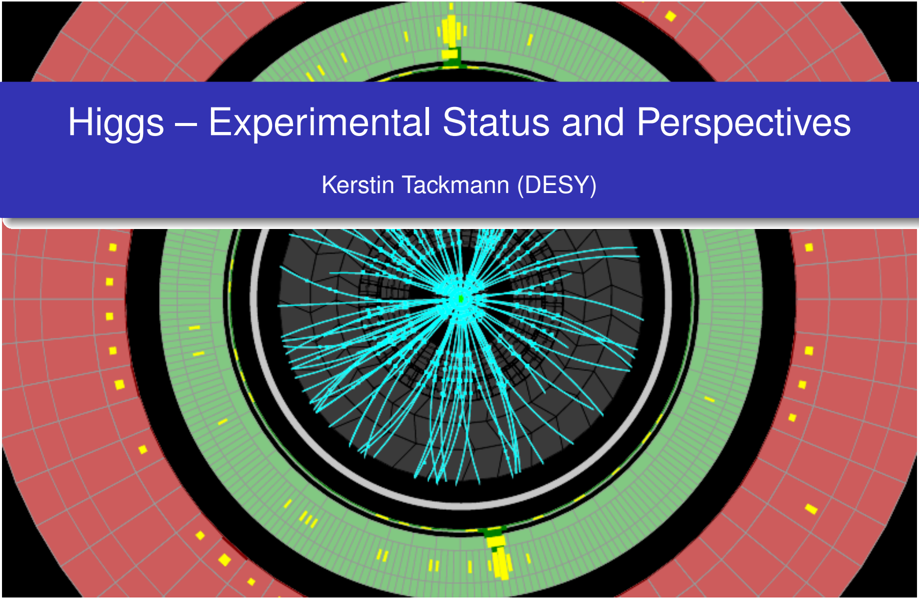
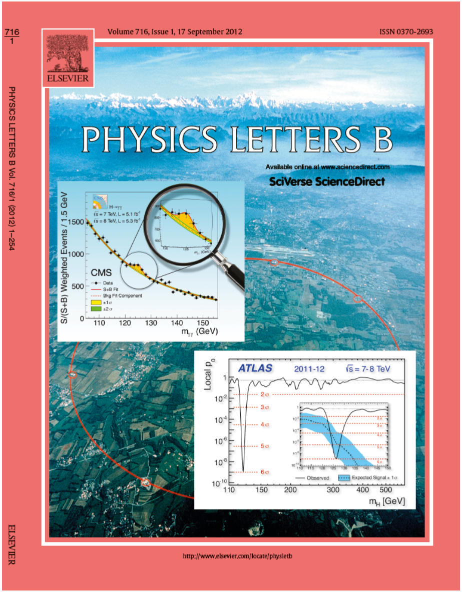
Higgs – Experimental Status and Perspectives

Kerstin Tackmann (DESY)



6th Annual Workshop of the Helmholtz Alliance “Physics at the Terascale”

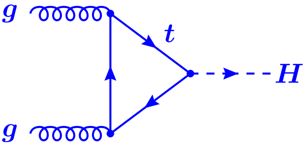
The News of this Summer

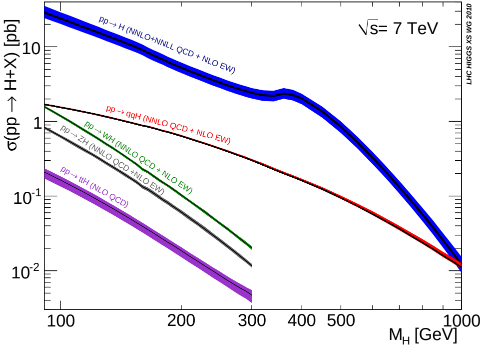


- Discovery of a new particle consistent with SM Higgs by ATLAS and CMS
- Overview of ATLAS and CMS results

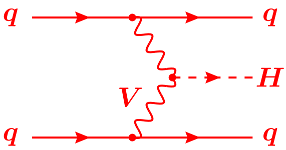
Higgs Boson Production at the LHC

Dominant process: Gluon fusion

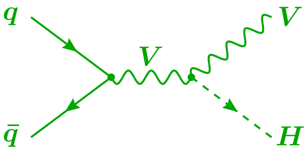




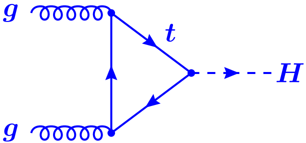
Vector boson fusion (VBF)



Associated production



Higgs Boson Production Processes

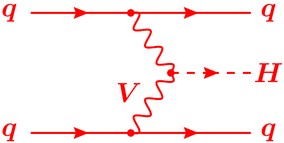


Gluon fusion

Dominant process at Tevatron and LHC

Higgs dominantly produced with small p_T

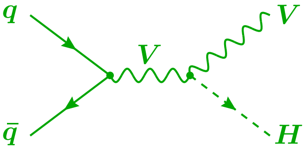
NLO correction increase LO cross section by $60 - 90\%$, NNLO corrections add another 30%



Vector boson fusion (VBF)

W mode dominates

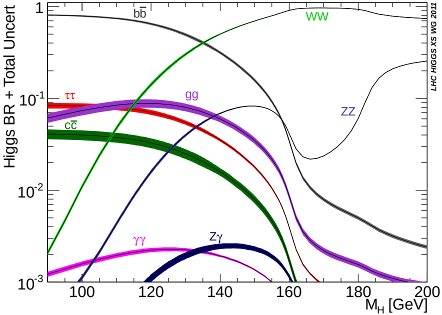
Two forward jets with large $\Delta\eta$



Associated production

Higgs at larger p_T recoiling against W or Z (reconstructed in lepton decay channels)

Higgs Boson Decays



$H \rightarrow \gamma\gamma$

Rare decay, but distinct signal

$H \rightarrow \tau\tau$

Enhanced in MSSM, also contributes to SM search

$H \rightarrow b\bar{b}$

Main search channel at LEP and Tevatron, important to study Higgs properties

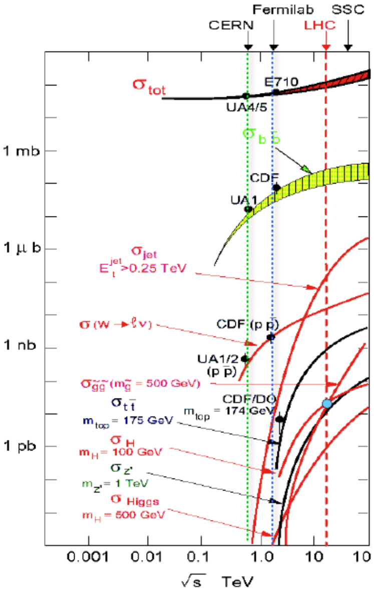
$H \rightarrow WW$

Large signal yield

$H \rightarrow ZZ$

Very clean signal if both $Z \rightarrow \ell\ell$

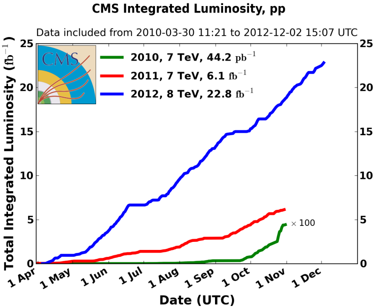
Production Cross Sections at Hadron Colliders

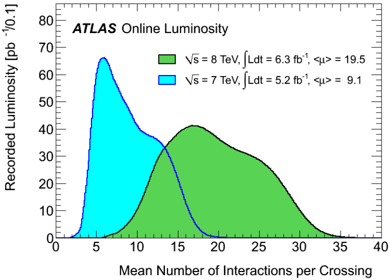


Process	Cross section (nb) at 14 TeV CM energy	Production rates (Hz) at $L=10^{34}$ cm^{-2}s^{-2}
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	150
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H (120 GeV)	0.04	0.4
H (180 GeV)	0.02	0.2

Many orders of magnitude between Higgs/New Physics and QCD backgrounds

Luminosity and Running Conditions





- ATLAS and CMS each collected $\sim 5\,\mathrm{fb}^{-1}$ @ $7\,\mathrm{TeV}$ and $\sim 20\,\mathrm{fb}^{-1}$ @ $8\,\mathrm{TeV}$
- Results shown here based on full $7\,\mathrm{TeV}$ data and up to $13\,\mathrm{fb}^{-1}$ of $8\,\mathrm{TeV}$ data
- Taken with $50\,\mathrm{ns}$ bunch spacing and up to almost 35 interactions/bunch crossing
- Large rise in instantaneous luminosity from $2 \times 10^{32} \to 7 \times 10^{33}$
- Large luminosity comes at the cost of high pileup ($\to$ many proton-proton collisions overlaid in the detector)

$H \to \gamma\gamma$: The Rare-But-Clean

Signature

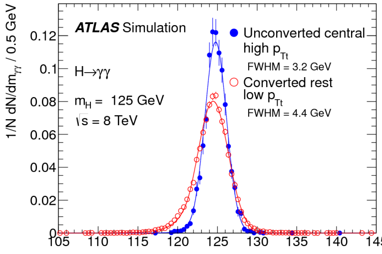
- 2 energetic isolated photons

- Small branching ratio, but good signal yield
  - ⋆ ATLAS: Expect ~ 190 signal events after all selections for $m_H = 125\,\text{GeV}$ in current data

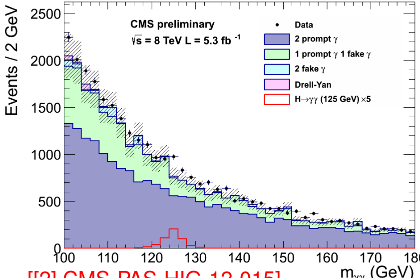
- Good mass resolution $\to$ clear peak over smooth background

- Main backgrounds
  - ⋆ irreducible ($\gamma\gamma$) ($30\,\text{pb}$)
  - ⋆ reducible (γjet) ($200\,\text{pb}$)
  - ⋆ reducible (jetjet) ($500\,\mu\text{b}$)

$\to$ Need powerful γ/jet separation ($\mathcal{O}(10^4)$)



[[1] Phys. Lett. B 716 (2012)]



[[2] CMS-PAS-HIG-12-015]

$H \rightarrow \gamma\gamma$: Mass Reconstruction

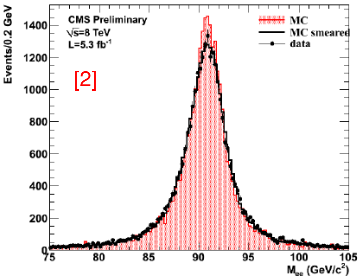
$$m^2_{\gamma\gamma} = 2E_1E_2(1 - \cos\alpha)$$

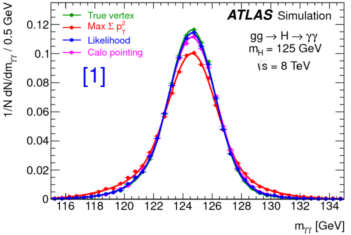
$Z \rightarrow e^+e^-$ used to

- derive energy calibration and resolution corrections
- determine trigger, identification and isolation efficiencies

Photon angle measurement to improve mass resolution

- ATLAS Longitudinal segmentation of calorimeter, conversion vertices, tracking information
- CMS Tracking information, p_T balance between tracks and photons, conversion vertices



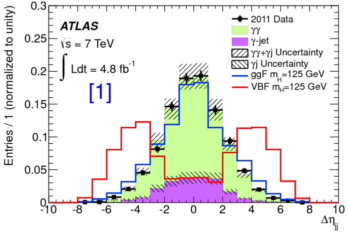


Angular contribution to mass resolution negligible

$H \rightarrow \gamma\gamma$: Event Categories

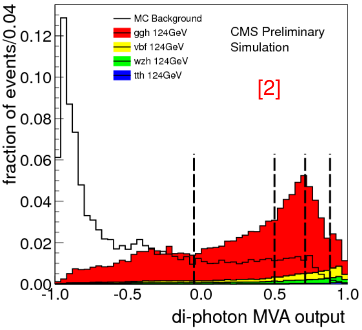
Separating events according to resolution and S/B increases sensitivity

- Separate out events with VBF-like signature: two jets with large angular separation
  - ⋆ Dijet category contains ∼70-80% VBF events and has efficiency of ∼25-30% for VBF events (ATLAS)

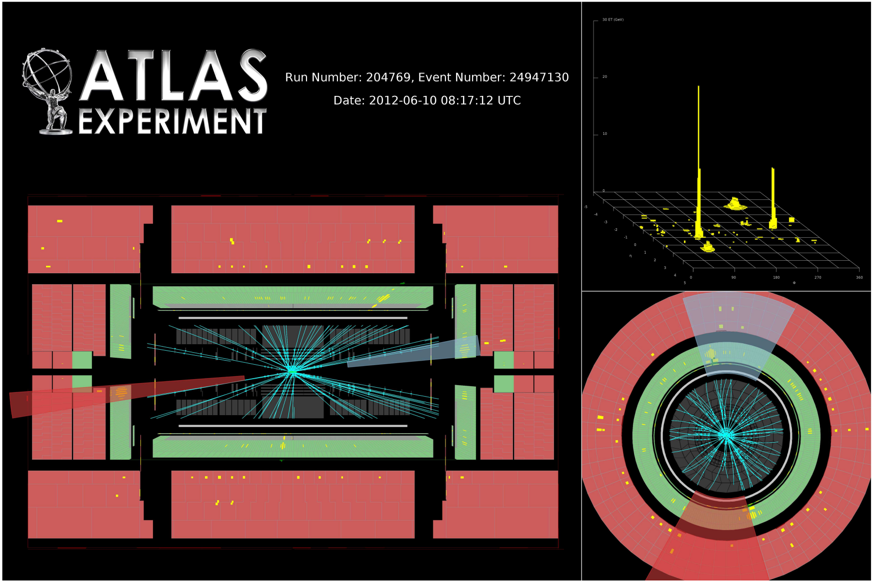


Classify remaining events

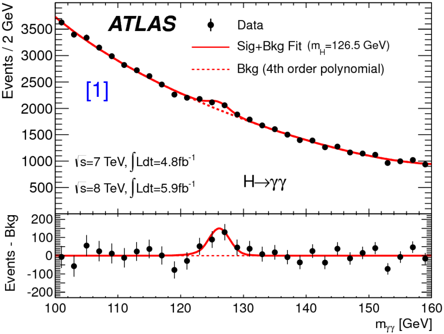
- ATLAS Photon direction, photon conversion status, diphoton p_{Tt}
- CMS Boosted decision tree based on photon momentum and direction, diphoton opening angle, mass resolution, photon identification

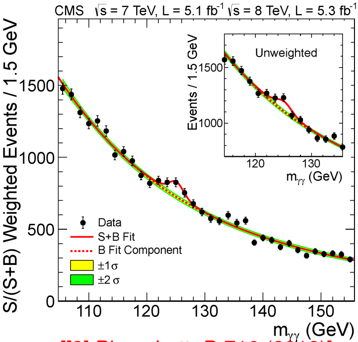


$H \to \gamma\gamma$: 2-Jets Candidate



$H \rightarrow \gamma\gamma$: Mass Spectra



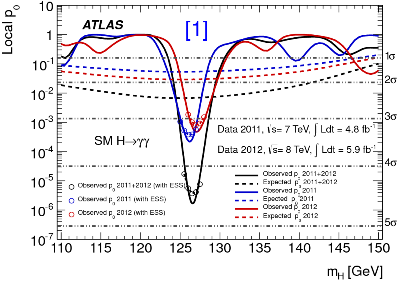


[[3] Phys. Lett. B 716 (2012)]

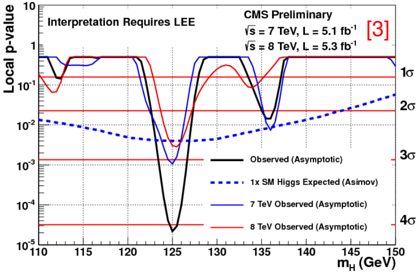
- Choice of background parametrization adjusted per category to limit size of potential biases to $<$20% of fitted signal yield uncertainty
- Chosen parametrizations: polynomials of different order, exponential (ATLAS), exponential of second order polynomial (ATLAS)

$H \rightarrow \gamma\gamma$: Compatibility with Background

ATLAS



CMS



Observed significance 4.5σ
Expected significance 2.4σ
at $126.5\,\mathrm{GeV}$

Observed significance 4.1σ
Expected significance 2.8σ
at $125\,\mathrm{GeV}$

SM Higgs boson excluded on either side of the excess

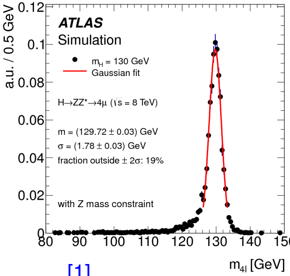
$H \to ZZ \to \ell\ell\ell\ell$: The Golden

Signature

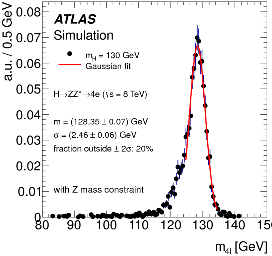
- 2 pairs of oppositely charged, same flavor leptons (down to $5\,\mathrm{GeV}$)
- One or both pairs compatible with $Z \to \ell^+\ell^-$

- Very clean channel, with excellent mass resolution $\sigma_{m_{4\ell}} < 2\,\mathrm{GeV}$ (4μ) to $\sim 2.5\,\mathrm{GeV}$ $(4e)$ (at $130\,\mathrm{GeV}$)

- Important: good lepton (e and μ) reconstruction and identification down to low momenta

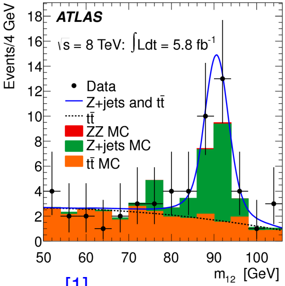


[1]



$\ell\ell + \mu\mu$

- No isolation and impact parameter significance requirement on subleading μ pair
- $Zb\bar{b}$ and $t\bar{t}$ clearly separated, components determined by fit
- Cross check with $e^{\pm}\mu^{\mp}\mu^{\pm}\mu^{\mp}$ (for $t\bar{t}$)

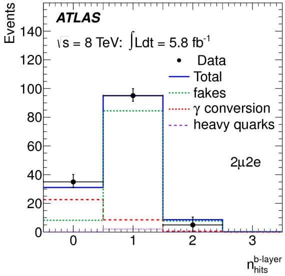


[1]

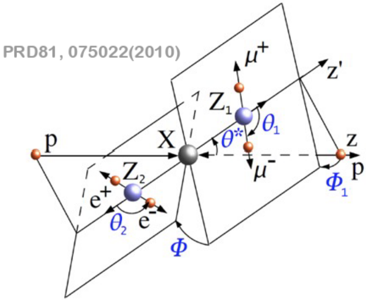
$\ell\ell + ee$ Main contribution: Z+jets (fakes, γ conversions, heavy flavor)

- Transition radiation
- Hits in innermost Pixel layer
- Energy fraction in first calo layer
- Containment of shower in ϕ

$\rightarrow$ Extract background from control regions with relaxed identification on subleading e pair and extrapolate to signal region



$H \to ZZ \to \ell\ell\ell\ell$: Angular Analysis @ CMS

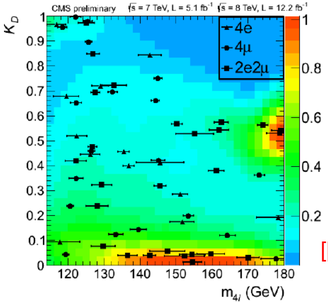


Spin 0 particle implies certain decay angle distributions

- Kinematics fully described by 2 invariant masses and 5 angles
- Kinematic discriminant

$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

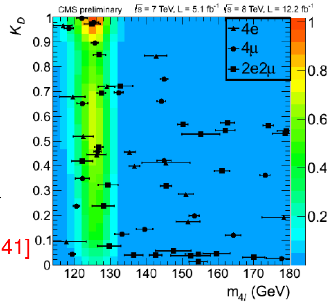
$$\vec{\Omega} = \{\theta^*, \Phi_1, \theta_1, \theta_2, \Phi\}$$



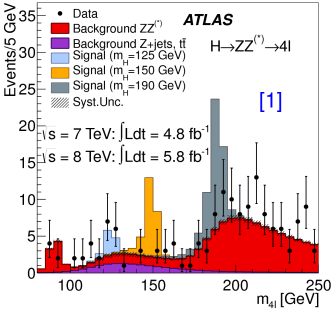
← data with background

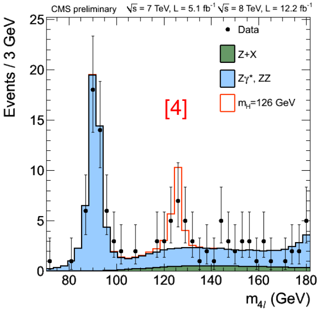
data with signal →

[[4] CMS-PAS-HIG-12-041]



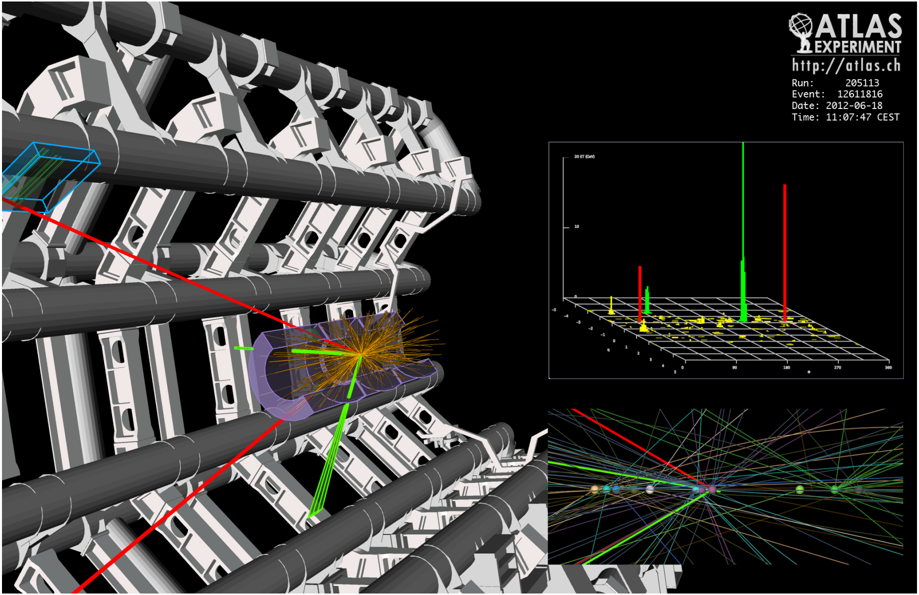
$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$: Spectra and Event Counts



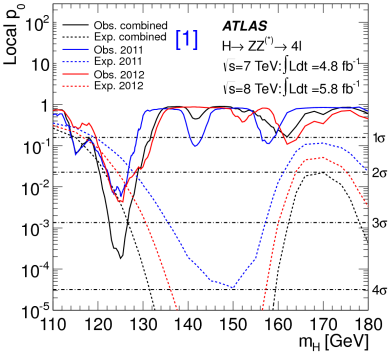


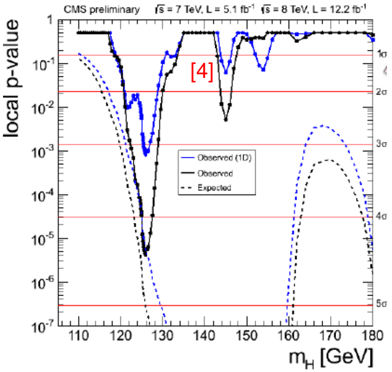
Expected signal/background and observed events in $m_H = 125 \pm 5$ GeV				
	Signal	$ZZ^{(*)}$	Z+jets	Observed
4μ	2.1 ± 0.3	1.12 ± 0.05	0.13 ± 0.04	6
2e2μ/2μ2e	2.3 ± 0.3	0.80 ± 0.05	1.3 ± 0.2	5
4e	0.9 ± 0.1	0.44 ± 0.04	1.1 ± 0.2	2
Total	5.3 ± 0.8	2.4 ± 0.1	2.5 ± 0.4	13

$H \to ZZ \to \ell\ell\ell\ell$ Candidate



$H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$: Compatibility with Bkgd





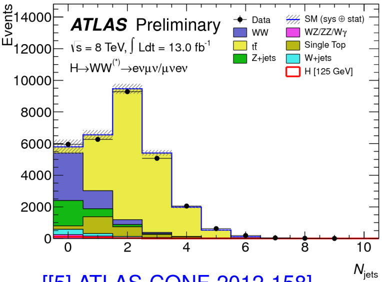
Observed local significance at $\mathbf{125\ GeV: 3.6\sigma}$

Exptected local significance at $\mathbf{125\ GeV: 2.7\sigma}$

Observed local significance at $\mathbf{126\ GeV: 4.5\sigma}$

$H \to WW \to \ell\nu\ell\nu$: The Abundant

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



[[5] ATLAS-CONF-2012-158]

Signature

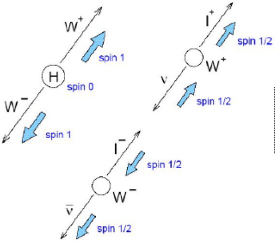
- 2 oppositely charged leptons
- Large missing E_T

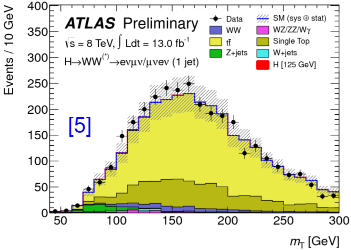
- Challenge: poor mass resolution due to 2ν
  - $\longrightarrow$ Transverse mass $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\text{miss}}|^2}$
    - ⋆ ATLAS Fit to m_T
    - ⋆ CMS 2d shape in m_T and $m_{\ell\ell}$ for 0, 1 jets, OF leptons and counting in m_T otherwise
- 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

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

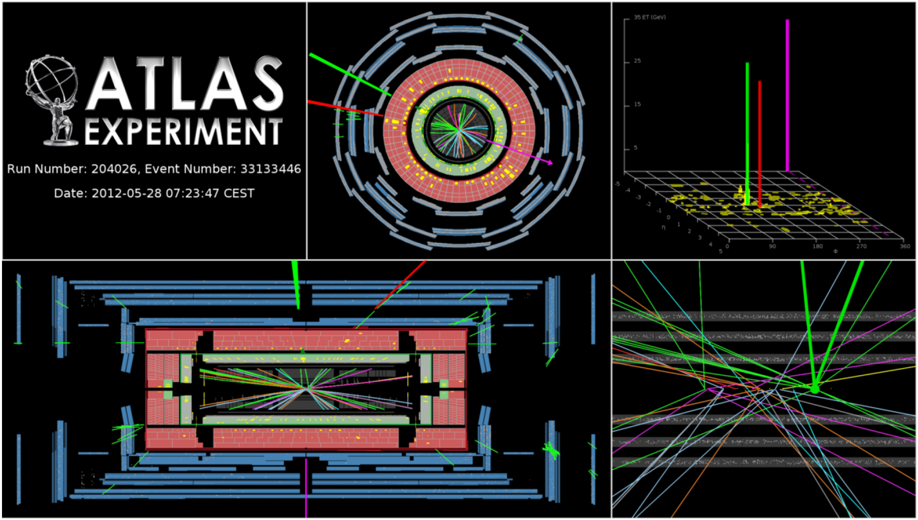
Control of large backgrounds crucial: suppressed by selection and measured in data control regions

- SM WW suppressed by topological cuts ($m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T). For low m_H constrained from signal free region with modified topological selection.
- W+jets suppressed by lepton selection (isolated, opposite sign). Estimated from region enriched in fake leptons.
- Drell-Yan suppressed by large E_T^{miss}, Z veto. Estimated from Z peak.
- top suppressed by b-jet veto and controlled by categorization into jet bins. Estimated from b-tagged events.

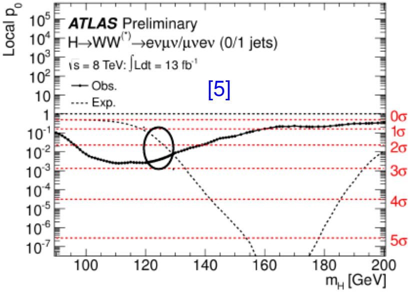




$WW \to e\nu\mu\nu$ Candidate @ ATLAS

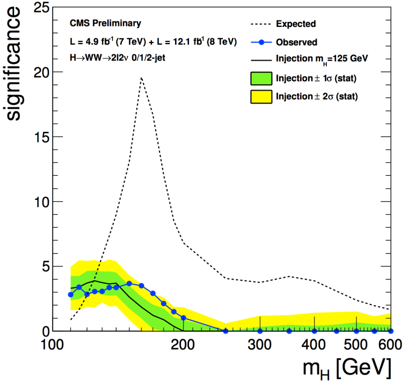


$H \to WW \to \ell\nu\ell\nu$: Results



ATLAS ($8\,\mathrm{TeV}$ only)

2.6σ (1.9σ) obs (exp) significance



[[6] CMS-PAS-HIG-12-042]

CMS

3.1σ (4.1σ) obs (exp) significance

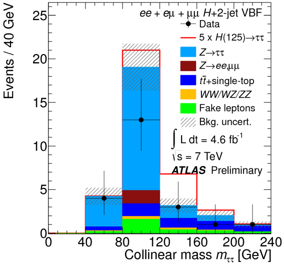
Signature

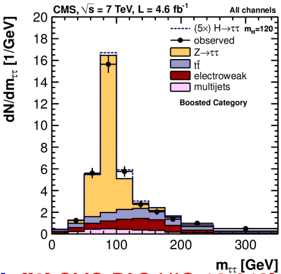
- Electron and/or muon
- Hadronically reconstructed τ_{had}
- Missing $\not{E}_T$

Events classified by

- τ decay mode (2 leptonic, leptonic+hadronic, 2 hadronic τ)
- Jet content (0, 1, 2 jets) and kinematics

Mass reconstruction possible due to collinearity of τ decay products, resolution $\mathcal{O}(15-20\%)$





[[7] ATLAS-CONF-2012-160] [[8] CMS-PAS-HIG-12-043]

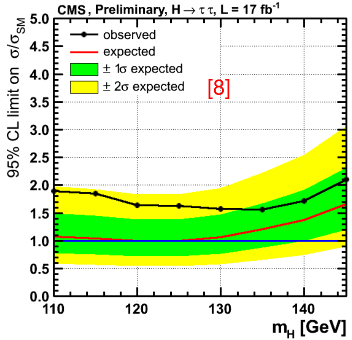
Include categories targetting

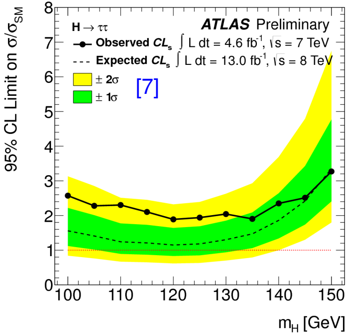
- VBF production
- VH production
- Good mass resolution
  - ⋆ Boosted objects

$H \to \tau\tau$: Backgrounds and Results

Main backgrounds

- $Z \to \tau\tau$ shape from embedding MC τ into data $Z \to \mu\mu$ and using MC
- $Z \to \ell\ell$ (+ jets) from corrected MC
- QCD and W+jets same-sign events and loosened selection





CMS Observed limit 1.66×SM at $125\ \mathrm{GeV}$ (expected limit 1.05× SM)

ATLAS Observed limit 1.9×SM at $125\ \mathrm{GeV}$ (expected limit 1.1× SM)

$H \to b\bar{b}$: The Unexpected?

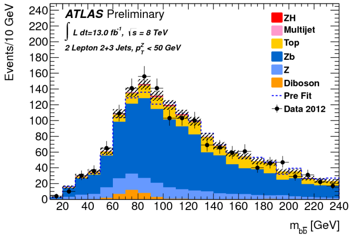
- $H \to b\bar{b}$ drowned in QCD backgrounds
- Feasible for Higgs produced in association with $W \to \ell\nu$, $Z \to \ell\ell$, $Z \to \nu\nu$
- Bins in $p_T^{W,Z}$ to exploit boosted topology

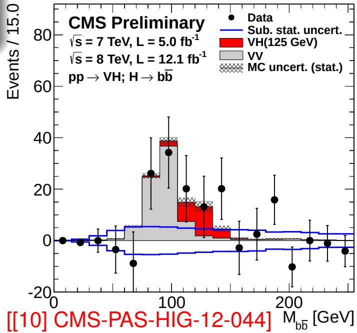
Signature

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

- Shape analysis of $m_{b\bar{b}}$
  CMS Boosted decision tree (20% improvement over cut-based analysis)
- Main backgrounds estimated from data (W/Z+jets, WW, $t\bar{t}$)
- Use SM WZ and ZZ with $Z \to b\bar{b}$ to validate analysis

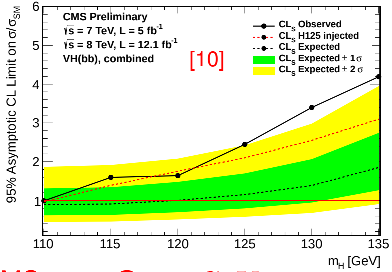
[[9] ATLAS-CONF-2012-161]



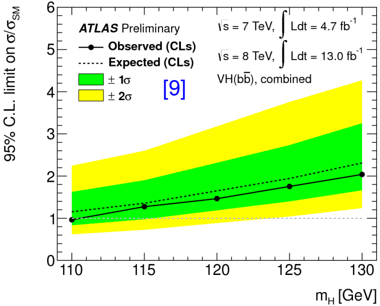


[[10] CMS-PAS-HIG-12-044]

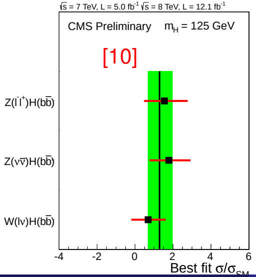
$H \rightarrow b\bar{b}$: Results



CMS 2.2σ @ $125\ \mathrm{GeV}$
Expected 2.1σ



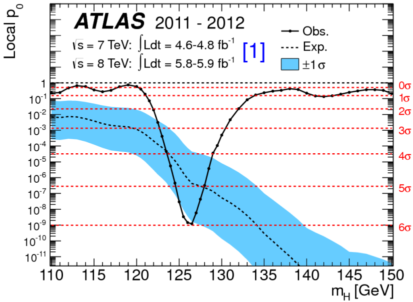
ATLAS $1.8\times$SM @ $125\ \mathrm{GeV}$
Expected $1.9\times$ SM



- Signal strength in subchannels as expected
- Searches for $H \rightarrow b\bar{b}$ produced in association with top quarks, current sensitivity about $4-5\times$ SM at $125\ \mathrm{GeV}$

Combination: Compatibility with Background

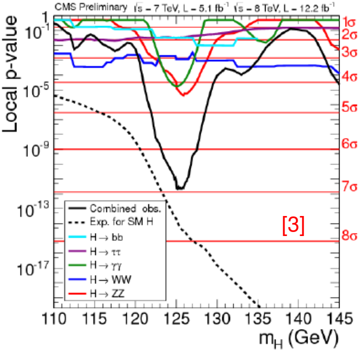
ATLAS



Observed local significance at $\mathbf{126.5\,GeV:\ 5.9\sigma}$

Exptected local significance at $\mathbf{126.5\,GeV:\ 4.9\sigma}$

CMS



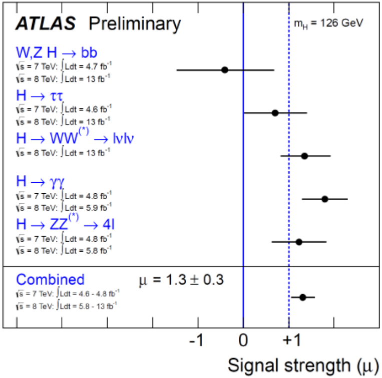
Observed local significance at $\mathbf{\sim 126\,GeV:\ 6.9\sigma}$

Exptected local significance at $\mathbf{\sim 126\,GeV:\ 7.8\sigma}$

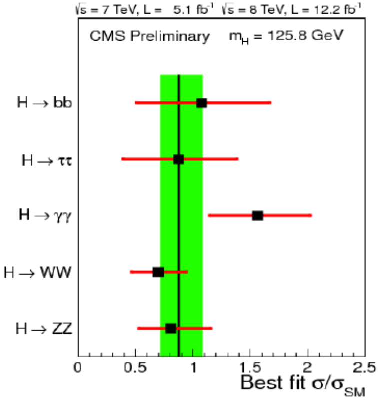
Now that we saw something, does it look like a Higgs?

Looking at the Signal Strength

Signal strength in the different decay channels



[[11] ATLAS-CONF-2012-162]



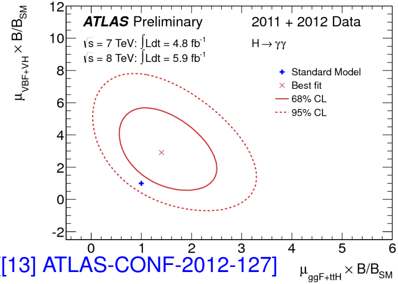
[[12] CMS-PAS-HIG-12-045]

$H \to ZZ$, $H \to \gamma\gamma$ and $H \to WW$ are the most sensitive

In agreement with SM within present uncertainties

Looking at Production Modes

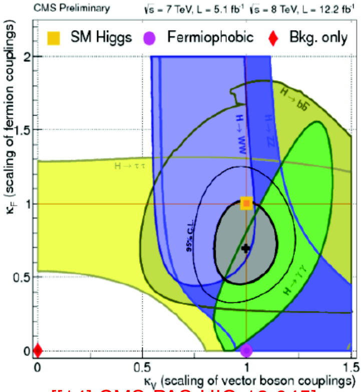
- Sensitivity to production modes in $H \to \gamma\gamma$ from separation into categories
- $gg \to H$ and $t\bar{t}H$ scale with $t\bar{t}H$ coupling
- VBF and VH scale with WWH/ZZH coupling



[[13] ATLAS-CONF-2012-127]

Consistent with SM within $\sim 1.5\sigma$

Separate Higgs couplings into vectorial and fermionic couplings

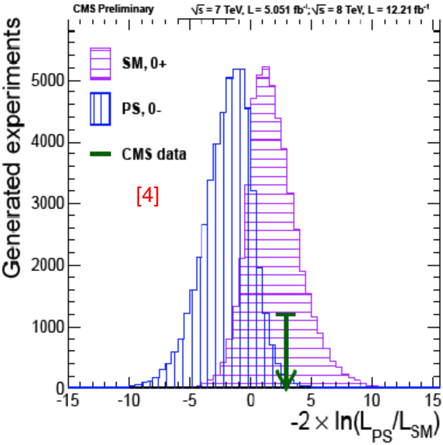


[[14] CMS-PAS-HIG-12-045]

Consistent with SM

Looking at the Spin/CP

- Angular distributions in $H \rightarrow ZZ \rightarrow 4\ell$ sensitive to spin and CP
- Compatibility with certain hypothesis (here 0^+ vs 0^-) assessed with likelihood tests
- Separation between hypotheses $\sim 2\sigma$
- Data consistent with 0^+ (0.6σ)
- Not very good consistency with 0^- (2.5σ)



- Could also test for consistency with 2^+
- Angular distributions in $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow 2\ell 2\nu$ can also be used

Conclusions

- Both ATLAS and CMS observe a narrow resonance around $125 - 126\,\mathrm{GeV}$ in the SM Higgs searches
- Main contributions from high-resolution channels $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ and from $H \to WW \to \ell\nu\ell\nu$
- Fermionic decays $H \to b\bar{b}$ and $H \to \tau\tau$ consistent with SM Higgs, but also with background fluctuation.
- (So far) observations are consistent with SM Higgs boson
- Dedicated searches in high-mass region ($H \to ZZ \to \ell\ell\nu\nu$, $H \to ZZ \to \ell\ell q\bar{q}$, $H \to WW \to \ell\nu q\bar{q}$) do not see any excess and exclude SM Higgs between $273\,\mathrm{GeV}$ and $600\,\mathrm{GeV}$

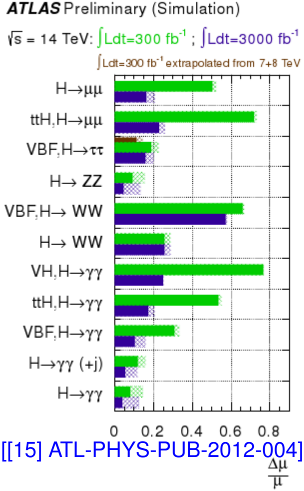
Outlook and Perspectives

Is this a (SM) Higgs?

- Better determination of couplings to different vectors and fermions
  - ⋆ For mass of $\sim \mathbf{125\,GeV}$, decays to both gauge bosons and heavy leptons accessible!
- Determine spin and CP
  - ⋆ Spin 1 already excluded from observation of $\gamma\gamma$ decay
  - ⋆ Possible admixture between CP even and odd

→ First measurements with the $\mathbf{7-8\,TeV}$ data, to be followed up with the $\mathbf{13-14\,TeV}$ data starting from 2015

- Look for rare decay modes ($\boldsymbol{H\to Z\gamma}$, $\boldsymbol{H\to\mu\mu}$)
- Measurement of trilinear Higgs coupling will need high luminosity after LHC lumi upgrade ($\mathbf{3\,ab^{-1}}$) or ILC



[[15] ATL-PHYS-PUB-2012-004]

	$300\,\mathrm{fb}^{-1}$	$3000\,\mathrm{fb}^{-1}$
κ_V	3.0% (5.6%)	1.9% (4.5%)
κ_F	8.9% (10%)	3.6% (5.9%)