Higgs to 2 photons in CMS

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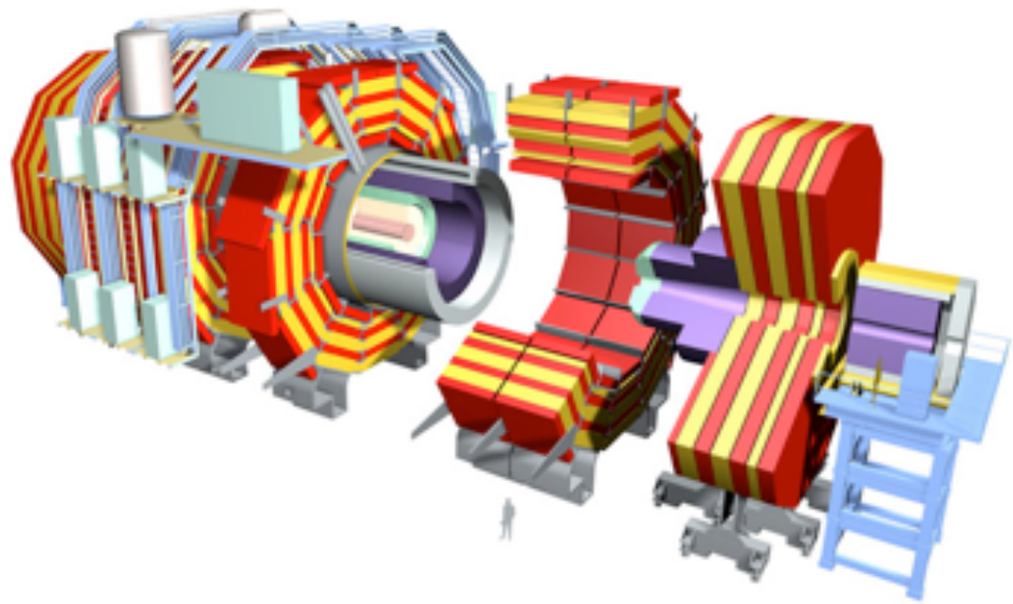
CMS collaboration

Overview

- Introduction
- Analysis flow
- Results
- H→Zγ search



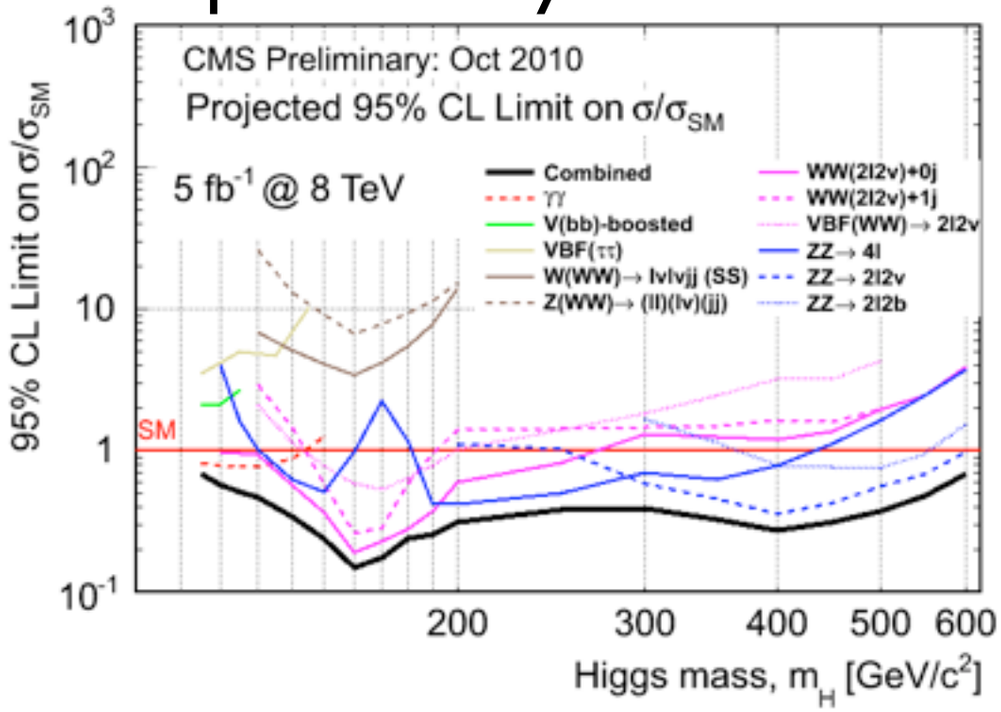
LHC France, 4 avril 2013

Introduction

Yesterday: discovery regime

- major channel for low mass Higgs searches
- very clean signature:
  - 2 isolated photons
  - narrow peak on top of a smoothly falling background

pre-history



Today: precise measurement regime

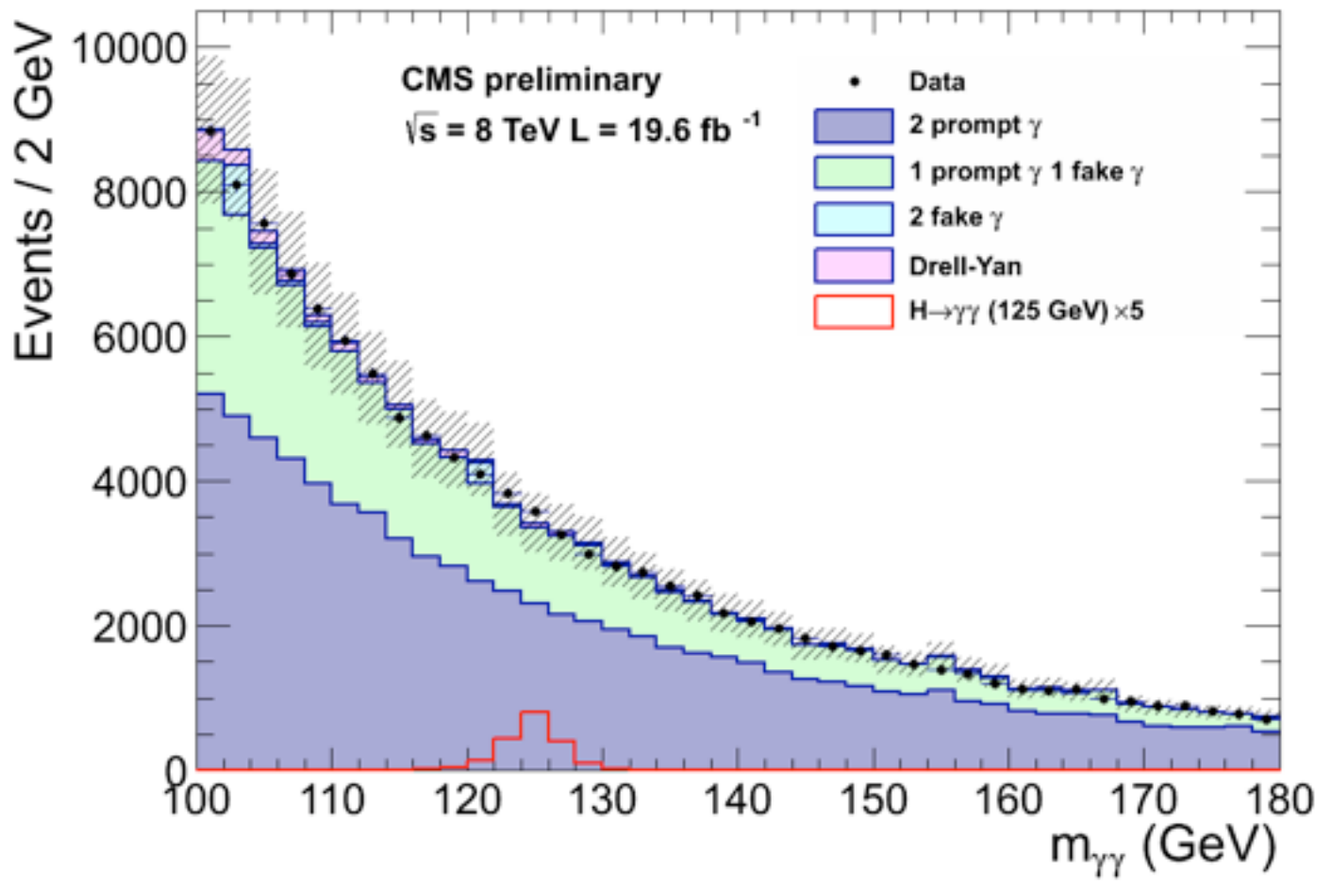
- mγ = 0, Hγγ coupling only through loops.
  - small branching fraction (Br ~ 0.0023)
  - very sensitive to any new massive charged particle
- yet sizeable number of events (e.g. compared to ZZ*→4ℓ)
  - access to exclusive production modes: VH couplings.

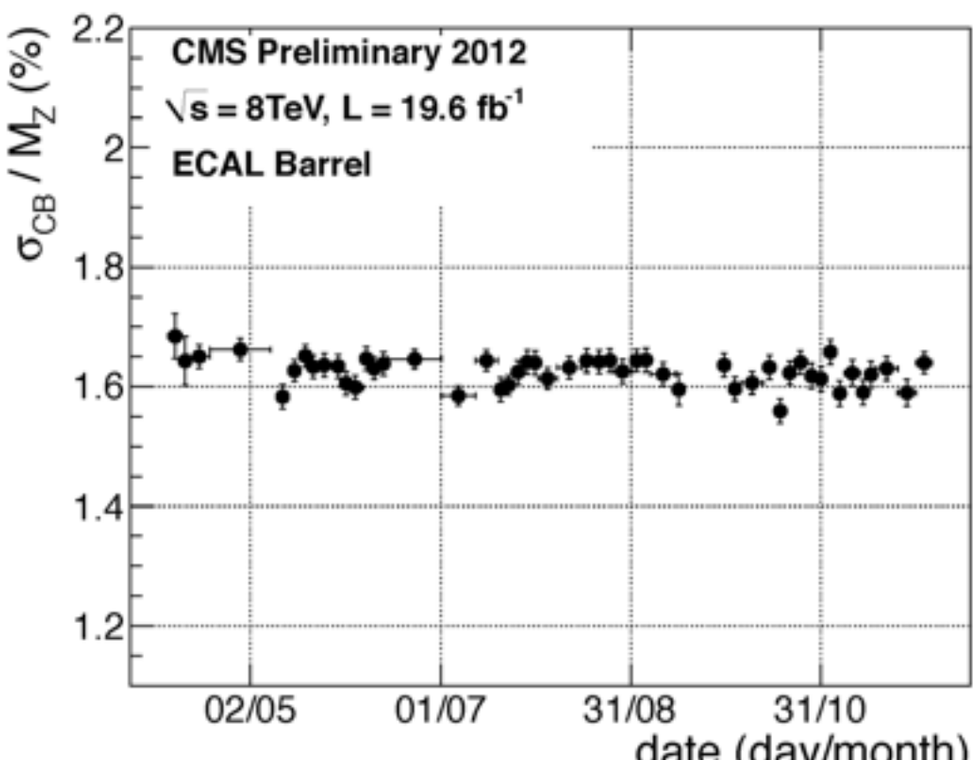
Challenges

- Tiny signal (S) vs large bkgd (B):
  - ✓ background determination
  - ✓ signal discrimination
- Signal discrimination based on:
  - ✓ event kinematics
  - ✓ diphoton mass resolution
  - ✓ jet rejection (shower shape in ECAL and PF isolation)
- Dominant backgrounds:
  - ✓ prompt diphoton: 70%
  - ✓ photon + jets: 30%
- Control samples:
  - ✓ Z→ee
  - ✓ Z→μμγ

$$m_{\gamma\gamma} = \sqrt{2\,\underline{E_{\gamma 1} E_{\gamma 2}}\,(1 - \underline{\cos\theta})}$$

ECAL PVz

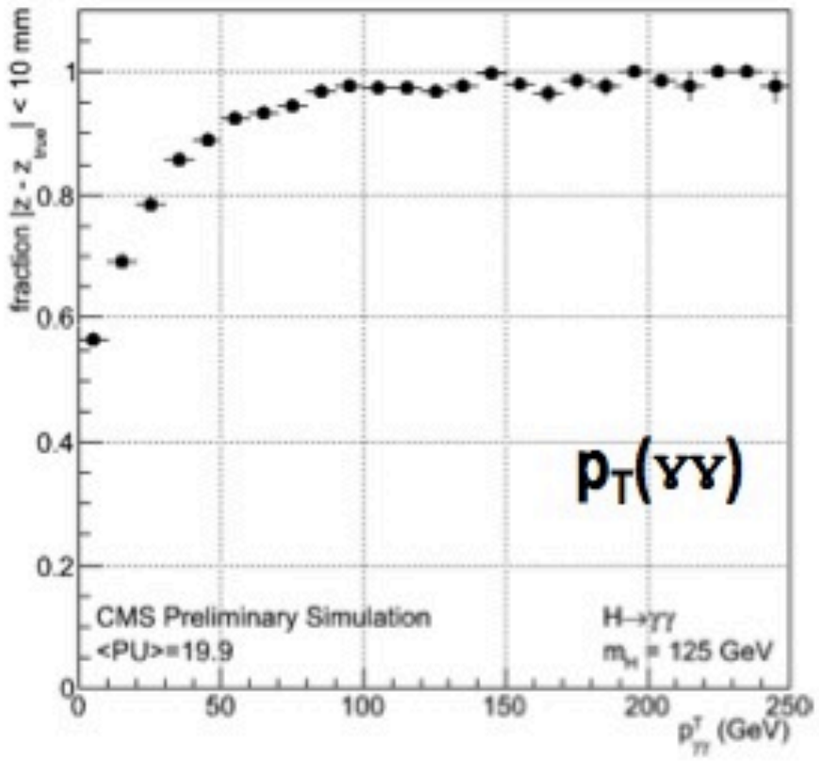


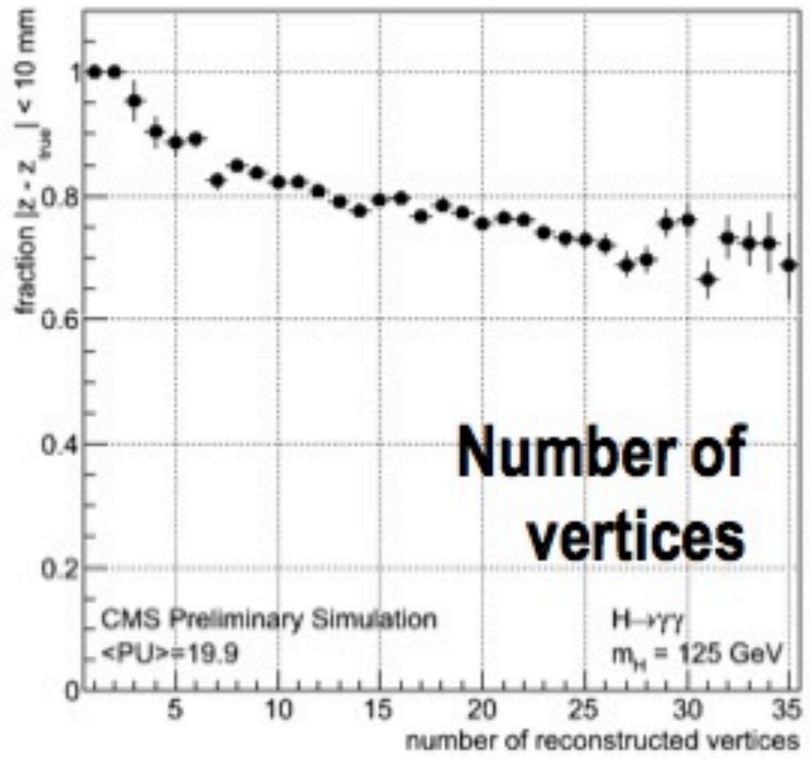


Primary vertex position

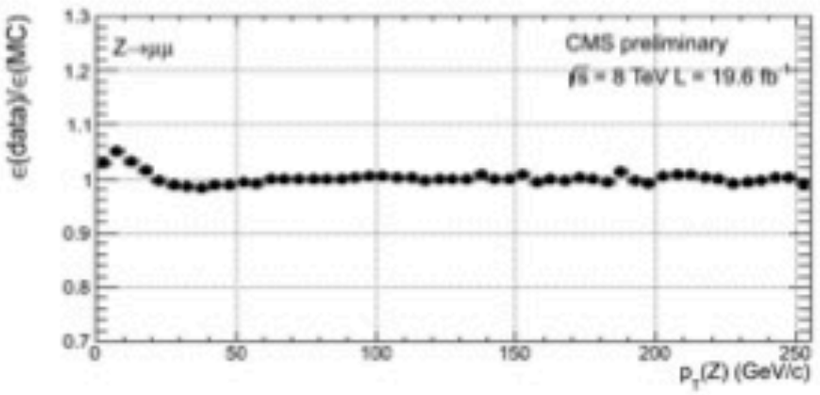
- No hard tracks from photons to identify the hard scatter primary vertex (PV).
- PV Z position affects mass resolution if σ_{ZPV} ~10mm (σ_{ZLHC} ~ 5cm)
- PV assignment via MVA method:
  $\sum p_T^2$, vertex recoil vs diγ system, γ conversion pointing
- Additional MVA estimates the per-event probability to identify the correct PV.
- Efficiencies checked in data: $Z \rightarrow \mu\mu$ (w/o tracks) and γ+jets (for γ conversion)

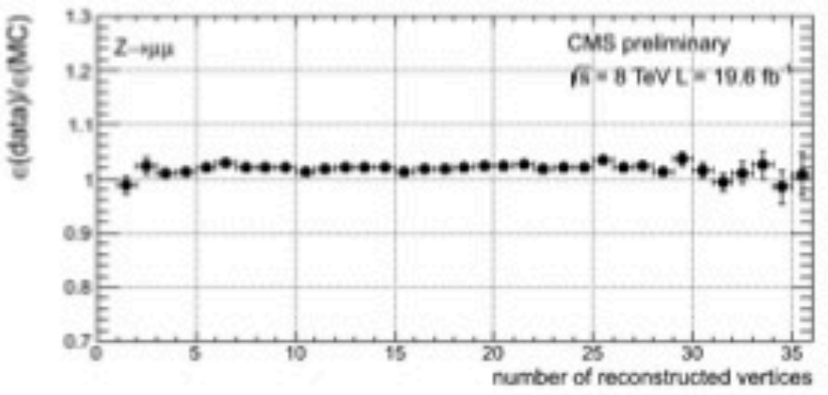
MC signal efficiency





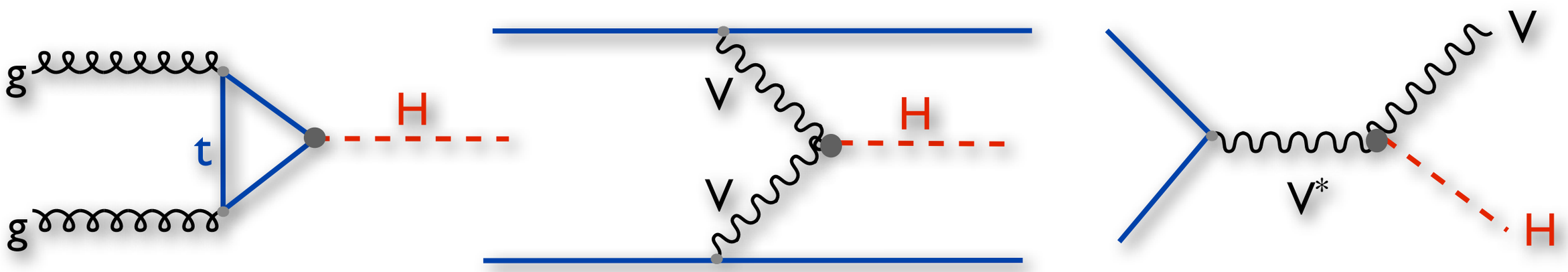
Data/MC ratio using Z→μμ





Analysis flow

- Two analysis in parallel: two different diphoton event pre-selection
  - ✓ fully cut-based analysis (CiC) with slightly lower systematic uncertainties
  - ✓ MVA analysis fully exploits the evt-by-evt properties: kinematic and photon quality
- Similar strategy: split diphoton sample into sub-samples with different S/B:
  - ✓ "exclusive" categories: associated production with jets (VBF) or vector boson (VH)
    - ✦ probe VBF and VH production modes
    - ✦ higher S/B than inclusive production
  - ✓ "inclusive" categories
    - ✦ CiC analysis: 4 categories using the detector-based quality of the event
    - ✦ MVA analysis: 4 categories based on a mass blinded BDT discriminant
- MVA analysis main result: better expected sensitivity



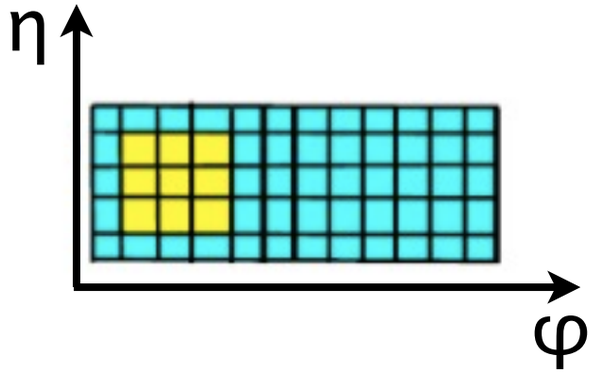
$\sigma(pp \to H) \sim 20pb$ $\sigma(pp \to qqH) \sim 1.6pb$ $\sigma(pp \to VH) \sim 0.7pb$

CiC inclusive categories

- CiC di-photon pre-selection (for all CiC analysis):
  - ✓ γ identification: cut-based see Elisabeth talk
  - ✓ cut efficiency controlled in Z→ee and Z→μμγ
  - ✓ kinematic cuts: $pT_1/m\gamma\gamma > 1/3$, $pT_2/m\gamma\gamma > 1/4$, $|\eta_1| < 2.5$, $|\eta_2| < 2.5$
- CiC inclusive categories based on detector properties:
  - ✓ barrel vs endcap (different resolution and S/B)
  - ✓ converted (R9 < 0.94) vs unconverted (R9 > 0.94) photon

converted photons discriminated by

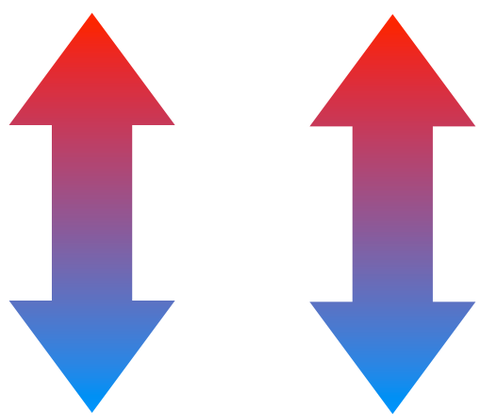
$R_9 = \Sigma E(3\times3)/E_{SC}$



Cat 0	Both photons in barrel	Both photons $R_9 > 0.94$
Cat 1	Both photons in barrel	At least one photon with $R_9 < 0.94$
Cat 2	At least one photon in endcaps	Both photons $R_9 > 0.94$
Cat 3	At least one photon in endcaps	At least one photon with $R_9 < 0.94$

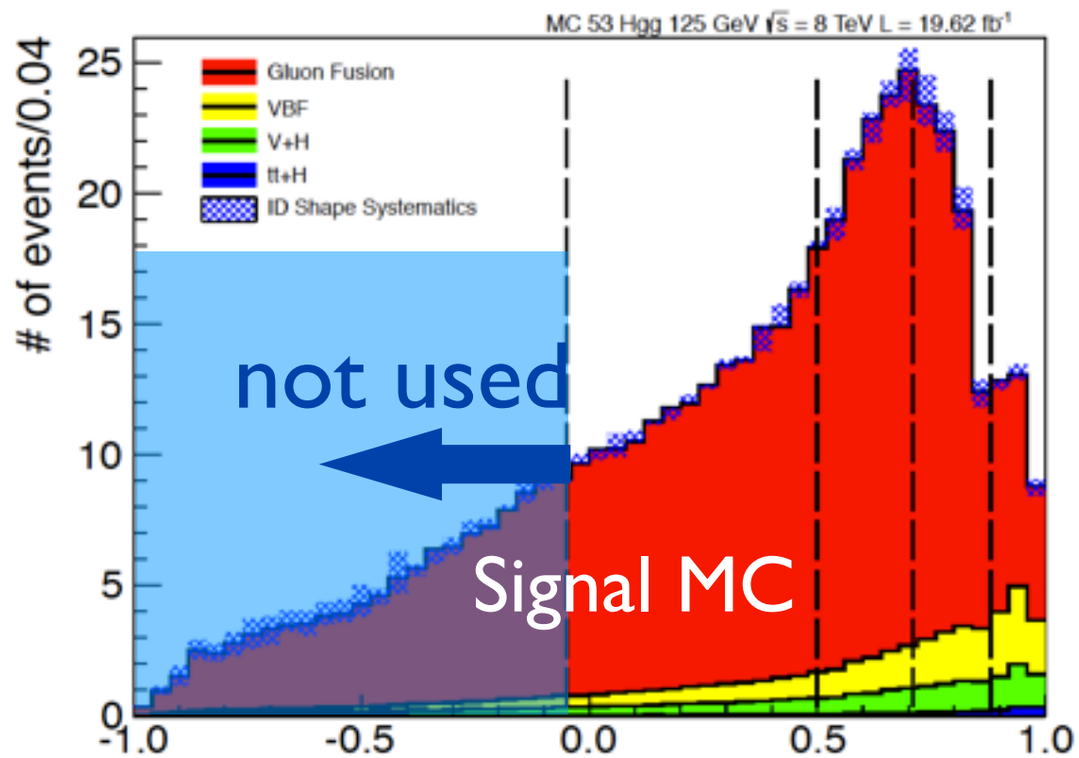
mass resolution

S/B

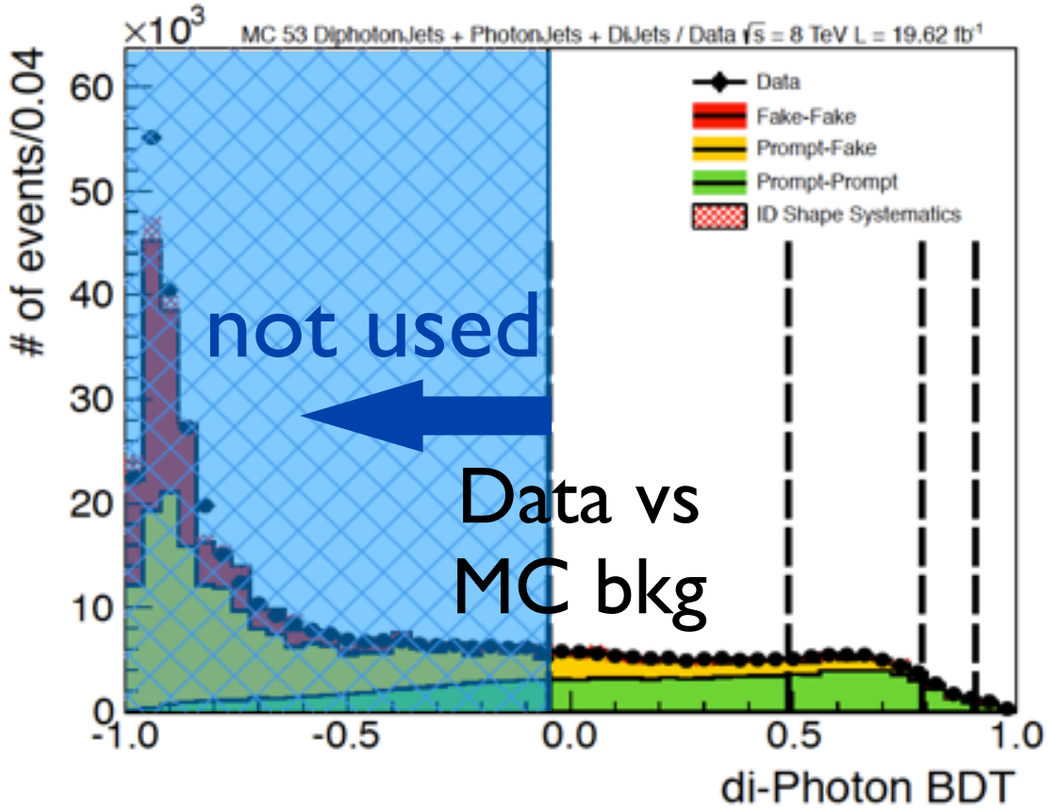


MVA inclusive categories

- Mass-blinded BDT discriminant:
  - ✓ $\eta_1, \eta_2, \Delta\varphi, pT_1/ m_{\gamma\gamma}, pT_2/ m_{\gamma\gamma}$
  - ✓ mass resolution:
    - ✦ ECAL energy resolution per γ
    - ✦ Correct PV assignment probability
  - ✓ photon quality: MVAid see Elisabeth
  - ✓ shape and efficiency controlled in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu\gamma$

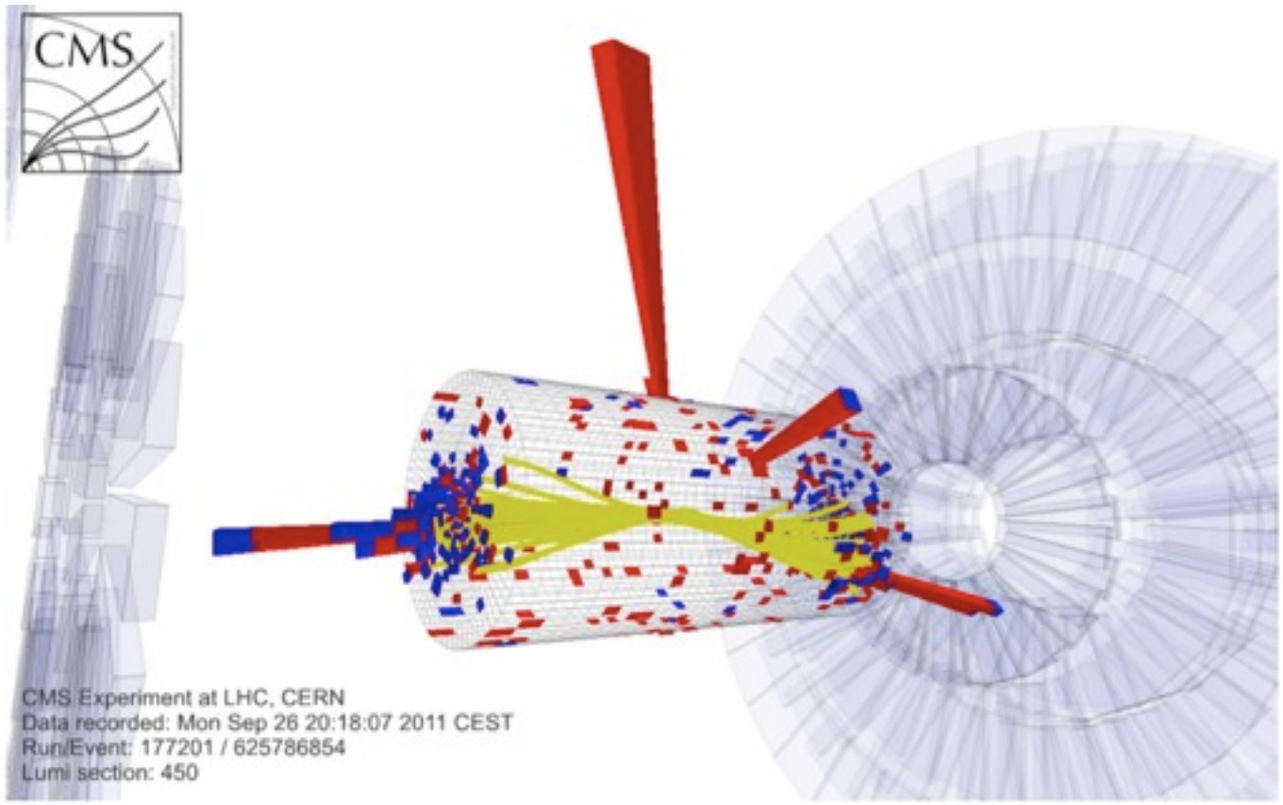


- MVA di-photon pre-selection (for all MVA analysis):
  - ✓ γ identification: MVAid > -0.2
  - ✓ kinematic cuts: same as CiC
  - ✓ di-γ MVA > -0.05
- 4 MVA inclusive categories

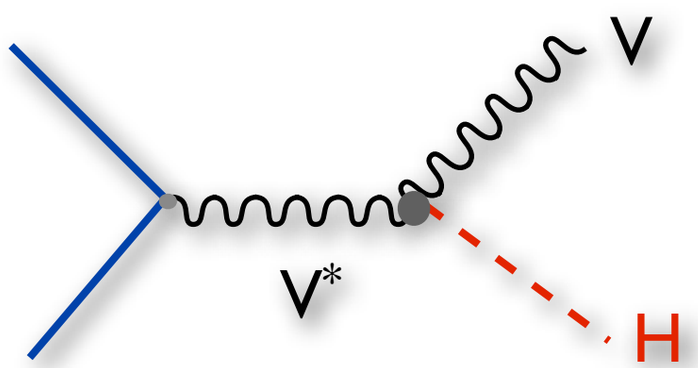


Exclusive categories

- Vector Boson Fusion (VBF): 2 forward jets with a gap in rapidity
  - ✓ CiC analysis : 2 categories 250< m_{jj} <500GeV and 500GeV < m_{jj}
  - ✓ MVA analysis: 2 categories based on a MVA using photons and jets kinematics (new)
  - ✓ In 2011 only one VBF cat for both analysis

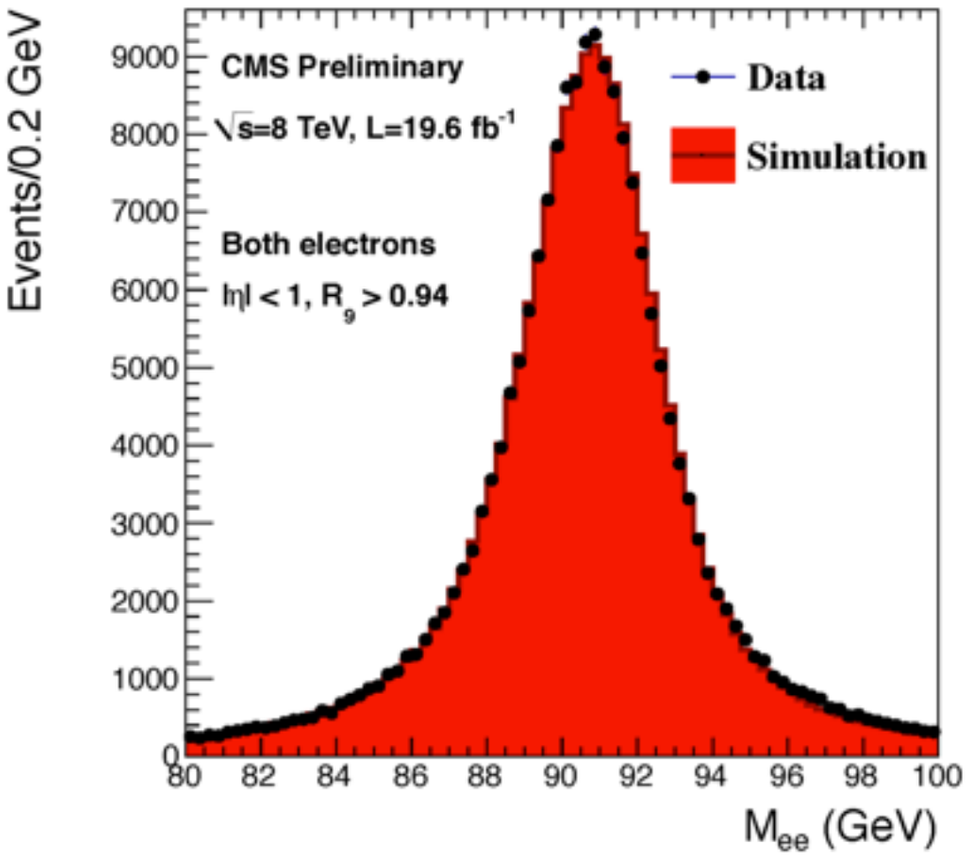


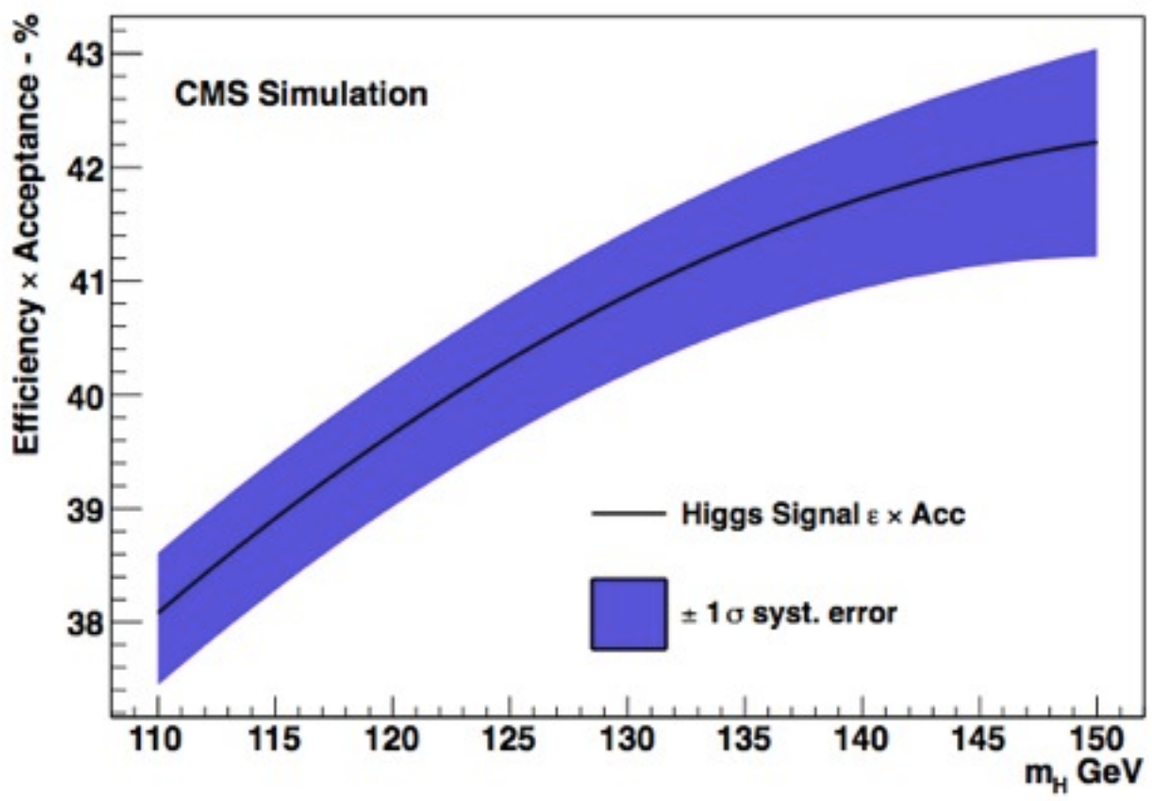
- VH: new in SM analysis for 8TeV dataset
  - ✓ only V leptonic decays $W \to \ell\nu$ (2x10%) $Z \to \ell\ell$ (2x3.5%) $Z \to \nu\nu$ (20%)
  - ✓ electron and muon tag categories: one lepton with pT > 20GeV, $\Delta R(\gamma,\ell) > 1.0$
  - ✓ Missing pT tag category: MET > 70GeV



Signal & Background model

- Background is estimated from data
  - ✓ fit the diphoton mass spectrum with a dedicated background shape
  - ✓ polynomials to accommodate for several potential truth background shape
  - ✓ polynomial order: bias below 20% of statistical uncertainties for several truth background shape
- Signal model:
  - ✓ MC simulation accounting for efficiency scale factor and photon energy resolution correction to match data in several R9 x η bins.
  - ✓ MVAid and $\sigma_{E\gamma}/E_\gamma$[exp] corrected using $Z \rightarrow ee$ events



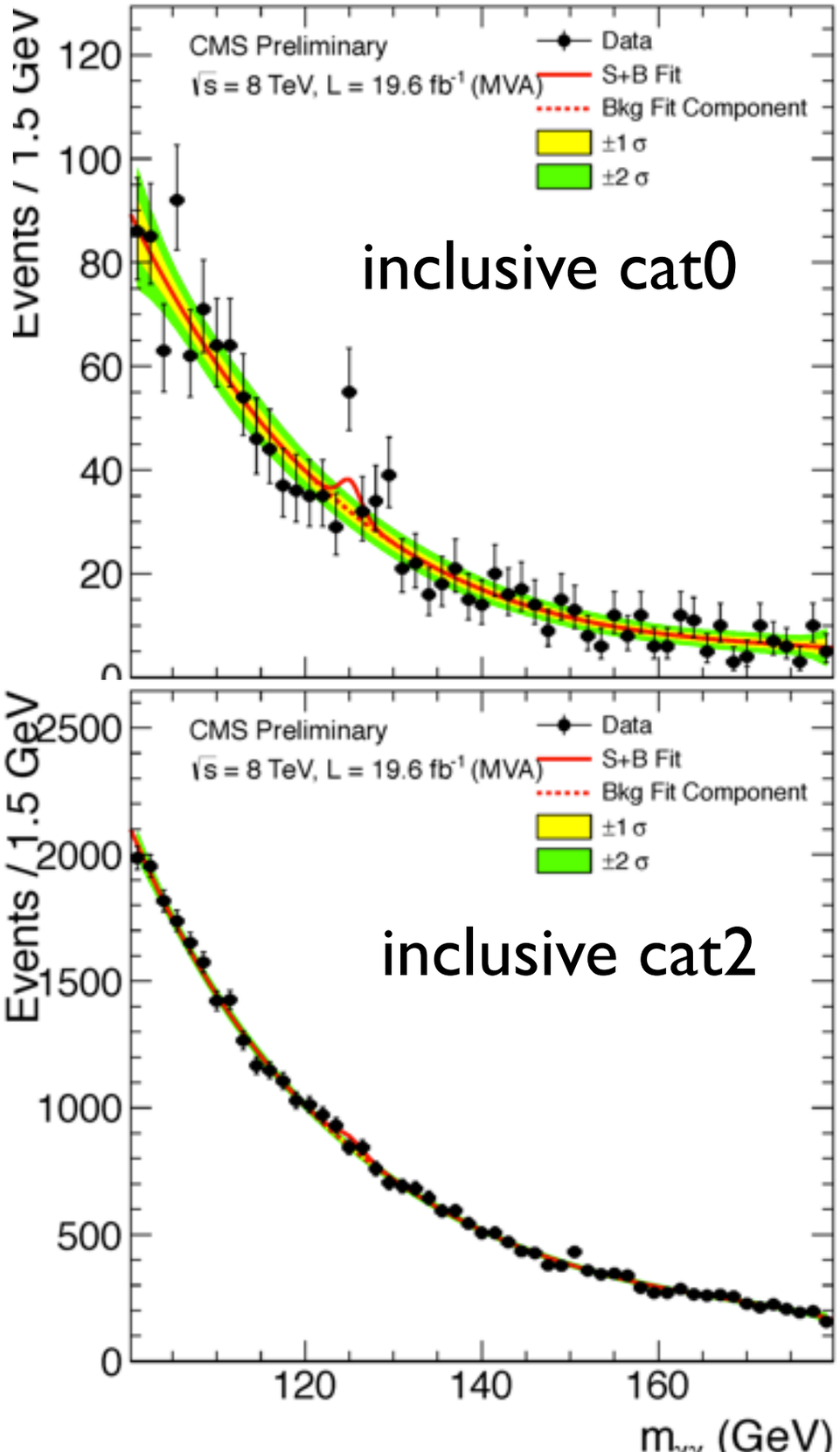


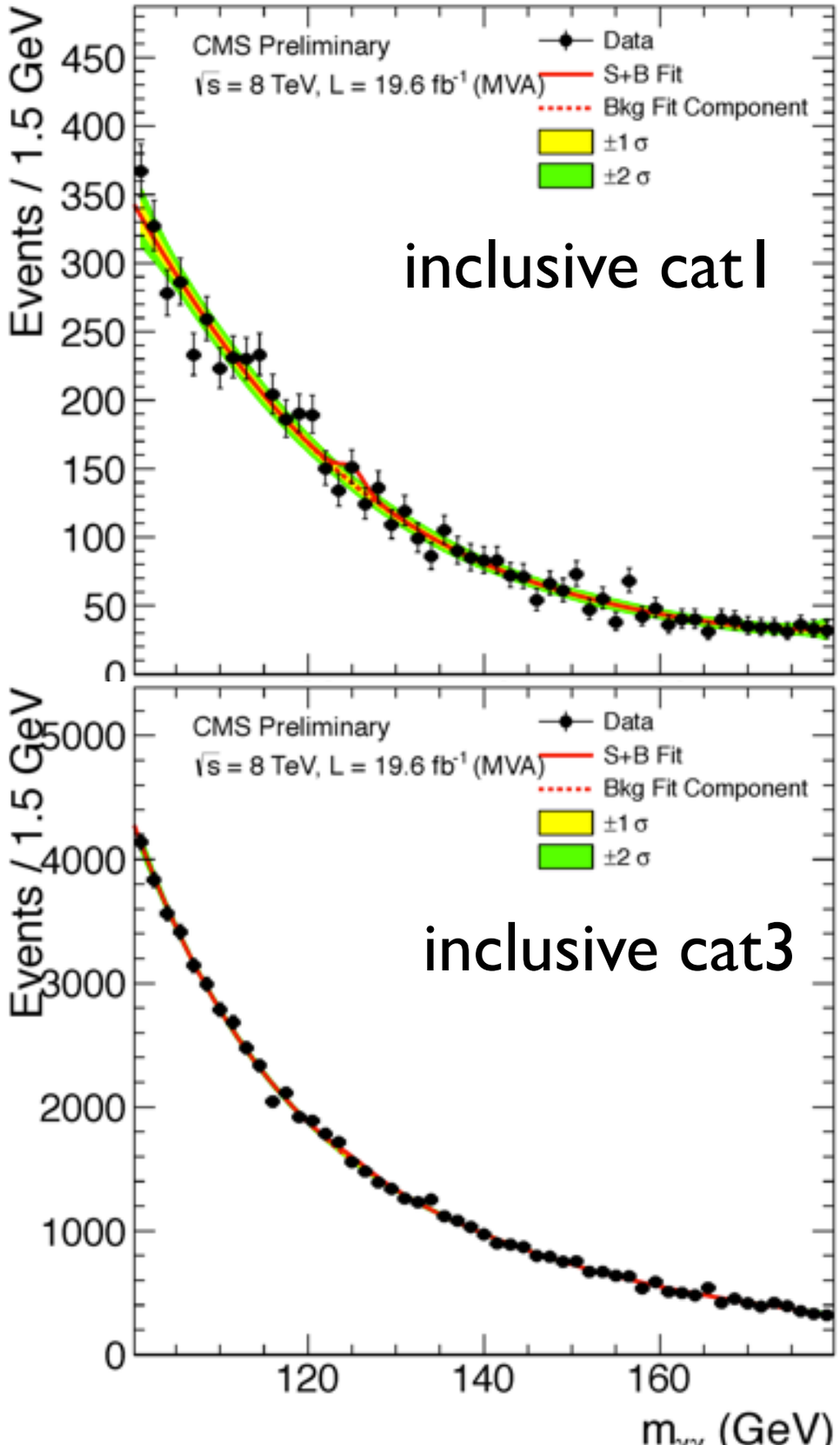
MVA analysis event yield

Expected signal and estimated background

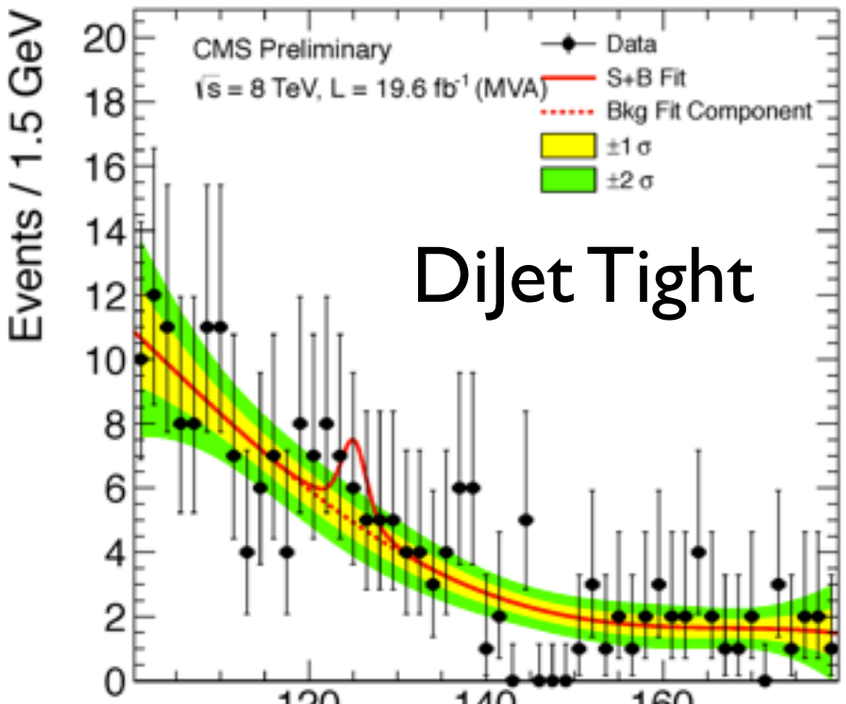
Event classes		SM Higgs boson expected signal (m_H=125 Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	S/B ($\pm 1.5\sigma_{eff}$)	Background $m_{\gamma\gamma} = 125$ GeV (ev./GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61.4%	16.8%	18.7%	3.1%	1.21		3.3	$\pm$ 0.4
	Untagged 1	16.3	87.6%	6.2%	5.6%	0.5%	1.26		37.5	$\pm$ 1.3
	Untagged 2	21.5	91.3%	4.4%	3.9%	0.3%	1.59		74.8	$\pm$ 1.9
	Untagged 3	32.8	91.3%	4.4%	4.1%	0.2%	2.47		193.6	$\pm$ 3.0
	Dijet tag	2.9	26.8%	72.5%	0.6%	–	1.73		1.7	$\pm$ 0.2
8 TeV 19.6 fb^{-1}	Untagged 0	17.0	72.9%	11.6%	12.9%	2.6%	1.36	0.16	22.1	$\pm$ 0.5
	Untagged 1	37.8	83.5%	8.4%	7.1%	1.0%	1.50	0.08	94.3	$\pm$ 1.0
	Untagged 2	150.2	91.6%	4.5%	3.6%	0.4%	1.77	0.04	570.5	$\pm$ 2.6
	Untagged 3	159.9	92.5%	3.9%	3.3%	0.3%	2.61	0.02	1060.9	$\pm$ 3.5
	Dijet tight	9.2	20.7%	78.9%	0.3%	0.1%	1.79	0.44	3.4	$\pm$ 0.2
	Dijet loose	11.5	47.0%	50.9%	1.7%	0.5%	1.87	0.14	12.4	$\pm$ 0.4
	Muon tag	1.4	0.0%	0.2%	79.0%	20.8%	1.85	0.31	0.7	$\pm$ 0.1
	Electron tag	0.9	1.1%	0.4%	78.7%	19.8%	1.88	0.20	0.7	$\pm$ 0.1
	E_T^{miss} tag	1.7	22.0%	2.6%	63.7%	11.7%	1.79	0.15	1.8	$\pm$ 0.1

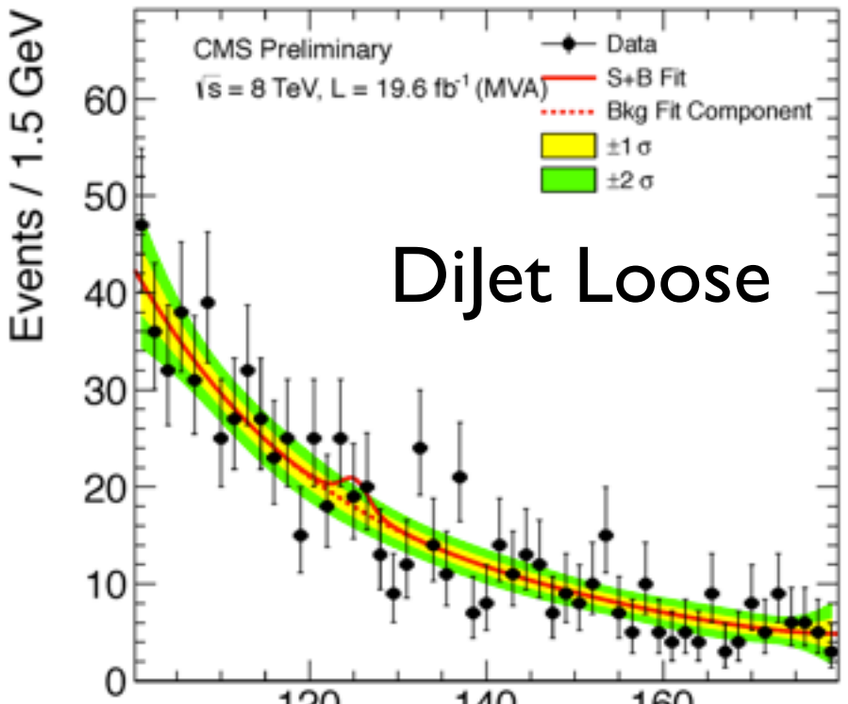
MVA mass spectra

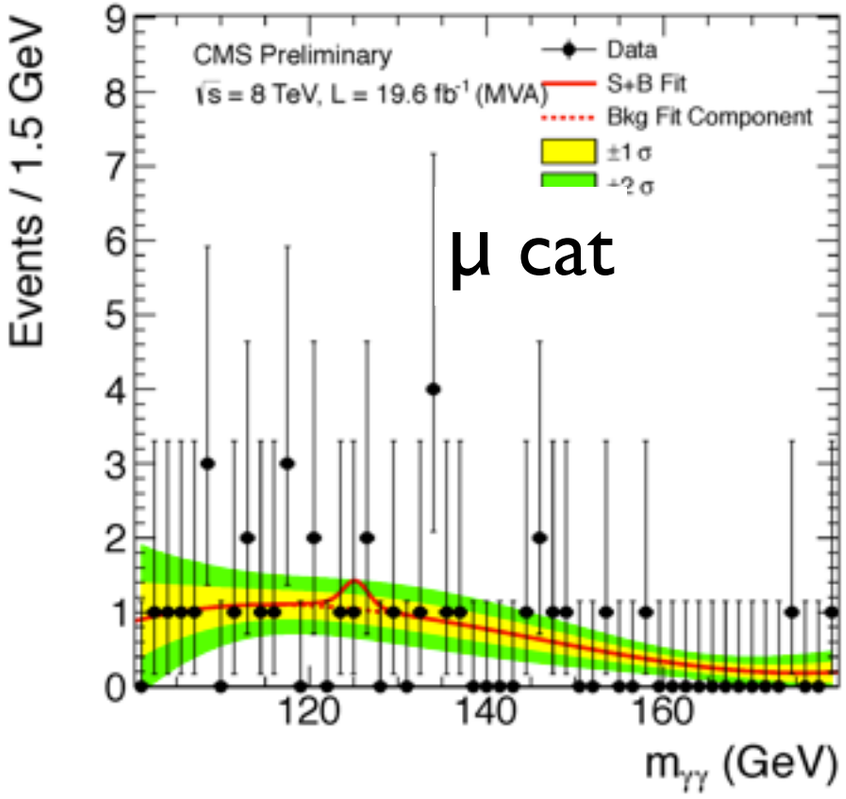


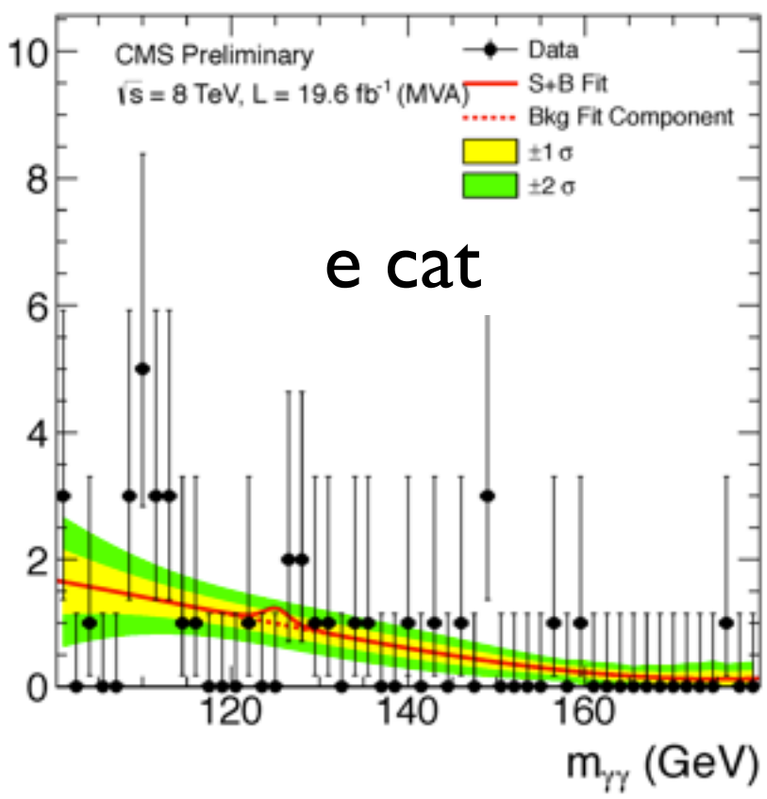


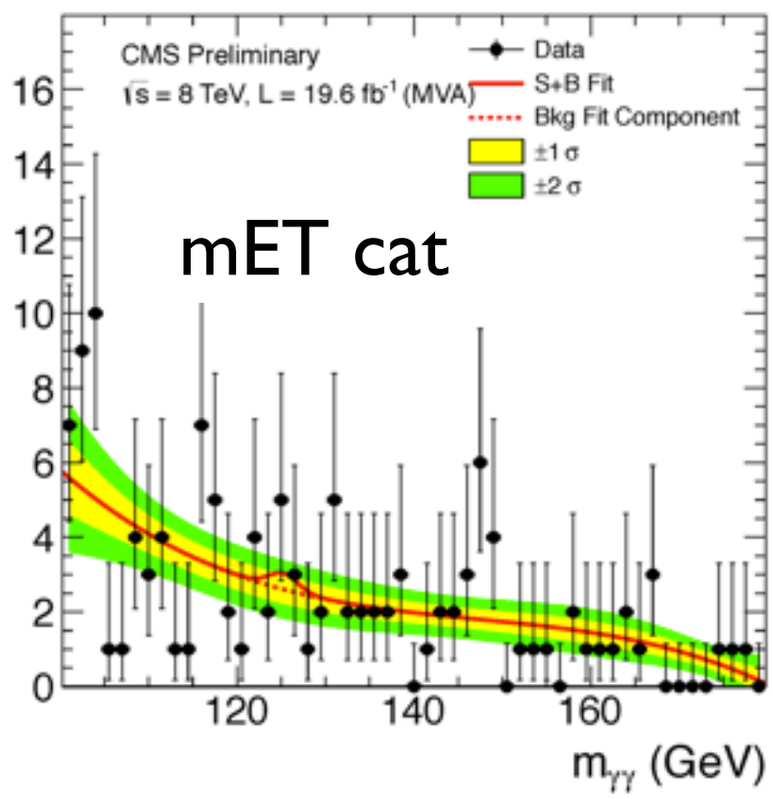
MVA mass spectra





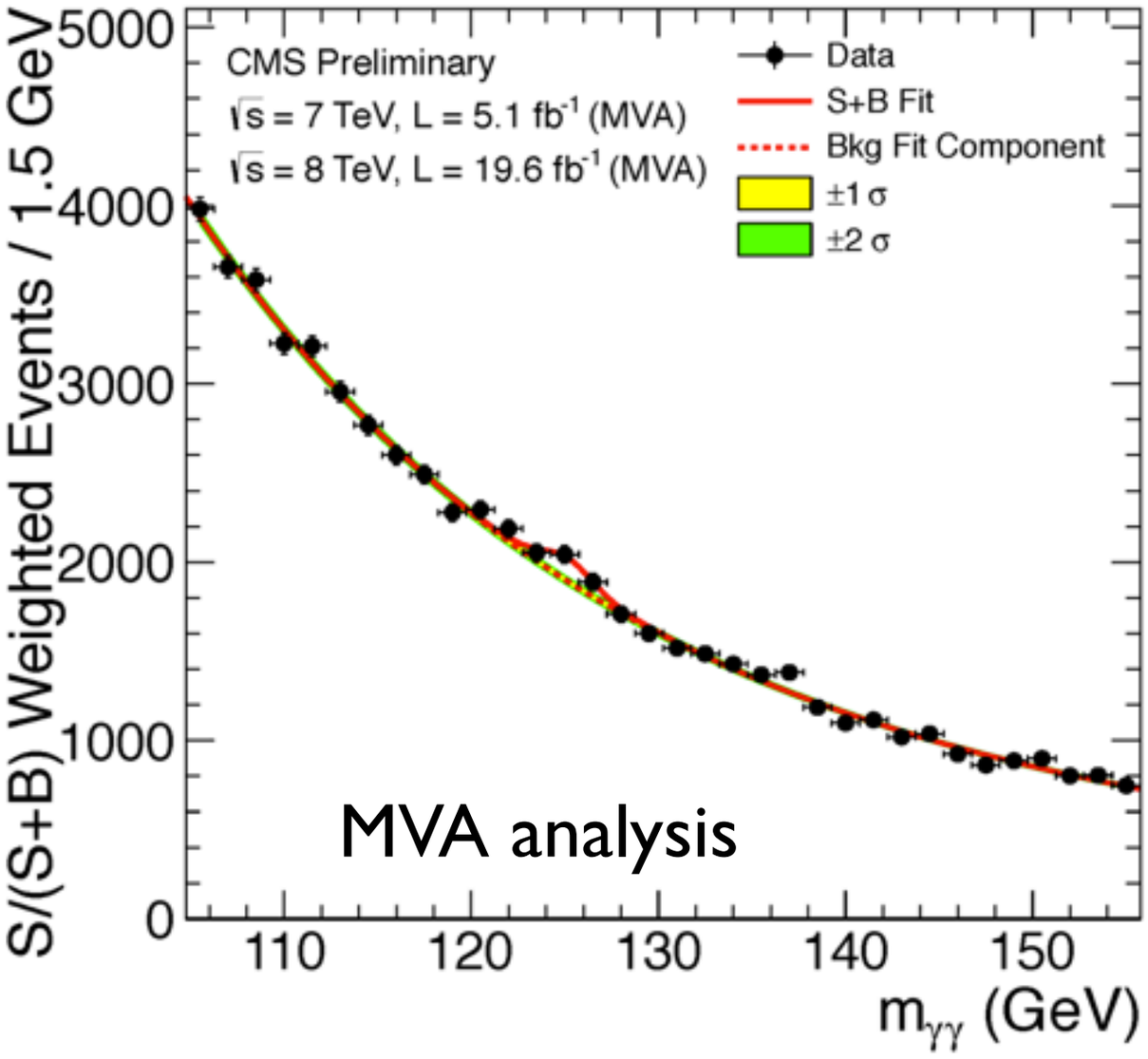


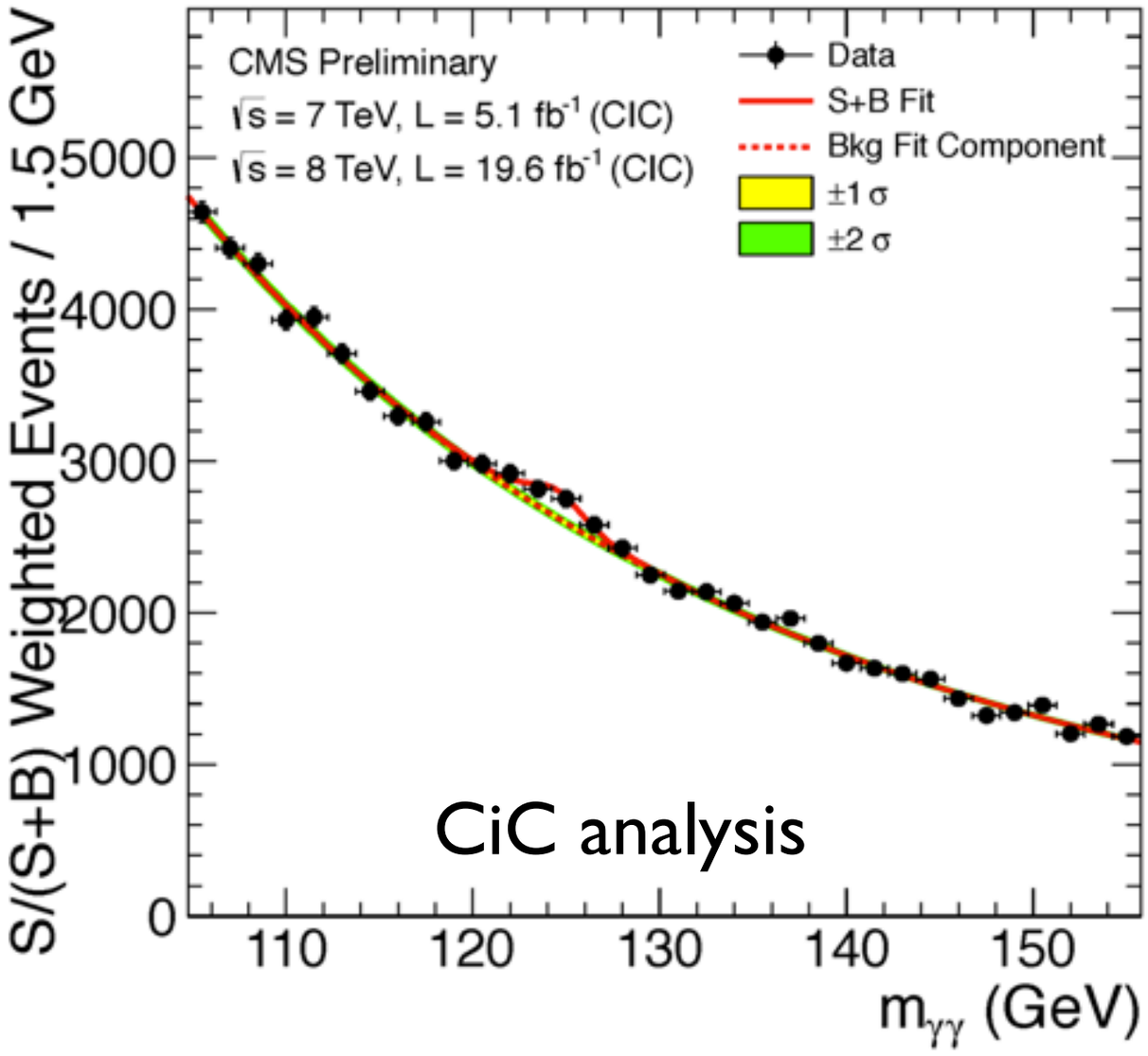




Mass spectra weighted

All categories weighted with S/(S+B)
7 + 8 TeV dataset



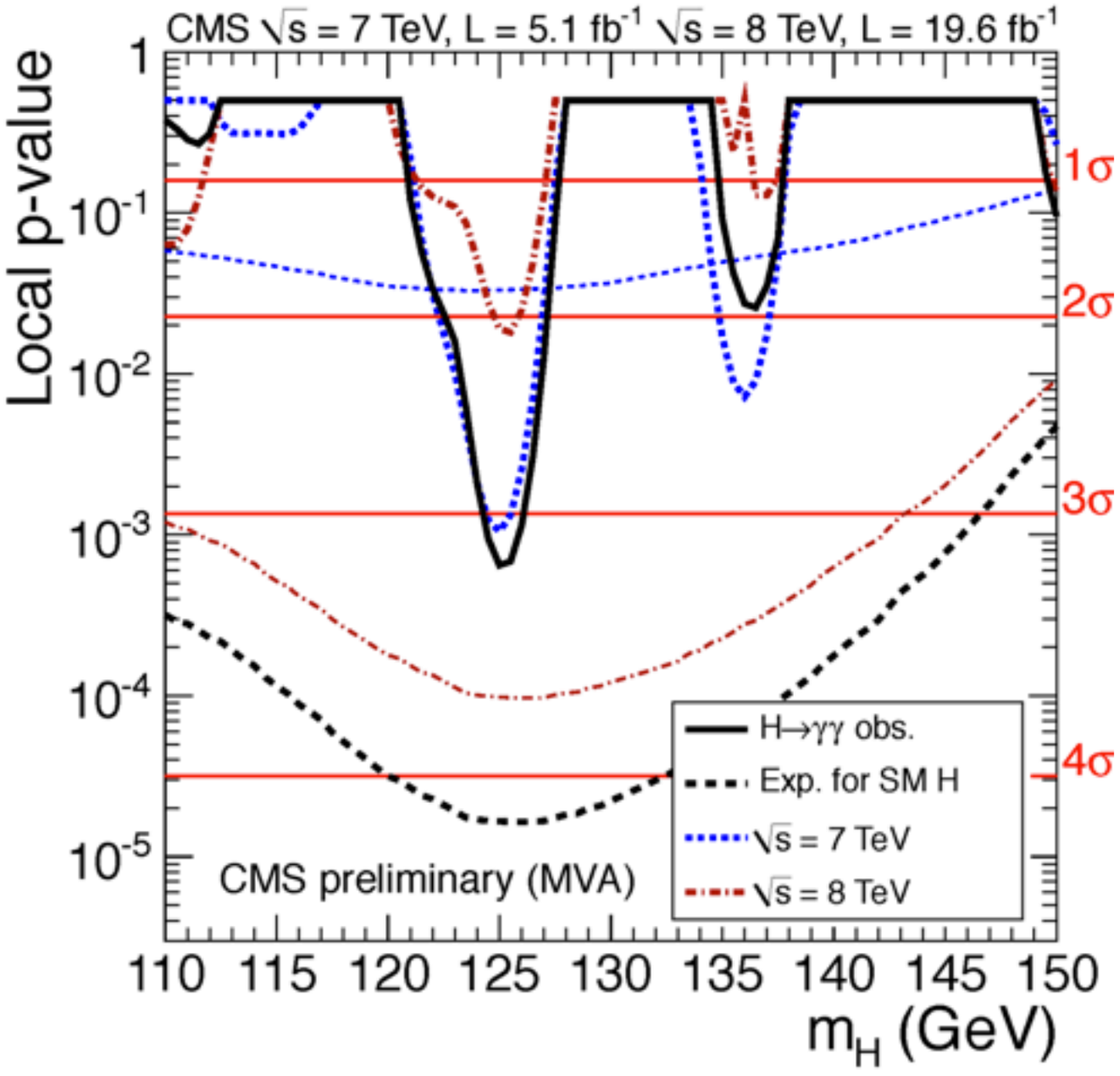


Systematic uncertainties

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.23%, 0.72%	0.93%, 0.36%
	$R_9 < 0.94$ (low η, high η)	0.25%, 0.60%	0.33%, 0.54%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.20%, 0.71%	0.88%, 0.12%
	$R_9 < 0.94$ (low η, high η)	0.20%, 0.51%	0.18%, 0.12%
Photon identification efficiency		1.0%	2.6%
Cut-based			
$R_9 >$ 0.94 efficiency (results in class migration)		4.0%	6.5%
MVA analyses			
Photon identification BDT		±0.01 (shape shift)	
(Effect of up to 4.3% event class migration.)			
Photon energy resolution BDT		±10% (shape scaling)	
(Effect of up to 8.1% event class migration.)			
Per event			
Integrated luminosity		4.4%	
Vertex finding efficiency		0.2%	
Trigger efficiency		1.0%	
Global energy scale		0.47%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
	Gluon-gluon fusion process	30%	
(Effect of up to 15% event migration among dijet classes.)			
Muon selection			
Muon identification efficiency		1.0%	
Electron selection			
Electron identification efficiency		1.0%	
$E_{\mathrm{T}}^{\mathbf{miss}}$ **selection**			
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut efficiency	Gluon-gluon fusion	15%	
	Vector boson fusion	15%	
	Associated production with W/Z	4%	
	Associated production with $t\bar{t}$	4%	
Production cross sections		Scale	PDF
Gluon-gluon fusion		+7.6% -8.2%	+7.6% -7.0%
Vector boson fusion		+0.3% -0.8%	+2.6% -2.8%
Associated production with W/Z		+2.1% -1.8%	4.2%
Associated production with $t\bar{t}$		+4.1% -9.4%	8.0%

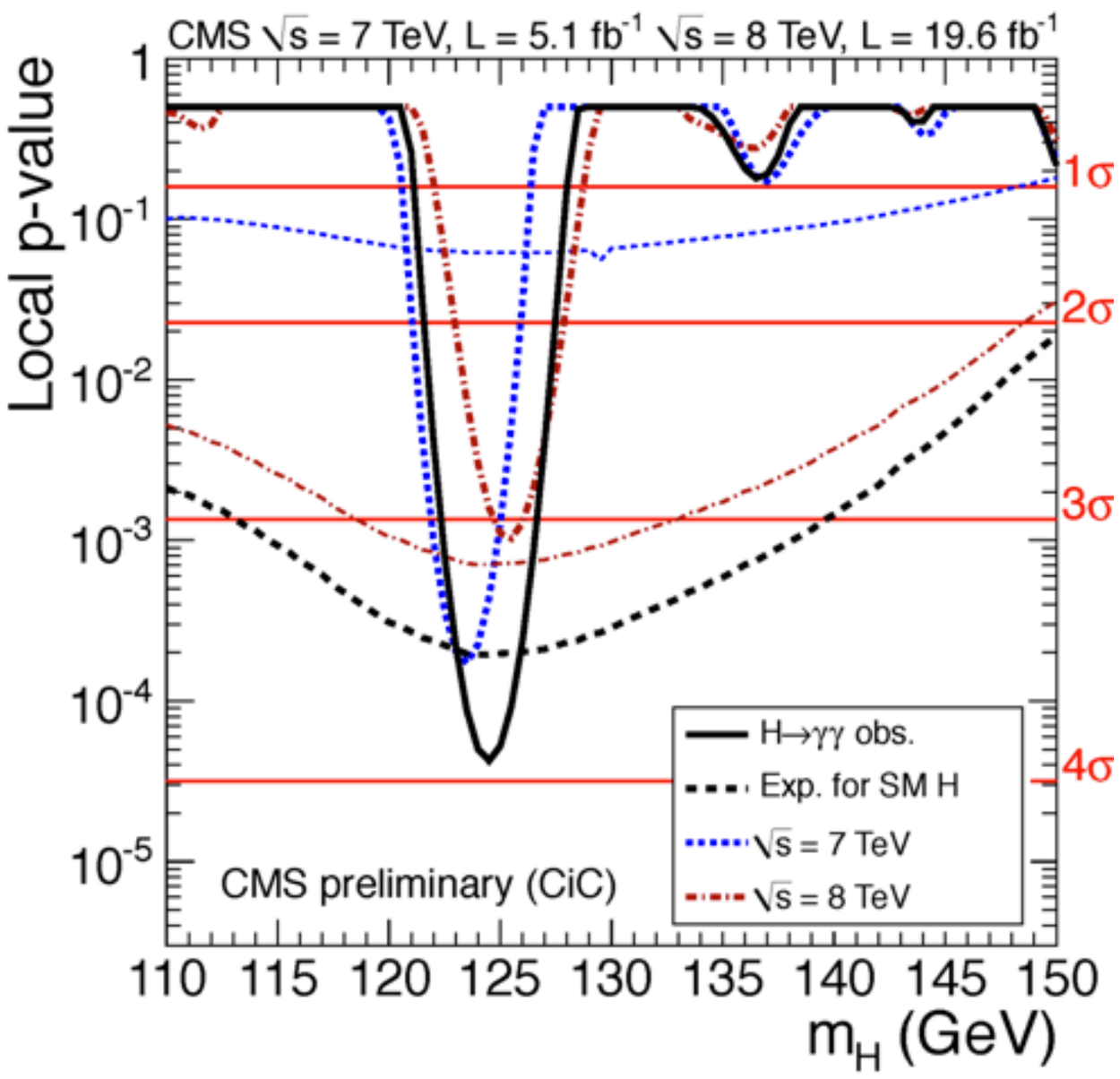
results p-value

7 + 8 TeV dataset



MVA analysis

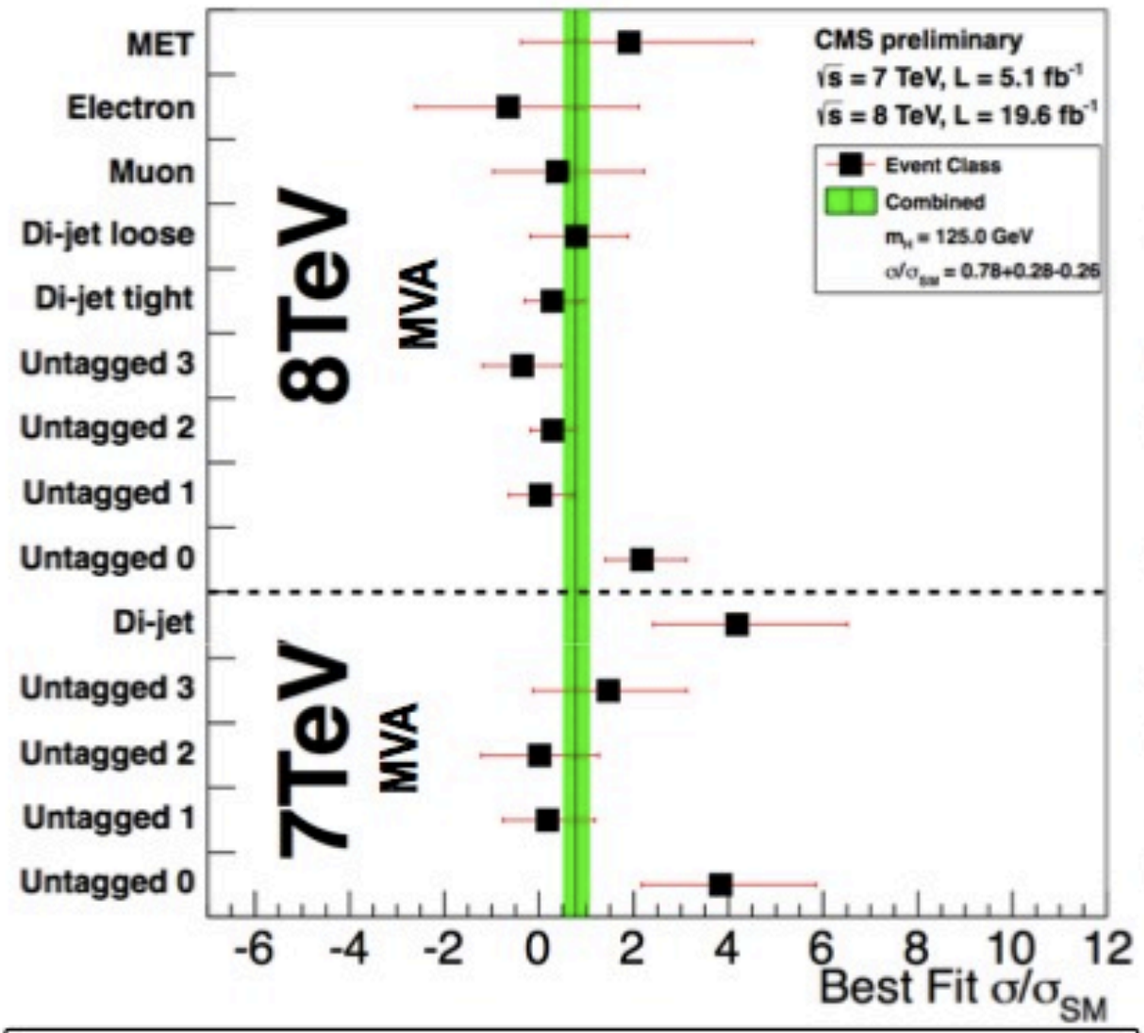
signi @ 125GeV: 3.2σ (4.2σ exp)



CiC analysis

signi @ 124.5GeV: 3.9σ (3.5σ exp)

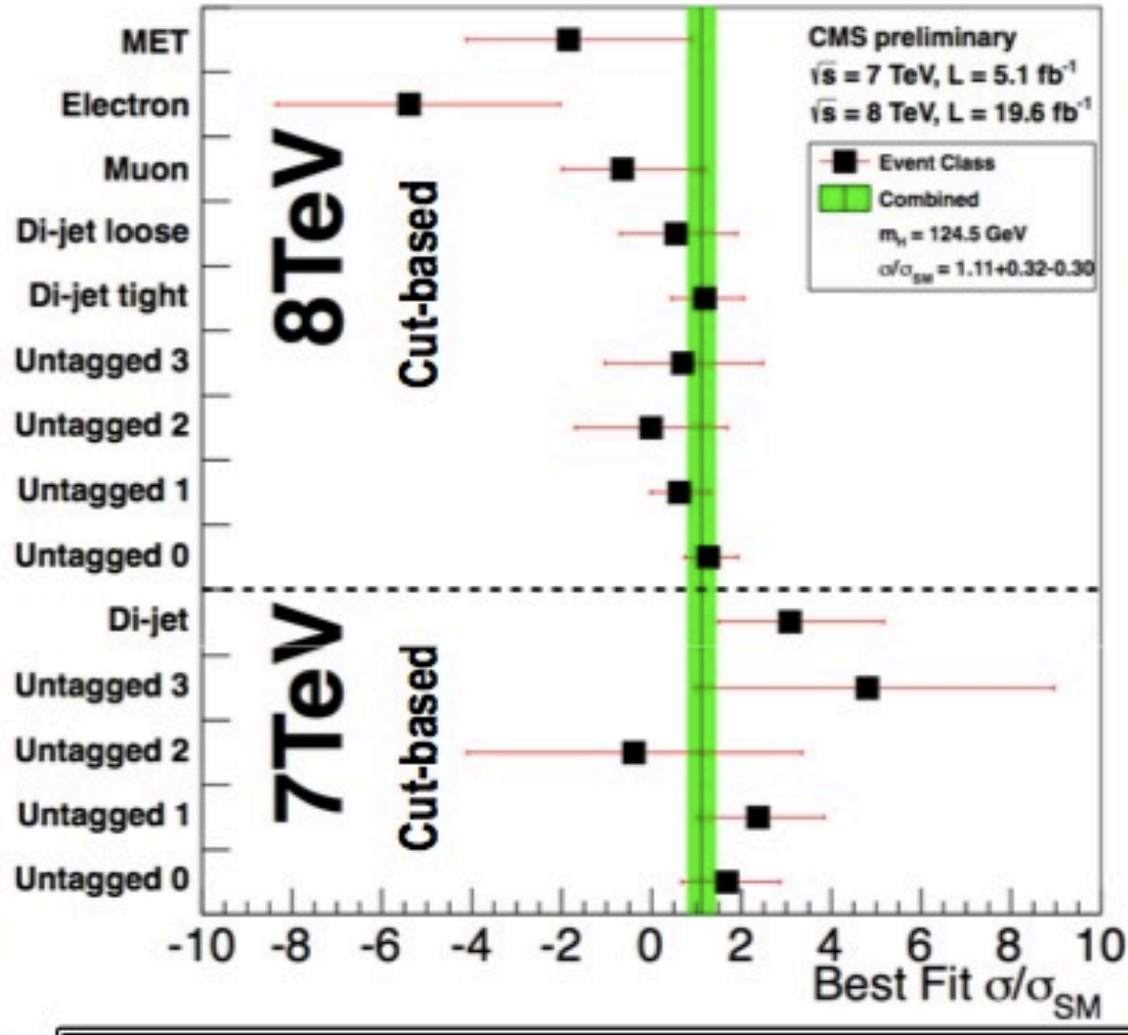
results: channel compatibility



7+8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.78^{+0.28}_{-0.26}$

7 TeV: σ/σ_{SM} @ 125.0 GeV = $1.69^{+0.65}_{-0.59}$

8 TeV: σ/σ_{SM} @ 125.0 GeV = $0.55^{+0.29}_{-0.27}$



7+8 TeV: σ/σ_{SM} @ 124.5 GeV = $1.11^{+0.32}_{-0.30}$

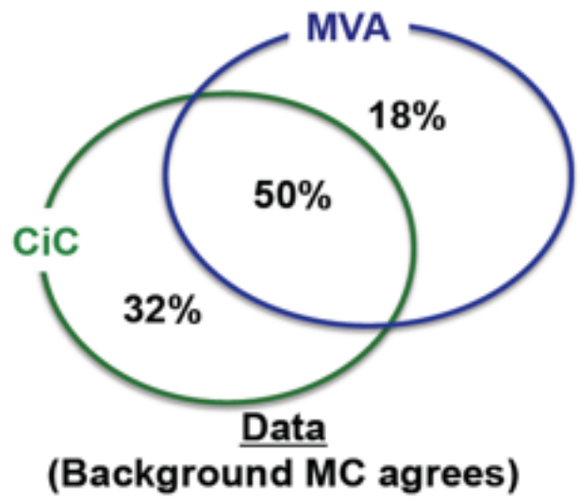
7 TeV: σ/σ_{SM} @ 124.5 GeV = $2.27^{+0.80}_{-0.74}$

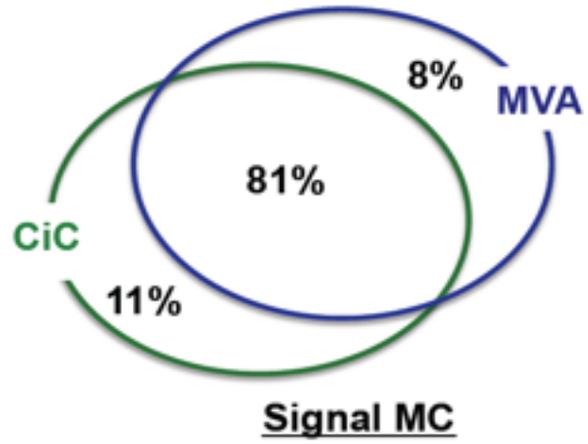
8 TeV: σ/σ_{SM} @ 124.5 GeV = $0.93^{+0.34}_{-0.32}$

Comparison with published result: 7TeV results are identical, 8TeV signal strength is significantly smaller (new data + re-analysis of 8TeV data)

CiC vs MVA analysis compatibility

- Two analysis found somewhat different results on the same dataset
- Low S/B: uncertainty on μ due to background statistical fluctuation
- Correlation between the 2 analysis is measured using JackKnife technique (M. Quenouille 1949, J.W. Tukey 1958):
  - ✓ split sample in several subsamples to get the variance and extrapolate back to full sample
  - ✓ correlation between CiC and MVA r = 0.76

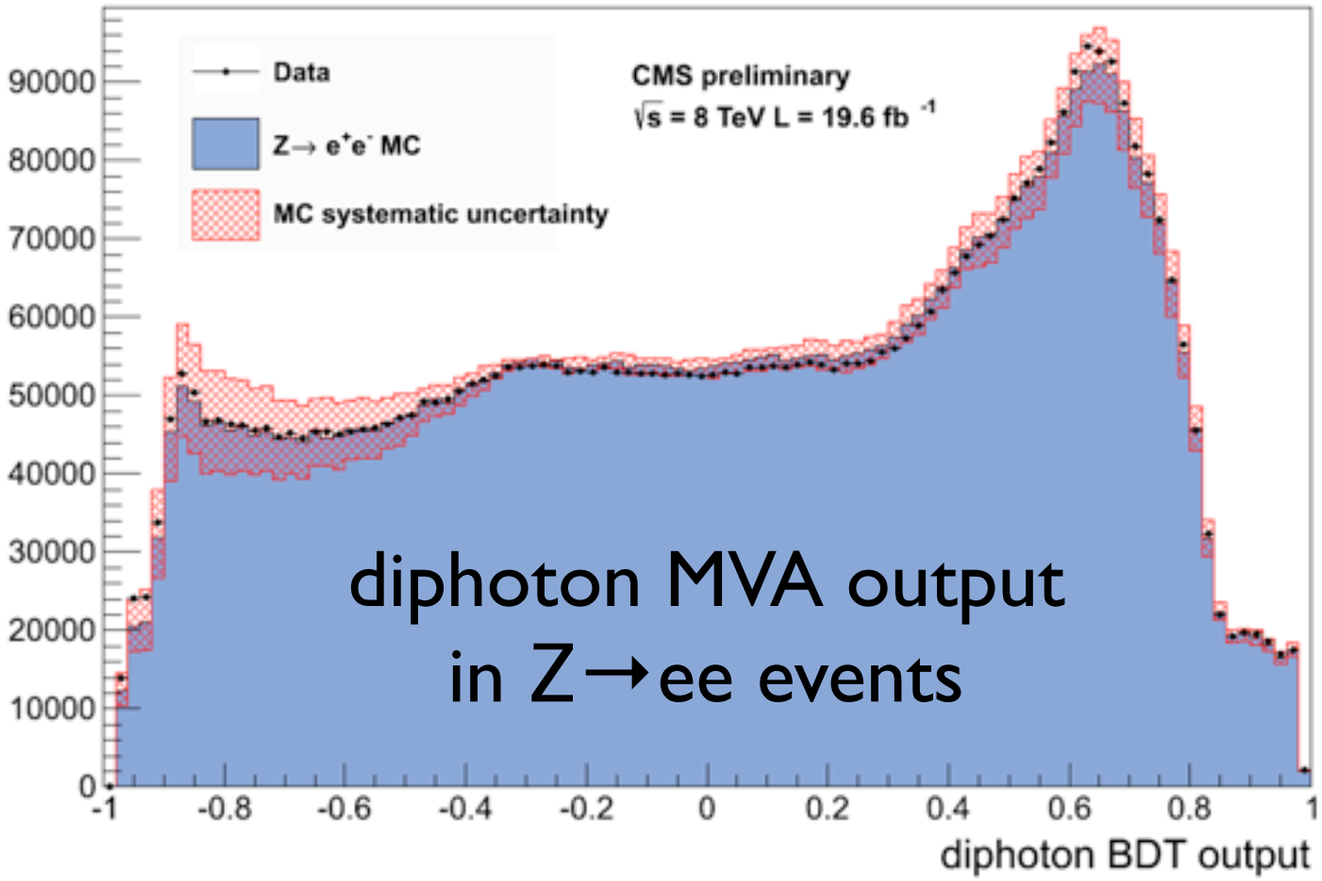




test	μ compatibility
CiC vs MVA 7+8 TeV	1.5 σ
CiC vs MVA 8 TeV	1.8 σ
published vs new MVA 8TeV/5.3fb^{-1}	1.6 σ
published vs new CiC 8TeV/5.3fb^{-1}	0.5 σ

- Huge number of tests performed: all within 2σ

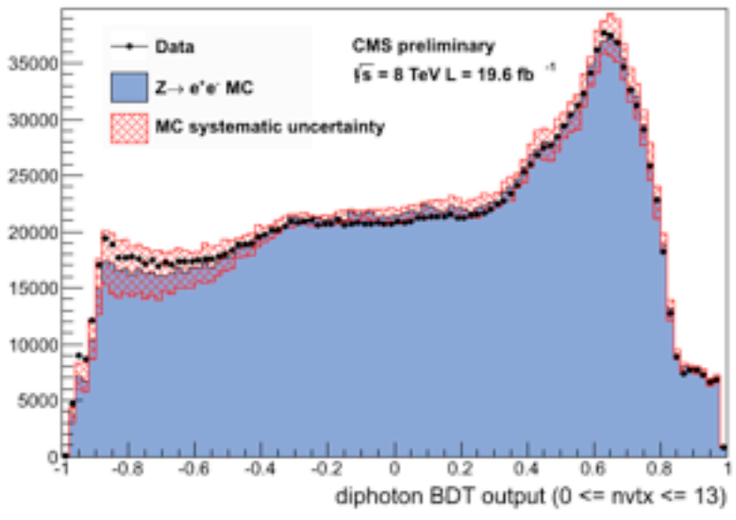
Some diphoton MVA checks



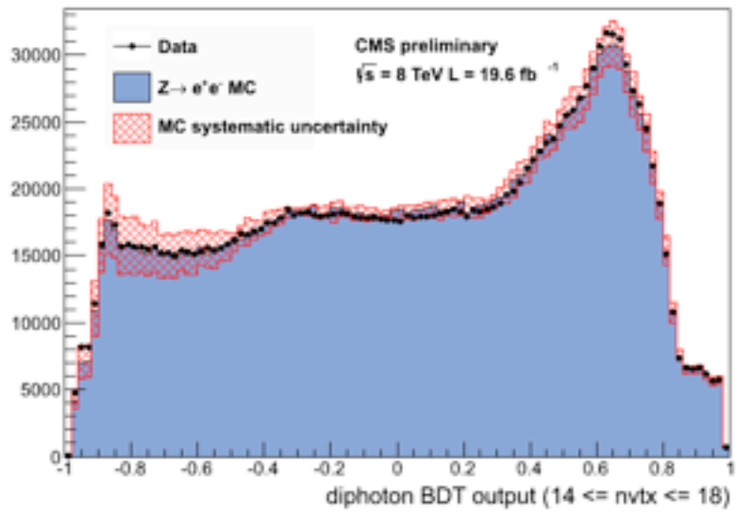
Inputs to the MVA are validated with $Z \rightarrow ee$ and $Z \rightarrow \mu\mu\gamma$

Systematic uncertainties:

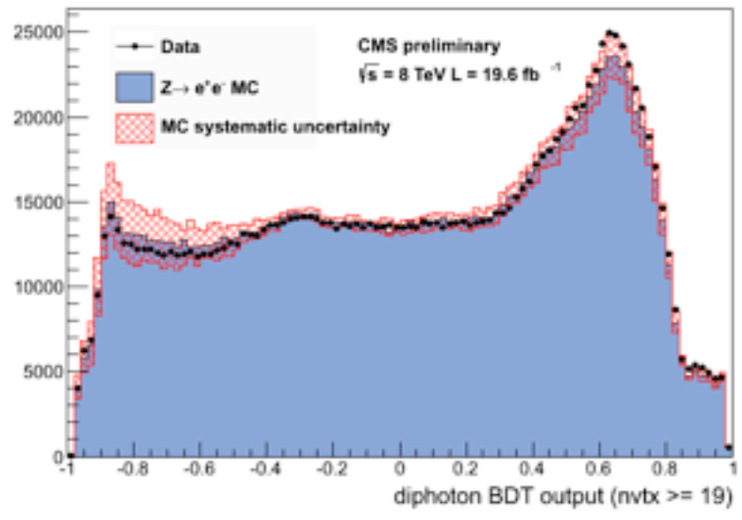
- $Mvald_\gamma$ within $\pm 1\sigma$
- $\sigma_{E\gamma}/E_\gamma$ within $\pm 1\sigma$



$0 \leq nPV < 14$

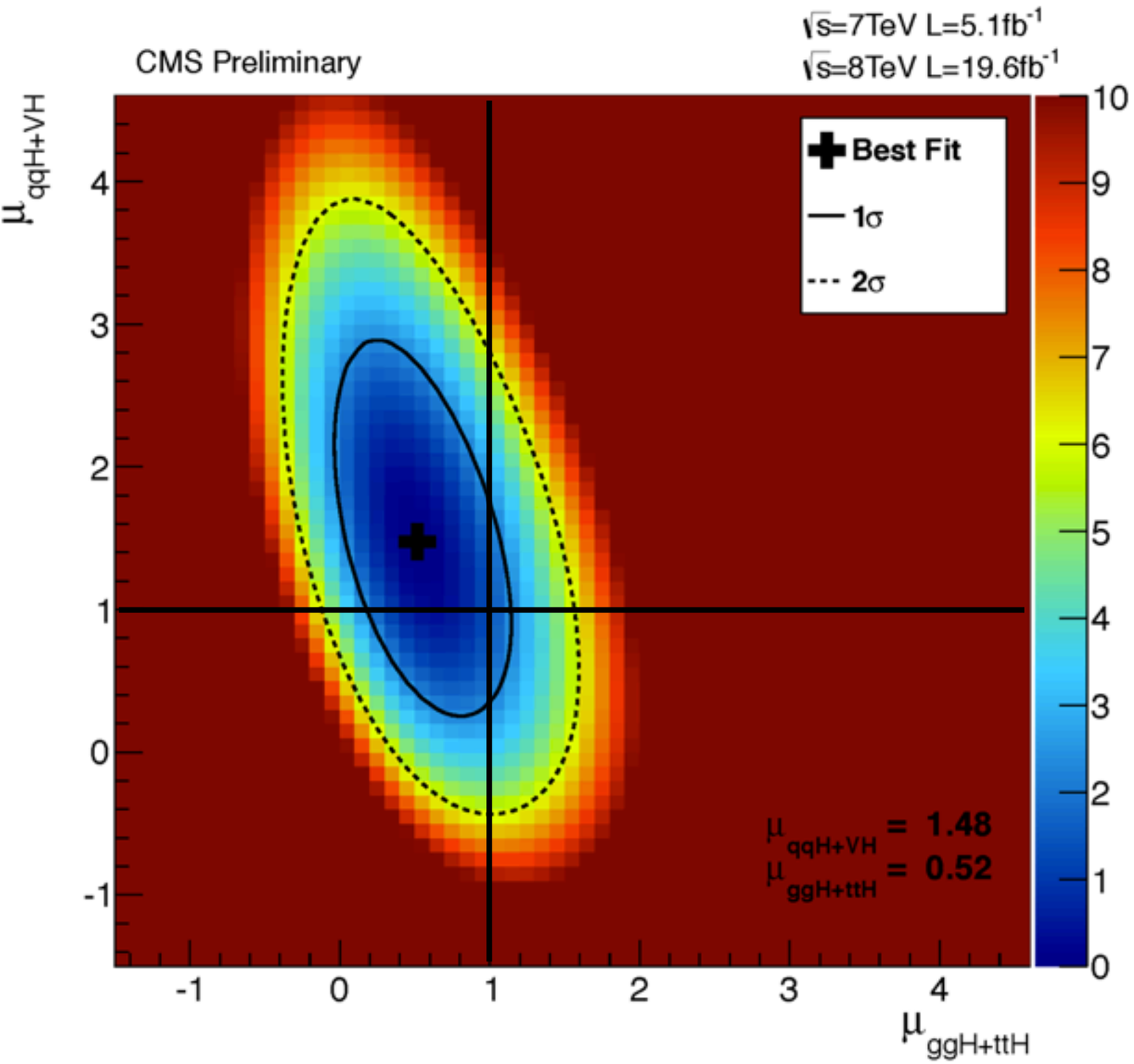


$14 \leq nPV < 19$



$19 \leq nPV$

Production mechanisms

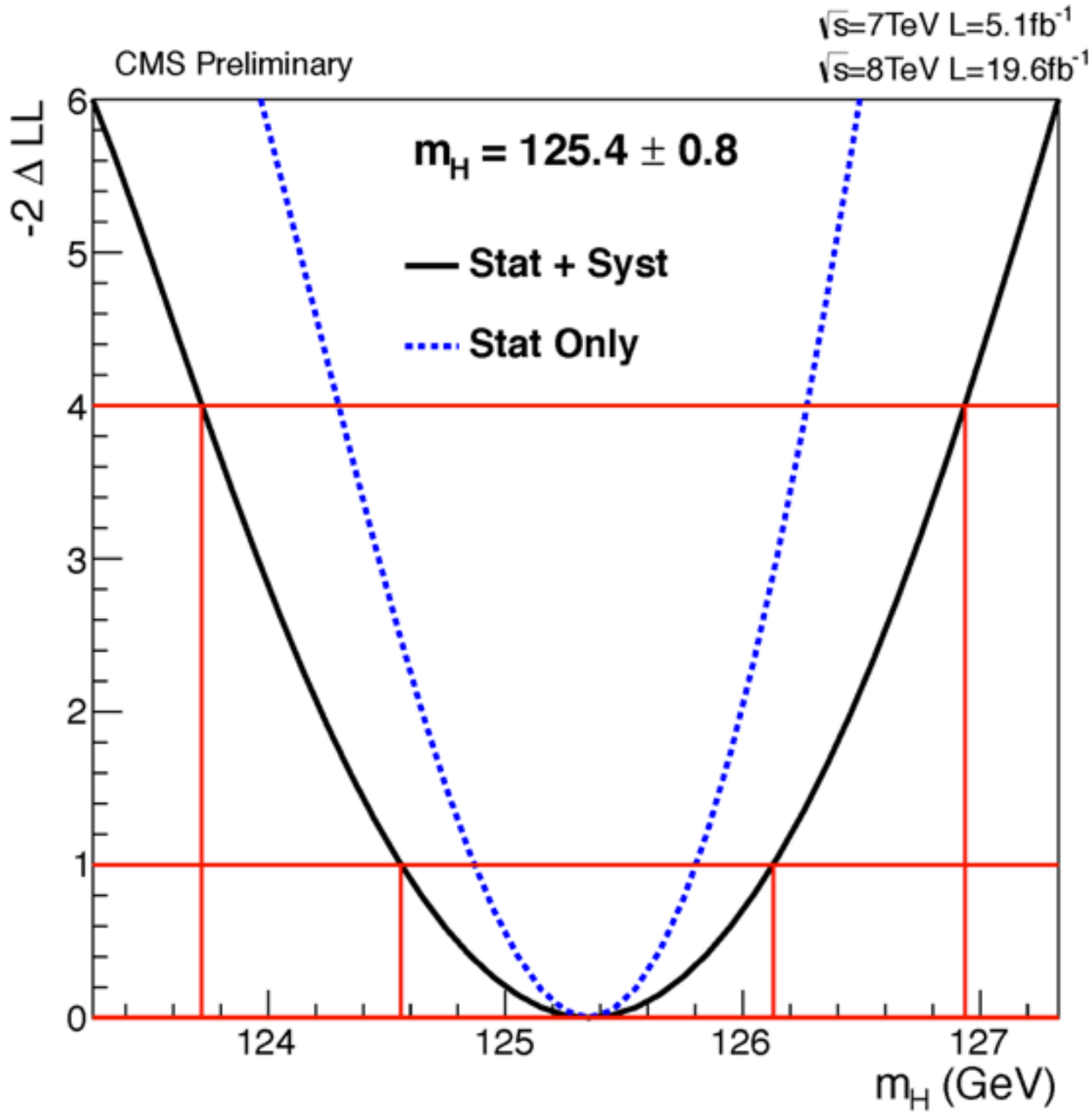


With 2 signal strength free parameter:

$\sigma(gg\rightarrow H) = \mu_{ggH+ttH}\ \sigma_{SM}(gg\rightarrow H)$
$\sigma(gg\rightarrow ttH) = \mu_{ggH+ttH}\ \sigma_{SM}(gg\rightarrow ttH)$
$\sigma(qq\rightarrow VH) = \mu_{qqH+VH}\ \sigma_{SM}(qq\rightarrow VH)$
$\sigma(\ VBF\ ) = \mu_{qqH+VH}\ \sigma_{SM}(VBF)$

$$\mu_{ggH+ttH} = 0.52^{+0.63}_{-0.56}$$
$$\mu_{qqH+VH} = 1.48^{+1,42}_{-1,22}$$

Mass determination



Main sources of systematic

- ECAL response linearity: 0.4% from Z→ee
- e→γ energy scale: 0.25% from different MC simulations

$\mu_{ggH+ttH}$ and μ_{qqH+VH} floated in the fit

$$m_H = 125.4 \pm 0.5 \pm 0.6 \text{ GeV}$$

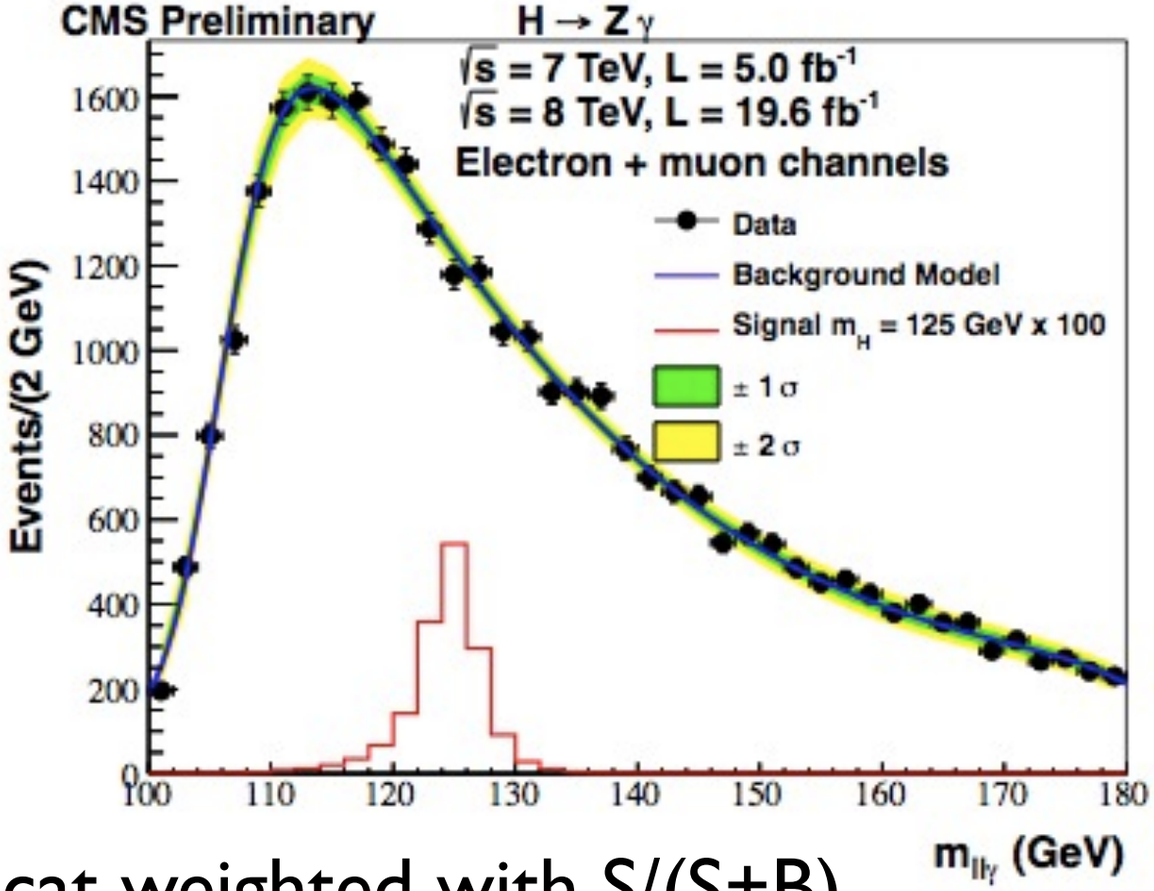
$\mathcal{H}\rightarrow Z\gamma$ search

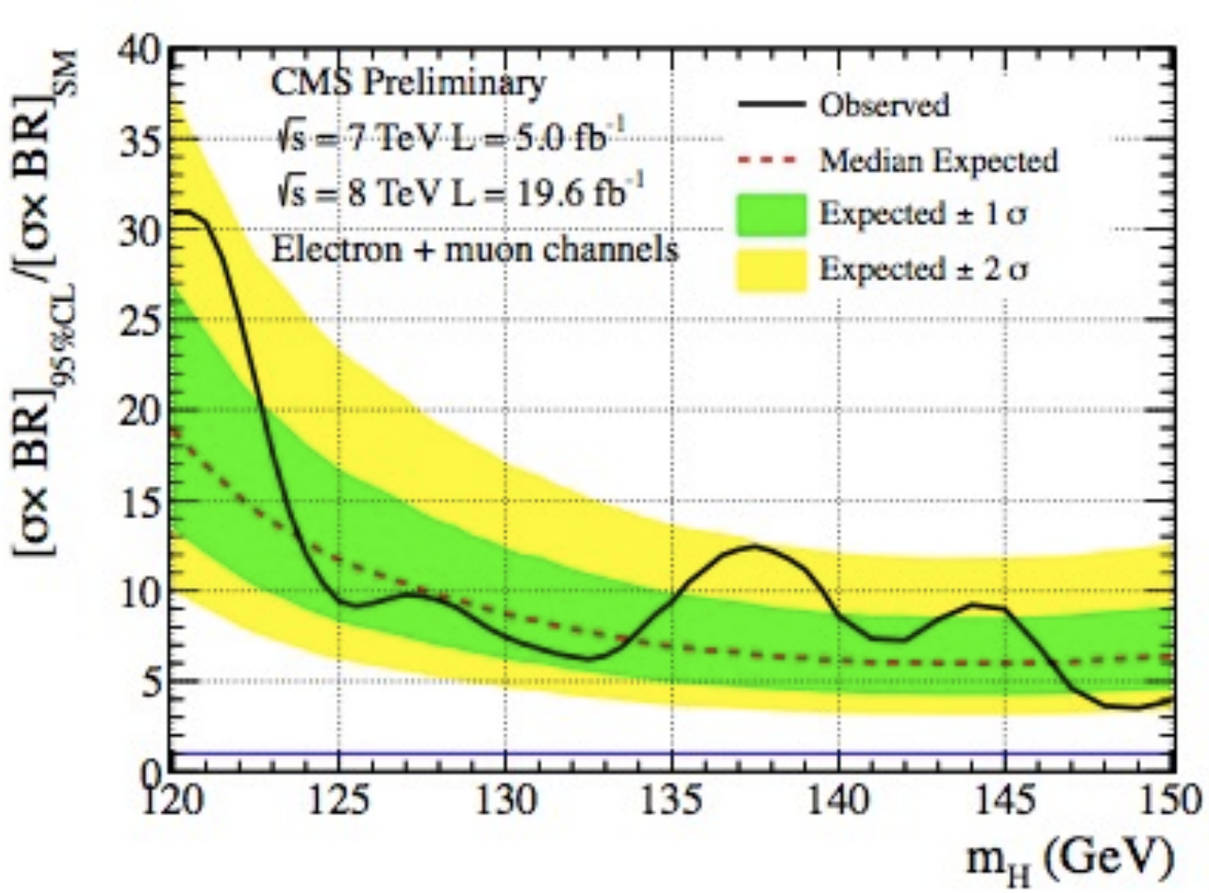
Similar decay as $H\rightarrow\gamma\gamma$ in SM (same loops), might be quite different in BSM models

Selection: 2 isolated leptons + 1 isolated photons with:

- $m(\ell\ell) > 50$GeV kills conversions
- $m(\ell\ell\gamma)+m(\ell\ell) > 185$GeV against Z radiative decays
- $\Delta R(\ell,\gamma) > 0.4$
- $p_T(\gamma)/m(\ell\ell\gamma) > 15/110$

Categorisation: 4 categories based on 3-body mass resolution





cat weighted with S/(S+B)

Conclusions

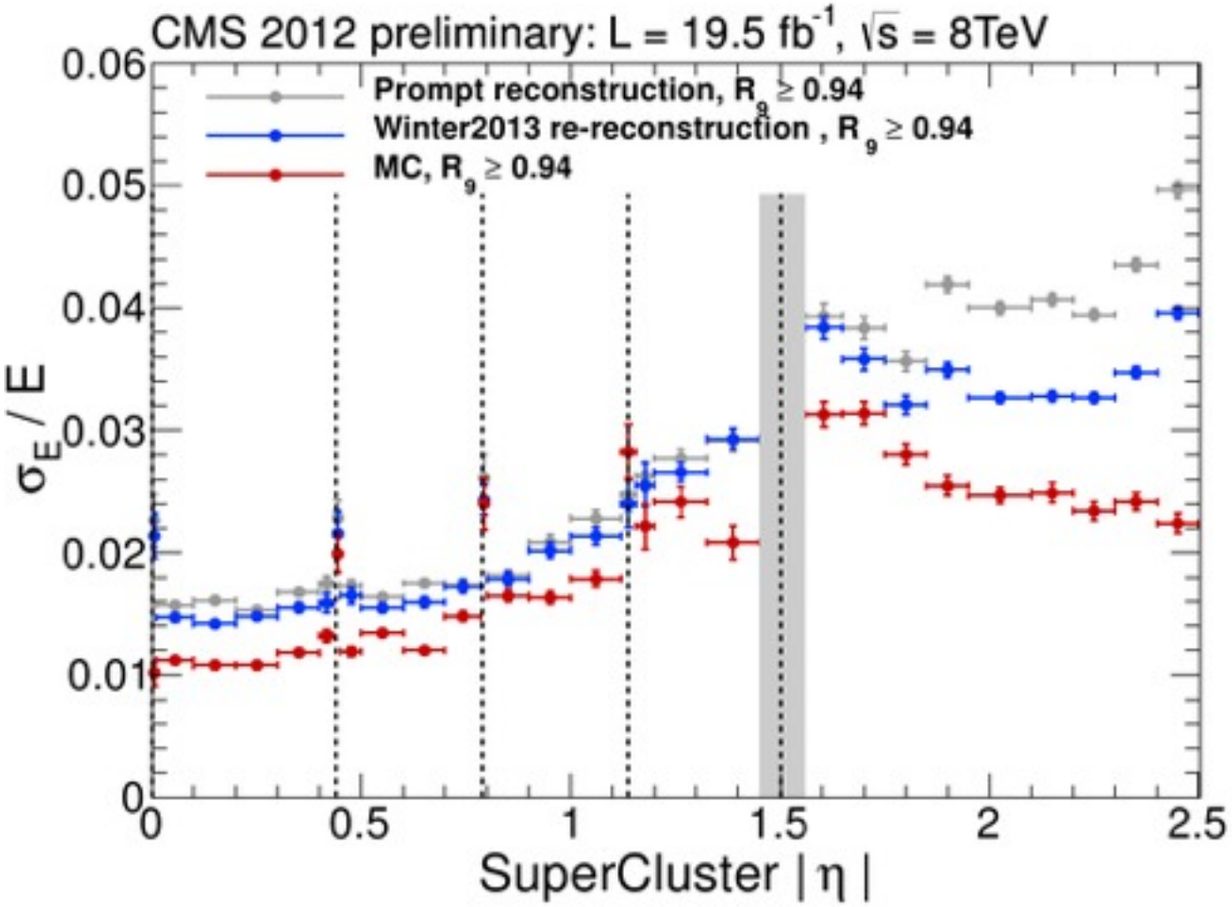
- CMS $H\to\gamma\gamma$ analysis with 5.1fb^{-1}@7TeV + 19.6fb^{-1}@8TeV: HIG-13-001
- CMS $H\to Z\gamma$ search with 5.1fb^{-1}@7TeV + 19.6fb^{-1}@8TeV: HIG-13-006
- $H\to\gamma\gamma$ 2 analysis presented. MVA analysis signal strength:

$$\mu = 0.8 \pm 0.3$$

- The 2012 dataset decreases the signal strength (both MVA and CiC analysis) which is now very consistent with SM
- Higgs mass:

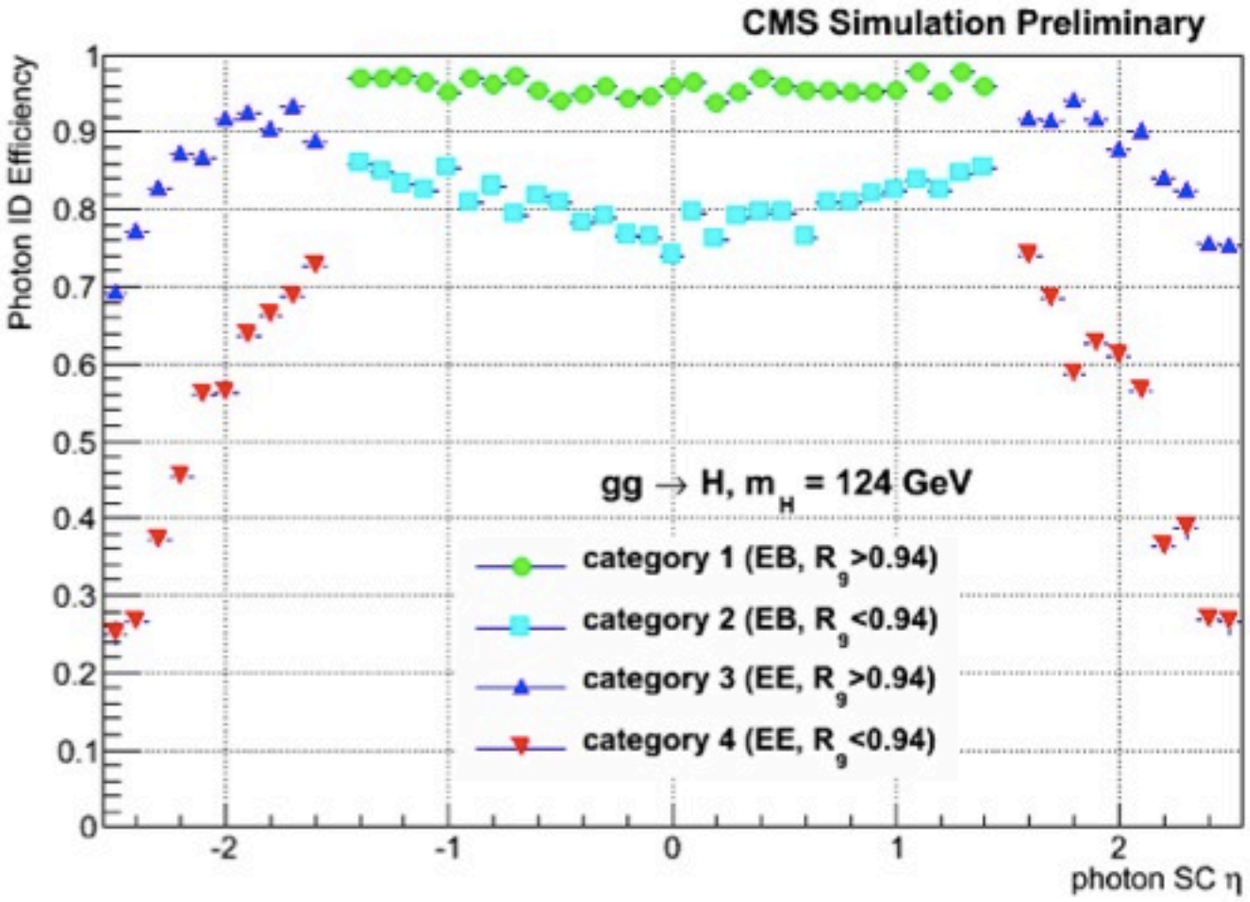
$$m_H = 125.4 \pm 0.5 \pm 0.6 \text{ GeV}$$

- More to come:
  - ECAL calibration not yet final, expect sizeable improved resolution
  - Analysis developments (?)
  - Spin analysis...

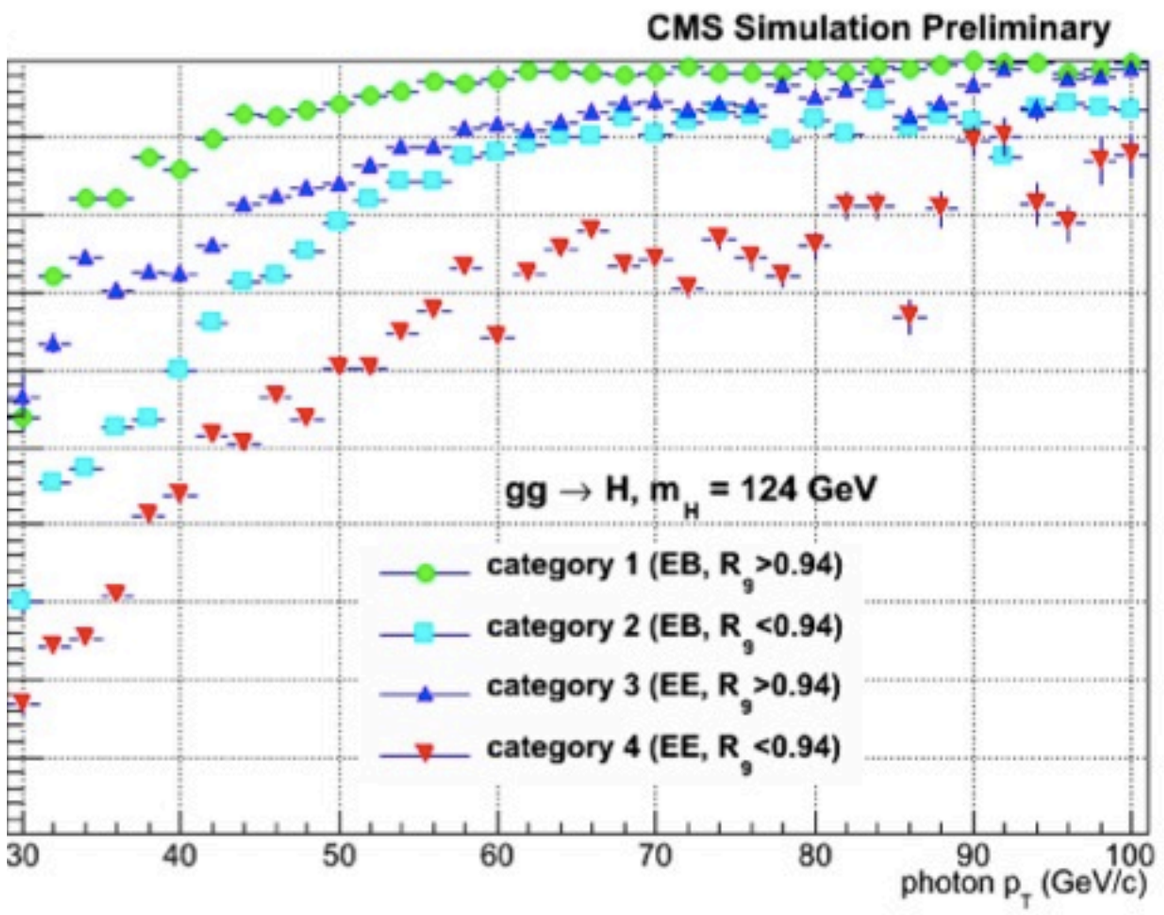


backup

γ identification

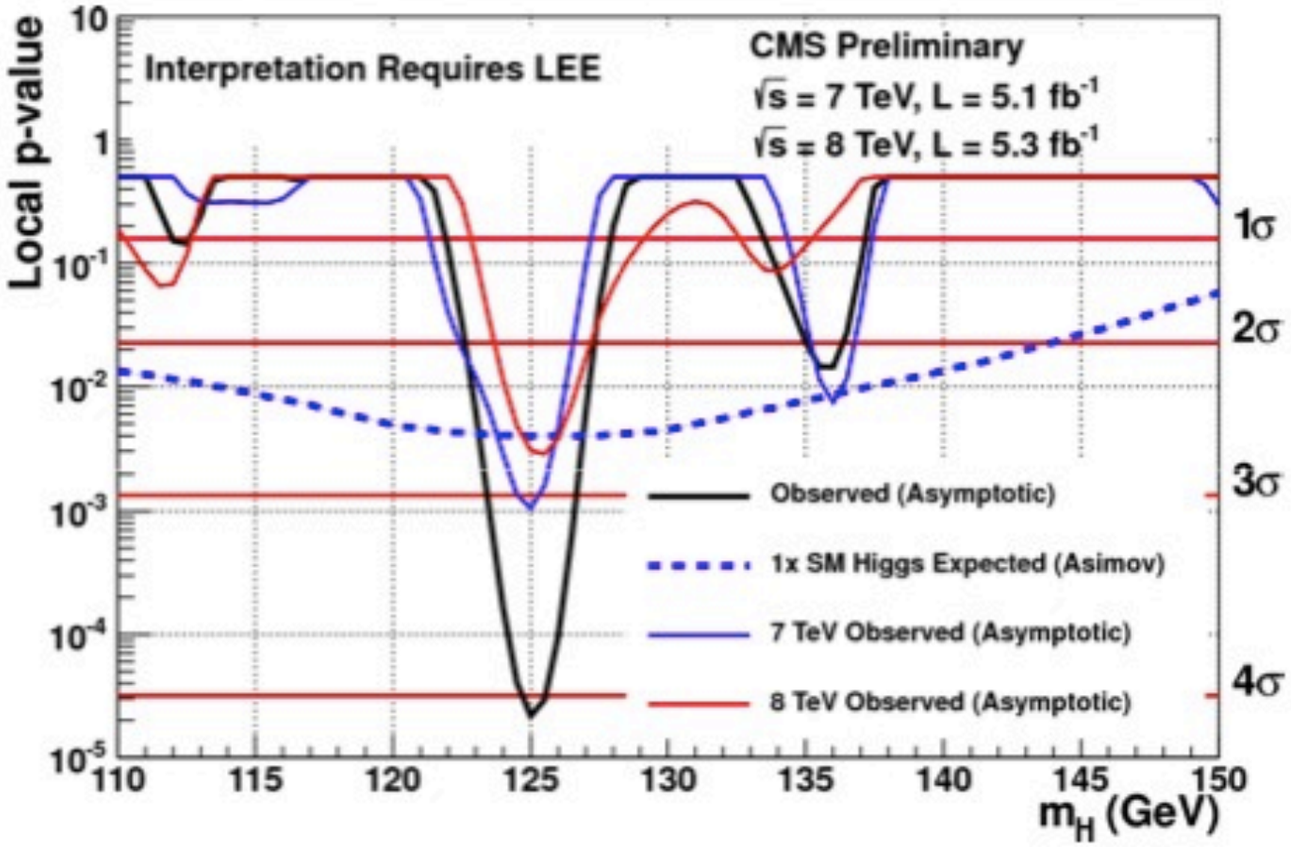


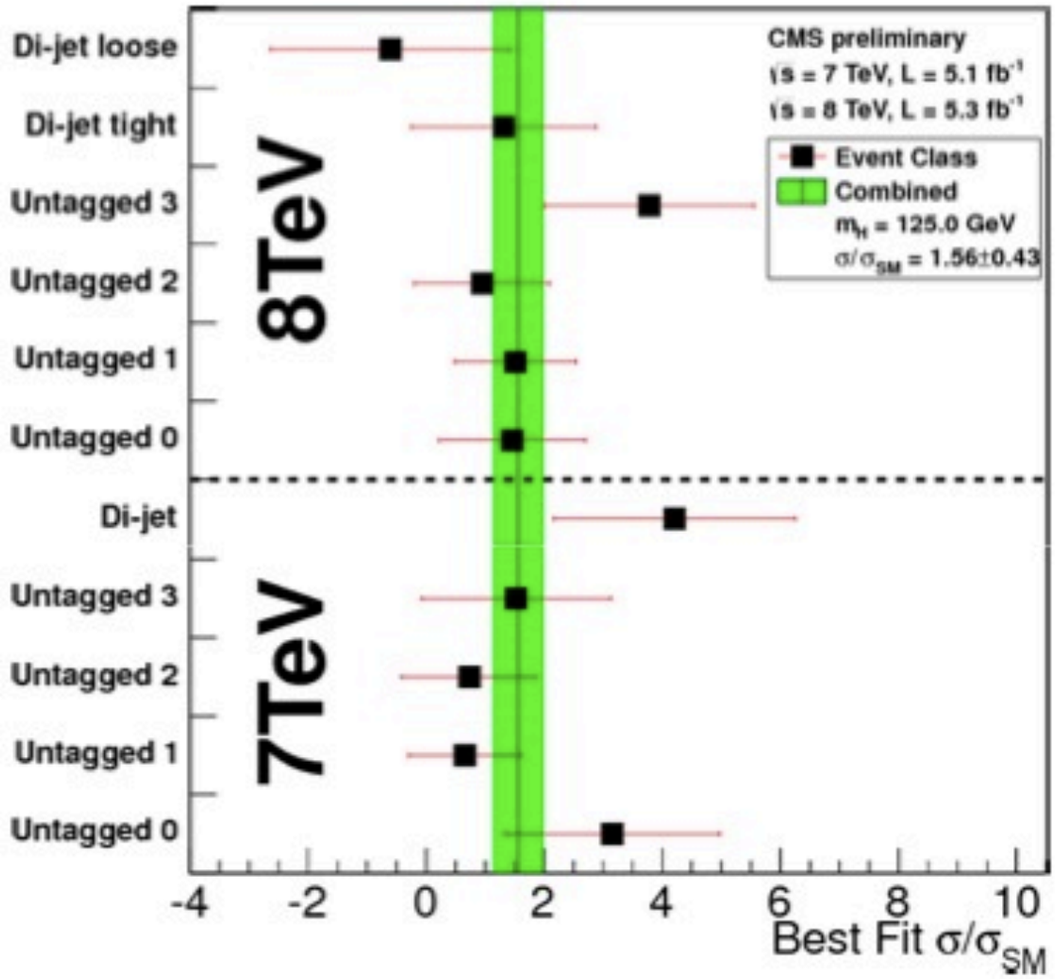
(a) η



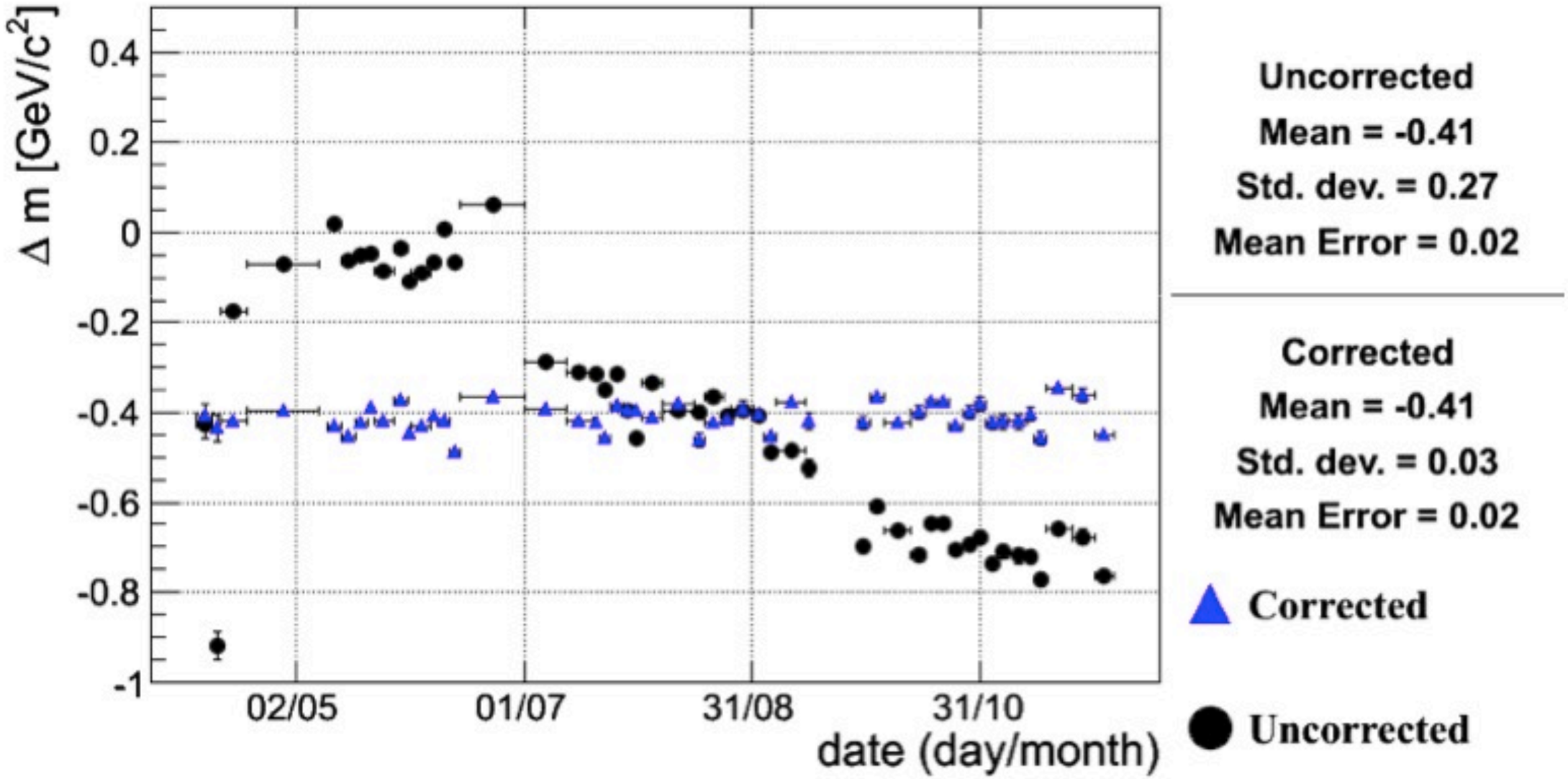
(b) p_T

July 2012 publication

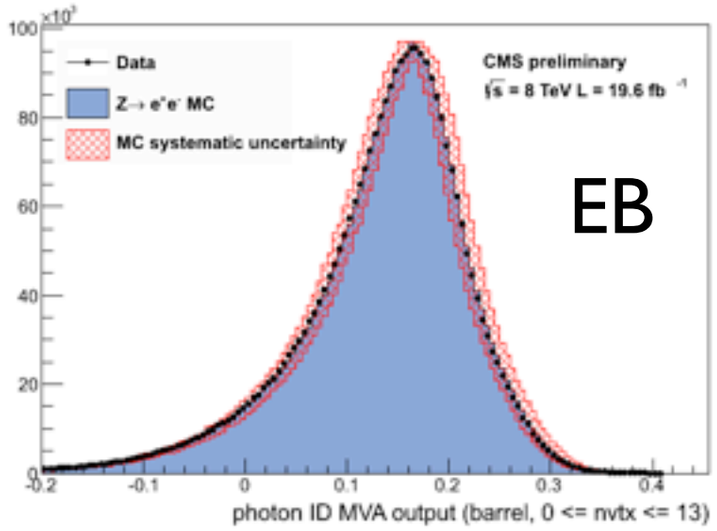




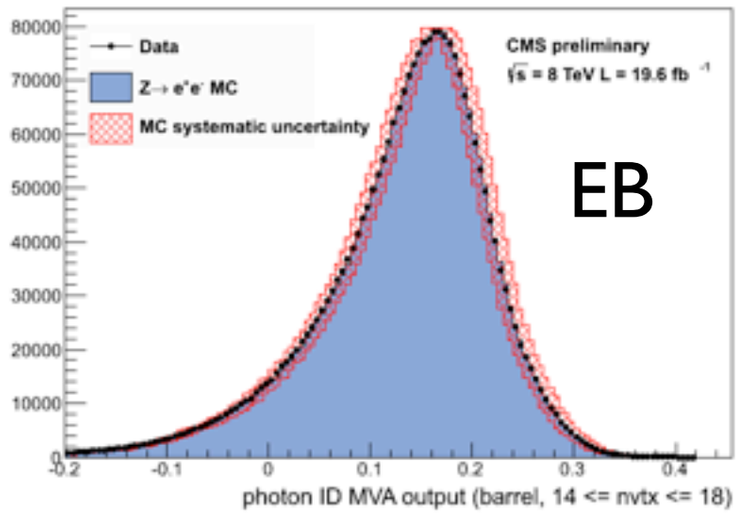
ECAL stability with time



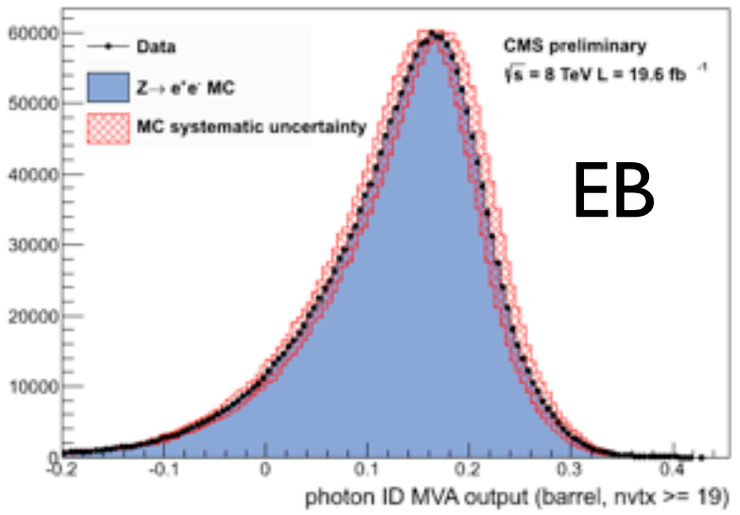
0 ≤ nPV < 14

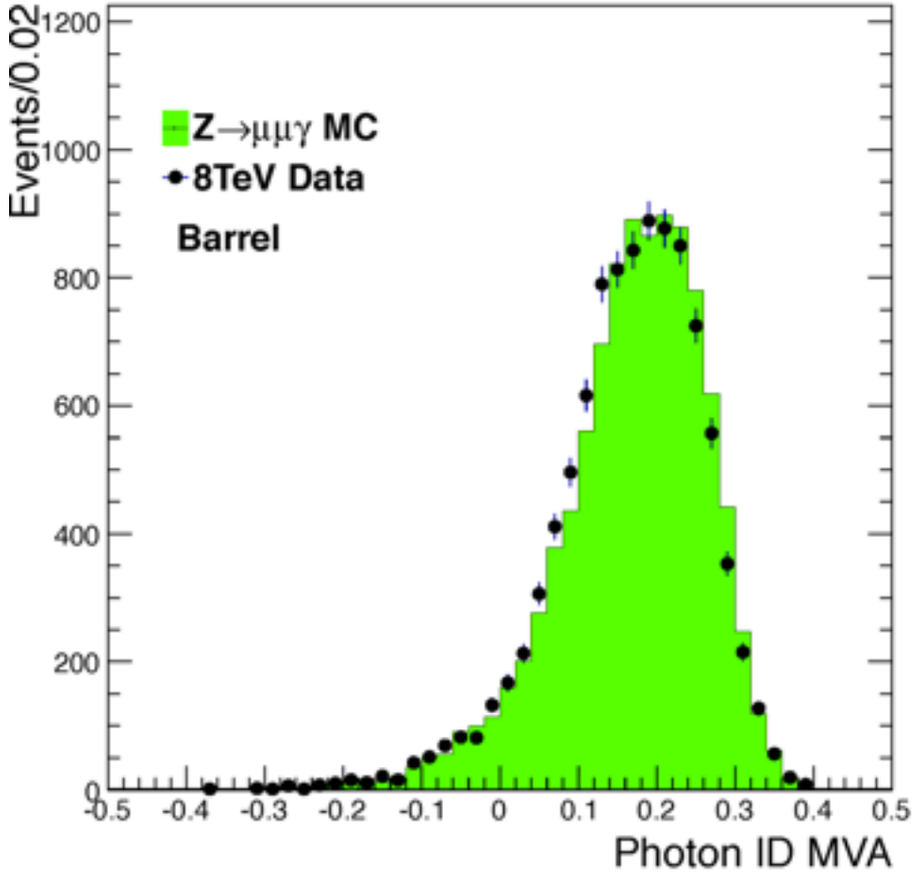


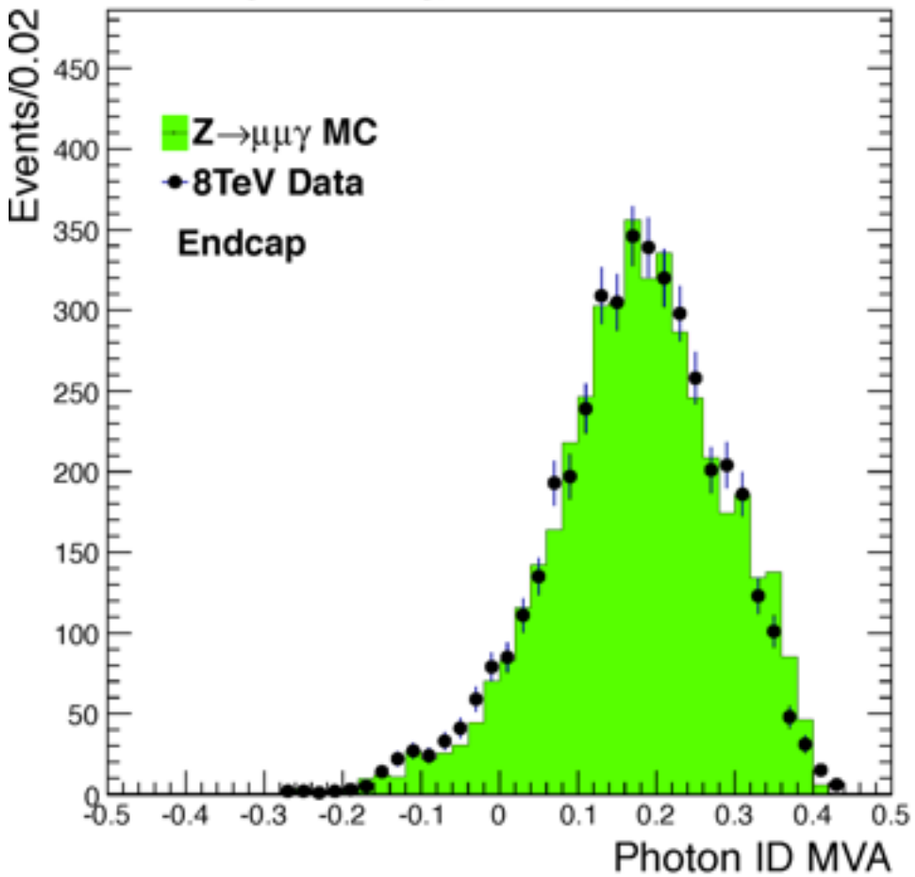
14 ≤ nPV < 19



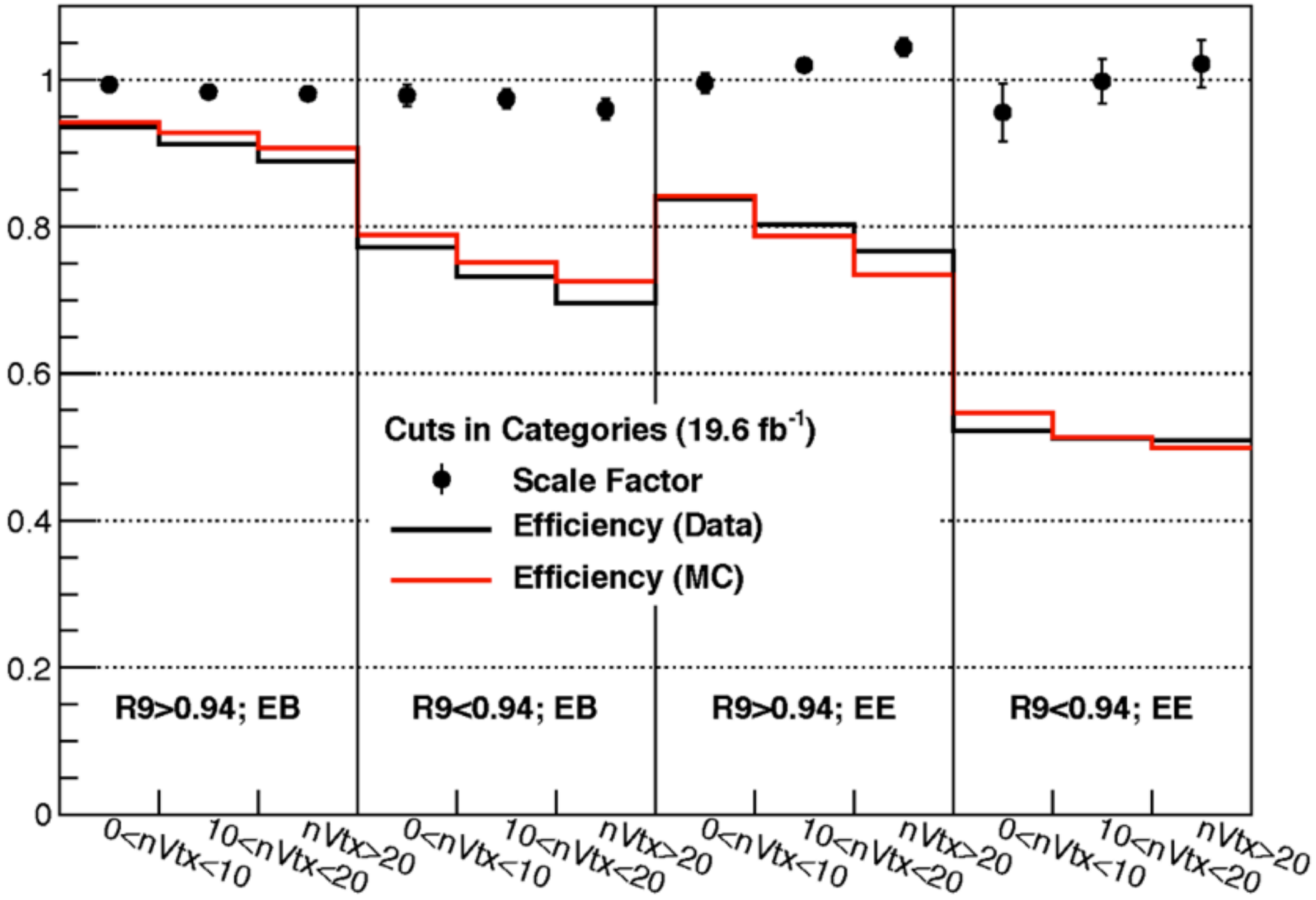
19 ≤ nPV







CiC id efficiency vs #vtx



$\mathcal{H}\to Z\gamma$ search

Categories:

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
	Event class 1	
	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 > 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 > 0.94$
Data Signal σ_{eff} FWHM	17% 30% 1.9 GeV 4.5 GeV	20% 34% 1.6 GeV 3.7 GeV
	Event class 2	
	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 1.4442$ $R_9 < 0.94$	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons $0 < \lvert\eta\rvert < 2.1$ and one lepton $0 < \lvert\eta\rvert < 0.9$ $R_9 < 0.94$
Data Signal σ_{eff} FWHM	26% 28% 2.1 GeV 5.0 GeV	31% 31% 1.9 GeV 4.6 GeV
	Event class 3	
	Photon $0 < \lvert\eta\rvert < 1.4442$ At least one lepton $1.4442 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $0 < \lvert\eta\rvert < 1.4442$ Both leptons in $\lvert\eta\rvert > 0.9$ or one lepton in $2.1 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	26% 23% 3.1 GeV 7.3 GeV	20% 18% 2.1 GeV 5.0 GeV
	Event class 4	
	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.5$ No requirement on R_9	Photon $1.566 < \lvert\eta\rvert < 2.5$ Both leptons $0 < \lvert\eta\rvert < 2.4$ No requirement on R_9
Data Signal σ_{eff} FWHM	31% 19% 3.3 GeV 7.8 GeV	29% 17% 3.2 GeV 7.5 GeV

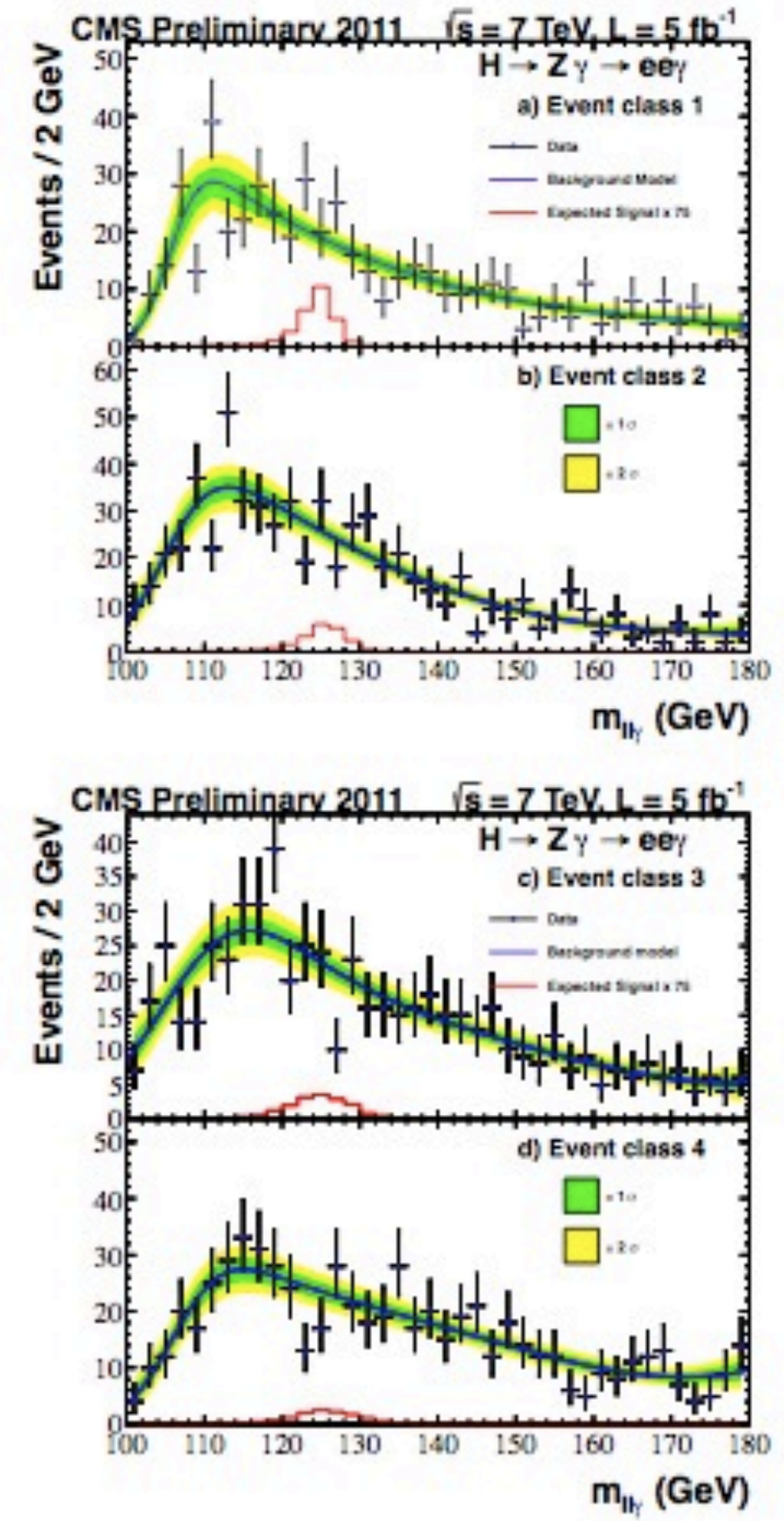
$\mathcal{H}\to Z\gamma$ search

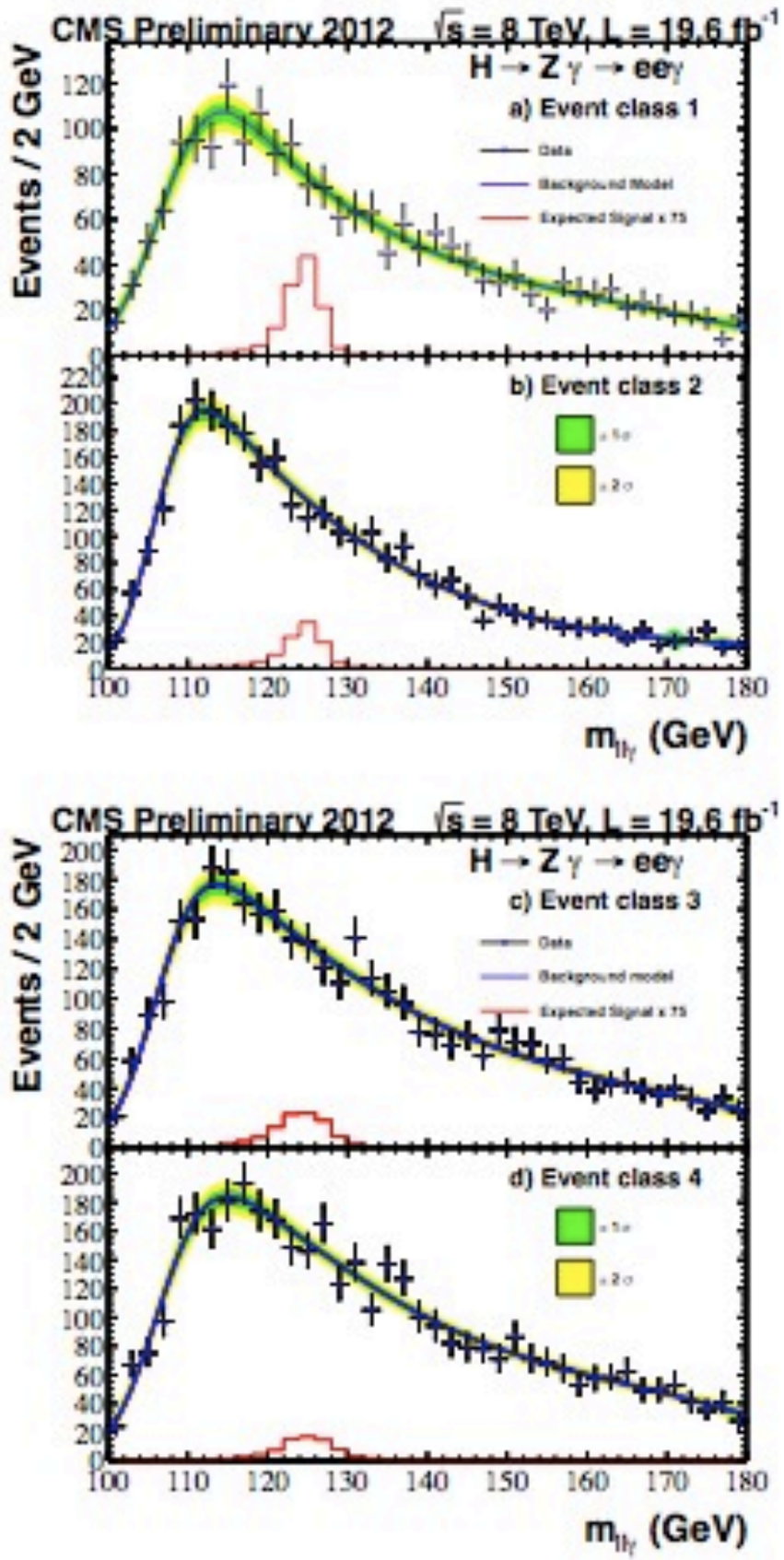
Systematics

Source	7 TeV	8 TeV
Integrated luminosity	2.2%	4.4%
Theory		
- Gluon-gluon fusion cross section (scale)	+12.5% -8.2%	+7.6% -8.2%
- Gluon-gluon fusion cross section (PDF)	+7.9% -7.7%	+7.6% -7.0%
- Vector boson fusion cross section (scale)	+0.5% -0.3%	+0.3% -0.8%
- Vector boson fusion cross section (PDF)	+2.7% -2.1%	+2.8% -2.6%
- W associate production (scale)	+0.7% -0.8%	+0.2% -0.7%
- W associate production (PDF)	+3.5% -3.5%	+3.5% -3.5%
- Z associate production (scale)	+1.7% -1.6%	+1.9% -1.7%
- Z associate production (PDF)	+3.7% -3.7%	+3.9% -9.7%
- Top pair associate production (scale)	+3.4% -9.4%	+3.9% -9.3%
- Top pair associate production (PDF)	+8.5% -8.5%	+7.9% -7.9%
Branching fraction	6.7%,9.4% -6.7%,-9.3%	6.7%,9.4% -6.7%,-9.3%
Trigger		
- Electron	0.5%	2.0%
- Muon	0.5%	3.5%
Selection		
- Photon Barrel	0.5%	0.6%
- Photon Endcap	1.0%	1.0%
- Electron	0.8%	0.8%
- Muon	0.7%	1.4%
Signal scale and resolution		
- Mean	1.0%	1.0%
- Sigma	5.0%	5.0%
Event migration	5.0%	5.0%
Pileup		
- Electron	0.6%	0.8%
- Muon	0.4%	0.4%

$\mathcal{H}\rightarrow Z\gamma$ search

eeγ





$\mathcal{H}\rightarrow Z\gamma$ search

$\mu\mu\gamma$