Standard Model Higgs Search at CMS

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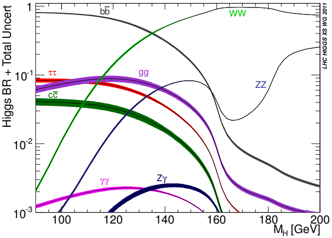
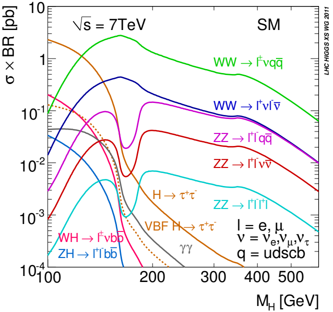
Les Rencontres de Physique de la Valle d'Aoste

Higgs Production and Decay at the LHC



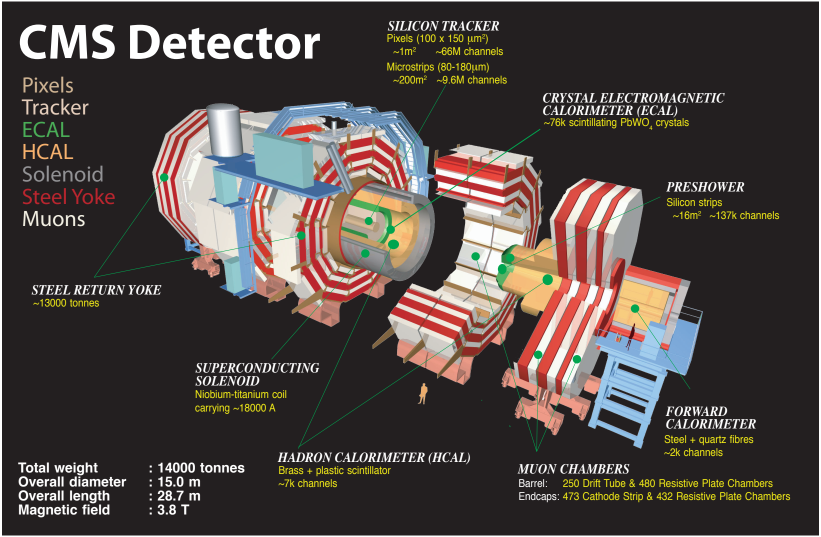
(a) BR



(b) $\sigma \times$BR

- Direct Searches before LHC: 95% exclusion for $m_h < 114.4$ GeV (LEP), and $156 < m_h < 176$ GeV (Tevatron)
- Indirect constraints from Electroweak data: $m_h < 169$ GeV (Gfitter)
- Low mass region is the most interesting for a Standard Model Higgs

The CMS Detector



Higgs Searches at CMS

- Full range of Higgs decay channels have been analyzed with full 2011 dataset (4.6-4.8 fb^{-1}) and submitted for publication

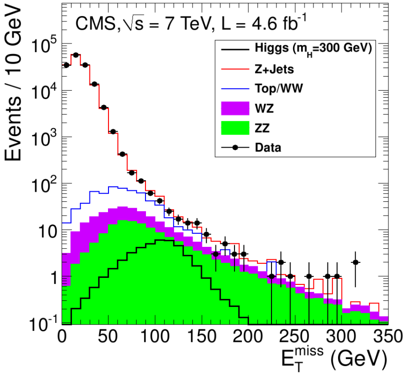
Channel	Mass Range (GeV)	Mass Resolution	Ref
$H \to \gamma\gamma$	110-150	1-3%	arXiv:1202.1487
$H \to \tau\tau$	110-145	20%	arXiv:1202.4083
$H \to b\bar{b}$	110-135	10%	arXiv:1202.4195
$H \to WW \to 2\ell 2\nu$	110-600	20%	arXiv:1202.1489
$H \to ZZ \to 4\ell$	110-600	1-2%	arXiv:1202.1997
$H \to ZZ \to 2\ell 2\nu$	250-600,	7%	arXiv:1202.3478
$H \to ZZ \to 2\ell 2q$	130-164, 200-600	3%	arXiv:1202.1416
$H \to ZZ \to 2\ell 2\tau$	190-600	10-15%	arXiv:1202.1487
Combination	110-600	1-20%	arXiv:1202.3617

- Search for a narrow mass peak in $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels, search for a broader excess in the other channels, due to the presence of jets or neutrinos in the final state

$H \to ZZ \to 2\ell 2\nu$

Event Selection:

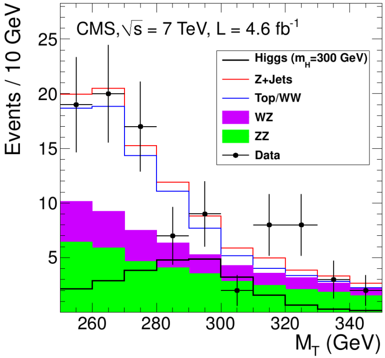
- Two opposite-charge, same-flavour leptons with $p_T > 20$ GeV consistent with Z mass
- $p_T^{\ell\ell} > 55$ GeV, $\not{E}_T > 70/80$ GeV, Veto events where $\not{E}_T$ is aligned with nearest jet
- b-tag, soft muon, third lepton vetoes

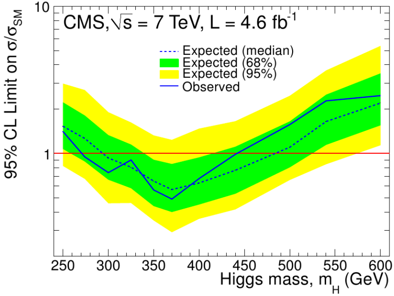


Background Estimation:

- Z+jets $\not{E}_T$ mis-measurement from γ+jet events re-weighted to Z kinematics
- Non-Z backgrounds ($t\bar{t}$, WW, tW, etc.) estimated from opposite-flavour events and $m_{\ell\ell}$ sidebands
- Non-resonant ZZ/WZ backgrounds estimated from Monte Carlo

$H \to ZZ \to 2\ell2\nu$ Results

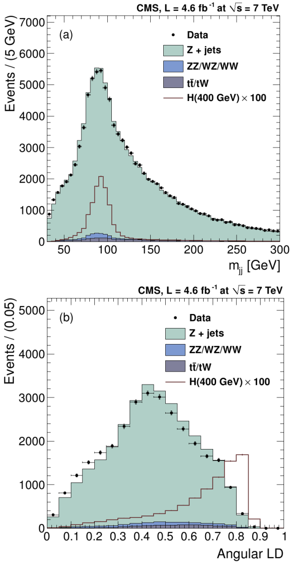




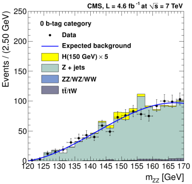
- Final results from binned likelihood fit to M_T distribution (shown here for $m_h = 300\mathrm{GeV}$ selection)
- No significant excess observed, 95% C.L exclusion for $270 < m_h < 440$ GeV

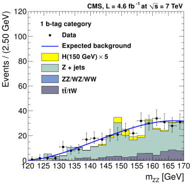
$H \to ZZ \to 2\ell 2q$

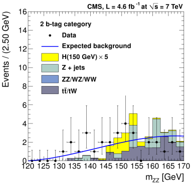
- Two opposite-charge, same-flavour leptons consistent with Z mass
- Two anti-k_T 0.5 particle flow jets in Z peak with $p_T > 30$ GeV, within tracking acceptance
- Analysis divided in 0/1/2 b-tag event categories
- Use of quark-gluon discriminant based on jet shape/constituents
- Additional use of angular likelihood discriminant at high mass
- Dominant Z+jets background estimated from m_{jj} sidebands

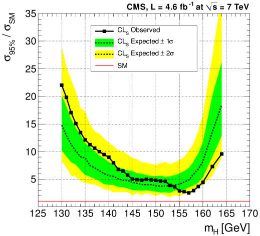


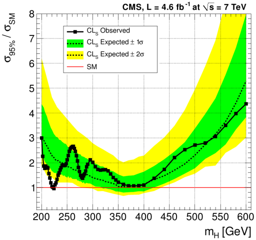
$H \to ZZ \to 2\ell 2q$ Results

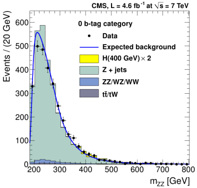


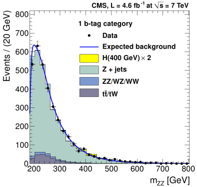


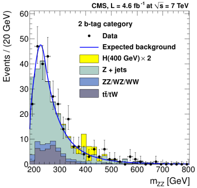








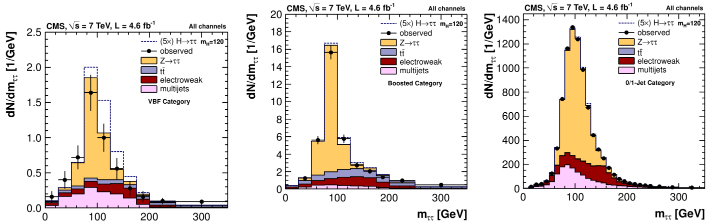




- Sensitivity approaching SM cross-section in high mass region

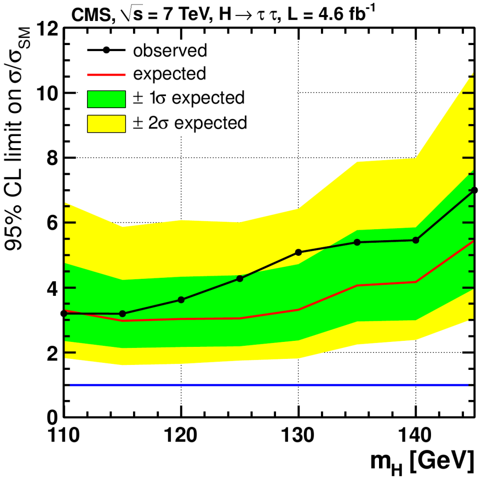
$H \to \tau\tau$

- Events selected in $e\tau_h$, $\mu\tau_h$ and $e\mu$ final states, with 20(17)/10 GeV electron (muon) p_T threshold, and 20 GeV hadronic tau p_T threshold
- $\tau\tau$ mass reconstructed using kinematic fit of visible products and $\not{E}_T$ with likelihood constraints on decay kinematics
- $Z \to \tau\tau$ background estimated from $Z \to \mu\mu$ events in data with μ replaced by simulated τ
- $W + jets$ and multijet background estimated from high transverse mass and same-sign control regions
- Events divided in 3 categories: di-jet VBF tagged, boosted (leading jet $p_T > 150$ GeV), remaining 0/1 jet events



(a) VBF (b) Boosted (c) 0/1 Jet

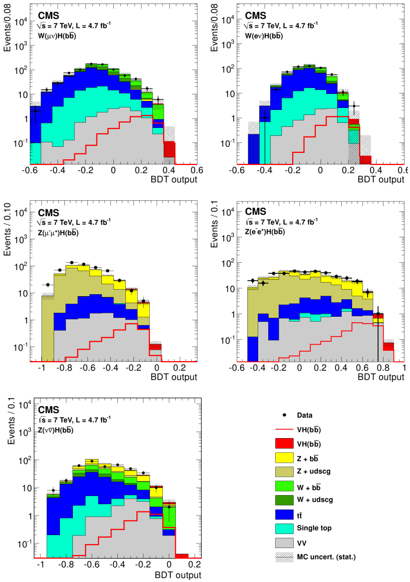
SM $H \to \tau\tau$ Results



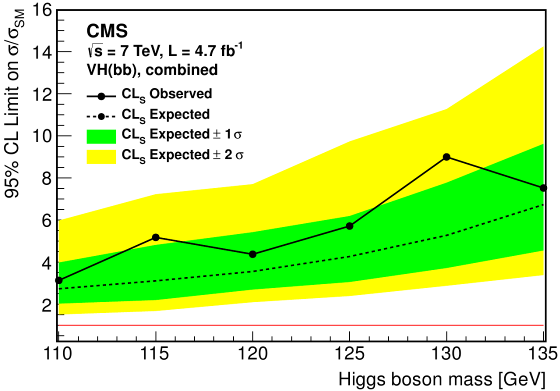
- Final results extracted from binned likelihood fit to $m_{\tau\tau}$ distribution
- Expected exclusion limit $\sim 3 \times \sigma_{SM}$ at low mass

$H \to bb$

- $H \to bb$ has high branching ratios but huge QCD backgrounds
- To achieve reasonable S/B, select $W/Z + H \to \ell\nu\ \ell\ell\ \nu\nu$ events with significant W/Z boost
- Require two central b-tagged jets (p_T threshold dependent on final state)
- MVA (mass-dependent) trained on dijet and W/Z kinematics, Cut and Count analysis on MVA output
- Background yields scaled from inverted b-tagging (W/Z+light flavour), tighter b-tagging plus extra jets ($t\bar{t}$), low $p_T^{W/Z}$(W/Z+$b\bar{b}$)



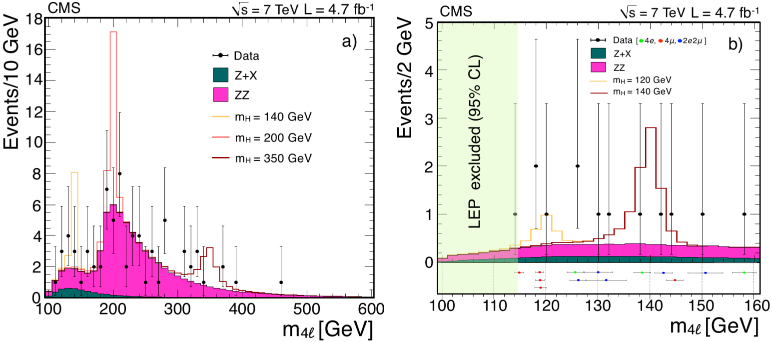
$H \to bb$ Results



- Expected 95% exclusion of $\sim 3\times$ Standard Model cross section in low mass region

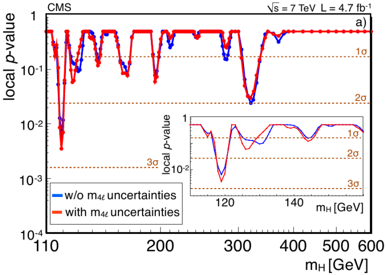
$H \to ZZ \to 4\ell$

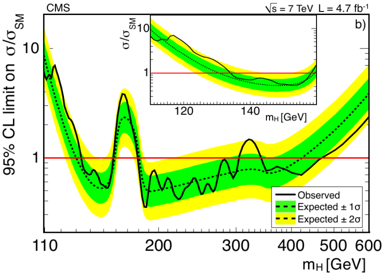
- "Golden channel" - Narrow mass peak on small background
- Select 4 leptons of appropriate charge and flavour combinations with $50 < m_{Z1} < 120$ GeV, $12 < m_{Z2} < 120$ GeV
- Electron acceptance: $|\eta| < 2.5$, $p_T > 7$ GeV, Muon acceptance: $|\eta| < 2.4$, $p_T > 5$ GeV
- Irreducible $ZZ \to 4\ell$ continuum background estimated from MC
- Reducible $Z + b\bar{b}$ and $t\bar{t}$ backgrounds estimated from Z + same-sign dilepton sample, with fake rates from Z + loose ℓ sample



$H \to ZZ \to 4\ell$ Results

- Results extracted from unbinned maximum likelihood fit to $m_{4\ell}$ distribution





Largest observed excesses:

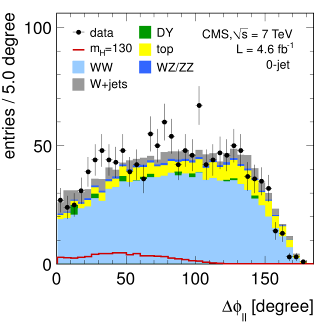
- 119.5 GeV: **Global: 1.6 σ**, (Local: 2.5 σ)
- 320.0 GeV: **Global: 1.0 σ**, (Local: 2.0 σ)

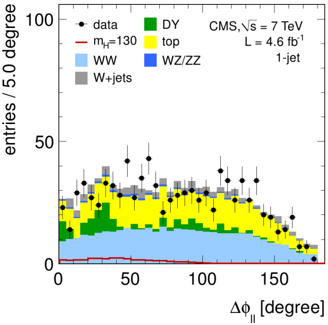
- 95% C.L. exclusion for 134-158, 180-305, 340-465 GeV

$H \to WW \to 2\ell 2\nu$

WW-level Event Selection:

- Two opposite charge leptons with 20/10 (15) GeV p_T threshold for opposite-flavour (same flavour) events
- Events further divided into 0-jet, 1-jet, di-jet VBF tagged categories
- N_{Vtx}-dependent cut on projected $\not{E}_T$ variable wrt nearest lepton (Minimum of global $\not{E}_T$ and vtx-associated charged particle $\not{E}_T$)
- Soft-muon and b-tag veto (also on soft jets in 0-jet bin), third lepton veto, Z-mass veto for same-flavour pairs

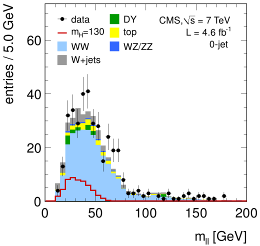


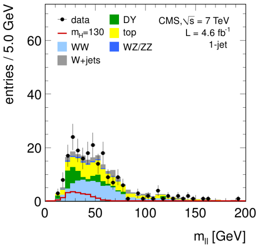


$H \to WW \to 2\ell 2\nu$

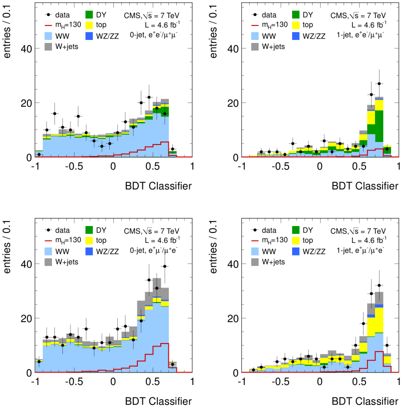
Background Estimation:

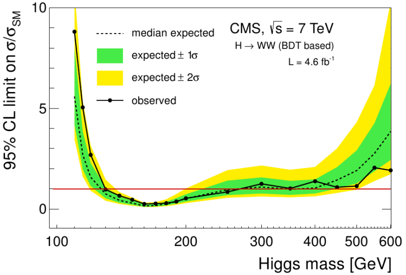
- W+jets background estimated from $\ell +$ loose ℓ sample, fake rates estimated from dijet sample
- $t\bar{t}$ background estimated from b-tagged events, tagging efficiency from double-b-tag sample
- $W\gamma^*$ estimated from three-lepton control sample
- $Z \to \ell\ell$ estimated from yield in Z-peak
- $Z \to \tau\tau$ estimated from embedded sample
- Small $W\gamma$ contribution estimated from simulation, cross-checked in same-sign events
- WW background estimated from high $m_{\ell\ell}$ control region (cut-based selection shown)





$H \to WW \to 2\ell 2\nu$: MVA Results

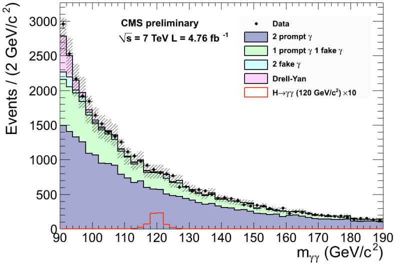




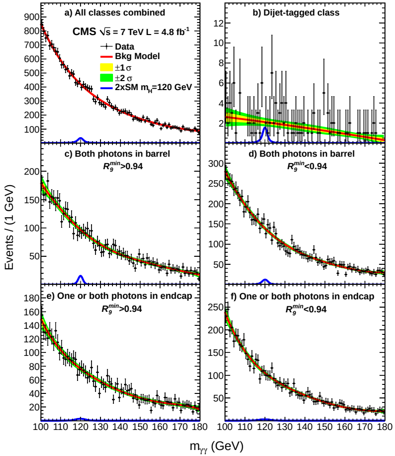
- BDT trained on lepton and $\not{E}_T$ kinematics to distinguish $H \to WW$ from WW
- Results extracted from binned likelihood fit of BDT output
- 95% C.L. exclusion for $129 < m_h < 270$ GeV
- Small excess at low mass

$H \to \gamma\gamma$

- Select two photons with $p_T > m_{\gamma\gamma}/3(4)$ with appropriate selection on shower shape and isolation
- Multivariate energy corrections for local and global electromagnetic cluster containment (Resolution and energy scale corrections from $Z \to ee$)
- Primary vertex selection ambiguous in high pileup" combine information on track recoil against di-photon system with conversion pointing where available (correct vertex in $\sim 83\%$ of events)

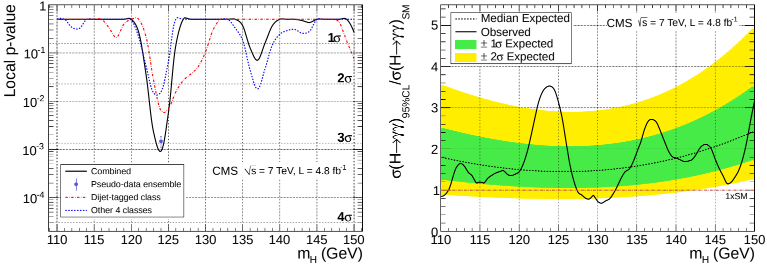


$H \rightarrow \gamma\gamma$



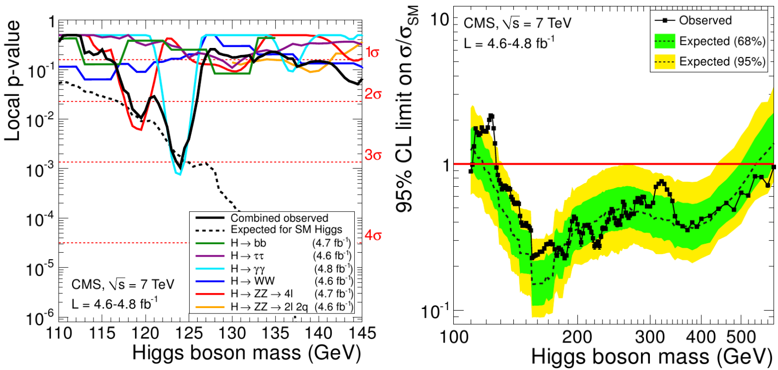
- Separate event class for di-jet VBF-tagged events
- Remaining events further subdivided into 4 event classes according to photon rapidity and shower shape (converted vs unconverted)
- Mass resolution and S/B varies significantly as a function of event class
- Background modelled directly from data using polynomial forms
- Bias estimated from alternate background forms, at least 5 times smaller than statistical uncertainty of background fit

$H \to \gamma\gamma$ Results



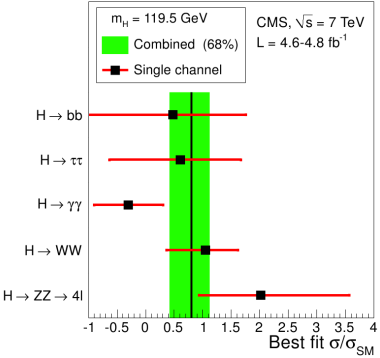
- Excess at 124 GeV with contribution from VBF-tagged and non-VBF-tagged events
- **Global significance 1.8 σ** , (Local significance 3.1 σ)
- 95% C.L. exclusion for $128 < m_h < 132$ GeV
- "More data are required to ascertain the origin of this excess."

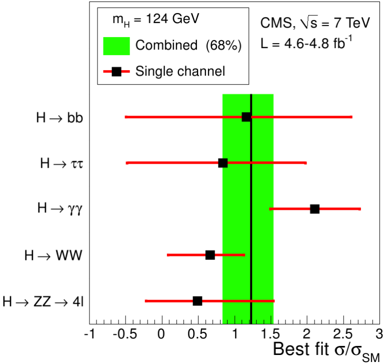
Combined Results



- 95% C.L. exclusion for $127 < m_h < 600$ GeV
- 99% C.L. exclusion for $129 < m_h < 525$ GeV
- Largest excess at 124 GeV dominated by $H \to \gamma\gamma$, smaller excess at 119.5 GeV by $H \to ZZ \to 4\ell$ with smaller contribution from $H \to WW$
- **Global significance: 1.5 σ in 110-600 GeV**, (2.1 σ in 110-145 GeV), (Local significance: 3.1 σ)

Combined Results



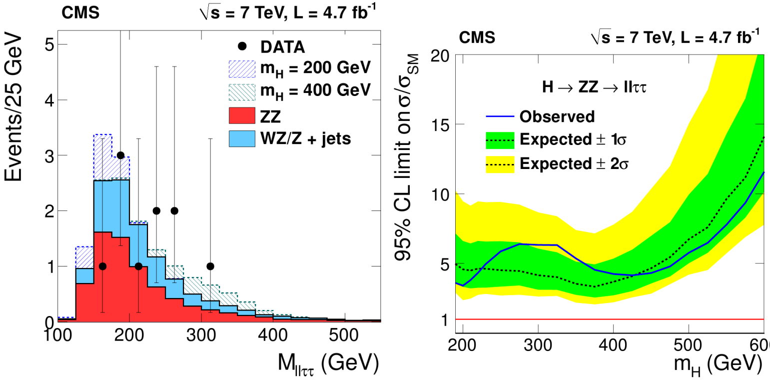


Conclusions

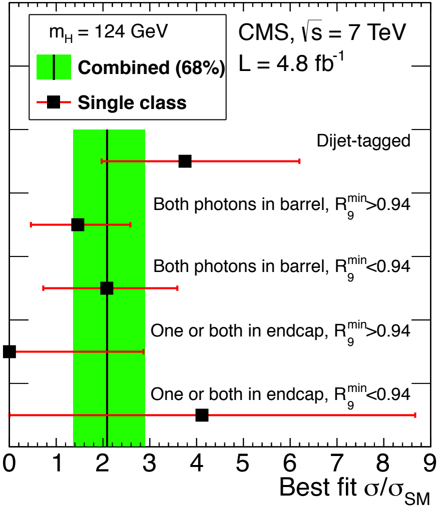
- Full 2011 CMS dataset (4.6-4.8fb^{-1}) analysed in a broad range of Higgs decay channels
- Standard model Higgs excluded at 95% C.L. for $127 < m_h < 600$ GeV
- Modest excess at ~124 GeV mainly from $H \to \gamma\gamma$: **Global significance: 1.5 σ** (or 2.1 σ optimistically), (Local significance 3.1 σ)
- If the Standard Model Higgs exists, its mass is very likely between 114.4 and 127 GeV
- "More data are required to ascertain the origin of the observed excess."

Backup: $H \to ZZ \to 2\ell 2\tau$

- Reconstructing one of the Z's in $\tau\tau$ decays (both leptonic and hadronically decaying taus) adds some branching ratio at high mass



Backup: $H \rightarrow \gamma\gamma$ Best Fit Cross-Sections

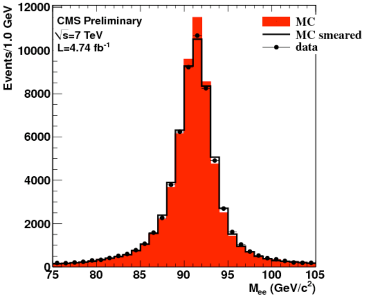


Backup: $H \rightarrow \gamma\gamma$ Event Classes

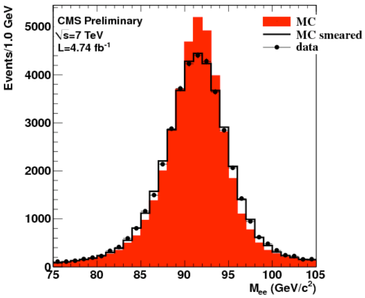
	Both photons in barrel		One or both in endcap		Dijet tag
	$R_9^{min} > 0.94$	$R_9^{min} < 0.94$	$R_9^{min} > 0.94$	$R_9^{min} < 0.94$	
SM signal expected	25.2 (33.5%)	26.6 (35.3%)	9.5 (12.6%)	11.4 (14.9%)	2.8 (3.7%)
Data (events/GeV)	97.5 (22.8%)	143.4 (33.6%)	76.7 (17.9%)	107.4 (25.1%)	2.3 (0.5%)
σ_{eff} (GeV)	1.39	1.84	2.76	3.19	1.71
FWHM/2.35 (GeV)	1.19	1.53	2.81	3.18	1.37

- Mass resolution and S/B varies significantly across event classes
- Mass resolution has some contribution from primary vertex selection ($\sim$ 17% of events with incorrect primary vertex)

Backup: $H \to \gamma\gamma$ Resolution from $Z \to ee$



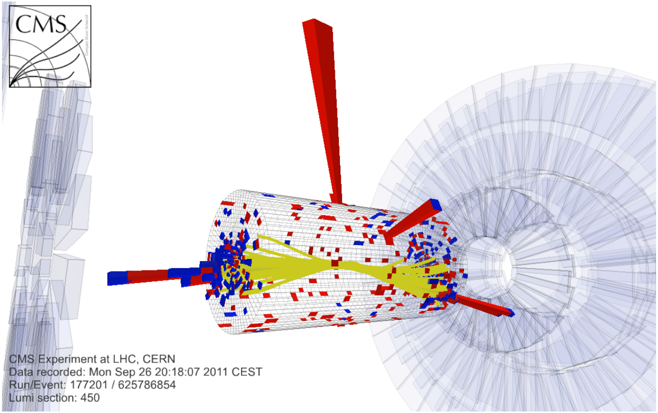
(f) Barrel-Barrel Unconverted



(g) Barrel-Endcap Unconverted

- Monte Carlo $\to$ data resolution smearing factor determined from $Z \to ee$ events
- Additional smearing on the Monte Carlo is relatively small in the barrel, larger in the endcap

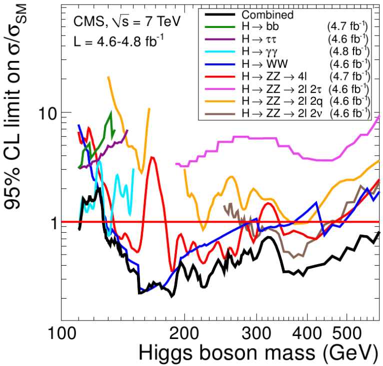
Backup: $H \to \gamma\gamma$ VBF-tagged Event Display

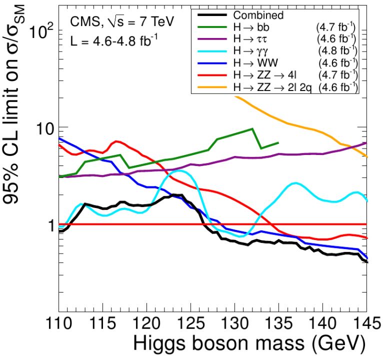


- γ_1: p_T = 193.9 GeV, η = -0.405
- γ_1: p_T = 78.0 GeV, η = 0.037
- Jet 1: p_T = 288.8 GeV, η = -2.022

- $m_{\gamma\gamma}$ = 121.9 GeV
- m_{jj} = 1460 GeV
- $\Delta\eta_j j$ = 3.882

Backup: Combination: Limits by Channel





Backup: Combination: Limits by Channel