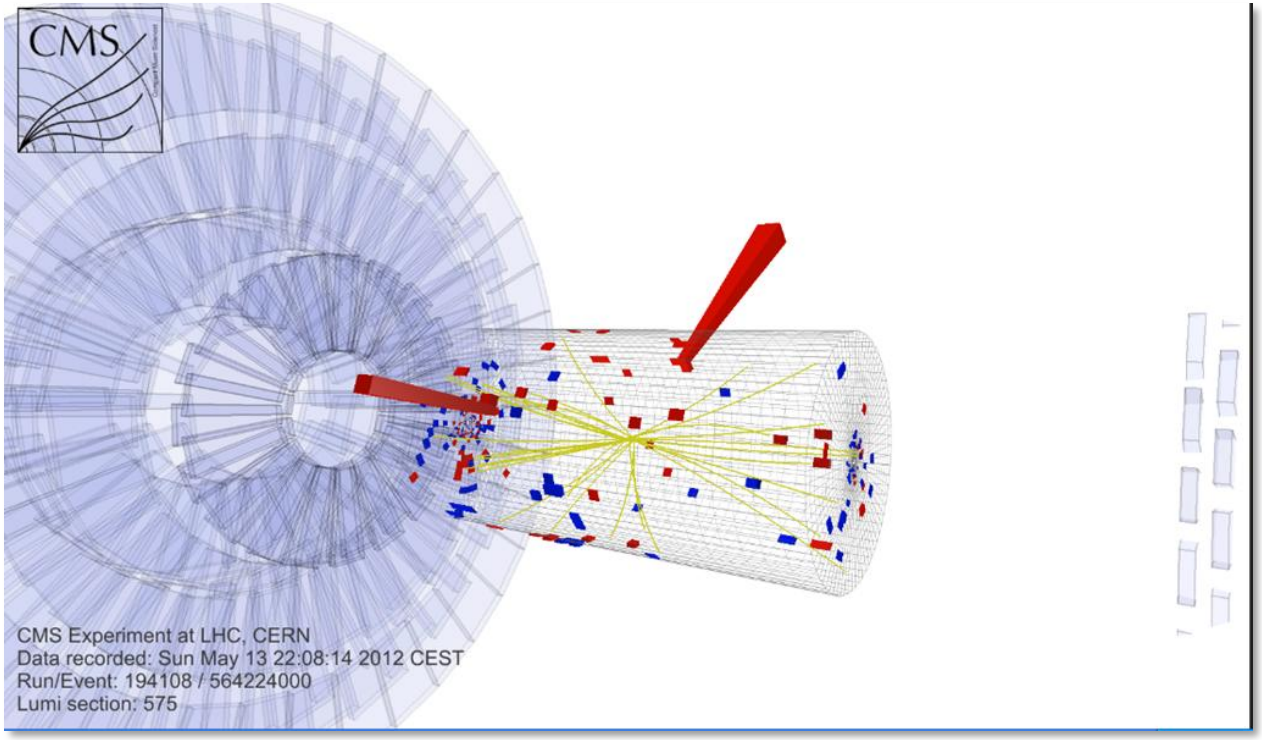
Search for the Higgs boson in the gamma gamma channel in CMS



Yu-Wei Chang, National Taiwan University

On behalf of the CMS Collaboration

Higgs Hunting 2012, Orsay-France

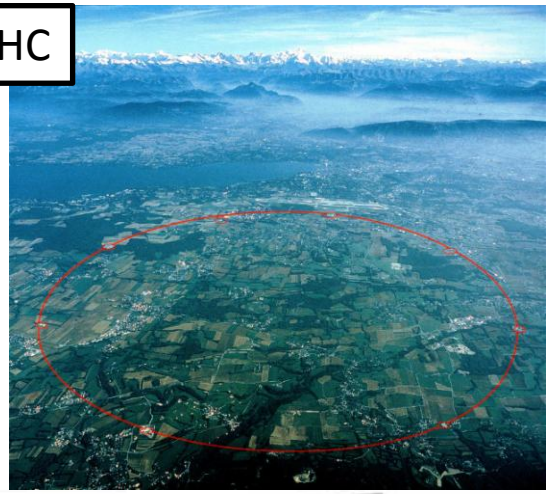
Overview

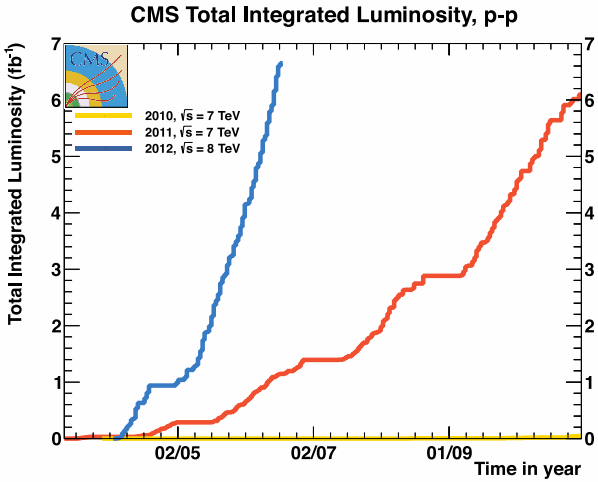
- Searches of 2 Higgs hypothesis are included:
  - the **Standard Model** (SM) Higgs → γγ
  - the **Fermiophobic** (FP) Higgs → γγ
- Results based on 2011 & 2012 data collected by CMS
  - 5.1 fb^{-1} 2011 data at $\sqrt{s}$ = 7 TeV
  - 5.3 fb^{-1} 2012 data at $\sqrt{s}$ = 8 TeV
- Search m_H window: [110-150] GeV
- Blind analysis in 2012

- 3 independent analysis used in SM search
  - **Mass fit Multi-Variate Analysis (MVA)**
  - Mass Sideband Background MVA
  - Cut-based analysis
- Analysis used in FP search
  - Basically consistent with SM cut-based analysis
  - Additional modifications based on the FP topology

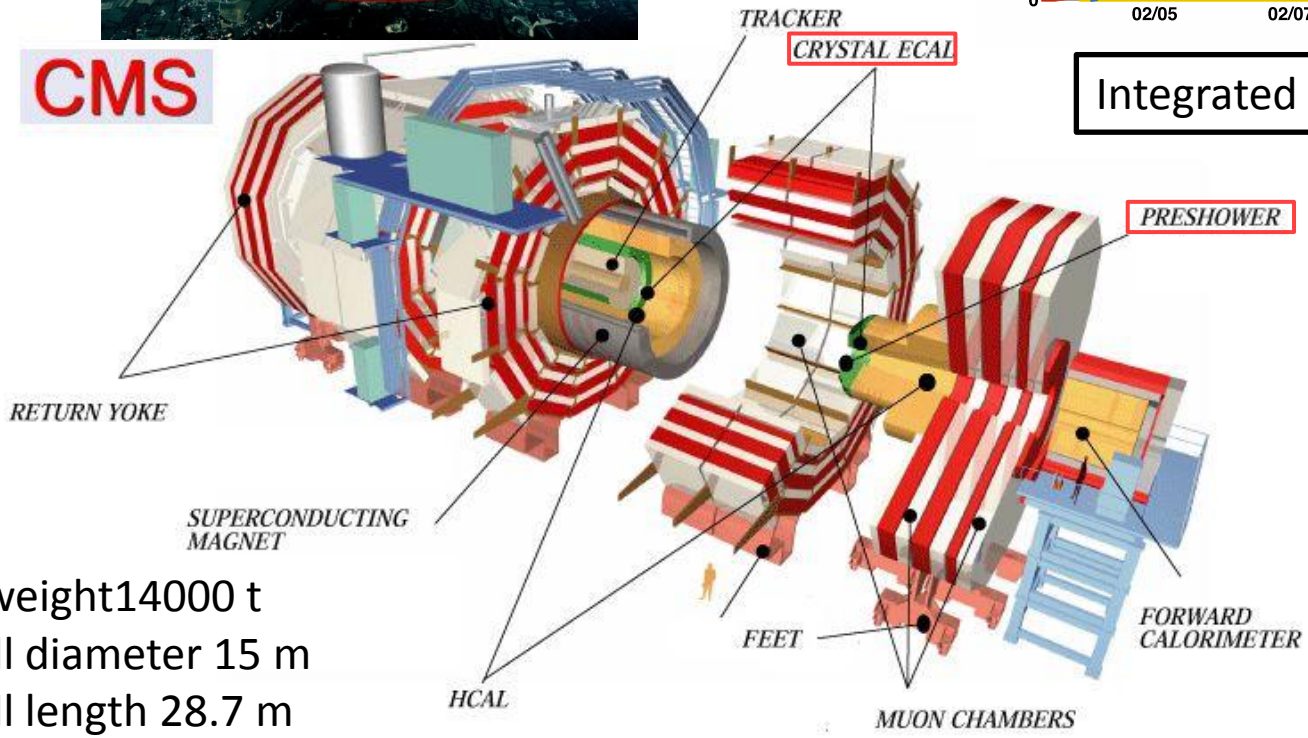
CERN-LHC and the CMS Detector

CERN-LHC



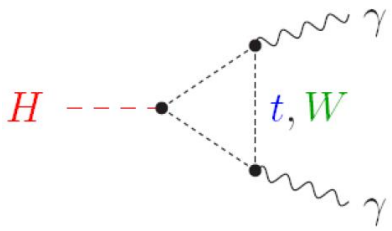


Integrated Luminosity



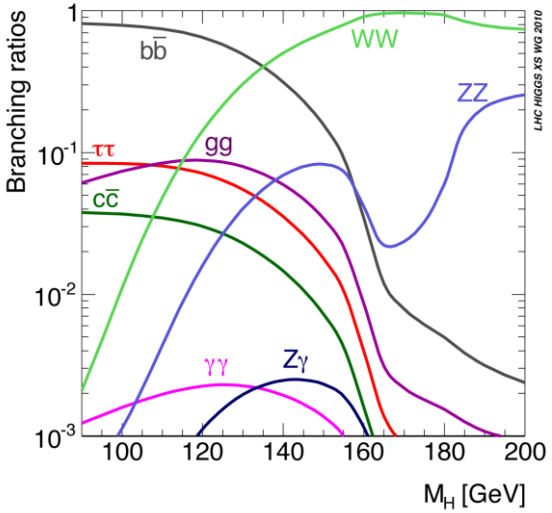
Total weight14000 t
Overall diameter 15 m
Overall length 28.7 m

Introduction

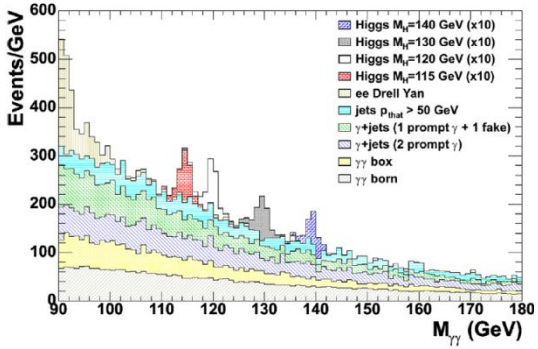


- A discovery channel at low masses
  - decay involves **virtual loops**
  - low signal branching ratio
  - clean signature
  - **identified as a narrow $m_{\gamma\gamma}$ peak on the top of continuous background**

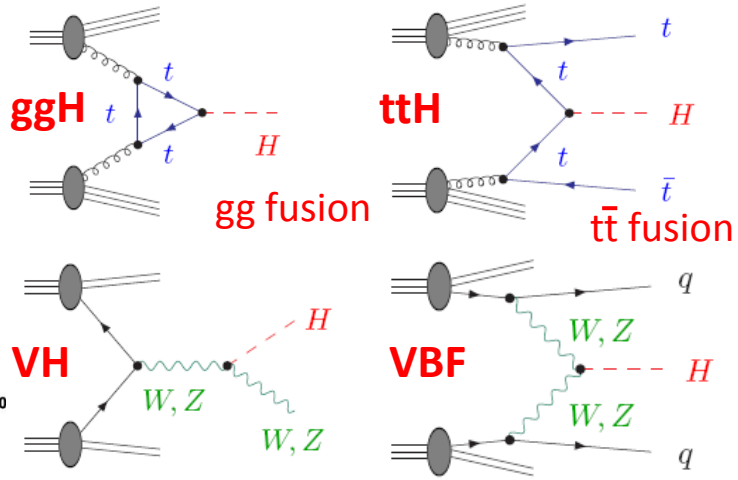
- Published 2011 result,
  [Phys. Lett. B710 (2012), no 3, 403]
  - Observe 3.1σ local (1.8σ-global) excess at 124 GeV
- The 2011 result here is reloaded
  - improved detector calibration



CMS Physics TDR, Volume II



Signal production procedures :



Analysis Strategy

- Main analysis uses Multi-Variate Analysis (**MVA**) technique to identify and to classify events:
  - improvement in expected limit about 15% with respect to the cut-based analysis
- Cross-checked with (independent) cut-based and mass sideband background MVA model
- Background model derived from data
- Final results extracted by fitting to the $m_{\gamma\gamma}$ distribution in **6 event classes**
- Mass resolution and signal to background ratio are crucial

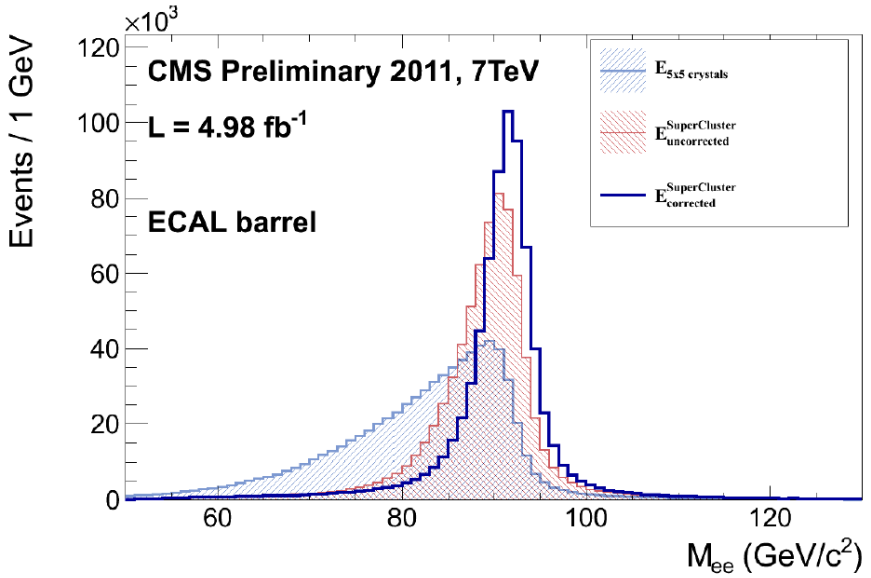
Energy Corrections

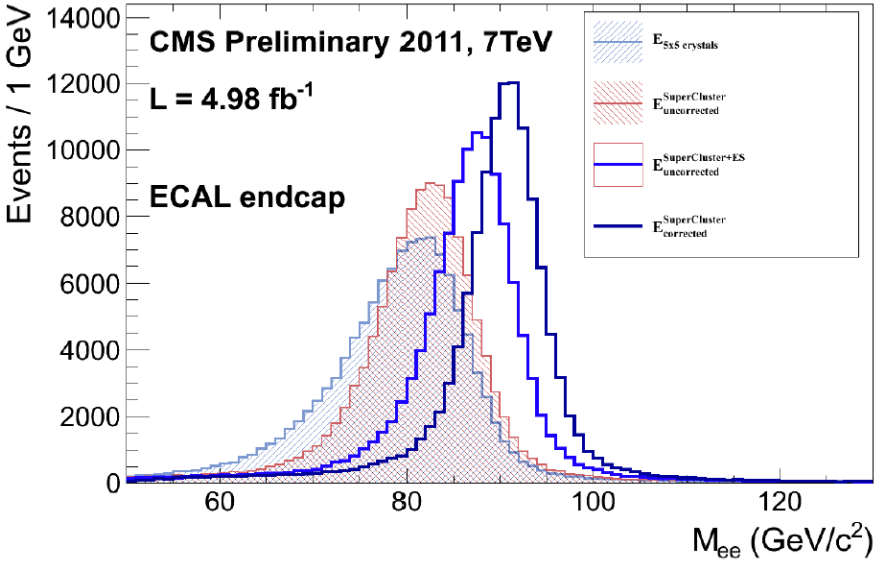
- Estimated energy in the ECAL:

$$E_{e,\gamma} = F \times \sum_{clusters} G\, c_i\, A_i$$

Corrections *Calibration*

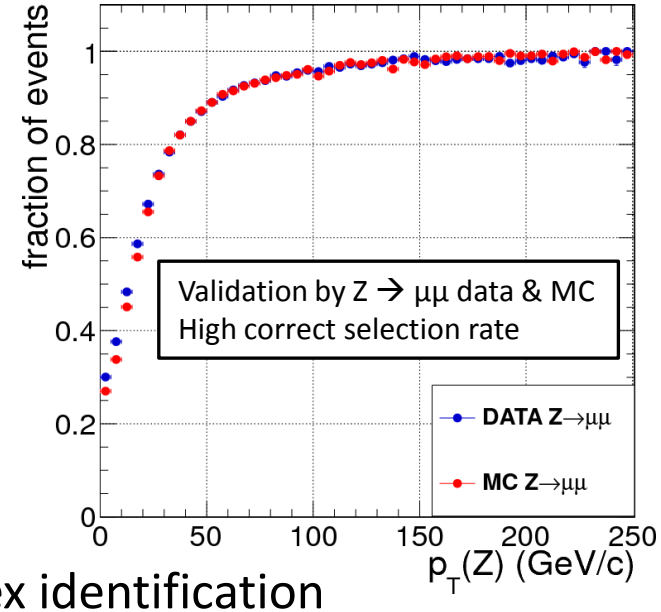
- Energy correction scheme
  - F = 1 for 5x5 crystal sum for the energy of unconverted photons
  - c_i - intercalibration constants (π^0)
  - transparency correction with laser monitoring (LM)
- ECAL cluster energies corrected using an MC trained multivariate regression
  - performed after individual crystal transparency correction and inter-calibration
  - also provides per photon energy resolution estimate

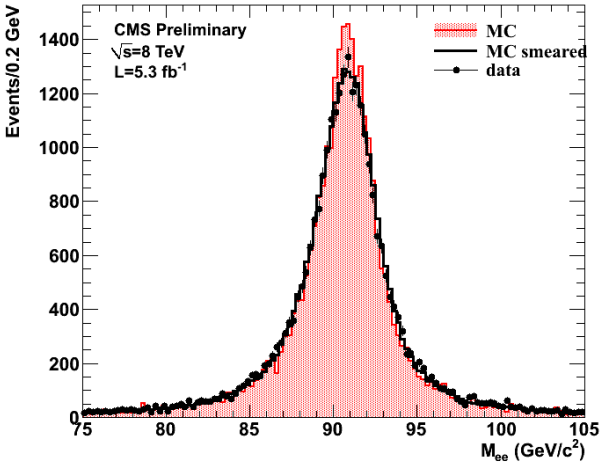




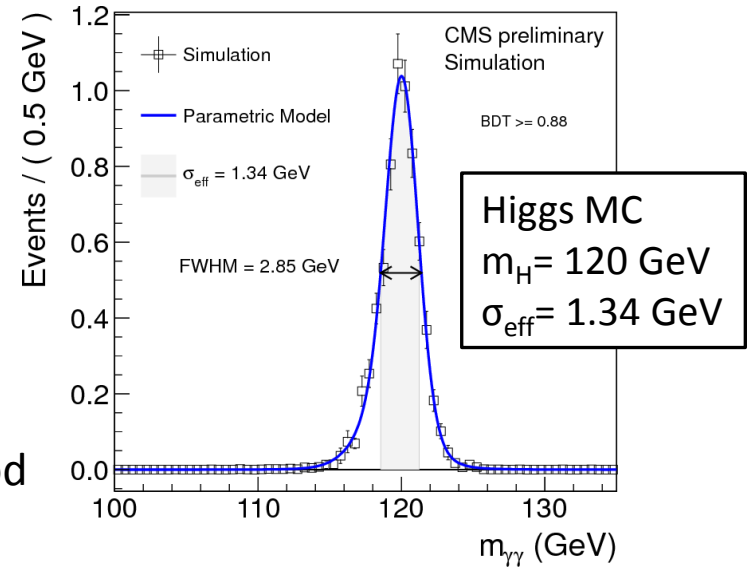
Vertex Selection and $m_{\gamma\gamma}$ Reconstruction

- Signal $m_{\gamma\gamma}$ resolution
  - The opening angle between photon pair affects the mass and resolution
  - Depend on the correct position of the primary vertex and correct reconstructed photon energy





Reconstructed mass using Z→ee data & MC

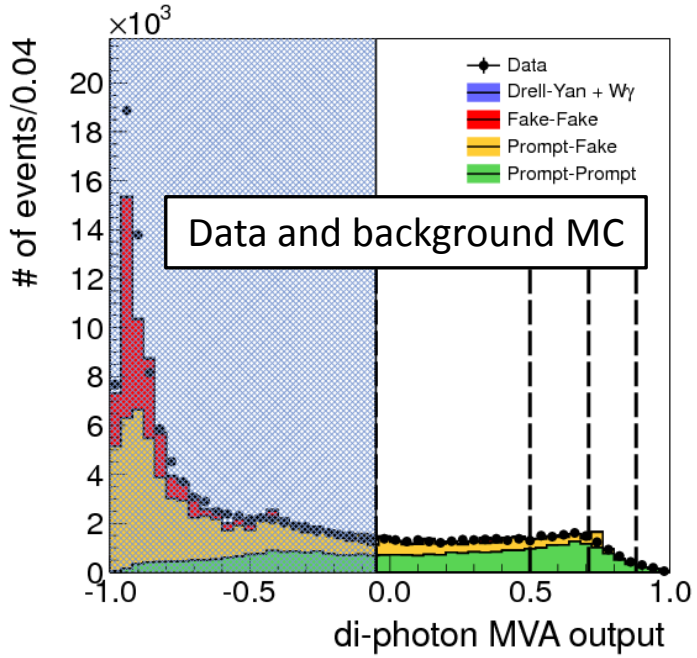


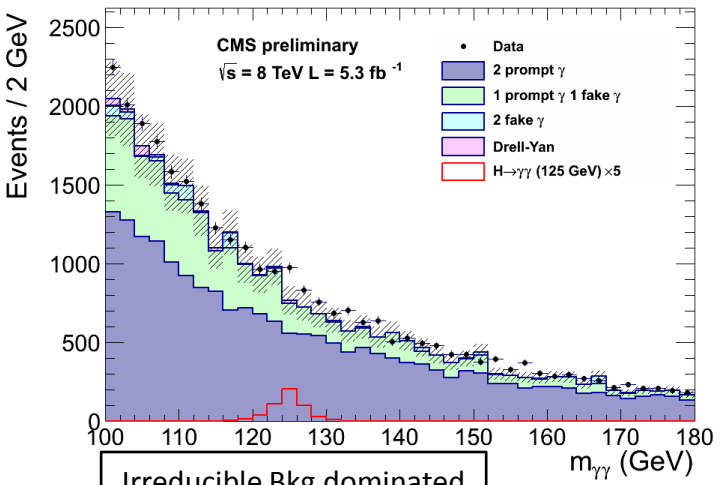
Higgs MC
m_H= 120 GeV
σ_{eff}= 1.34 GeV

- Vertex identification
  - Use MVA Boosted Decision Tree (BDT) method
  - Input information from tracks and photons

Event Selection

- MVA Photon ID separates prompt photons from π^0 emerged from jets
  - MVA BDT input variables based on :
    - Shower Topology
    - Particle Isolation
    - The median energy density per solid angle
    - Supercluster pseudorapidity
- Form Higgs candidate from two isolated leading photons
  - $p_T^{lead}/m_{\gamma\gamma} > 1/3$, $p_T^{sub\text{-}lead}/m_{\gamma\gamma} > 1/4$
- Event selection based on diphoton MVA output
  - photon-like kinematic characteristics
  - signal-like kinematic characteristics
    - predominantly giving high score to high $p_T^{\gamma\gamma}$
  - good diphoton mass resolution
- Diphoton MVA input variables are designed to be $m_{\gamma\gamma}$ independent

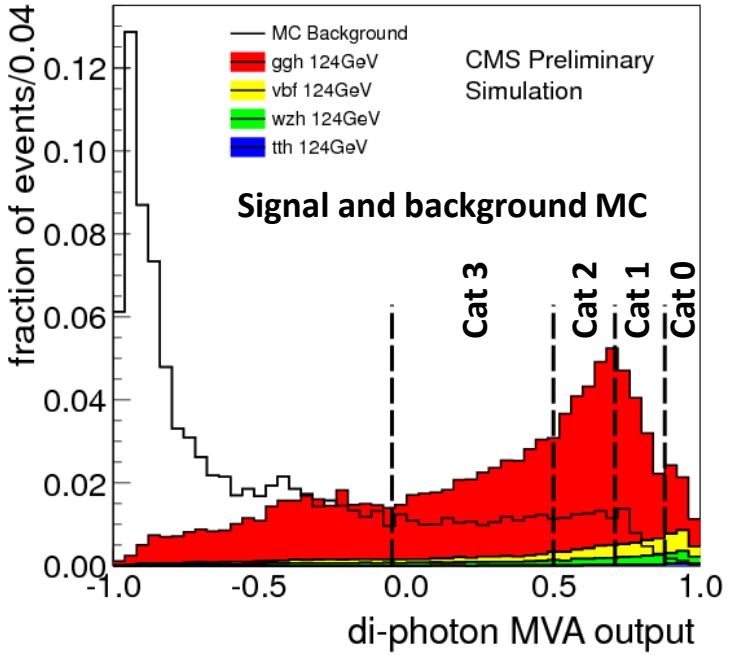


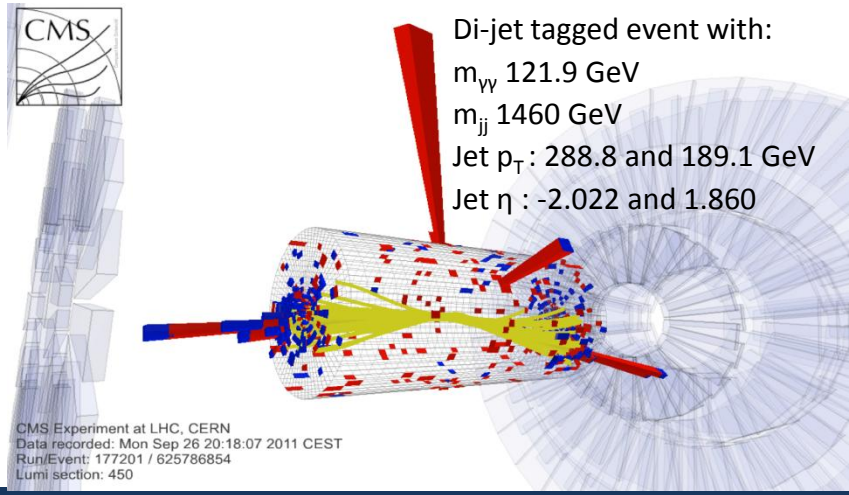


Irreducible Bkg dominated
2 prompt photons - 70%

Event Categorization

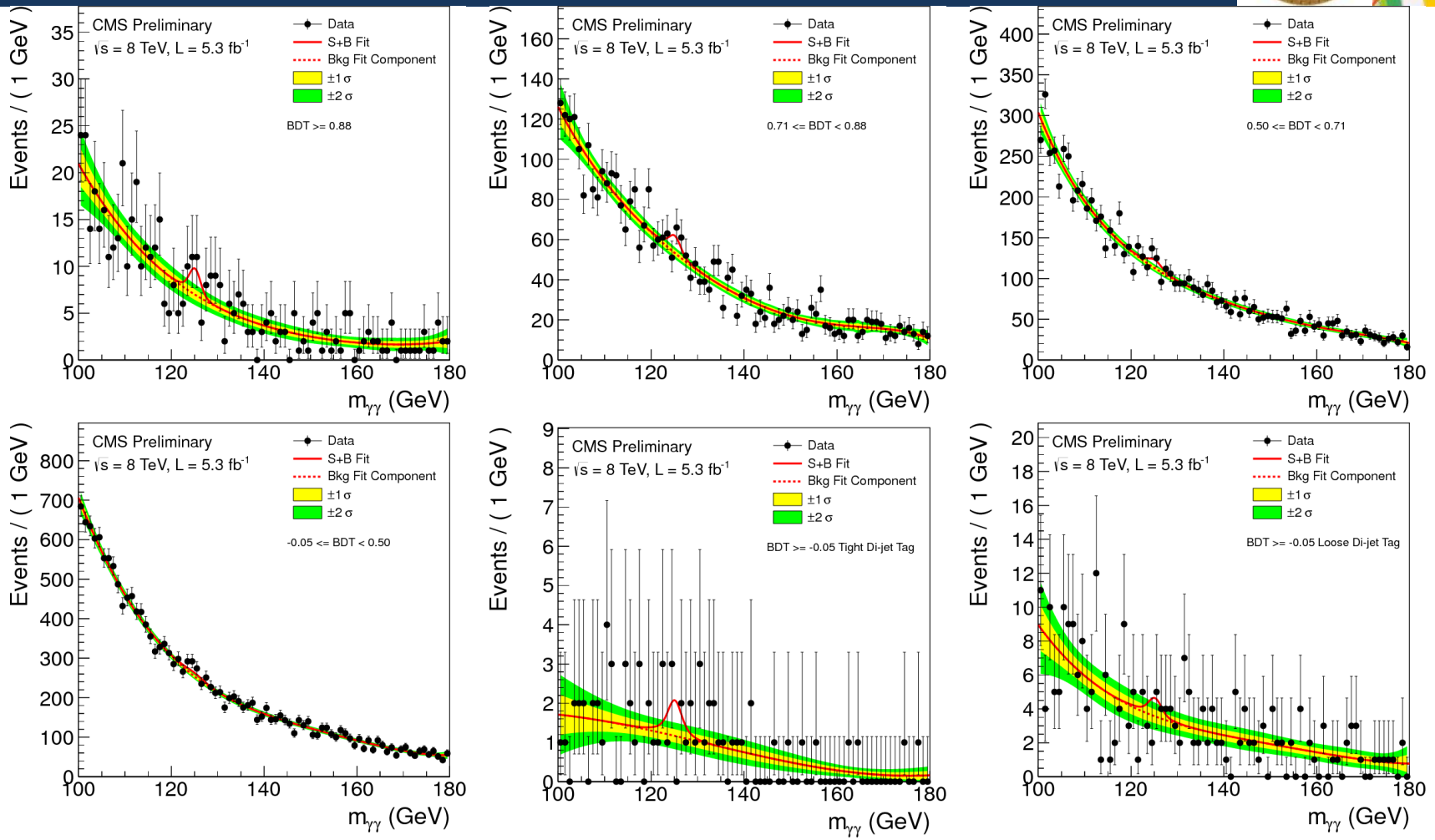
- To improve the analysis sensitivity
- Event with 6 categories:
  - **4 diphoton MVA categories**
    - Boundaries optimized to give the best expected limit
  - **2 dijet-tagged categories**
- Exclusive selection of di-photon events with VBF-like topology:
  - two high p_T jets with wide separated in η
  - **Higher S/B**
- Use 2 categories based on m_{jj} and jet p_T in 2012 analysis





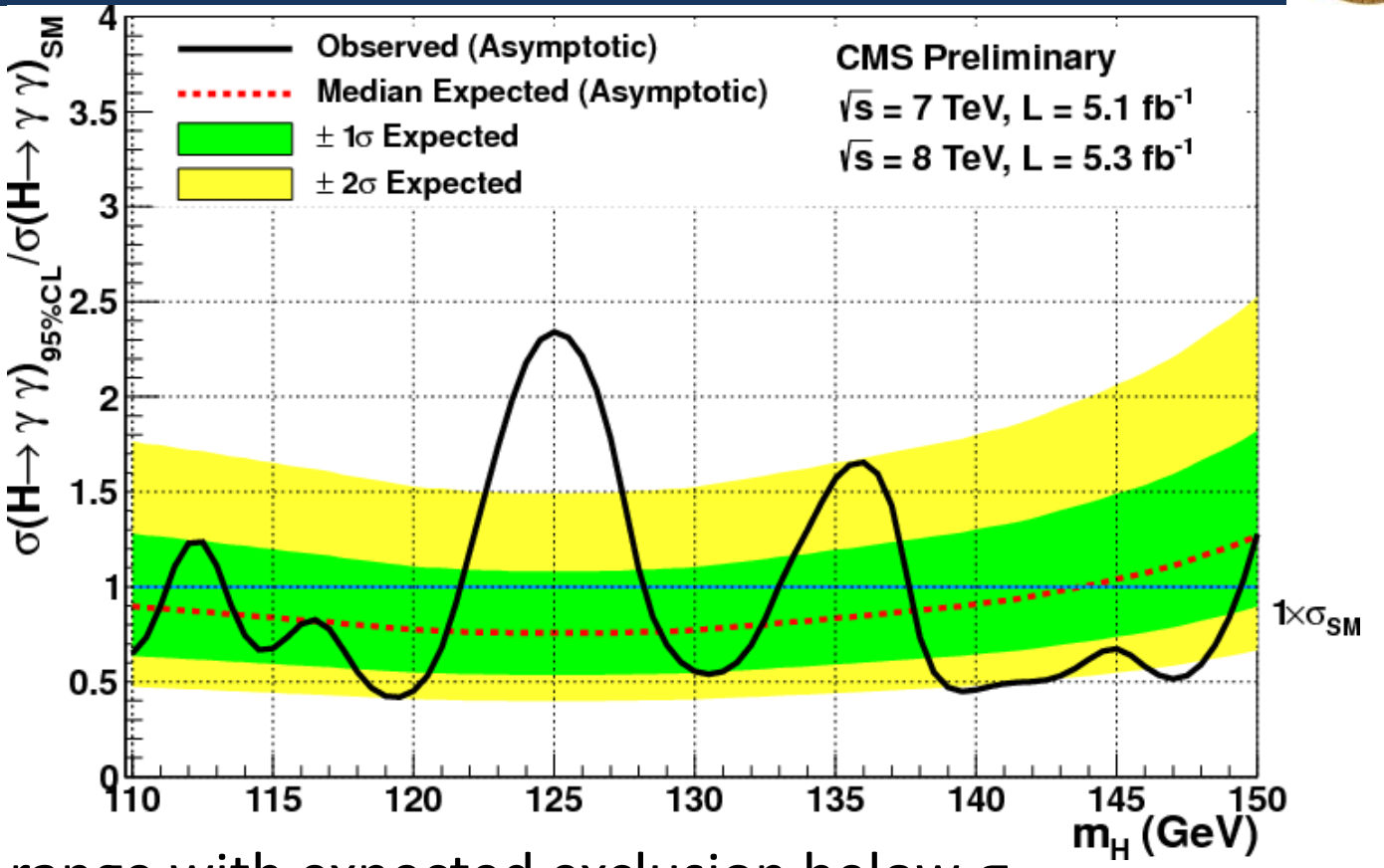
Result of the Search for the SM H → γγ

8 TeV Mass Distribution in Categories



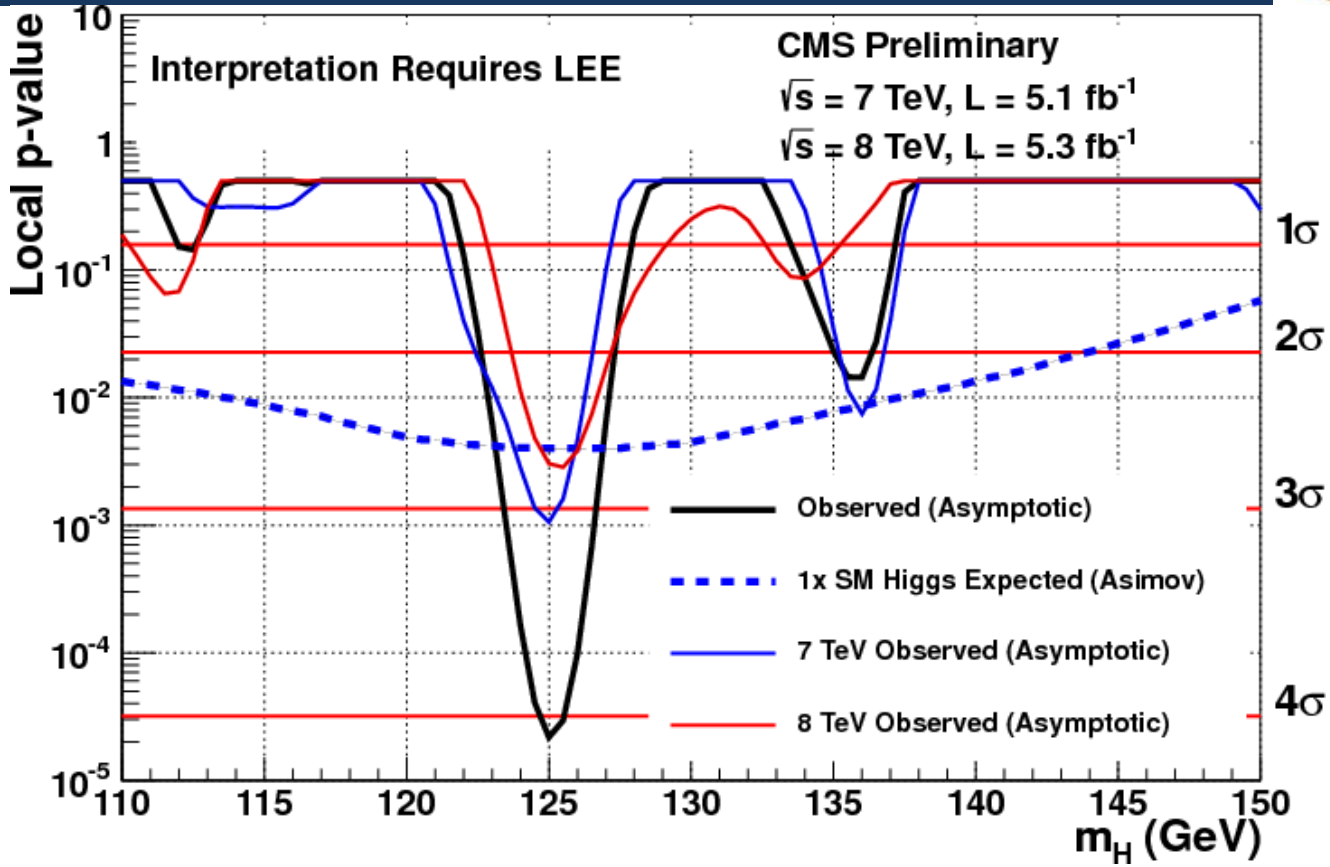
- Background modeling: polynomial shape with order from 3 to 5
- Potential bias from background model is negligible
  - ≦ 20% of statistical uncertainty

95% CL Exclusion for SM H→γγ



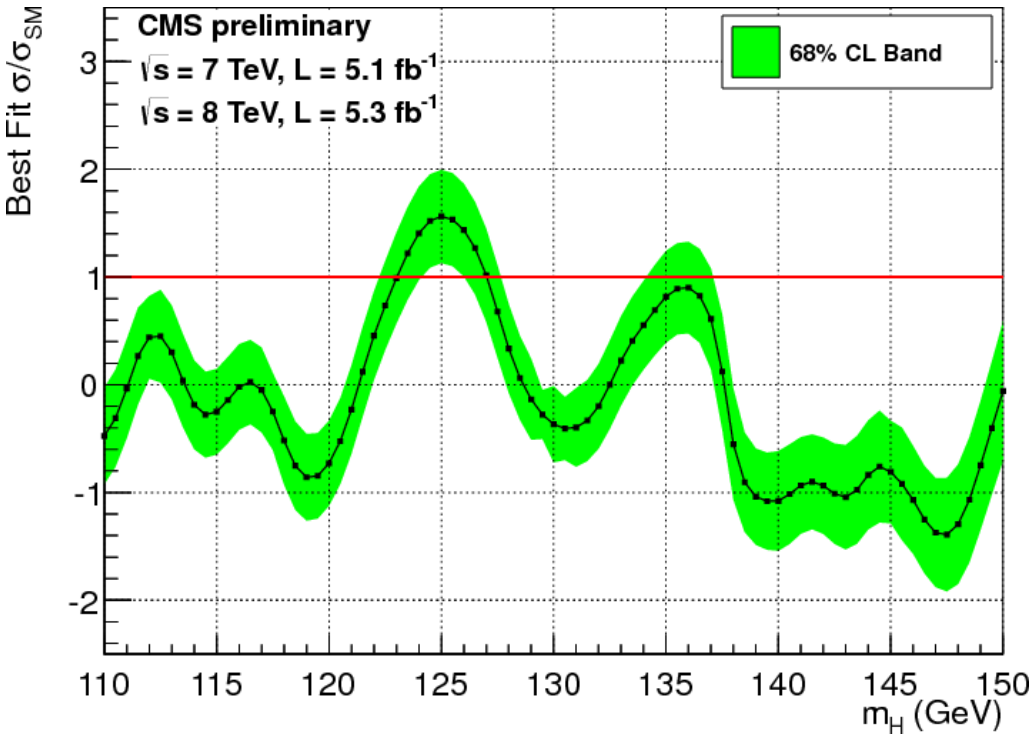
- Large range with expected exclusion below σ_{SM}
- Largest excess at 125 GeV
- Cross-checked with (independent) cut-based and sideband background model:
  - give similar results within experimental uncertainties

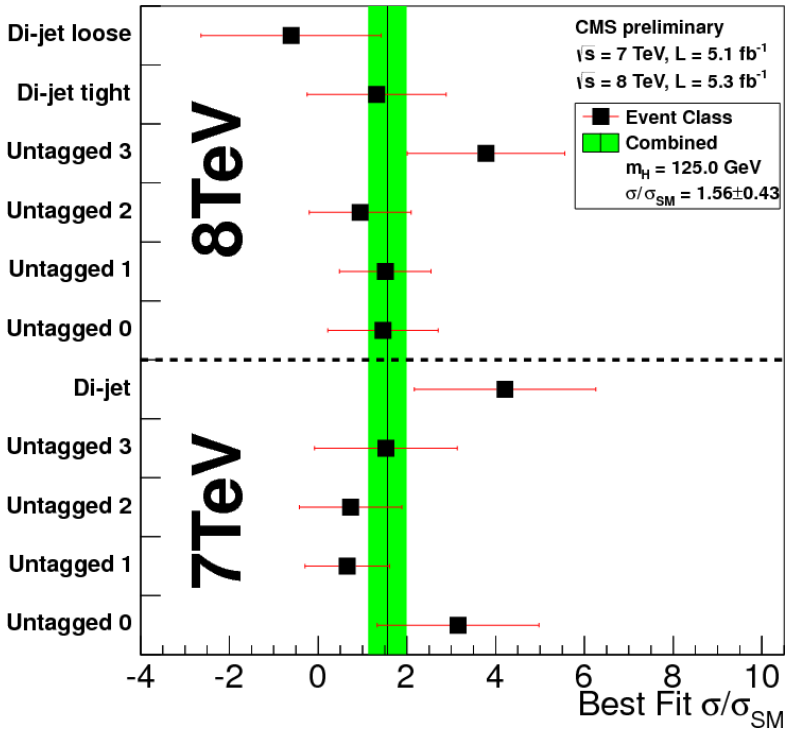
P-Value & Significance



- Minimum local p-value at 125 GeV with a local significance 4.1 σ
- New state around 125 GeV is observed
- Appears consistently in 2011 and 2012 data
- 3.2 σ global significance in the full search range (110-150 GeV)

Signal Strength





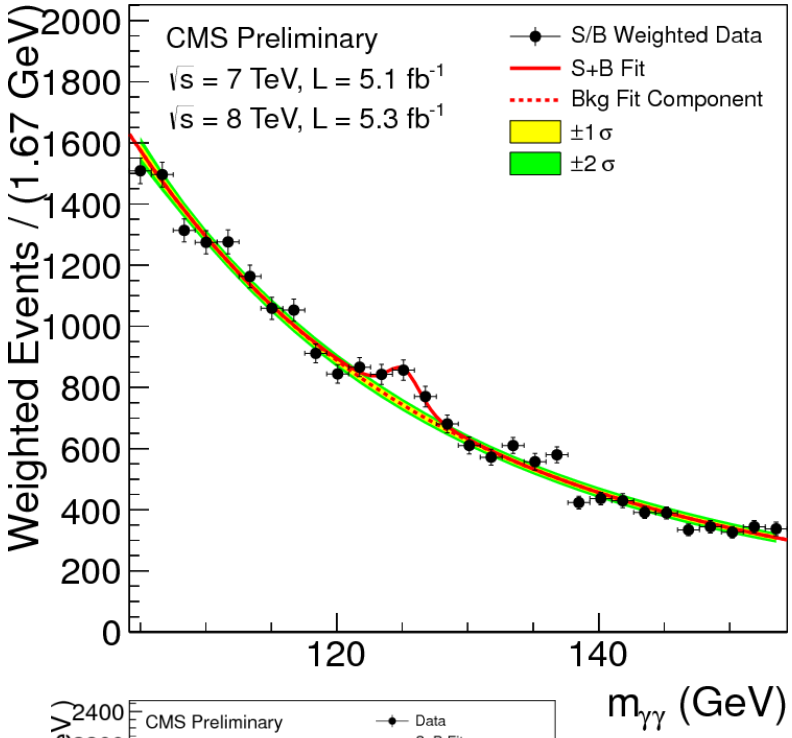
- Combined best fit signal strength at 125 GeV :

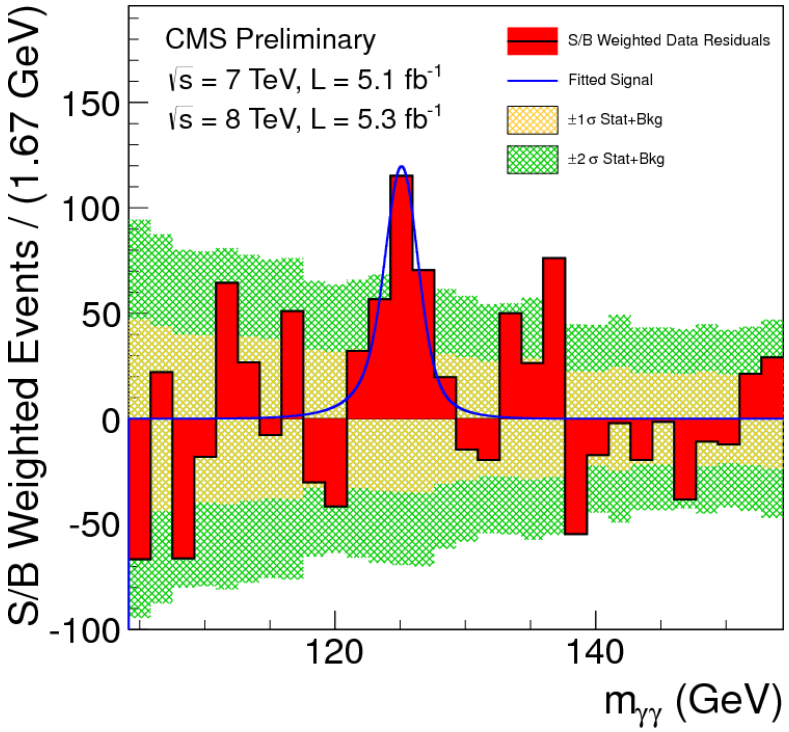
  $\sigma/\sigma_{SM} = 1.56 \pm 0.43$

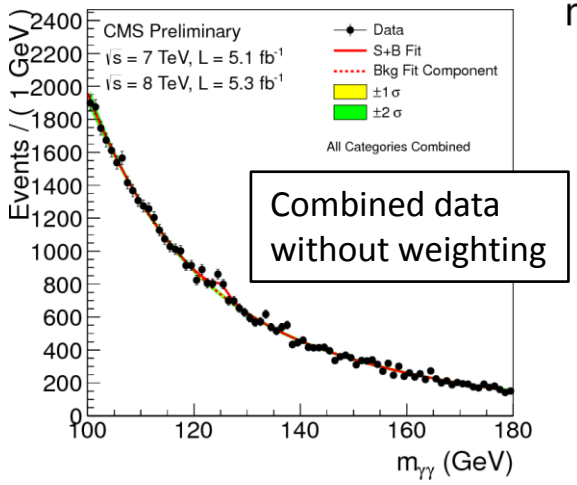
- In agreement with the SM expectation within uncertainties

- Best fit signal strength consistent between different categories

S/B Weighted Mass Distribution





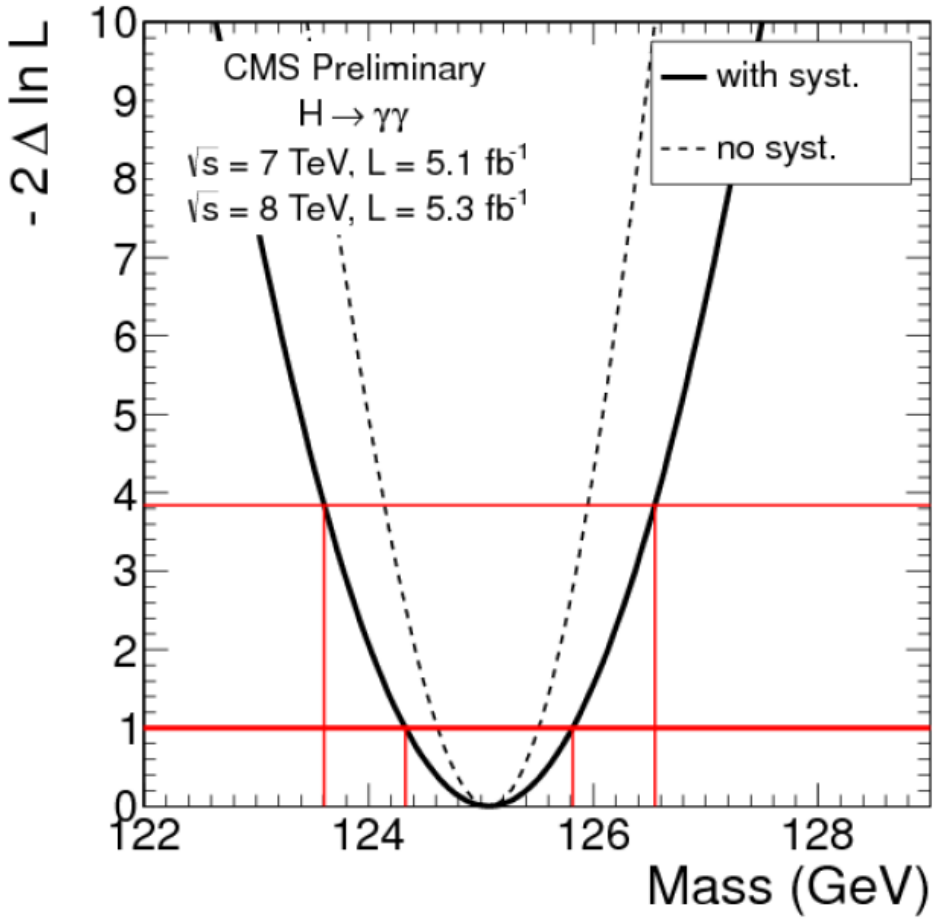


Combined data without weighting

- Sum of mass distributions for each event class, weighted by S/B

Mass Estimation

- To reduce model dependence
  - allow for free signal strength in the MVA and dijet-tagged categories and fit for the common mass m_X.
- The dominant systematic uncertainty
  - Energy scale (0.47% correlates between categories)



$$m_X = 125.1 \pm 0.4(\text{stat}) \pm 0.6(\text{syst})\ \text{GeV}$$

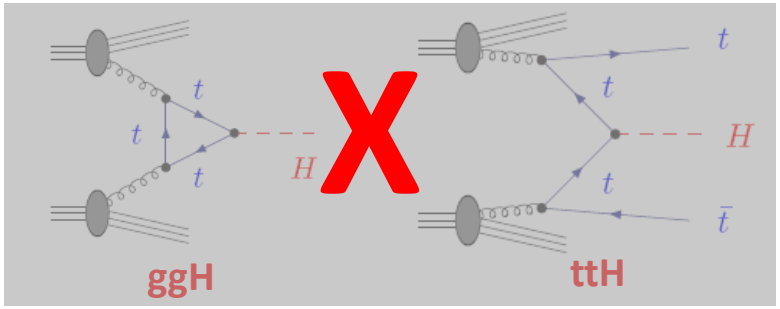
The result in the context of FP model with alternative EWSB mechanism

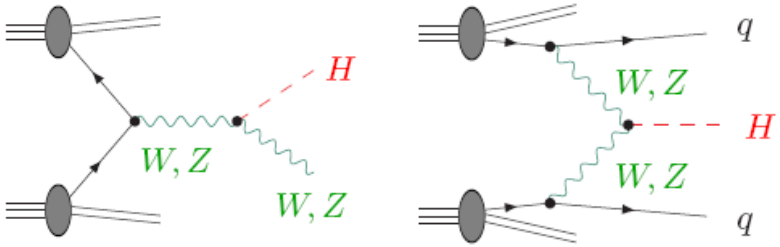
Introduction of Fermiophobic Higgs

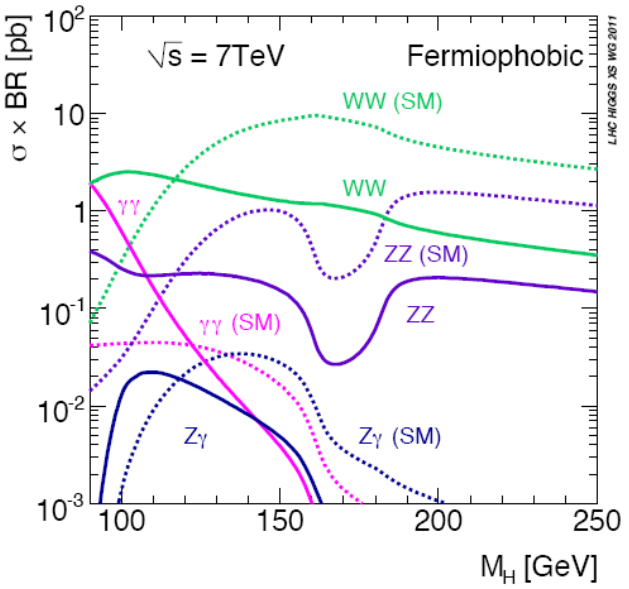
- In the Fermiophobic interpretation the Higgs boson couples at tree level only with W and Z.
- Decay modes: WW, ZZ, Zγ and γγ

- Testing beyond the SM scenario of EWSB (2 HDM)
  - suppressed fermion couplings
    ➔ enhance B(H → γγ)
  - the Fermiophobic model is extreme case
  - **part of a couplings measurement program**

- 2011 result, CERN-PH-EP-2012-174, submitted to JHEP



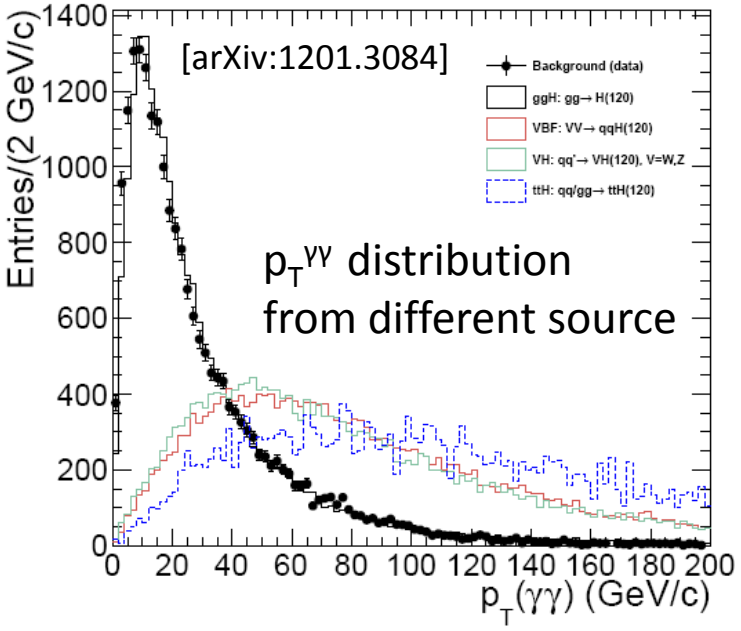


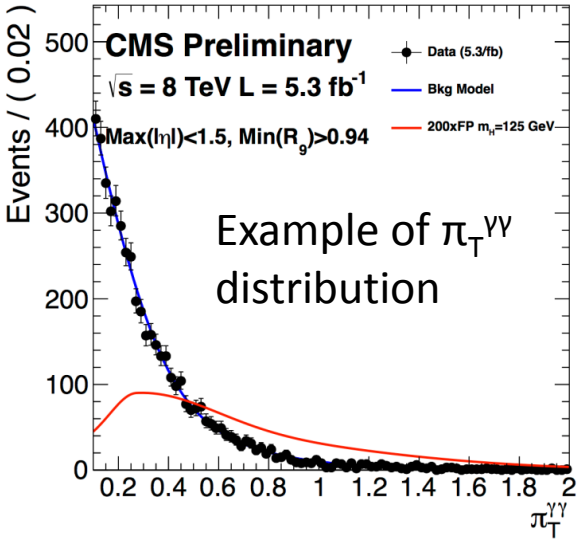


Analysis Strategy of FP Higgs → γγ

- **Cut-based photon ID selection**
- VBF and VH production only
  - boosted kinematics
  - possibility to tag on recoil objects
  - Mutually exclusive sub-channels:

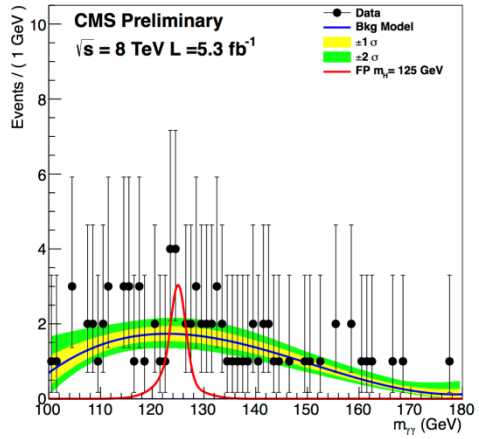
    (S/B at m_H = 120 GeV)
    - 2 dijet-tagged sub-channels (VBF), S/B ∼ 1
    - 2 lepton-tagged sub-channels (VH), S/B ≧ 1
    - 1 MET-tagged sub-channels (VH), S/B < 1
    - 4 untagged sub-channels, S/B << 1

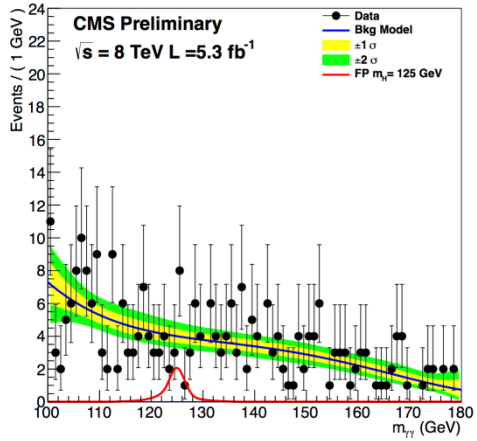


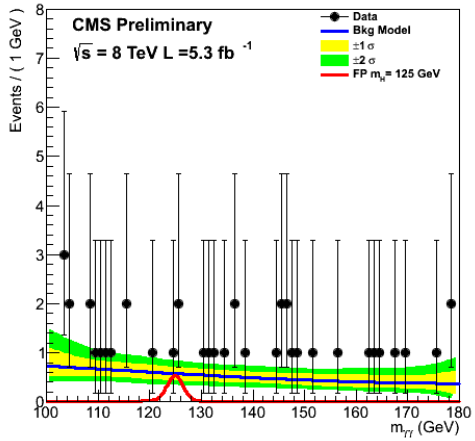


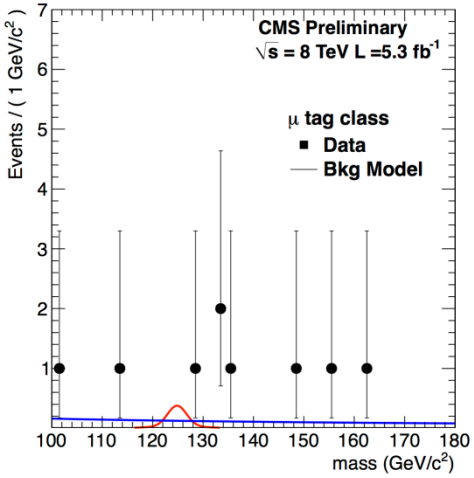
- Use 1D $m_{\gamma\gamma}$ fit for tagged sub-channels
- Use 2D ($m_{\gamma\gamma}$, $\pi_T^{\gamma\gamma}$) fit for untagged sub-channels
  - $\pi_T^{\gamma\gamma}$ (= $p_T^{\gamma\gamma}$/ $m_{\gamma\gamma}$)

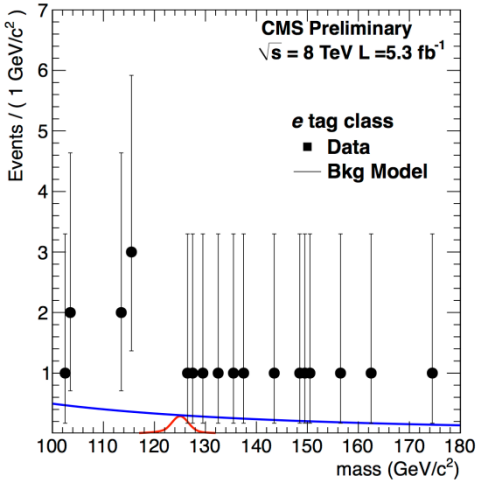
8 TeV Mass Distribution in Exclusive Sub-channels





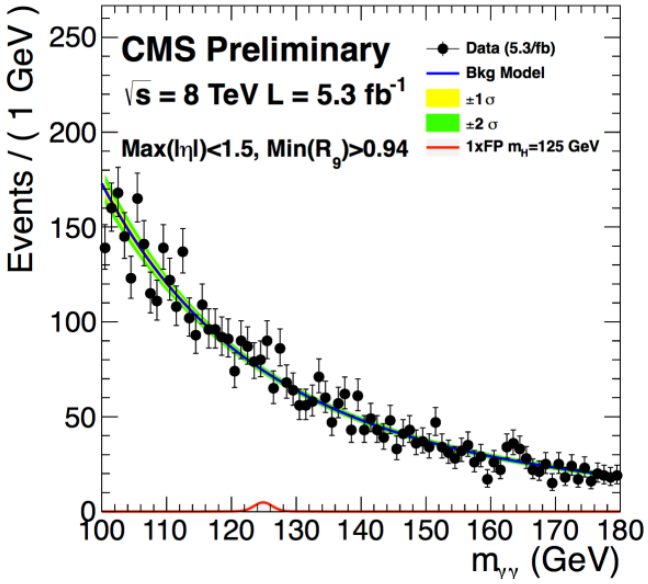


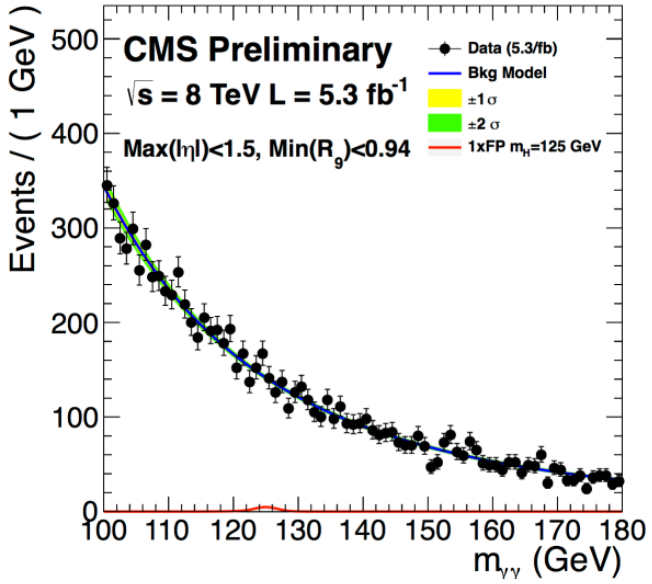


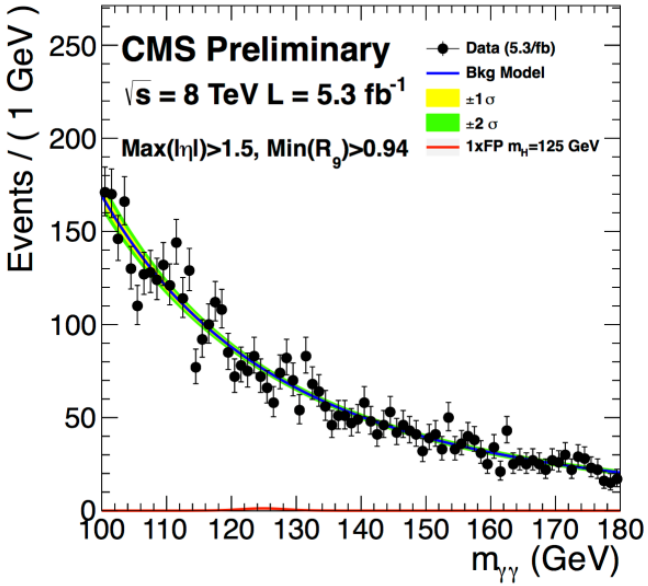


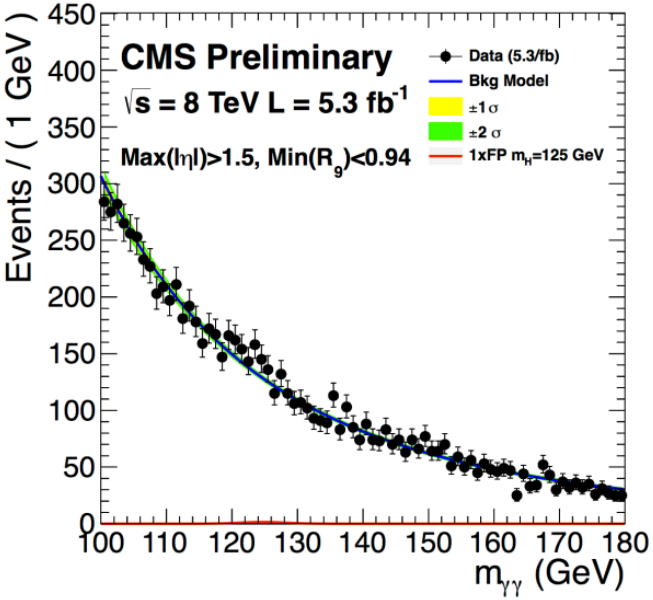
- Background modeling:
  - polynomial shape with order from 3 to 4 for dijet and MET tagged sub-channels
  - Power law for lepton tagged sub-channels
- Potential bias from background model is negligible

8 TeV Mass Distribution in Untagged Sub-channels

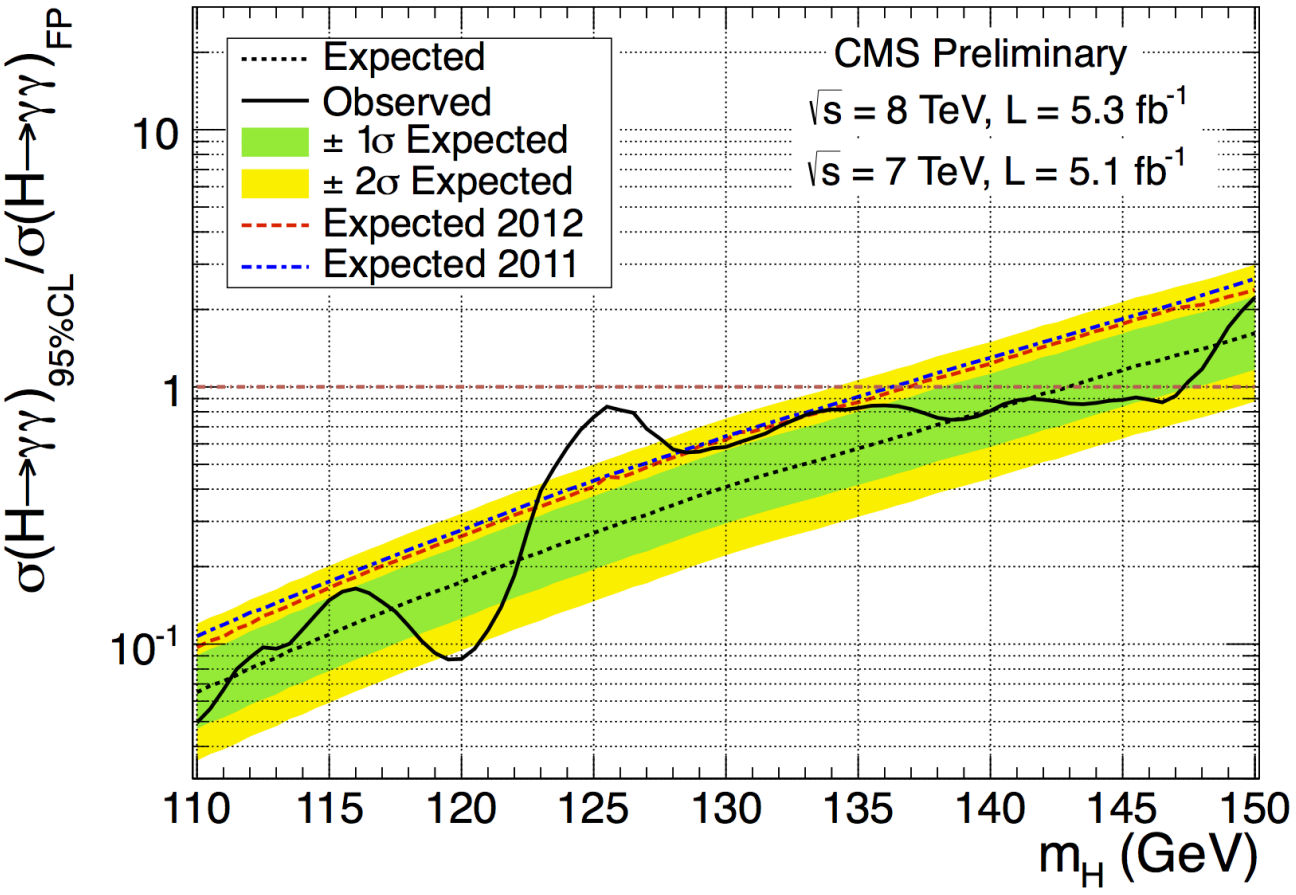






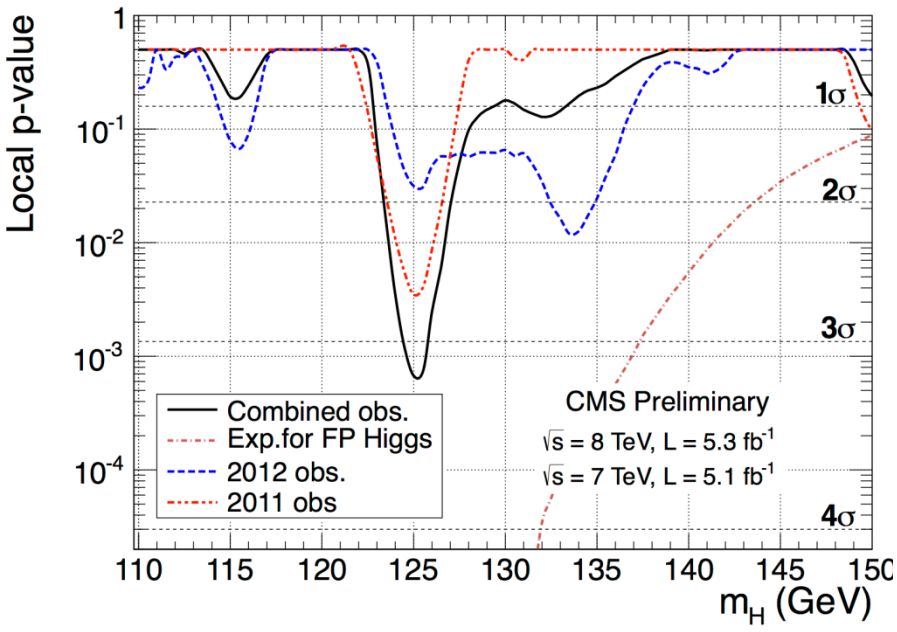


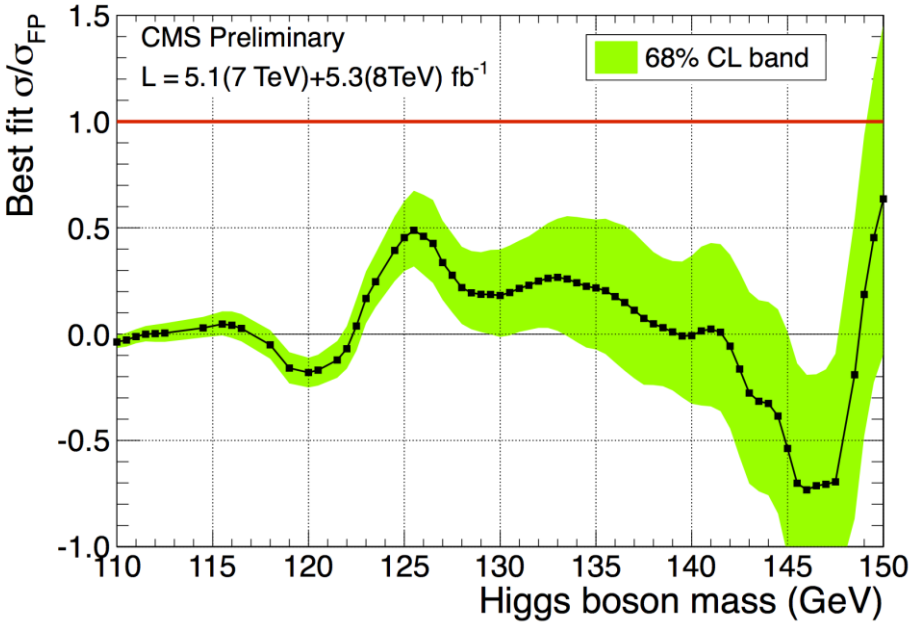
95% CL Exclusion for FP H→γγ



- The exclusion range of FP H → γγ at 95% C.L. is [110-147] GeV.
- At 99% C.L. we exclude the FP H → γγ in the range [110-134] GeV.
- **The new state at 125 GeV observed in SM is at 99% C.L. excluded as FP**

P-Value & Signal Strength (FP)





- Largest excess at 125.5 GeV with a local significance 3.2 σ
- The observed signal strength at 125.5 GeV :

  $\sigma/\sigma_{FP} = 0.49 \pm 0.18$
- The deviation is too weak to be consistent with the Fermiophobic hypothesis

Summary

- The results of the search of H → γγ in CMS have been presented:
  - In contexts of both the Standard Model and the Fermiophobic interpretation.
  - Using 5.1 fb^{-1} 7 TeV and 5.3 fb^{-1} 8TeV pp collision data collected by CMS.
  - We have reached the expected sensitivity in the low mass range.

The Standard Model H → γγ :

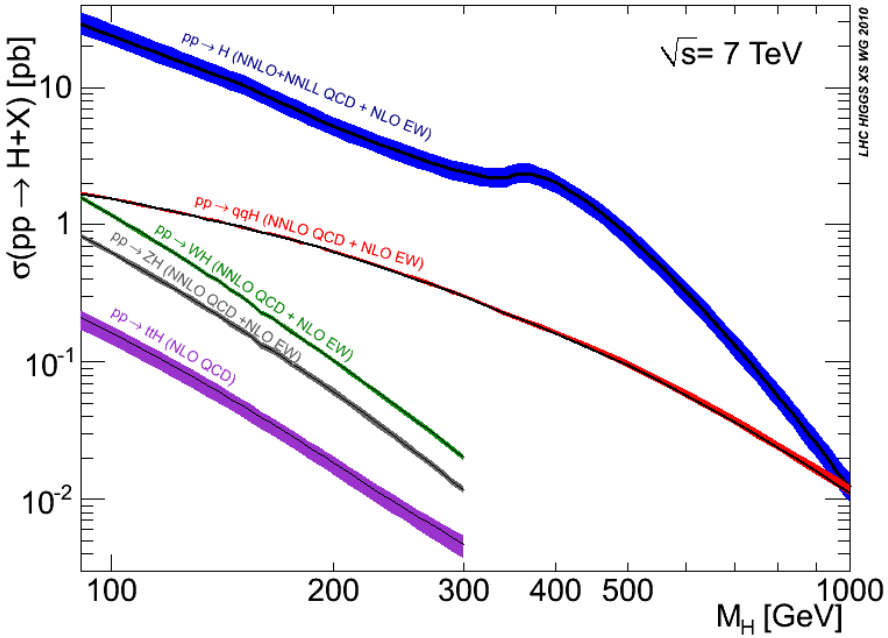
- Evidence of a new resonance decaying into two photons and appears **consistently in 2011 and 2012** data with **a mass of 125.1 ± 0.7 GeV** is observed at **4.1 σ significance**.
- Observed massive state is **compatible with a Standard Model Higgs hypothesis within experimental uncertainties**.

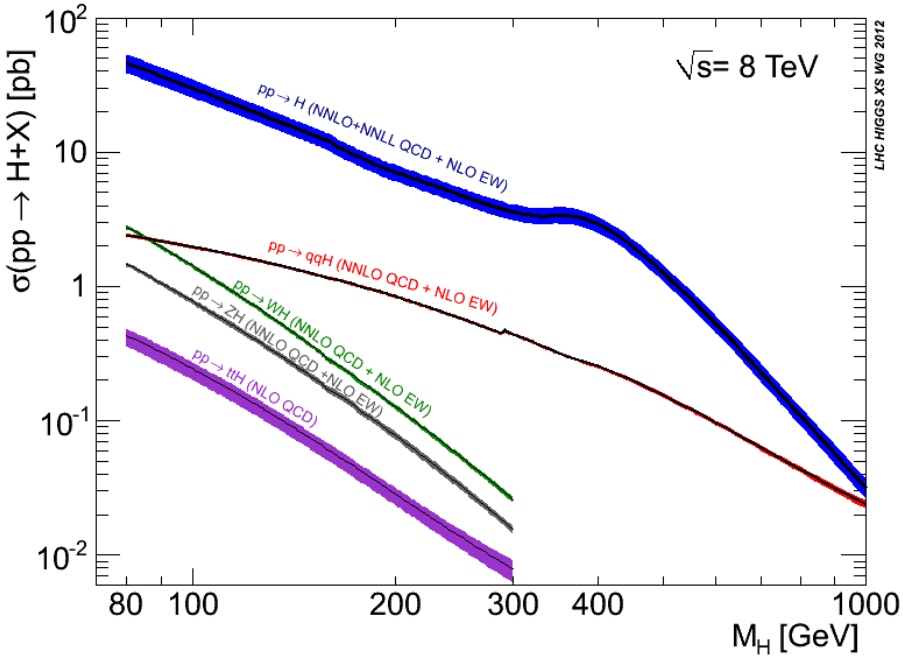
The Fermiophobic H → γγ :

- The FP Higgs boson is excluded at 95% C.L. in the interval [110-147] GeV.
- **At 99% C.L. the largest excess at 125.5 GeV is excluded as a pure FP Higgs.**

Backup

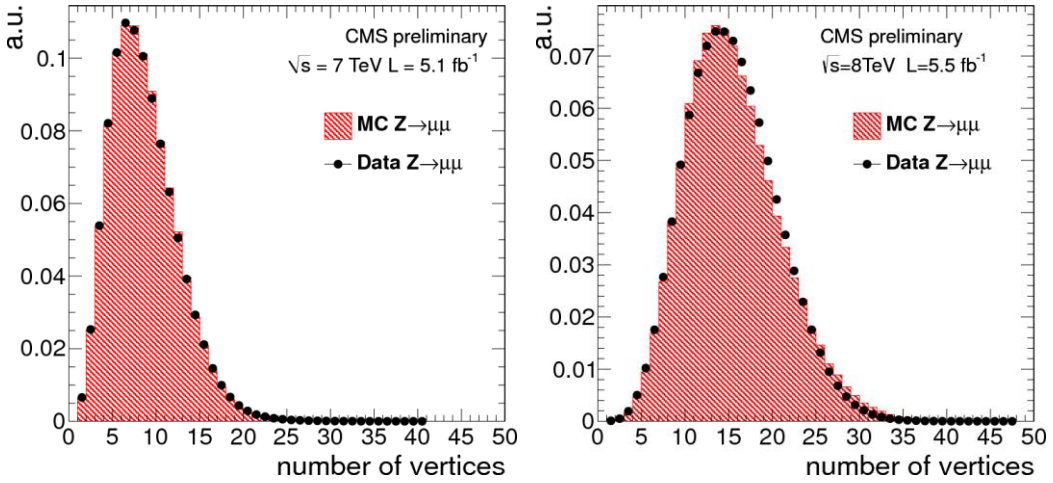
Higgs production cross sections



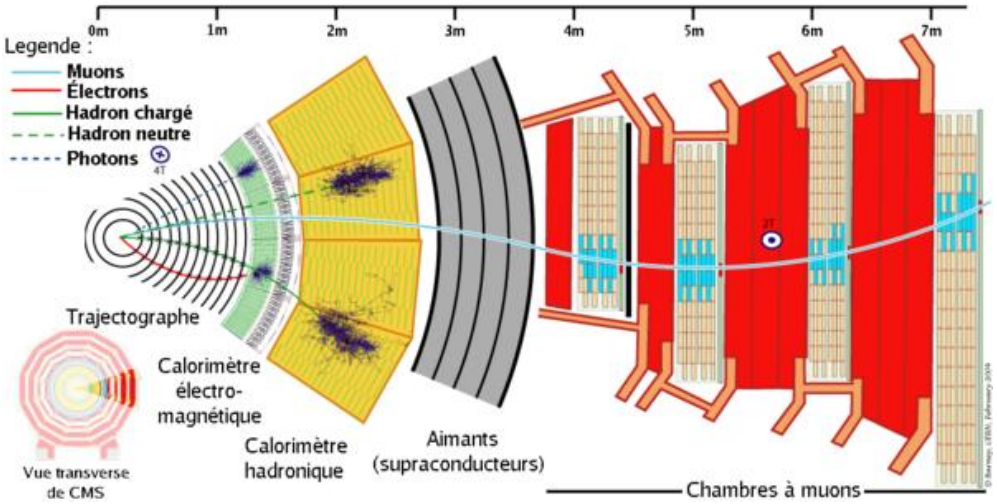


Data and Reconstruction Challenge

- Increasing pile-up environment in 2012 data taking
  - mean pile-up (PU) 19 events (MC reweighting)

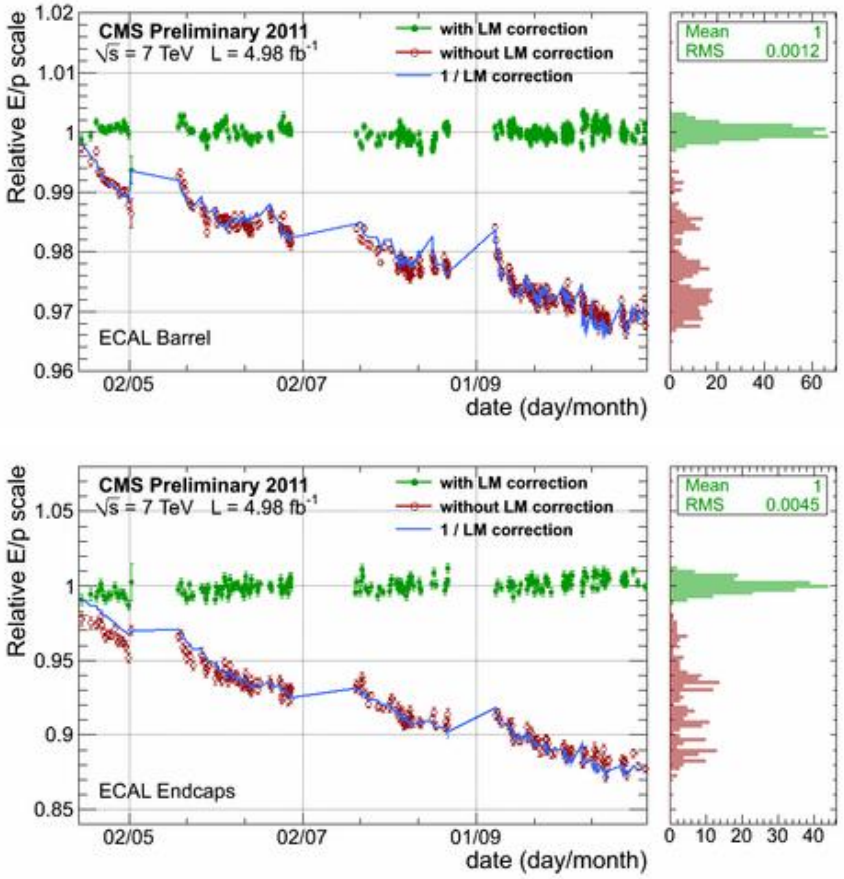


- Particle Flow (PF) algorithm:
  - provides a global event description in form of list of particles
  - improvements in jet, τ and E_T^{miss} measurement
- Improves reconstruction performance at high PU



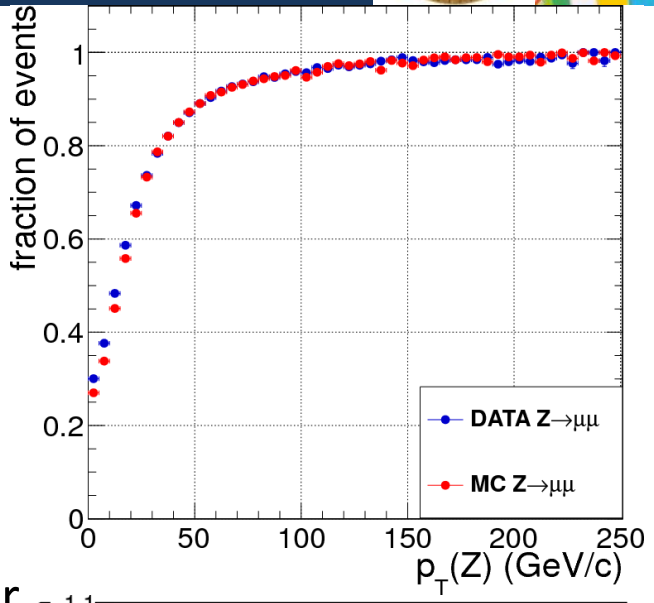
ECAL Calibration

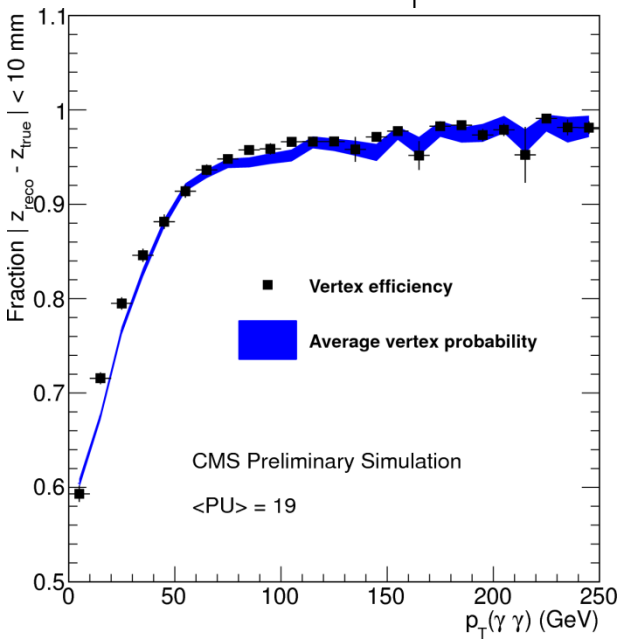
- Dedicated calibration scheme:
  - inter-crystal calibration: π^0, η
  - crystal transparency correction (laser monitoring system)
- The energy scale stability after the response corrections:
  - barrel: 0.12% (2.5% loss)
  - endcap: 0.45% (10% loss)
- Exploit W → eν (E/p) and Z^0 → ee control samples to derive energy scale and resolution systematics



Vertex Location

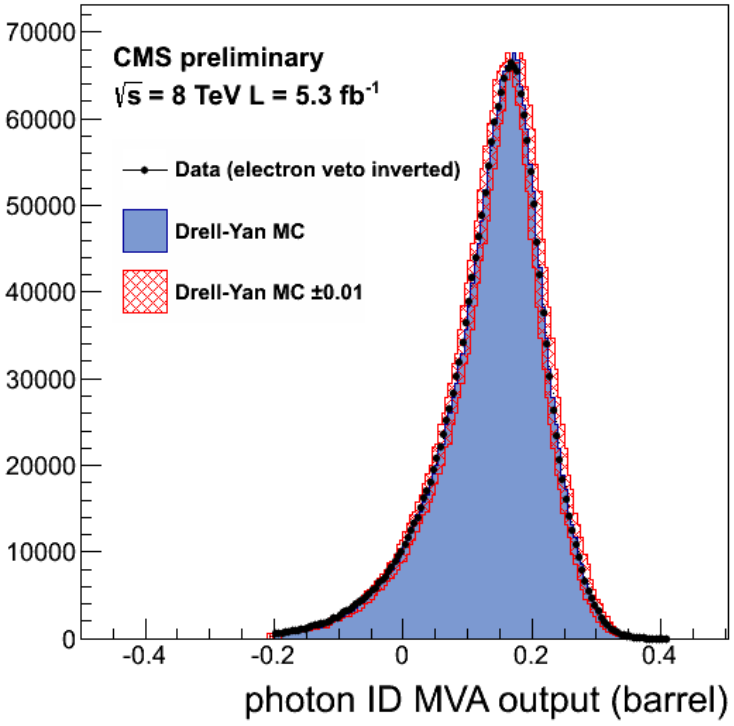
- Signal $m_{\gamma\gamma}$ resolution
  - The opening angle between photon pair affects the invariant mass and resolution
  - Depend on the correct position of the primary vertex
- Vertex identification
  - Use MVA Boosted Decision Tree method
  - Input information from tracks and photon pair
- High efficiency for the boosted Higgs:
  - presence of hard recoil objects
  - efficiency falls down with PU
- Correct vertex finding probability also estimated using a diphoton BDT

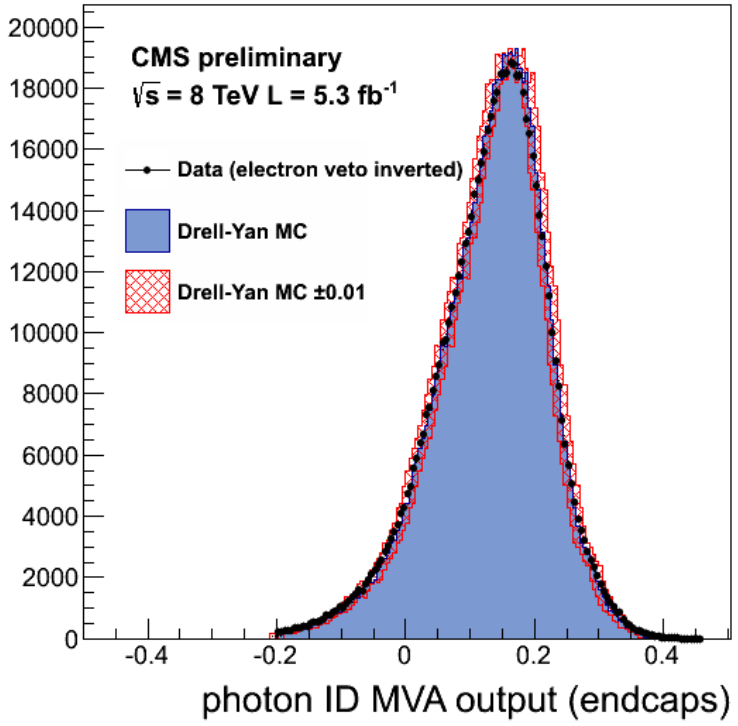




MVA Photon ID

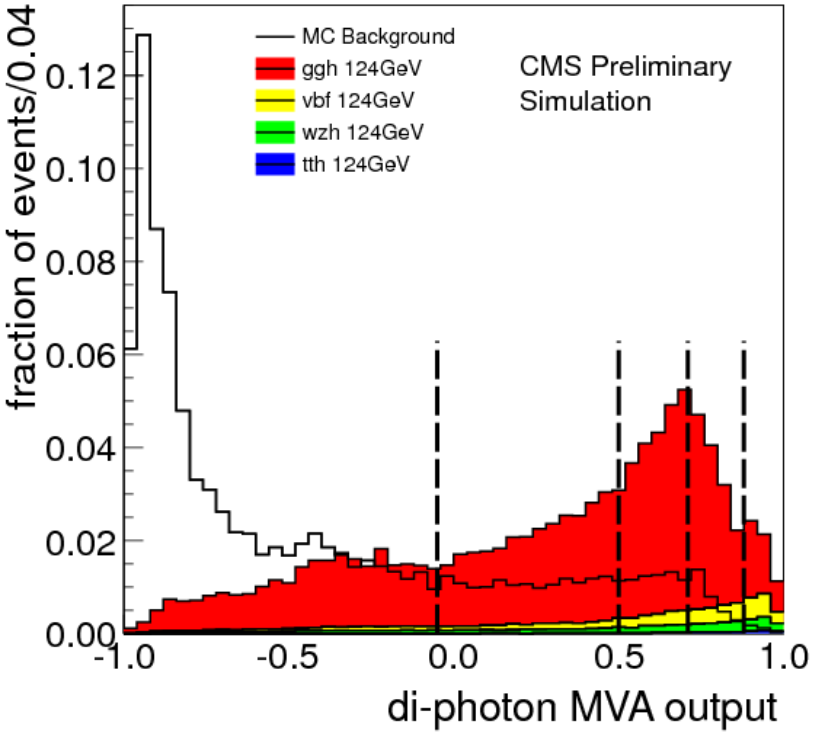
- MVA Photon ID separates prompt photons from π^0 emerged from jets
  - MVA BDT inputs
    - Shower Topology Variables (preshower shape in endcaps)
    - Isolation Variables
    - The median energy density per solid angle
    - Supercluster pseudorapidity





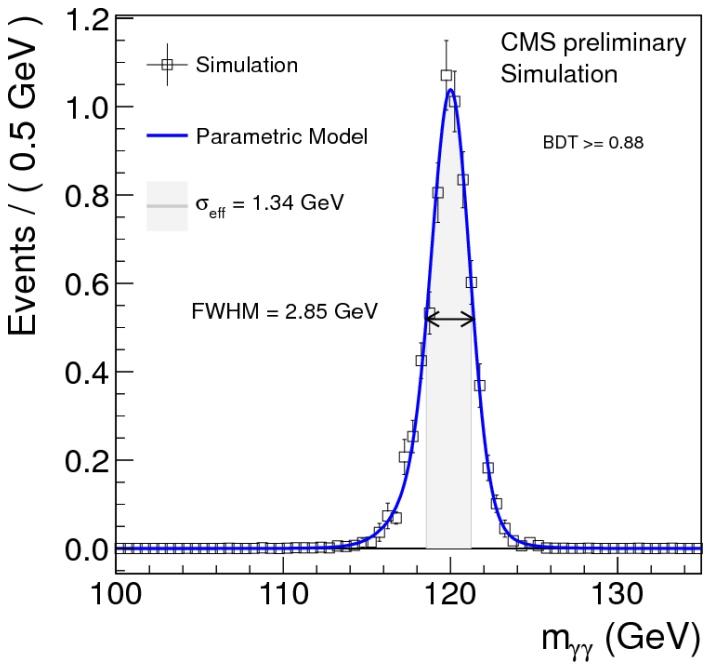
Event Categorization (MVA)

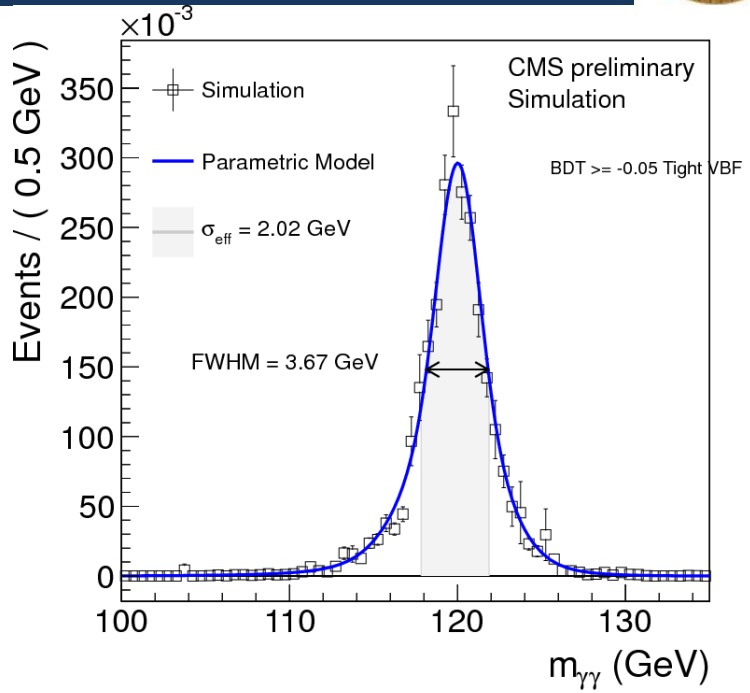
- The MVA classifies with a high score events with:
  - signal-like kinematic characteristics
  - predominantly giving high score to high $p_T^{\gamma\gamma}$
  - good diphoton mass resolution
  - photon-like values from the photon identification BDT
- MVA input variables are designed to be mass independent
- Fit $m_{\gamma\gamma}$ in each of 6 categories:
  - 4 diphoton MVA categories
  - 2 dijet-tagged categories



- MVA categories based on diphoton MVA output
- Boundaries optimized to give the best expected limit using MC background

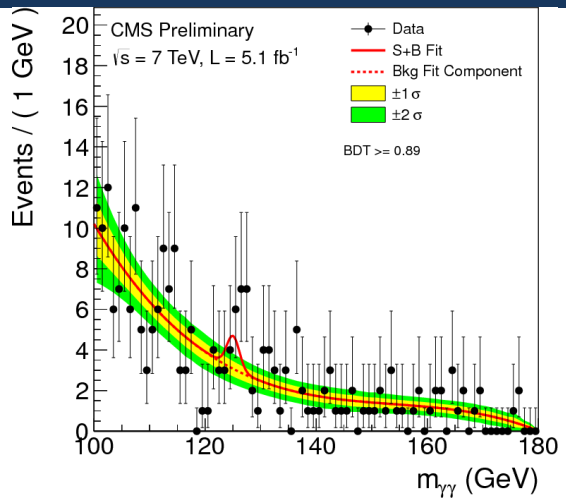
Signal Model & Mass Resolution

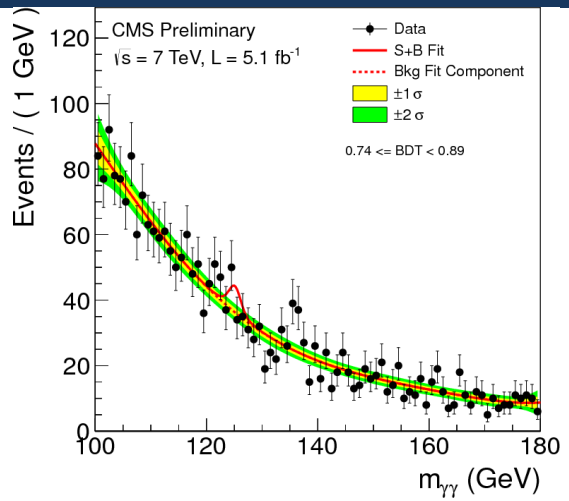


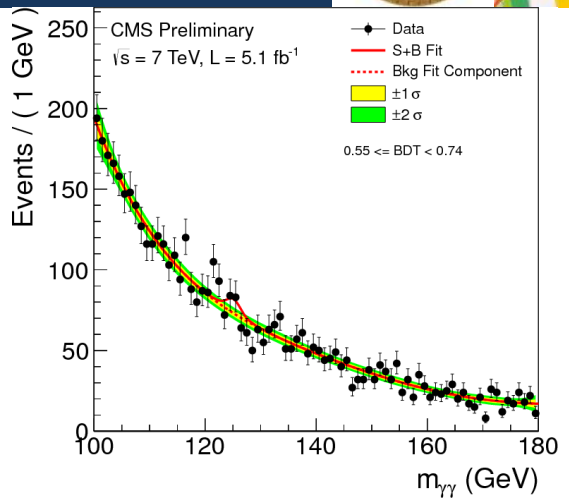


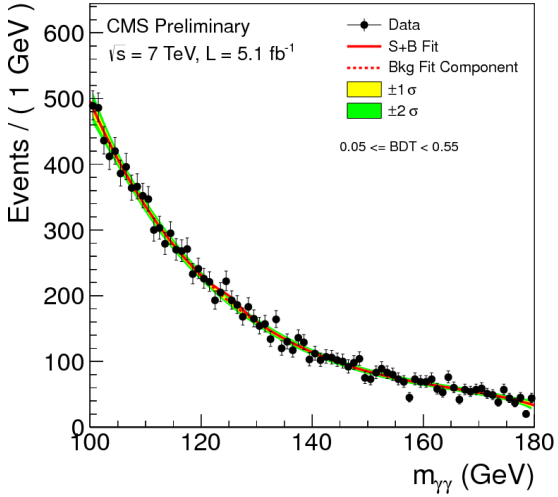
Event classes		expected signal (m_H=125 GeV) Total	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)	
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	1.38	1.23	7.4	± 0.6
	Untagged 1	21.0	1.53	1.31	54.7	± 1.5
	Untagged 2	30.2	1.94	1.55	115.2	± 2.3
	Untagged 3	40.0	2.86	2.35	256.5	± 3.4
	Dijet tight	2.6	2.06	1.57	1.3	± 0.2
	Dijet loose	3.0	1.95	1.48	3.7	± 0.4

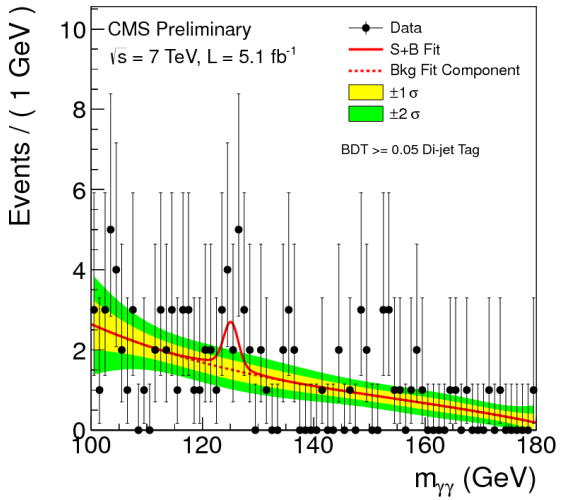
7 TeV Mass Distributions (SM H→γγ)





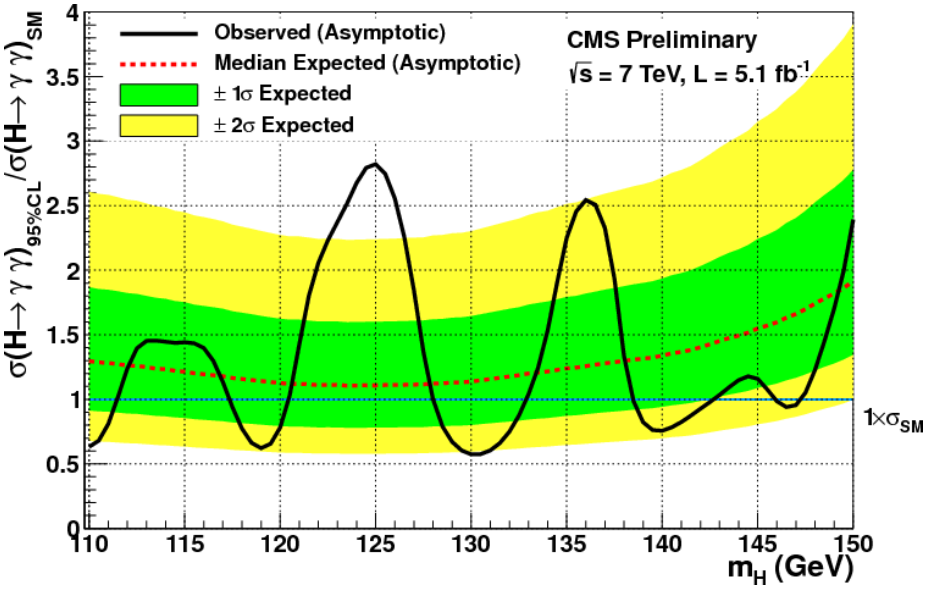


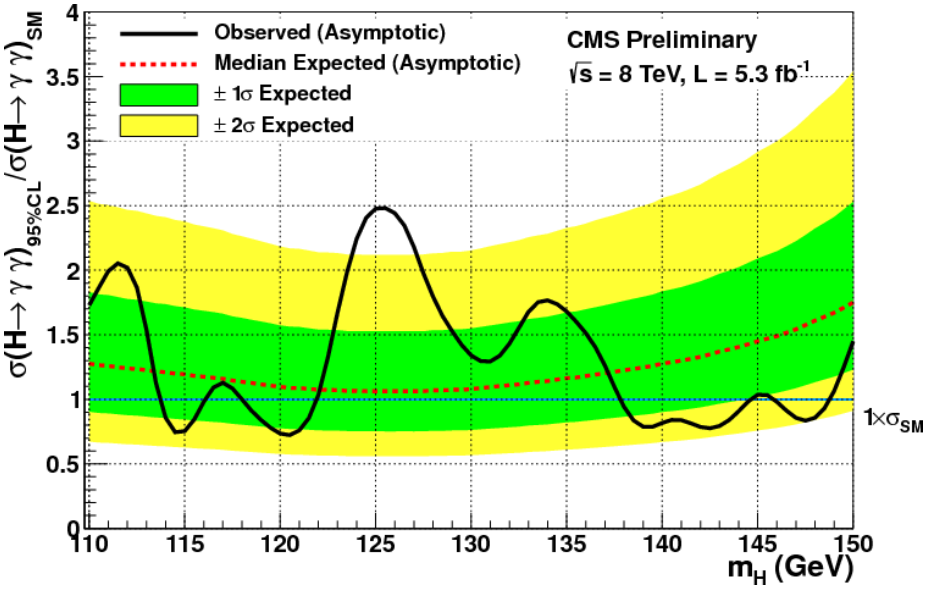




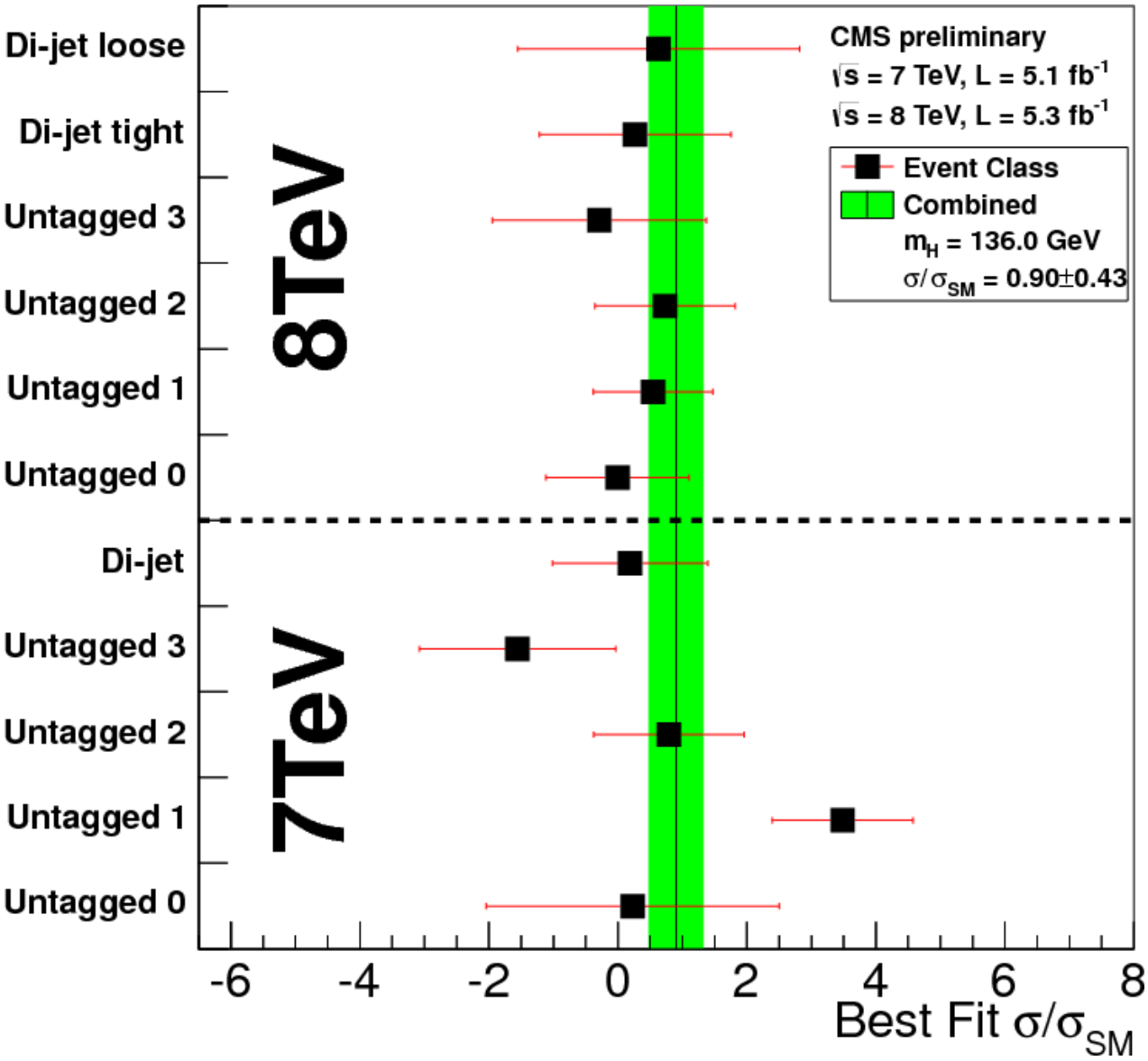
- Potential bias from background model is negligible
  - ≦ 20% of statistical uncertainty

95% C.L. Exclusion Limit (SM H→γγ MVA)

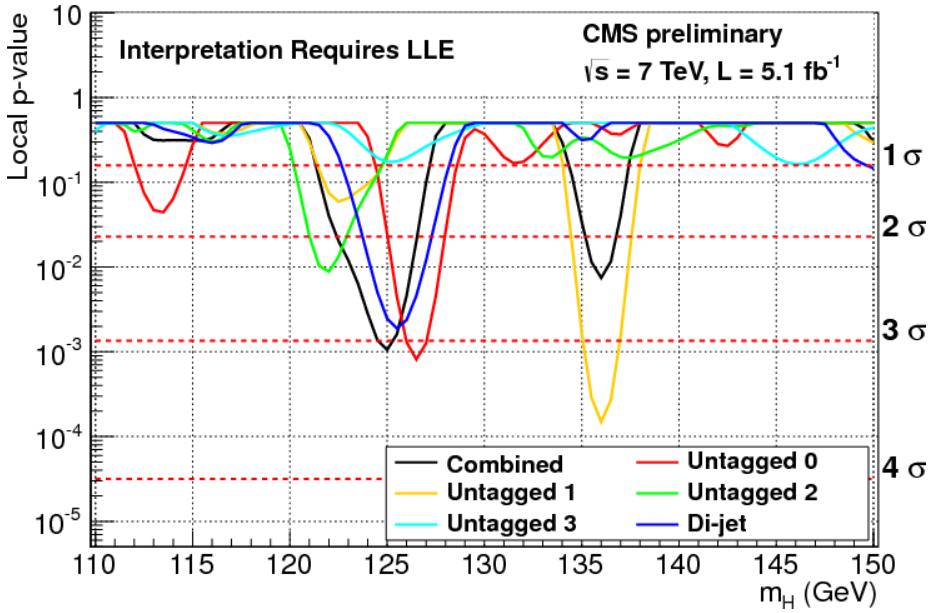


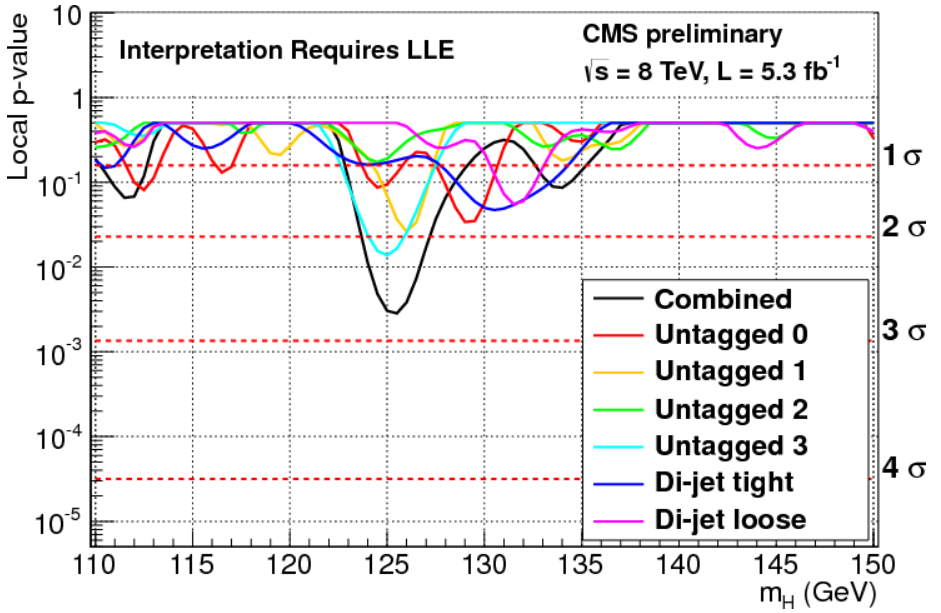


Signal Strength at 136 GeV

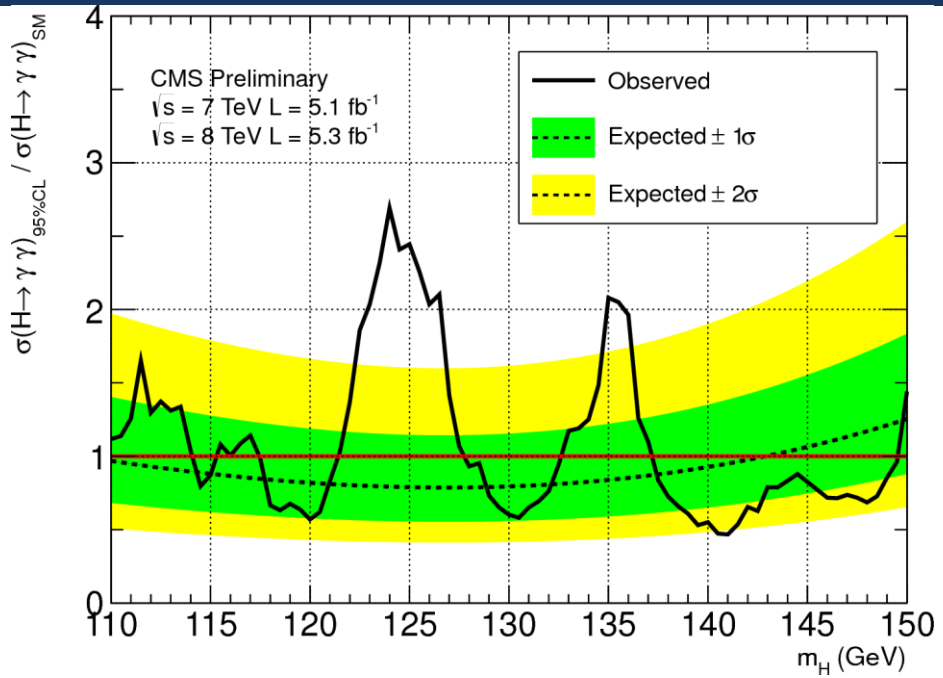


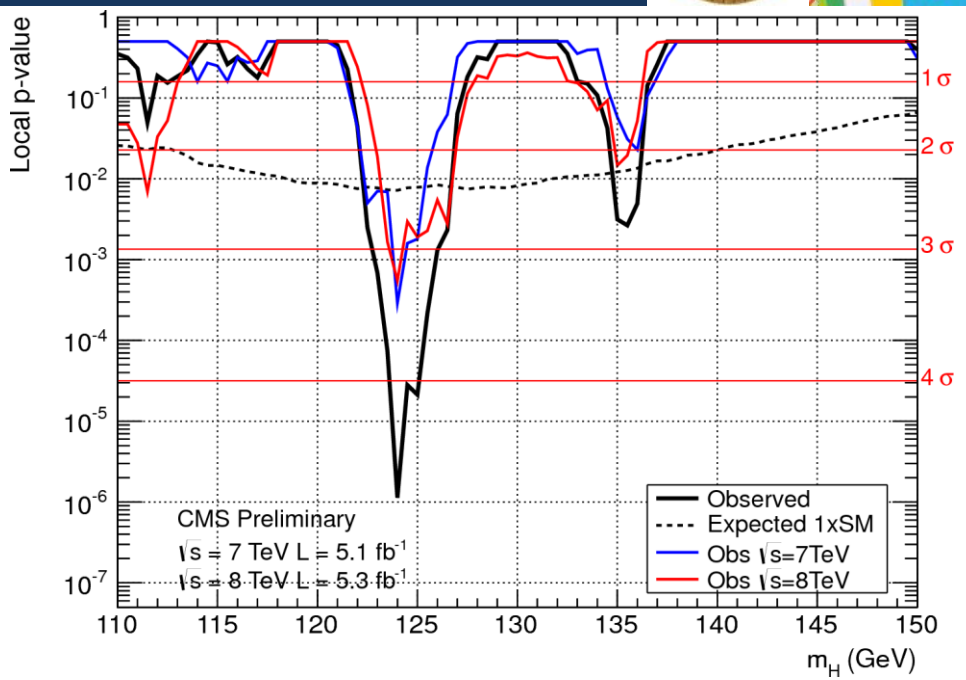
P-values per Class (SM H→γγ MVA)

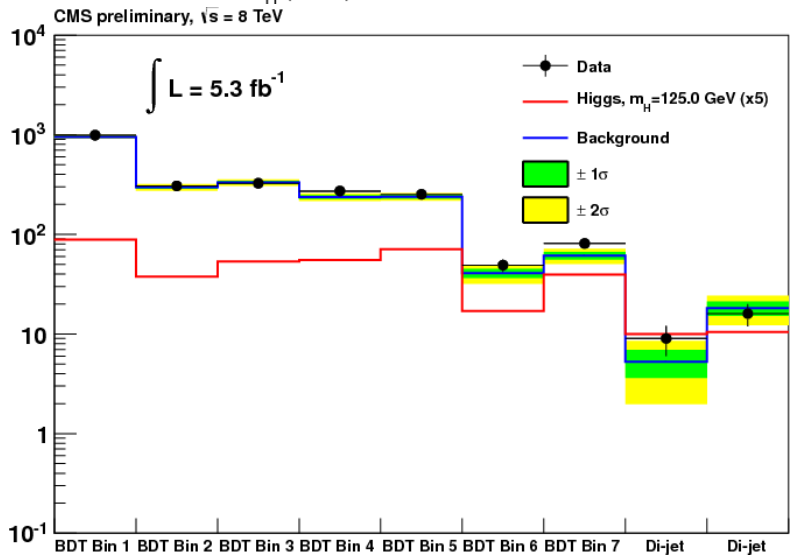




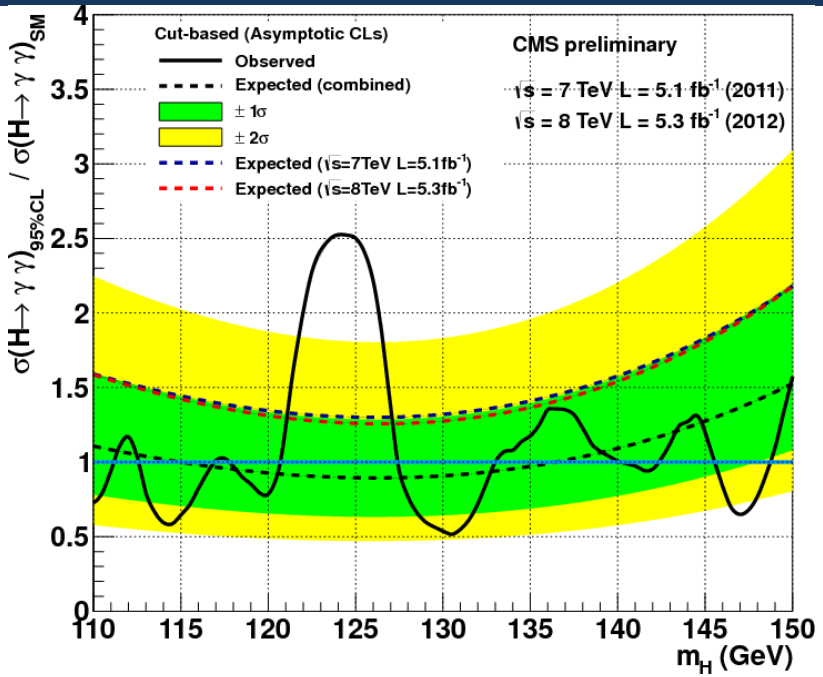
Results of SM H→γγ Mass Sideband Background MVA

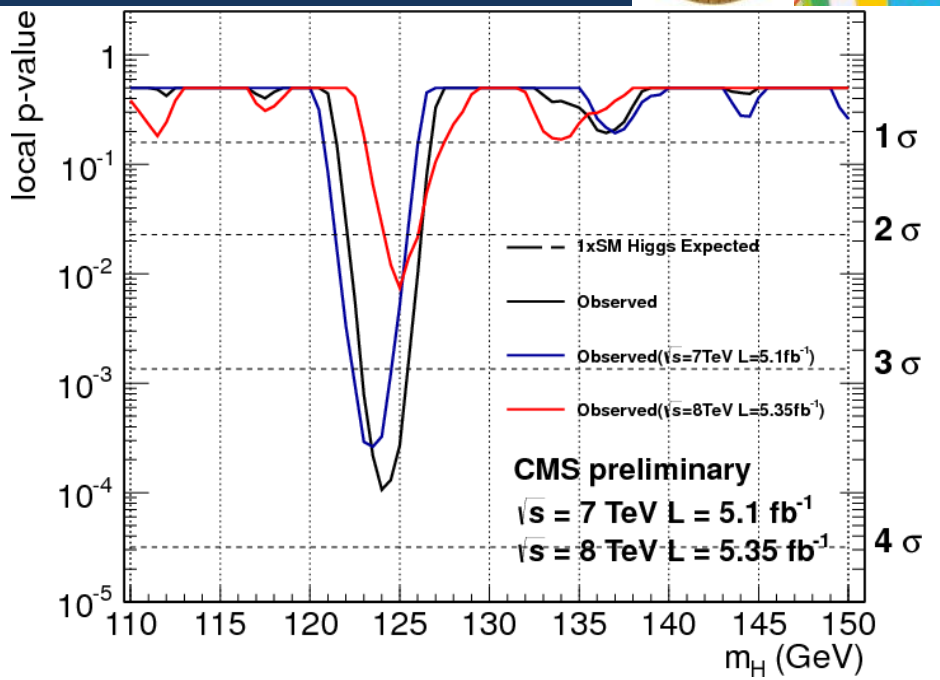


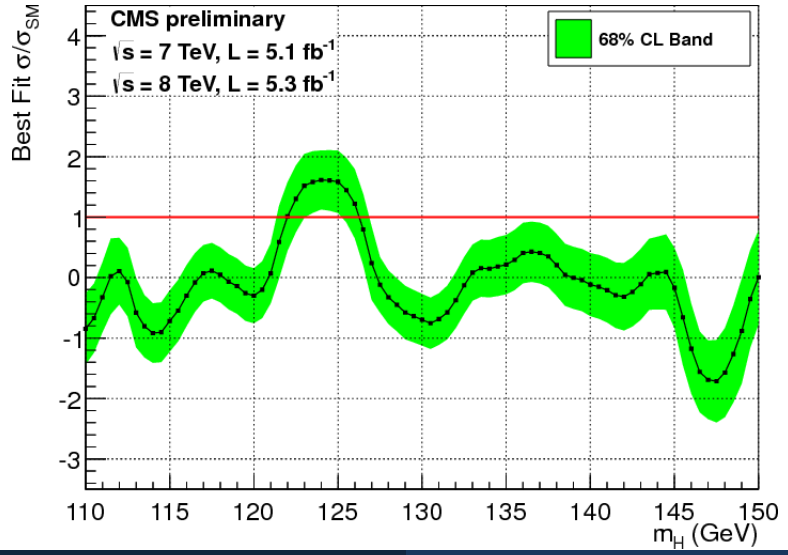




Results of SM H→γγ Cut-based Analysis

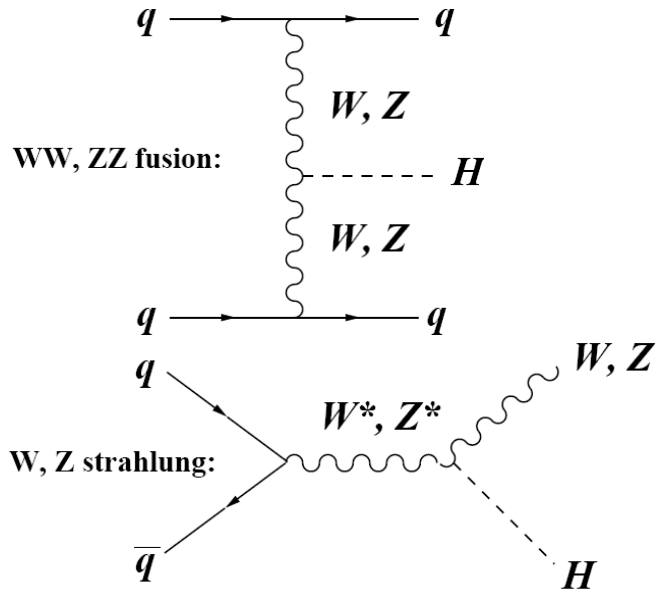


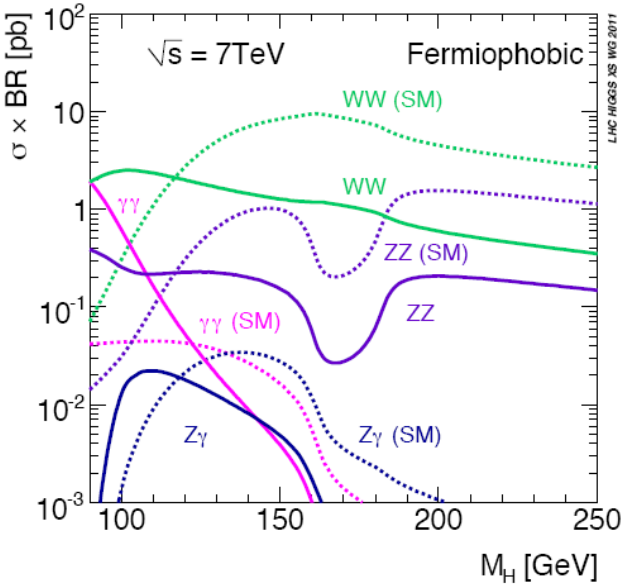




Fermiophobic Higgs

- In the Fermiophobic interpretation the Higgs boson couples at tree level only with W and Z.
- Decay modes: WW, ZZ, Zγ and γγ
- Testing beyond the SM scenario of EWSB (2 HDM)
  - suppressed fermion couplings
    ➔ enhance B(H → γγ)
  - the Fermiophobic model is extreme case
  - **part of a couplings measurement program**
- LEP, Tevatron and ATLAS excluded at 95% C.L. a Fermiophobic Higgs boson lighter than 121 GeV.

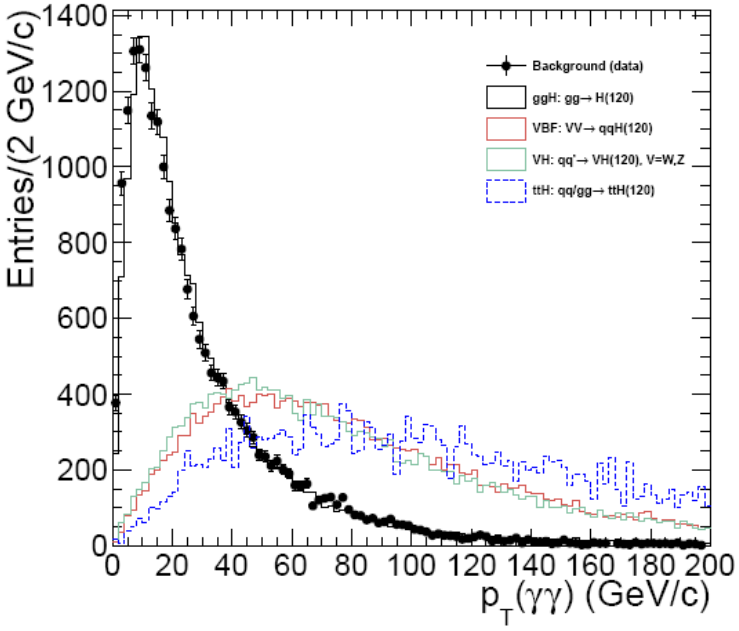




Analysis Strategy of FP Higgs → γγ

- Cut-based analysis
- VBF and VH production
  - boosted kinematics
  - possibility to tag on recoil objects
- Mutually exclusive sub-channels:

  (S/B at m_H = 120 GeV)
  - 2 dijet-tagged classes (VBF)
    - S/B ∼ 1
  - 2 lepton-tagged classes (VH)
    - S/B ≧ 1
  - 1 MET-tagged classes (VH)
    - S/B < 1
  - 4 untagged classes based on pseudorapidity and shower shape
    - S/B << 1



[arXiv:1201.3084]

channel	leading photon	trailing photon
dijet-tag	p_T/m>60/120	p_T >25 GeV
lepton-tag	p_T/m>45/120	p_T >25 GeV
MET-tag	p_T/m>45/120	p_T >25 GeV
untagged	p_T/m>40/120	p_T/m>30/120

The order of event tagging:
muon → electron → di-jet → MET → untagged

FP H→γγ Exclusive Sub-channels

- Di-jet tag
  - The same selection as cut-based di-jet selection in SM analysis
  - 1 category in 2011 and 2 categories in 2012 analysis
- Lepton tag
  - CMS Standard cut-based lepton ID updated in 2012 analysis to cope with new data taking conditions
  - ΔR(l, γ) > 1. (reject FSR γ), |ΔM(eγ, Z)| > 5 GeV (reject Zγ)
- MET tag (only 2012 analysis)
  - γ in the endcap are not considered due to negligible contribution
  - MET > 70 GeV

	$E_{\mathrm{T}}^{\mathrm{miss}}$ tag	Dijet high m_{jj}	Dijet low m_{jj}	Lepton tag
Signal ($m_{\mathrm{H}} = 120\,\mathrm{GeV}$)	3.8	21.5	15.3	5.7
Data ($115 < m_{\gamma\gamma} < 125\,\mathrm{GeV}$)	4	20	36	6
Data ($100 < m_{\gamma\gamma} < 180\,\mathrm{GeV}$)	41	84	271	30
σ_{eff} (GeV)	1.91	1.98	2.02	2.0

2D-fit for Untagged Sub-channels

- Event classification based on η_{SC} and shower shape properties of photons
- Exploit harder VBF, VH $p_T^{\gamma\gamma}$ spectrum: $\pi_T^{\gamma\gamma}$ (= $p_T^{\gamma\gamma}$/ $m_{\gamma\gamma}$)> 0.1
- In the untagged class a 2D model is constructed by using ($m_{\gamma\gamma}$, $\pi_T^{\gamma\gamma}$) :

$$\mathcal{L}(\mathrm{m}|\vec{\theta}) = \frac{e^{-\mu_s n_s + n_b}}{N!} \prod_{i=1}^{N} (\mu_s n_s \mathcal{P}_s^i(\mathrm{m}|\vec{\theta}_1) + n_b \mathcal{P}_b^i(\mathrm{m}|\vec{\theta}_2))$$

$$\mathcal{P}_s^i = \mathcal{M}_s^i(\mathrm{m}^{\gamma\gamma}|\vec{\theta}) \times \mathcal{K}_s^i(\pi_{\mathrm{T}}^{\gamma\gamma}|\vec{\theta})$$

$$\mathcal{P}_b^i = \mathcal{M}_b^i(\mathrm{m}^{\gamma\gamma}, \pi_{\mathrm{T}}^{\gamma\gamma}|\vec{\theta}) \times \mathcal{K}_b^i(\pi_{\mathrm{T}}^{\gamma\gamma}|\vec{\theta})$$

$$\mathcal{M}_s(\mathrm{m}^{\gamma\gamma}|m_0, \sigma_{CB}, \alpha, n, f_G, \sigma_G) = (1 - f_G)\mathcal{C}(\mathrm{m}^{\gamma\gamma}|m_0, \sigma_{CB}, \alpha, n) + f_G \mathcal{G}(\mathrm{m}^{\gamma\gamma}|m_0, \sigma_G)$$

Crystal-ball *Gaussian*

$$\mathcal{K}_s(\pi_{\mathrm{T}}^{\gamma\gamma}|\mu_c, \sigma_c, f_c, \mu_o, \sigma_L, \sigma_R) = f_c \mathcal{G}(\pi_{\mathrm{T}}^{\gamma\gamma}|\mu_c, \sigma_c) + (1 - f_c)\mathcal{B}(\pi_{\mathrm{T}}^{\gamma\gamma}|\mu_o, \sigma_L, \sigma_R)$$

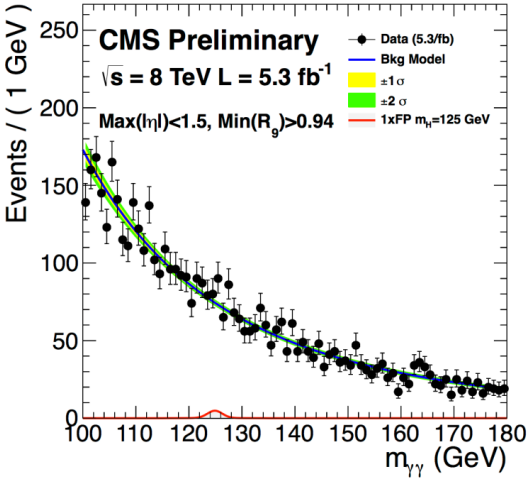
Gaussian *Bifurcated Gaussian*

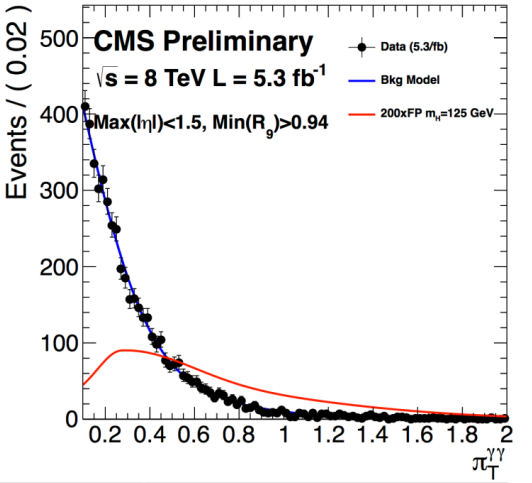
$$\mathcal{M}_b(\mathrm{m}, \pi_{\mathrm{T}}|a_0, a_1) = \mathrm{m}^{a_0 + a_1 \pi_{\mathrm{T}}}$$

Power law

$$\mathcal{K}_b(\pi_{\mathrm{T}}^{\gamma\gamma}|\tau_B, f_d, \sigma_G) = f_d \mathcal{E}(\pi_{\mathrm{T}}^{\gamma\gamma}|\tau_B) + (1 - f_d)\mathcal{G}(\pi_{\mathrm{T}}^{\gamma\gamma}|0, \sigma_G)$$

Exponential *Gaussian*





	Untagged			
	(a)	(b)	(c)	(d)
Signal ($m_H = 120$ GeV)	29.2	37.9	18.5	22.0
Data ($115 < m_{\gamma\gamma} < 125$ GeV)	683	1712	902	1755
Data ($100 < m_{\gamma\gamma} < 180$ GeV)	4992	9546	5105	8574
σ_{eff} (GeV)	1.44	2.00	3.72	3.76

2012 Cut-based Photon Selection

	barrel		endcap	
	$R_9 > 0.94$	$R_9 < 0.94$	$R_9 > 0.94$	$R_9 < 0.94$
PF isolation sum, chosen vertex	6	4.7	5.6	3.6
PF isolation sum worst vertex	10	6.5	5.6	4.4
Charged PF isolation sum	3.8	2.5	3.1	2.2
$\sigma_{i\eta i\eta}$	0.0108	0.0102	0.028	0.028
H/E	0.124	0.092	0.142	0.063
R_9	0.94	0.298	0.94	0.24

- CiC4PF Photon ID cuts
- Use PF Isolation to improve performance at 2012 high PU

Selection Cuts for FP Exclusive Sub-channels

Electron ID cuts

	loose WP	
	Barrel	Endcap
$\sigma_{i\eta i\eta}$	0.01	0.03
$\Delta\phi_{in}$	0.015	0.010
$\Delta\eta$	0.007	0.009
$\sigma_{i\eta i\eta}$	0.01	0.03
H/E	0.12	0.10
d_0 w.r.t. selected vertex	< 0.02 cm	
d_z w.r.t. selected vertex	< 0.2 cm	
$\lvert 1/E - 1/p \rvert$	0.05	
Combined relative PF isolation	0.15	
vertex fit probability (conv. rej)	10^{-6}	
missing hits (conv. rej.)	1	

Muon ID cuts

Description	criterion
Number of pixel hits	> 0
χ^2/n.d.f	< 10
Number of muon hits	> 0
Number of matched muon stations	> 1
Number of tracker layers	> 5
d_0 w.r.t. selected vertex	< 0.02 cm
d_z w.r.t. selected vertex	< 0.05 cm
Combined relative PF isolation	< 0.2

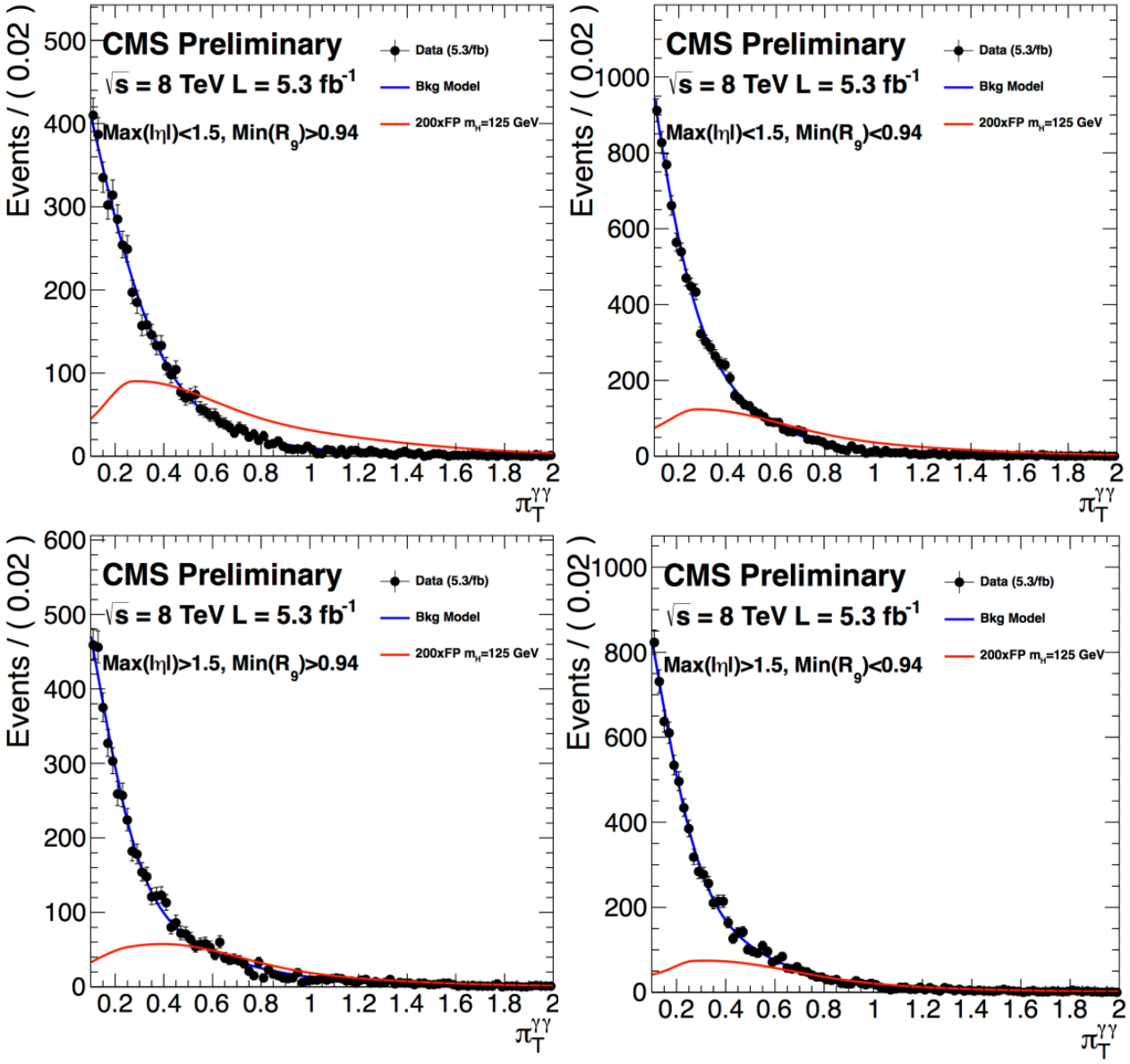
Jet ID cuts

jetη	β^*	RMS
$\eta < 2.5$	$< 0.2 \log N_{vtx} - 0.64$	< 0.06
$2.5 < \eta < 2.75$	$< 0.3 \log N_{vtx} - 0.64$	< 0.05
$2.75 < \eta < 3$	-	< 0.05
$3 < \eta < 4.7$	-	< 0.055

Di-jet event selection

Variable	cut VBF cat1	VBF cat2
$p_T^{\gamma_1}/m_{\gamma\gamma}$	> 0.5	> 0.5
$p_T^{\gamma_2}$	> 25 GeV	> 25 GeV
$p_T^{j_1}$	> 30 GeV	> 30 GeV
$p_T^{j_2}$	> 30 GeV	> 20 GeV
$\lvert\Delta\eta_{j_1 j_2}\rvert$	> 3.0	> 3.0
$\lvert Z \rvert$	< 2.5	< 2.5
$M_{j_1 j_2}$	> 500 GeV	> 250 GeV
$\lvert\Delta\phi(\mathrm{jj}, \gamma\gamma)\rvert$	> 2.6	> 2.6

8 TeV $\pi_T^{\gamma\gamma}$ Distribution in Untagged Sub-channels



2011 & 2012 Results of FP H→γγ

