Search for A → ZH → $\nu\nu b\bar{b}/llt\bar{t}$ at $\sqrt{s}$=13TeV with the ATLAS detector

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Motivation

- Generation of cosmic matter-antimatter asymmetry → One of the biggest open questions in particle physics and cosmology
- Sakharov conditions: i) Baryon number violation ii) C and CP violation iii) Departure from thermal equilibrium

- SM unable to generate baryon asymmetry of sufficient size

- Extend scalar sector → Two-Higgs-doublet models (**2HDMs**)

2HDMs

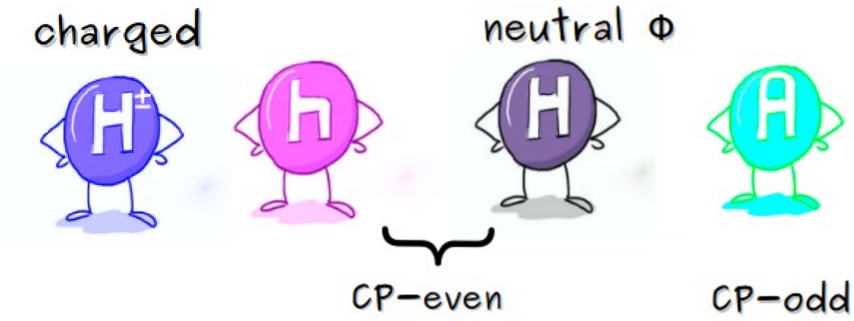
- Scalar potential

$$V = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+\lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \left(\Phi_2^\dagger \Phi_1\right)^2\right]$$

- Two complex SU(2) doublets Φ_1, Φ_2 → 8 fields

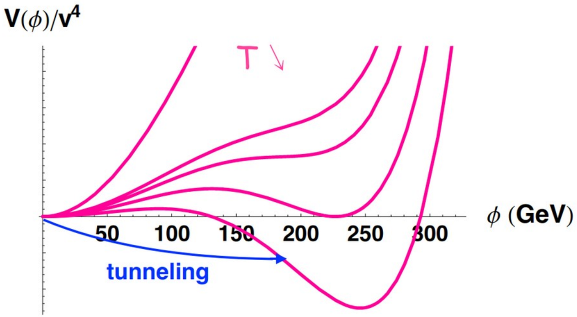
$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

- After EWSB three get "eaten" to give mass to $W^\pm$, Z^0 gauge bosons → five physical scalar fields



2HDMs and the Electroweak Phase Transition

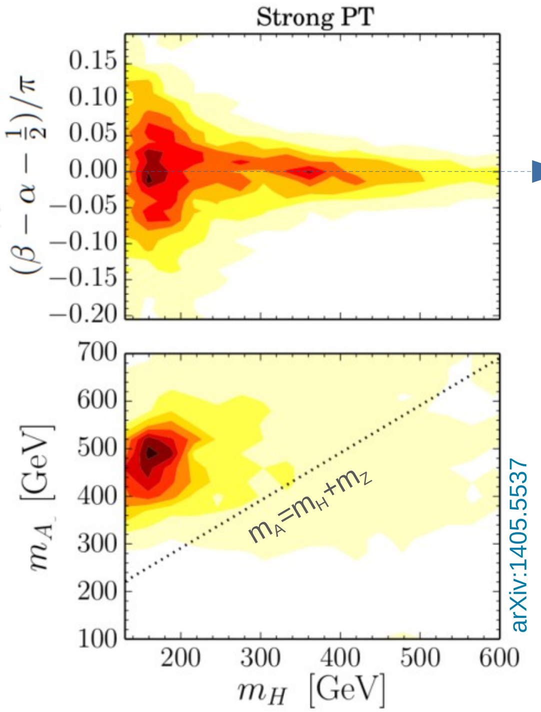
1^{st} order phase transition



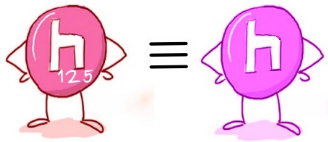
ATLAS-16-09-21-Servant.pdf

EW symmetry breaking can lead to baryogenesis only if the phase transition is of the first order

Strong phase transition → $\upsilon_c/T_c \geq 1$



arXiv:1405.5537



Alignment limit ($\beta \approx \alpha + \pi/2$)

$H^{SM} = h\sin(\alpha-\beta) - H\cos(\alpha-\beta)$

Physical parameters

i. Masses m_H, m_A, $m_{H\pm}$

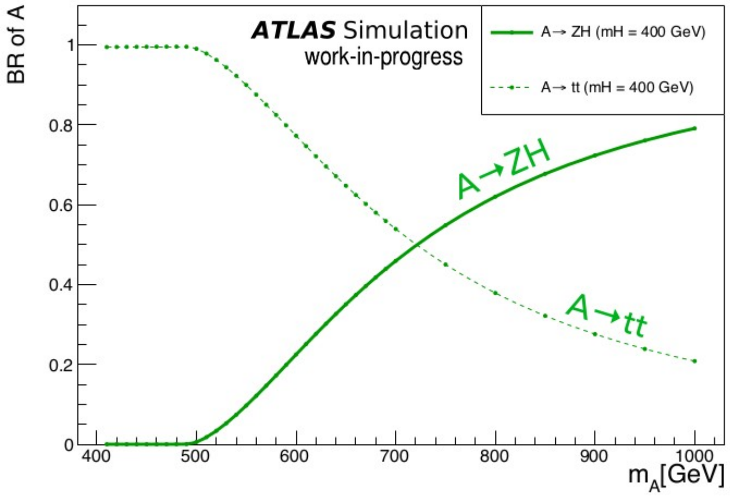
ii. β angle $\tan\beta \equiv \dfrac{v_2}{v_1}$

iii. α angle (CP-even states mixing)

iv. Dimensionful parameter of the potential m_{12}

The A → ZH decay

A → ZH “smoking gun” signature of 2HDMs with strong EWPT!

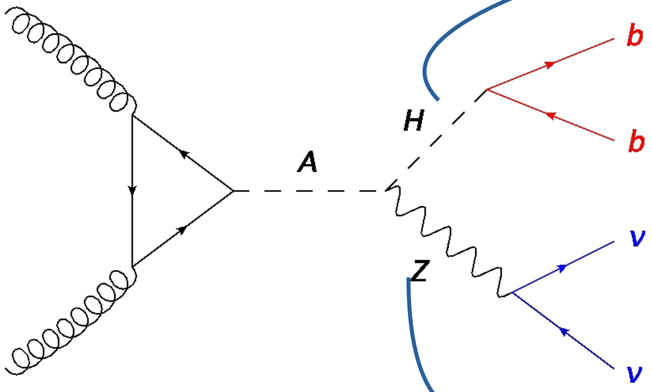


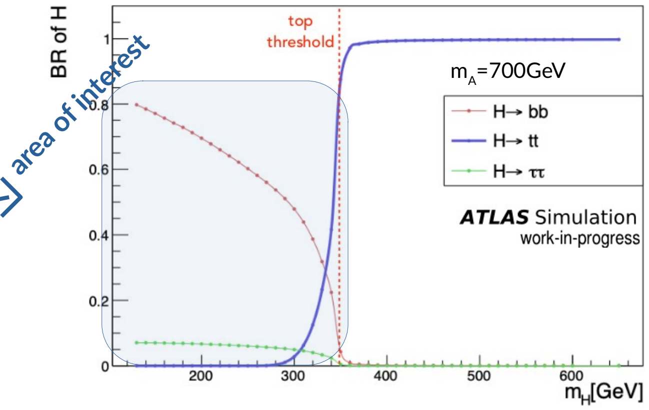
- EWPT in 2HDMs strongly favours a heavy CP-odd state A with a mass splitting $m_A - m_H \geq \upsilon$ (necessary condition for baryogenesis)

The decay A→ZH strongly favoured:

- ➢ large amount of phase space available
- ➢ coupling $g_{AZH} \sim \sin(\beta\text{-}\alpha)$ unsuppressed in the alignment limit Vs coupling $g_{AZh} \sim \cos(\beta\text{-}\alpha)$ vanishes

The ZH → ννb$\bar{b}$ decay





$$Br(Z \rightarrow \nu\bar{\nu}) \approx 21\%$$
$$Br(Z \rightarrow \ell^+\ell^-) \approx 10\%$$

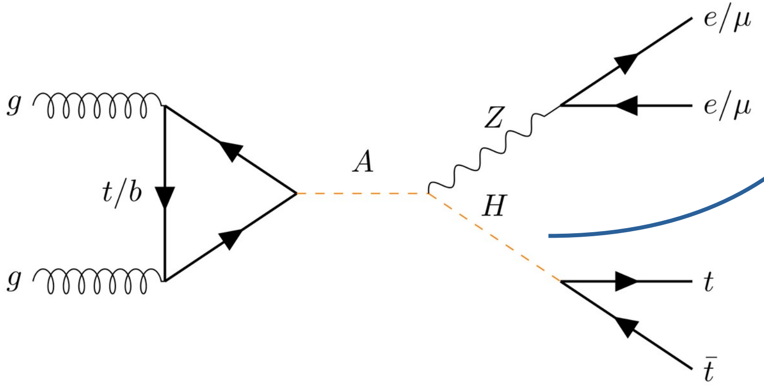
Sensitivity improvement at 0-L channel for high m_A

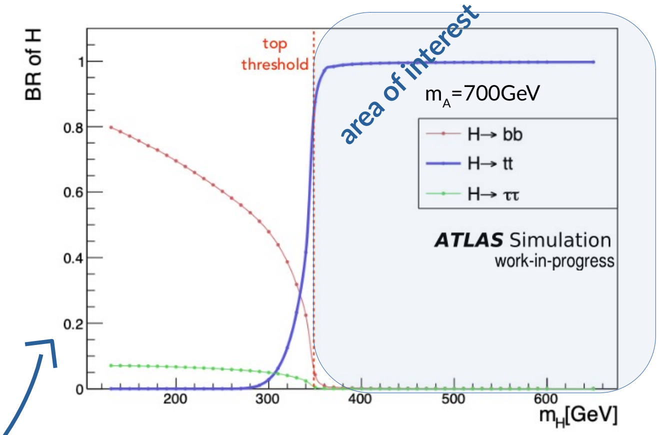
- Dominant background ($t\bar{t}$) suppressed at high m_A
- m_A resolution for 2-L channel worsens

No previous analysis with Z → νν

Previous measurements for m_H up to ~ 250GeV

The ZH → $ll t\bar{t}$ decay





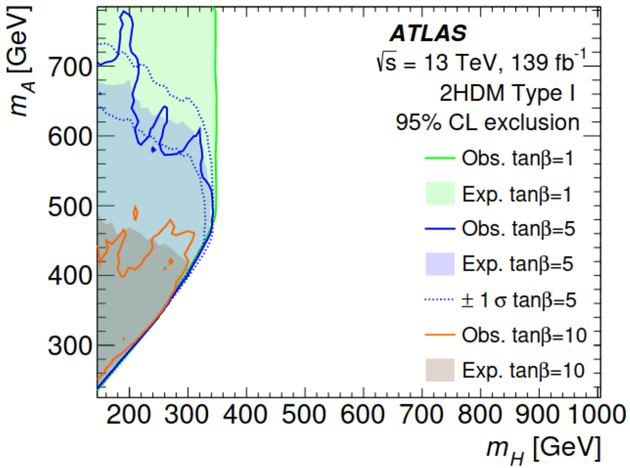
$H \to t\bar{t}$ dominant for m_H > 350 GeV (above the top threshold)

No previous ZH resonance search with $H \to t\bar{t}$!

Previous A → ZH analyses

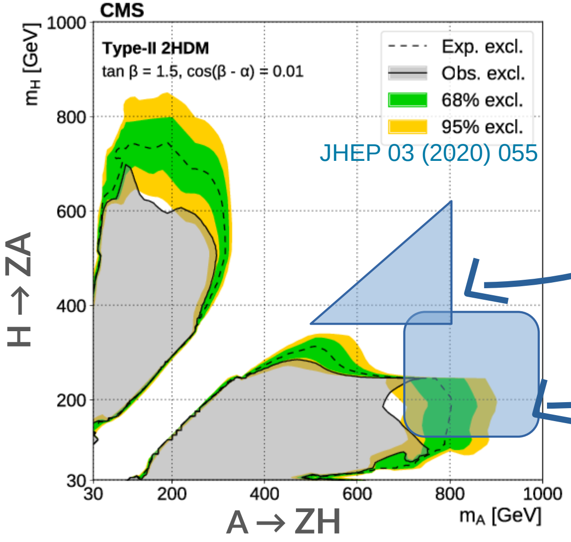
- ATLAS: $AZH \rightarrow l^+l^-b\bar{b}/l^+l^-W^+W^-$

  EPJC 81 (2021) 396



- CMS: $AZH \rightarrow l^+l^-b\bar{b}/l^+l^-\tau\tau$

  Phys. Lett. B 759 (2016) 369



$AZH \rightarrow llt\bar{t}$
Expected exclusion for m_H>350GeV

$AZH \rightarrow \nu\nu b\bar{b}$
Expected exclusion for high m_A

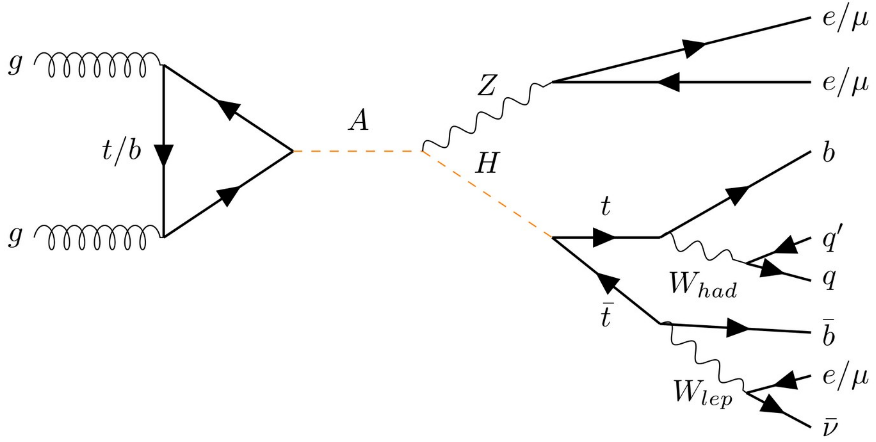
Signal signature $llt\bar{t}$

Signal signature

- 3 leptons (at least one OSSF)
- 2 b-jets
- At least 4 jets

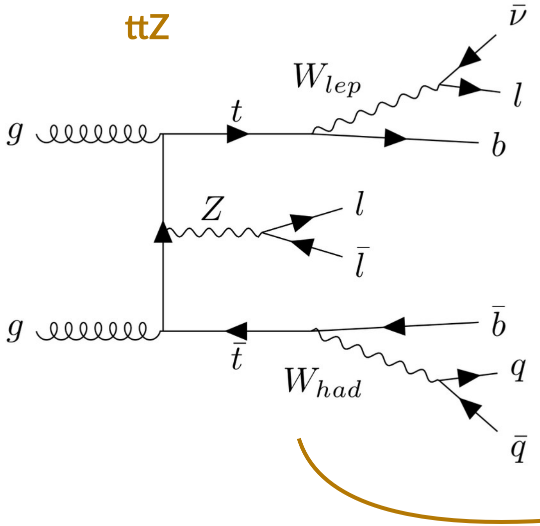
Object reconstruction

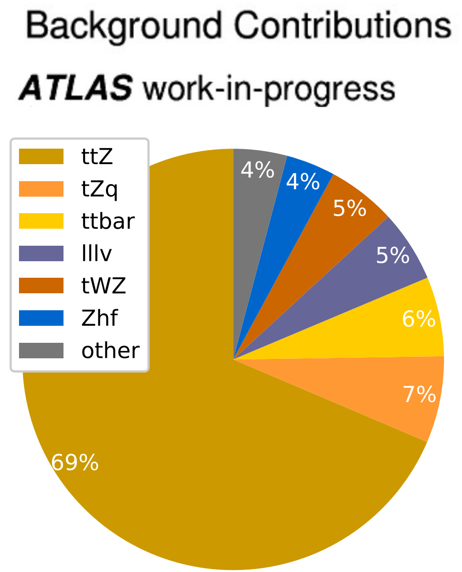
- Z boson → 2 OSSF leptons ($e^+e^-/\mu^+\mu^-$), if more than one pairs (eee/μμμ) consider pair with mass closer to m_Z
- One leptonic top decay → Lepton not from Z and b-jet with min ΔR to this lepton
- One hadronic top decay → 2 light jets with mass closest to m_W and b-jet not from leptonic top



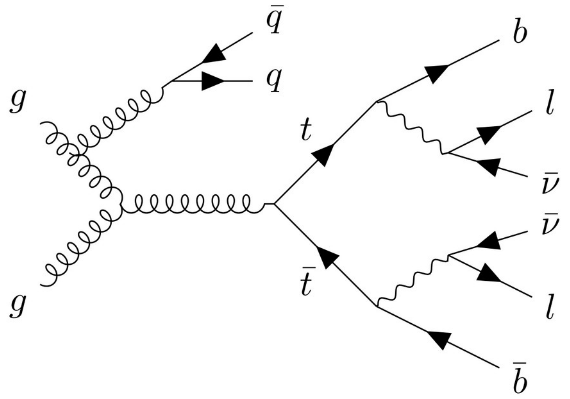
Dominant backgrounds llt$\bar{t}$

ttZ





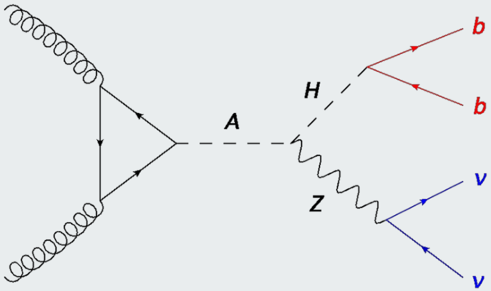
tt+fake lepton



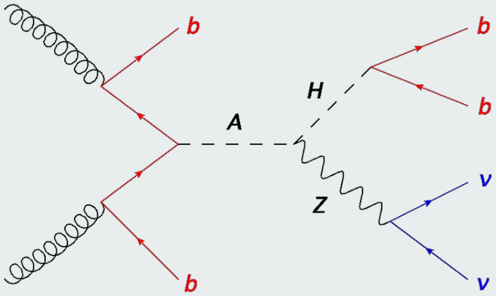
No resonance in m_Z!

Signal signature vvb$\bar{b}$

gluon fusion



b-associated production



Signal signature

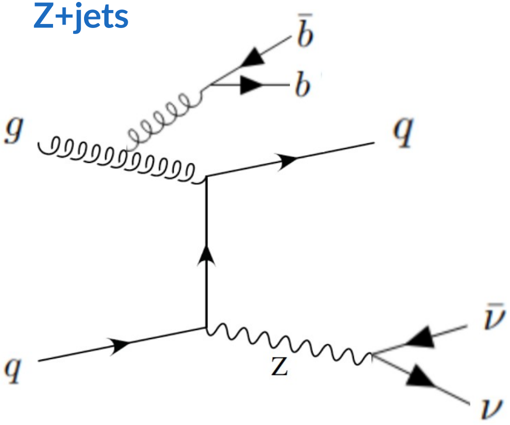
- Zero-lepton channel
- Missing transverse momentum (E_T^{miss}>150GeV)
- At least 2 b-jets

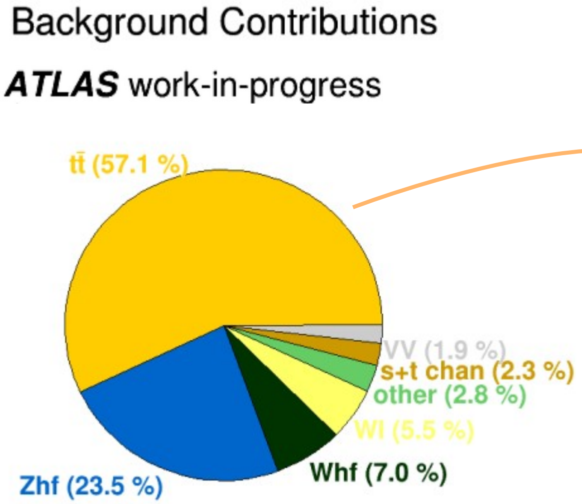
Object reconstruction

- H candidate → Two leading b-jets
- VH (A) candidate (transverse mass) → H+E_T^{miss}

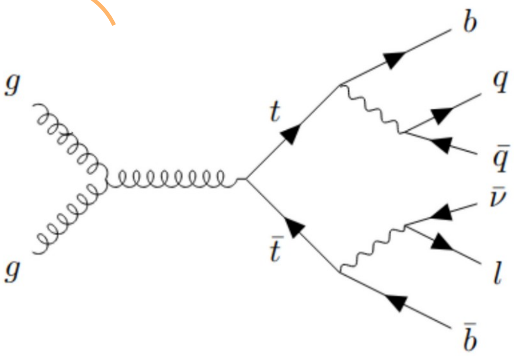
Dominant backgrounds $\nu\nu b\bar{b}$

Z+jets





$t\bar{t}$



Event Selection

Assess improvement after each cut

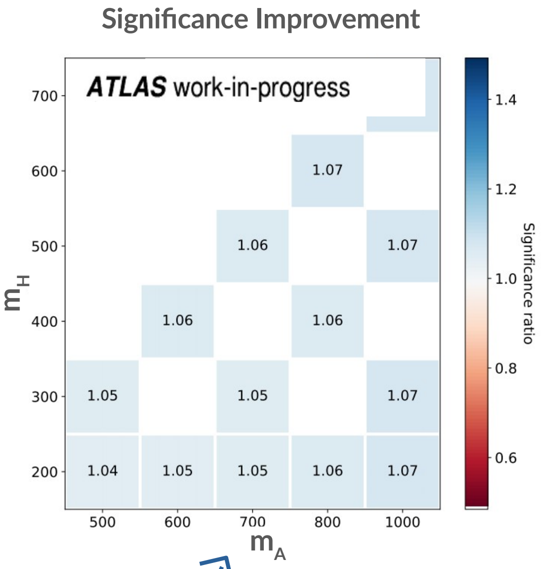
- Calculate significance before and after the cut
- Asymptotic log-likelihood ratio formula

$$\mathcal{S} = \sqrt{2[(s_i + b_i)ln(1 + \frac{s_i}{b_i}) - s_i]}$$

where s_i the signal and b_i the background

The significance is computed for each bin i and then added in quadrature using the $m_T(VH)$ variable

$$\text{ratio} = \frac{\textbf{Significance after cut}}{\textbf{Significance before cut}}$$



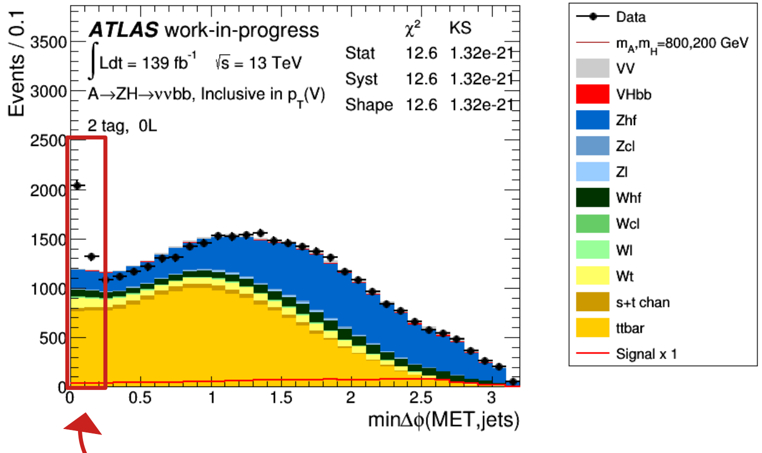
Event Selection $\nu\nu b\bar{b}$

Suppress multijet background

- ➢ $\min\Delta\varphi(E_T^{miss}, jets) > \pi/10$
- ➢ E_T^{miss} sig > 10

$$\mathcal{S} = \frac{E_T^{miss}}{\sqrt{H_T}} \quad \text{or} \quad \mathcal{S} = \frac{E_T^{miss}}{\sqrt{\sum E_T}}$$

- Suppress events with fake E_T^{miss}
- Apply cut on the minimum value sufficient to cut the multijet background



Multijet bkg expected in first bins

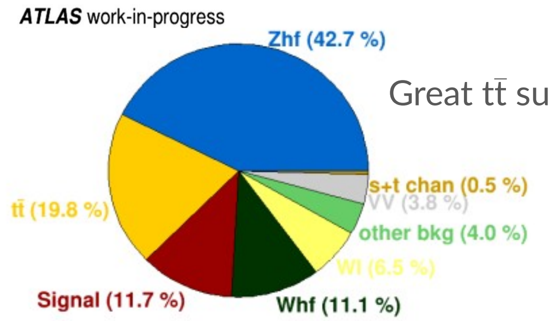
Event Selection vv$b\bar{b}$

Suppress $t\bar{t}$ bkg

- $m_{top}^{b,near}$ > 180GeV & $m_{top}^{b,far}$ > 200GeV

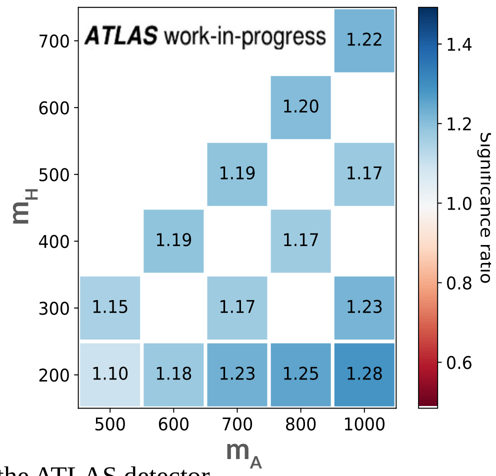
$$m_{top}^{b,near/far} = \sqrt{2p_T^{b,near/far} E_T^{miss}(1 - cos[\Delta\varphi(p_T^{b,near/far}, E_T^{miss}))]}$$

mass of the farthest and nearest jet (from the two leading b-jets) from the E_T^{miss} vector



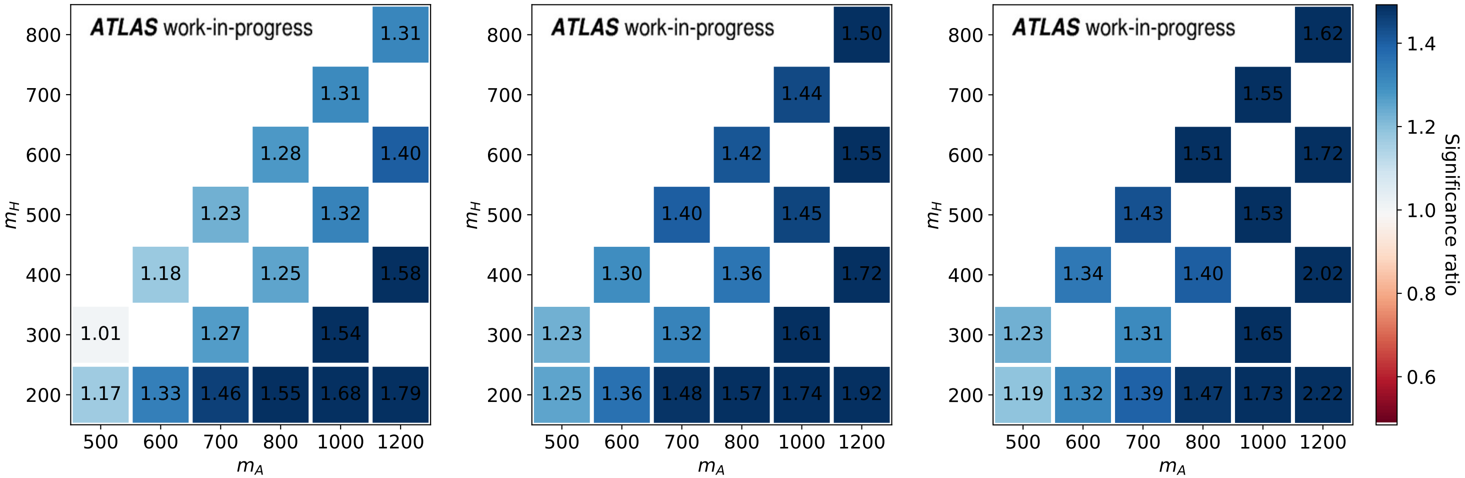
Great $t\bar{t}$ suppression!

Significance improvement



Significance improvement

ggF 2tag | bbA 2tag | bbA 3+tag



Significance improvement after the cut optimisation

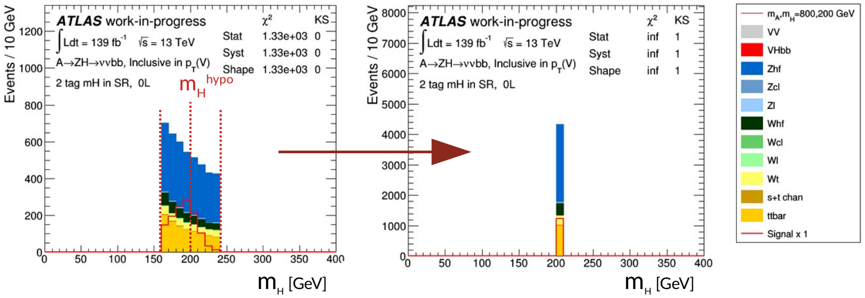
m_{bb} binning

bb system four-vector is scaled so that it reproduces the mass of the H boson

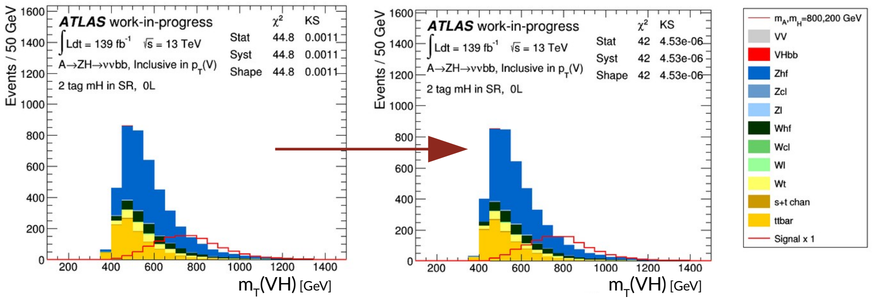
- Test different m_H hypotheses m_H^{hypo}
- The m_H resolution is approximately $m_H^{hypo}/10$
- Define m_H window as $m_H^{hypo} \pm 2res$ (Signal Region)
- Events in SR → Rescale $p(b_{1,2}) \rightarrow p(b_{1,2}) \cdot m_H^{hypo}/m_H$

Hypothesis m_H^{hypo} = 200GeV

Before rescaling **After rescaling**



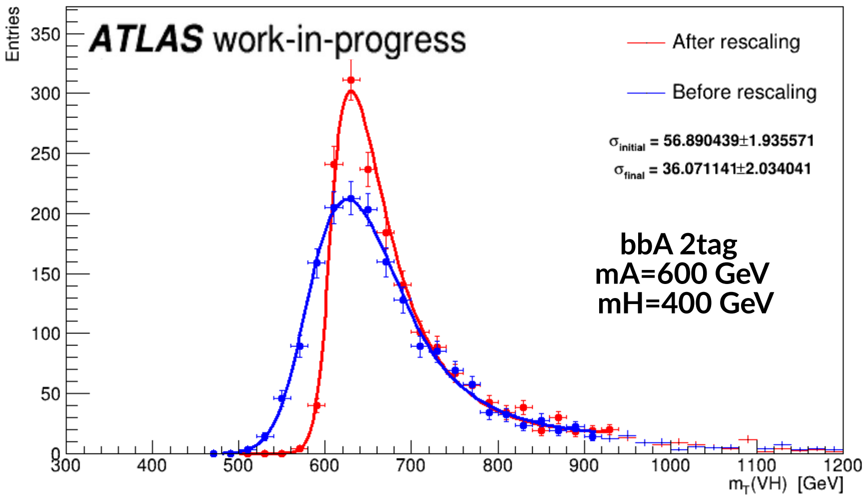
Before rescaling **After rescaling**



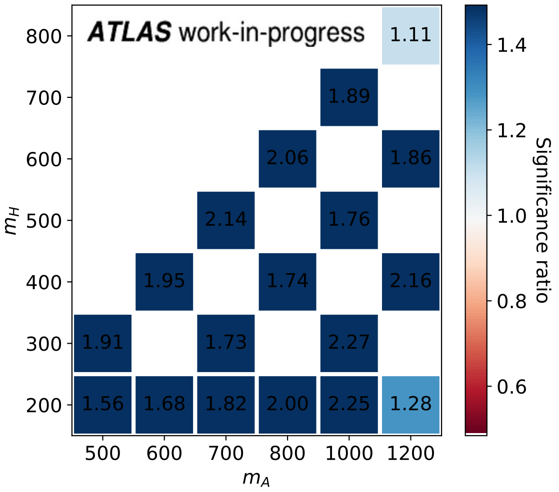
m_{bb} binning

Fit the reconstructed m_T(VH) mass for each signal hypothesis (m_A,m_H) with the **Bukin function**

~11 % average resolution improvement



Great significance improvement with the mH window definition and rescaling



Preliminary results

Hybrid fit

Background only fit to:

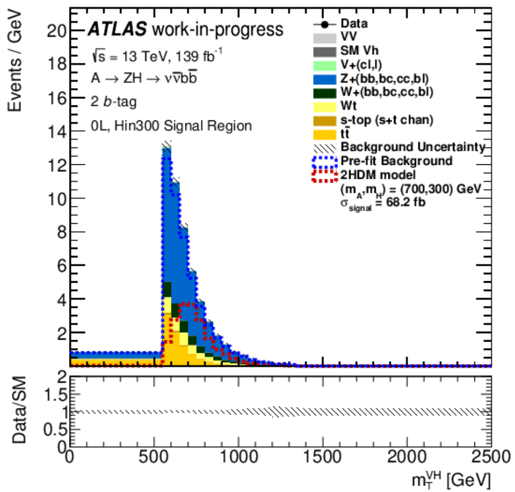
- Asimov data in SR
- Data in CRs

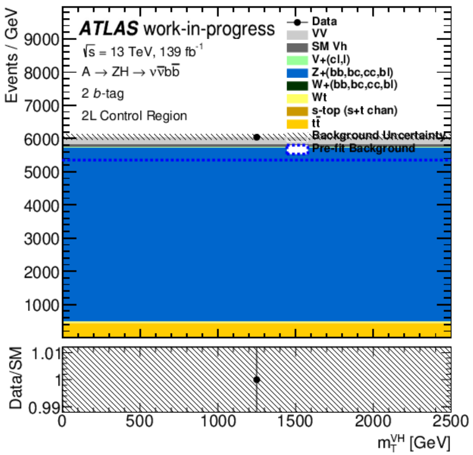
➢ Single bin for the fit variable in CRs

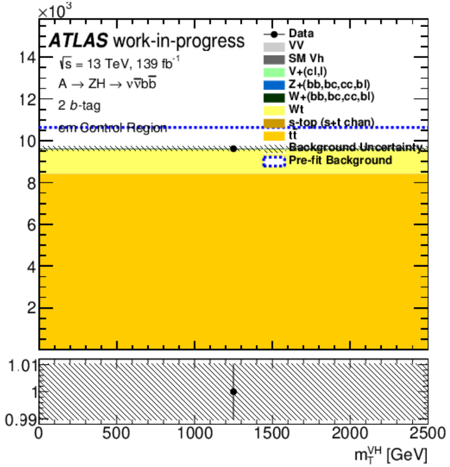
➢ Asimov data in SR reproduce the sum of the backgrounds

➢ Scaled backgrounds using the normalisation factors from the fit to data in the CRs

SFs: 0.89 for ttbar (from eμ) and 1.16 for Zhf (from 2L)

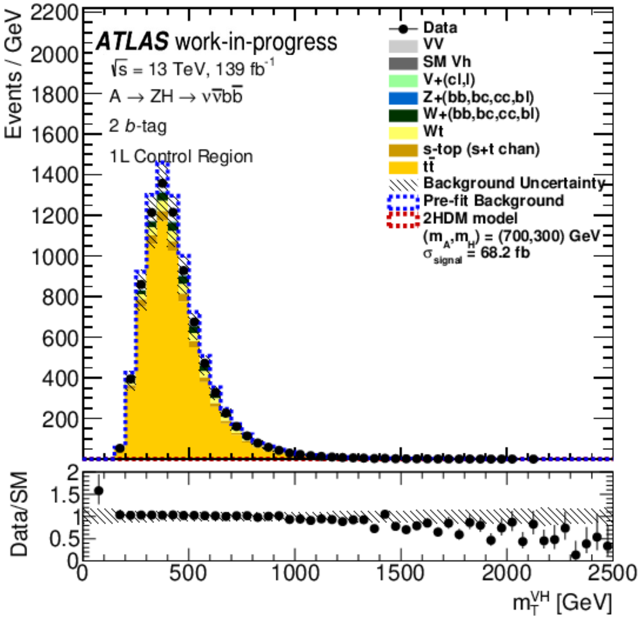


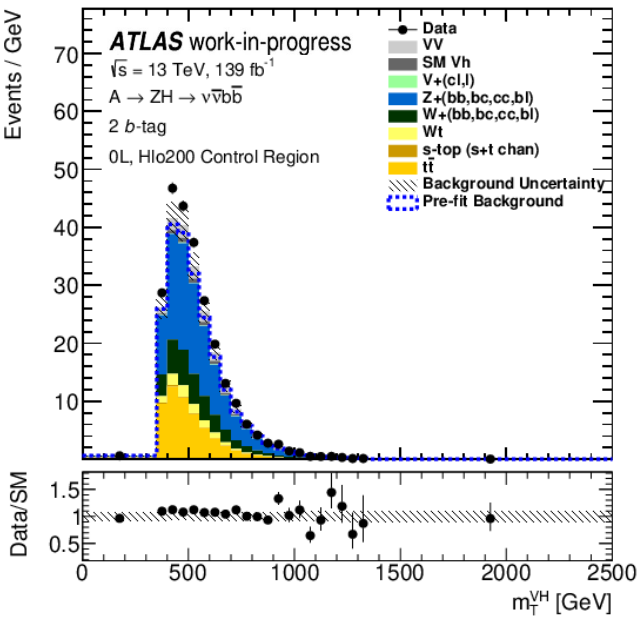




Preliminary results

- Validate the impact of the shape uncertainties from fit discriminant distributions in VRs (1L and Hlo200)



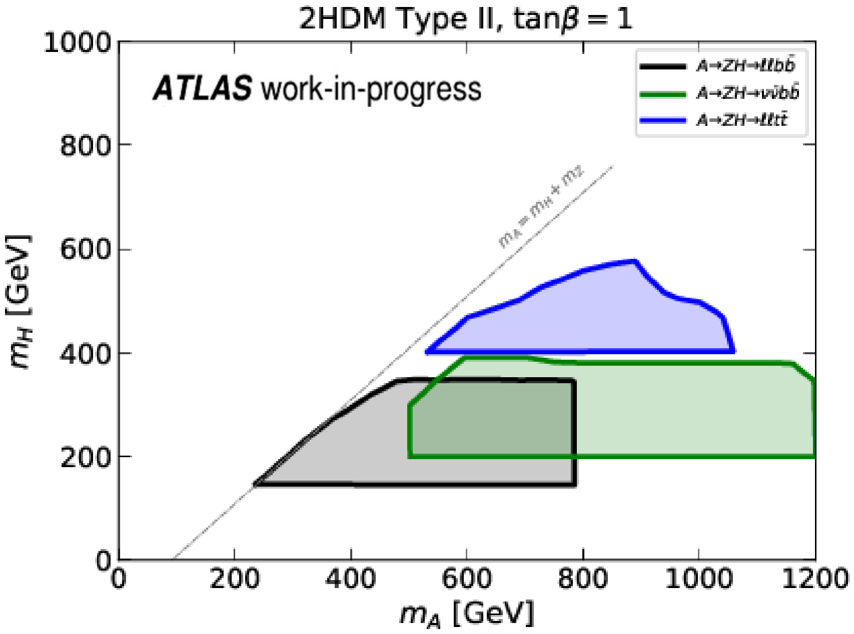


Summary and future work

- Significance improvement after the cuts
- Exclusion of high m_A with large mass splitting
- Preliminary fit results in good agreement

Upcoming steps

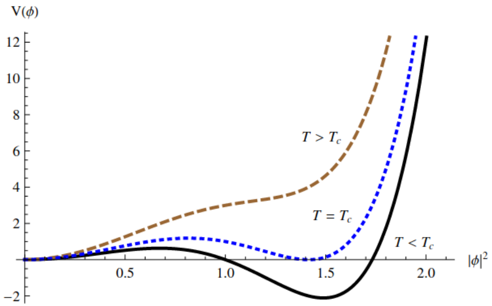
- Unblinding and extraction of upper limits for signal cross-section

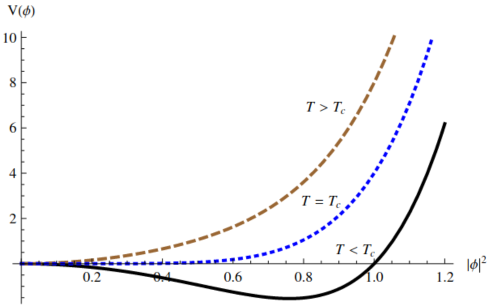


Thank you for your time!

Back-up slides

Why first-order PT





- Universe cools to below T_c (PT) → bubbles of the true vacuum (broken phase) start forming within the sea of the false vacuum (unbroken phase)
- False vacuum continues to exist below T_c as the transition is first order

arXiv:hep-ph/9611462

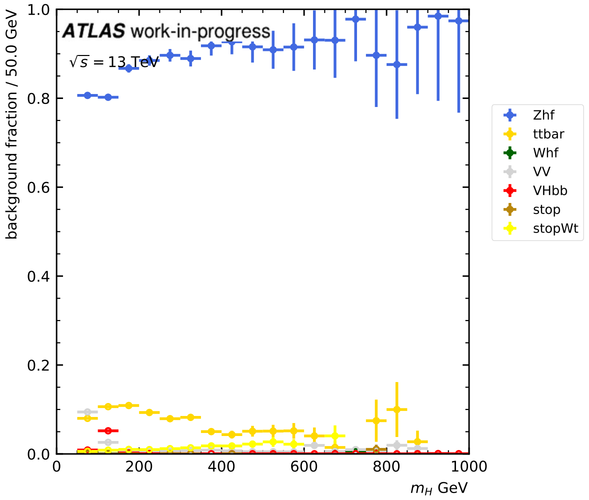
- As the temperature falls, the bubbles start growing → bubbles of the true vacuum nucleate and fill up the entire universe
- Different regions of the universe pass through the phase boundary between the broken and the unbroken phase
- The transition being discontinuous, the order parameter jumps rapidly across these boundaries → The system is driven away from equilibrium, as the baryon number violating processes are not fast enough to keep pace with this rapid change

Objects

- **Leptons:** p_T>7GeV and |η|<2.5
- **Jets:** p_T>25GeV and |η|<2.5
- **$E_T$miss** built from non-interacting particles
- **b-tagging** performed using b-hadrons with p_T>5GeV (70% b-jet efficiency)

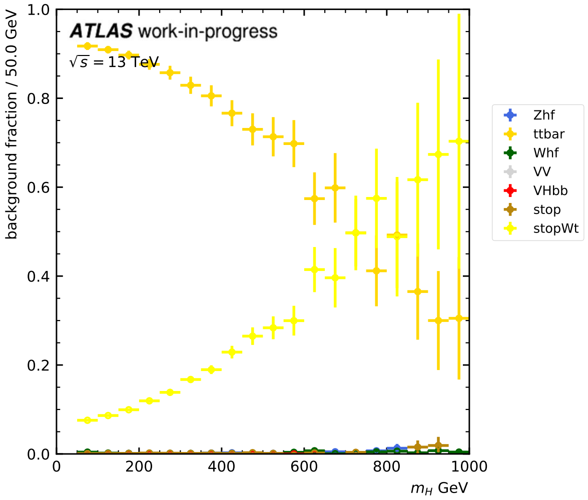
Background composition in CRs vvbb̄

2-lepton



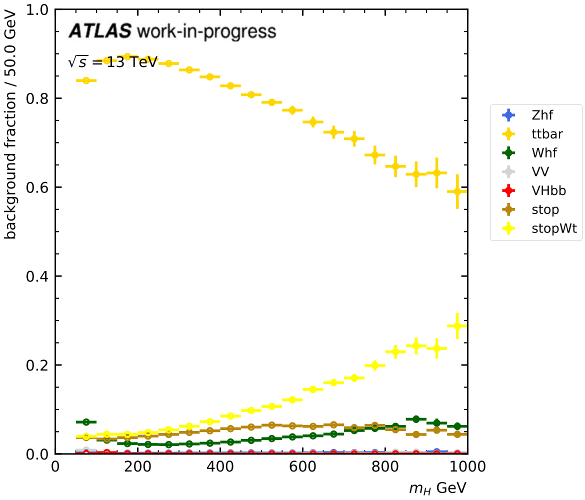
Two same flavour leptons (ee/μμ)

eμ



Two opposite flavour leptons (eμ)

1-lepton

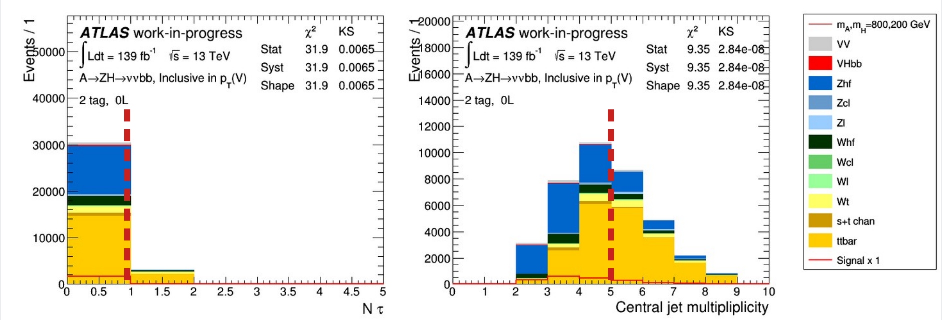


One lepton (e/μ)

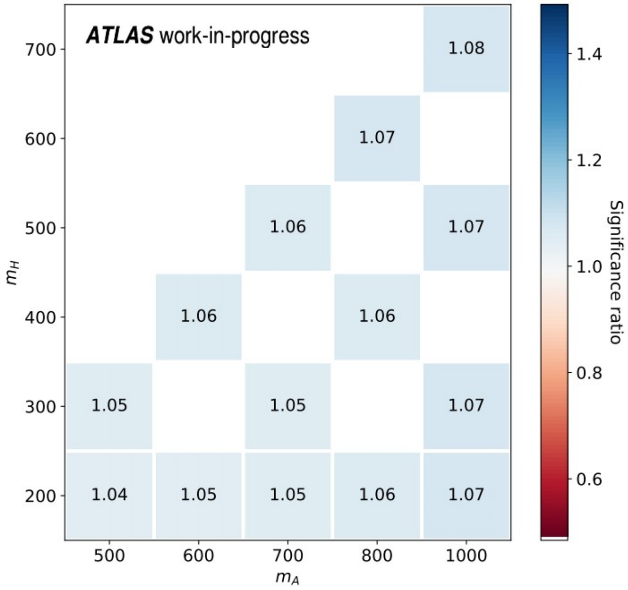
Event Selection $\nu\nu b\bar{b}$

Cuts

- **Tau veto** → Reduce $t\bar{t}$ bkg with $t \to Wb \to \tau\nu_\tau b$
- **$2 \leq N_{jets} < 6$**



Significance Improvement



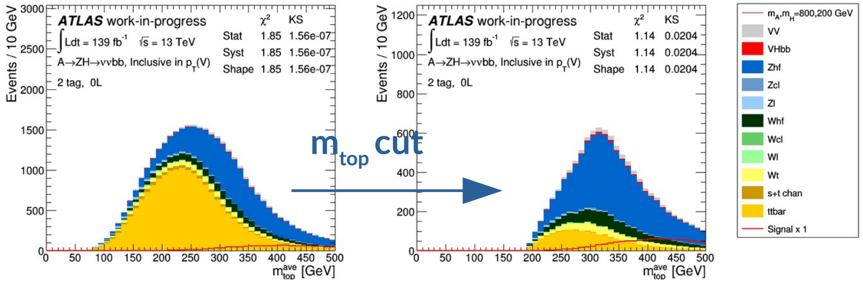
Event Selection ννbb̄

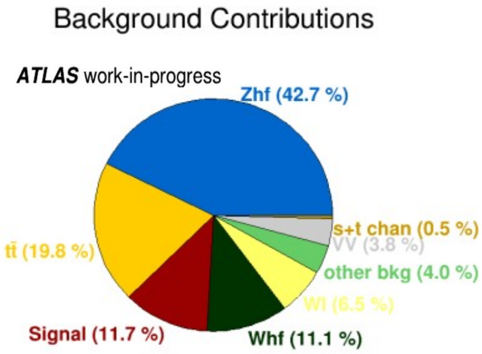
Cuts

- Tau veto
- $2 \leq N_{jets} < 6$
- $\min\Delta\varphi(E_T^{miss}, jets) > 0.319$
- E_T^{miss} sig > 10
- **$m_{top}^{b,near}$ > 180GeV & $m_{top}^{b,far}$ > 200GeV →** Suppress $t\bar{t}$ bkg

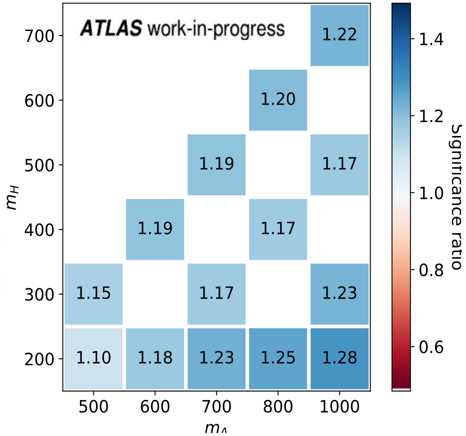
$$m_{top}^{b,near/far} = \sqrt{2p_T^{b,near/far} E_T^{miss}(1 - cos[\Delta\varphi(p_T^{b,near/far}, E_T^{miss}))]}$$

mass of the farthest and nearest jet (from the two leading b-jets) from the E_T^{miss} vector





Great $t\bar{t}$ supression!



Event Selection $\nu\nu b\bar{b}$

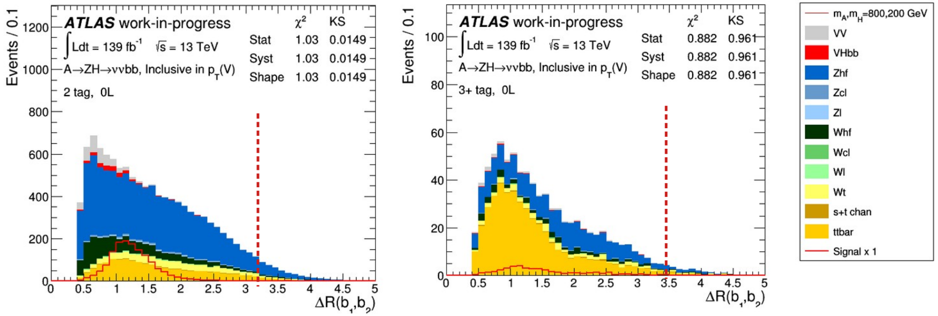
Cuts

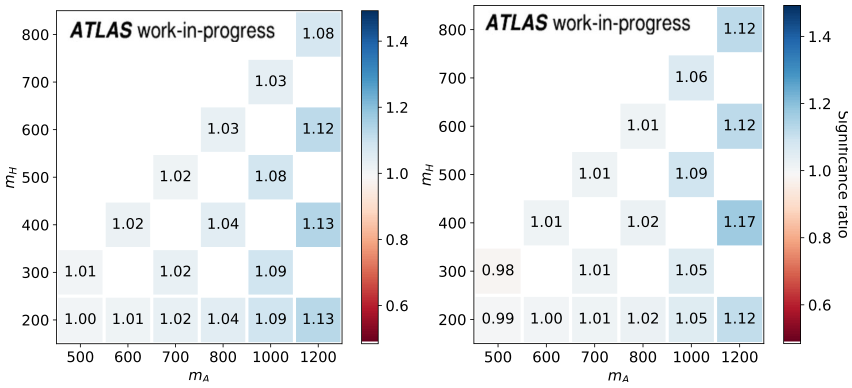
- Tau veto
- $2 \leq N_{jets} < 6$
- $\min\Delta\varphi(E_T^{miss}, jets) > 0.319$
- E_T^{miss} sig > 10
- $m_{top}^{near} > 180GeV$ & $m_{top}^{far} > 200GeV$
- **$\Delta R(b_1,b_2) < 3.3$, for 2tag region**

  $\Delta R(b_1,b_2) < 3.5$, for 3+tag region

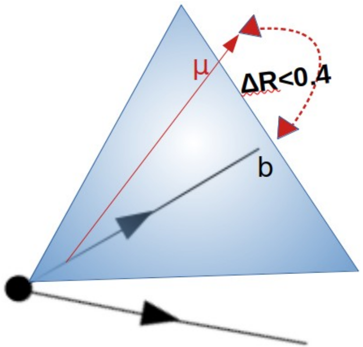
ggF 2tag

bbA 3+tag





Muon-in-jet correction

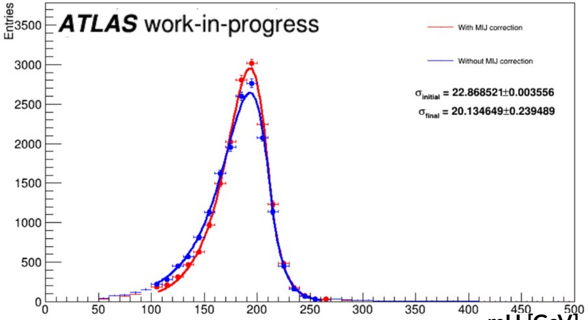


Correct the jet if a muon is found within the jet cone
- ➢ Targets semi-leptonic decays of B hadrons
- ➢ $p_T(\mu)$>5GeV and ΔR<0.4
- ➢ If multiple muons are matched → the nearest muon to the jet axis is used

Fit m_H and m_A with the Bukin function, with and without the muon-in-jet correction

H mass distribution

ggF mA600_mH200



mH [GeV]

Average resolution improvement after the correction
- ➢ m_H ~ 11%
- ➢ m_A ~ 4%

Event Selection vvb$\bar{b}$

Cut	Regions				
	2L	**eμ**	**1L**	**Hlo/ Hhi**	**Hin**
N jets	2-5				
N b-jets	≥ 2				
m_H^{cand}	≥ 50 GeV				
N τ-leptons	0				
$p_T(V)$	≥ 150 GeV				
$\min_i \Delta\phi(E_{\text{T}}^{\text{miss}}, \vec{p}_i^{\,\text{jet}})$	$> \pi/10$				
$\Delta R(b_1, b_2)$	< 3.3 (2 b-jets) < 3.5 (≥ 3 b-jets)				
N leptons	2		1	0	
Lepton flavour	$ee/\mu\mu$	$e\mu$	e/μ	-	
$p_{\text{T}}(\ell_1)$	> 27 GeV			-	
$\lvert m_Z^{\text{cand}} - m_Z \rvert$	< 10 GeV	-			
$\mathcal{S}_{\text{MET}}$	< 5	-	> 3	> 10	
$m_{\text{top}}^{\text{near}}$	-			> 180 GeV	
$m_{\text{top}}^{\text{far}}$	-			> 200 GeV	
$\lvert m_H^{\text{cand}} - m_H^{\text{hypo}} \rvert$	-			$> 0.2 \cdot m_H^{\text{hypo}}$	$< 0.2 \cdot m_H^{\text{hypo}}$

Event Selection $llt\bar{t}$

<table>
<tr><th rowspan="2">Cut</th><th colspan="7">Regions</th></tr>
<tr><th>ss_Zin</th><th>ss_Zout</th><th>L3hi_Zout</th><th>Hlo/Hhi</th><th>Hin</th><th>L3lo_Zin</th><th>L3lo_Zout</th></tr>
<tr><td>N leptons</td><td colspan="7">3</td></tr>
<tr><td>p_T (ℓ_1)</td><td colspan="7">$\geq$ 27 GeV</td></tr>
<tr><td>N jets</td><td colspan="7">≥ 4</td></tr>
<tr><td>N b-jets</td><td colspan="7">2</td></tr>
<tr><td>$\left|\eta^{ZH-r.fr.}_{H-cand}\right|$</td><td colspan="7">$< 2.2 + 0.0004 \cdot m_H^{cand} - 0.0011 \cdot m_A^{cand}$</td></tr>
<tr><td>p_T (ℓ_3)</td><td colspan="5">$\geq$ 13 GeV</td><td colspan="2">$\geq$ 7 & $\leq$ 13 GeV</td></tr>
<tr><td>Lepton flavour</td><td colspan="2">$ee\mu/\mu\mu e$</td><td colspan="5">$eee/ee\mu/\mu\mu e/\mu\mu\mu$</td></tr>
<tr><td>OSSF lepton pairs</td><td colspan="2">0</td><td colspan="5">≥ 1</td></tr>
<tr><td>$|m_Z^{cand} - m_Z|$</td><td>$\leq$ 10 GeV</td><td colspan="2">$\geq$ 10 & $\leq$ 20 GeV</td><td colspan="3">$\leq$ 10 GeV</td><td>$\geq$ 10 & $\leq$ 20 GeV</td></tr>
<tr><td rowspan="2">$|m_H^{cand} - m_H^{hypo}|$ $m_H^{hypo} < 500$ GeV
$m_H^{hypo} > 500$ GeV</td><td colspan="3" rowspan="2">-</td><td>$> 0.32 \cdot m_H^{hypo}$</td><td>$< 0.32 \cdot m_H^{hypo}$</td><td colspan="2" rowspan="2">-</td></tr>
<tr><td>$> 0.24 \cdot m_H^{hypo}$</td><td>$< 0.24 \cdot m_H^{hypo}$</td></tr>
</table>

E_T^{miss} significance

- The reconstructed E_T^{miss} in ATLAS is characterised by two main contributions:
  i. Hard objects (fully reconstructed and calibrated objects: muons, electrons, photons, τ-leptons, and jets)
  ii. Soft term (additional signals which are not associated with any of the reconstructed hard objects)

$$E_T^{miss} = -\left(\sum_{i \in \text{muons}} p_T{}^i + \sum_{i \in \text{electrons}} p_T{}^i + \sum_{i \in \text{photons}} p_T{}^i + \sum_{i \in \text{hadronic } \tau} p_T{}^i + \sum_{i \in \text{jets}} p_T{}^i + \sum_{i \in \text{Soft Term}} p_T{}^i \right)$$

- The E_T^{miss} significance S helps to separate events in which the reconstructed E_T^{miss} originates from weakly interacting particles, from those in which E_T^{miss} is consistent with contributions coming from particle measurement, resolutions and inefficiencies

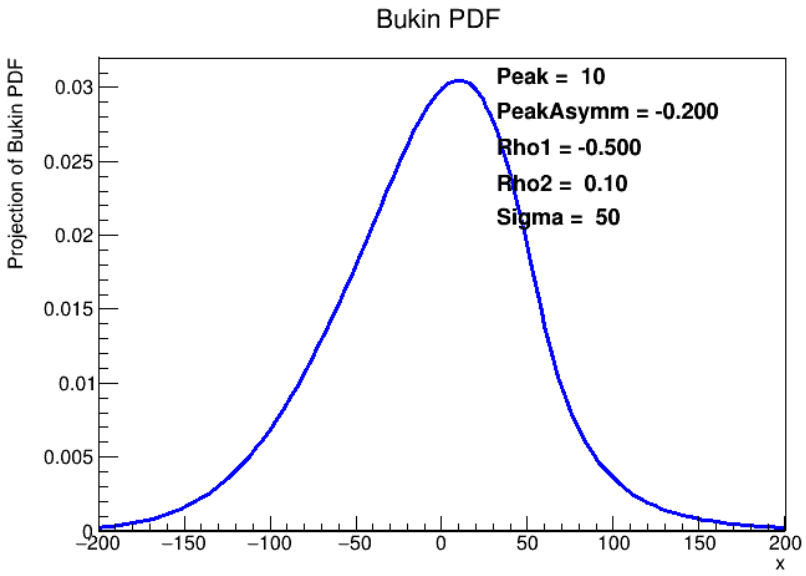
$$\mathcal{S} = \frac{E_T^{miss}}{\sqrt{H_T}} \quad \text{or} \quad \mathcal{S} = \frac{E_T^{miss}}{\sqrt{\sum E_T}}$$

event-based approximations to the total E_T^{miss} resolution

Object-based missing transverse momentum significance in the ATLAS detector

Bukin Fit

- Fitting function for asymmetric peaks



classRooBukinPdf

Fit parameters

- Xp: peak position
- Sigma: gaussian width
- Xi: asymmetry parameter
- Rho1: parameter of the left tail
- Rho2: parameter of the right tail

Theory systematic uncertainties

Systematic uncertainties arise from the MC modelling of the background and signal processes

Sources:

- Missing higher orders in the calculation of the inclusive matrix elements
- Uncertainties from the choice of PDFs
- Merging-scale uncertainties
- Resummation scale uncertainties
- Matching uncertainties
- Parton shower/hadronisation uncertainties

Background	Systematic
ttbar (dominant)	Scales, PDF
	ISR/FSR
	ME/Matching
	PS/Hadronisation
Z+heavy flavour jets (dominant)	Scales, PDF
	CKKW/QSF
W+heavy flavour jets	ME/PS
Wt	Scales, PDF
	ISR/FSR
	ME/Matching
	PS/Hadronisation
	ttbar-Wt Interference
Single top	Scales, PDF
	ISR/FSR
	PS/Hadronisation
VV	Scales, PDF
	NLO merging
SM Higgs	Scales, PDF
	PS/Hadronisation

Theory systematic uncertainties

Inclusive Normalisation Uncertainty

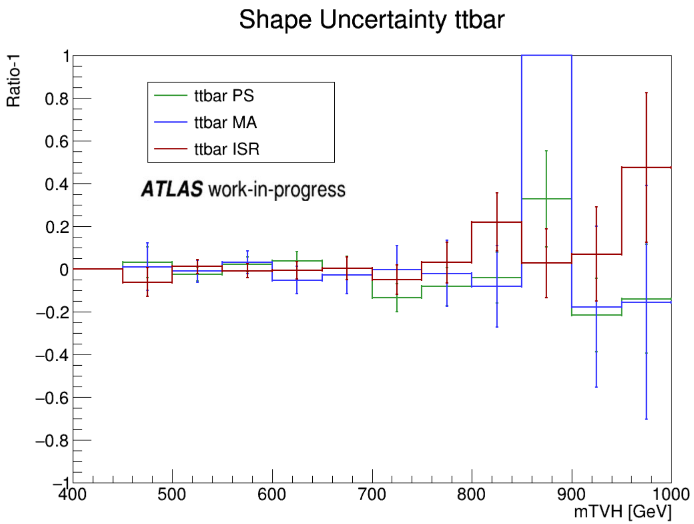
$$\sigma_{\text{norm}} = \sqrt{\sum_i \left(1 - \frac{N^{\text{alt},i}}{N^{\text{nom}}}\right)^2}$$

where i runs over all alternative MC generators considered for a given process and N corresponds to the total expected background yield in all regions

Shape Uncertainty

$$\text{shape uncertainity} = \frac{var - nom}{nom}$$

Sample	Systematic	Normalisation Uncertainty
ttbar	Scales	+10.5/-11.2
	PDF	1.5
	ISR	-0.8/+10.7
	FSR	+3.1/-19.4
	ME (matching)	7.4
	PS	8.2
	Total	23.5



Theory systematic uncertainties

Acceptance Uncertainty

$$\sigma_{\text{accept}} = \sqrt{\sum_i \left(1 - \frac{N_{\text{SR}}^{\text{alt},i}}{N_{\text{CR}}^{\text{alt},i}} \Big/ \frac{N_{\text{SR}}^{\text{nom}}}{N_{\text{CR}}^{\text{nom}}}\right)^2}$$

where i runs over all alternative MC generators considered

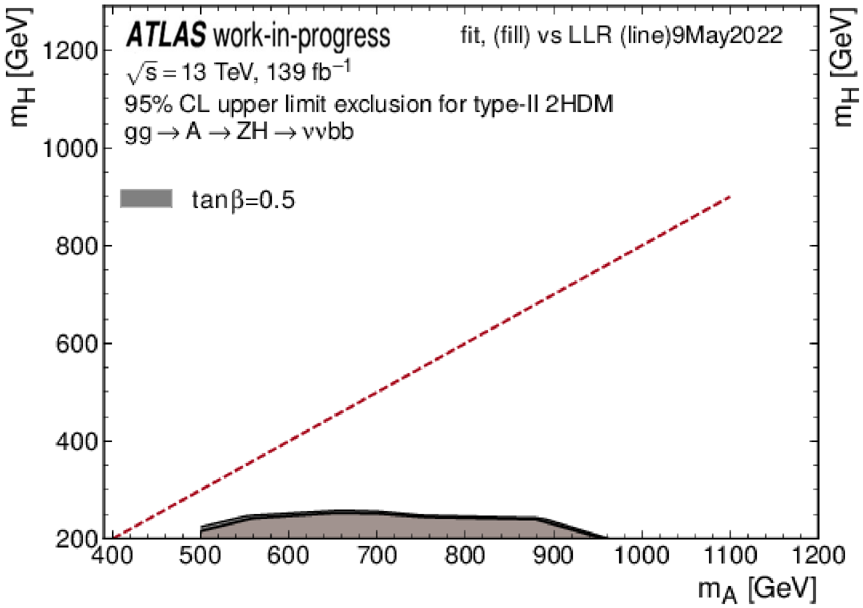
Normalisation/Acceptance differences between the various analysis regions

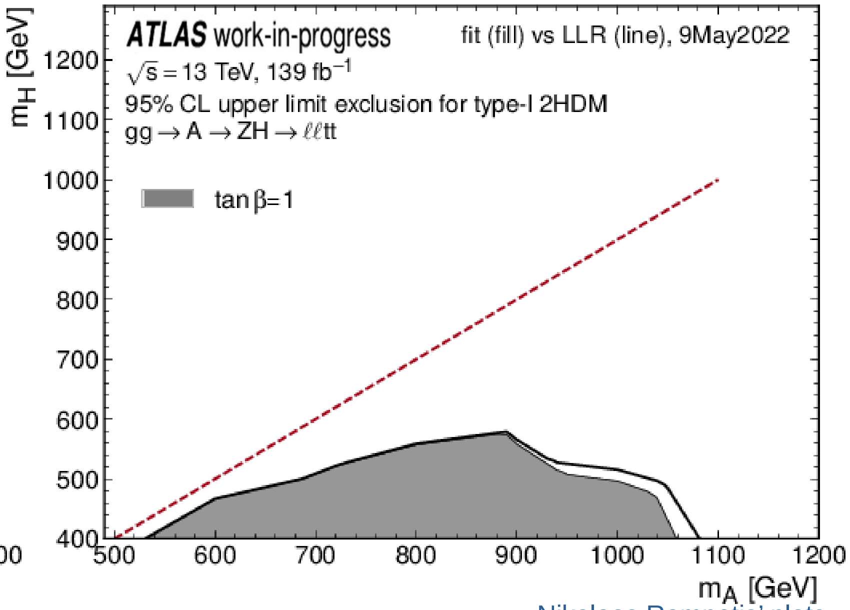
Sample	Systematic	Regions			
		1L/SR	$e\mu$/SR	2L/SR	2-tag/3p-tag
$t\bar{t}$	Scales	-	+5.0/-3.1	+6.2/-3.7	-
	PDF	-	-	-	-
	ISR	-0.6/+2.6	-0.5/+9.0	-0.9/+12.1	-0.07/-1.2
	FSR	+1.4/-1.9	+1.3/-0.4	-	+2.8/-2.6
	ME (matching)	2.6	-4.3	-9.2	-
	PS	6.6	7.6	8.0	10.5
	Total	10.2	12.5	16.8	11.3

Sample	Systematic	Regions					
		$m_H^{hypo} = 200GeV$		$m_H^{hypo} = 300GeV$		$m_H^{hypo} = 400GeV$	
		mHlo/SR	mHhi/SR	mHlo/SR	mHhi/SR	mHlo/SR	mHhi/SR
$t\bar{t}$	Scales	+0.7/-1.4	+1.5/-1.4	+1.6/-2.0	+1.4/-1.0	+1.5/-1.9	+3.1/-2.4
	PDF	-	-	-	-	-	1.0
	ISR	-0.7/-1.4	+0.2/+3.7	-0.9/-5.0	-0.3/-1.3	-	-1.0/+11.8
	FSR	-1.9/+3.9	-2.2/+1.0	+0.2/+2.5	-1.9/+1.6	+1.6/+1.4	-0.2/-1.4
	ME (matching)	4.4	5.1	-	6.1	-4.9	-
	PS	-	-	-	-3.2	2.8	-1.9
	Total	5.4	5.8	3.1	7.3	6.0	7.3

Initial validation

- Expected exclusion obtained from a stat-only fit to Asimov data (filled area) and from the LLR (line)
- Good agreement between stat-only fit and LLR





Nikolaos Rompotis' plots