Evidence for a narrow resonance in the search for the Standard Model Higgs Boson in the di-photon channel at CMS

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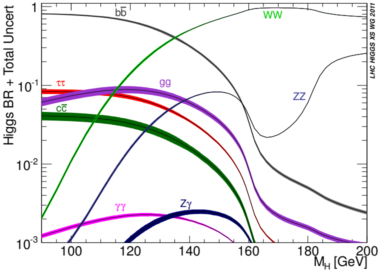
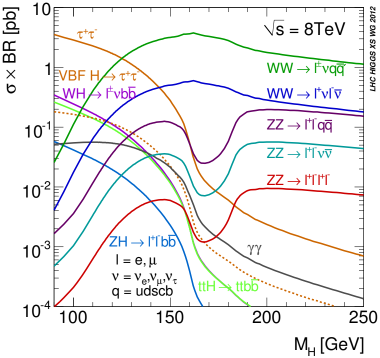
Introduction

- Di-photon channel is the most sensitive Higgs decay mode at low masses, and allows for a relatively precise determination of the mass in case of evidence/discovery



(a) Branching Ratios

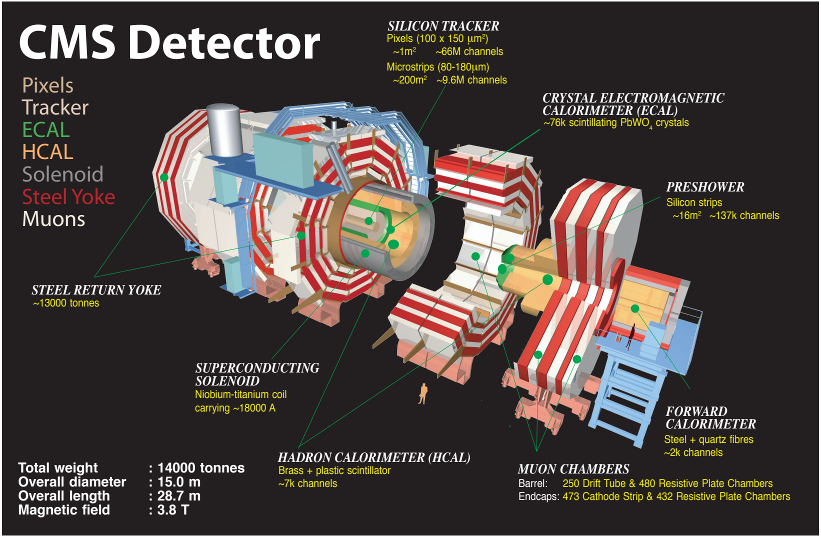


(b) Cross Sections

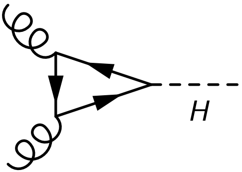
Introduction

- Higgs→di-photon search at CMS simple in principle: Search for a small but narrow mass peak on a large, smoothly falling background
- Irreducible background from QCD di-photon production, reducible background from QCD γ+jets and multi-jet production with one or more jets faking a photon
- Standard Model search is carried out in inclusive and vector-boson-fusion tagged channels,
    - **Main Result: Mass-Factorized Multivariate Analysis:** Photon selection and event classification using multivariate techniques, fit to $m_{\gamma\gamma}$ distribution in event classes
    - Cross-check with alternate background modelling and signal extraction using BDT including the mass
    - Cross-check with cut-based analysis: Photon selection and signal extraction in 4 categories of detector region and converted/unconverted

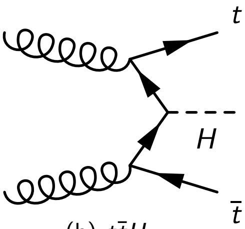
The CMS Detector



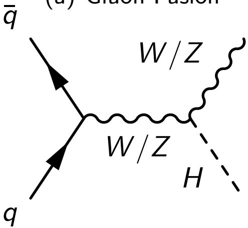
Higgs Production Processes



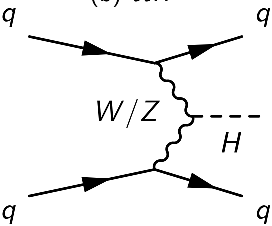
(a) Gluon Fusion



(b) $t\bar{t}H$



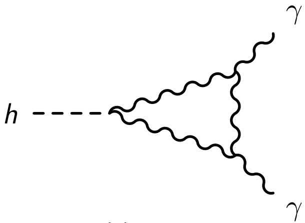
(c) W/ZH



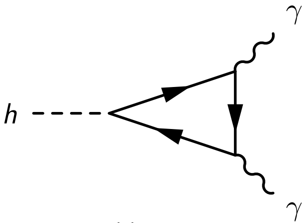
(d) VBF

Higgs→ $\gamma\gamma$ Decay

- No tree-level $h\gamma\gamma$ vertex, decay proceeds through W and fermion (top) loops which interfere destructively
- Branching ratio to two photons very sensitive to fermion vs boson couplings and possible new particles in the loop



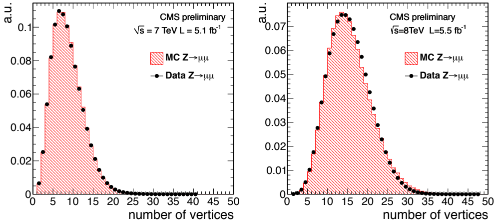
(e) W loop



(f) t loop

Dataset

- 5.1 fb^{-1} of 7 TeV data from 2011, 5.3 fb^{-1} of 8 TeV data from 2012



(a) 7 TeV, $< \text{NPU} >= 9.5$

(b) 7 TeV, $< \text{NPU} >= 18.7$

- Large number of pileup interactions, interaction region extended in z direction with σ = 5-6 cm
- 7 TeV data with refined calibration constants produced after the end of the run, 8 TeV data with Prompt Reconstruction

Monte Carlo: Signal

- Signal Monte Carlo (with corrections and scale factors) used to model acceptance, efficiency and line-shape
- All samples (also bkg) with full Geant4-based detector simulation, in time, and ($\pm$50 ns) OOT pileup
- In-time pileup re-weighted to expected number of interactions in data
- POWHEG (+Pythia 6 showering) for gluon fusion and VBF signal, Pythia 6 for VH and ttH
- For 7 TeV gluon fusion samples, Higgs p_T is re-weighted to HQT (NNLO+NNLL) prediction
- For 8 TeV POWHEG parameters have been tuned to match NNLO+NNLL prediction
- Theoretical uncertainties on acceptance/kinematics (category migration) evaluated by 2D reweighting of Higgs $y - p_T$ to MC@NLO prediction with varied renormalization/factorization scales and PDF variations

Monte Carlo: Background

- Background Monte Carlo not used for final result, only to optimize analysis, train MVA's
- Background mis-modelling will not render analysis incorrect, only suboptimal
- Di-photon Backgrounds: Madgraph di-photon + (up to 2) jets (covers Born and ISR/FSR contributions), Pythia6 for Box contribution
- Photon-Jet and QCD Backgrounds: Pythia6 with EM enrichment filters (EM fraction and isolation cuts after parton showering)
- Pythia Photon-jet and di-jet processes with two prompt photons (1 or 2 added by ISR/FSR in parton shower) removed to avoid double-counting with madgraph
- EM enrichment filters have very low efficiency ($10^{-4} - 10^{-2}$), QCD processes have huge cross-sections, difficult to produce large Monte Carlo statistics for background with fake photons

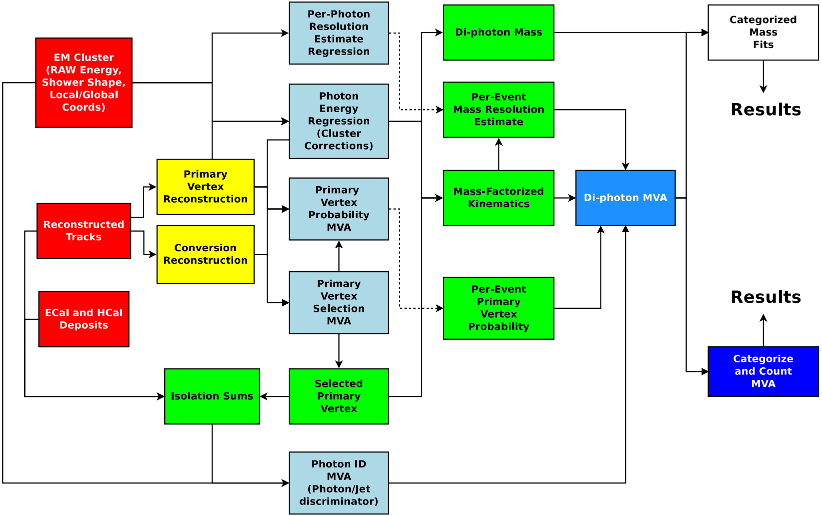
Analysis Overview

1. Primary Vertex Selection (Vertex Selection MVA)
   - Recoil Tracks
   - Converted Photons
   - Per-event vertex probability estimate with additional Vertex Probability MVA
2. Photon Selection
   - $m_{\gamma\gamma}/3(4)$ relative p_T thresholds, Loose Preselection in $(2\eta \times 2R_9)$ categories, Photon ID MVA to give per-object photon/π^0 discriminator
3. Photon Trigger and Identification Efficiency
   - Trigger Efficiency and Preselection Scale Factors from $Z \to ee$
   - Electron Veto scale factors from $Z \to \mu\mu\gamma$
4. Multivariate Regression for EM Cluster corrections with per-photon resolution estimate
5. Energy Scale and Resolution corrections from $Z \to ee$

Analysis Overview (Continued)

6. Event Classification
   - Train di-photon MVA on resolution and mass-factorized kinematics
   - Event Classes (4MVA+2 VBF Tag) exploiting different resolution and S/B
7. Signal modelling from Monte Carlo with smearing and scale factors applied
8. Background modelling from fit to data
9. Statistical Interpretation
   a **Main Result**:Limits/Significance using maximum likelihood fit to $m_{\gamma\gamma}$ distribution in 5+6 categories
   b Cross-check: Limits/Significance using complementary mass-sideband background model with final two-input BDT combining mass and diphoton MVA

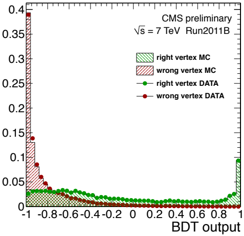
Analysis Overview



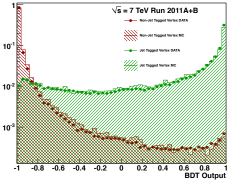
- Strategy: Process available information into quantities with straightforward physical interpretations in order to combine per-event knowledge of expected mass resolution and S/B into a single "Di-photon MVA" variable

Primary Vertex Selection MVA

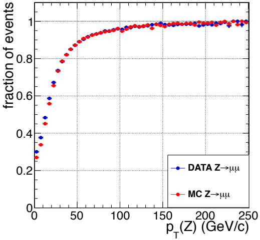
- Per-vertex MVA to select hard interaction from pileup vertices (select Vtx with highest MVA score)
- Input Variables: $\sum p_T^2$, two variables related to di-photon-recoil balancing, $\Delta z_{conv}/\sigma_{conv}$ (in case of reconstructed conversion)



(c) $Z \to \mu\mu$



(d) γ+jets (w/ conversion)

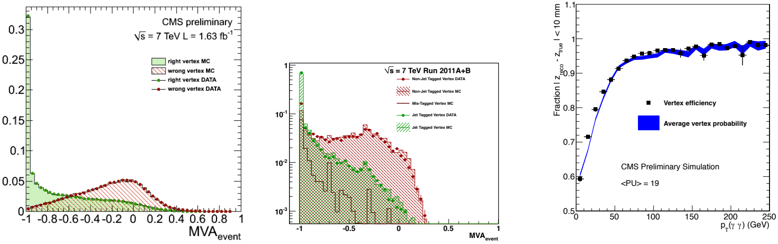


(e) $Z \to \mu\mu$

- Inclusive vertex selection efficiency $\sim$80 %

Per-Event Vertex Probability

- Per-event MVA trained to identify events where correct vs incorrect primary vertex has been identified by per-vtx MVA
- Inputs: $p_T^{\gamma\gamma}, N_{vtx}, VtxMVA_{0-2}, \Delta z_{vtx}^{1-2}, N_{conversions}$



(f) $Z \to \mu\mu$ (g) γ+jets (w/ conversion) (h) $h \to \gamma\gamma$ MC

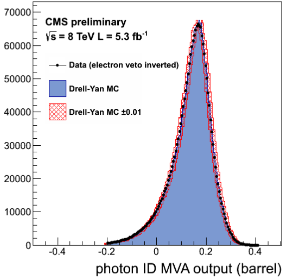
- Vertex selection probability given by linear function of MVA output

Photon Selection

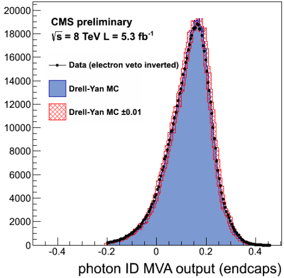
- Geometric acceptance driven by overlap of Ecal and tracker fiducial coverage: Barrel: $|\eta| < 1.44$, Endcap: $1.57 < |\eta| < 2.5$
- Relative p_T thresholds of $m_{\gamma\gamma}/3(4)$ for the leading (sub-leading) photon: Makes acceptance more uniform as a function of Higgs mass and reduces kinematic shaping of the background mass spectrum
- Veto electrons
- Need to discriminate between prompt isolated photons, and fakes from jets (mainly collimated $\pi^0/\eta^0 \to \gamma\gamma$ decays)
- Two handles:
  - Shower Shape: Two photons from π^0/η^0 produce a wider EM cluster on average.
  - Isolation: Select against additional particles produced in the jet alongside the leading π^0/η (some complications from pileup)

Photon Identification: MVA

- Start with a very loose pre-selection matching trigger requirements for signal
- Construct a multivariate discriminator using a BDT trained on prompt photons vs fakes from jets in MC, using shower and isolation variables as input
- Only a loose cut (> -0.2) on the ID MVA value, which is fed forward to the final di-photon MVA
- MVA Output validated on $Z \rightarrow ee$ events



(i) Barrel



(i) Endcap

Regression Energy Corrections

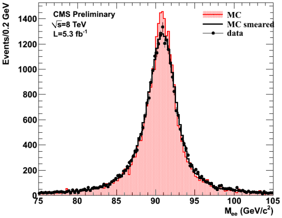
- Photon energy reconstruction in CMS:

$$E_{e/\gamma} = F_{e,\gamma}(\bar{x}) \times \sum_{i}^{N_{crystals}} G(GeV/ADC) \times S_i(t) \times c_i \times A_i$$

- Two main components to photon energy resolution which at least partly factorize:
  1. Crystal level calibration (ADCtoGEV, Intercalibration, transparency corrections)
  2. Higher level reconstruction (Shower containment, crack/gap corrections, PU effects)
- Shower containment is complex and not clear if/how different contributions factorize
- Best performance is obtained with multivariate regression using BDT with cluster η, ϕ, shower shape variables, local coordinates, and number of primary vertices/median energy density as input
- Regression is trained on real photons in Monte Carlo, using the ratio of the generator level energy to the raw cluster energy, also provides a per photon estimate of the energy resolution

Energy Scale and Resolution

- Photon Energy Scale and Resolution in data measured with $Z \to ee$ events, applying either final photon-trained regression corrections, or equivalent electron-trained version
- Monte Carlo is smeared to match data resolution
- Data energy scale is adjusted to match Monte Carlo peak position in MC
- Systematics on electron$\to$ photon extrapolation from reweighting shower shape distribution and changing p_T cuts on $Z \to ee$ sample, and comparing results with electron vs photon trained regression corrections



(k) $|\eta| < 1$, non-showering

Di-Photon MVA

- Basic Strategy: Train di-photon mva on Signal and Background MC with input variables which are to 1st order independent of $m_{\gamma\gamma}$
- Goal is to encode all relevant information on signal vs background discrimination (aside from $m_{\gamma\gamma}$ itself) into a single variable
- Can then simply categorize on Di-photon MVA output (4 categories, with cut values optimized against expected limit/significance using MC background, plus additional VBF Dijet tag categories with loose cut on di-photon MVA)
- Or alternatively employ combined cut and count MVA/mass sideband procedure

Di-Photon MVA Input Variables

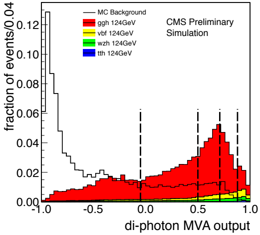
- Input variables cover kinematics (sans mass), per-event resolution and vertex probability, and photon ID
- Input Variables:
  1. $p_T^1/m_{\gamma\gamma}$
  2. $p_T^2/m_{\gamma\gamma}$
  3. η_1
  4. η_2
  5. $\cos\Delta\phi_{\gamma\gamma}$
  6. $\sigma_m/m_{\gamma\gamma}$ (Right Vtx Hypothesis)
  7. $\sigma_m/m_{\gamma\gamma}$ (Wrong Vtx Hypothesis)
  8. p_{vtx}
  9. $IDMVA_1$
  10. $IDMVA_2$
- σ_m constructed from per-photon σ_E estimate from regression, adding also beamspot width contribution for wrong vtx hypothesis
- Per-event primary vertex selection probability p_{vtx} comes from per-event vertex MVA

Resolution

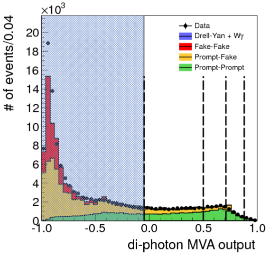
- Since input variables are mass-independent, MVA is not sensitive to mass resolution (since inclusive S/B in full mass range does not change with resolution)
- Correct this by weighting the signal events during training by 1/resolution, taking into account right and wrong primary vertex hypotheses weighted by the per-event probability
- $w_{sig} = \frac{p_{vtx}}{\sigma_m^{right}/m_{\gamma\gamma}} + \frac{1-p_{vtx}}{\sigma_m^{wrong}/m_{\gamma\gamma}}$
- $\frac{\sigma_m^{right}}{m_{\gamma\gamma}} = \frac{1}{2}\sqrt{\frac{\sigma_{E1}^2}{E_1^2} + \frac{\sigma_{E2}^2}{E_2^2}}$
- $\frac{\sigma_m^{wrong}}{m_{\gamma\gamma}} = \sqrt{\left(\frac{\sigma_m^{right}}{m_{\gamma\gamma}}\right)^2 + \left(\frac{\sigma_m^{vtx}}{m_{\gamma\gamma}}\right)^2}$
- With σ_m^{vtx} computed analytically from beamspot width and calorimeter positions of the photons

Di-Photon MVA Output

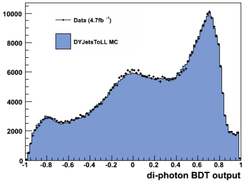
- Lowest score region not included in the analysis
- Di-photon MVA output for signal-like events can be validated with $z \rightarrow ee$ events by inverting electron veto in the pre-selection
- Analysis does not rely on MVA shape of Monte Carlo background



(l) Higgs MC



(m) Full Selection



(n) Inverted e-Veto

Event Classification

- Events classified according to di-photon MVA output
- Event class boundaries optimized against expected limit/significance using Monte Carlo background, by iteratively scanning for optimum event class boundary
- Low-score region dropped completely from analysis (negligible contribution to sensitivity)
- Additional event classes for VBF di-jet tagging, adding a loose cut on the di-photon MVA output

Di-jet Tagging

- Exclusive categories of events enriched in VBF Higgs production, and with enhanced S/B are selected by tagging forward jets with VBF-like kinematics
- In 8 TeV data, Jet identification algorithm based on jet shapes and primary vertex association (in the tracker acceptance) to suppress pileup
- One di-jet tag event class for 7 TeV data, two event classes for 8 TeV (sub-divided into loose and tight classes based on di-jet mass and jet p_T)
- Lowest di-photon MVA score region dropped also for di-jet tagged events
- Expected gluon-fusion contamination of $20 - 50\%$ depending on event class, with a systematic uncertainty of $\sim 50\%$, dominated by underlying event/parton shower uncertainties

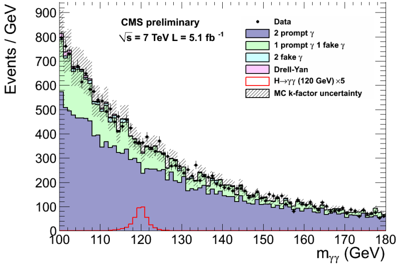
Event Classes

Expected signal and estimated background									
Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 $\pm$ 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 $\pm$ 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 $\pm$ 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 $\pm$ 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 $\pm$ 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 $\pm$ 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 $\pm$ 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 $\pm$ 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 $\pm$ 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 $\pm$ 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 $\pm$ 0.4

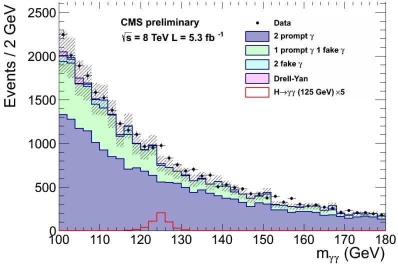
- 180 Events expected for a Standard Model Higgs with $m_h = 125$ GeV
- Large variation in resolution and S/B across categories
- Better resolution in 7 TeV data due to use of more refined calibration constants vs prompt reconstruction for 8 TeV data (calibration to be updated in future results)

$m_{\gamma\gamma}$ Distribution: Data vs MC

- Data and MC shown after lower cut on di-photon MVA
- Reasonable agreement in shape and normalization, but no precise measurement in data of the prompt/fake fractions
- Inclusive distribution is not optimal for bump-hunting (even by eye)



(o) 7 TeV



(p) 8 TeV

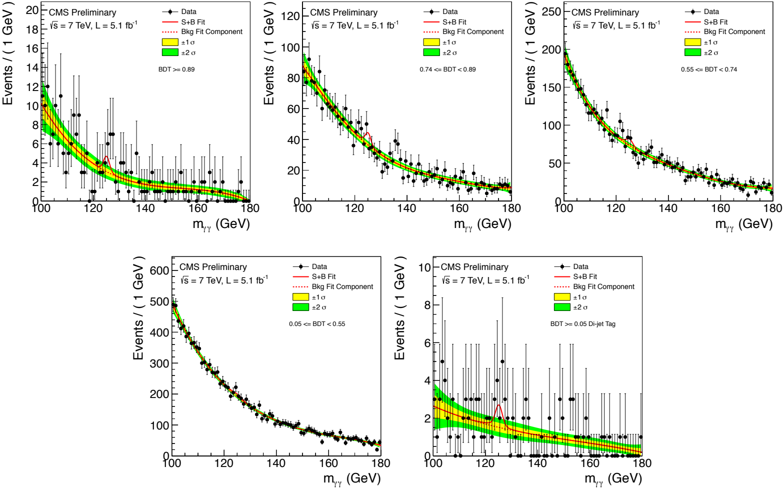
Signal Modelling

- Signal model constructed from Monte Carlo with efficiency scale factors, and with the photon energy smeared to match data resolution
- Empirical functional form fit to MC (sum of Gaussians), fit interpolated between MC mass points
- Final signal model proper mix of $gg \rightarrow h$, VBF production, W/Z associated production, and $t\bar{t}$ associated production in each category

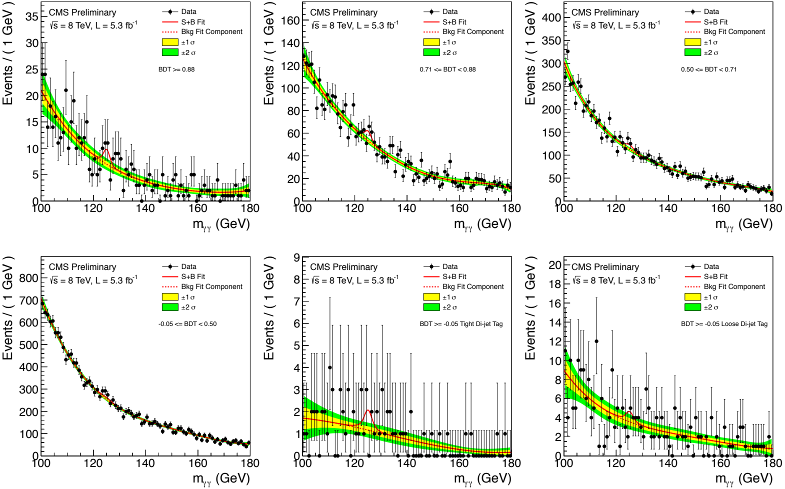
Background Modelling

- Narrow mass peak and smooth background mass spectrum means that background can be modelled directly from data
- Non-trivial event classification, together with several possible effects (kinematic turn-on of fake rate, efficiency, event class fractions) combined with limited Monte Carlo description and statistics (especially for fakes from jets) $\rightarrow$ no reliable first-principles prediction of the background shape
- Logic: Use a functional form with sufficient freedom to cover any reasonable background shape (smooth and continuous)
- 3rd-5th order (depending on event class) polynomials tested against many possible background shapes, largest residual biases at least 5 times smaller than statistical uncertainty

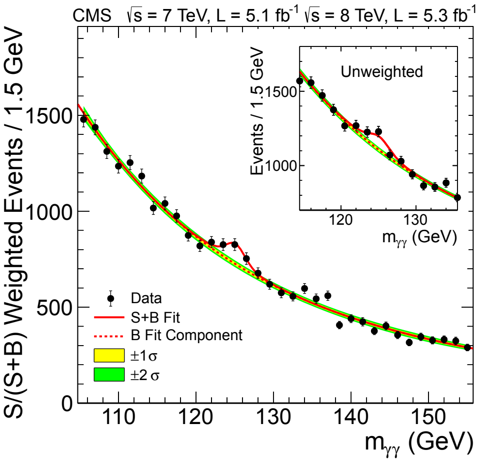
S+B Fits - 7 TeV


CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
BDT >= 0.89
0.74 <= BDT < 0.89
0.55 <= BDT < 0.74
0.05 <= BDT < 0.55
BDT >= 0.05 Di-jet Tag
Events / (1 GeV)
$m_{\gamma\gamma}$ (GeV)

S+B Fits - 8 TeV

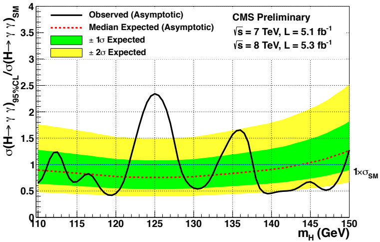

CMS Preliminary
$\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
BDT >= 0.88
0.71 <= BDT < 0.88
0.50 <= BDT < 0.71
-0.05 <= BDT < 0.50
BDT >= -0.05 Tight Di-jet Tag
BDT >= -0.05 Loose Di-jet Tag
Events / (1 GeV)
$m_{\gamma\gamma}$ (GeV)

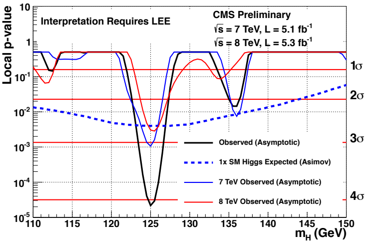
S+B Fit - Weighted Combination



- Results extracted from simultaneous fit to 11 event classes, but combined mass spectrum useful for visualisation
- Combination of all 11 event classes, weighted by $S/(S+B)$ for a $\pm\sigma_{eff}$ window in each event class
- Weights are normalised to preserve the fitted number of signal events
- Un-weighted combination of 11 categories shown in inset

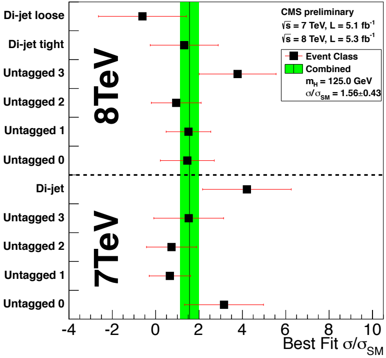
Results: Limits and p-values



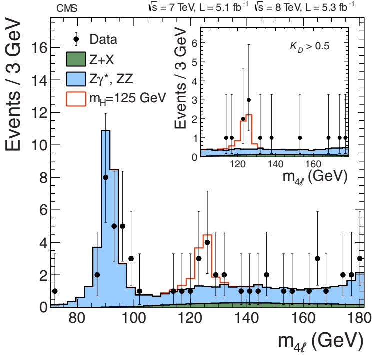


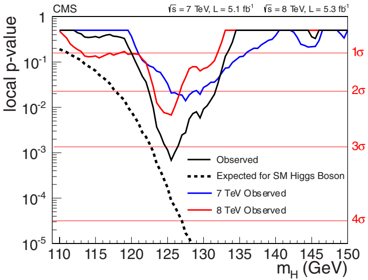
- Excess at 125 GeV with contribution from 7 TeV and 8 TeV data
- **Global significance 3.2 σ , Local significance 4.1 σ**
- From CMS $\gamma\gamma$ channel alone, this constitutes evidence for a new state
- Cut-based and MVA-based cross-check analyses yield consistent results
- Is it the Standard Model Higgs?

Best Fit Signal Cross Sections: 125 GeV



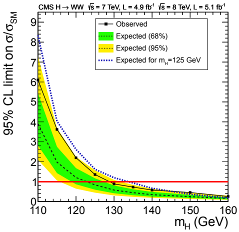
- Contribution from most event classes in both 7 *TeV* and 8 *TeV* data
- Best fit ratio to standard model cross section at 125.0 GeV: 1.56 ± 0.43
- Consistent with Standard Model Higgs, but with large uncertainties at the moment



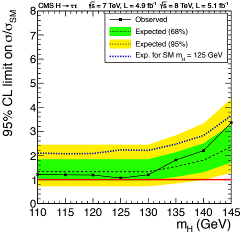


- Excess in 4ℓ channel consistent in mass with $\gamma\gamma$
- Local significance for 4ℓ: 3.2σ

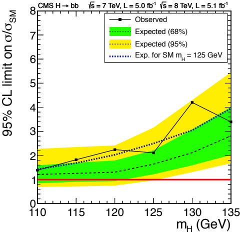
The Other Channels



(q) $H \to WW \to 2\ell 2\nu$



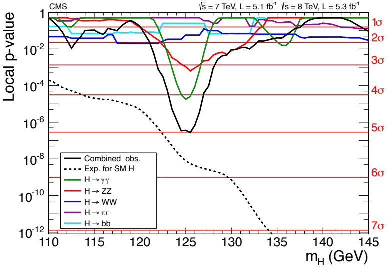
(r) $H \to \tau\tau$

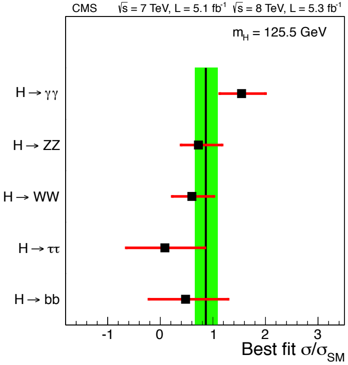


(s) $H \to b\bar{b}$

- Other channels at or near Standard Model sensitivity
- Does the new particle couple to taus?

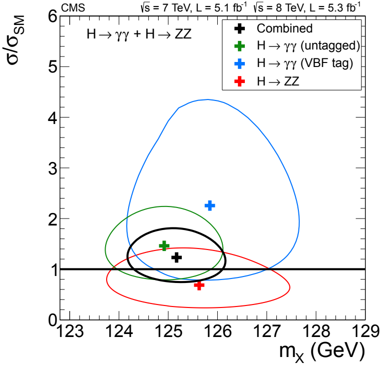
The Big Picture





- 5σ Observation when main channels are combined (mainly from $\gamma\gamma$ and 4ℓ)
- Big picture is broadly consistent with a SM Higgs so far
- More data needed for more precise statements on the nature of the new state

Mass



- Mass determination driven by $H \to \gamma\gamma$ at the moment
- Statistical and systematic uncertainties are comparable, largest systematic from extrapolation in p_T from Z peak to 125 GeV
- Work ongoing to reduce systematic uncertainties, 4μ events will play a more important role with more data
- Combined fit from $\gamma\gamma$ and 4ℓ:

  $m_X =$

  $125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})$ GeV

Conclusions

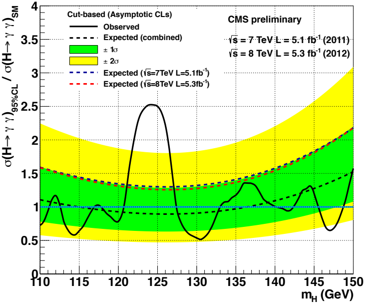
- Search for the Standard Model Higgs in di-photons at CMS using 5.1 fb^{-1} at 7 TeV + 5.3 fb^{-1} at 8 TeV yields evidence for a new narrow di-photon resonance around 125 GeV
- Cross-check analyses give consistent results with main MVA analysis
- Combination with $H \rightarrow ZZ \rightarrow 4\ell$ and other channels gives a 5σ observation
- New particle broadly consistent with a Standard Model Higgs
- More data required to precisely characterize the properties of the new state

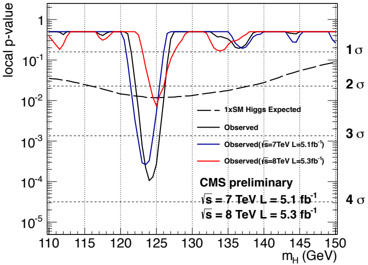
Prospects

- 8 TeV data-taking continuing
- Expect updated results for HCP in just a few weeks with over twice as much 8 TeV data as for ICHEP, results with full 2011+2012 dataset likely for Moriond
- Many interesting results more data: couplings, spin, parity
- In the longer term, rarer final states can be explored (VBF/VH/ttH tagging for more decay modes, $H \to Z\gamma$, eventually $H \to \mu\mu$, and perhaps $H \to HH$)

Backup: Cuts-in-Categories Analysis

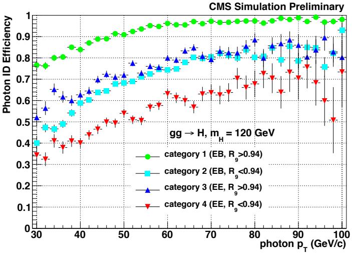
- Cuts-in-categories cross check analysis with cut-based Photon ID and event classification
- Photon ID with cut-based selection in 4 photon categories *Barrel*/*Endcap*×convertex/unconverted
- Cut-based Event classification: 4 event classes based on barrel/endcap and converted/unconverted photons (plus di-jet tag classes)



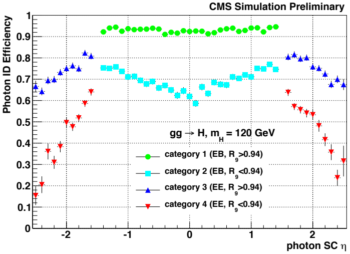


Backup: Photon Selection: Cuts in Categories

- Photon selection consists of cuts on several shower shape and isolation variables
- Unconverted photons have less background and better resolution, more fakes in general in the Endcap, so vary cuts according to 4 photon categories (Barrel/Endcap$\times$ Unconverted/Converted)

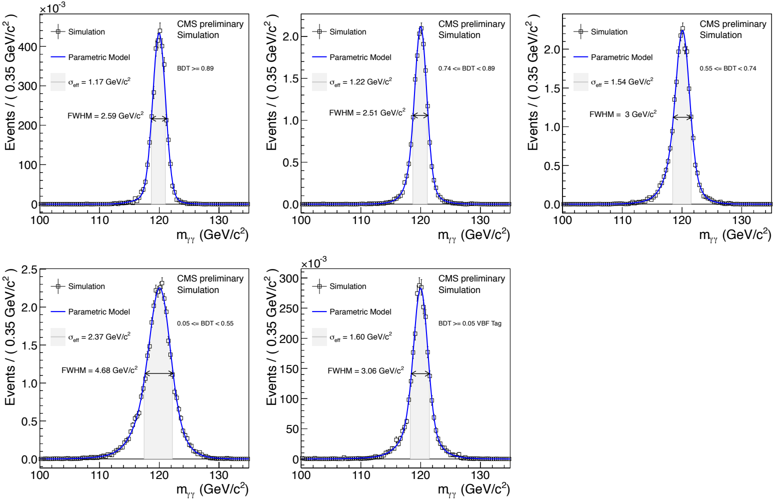


(t) ϵ vs p_T

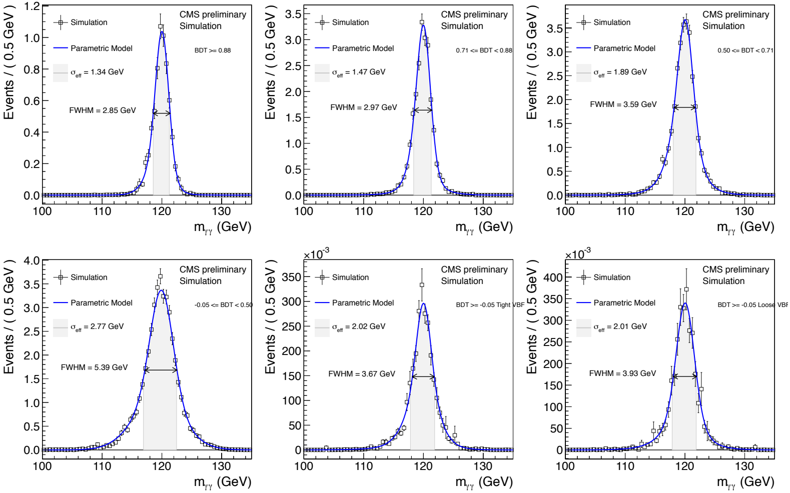


(u) ϵ vs η

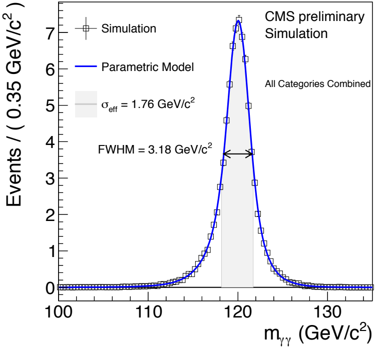
Backup: Signal Model 7 TeV



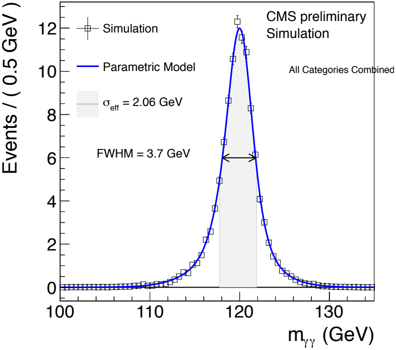
Backup: Signal Model 8 TeV



Backup: Signal Model - Inclusive



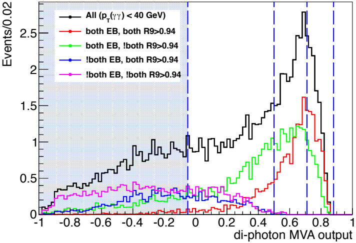
(a) 7 TeV



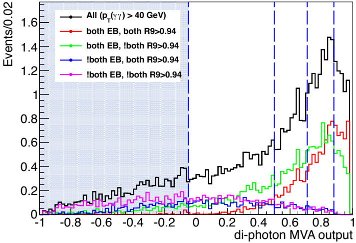
(b) 8 TeV

- Inclusive resolution can only be interpreted relative to acceptance
- 7 TeV better than 8 TeV due mainly to more refined calibration constants so far

Backup: MVA Event Classification - Link to η, R_9, $p_T^{\gamma\gamma}$ Classes



(c) ($p_T^{\gamma\gamma} < 40$ GeV)

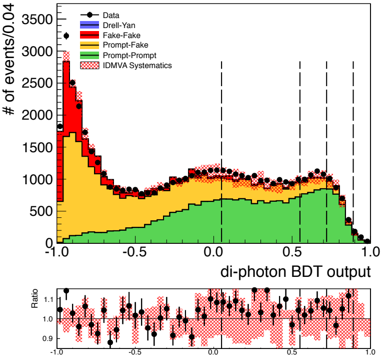


(d) ($p_T^{\gamma\gamma} > 40$ GeV)

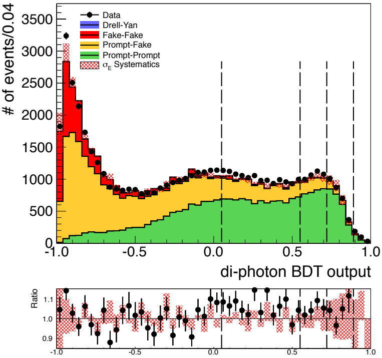
- Highest score region is exclusively boosted events
- Reasonable correlation with $\eta \times R_9$ event classification

Backup: Di-Photon MVA Systematic Uncertainties

- Shape systematic uncertainties on Photon ID MVA and σ_E/E propagated through as shape variation/category migration on di-photon MVA output
- Shown here applied to background MC (not used in the analysis, large uncertainties on k-factors/composition not shown here)



(e) Photon ID

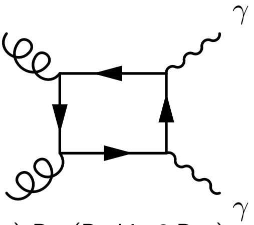


(f) σ_E

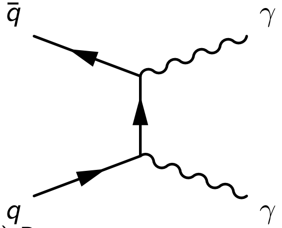
Backup: MVA Systematic Uncertainties

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon selection efficiency		0.8%	2.2%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.60%	0.90%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.52%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Photon identification BDT	(Effect of up to 4.3% event class migration.)	$\pm$0.01 (shape shift)	
Photon energy resolution BDT	(Effect of up to 8.1% event class migration.)	$\pm$10% (shape scaling)	
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	50%	
	(Effect of up to 15% event migration among dijet classes.)		
Production cross sections		Scale	PDF
Gluon-gluon fusion		+12.5% -8.2%	+7.9% -7.7%
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Associated production with $t\bar{t}$		+3.6% -9.5%	8.5%
Scale and PDF uncertainties	(Effect of up to 12.5% event class migration.)	(y, p_T)-differential	

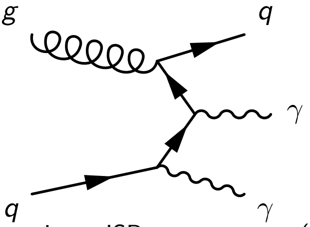
Backup: Di-photon Backgrounds



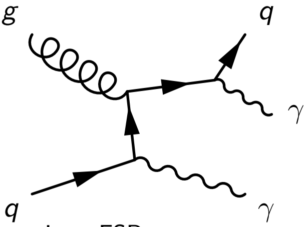
(g) Box(Pythia 6 Box)



(h) Born
(Madgraph $\gamma\gamma$ + jets)

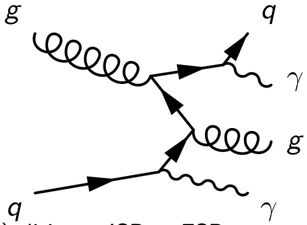


(i) γ+jet + ISR
(Madgraph $\gamma\gamma$ + jets)

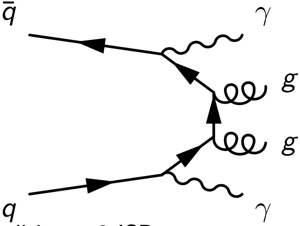


(j) γ+jet+ FSR
(Madgraph $\gamma\gamma$ + jets)

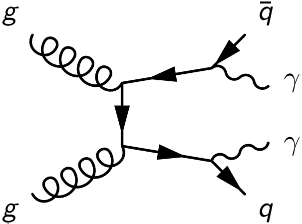
Backup: Di-photon Backgrounds



(k) di-jet + ISR + FSR
(Madgraph $\gamma\gamma$ + jets)

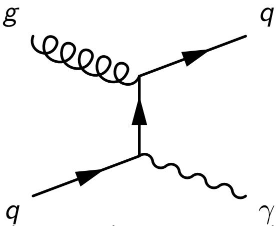


(l) di-jet + 2 ISR
(Madgraph $\gamma\gamma$ + jets)

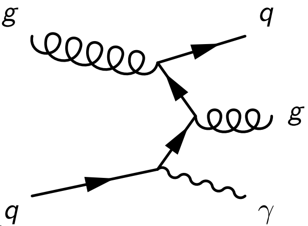


(m) di-jet + 2 FSR
(Madgraph $\gamma\gamma$ + jets)

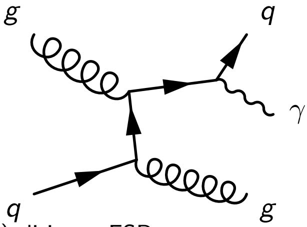
Backup: Photon + Jet Backgrounds



(n) γ + jet(Pythia 6 γ+jet)

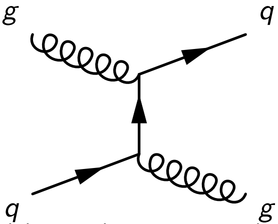


(o) di-jet + ISR
(Pythia 6 di-jet)



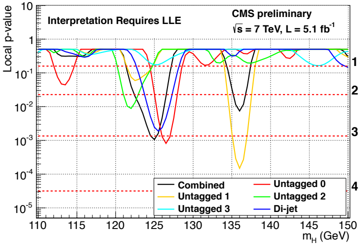
(p) di-jet + FSR
(Pythia 6 di-jet)

Backup: Di-Jet Backgrounds

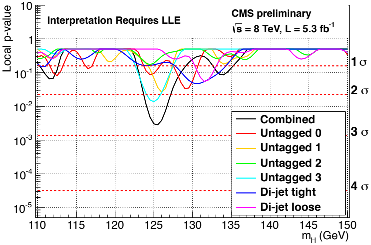


(q) di-jet(Pythia 6 di-jet)

Backup: p-values Per Event Class

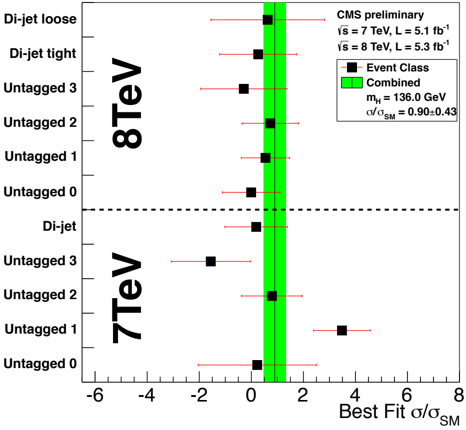


(r) 7 TeV

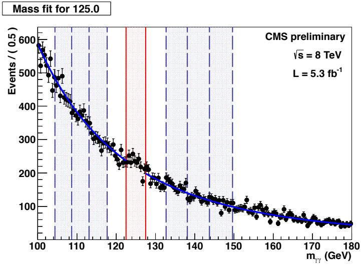


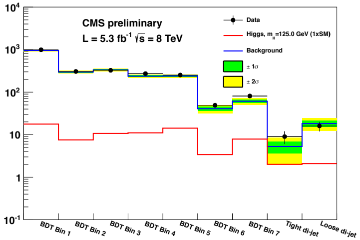
(s) 8 TeV

Backup: Best Fit Cross Section: 136 GeV



Backup: Mass Sideband MVA





Backup: Mass Sideband MVA Results