Higgs to gamma gamma at CMS

Higgs Hunting Orsay 2013

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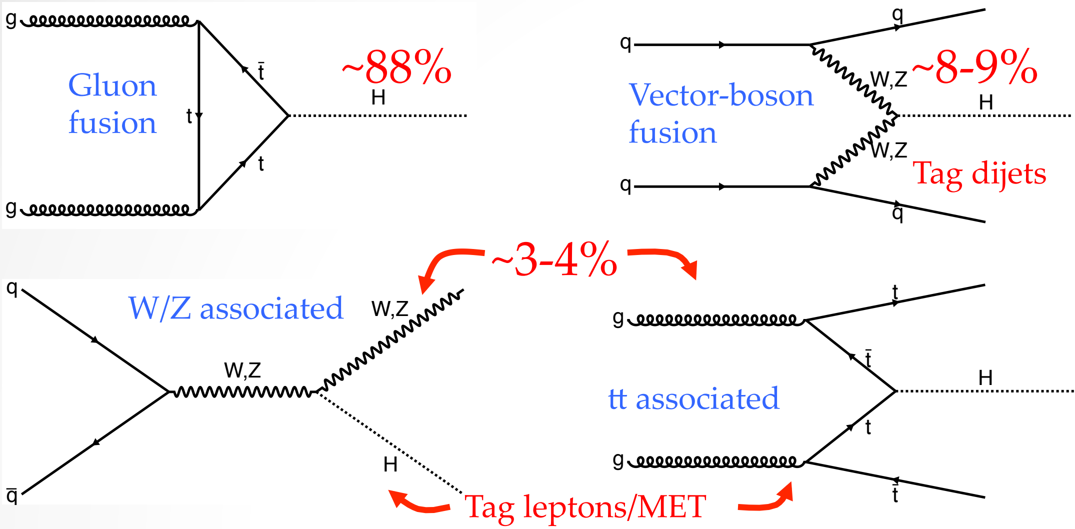
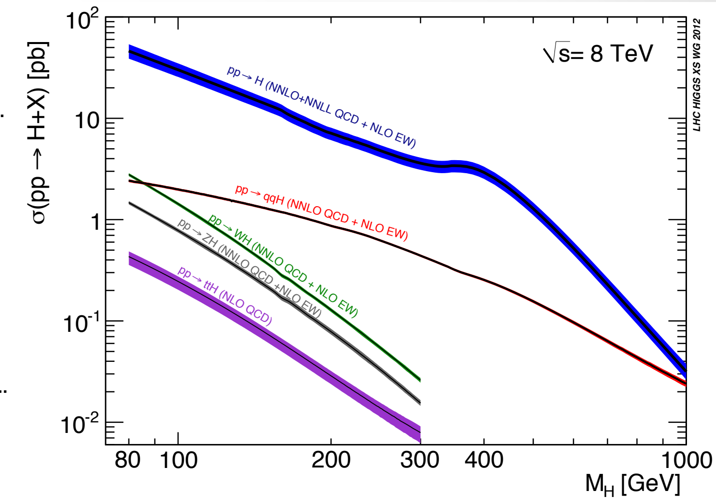
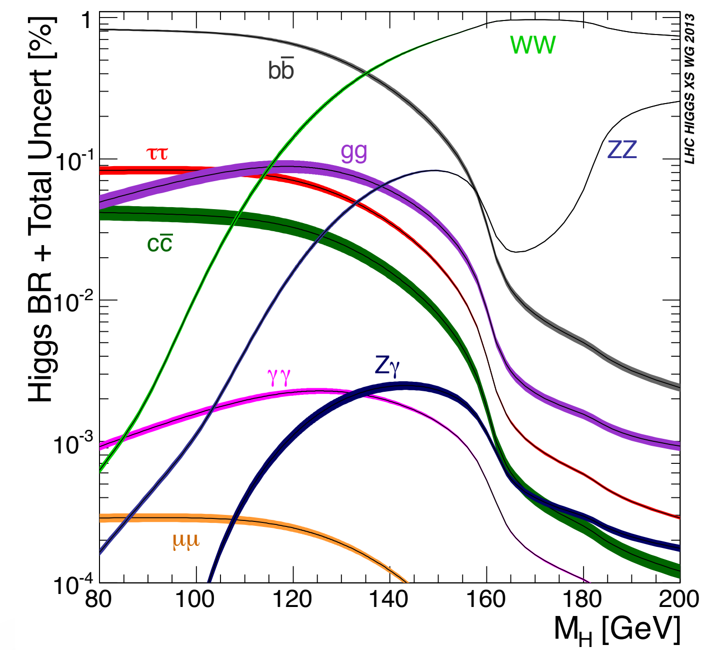
On Behalf of the CMS Collaboration

Introduction





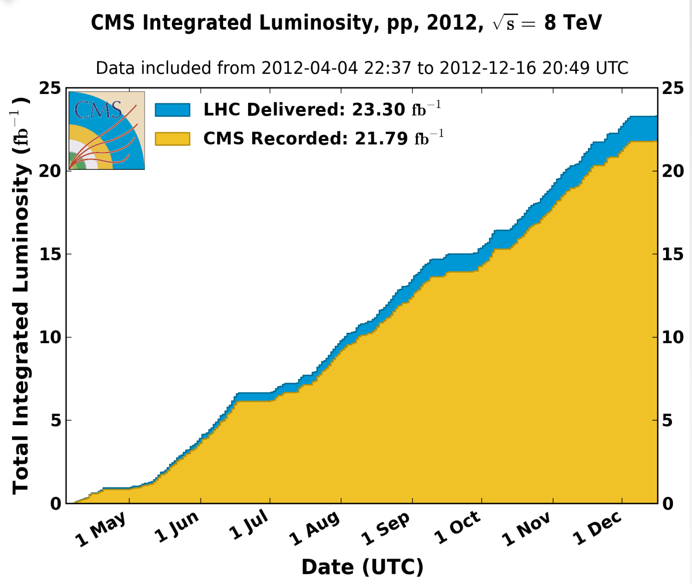


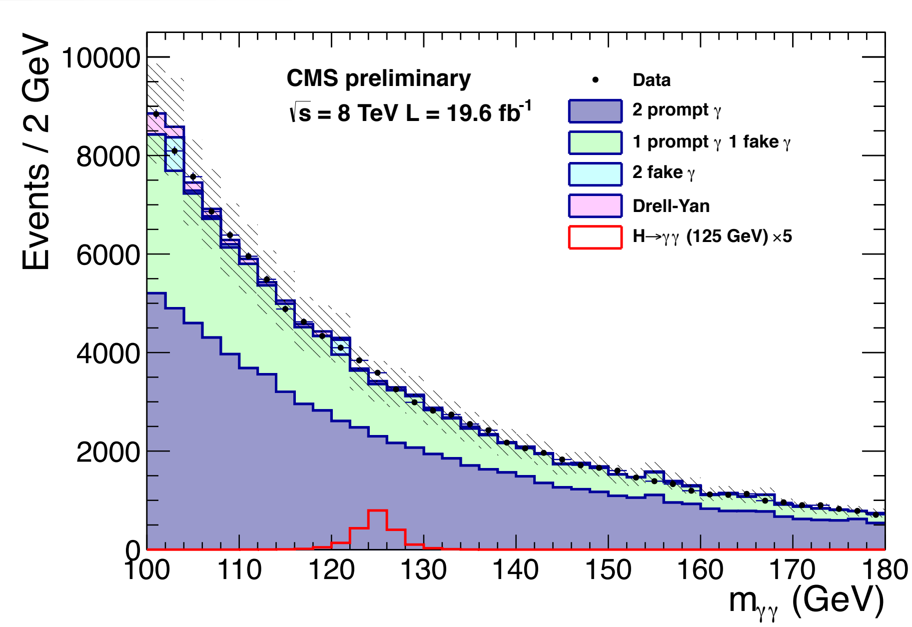
- Low BR ~0.2%
- Clean final state
- Can reconstruct mass with good precision

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\alpha)}$$

Overview

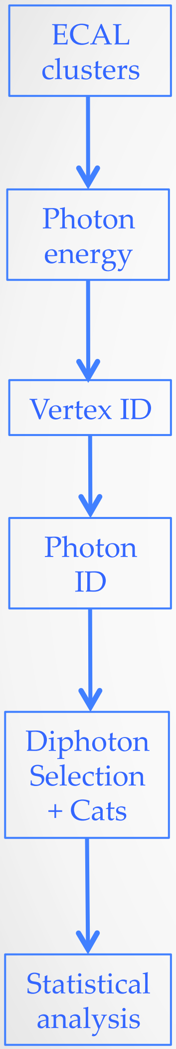
- Main result as presented at Moriond - **CMS-PAS-HIG-13-001**
  - Multivariate (MVA) approach
  - Cut-based approach
- Properties and spin analysis - **CMS-PAS HIG-13-016**
  - Uses the cut-based selection
- ttH specific analysis – **CMS-PAG-HIG-13-015**
- H→Zγ analysis – **CMS-PAG-HIG-13-006**
- Use full dataset available 2011 ($5.1fb^{-1}$) + 2012 ($19.6fb^{-1}$)
  - Spin analysis uses just 2012
- *Legacy* paper towards end of the year





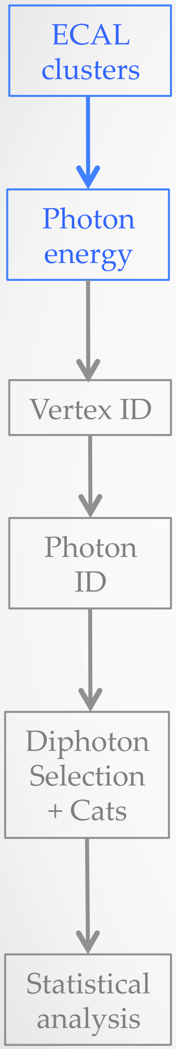
- Looking for a small peaking signal on a large falling background
  - MC only used for cut and MVA optimisation
  - Background for analysis is data driven
- Background composition
  - prompt-prompt (irreducible) pp→γγ ~70%
  - prompt-fake (reducible) pp→γ+jet ~30%
  - fake-fake (reducible) pp→jet+jet <1%

Analysis Strategy



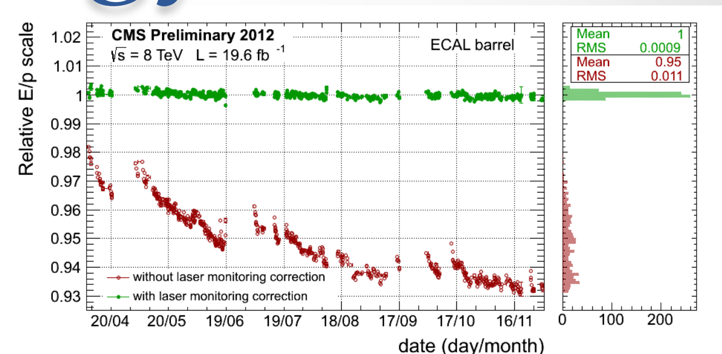
- Select events with two high energy, isolated photons
- Separate events into non-overlapping categories with different S/B and different resolution
- Particular exclusive tagged categories
  - Improve S/B in certain categories
  - Separate production modes for coupling measurements
- Background estimated in data
  - Fit $\gamma\gamma$ invariant mass distribution to data
- Two analyses
  - Multivariate approach → main result, couplings, second Higgs
  - Cut based approach → cross check, spin analysis

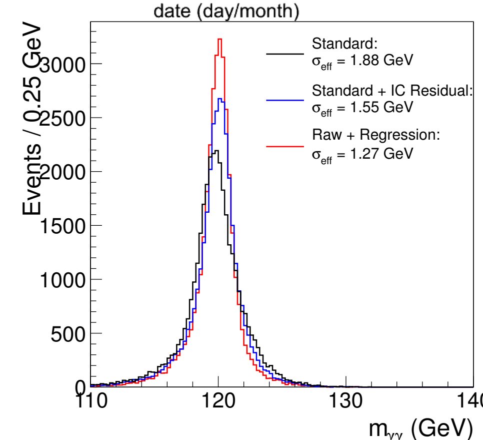
Photon Energy

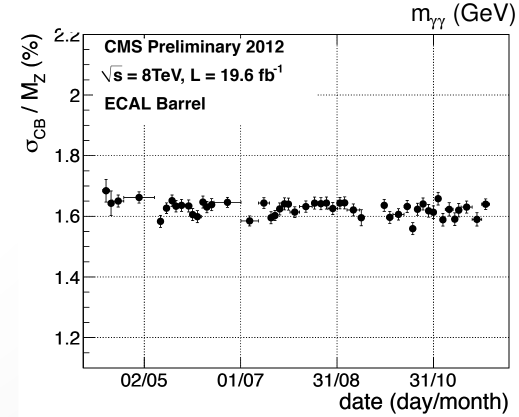


$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\alpha)}$$

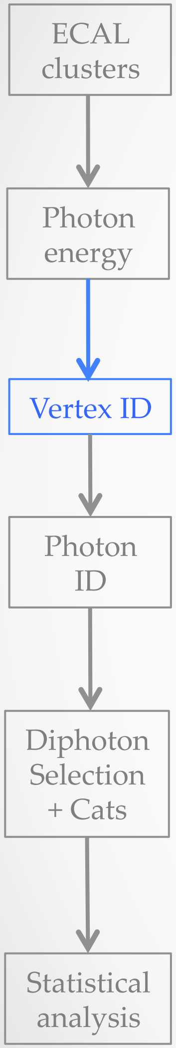
- Single Crystal
  - Energy calibration (**CMS-PAS-EGM-11-001**)
  - Transparency loss correction
  - Inter-calibration -> uniform η-ϕ response
- SuperClustering (SC)
  - Some photons convert in tracker
  - $R_9 = E_{3x3}/E_{SC}$ (>0.94 is unconverted)
- Energy regression correction
  - BDT target = E_{raw}/E_{true}
  - Input variables: SC position, shower shape variables, median energy density per event (ρ)
  - Improve σ_{eff} by ~30%
- Also provide per photon energy resolution estimate
- Monitored with Z→ee
  - Resolution stable with time





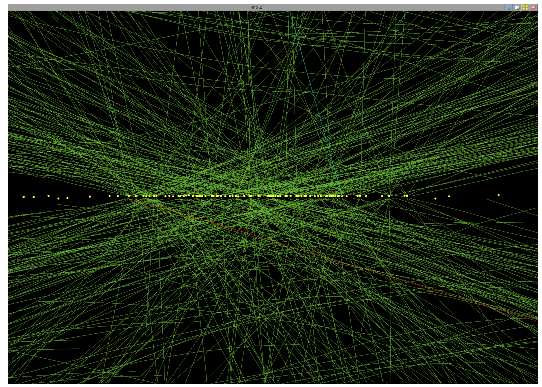


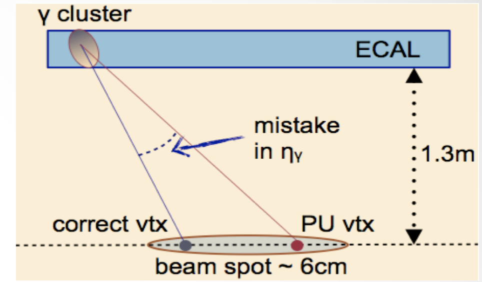
Vertex Identification



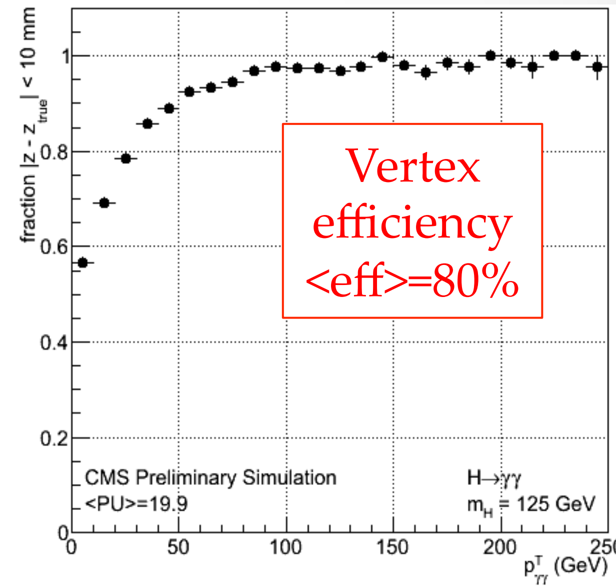
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1 - \cos\alpha)}$$

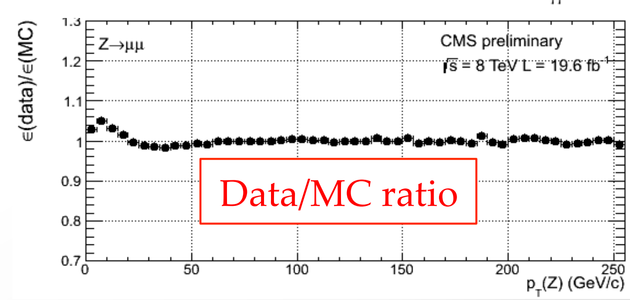
- Pileup (PU)
  - multiple collisions per event
  - $\langle PU \rangle_{2012} = 20$



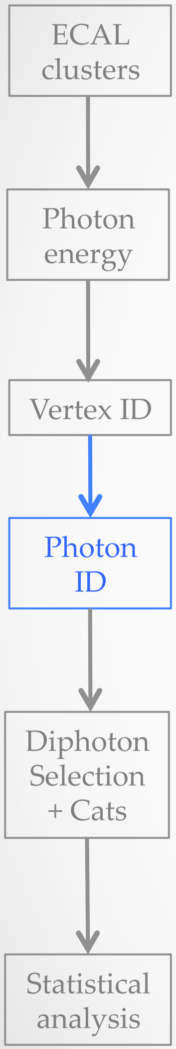


- Use a Boosted Decision Tree (BDT)
  - Σp_T^2 of all tracks
  - Track recoil/imbalance with respect to $p_T(\gamma\gamma)$
  - Pointing from conversion tracks
- Control samples for validation
  - $Z \rightarrow \mu\mu$ for unconverted photons
  - γ+jet for converted photons
- Also have an additional BDT which provides, per-event, the correct vertex probability

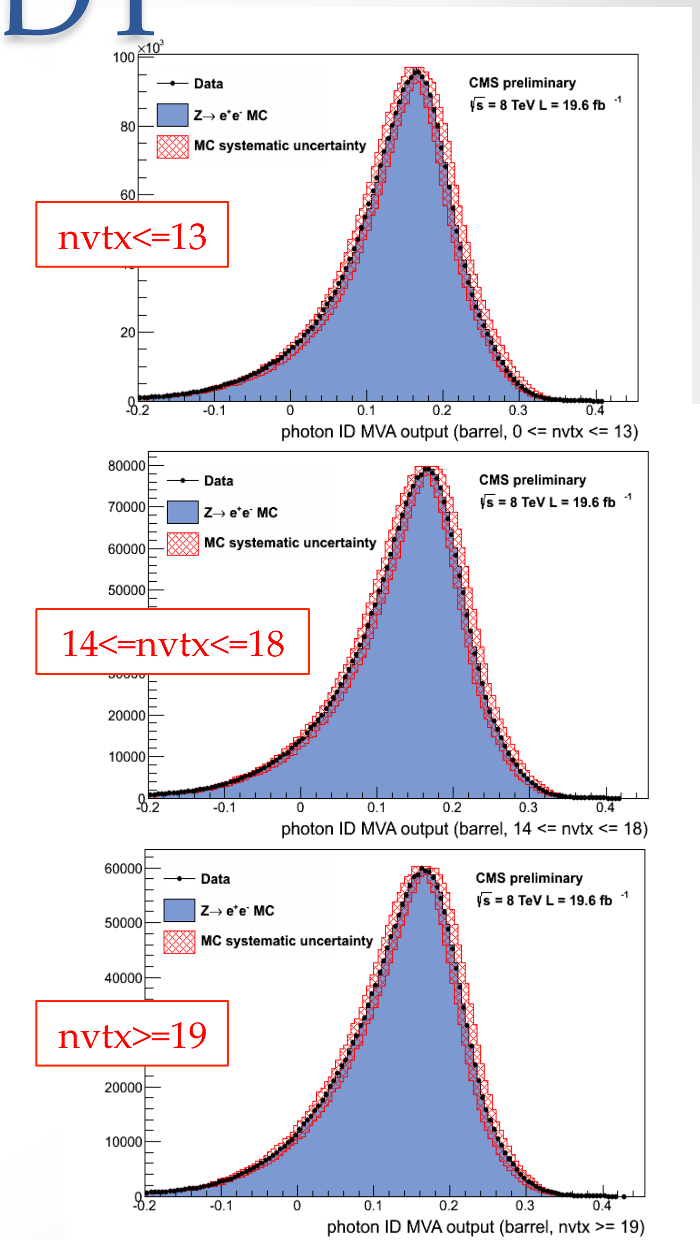




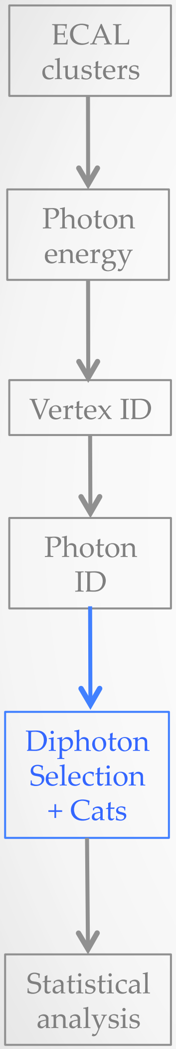
Photon ID BDT



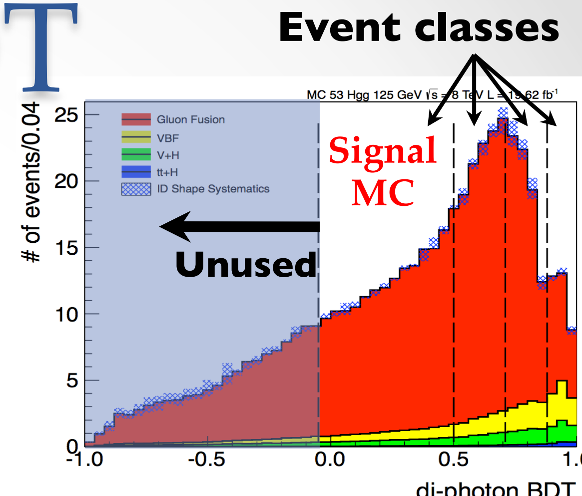
- Used to reject fakes
  - Neutral mesons (mainly π^0) decay into two ~collinear photons (look similar to single high E_T γ)
- Input variables
  - Several shower shape variables (MC corrected to match data)
  - Isolation
    - Particle-flow energy around photon candidate
  - Average energy density per event (ρ)
    - Correlated to PU
  - Photon position η (to exploit correlations)
- Output
  - Validated with Z→ee and Z→μμγ
  - Shape corrections derived with Z→ee

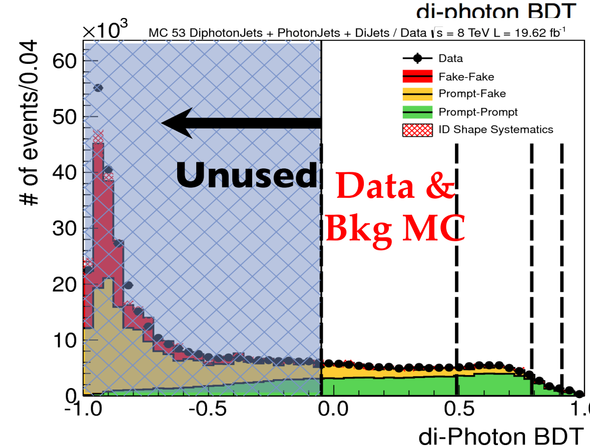


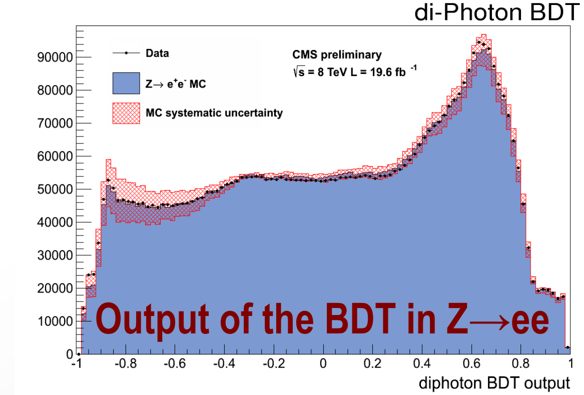
Diphoton BDT



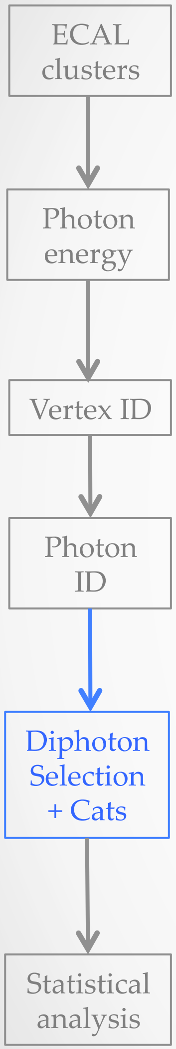
- Produces a single discriminant (BDT) from
  - Event kinematics
    - $p_T(\gamma_1)/m_{\gamma\gamma}$, $p_T(\gamma_2)/m_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$
  - Event resolution
    - mass resolution (right vertex), mass resolution (wrong vertex), vertex probability
  - Photon quality
    - photon ID MVA output for each γ
- Mass blind!
- Optimise four category boundaries to increase signal sensitivity
- Validated with Z→ee
  - systematics propagated through







Cut Based Analysis

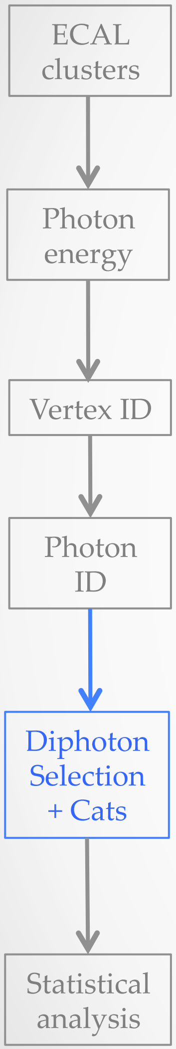


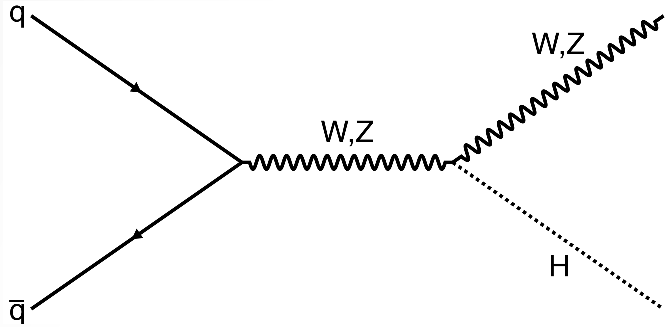
- Photon selection is optimised in four categories
  - photon in barrel (EB) or endcap (EE) - $|\eta|<1.444$
  - photon is flagged as converted or unconverted - $R_9>0.94$

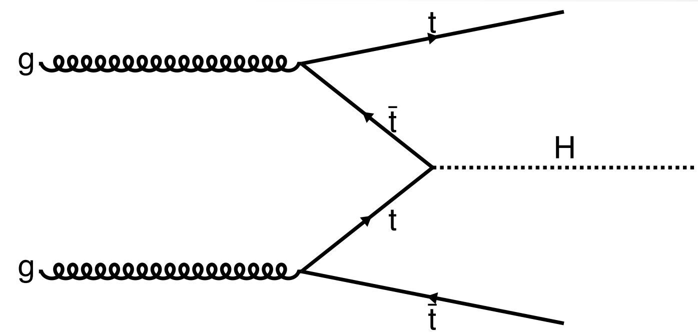
- Efficiency corrections derived from Z→ee events in data/MC

- Split diphoton events into 4 natural categories with
  - Cat0 - both photons in barrel AND both photons unconverted
  - Cat1 - both photons in barrel AND at least one conversion
  - Cat2 - at least one photon in endcap AND both photons unconverted
  - Cat3 - at least one photon in endcap AND at least one conversion

Lepton/MET tag

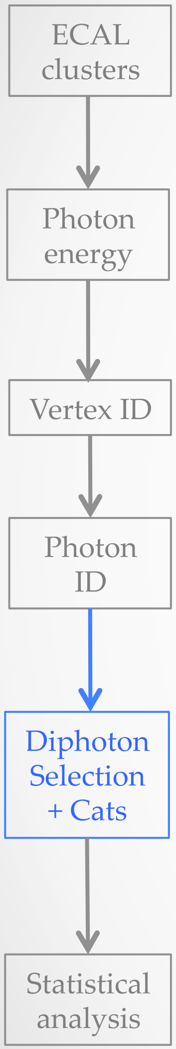


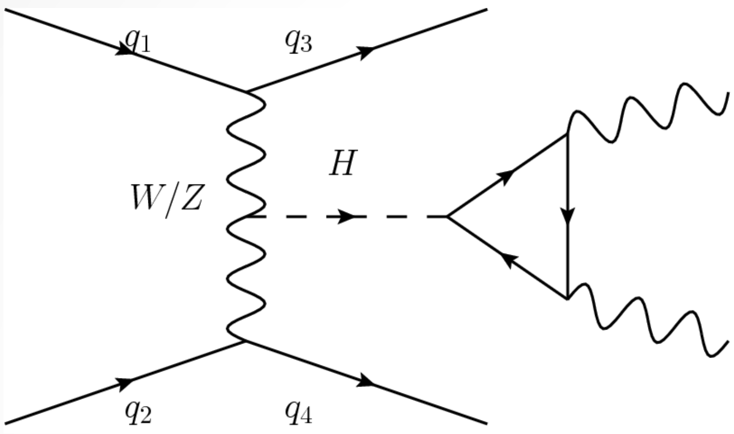




- Tagging leptonic decays of associated W, Z or top in Higgs production
- 3 additional analysis categories for 2012 only
  - muon, electron, MET
- On top of standard diphoton selection:
  - require high energy electron or muon (p_T>20 GeV)
  - or large MET (>70 GeV)
- High S/B but very low yield

Dijet tag



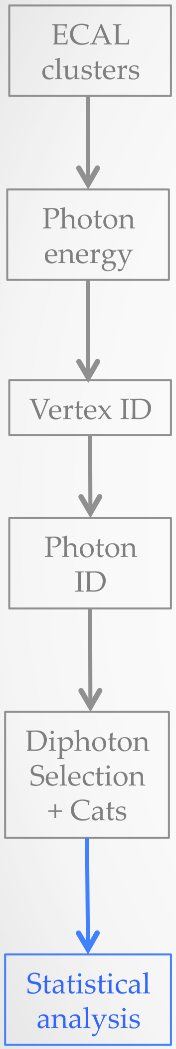


- Tagging two high p_T jets with characteristic topology from VBF Higgs production

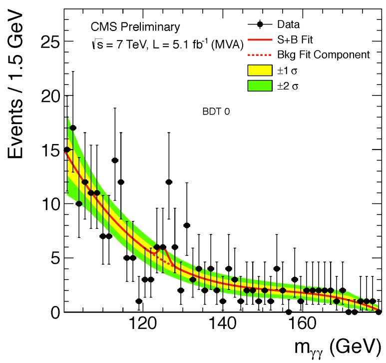
> - Two forward high p_T jets
> - Large m_{jj}
> - high $\Delta\eta(jj)$
> - $\Delta\phi(jj-\gamma\gamma)$

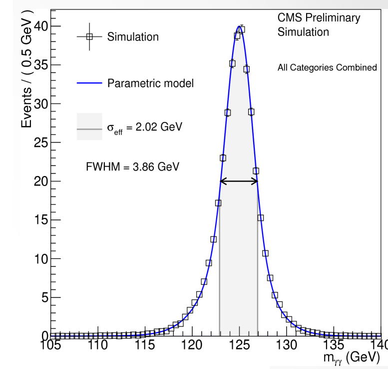
- PU ID rejects jets from PU
- Additional analysis categories
  - 2011 - 1 additional category
  - 2012 - 2 additional categories (tight and loose dijet selection)
- High S/B but considerable gluon fusion contamination
- MVA analysis uses a BDT for categorisation
- Cut-based analysis uses a cut based selection

Signal and Background Models



- Background - 3rd-5th order polynomial in each cat
  - Chosen such that systematic is negligible
- Signal - sum of Gaussians in each category for each process
  - σ/m for all events ~1.6%
  - σ/m for best events ~1%

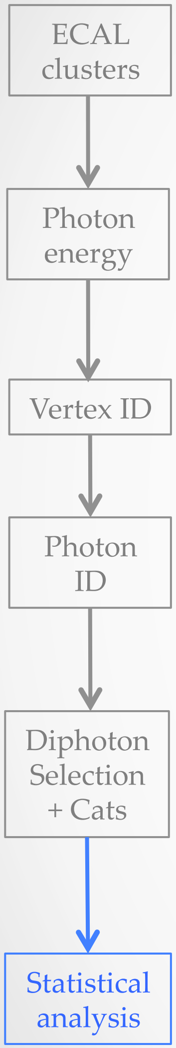




Expected signal and estimated background

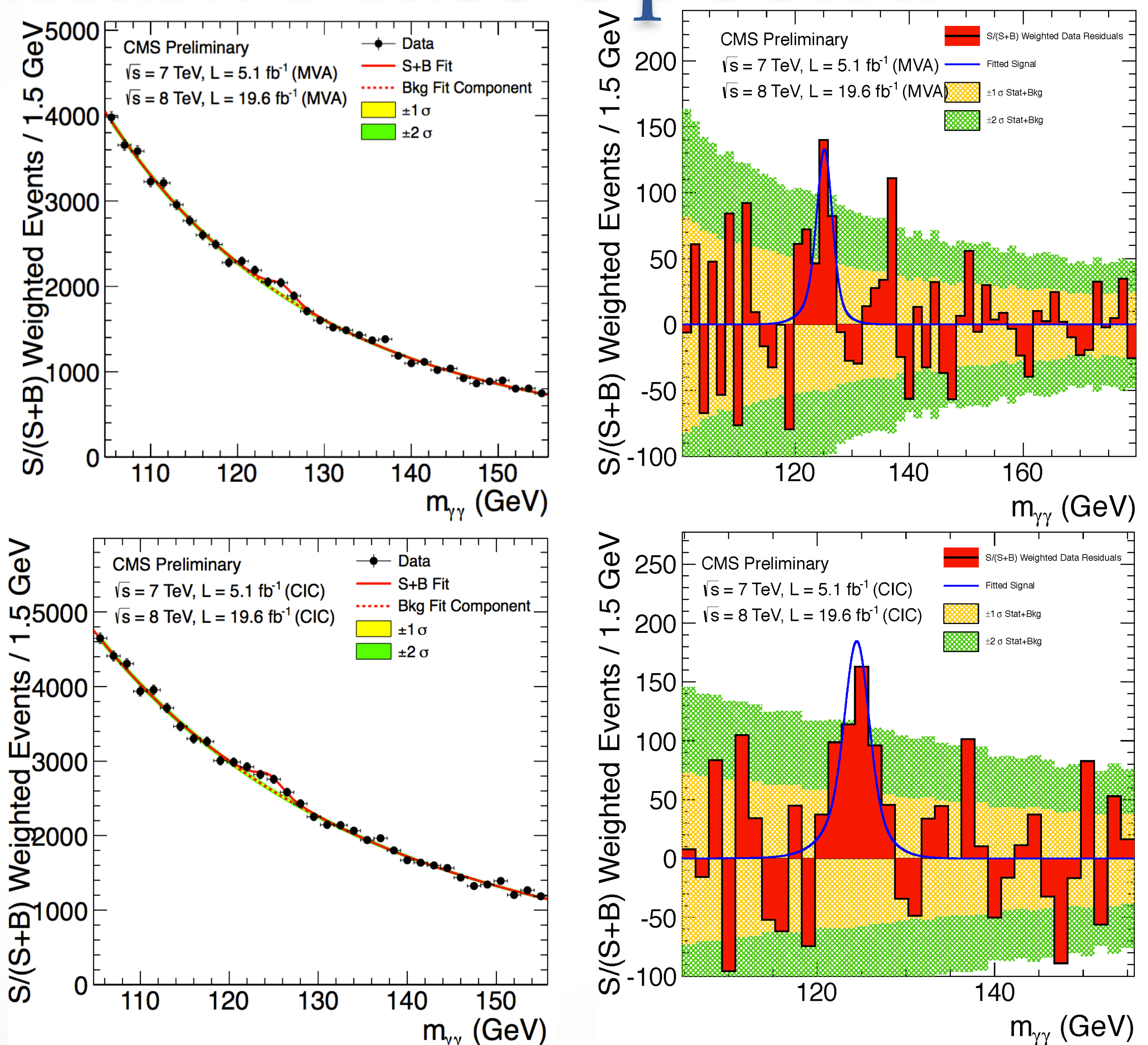
Event classes		SM Higgs boson expected signal (m_H=125 GeV) Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73	1.37	1.7 ± 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	1.27	22.1 ± 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	1.39	94.3 ± 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	1.54	570.5 ± 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	2.14	1060.9 ± 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	1.50	3.4 ± 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	1.60	12.4 ± 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	1.52	0.7 ± 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	1.54	0.7 ± 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	1.64	1.8 ± 0.1

Invariant Mass Spectra



MVA

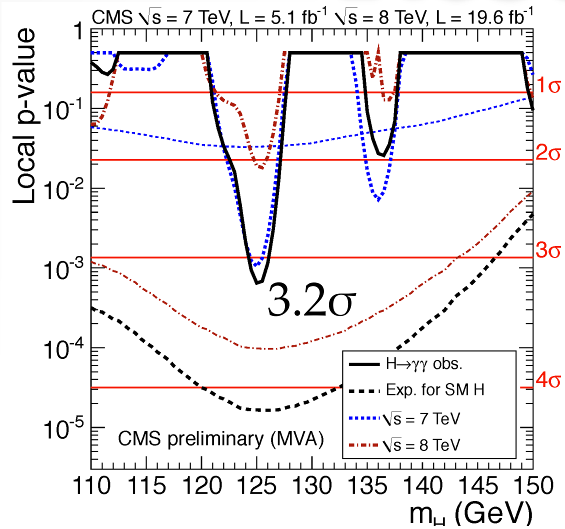
Cut Based

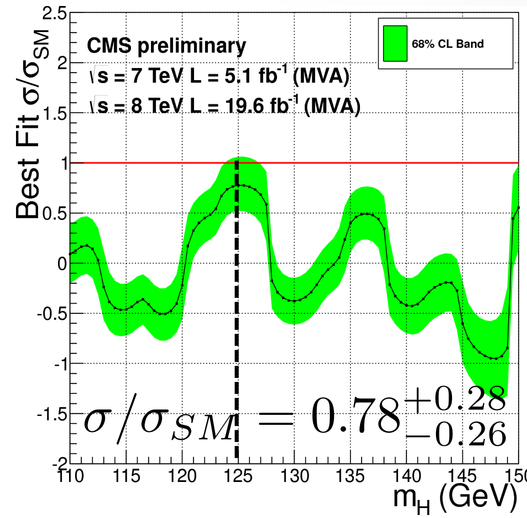


Results I

ECAL clusters → Photon energy → Vertex ID → Photon ID → Diphoton Selection + Cats → Statistical analysis

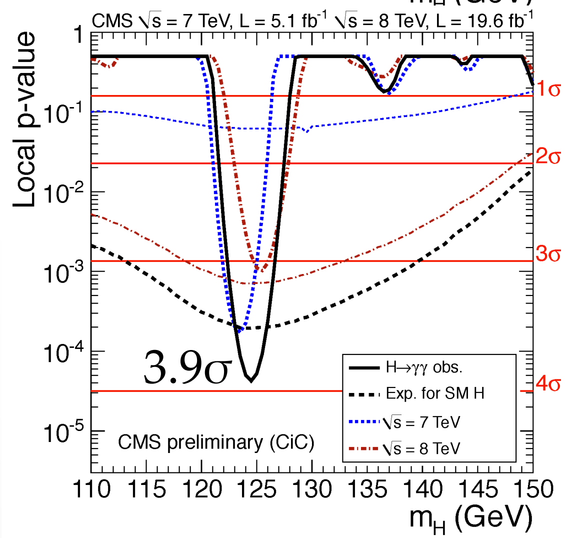
MVA

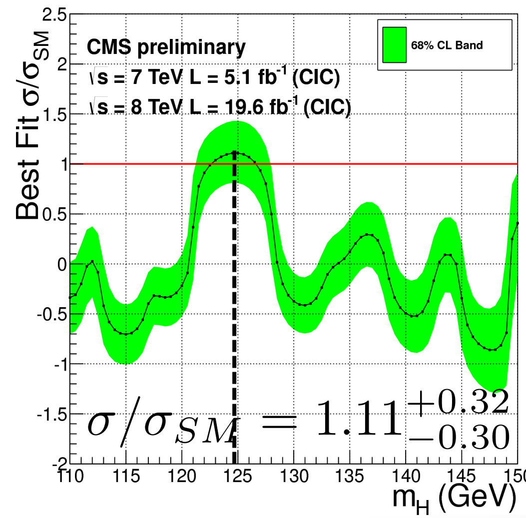




m_H=125 GeV

Cut Based

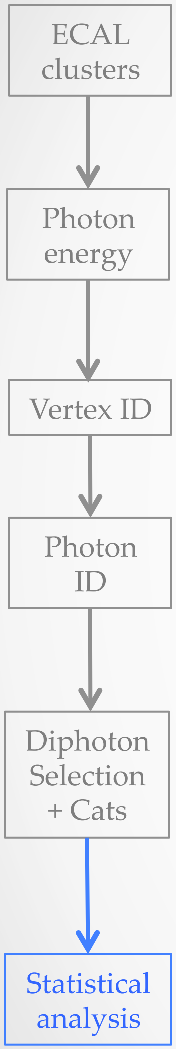




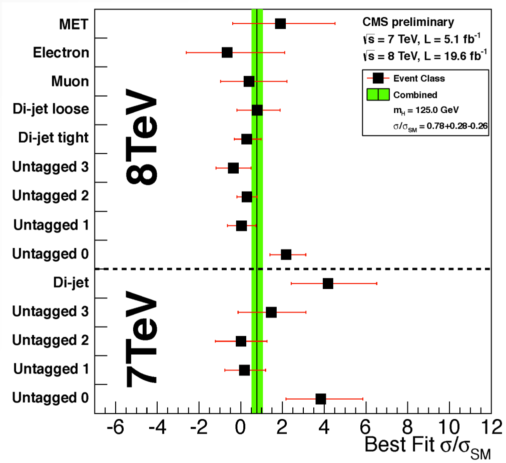
m_H=124.5 GeV

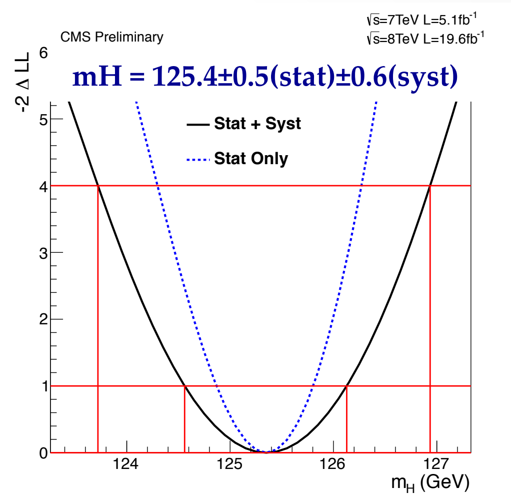
Compatible within 1.5σ (when correlations are taken into account)

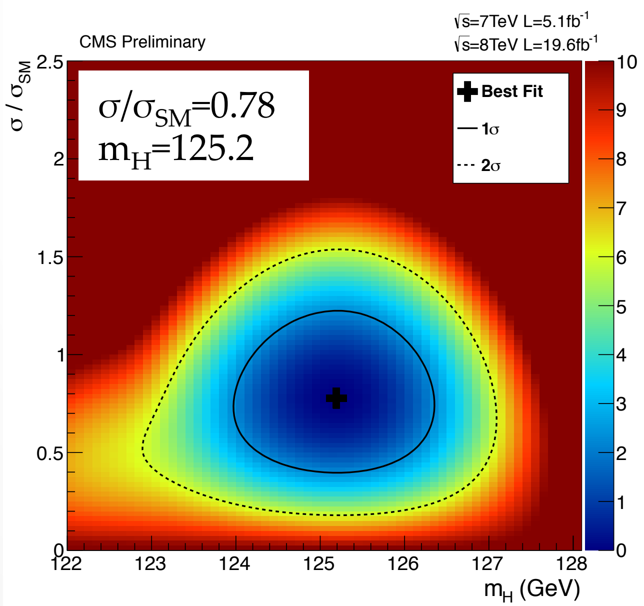
Results II

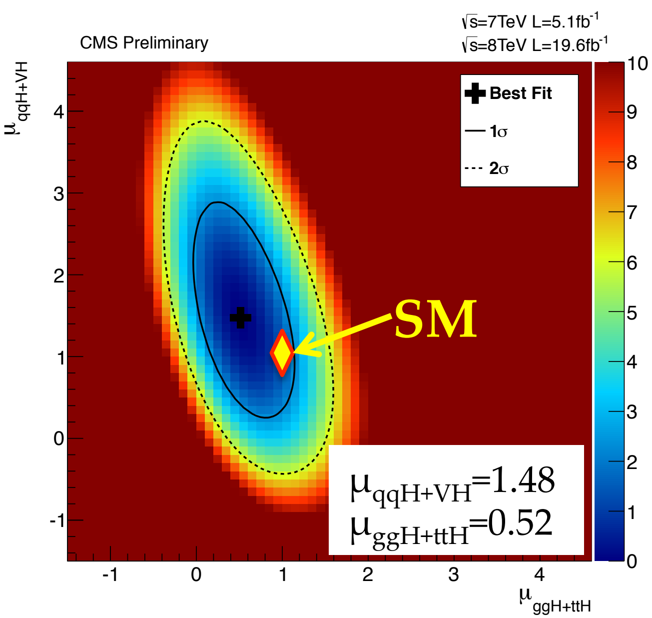


MVA analysis

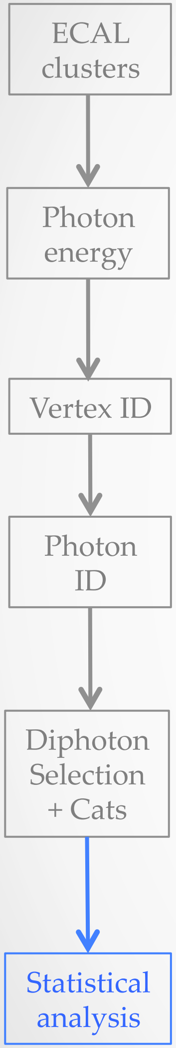




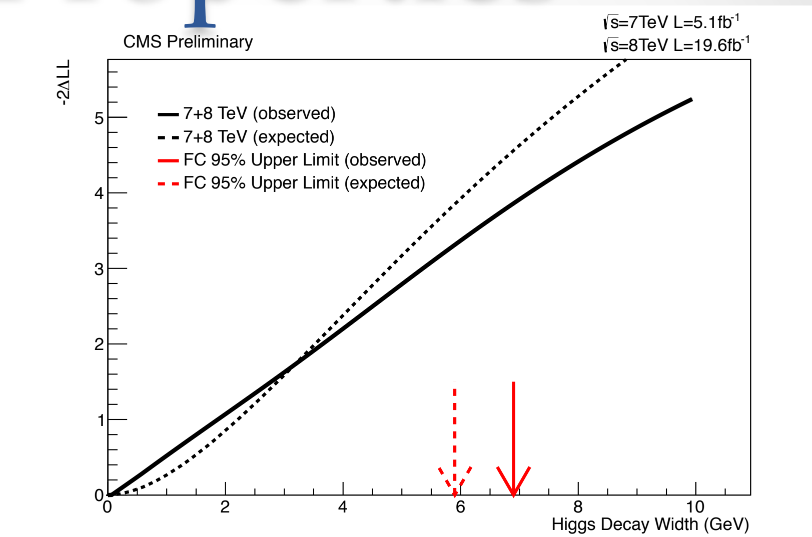


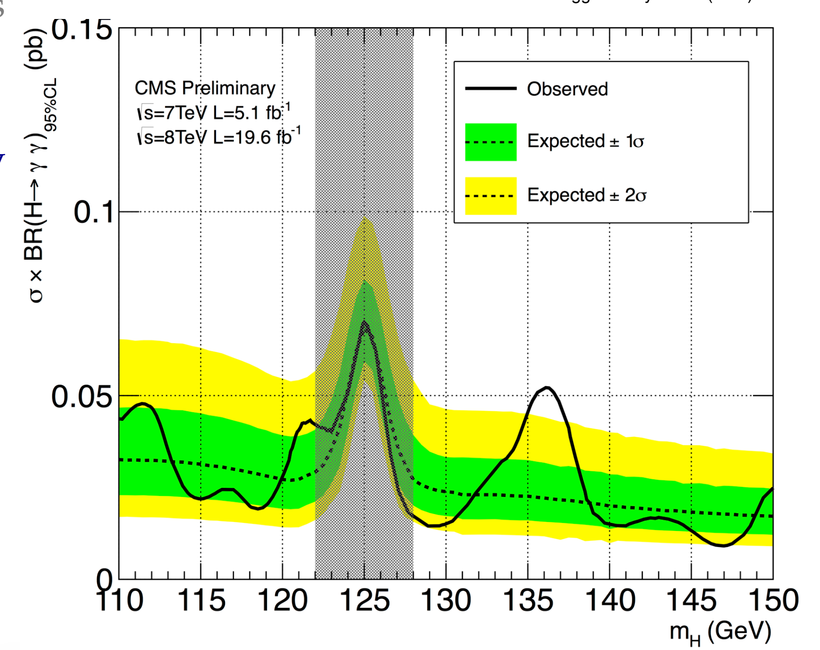


Results III - Properties

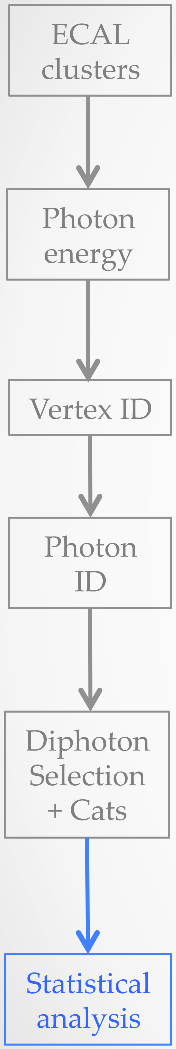


- Use MVA analysis with additional terms in the likelihood
- Upper limit on natural width
  - Observed <6.9 GeV at 95%CL
  - Expected <5.9 GeV at 95% CL
- Limit on second SM-like Higgs
  - assume state at 125 is SM like and is part of the background
  - Set limit on second SM like state elsewhere
  - Local p-value of excess at 136.5 GeV ~ 2.9σ

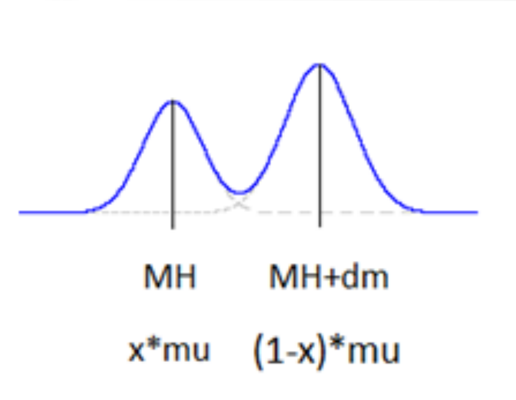




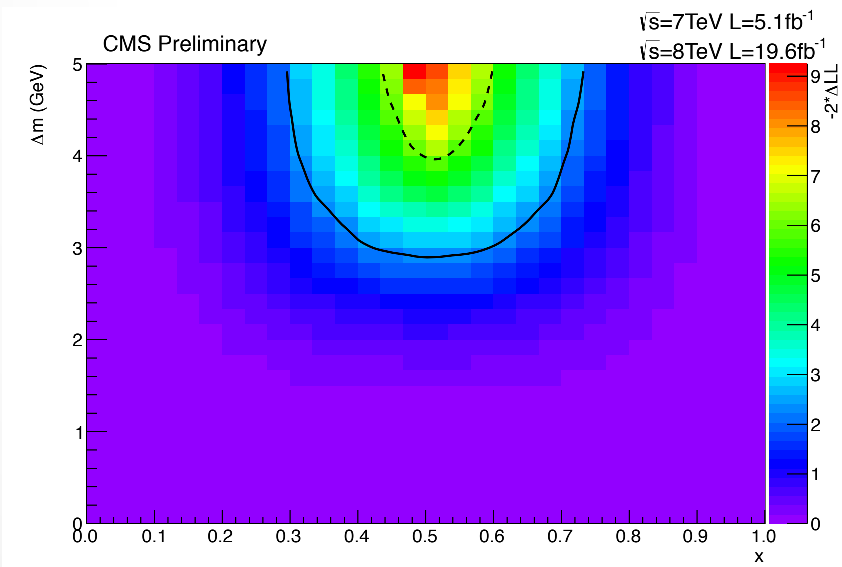
Results IV - Properties



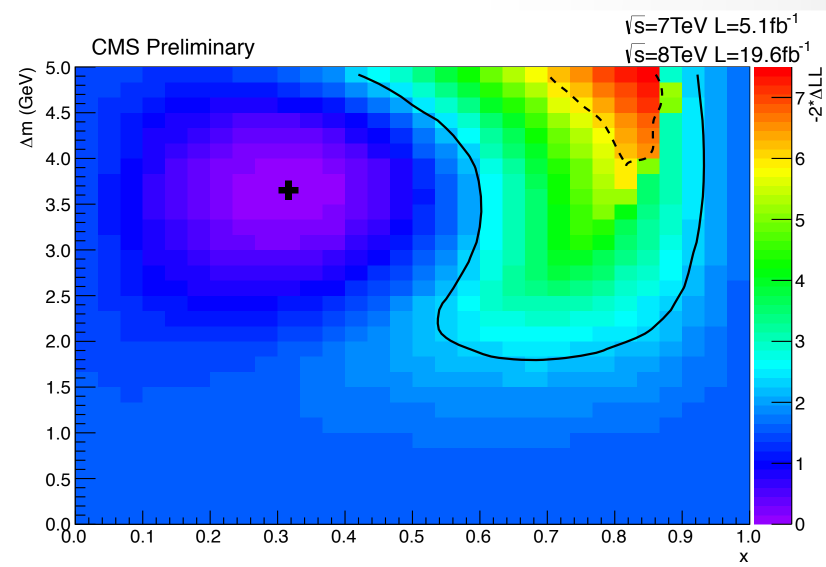
- Limit on two degenerate Higgs
  - both have SM couplings
  - assume signal lower in mass contains fraction of the signal, x



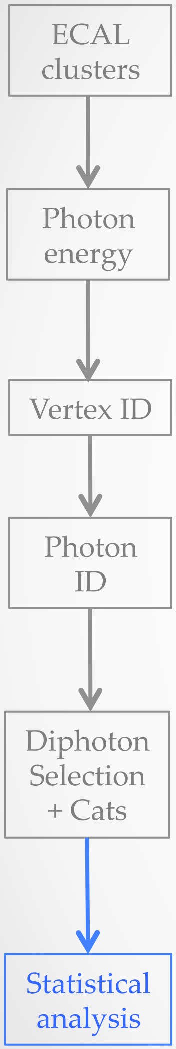
Expected



Observed

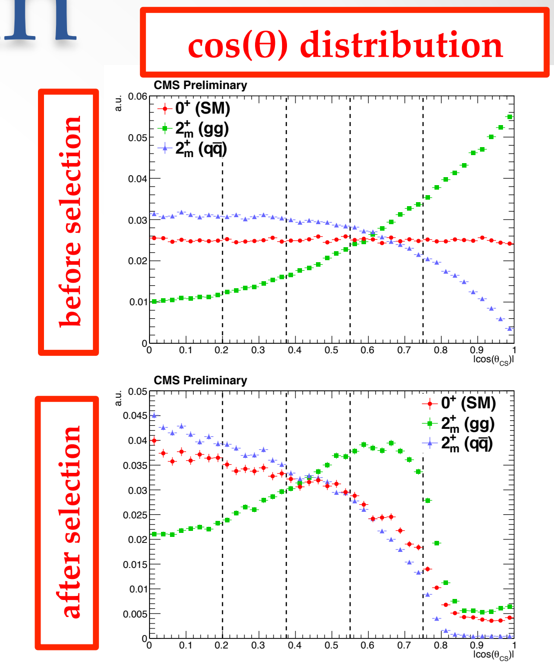


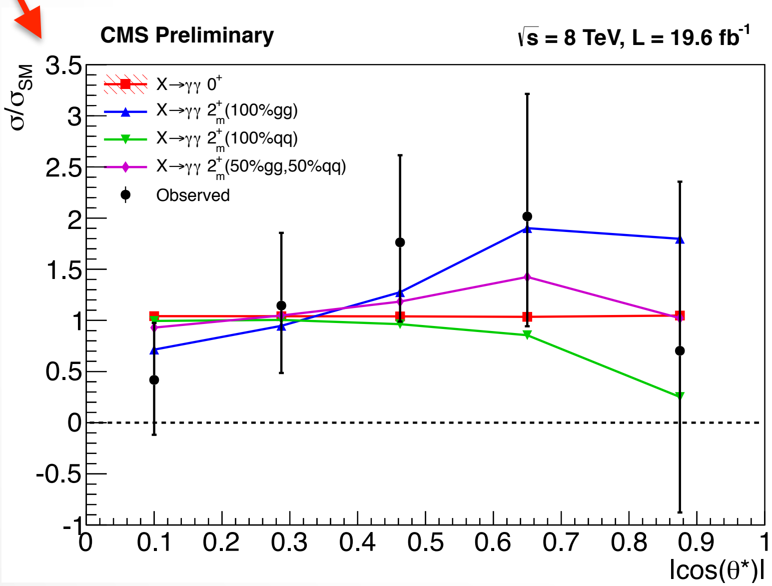
Results V - Spin

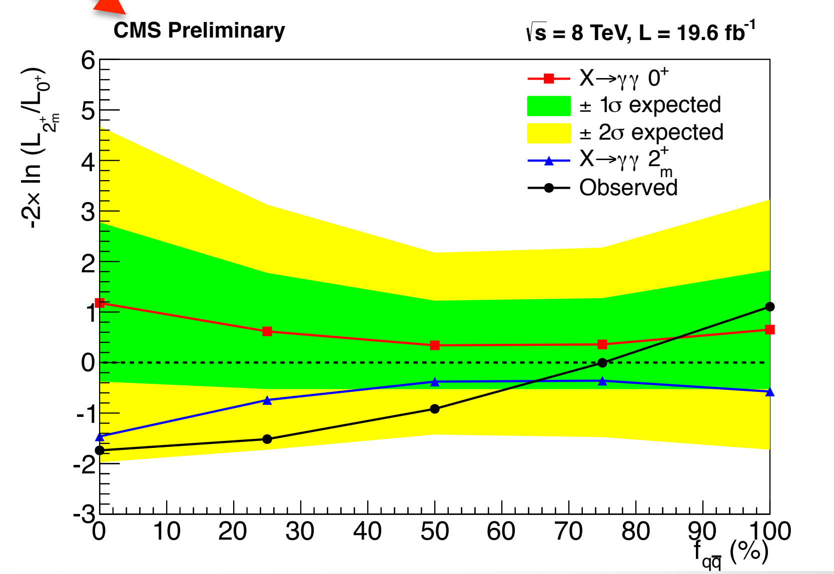


- Uses cut-based analysis selection
  - No exclusive mode tags, 4 inclusive categories kept
  - 5 additional categories in $\cos(\theta_{CS})$ = 20 categories total
- Use spin-2_m^+ model - graviton with minimal couplings
  - produced by gluon fusion (gg) and quark-antiquark annihilation ($q\bar{q}$)

1. Extract signal yield in bins of $\cos(\theta_{CS})$
2. Fit all 20 categories together and plot likelihood ratio of spin2/spin0 varying spin-2 production from $q\bar{q}$





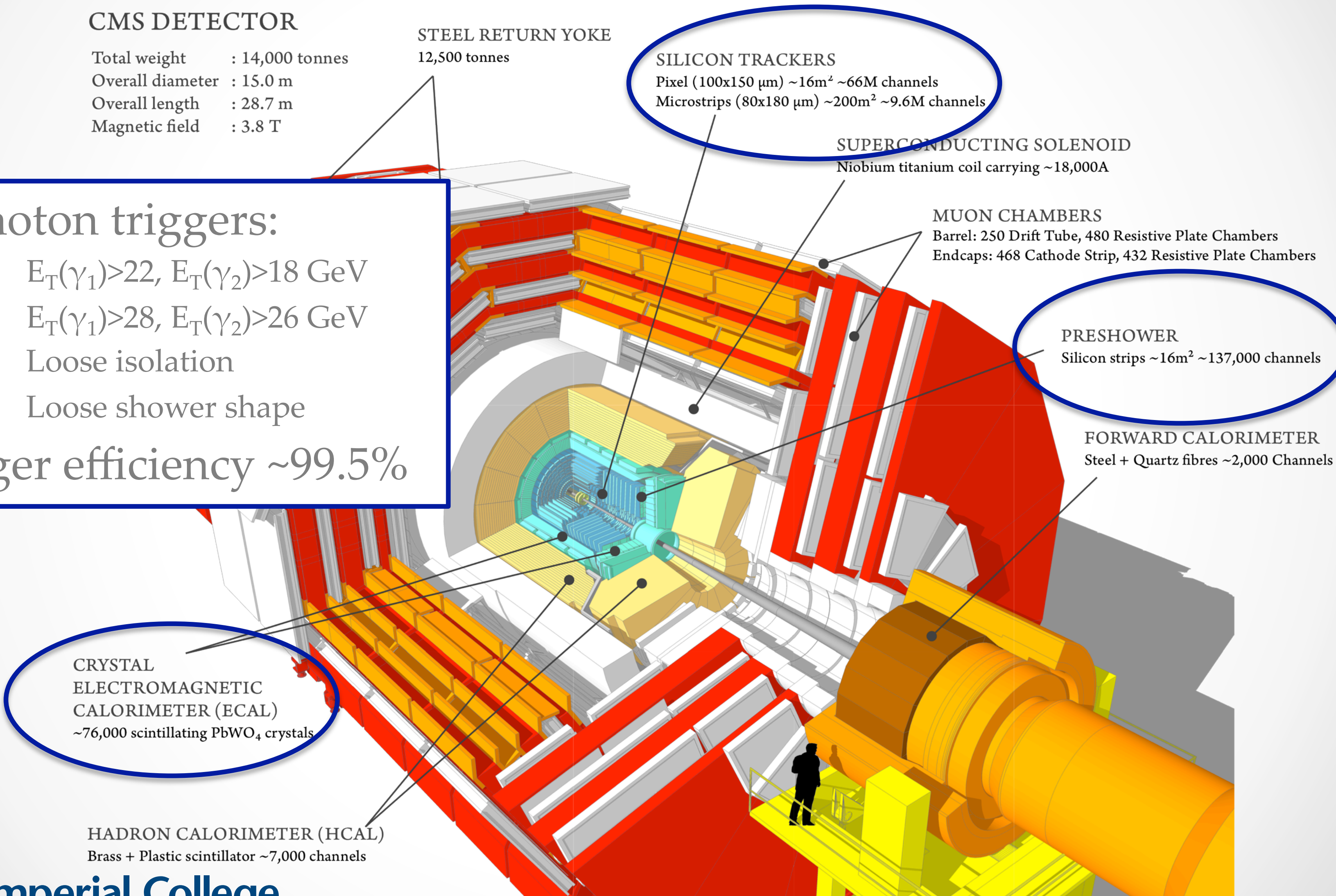


Summary

- Results from the $H \rightarrow \gamma\gamma$ search at CMS have been presented
  - Excess with an observed significance of 3.2σ (expected 4.2σ)
  - Best fit signal strength (at m_H=125GeV) $\sigma/\sigma_{SM} = 0.78^{+0.28}_{-0.26}$
  - Mass measurement: m_H = 125.4±0.5(stat)±0.6(syst)
  - Couplings measurement: compatible with SM at < 1σ
- Properties of the new state investigated
  - Exclusion limits set on second Higgs
  - Upper limit on natural width
  - Spin analysis
    - Unable to exclude spin-2 graviton with minimal couplings
  - ttH specific analysis
    - Observed (expected) upper limit at 95% 5.4 (5.3) x SM

BACK UP

CMS detector



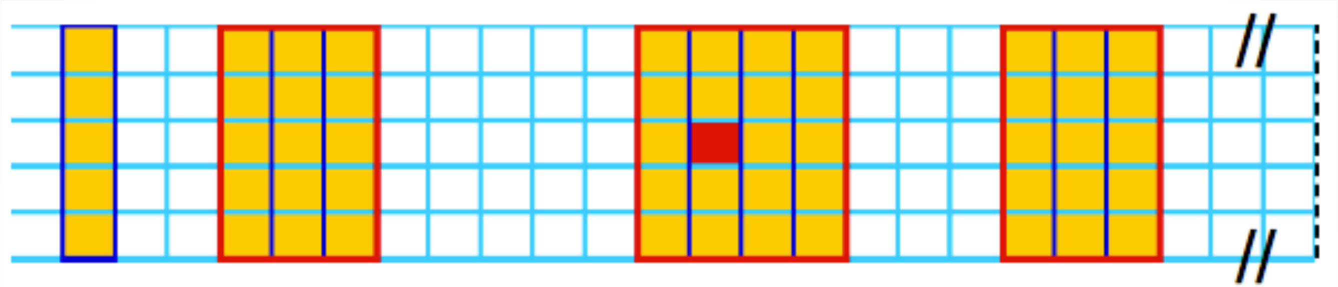
Diphoton triggers:

- $E_T(\gamma_1)>22$, $E_T(\gamma_2)>18$ GeV
- $E_T(\gamma_1)>28$, $E_T(\gamma_2)>26$ GeV
- Loose isolation
- Loose shower shape

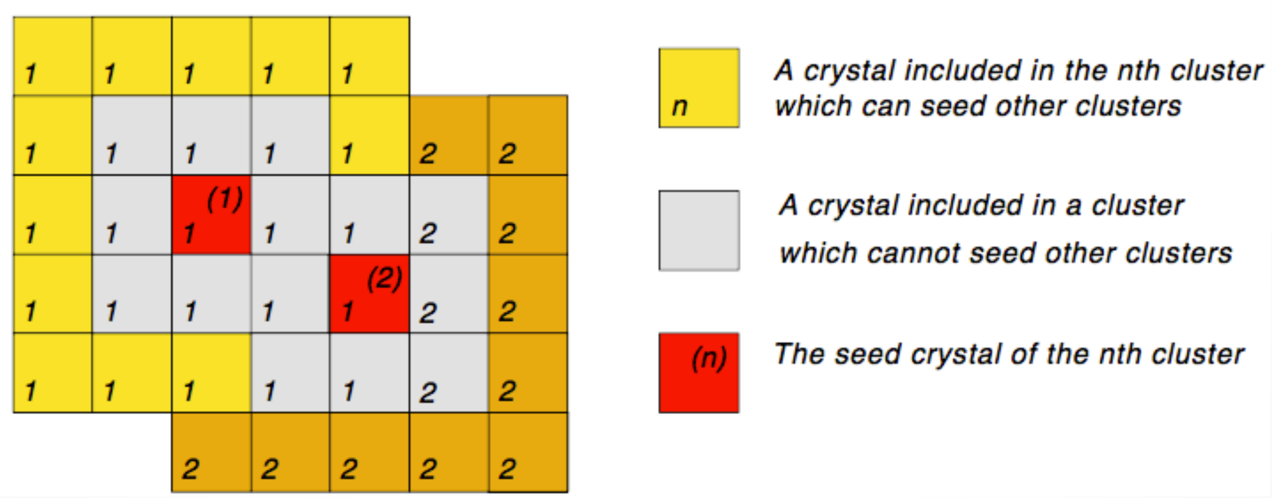
Trigger efficiency ~99.5%

SuperClustering

- ECAL-barrel = “Hybrid algorithm”



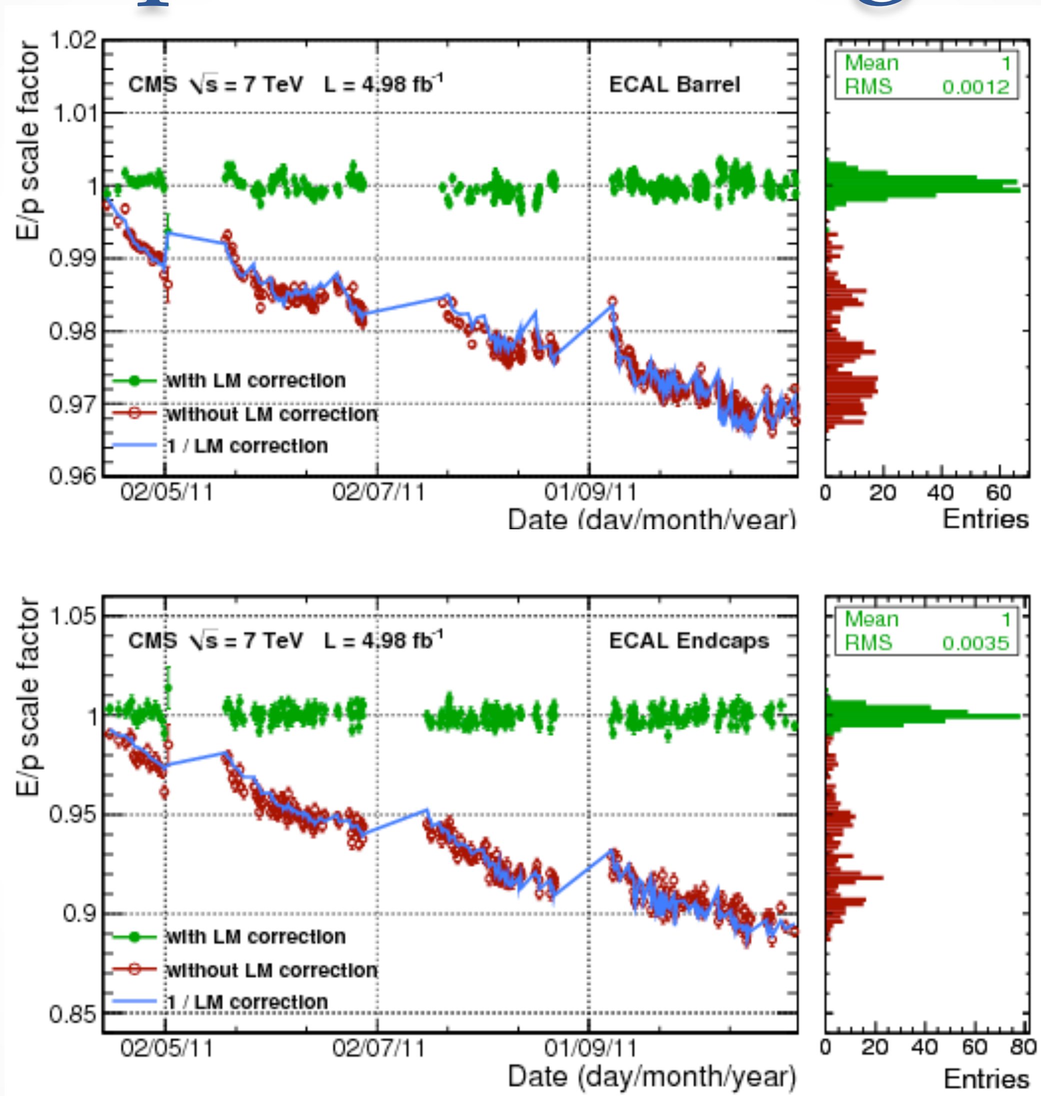
- ECAL-endcap = “Multi-5x5”



SuperClustering II

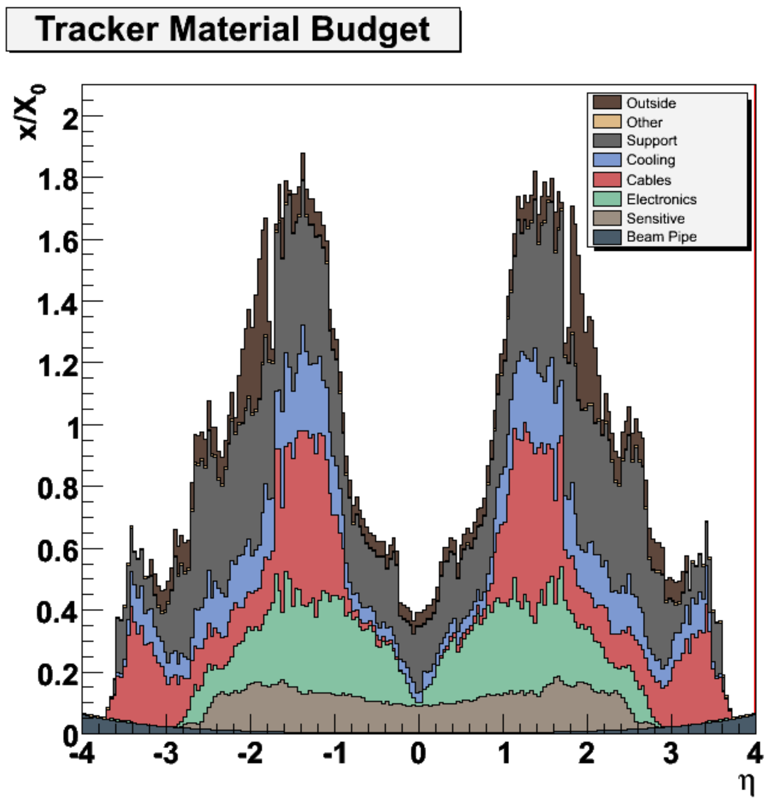
Barrel

Endcap

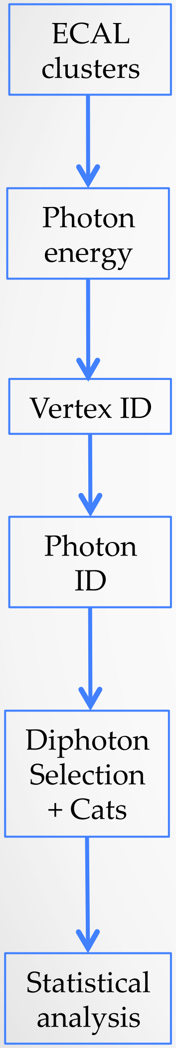


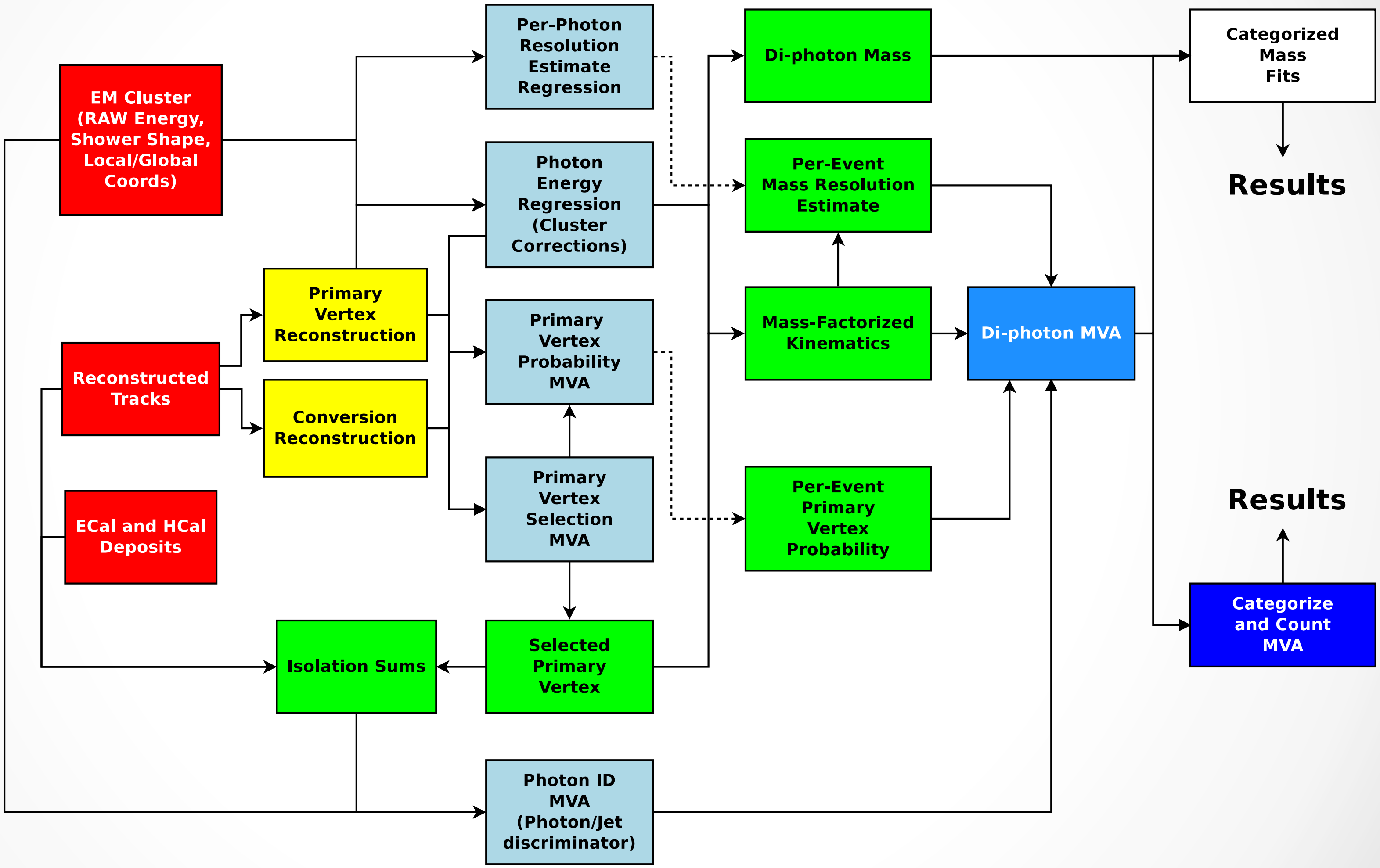
Tracker material

- About 40% of photons convert in tracker
  - ~2/3 of diphoton events contain at least one conversion



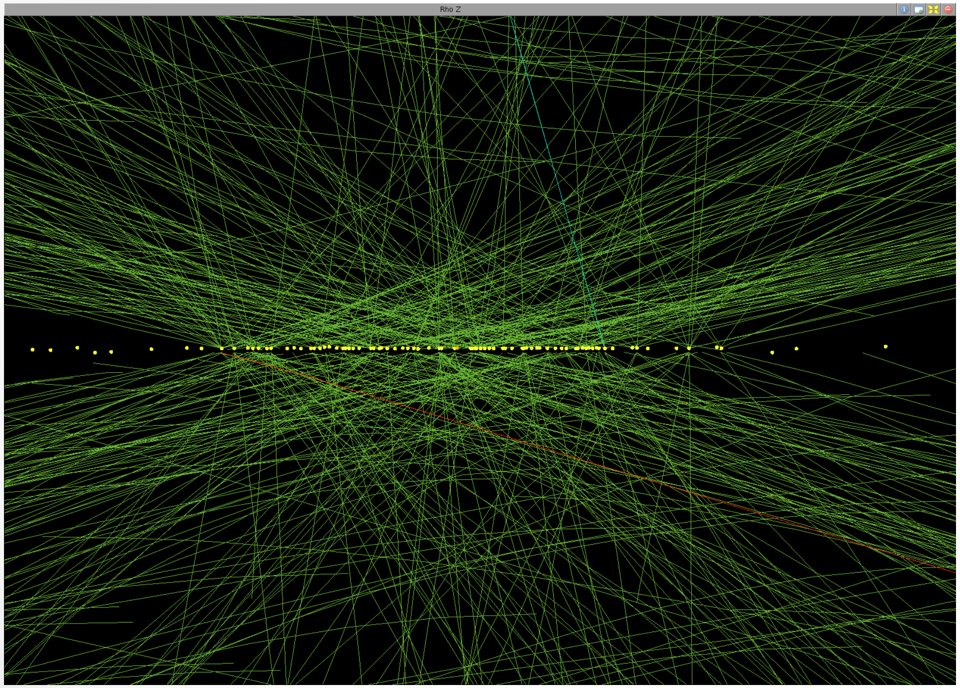
Analysis Flow

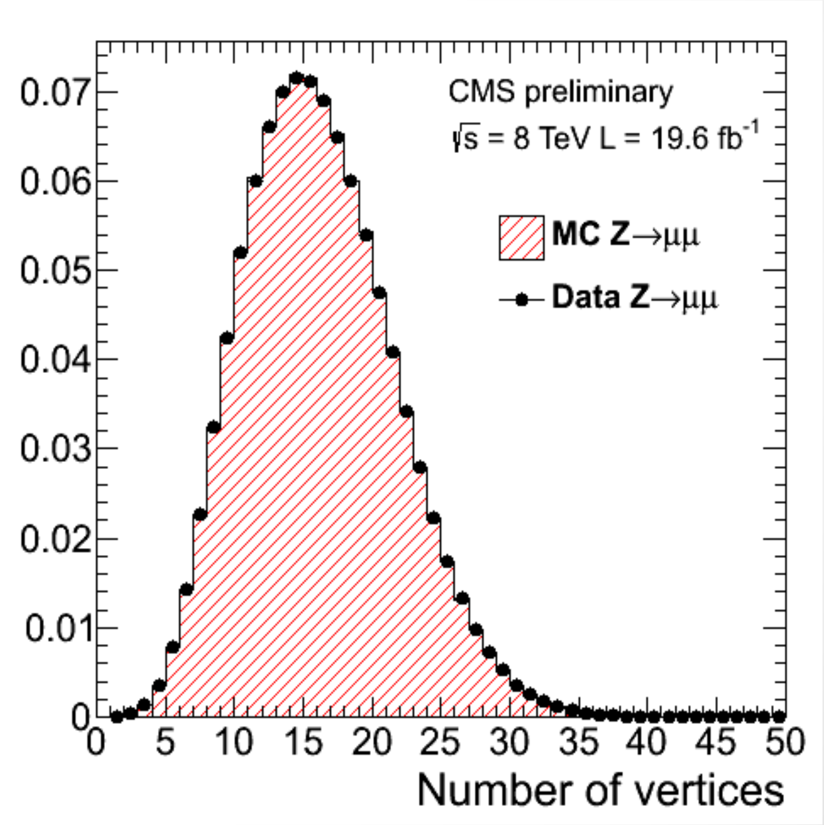




Pileup (PU)

- Beam condition yield multiple collisions per event
  - $\langle PU_{2012} \rangle = 20$
  - Beam spot with ~6cm





Event classification

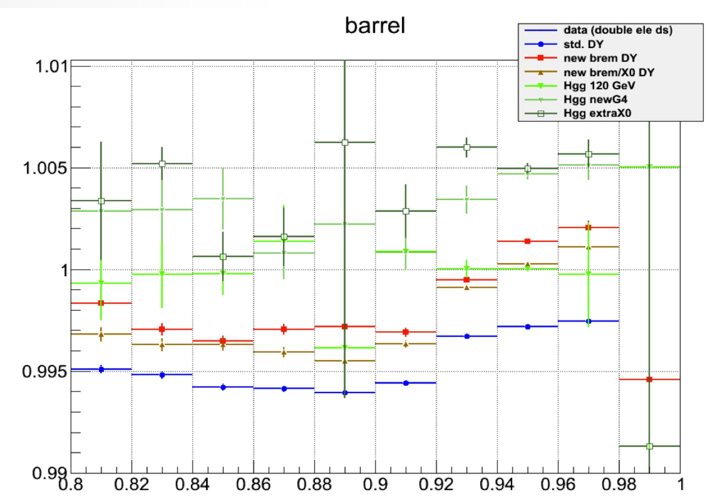
- Separate events into classes to improve sensitivity
- Tag exclusive modes in this order:

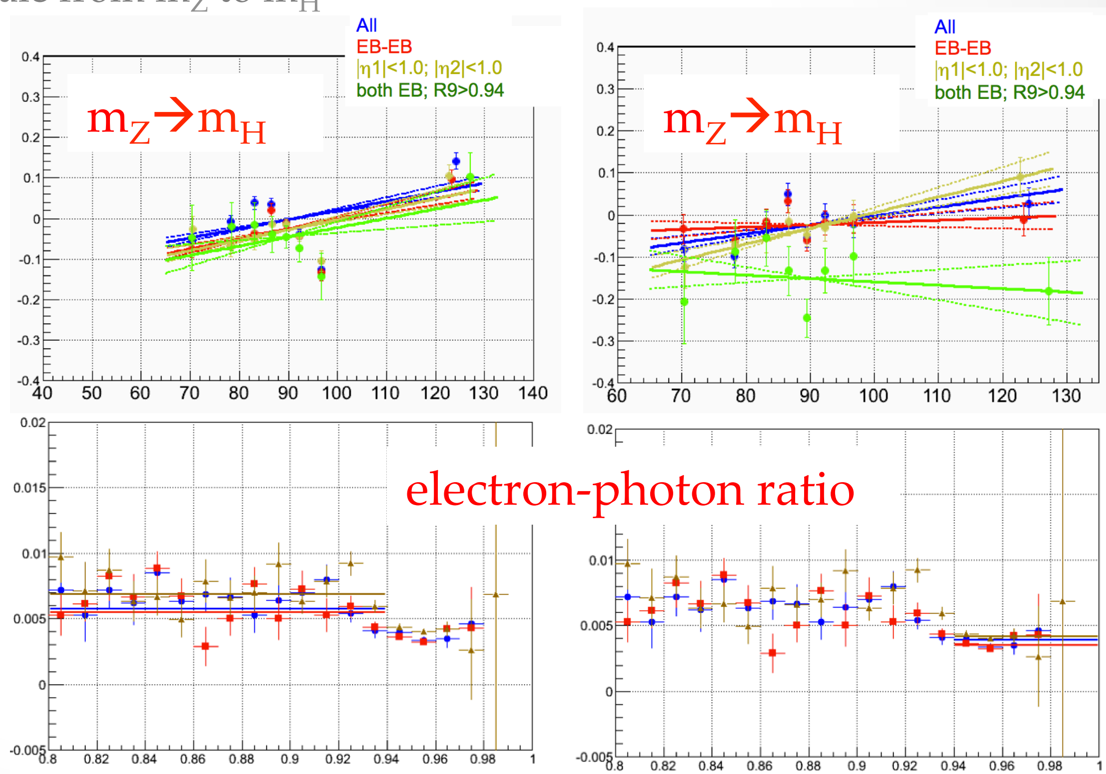
tag muon	TTH
tag electron	VH
tag dijets	VBF
tag MET	GGH
untagged	

- Untagged events
  - use diphoton MVA to classify further into 4 categories
  - use cut based selection and classify in η, R_9

Energy scale

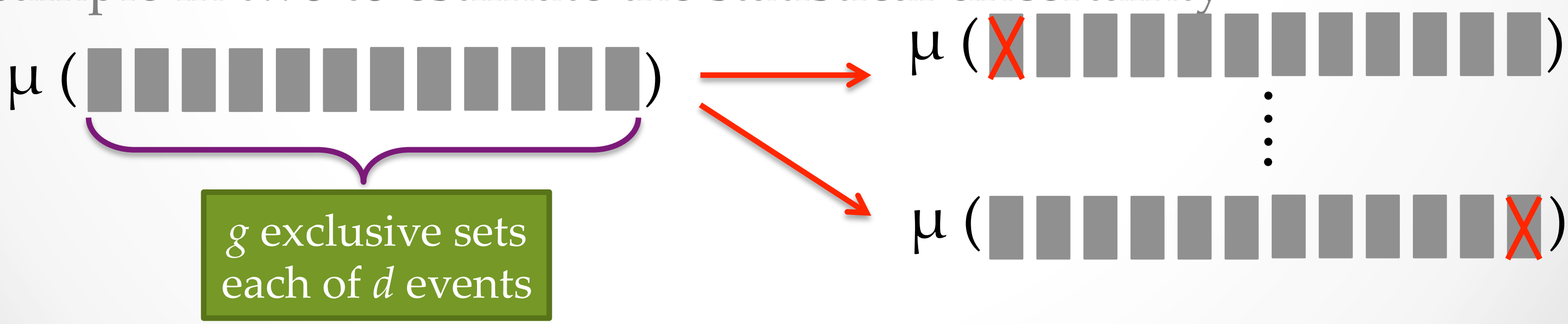
- Important input to mass measurement
- Use Z→ee where electrons are reconstructed *exactly* the same as photons
- Add fully correlated error which considers:
    - imperfect MC simulations of the difference between electrons and photons
    - the need to extrapolate the scale from m_Z to m_H





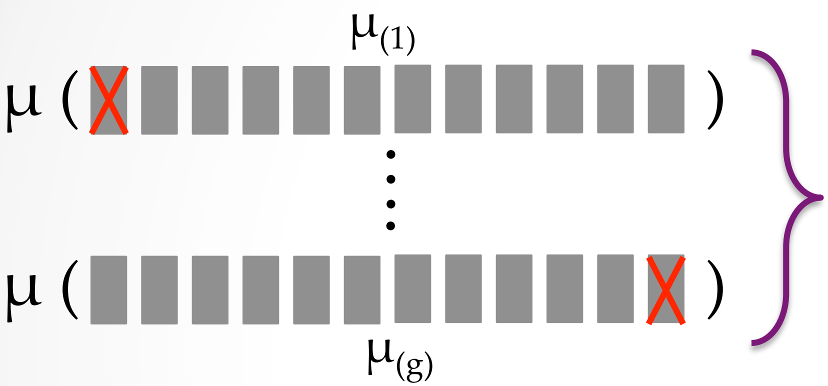
Jackknife resampling

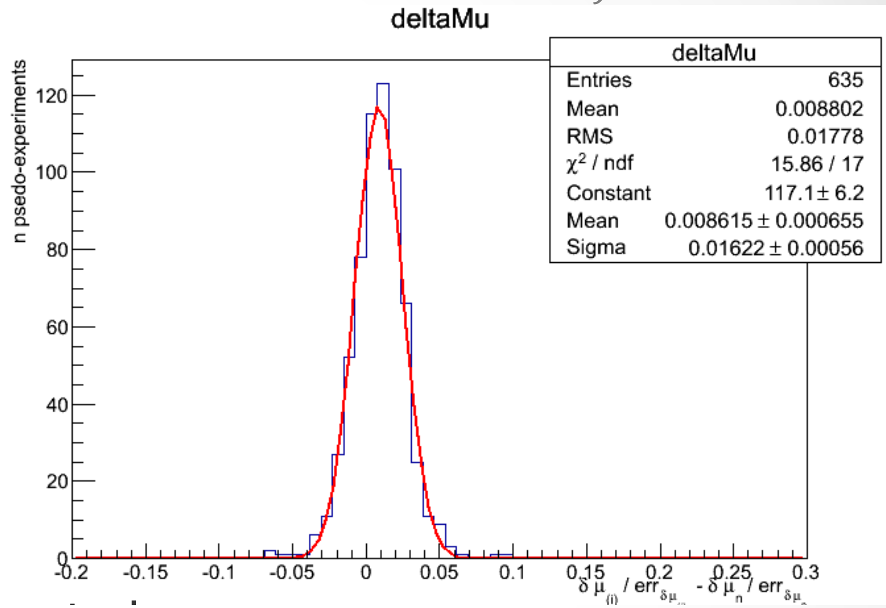
- Given an estimator (an observable – in this case μ) of a dataset you can obtain the expected variance of the estimator
- Cut (jackknife) the sample into multiple exclusive subsets and re-evaluate the estimator
- If you start with n events you remove exclusive sets of d events
- Thus you have $g=n/d$ samples of n-d events on which you re-calculate μ
- Analogous to the familiar undergraduate method of splitting a sample in two to estimate the statistical uncertainty



Jackknife resampling

- The estimator properties can be extracted from the jackknife histogram





- For example the variance:

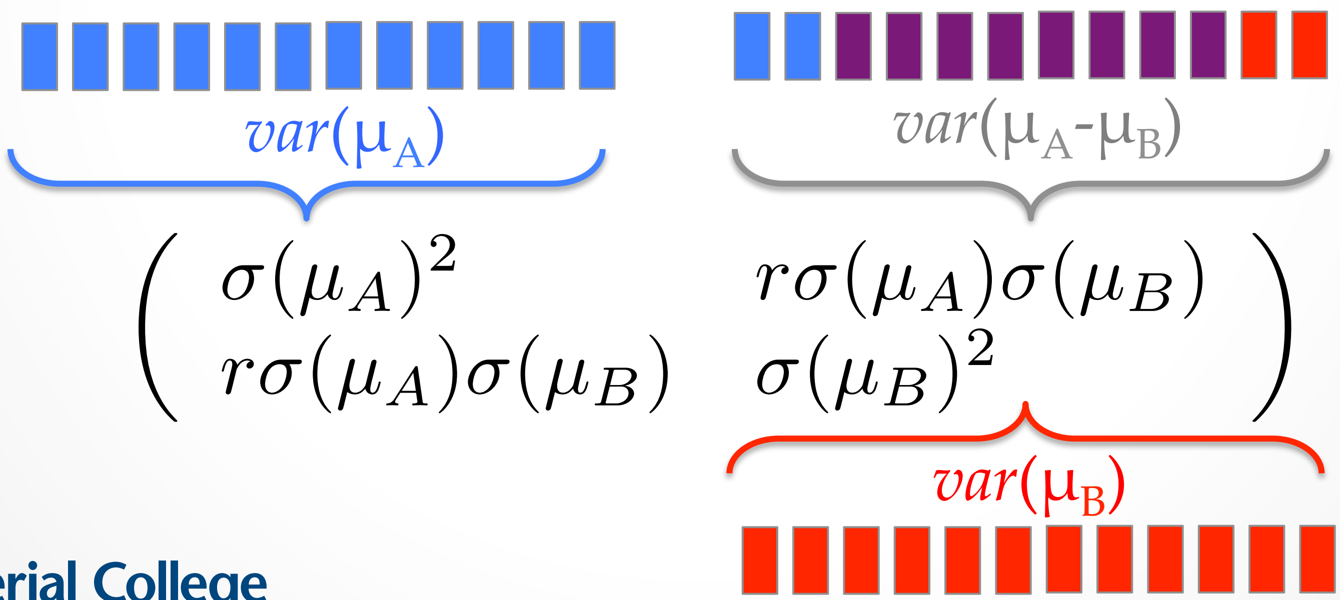
$$\mathrm{var}_J(\mu) := \frac{g-1}{g}\sum(\mu_{(j)} - \bar{\mu}_d)^2 = \frac{(g-1)^2}{g}\mathrm{var}(\mu_{(j)})$$

NOTE: g=2 recovers the familiar formula

where $\bar{\mu}_d = \frac{1}{g}\sum \mu_{(j)}$

Jackknife resampling

- Given two analyses there are three datasets
  - Events selected by Analysis A (CutBased)
  - Events selected by Analysis B (MVA)
  - Events selected by either A or B (i.e. A ∪ B) of which the majority are in common
- Use the jackknife to estimate
  - $\sigma(\mu_A)$, $\sigma(\mu_B)$ and $\sigma(\delta\mu) = \sigma(\mu_A - \mu_B)$



$$\begin{pmatrix} \sigma(\mu_A)^2 & r\sigma(\mu_A)\sigma(\mu_B) \\ r\sigma(\mu_A)\sigma(\mu_B) & \sigma(\mu_B)^2 \end{pmatrix}$$

Jack-knife Resampling

Estimate the best fit of the signal strength modifier of the Hgg analysis:
method 1 : $0.78^{+0.28}_{-0.26}$
method 2 : $1.1^{+0.32}_{-0.30}$

One sample of data, two methods to extract one parameter.
The results are correlated because they share the same dataset. Are the two results compatible ?

$$\rho_{X,Y} = \mathrm{corr}(X,Y) = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y},$$

1) Get the correlation coefficient:
   i.e. calculate the variance of the first and the second measurement and the variance of the overlapping events
2) Calculate the difference between the two results using

$$\sigma_x^2 + \sigma_y^2 - 2\rho\sigma_x\sigma_y$$

Use resampling techniques (in this case a Jackknife) to get the variances

Jack-knife Resampling II

Remove one (or N) point from the sample distribution

and calculate the new sample average:

$$\bar{x}_{(i)} = \frac{n\bar{x} - x_i}{n-1} = \frac{1}{n-1}\Sigma_{j\neq i} x_j$$

dot notation
(on the sample at hand)

$$\bar{x}_{(\cdot)} = \Sigma_{i=1}^{n} \frac{x_{(i)}}{n}$$

(here trivially $\bar{x}_{(\cdot)} = \bar{x}$)

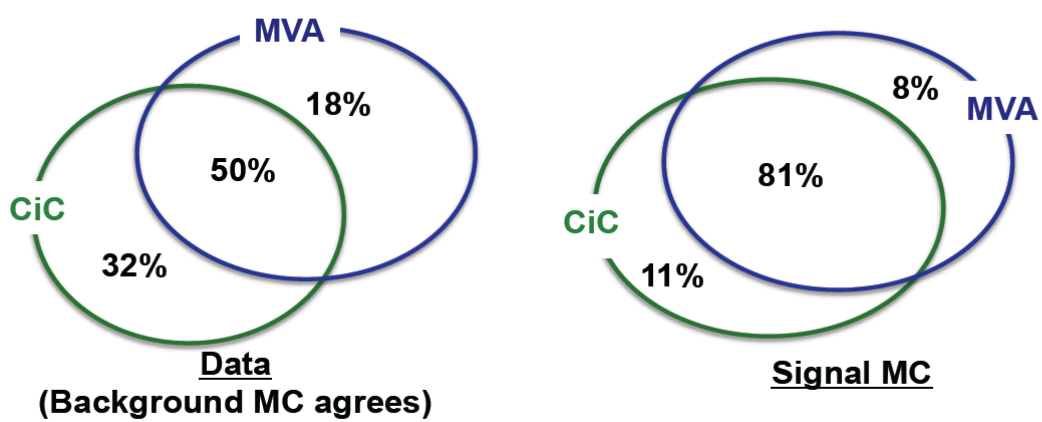
The jackknife estimate of the standard error is defined as:

$$\bar{\sigma}_J = \left[\frac{n-1}{n}\Sigma_{i=1}^{n}\left(\bar{x}_{(i)} - \bar{x}_{(\cdot)}\right)^2\right]^{1/2}$$

$$\Rightarrow \boxed{\hat{\sigma} = \bar{\sigma}_J}$$

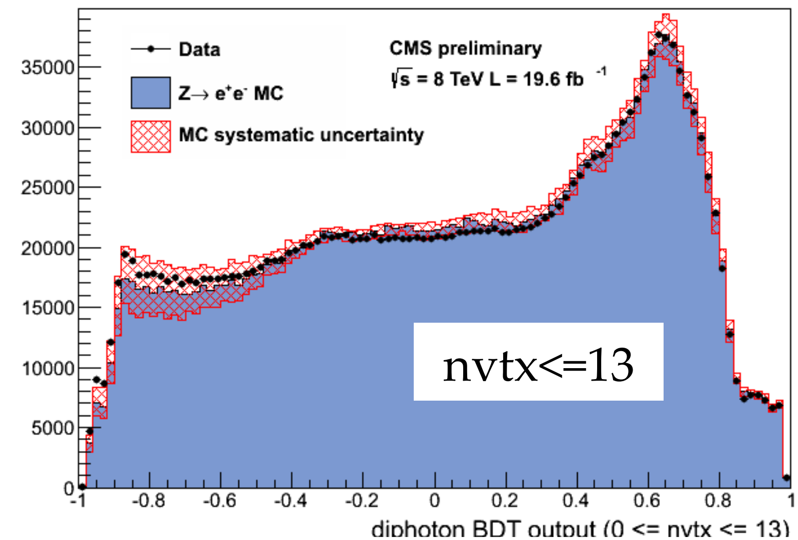
Jack-knife Resampling III

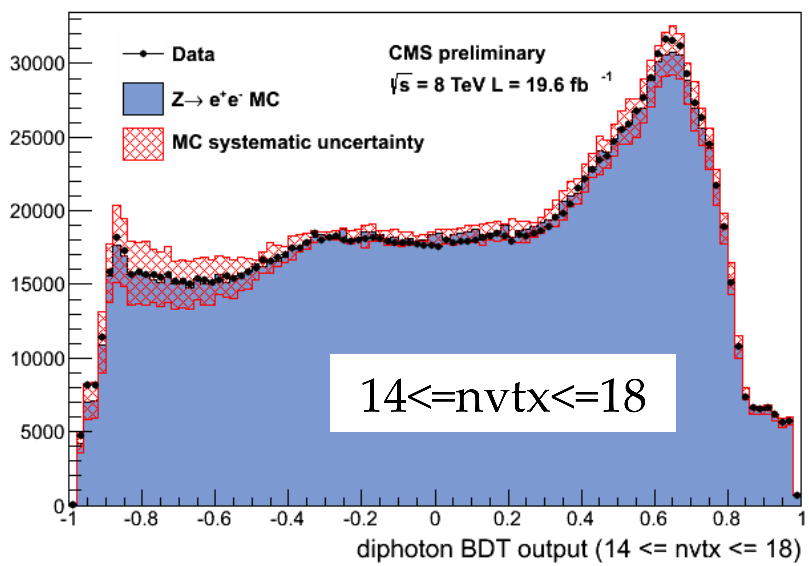
	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

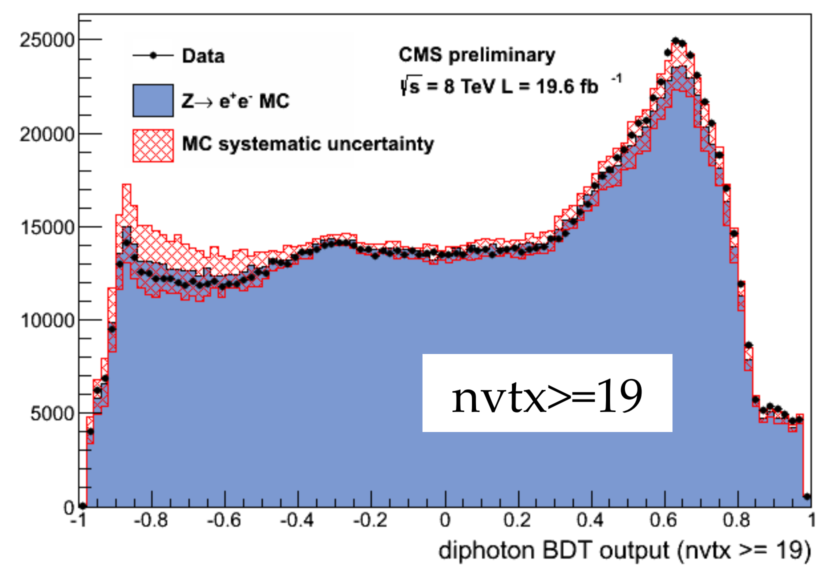


Diphoton MVA Validation

- Inputs are validated with
  - Z→ee (electrons reconstructed as photons)
  - Z->μμγ
- Empirical corrections derived for inputs
  - use Drell-Yan data/MC comparison
  - correct resolution and photonID
- Systematic uncertainties propagated through BDT
  - resolution and photonID
  - implemented as category migration

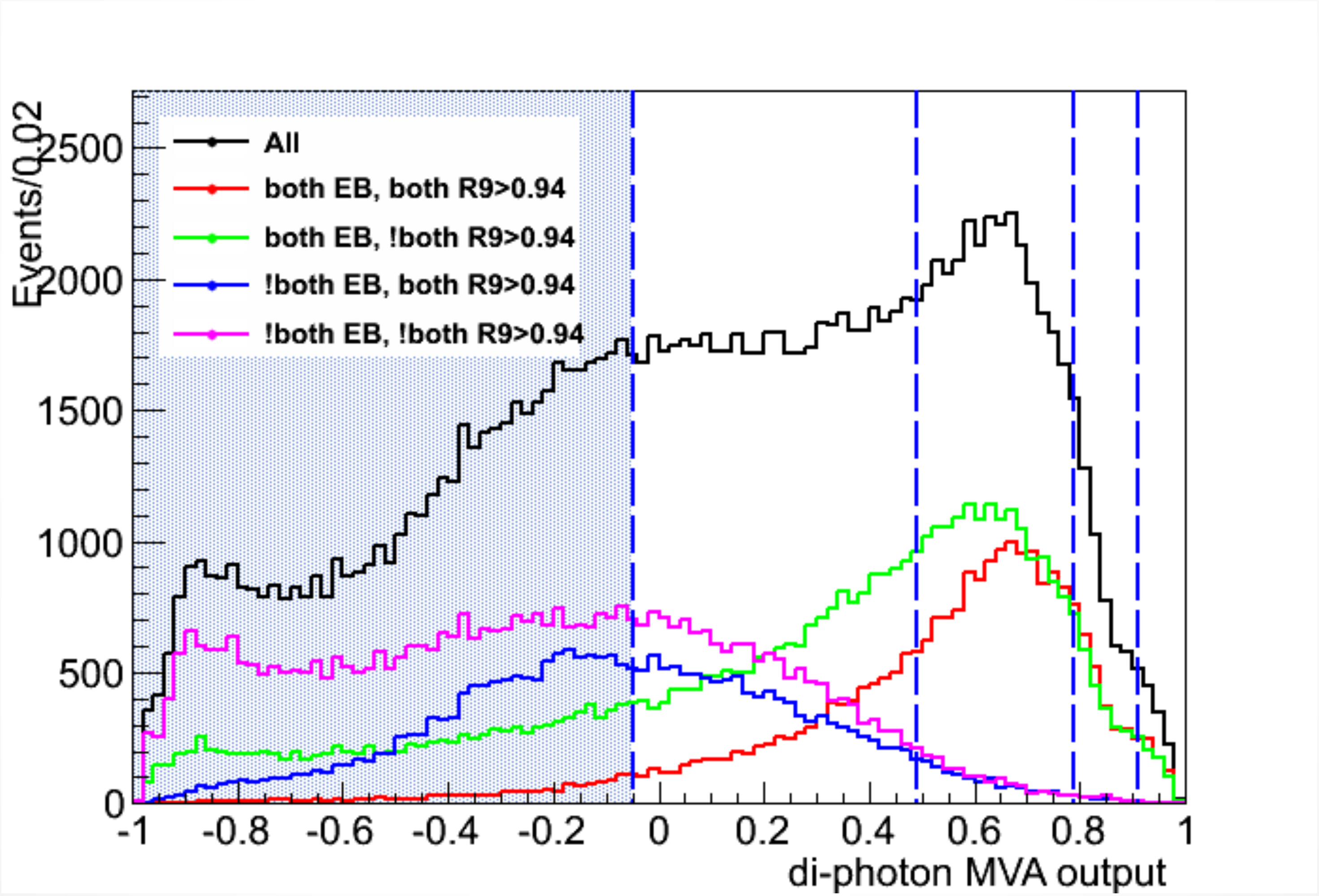






MVA-CiC comparison

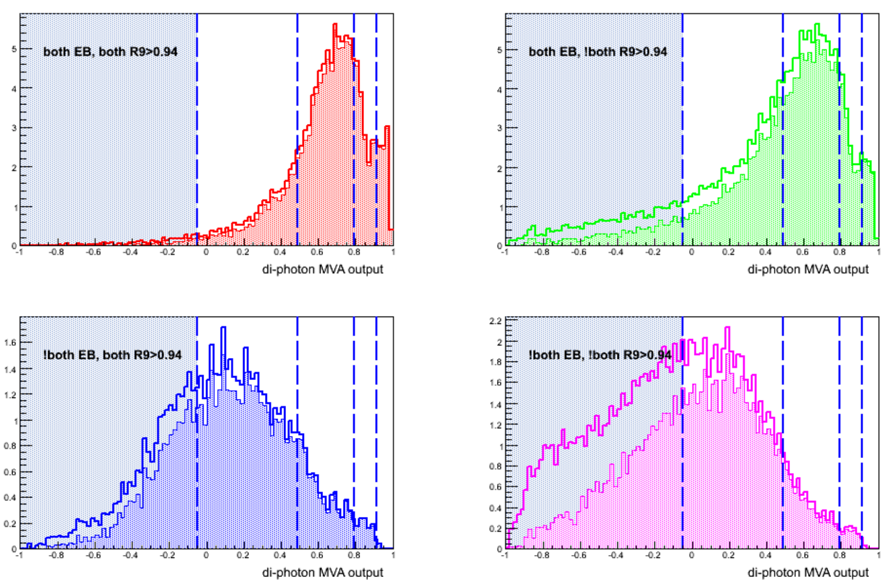
- MVA output for data events which pass CiC selection



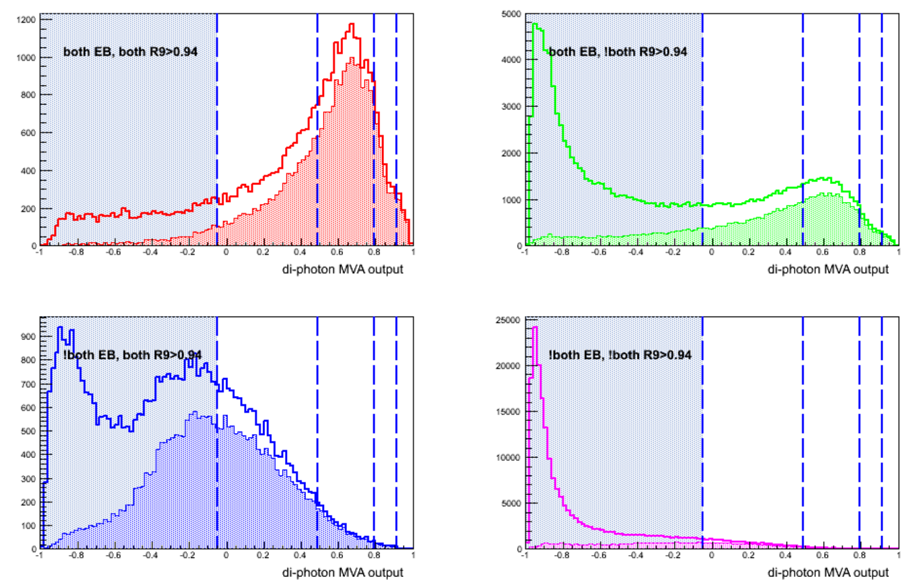
MVA-CiC comparison II

- Events which pass MVA selection
  - Events which also pass CiC are shaded

Signal

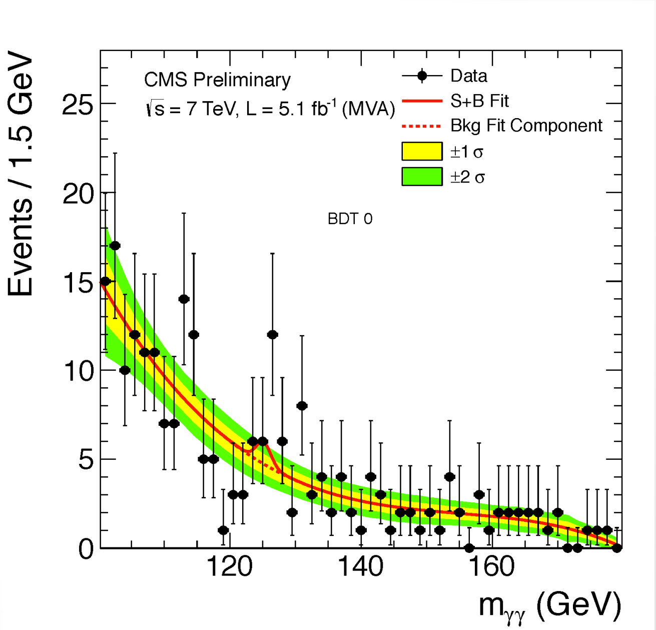


Data



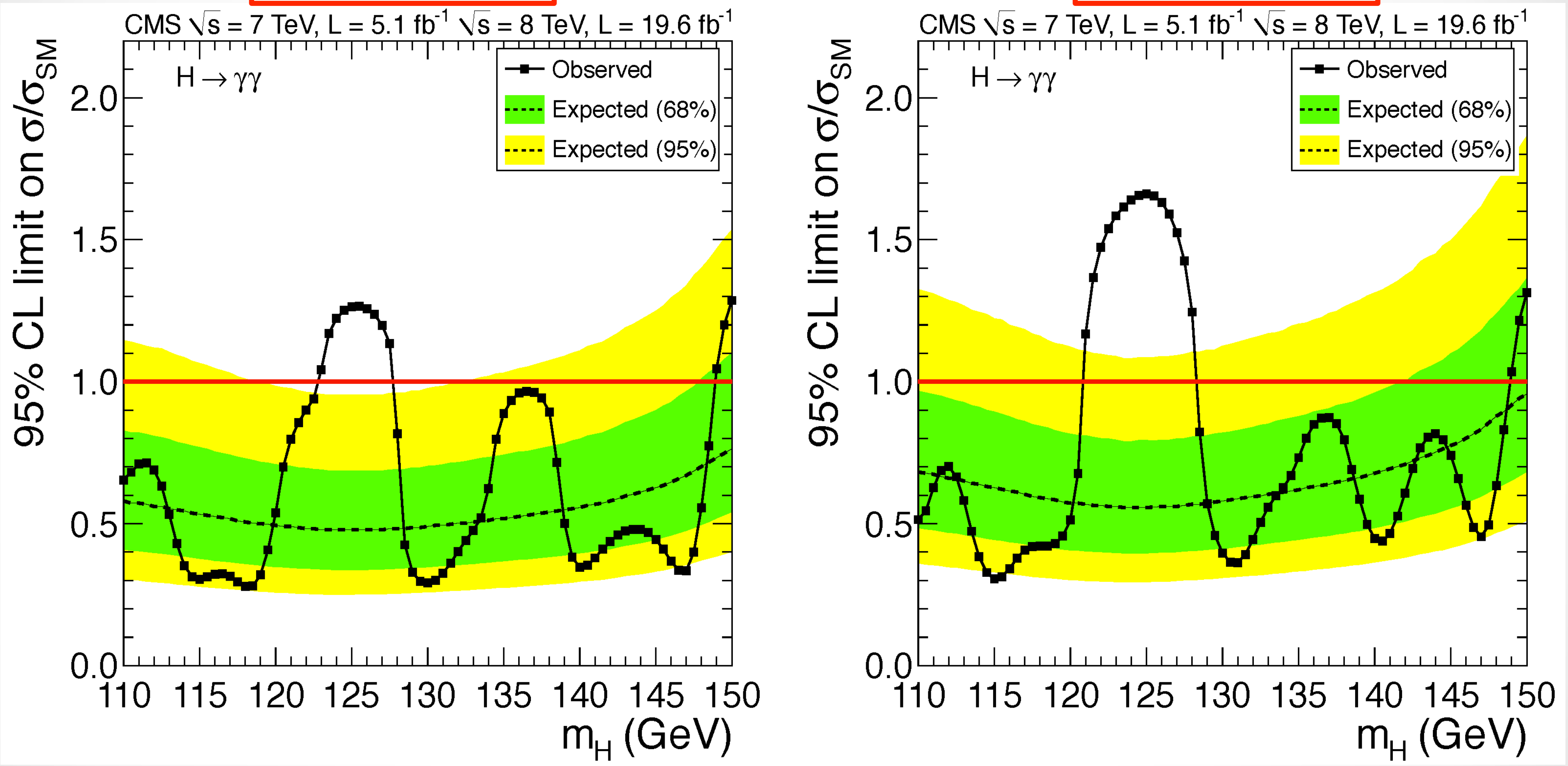
Background Model Choice

- For each category fit with different functional forms
  - exponentials sums, power laws, laurent series, polynomials
- Choose the lowest order of each which fits the data well
  - G.O.F test with unbinned like F-test - p(N+1)<0.05
  - Determines "truth" functions
- Throw toy MC from the truth functions
- Choose the lowest order functional form such that
  - bias on signal strength < 20% statistical uncertainty on background
  - neglect any systematics on background
  - choices are 3rd-5th order polynomails



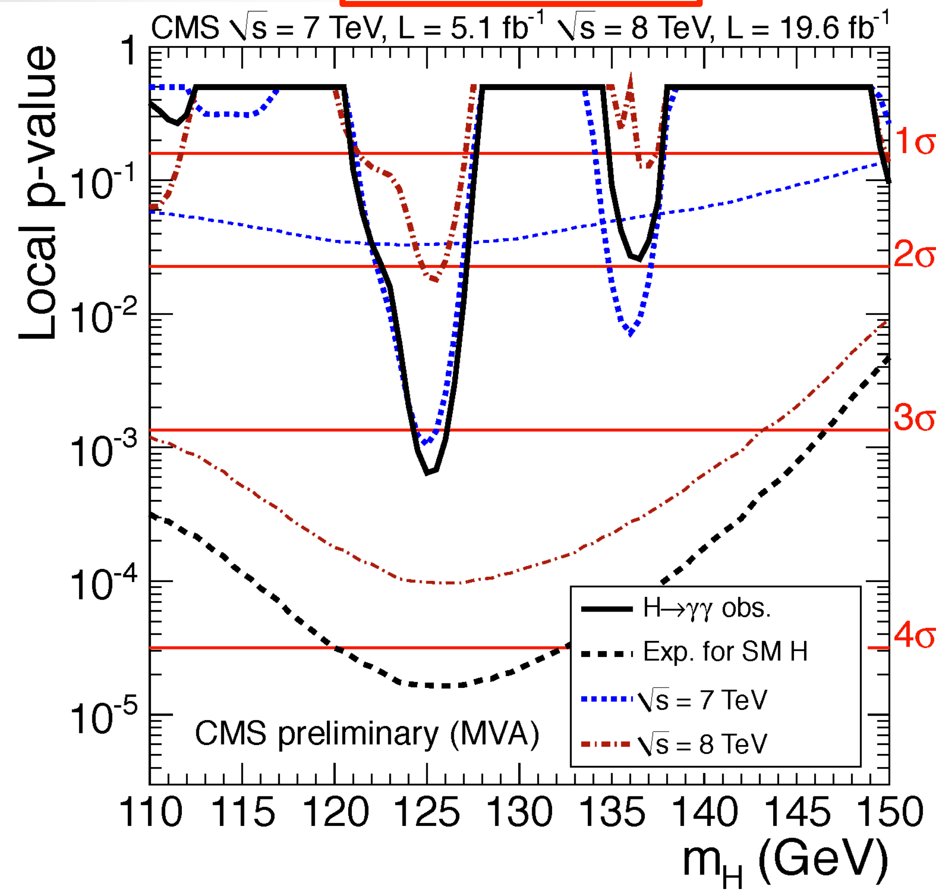
Limit

MVA | **Cut Based**

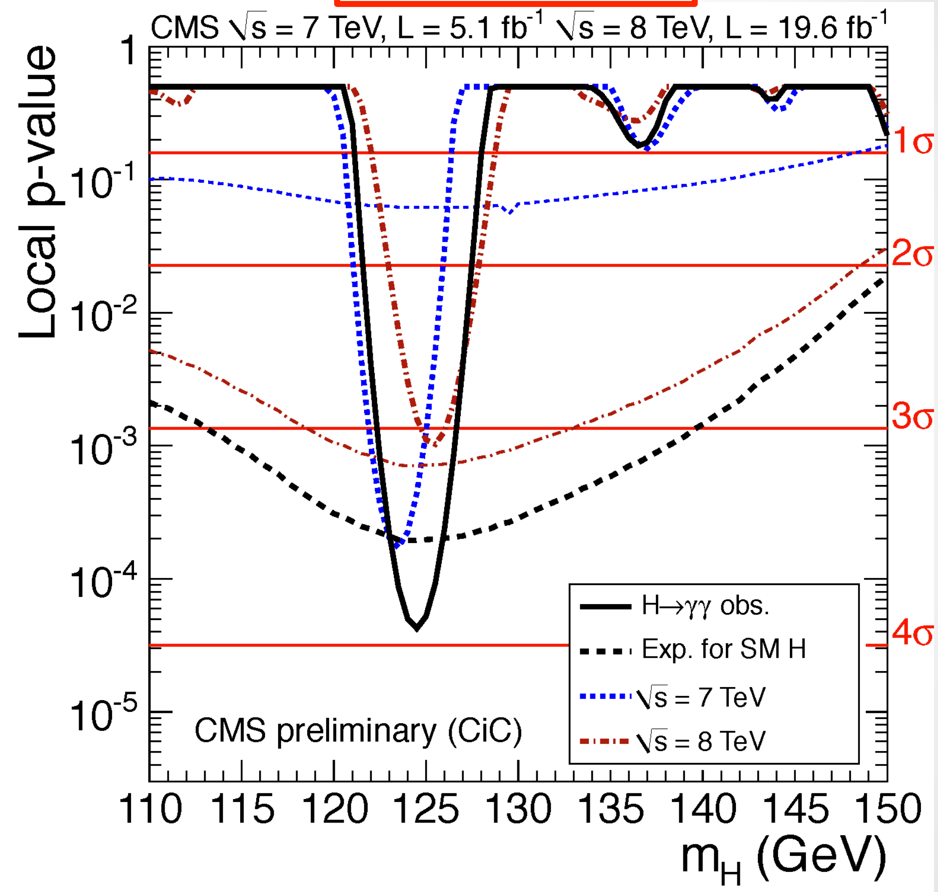


P-value

MVA

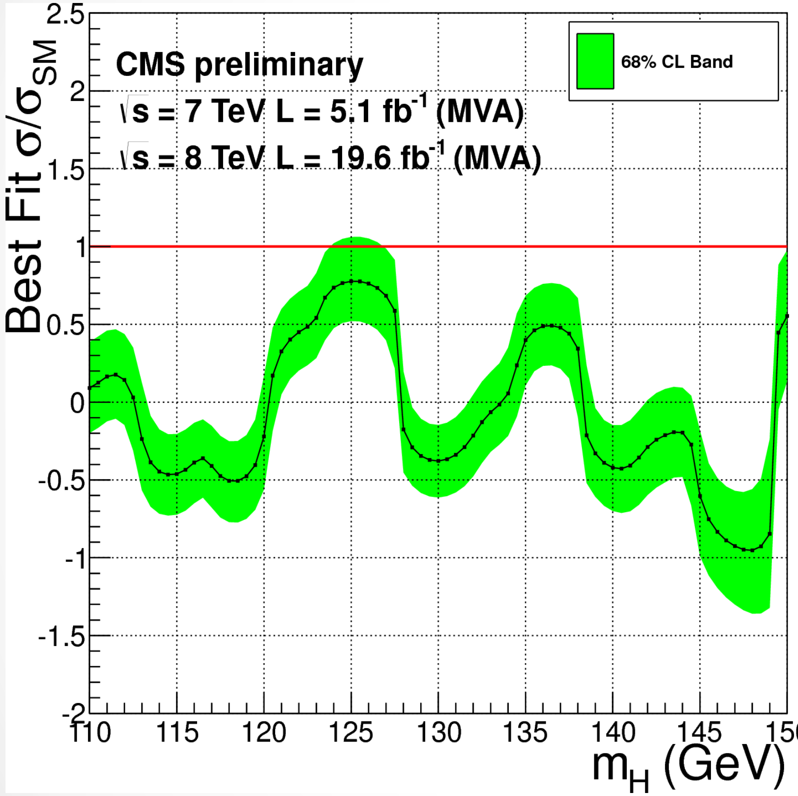


Cut Based

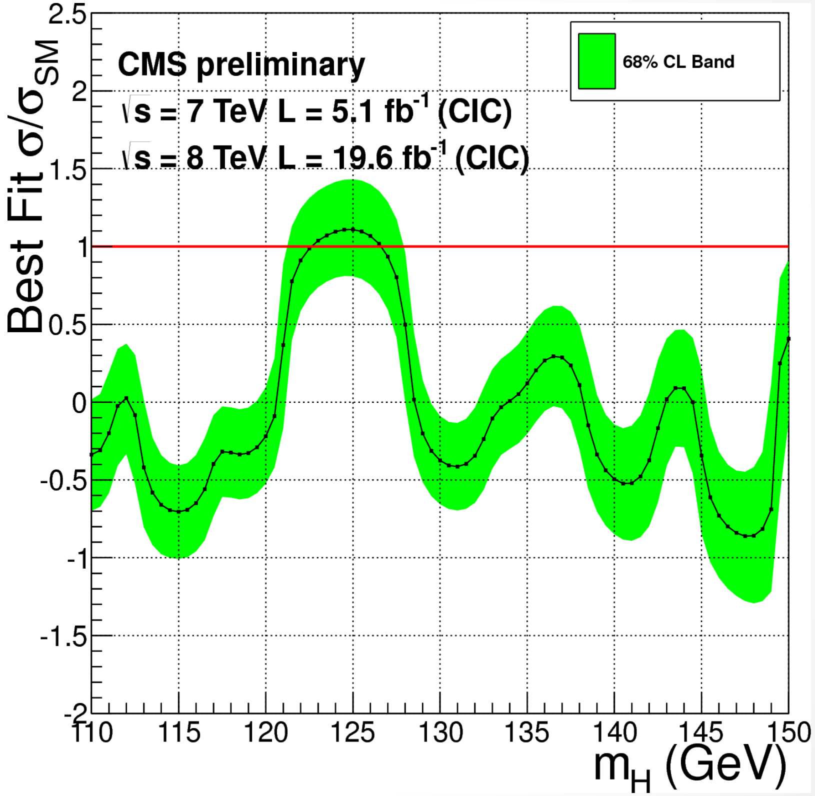


Signal Strength

MVA

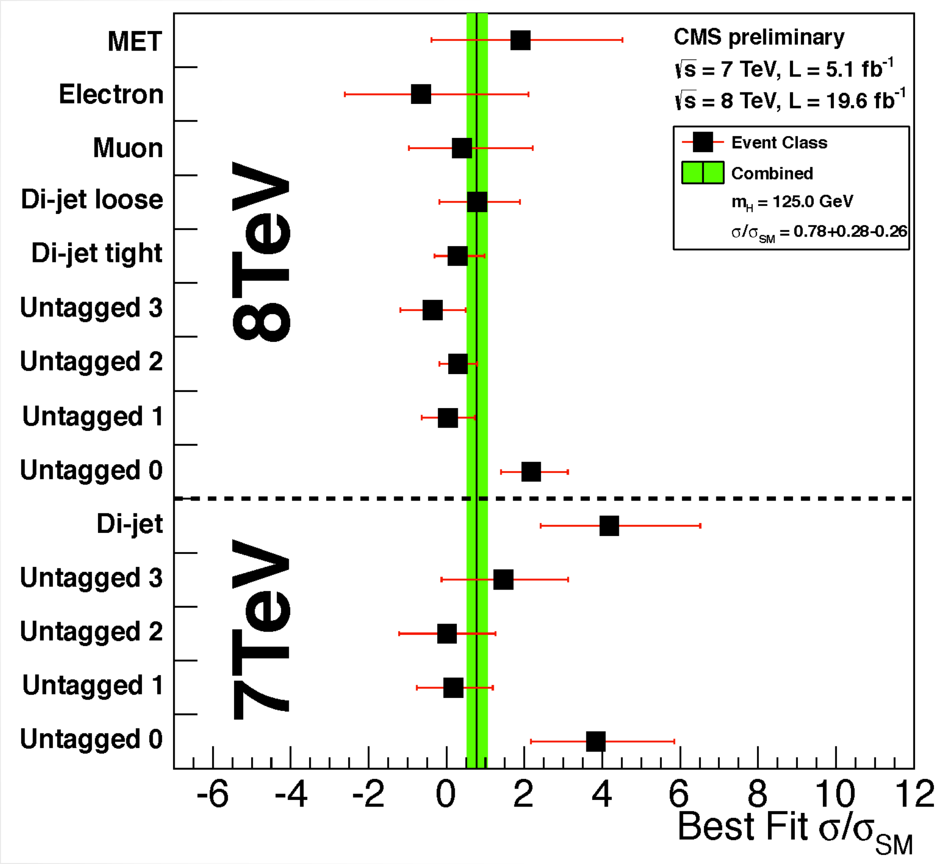


Cut Based

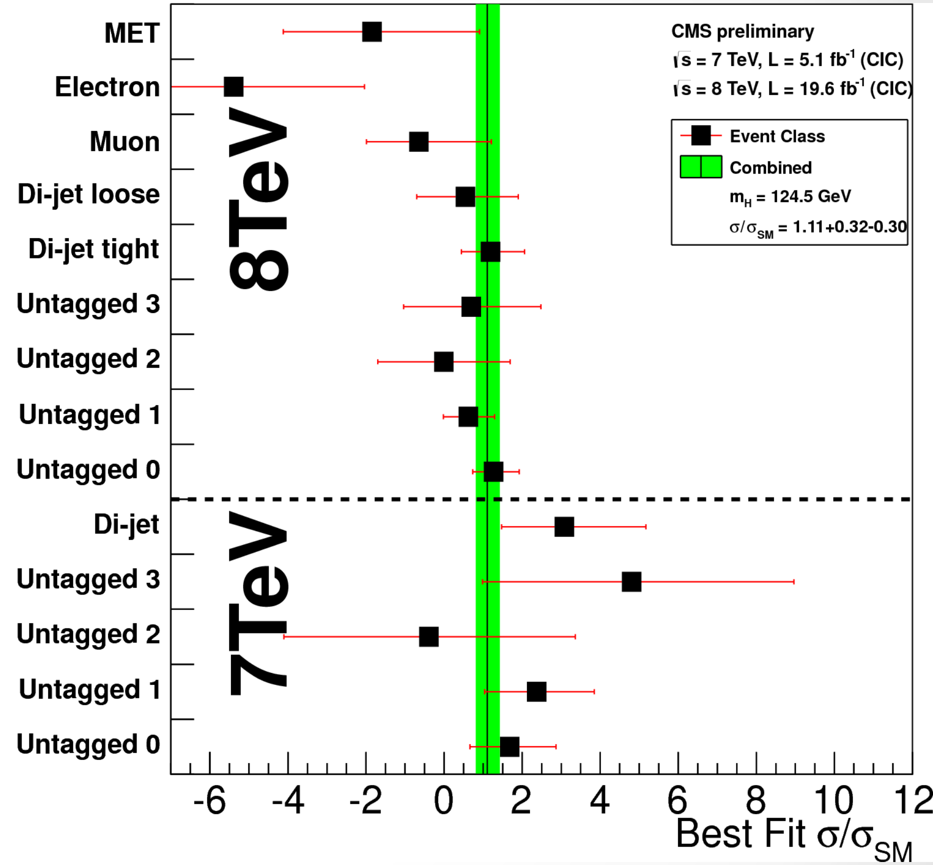


Channel Compatibility

MVA

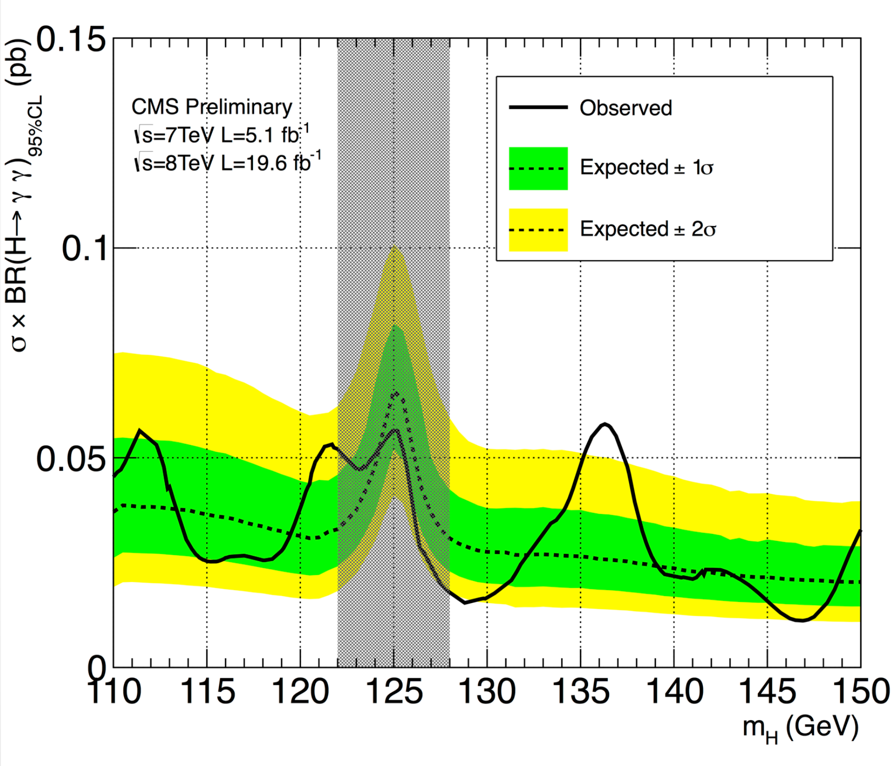


Cut Based

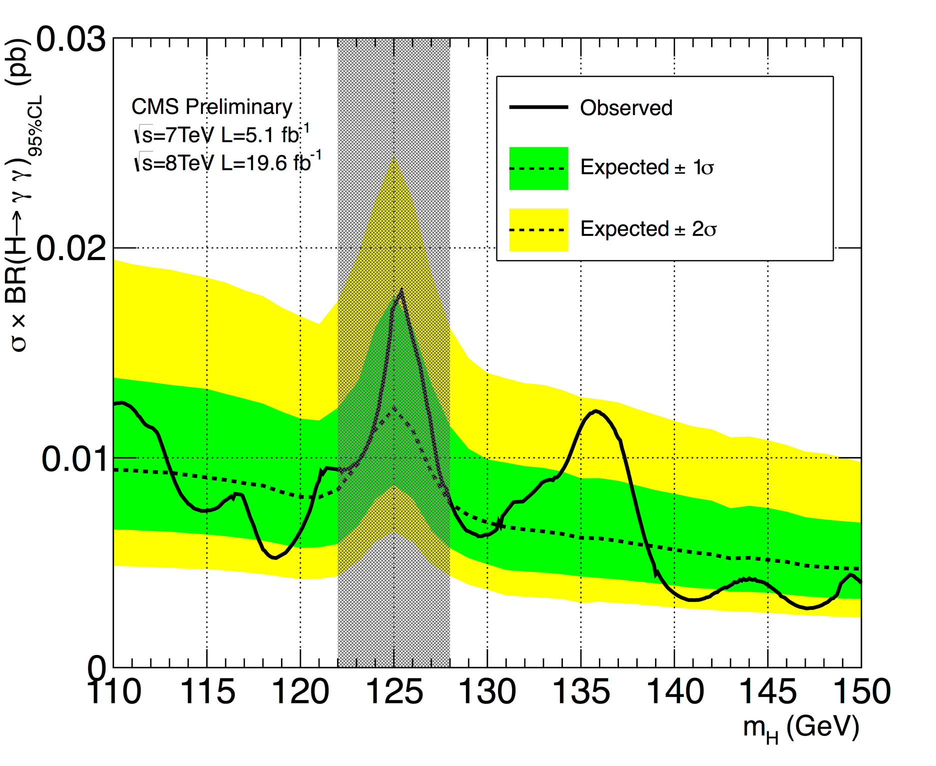


Second Higgs

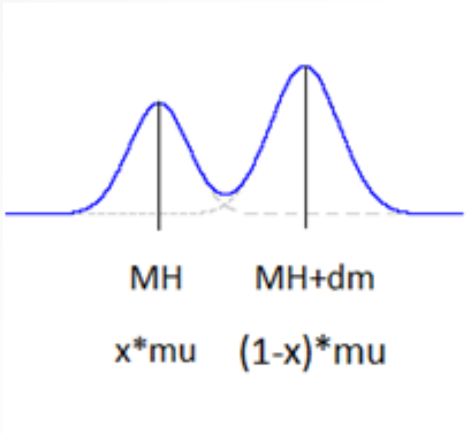
Second Higgs has ggH and ttH coupling only



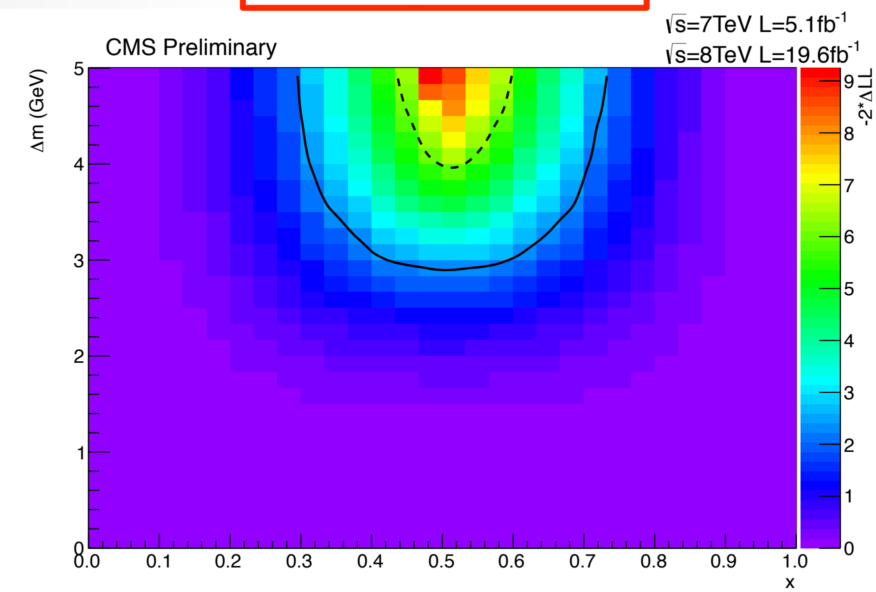
Second Higgs has qqH and VH coupling only



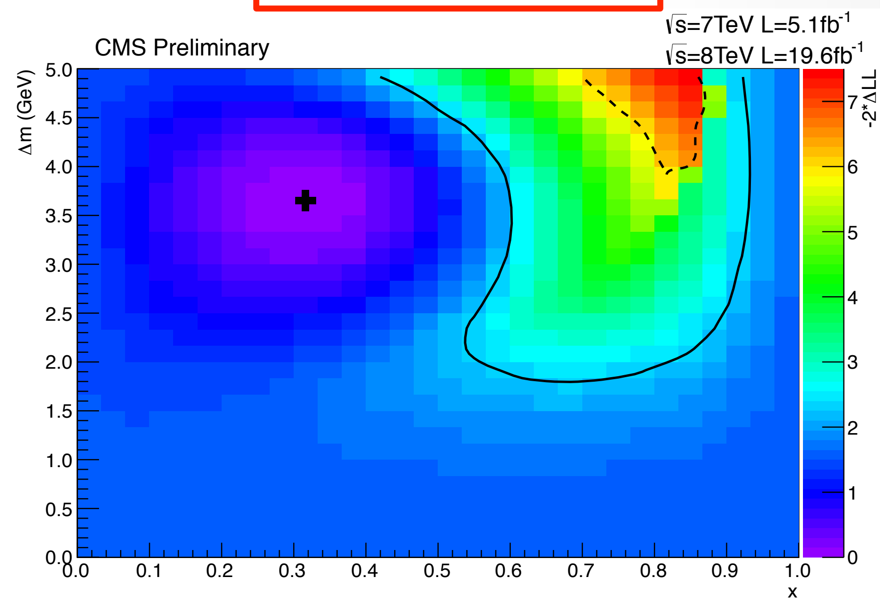
Two Higgs



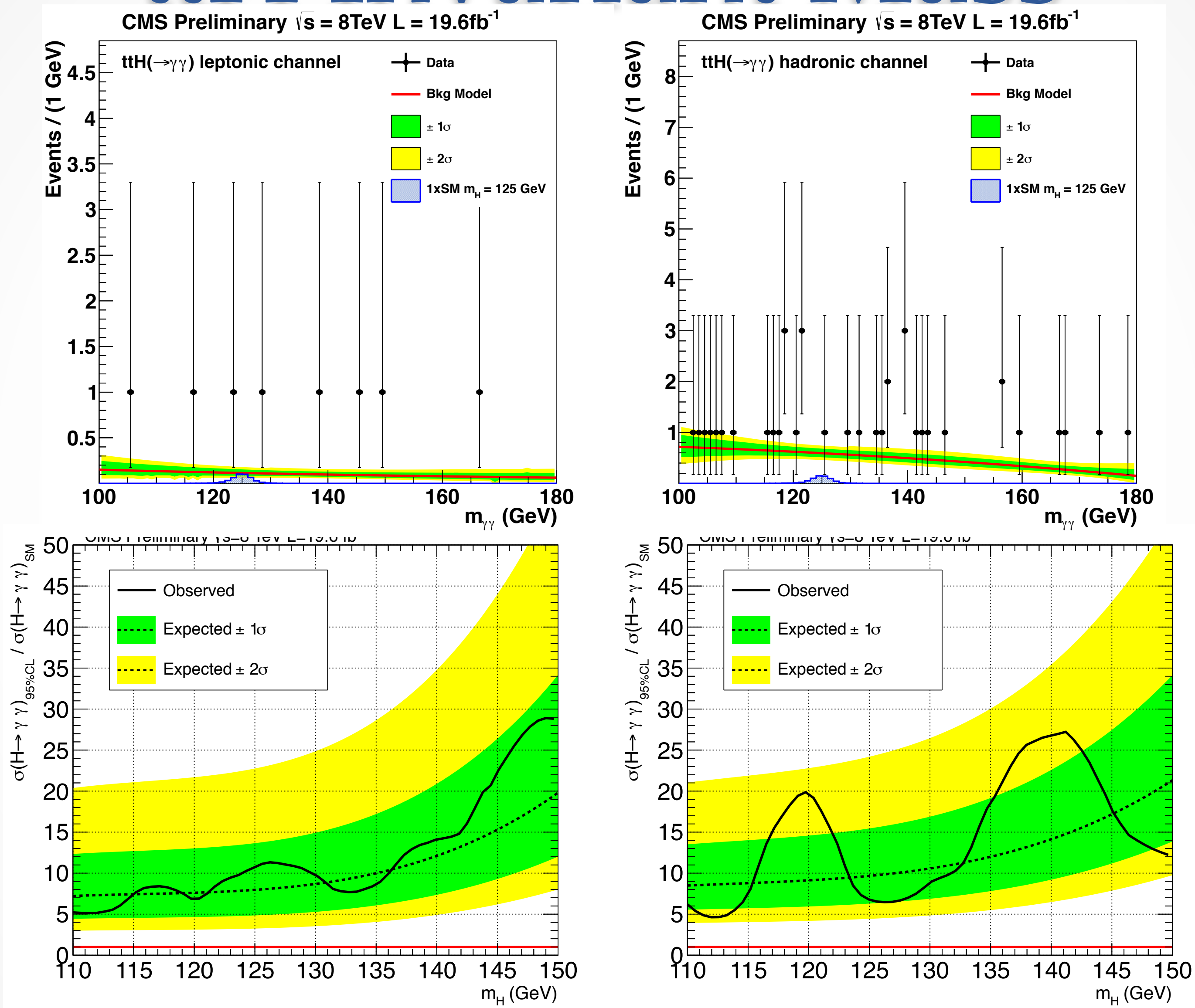
Expected



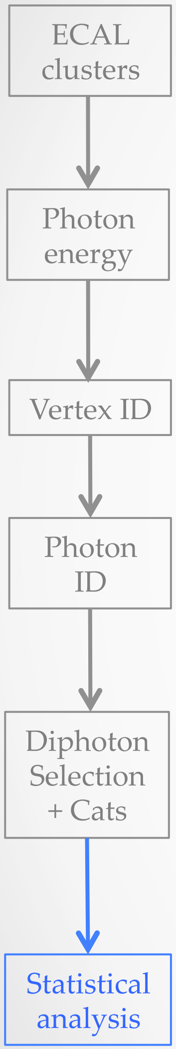
Observed



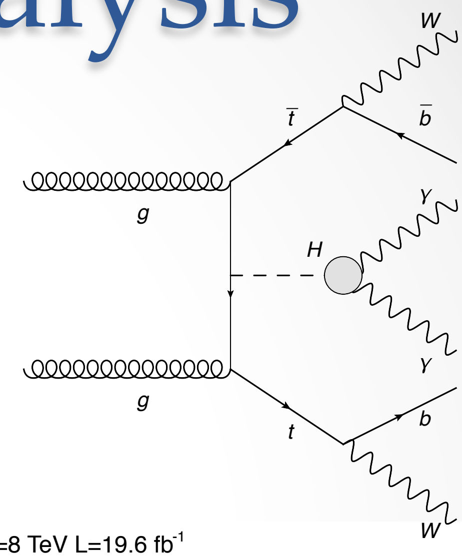
ttH Invariant Mass

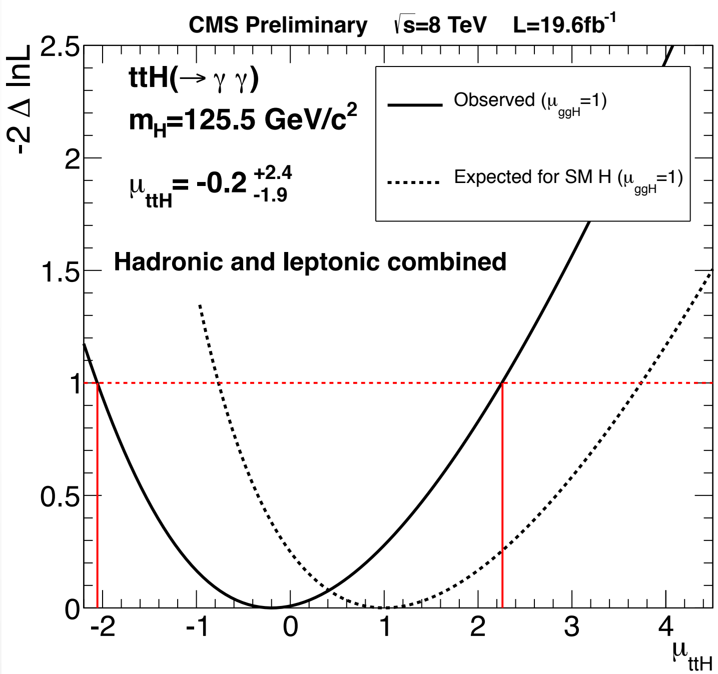


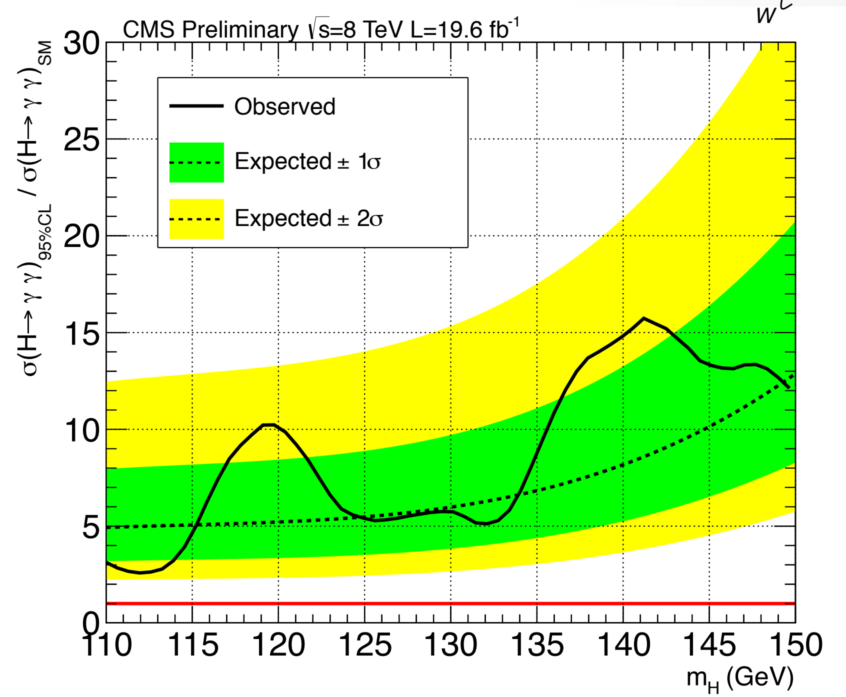
Results III - ttH analysis



- Separate specific analysis looking for H→γγ from tt production
  - Hadronic channel
  - Leptonic channel
  - Will be incorporated into main analysis for *legacy* result
  - Observed (expected) upper limit at 95% 5.4 (5.3) x SM







Zγ Result

- CMS-PAG-HIG-13-006
- Strategy similar to H→γγ (signal/background modelling)
- 4 event classes based on lepton/photon η and high/low R_9