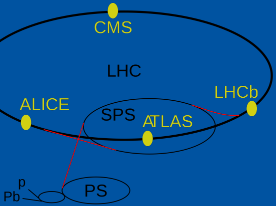


High p_T Physics at the LHC
Lecture 4: Higgs Physics and Advanced Topics

Warwick Week 2024

22nd March 2024

Andy Chisholm (University of Birmingham)

Overview

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

The Brout-Englert-Higgs Mechanism

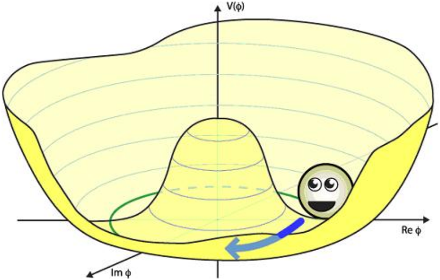


Figure from Philip Tanedo

- 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 ✓

Fermion masses in the Standard Model

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

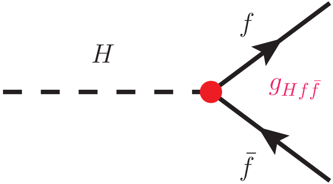
$$\mathcal{L}_{\text{fermion}} = -y_f \cdot \left[\bar{\psi}_L \phi \psi_R + \bar{\psi}_R \bar{\phi} \psi_L\right]$$

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 ✗

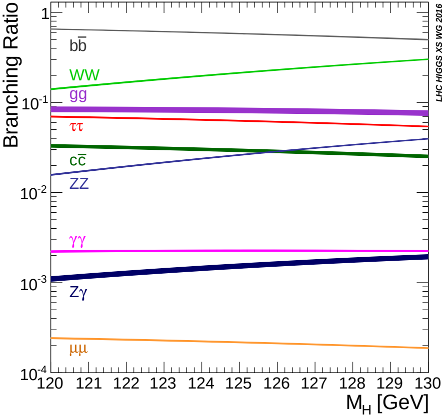


While Yukawa couplings provide concrete predictions for $Hf\bar{f}$ interactions, they fail to describe the origin of the fermion mass hierarchy i.e. why is $m_t/m_e \approx \mathcal{O}(10^5)$!?

Decays of a 125 GeV Higgs boson

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

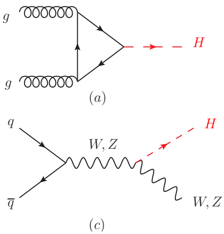
- $H \to b\bar{b}$ is the most common decay, with $\mathcal{B}(H \to b\bar{b}) \approx 58\%$
- Decays to fermions (i.e. $H \to q\bar{q}, \ell^+\ell^-$) directly sensitive to Yukawa couplings ($\Gamma \propto y_f^2$)
- Decays $H \to ZZ^*$ and $H \to WW^*$ probe heart of EWSB (coupling determined by shape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



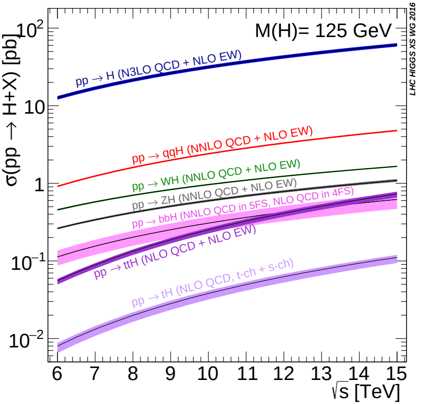
At $m_H = 125$ GeV, the channels $H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$ and $H \to \gamma\gamma$ exhibit the most favourable signal to background at the LHC

Production of a 125 GeV Higgs boson 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

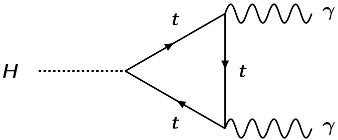


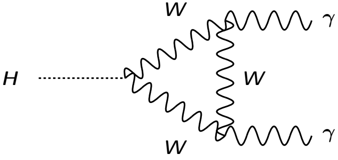
- a) Gluon fusion process $gg \to H$ is dominant ($\approx 88\%$)
- b) Vector boson fusion (VBF) $q\bar{q} \to q\bar{q}H$ is the sub-leading process ($\approx 7\%$)
- c) Associated production with a W or Z boson “Higgsstrahlung” ($\approx 4\%$)
- d) Associated production with $t\bar{t}$ ($\approx 1\%$)

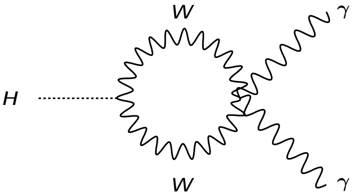
Modes sensitive to different couplings, important to study them all. Some channels facilitate the study of experimentally challenging decays e.g. $Z(\ell^+\ell^-)H(b\bar{b})$

$H \to \gamma\gamma$ Decay

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





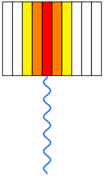


Photon Reconstruction

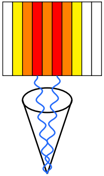
ECal. designed to initiate EM shower of incident photon, energy can be measured and direction inffered based on location of signal calorimeter cells w.r.t. beam spot

Challenge 1: Neutral Hadrons

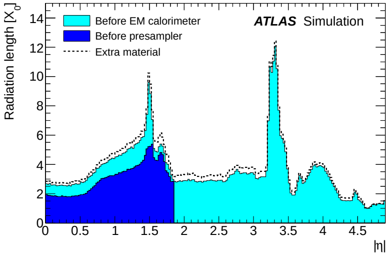
- Jets containing a high fraction of neutral hadrons are the main background to photon reconstruction
- Primarily caused by $\pi^0 \rightarrow \gamma\gamma$ decays (i.e. two photons with a small angular separation)
- Mitigated by considering the "shape" of the calorimeter signal (single or overlapping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



γ



$\pi^0 \rightarrow \gamma\gamma$

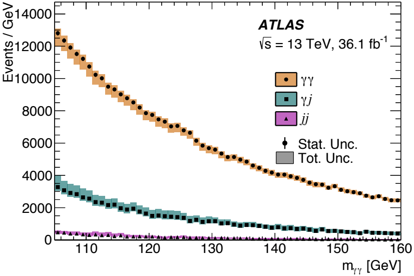


Challenge 2: Material Interactions

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

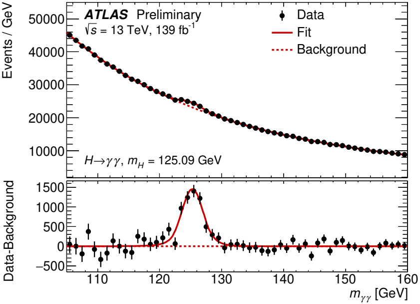
$H \rightarrow \gamma\gamma$ Analysis Strategy

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

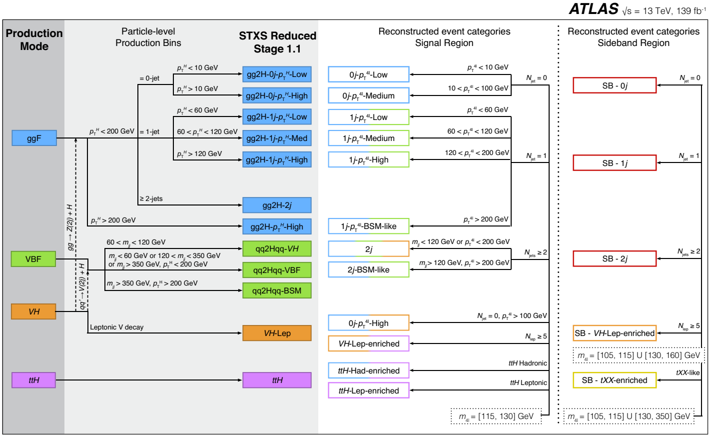


- Dominant "irreducible" background from non-resonant QCD production of two isolated photons
- Residual background due to one or both photons being "fake" from multi-jet production
- Judicious "shower shape" based photon ID selection reduces this to $\approx 20\%$ of total backgound

- 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 backgound



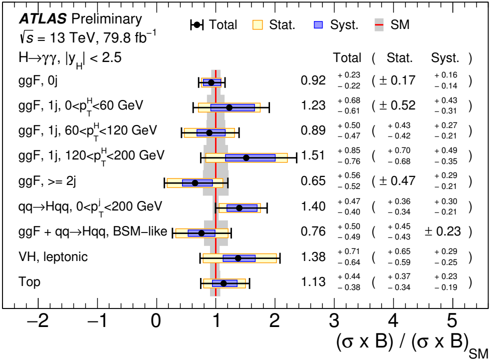
Interlude: Simplified Template Cross-section (STXS) framework



- 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

Recent production measurements with $H \to \gamma\gamma$ (ATLAS-CONF-2018-028)

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



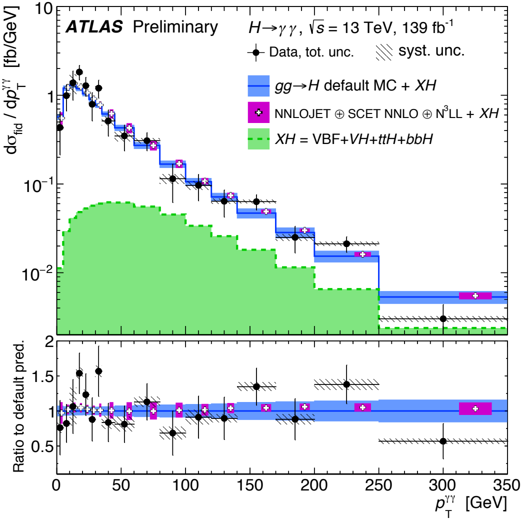
Summary of the measured simplified template cross sections (STXS)

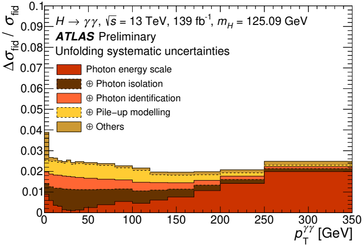
- Wide range of inclusive and differential fiducial (phase space →) cross section measurements
- Global signal strength consistent with SM $\mu = 1.06 \pm 0.08\,(\text{stat.})^{+0.08}_{-0.07}\,(\text{exp.})^{+0.07}_{-0.06}\,(\text{theo.})$

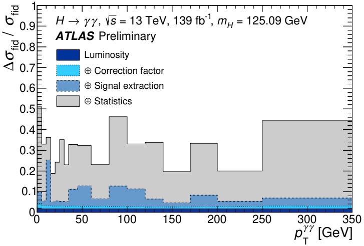
Objects	Definition
Photons	$\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, $p_T^{\text{iso},0.2}/p_T^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_T > 30\,\text{GeV}$, $\lvert y\rvert < 4.4$
– Central jets	$\lvert y\rvert < 2.5$
– b-jets	$\lvert y\rvert < 2.5$, $\Delta R(\text{jet}, b\text{-hadron}) < 0.4$ for b-hadrons with $p_T > 5$ GeV
Leptons, $\ell = e$ or μ	electrons: $p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.47$ (excluding $1.37 < \lvert\eta\rvert < 1.52$) muons: $p_T > 10\,\text{GeV}$, $\lvert\eta\rvert < 2.7$

Fiducial region	Definition
Diphoton fiducial	$N_\gamma \geq 2$, $p_T^{\gamma_1} > 0.35 \cdot m_{\gamma\gamma}$, $p_T^{\gamma_2} > 0.25 \cdot m_{\gamma\gamma}$
$N_{b\text{-jets}}$ measurement	Diphoton fiducial, $N_{\text{jets}}^{\text{Cen}} \geq 1$, $N_{\text{leptons}} = 0$

$H \rightarrow \gamma\gamma$ Differential Cross Sections: p_{T}^{H} (ATLAS-CONF-2019-029)



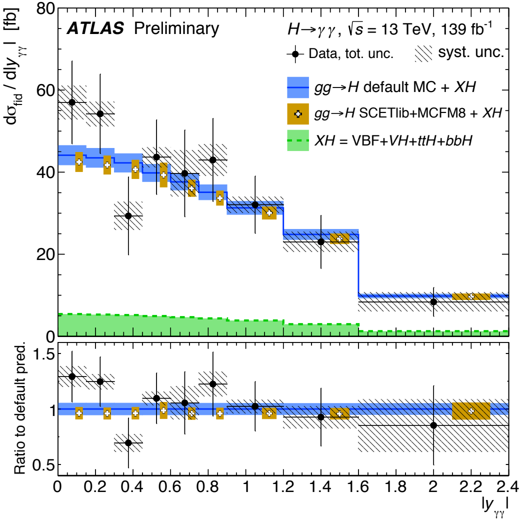




- χ^2 probability for compatiblity of data with default SM distribution† is 44%
- p_{T}^{H} exhibits lowest compatiblity with SM of distributions measured (still very high!)

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

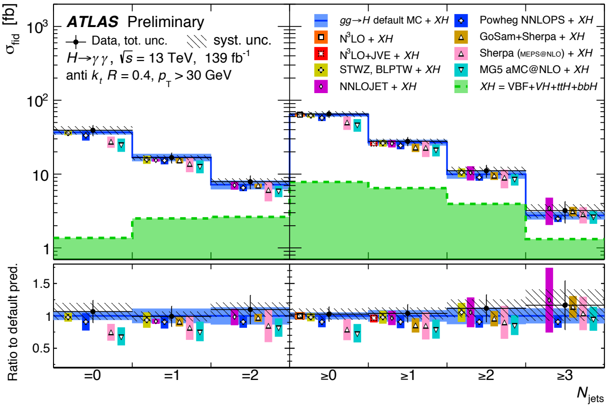
$H \rightarrow \gamma\gamma$ Differential Cross Sections: y^H (ATLAS-CONF-2019-029)

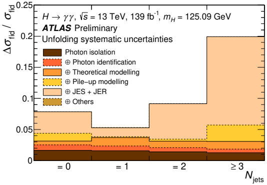


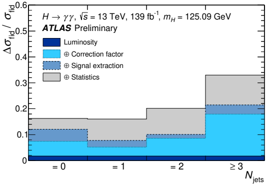
- χ^2 probability for compatiblity of data with default SM distribution† is 68%

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

$H \to \gamma\gamma$ Differential Cross Sections: N_{jets} (ATLAS-CONF-2019-029)



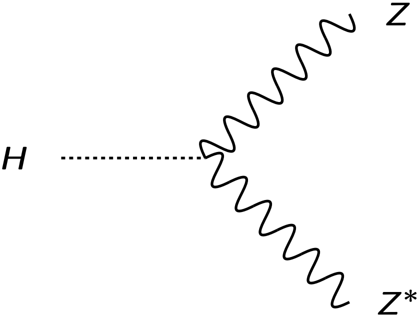




- Multiplicity of associated jets, both inclusive and exclusive bins
- Sensitive to contributions from VH and $t\bar{t}H$ production at high N_{jets}
- χ^2 probability for compatiblity of data with default SM distribution† is 96%

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

$H \rightarrow ZZ^*$ Decay



- Tree level decay, directly sensitive to *HZZ* coupling
- Reasonably high branching fraction, $\mathcal{B}(H \rightarrow ZZ^*) \approx 3\%$
- Feasibilty 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 $\mathcal{B}(H \rightarrow ZZ^* \rightarrow 4\ell) \approx 10^{-4}$
- Very sensitive to spin / parity properties of Higgs boson given multiple measurable angular distributions

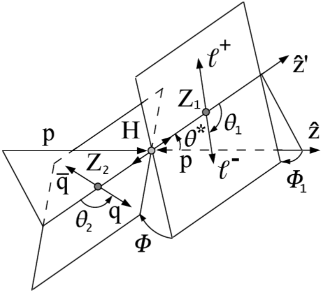
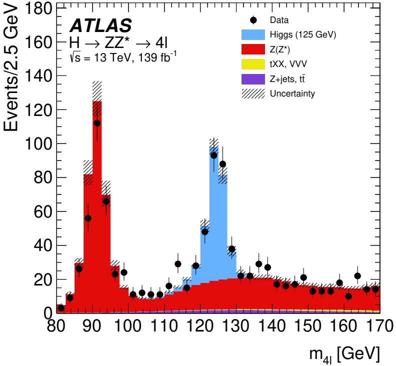
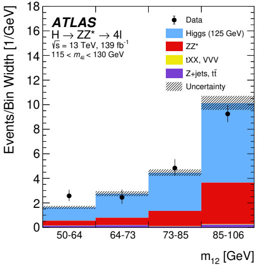


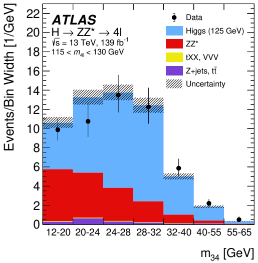
Figure: CMS-HIG-12-024

$H \to ZZ^* \to 4\ell$ Analysis Strategy

Study events containing four isolated high p_T electron/muon candidates





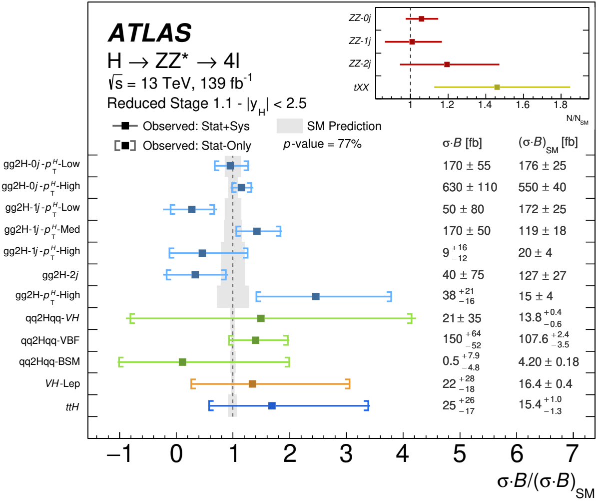


- Very good resolution in $m_{4\ell}$ and $S/B \approx 1$, described as “golden channel”
- Background dominated by “irreducible” nonresonant $Z(Z/\gamma^*)$ production, with much smaller contributions from $Z+$jets and $t\bar{t}$

Figures: arXiv:2004.03969

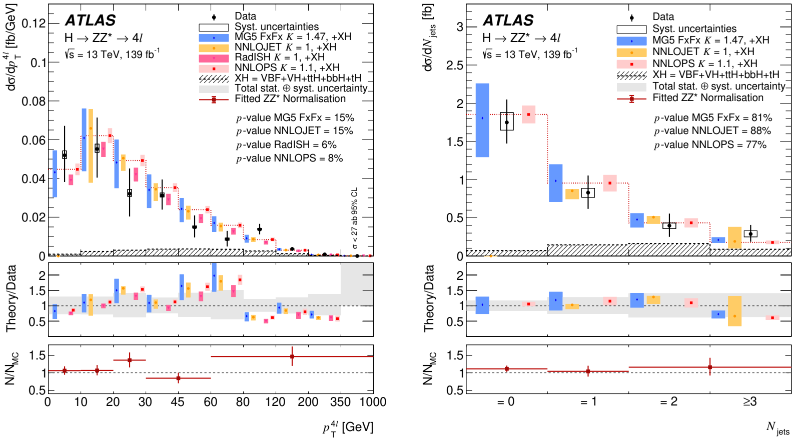
Latest measurements with $H \rightarrow ZZ^* \rightarrow 4\ell$ (ATLAS-HIGG-2018-28)

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



"Reduced Stage 1.1" STXS (cross-sections)

$H \to ZZ^* \to 4\ell$ Differential Cross Sections (ATLAS-HIGG-2018-29)

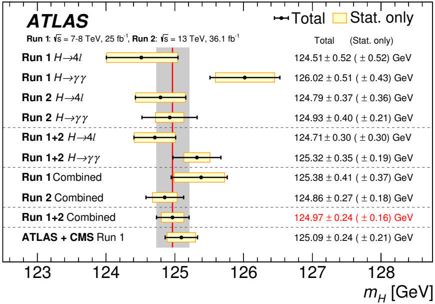


- Differential measurements of p_{T}^{H} and associated jet multiplicity
- p-values for compatiblity of p_{T}^{H} data with predictions reasonably low...

Measurements of m_H (arXiv:1806.00242)

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

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



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

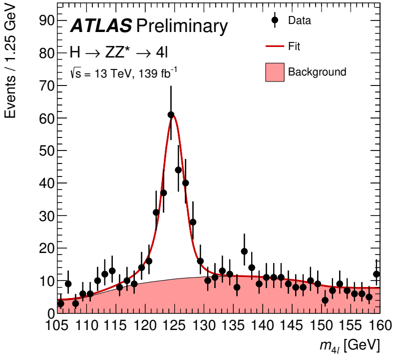
$$\boxed{m_H = 124.97 \pm 0.24\ \text{GeV}}$$

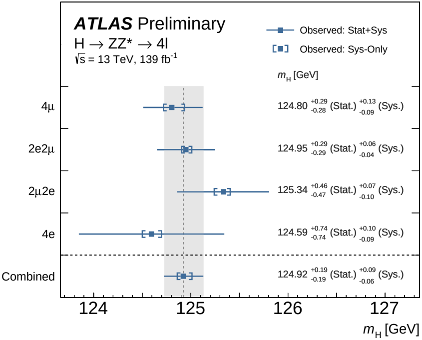
Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20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

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

Updated measurements of m_H with $H \to 4\ell$ (ATLAS-CONF-2020-005)

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





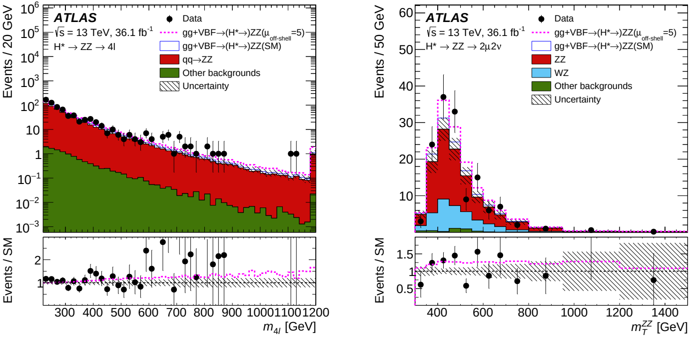
- Methodology as on previous slide, **single measurement more precise than combination with $36\,\mathrm{fb}^{-1}$**, still limited by statistics...
- Systematic uncertainty dominated by muon momentum scale uncertainty

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

Measurement of Γ_H from off-shell production (arXiv:1808.01191)

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

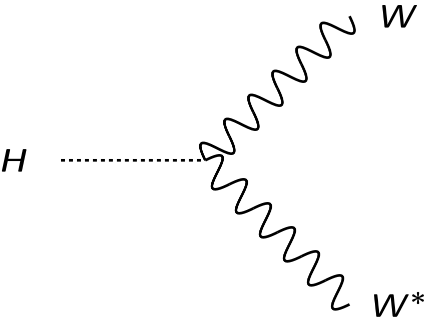
- Best direct limit from CMS $\Gamma_H < 1.10$ GeV at 95% CL with $H \to 4\ell$ (arXiv:1706.09936), very far from SM (≈ 4 MeV)
- Much more sensitive, though assmumes that any BSM physics would affect κ_g and κ_Z identically for on/off-shell production and not modify interference of S and B
- Recent result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

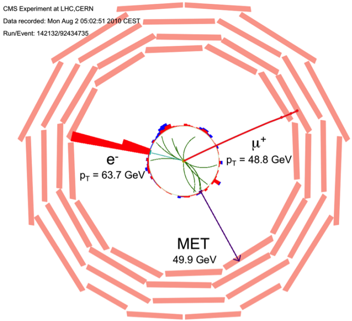


Observed (expected) upper limit of $\Gamma_H < 14.4(15.2)$ MeV at 95% CL

$H \to WW^*$ Decay

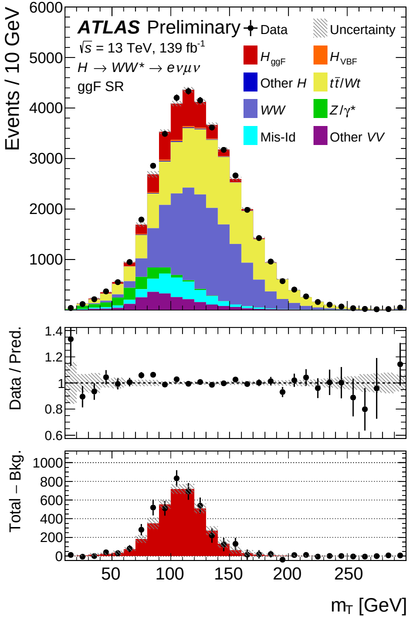
- Tree level decay, directly sensitive to HWW coupling
- Second highest branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \to WW^*) \approx 21\%$
- Feasibilty of experimental study driven by characteristics of W boson decays





- Most effective channel considers $W \to e\nu$ and $W \to \mu\nu$ 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 $Z \to e^+e^-, \mu^+\mu^-$

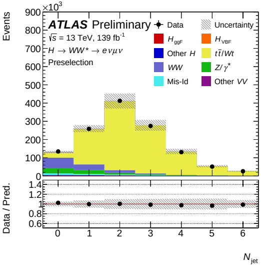
$H \rightarrow WW^*$ analysis strategy

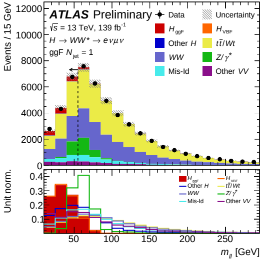


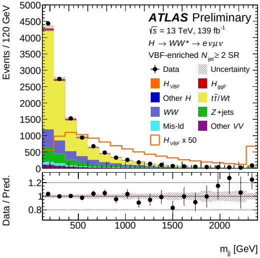
- Target opposite sign $e\mu$ final state, dominant backgrounds WW (≤ 1 jet) and $t\bar{t}$ production (≥ 2 jets)
- Transverse component of di-neutrino system reconstructed as $E_{\mathrm{T}}^{\mathrm{miss}}$
- Consider transverse mass of the $e\mu$ system as signal to backgound discriminant

← Clear $H \rightarrow WW^*$ signal in transverse $e\mu$ mass distribution

$H \to WW^*$ with ggH and VBF production (ATLAS-CONF-2021-014)

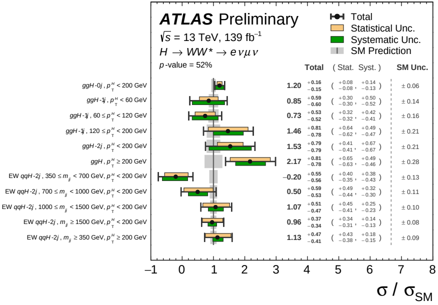




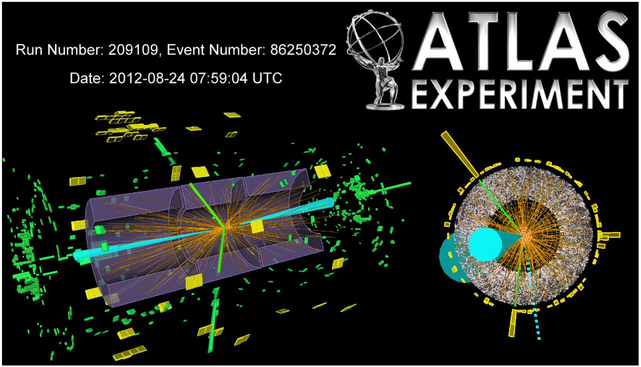


- Categories based on jet multiplicity used to separate ggH and VBF production
- ggH-like categories further purified using leptonic variables
- DNN trained on kinematic variables (m_{jj}, Δy_{jj} etc.) used further purify VBF category

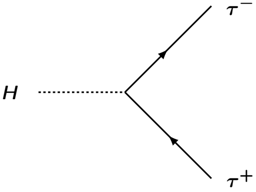
Final STXS region measurements →



$H \to \tau\tau$ Decay



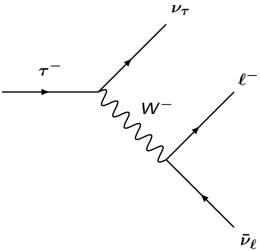
Candidate VBF $H \to \tau\tau$ event in 8 TeV data

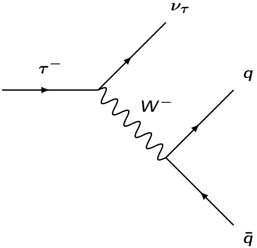


- Tree level decay, directly sensitive to $H\tau\tau$ Yukawa coupling
- Largest leptonic branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \to \tau\tau) \approx 6\%$
- Most experimentally accesible channel to study Higgs boson coupling to leptons

τ decays

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





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

Leptonic Decays:

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

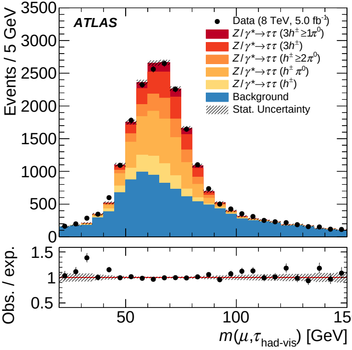
Hadronic Decays:

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

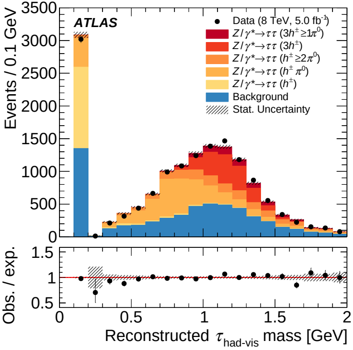
"1-prong": exactly one charged particle (inc. e/μ) and any number of neutrals $\mathcal{B} \approx 85\%$
"3-prong": exactly three charged particles (hadrons) and any number of neutrals $\mathcal{B} \approx 15\%$

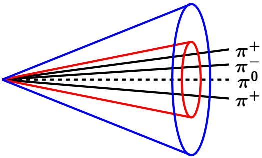
Hadronic τ decay reconstruction

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



Reminder: m_τ = 1.78 GeV

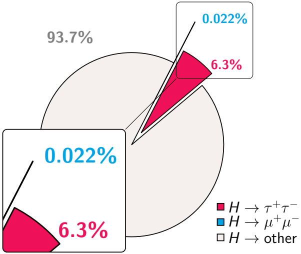




- Identify energy deposit in calorimeter, matched to tracks, which is is **concentrated within a narrow cone**, with **no further hadronic activity in broader cone**
- Reconstruct 4-vector from "visible" decay products, though $m_{\tau,\text{vis.}} < m_\tau$ due to neutrino
- $Z \to \tau(\mu\nu_\tau)\tau(\nu_\tau$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

$H \rightarrow \tau^+\tau^-$ (ATLAS-CONF-2021-044)

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

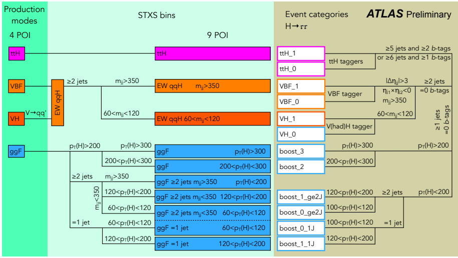
Analysis Strategy

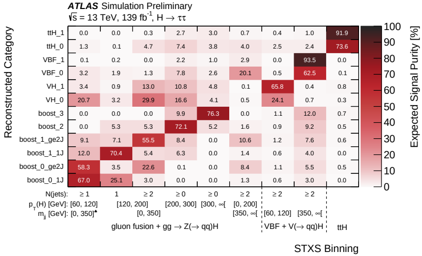
- Three decay channels considered: $\tau_{\text{had}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{e,\mu}$ and $\tau_e\tau_\mu$
- Mitigate large $Z \rightarrow \tau^+\tau^-$ background with MVA production mode taggers
- Validate $Z \rightarrow \tau^+\tau^-$ modelling with MC using kinematic "embedding" 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 ($139\,\text{fb}^{-1}$), uses novel production mode tagging methods to mitigate large $Z \rightarrow \tau^+\tau^-$ background

$H \to \tau^+\tau^-$ (ATLAS-CONF-2021-044)

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



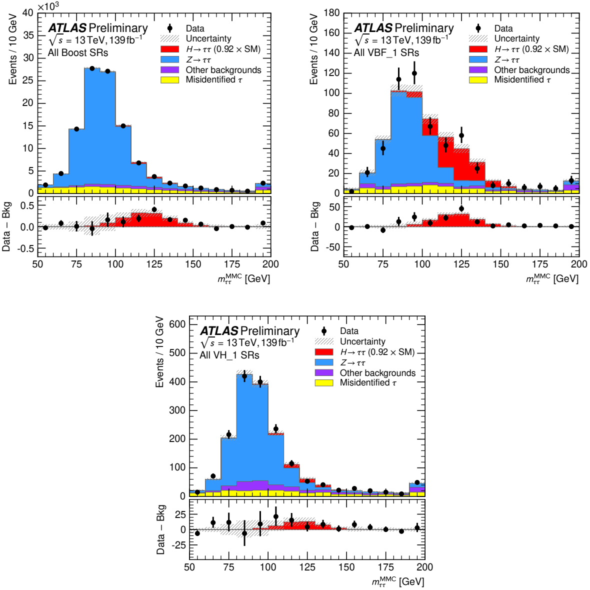


	gluon fusion + gg → Z(→ qq)H						VBF + V(→ qq)H		ttH
N(jets):	≥ 1	1	≥ 2	≥ 0	≥ 0	≥ 2	≥ 2	≥ 2	
p_T(H) [GeV]:	[60, 120]	[120, 200]		[200, 300]	[300, ∞[	[0, 200]			
m_{jj} [GeV]:	[0, 350]♠		[0, 350]			[350, ∞[	[60, 120]	[350, ∞[	
ttH_1	0.0	0.0	0.3	2.7	3.0	0.7	0.4	1.0	91.9
ttH_0	1.3	0.1	4.7	7.4	3.8	4.0	2.5	2.4	73.6
VBF_1	0.1	0.2	0.0	2.2	1.0	2.9	0.0	93.5	0.0
VBF_0	3.2	1.9	1.3	7.8	2.6	20.1	0.5	62.5	0.1
VH_1	3.4	0.9	13.0	10.8	4.8	0.1	65.8	0.4	0.8
VH_0	20.7	3.2	29.9	16.6	4.1	0.5	24.1	0.7	0.3
boost_3	0.0	0.0	0.0	9.9	76.3	0.0	1.1	12.0	0.7
boost_2	0.0	5.3	5.3	72.1	5.2	1.6	0.9	9.2	0.5
boost_1_ge2J	9.1	7.1	55.5	8.4	0.0	10.6	1.2	7.6	0.6
boost_1_1J	12.0	70.4	5.4	6.3	0.0	1.4	0.6	4.0	0.0
boost_0_ge2J	58.3	3.5	22.6	0.1	0.0	8.4	1.1	5.5	0.5
boost_0_1J	67.0	25.1	3.0	0.0	0.0	1.3	0.6	3.0	0.0

(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%)

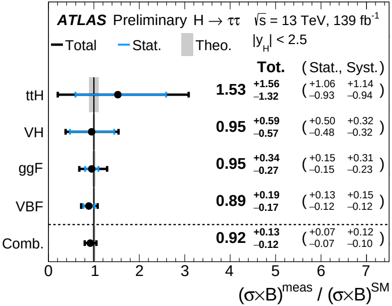
- Four multivariate production mode taggers trained with kinematic, angular and τ property variables for: **VBF**, **V(had.)H**, **$t\bar{t}H$ (vs. $t\bar{t}$ or $Z \to \tau^+\tau^-$)**
- VBF, VH and $t\bar{t}H$ enriched regions defined and split into two categories ("_1" = enriched subset, "_0" = remainder)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

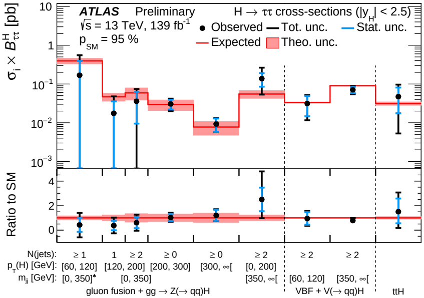
$H \to \tau^+\tau^-$ (ATLAS-CONF-2021-044)



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

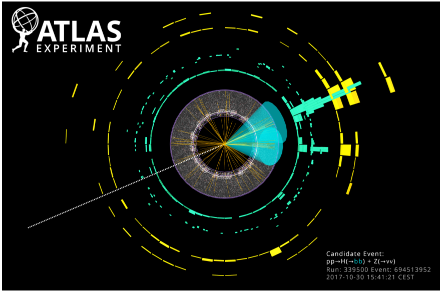
$H \to \tau^+\tau^-$ (ATLAS-CONF-2021-044)



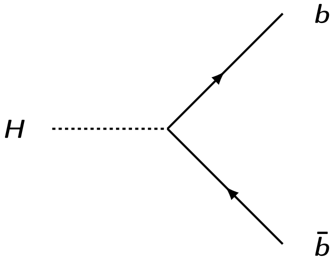


$H \to b\bar{b}$ Decay

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



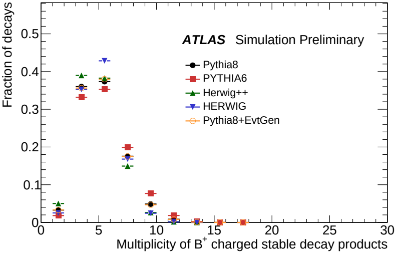
Candidate $pp \to Z(\nu\nu)H$, $H \to b\bar{b}$ event in 13 TeV data



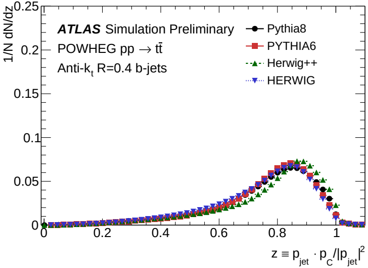
- **Solution 1:** Consider production channels with additional hard objects, such as $(W/Z)H$ and VBF production, to reduce multi-jet background
- **Solution 2:** Use b-tagging techniques to identify products of b-quark fragmentation

b-tagging: Properties of *b*-hadrons

- **Lifetime:** Long enough to lead to a measureable 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)



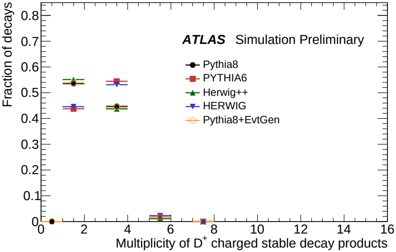
Left: Mean charged multiplicity in B^+ mesons decays



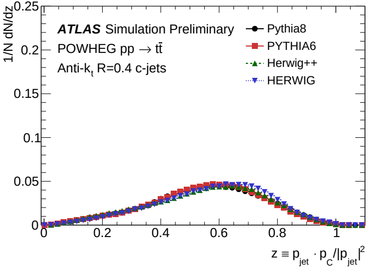
Right: *b*-quark fragmentation function

Properties of *c*-hadrons

- **Lifetime:** Shorter than the *b*-hadrons by around a factor of 2-3, still enough for measureable 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 $\approx$ 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)

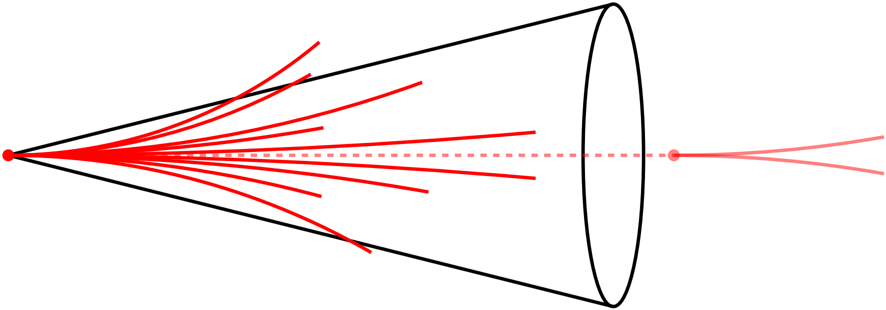


Left: Mean charged multiplicity in D^+ mesons decays



Right: *c*-quark fragmentation function

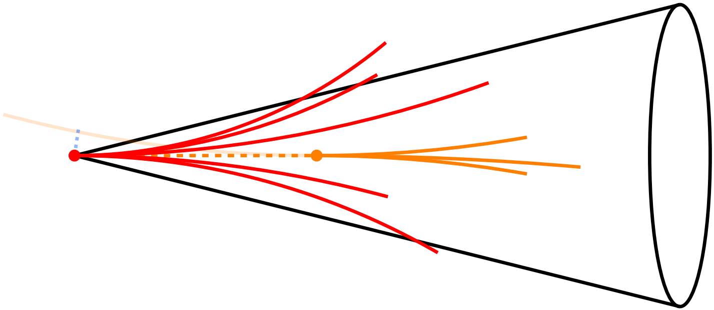
b-tagging: Anatomy of a light flavour (u, d, s) jet



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**

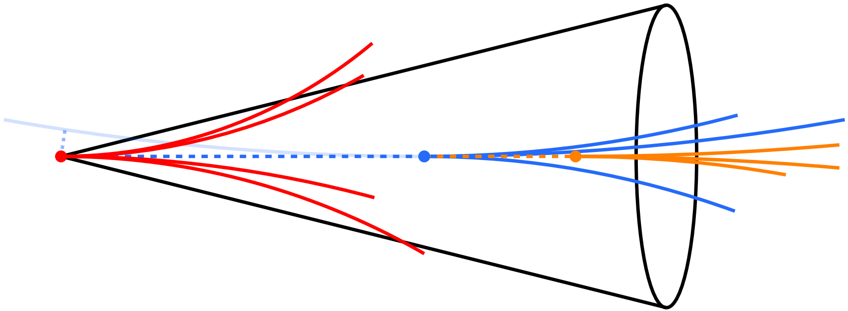
Anatomy of a *c*-jet



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**

b-tagging: Anatomy of a *b*-jet



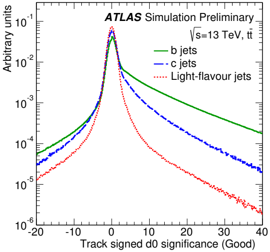
Typical Experimental Signature

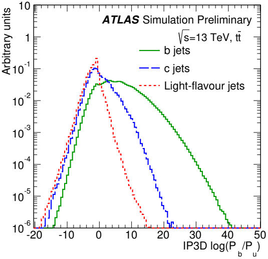
- *b*-quark fragments into a *b*-hadron which carries most of the jet energy
- Most *b*-hadrons (≈ 90%) decay into *c*-hadrons
- *b*-hadron decay vertex often displaced from the primary *pp* vertex by a few mm
- Subsequent *c*-hadron decay vertex often displaced by a further few mm
- Tracks from both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

Exploiting *b*-hadron properties: Track Impact Parameters (IP)

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

- 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





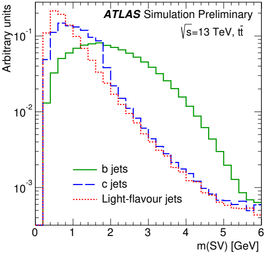
Left: Transverse IP significance distribution

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

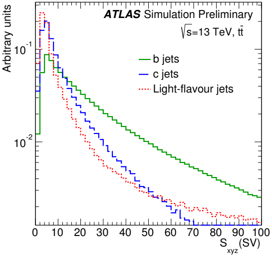
Exploiting *b*-hadron properties: Secondary Vertices (SV)

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

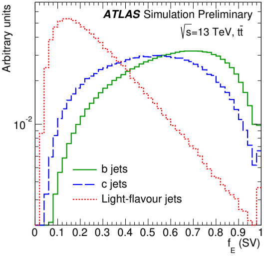
- Attempt to reconstruct a secondary vertex from high IP tracks associated with jet
- Use invariant mass of tracks at SV to discriminate *b* or *c*-hadron decay vertices from V^0 decays or material interations
- Further exploit hard *b*-jet fragmentation, SV should carry a large fraction of jet energy
- ✓ SV found in up to ≈ 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

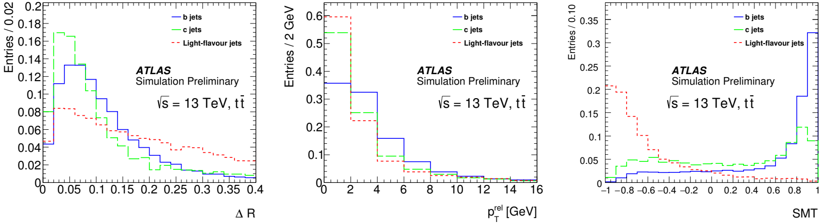


Right: Energy fraction of SV tracks

Exploiting *b*-hadron properties: Leptons (Muons)

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

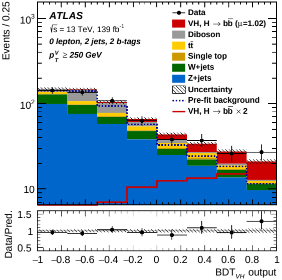


Left: Δ*R* of muon w.r.t. jet axis   Centre: p_T of muon relative to the jet axis   Right: BDT built from muon observables

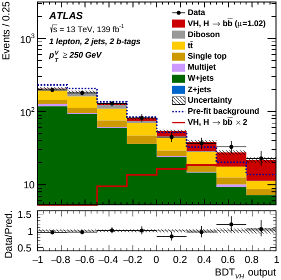
$H \to b\bar{b}$ with VH associated production I (arXiv:2007.02873)

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

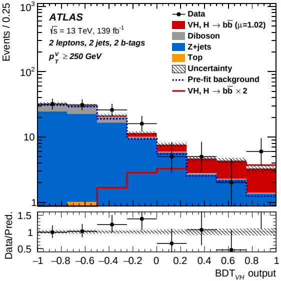
- Search for events with 0, 1 or 2 leptons ($Z \to \nu\nu$, $W \to \ell\nu$ and $Z \to \ell\ell$) and ≥ 2 b-tagged jets, focus on high p_T^V events to suppress $V +$ jets and $t\bar{t}$ background
- Recently **updated with 139 fb^{-1} of 13 TeV data** from LHC Run 2 (2015 - 2018)
- **BDT used as nominal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

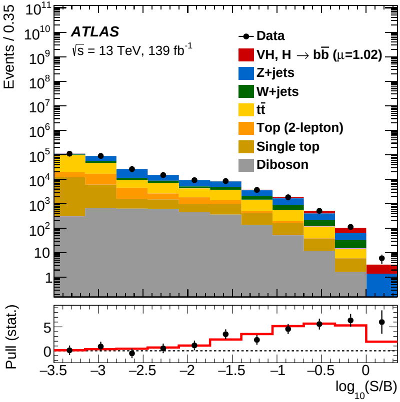


2 lepton (2 jets)

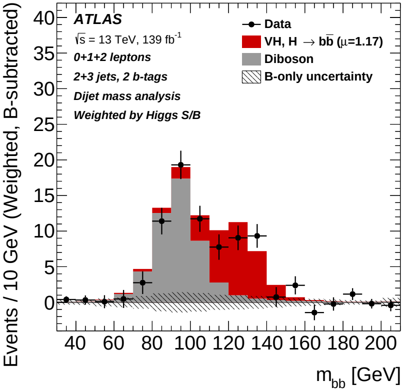
$H \to b\bar{b}$ with VH associated production II (arXiv:2007.02873)

VH, $H \to b\bar{b}$ 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 $VZ(b\bar{b})$: $\mu = \mathbf{0.93^{+0.15}_{-0.14}}$



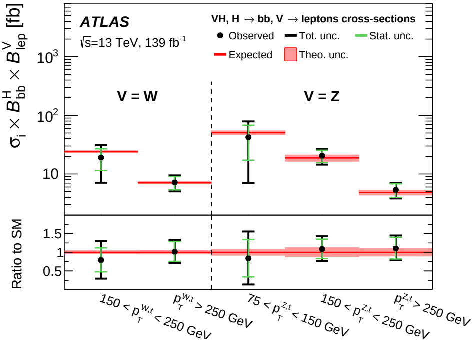
Combined $\log(S/B)$ distribution for multivariate analysis



Bkgd. subtracted $m_{b\bar{b}}$ distribution for CBA, weighted by per-event S/B

$H \to b\bar{b}$ with VH associated production III (arXiv:2007.02873)

- "Theory" systematics largest for signal strength measurement, particularly signal and V + jets background modelling
- Experimental systematics dominated by b-tagging uncertainties
- STXS measurements still limited by statistics

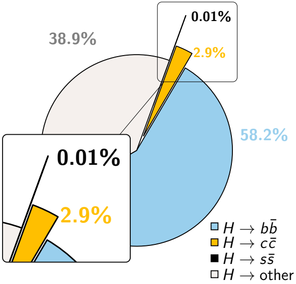


STXS measurements for *VH* production

Source of uncertainty		σ_μ VH	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 + jets		0.032	0.013	0.059
W + 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

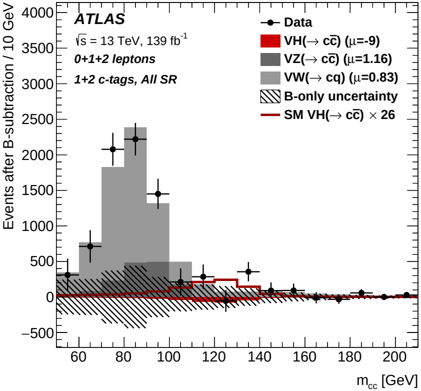
$VH, H \to c\bar{c}$ (arXiv:2201.11428)

The $H \to c\bar{c}$ 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**

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

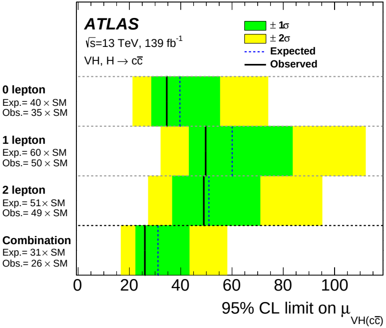


↑ **Background subtracted di-jet invariant mass distributions for events with 1 or 2 *c*-tagged jets**

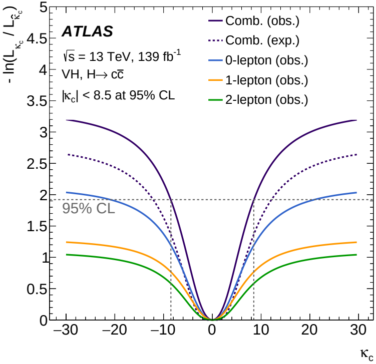
Latest ATLAS analysis, based on full Run 2 dataset ($139\,\text{fb}^{-1}$), exploits $(W/Z)H$ production and novel *c*-tagging to mitigate large multi-jet backgrounds

$VH, H \to c\bar{c}$ (arXiv:2201.11428)

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



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



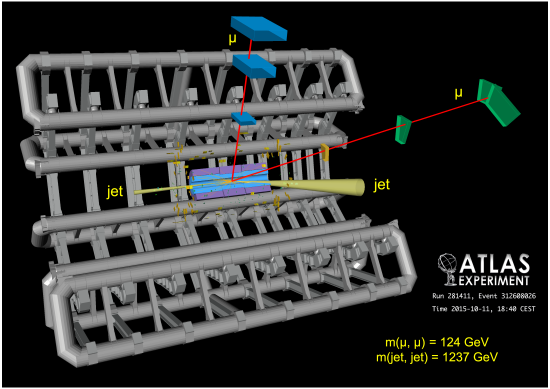
- Systematic uncertainties (primarily background modelling) limit sensitivity

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

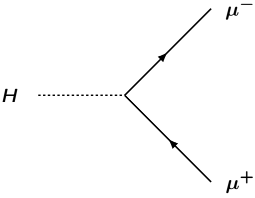
Analysis now sensitive to $\mathcal{B}(H \to c\bar{c}) < 100\%$ allowing important direct coupling interpretation, constraint of $|\kappa_c| < 8.5$ at 95% CL observed

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

$H \to \mu^+\mu^-$ Decay



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

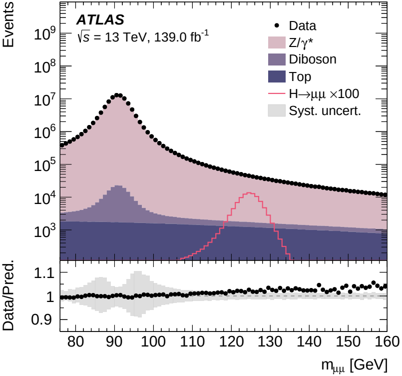


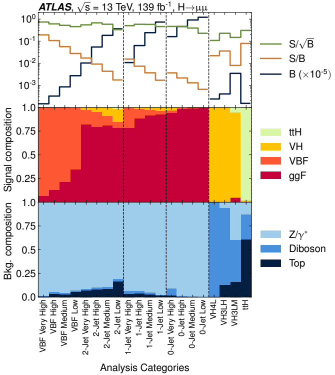
- Tree level decay, directly sensitive to $H\mu\mu$ Yukawa coupling
- Small branching fraction for $m_H = 125$ GeV at $\mathcal{B}(H \to \mu^+\mu^-) \approx 2 \times 10^{-4}$
- Most promising channel to study Higgs boson coupling to second generation fermions

Search for $H \to \mu^+\mu^-$ I (arXiv:2007.07830)

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 backgound is $Z \to \mu^+\mu^-(+\text{jets})$, exploiting Higgs production modes can help reduce this substantially
- In events with exactly two muons, classify with BDTs trained with production mode sensitive variables

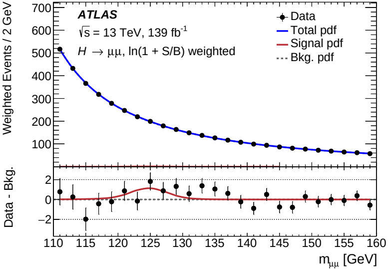


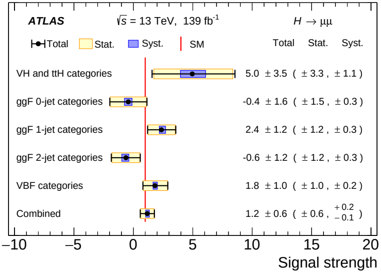


Relative sensitivity of the analysis categories ↑

Search for $H \to \mu^+\mu^-$ II (arXiv:2007.07830)

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

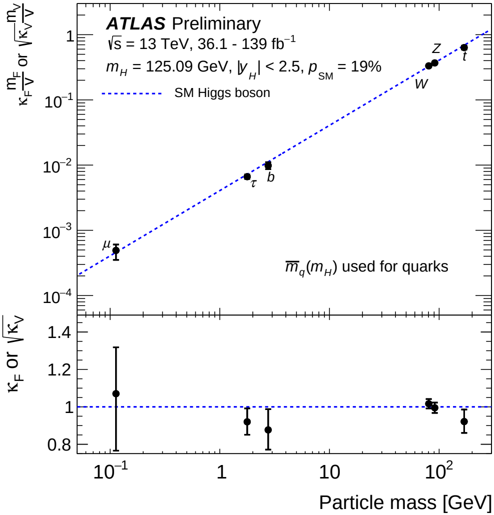




Approaching sensitivity to SM prediction!

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

Latest ATLAS 125 GeV Higgs combination with 13 TeV data



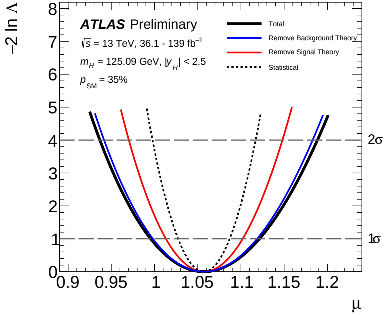
Reduced coupling strength modifiers as a function of fermion/boson mass, assuming no BSM contributions to Γ_H and the SM structure of loop processes

Combination of ATLAS Measurements I (ATLAS-CONF-2021-053)

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

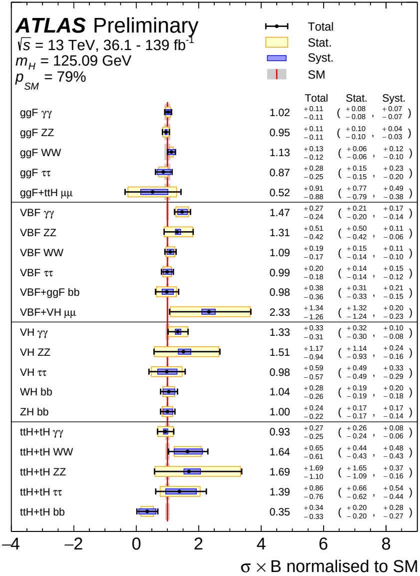
- Methodology similar (e.g. κ framework etc.) to well known Run 1 ATLAS+CMS combination (arXiv:1606.02266)
- All performed with 13 TeV data, most channels updated with 139 fb^{-1} dataset

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



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

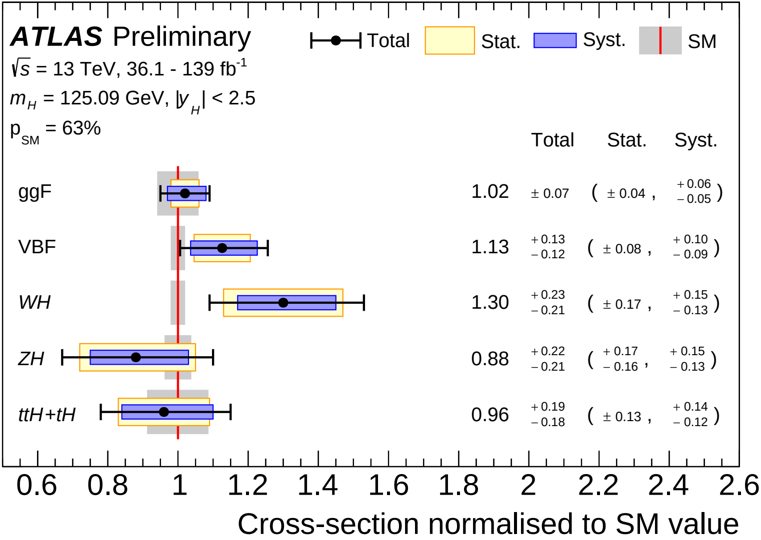
Combination of ATLAS Measurements II (ATLAS-CONF-2021-053)



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

Combination of ATLAS Measurements III (ATLAS-CONF-2021-053)

Cross sections relative to SM prediction



Summary

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!