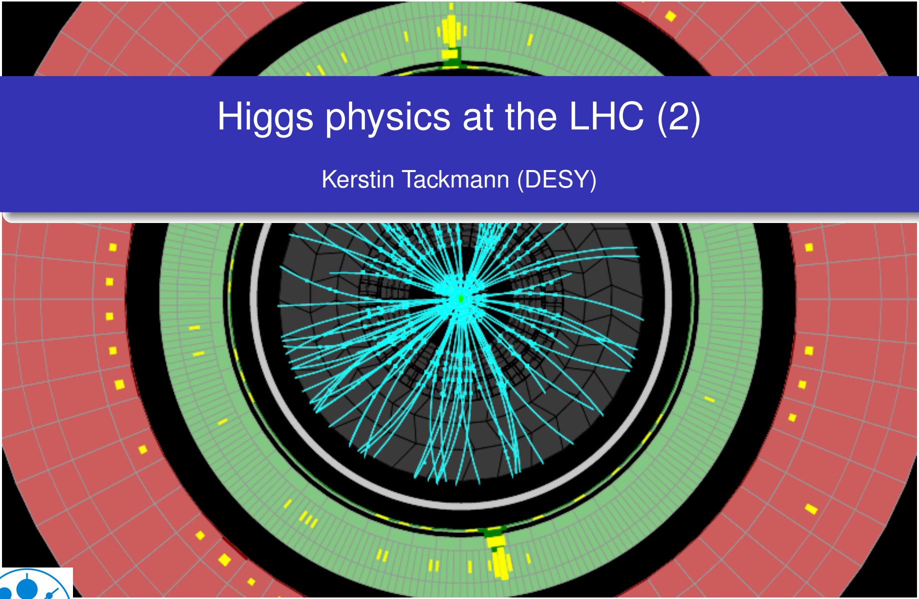


Higgs physics at the LHC (2)

Kerstin Tackmann (DESY)

PRISMA/Symmetry Breaking Annual Retreat 2017

Outline

Topics from yesterday

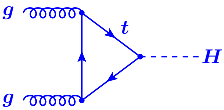
- Overview LHC, proton collisions, and the experiments
- The Higgs boson in the SM
- A close look at the $H \to \gamma\gamma$ analysis: analysis techniques

Topics for today

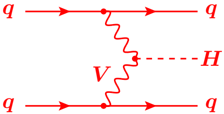
- Overview of Higgs measurements and searches (in other decay channels) and combined results
- What we really want to understand to answer the question whether this particle is the Higgs boson as predicted by the SM:
  - ⋆ How does it couple to the SM particles?
    - ▶ Study its production processes and decay (branching ratios)
  - ⋆ Does it have $J^P = 0^+$?
  - ⋆ Are there other Higgs particles? This would be a very clear sign of physics beyond the SM
- Both differential measurements as well as non-differential measurements are useful to tackle these questions

Separation of production processes

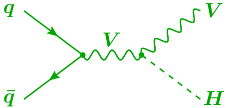
Separate Higgs production processes by using their specific topologies:



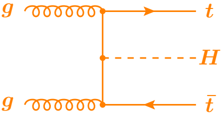
Tends to have low p_T



2 forward jets, little hadronic activity in between



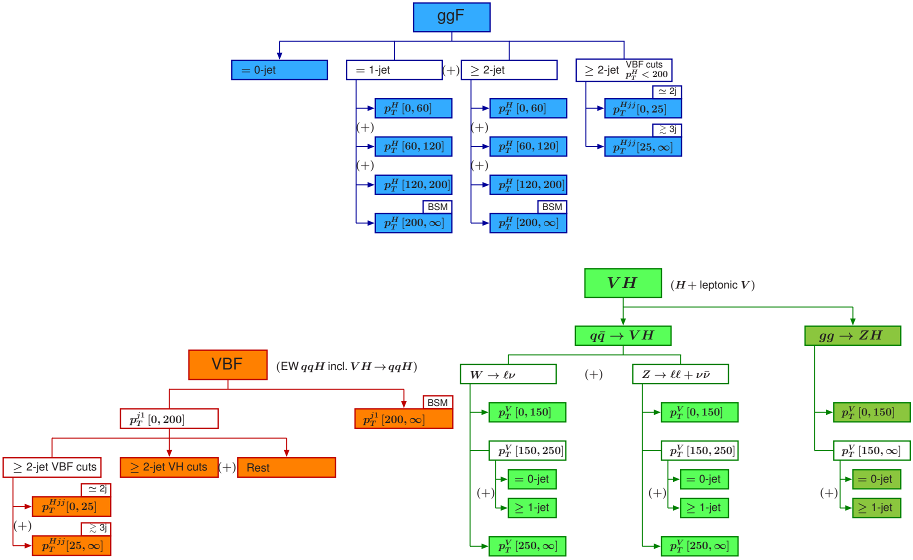
Tag W and Z leptonic and hadronic decays



Tag 2 top quarks

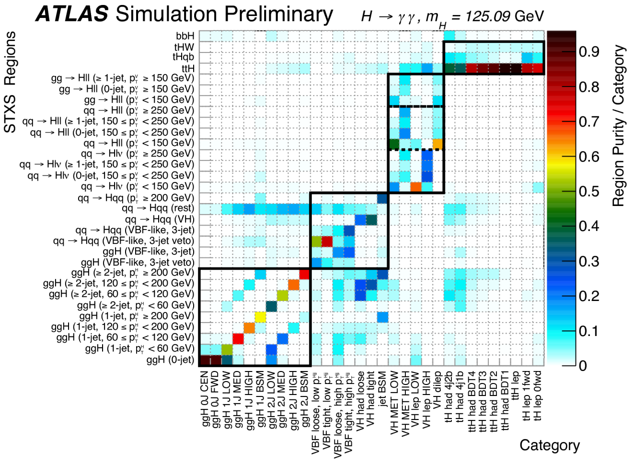
- Experimentally this is achieved by splitting events into mutually exclusive categories
- Categories are never pure in one production process, “only” enriched $\rightarrow$ employ a combined fit across all categories (essentially an unfolding process)
- Split into kinematic regions (per production process) to limit theoretical uncertainties in the measurements (“Simplified template cross sections” = STXS)

Simplified Template Cross Sections definitions



$H \to \gamma\gamma$: "Couplings analysis"

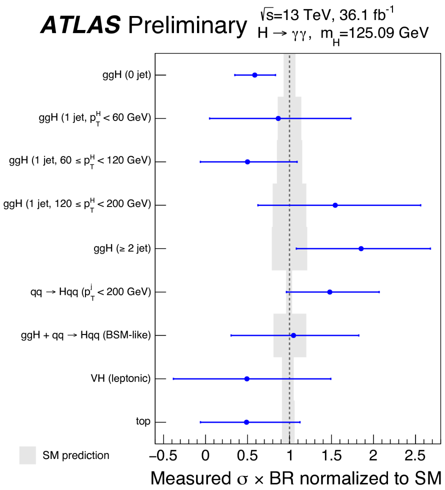
Most analysis steps are the same as in the cross section measurement discussed yesterday (with a different way of defining "bins"), but



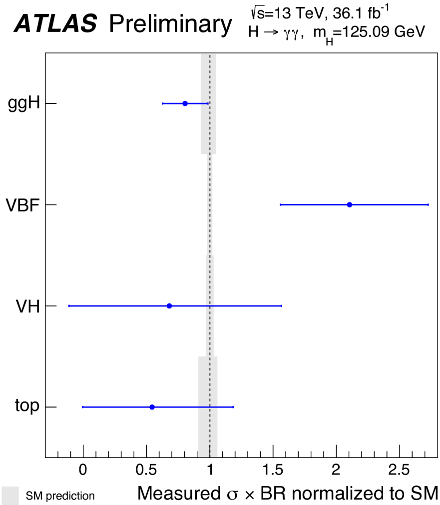
- Separation of production processes
- Likelihood fit based unfolding

$H \rightarrow \gamma\gamma$: Results

Merged to nine measured cross sections

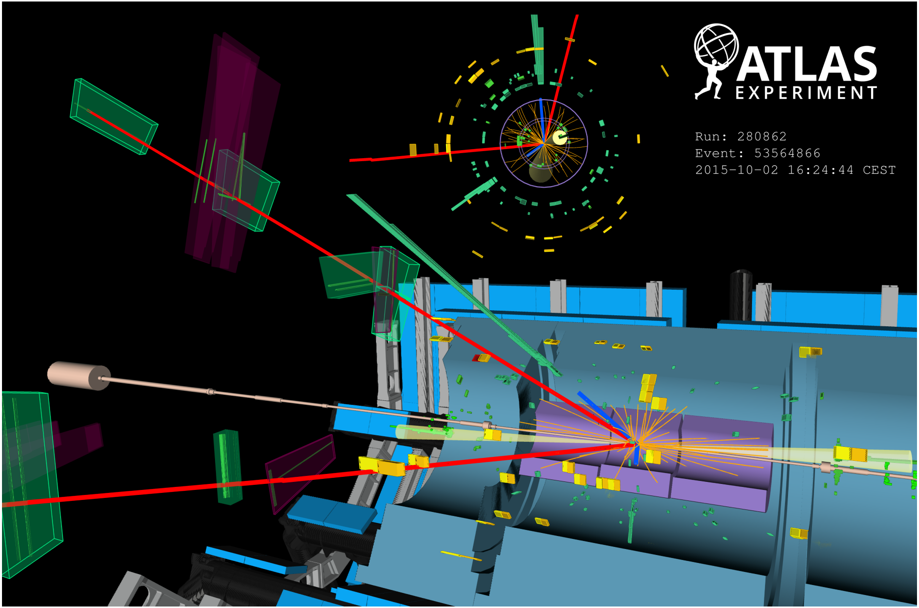


Merged to production processes



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

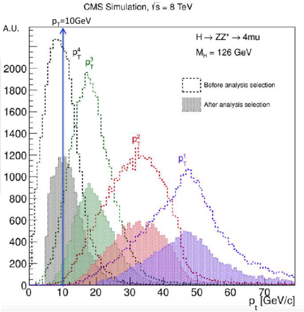
$H \to ZZ^* \to 4\ell$ candidate



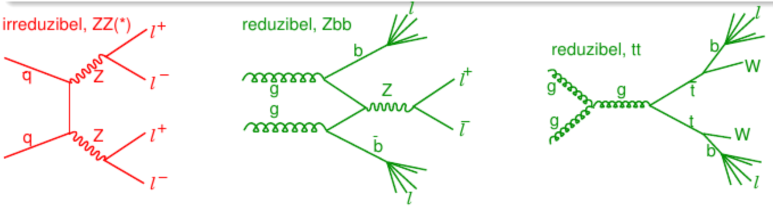
$H \to ZZ^* \to 4\ell$: the golden channel

Signature

- 2 pairs of oppositely charged, same flavor leptons (down to $5\,\mathrm{GeV}$)
- One compatible with $Z \to \ell^+\ell^-$

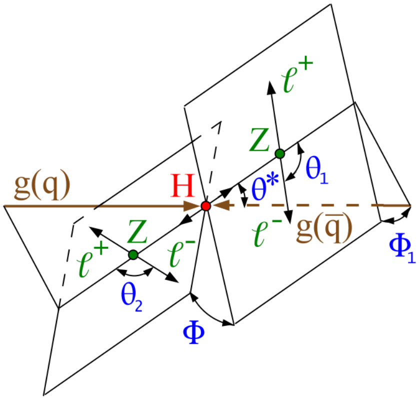


- Needs high efficiency for lepton reconstruction and identification at low p_T
- Very clean channel (good signal/background), with excellent mass resolution $\sigma_{m_{4\ell}} < 2\,\mathrm{GeV}$ (4μ) to $\sim 2.5\,\mathrm{GeV}$ $(4e)$ (at $130\,\mathrm{GeV}$)



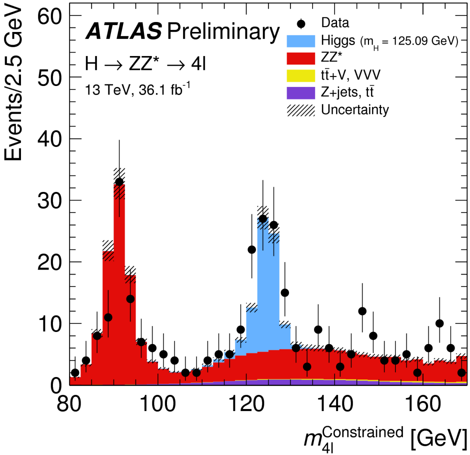
$H \to ZZ^* \to 4\ell$: kinematics

- Small branching ratio ($\mathcal{B}(Z \to \ell\ell) = 3.4\%$)
- Full event kinematics can be measured
  - ⋆ 2 production and 3 decay angles
  - ⋆ Z boson invariant masses

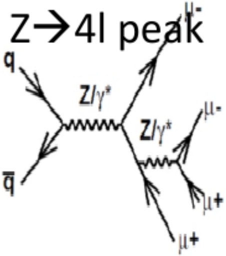


- Can be used to suppress SM ZZ background
- Can be used to study Higgs spin and CP

$H \to ZZ^* \to 4\ell$: invariant mass spectrum



- $Z \to 4\ell$ conveniently located close to $H \to 4\ell$
- Very useful as cross check for lepton reconstruction, identification and calibration and for analysis techniques

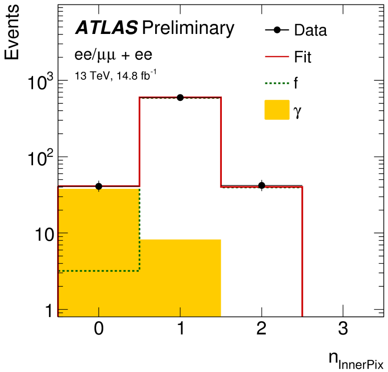


$H \rightarrow ZZ^* \rightarrow 4\ell$: Background estimation

- Main background SM ZZ^* estimated from simulation
- Z+jets and $t\bar{t}$ backgrounds estimated from the data

Example: if subleading $Z^* \rightarrow ee$

- Fake/background electron candidate from light-flavor jets (f), photon conversions (γ) and heavy-flavor hadrons decaying to electrons
- Determine f and γ from fit in control region
  - ⋆ Control region "$3\ell + X$": relax requirements on lowest-p_T lepton (electron)
  - ⋆ Fit to distribution of number of hits in innermost Si layer to determine normalization of backgrounds
  - ⋆ Use MC to "transfer" estimated backgrounds to signal region



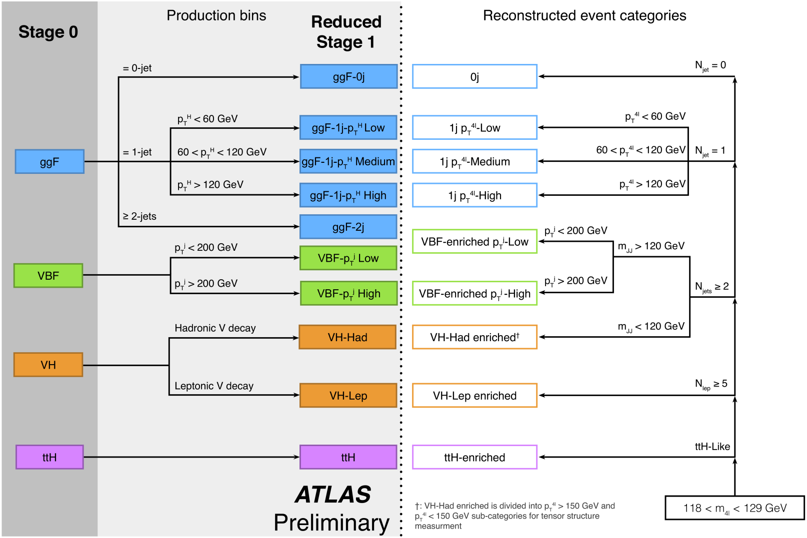
type	data fit	efficiency [%]	SR yield
f	1228 ± 35	0.23 ± 0.03	2.62 ± 0.08 ± 0.36
γ	79 ± 10	0.76 ± 0.05	0.55 ± 0.08 ± 0.04
q	(MC-based estimation)		2.50 ± 0.77

$H \to ZZ^* \to 4\ell$: Background estimation

Decay channel	Signal (full mass range)	Signal	ZZ^*	Other backgrounds	Total expected	Observed
4μ	21.0 ± 1.7	19.7 ± 1.6	7.5 ± 0.6	1.00 ± 0.21	28.1 ± 1.7	32
$2e2\mu$	15.0 ± 1.2	13.5 ± 1.0	5.4 ± 0.4	0.78 ± 0.17	19.7 ± 1.1	30
$2\mu 2e$	11.4 ± 1.1	10.4 ± 1.0	3.57 ± 0.35	1.09 ± 0.19	15.1 ± 1.0	18
$4e$	11.3 ± 1.1	9.9 ± 1.0	3.35 ± 0.32	1.01 ± 0.17	14.3 ± 1.0	15
Total	59 ± 5	54 ± 4	19.7 ± 1.5	3.9 ± 0.5	77 ± 4	95

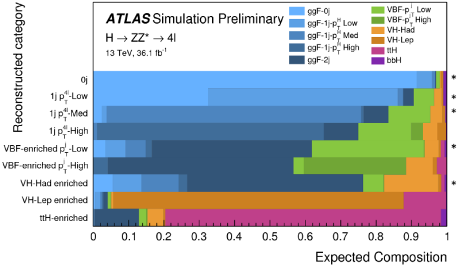
$H \to ZZ^* \to 4\ell$: Event categories

- Event categories in $H \to 4\ell$ chosen to mimic closely the STXS bins

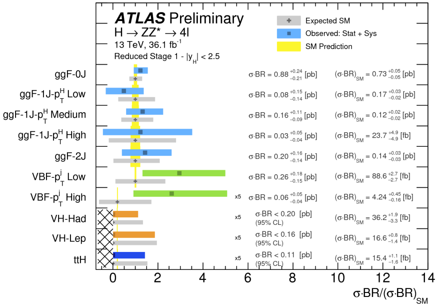


$H \to ZZ^* \to 4\ell$: STXS measurements

Category composition

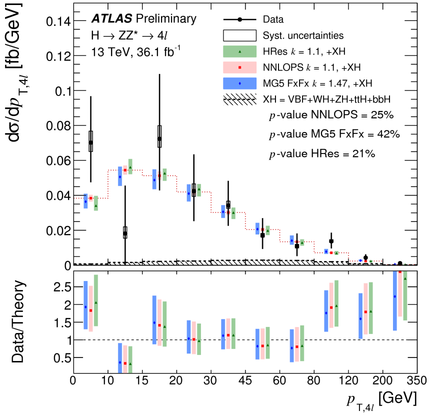


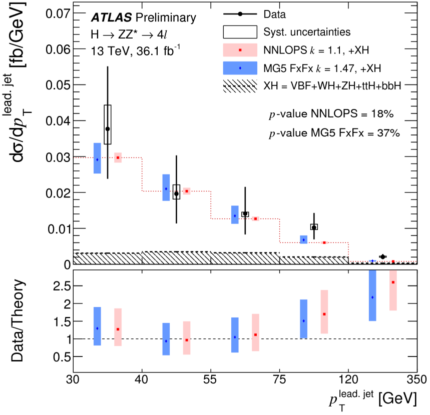
Measurements



- Measurements normalized to SM prediction for plots, but SM prediction not folded into the measurements
- Good agreement with SM predictions

$H \to ZZ^* \to 4\ell$: Differential measurements





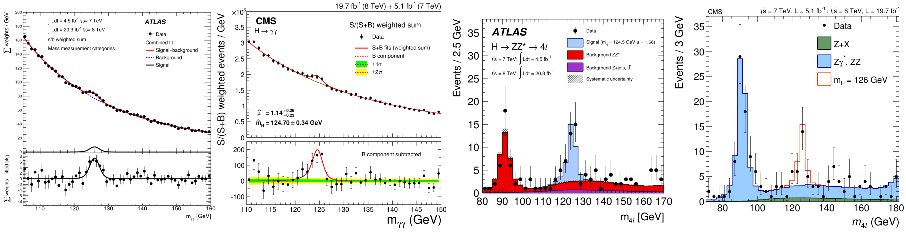
- Comparison with default MC: p-value 25%
- Other predictions normalized to N^{3}LO total xs

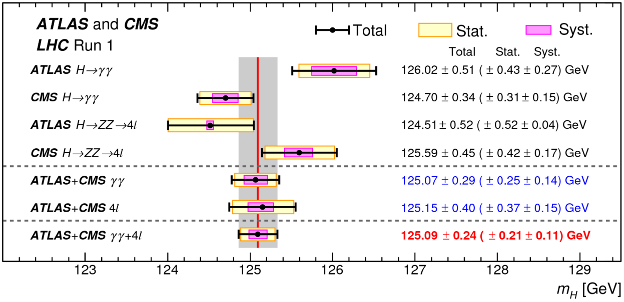
- Comparison with default MC: p-value 18%

Higgs mass

What is its mass?

Likelihood scan in m_H in the two high-resolution channels $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ (combined ATLAS+CMS)



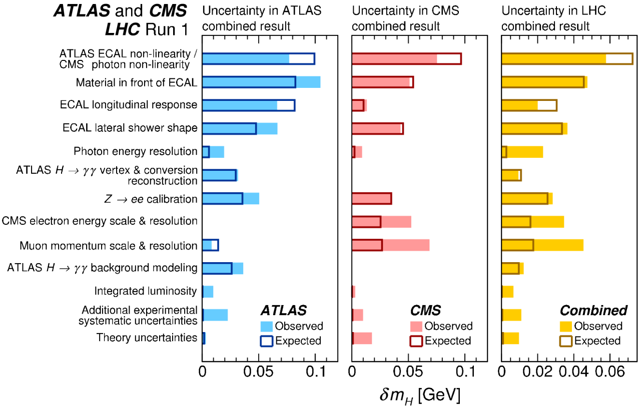


$(125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))$ GeV

Statistical uncertainties dominate

What is its mass? – Systematic uncertainties

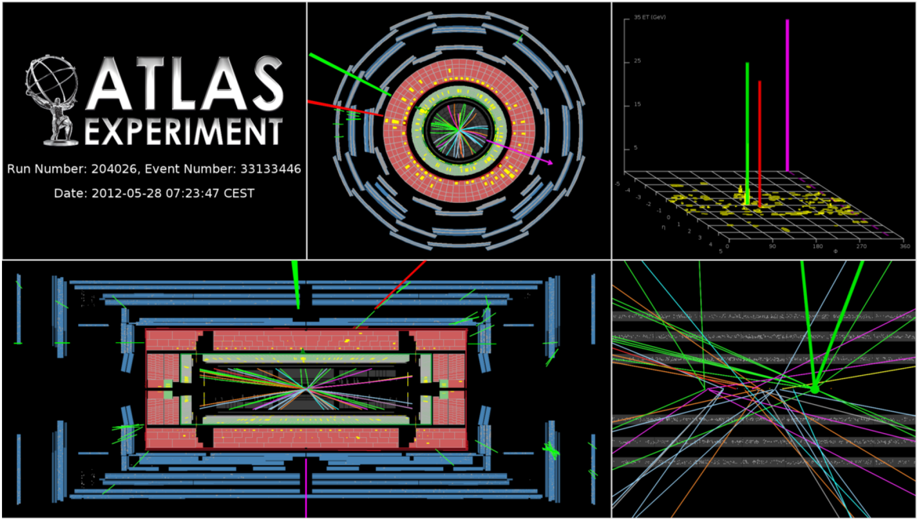
- Dominated by EM energy scale uncertainties



- Significant amount of effort for Run1 precision calibration
- Changes in operational conditions and detector material for Run2 require repeating many studies with Run2 data

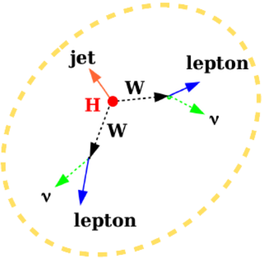
$H \to WW^* \to \ell\nu\ell\nu$

$H \to WW^* \to e\nu\mu\nu$ candidate



$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$: the abundant

- Most sensitive channel in a wide mass range $m_H \sim (130 - 180)\ \mathrm{GeV}$



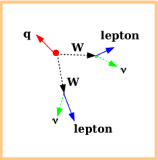
Signature

- 2 oppositely charged leptons
- Large missing E_T

- Challenge: poor mass resolution due to 2ν

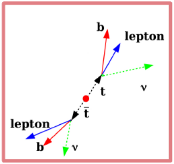
  $\rightarrow$ Transverse mass $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}|^2}$

WW → ℓυℓυ



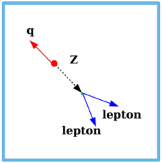
Irriducible backgrounds

tt→WWbb→ℓυℓυbb



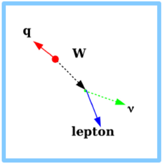
Characterized by b-jets

DY →ℓℓ



Mismeasured MET

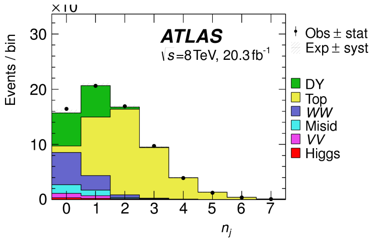
W +jets → ℓυ +jets



Fake lepton from a misidentified jet

$H \to WW^* \to \ell\nu\ell\nu$: the abundant

- Most sensitive channel in a wide mass range $m_H \sim (130 - 180)$ GeV



Signature

- 2 oppositely charged leptons
- Large missing E_T

- Challenge: poor mass resolution due to 2ν
  $\rightarrow$ Transverse mass $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}}|^2}$

- Classify events by number of jets (jets matched to hard interaction primary vertex to suppress pileup)
  - ⋆ 0 jets dominated by WW bkgd, sensitive to $gg \to H$
  - ⋆ 1+2 jets dominated by top background
  - ⋆ 2 jets selection to isolate VBF production
- Backgrounds constrained from background-enriched control regions
- Spin-0: correlated lepton emission, require small $\Delta\phi_{\ell\ell}$

$H \to WW^* \to \ell\nu\ell\nu$: the abundant

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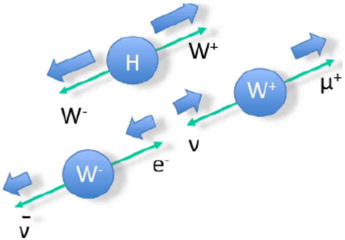

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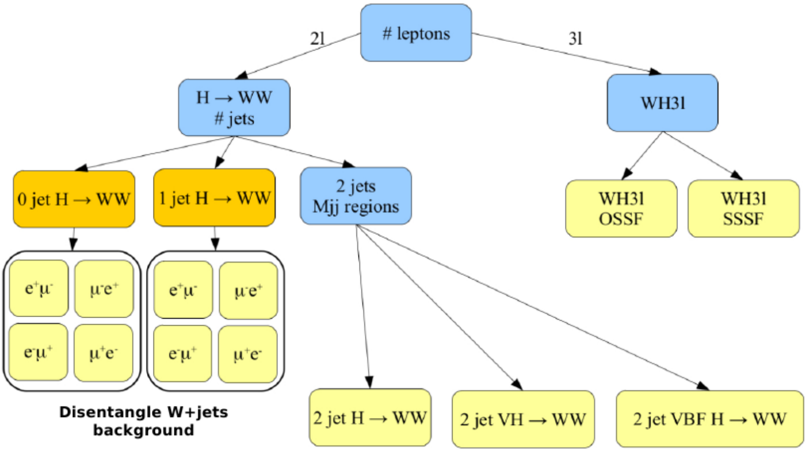
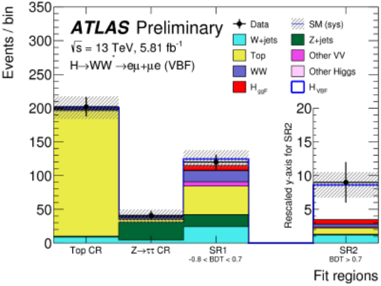
$H \to WW^* \to \ell\nu\ell\nu$: Categorization

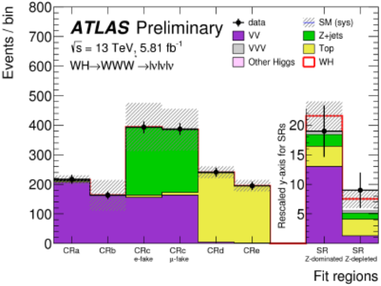
- Events categorized according to number of leptons, number of jets, kinematics of jets, lepton flavor

Example from CMS:



$H \to WW^* \to \ell\nu\ell\nu$: Backgrounds



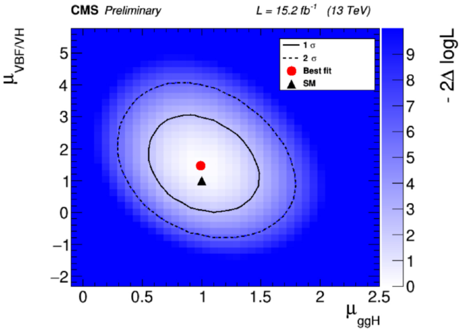


- Simultaneous fit in signal and control regions
- Top control region: require b-tag
- $Z \to \tau\tau$ control region: $m_{\tau\tau}$ compatible with m_Z, $m_{\ell\ell} < 80$ GeV
- Irreducible Z background in WH selection

$H \to WW^* \to \ell\nu\ell\nu$: Results

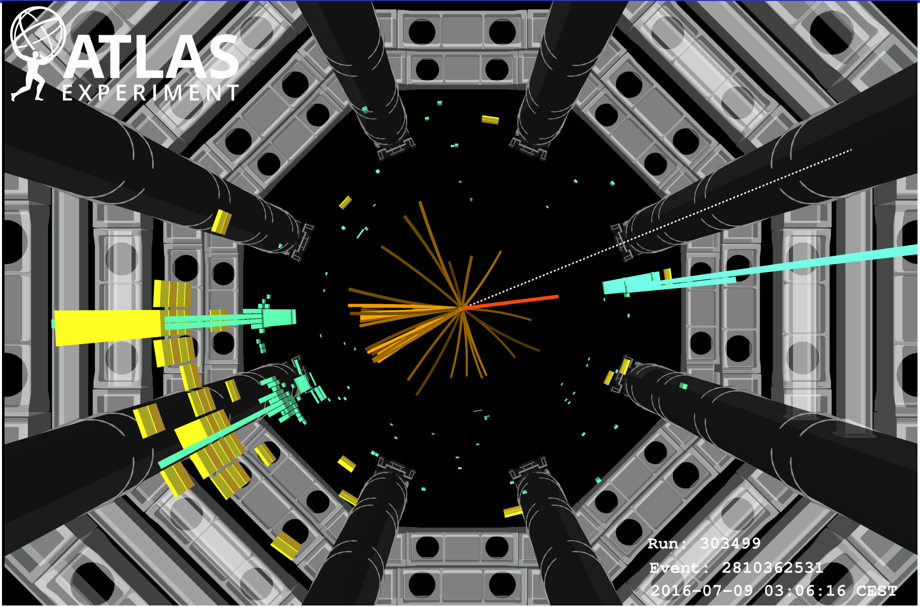
- Results so far only public on a subset of 2015+2016 data
- Very sensitive channel thanks to large $H \to WW^*$ branching ratio $\to$ important contribution to combined measurements of Higgs boson properties

category	significance	σ/σ_{SM}
0-jet	2.7 (2.9)	$0.9^{+0.4}_{-0.3}$
1-jet	2.1 (2.5)	$1.1^{+0.4}_{-0.4}$
2-jet	2.0 (1.0)	$1.3^{+1.0}_{-1.0}$
VBF 2-jet	2.2 (1.5)	$1.4^{+0.8}_{-0.8}$
VH 2-jet	1.0 (0.4)	$2.1^{+2.3}_{-2.2}$
WH 3-lep	0.0 (0.5)	$-1.4^{+1.5}_{-1.5}$
combination	4.3 (4.1)	$1.05^{+0.27}_{-0.25}$

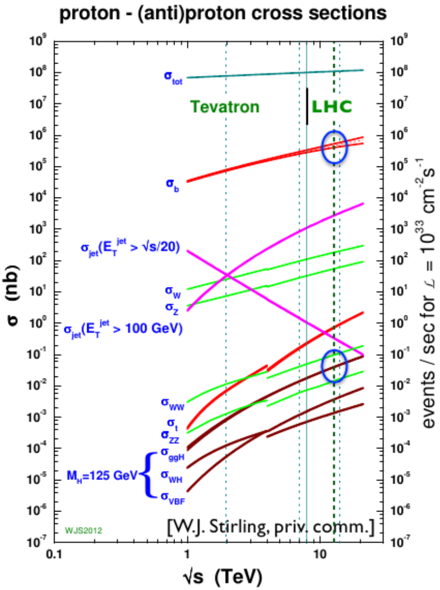


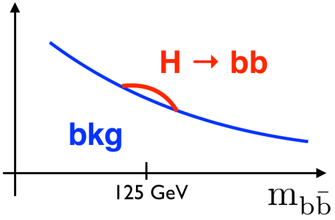
$H \to b\bar{b}$

$H \rightarrow b\bar{b}$ candidate



$H \rightarrow b\bar{b}$





- Production of b-jets through QCD processes orders of magnitudes more abundant than Higgs production
- Needs exploitation of signatures of specific production modes

$H \to b\bar{b}$

$gg \to H$

- Very large multijet background
- Triggering possible at large p_T
- First jet substructure analysis $p_T > 450$ GeV

VBF

- Large multijet background
- Trigger and background estimation challenging
- γ requirement helps to improve S/B

VH

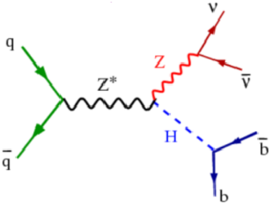
- Use leptonic V decays to trigger and suppress multijet backgrounds
- Main channel to search for $H \to b\bar{b}$

$t\bar{t}H$

- Challenging due to combinatorics and large $t\bar{t}b\bar{b}$ backgrounds
- Leptonic t decays used for triggering

$H \to b\bar{b}$ in VH production

MET > 150 GeV



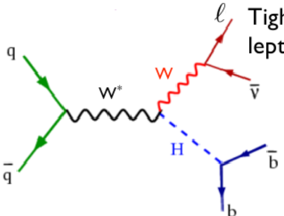
(+ additional criteria to suppress multi-jet)

Signature

- 2 b-tagged jets
- Lepton(s) ($W \to \ell\nu$, $Z \to \ell\ell$)
- Missing E_T ($W \to \ell\nu$, $Z \to \nu\nu$)

$p_T\ (\ell\nu) > 150$ GeV

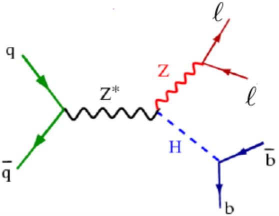
Tightly isolated lepton



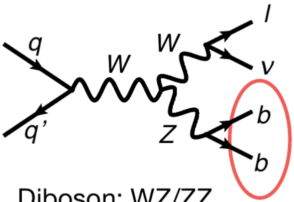
(+ MET > 30 GeV in electron channel)

$|m_{\ell\ell} - 91\ \mathrm{GeV}| < 10$ GeV

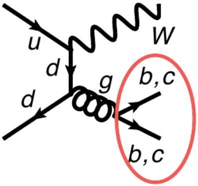
$p_T\ (\ell\ell) > 75$ GeV



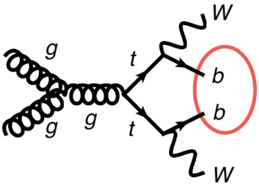
$H \to b\bar{b}$: backgrounds



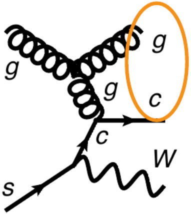
Diboson: WZ/ZZ



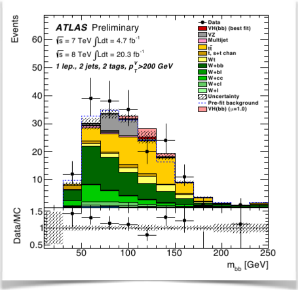
V+bb
V+cc
gluon splitting

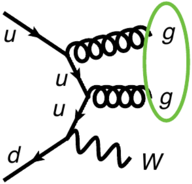


ttbar



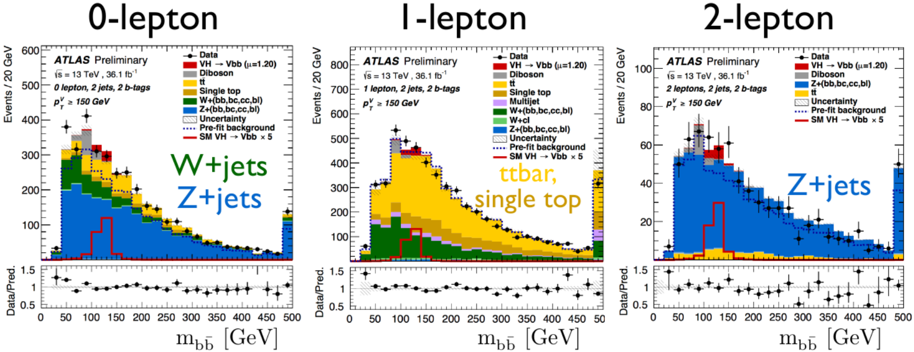
W+c





W+light

$H \to b\bar{b}$: backgrounds



- Main backgrounds from Z+jets, W+jets, $t\bar{t}$ and single top
- Resonant VZ background important for validation of the analysis

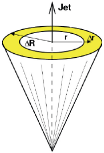
Jet reconstruction (I)

Particles are clustered into jets to allow for comparison with perturbative predictions

- Jet clustering can be performed on calorimeter clusters (e.g. ATLAS), tracks, all reconstructed objects (e.g. CMS) (in data) or simulated particles (for predictions)
- Jet clustering algorithms must be infrared insensitive (insensitive to soft and to collinear parton emissions). Then, they are infrared safe perturbatively and allow for perturbative predictions.

Common algorithms

Cone algorithms



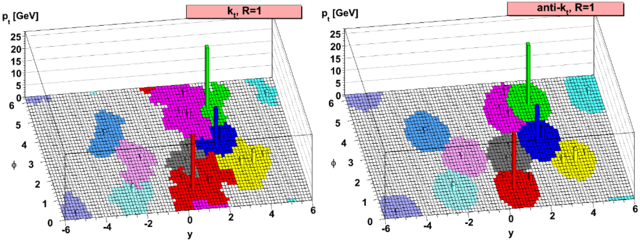
- A jet is defined by a cone of size $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.
- Splitting and merging procedure to avoid overlapping jets
- In general not infrared insensitive/safe (but infrared safe version exists: SISCone)

Jet reconstruction (II)

(Anti-)k_T algorithms

- Objects are clustered based on their distance in momentum space: $d_i = k_{Ti}^{2p}$ and $d_{ij} = \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2}$
- Object i and j are merged if $d_{ij} < d_i$
- $p = 1$: k_T algorithm, $p = -1$: anti-k_t algorithm, $p = 0$: Cambridge-Aachen algorithm
- Infrared insensitive/safe
- Anti-k_t: hard objects tend to cluster first, ∼circular jets

Anti-k_t algorithm is used by ATLAS (typically $R = 0.4$) and CMS

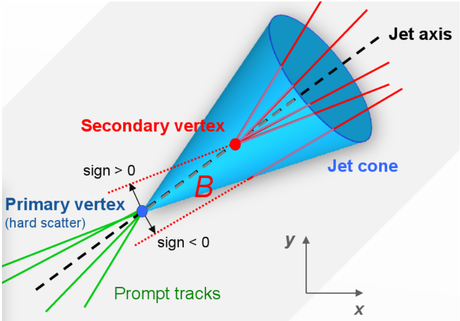


b-tagging

Hadrons with b-flavor decay through weak interaction with picosecond ($|V_{cb}| \sim 0.04$) lifetime $\rightarrow$ this is exploited to “tag” b-jets

b-tagging methods based on

- Track impact parameter significance
- Reconstructed secondary vertices
- Presence of leptons ($BF(b \rightarrow X\ell\nu) \sim 10\%$ per ℓ)

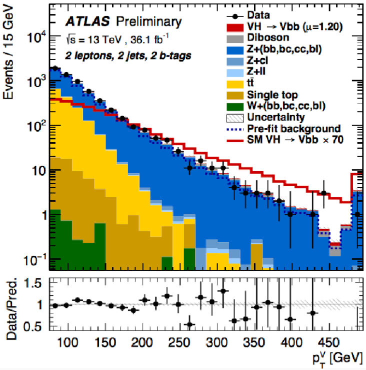


b-jet efficiency	light jet mistag rate	c-jet mistag
85%	3%	~33%
77%	0.7%	~16%
70%	0.3%	~8%
50%	<0.1%	~2.9%

$H \to b\bar{b}$: categorization

Signal regions/categories defined by

- Number of leptons (0/1/2)
- Number of jets: exactly 2 or 3 jets (0,1 lepton), 2 or $\geq$3 jets (2 lepton)
- Vector boson p_T:
  75 GeV $< p_T < 150$ GeV,
  $p_T > 150$ GeV (2 lepton)
  - ⋆ 0/1 lepton: $p_T > 150$ GeV

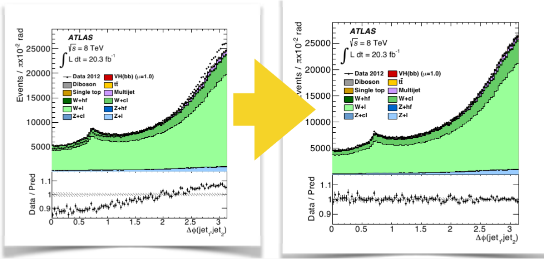


Channel	SR/CR	Categories			
		75 GeV $< p_T^V < 150$ GeV		$p_T^V > 150$ GeV	
		2 jets	3 jets	2 jets	3 jets
0-lepton	SR	-	-	BDT	BDT
1-lepton	SR	-	-	BDT	BDT
2-lepton	SR	BDT	BDT	BDT	BDT
1-lepton	W + HF CR	-	-	Yield	Yield
2-lepton	$e\mu$ CR	m_{bb}	m_{bb}	Yield	m_{bb}

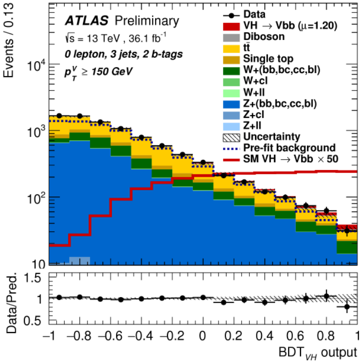
Backgrounds constrained from control regions

$H \to b\bar{b}$: Analysis strategy

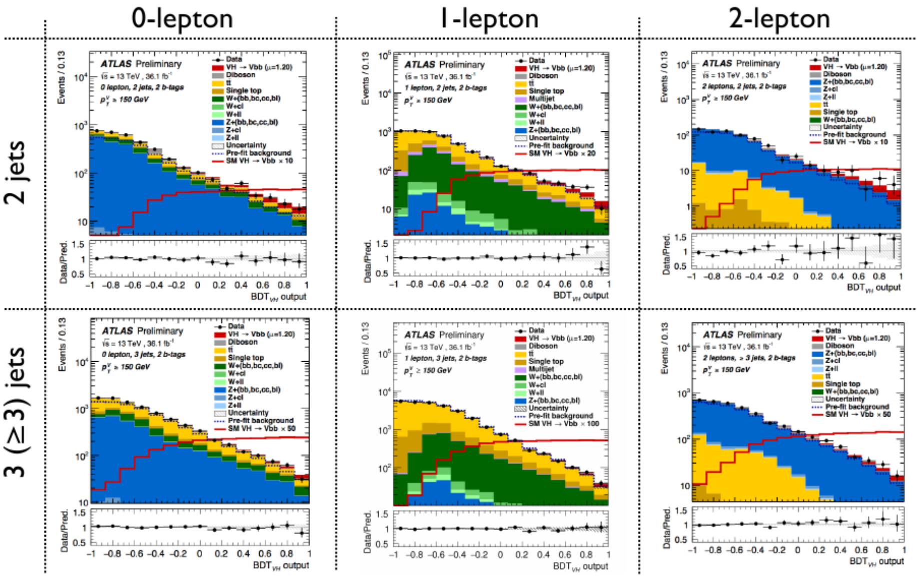
- Analysis performs likelihood fit to all signal and control categories
- Shapes and relative normalizations across regions parametrized by nuisance parameters, constrained within systematic uncertainties
- Data determines value and uncertainty



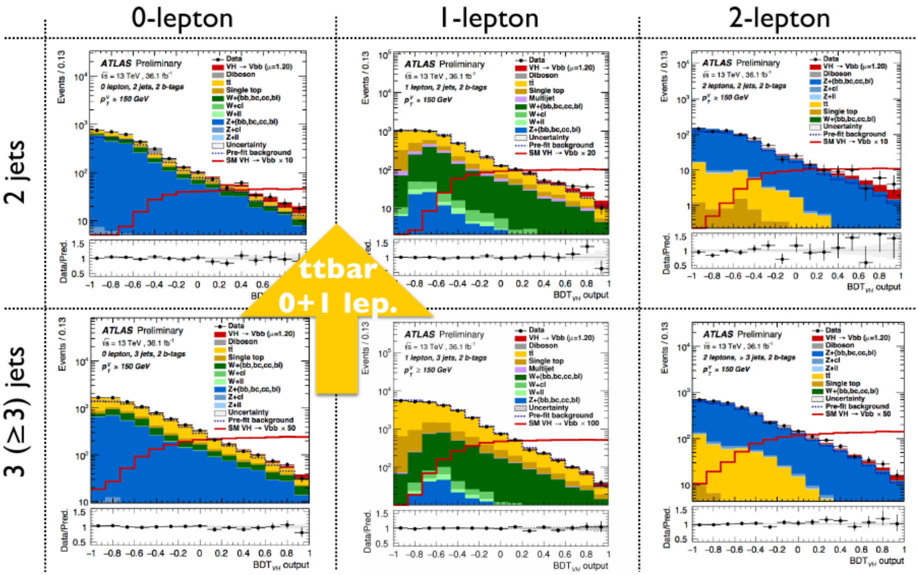
- Boosted decision tree used to combine all observables into one discriminant per category



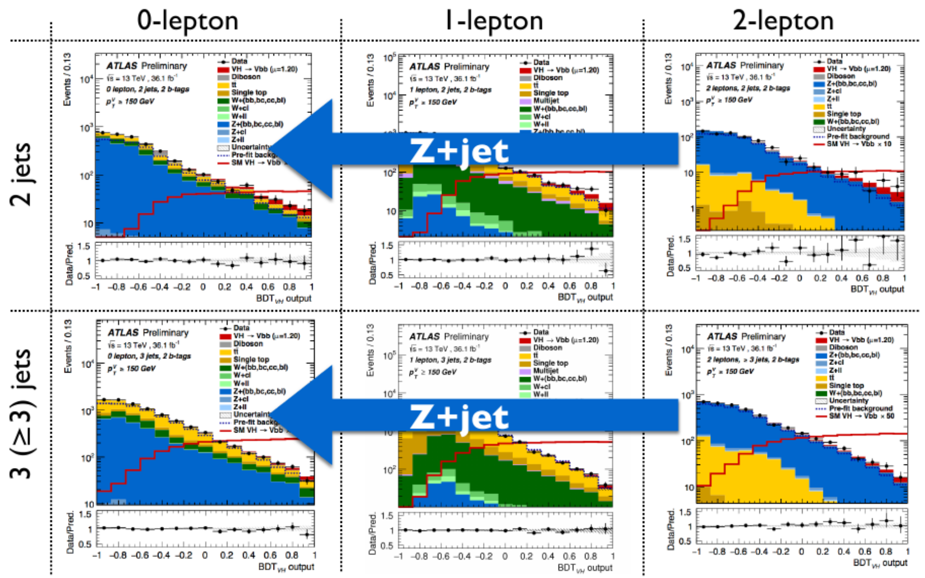
$H \to b\bar{b}$: background estimation



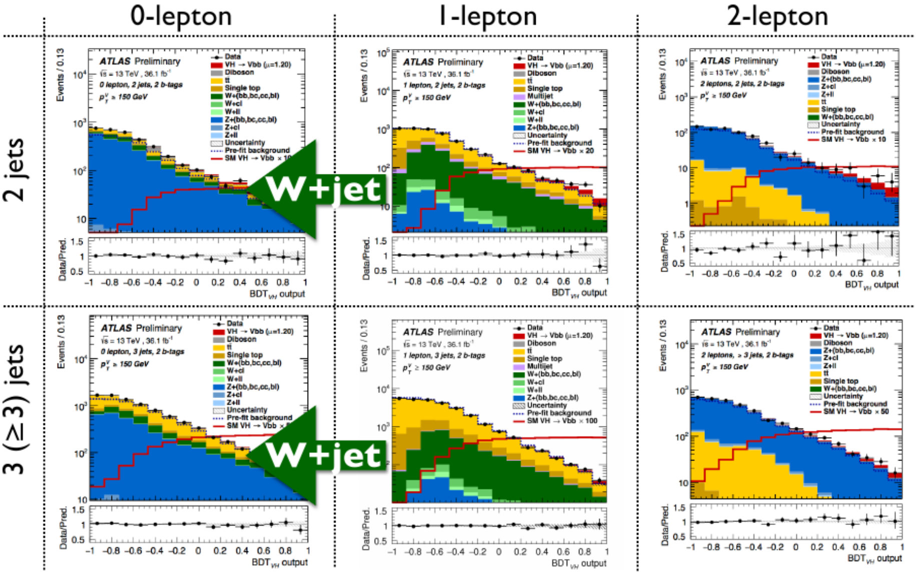
$H \to b\bar{b}$: background estimation



$H \rightarrow b\bar{b}$: background estimation

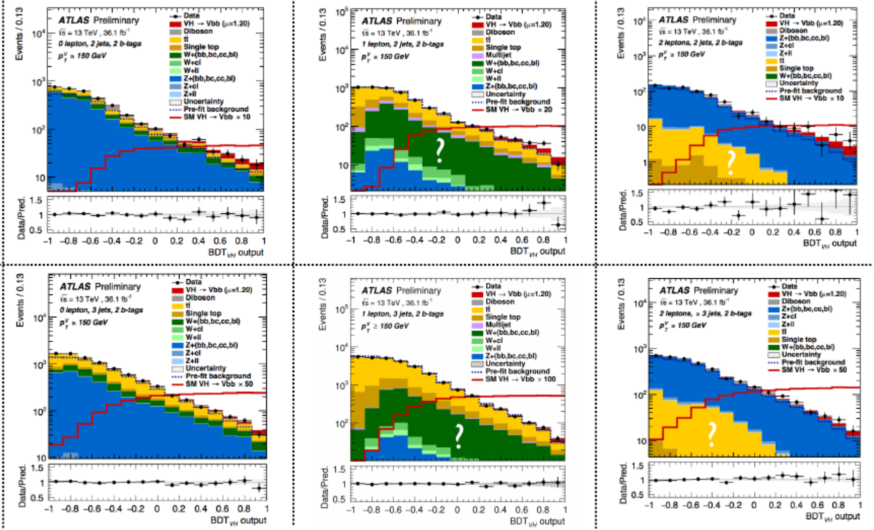


$H \to b\bar{b}$: background estimation



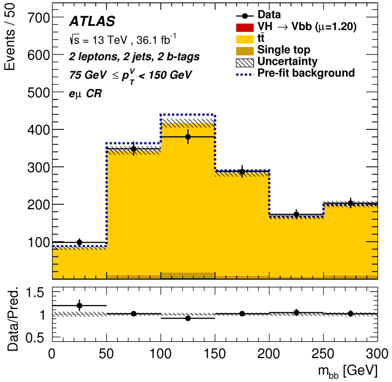
$H \to b\bar{b}$: background estimation

	0-lepton	1-lepton	2-lepton
2 jets			
3 ($\geq$ 3) jets			

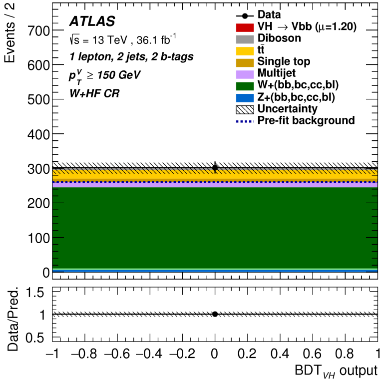


$H \to b\bar{b}$: background control regions

$t\bar{t}$ CR



W+HF CR



- 2 lepton channel ($e\mu$)
- Constraint on $m_{b\bar{b}}$ shape
- $>$99% pure

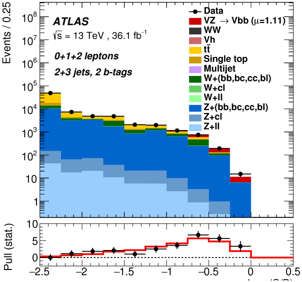
- 1 lepton channel
- Constraint on yield
- 75-80% pure

$H \to b\bar{b}$: Systematic uncertainties

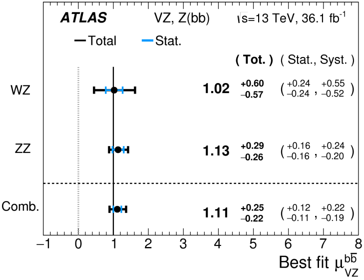
Source of uncertainty		σ_μ
Total		0.39
Statistical		0.24
Systematic		0.31
Experimental uncertainties		
Jets		0.03
E_T^{miss}		0.03
Leptons		0.01
b-tagging	*b*-jets	0.09
	c-jets	0.04
	light jets	0.04
	extrapolation	0.01
Pile-up		0.01
Luminosity		0.04
Theoretical and modelling uncertainties		
Signal		0.17
Floating normalisations		0.07
Z+jets		0.07
W+jets		0.07
$t\bar{t}$		0.07
Single top-quark		0.08
Diboson		0.02
Multijet		0.02
MC statistical		0.13

- Systematic uncertainties are dominant
- *Main systematic uncertainties:*
  - Signal modeling (dominated by extrapolation uncertainty from high $p_T(V)$ to inclusive phase space, and presently by Pythia 8 vs Herwig 7 comparison)
    - Signal uncertainty doesn't affect the significance (expected significance = 3.0σ)
  - Background modeling
    (similar contribution from all the backgrounds with a statistical
    component from floating normalisations)
  - B-tagging calibration uncertainty
  - Limited size of Monte Carlo samples (despite generator slicing/filtering)

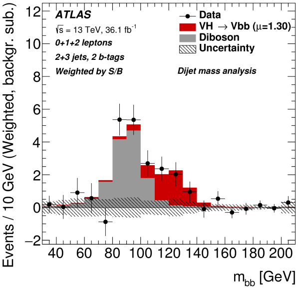
$H \to b\bar{b}$: $VZ(\to b\bar{b})$ cross check



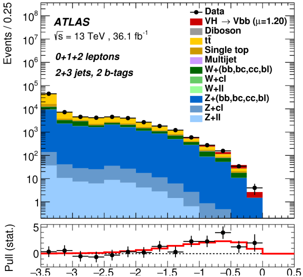
- Testing the analysis with $VZ(\to b\bar{b})$
- Significance: $\mathbf{5.8}\,\boldsymbol{\sigma}$ observed, $\mathbf{5.3}\,\boldsymbol{\sigma}$ expected



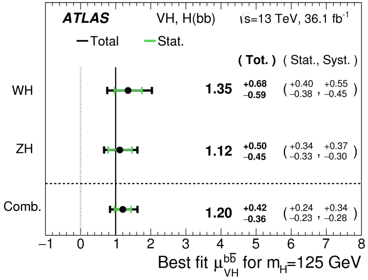
from a cross check analysis of $m_{b\bar{b}}$

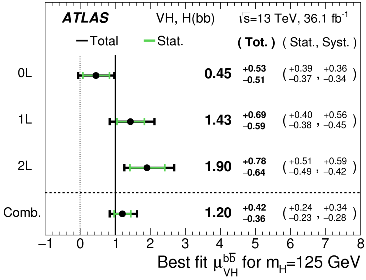


$H \rightarrow b\bar{b}$: Results

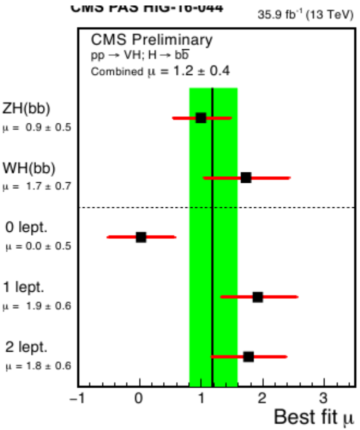


- Testing the analysis with $VZ(\rightarrow b\bar{b})$
- Significance: $3.5\,\sigma$ observed, $3.0\,\sigma$ expected





$H \to b\bar{b}$: Results from CMS and combination of Runs

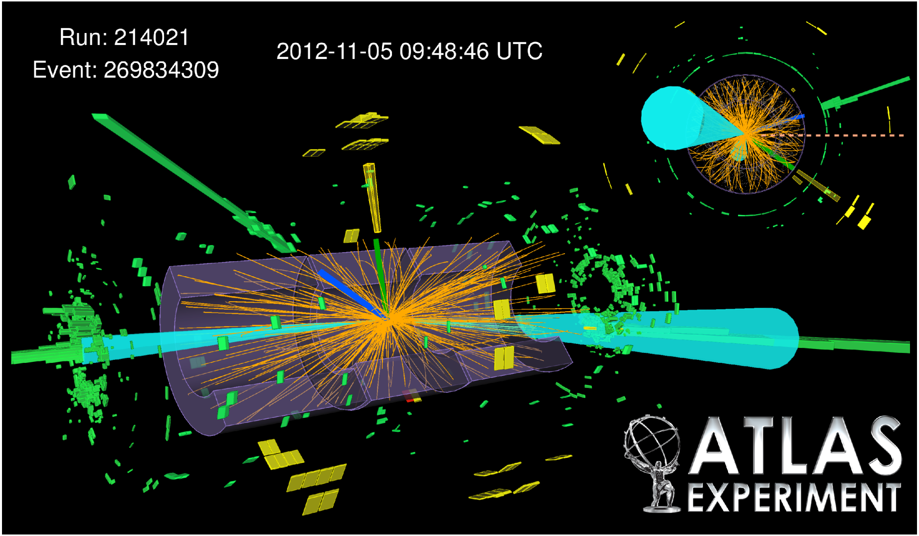


Significance, CMS obs. (exp.), σ	Significance, ATLAS obs. (exp.), σ
0.0(1.5)	0.5(1.7)
3.2(1.5)	2.3(1.8)
3.1(1.8)	3.6(1.9)
3.3(2.8)	**3.5(3.0)**

- Both experiments have separately evidence for $H \to b\bar{b}$ decays now!

$H \to \tau\tau$

$H \to \tau\tau$ candidate

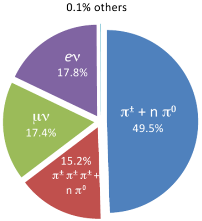


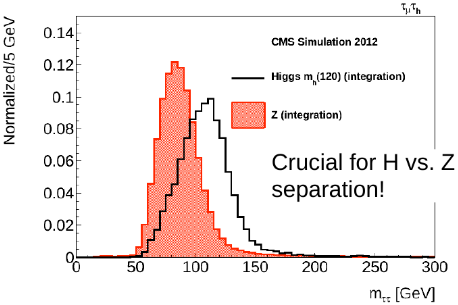
$H \to \tau\tau$

Signature

- Electron and/or muon
- Hadronically reconstructed τ_{had}
- Missing E_T

(depending on τ decay mode)



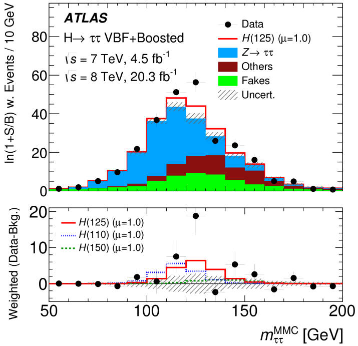


- Most important background: $Z \to \tau\tau$
- Only separation between $H \to \tau\tau$ and $Z \to \tau\tau$ via $m_{\tau\tau}$
- Mass reconstruction possible due to collinearity of τ decay products, resolution $\mathcal{O}(13 - 20\%)$

$H \to \tau\tau$: Categorization

Events categorized by

- τ decay mode
  - ⋆ dileptonic
  - ⋆ leptonic-hadronic
  - ⋆ dihadronic
- Jet content: 0/1/2 jets
  - ⋆ "Boosted": high-p_T $\tau\tau$ system or jet to enrich in ggF vs. non-Higgs
  - ⋆ VBF: 2 jets with large m_{jj} and $\Delta\eta_{jj}$



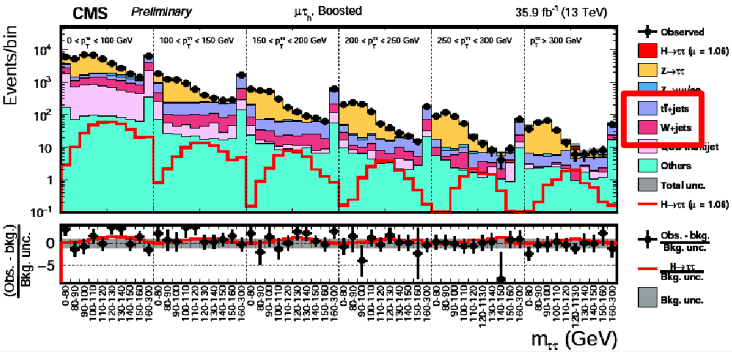
$H \to \tau\tau$: Backgrounds

$Z \to \tau\tau$

- Estimated by embedding simulated $Z \to \tau\tau$ events in $Z \to \mu\mu$ data events or using simulated $Z \to \tau\tau$ events

Other backgrounds: multijets, W+jets, Z+jets, $t\bar{t}$ (for dilep)

- Typically estimated in control regions where the tau identification or opposite-sign requirements are inverted or with kinematic selections

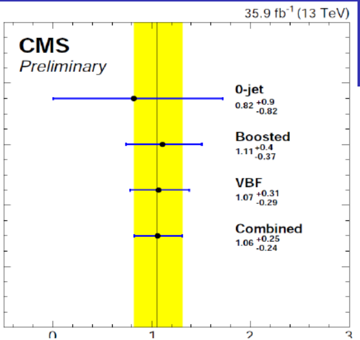


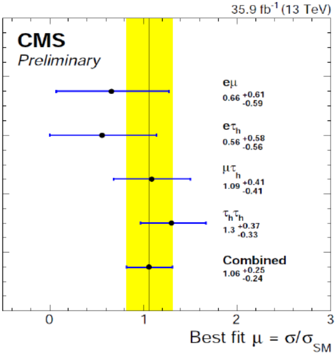
$H \to \tau\tau$: Results

- Run1: 5.5 σ (expected 5.0 σ) from combination of ATLAS and CMS results
- Run2 CMS: 4.9 σ observed
- Combined with Run1 5.9 σ

- Most sensitive category: VBF
- Most sensitive τ decay channels: leptonic-hadronic and dihadronic

- Dominant uncertainties: τ an jet energy scale, background estimation





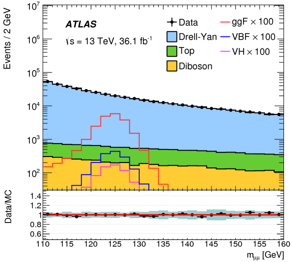
$H \rightarrow \mu\mu$

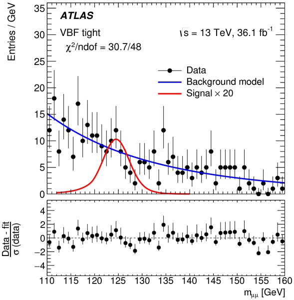
Rare decays: $H \to \mu\mu$

SM: BF($H \to \mu\mu$)= 0.02%

- Clean probe of Higgs couplings to 2nd generation fermions
- Signature: 2 opposite-sign, isolated muons
- Good $m_{\mu\mu}$ resolution $\sigma(m_{\mu\mu})/m_{\mu\mu}$ ~1.5-2.5%
- Large background from $Z/\gamma^* \to \mu\mu$, smaller contributions from $t\bar{t}$, WW, ... (S/B~0.4%)
- Observed (expected) upper limit on μ is 2.8 (2.9) combining 7, 8, and 13 TeV data

→ Higgs boson couplings are not flavor universal

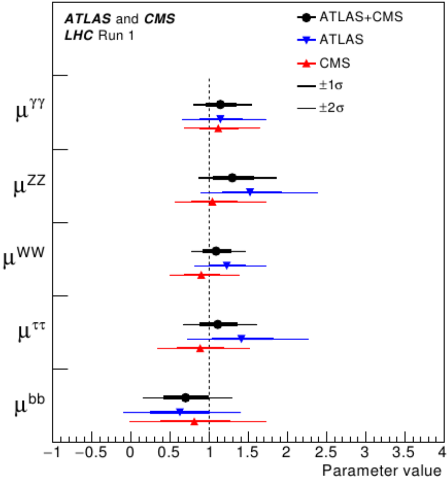




Combining results from the different decay channels

How does it decay?

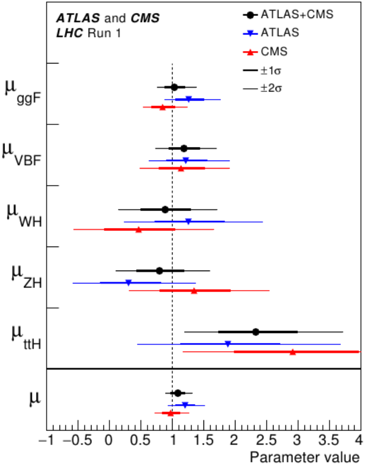
- Measured from the different decay channels, assuming SM production
- $H \to ZZ^*$, $H \to \gamma\gamma$ and $H \to WW^*$ are the most sensitive
- $H \to \tau\tau$ observed with 5.5 σ significance (5.0 σ expected)
- News from Run2: evidence for $H \to b\bar{b}$: 3.5 σ (3.0 σ expected) from ATLAS and 3.3 σ (2.8 σ expected) from CMS



How is it produced?

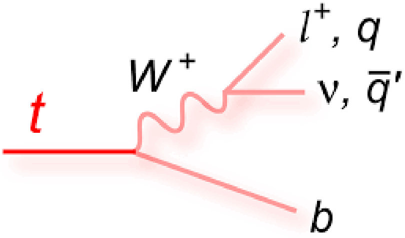
- Measured from the different decay channels, assuming SM decays
- Significant observation of VBF production

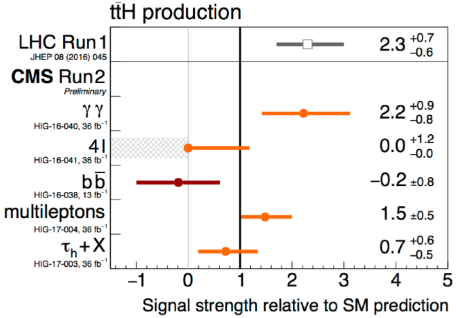
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0



$t\bar{t}H$

- Direct access to Higgs–top coupling
- Complex final states due to large multiplicity of the final state
- $H \to b\bar{b}$: $t\bar{t}b\bar{b}$ production about 30 times larger than signal and with large theoretical uncertainties
- $H \to WW^*, ZZ^*, \tau\tau$: large backgrounds, including from misidentified leptons
- $H \to ZZ^*, \gamma\gamma$: quite clean, but very few events





How does it couple to other particles?

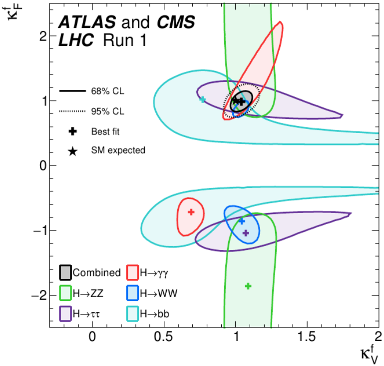
- LO-inspired coupling scale factors κ_j:

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$+ \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu}\right) H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

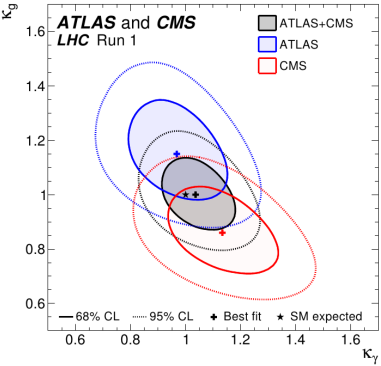
- κ_j defined such that $\kappa_j = 1$ for SM (including higher-order corrections)
- Effective coupling scale factors κ_γ and κ_g treated as function of more fundamental scale factors κ_t, κ_b, κ_W, ... for some tests

How does it couple to other particles?

Introduce scale factors κ_i in the coupling to SM particles and measure the size of the scale factors from data



Scaling of couplings to vector bosons and fermions

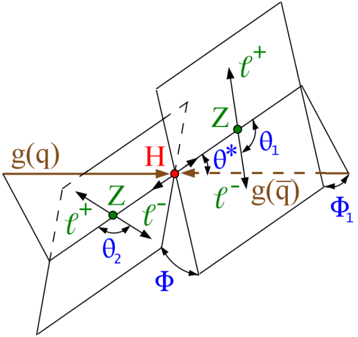


Effective scaling of couplings to gluons and photons

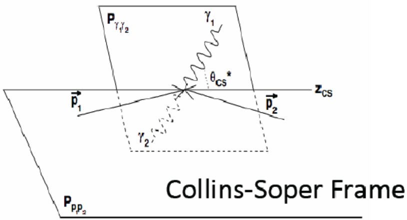
Spin and CP studies

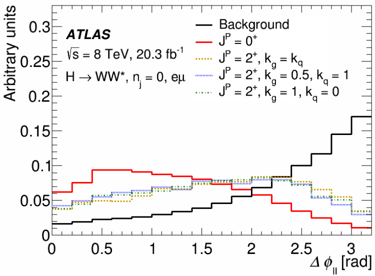
Spin and CP tests

- Observation of $H \to \gamma\gamma \Rightarrow J \neq 1$ (Landau-Yang theorem)
- Observation of $H \to WW^*/ZZ^*$ disfavors the CP-odd hypothesis (can occur through loops)



Spin and CP tests use angular and kinematic distributions in bosonic decays

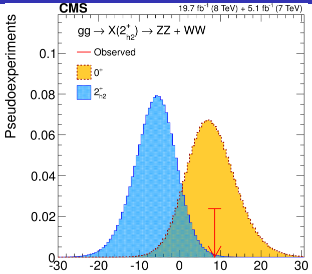




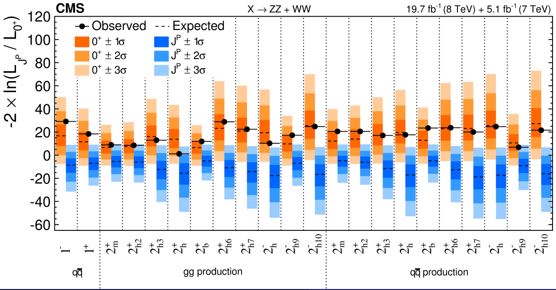
Spin and CP tests: Fixed hypotheses

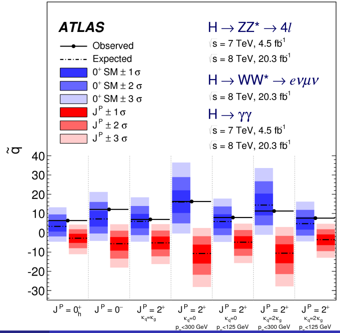
Combining information from $H \to ZZ^*$, $H \to WW^*$ (and $H \to \gamma\gamma$ in ATLAS)

- Testing alternative spin and CP hypotheses against SM 0^+
- Spin 2: various models tested



Alternative tested $0^{\pm}$, $1^{\pm}$ and $2^{\pm}$ typically excluded at $>$99% CL





Spin and CP tests: CP mixing ATLAS

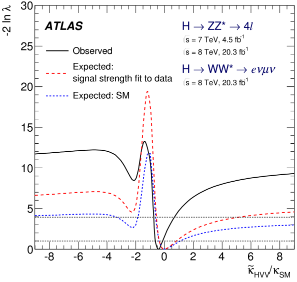
SM 0^+ and BSM $0^\pm$ Lagrangrian:

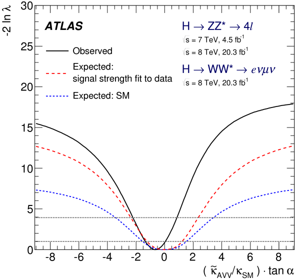
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+\tilde{W}^{-\mu\nu}\right]\Big\}X_0$$

- Admixture of BSM 0^+ and BSM 0^- tested separately
- Combination under the assumption of same admixture in $H \to ZZ^*$ and $H \to WW^*$

Coupling ratio	Best-fit value	95% CL Exclusion Regions	
Combined	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{\rm SM}$	-0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{\rm SM}) \cdot \tan\alpha$	-0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

No significant admixture of non-SM CP states





Spin and CP tests: CP mixing CMS

Anomalous couplings (compatible with Lorentz and gauge invariance)

$$A(\mathrm{HVV}) \sim \left[a_1^{VV} + \frac{\kappa_1^{VV} q_{V1}^2 + \kappa_2^{VV} q_{V2}^2}{\left(\Lambda_1^{VV}\right)^2} \right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

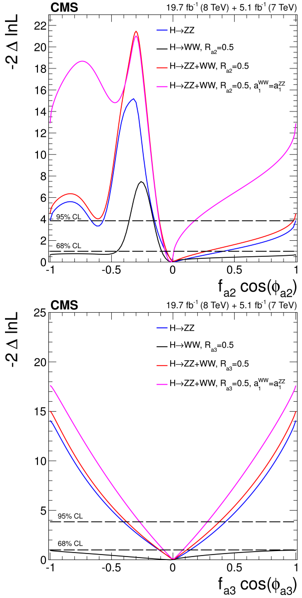
Tested parameters

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1} / \left(\Lambda_1\right)^4 + \ldots}$$

$$\phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

Combination of $H \to ZZ^*$ and $H \to WW^*$

$$r_{ai} = \frac{a_i^{WW} / a_1^{WW}}{a_i / a_1}, \text{ or } R_{ai} = \frac{r_{ai}|r_{ai}|}{1 + r_{ai}^2}$$

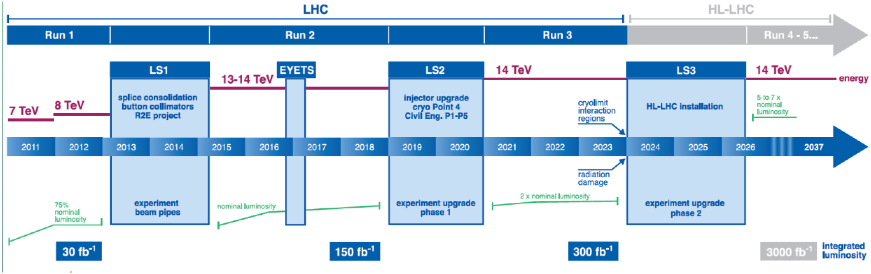


Summary

- After the discovery of a Higgs-like boson in 2012 we are now studying the properties of the new particle in detail
- Within the present uncertainties, everything looks consistent with the SM Higgs boson
  - ⋆ All models for tested models for $J = 2$ excluded
  - ⋆ Limits on possible admixture of odd parity contributions
  - ⋆ Production and decays consistent with SM within uncertainties
- Rare decays ($H \to \mu\mu$, $H \to Z\gamma$, ...) will get into reach with larger datasets
- We have only taken a small fraction (few %) of the total expected LHC dataset $\to$ measurements will become much more precise over the next (many) years
- So far no sign of other Higgs bosons (heavier, lighter, CP-odd, charged, ...) despite active search program

Extras

Future LHC upgrades and data taking



- Only a small fraction of the planned data has been taken so far
- Shutdowns for upgrade of accelerators and detectors scheduled
- High luminosity (HL) LHC (after LS3) will require substantial upgrades to LHC and the detectors

Setting exclusion limits (I)

"A signal with up to which signal scaling factor μ could hide in the data"?

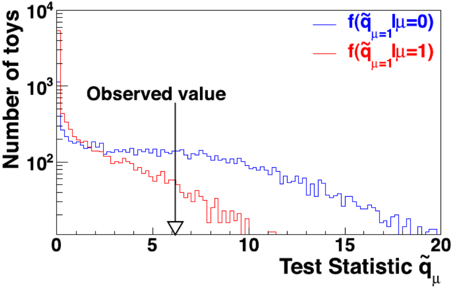
Profile likelihood ratio

$$\tilde{q}_\mu = -2\ln\frac{L(\text{data}|\mu,\hat{\hat{\theta}}_\mu)}{L(\text{data}|\hat{\mu},\hat{\theta})}$$

- $\hat{\hat{\theta}}_\mu$ conditional maximum given μ
- $\hat{\mu},\hat{\theta}$ corresponding to global maximum of the likelihood
- Large $\tilde{q}_\mu$ correspond to disagreement between data and hypothesis μ

Setting exclusion limits (II)

- Find observed $\tilde{q}_{\mu}^{\mathrm{obs}}$ for a given μ
- From pseudo MC construct PDFs $f(\tilde{q}_{\mu}|\mu, \hat{\theta}_{\mu,\mathrm{obs}})$ and $f(\tilde{q}_{\mu}|0, \hat{\theta}_{0,\mathrm{obs}})$ of $\tilde{q}_{\mu}$



- Determine p-value for hypothesis μ and 0:
  $p_{\mu} = \int_{\tilde{q}_{\mu,\mathrm{obs}}}^{\infty} f(\tilde{q}_{\mu}|\mu, \hat{\theta}_{\mu,\mathrm{obs}}) \mathrm{d}\tilde{q}_{\mu}$
  $1 - p_b = \int_{\tilde{q}_{\mu,\mathrm{obs}}}^{\infty} f(\tilde{q}_{\mu}|0, \hat{\theta}_{0,\mathrm{obs}}) \mathrm{d}\tilde{q}_{\mu}$
- From p_{μ} and p_b compute $\mathrm{CL}_s(\mu)$ as $\mathrm{CL}_s(\mu) = p_{\mu}/(1 - p_b)$
- Find the 95% upper bound $\mu = \mu_{95,\mathrm{obs}}$ by finding the μ for which $\mathrm{CL}_s(\mu) = 0.05$
  - ⋆ Dividing by $1 - p_b$ is to be conservative and to avoid that downward fluctuations of the background contribute to the p-value

Reading Exclusion Plots

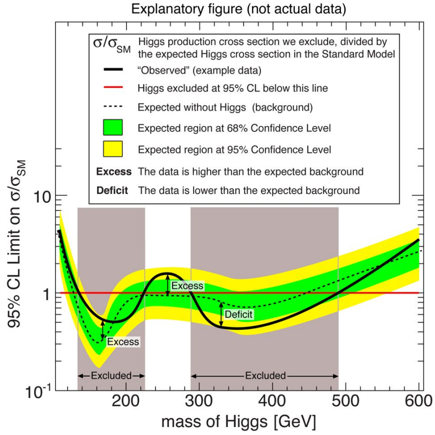


Figure A

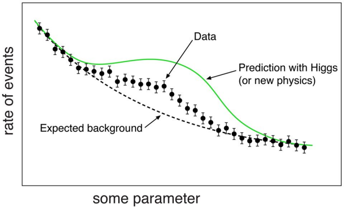


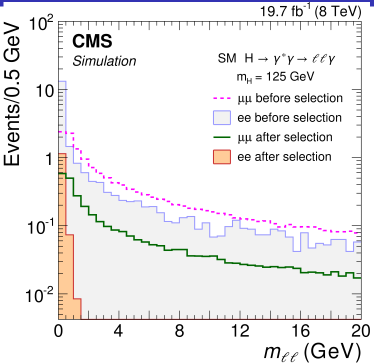
Figure B

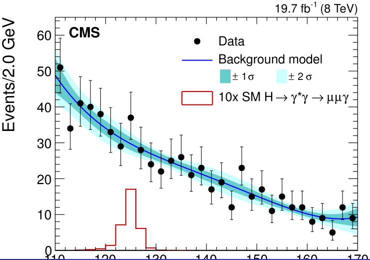
"Given the background expectation (and the observed data), how many times the SM expectation can we rule out?"

Rare decays: $H \to \gamma^*\gamma \to \ell\ell\gamma$

[arXiv:1507.03031 [hep-ex]]

- Non-trivial angular distributions and forward-backward asymmetry in 3-body decay $H \to \ell\ell\gamma$ allow for interesting property measurements
- Signature: 2 opposite-sign same flavor leptons ($m_{\mu\mu(ee)}$ <20 (1.5) GeV, veto J/ψ and Υ), 1 isolated photon ($p_T^\gamma > 0.3 m_{\ell\ell\gamma}$)
  - ⋆ $m_{\ell\ell}$ and p_T^γ cuts suppress $H \to Z\gamma$
  - ⋆ Select $m_{\mu\mu}$ close to J/ψ mass for $H \to J/\psi\gamma$, p_T^γ >40 GeV





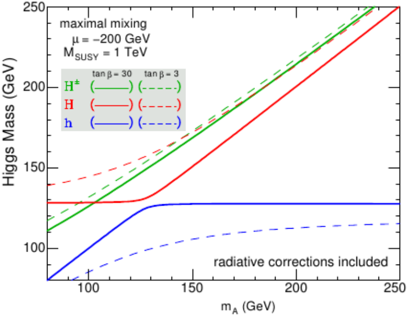
BR($H \to \gamma^*\gamma \to \ell\ell\gamma$) <7.7×SM @ 95% CL (exp. 6.4×SM)

BR($H \to J/\psi\gamma$) <1.5×10^{-3} @ 95% CL

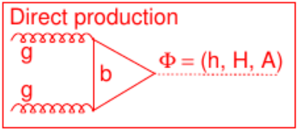
Higgs sector in the MSSM

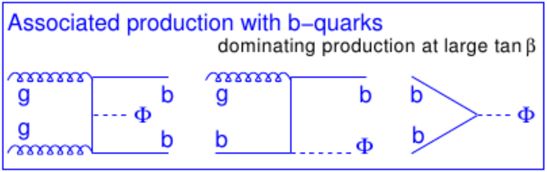
Need (at least) 2 complex doublets ($\phi_{u/d}$, giving mass terms for up- and down-type quarks)
$\rightarrow$ 5 physical Higgs bosons: h, H, A, $H^{\pm}$

Can be described by two free parameters: m_A and $\tan\beta = v_u/v_d$ ($v_{u/d}$ vaccum expectation value of $\phi_{u/d}$)



Additional production modes might become important





Supersymmetry solves a number of "problems"

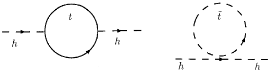
Dark matter

Natural dark matter candidate if LSP is neutral

- Weak interaction strength and TeV-scale mass would give the correct dark matter abundance

Hierarchy/finetuning problem

Higher-order corrections to Higgs mass m_H quadratically divergent: $m_H^2 = m_0^2 - C m_f^2 \Lambda^2 + \ldots$
(Λ high cut-off scale, where new physics cuts off loop integration)



$\Rightarrow m_H$ sensitive to highest scale, need large cancellations (unless new physics at a rather low scale)

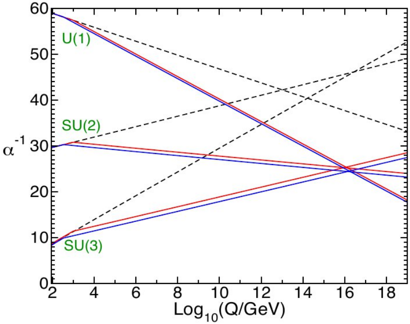
- Supersymmetric correction $+C m_{\tilde{f}}^2 \Lambda^2$ cancels divergence (term-by-term) as long as $m_{\tilde{f}} \neq m_f$ (still ok for $m_{\tilde{f}} \approx \mathcal{O}(1\,\mathrm{TeV})$)

Supersymmetry solves a number of “problems”

Gauge unification

Allows for unification of coupling constants (in principle)

- Intriguing, but not necessarily easy to realize in a working model



SUSY breaking

Many possibilities to break supersymmetry (softly, i.e. without reintroducing hierarchy problems), e.g. through gravitational interactions (at high scales) or gauge interactions with a non-supersymmetric "hidden sector"

Free parameters in the often-used mSUGRA model

m_0	common boson mass (at GUT scale)
$m_{1/2}$	common fermion mass (at GUT scale)
$\tan\beta$	v_u/v_d
A_0	trilinear scalar coupling (at GUT scale)
sgnμ	sign of Higgs potential parameter