uncertainty source

Backup

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

Light lepton efficiencies:

- real eff (1), fake eff (6 μ, 2 el, 3 prompt background subtraction theory uncertainties), 4ℓ fake rate (1), 2ℓSS1τ (10)

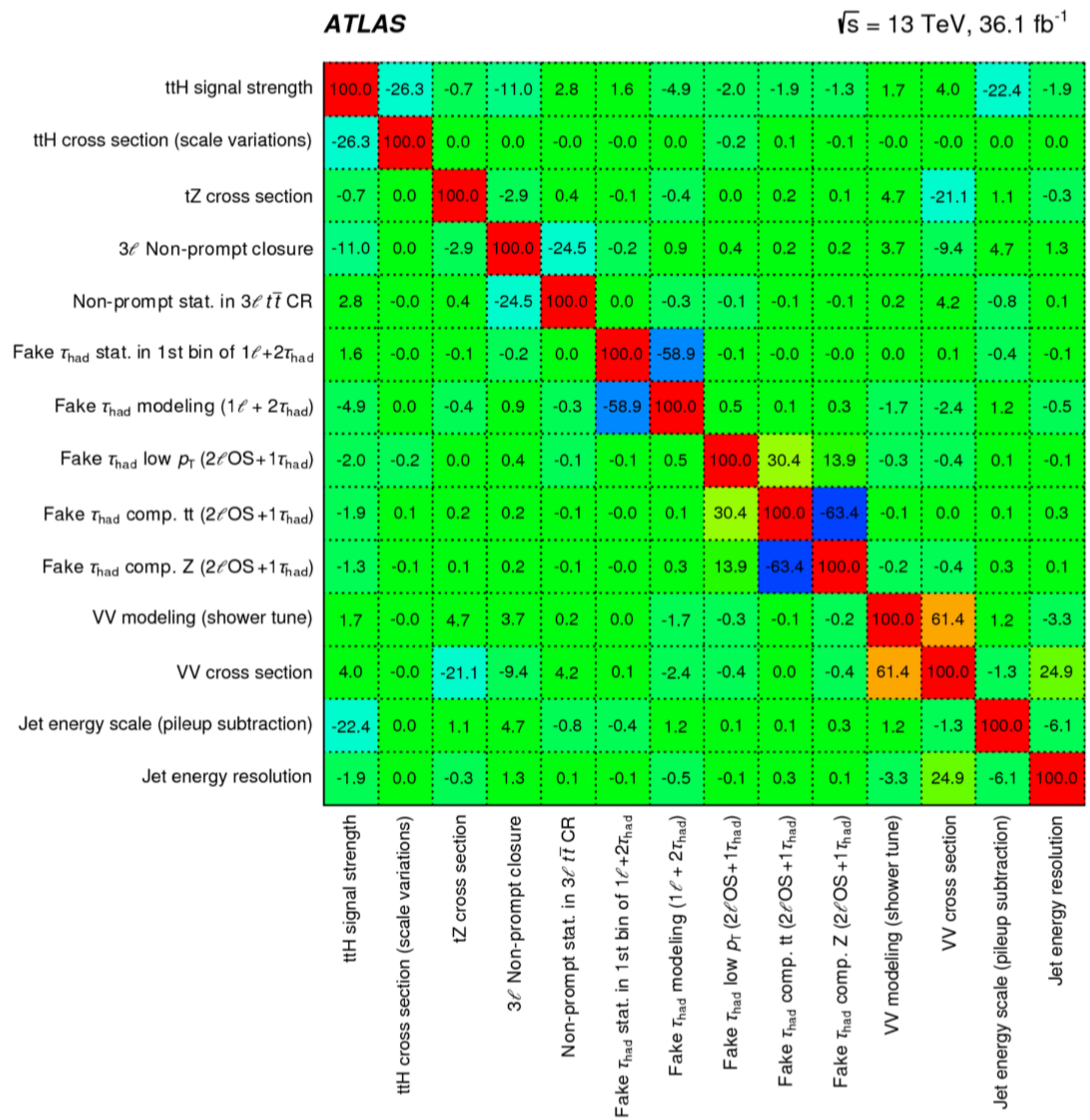
ɣ conversion fraction and non-closure uncertainties:

- Uncorrelated across channels (ee, eμ, Xee, Xeμ, 2ℓSS1τ), affecting only normalisation

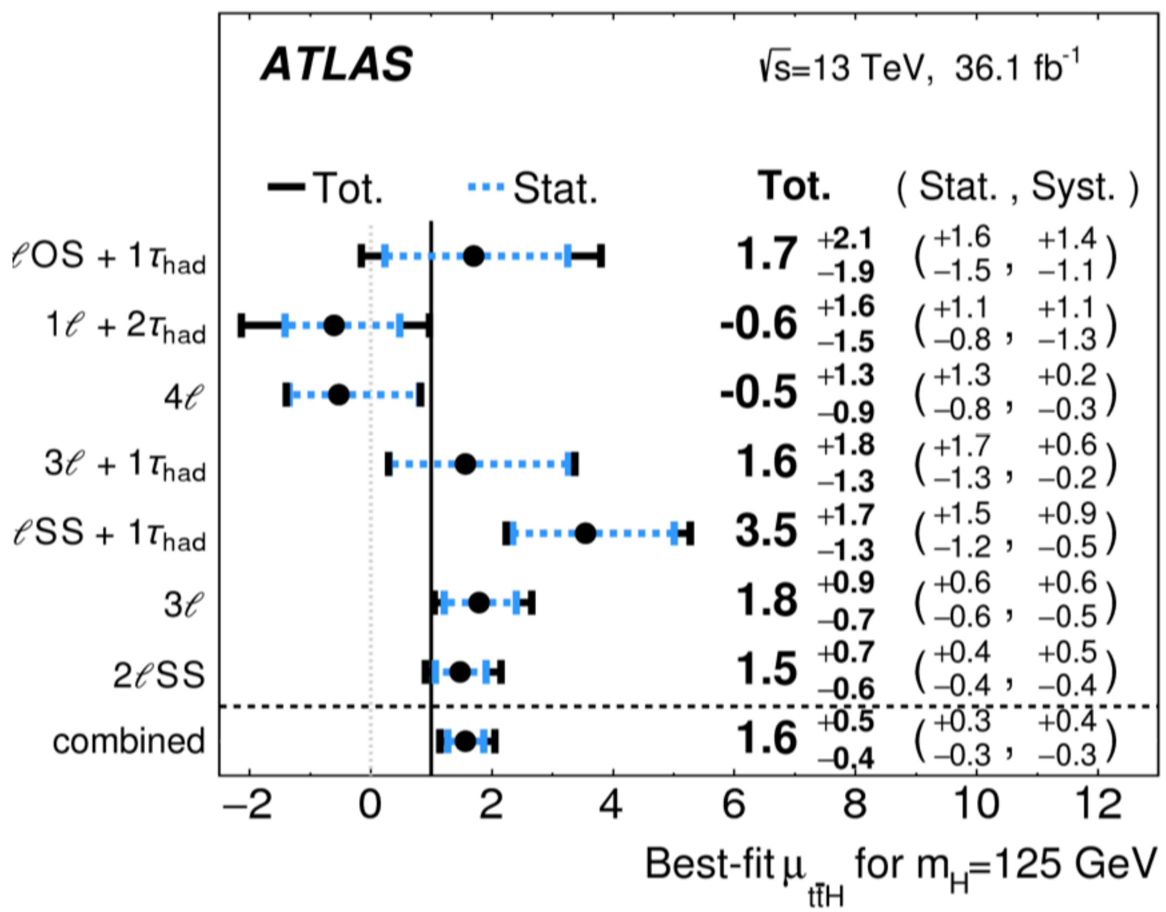
Electron charge miss assignment:

- Anti-correlated among background in SR and subtraction from fake rate calculation

Backup


ATLAS
√s = 13 TeV, 36.1 fb^{-1}
ttH signal strength 100.0 -26.3 -0.7 -11.0 2.8 1.6 -4.9 -2.0 -1.9 -1.3 1.7 4.0 -22.4 -1.9
ttH cross section (scale variations) -26.3 100.0 0.0 0.0 -0.0 -0.0 0.0 -0.2 0.1 -0.1 -0.0 -0.0 0.0 0.0
tZ cross section -0.7 0.0 100.0 -2.9 0.4 -0.1 -0.4 0.0 0.2 0.1 4.7 -21.1 1.1 -0.3
3ℓ Non-prompt closure -11.0 0.0 -2.9 100.0 -24.5 -0.2 0.9 0.4 0.2 0.2 3.7 -9.4 4.7 1.3
Non-prompt stat. in 3ℓ $t\bar{t}$ CR 2.8 -0.0 0.4 -24.5 100.0 0.0 -0.3 -0.1 -0.1 -0.1 0.2 4.2 -0.8 0.1
Fake τ_{had} stat. in 1st bin of 1ℓ+2τ_{had} 1.6 -0.0 -0.1 -0.2 0.0 100.0 -58.9 -0.1 -0.0 -0.0 0.0 0.1 -0.4 -0.1
Fake τ_{had} modeling (1ℓ + 2τ_{had}) -4.9 0.0 -0.4 0.9 -0.3 -58.9 100.0 0.5 0.1 0.3 -1.7 -2.4 1.2 -0.5
Fake τ_{had} low p_T (2ℓOS+1τ_{had}) -2.0 -0.2 0.0 0.4 -0.1 -0.1 0.5 100.0 30.4 13.9 -0.3 -0.4 0.1 -0.1
Fake τ_{had} comp. tt (2ℓOS+1τ_{had}) -1.9 0.1 0.2 0.2 -0.1 -0.0 0.1 30.4 100.0 -63.4 -0.1 0.0 0.1 0.3
Fake τ_{had} comp. Z (2ℓOS+1τ_{had}) -1.3 -0.1 0.1 0.2 -0.1 -0.0 0.3 13.9 -63.4 100.0 -0.2 -0.4 0.3 0.1
VV modeling (shower tune) 1.7 -0.0 4.7 3.7 0.2 0.0 -1.7 -0.3 -0.1 -0.2 100.0 61.4 1.2 -3.3
VV cross section 4.0 -0.0 -21.1 -9.4 4.2 0.1 -2.4 -0.4 0.0 -0.4 61.4 100.0 -1.3 24.9
Jet energy scale (pileup subtraction) -22.4 0.0 1.1 4.7 -0.8 -0.4 1.2 0.1 0.1 0.3 1.2 -1.3 100.0 -6.1
Jet energy resolution -1.9 0.0 -0.3 1.3 0.1 -0.1 -0.5 -0.1 0.3 0.1 -3.3 24.9 -6.1 100.0
ttH signal strength
ttH cross section (scale variations)
tZ cross section
3ℓ Non-prompt closure
Non-prompt stat. in 3ℓ $t\bar{t}$ CR
Fake τ_{had} stat. in 1st bin of 1ℓ+2τ_{had}
Fake τ_{had} modeling (1ℓ + 2τ_{had})
Fake τ_{had} low p_T (2ℓOS+1τ_{had})
Fake τ_{had} comp. tt (2ℓOS+1τ_{had})
Fake τ_{had} comp. Z (2ℓOS+1τ_{had})
VV modeling (shower tune)
VV cross section
Jet energy scale (pileup subtraction)
Jet energy resolution

Backup



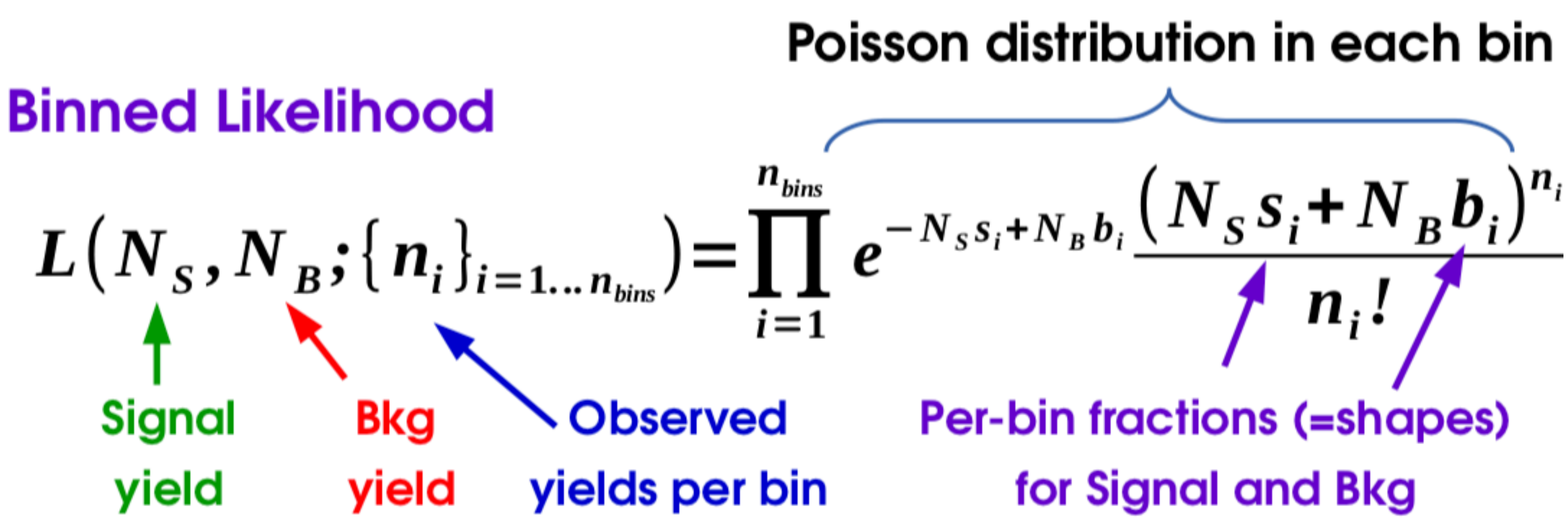
Channel	Significance	
	Observed	Expected
$2\ell OS+1\tau_{had}$	0.9σ	0.5σ
$1\ell+2\tau_{had}$	-	0.6σ
4ℓ (*)	-	0.8σ
$3\ell+1\tau_{had}$	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.7σ	1.9σ
Combined	4.1σ	2.8σ

Statistical Model

- A maximum-likelihood fit is performed on all bins in the 25 categories simultaneously to extract the ttH signal strength (free parameter) (μ)

  $$\mu_{t\bar{t}H} = \sigma/\sigma_{SM}$$

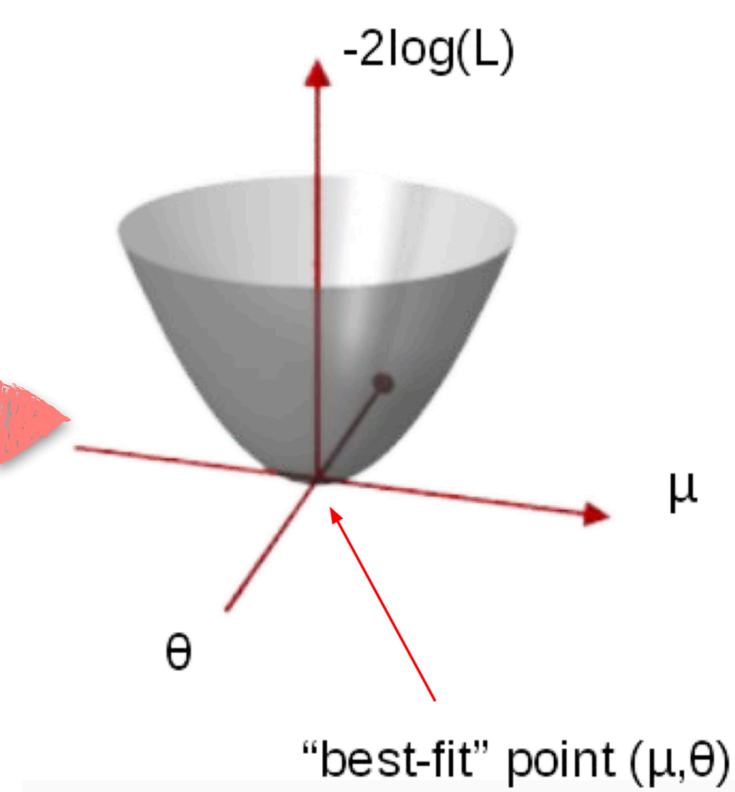
- The statistical analysis of the data uses a binned likelihood function L(μ, θ), which is constructed from a product of Poisson PDFs (the number of observed events in a given bin (n))

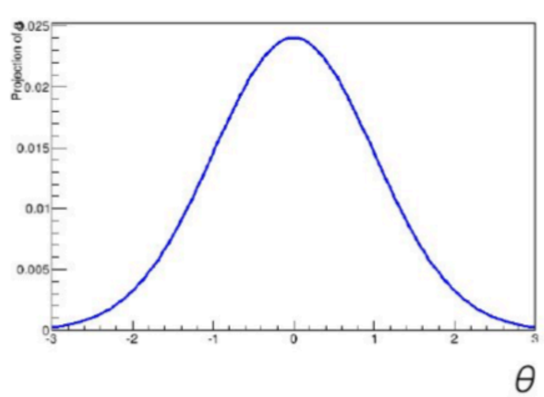


Systematics and Profile Likelihood

~200 NPs in the analysis

- Nuisance parameters (NPs, $\boldsymbol{\theta}$), which encode all the uncertainties on quantities that can affect the model for signal and background (knowledge)
- NP probability density functions (Gaussian) are constrained by the auxiliary measurements of the parameters (unlike μ)
- N-dimensional likelihood maximisation

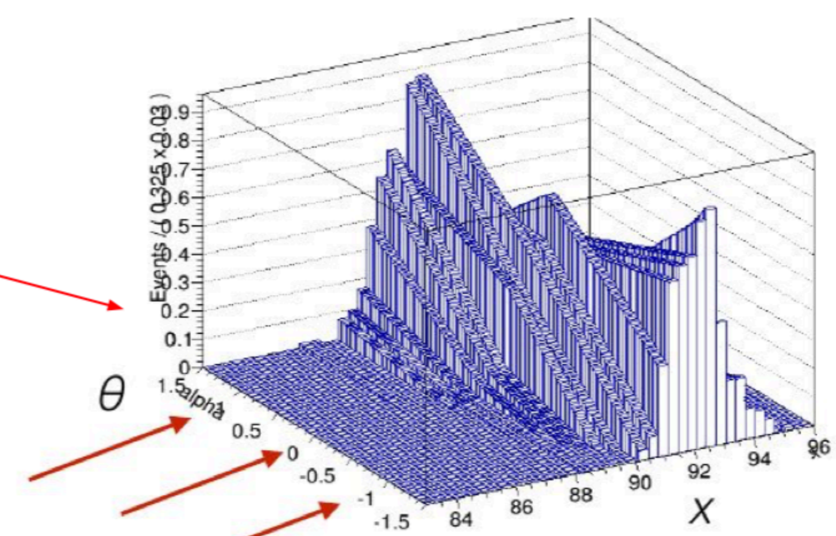




$$L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \boldsymbol{\theta}) =$$

$$\prod_{i \in bins} P(n_i | \mu S(\boldsymbol{\theta}) + B(\boldsymbol{\theta})) \times$$

$$\prod_{j \in n.p.} G(\theta_j^0 | \theta_j)$$



- Therefore total number of expected events in a given bin depends on μ and θ

Testing Model

- What values to use when defining the hypotheses ? → H(μ=0, θ=?) Answer: let the data choose the best-fit values

- Significance is given by the profile-likelihood ratio:

Profile likelihood ratio only dependent on μ

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\hat{\theta}}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

Maximize L for a given μ 'conditional' likelihood

Maximize L 'unconditional' likelihood

- Construct Test statistics (how well the observed data agrees with the background-only hypothesis)

$$q_0 = \begin{cases} -2ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

reject background-only

increasing level of incompatibility

- In particle physics, the rejection of the background-only hypothesis to claim for a discovery is achieved for a significance of Z ≥ 5, corresponding to $p \leq 2.87 \times 10^{-7}$

$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

$$Z_0 = \Phi^{-1}(1 - p_0)$$

-