$t\bar{t}H$ and Exotics in $t\bar{t}+b\bar{b}$ final states

with the ATLAS experiment

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New Phenomena at the TeV Scale With Top Quarks
NPTEV-TQP2020

ATLAS EXPERIMENT

ma per seguir virtute e canoscenza
SISSA

Workshop "DaMESyFLa in the Higgs era"
15-17 March 2017, SISSA Trieste

Introduction

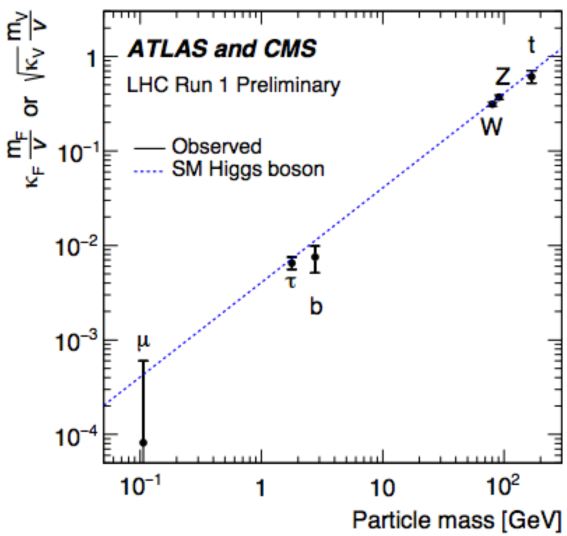
- Title: "$t\bar{t}H$ and Exotics in $t\bar{t}+b\bar{b}$ final states with the ATLAS experiment"
  - *alias* "What I have been working on in the past several years"
    - or "Why I have been working on this for so many years"
  - most of the material based on latest ATLAS conference note on **$t\bar{t}H$ search in $H \rightarrow b\bar{b}$ channel at 13 TeV**, released for **ICHEP 2016** ▹ ATLAS-CONF-2016-080

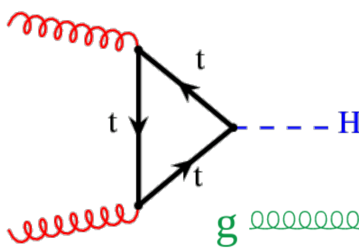
- What I will talk about:
  - latest **results** from 13 TeV data
  - **details** on different aspects of the analysis techniques, mainly:
    - analysis **strategies** for complicated final states
    - profile-likelihood **fit** technique
    - **$t\bar{t}$ background** modeling
    - **multi-variate techniques** for signal discrimination

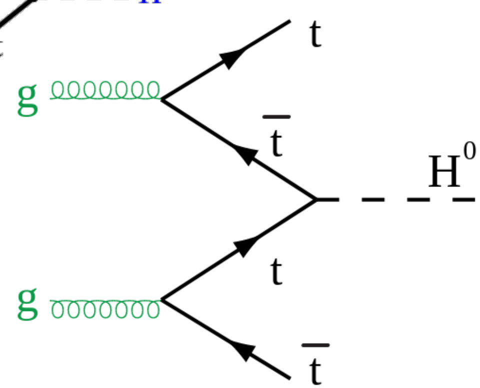
ttH(bb) analysis in ATLAS
ttH: importance and overview

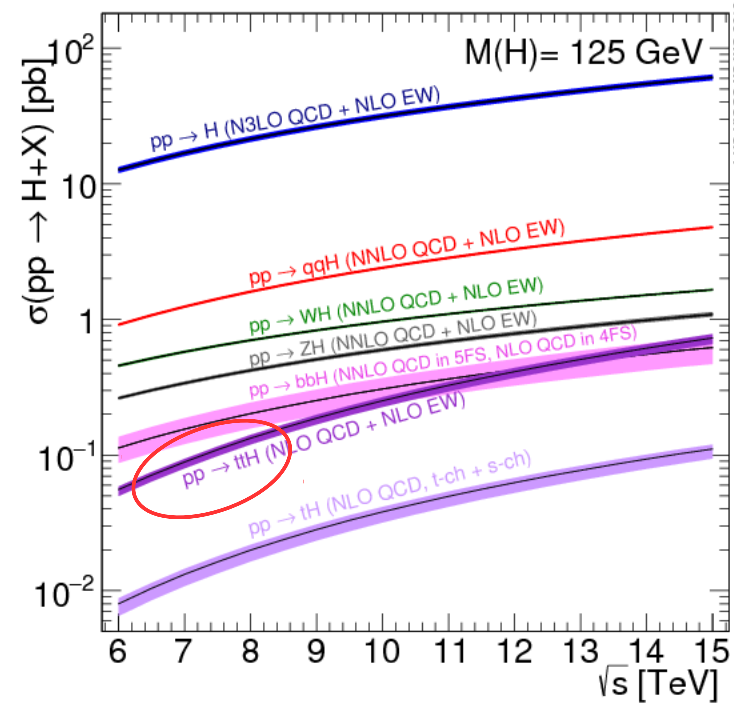
- Associated production of SM Higgs boson with top-quark pair:
  - still not estabilished experimentally
  - important to assess **y_t at tree level**
  - CP properties of $t\bar{t}H$ coupling?

▹ arXiv:1501.03157 [hep-ph]







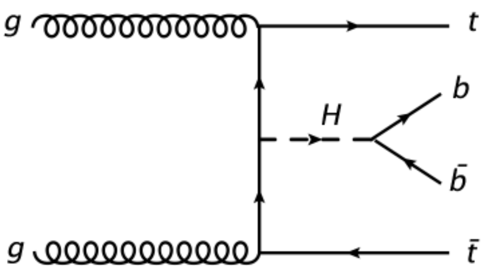


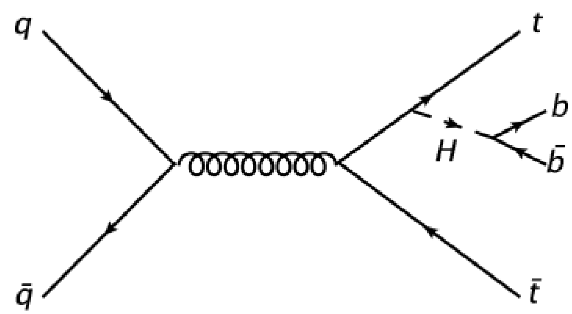
- Not convinced?
  - from experiment point of view, other reasons to look at $t\bar{t}H$:
    - **compilcated signature**, with many final state objects, huge irreducible backgrounds (espcially $H\rightarrow b\bar{b}$ channel)...
    - interesting **New Physics** processes have similar signatures

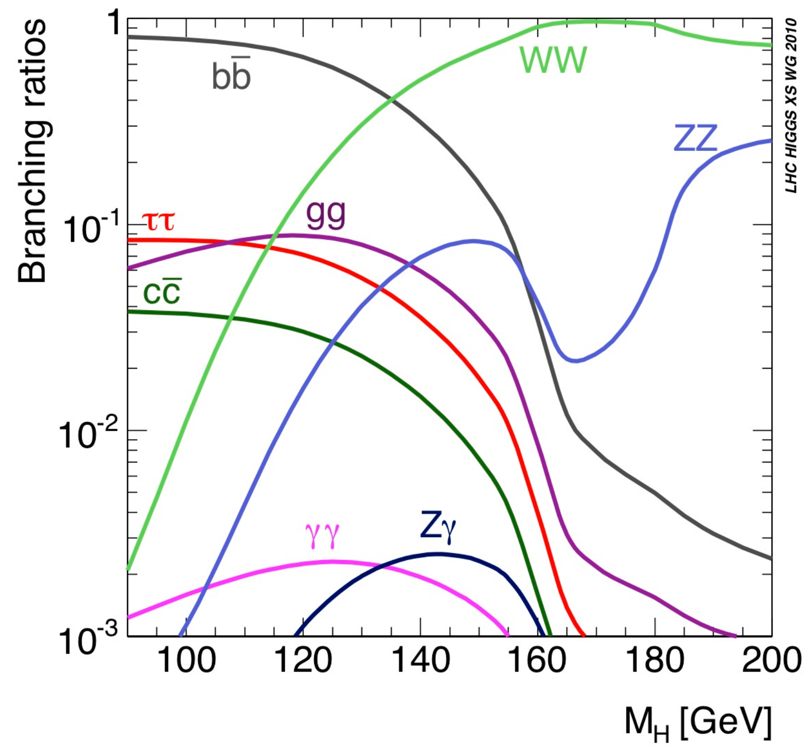
ttH(bb) analysis in ATLAS

The ttH, H → bb chanel

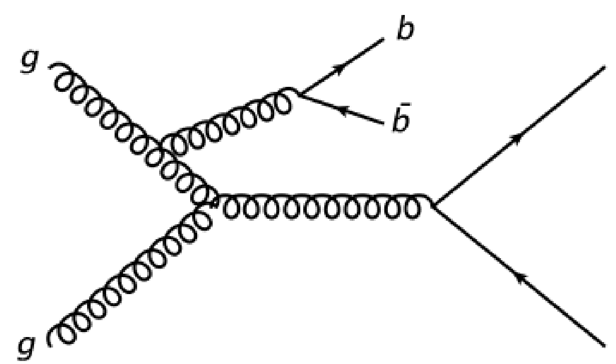
- **Opportunities** and **challenges**:
  - *H*→*b$\bar{b}$* highest BR
  - *H* decay fully visible







- huge **irreducible background:** ***t$\bar{t}$+b$\bar{b}$*** from QCD radiation
- ***b*-tagging** never perfect: lower efficiency, more background entering selection
- **combinatorial** background

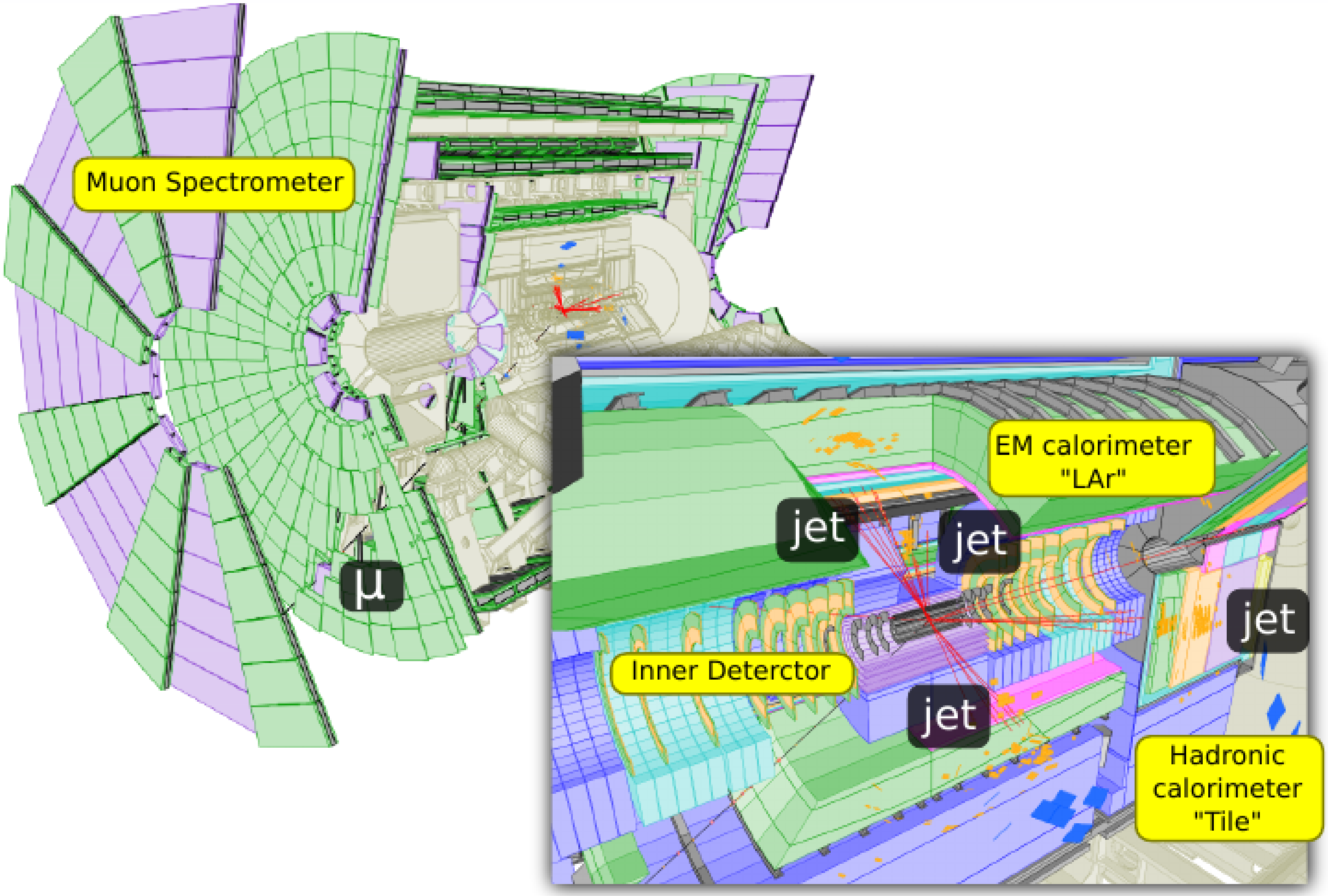


- Use semi-leptonic or dileptonic *t$\bar{t}$* decays to trigger events:

  lepton + 6 jets
  or opposite-sign dilepton + 4 jets

ttH(bb) analysis in ATLAS

ATLAS in a nut shell

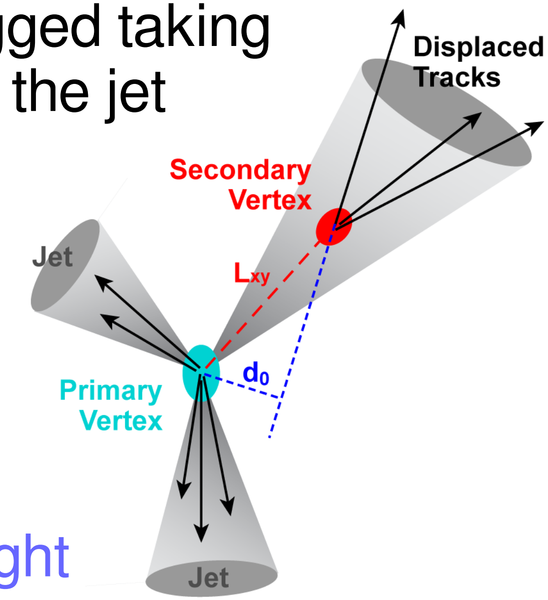


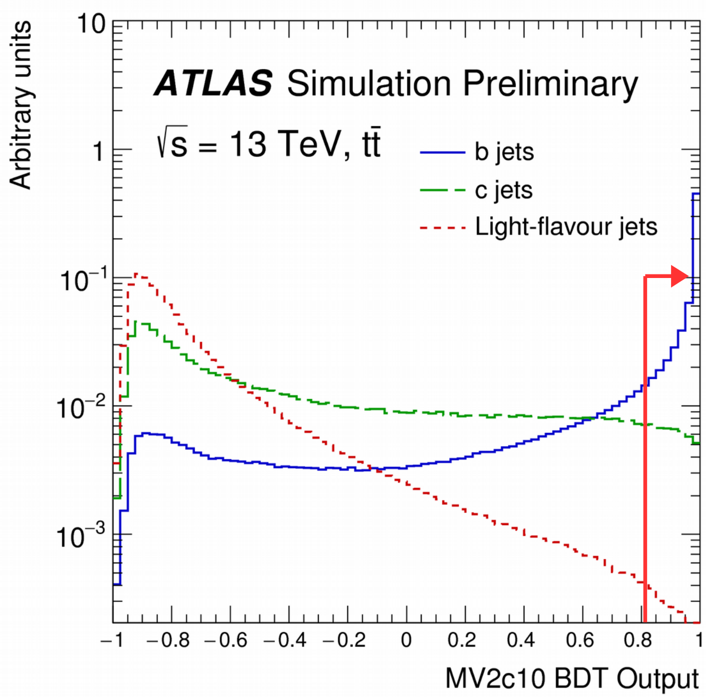
- **Run 1** collected 5 + 20 fb^{-1} of pp data at 7-8 TeV in 2010-2012
- **Run 2** collected so far ~**36 fb^{-1}** at **13 TeV** in 2015-2016
  - expected to re-start to take data next ~May

- Results shown here based on ≤ 13.2 fb^{-1} at 13 TeV

ttH(bb) analysis in ATLAS
b-tagging

- Jets originated from *b*-quark fragmentation can be tagged taking advantage of presense of a **secondary vertex** within the jet
  - ATLAS uses advanced **muti-variate techniques** to combine several observables for each jet to distinguish *b*-jets from non-*b*-jets (*c* or light)
    - **mv2c10** algorithm ▹ **ATL-PHYS-PUB-2016-012**
    - different working points, with different efficiencies and rejections *vs. c* and light



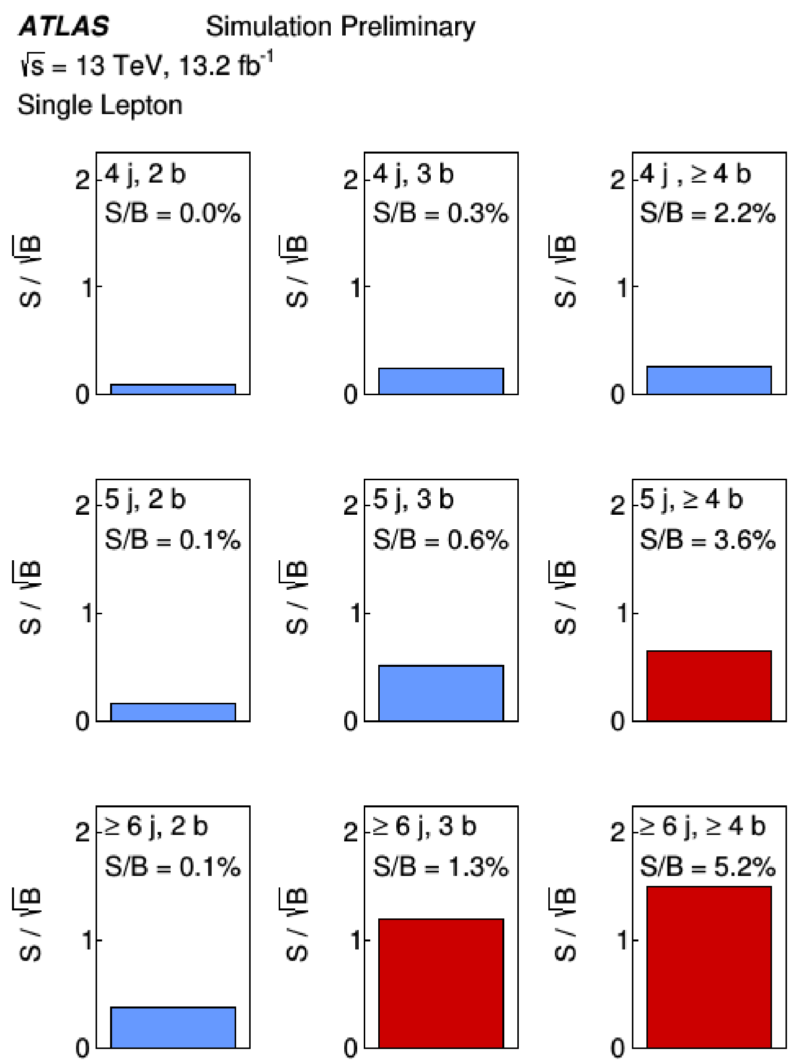


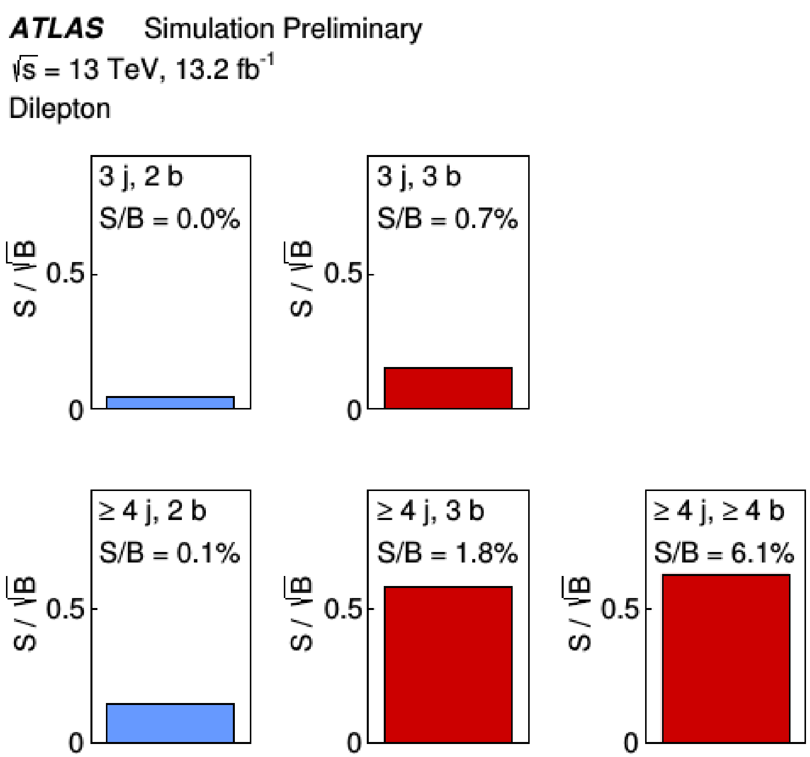
BDT Cut Value	b-jet Efficiency [%]	c-jet Rejection	Light-jet Rejection	τ Rejection
0.9349	60	34	1538	184
0.8244	70	12	381	55
0.6459	77	6	134	22
0.1758	85	3.1	33	8.2

- input variables not expected to be perfectly modeled by MC simulation
  - ***b*-tagging calibrations** needed, to correct MC according to *b*-tagging efficiencies measured in data, separately for *b*-, *c*- and light jets

ttH(bb) analysis in ATLAS
Analysis Strategy

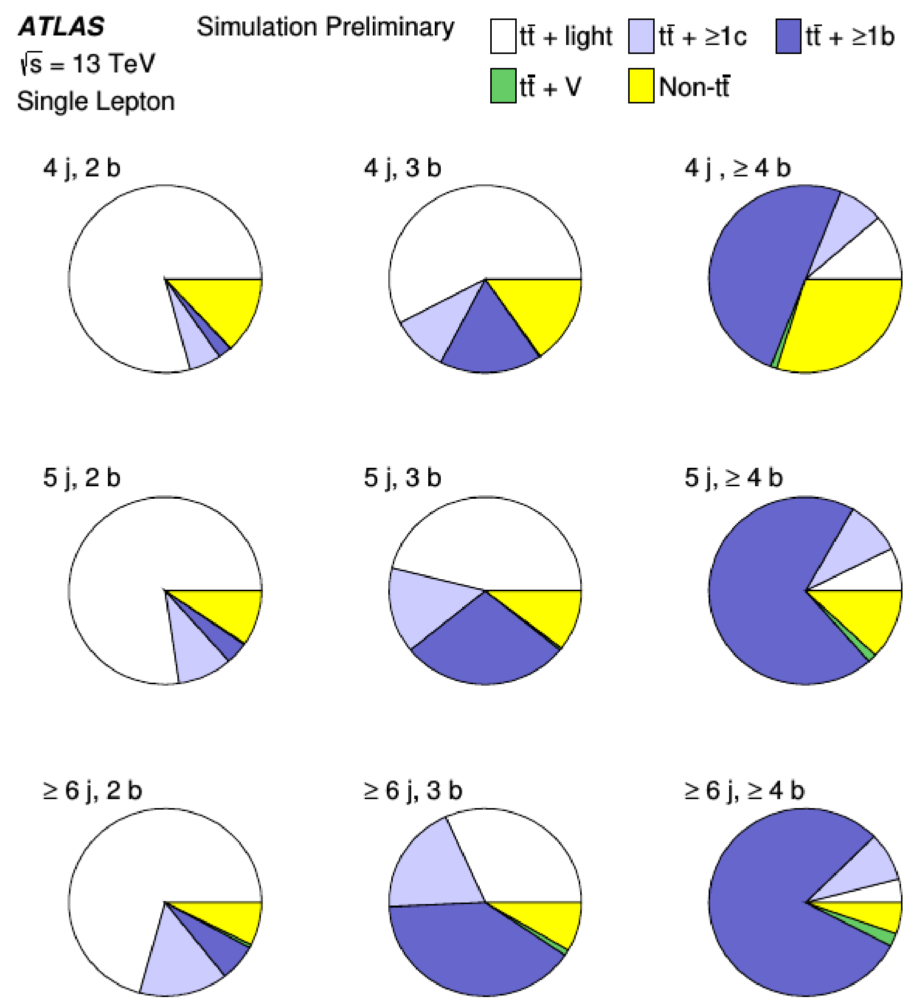
- *Divide et impera*:
  - events passing pre-selection categorised accoring to **jet and *b*-tagged jet multiplicity**
  - these different regions have different:
    - **signal content**

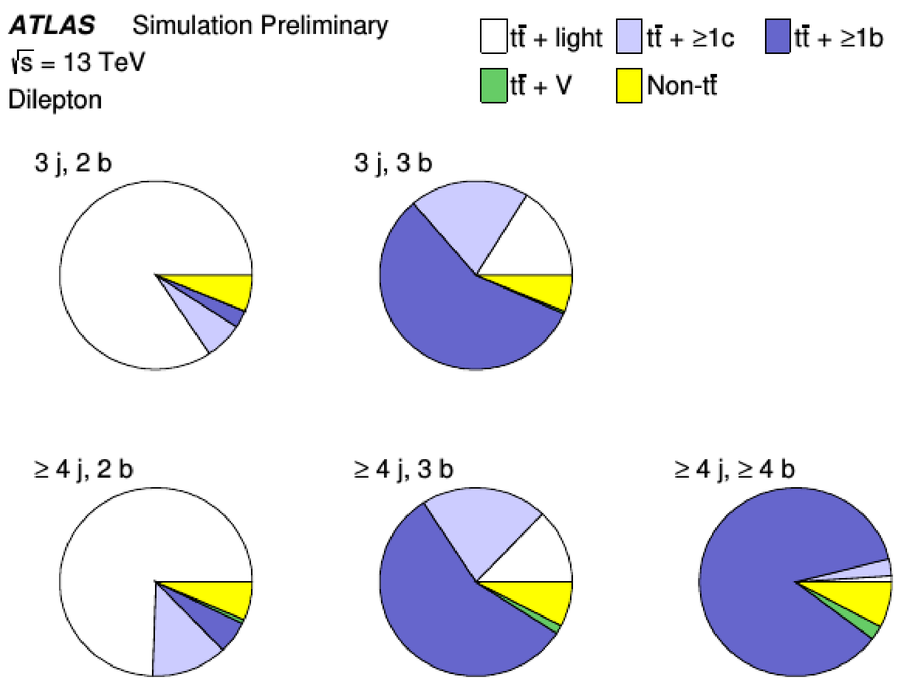




ttH(bb) analysis in ATLAS
Analysis Strategy - II

- *Divide et impera*:
  - events passing pre-selection categorised accoring to **jet and *b*-tagged jet multiplicity**
  - these different regions have different:
    - signal content
    - **background composition**

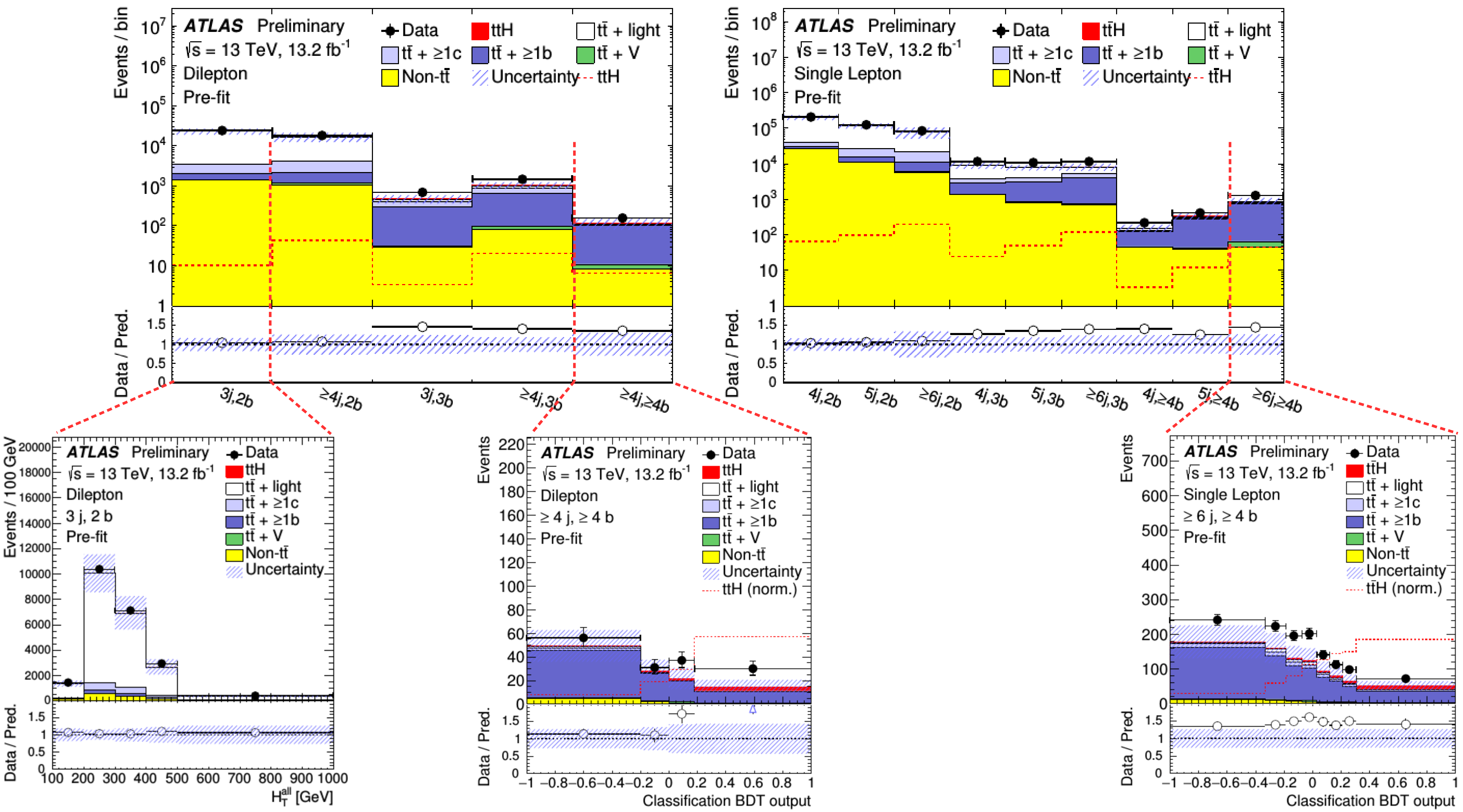




ttH(bb) analysis in ATLAS

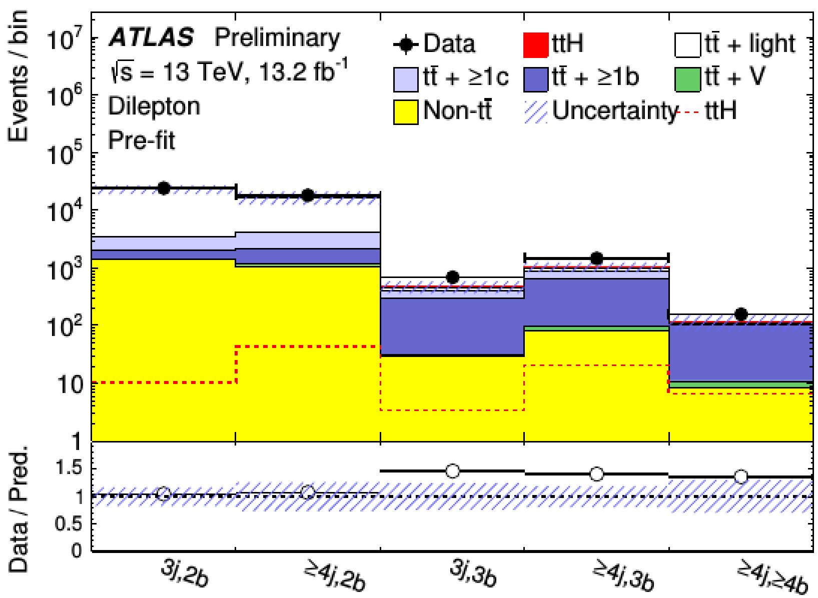
Analysis Strategy - III

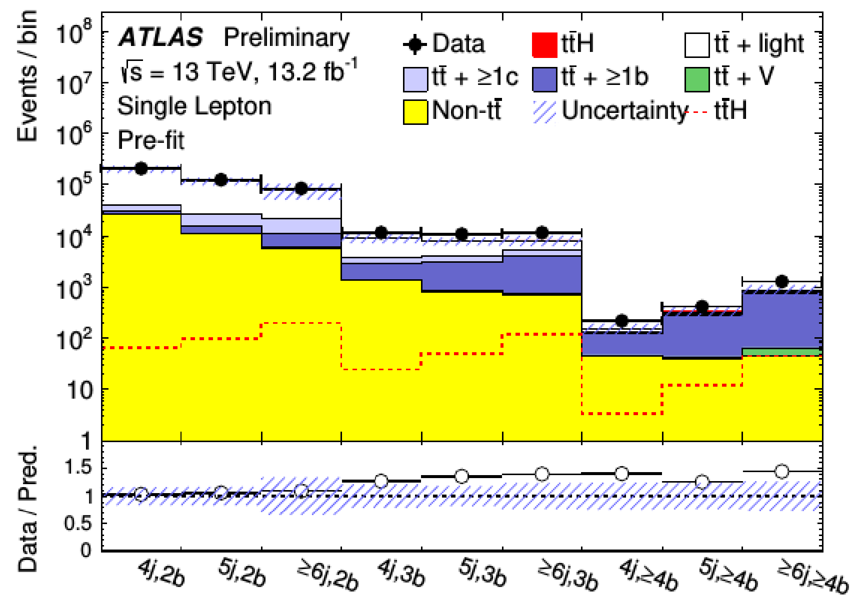
- In each region (control and signal) a kinematical distribution is built:
  - $H_T = \sum p_T^{jet}$ ($+p_T^{lep}$ for dilep) or multi-variate disriminant



ttH(bb) analysis in ATLAS
Analysis Strategy - IV

- Considering **all regions and bins** in the analysis has several **advantages**:



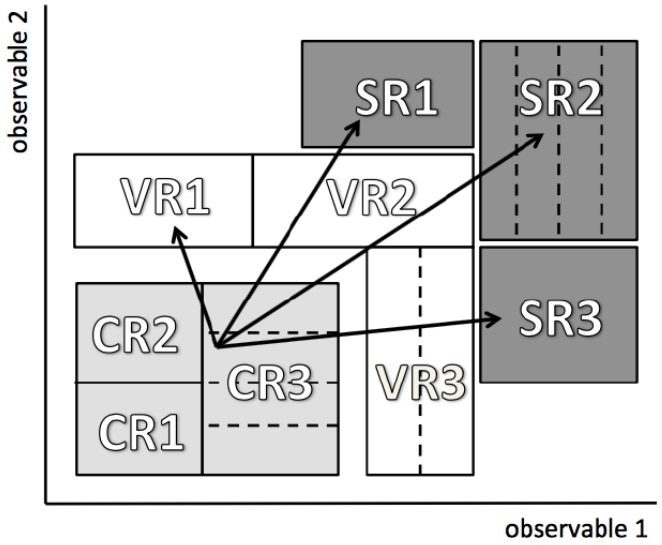


  - **recover signal** not entering the most sensitive SR
  - give confidence in the background modeling in regions with no signal
  - allow to **extract information** from the data on backgrounds and detector effects:
    - "*in situ* calibration" or "**systematic uncertainty constraint**"

ttH(bb) analysis in ATLAS
Profile Likelihood Fit

- The **profile likelihood** technique is used when fitting models with more than one unknown parameter:
  - parameter(s) of interest (*POI* or μ)
  - nuisance parameter(s) ($\boldsymbol{\theta}$)

Model systematic uncertainties of a physics quantity

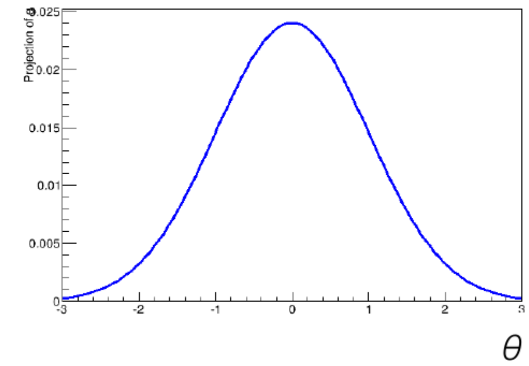


- Many analyses have this structure:
  - split into control, validation, signal regions, each with multiple bins and observables
- Build a global likelihood function for all the bins, including all the parameters:
  - written as product of Poisson measurements in CRs and SRs plus a probability density function for systematics

$$L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu_{\text{sig}}, \boldsymbol{b}, \boldsymbol{\theta}) = P_{\text{SR}} \times P_{\text{CR}} \times C_{\text{syst}}$$
$$= P(n_S | \lambda_S(\mu_{\text{sig}}, \boldsymbol{b}, \boldsymbol{\theta})) \times \prod_{i \in \text{CR}} P(n_i | \lambda_i(\mu_{\text{sig}}, \boldsymbol{b}, \boldsymbol{\theta})) \times C_{\text{syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta})$$

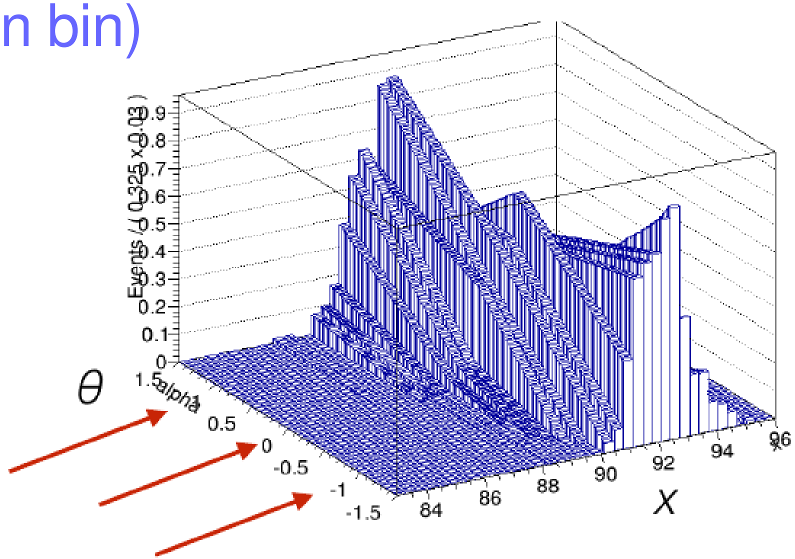
ttH(bb) analysis in ATLAS
Profile Likelihood Fit - nuiscances

- Inclusion of systematic uncertainties implies:
  - "prior" or "penalty term" (usually Gaussian) in C_{syst}, reflecting *a priori* knowledge of certain parameter
    - from previous data, calibration, theory prediction



$$L(\mu,\theta) = L_{Pois}(\mu,\theta) \cdot \prod_p \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{\theta_p^2}{2}\right)$$

  - dependence of predicted ***s*** and ***b*** on the parameters ***θ***
    - begin with templates of *x* (***s*** or ***b*** in a given bin) at given values of *θ* = [-1,0,1]
    - then continuous interpolation between variations and nominal templates



ttH(bb) analysis in ATLAS
Profile Likelihood Fit - nuiscances - II

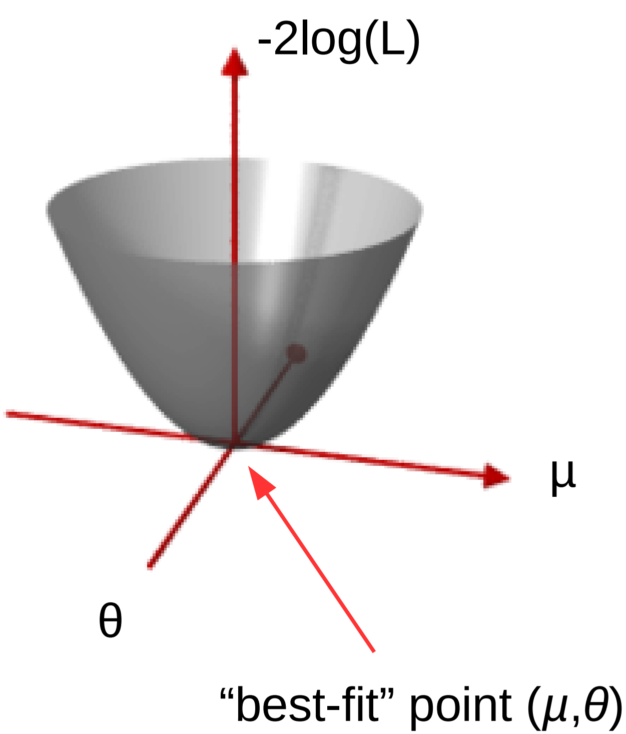
- **Example of nuisance parameters:**
  - **JES** (jet energy scale):
    - jet energy calibration gives correction of MC for jet p_T spectrum, with uncertainties (+1σ, -1σ)
    - MC prediction for ***s*** and ***b*** corrected by this calibration is taken as nominal
    - MC prediction for ***s*** and ***b*** corrected by this calibration + 1 σ is taken as $\boldsymbol{s}(\theta_{\mathrm{JES}}=1)$, $\boldsymbol{b}(\theta_{\mathrm{JES}}=1)$
    - MC prediction for ***s*** and ***b*** corrected by this calibration - 1 σ is taken as $\boldsymbol{s}(\theta_{\mathrm{JES}}=-1)$, $\boldsymbol{b}(\theta_{\mathrm{JES}}=-1)$
  - **Parton Shower and Hadronisation** for $t\bar{t}$:
    - nominal $t\bar{t}$ background prediction taken from MC generated with Powheg+Pythia
    - $\boldsymbol{b}^{t\bar{t}}(\theta_{\mathrm{PS}}=1)$ taken from MC generated with Powheg+Herwig
    - $\boldsymbol{b}^{t\bar{t}}(\theta_{\mathrm{PS}}=-1)$ built symmetrising: $\boldsymbol{b}^{t\bar{t}}(\theta_{\mathrm{PS}}=0) - (\boldsymbol{b}^{t\bar{t}}(\theta_{\mathrm{PS}}=1)+\boldsymbol{b}^{t\bar{t}}(\theta_{\mathrm{PS}}=0))$

ttH(bb) analysis in ATLAS

Profile Likelihood Fit - minimisation

- With such a likelihood defined
  measurement of the parameter of interest (*POI*, or μ)
  becomes a ***N*-dimensional** likelihood maximisation
  (or log-likelihood minimisation) problem

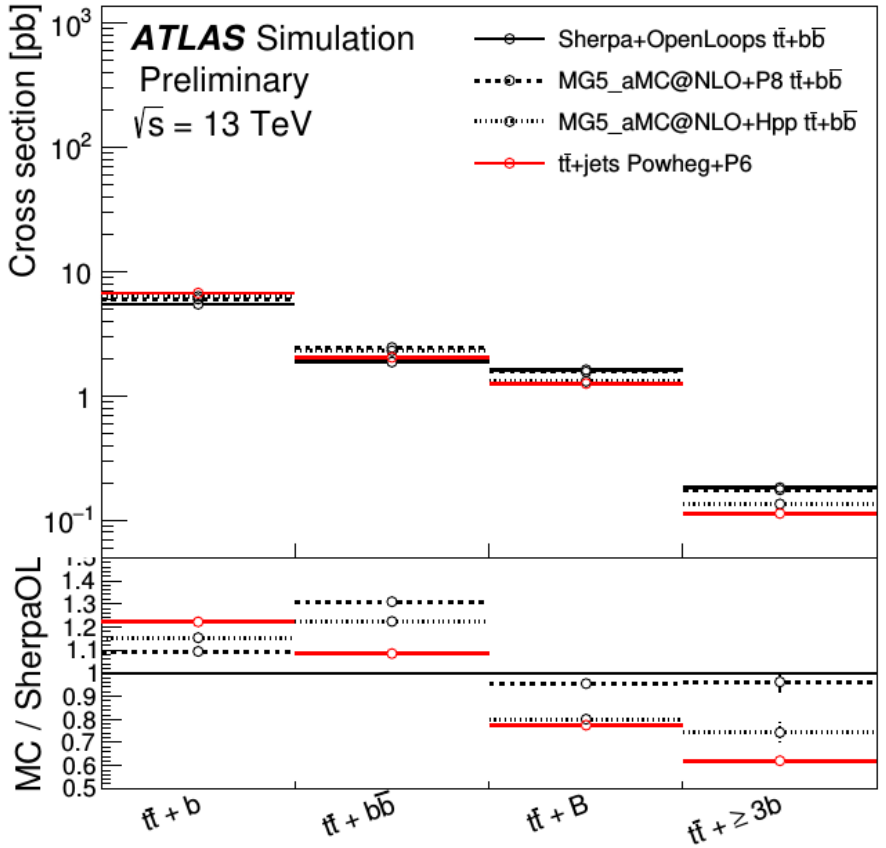
$$N = N_{POI} + N_{NP}$$



- The result of the fit is:
  - a **value for the *POI***, with its **uncertainty**
  - and a set of **values for the *NPs***, with their uncertainties
    - post-fit uncertainty on a *NP* smaller than the prior → improved knowledge on that *NP*
    - **uncertainty on *POI* affected** by the presence of *NPs*, by their priors and post-fit uncertainty, and correlations between *NPs* and *POI*
    - **fitted value of *POI* depends** on the *NPs* as well (!)

ttH(bb) analysis in ATLAS
tt background modeling

- $t\bar{t}$+jets dominant background:
  - while ***$t\bar{t}$* predictions** available with **high precision** (NNLO, differential), QCD emission of **extra jets** (light and heavy flavour (HF)) suffer from **larger uncertainties** in perturbative predictions and from parton shower
- In ATLAS $t\bar{t}H(b\bar{b})$ analysis:
  - NLO+PartonShower $t\bar{t}$ events (5FS) generated with **Powheg+Pythia6**
  - **split** into *$t\bar{t}$+light*, *$t\bar{t}$+≥1c*, *$t\bar{t}$+≥1b*
    - categorisation made considering flavour of hadrons inside particle jets not matched to partons from *t* decay
  - *$t\bar{t}$*+light and *+≥1c* **corrected to NNLO** for p_T^{t} and $p_T^{t\bar{t}}$
  - *$t\bar{t}$+≥1b* **corrected to dedicated *$t\bar{t}$+$b\bar{b}$*** NLO+PartonShower prediction from **SherpaOpenLoops** (sub-categories and kinematics)



ttH(bb) analysis in ATLAS
tt background modeling - systematics

- Sophisticated set of **systematic uncertainties** related to tt modelling:
  - 3 alternative MC predictions compared to nominal for 5FS:
    - **parton shower and hadronisation** variation from Powheg+**Herwig++**
    - **NLO matrix element generator** variation from **aMC@NLO**
    - "**radiation**" variations (up/down) obtained by varying different parameters in Powheg+Pythia6 controlling amount of ISR/FSR
  - NNLO x-section uncertainty applied to $t\bar{t}$+light normalisation
  - **$t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$** normalisations left **free-floating** in the fit
  - *for $t\bar{t}+\geq 1b$:*
    - full set of dedicated **uncertainties on SherpaOpenLoops** applied
    - **residual uncertainties** from the three sources above after correcting each of them to nominal SherpaOpenLoops kinematics
    - 2 **alternative 4FS $t\bar{t}+b\bar{b}$** predictions (**aMC@NLO**+Pythai8/+Herwig++) used to derive additional ME and PS uncertainties on reweighting
  - for *$t\bar{t}+\geq 1c$:*
    - correction to dedicated 4FS $t\bar{t}+c\bar{c}$ predictions (aMC@NLO+Pythai8) used as additional systematic

ttH(bb) analysis in ATLAS
tt background modeling - systematics - II

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	$t\bar{t}+\geq1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC+ Pythia8	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq1c$

ttH(bb) analysis in ATLAS
tt background modeling - MC settings

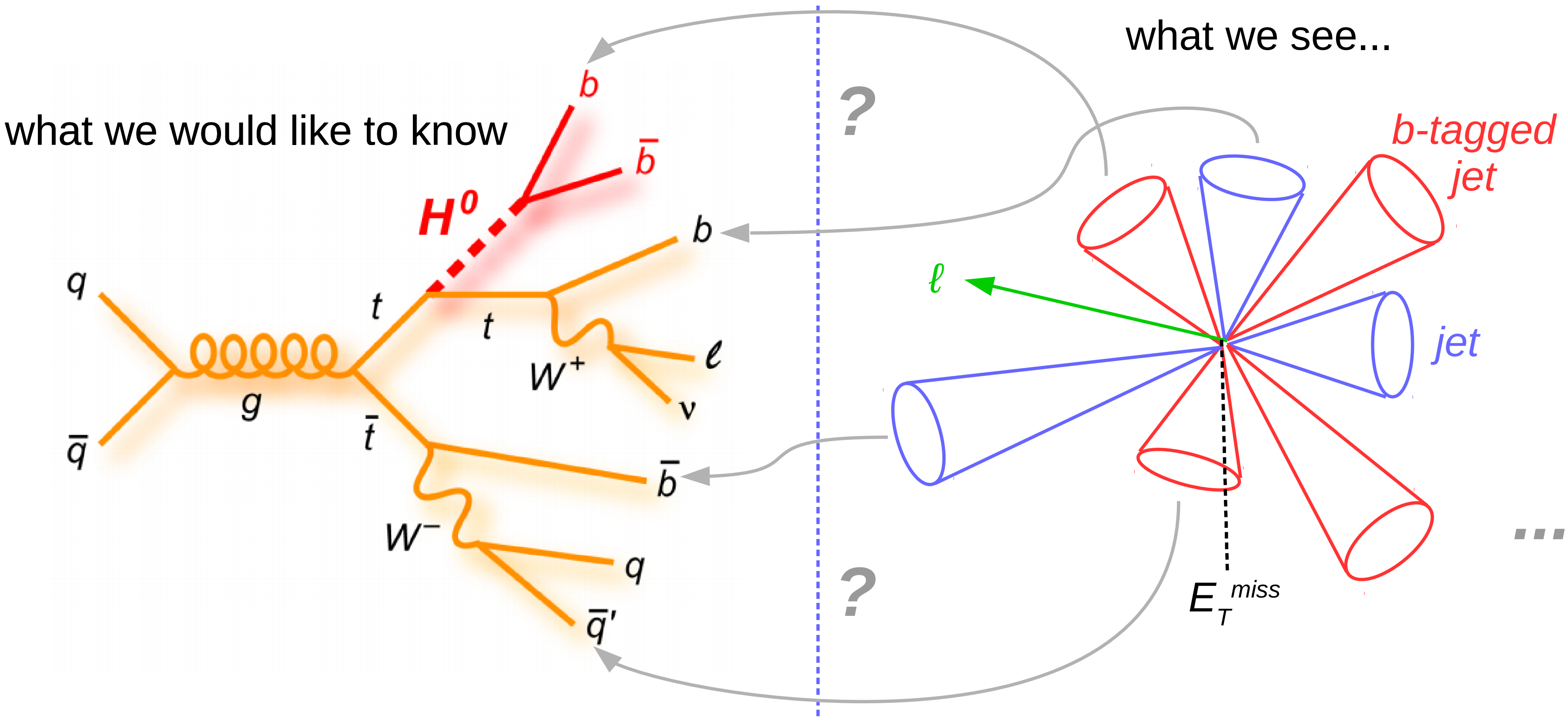
ME gen. PS/UE gen.	MG5_aMC Herwig++ 2.7.1	MG5_aMC Pythia 8.210	SherpaOL Sherpa
Renorm. scale	μ_{CMMPS}	μ_{CMMPS}	μ_{CMMPS}
Fact. scale	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$	$H_{\mathrm{T}}/2$
Resumm. scale	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$f_{\mathrm{Q}}\sqrt{\hat{s}}$	$H_{\mathrm{T}}/2$
ME PDF	NNPDF3.0 4F	NNPDF3.0 4F	CT10 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	Author's tune

ME gen. PS/UE gen.	Powheg-Box Pythia 6.428	Powheg-Box Herwig++2.7.1	MG5_aMC Herwig++2.7.1	Powheg-Box Pythia 6.428	Powheg-Box Pythia 6.428
Ren. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
Fact. scale	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$\sqrt{m_t^2 + \frac{1}{2}(p_{\mathrm{T,t}}^2 + p_{\mathrm{T,\bar{t}}}^2)}$	$\frac{1}{2} \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$	$2 \cdot \sqrt{m_t^2 + p_{\mathrm{T,t}}^2}$
hdamp	m_t	m_t	–	$2 \cdot m_t$	m_t
ME PDF	CT10	CT10	CT10	CT10	CT10
PS/UE PDF	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1	CTEQ6L1
Tune	P2012	UE-EE5	UE-EE5	P2012 radHi	P2012 radLo

ttH(bb) analysis in ATLAS

Event reconstruction

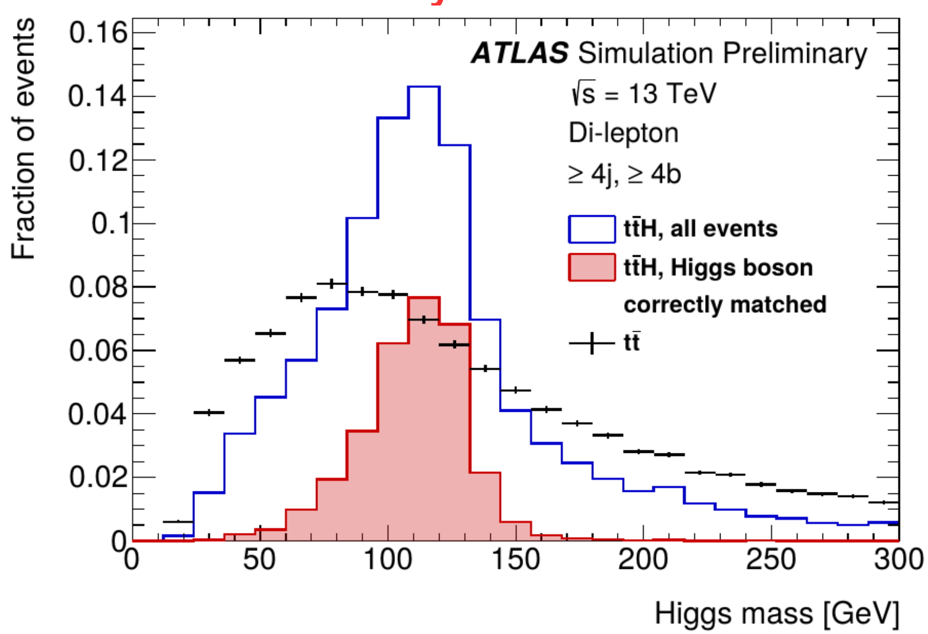
- **The event reconstruction issue:**

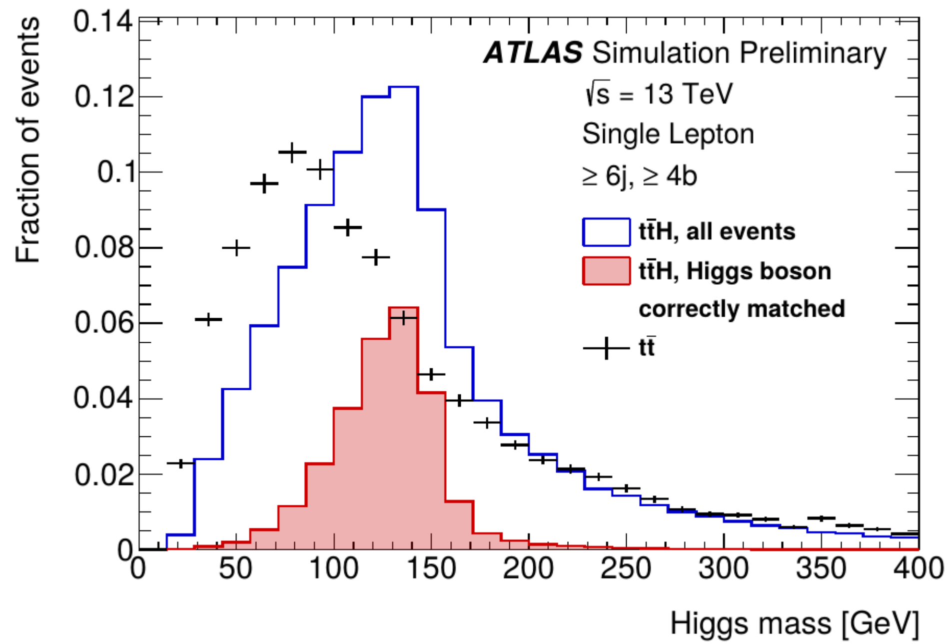


- **pairing jets with partons** from t^{had}, t^{lep}, H not an easy task
  - jet energy resolution, jets falling outside acceptance, mis-*b*-tags, additional radiation, pile-up...
- can use a **multi-variate technique** to solve the problem in the best possible way → boosted-decision-tree (BDT) used by ATLAS

ttH(bb) analysis in ATLAS
Event reconstruction - II

- BDT-based $t\bar{t}H$ system reconstruction, "**reconstruction BDT**":
  - build a BDT to distinguish **correct combinations** *vs.* **incorrect** ones in simulated $t\bar{t}H$ events:
    - treat each combination of jet-parton assignments as a different event
    - treat correct combinations as signal, incorrect ones as background
    - use many variables for each combination, like angle between jets in H candidate, mass of hadronic t, angle between t and H...
  - take the **combination with highest BDT score** in data as most likely correct combination





ttH(bb) analysis in ATLAS
Multi-variate discriminant

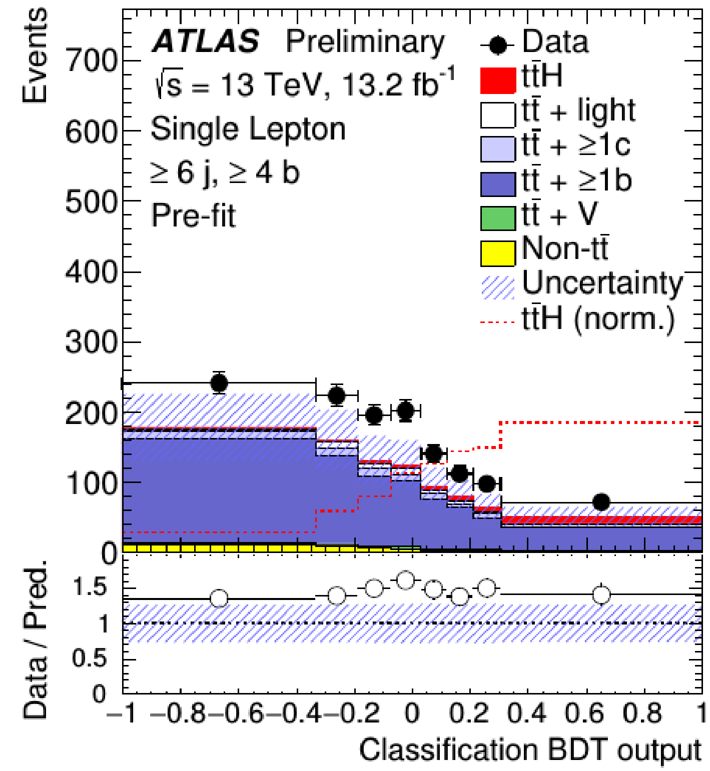
- After system reconstruction, "**classification BDT**" to distinguish $t\bar{t}H$ from $t\bar{t}$
  - combine outputs of reconstruction BDT with other kinematic variables

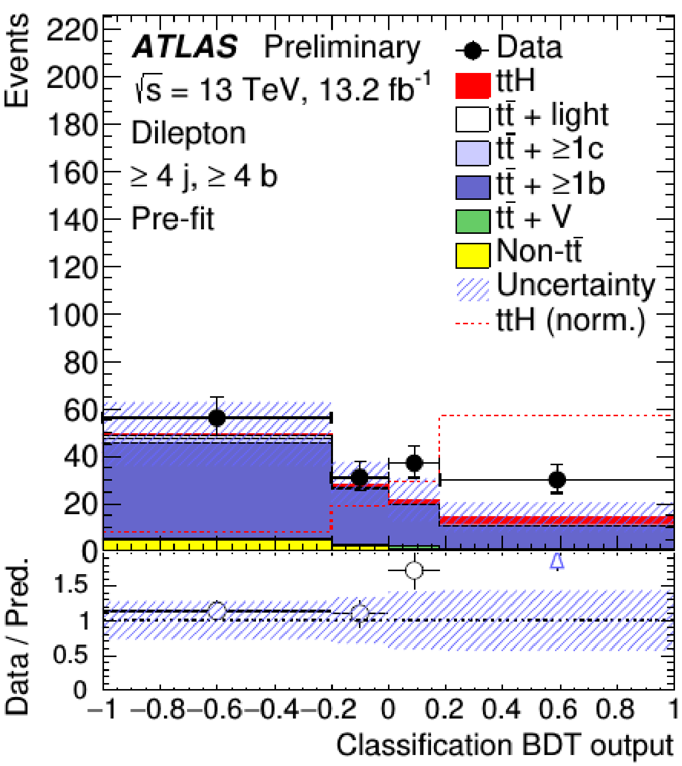
Variable	Definition	Region		
		≥ 6j, ≥ 4b	≥ 6j, 3b	5j, ≥ 4b
General kinematic variables				
$\Delta R^{\text{avg}}_{\text{bb}}$	Average ΔR for all b-tagged jet pairs	✓	✓	✓
$\Delta R^{\text{max}\ p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	–	–
$\Delta\eta^{\text{max}}_{\text{jj}}$	Maximum $\Delta\eta$ between any two jets	✓	✓	✓
$m^{\text{min}\ \Delta R}_{\text{bb}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	–
$m^{\text{min}\ \Delta R}_{\text{jj}}$	Mass of the combination of any two jets with the smallest ΔR	–	–	✓
$m^{\text{max}\ p_T}_{\text{bj}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	–	✓	–
$p^{\text{jet5}}_{\text{T}}$	p_{T} of the fifth leading jet	✓	✓	✓
$\text{N}^{\text{Higgs 30}}_{\text{bb}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\text{N}^{\text{jet}}_{40}$	Number of jets with $p_{\text{T}} \geq 40$ GeV	–	✓	–
$H^{\text{had}}_{\text{T}}$	Scalar sum of jet p_{T}	–	✓	✓
$\Delta R^{\text{min}\ \Delta R}_{\text{lep-bb}}$	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 [41] built with all jets	✓	✓	✓
Centrality	Scalar sum of the p_{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_{H}	Higgs boson mass	✓	✓	✓
$m_{\text{H},b_{\text{lep top}}}$	Mass of Higgs boson and b-jet from leptonic top	✓	–	–
$\Delta R_{\text{Higgs bb}}$	ΔR between b-jets from the Higgs boson	✓	✓	✓
$\Delta R_{\text{H},t\bar{t}}$	ΔR between Higgs boson and $t\bar{t}$ system	✓*	✓*	✓*
$\Delta R_{\text{H,lep top}}$	ΔR between Higgs boson and leptonic top	✓	–	–
$\Delta R_{\text{H},b_{\text{had top}}}$	ΔR between Higgs boson and b-jet from hadronic top	–	✓*	✓*

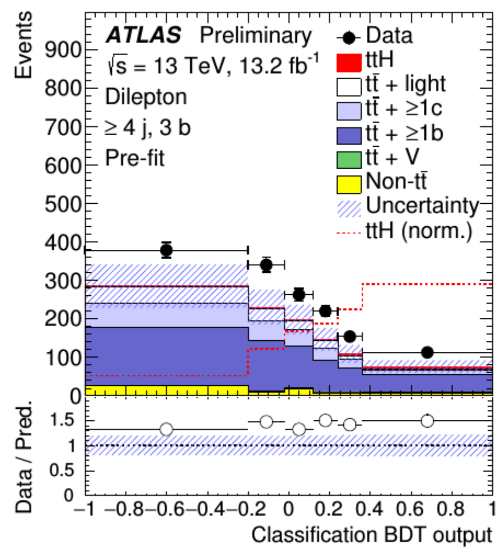
Variable	Definition	Region		
		≥ 4j, ≥ 4b	≥ 4j, 3b	3j, 3b
General kinematic variables				
$\Delta\eta^{\text{avg}}_{bb}$	Average $\lvert\Delta\eta\rvert$ among pairs of b-jets	✓	–	–
$\Delta\eta^{\text{max}}_{\text{bb}}$	Maximum $\Delta\eta$ between any two b-jets	–	✓	✓
$\Delta\eta^{\text{avg}}_{\text{jj}}$	Average $\Delta\eta$ among jet pairs	–	✓	–
$\Delta R^{\text{max}\ p_T}_{bb}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	✓	✓	✓
$\Delta R^{\text{Higgs}}_{\text{bb}}$	ΔR between the two b-tagged jets with mass closest to the Higgs boson mass	✓	–	–
$\Delta R^{\text{max m}}_{\text{bb}}$	ΔR between the two b-jets with the largest invariant mass	✓	✓	✓
$m^{\text{max}\ p_T}_{\text{bb}}$	Mass of the two b-tagged jets with the largest vector sum p_{T}	–	–	✓
$m^{\text{Higgs}}_{\text{bb}}$	Mass of the two b-tagged jets closest to the Higgs boson mass	✓	✓	✓
$m^{\text{min}}_{\text{bb}}$	Minimum mass of two b-tagged jets	–	–	✓
$m^{\text{min}\ \Delta R}_{\text{bb}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	✓	✓	✓
$p^{\text{min}}_{\text{T},b}$	Minimum b-tagged jet p_{T}	–	–	✓
$H^{\text{all}}_{\text{T}}$	Scalar p_{T} sum of all leptons and jets	–	✓	✓
$\text{N}^{\text{Higgs 30}}_{\text{bb}}$	Number of b-jet pairs with invariant mass within 30 GeV of the Higgs boson mass	✓	–	✓
$\text{N}^{\text{Higgs 30}}_{\text{jj}}$	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 [41] 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	✓(*)	✓(*)	–
$\Delta\eta^{\text{min}}_{\text{H},l}$	Minimum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta^{\text{max}}_{\text{H},l}$	Maximum $\Delta\eta$ between the Higgs boson and a lepton	✓*	✓	–
$\Delta\eta^{\text{min}}_{\text{H,b}}$	Minimum $\Delta\eta$ between the Higgs boson and a b-jet	✓*	–	–

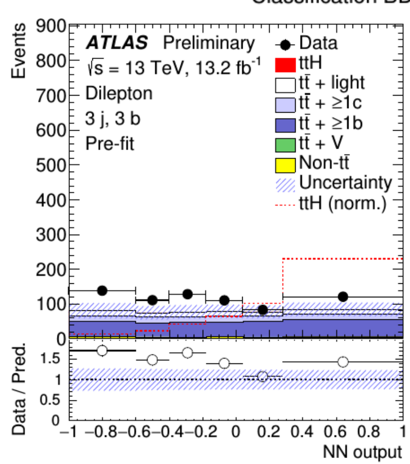
ttH(bb) analysis in ATLAS
Multi-variate discriminant - II

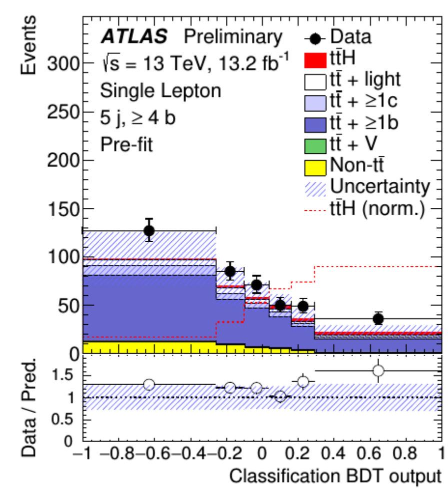
- After system reconstruction, "**classification BDT**" to distinguish $t\bar{t}H$ from $t\bar{t}$
  - combine outputs of reconstruction BDT with other kinematic variables
    - done separately for each of the SRs

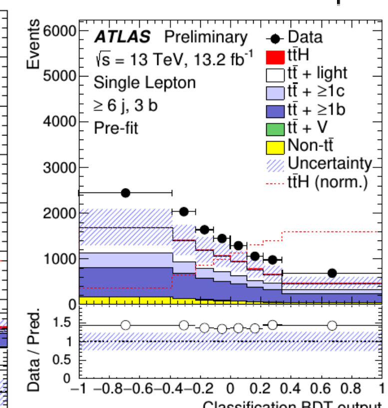




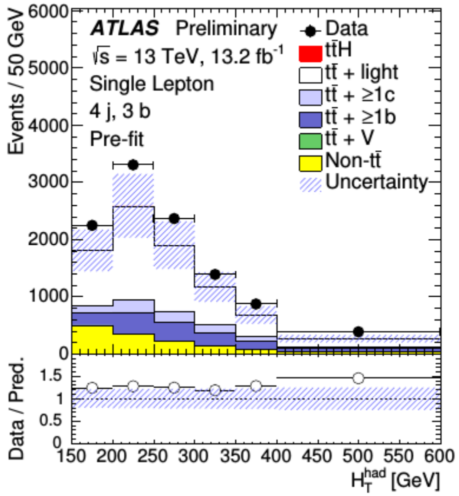


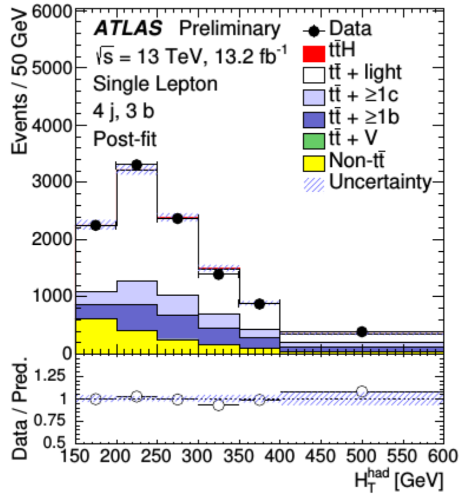






ttH(bb) analysis in ATLAS
Fit and results





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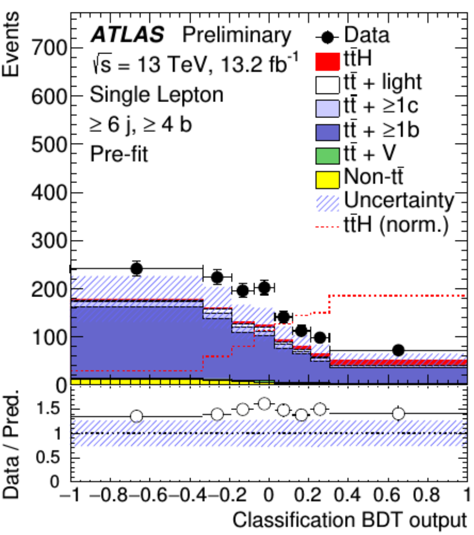
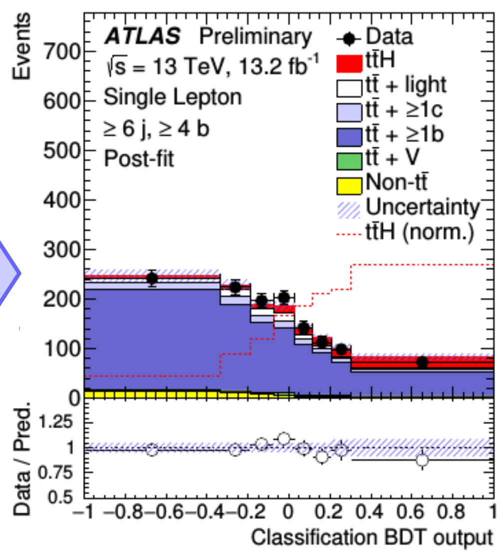
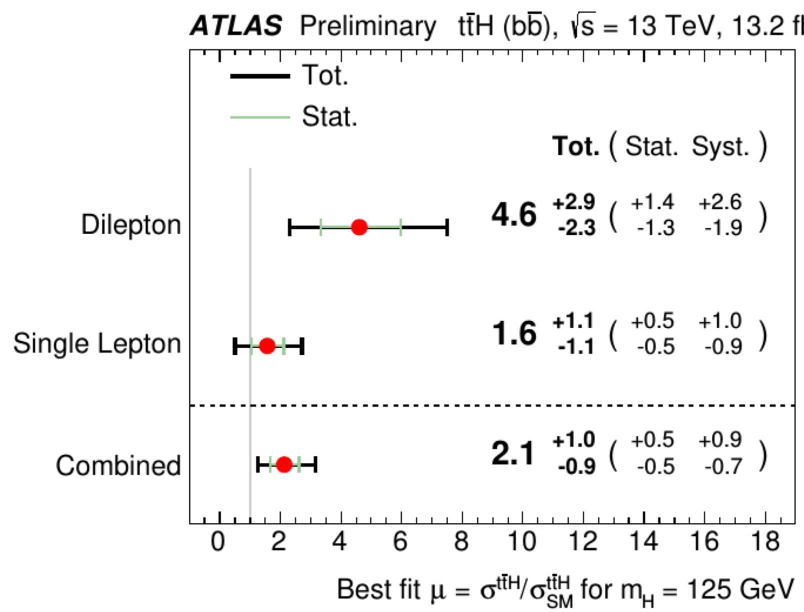


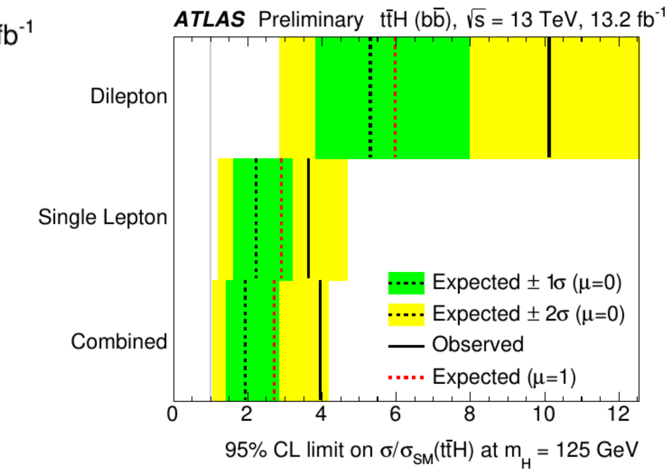


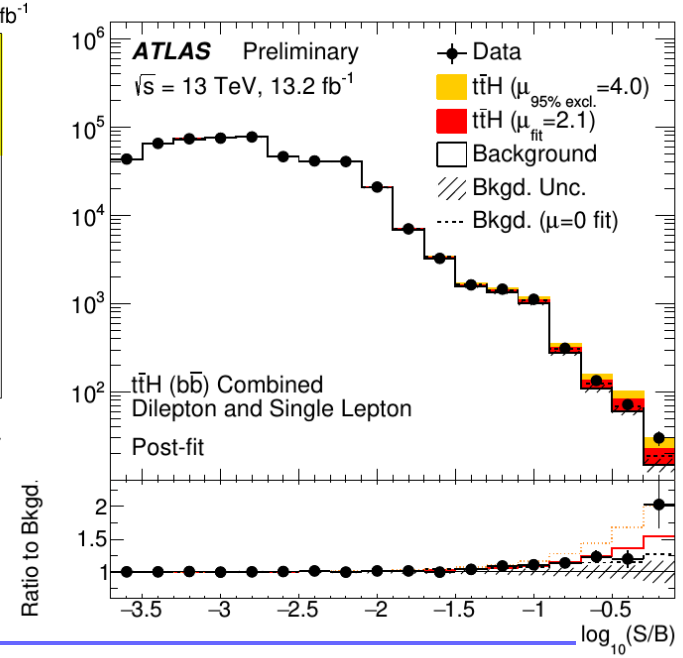
- Symultaneous fit on all CRs and SRs
  - main output is value of $\mu_{t\bar{t}H}$, with its uncertainty
    - we also get interesting additional information, e.g. $t\bar{t}$+HF normalisation "pulled" to ~1.5 x SM prediction...
- **Systematics ranked** according to contribution to total error

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

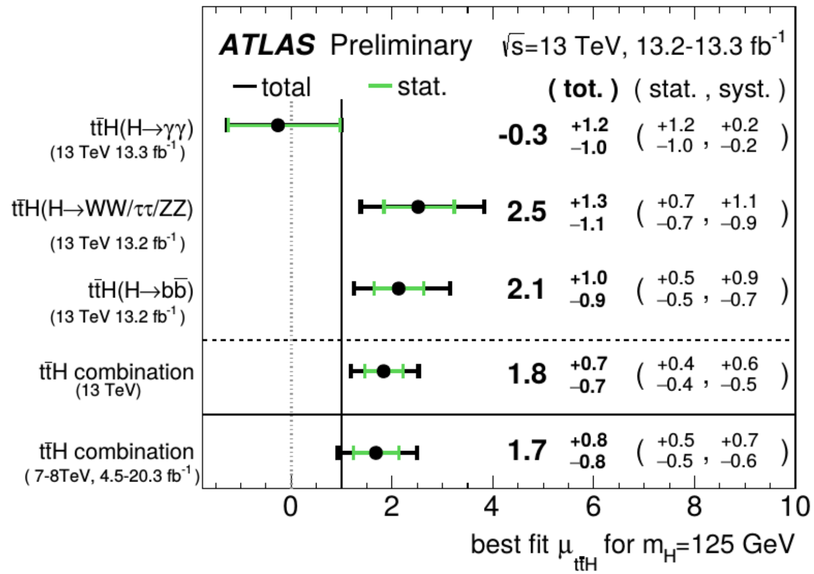
ttH(bb) analysis in ATLAS
Results and combination

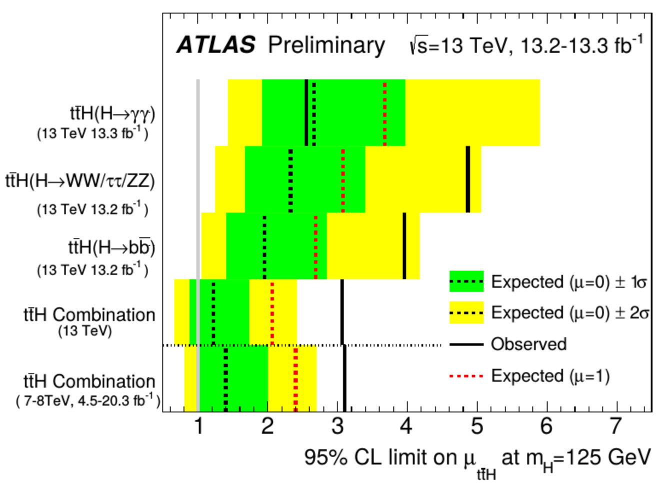


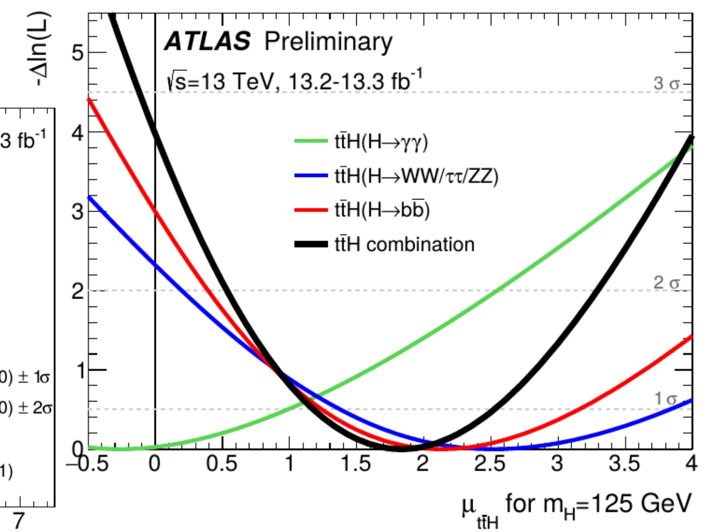




- This result is **combined** with other $t\bar{t}H$ channels: ▹ ATLAS-CONF-2016-068

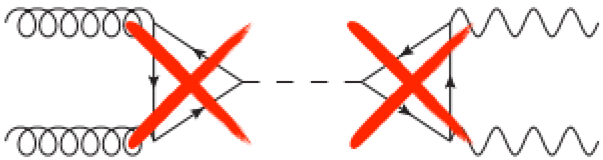






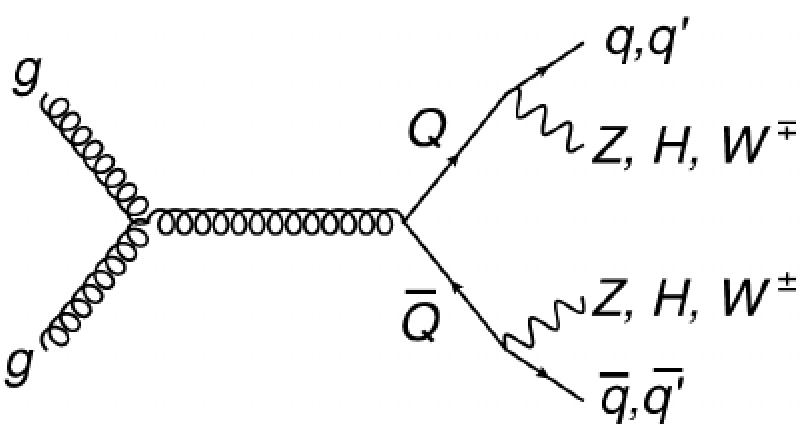
ttH(bb)-like signals

VLQ

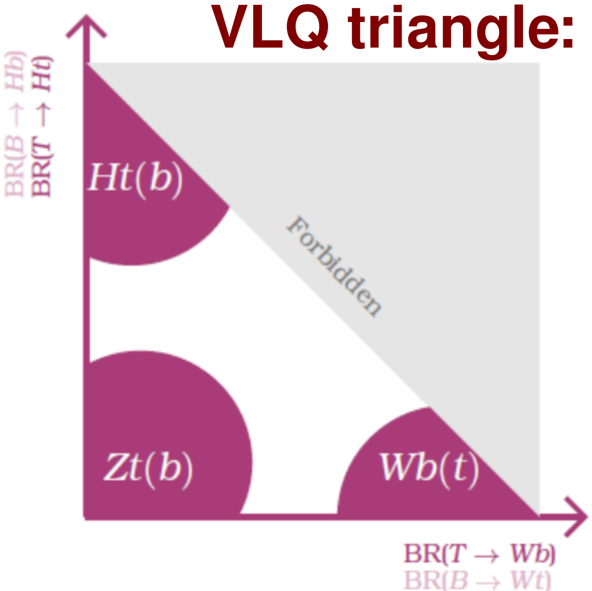


- 'Vector-like' quarks (VLQ)?
  - spin ½ but trasform as triplets (V coupling instead of V-A)
    - simplest coloured fermions still allowed by experimental data (4^{th} generation quarks excluded by Higgs data)
  - expected at **~TeV scale** (Naturalness, partial-compositness...)
  - large $y_t \Rightarrow$ sizable **mixing with 3^{rd} generation** ('top partners')
    - **decay** to SM particles through mixing with 3^{rd} generation
    - simple case (singlets):

```
T(+2/3) ↔ t → Wb,Ht,Zt
B(-1/3) ↔ b → Wt,Hb,Zb
```

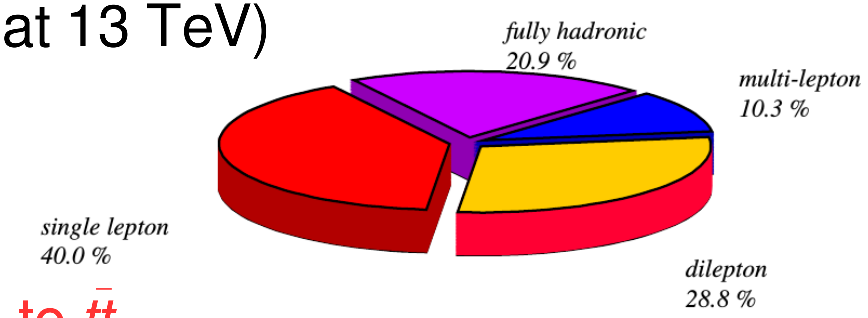


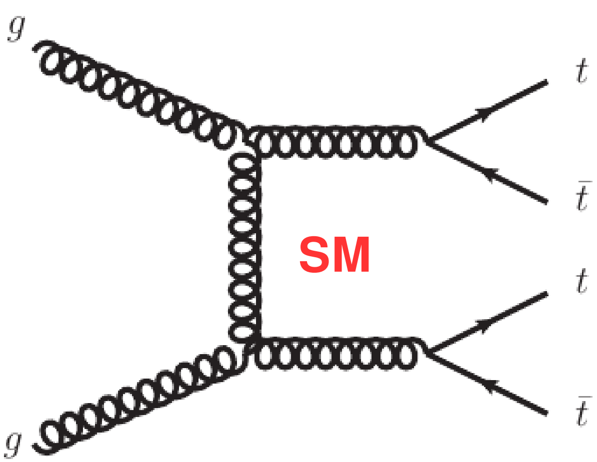
Limits often given in VLQ triangle:

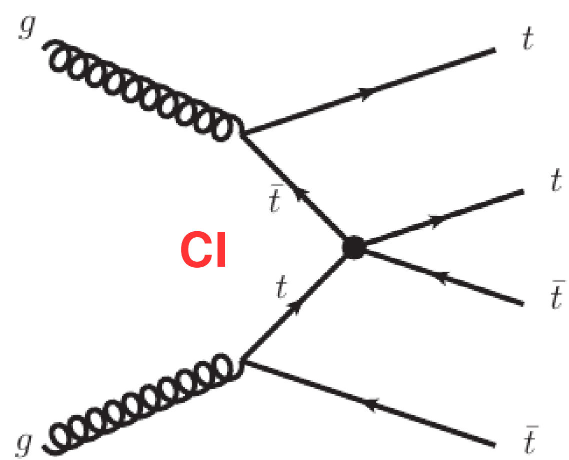


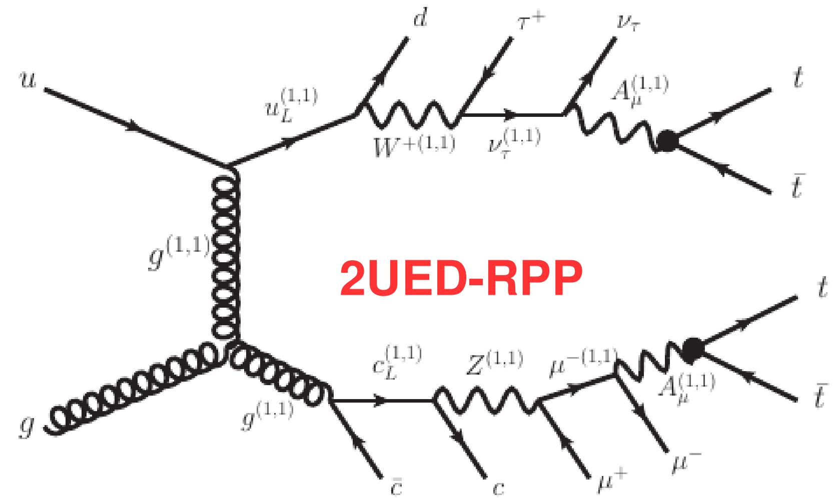
ttH(bb)-like signals
Four-top quark production

- $t\bar{t}t\bar{t}$ production in SM → small x-sec (~ 9 fb at 13 TeV)
- production enhanced in BSM scenarios:
  - via effective **contact interactions** (CI)
  - pair production of **resonances** dacaying to $t\bar{t}$
  - **2HDM**: $t\bar{t}H/A$, $H/A \rightarrow t\bar{t}$ (*see later*)









- Final states with many jets and/or leptons, not necessarely very energetic (!)

ttH(bb)-like signals

Heavy Higgs and tt resonances

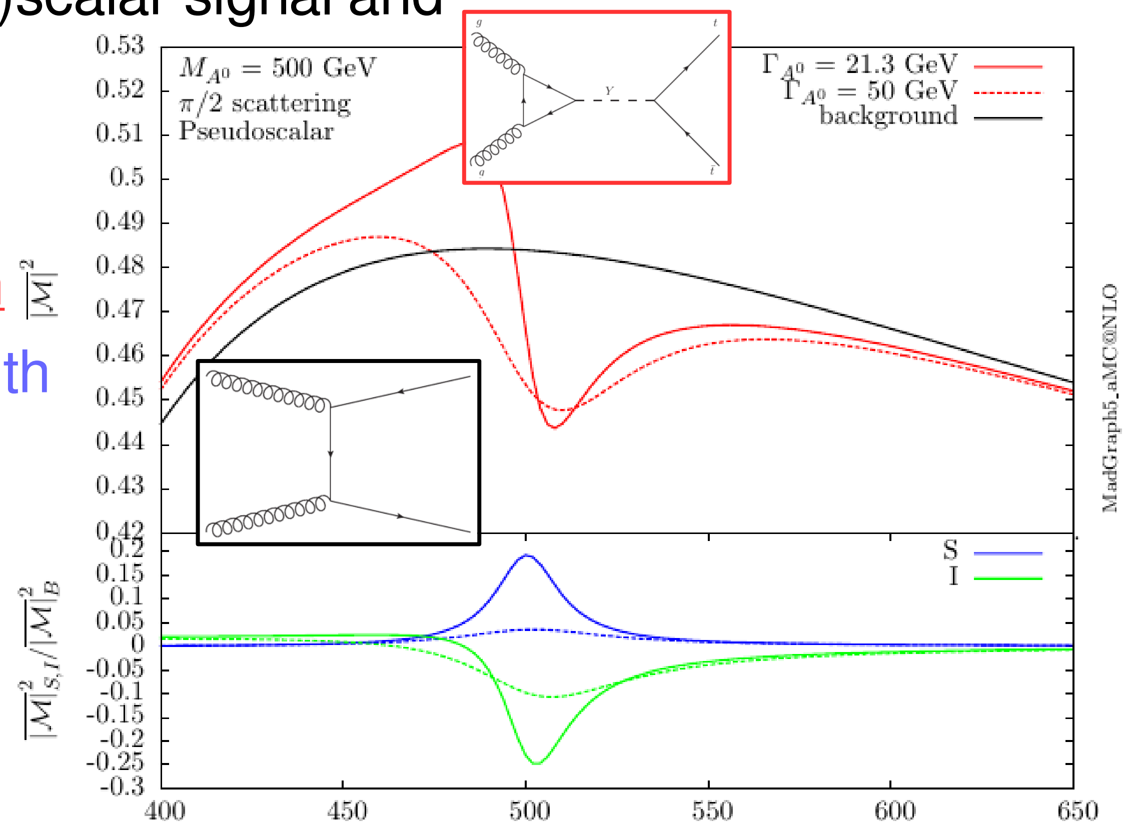
- Apart from 'simple' case of $Z'/g_{kk} \rightarrow t\bar{t}$
- Current experimental constraints in view of 2-Higgs Doublet Models favour heavy neutral Higgs $\rightarrow t\bar{t}$:
  - 125 GeV Higgs couplings = SM
    - ⇒ '**alignment limit**' ($sin(\beta\text{-}\alpha)$=1)
    - ⇒ H/A couplings with W, $Z \rightarrow 0$
    - ⇒ H/A couplings with fermions ($Y^{H/A}$) depend only tanβ:

(alignment limit)	Type I	Type II
$Y^{H/A}(u)$ [y_u]	1/tanβ	1/tanβ
$Y^{H/A}(d,\ell)$ [$y_{d,\ell}$]	1/tanβ	tanβ

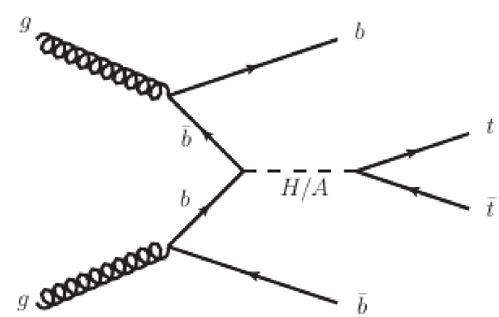
  - High $\tan\beta$ values excluded by $H/A \rightarrow \tau\tau$ searches
  - Low and intermediate $\tan\beta$ and $m_{H/A}$ > 350 GeV:
    - ⇒ ***$H/A \rightarrow t\bar{t}$* dominant (!)**

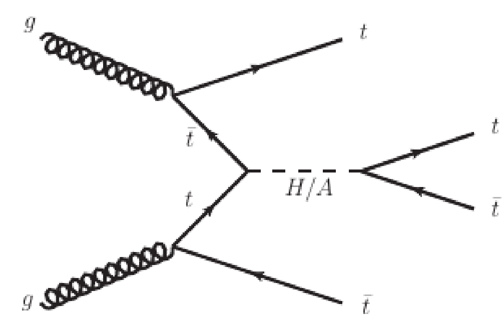
ttH(bb)-like signals
Heavy Higgs and tt resonances - II

- **Interference** between (pseudo)scalar signal and SM non-resonant background recently studied:
  - ▹ arXiv:1606.04149 [hep-ph]
  - **peak reduction & distortion**
    - ▸ more important for larger width



- Analysis strategy for $t\bar{t}$ resonance has to evolve:
  - inclusion of interference in simulation
  - usage of angular / spin-correlation aware variables in addition of the $m_{t\bar{t}}$ scan
  - look at **associated production** (with $t\bar{t}$ or $b\bar{b}$):

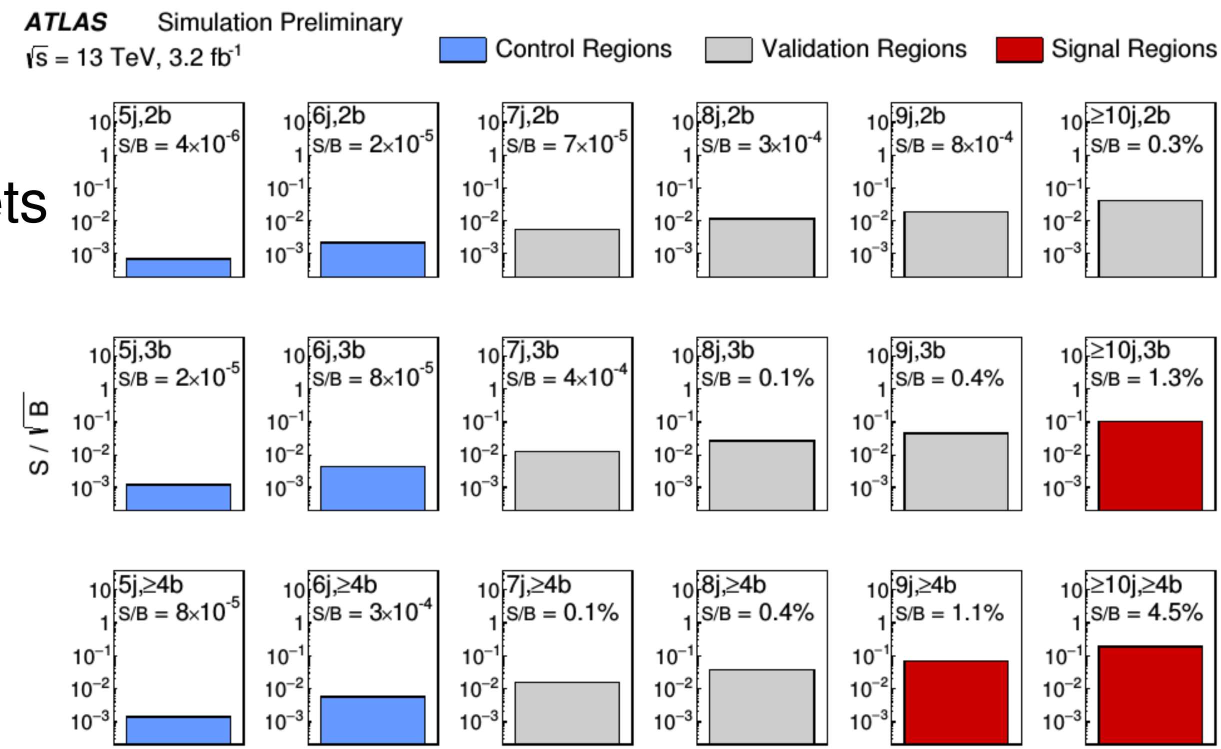


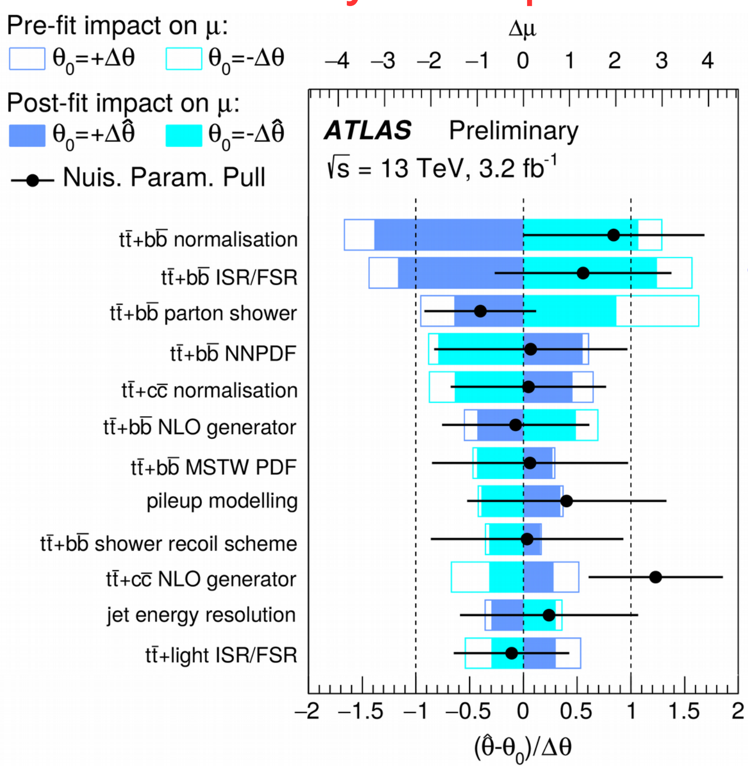


ttH(bb)-like analyses in ATLAS
Four top search in ℓ+jets

▸ ALAS-CONF-2016-020 (3.2 fb^{-1})

- Analysis targeting 4-top final states in **resolved** ℓ+jets
  - ▸ 1e/μ + ≥ 10 j , ≥ 4 b
- Background ***$t\bar{t}$+$b\bar{b}$+jets***:
  - – hard to model with current theory / MC predictions!



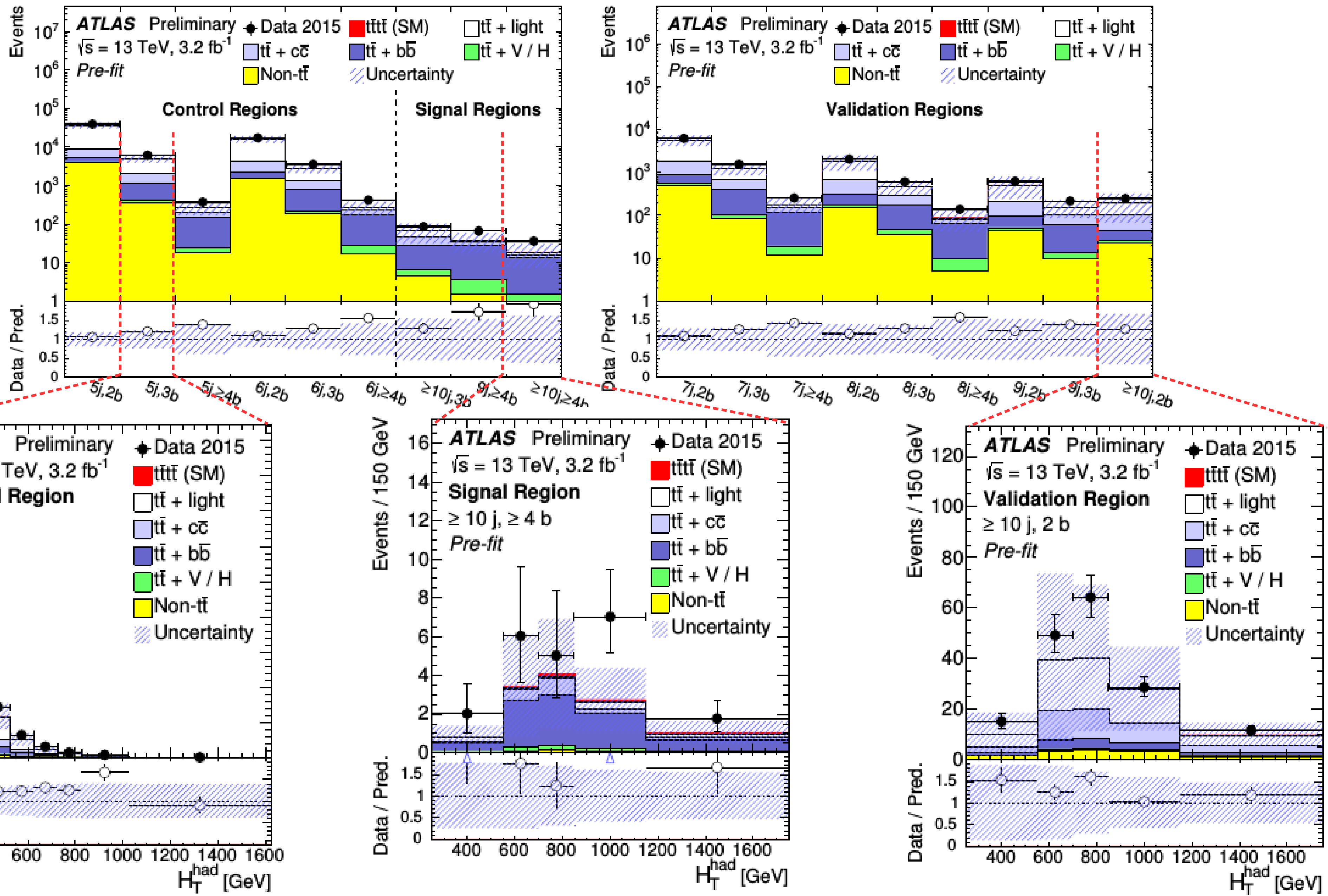


- Analysis strategy similar to ttH(bb):
  - – **split** in **N(jets)** and **N(b-tags)**
  - – symultaneous profile likelihood fit of H_T^{had} in all CRs and SRs
  - – **Validation Regions** not fitted:
    - ▸ used to validate the CR → SR extrapolation

ttH(bb)-like analyses in ATLAS
Four top search in ℓ+jets - II

Pre-Fit

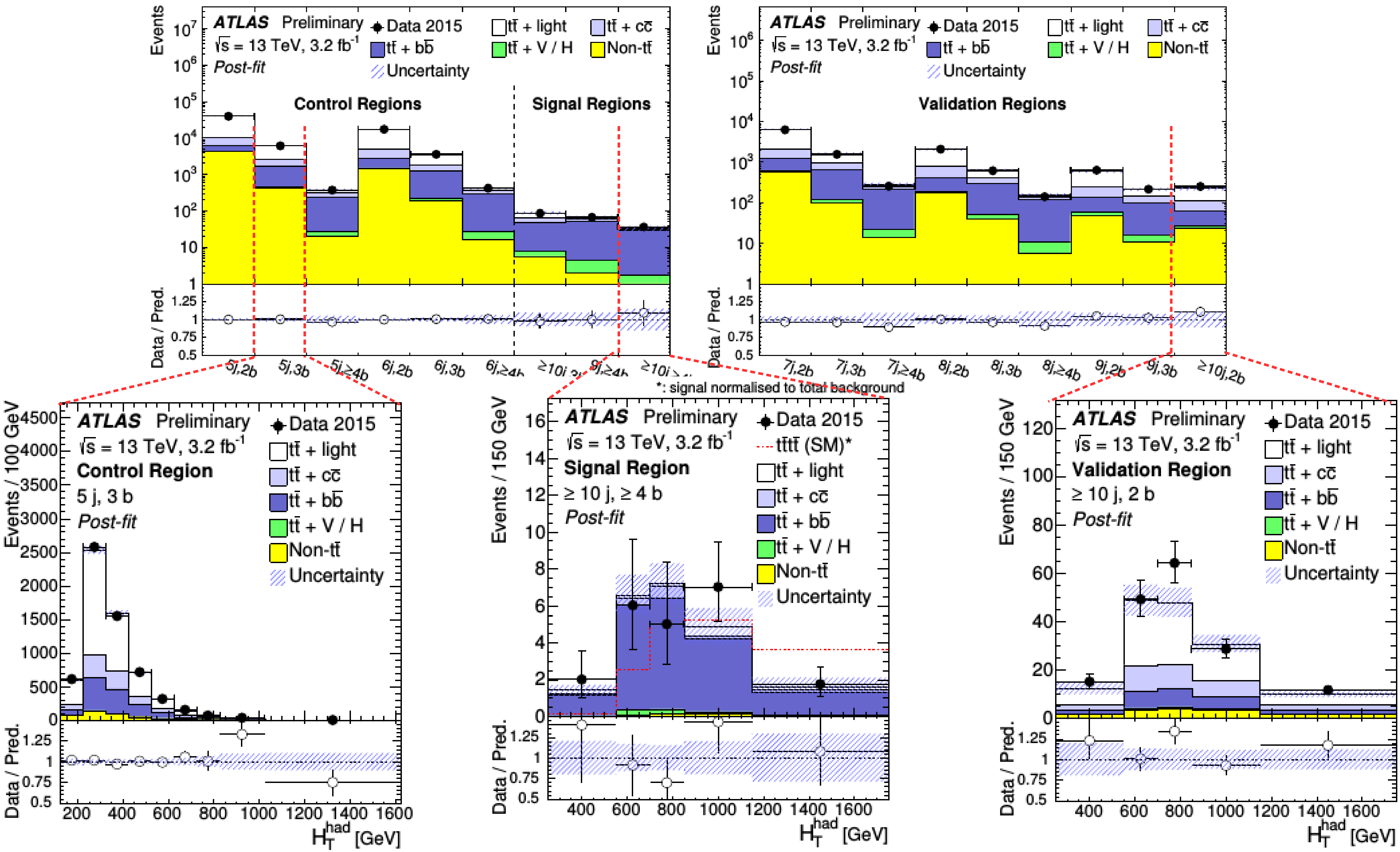
- Expected limit on 4 tops: **16 x SM**



ttH(bb)-like analyses in ATLAS
Four top search in ℓ+jets - III

Post B-only Fit

- Observed limit on 4 tops: **21 x SM**

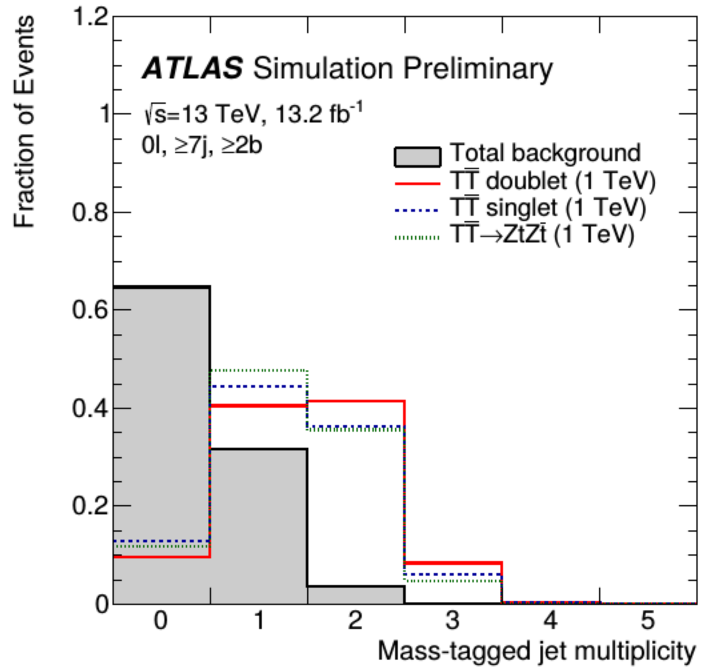


ttH(bb)-like analyses in ATLAS
Search for VLQ

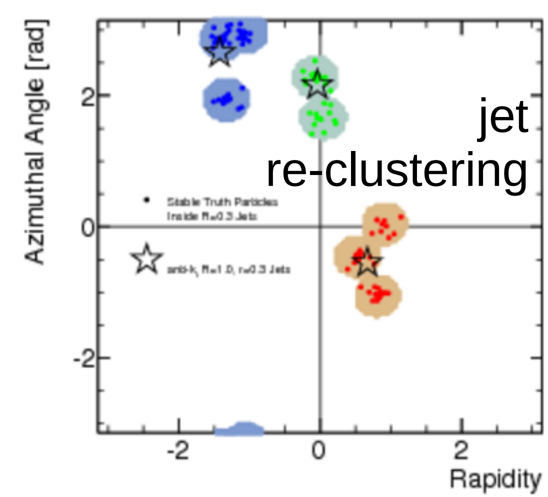
▹ ALAS-CONF-2016-104 (13.2 fb^{-1})

- Search targeting different signals in 0-1ℓ + (b)jets:
  - **VLQ** focusing on $TT \rightarrow H(b\bar{b})t$+$X$
  - **new 0ℓ**, high-MET ($TT \rightarrow H(b\bar{b})t$, $Z(\nu\nu)t$)
  - **4-top** events (SM, CI, 2UED)
  - **2HDM**: $t\bar{t}H/A(t\bar{t})$, $b\bar{b}H/A(t\bar{t})$, $tbH^{+}(tb)$
- Selecting events with ≥ 6 j (≥ 7 j for 0ℓ)
- Events categorised *vs.* **N(b-tags)** and **N(mass-tagged jets)**:

→ re-clustered jets (anti-k_t 1.0) with p_T > 300 GeV, $|\eta|$ < 2, m > 100 GeV

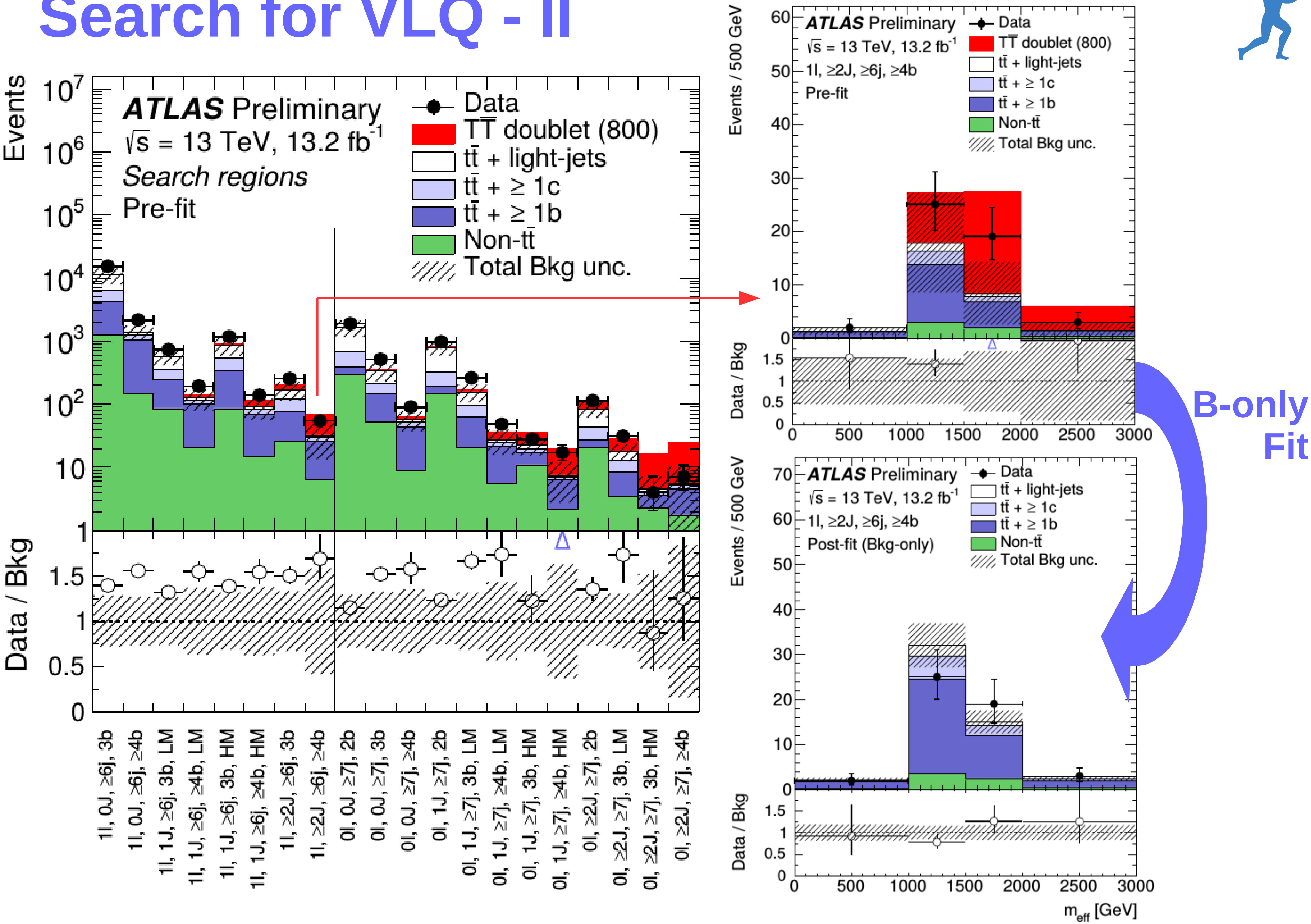


- Fit m_{eff} in each region
- Split some of the SRs into high/low mass (HM / LM):
  - 1ℓ: $m_{bb}^{min\Delta R}$ > or < 100 GeV
  - 0ℓ: $m_{T,min}^{b}$ > or < 160 GeV



ttH(bb)-like analyses in ATLAS

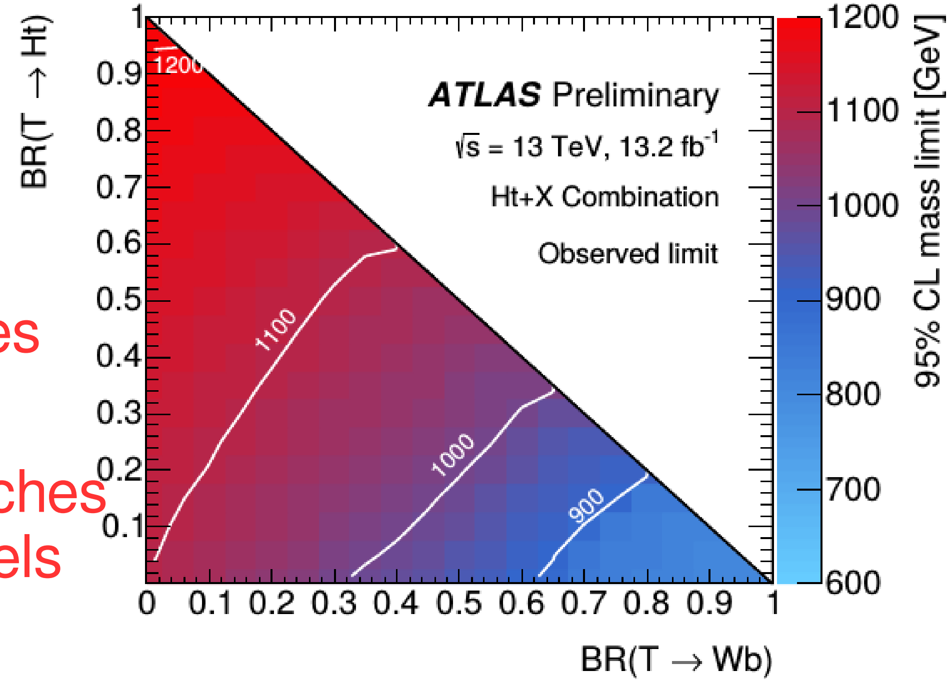
Search for VLQ - II



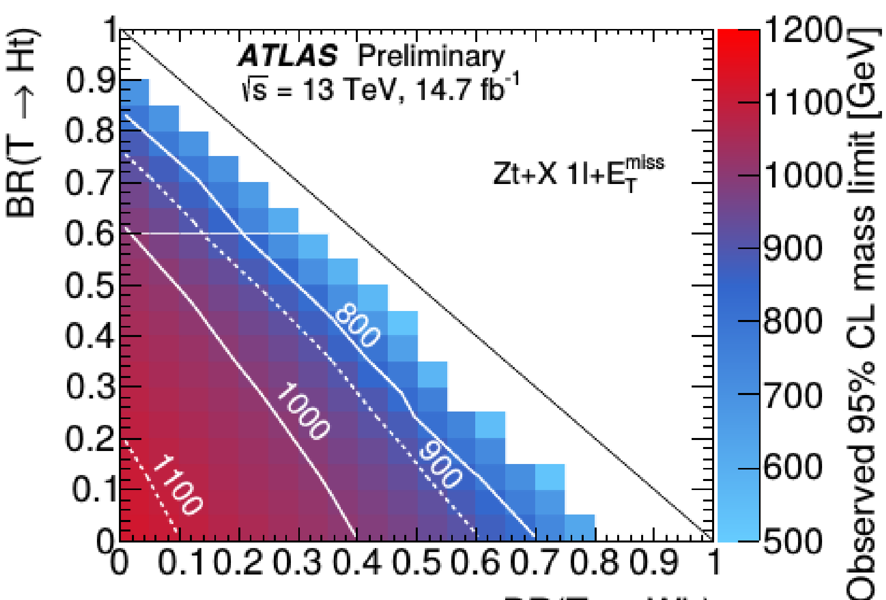
ttH(bb)-like analyses in ATLAS

Search for VLQ - III

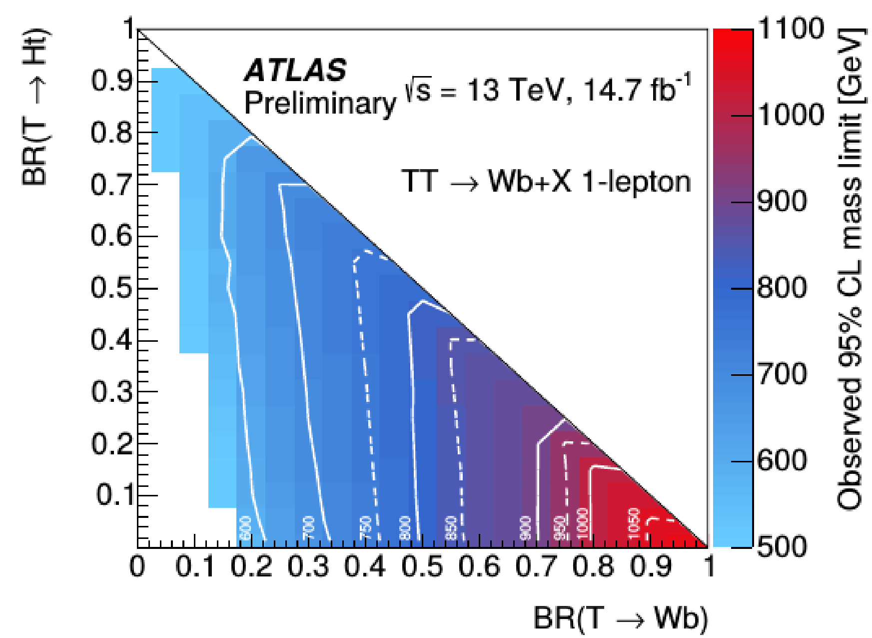
- Results:
  - no excess
    - stringent **limits on VLQ** masses **~1 TeV**
    - **complementary** to other searches focusing on other decay channels



▹ ALAS-CONF-2016-101 (14.7 fb-1)

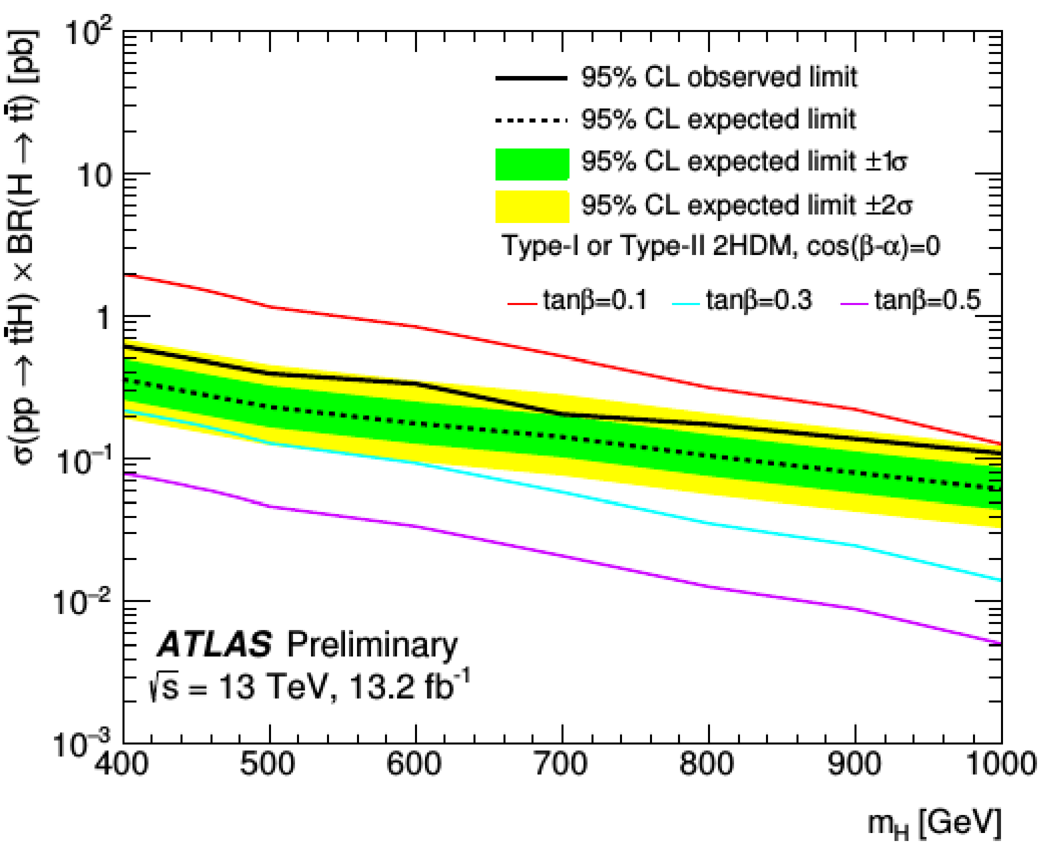


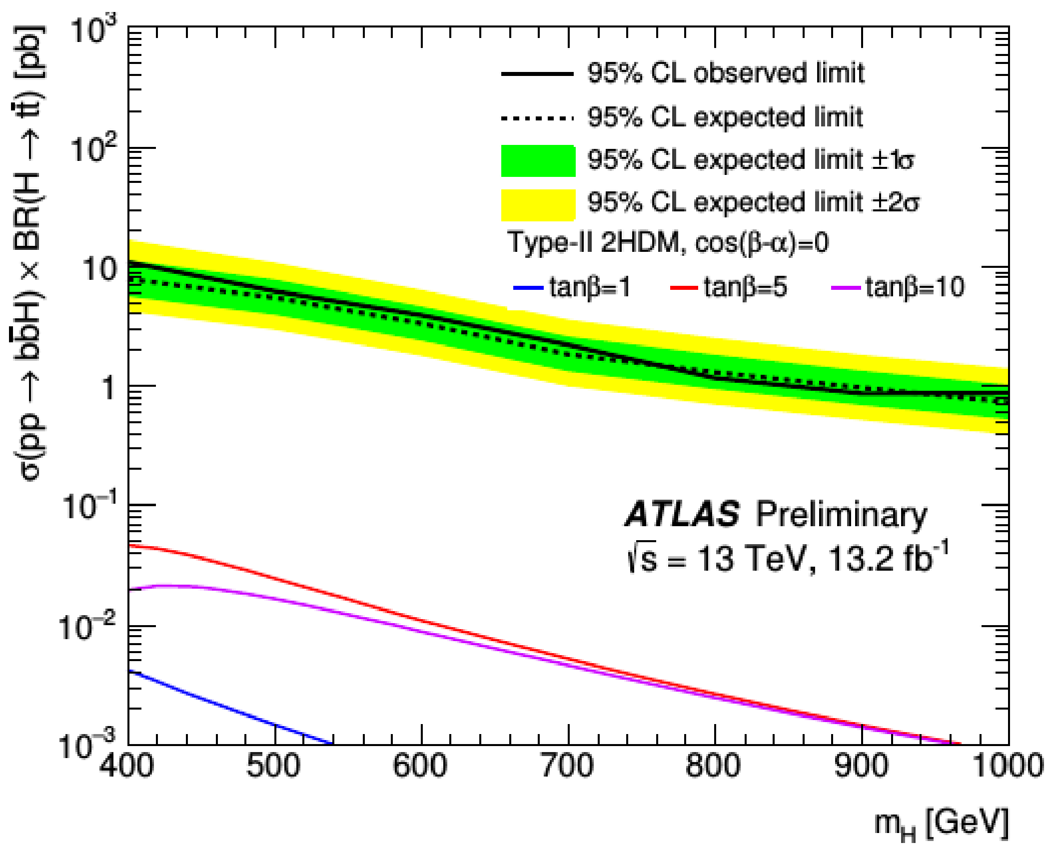
▹ ALAS-CONF-2016-102 (14.7 fb-1)



ttH(bb)-like analyses in ATLAS
Interpretation in 2HDM

- First limits on $t\bar{t}H/A$, $b\bar{b}H/A$ ($H/A \to t\bar{t}$)
  - for ***$t\bar{t}H/A$*** starting to exclude low *tanβ* regions up to ~1 TeV, not yet sensitive for *tanβ* ~ 1
  - for ***$b\bar{b}H/A$*** not sensitive enough:
    - **dedicated analysis** strategy needed (associated *b* are soft!)





Conclusions

- Main message:
  - shown some of the details of an ATLAS data analysis
  - highlighted challenges and opportunities of complicated final states

$t\bar{t}+b\bar{b}$ is a perfect place
where your preferred New Physics model
can hide its signature

Backup

ttH(bb) analysis in ATLAS
Profile Likelihood Fit - significance

- 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

- Where the test statistic is (example background-only):

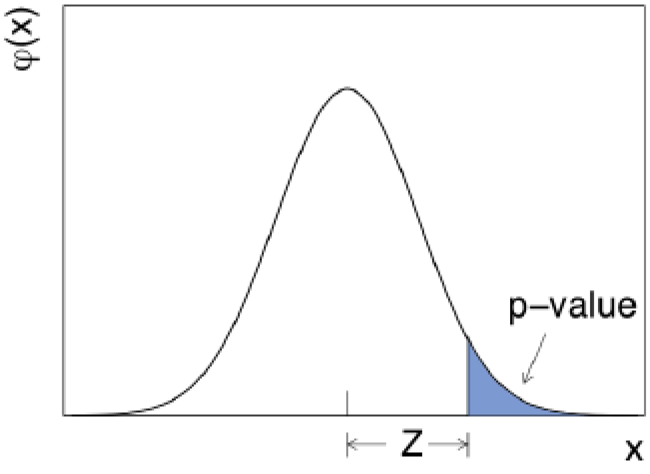
$$q_0 = \begin{cases} -2ln\lambda(0) & \hat{\mu} \geq 0 \\ 0 & \hat{\mu} < 0 \end{cases}$$

reject background-only

- From this we can build p-value and significance:

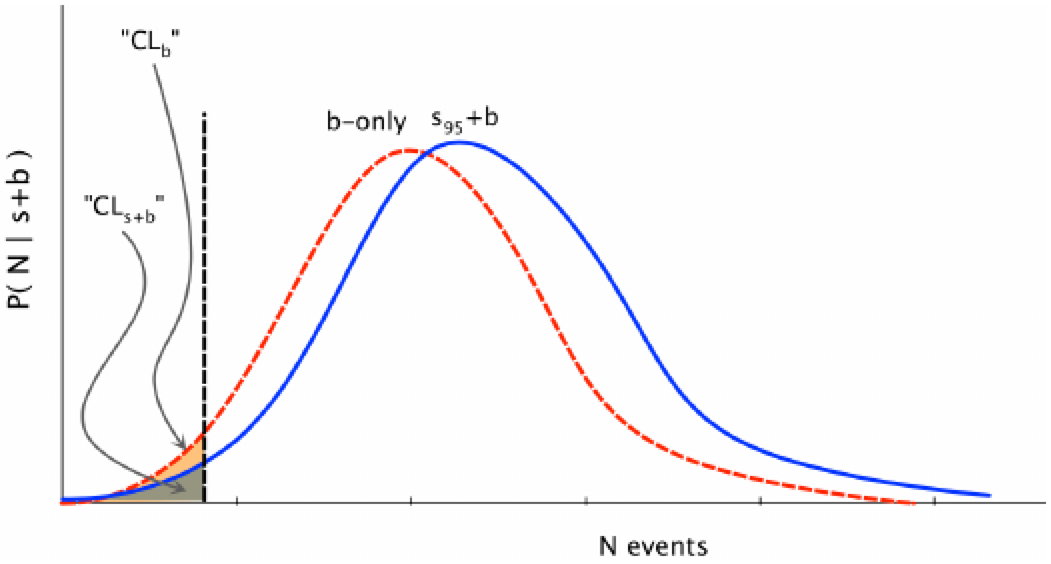
$$p_0 = \int_{q_{0,\mathrm{obs}}}^{\infty} f(q_0|0)\, dq_0$$

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



ttH(bb) analysis in ATLAS
Profile Likelihood Fit - limit setting

- When looking for a tiny signal on top of background, worry to exclude signal due to a downward fluctuation



Using CLs+b, one would expect to exclude the signal 5 % of the time

$$CL_s = CL_{s+b}/CL_b$$

test signal hypothesis:

only exclude if $CL_s < 5$ %

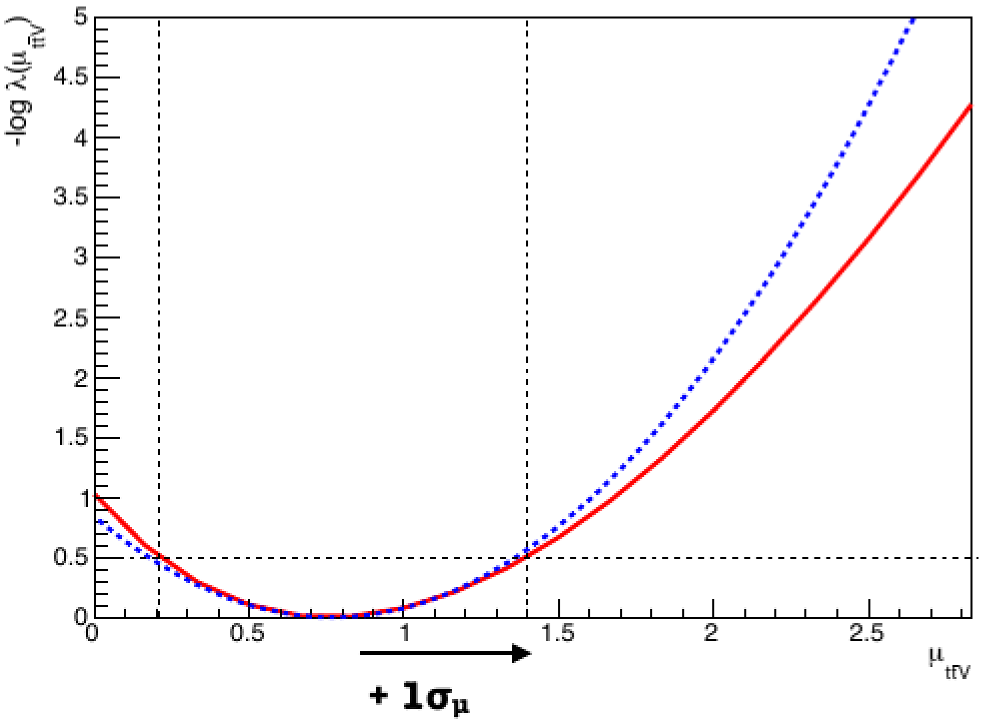
- So we use **CL_s** to test a signal hypothesis (not a probability)
  - a downward fluctuation in S+B will not exclude signal since CL_b with also be small
  - conservative approach

ttH(bb) analysis in ATLAS

Profile Likelihood Fit - asymptotic regime

- In large statistics data samples, the distribution of the test statistic is known according to Wilks' Theorem (independenlty on the prior!)
  - as a result, one can directly calculate p-value and significance:

$$-2\log\lambda(\mu) = -2(\log L(\mu,\hat{\hat{\theta}}) - \log L(\hat{\mu},\hat{\theta})) = \left(\frac{\mu-\hat{\mu}}{\sigma_\mu}\right)^2$$



- distributed as a χ2
- results in parabolic shape around the minimum

- This theorem holds true for even as few as ~ O(10) events in a data sample
- Saves from running very time consuming pseudo-experiments