

High p_T Physics at the LHC

Lecture 4: Higgs Physics and Advanced Topics

Warwick Week 2023

13th April 2023

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I will take a slightly different approach in this lecture...

- Our understanding of the (125 GeV) Higgs boson is still developing rapidly
- This lecture will review the current state of the art and will be more “technical” (don't worry, I will explain!)
- Along the way, I will make several interludes to discuss more advanced experimental techniques

Outline of Lecture

- Introduction to the Higgs boson
- Review of main production and decays modes for $m_H = 125$ GeV
- Summary of selected recent experimental results
- Several interludes on event reconstruction techniques

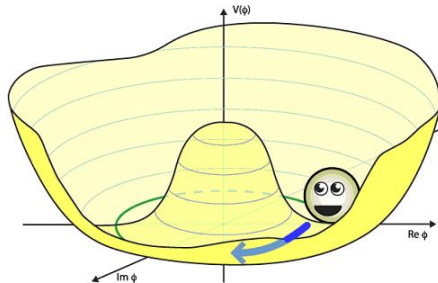


Figure from Philip Tanedo

- Introduce a complex scalar $SU(2)$ doublet ϕ to the SM (4 d.o.f.)
- If potential $V(\phi)$ has a non-zero VEV, the EW symmetry is spontaneously broken
- Leads to Goldstone bosons (3 d.o.f.) which mix with W^\pm and Z fields
- Provides gauge invariant mass terms (and long. pol.) to the W^\pm and Z ✓
- Predicts the fourth d.o.f. should manifest as a scalar “Higgs” boson!

In 2012 a particle with a mass of 125 GeV, consistent with the SM Higgs boson, was discovered by ATLAS and CMS ✓



“Yukawa” couplings between the Higgs (ϕ) and fermion (ψ) fields are possible:

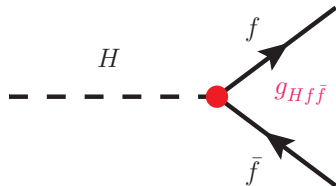
$$\mathcal{L}_{\text{fermion}} = -y_f \cdot [\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L]$$

If $V(\phi)$ has a non-zero VEV, expansion leads to (h is the physical Higgs field):

$$\mathcal{L}_{\text{fermion}} = \underbrace{-\frac{y_f v}{\sqrt{2}} \cdot \bar{\psi} \psi}_{\text{mass term}} - \underbrace{\frac{y_f}{\sqrt{2}} \cdot h \bar{\psi} \psi}_{\text{Yukawa coupling term}}$$

Results in Higgs–fermion coupling proportional to the fermion mass ($g_{Hf\bar{f}} = m_f/v$)

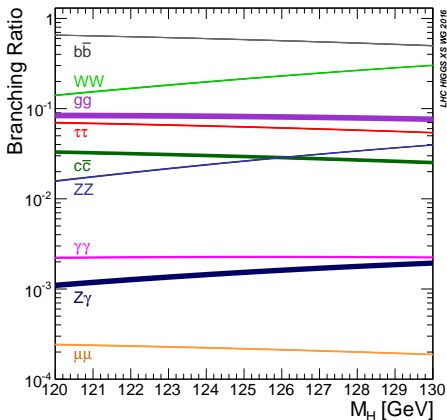
- Gauge invariant fermion mass terms in SM ✓
- y_f “predicted” in SM given knowledge of v and m_f ($v \approx 246$ GeV from EW observables) ✓
- Offers no fundamental insight into the observed fermion mass hierarchy ✗



While Yukawa couplings provide concrete predictions for $Hf\bar{f}$ interactions, they fail to describe the origin of the fermion mass hierarchy i.e. why is $m_t/m_e \approx \mathcal{O}(10^5)$!?

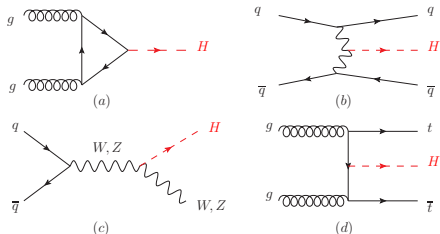
Total decay width of SM 125 GeV Higgs boson is around 4 MeV, far below ATLAS/CMS detector resolution!

- $H \rightarrow b\bar{b}$ is the most common decay, with $\mathcal{B}(H \rightarrow b\bar{b}) \approx 58\%$
- Decays to fermions (i.e. $H \rightarrow q\bar{q}, \ell^+\ell^-$) directly sensitive to Yukawa couplings ($\Gamma \propto y_f^2$)
- Decays $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ probe heart of EWSB (coupling determined by shape of $V(\phi)$), for $m_H = 125$ GeV one W/Z is always off-shell
- The decays $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ are loop induced, no direct $H\gamma\gamma/gg$ coupling



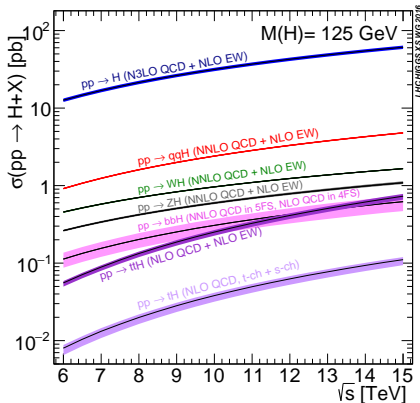
At $m_H = 125$ GeV, the channels $H \rightarrow ZZ^* \rightarrow \ell^+\ell^-\ell^+\ell^-$ and $H \rightarrow \gamma\gamma$ exhibit the most favourable signal to background at the LHC

Total cross-section at $\sqrt{s} = 13$ TeV is around 55 pb, this is actually not such a small cross-section (given LHC lumi.), over 7M Higgs produced in LHC Run 2!



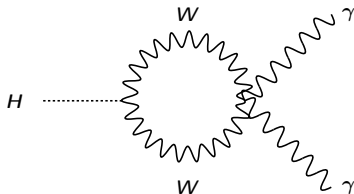
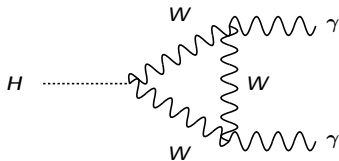
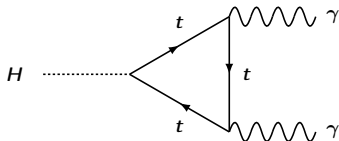
Diagrams: arXiv:1708.00794

- a) Gluon fusion process $gg \rightarrow H$ is dominant ($\approx 88\%$)
- b) Vector boson fusion (VBF) $q\bar{q} \rightarrow q\bar{q}H$ is the sub-leading process ($\approx 7\%$)
- c) Associated production with a W or Z boson “Higgsstrahlung” ($\approx 4\%$)
- d) Associated production with $t\bar{t}$ ($\approx 1\%$)



Modes sensitive to different couplings, important to study them all. Some channels facilitate the study of experimentally challenging decays e.g. $Z(\ell^+\ell^-)H(b\bar{b})$

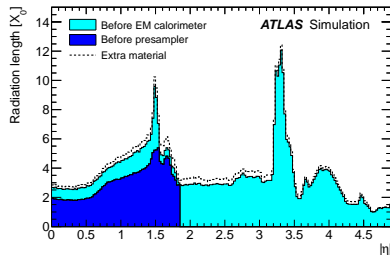
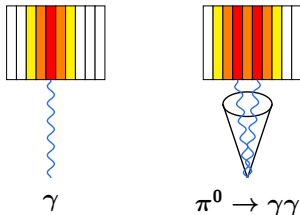
- Decay induced through fermion (mostly top quark) or W boson loop diagrams (with interfering amplitudes)
- Rather low branching fraction
 $\mathcal{B}(H \rightarrow \gamma\gamma) \approx 2 \times 10^{-3}$
- Characterised by two high $p_T \approx m_H/2$ photons, isolated from hadronic activity



ECal. designed to initiate EM shower of incident photon, energy can be measured and direction inferred based on location of signal calorimeter cells w.r.t. beam spot

Challenge 1: Neutral Hadrons

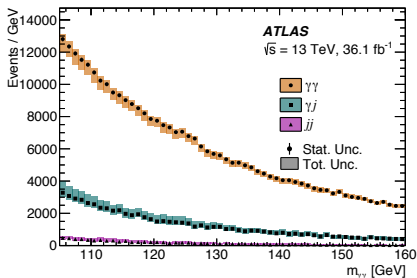
- Jets containing a high fraction of neutral hadrons are the main background to photon reconstruction
- Primarily caused by $\pi^0 \rightarrow \gamma\gamma$ decays (i.e. two photons with a small angular separation)
- Mitigated by considering the “shape” of the calorimeter signal (single or overlapping photons?)



Challenge 2: Material Interactions

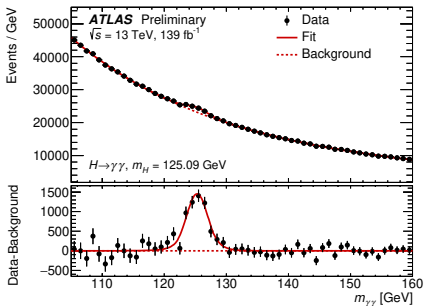
- Much material (tracking detectors) in front of the EM calorimeter
- High probability ($\approx 30\%$) that a photon will convert to $\gamma \rightarrow e^+e^-$ before reaching the calorimeter
- Attempt to reconstruct the final state electrons to recover this “inefficiency”

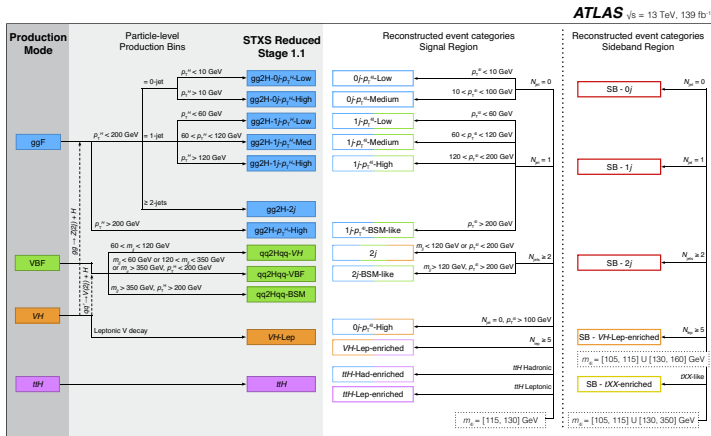
Strategy: Look for events containing two isolated high p_T photon candidates



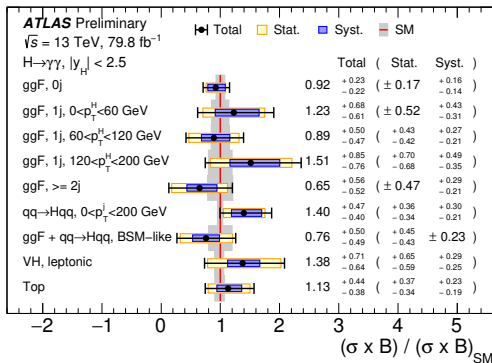
- Dominant “irreducible” background from non-resonant QCD production of two isolated photons
- Residual background due to one or both photons being “fake” from multi-jet production
- Judicious “shower shape” based photon ID selection reduces this to $\approx 20\%$ of total background

- Fully reconstructed final state with excellent resolution in $m_{\gamma\gamma}$
- Search for “bump” consistent with $m_{\gamma\gamma}$ resolution ($\approx 1.5\%$) on top of smoothly falling background





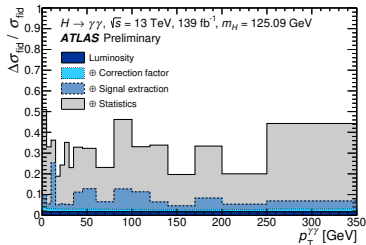
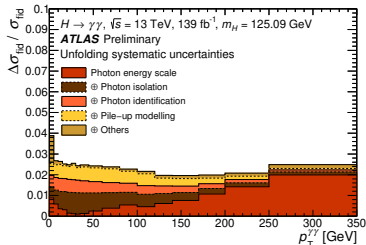
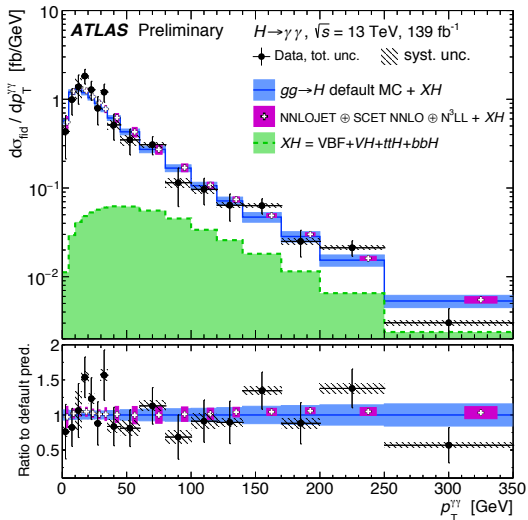
- Measurement strategy detailed in [LHC-HXSWG YR4 \(arXiv:1610.07922\)](#)
- Cross-section for Higgs production in for various sub-processes for a simplified fiducial volume defined as $|y_H| < 2.5$
- Theoretical uncertainties on overall signal cross sections are removed but kept if they cause migration between categories

$H \rightarrow \gamma\gamma$ production measurements with 80 fb^{-1} 13 TeV dataset

Summary of the measured simplified template cross sections (STXS)

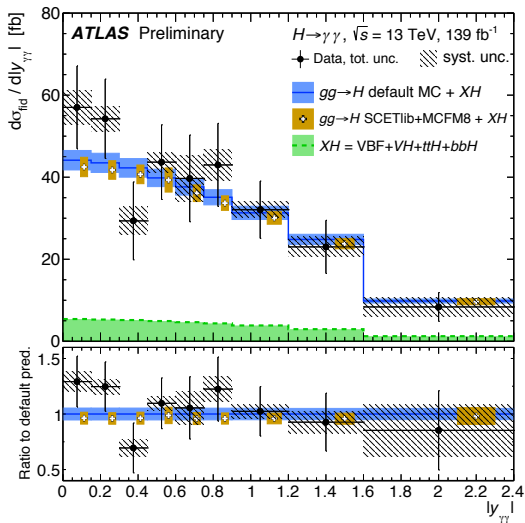
- Wide range of inclusive and differential fiducial (phase space \rightarrow) cross section measurements
- Global signal strength consistent with SM
 $\mu = 1.06 \pm 0.08$ (stat.) $^{+0.08}_{-0.07}$ (exp.) $^{+0.07}_{-0.06}$ (theo.)

Objects	Definition
Photons	$ \eta < 1.37$ or $1.52 < \eta < 2.37, p_T^{\text{min},0.2} / p_T^1 < 0.05$
Jets	anti- $k_t, R = 0.4, p_T > 30 \text{ GeV}, \eta < 4.4$
- Central jets	$ \eta < 2.5$
- b-jets	$ \eta < 2.5, \Delta R(\text{jet}, b\text{-hadron}) < 0.4$ for b-hadrons with $p_T > 5 \text{ GeV}$
Leptons, $\ell = e$ or μ	electrons: $p_T > 10 \text{ GeV}, \eta < 2.47$ (excluding $1.37 < \eta < 1.52$) muons: $p_T > 10 \text{ GeV}, \eta < 2.7$
Fiducial region	Definition
Diphoton fiducial	$N_\gamma \geq 2, p_T^1 > 0.35 \cdot m_{\gamma\gamma}, p_T^2 > 0.25 \cdot m_{\gamma\gamma}$
$N_{b\text{-jets}}$ measurement	Diphoton fiducial, $N_{b\text{-jets}}^{\text{max}} \geq 1, N_{\text{photons}} = 0$



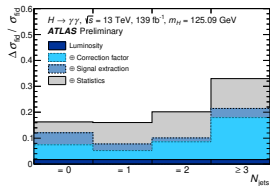
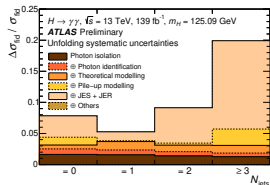
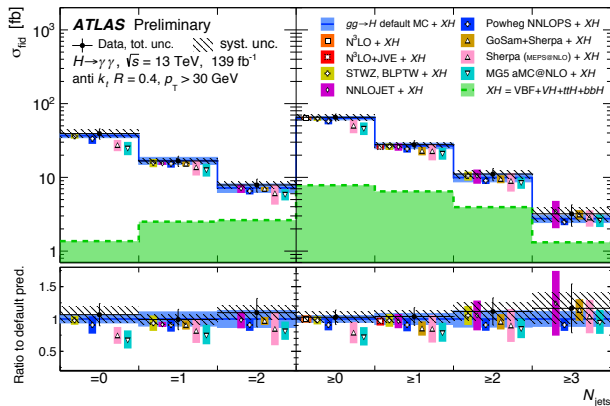
- χ^2 probability for compatibility of data with default SM distribution[†] is 44%
- p_T^H exhibits lowest compatibility with SM of distributions measured (still very high!)

[†] POWHEG NNLOPS normalised to YR4 N³LO (QCD) and NLO(EW) cross section



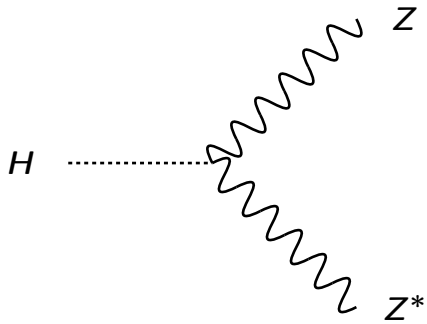
■ χ^2 probability for compatibility of data with default SM distribution[†] is 68%

[†] POWHEG NNLOPS normalised to YR4 N³LO (QCD) and NLO(EW) cross section



- Multiplicity of associated jets, both inclusive and exclusive bins
- Sensitive to contributions from VH and $t\bar{t}H$ production at high N_{jets}
- χ^2 probability for compatibility of data with default SM distribution[†] is 96%

[†] POWHEG NNLOPS normalised to YR4 $N^3\text{LO}$ (QCD) and NLO(EW) cross section



- Tree level decay, directly sensitive to HZZ coupling
- Reasonably high branching fraction, $B(H \rightarrow ZZ^*) \approx 3\%$
- Feasibility of experimental study driven by characteristics of Z boson decays

- Most effective channel considers only $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ decays
- Reduces branching fraction to $B(H \rightarrow ZZ^* \rightarrow 4\ell) \approx 10^{-4}$
- Very sensitive to spin / parity properties of Higgs boson given multiple measurable angular distributions

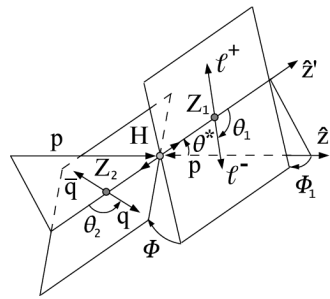
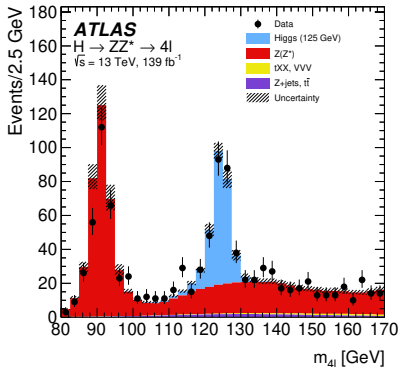
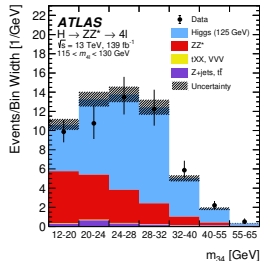
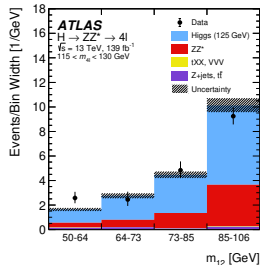


Figure: CMS-HIG-12-024

Study events containing four isolated high p_T electron/muon candidates

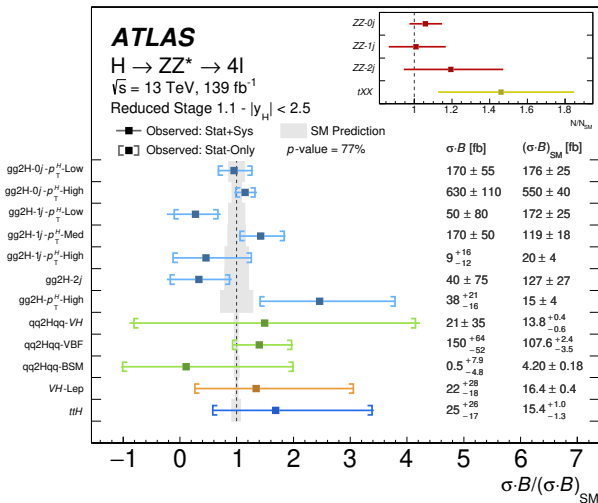


- Very good resolution in $m_{4\ell}$ and $S/B \approx 1$, described as “golden channel”
- Background dominated by “irreducible” nonresonant $Z(Z/\gamma^*)$ production, with much smaller contributions from Z + jets and $t\bar{t}$

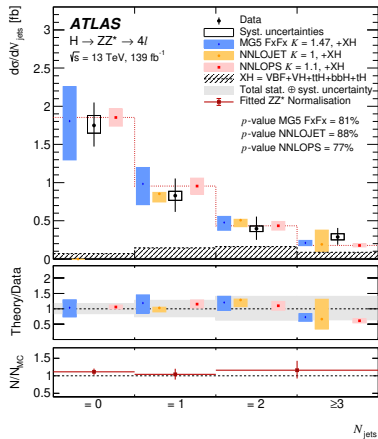
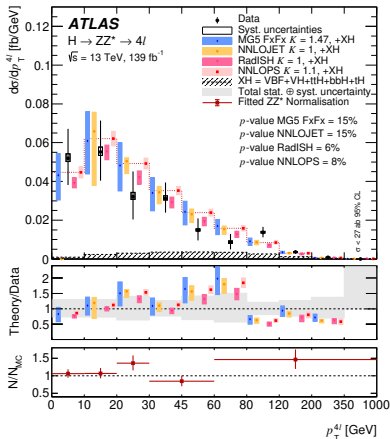


Figures: arXiv:2004.03969

$H \rightarrow ZZ^* \rightarrow 4\ell$ production measurements updated with 139 fb^{-1} 13 TeV dataset, global signal strength $\mu = 1.01 \pm 0.08$ (stat.) ± 0.04 (exp.) ± 0.05 (theo.)



“Reduced Stage 1.1” STXS (cross-sections)



- Differential measurements of p_T^H and associated jet multiplicity
- p -values for compatibility of p_T^H data with predictions reasonably low...

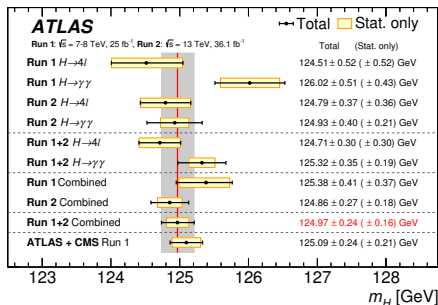
Latest combined measurement in $H \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels, based on 36 fb^{-1} of 13 TeV data and updated energy/momentum scale calibrations

- Per-event method used in $H \rightarrow 4\ell$ case, cross-checked with template method
- Likelihood fit with analytical PDF used for $H \rightarrow \gamma\gamma$ channel
- Uncertainty on combined m_H value dominated by systematics
- Precision on a par with Run 1 ATLAS + CMS combination

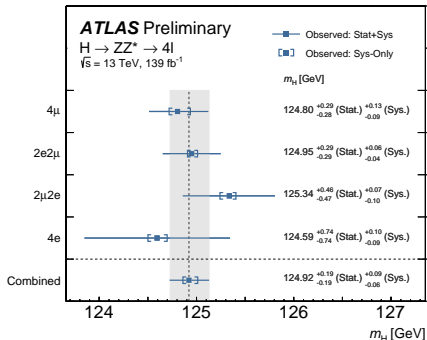
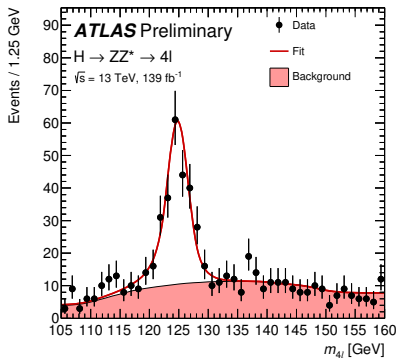
Run 2 $H \rightarrow \gamma\gamma$ systematics dominated

$$m_H = 124.97 \pm 0.24 \text{ GeV}$$

$H \rightarrow 4\ell$ still very statistically limited
(bright prospects for potential Run 2 combination with CMS)



Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \rightarrow ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \rightarrow \gamma\gamma$ background modelling	20
$H \rightarrow \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

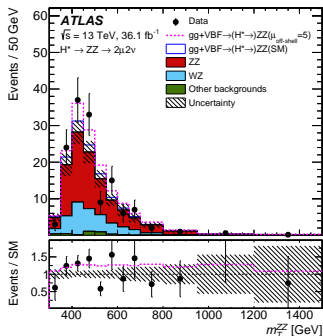
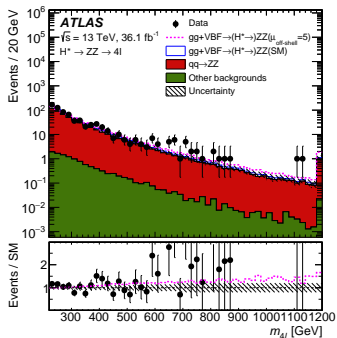
Latest measurement in $H \rightarrow 4\ell$ alone, based on 139 fb^{-1} of 13 TeV data

- Methodology as on previous slide, **single measurement more precise than combination with 36 fb^{-1}** , still limited by statistics...
- Systematic uncertainty dominated by muon momentum scale uncertainty

$$m_H = 124.92 \pm 0.19 \text{ (stat.)}^{+0.09}_{-0.06} \text{ (syst.) GeV}$$

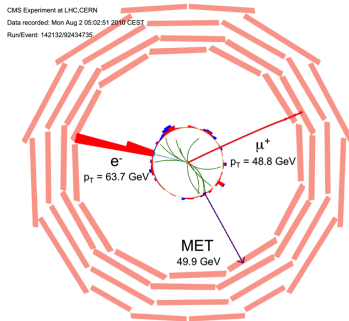
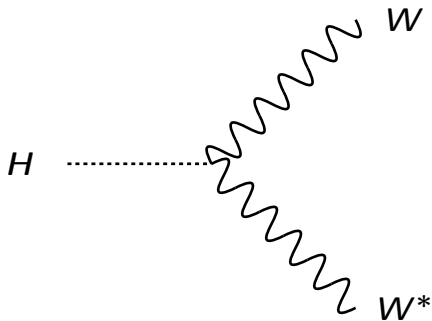
Ratio of on/off-shell signal strengths for $gg \rightarrow H \rightarrow VV^*$ sensitive to Γ_H

- Best direct limit from CMS $\Gamma_H < 1.10$ GeV at 95% CL with $H \rightarrow 4\ell$ (arXiv:1706.09936), very far from SM (≈ 4 MeV)
- Much more sensitive, though assumes that any BSM physics would affect κ_g and κ_Z identically for on/off-shell production and not modify interference of S and B
- Recent result with $H \rightarrow ZZ^* \rightarrow 4\ell(\ell\ell\nu\nu)$ based on 80 fb^{-1} 13 TeV data

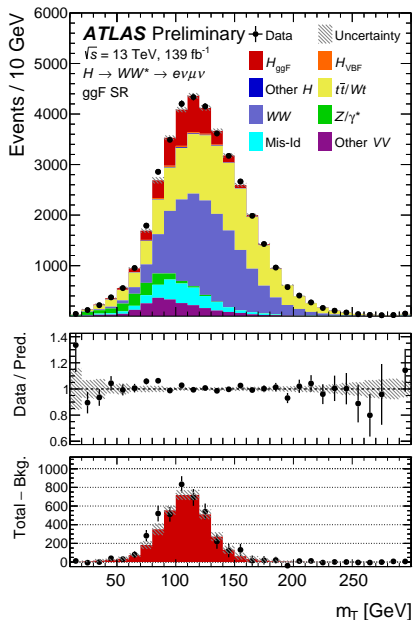


Observed (expected) upper limit of $\Gamma_H < 14.4(15.2)$ MeV at 95% CL

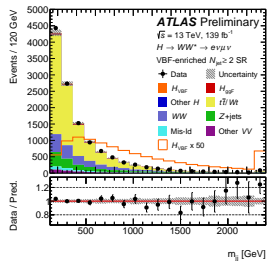
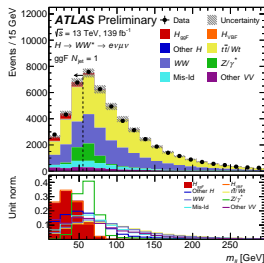
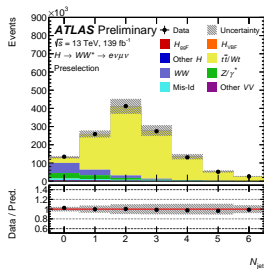
- Tree level decay, directly sensitive to HWW coupling
- Second highest branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \rightarrow WW^*) \approx 21\%$
- Feasibility of experimental study driven by characteristics of W boson decays



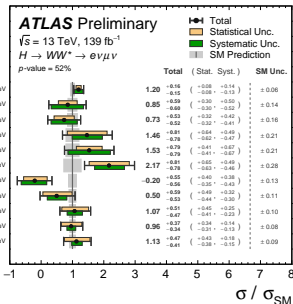
- Most effective channel considers $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays only
- Since only two charged leptons are in the final state, the most effective strategy is to consider $W(e\nu)W(\mu\nu)$ only, to avoid large backgrounds from $Z \rightarrow e^+e^-, \mu^+\mu^-$



- Target opposite sign $e\mu$ final state, dominant backgrounds WW (≤ 1 jet) and $t\bar{t}$ production (≥ 2 jets)
 - Transverse component of di-neutrino system reconstructed as E_T^{miss}
 - Consider transverse mass of the $e\mu$ system as signal to background discriminant
- ← **Clear $H \rightarrow WW^*$ signal in transverse $e\mu$ mass distribution**

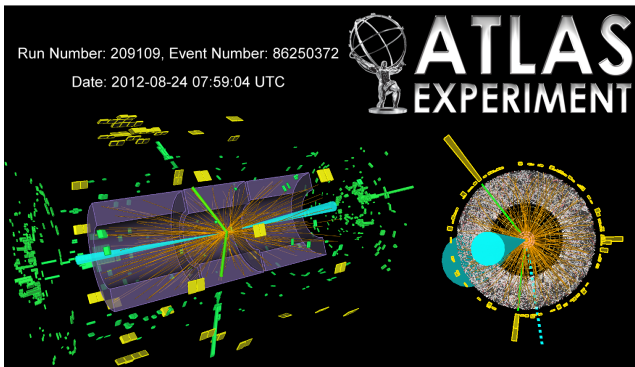


- Categories based on jet multiplicity used to separate ggH and VBF production
- ggH -like categories further purified using leptonic variables
- DNN trained on kinematic variables ($m_{jj}, \Delta y_{jj}$ etc.) used further purify VBF category

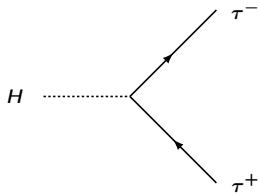


Final STXS region measurements \rightarrow

σ / σ_{SM}

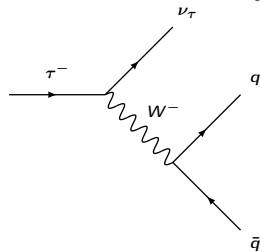
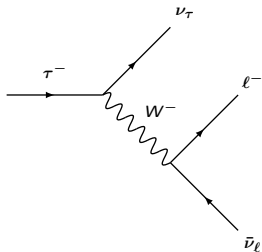


Candidate VBF $H \rightarrow \tau\tau$ event in 8 TeV data



- Tree level decay, directly sensitive to $H\tau\tau$ Yukawa coupling
- Largest leptonic branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \rightarrow \tau\tau) \approx 6\%$
- Most experimentally accessible channel to study Higgs boson coupling to leptons

Leptonic: $\tau^- \rightarrow \nu_\tau \bar{\nu}_\ell \ell^-$ with
 $\ell = e, \mu$



Hadronic: $\tau^- \rightarrow \nu_\tau + \text{hadrons}$

Leptonic Decays:

- Always two neutrinos in the final state, charged lepton (e, μ) is the only “visible” particle
- $\mathcal{B}(\tau^- \rightarrow \nu_\tau \bar{\nu}_\ell \ell^-) \approx 17\%$ (for $\ell = e, \mu$ separately, around 35% together)
- Typically experimentally indistinguishable from isolated e, μ , need more information to identify e.g. $Z \rightarrow \tau(\text{lep.})\tau(\text{had.})$

Hadronic Decays:

- Neutrino accompanied a system of charged and neutral hadrons, looks like “narrow” hadronic jet $\mathcal{B}(\tau^- \rightarrow \nu_\tau \text{ hadrons}) \approx 65\%$
- e.g. $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ ($\approx 25\%$), $\tau^- \rightarrow \pi^- \nu_\tau$ ($\approx 11\%$), $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ ($\approx 9\%$)

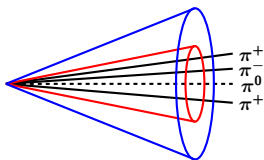
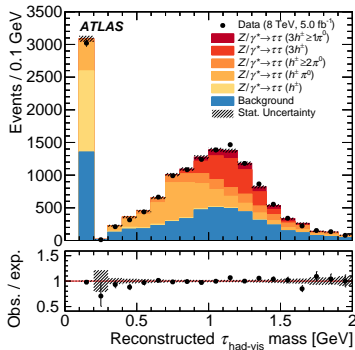
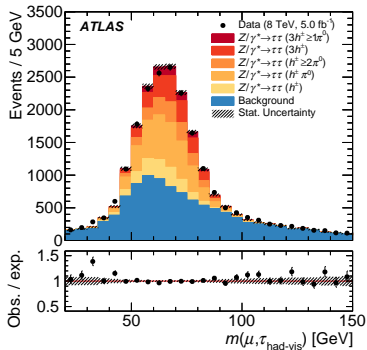
“1-prong”: exactly one charged particle (inc. e/μ) and any number of neutrals $\mathcal{B} \approx 85\%$

“3-prong”: exactly three charged particles (hadrons) and any number of neutrals $\mathcal{B} \approx 15\%$

Hadronic τ decay reconstruction

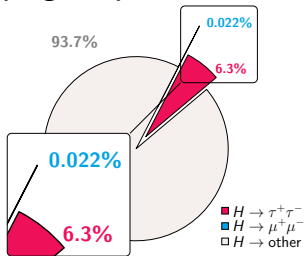
Eur. Phys. J C 76 (2016) 295 (arXiv:1512.05955)

Reminder: $m_\tau = 1.78$ GeV



- Identify energy deposit in calorimeter, matched to tracks, which is **concentrated within a narrow cone**, with **no further hadronic activity in broader cone**
- Reconstruct 4-vector from “visible” decay products, though $m_{\tau, \text{vis.}} < m_\tau$ due to neutrino
- $Z \rightarrow \tau(\mu\nu_\tau)\tau(\nu_\tau \text{ hadrons})$ often used as control channel to calibration algorithms

The $H \rightarrow \tau^+ \tau^-$ decay represents the most sensitive probe of the Higgs boson's coupling to leptons, second most copious fermionic decay at $m_H = 125$ GeV!



↑ 125 GeV SM Higgs boson branching fractions

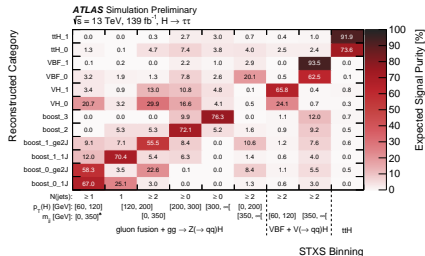
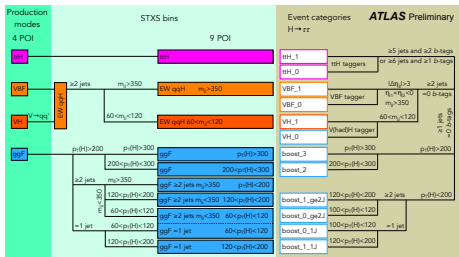
- ✓ High rate decay mode offers great opportunity to study the Yukawa mechanism in detail
- ✗ Complicated by experimental challenges associated with τ lepton decay reconstruction

Analysis Strategy

- Three decay channels considered: $\mathcal{T}_{\text{had}} \mathcal{T}_{\text{had}}$, $\mathcal{T}_{\text{had}} \mathcal{T}_{e,\mu}$ and $\mathcal{T}_e \mathcal{T}_\mu$
- Mitigate large $Z \rightarrow \tau^+ \tau^-$ background with MVA production mode taggers
- Validate $Z \rightarrow \tau^+ \tau^-$ modelling with MC using kinematic “embedding” technique
- Use “Missing Mass Calculator” (MMC) algorithm to improve $\tau^+ \tau^-$ mass resolution, accounting neutrino energy losses

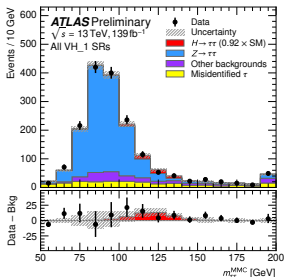
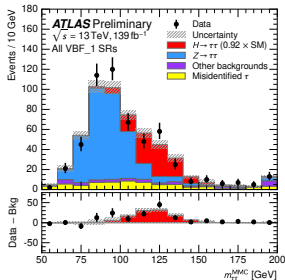
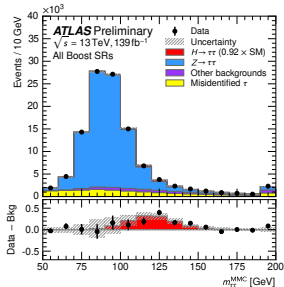
Latest ATLAS analysis, based on full Run 2 dataset (139 fb^{-1}), uses novel production mode tagging methods to mitigate large $Z \rightarrow \tau^+ \tau^-$ background

Design event categorisation strategy to optimise sensitivity and achieve good alignment with fiducial regions defined in STXS stage 1.2 scheme

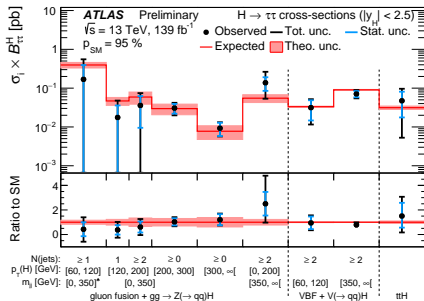
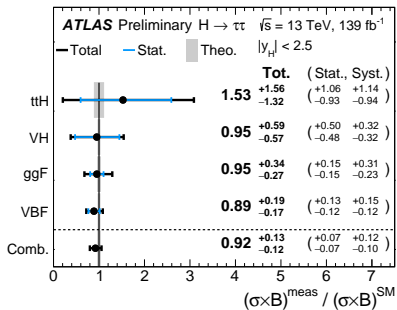


(left) Production mode fit POIs, STXS fit bins targeted and corresponding event categories (right) Relative contribution from signal in each reconstructed category to various STXS bins (i.e. rows sum to 100%)

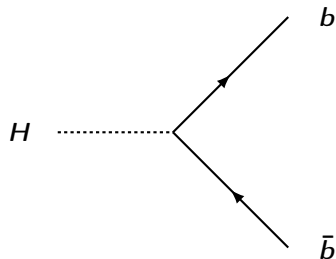
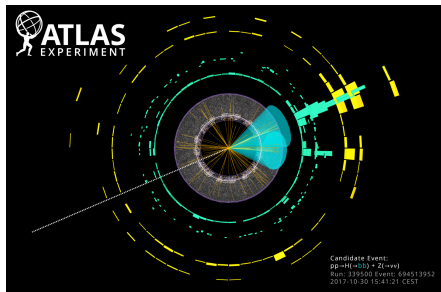
- Four multivariate production mode taggers trained with kinematic, angular and τ property variables for: **VBF**, **V(had.)H**, **$t\bar{t}H$** (vs. $t\bar{t}$ or $Z \rightarrow \tau^+ \tau^-$)
- VBF**, **VH** and **$t\bar{t}H$** enriched regions defined and split into two categories (“_1” = enriched subset, “_0” = remainder)
- Six “boosted” categories defined by p_T^H and jet multiplicity target high p_T^H ggH production



$m_{\tau^+\tau^-}^{\text{MMC}}$ distributions for the sum of boosted (left) and individual purified VBF (centre) and VH (right) categories



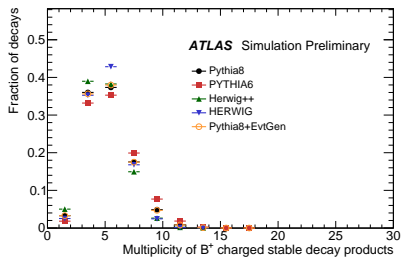
- Tree level decay, directly sensitive to $Hb\bar{b}$ Yukawa coupling
- Highest branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \rightarrow b\bar{b}) \approx 58\%$
- **Huge background from multi-jet production at the LHC, impossible to observe with an inclusive di-jet analysis!**



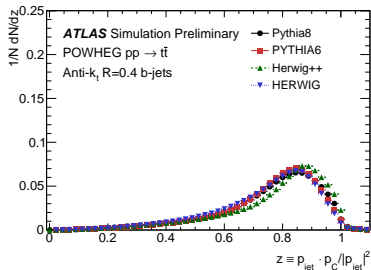
Candidate $pp \rightarrow Z(\nu\nu)H, H \rightarrow b\bar{b}$ event in 13 TeV data

- **Solution 1:** Consider production channels with additional hard objects, such as $(W/Z)H$ and VBF production, to reduce multi-jet background
- **Solution 2:** Use b -tagging techniques to identify products of b -quark fragmentation

- **Lifetime:** Long enough to lead to a measurable decay length (around 5mm for a 50 GeV boost)
- **Mass:** Weakly decaying b -hadrons have masses around 5 GeV, leading to high decay product multiplicities (average of 5 charged particles per decay)
- **Fragmentation:** Much harder than jets initiated by other species (b -hadrons carry around 75% of jet energy, on average)



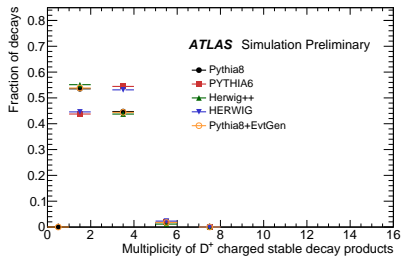
Left: Mean charged multiplicity in B^+ mesons decays



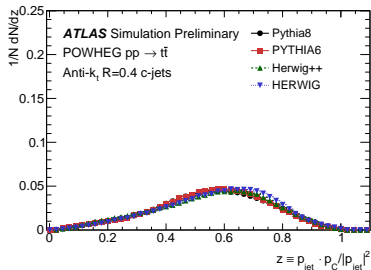
Right: b -quark fragmentation function

Properties of c -hadrons

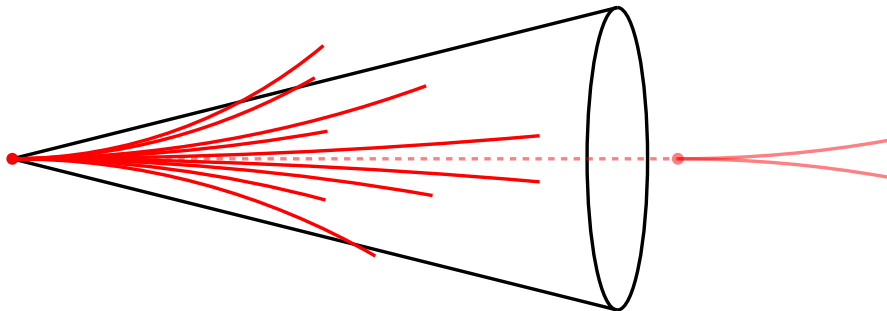
- **Lifetime:** Shorter than the b -hadrons by around a factor of 2-3, still enough for measurable decay length (around 1-3mm for a 50 GeV boost)
- **Mass:** Weakly decaying c -hadrons have masses around 2 GeV, around $2-3\times$ lower than b -hadrons (mean of ≈ 2 charged particles per decay)
- **Fragmentation:** Softer than b -jets, but still harder than jets initiated by light species (c -hadrons carry around 55% of jet energy, on average)



Left: Mean charged multiplicity in D^+ mesons decays

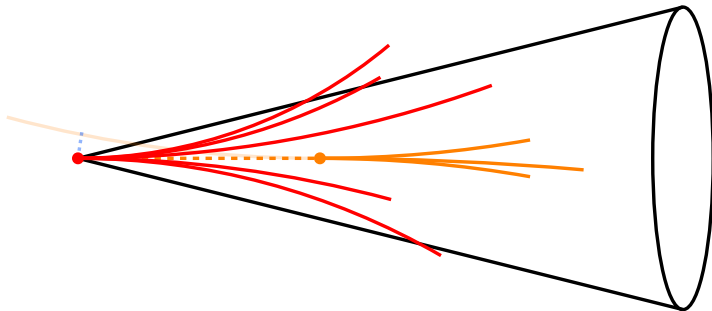


Right: c -quark fragmentation function



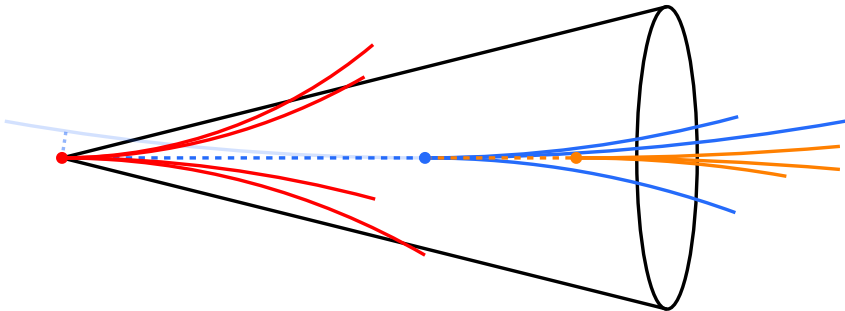
Typical Experimental Signature

- Light-quarks hadronise into many **light hadrons** which share the jet energy
- Tracks from this vertex often have impact parameters consistent with zero
- **Long-lived light hadrons** (e.g. K_S^0 , Λ^0) can be produced, though they are more likely to decay very far (many cm) from the primary pp vertex



Typical Experimental Signature

- c -quark fragments into a c -hadron which carries around half of the jet energy
- c -hadron decay vertex often displaced from the primary pp vertex by a few mm
- Tracks from this vertex can often have large impact parameters

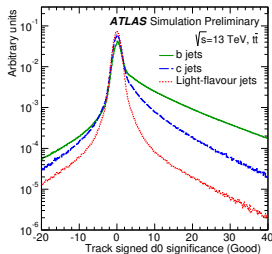


Typical Experimental Signature

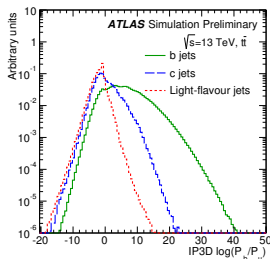
- b -quark fragments into a b -hadron which carries most of the jet energy
- Most b -hadrons ($\approx 90\%$) decay into c -hadrons
- b -hadron decay vertex often displaced from the primary pp vertex by a few mm
- Subsequent c -hadron decay vertex often displaced by a further few mm
- Tracks from both of these vertices often have large impact parameters

The signed IPs of tracks associated to jets are powerful jet flavour discriminants:

- Exploit “sign” of impact parameter: positive if track point of closest approach to PV is downstream of plane defined by the PV and jet axis
- Tracks from b -hadrons tend to have highly significant (IP/σ_{IP}) positive IPs, while most tracks from the PV have a narrow, symmetric distribution
- ✓ Very inclusive and highly efficient
- ✗ Relies upon accurate measurement of jet axis, sensitive to “mis-tag” high IP tracks from V^0 or material interactions, IP/σ_{IP} difficult to model in detector simulation



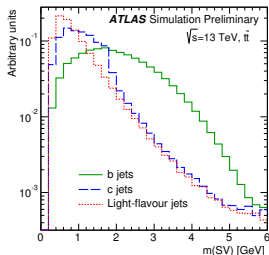
Left: Transverse IP significance distribution



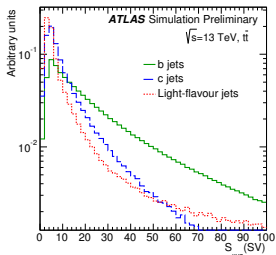
Right: likelihood ratio discriminant based on 3D IPs of tracks

Exploit expectation of a secondary vertex from either b or c -hadron decays:

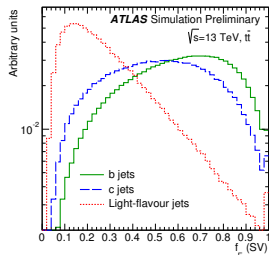
- Attempt to reconstruct a secondary vertex from high IP tracks associated with jet
- Use invariant mass of tracks at SV to discriminate b or c -hadron decay vertices from V^0 decays or material interactions
- Further exploit hard b -jet fragmentation, SV should carry a large fraction of jet energy
- ✓ SV found in up to $\approx 80\%$ of b -jets but only a few % of light flavour jets
- ✗ Degraded light jet rejection as jet p_T increases, careful considerations to mitigate “tagging” of material interactions required



Left: Inv. mass of tracks at SV



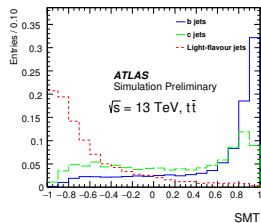
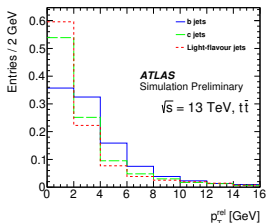
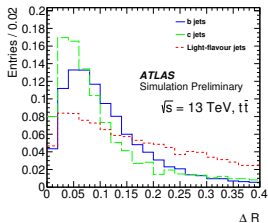
Centre: 3D SV decay length significance



Right: Energy fraction of SV tracks

Exploit the large branching fractions for the semi-leptonic c/b hadron decays and the clean “muon-in-jet” experimental signature:

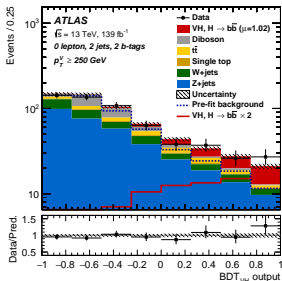
- Expect much higher rate of muons within b/c -jets, relative to light flavour jets, due to the decays $B \rightarrow \mu\nu X$ and $B \rightarrow DX \rightarrow \mu\nu X'$ (\mathcal{B} of around 10% each)
- ✓ Complementary to SV and IP based taggers, different c/b hadron properties exploited and ATLAS detector components employed
- ✗ Light flavour jet backgrounds from muons produced in π/K decays in flight difficult to model in simulation



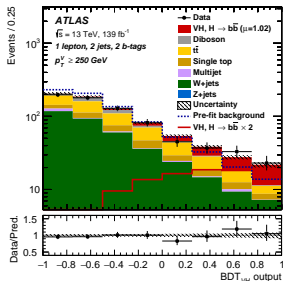
Left: ΔR of muon w.r.t. jet axis Centre: p_T of muon relative to the jet axis Right: BDT built from muon observables

VH channel traditionally expected to be brightest hope of finding $H \rightarrow b\bar{b}$ at LHC

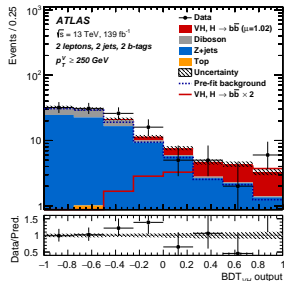
- Search for events with 0, 1 or 2 leptons ($Z \rightarrow \nu\nu$, $W \rightarrow l\nu$ and $Z \rightarrow \ell\ell$) and ≥ 2 b -tagged jets, focus on high p_T^V events to suppress $V + \text{jets}$ and $t\bar{t}$ background
- Recently updated with 139 fb^{-1} of 13 TeV data from LHC Run 2 (2015 - 2018)
- BDT used as nominal S/B discriminant: trained with kinematic variables (e.g. $m_{b\bar{b}}$, p_T^V , E_T^{miss} , ΔR_{bb} , p_T^b etc.) in each channel
- Eight signal regions used: (3 lepton multiplicity) \times (2 jet multiplicity) + 1 additional jet multiplicity and 1 additional p_T^V region for 2 lepton channel



0 lepton (2 jets)



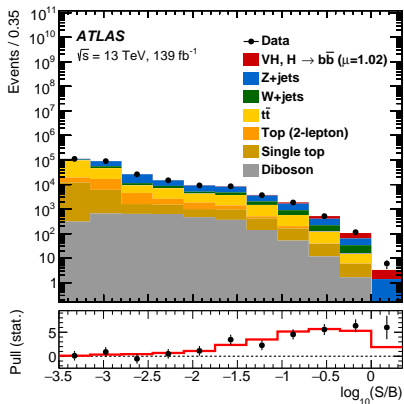
1 lepton (2 jets)



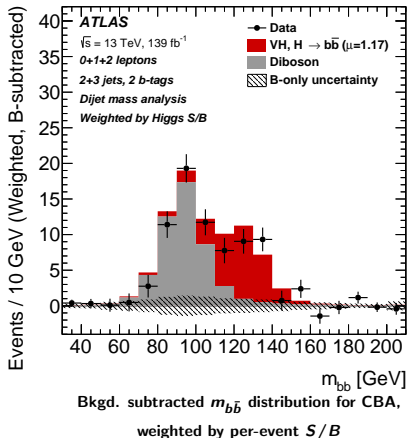
2 lepton (2 jets)

$VH, H \rightarrow b\bar{b}$ signal now very clearly visible by eye! For 13 TeV (Run 2) alone, observed (expected) significance is $6.7(6.7)\sigma$, signal strength $\mu_{VH(b\bar{b})} = 1.02^{+0.18}_{-0.17}$

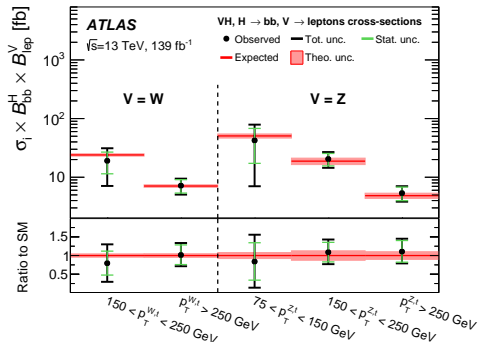
- Cut-based analysis (CBA) also performed as a cross-check, selection performed using many of the same variables used in BDT
- Parallel “validation” analysis of $VZ(b\bar{b})$: $\mu = 0.93^{+0.15}_{-0.14}$



Combined $\log(S/B)$ distribution for multivariate analysis



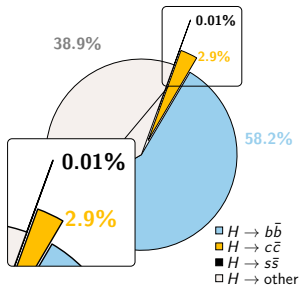
- “Theory” systematics largest for signal strength measurement, particularly signal and $V + \text{jets}$ background modelling
- Experimental systematics dominated by b -tagging uncertainties
- STXS measurements still limited by statistics



STXS measurements for VH production

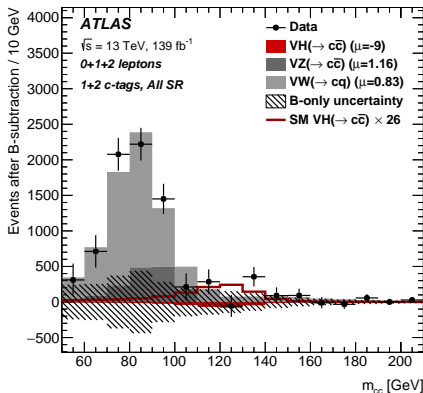
Source of uncertainty	VH	$\frac{\sigma_{\mu}}{WH}$	ZH	
Total	0.177	0.260	0.240	
Statistical	0.115	0.182	0.171	
Systematic	0.134	0.186	0.168	
Statistical uncertainties				
Data statistical	0.108	0.171	0.157	
$t\bar{t} e\mu$ control region	0.014	0.003	0.026	
Floating normalisations	0.034	0.061	0.045	
Experimental uncertainties				
Jets	0.043	0.050	0.057	
E_T^{miss}	0.015	0.045	0.013	
Leptons	0.004	0.015	0.005	
b -tagging	b -jets	0.045	0.025	0.064
	c -jets	0.035	0.068	0.010
	light-flavour jets	0.009	0.004	0.014
Pile-up	0.003	0.002	0.007	
Luminosity	0.016	0.016	0.016	
Theoretical and modelling uncertainties				
Signal	0.052	0.048	0.072	
$Z + \text{jets}$	0.032	0.013	0.059	
$W + \text{jets}$	0.040	0.079	0.009	
$t\bar{t}$	0.021	0.046	0.029	
Single top quark	0.019	0.048	0.015	
Diboson	0.033	0.033	0.039	
Multi-jet	0.005	0.017	0.005	
MC statistical	0.031	0.055	0.038	

The $H \rightarrow c\bar{c}$ decay offers a unique opportunity to directly probe the poorly constrained coupling of the Higgs boson to second generation quarks



↑ 125 GeV SM Higgs boson branching fractions

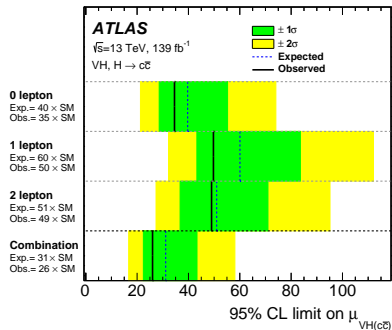
- $H \rightarrow c\bar{c}$ now one of the largest contributions to Γ_H (by SM expectation) yet to be established experimentally!



↑ Background subtracted di-jet invariant mass distributions for events with 1 or 2 c-tagged jets

Latest ATLAS analysis, based on full Run 2 dataset (139 fb^{-1}), exploits $(W/Z)H$ production and novel c-tagging to mitigate large multi-jet backgrounds

↓ 95% CL upper limits on the $VH, H \rightarrow c\bar{c}$ signal strength, from the three individual channels and combination

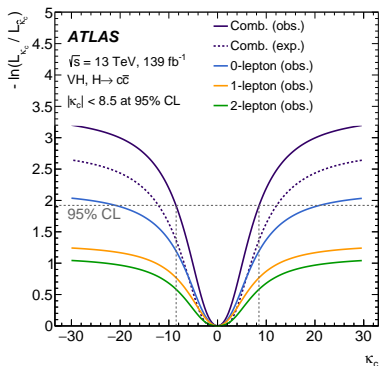


■ Systematic uncertainties (primarily background modelling) limit sensitivity

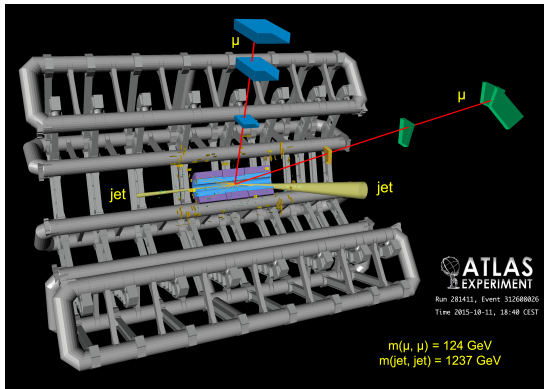
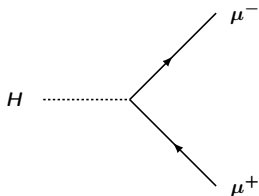
Analysis now sensitive to $\mathcal{B}(H \rightarrow c\bar{c}) < 100\%$ allowing important direct coupling interpretation, constraint of $|\kappa_c| < 8.5$ at 95% CL observed

Complementary to indirect constraints from differential measurements of p_T^H with $H \rightarrow \gamma\gamma$ ($-19 < \kappa_c < 24$) and $H \rightarrow 4\ell$ ($-12 < \kappa_c < 11$)

↓ Constraint on c -quark coupling modifier κ_c in a simple scenario where all other Higgs couplings are SM-like



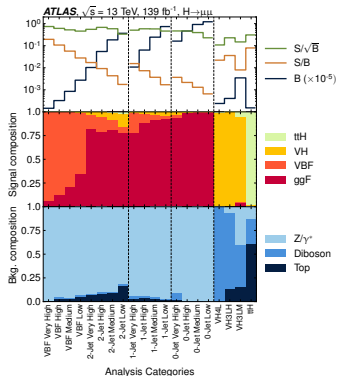
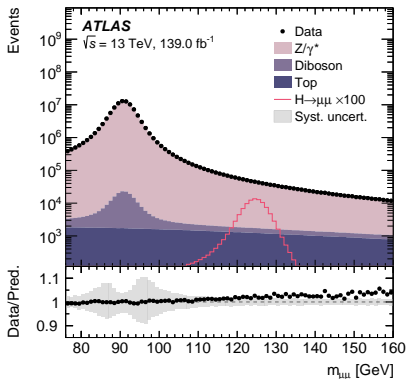
$$\mu = \kappa_c^2 / (1 + \mathcal{B}(H \rightarrow c\bar{c}) \cdot (\kappa_c^2 - 1))$$

Candidate VBF $H \rightarrow \mu^+ \mu^-$ event in 13 TeV data

- Tree level decay, directly sensitive to $H\mu\mu$ Yukawa coupling
- Small branching fraction for $m_H = 125 \text{ GeV}$ at $\mathcal{B}(H \rightarrow \mu^+ \mu^-) \approx 2 \times 10^{-4}$
- Most promising channel to study Higgs boson coupling to second generation fermions

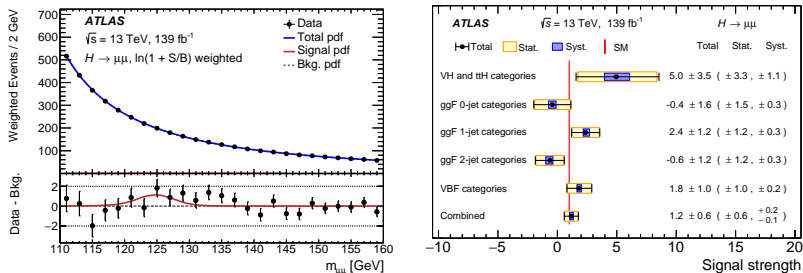
Perhaps the most promising probe of SM Higgs coupling to second generation

- ATLAS search recently updated with 139 fb^{-1} of 13 TeV data
- Dominant background is $Z \rightarrow \mu^+ \mu^-$ (+jets), exploiting Higgs production modes can help reduce this substantially
- In events with exactly two muons, classify with BDTs trained with production mode sensitive variables



Relative sensitivity of the analysis categories \uparrow

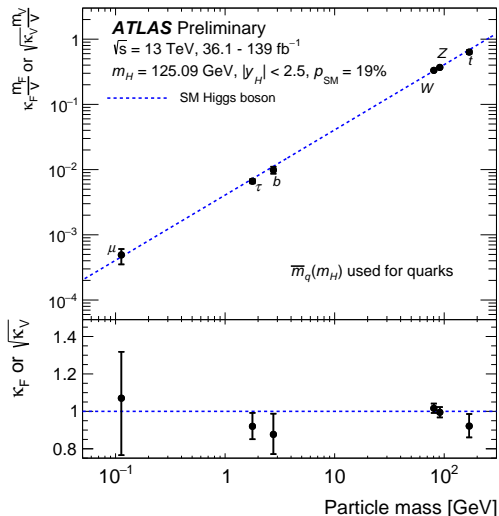
$m_{\mu^+ \mu^-}$ used as S/B discriminant, fit to each category using analytic functions for signal and background shape, weighted sum of fit results shown below



Approaching sensitivity to SM prediction!

- Observed (expected) significance $2.0(1.7)\sigma$, measured signal strength $\mu = 1.2 \pm 0.6$
- Sensitivity driven by VBF targeted categories, still very much limited by statistics

Latest ATLAS 125 GeV Higgs combination with 13 TeV data

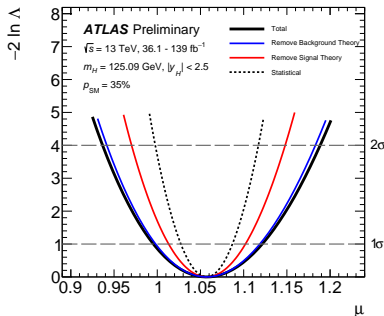


Reduced coupling strength modifiers as a function of fermion/boson mass, assuming no BSM contributions to Γ_H and the SM structure of loop processes

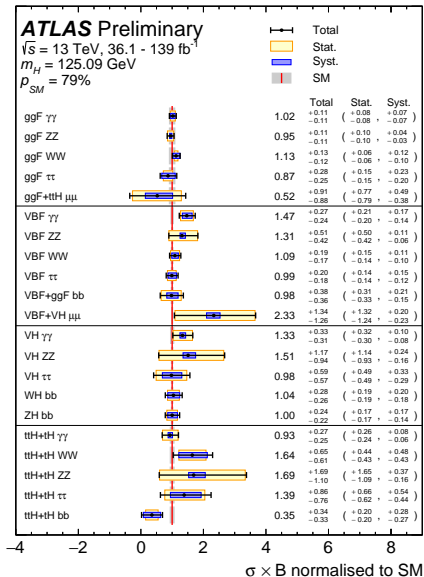
Latest combination of ATLAS measurements with all main channels probes compatibility with SM production/decay properties

- Methodology similar (e.g. κ framework etc.) to well known Run 1 ATLAS+CMS combination (arXiv:1606.02266)
- All performed with 13 TeV data, most channels updated with 139 fb⁻¹ dataset

Decay channel	Target Production Modes	\mathcal{L} [fb ⁻¹]	Ref.	Used in combined measurement
$H \rightarrow \gamma\gamma$	ggF, VBF, WH, ZH, ttH, tH	139	[10]	Everywhere
$H \rightarrow ZZ^*$	ggF, VBF, WH, ZH, ttH(4f)	139	[11]	Everywhere
	ttH	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow WW^*$	ggF, VBF	139	[12]	Everywhere
	ttH	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow \tau\tau$	ggF, VBF, WH, ZH, ttH($\tau_{had}\tau_{had}$)	139	[13]	Everywhere
	ttH	36.1	[19]	Everywhere but STXS and SMEFT
$H \rightarrow b\bar{b}$	WH, ZH	139	[14,15,16]	Everywhere
	VBF	126	[17]	Everywhere
$H \rightarrow \mu\mu$	ggF, VBF, WH, ttH	139	[18]	Everywhere
	VBF	139	[18]	Everywhere
$H \rightarrow \mu\mu$	ggF, VBF, VH, ttH	139	[20]	Everywhere but STXS and SMEFT
$H \rightarrow Z\gamma$	ggF, VBF, VH, ttH	139	[21]	Everywhere but STXS and SMEFT
$H \rightarrow \nu\nu$	VBF	139	[22]	Sec. 6.2 & 6.3

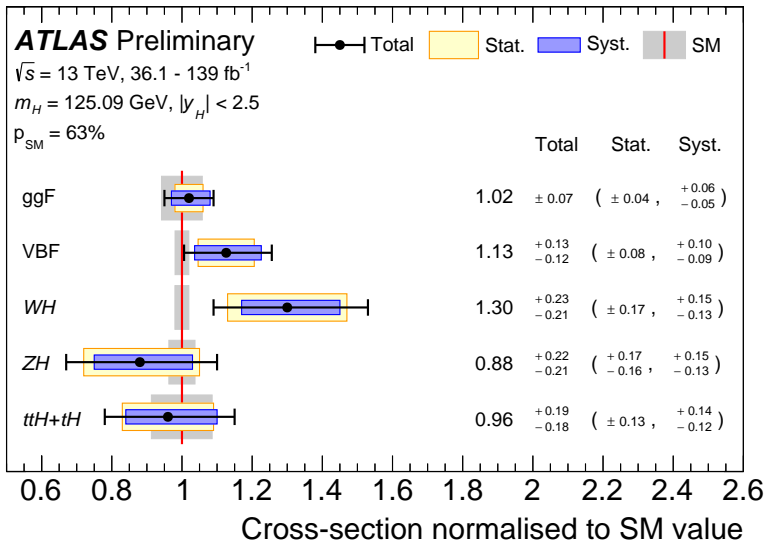


← Global signal strength
 $\mu = 1.06 \pm 0.06$



- Despite “hints” at $\geq 1\sigma$ deviations in global signal strengths for individual channels, combined measurements very compatible with SM

Cross sections relative to SM prediction



The experimental characterisation of the 125 GeV Higgs boson is advancing rapidly, many ATLAS/CMS results now use with full (140 fb^{-1}) Run 2 dataset!

- Around 90% of total width (by SM expectation) is now accounted for experimentally
- All main production mechanisms have also been unambiguously observed
- To date, all measurements seem to indicate properties in very good agreement with the SM!
- However, surprises may be lurking in the very poorly studied couplings to the first and second generation fermions
- Remember, the Yukawa picture is really just an “effective” description, new physics is required to understand the fermion mass hierarchy!