New results on Higgs boson coupling to heavy flavor

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Stony Brook University
Santa Fe Jets and Heavy Flavor
Jan 31st, 2018

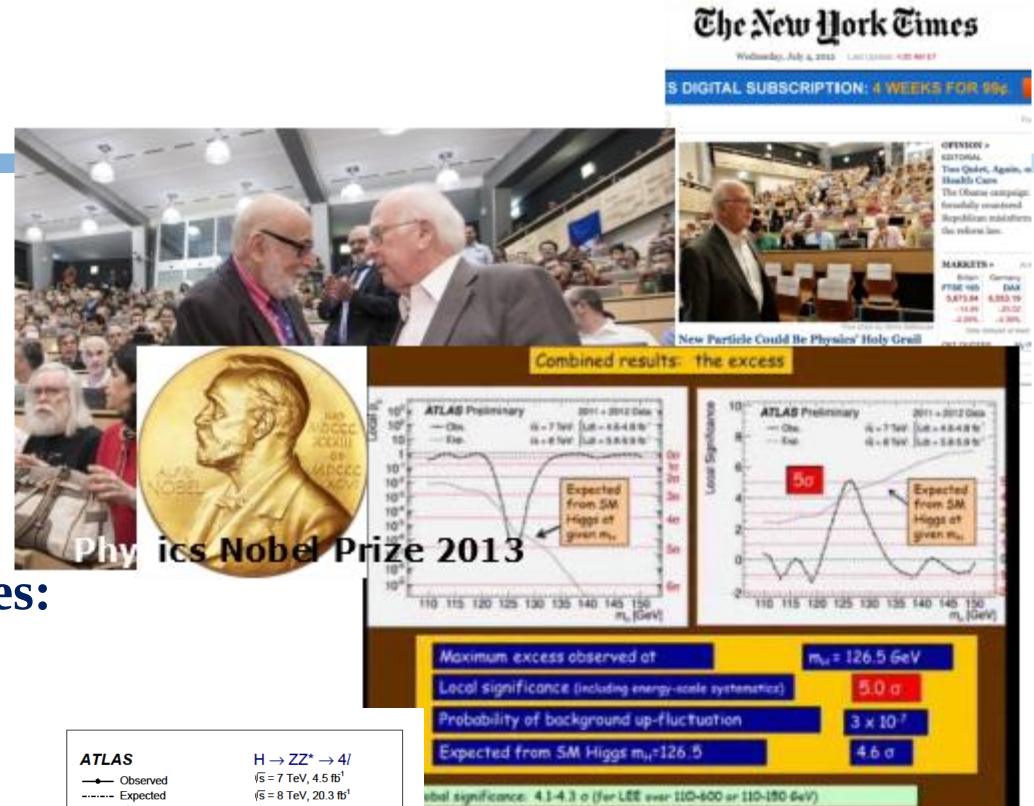
A Short Outline

- **Some words of context**
- **ttH analyses:**
  - *ttH(ZZ*→4l)*
  - *ttH(γγ)*
  - *ttH(bb)*
  - *ttH(WW*, ττ, ZZ*)*
- **H→bb:**
  - *VBF+γ, H→bb*
  - *VH(bb)*
- **H→cc**
- **Conclusions**

Context

A Bit Of History

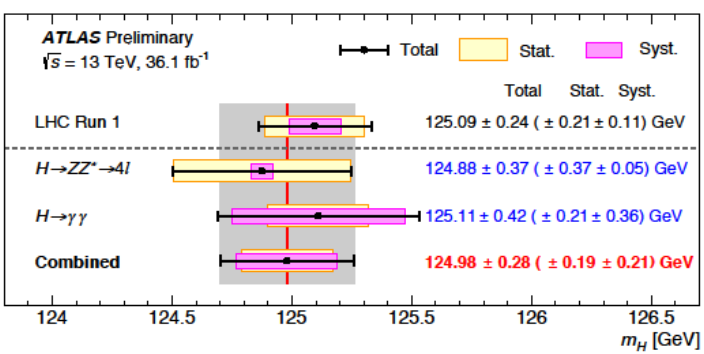
- **Higgs boson discovery 2012:**
  - ATLAS and CMS experiments
  - 48 years after its prediction
  - Nobel Prize in 2013

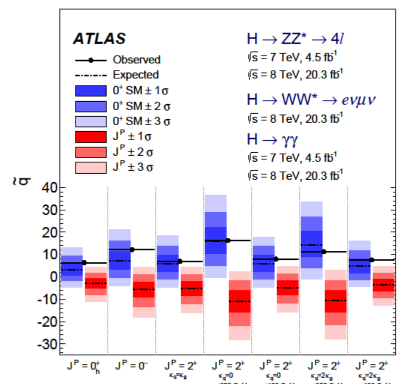


- **Measure observed particle properties:**
  - Rich area of physics.

Mass measurements (high precision):

Run 1	ATLAS + CMS	125.09 ± 0.24 GeV
Run 2	ATLAS	124.98 ± 0.28 GeV
	CMS	125.26 ± 0.21 GeV

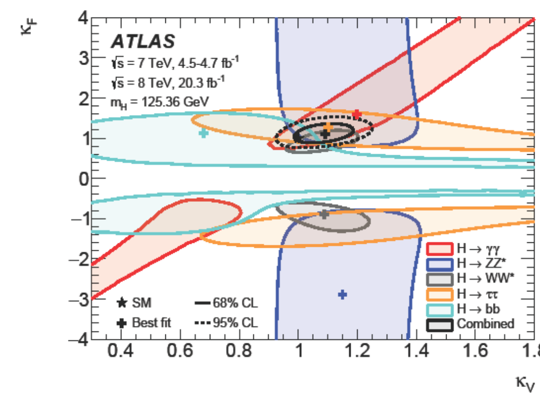




Spin and Parity:

→ Compatible with SM 0^+

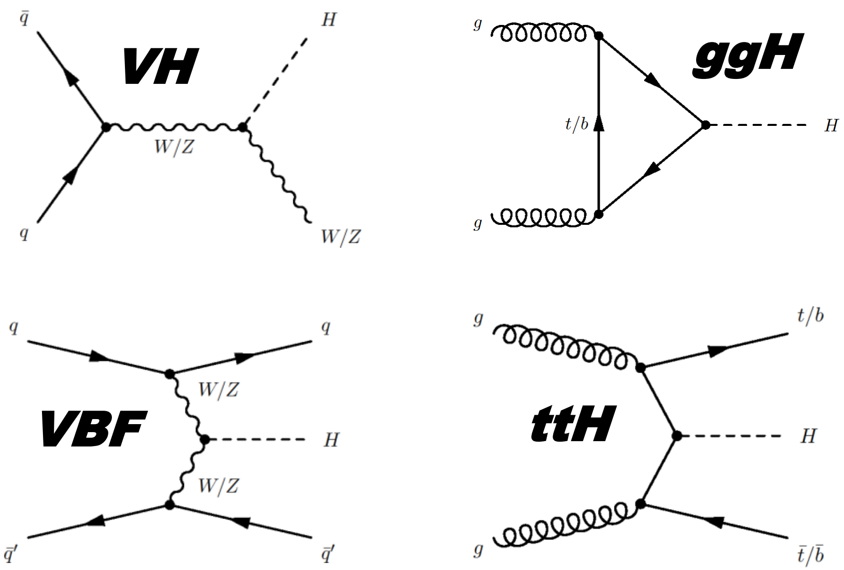
Couplings



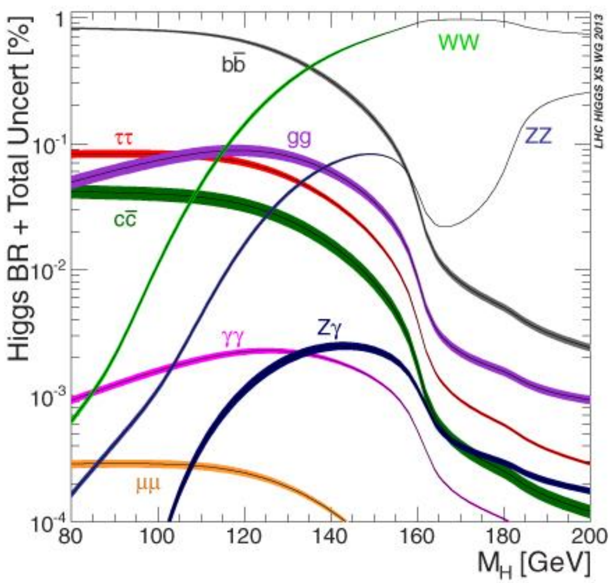
Higgs Boson Searches at LHC

Searches in various production modes and final states.

- **Higgs boson production at LHC**



- **Higgs boson decay modes**



Prod	*ggH*	*VBF*	*VH*	*ttH*
σ (pb) (13 TeV)	**48.5**	3.78	2.25	**0.507**
Yukawa Coupling	**Top, b, …, BSM**	Vector Boson	Vector Boson	**Top**

Couplings Measurements: Overview

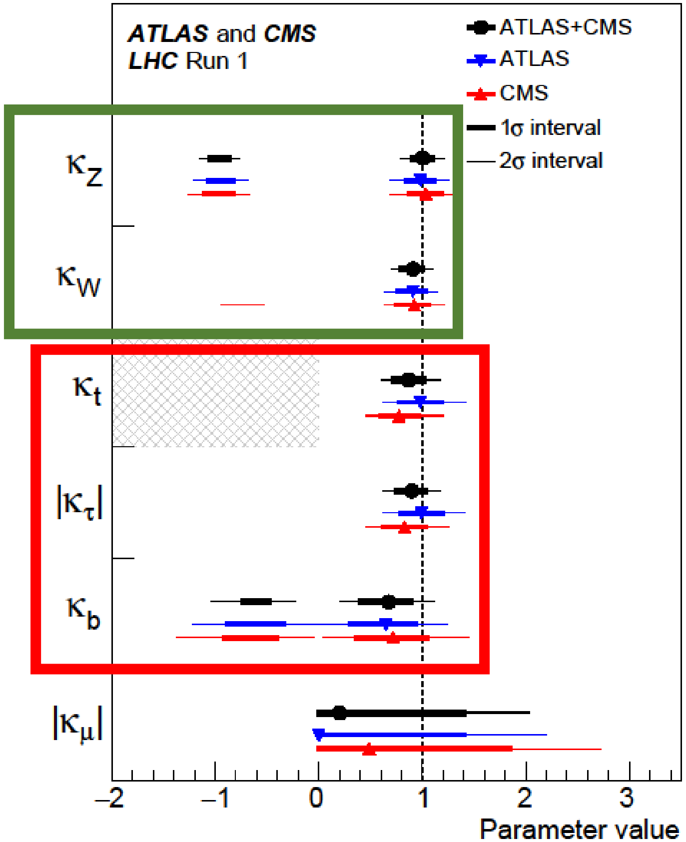
- **Coupling measurements:** **Kappa Framework $\kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$**

Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
Exp Unc.	10%	10%	15%	15%	25%

Couplings to vector bosons / **Coupling to fermions**

Fit to Asimov dataset

- **Best constraints on Higgs boson couplings**
- **From ATLAS+CMS Run 1 combination:**
  - **JHEP 08 (2016) 045**



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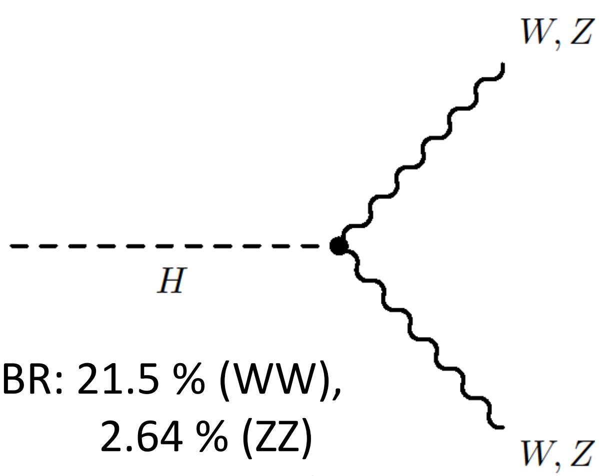
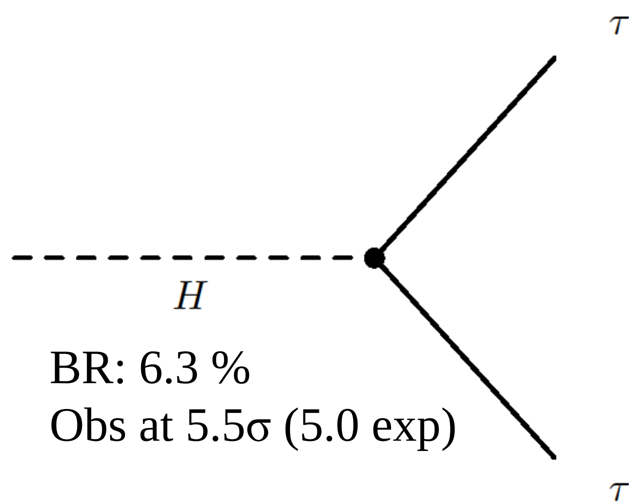
- High precision:
  - All 3 decay modes observed in Run 1 data

Today's interest



BR: 21.5 % (WW),
2.64 % (ZZ)
Stop counting σ's



BR: 6.3 %
Obs at 5.5σ (5.0 exp)

We Have Run 1 Couplings Measurements

- **Coupling measurements:** **Kappa Framework $\kappa_j^{\,2} = \Gamma^j / \Gamma^j_{SM}$**

Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
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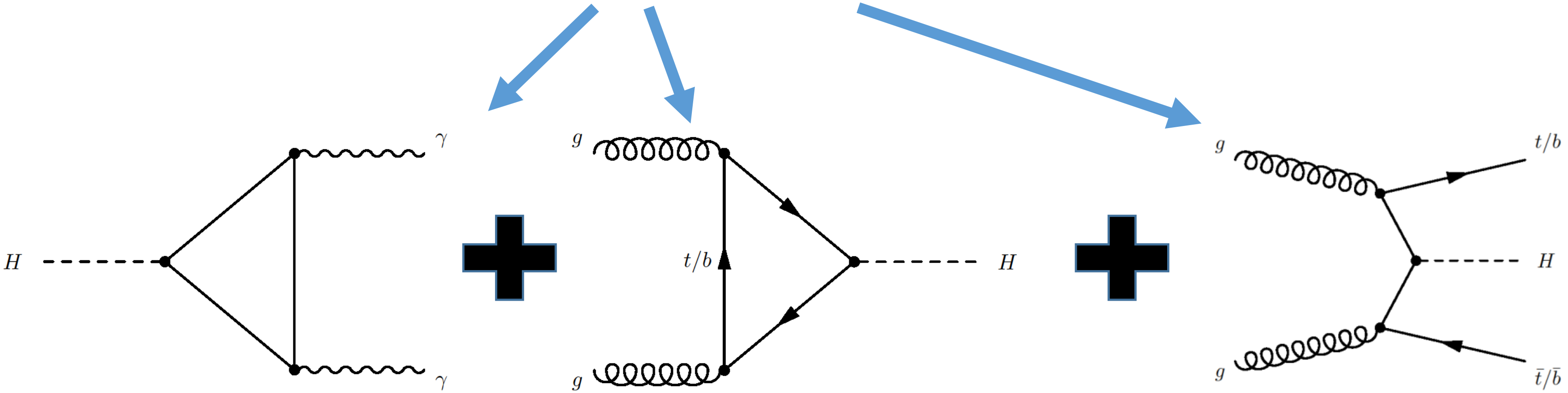
- **Largest Yukawa coupling in the SM**
- **Good constraint on top Yukawa coupling with respect to other couplings**
- **Combines indirect and direct measurements**



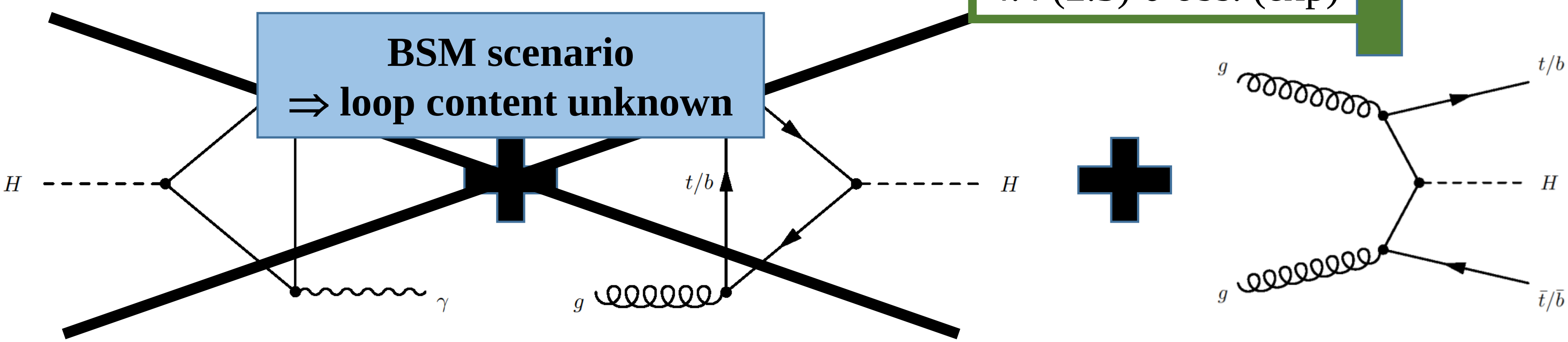
top quark contribution to the loop is fixed in SM. But, what if there is BSM ?

We Have Run 1 Couplings Measurements

- **Coupling measurements: Kappa Framework $\kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$**

Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
Exp Unc.	10%	10%	15%	~~15%~~ **30%**	25%

ATLAS+CMS Run 1
$\mu = 2.3^{+0.7}_{-0.6}$
4.4 (2.3) σ obs. (exp)



We Have Run 1 Couplings Measurements

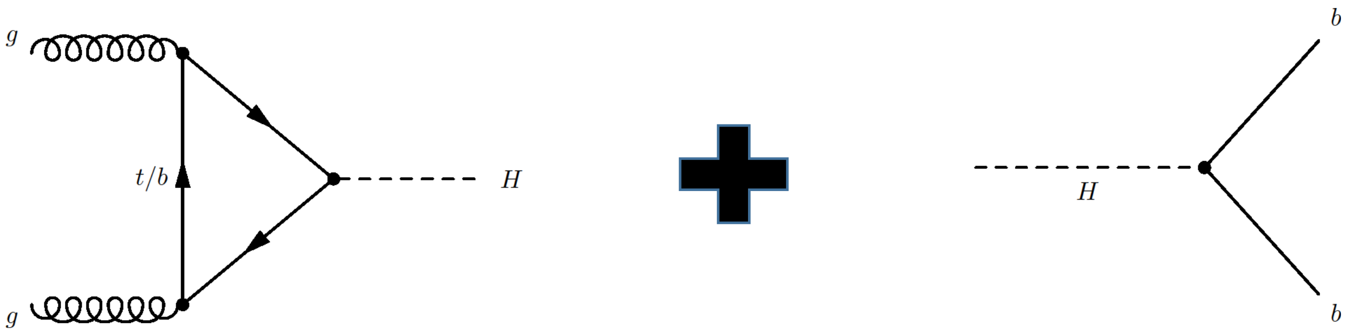
- **Coupling measurements:** **Kappa Framework $\kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$**

Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
Exp Unc.	10%	10%	15%	15%	25%

b quark has highest branching ration

⇒ crucial to constrain Higgs boson width.

Coupling to b: involved in **indirect** and **direct** measurements



Similar to top, but sub-leading contribution in loops

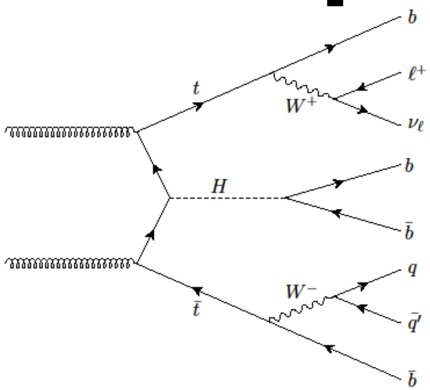
=> **most of the sensitivity from Run 1 H → bb searches**

ttH analysis

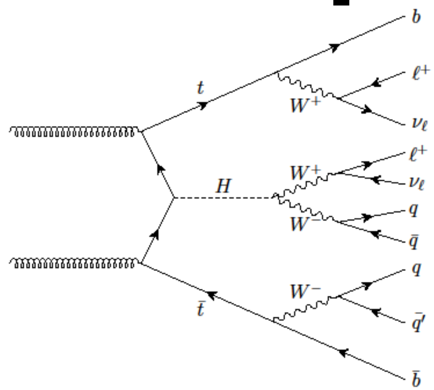
ttH Channels

- **ttH: direct access to κ_t**
  - Constrain BSM in loops
- **Small cross section + complex final state**
  - Divided in 4 analyses ttH(bb), ttH(multi-leptons), ttH(γγ), ttH(ZZ*→4l)

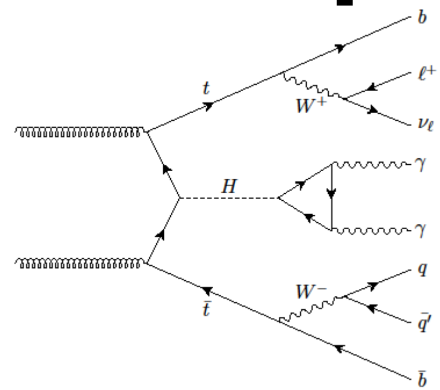
BR ← 58.1% | 30.4% (ZZ+WW+ττ) | 0.227% | 0.013%



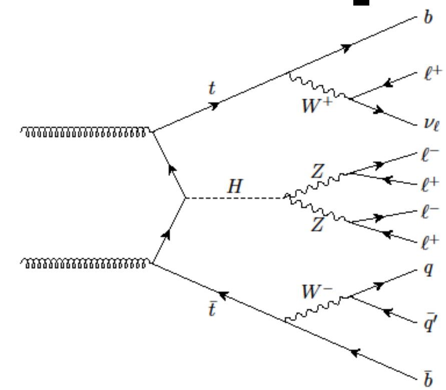
ttH(bb)



ttH(multi-leptons)



ttH(γγ)



ttH(ZZ*→4l)

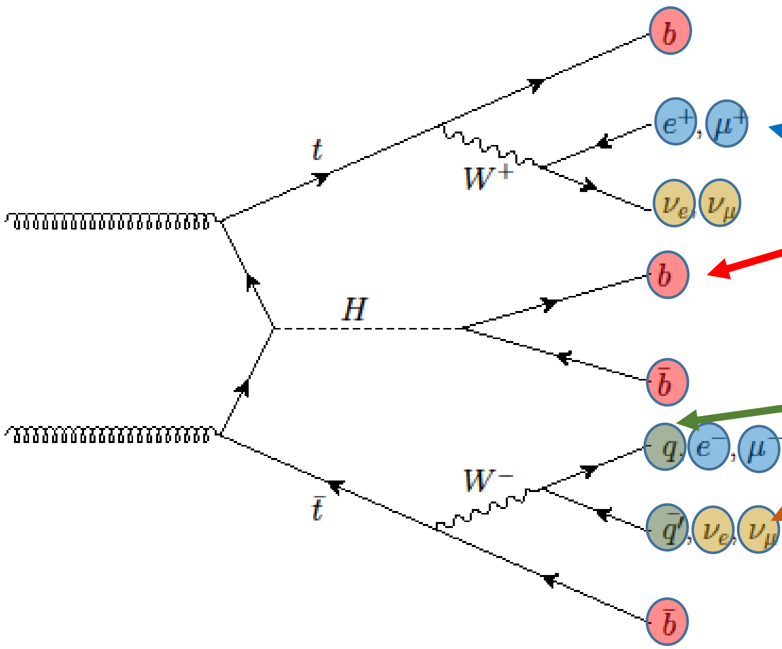
1 to 6% | 4 to 34% | 11 to 52% | 500% → **Purity S/B**

ttH(bb)

arXiv:1712.08895

ttH(bb) A Complex Final State

- The ttH(bb) search is a complex analysis

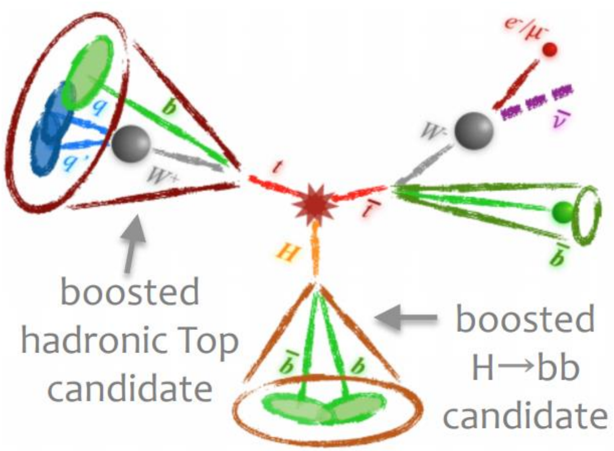


Busy final state:

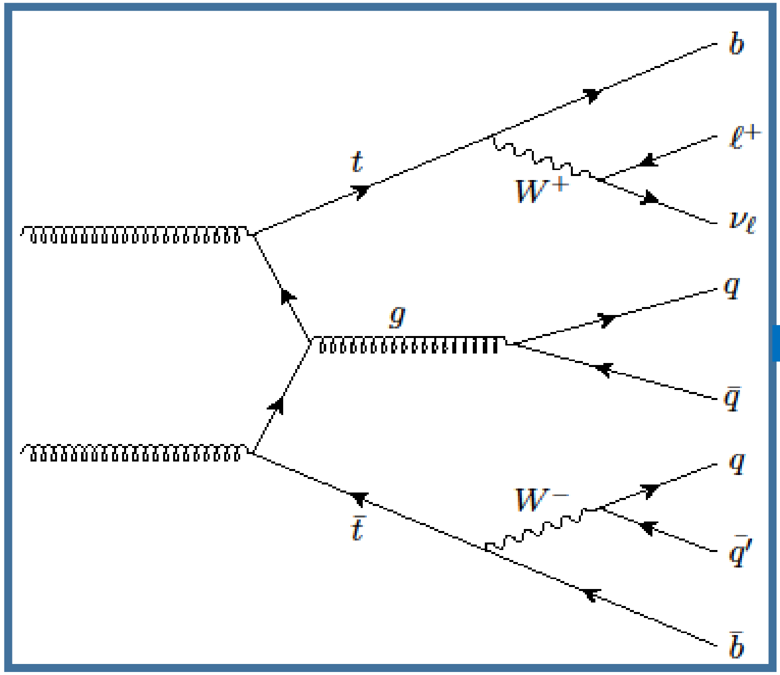
- 1 or 2 leptons ⇒ single or di-lepton channels
- 4 b-jets ⇒ b-tagging is a crucial input !
  - with perfect b-tagging, 6 Higgs boson candidates
- 0 or 2 additional jets (6 jets in single lepton)
- 1 or 2 neutrinos ⇒ no real impact of MET

Run 2 addition: boosted selection

- ✓ Targets high p_T Higgs and tops
- ✓ For future differential measurements



How To Deal With tt+jets



Main challenge

tt+jets background:

→ 350 times bigger than ttH(bb)

→ 82% of the background

Split in 3 components:

→ tt+light

→ tt+≥1c

→ **tt+≥1b: irreducible**

Strategy:

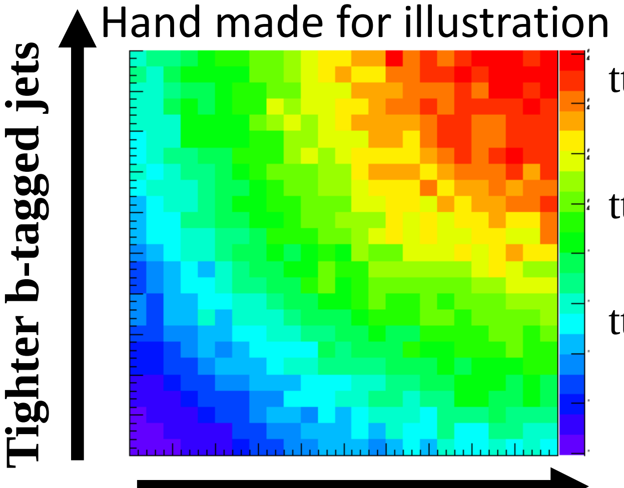
- Separate signal and each tt+jets components
- Fit all components to data simultaneously

How To Deal With tt+jets

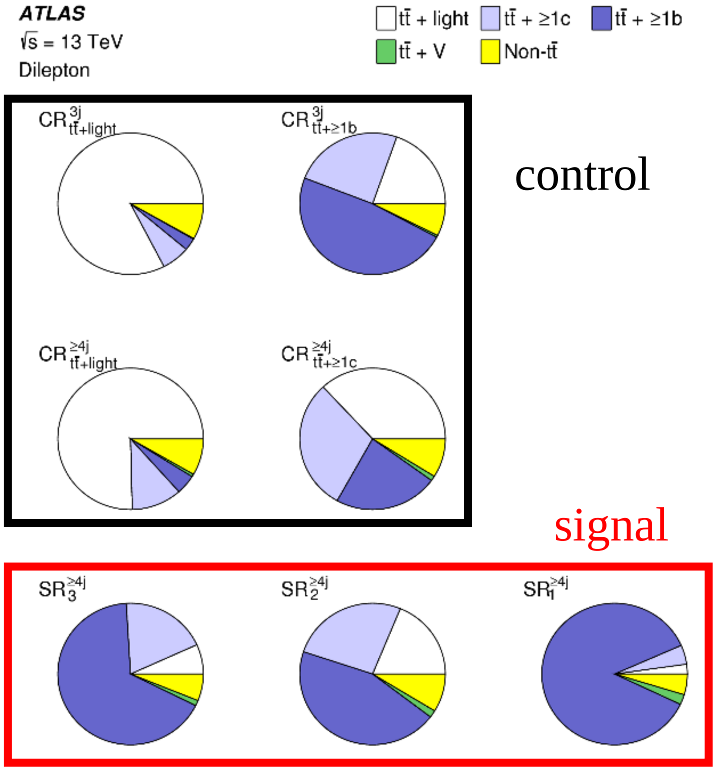
- **Separate signal and tt+jets components**:
  - Advanced categorization to define control regions enriched in tt+light, tt+≥1c and tt+≥1b
  - MVA technics to separate tt+≥1b and ttH(bb)
- Fit all components to data simultaneously

Categorization:
Use N(jets) and N(b-tags) at multiple working points

Hand made for illustration



19 categories defined



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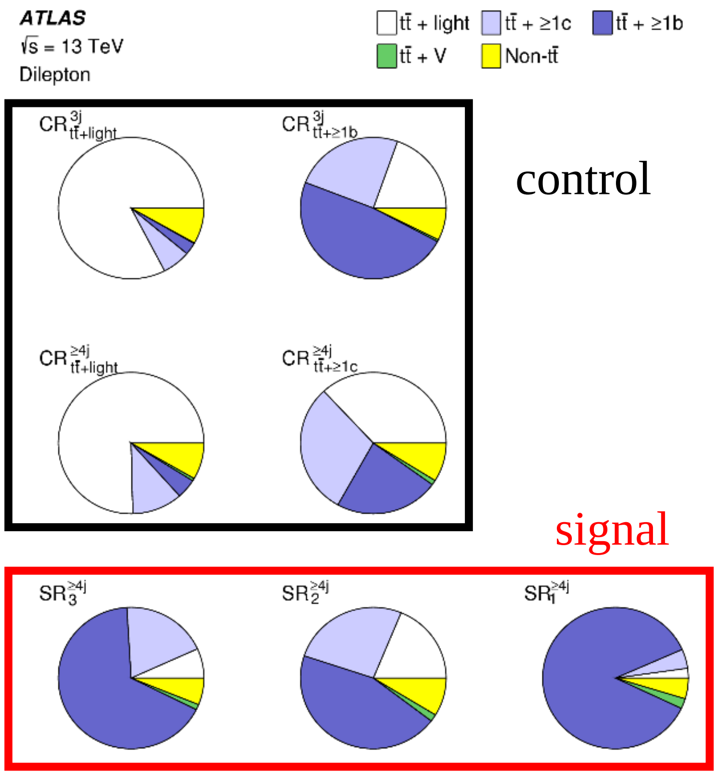
Categorization:
Use N(jets) and N(b-tags) at multiple working points

b-tagging can't separate ttH(bb) and tt+bb (4 b-quarks)
⇒ Maximum purity 5.4%

19 categories defined



control

signal

How To Deal With tt+jets

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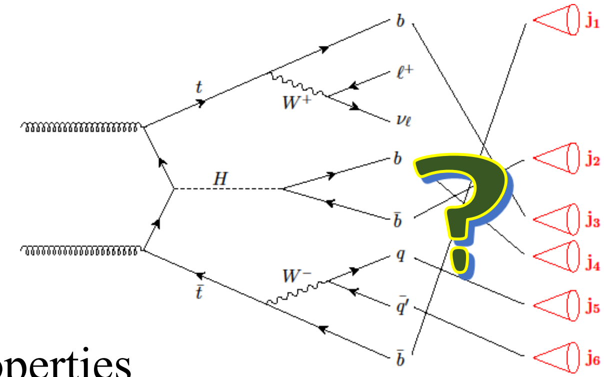
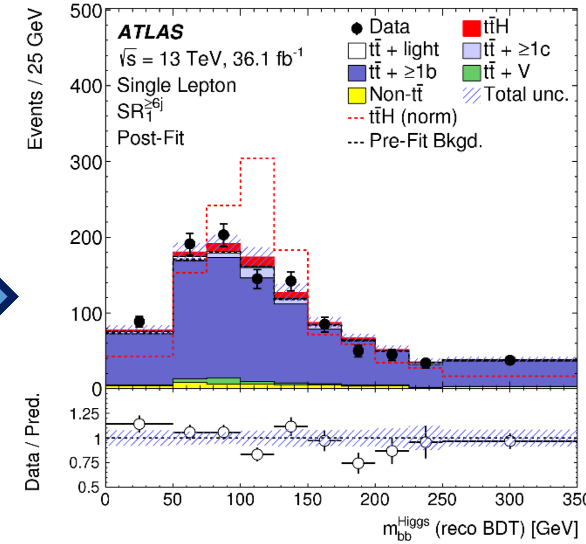
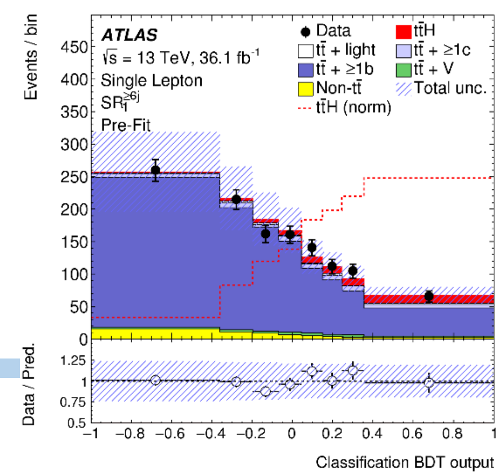


Reconstructed Higgs mass



Step 1: reconstruction
→ Exploit final state properties
→ BDT to find best matching reco objets ↔ final state particles

Step 2: Final BDT for ttH(bb) VS tt+bb separation:
→ combines step 1 output with b-tag and general variables



How To Deal With tt+jets

- **Separate signal and tt+jets components**:
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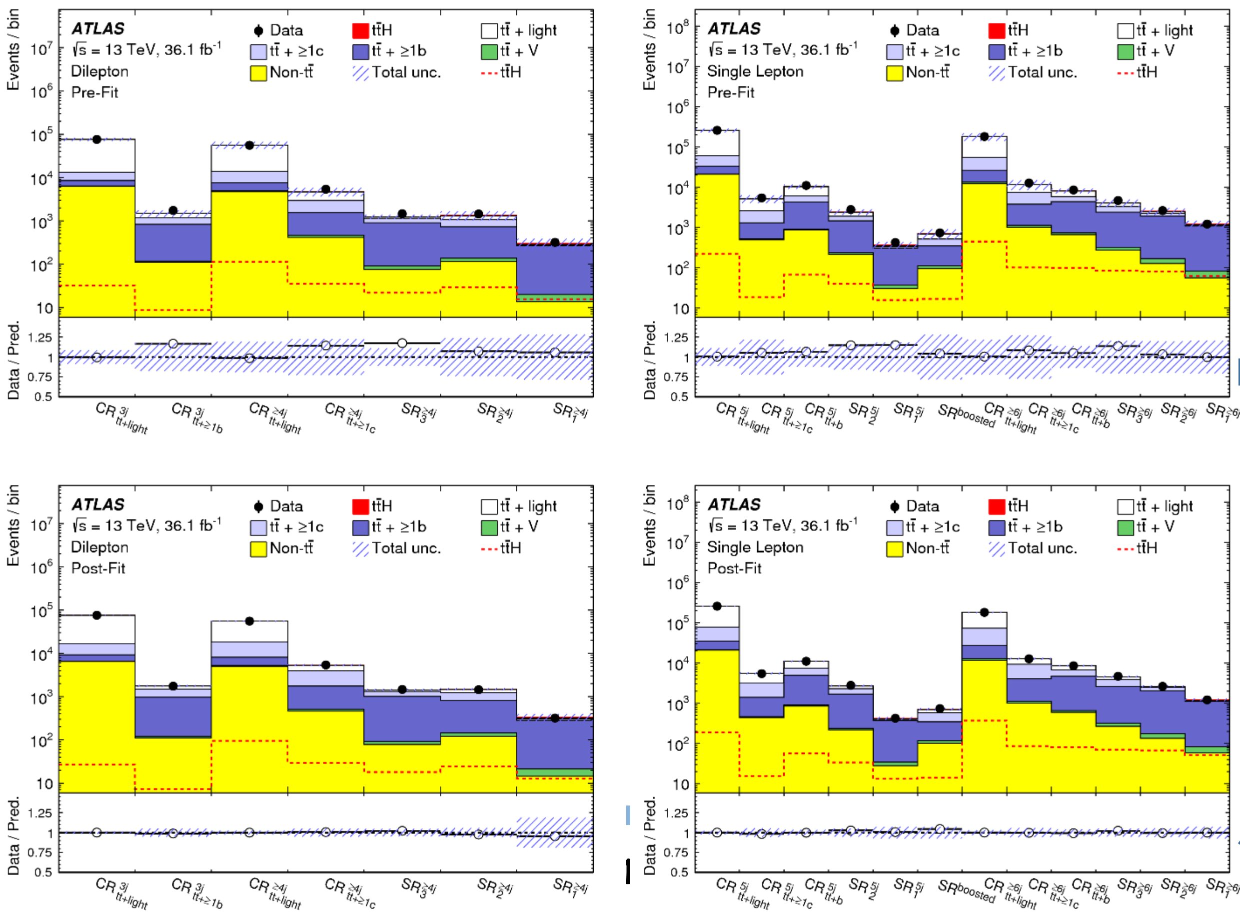
Match observed data



Constrain modeling uncertainties

ttH(bb) result

- **Separate signal and tt+jets components**:
  - Advanced categorization to define control regions enriched in tt+light, tt+≥1c and tt+≥1b
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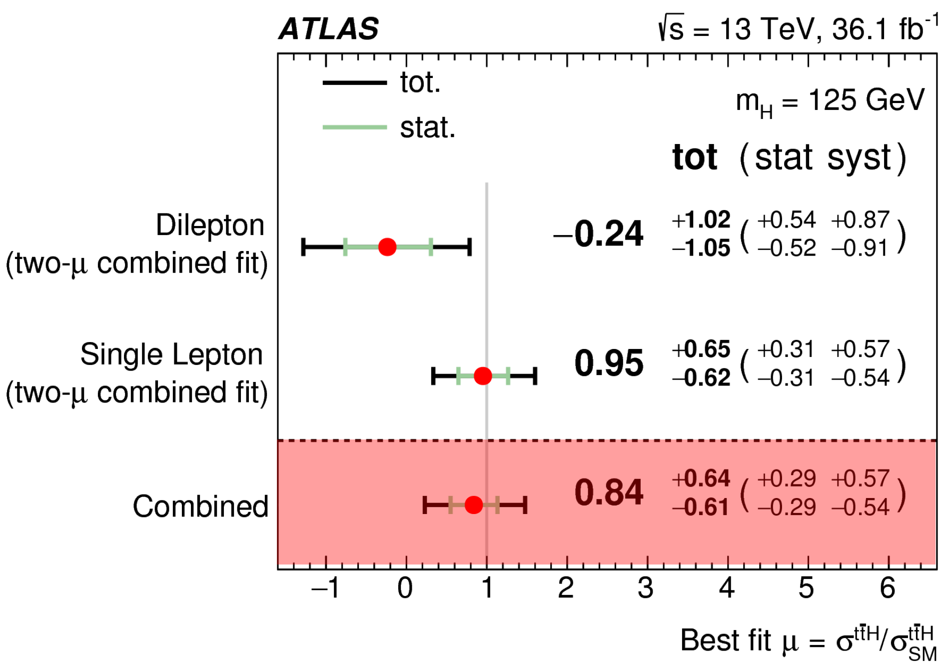
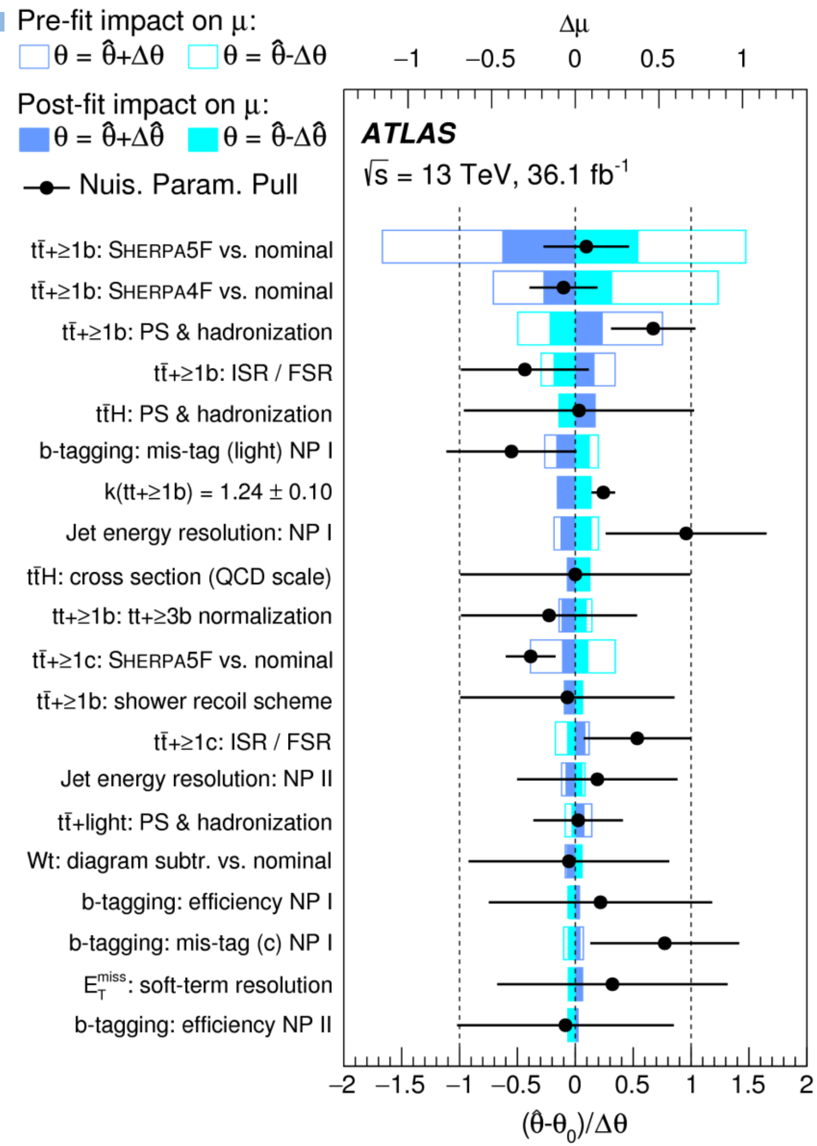


Observed $\mu = 0.84^{+0.64}_{-0.61}$
⇒ 1.1σ significance (1.4 exp)

In terms of upper limit:
⇒ μ < 2 x SM at 95% CL

And What About The Modeling ?

Impact of and corrections applied to the 20 most important uncertainties



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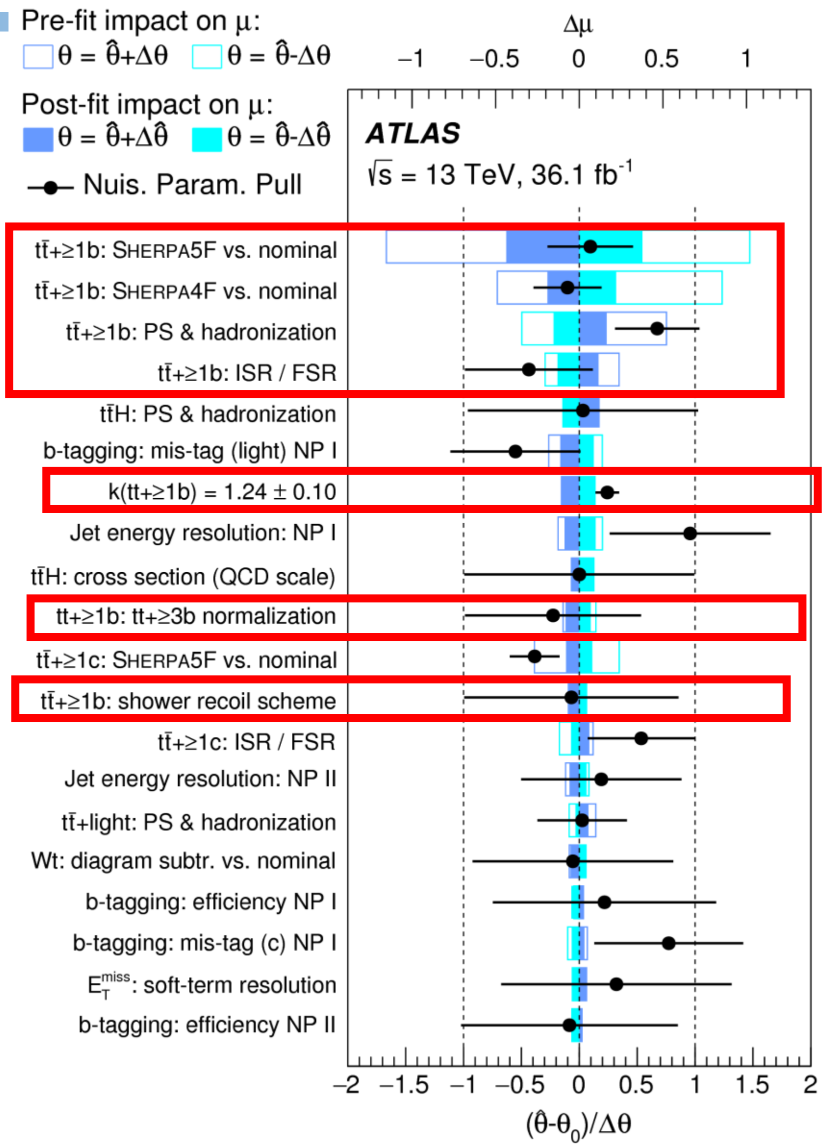
tt+≥1b uncertainties



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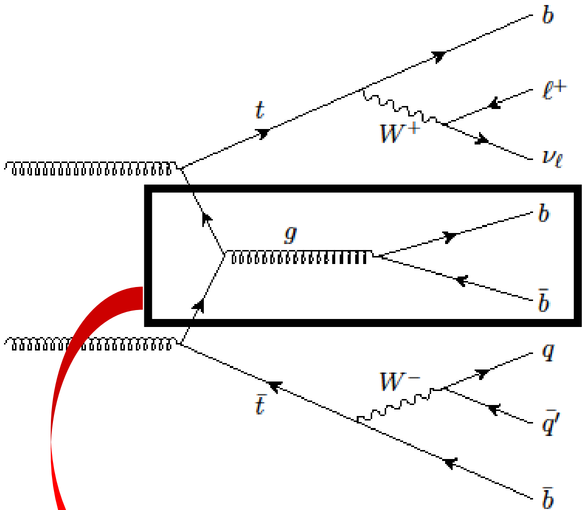
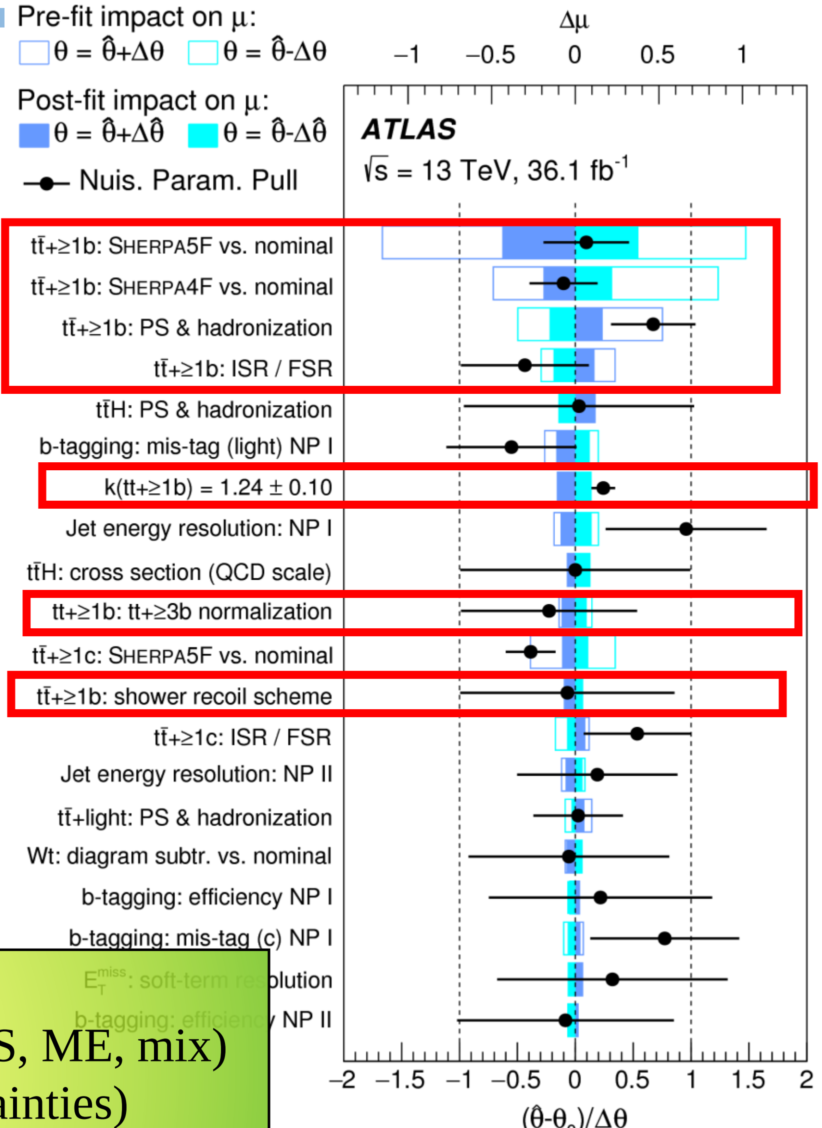




Very little guidance how to model additional g→bb

Various model tested:

→ Different predictions (g→bb from PS, ME, mix)

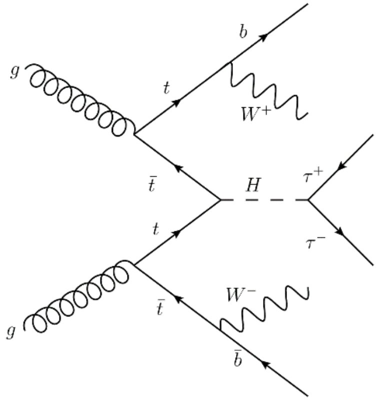
All giving the same results (within uncertainties)

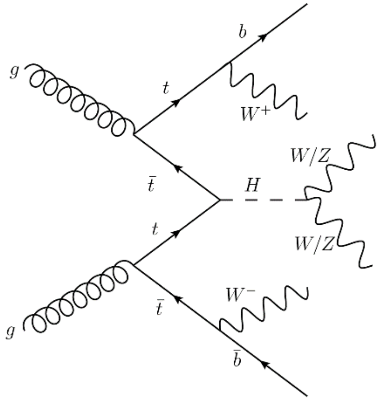
→ Confidence in signal extraction

ttH(WW*, ττ, ZZ*)

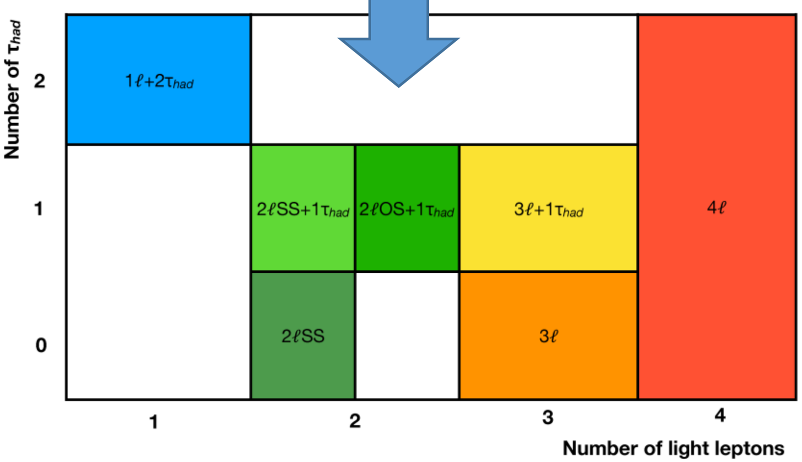
arXiv:1712.08891

ttH(multi-leptons)

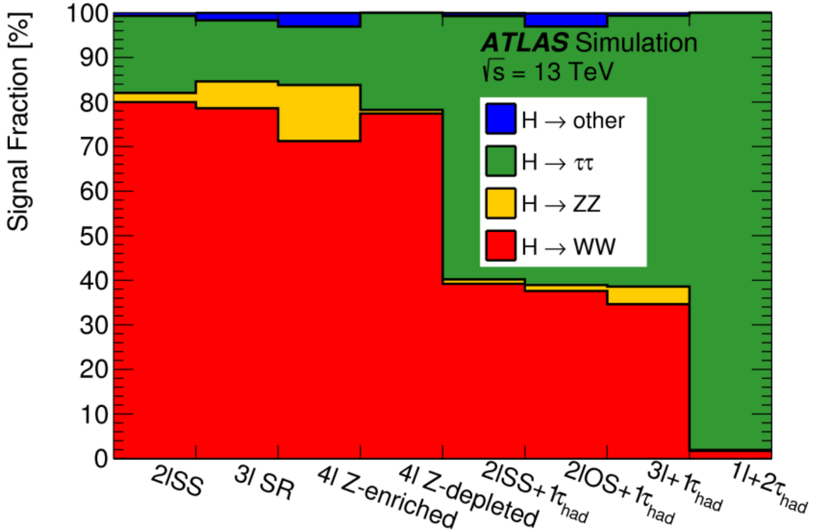




Combines many possible signatures
Categorized with N(leptons: e, μ) and
N(τ: hadronic)



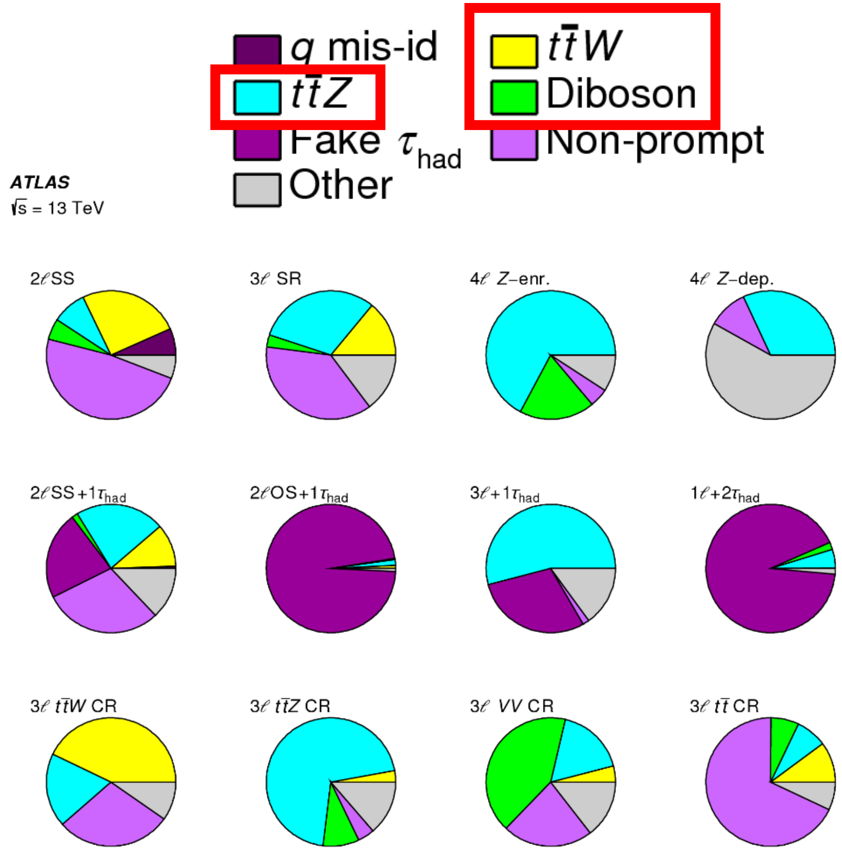
The needs of the many (leptons) outweigh the needs of the few



Primarily targeting H→WW*, ττ, ZZ*

ttH(multi-leptons): Associated Backgrounds

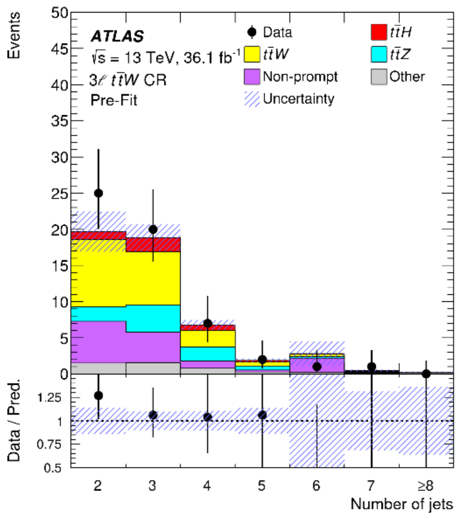
Selection leads to 2 main background types

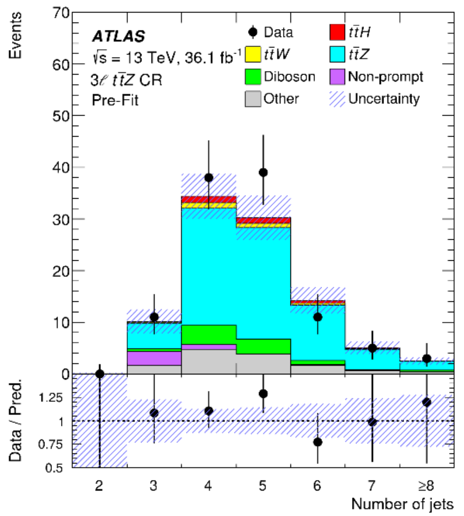


Prompt lepton backgrounds: ttW, ttZ, di-boson

→ Use Monte Carlo prediction

→ Validated in control regions





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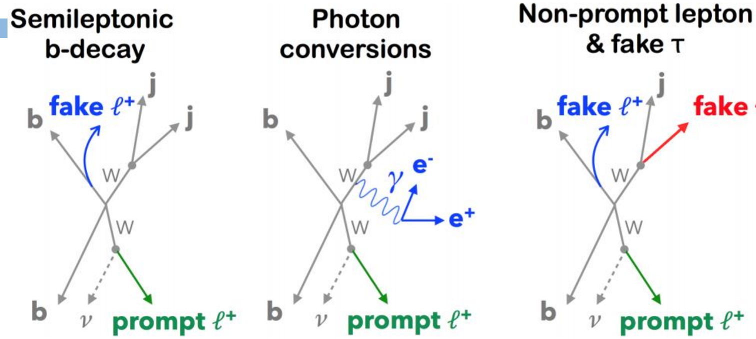
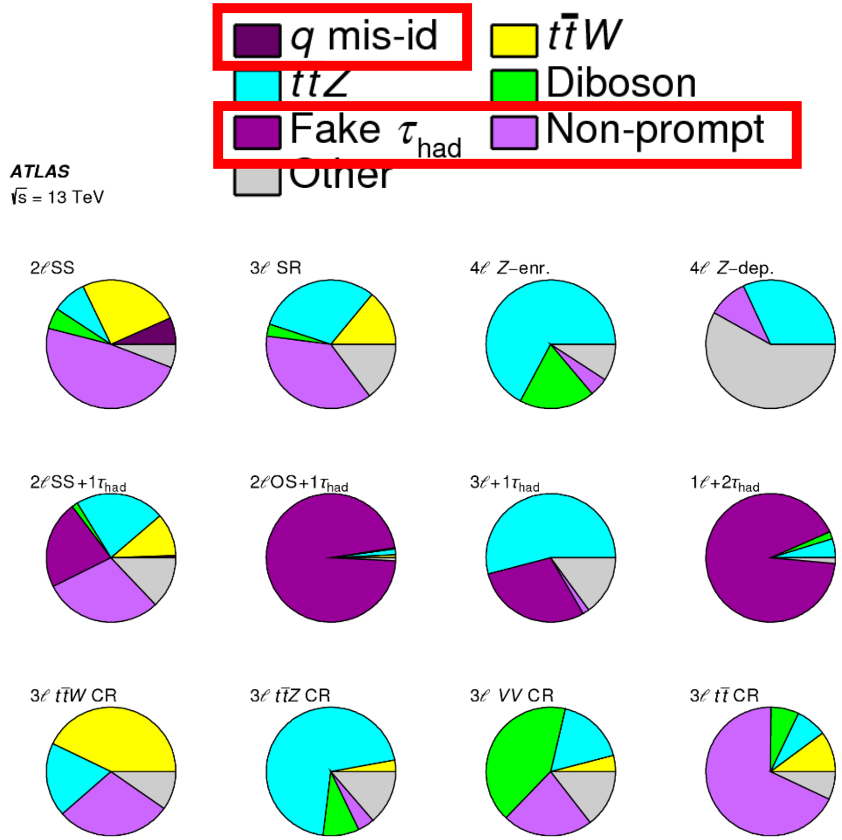
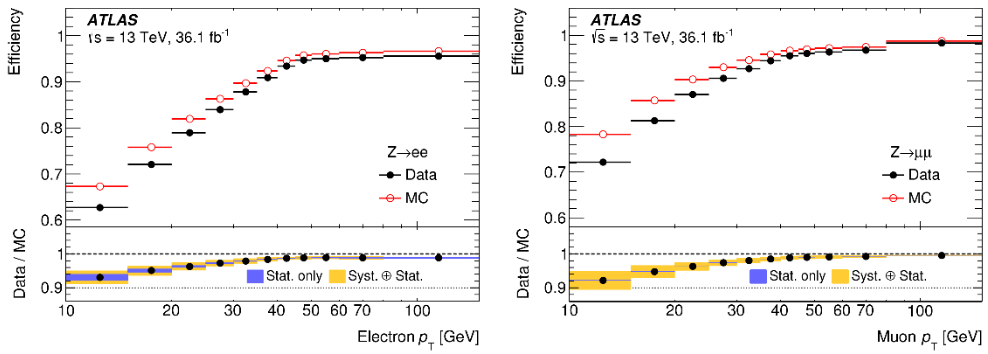




Non-prompt leptons, τ and charge misassignment:

→ Data driven estimate in control regions

→ Reduced by applying cuts on dedicated BDTs



Prompt e and μ identification efficiencies for the chosen BDT working point

ttH(multi-leptons): Fit Strategy

- Further reduce background contributions with BDTs
- Fit all components to data simultaneously

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Similar strategy as ttH(bb), but:

→ several backgrounds to isolate

→ independent MVAs for each categories (with enough statistic)

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\mathrm{had}}$	$2\ell\mathrm{SS}+1\tau_{\mathrm{had}}$	$2\ell\mathrm{OS}+1\tau_{\mathrm{had}}$	$3\ell+1\tau_{\mathrm{had}}$
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	-	-	-	-	-

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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	$t\bar{t}$	-
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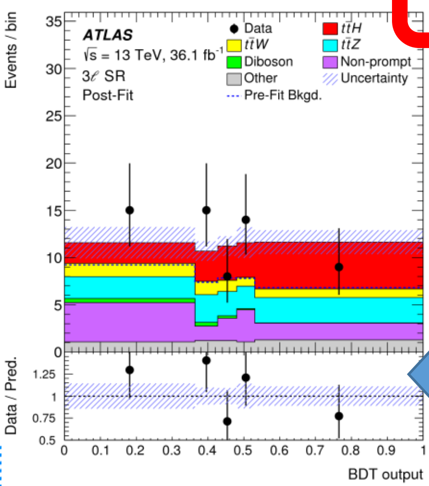
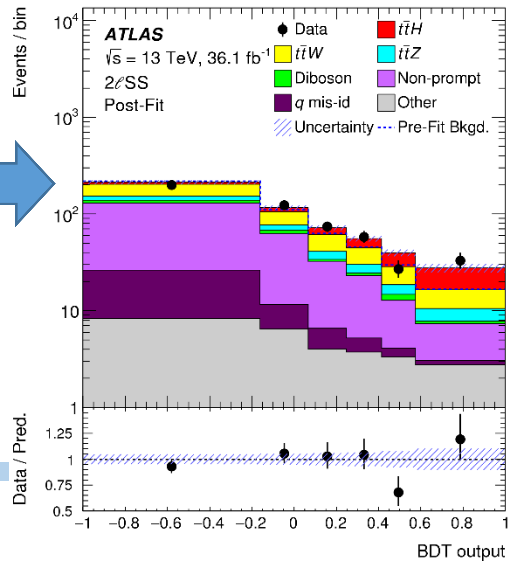
Control regions	-	4	-	-	-	-	-

Multi-dimension BDT (1 per process)



Output in 2 same-sign lepton category



In 3l: built 5 categories (4bkg + 1sig)
Discriminant = signal focused BDT

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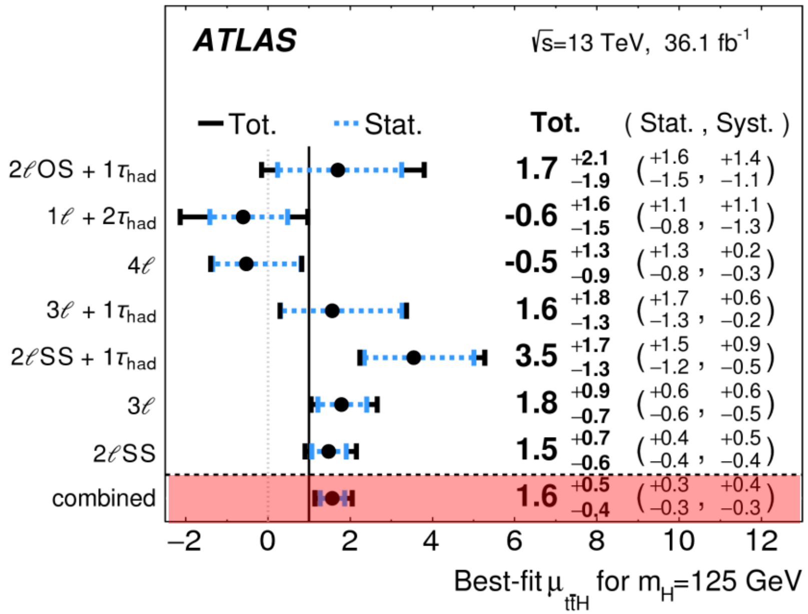


Channel	Significance Observed	Significance Expected
$2\ell OS+1\tau_{had}$	0.9σ	0.5σ
$1\ell+2\tau_{had}$	–	0.6σ
4ℓ	–	0.8σ
$3\ell+1\tau_{had}$	1.3σ	0.9σ
$2\ell SS+1\tau_{had}$	3.4σ	1.1σ
3ℓ	2.4σ	1.5σ
$2\ell SS$	2.7σ	1.9σ
Combined	4.1σ	2.8σ

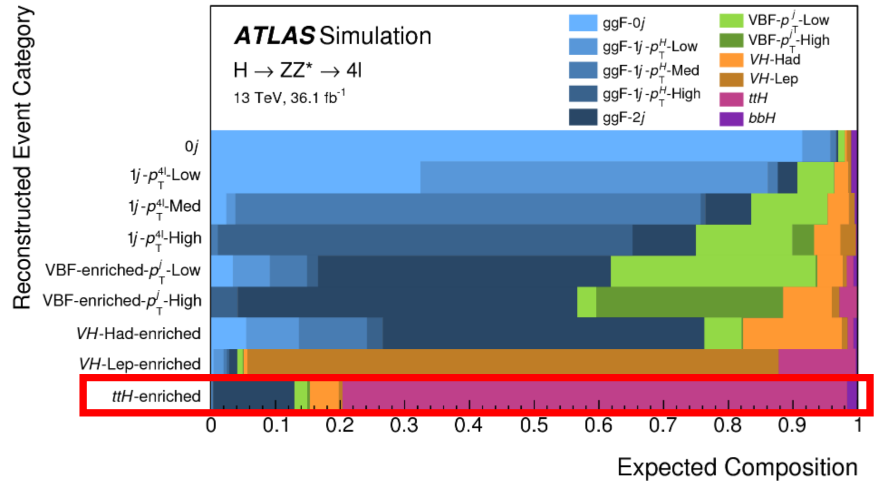
Observed signal strength: $\mu = 1.6^{+0.5}_{-0.4}$
Corresponding to a 4.1σ observed significance (for 2.8σ expected)

$t\bar{t}H(ZZ^* \rightarrow 4l)$

arXiv:1712.02304

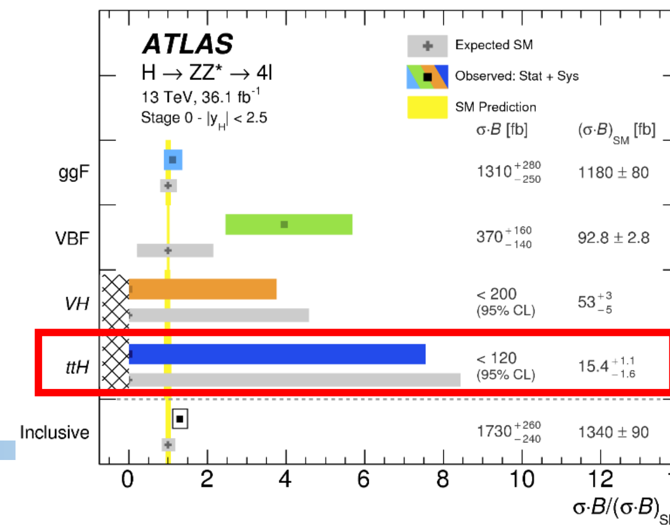
ttH(ZZ*→4l): A New Player

- **Included in main H→ZZ*→4l analysis:**
  - "ttH enriched category":
    1 b-tag + (≥4 jets or 1 lepton and ≥2jets)
- **Very pure channel**
- **Very low stat: 0.39 ttH events expected**
  0 observed



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

Setting upper limits at 120 fb at the 95% CL (8 times SM)



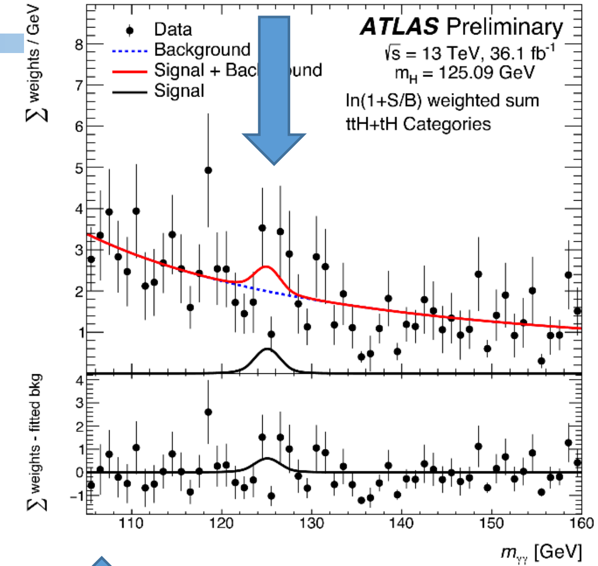
ttH($\gamma\gamma$)

ATLAS-CONF-2017-045

ttH(γγ)

- Included in main H→γγ analysis
- Rely on excellent M(γγ) resolution over a continuous background

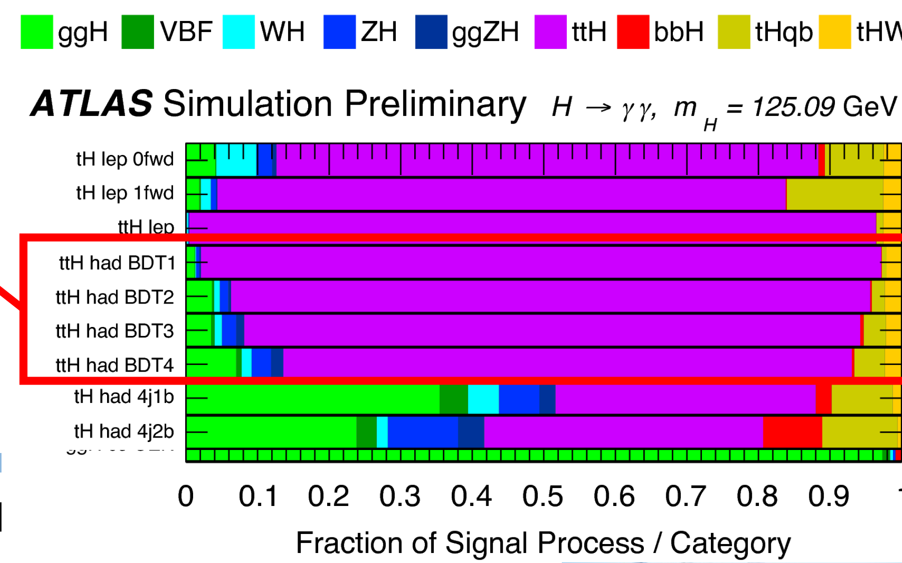
Signal as double sided crystal ball around 125 GeV



Extract background from side bands

Strategy:

- ➢ Use H→γγ selections
- ➢ "Enriched ttH category":
  - ➢ high N(jets), N(b-tags)
  - ➢ 0 or 1 lepton ⇒ hadronic or semi-lep categories
  - ➢ In hadronic categories:
    - ➢ BDT to discriminate ggH and ttH
    - ➢ Used to refine categorisation



ttH(γγ)

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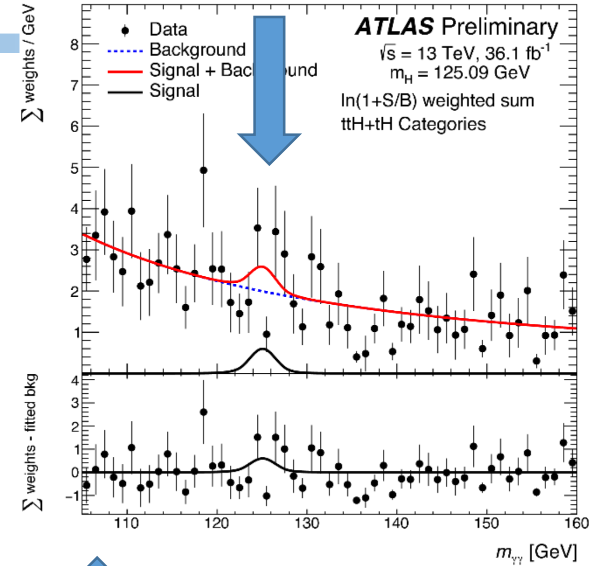
Signal as double sided crystal ball around 125 GeV



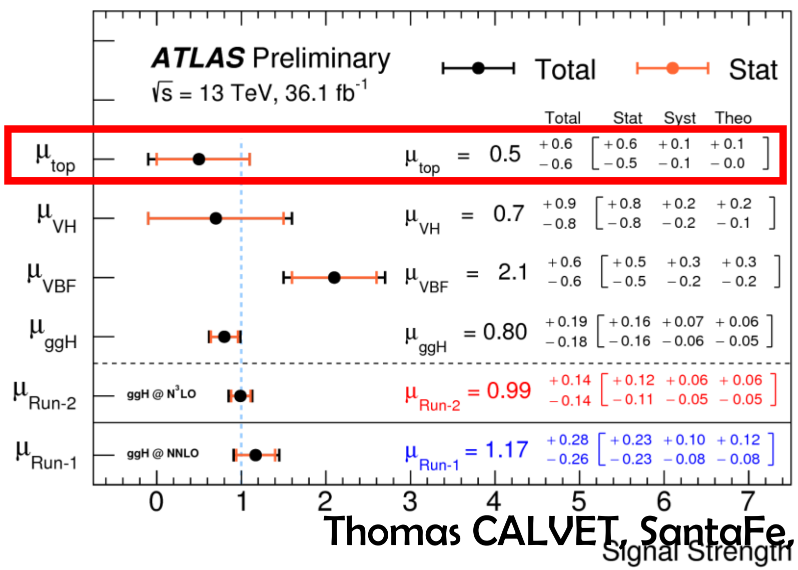
Extract background from side bands

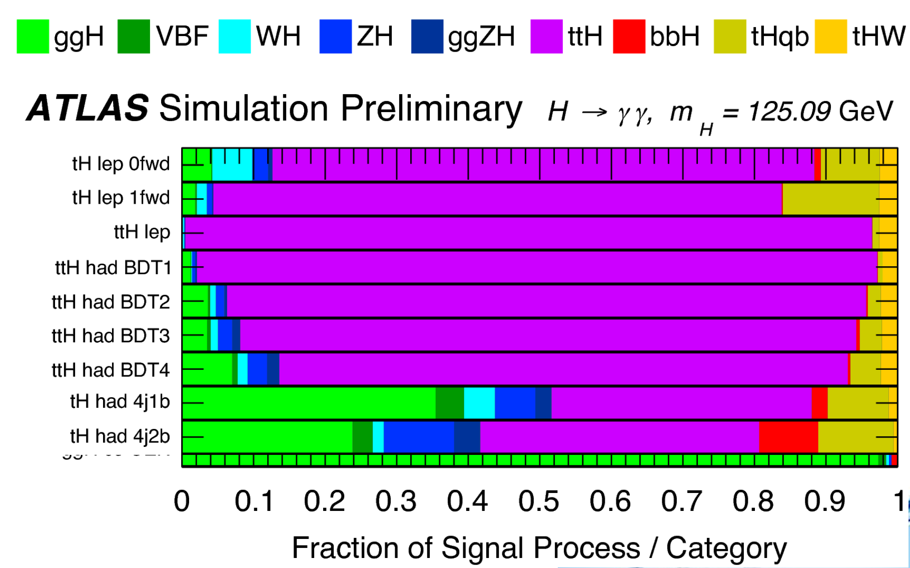
Strategy:

- ➢ Use H→γγ selections
- ➢ "Enriched ttH category"
- ➢ Consider categories enriched in tH

Combined fit with other H→γγ channels

➢ **μ(ttH) = 0.5 ± 0.6**





ttH combination

arXiv:1712.08891

Combination Of ttH Analyses: Result

Best fit value: **μ = 1.2 ± 0.3**

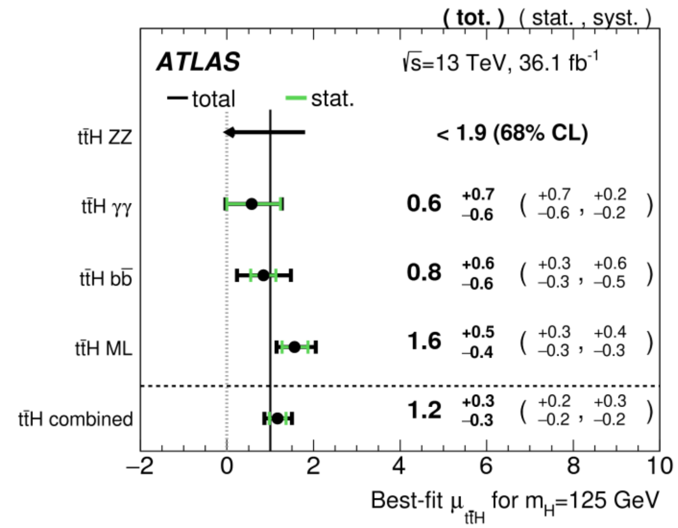
→ **Compatible with SM**

→ **Syst limited:**

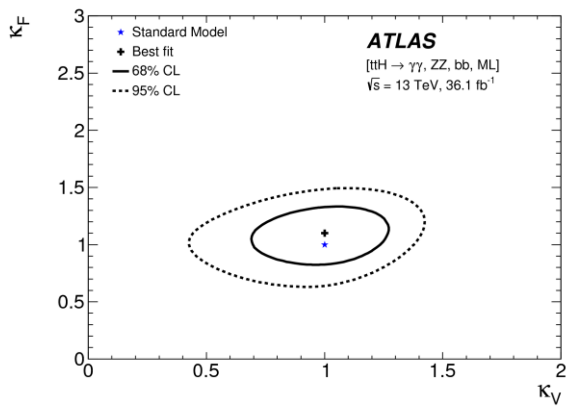
- → Channel specific modeling unc.
- → Signal uncertainties

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

Evidence of ttH production:
4.2σ (exp: 3.8σ)
Measured Cross section:
790^{+230}_{-210} fb (SM: 507^{+35}_{-50} fb)



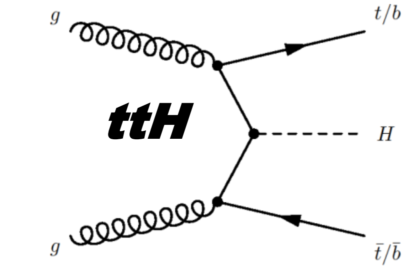
Kappa coupling: fermions against bosons

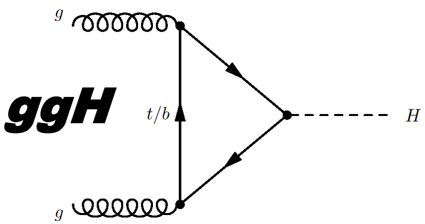


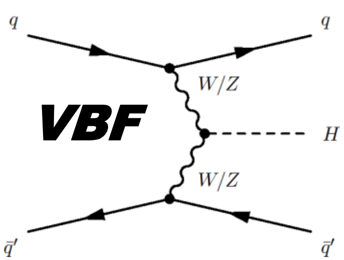
$H \rightarrow bb$ analysis

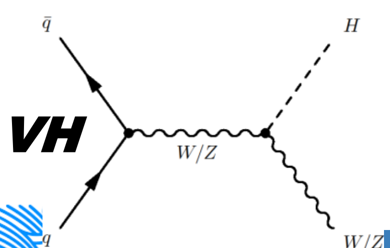
Where To Search For H→bb ?

- **4 production modes are available:**



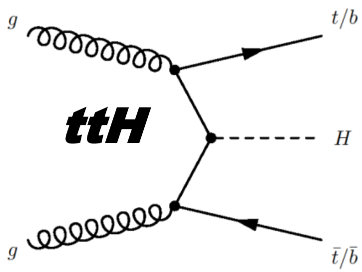




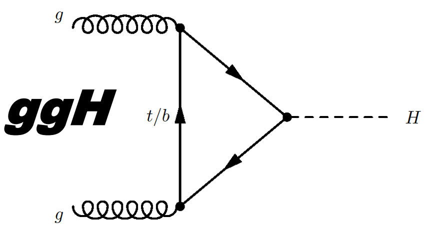


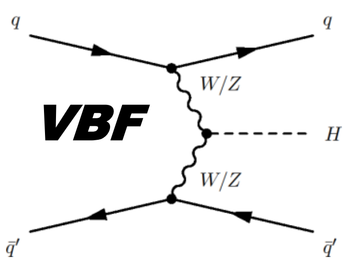
Where To Search For H→bb ?

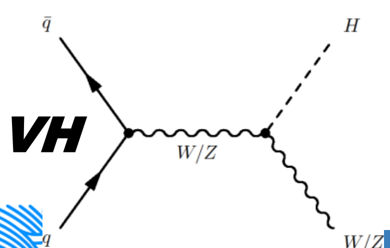
- **4 production modes are available:**



Already discussed: need tt+bb ✓







Where To Search For H→bb ?

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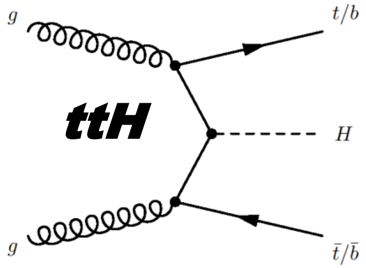
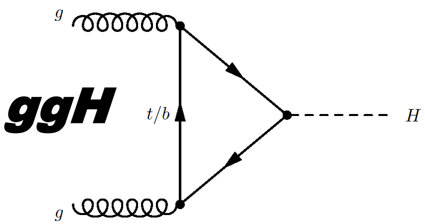


Already discussed: need tt+bb ✓

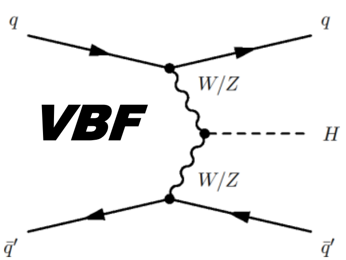


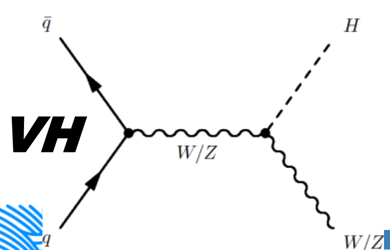
Only 2 b-jets in the final state

⇒ Large multi-jet contamination

⇒ Not viable

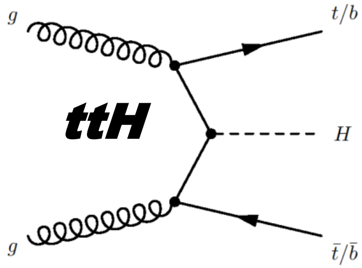
May be possible at high p_T in boosted regime (see CMS paper: arXiv:1709.05543)



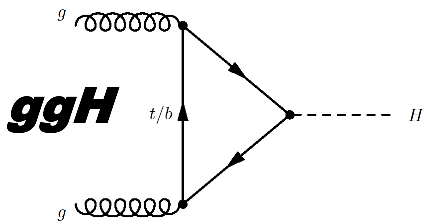


Where To Search For H→bb ?

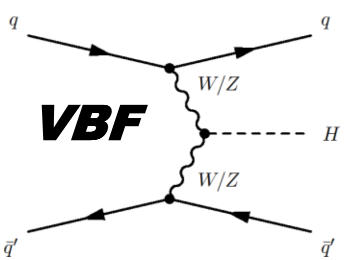
- **4 production modes are available:**



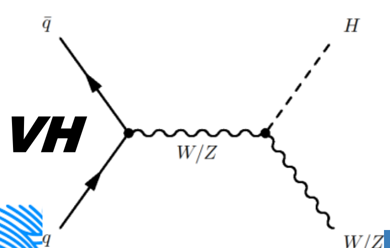
→ Already discussed: need tt+bb ✓



→ Not yet viable ✗ (boosted ?)



→ 2jets + 2b-jets ⇒ large multi-jet background
→ Cross section: 3.78pb
→ However: large increase in S/B with an additional photon



→ The most sensitive channel:
→ Relatively high σ x BR (2.25pb x 58%)
→ uses leptonic W/Z decays to trigger

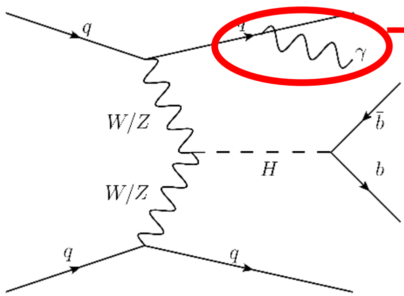
To discuss (VBF, VH)

VBF+γ, $H\rightarrow bb$

ATLAS-CONF-2016-063

VBF+γ With H → bb

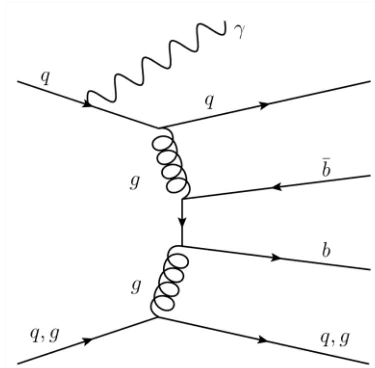
ATLAS-CONF-2016-063



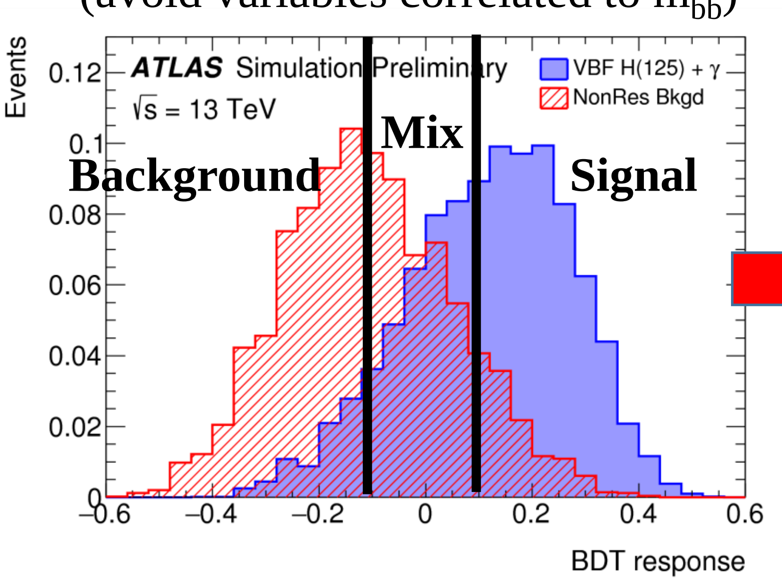
Trigger additional photon:

⇒ large loss in cross section

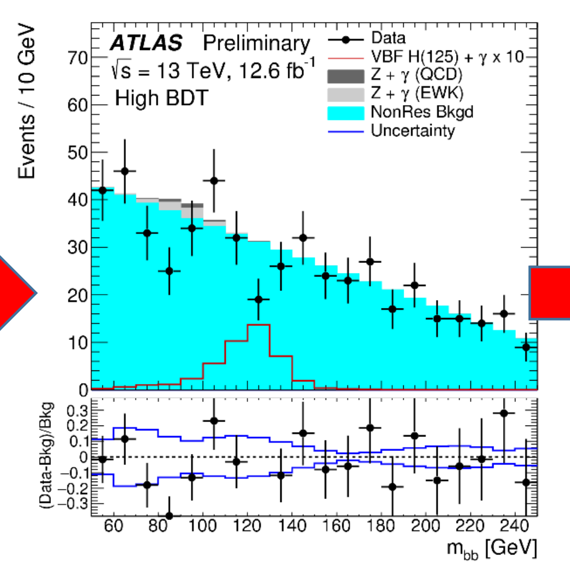
⇒ drastic multi-jet reduction + background destructive interference



Step1: Signal VS background BDT to define 3 regions (avoid variables correlated to m_{bb})



Step 2: Fit m_{bb} in each regions



Low sensitivity:

0.4σ exp

$\mu = -3.9^{+2.8}_{-2.7}$

Done at 12.6 fb^{-1}

will need stat

VH(bb)

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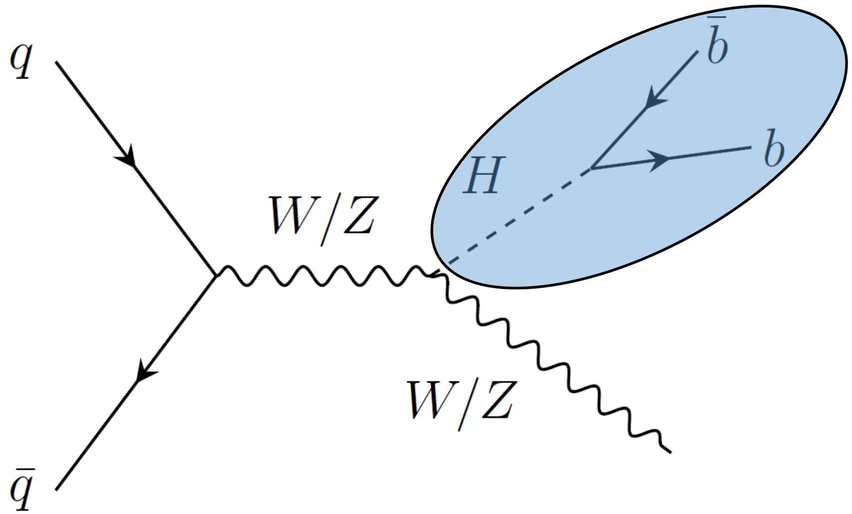
VH(bb) The Savior



Reconstruction of the 2 b is a key ingredient

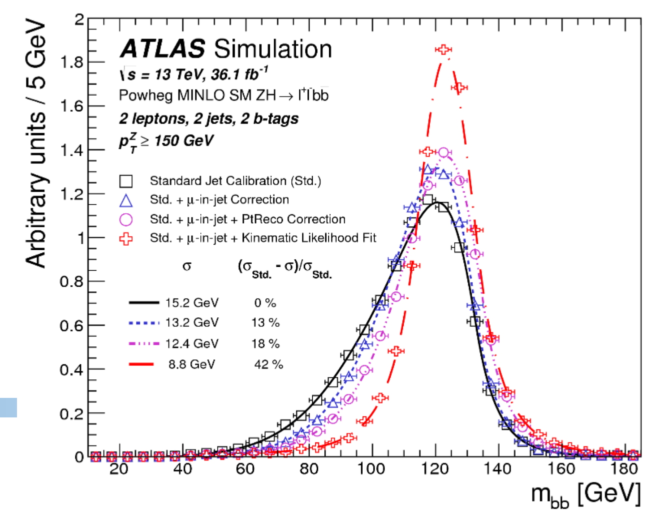
Precise $p_T(b)$ measurements

"Re-calibrate" b-jets:

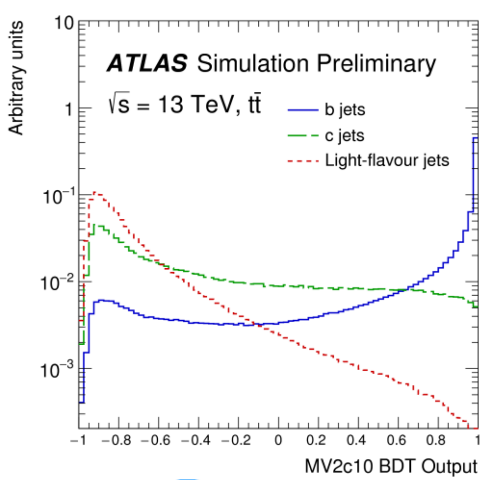
→ Muon in jet corrections

or { → Use response from MC (PtReco)
→ 2l channel: fit llbb transverse kinematic }

Improves m_{bb} resolution by up to 40%



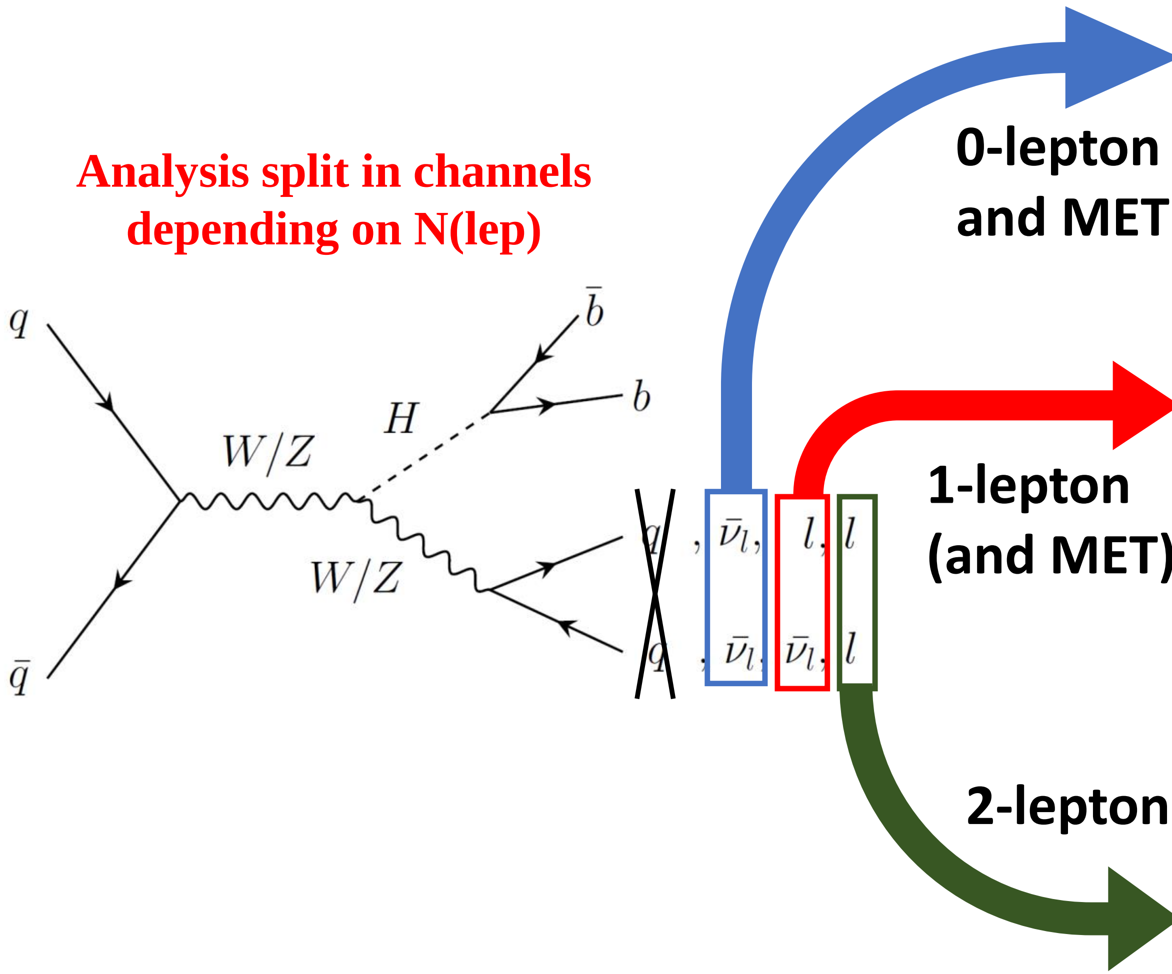
High performance b-tag

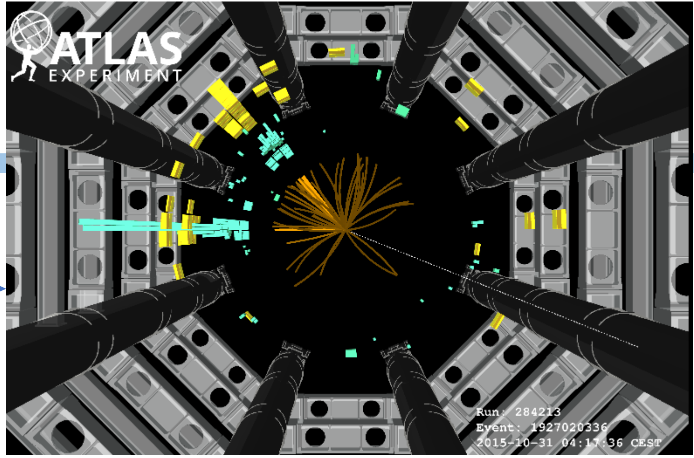


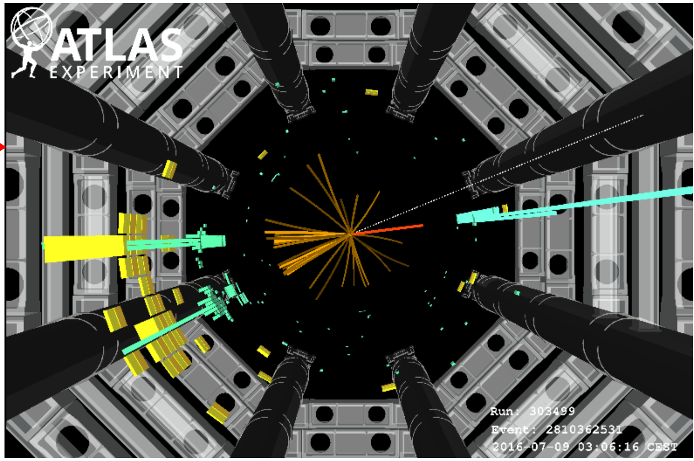
Flavor	Efficiency
b-jet	70%
c-jet	8.2%
light-jet	0.3%

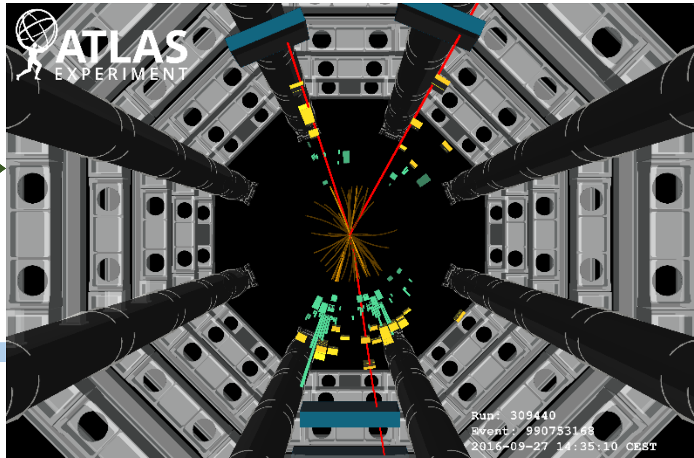
VH(bb) Channels

Analysis split in channels depending on N(lep)

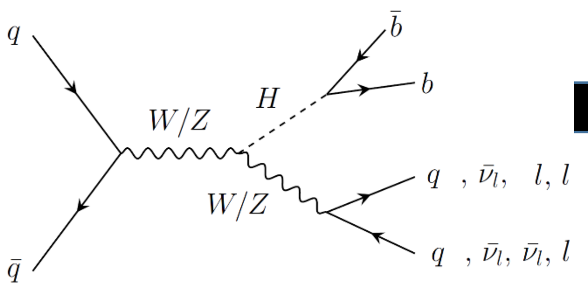








VH(bb) Final Categories



Further categorize events:

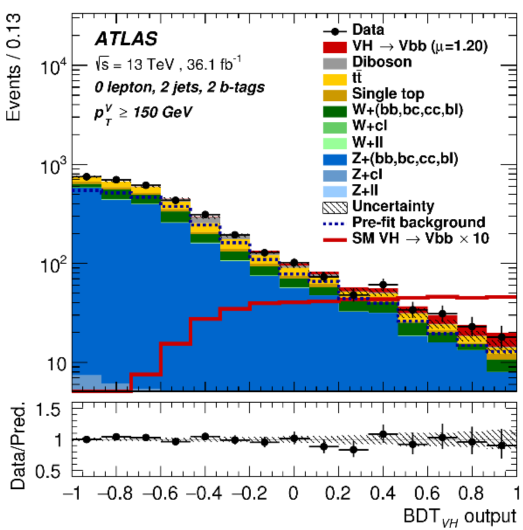
→ Sensitive to relatively high $p_T(V)$

→ Also split in 2 or 3 jets

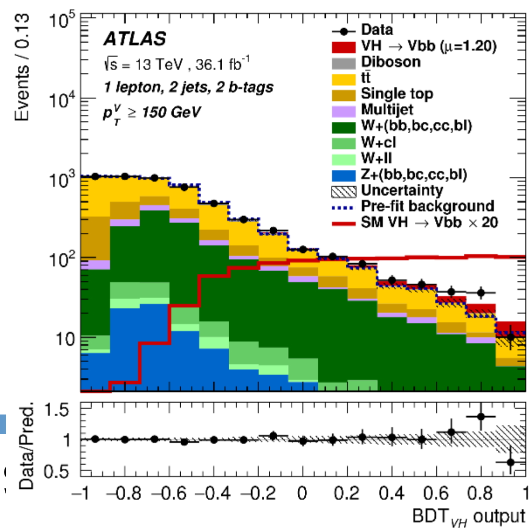
Channel	SR/CR	Categories			
		75 GeV $< p_T^V <$ 150 GeV		$p_T^V >$ 150 GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	✓	✓
1-lepton	SR	-	-	✓	✓
2-lepton	SR	✓	✓	✓	✓

Main backgrounds:

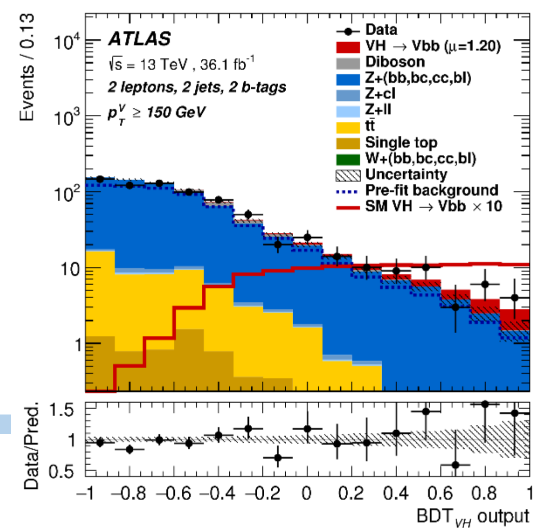
Z+HF, W+HF, ttbar



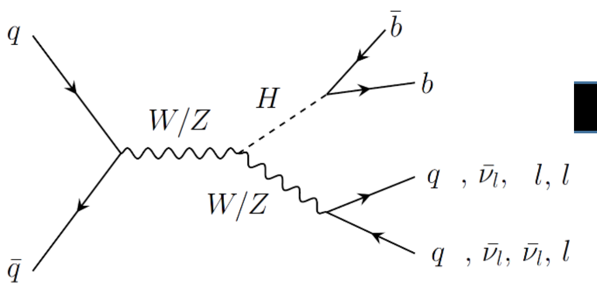
W+HF, ttbar



Z+HF, ttbar



VH(bb) Final Categories



Further categorize events:

→ Sensitive to relatively high $p_T(V)$

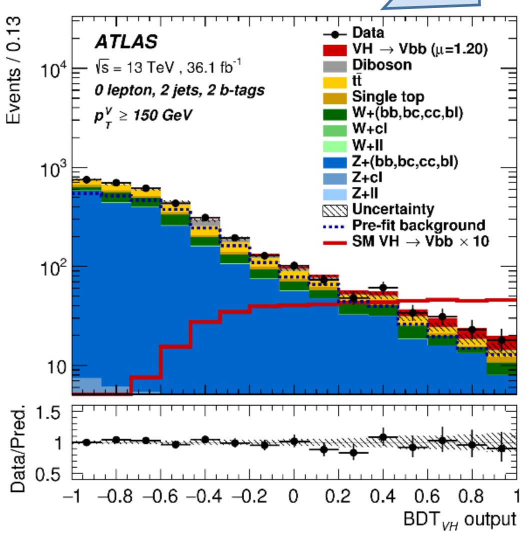
→ Also split in 2 or 3 jets

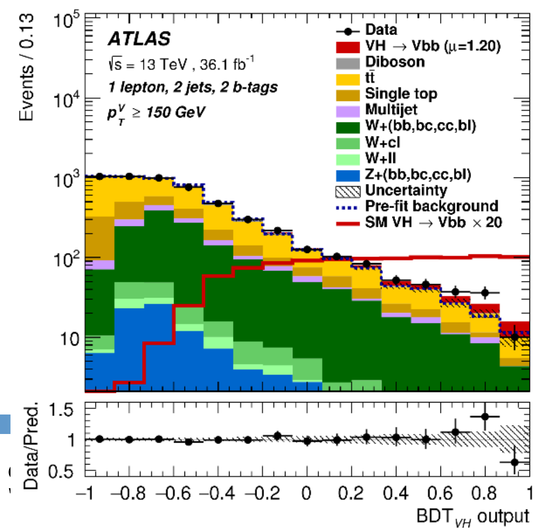
Channel	SR/CR	Categories: $75\text{ GeV} < p_T^V < 150\text{ GeV}$		$p_T^V > 150\text{ GeV}$	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	$W+\text{HF}$ CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

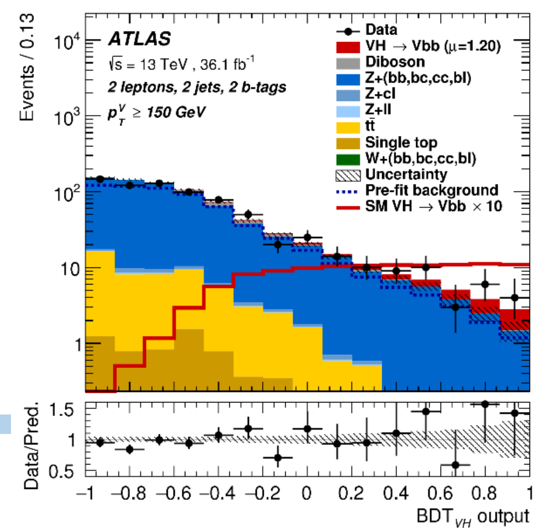
Add ttbar (+single top) and W+HF control regions

Reduce impact of backgrounds

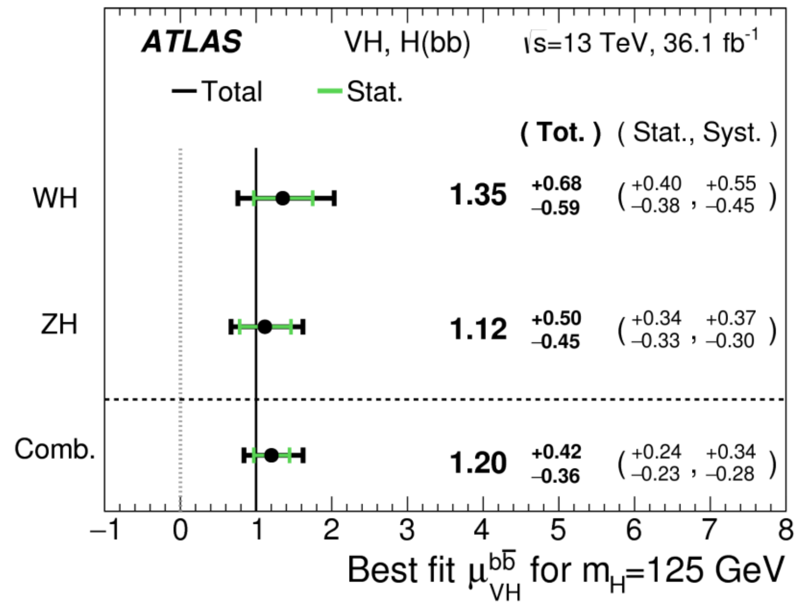
Fit BDT

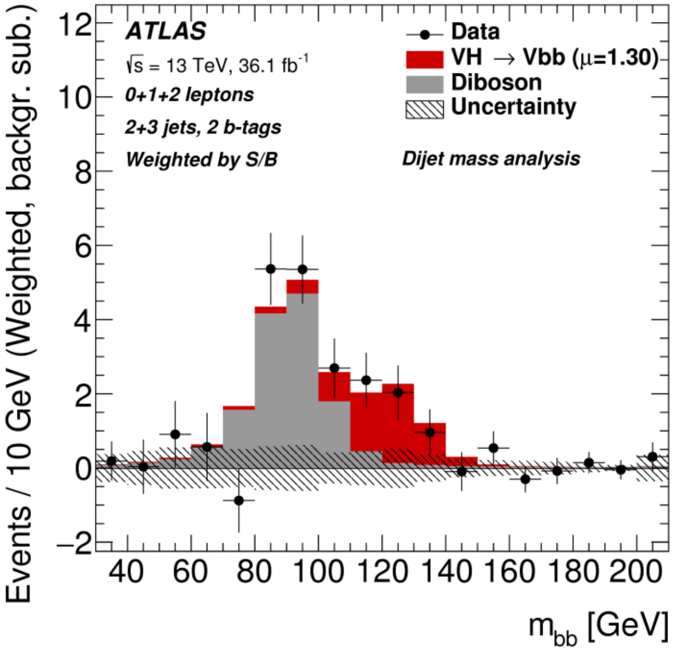






VH(bb) Run 2 Results





Best fit $\mu = 1.20^{+0.42}_{-0.36}$

→ compatible with SM

→ High channel compatibility

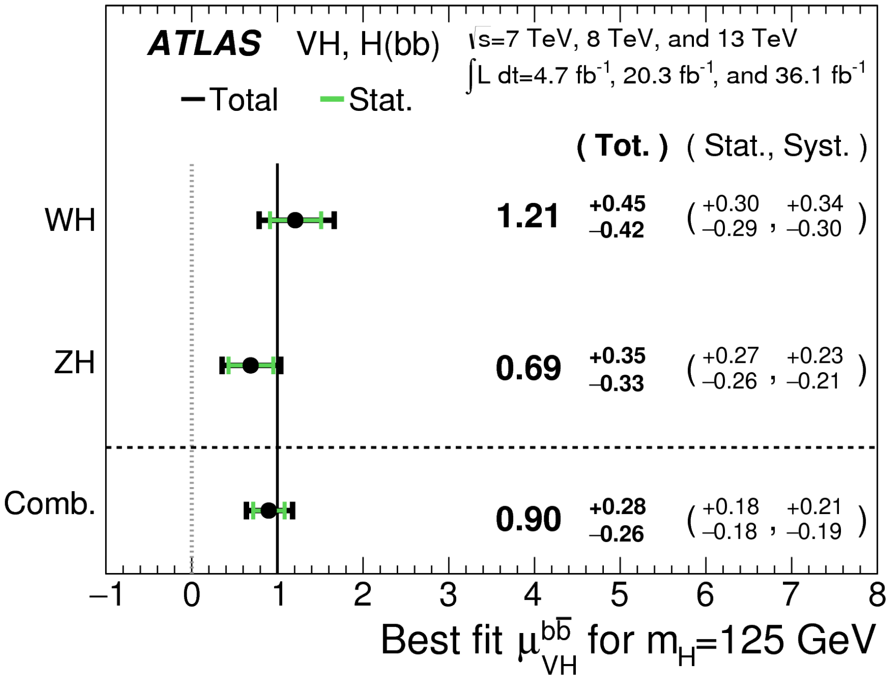
Obs (exp) Significance: 3.5 (3.0) σ

H→bb mass peak emerges clearly from backgrounds !

Fitting m_{bb} yields compatible results:

→ $\mu = 1.30^{+0.28}_{-0.27}$ (stat) $^{+0.37}_{-0.29}$ (syst)

VH(bb) Run 1 + Run 2 Results



Evidence of H→bb decay!

Best fit μ = $0.90^{+0.28}_{-0.26}$

→ compatible with SM

Obs (exp) Significance: 3.6 (4.0) σ

$H \rightarrow cc$ in VH(cc)

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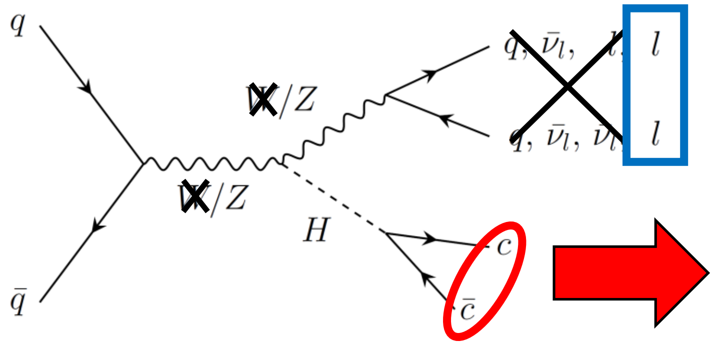
ZH(cc): A VH(bb) “Spin Off” Target c-jets !

Focus on ZH(cc) in the 2-lep channel:



Signal with relatively high $p_T(Z)$

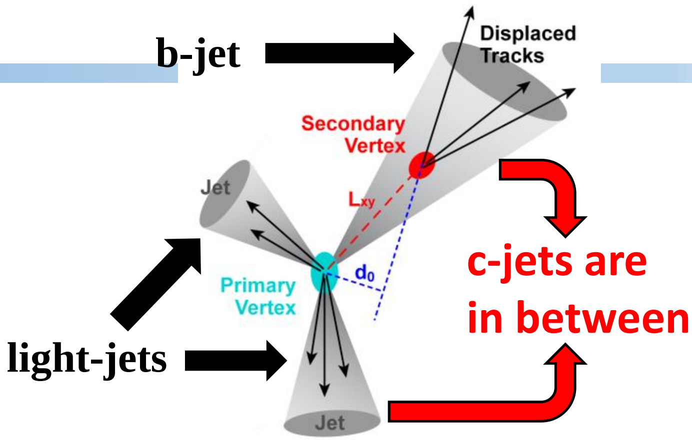
→ Categorization with $p_T(Z)$ (same as VH(bb))

Require c-jet identification !

Standard b-tagging: b-jet VS c-jet (no c- VS light- jets)

⇒ build dedicated c-taggers

c-tagging



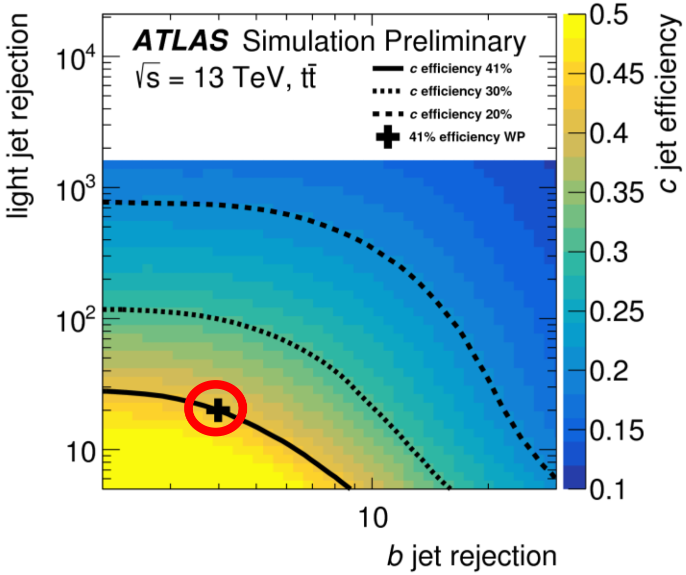
Flight path lengths: b-hadron > c-hadron > light-hadron

c-jet identification:

→ Same input variables as standard b-tagging
→ 2 BDT: c- VS light- and c- VS b- jets
→ Working point efficiencies: 41% c-jets, 25% b-jet, 5% light-jets

c-jet calibration:

→ Same methods as standard b-tagging
→ b-jets in t→Wb events
→ c-jets in W→cs, cd events



ZH(cc): A VH(bb) "Spin Off" Target c-jets !

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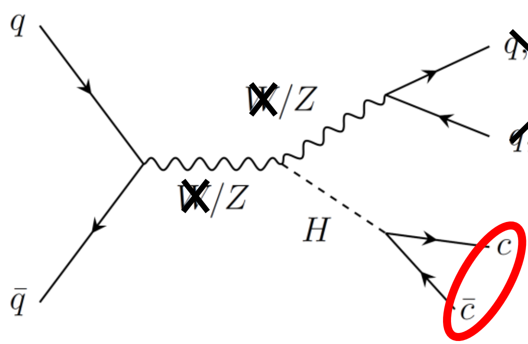


Signal with relatively high $p_T(Z)$

→ Categorization with $p_T(Z)$ (same as VH(bb))

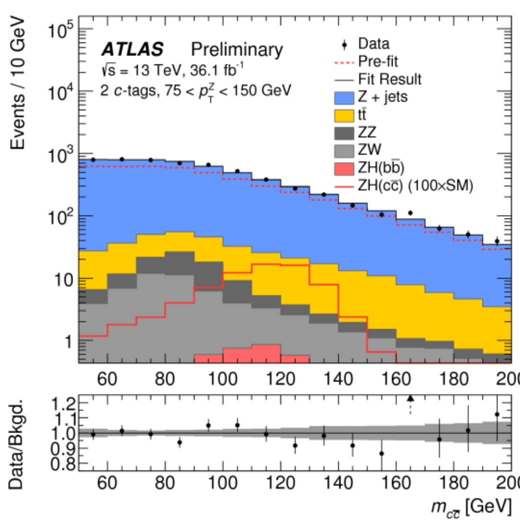
Use identified c-jets:

→ Reject background: cuts on cc system

50 GeV < m_{cc} < 200 GeV, small ΔR_{cc} (2.2 to 1.3, depend on $p_T(V)$)

→ Refine categorization: 1 or 2 c-tags

Fit m_{cc} in all categories



Best fit: μ = – 69 ± 100

→ Mostly limited by flavor tagging uncertainties (73%)

Upper limit: 2.7pb (110 x SM)

→ Expected 3.9pb (150 x SM)

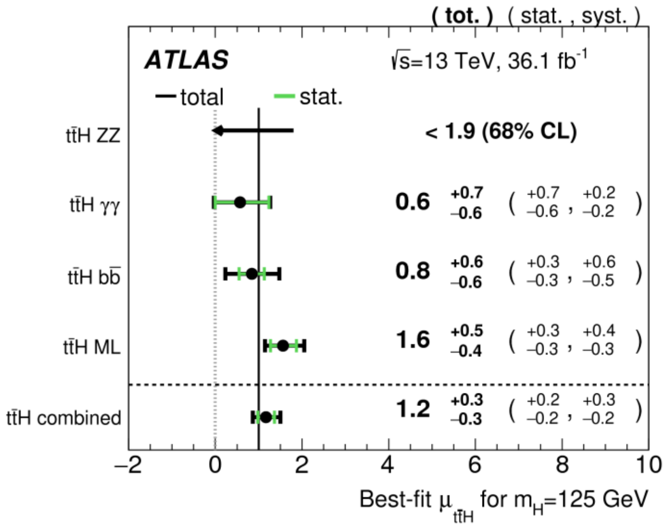
Conclusions

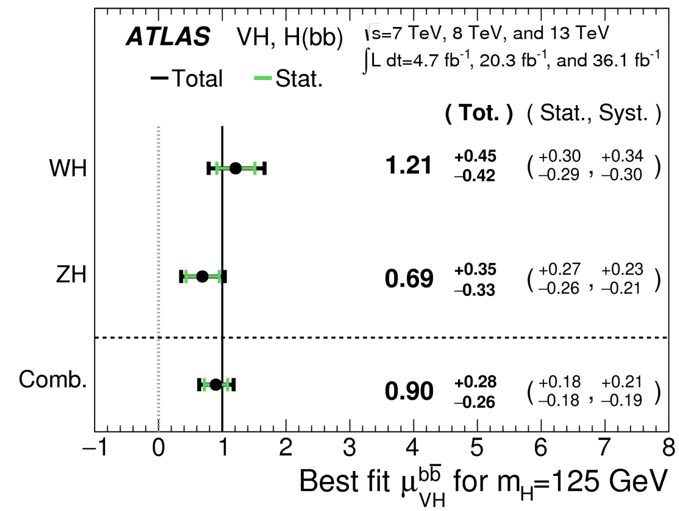
A Good Timing For An ATLAS Higgs Talk

- **Evidence of ttH production in ATLAS 13 TeV data**

- **Evidence of $H \rightarrow bb$ decay in VH(bb) analysis with ATLAS 13 TeV data**

Some More Conclusions Though





Uncertainty on μ_{ttH} improved by factor 2 compared to Run 1

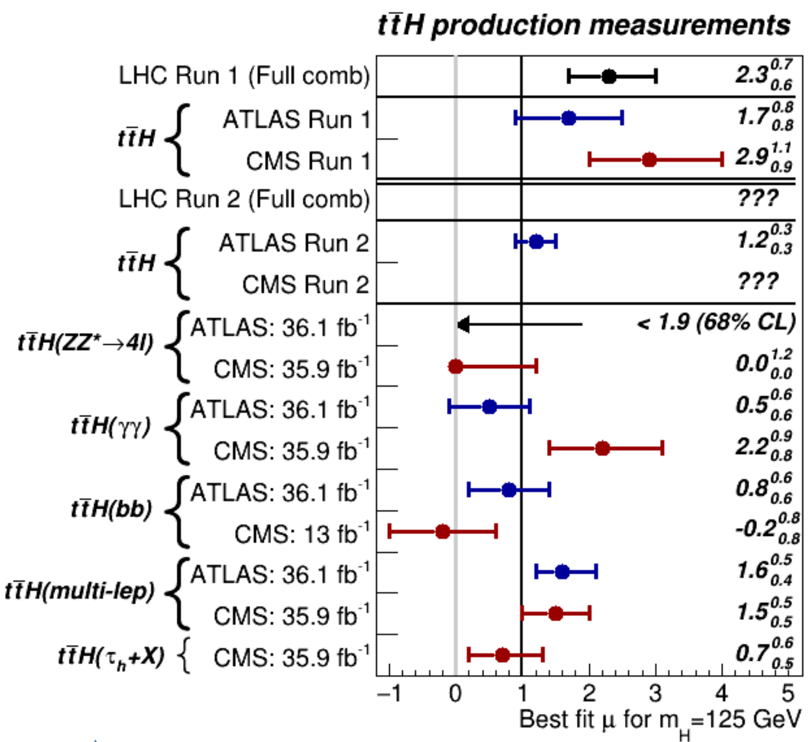
Uncertainty on $\mu_{VH(bb)}$ improved by factor 1.5 compared to Run 1

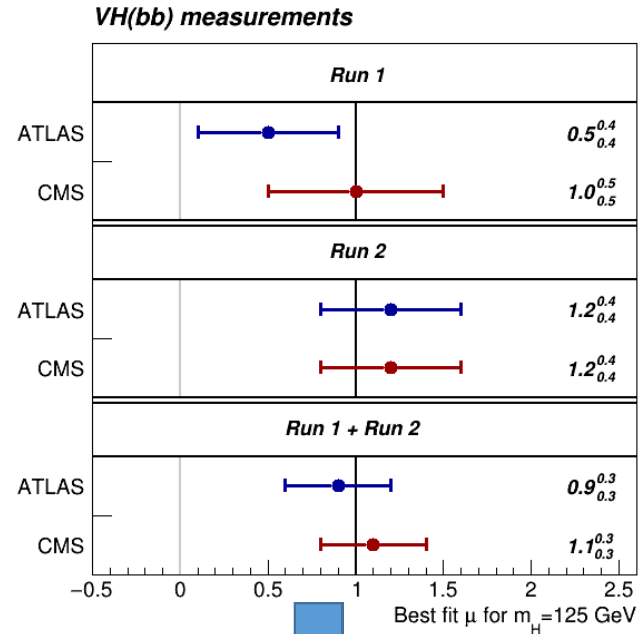
Coupling	κ_Z	κ_W	κ_τ	κ_t **(ttH+ggH)**	κ_t **(ttH)**	κ_b
Exp Unc.	10%	10%	15%	15%	~~30%~~	~~25%~~

If improvement μ = improvement κ **~15%** **~17%**

Personal optimistic computation

And There Are Also CMS Results





CMS also has **H→bb evidence**
From VH(bb) : arXiv:1709.07497

Most ttH channels at 36 fb^{-1}

Coupling	**κ** [illegible]	[illegible]	[illegible]	**κ_t (ttH+ggH)**	**κ_t (ttH)**	**κ_b**
Exp Unc.	10 [illegible]	[illegible]	[illegible]	15%	30%	25%

Even more to gain !

Thank you for you attention

backup

Intro

Couplings Measurements: Why κ_t

- **Coupling measurements:** **Kappa Framework $\kappa_j^2 = \Gamma^j / \Gamma^j_{SM}$**

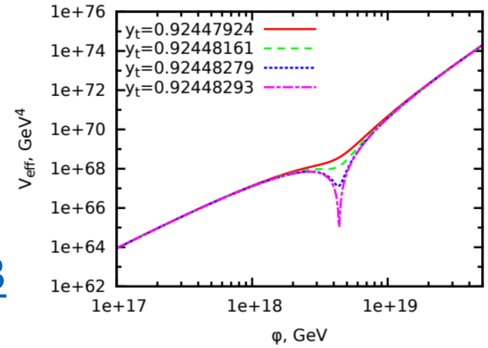
Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
Exp Unc.	10%	10%	15%	15%	25%

Why κ_t ?

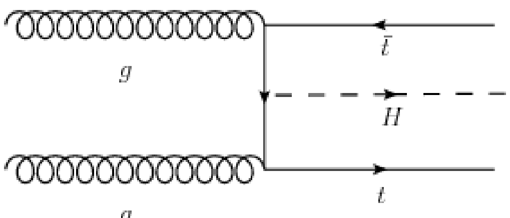
Top quark: largest Yukawa coupling

→ Higgs potential sensitive to small changes in κ_t
→ Investigate stability of the Higgs field

arXiv: 1411.1923

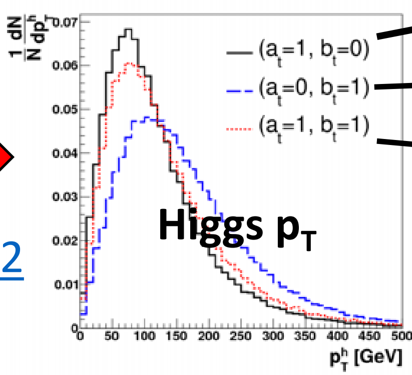


κ_t directly involved in ttH production



Sensitive to Higgs boson CP nature

arXiv: 1501.03157v2



Scalar (SM)
Pseudo-scalar
CP-mixing

Couplings Measurements: Why κ_b

- **Coupling measurements:** **Kappa Framework $\kappa_j^{\,2} = \Gamma^j / \Gamma^j_{SM}$**

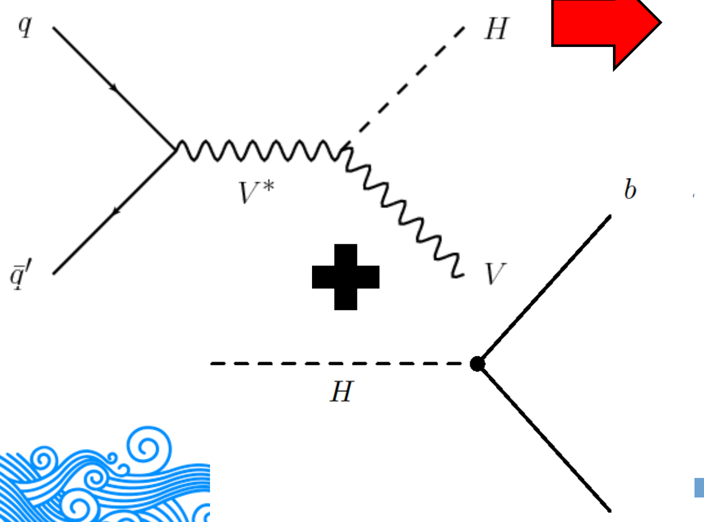
Coupling	κ_Z	κ_W	κ_τ	κ_t	κ_b
Exp Unc.	10%	10%	15%	15%	25%

Why κ_b ?

b quark has highest branching ration

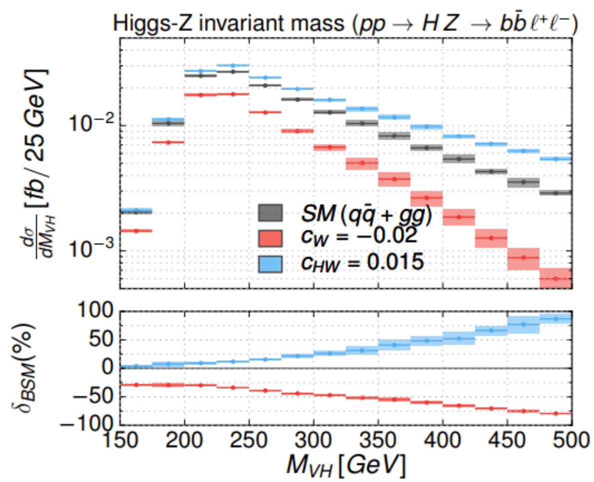
$\Rightarrow$ crucial to characterize Higgs boson width.

κ_b measured mainly with H→bb in VH production



VH invariant mass sensitive to BSM effects in EFT

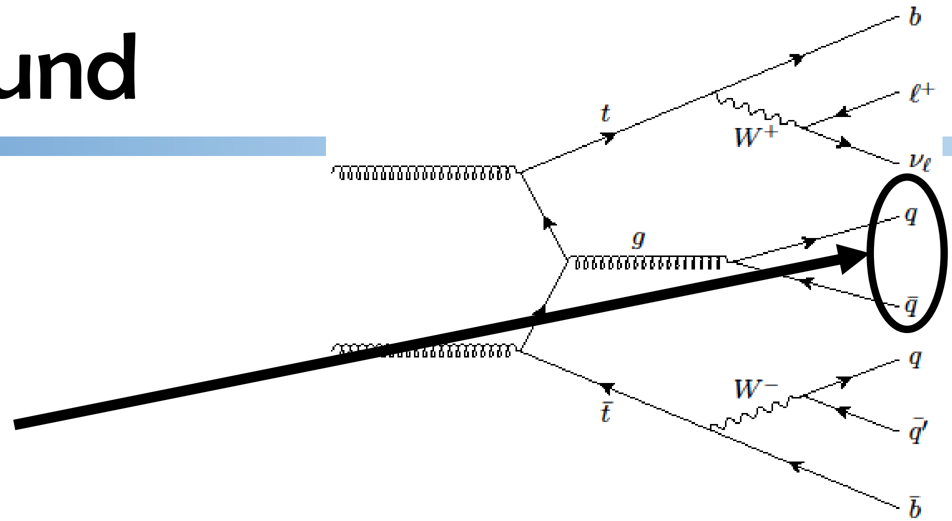
arXiv: 1512.02572



ttH(bb)

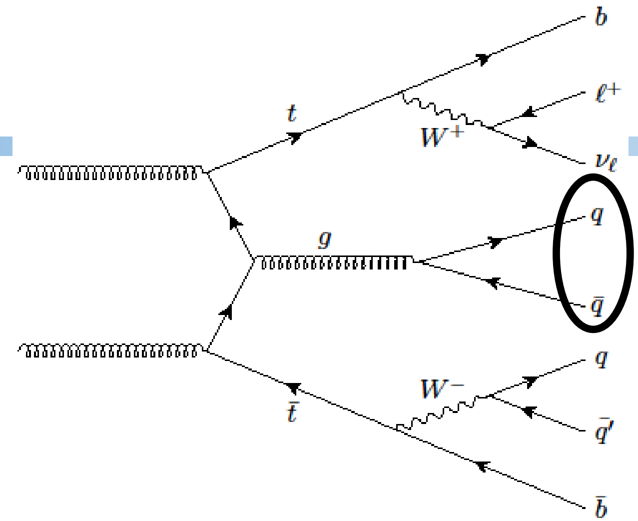
The tt+jets Background

- **After selection mostly tt+jets:**
  - 92% of the background
  - 350 times bigger than signal
- **Divided in 3 components:**
  - Depending on additional jet flavor



Component	**tt+lights**	**tt+≥1c**	**tt+≥1b**
Phase space	Low N(b-tags): → negligible in signal regions	Medium N(b-tags): → not significant in signal regions	High N(b-tags) → leading contribution in signal regions
Modelling	Relatively well known: → Generator tuned 7 TeV data → Parton Shower tuned 8&13 TeV data	No alternative measurement → Hard to identify c-jets	Not well known: → Hard to model theoretically → Large uncertainties (~ 25 to 35%)

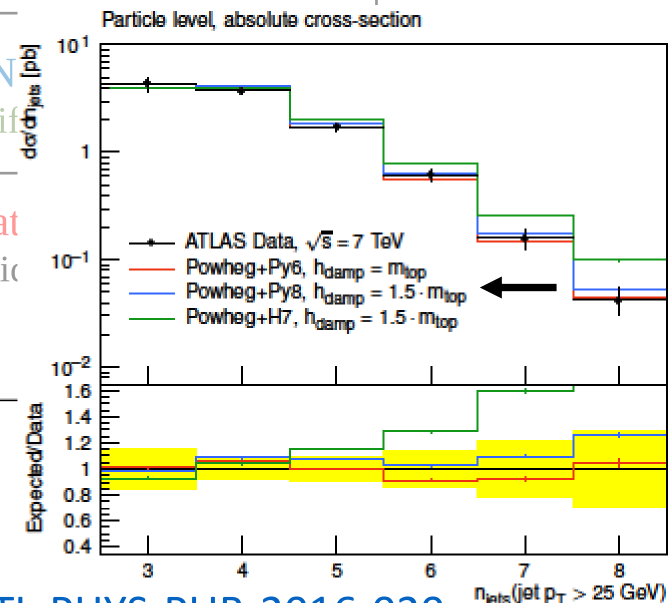
The tt+jets Background



- After selection mostly tt+jets
- Divided in 3 components

1% in best signal region

Component	tt+lights	tt+≥1c	tt+≥1b
Phase space	Low N(b-tags): → negligible in signal regions	Medium N → not signif	tion in
Modelling	Relatively well known: → Generator tuned 7 TeV data → Parton Shower tuned 8&13 TeV data	No alternat → Hard to i	neoretically ies



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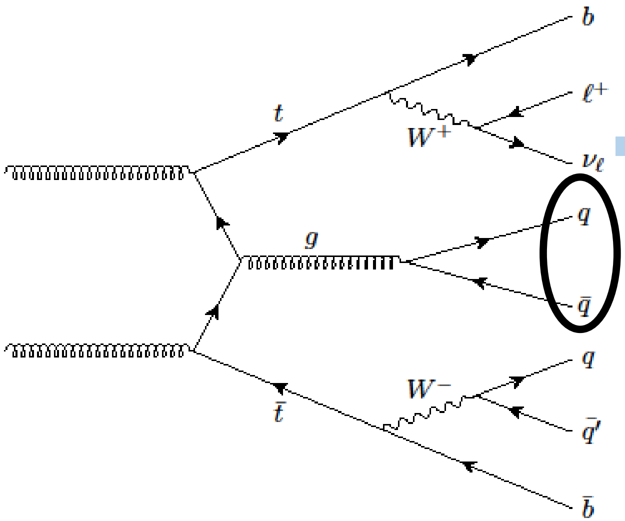
The tt+jets Background



- **After selection mostly tt+jets**
- **Divided in 3 components**

Component	**tt+lights**	**tt+≥1c**	**tt+≥1b**
Phase space	Low N(b-tags): → negligible in signal regions	Medium N(b-tags): → not significant in signal regions	High N(b-tags) → leading contribution in signal regions
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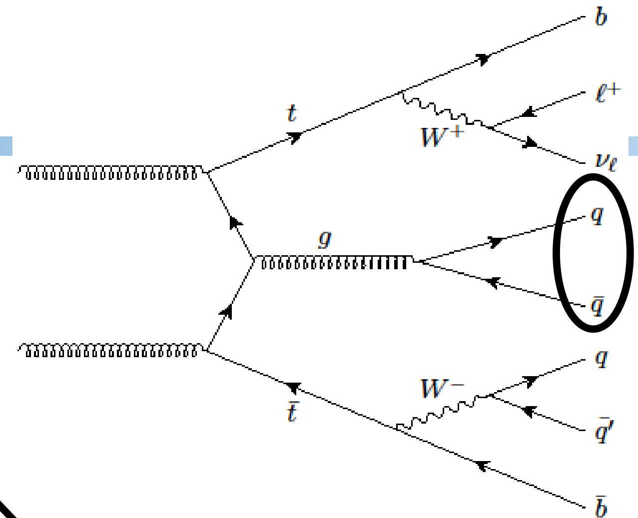
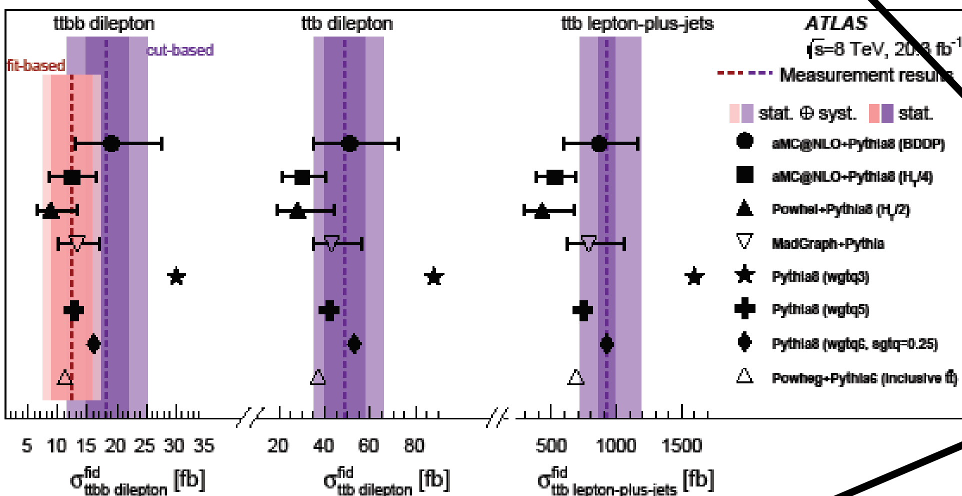
The tt+jets Background



- After selection mostly tt+jets
- Divided in 3 components

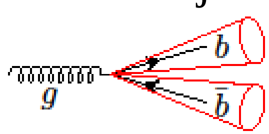
83% of the events in best signal regions



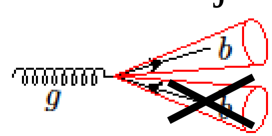
Component	tt+≥1b
Phase space	High N(b-tags) → leading contribution in signal regions
Modelling	Not well known: → Hard to model theoretically → Large uncertainties (~ 25 to 35%)

Further split in sub-components

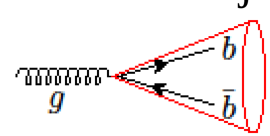
tt+bb: +2 b-jets



tt+b: +1 b-jets



tt+B: +1 bb-jets



tt+≥3b: the rest

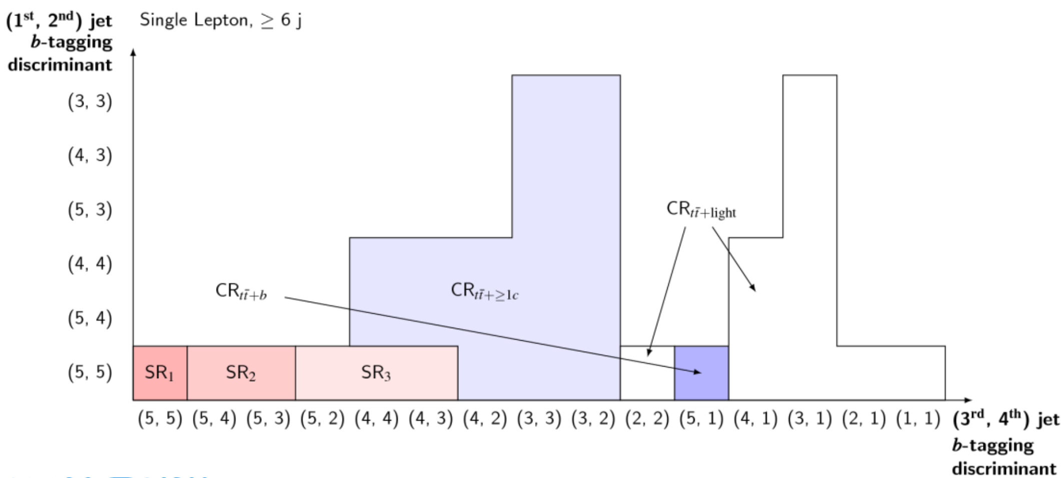
How To Deal With tt+jets

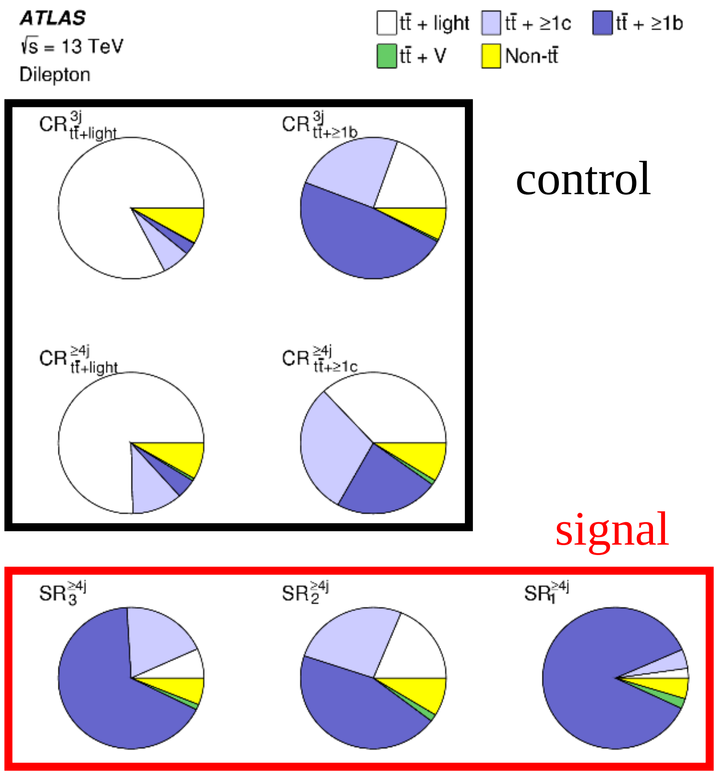
- **Separate signal and tt+jets components**:
  - Advanced categorization to define control regions enriched in tt+light, tt+≥1c and tt+≥1b
  - MVA technics to separate tt+≥1b and ttH(bb)
- Fit all components to data simultaneously

19 categories defined

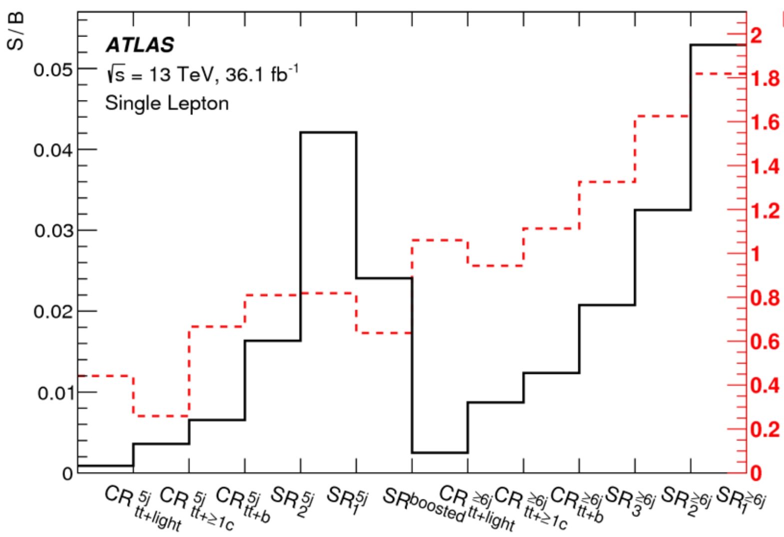
Categorization:
Use N(jets) and N(b-tags) at multiple working points

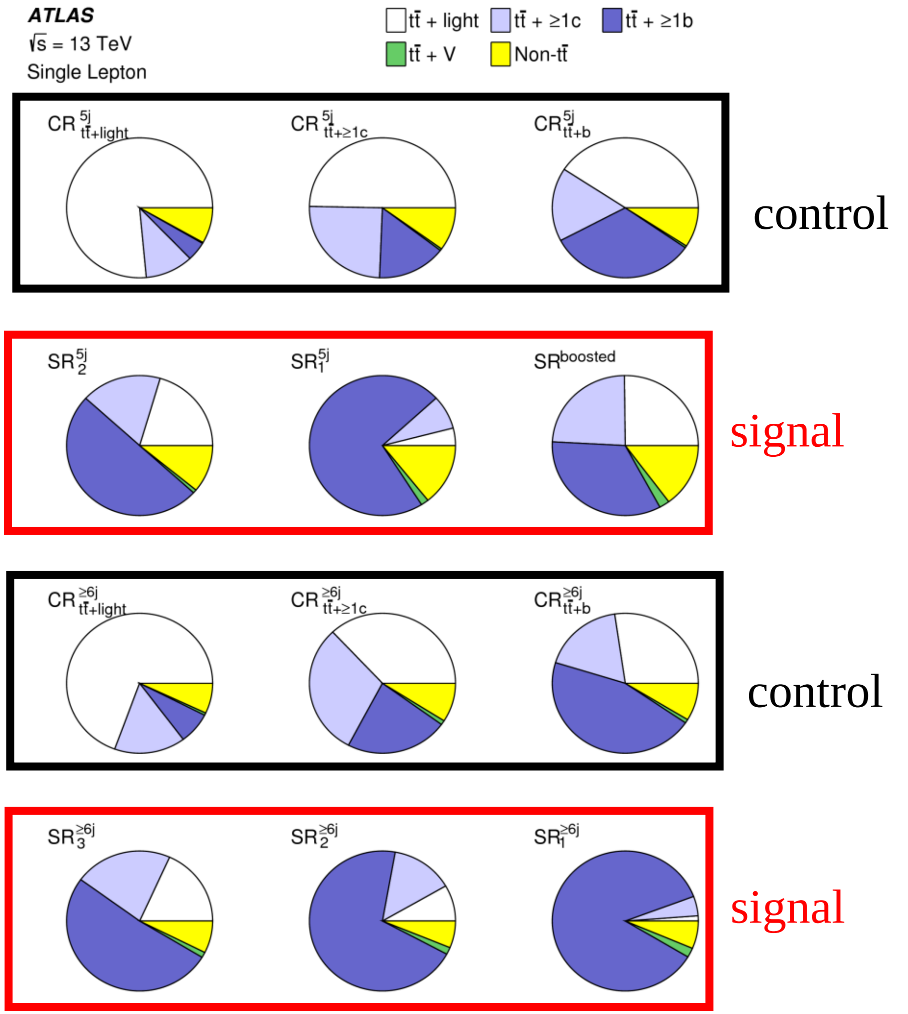
In reality, for each channel, N(jet)





Single Lepton Categories





BDT Input Variables: Dilepton

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

BDT Input Variables: Single-Lepton

Variable	Definition	$SR^{\geq 6j}_{1,2,3}$	$SR^{5j}_{1,2}$
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	–	✓
$N^{Higgs\ 30}_{bb}$	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	✓	✓
$m_{H,b_{lep\ top}}$	Mass of Higgs candidate and b-jet from leptonic top candidate	✓	–
ΔR^{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	✓*	✓*
$\Delta R_{H,lep\ top}$	ΔR between Higgs candidate and leptonic top candidate	✓	–
$\Delta R_{H,b_{had\ top}}$	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 $SR^{\geq 6j}_{1}$ only)	✓	–
Variables from b-tagging (not in $SR^{\geq 6j}_{1}$)			
$w^{Higgs}_{b\text{-tag}}$	Sum of b-tagging discriminants of jets from best Higgs candidate from the reconstruction BDT	✓	✓
B^{3}_{jet}	3^{rd} largest jet b-tagging discriminant	✓	✓
B^{4}_{jet}	4^{th} largest jet b-tagging discriminant	✓	✓
B^{5}_{jet}	5^{th} largest jet b-tagging discriminant	✓	✓

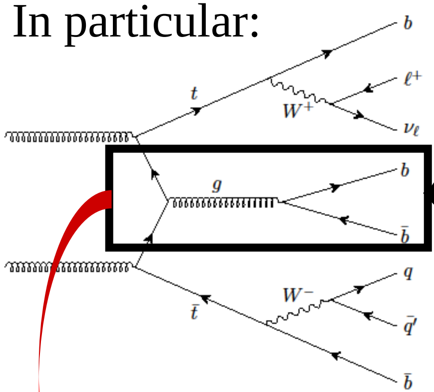
And What About The Modelin

tt+≥1b modeling uncertainties ⇔ main limitation

Build a complex model:

→ Aim: test in data all unknowns in tt+≥1b modeling

In particular:



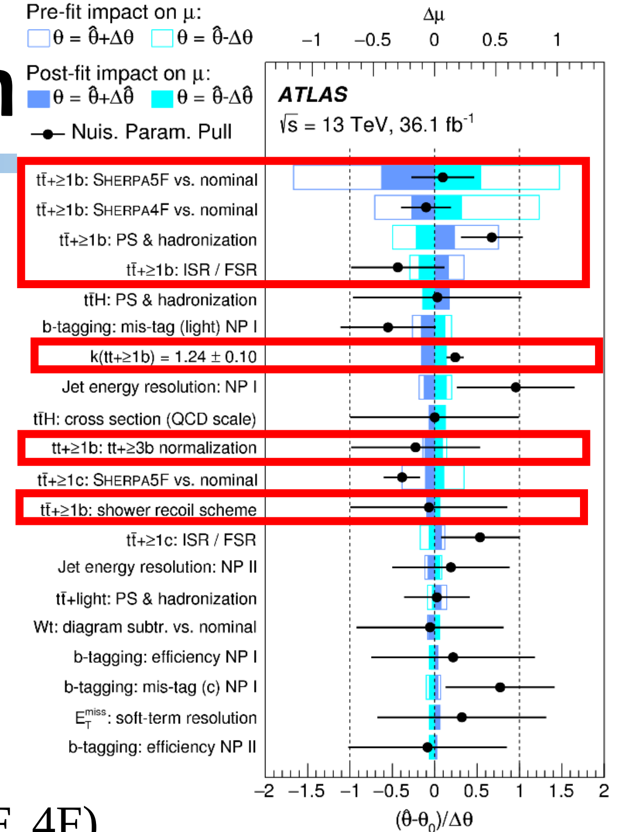
In best ttbar MC: Powheg+Pythia8

→ g -> bb from Parton Shower

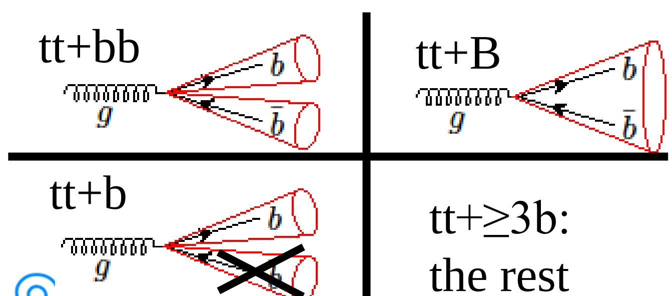
Generated Sherpa+OpenLoops:

→ Massive b-quarks (4 flavor PDF, 4F)

→ g -> bb from Matrix Element at NLO



Split in several components:



Best modeling can differ:

→ tt+bb, tt+b: best model by ME ?

→ tt+B: gluon splitting at low angles PS ?

→ tt+≥3b anyway combination ME and PS

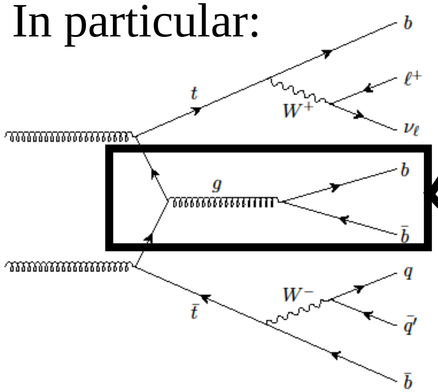
And What About The Modelin

tt+≥1b modeling uncertainties ⇔ main limitation

Build a complex model:

→ Aim: test in data all unknowns in tt+≥1b modeling

In particular:



In best ttbar MC: Powheg+Pythia8

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Generated Sherpa+OpenLoops:

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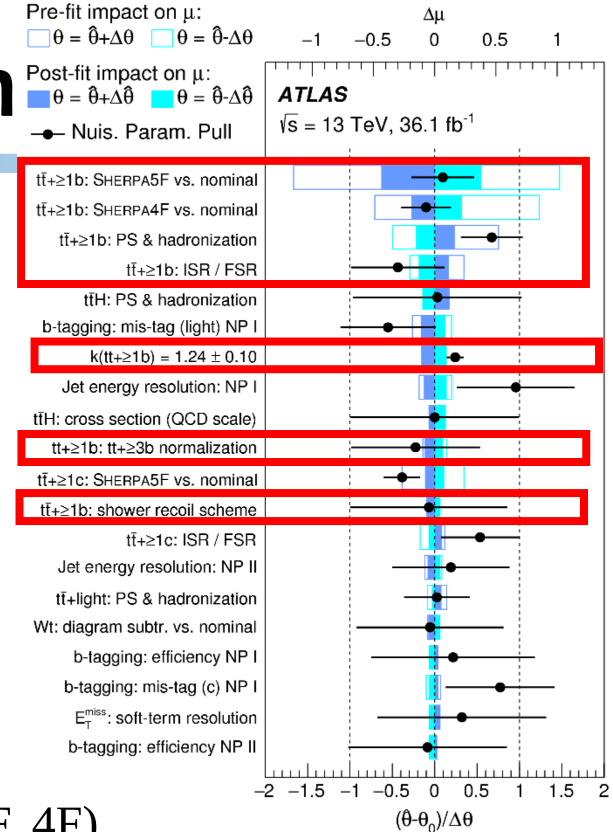


→ No discrimination in data
→ No recipe to mix 4F and 5F

Various model tested:

→ Different 4F/5F mix

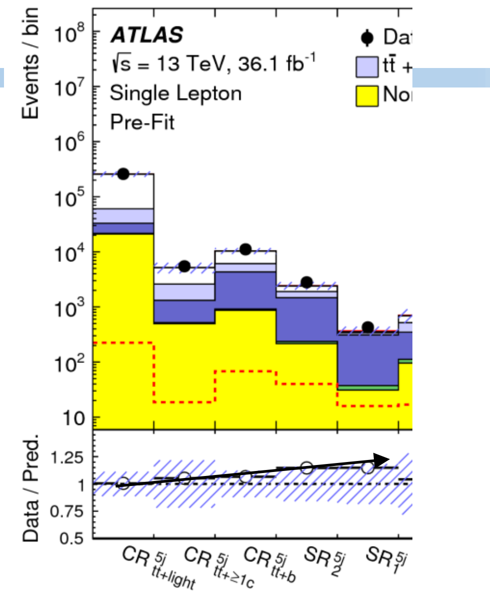
→ Different MC samples

All giving the same results

→ Confidence in signal extraction

tt+jets uncertainties

- **Philosophy: cover and test all modelling unknowns**
- **tt+jets modelling uncertainties:**
  - 6% ttbar cross-section uncertainty
  - tt+≥1c and tt+≥1b normalizations un-constrained
    - Known offset: Run 1 + 50% tt+≥1b
    - Also in Run 2 data/MC
  - Consider all relevant MC variations
    - Uncorrelated across tt+light, tt+≥1c, tt+≥1b
    - tt+light, tt+≥1c, tt+≥1b fractions fixed to PP8



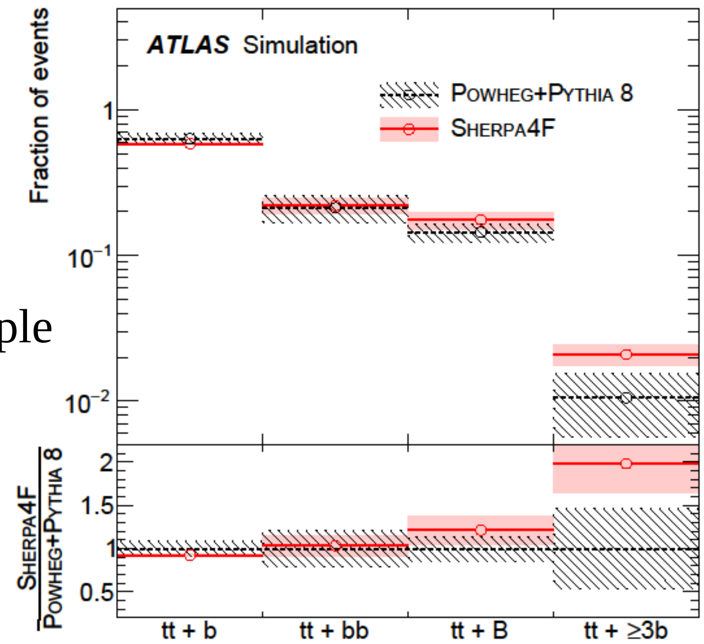
Variation:	Generator	PS and hadronisation	Radiation
MC sample:	Sherpa 2.2.1 (incl ttbar)	Powheg+Herwig7	Up/Dow radiation samples
Reference:	Powheg+Pythia8	Powheg+Pythia8	Powheg+Pythia8

Typically large norm+shape uncertainties (few % to 30%)

tt+HF additional uncertainties

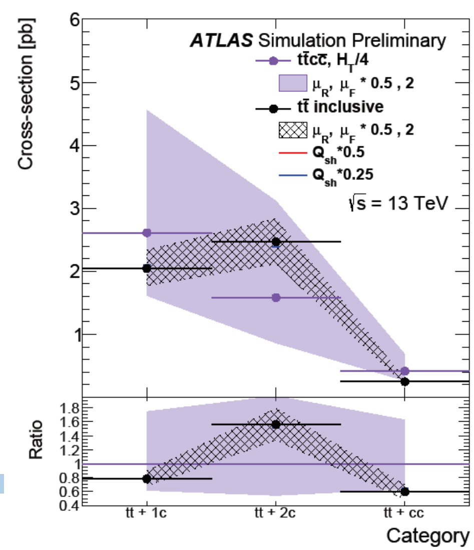
tt+≥1b additional uncertainties

- **Also account differences between tt+bb (Sherpa+OpenLoops 4F) and ttbar generators (PP8):**
  - Uncertainties on tt+b, bb, B, ≥3b fractions:
    - Use 8 variations of the Sherpa+OpenLoops sample
    - Add 50% prior unc. on tt+≥3b
  - Kinematic difference: Sherpa4F vs Nominal
    - Compare BDT shape in Sherpa+OpenLoops and PP8



tt+≥1c additional uncertainties

- **Similarly to tt+bb, exist tt+cc generator**
  - No hint from data which is the best
  - tt+cc subdominant compared to tt+bb
- **Use difference 5F and 3F as a systematic**



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Yields

Sample	$CR^{3j}_{t\bar{t}+\text{light}}$ Pre-fit	$CR^{3j}_{t\bar{t}+\text{light}}$ Post-fit	$CR^{3j}_{t\bar{t}+\geq 1b}$ Pre-fit	$CR^{3j}_{t\bar{t}+\geq 1b}$ Post-fit	$CR^{\geq 4j}_{t\bar{t}+\text{light}}$ Pre-fit	$CR^{\geq 4j}_{t\bar{t}+\text{light}}$ Post-fit	$CR^{\geq 4j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{\geq 4j}_{t\bar{t}+\geq 1c}$ Post-fit
$t\bar{t}H$	32.2 ± 3.8	27 ± 20	8.7 ± 1.1	7.3 ± 5.4	114 ± 11	95 ± 70	35.3 ± 3.6	29 ± 22
$t\bar{t}$ + light	63 100 ± 5500	59 100 ± 1400	290 ± 110	255 ± 44	42 500 ± 9700	37 100 ± 1300	1730 ± 730	1410 ± 180
$t\bar{t} + \geq 1c$	4800 ± 2100	7700 ± 1100	360 ± 160	536 ± 89	6300 ± 2800	10 300 ± 1400	1410 ± 590	2160 ± 290
$t\bar{t} + \geq 1b$	2130 ± 230	2620 ± 240	710 ± 140	848 ± 75	2510 ± 280	2850 ± 290	1080 ± 120	1240 ± 110
$t\bar{t} + V$	113 ± 31	112 ± 29	7 ± 27	7 ± 30	350 ± 180	330 ± 170	52 ± 41	50 ± 39
Non-$t\bar{t}$	6300 ± 1500	6500 ± 1200	110 ± 29	112 ± 23	4700 ± 1100	4930 ± 910	420 ± 120	460 ± 100
Total	76 400 ± 6500	76 010 ± 390	1500 ± 260	1765 ± 60	56 000 ± 11 000	55 650 ± 420	4700 ± 1100	5350 ± 120
Data	76 025		1744		55 627		5389	

Sample	$SR^{\geq 4j}_{3}$ Pre-fit	$SR^{\geq 4j}_{3}$ Post-fit	$SR^{\geq 4j}_{2}$ Pre-fit	$SR^{\geq 4j}_{2}$ Post-fit	$SR^{\geq 4j}_{1}$ Pre-fit	$SR^{\geq 4j}_{1}$ Post-fit
$t\bar{t}H$	21.9 ± 2.5	18 ± 13	29.1 ± 4.2	25 ± 18	15.6 ± 2.5	12.9 ± 9.5
$t\bar{t}$ + light	83 ± 41	95 ± 30	250 ± 110	215 ± 43	6.4 ± 9.9	11.1 ± 9.3
$t\bar{t} + \geq 1c$	235 ± 61	313 ± 53	340 ± 210	427 ± 89	12.6 ± 9.4	25.8 ± 7.8
$t\bar{t} + \geq 1b$	819 ± 85	917 ± 71	590 ± 96	669 ± 59	247 ± 61	263 ± 20
$t\bar{t} + V$	15 ± 35	15 ± 34	22 ± 38	22 ± 39	7 ± 56	7 ± 57
Non-$t\bar{t}$	75 ± 17	78 ± 16	115 ± 36	121 ± 29	13.6 ± 3.8	14.6 ± 3.8
Total	1250 ± 140	1436 ± 55	1350 ± 320	1479 ± 66	302 ± 85	334 ± 59
Data	1467		1444		319	

Yields

Sample	$CR^{5j}_{t\bar{t}+\text{light}}$ Pre-fit	$CR^{5j}_{t\bar{t}+\text{light}}$ Post-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{5j}_{t\bar{t}+\geq 1c}$ Post-fit	$CR^{5j}_{t\bar{t}+b}$ Pre-fit	$CR^{5j}_{t\bar{t}+b}$ Post-fit
$t\bar{t}H$	224 ± 22	190 ± 140	18.7 ± 2.5	15 ± 12	68.0 ± 7.6	57 ± 42
$t\bar{t}$ + light	197 000 ± 26 000	179 900 ± 4900	2580 ± 720	2300 ± 210	4250 ± 920	3560 ± 240
$t\bar{t} + \geq 1c$	27 500 ± 4300	44 100 ± 5500	1280 ± 500	1840 ± 250	1770 ± 270	2590 ± 390
$t\bar{t} + \geq 1b$	11 300 ± 1100	13 500 ± 1300	790 ± 130	944 ± 94	3400 ± 440	4030 ± 320
$t\bar{t} + V$	589 ± 55	584 ± 54	23.2 ± 4.1	21.3 ± 2.9	48.1 ± 5.9	46.6 ± 5.4
Non-$t\bar{t}$	21 300 ± 4100	20 900 ± 3200	520 ± 180	440 ± 100	960 ± 190	860 ± 160
Total	258 000 ± 29 000	259 320 ± 910	5200 ± 1100	5560 ± 160	10 400 ± 1300	11 140 ± 290
Data	259 320		5465		11 095	

Sample	SR^{5j}_{2} Pre-fit	SR^{5j}_{2} Post-fit	SR^{5j}_{1} Pre-fit	SR^{5j}_{1} Post-fit	SR^{boosted} Pre-fit	SR^{boosted} Post-fit
$t\bar{t}H$	40.1 ± 5.1	34 ± 25	15.9 ± 2.1	13.3 ± 9.8	16.9 ± 1.9	14 ± 10
$t\bar{t}$ + light	500 ± 210	393 ± 67	15 ± 33	12.5 ± 9.3	180 ± 120	112 ± 32
$t\bar{t} + \geq 1c$	436 ± 92	610 ± 100	30 ± 17	28 ± 14	168 ± 70	235 ± 39
$t\bar{t} + \geq 1b$	1230 ± 200	1450 ± 110	273 ± 53	335 ± 25	236 ± 89	229 ± 33
$t\bar{t} + V$	19.9 ± 2.9	19.7 ± 2.4	6.4 ± 1.3	6.4 ± 1.2	16.1 ± 2.9	16.6 ± 2.4
Non-$t\bar{t}$	269 ± 64	220 ± 52	54 ± 11	28.1 ± 8.4	104 ± 30	101 ± 26
Total	2440 ± 390	2724 ± 70	371 ± 68	423 ± 23	710 ± 200	708 ± 40
Data	2798		426		740	

Yields

Sample	$CR^{\geq 6j}_{t\bar{t}+\text{light}}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+\text{light}}$ Post-fit	$CR^{\geq 6j}_{t\bar{t}+\geq 1c}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+\geq 1c}$ Post-fit	$CR^{\geq 6j}_{t\bar{t}+b}$ Pre-fit	$CR^{\geq 6j}_{t\bar{t}+b}$ Post-fit
$t\bar{t}H$	450 ± 48	370 ± 280	102 ± 13	87 ± 64	100 ± 12	83 ± 61
$t\bar{t}$ + light	125 000 ± 34 000	108 200 ± 4300	4300 ± 2000	3350 ± 430	2220 ± 520	1820 ± 170
$t\bar{t} + \geq 1c$	28 400 ± 7200	45 700 ± 5100	3600 ± 1300	5300 ± 680	1460 ± 330	2080 ± 300
$t\bar{t} + \geq 1b$	13 100 ± 1800	14 600 ± 1400	2660 ± 540	2950 ± 280	3670 ± 500	4080 ± 320
$t\bar{t} + V$	1010 ± 120	996 ± 91	118 ± 21	118 ± 14	70.5 ± 8.5	67.9 ± 7.2
Non-$t\bar{t}$	12 600 ± 3000	11 800 ± 2000	1060 ± 340	1000 ± 210	710 ± 160	600 ± 110
Total	181 000 ± 39 000	181 690 ± 860	11 800 ± 3200	12 810 ± 260	8200 ± 1100	8730 ± 230
Data	181 706		12 778		8576	

Sample	$SR^{\geq 6j}_{3}$ Pre-fit	$SR^{\geq 6j}_{3}$ Post-fit	$SR^{\geq 6j}_{2}$ Pre-fit	$SR^{\geq 6j}_{2}$ Post-fit	$SR^{\geq 6j}_{1}$ Pre-fit	$SR^{\geq 6j}_{1}$ Post-fit
$t\bar{t}H$	85 ± 10	71 ± 52	81 ± 10	68 ± 50	62 ± 11	51 ± 38
$t\bar{t}$ + light	750 ± 370	586 ± 98	210 ± 210	96 ± 33	14 ± 10	12.1 ± 5.8
$t\bar{t} + \geq 1c$	880 ± 350	1330 ± 190	350 ± 100	473 ± 99	53 ± 33	44 ± 20
$t\bar{t} + \geq 1b$	2100 ± 420	2290 ± 170	1750 ± 370	1850 ± 130	1010 ± 240	1032 ± 59
$t\bar{t} + V$	51.2 ± 7.4	50.8 ± 5.9	40.8 ± 5.7	40.3 ± 4.8	25.8 ± 3.7	25.3 ± 3.2
Non-$t\bar{t}$	303 ± 82	267 ± 63	155 ± 52	134 ± 46	75 ± 20	58 ± 17
Total	4140 ± 850	4590 ± 110	2550 ± 510	2657 ± 82	1220 ± 250	1223 ± 42
Data	4698		2641		1222	

ttH(multi-leptons)

Selections

Channel	Selection criteria
Common	$N_{\text{jets}} \geq 2$ and $N_{b\text{-jets}} \geq 1$
2ℓSS	Two very tight light leptons with $p_{\text{T}} > 20$ GeV Same-charge light leptons Zero medium τ_{had} candidates $N_{\text{jets}} \geq 4$ and $N_{b\text{-jets}} < 3$
3ℓ	Three light leptons with $p_{\text{T}} > 10$ GeV; sum of light-lepton charges ± 1 Two same-charge leptons must be very tight and have $p_{\text{T}} > 15$ 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)
1ℓ+$2\tau_{\text{had}}$	One tight light lepton with $p_{\text{T}} > 27$ GeV Two medium τ_{had} candidates of opposite charge, at least one being tight $N_{\text{jets}} \geq 3$
2ℓSS+$1\tau_{\text{had}}$	Two very tight light leptons with $p_{\text{T}} > 15$ GeV Same-charge light leptons One medium τ_{had} candidate, with charge opposite to that of the light leptons $N_{\text{jets}} \geq 4$ $\lvert m(ee) - 91.2\text{ GeV}\rvert > 10$ GeV for ee events
2ℓOS+$1\tau_{\text{had}}$	Two loose and isolated light leptons with $p_{\text{T}} > 25, 15$ GeV One medium τ_{had} candidate Opposite-charge light leptons One medium τ_{had} candidate $m(\ell^+\ell^-) > 12$ GeV and $\lvert m(\ell^+\ell^-) - 91.2\text{ GeV}\rvert > 10$ GeV for the SFOC pair $N_{\text{jets}} \geq 3$
3ℓ+$1\tau_{\text{had}}$	3ℓ selection, except: One medium τ_{had} candidate, with charge opposite to the total charge of the light leptons The two same-charge light leptons must be tight and have $p_{\text{T}} > 10$ GeV The opposite-charge light lepton must be loose and isolated

Fake And Non-Prompt Leptons

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\text{had}}$	2ℓSS$+1\tau_{\text{had}}$	2ℓOS$+1\tau_{\text{had}}$	$3\ell+1\tau_{\text{had}}$
Non-prompt lepton strategy	DD (MM)	DD (MM)	semi-DD (SF)	MC	DD (FF)	MC	MC
Fake τ_{had} strategy	–	–	–	DD (SS data)	semi-DD (SF)	DD (FF)	semi-DD (SF)
Control Region Selection							
Light lepton	1T*, 1L		3L	1T	1T*, 1L	2L†	–
τ_{had}	0M			1T, 1M	≤ 1M	1L	–
N_{jets}	$2 \leq N_{\text{jets}} \leq 3$		$1 \leq N_{\text{jets}} \leq 2$	≥ 3	$2 \leq N_{\text{jets}} \leq 3$	≥ 3	–
$N_{b\text{-jets}}$	≥ 1					$= 0$	–

Mostly data-driven estimates:

→ Matrix Method (MM): derives real and fake efficiencies from control regions

→ Fake Factor (FF): derives fake efficiencies from control regions

→ Semi-data driven: correction factors for MC from control regions

Uncertainties:

→ Closure test

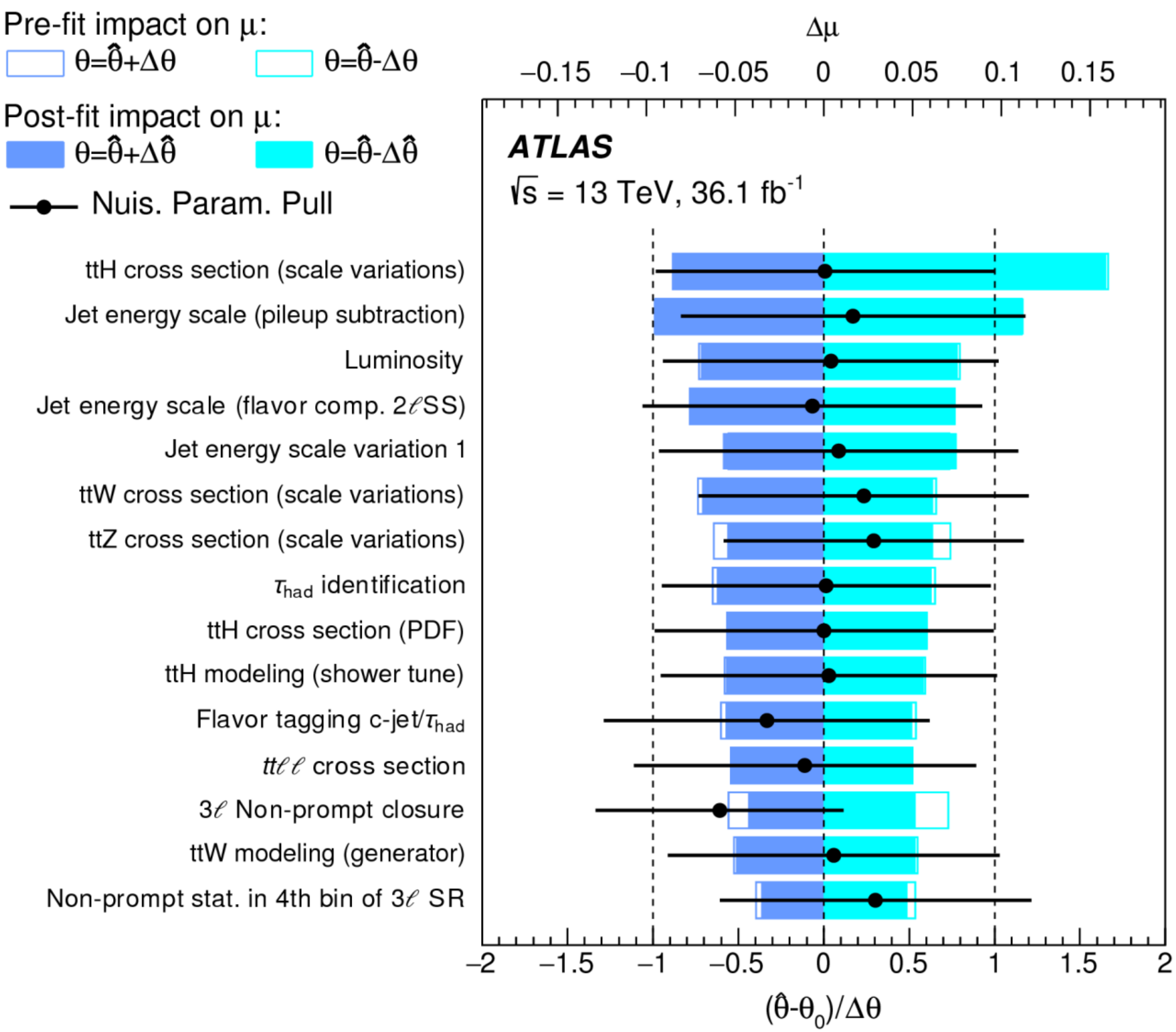
→ Control region choice

→ Prompt subtraction and modeling

BDT Input Variables

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

ttH(multi-lepton): Post-Fit Systematics



Yields

Category	Non-prompt	Fake τ_{had}	q mis-id	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Other	Total Bkgd.	$t\bar{t}H$	Observed
Pre-fit yields										
2ℓSS	233 ± 39	–	33 ± 11	123 ± 18	41.4 ± 5.6	25 ± 15	28.4 ± 5.9	484 ± 38	42.6 ± 4.2	514
3ℓ SR	14.5 ± 4.3	–	–	5.5 ± 1.2	12.0 ± 1.8	1.2 ± 1.2	5.8 ± 1.4	39.1 ± 5.2	11.2 ± 1.6	61
3ℓ $t\bar{t}W$ CR	13.3 ± 4.3	–	–	19.9 ± 3.1	8.7 ± 1.1	< 0.2	4.53 ± 0.92	46.5 ± 5.4	4.18 ± 0.46	56
3ℓ $t\bar{t}Z$ CR	3.9 ± 2.5	–	–	2.71 ± 0.56	66 ± 11	8.4 ± 5.3	12.9 ± 4.2	93 ± 13	3.17 ± 0.41	107
3ℓ VV CR	27.7 ± 8.7	–	–	4.9 ± 1.0	21.3 ± 3.4	51 ± 30	17.9 ± 6.1	123 ± 32	1.67 ± 0.25	109
3ℓ $t\bar{t}$ CR	70 ± 17	–	–	10.5 ± 1.5	7.9 ± 1.1	7.2 ± 4.8	7.3 ± 1.9	103 ± 17	4.00 ± 0.49	85
4ℓ Z-enr.	0.11 ± 0.07	–	–	< 0.01	1.52 ± 0.23	0.43 ± 0.23	0.21 ± 0.09	2.26 ± 0.34	1.06 ± 0.14	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	< 0.01	0.04 ± 0.02	< 0.01	0.06 ± 0.03	0.11 ± 0.03	0.20 ± 0.03	0
$1\ell+2\tau_{had}$	–	65 ± 21	–	0.09 ± 0.09	3.3 ± 1.0	1.3 ± 1.0	0.98 ± 0.35	71 ± 21	4.3 ± 1.0	67
2ℓSS$+1\tau_{had}$	2.4 ± 1.4	1.80 ± 0.30	0.05 ± 0.02	0.88 ± 0.24	1.83 ± 0.37	0.12 ± 0.18	1.06 ± 0.24	8.2 ± 1.6	3.09 ± 0.46	18
2ℓOS$+1\tau_{had}$	–	756 ± 80	–	6.5 ± 1.3	11.4 ± 1.9	2.0 ± 1.3	5.8 ± 1.5	782 ± 81	14.2 ± 2.0	807
$3\ell+1\tau_{had}$	–	0.75 ± 0.15	–	0.04 ± 0.04	1.38 ± 0.24	0.002 ± 0.002	0.38 ± 0.10	2.55 ± 0.32	1.51 ± 0.23	5
Post-fit yields										
2ℓSS	211 ± 26	–	28.3 ± 9.4	127 ± 18	42.9 ± 5.4	20.0 ± 6.3	28.5 ± 5.7	459 ± 24	67 ± 18	514
3ℓ SR	13.2 ± 3.1	–	–	5.8 ± 1.2	12.9 ± 1.6	1.2 ± 1.1	5.9 ± 1.3	39.0 ± 4.0	17.7 ± 4.9	61
3ℓ $t\bar{t}W$ CR	11.7 ± 3.0	–	–	20.4 ± 3.0	8.9 ± 1.0	< 0.2	4.54 ± 0.88	45.6 ± 4.0	6.6 ± 1.9	56
3ℓ $t\bar{t}Z$ CR	3.5 ± 2.1	–	–	2.82 ± 0.56	70.4 ± 8.6	7.1 ± 3.0	13.6 ± 4.2	97.4 ± 8.6	5.1 ± 1.4	107
3ℓ VV CR	22.4 ± 5.7	–	–	5.05 ± 0.94	22.0 ± 3.0	39 ± 11	18.1 ± 5.9	106.8 ± 9.4	2.61 ± 0.82	109
3ℓ $t\bar{t}$ CR	56.0 ± 8.1	–	–	10.7 ± 1.4	8.1 ± 1.0	5.9 ± 2.7	7.1 ± 1.8	87.8 ± 7.9	6.3 ± 1.8	85
4ℓ Z-enr.	0.10 ± 0.07	–	–	< 0.01	1.60 ± 0.22	0.37 ± 0.15	0.22 ± 0.10	2.29 ± 0.28	1.65 ± 0.47	2
4ℓ Z-dep.	0.01 ± 0.01	–	–	< 0.01	0.04 ± 0.02	< 0.01	0.07 ± 0.03	0.11 ± 0.03	0.32 ± 0.09	0
$1\ell+2\tau_{had}$	–	58.0 ± 6.8	–	0.11 ± 0.11	3.31 ± 0.90	0.98 ± 0.75	0.98 ± 0.33	63.4 ± 6.7	6.5 ± 2.0	67
2ℓSS$+1\tau_{had}$	1.86 ± 0.91	1.86 ± 0.27	0.05 ± 0.02	0.97 ± 0.26	1.96 ± 0.37	0.15 ± 0.20	1.09 ± 0.24	7.9 ± 1.2	5.1 ± 1.3	18
2ℓOS$+1\tau_{had}$	–	756 ± 28	–	6.6 ± 1.3	11.5 ± 1.7	1.64 ± 0.92	6.1 ± 1.5	782 ± 27	21.7 ± 5.9	807
$3\ell+1\tau_{had}$	–	0.75 ± 0.14	–	0.04 ± 0.04	1.42 ± 0.22	0.002 ± 0.002	0.40 ± 0.10	2.61 ± 0.30	2.41 ± 0.68	5

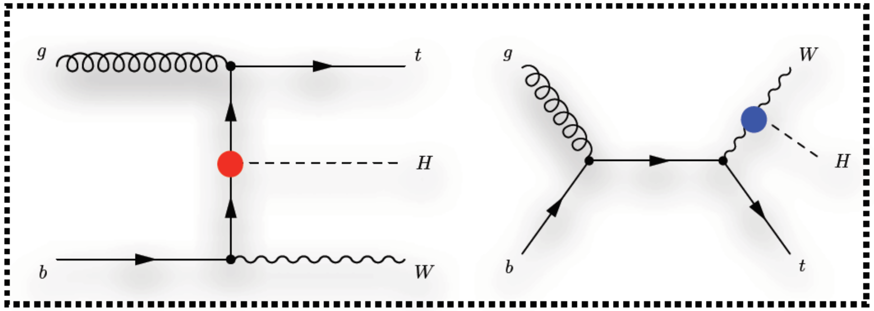
tH in ttH($\gamma\gamma$)

ttH(γγ)

- Included in main H→γγ analysis
- Rely on excellent M(γγ) resolution over a continuous background

Strategy:

- ➢ Use H→γγ selections
- ➢ "Enriched ttH category"
- ➢ Consider categories enriched in tH

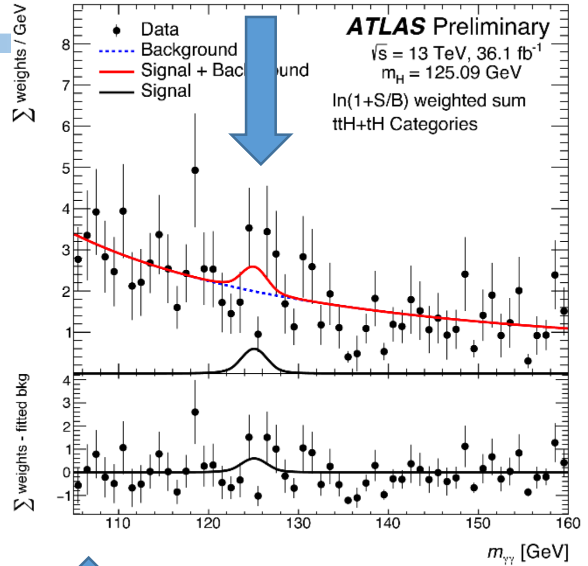


Interference in WtH production:

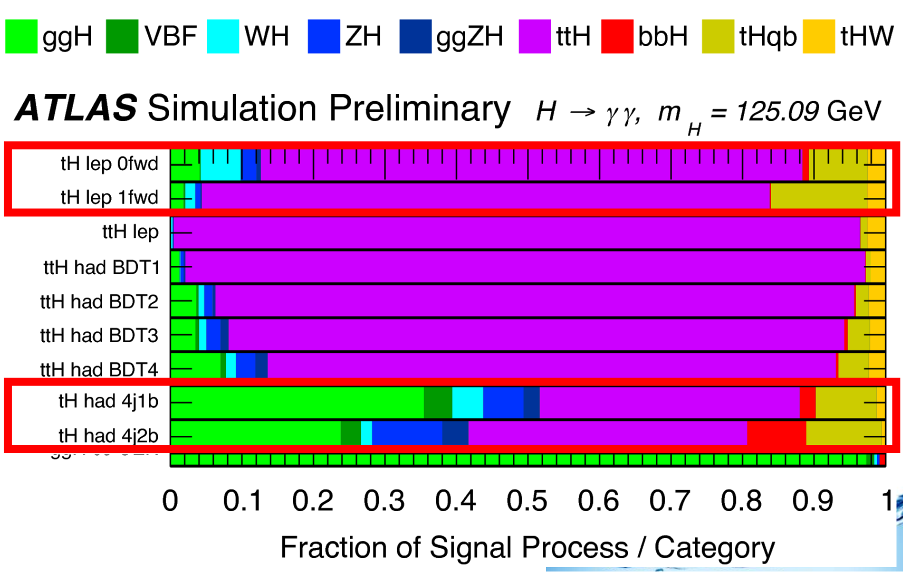
⇒ sensitivity to κ_t sign

⇒ anomalous top Yukawa couplings

Signal as double sided crystal ball around 125 GeV



Extract background from side bands



ttH summary

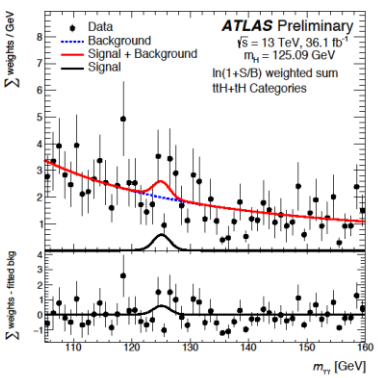
Combination Of ttH Analyses: Summary

– ttH analysis divided in 4 channels:

a) H ⟶ bb: arXiv:1712.08895
b) H ⟶ multi-leptons: arXiv:1712.08891
c) H ⟶ γγ: ATLAS-CONF-2017-045
d) H ⟶ ZZ* ⟶ 4l: arXiv:1712.02304

– 4 different challenges:

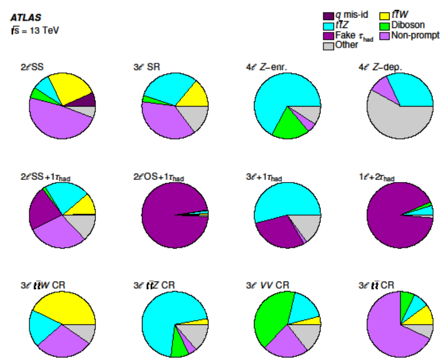
ttH(γγ)



Excellent M(γγ) resolution over continuous background
Small syst uncertainties

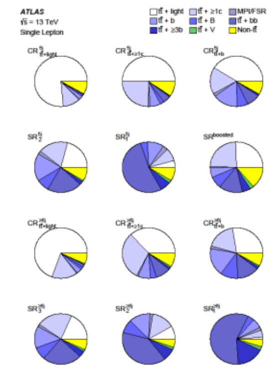
ML and bb { ⟶ Similar strategy: categorisation + MVA
⟶ Different backgrounds

ttH(multi-leptons)



⟶ ttV + fakes and non-prompt
⟶ Stat and Syst error similar

ttH(bb)



⟶ tt+≥1b
⟶ Syst limited

ttH(ZZ*⟶4l):

✓ Excellent S/B
✓ Small: 0.3 ttH events

Expect important improvement from combination

VH(bb)

Yields

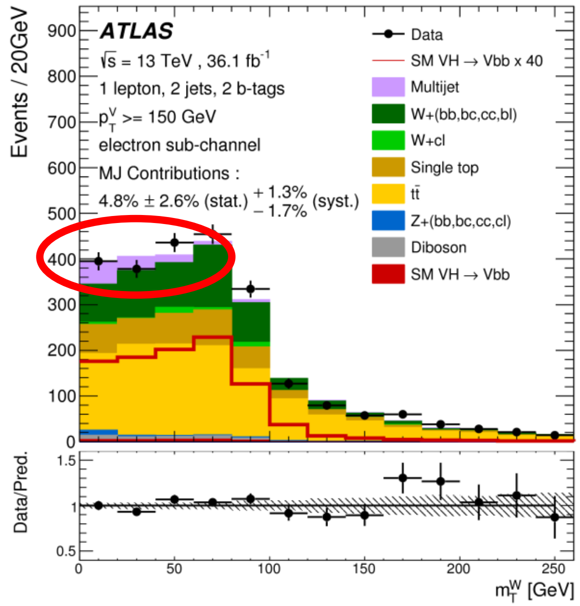
Z/W → ll, lνν, νν related

H → bb related

Selection	0-lepton	1-lepton: e sub-channel	1-lepton: μ sub-channel	2-lepton
Trigger	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$	Single lepton
Leptons	0 loose leptons with $p_{\mathrm{T}} > 7$ GeV	1 tight electron $p_{\mathrm{T}} > 27$ GeV	1 medium muon $p_{\mathrm{T}} > 25$ GeV	2 loose leptons with $p_{\mathrm{T}} > 7$ GeV ≥ 1 lepton with $p_{\mathrm{T}} > 27$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 150 GeV	> 30 GeV	–	–
$m_{\ell\ell}$	–	–		$81 \text{ GeV} < m_{\ell\ell} < 101$ GeV
Jets	Exactly 2 or 3 jets			Exactly 2 or ≥ 3 jets
Jet p_{T}	> 20 GeV			
b-jets	Exactly 2 b-tagged jets			
Leading b-tagged jet p_{T}	> 45 GeV			
H_{T}	> 120 (2 jets), >150 GeV (3 jets)	–		–
$\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{\mathrm{jets}})]$	$> 20^{\circ}$ (2 jets), $> 30^{\circ}$ (3 jets)	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{bb})$	$> 120^{\circ}$	–		–
$\Delta\phi(\vec{b}_1, \vec{b}_2)$	$< 140^{\circ}$	–		–
$\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{E}_{\mathrm{T,trk}}^{\mathrm{miss}})$	$< 90^{\circ}$	–		–
p_{T}^{V} regions	> 150 GeV			(75, 150] GeV, > 150 GeV
Signal regions	✓	$m_{bb} \geq 75$ GeV or $m_{\mathrm{top}} \leq 225$ GeV		Same-flavour leptons Opposite-sign charge ($\mu\mu$ sub-channel)
Control regions	–	$m_{bb} < 75$ GeV and $m_{\mathrm{top}} > 225$ GeV		Different-flavour leptons

The Multi-Jet Background

- Negligible in 0-lep and 2-lep
- Data driven in 1-lep:
  - Define "multij-jet CR": invert lepton isolation cut "anti-tight"
  - Extract background shape from CR (both m_t^W and BDT variables)
  - Fit m_T^W in SR to extract normalization



Systematic Uncertainty: List

Z + jets	
$Z + ll$ normalisation	18%
$Z + cl$ normalisation	23%
$Z + bb$ normalisation	Floating (2-jet, 3-jet)
$Z + bc$-to-$Z + bb$ ratio	30 – 40%
$Z + cc$-to-$Z + bb$ ratio	13 – 15%
$Z + bl$-to-$Z + bb$ ratio	20 – 25%
0-to-2 lepton ratio	7%
m_{bb}, p_T^V	S
W + jets	
$W + ll$ normalisation	32%
$W + cl$ normalisation	37%
$W + bb$ normalisation	Floating (2-jet, 3-jet)
$W + bl$-to-$W + bb$ ratio	26% (0-lepton) and 23% (1-lepton)
$W + bc$-to-$W + bb$ ratio	15% (0-lepton) and 30% (1-lepton)
$W + cc$-to-$W + bb$ ratio	10% (0-lepton) and 30% (1-lepton)
0-to-1 lepton ratio	5%
W + HF CR to SR ratio	10% (1-lepton)
m_{bb}, p_T^V	S
$t\bar{t}$ (all are uncorrelated between the 0+1 and 2-lepton channels)	
$t\bar{t}$ normalisation	Floating (0+1 lepton, 2-lepton 2-jet, 2-lepton 3-jet)
0-to-1 lepton ratio	8%
2-to-3-jet ratio	9% (0+1 lepton only)
W + HF CR to SR ratio	25%
m_{bb}, p_T^V	S
Single top quark	
Cross-section	4.6% (s-channel), 4.4% (t-channel), 6.2% (Wt)
Acceptance 2-jet	17% (t-channel), 35% (Wt)
Acceptance 3-jet	20% (t-channel), 41% (Wt)
m_{bb}, p_T^V	S (t-channel, Wt)
Multi-jet (1-lepton)	
Normalisation	60 – 100% (2-jet), 100 – 400% (3-jet)
BDT template	S

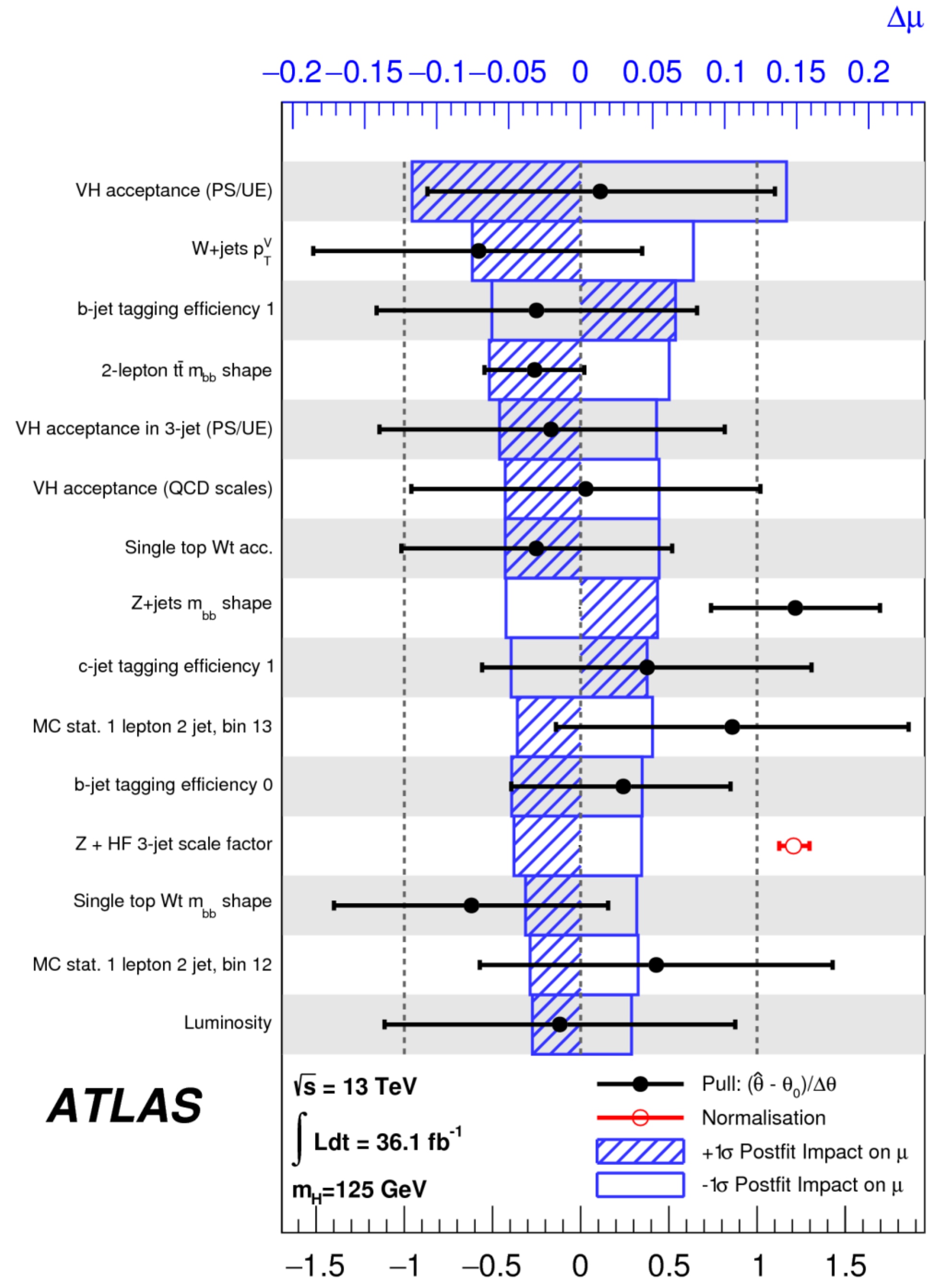
7 un-constrained normalizations !

Systematic Uncertainties: List

ZZ	
Normalisation	20%
0-to-2 lepton ratio	6%
Acceptance from scale variations (var.)	10 – 18% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	5.6% (0-lepton), 5.8% (2-lepton)
Acceptance from PS/UE var. for 3 jets	7.3% (0-lepton), 3.1% (2-lepton)
m_{bb}, p_{T}^{V}, from scale var.	S (correlated with WZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE var.	S (correlated with WZ uncertainties)
m_{bb}, from matrix-element var.	S (correlated with WZ uncertainties)
WZ	
Normalisation	26%
0-to-1 lepton ratio	11%
Acceptance from scale var.	13 – 21% (Stewart–Tackmann jet binning method)
Acceptance from PS/UE var. for 2 or more jets	3.9%
Acceptance from PS/UE var. for 3 jets	11%
m_{bb}, p_{T}^{V}, from scale var.	S (correlated with ZZ uncertainties)
m_{bb}, p_{T}^{V}, from PS/UE var.	S (correlated with ZZ uncertainties)
m_{bb}, from matrix-element var.	S (correlated with ZZ uncertainties)
WW	
Normalisation	25%

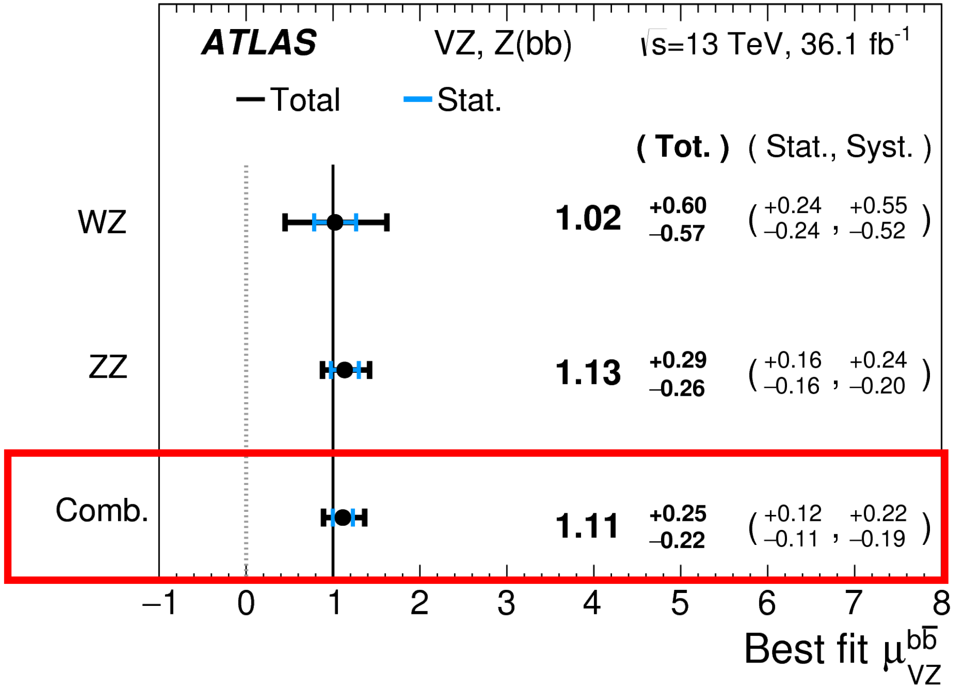
Systematic Uncertai

Process	Normalisation factor
$t\bar{t}$ 0- and 1-lepton	0.90 ± 0.08
$t\bar{t}$ 2-lepton 2-jet	0.97 ± 0.09
$t\bar{t}$ 2-lepton 3-jet	1.04 ± 0.06
W + HF 2-jet	1.22 ± 0.14
W + HF 3-jet	1.27 ± 0.14
Z + HF 2-jet	1.30 ± 0.10
Z + HF 3-jet	1.22 ± 0.09



The di-boson Validation

- **Analysis repeated to fit VZ:**
  - Lower p_T^{bb} and m_{bb}
  - Change BDT signal: VZ instead of VH



5.8σ obs (5.3σ exp)✓
Compatible with SM ✓