SEARCH FOR THE HIGGS BOSON IN THE CHANNEL $H \rightarrow \gamma\gamma$

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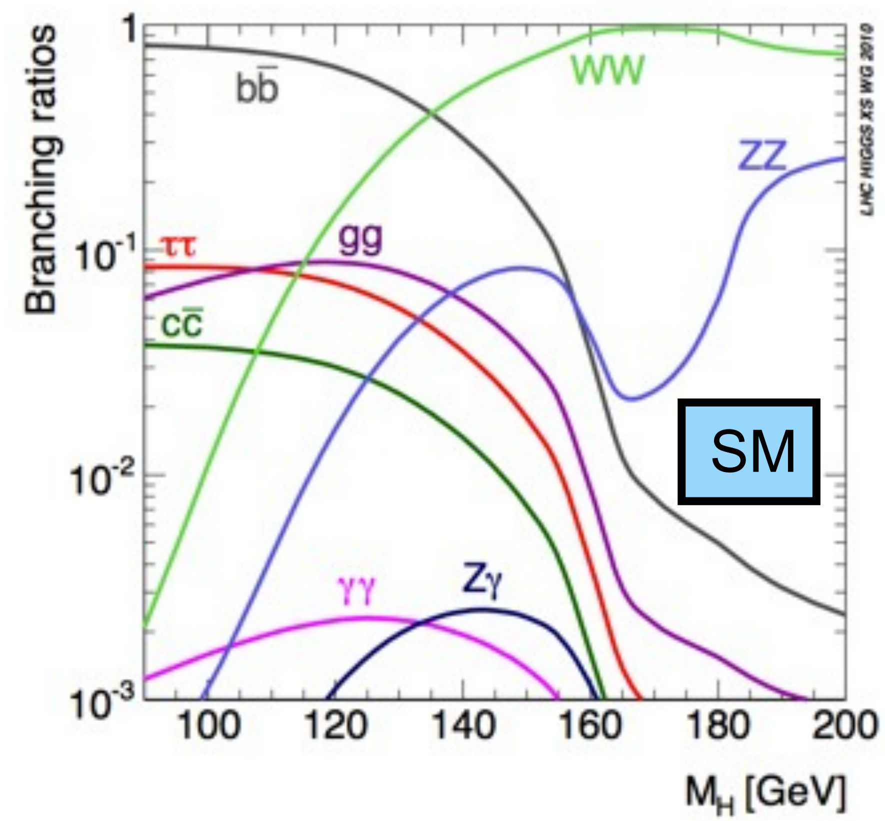
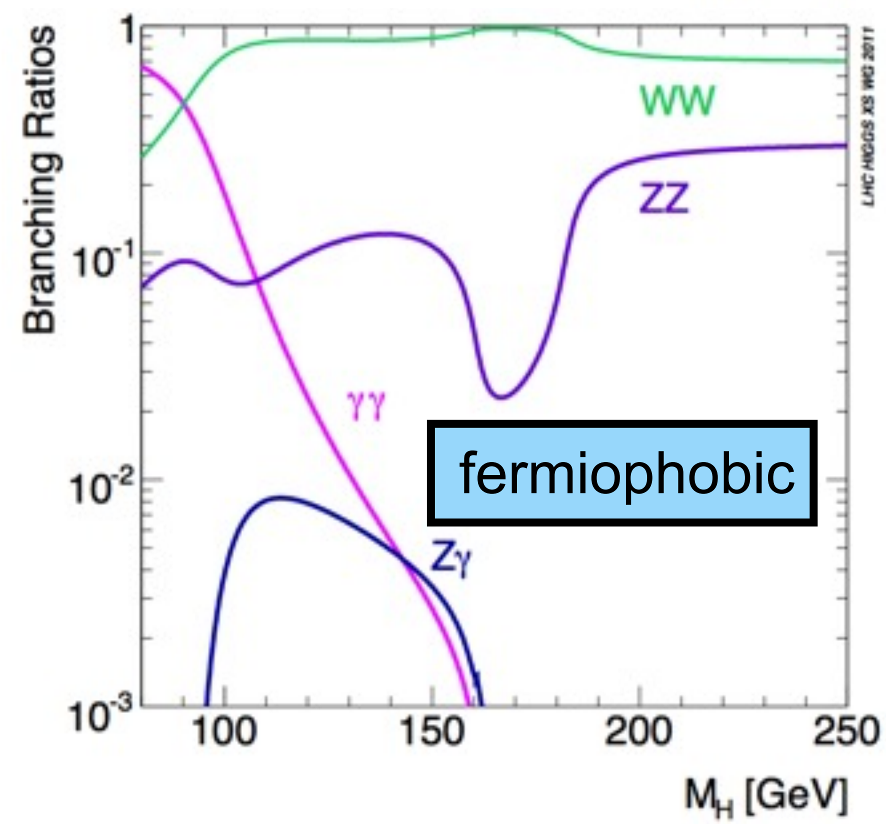
$H \rightarrow \gamma\gamma$

- **Light Higgs favored** by precision electroweak tests
- **$H \rightarrow \gamma\gamma$ one of the most sensitive** channels at low masses despite the small branching ratio
  - **striking signature** (two photons, peak in invariant mass)
- **Very interesting channel** in alternative models (e.g **Fermiophobic** Higgs)
  - high branching ratio for di-photon decay
  - early exclusion/discovery





CMS ELECTROMAGNETIC CALORIMETER

- **Discovery** **potential dependent on** di-photon **invariant mass resolution**

  CMS: em crystal calorimeter

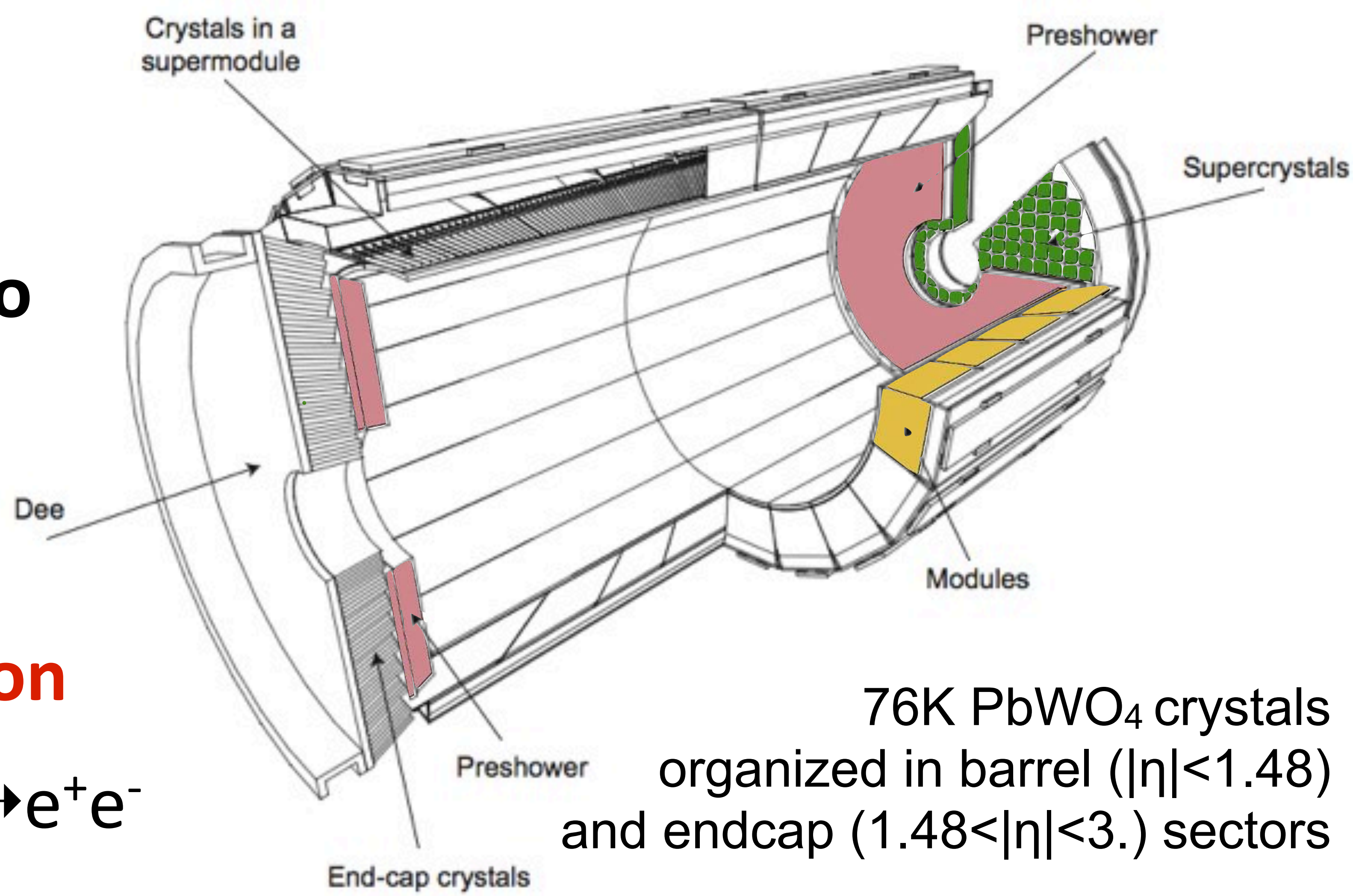
- **Design energy resolution** of ECAL ~**0.5% for E(γ) >100GeV** (for unconverted γ in barrel)
- Critical issues:

  ➪ **transparency loss due to radiation damage**

  use of laser monitoring

  ➪ **on-site energy calibration**

  use of $\pi^0 \to \gamma\gamma$, E_e/p_e, $Z \to e^+e^-$

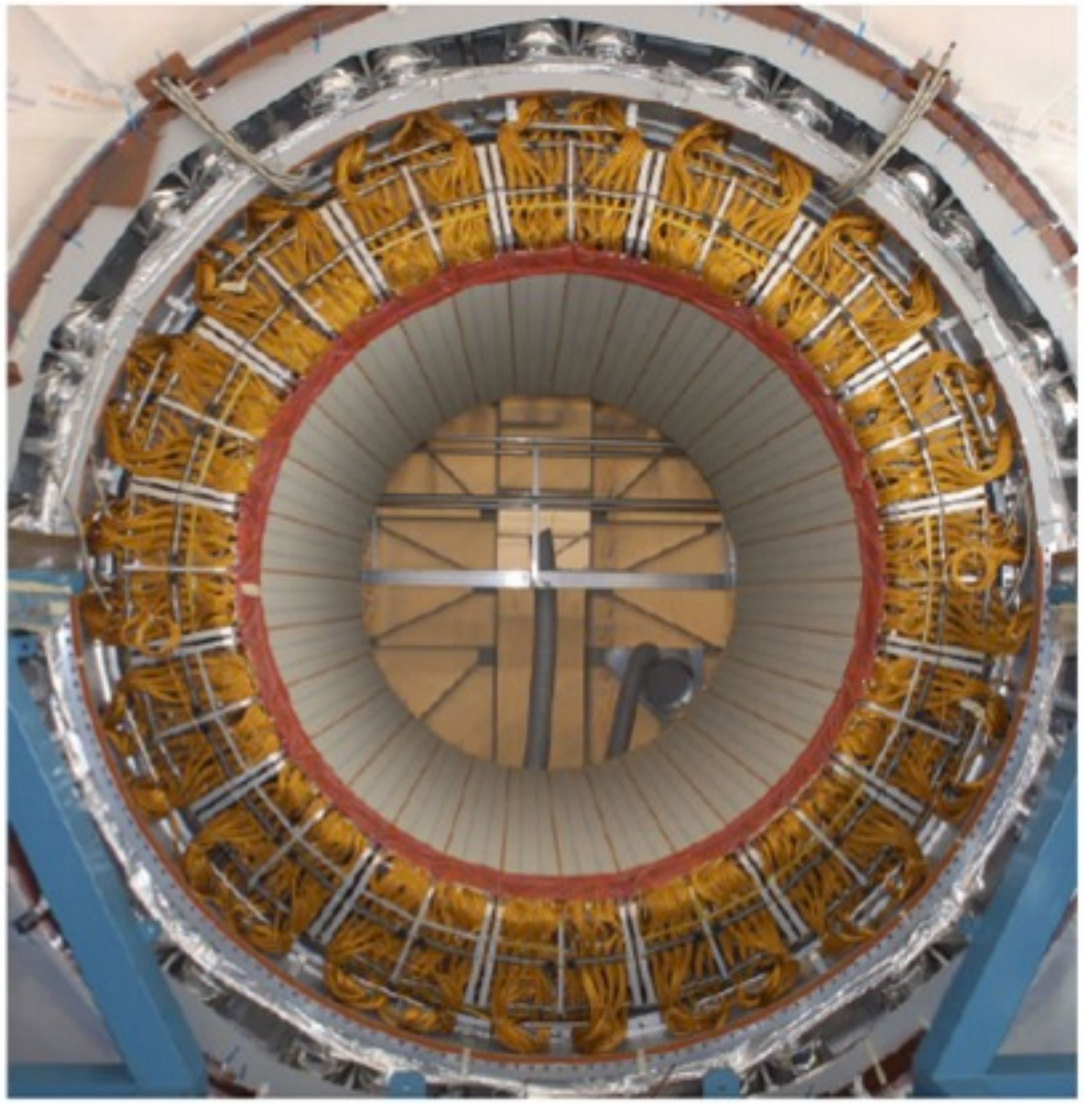


76K $PbWO_4$ crystals organized in barrel ($|\eta|<1.48$) and endcap ($1.48<|\eta|<3.$) sectors

ATLAS Electromagnetic Calorimeter

ATLAS: LAr accordion calorimeter

- Accordion segmentation allows for:
  - **crack-less geometry**
  - **uniformity**
  - **able to reconstruct photon direction**
- **Design resolution:**
  - stochastic term: 10%
  - at 100 GeV expect about 1.5% resolution
- **Critical issue:**
  - understanding of material in front of calorimeter



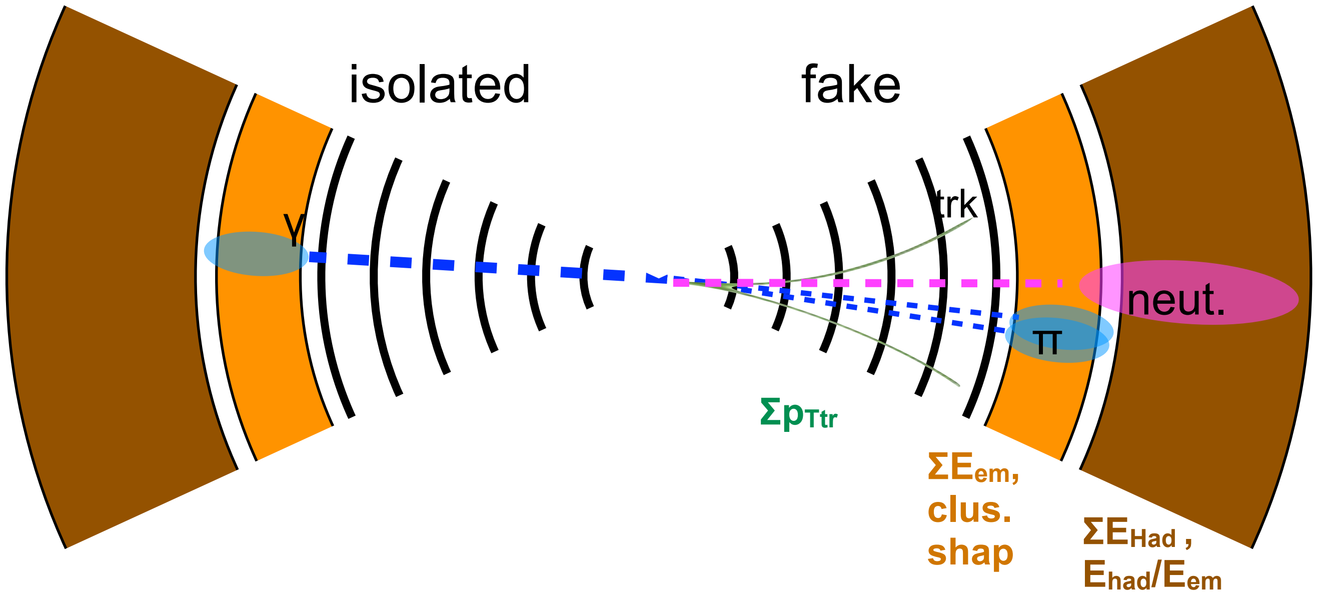
ANALYSIS STRATEGY

STEP	CRITICAL ISSUES
1) two isolated photons with large transverse momentum $p_T(\gamma_1)>40GeV$, $p_T(\gamma_2)>30,25GeV$	• isolation to reject γ+jet and QCD background • determine efficiency from data
2) di-photon mass reconstruction $m_H^2 = 2E_1E_2(1-cos\theta)$	• vertex determination in presence of multiple interactions pile-up (PU) • energy scale and resolution
3) signal extraction	• event categories to maximize sensitivity • background shape

Background Rejection

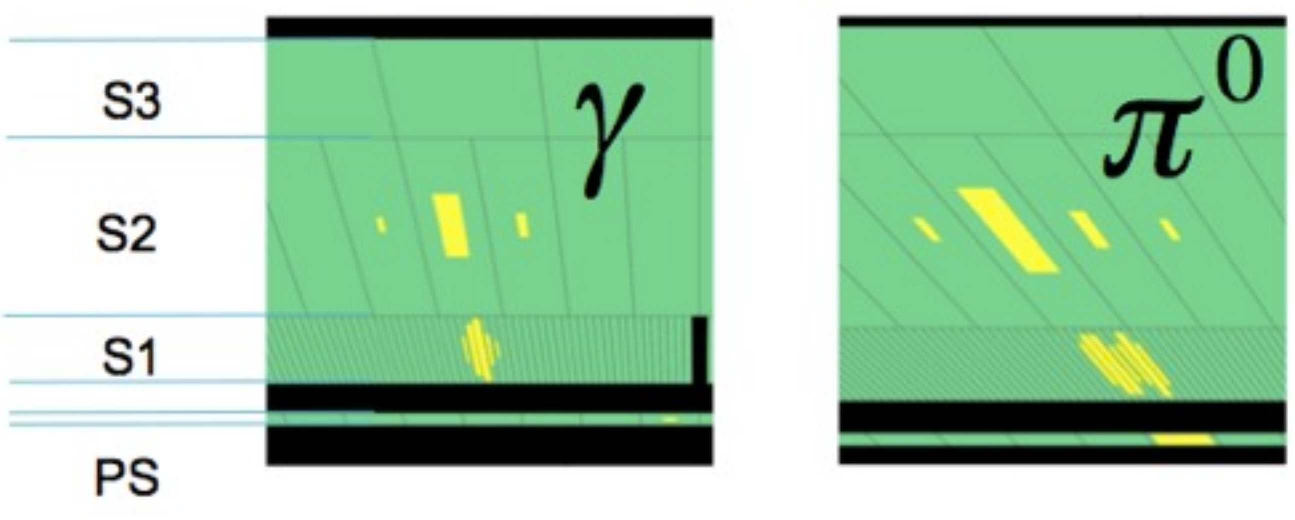
- **photon isolation** variables evaluated within a cone of $\sqrt{\Delta\eta^2+\Delta\phi^2}=0.3\text{-}0.4$ to reject γ+jet and QCD background
  - CMS: based on **Σp_{Ttrk}, energy deposited in em and hadronic calorimeters. Corrected for PU** via subtraction of PU energy density
  - ATLAS: based on **energy deposited in calorimeter**
- **shower shape** to reject $\pi^0 \rightarrow \gamma\gamma$

CMS



ATLAS

π^0-γ Rejection

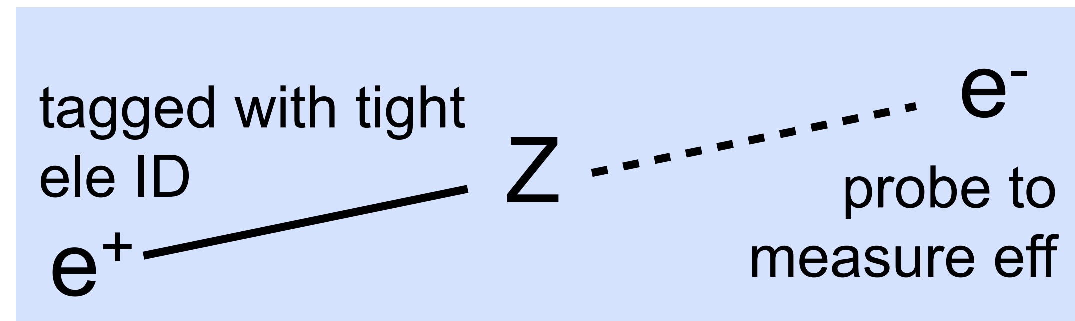


SELECTION EFFICIENCY

photon ID and trigger efficiency is determined from **data control samples**

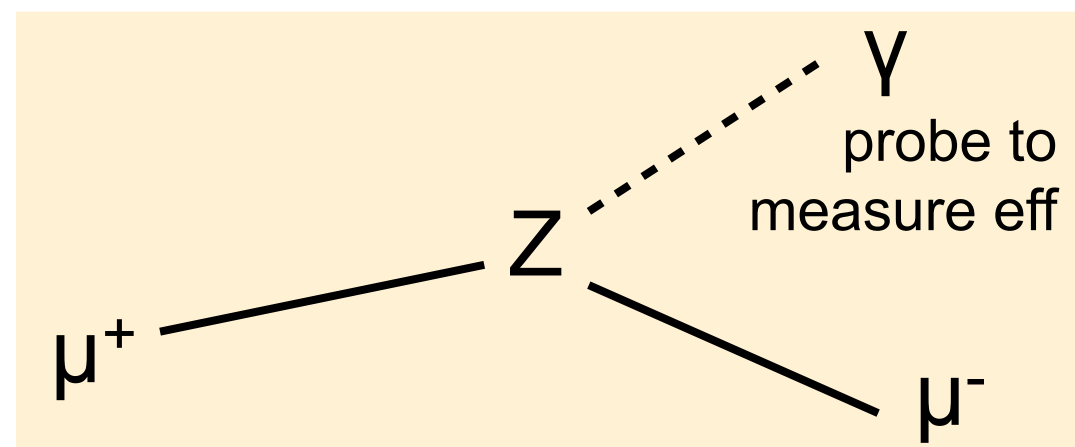
1) **$Z \to e^+e^-$ with tag and probe**:

- one electron selected with ele-ID (tag), other used to measure trigger and offline selection efficiency (probe)



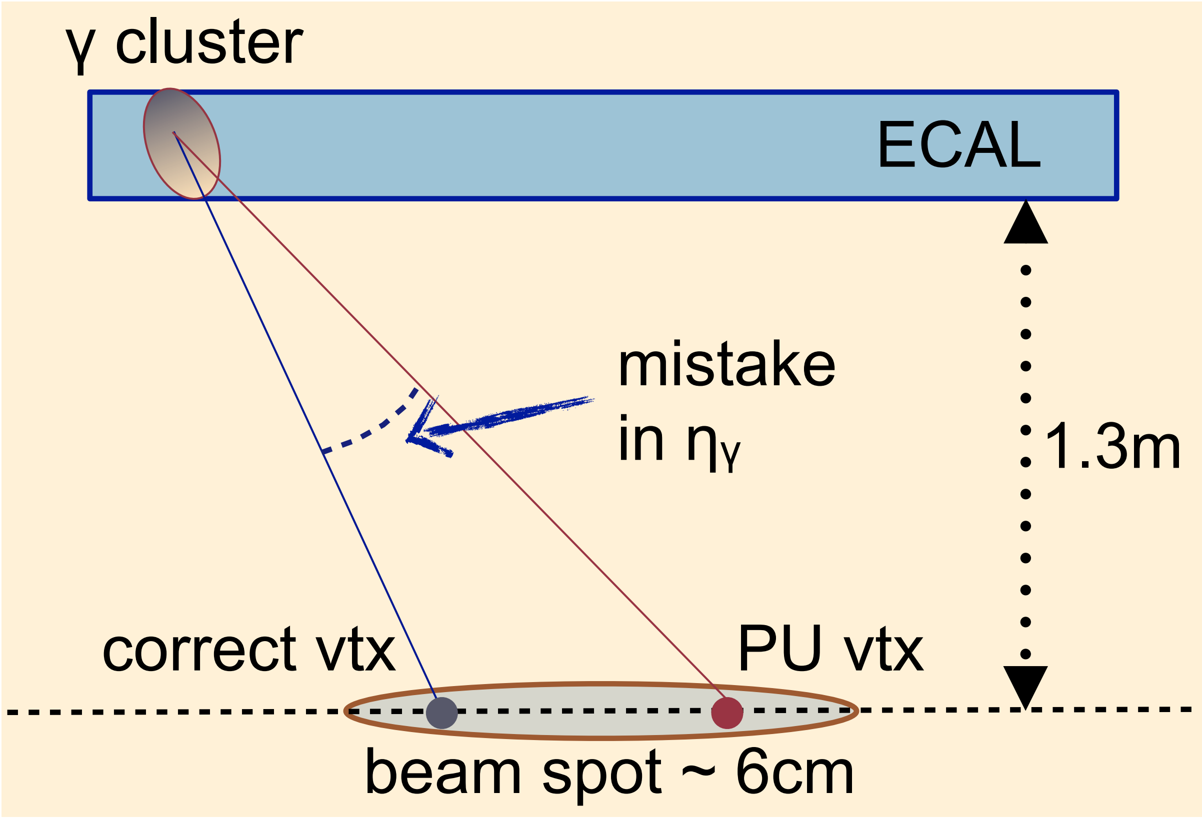
2) **$Z \to \mu^+\mu^-\gamma$** (CMS only):

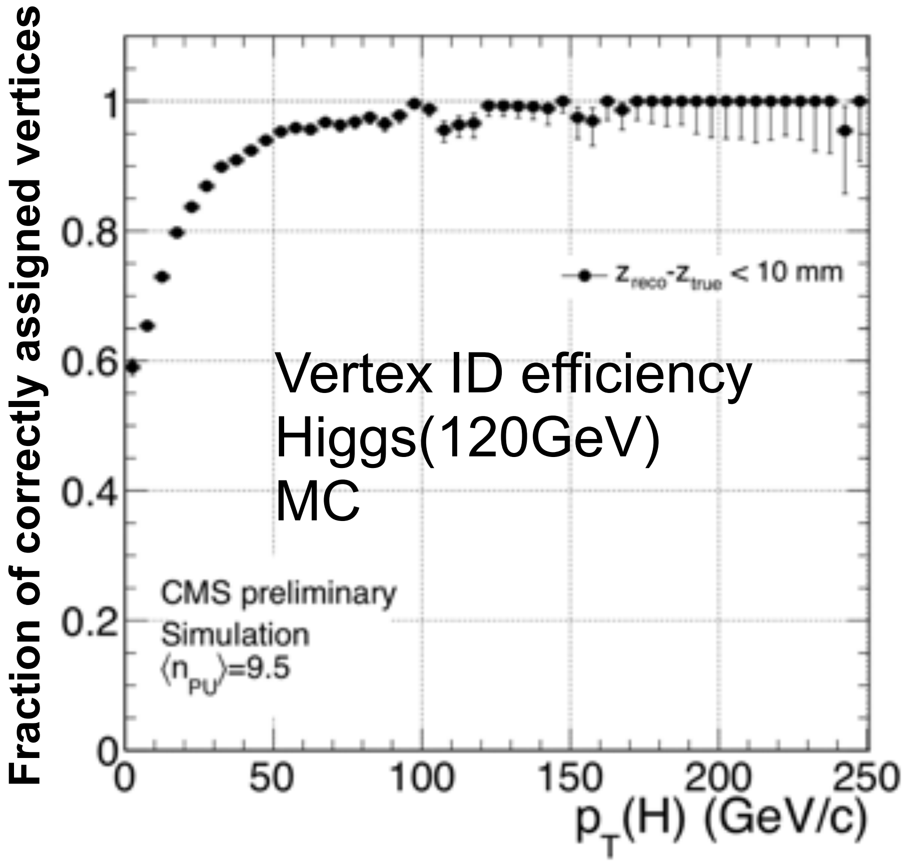
- select muons and photon (w/o electron veto) to make Z mass
- use γ to derive electron veto efficiency



CMS Vertex Determination

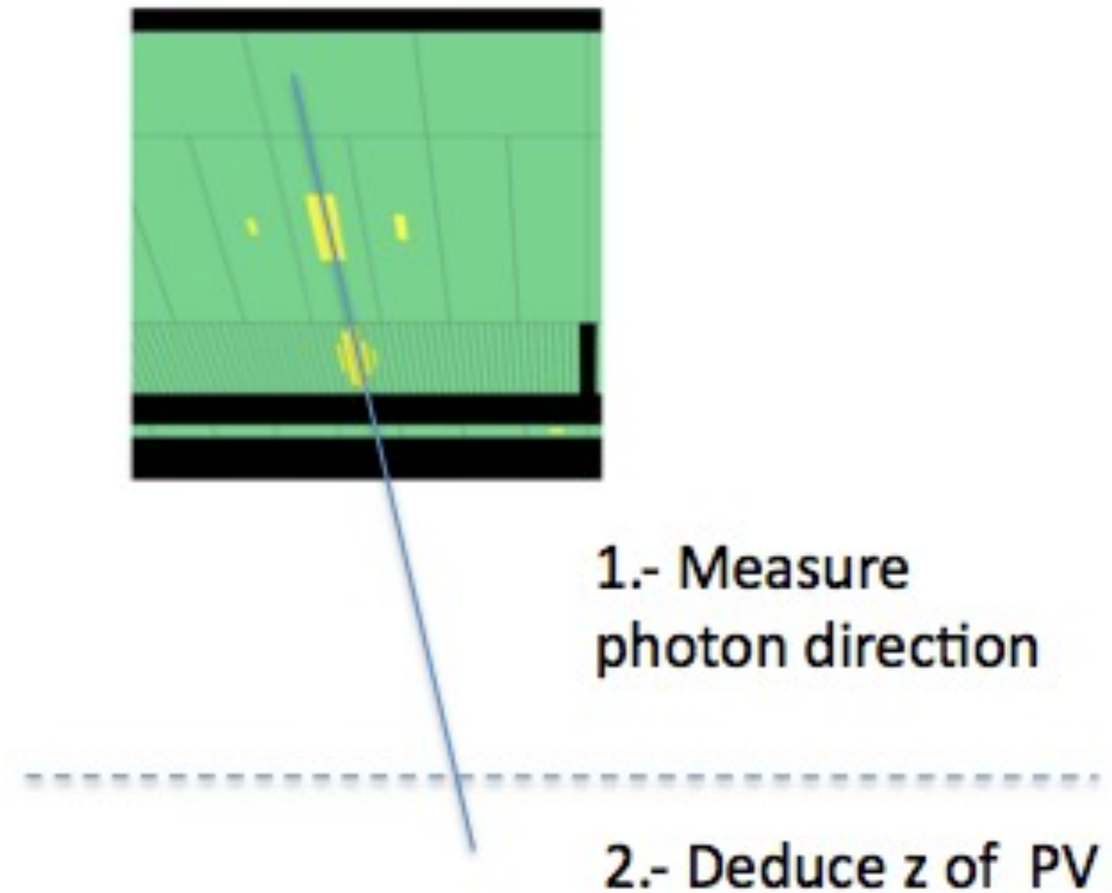
- **large pile-up conditions**
  - ➪ $\langle N_{PU} \rangle \sim 10$
- di-photon invariant **mass resolution affected by vertex** choice
- CMS **vtx determination** based on
  - **tracks belonging to vertex** combined **with di-photon kinematics**
    - use of $\Sigma p_T{}^2{}_{trk}$ and p_T balancing
  - **conversion-track** finding and projection on beam spot
- performance **cross-checked using** $\mathbf{Z \rightarrow \mu^+\mu^-}$ after removing muon tracks

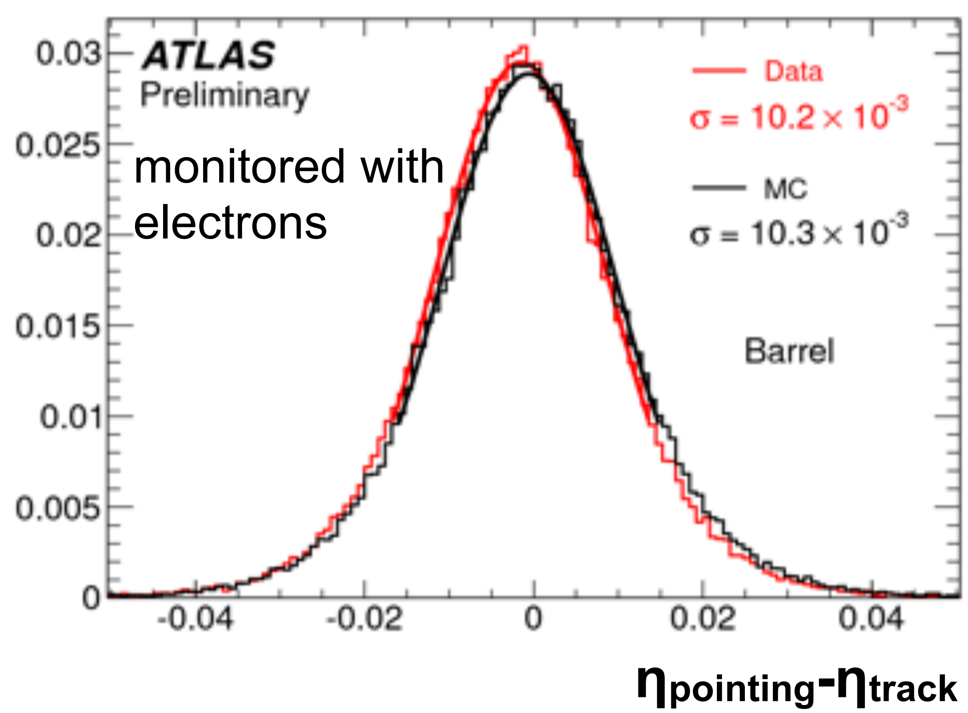


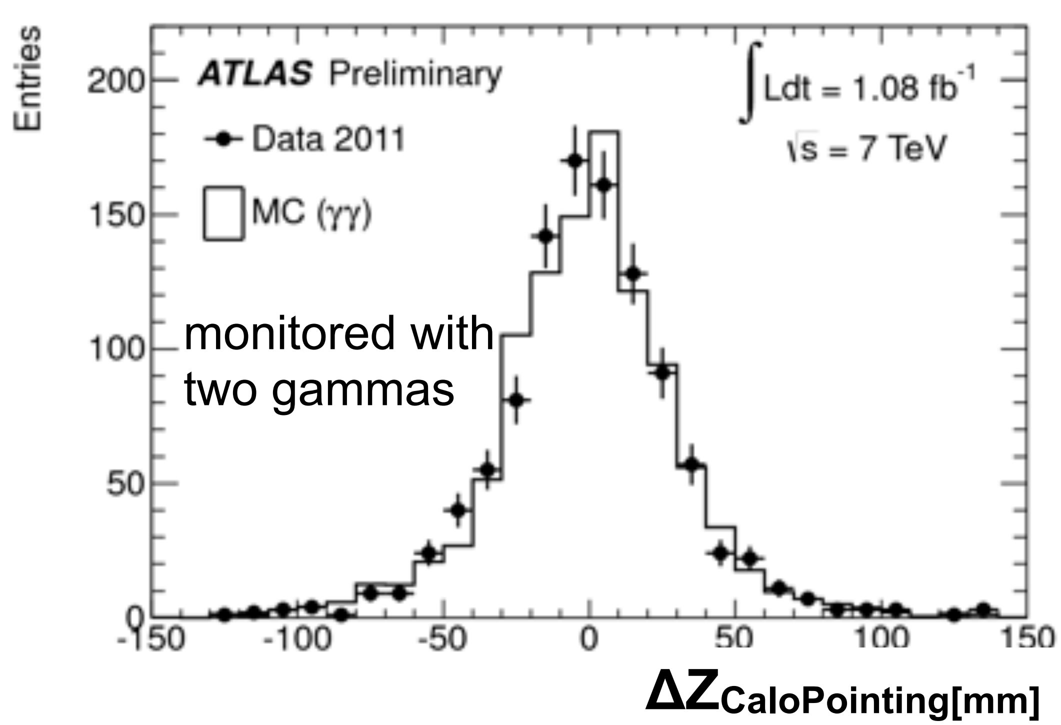


ATLAS Vertex Determination

- **ATLAS calorimeter design** allows for **determination of γ direction**
- Additional use of **conversions** reconstructed with tracker and **recoiling tracks**
- Pointing **resolution** ~1.6cm (unconv.) and ~0.6cm (conv.)



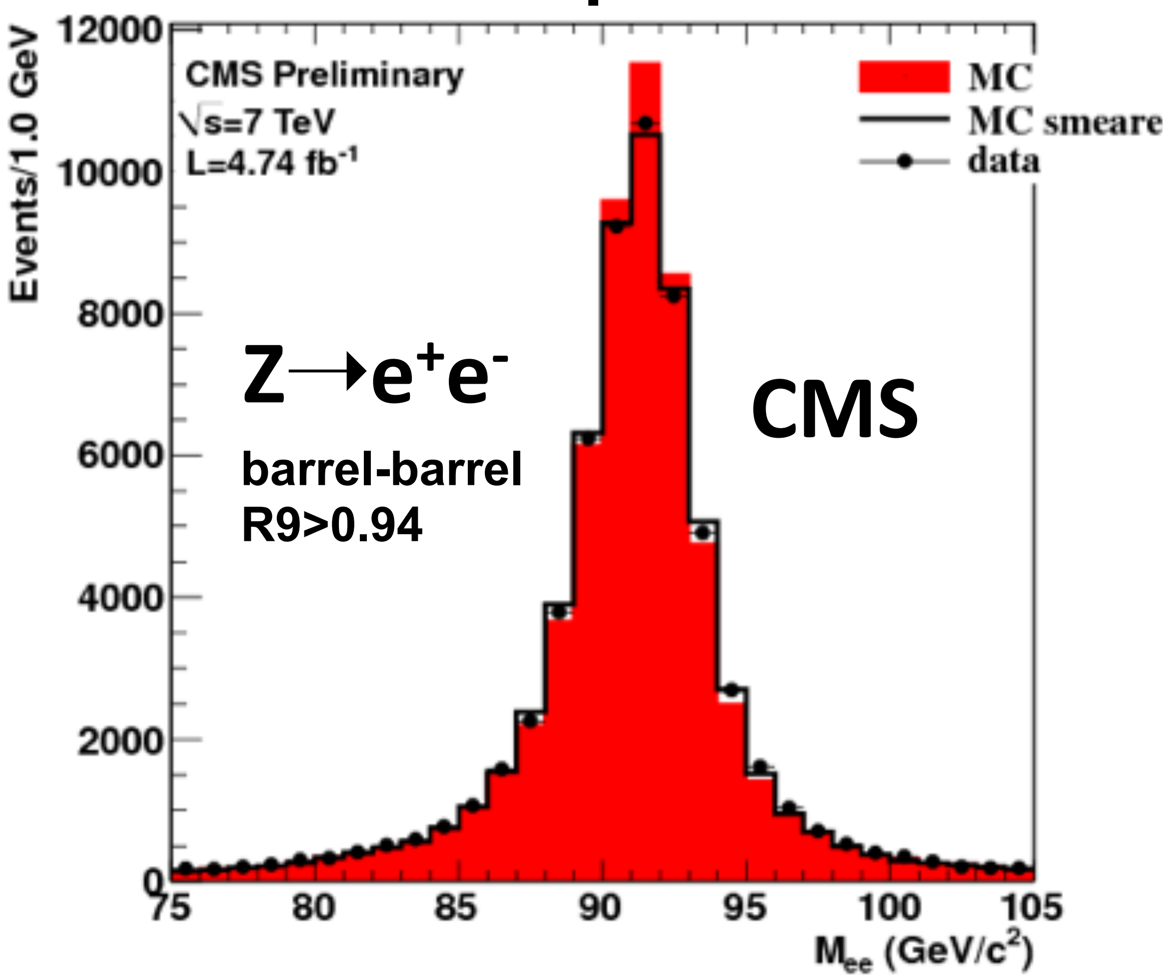


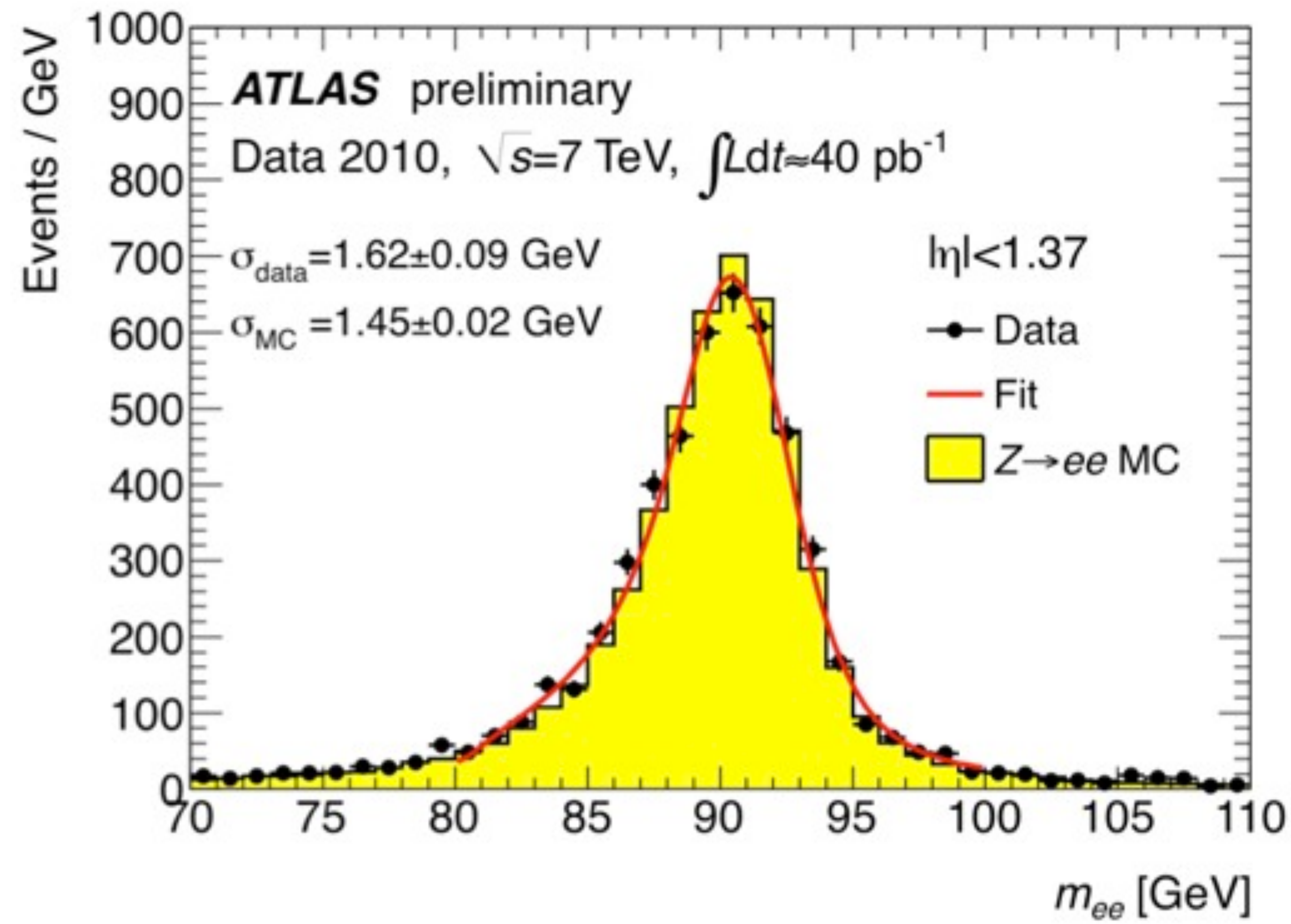


PHOTON ENERGY SCALE AND RESOLUTION

- **$Z \rightarrow e^+e^-$ invariant mass** to determine **energy scale and resolution from data**
- **photon energy smeared** on MC to match data to model Higgs signal

examples of resolution monitoring using $Z \rightarrow ee$ events

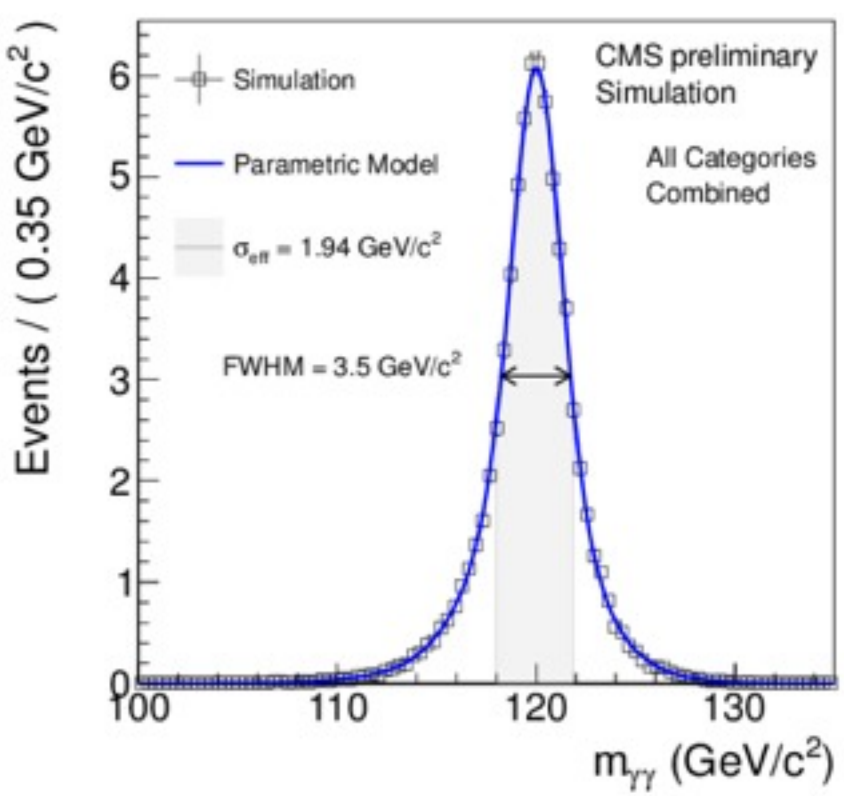


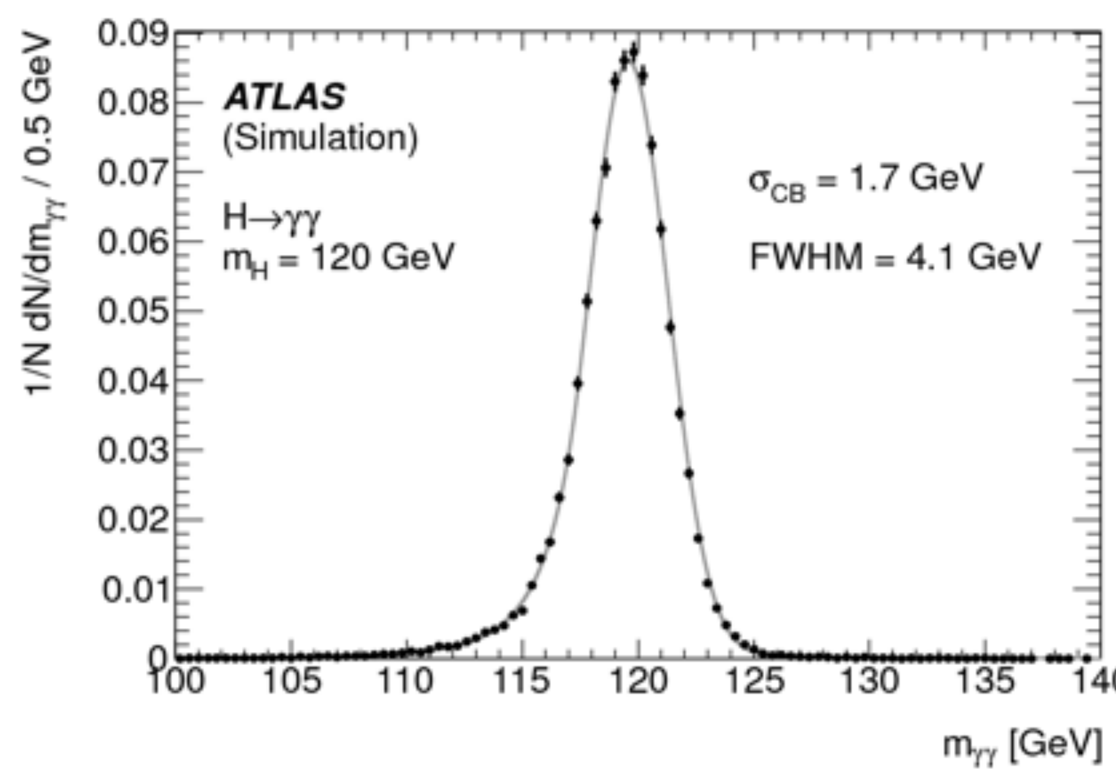


M(γγ) RESOLUTION

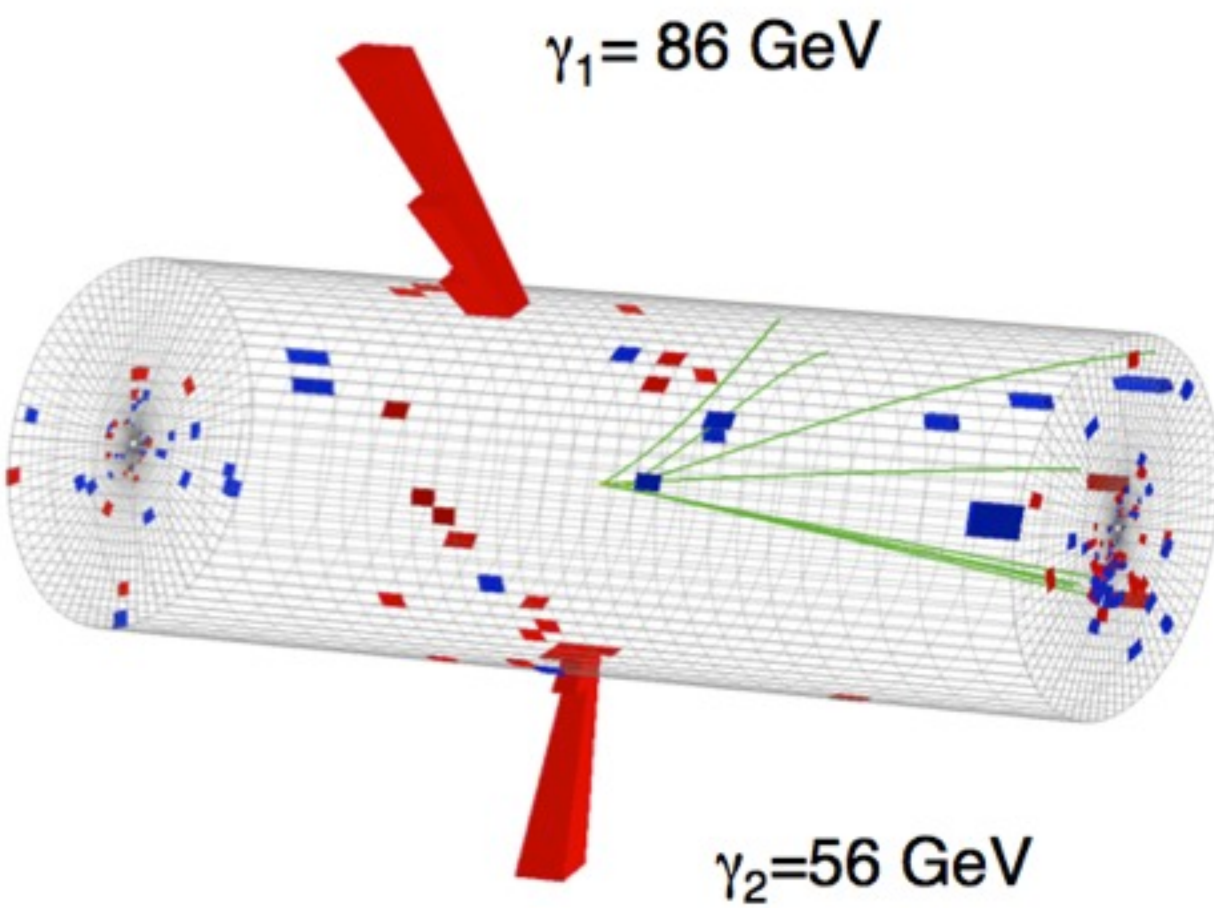
- In both detectors **m(γγ) resolution** depends on **photon kinematics, conversion probability, and pseudorapidity**
- CMS performs better in central region, ATLAS in forward
- Overall **performance for Higgs signal quite similar**

CMS		ATLAS	
best resolution cat.	worst resolution cat.	best resolution cat.	worst resolution cat.
FWMH ~ 2.8GeV	FWMH ~ 7.2GeV	FWMH~3.3GeV	FWMH~5.9GeV

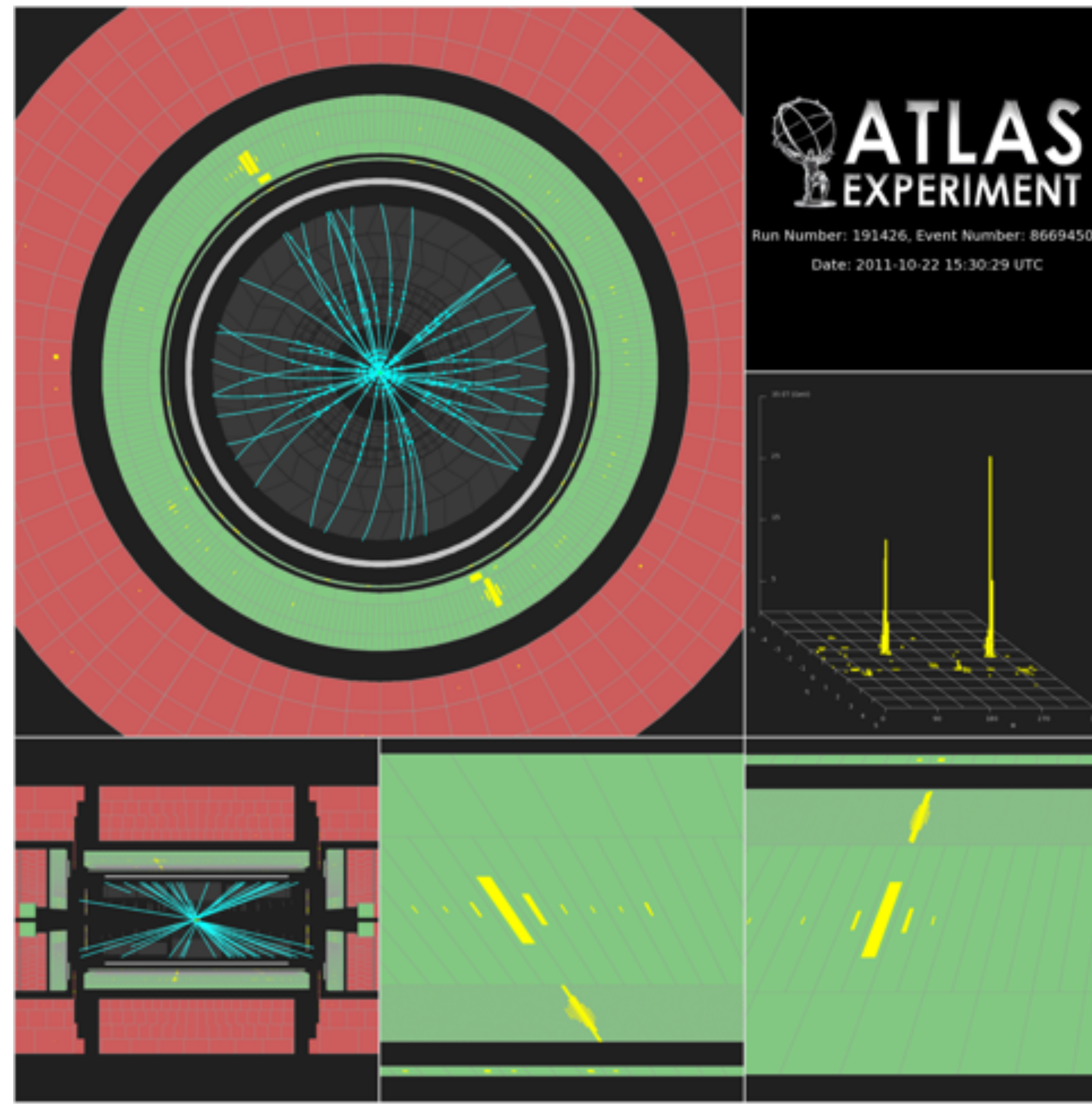




EVENT DISPLAYS



γ_1=64.2GeV γ_2=61.4GeV
diphoton mass = 126.6GeV



PHOTON-BASED CATEGORIES

- **Event categories** to
  - maximize statistical power
  - exploit differences in kinematics between signal and backgrounds
  - identify regions of the detector with very different performance
- **CMS: 4 photon-based categories**

2 η regions	$\otimes$	2 cluster shape categories

- **ATLAS: 9 photon-based categories**

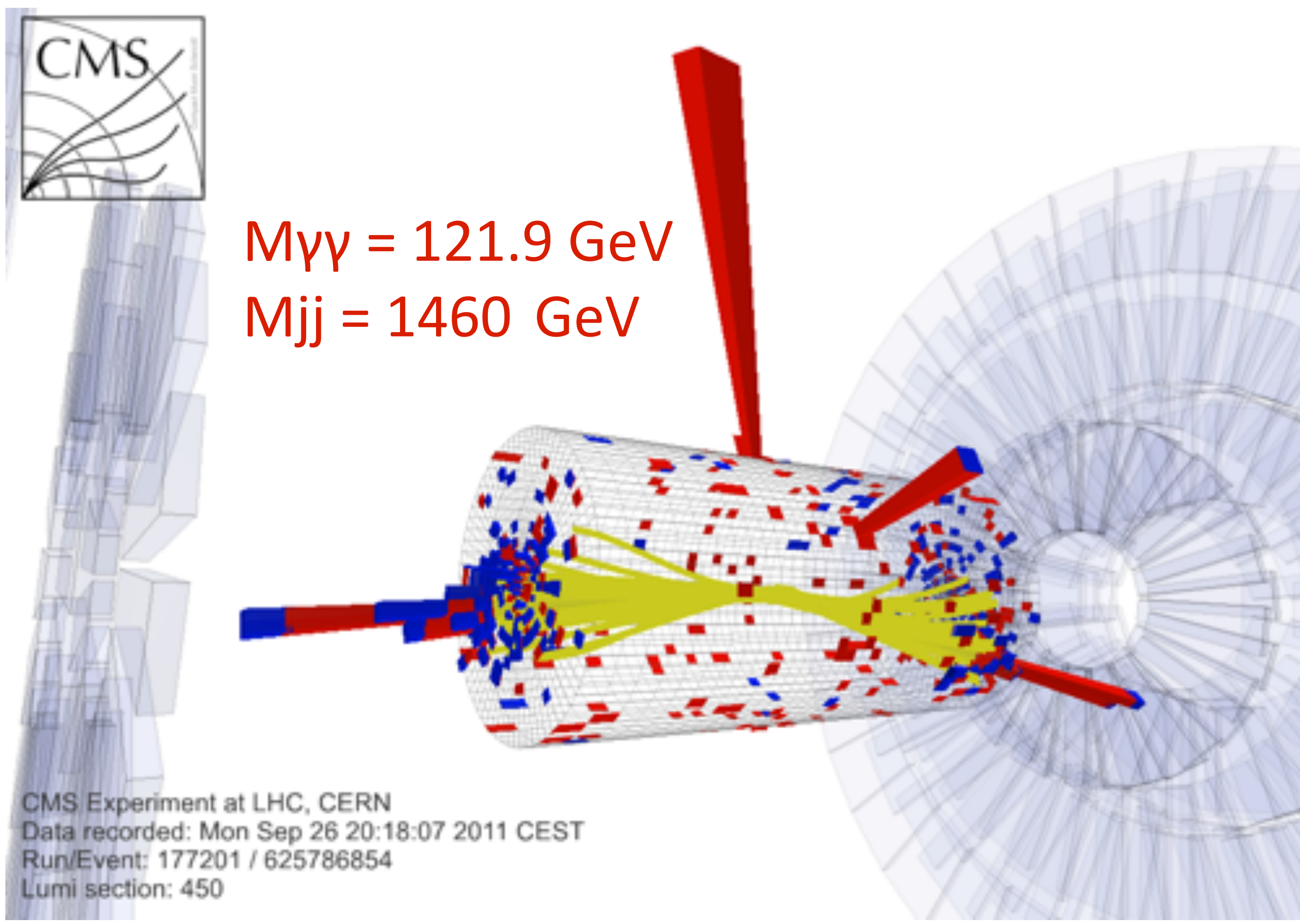
2/3 η regions	$\otimes$	2 categories with conversions	$\otimes$	2 $p_T(\gamma\gamma)$ categories (except for conversions in transition region)

DIJET TAGGED CATEGORY (CMS)

- **Dijet category** (CMS only) added to:
  - improve sensitivity to UL determination (about 10%)
  - isolate events produced by VBF mode

vector boson fusion

- **Dijet VBF selection** added on top of two photons identification
  - two high p_T jets: > 30 GeV (> 20 GeV) for leading (sub-leading) jet
  - $|\Delta\eta(\text{jets})| > 2.5$
  - m(dijet) > 350 GeV
- **Not 100% pure VBF category**
  - GluGlu contamination about 30%
  - contamination affected by large systematics
    - assigned a 70% uncertainty

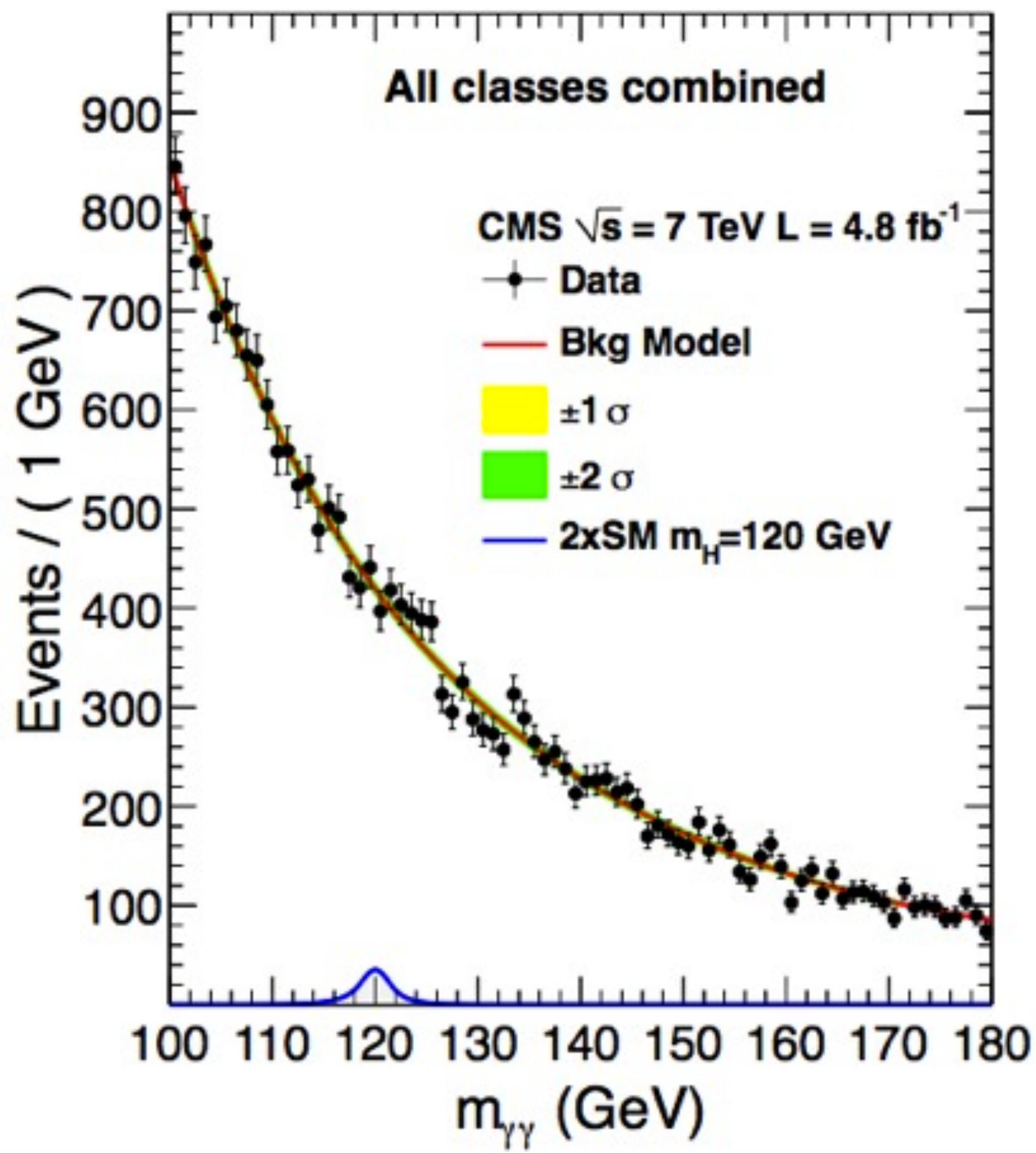


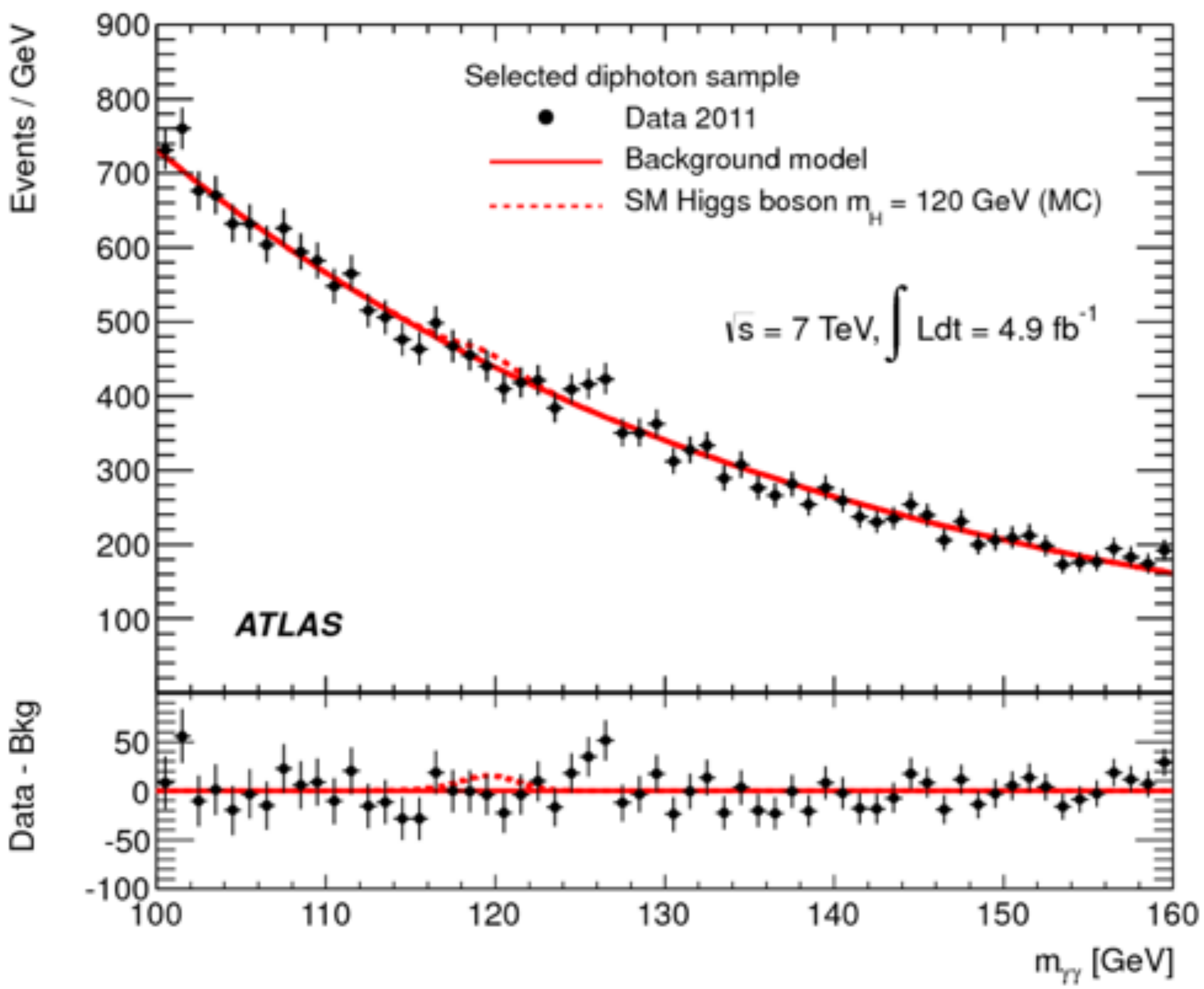
Signal Extraction

- **Signal shape from MC** after smearing obtained on data ($Z \rightarrow ee$)
  - **CMS**: sum of gaussians
  - **ATLAS**: crystal ball (gaussian with exp. tail)
- **Bkg is extracted from m(γγ) data distribution**
  - fitted with a smooth function
    - **CMS**: 5th order polynomial
    - **ATLAS**: exponential
  - background estimate from MC not used: just a cross-check for data-MC comparison
- **Limits on cross section** extracted with **modified frequentist approach (CLs)** using profile likelihood

$M_{\gamma\gamma}$ SPECTRUM

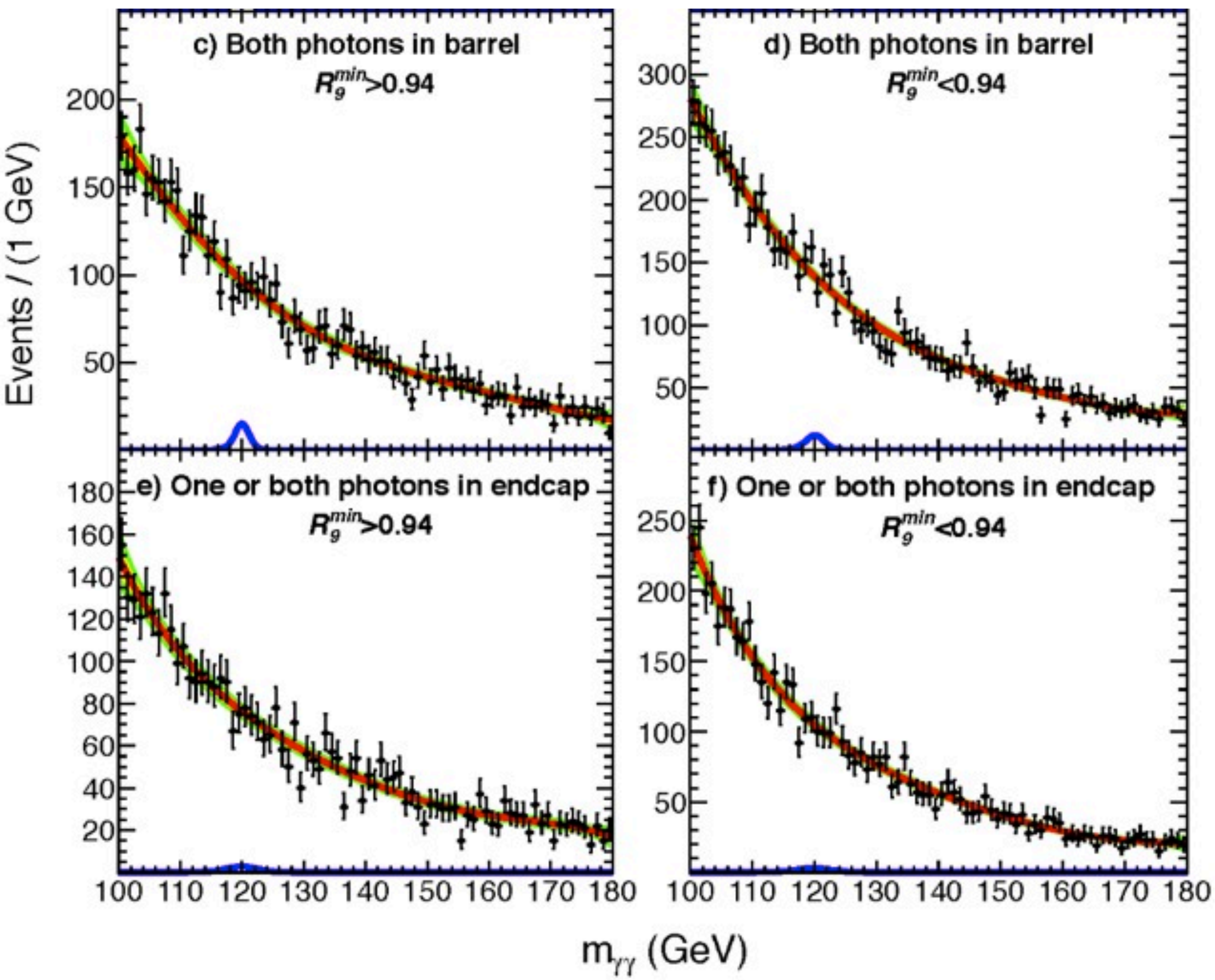
- **m(γγ) spectrum** (all categories added up)
- most relevant structure is excess at about 124-126GeV in both plots



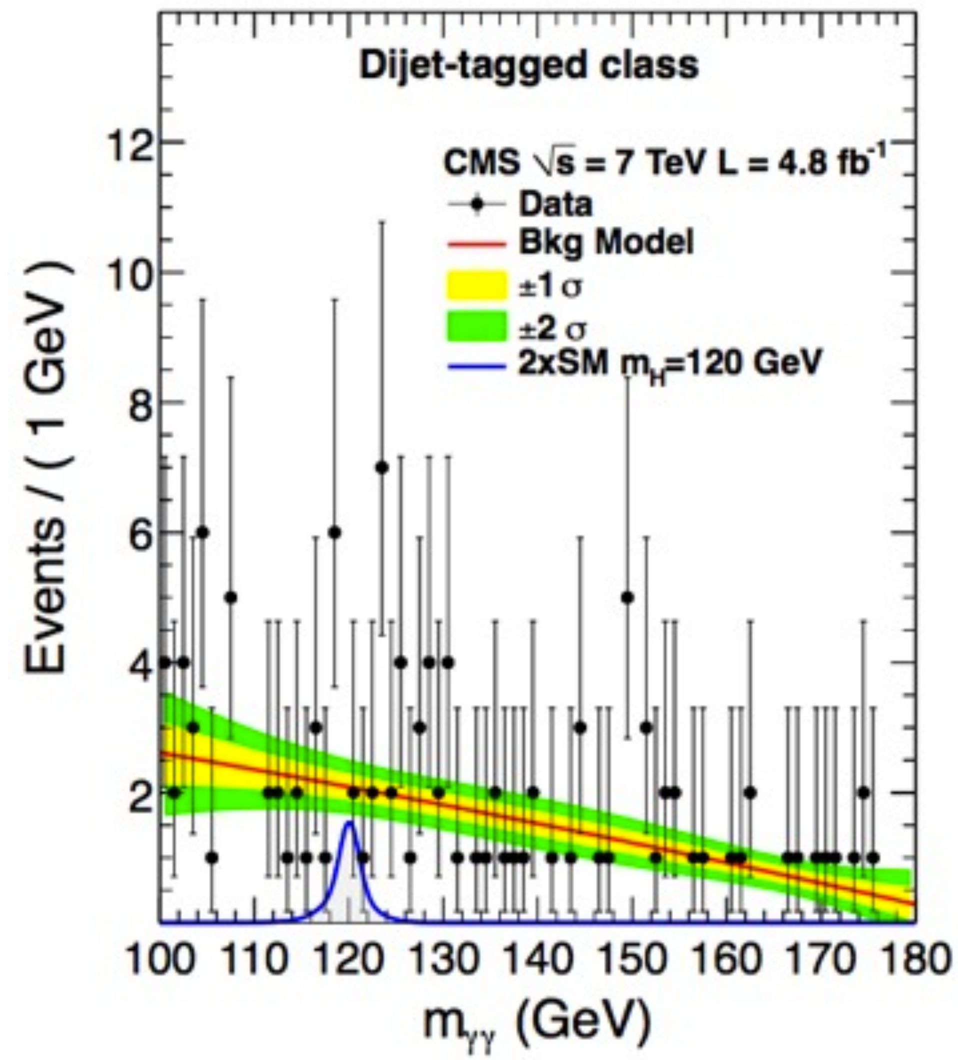


SPECTRUM IN CATEGORIES (CMS)

photon-based categories

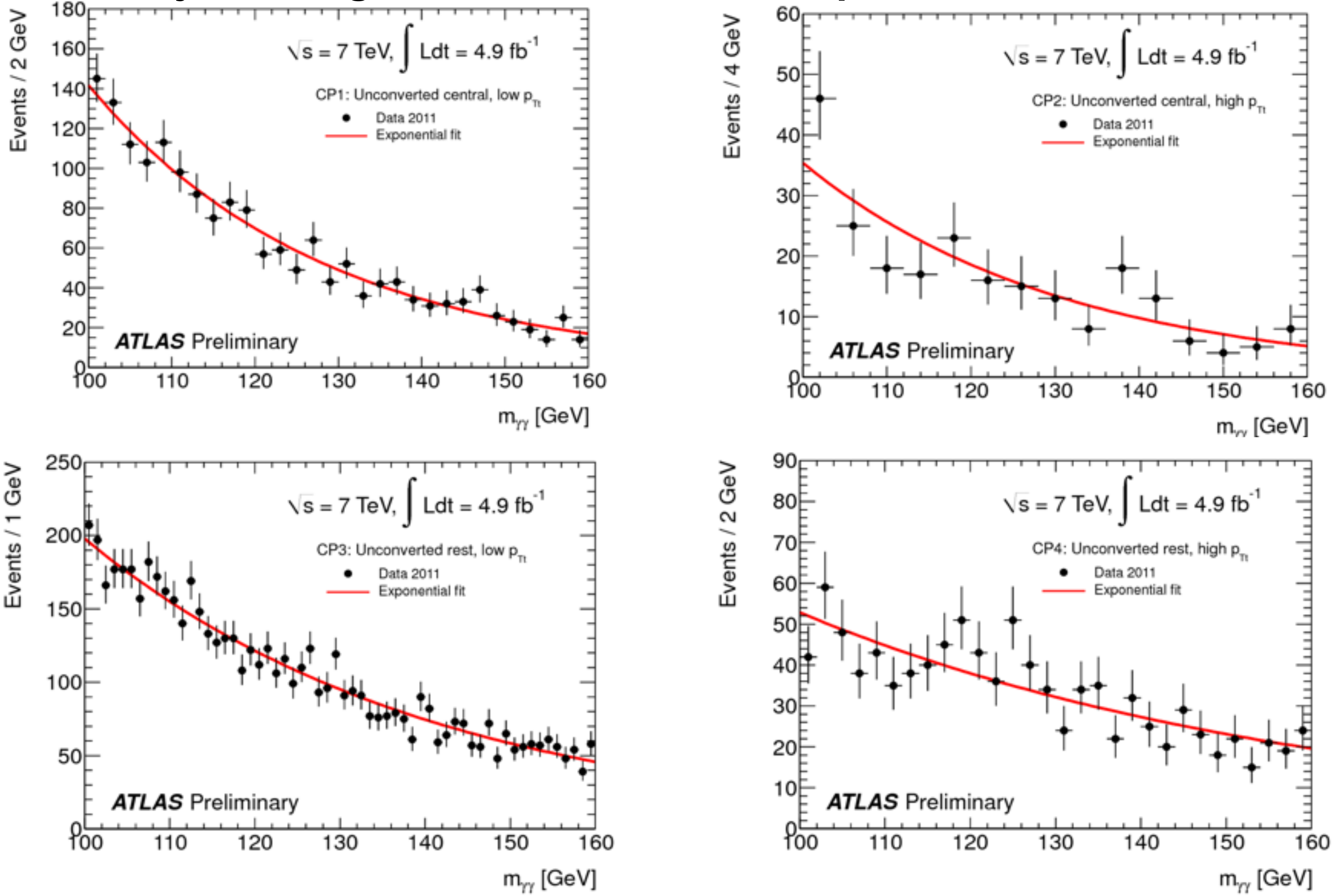


dijet category



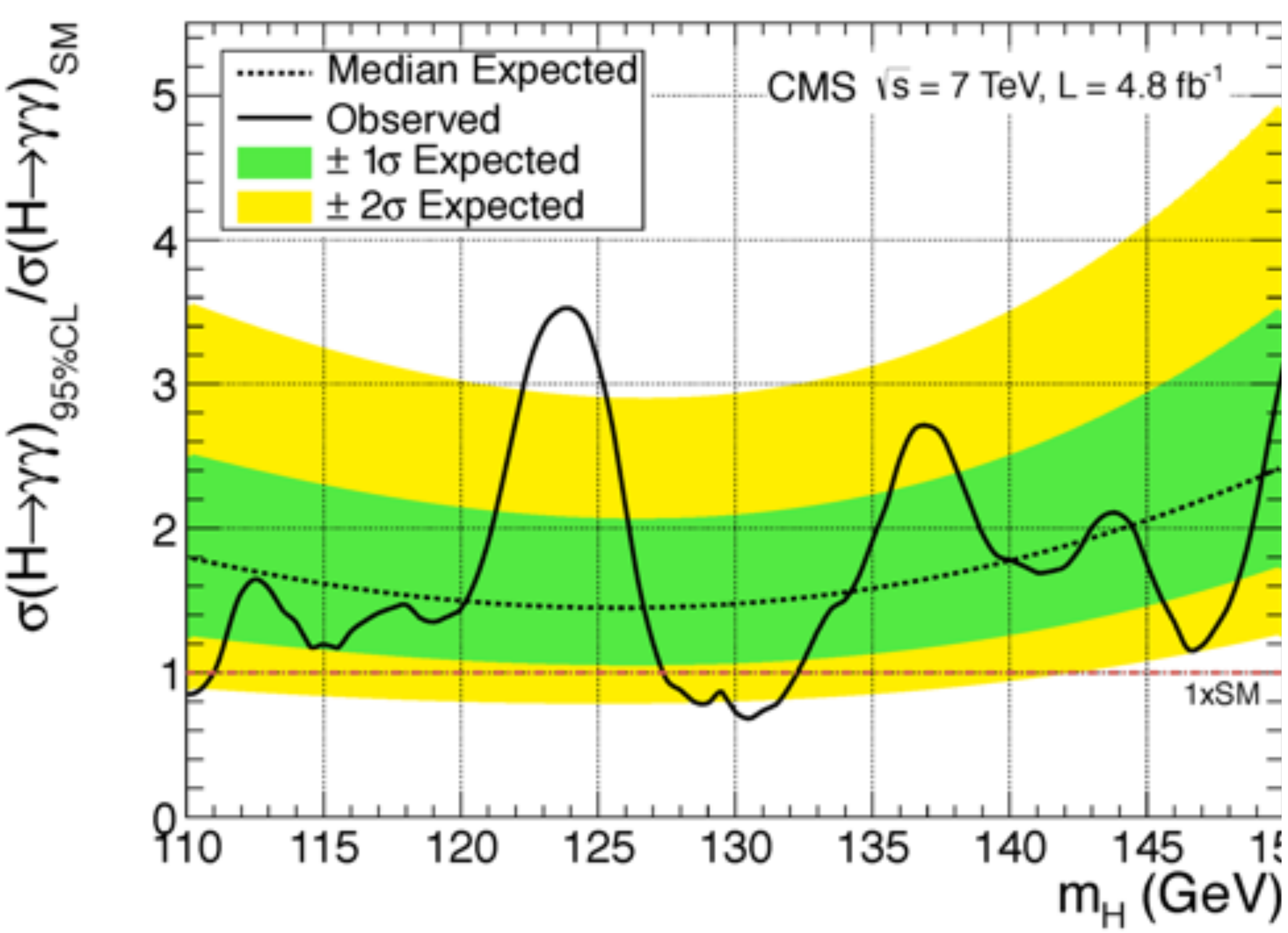
SPECTRUM IN CATEGORIES (ATLAS)

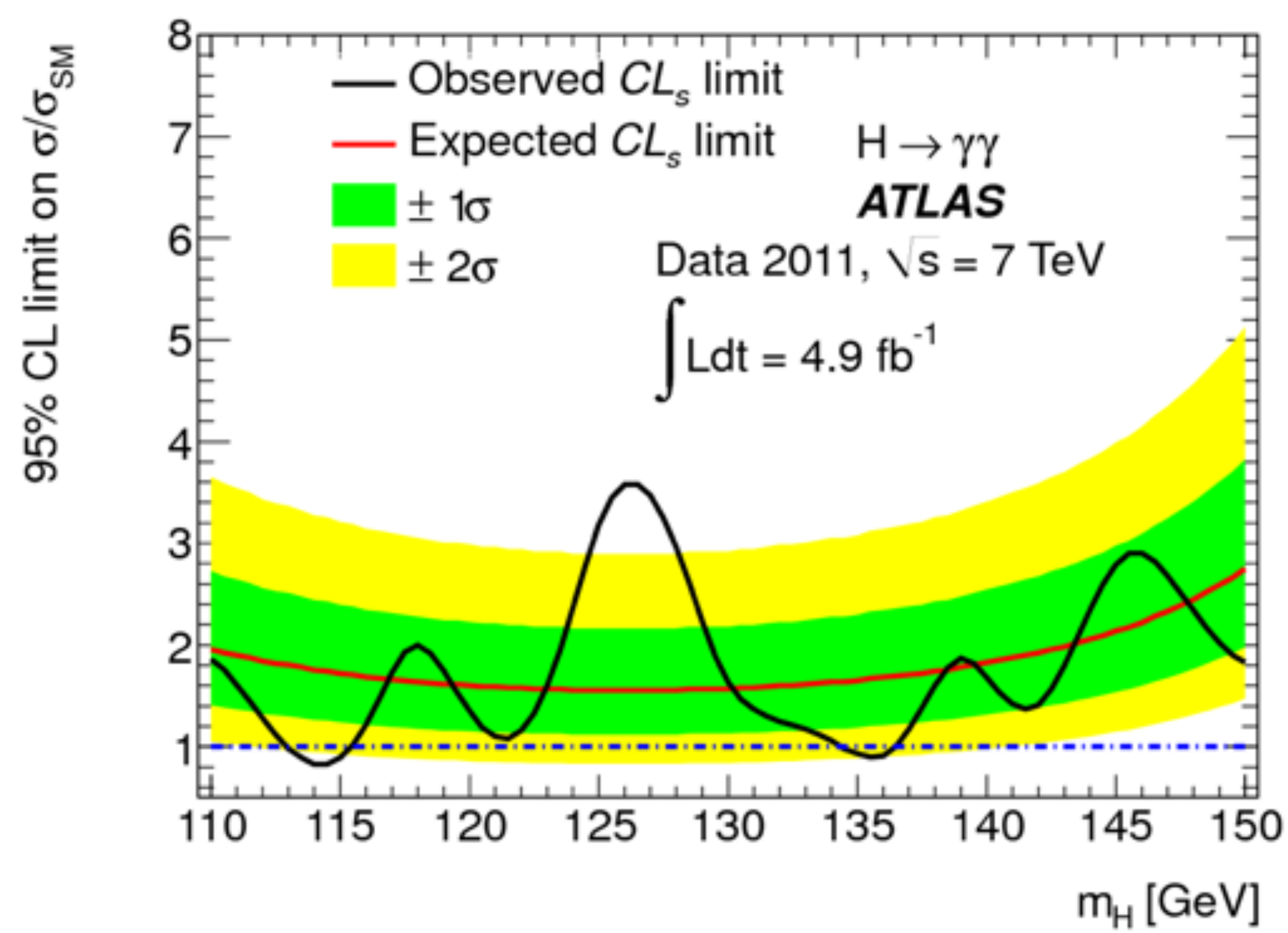
just categories with unconverted photons shown



UPPER LIMIT ON CROSS SECTION

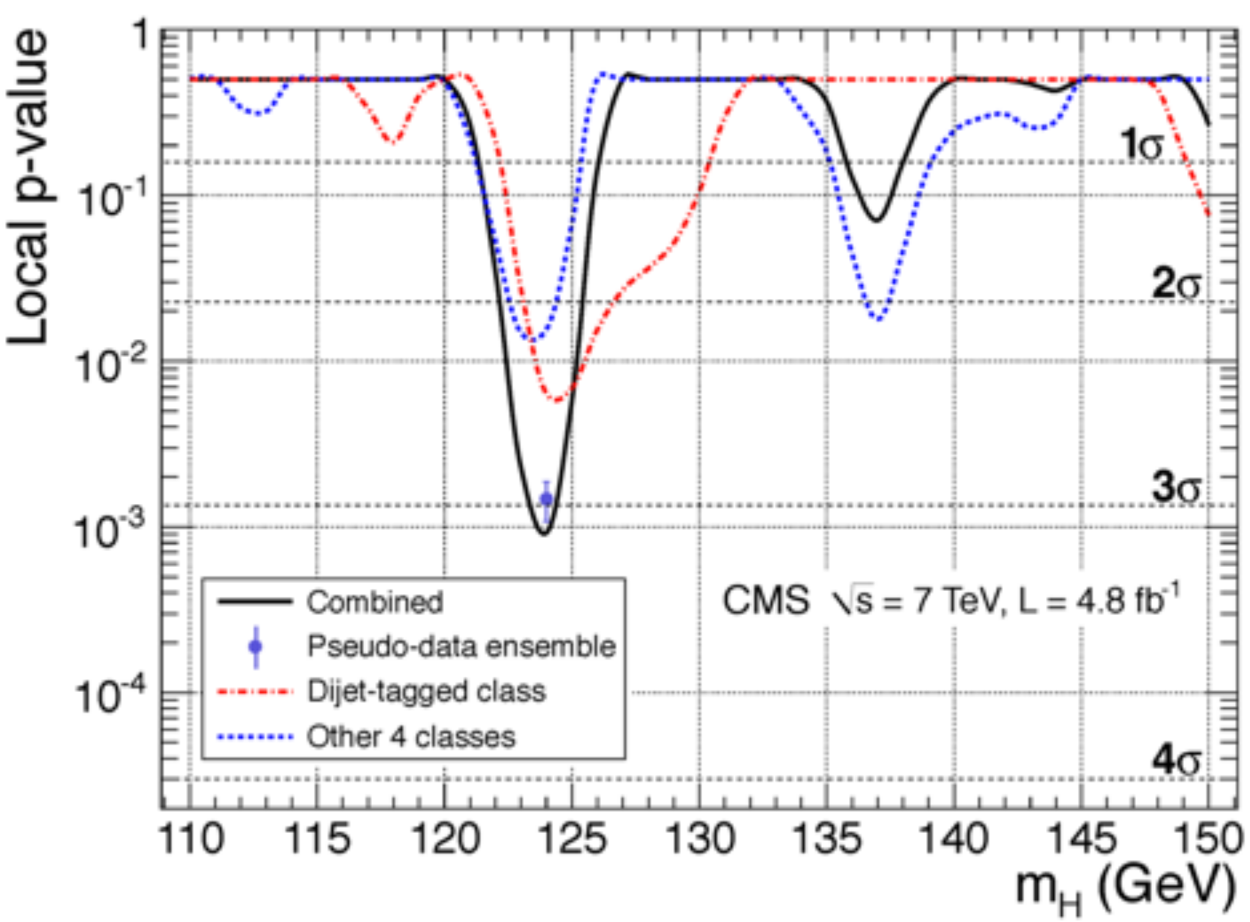
- **Expected exclusion at 120 GeV: CMS ~1.5xSM, ATLAS ~1.6xSM**
- **Observed exclusion**:
  - CMS: 128 GeV < m_H < 132 GeV
  - ATLAS: 113 GeV < m_H < 115 GeV, 134.5 GeV < m_H < 136 GeV
- **Excess at about 124-126 GeV seen in both experiments**

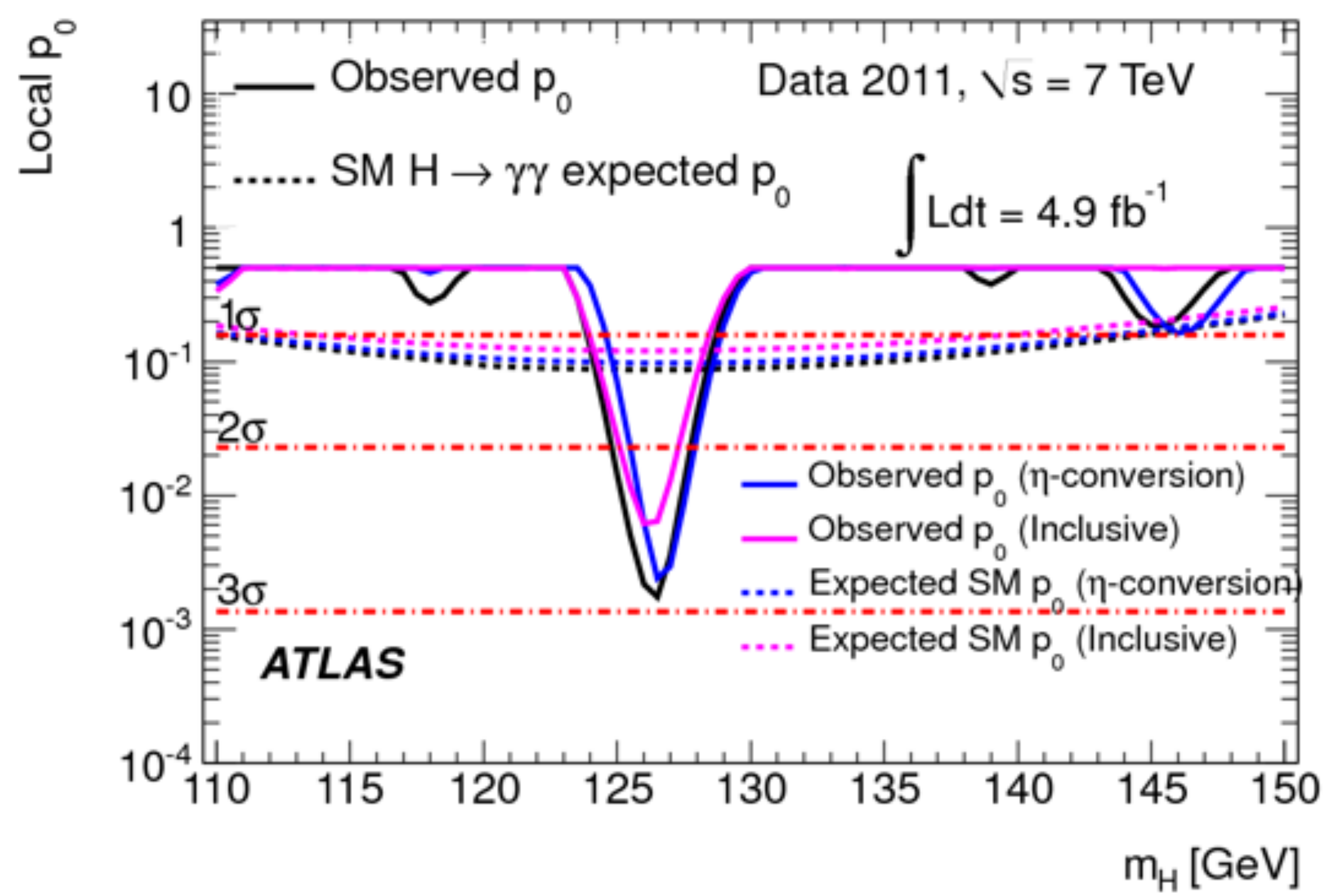




Significance of Excess (P-Values)

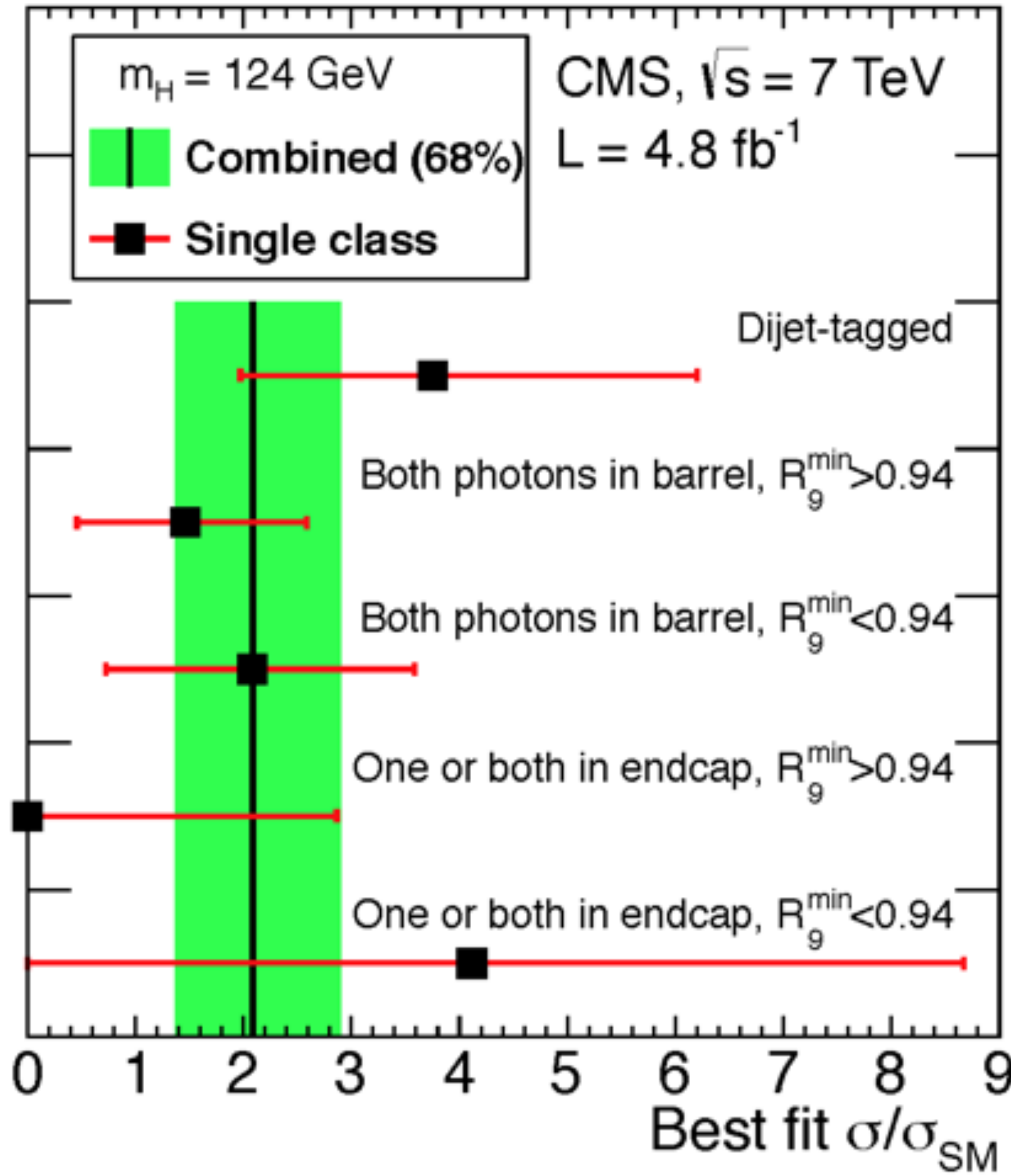
- **3σ local significance excess for both experiments**
- **Global** significance (including look-elsewhere-effect) is **about 2σ**
- **Position of maximum of significance is slightly different**
  - 124GeV for CMS, 126 GeV for ATLAS



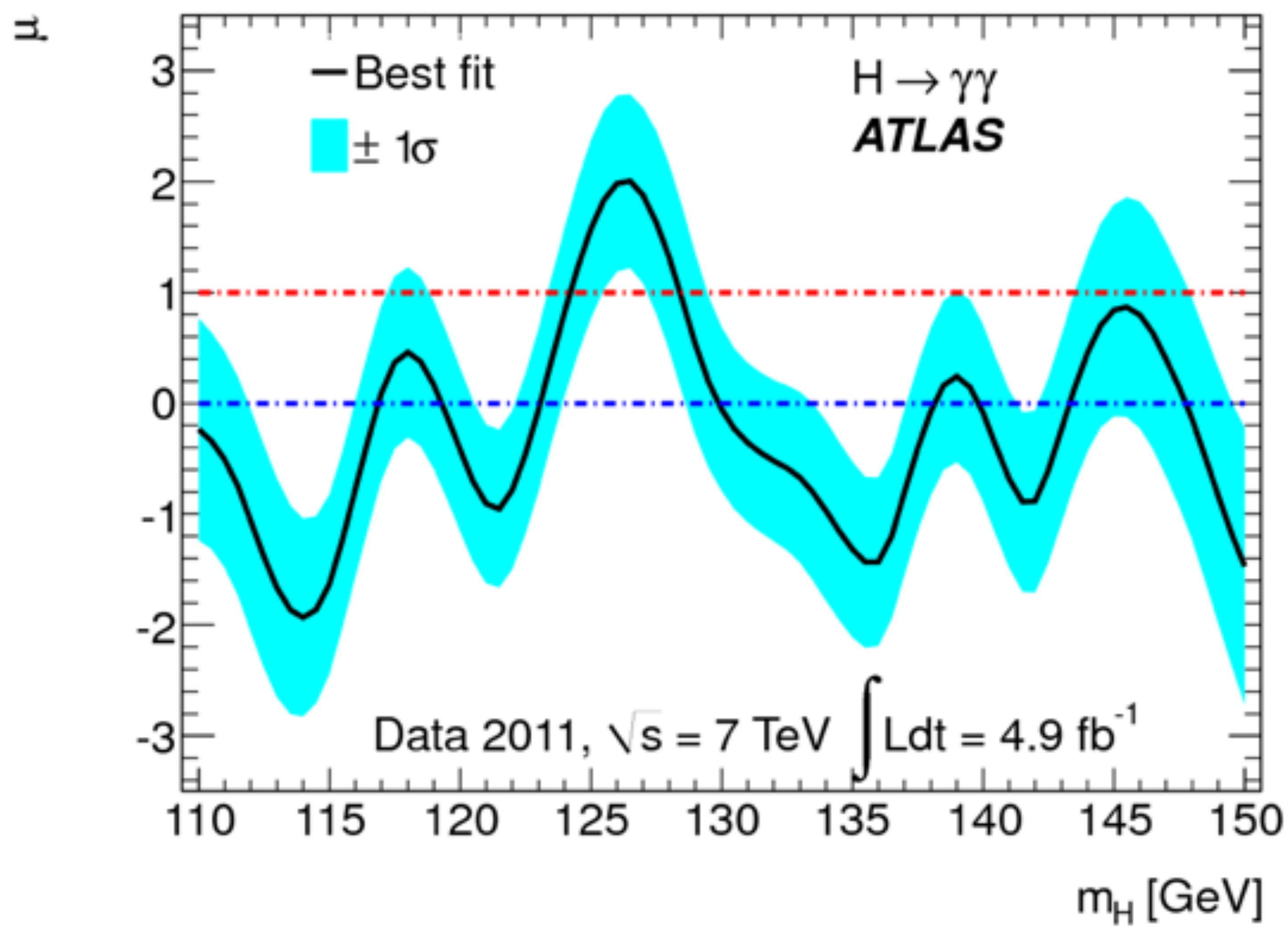


BEST FIT COMPARED TO SM

Preferred value by fit about x2 SM (with large uncertainty)



$\mu = \sigma_{MEAS}/\sigma_{SM}$

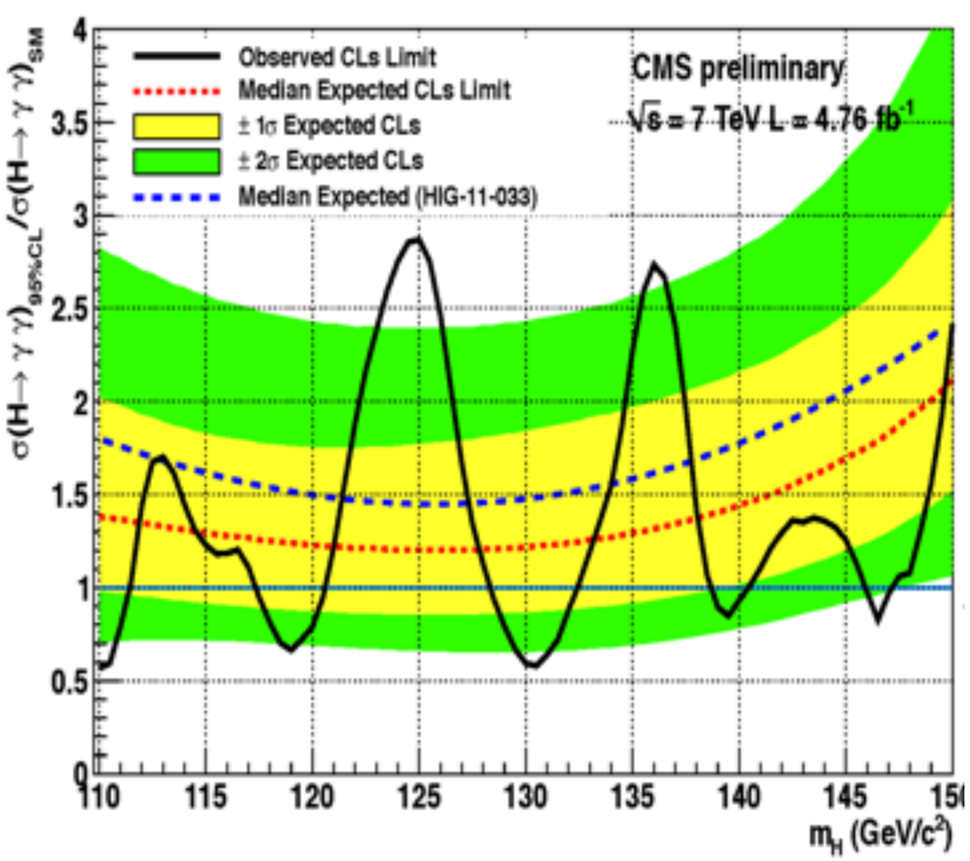


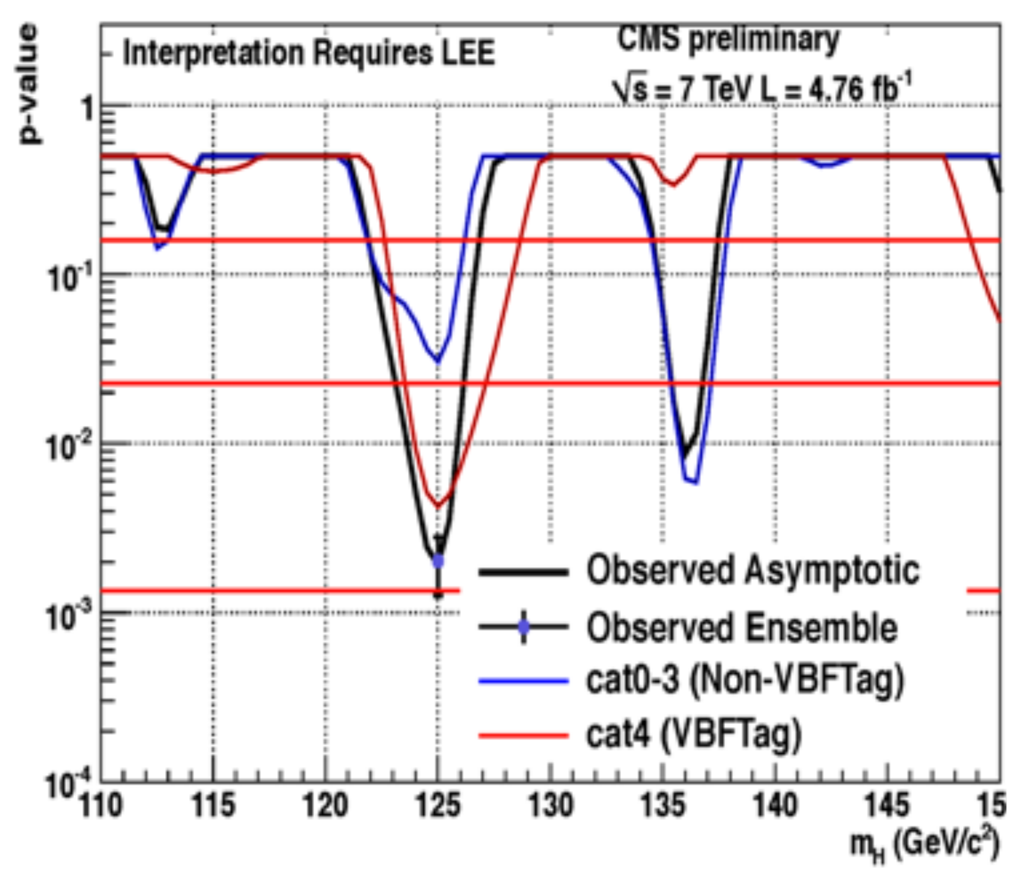
SYSTEMATICS

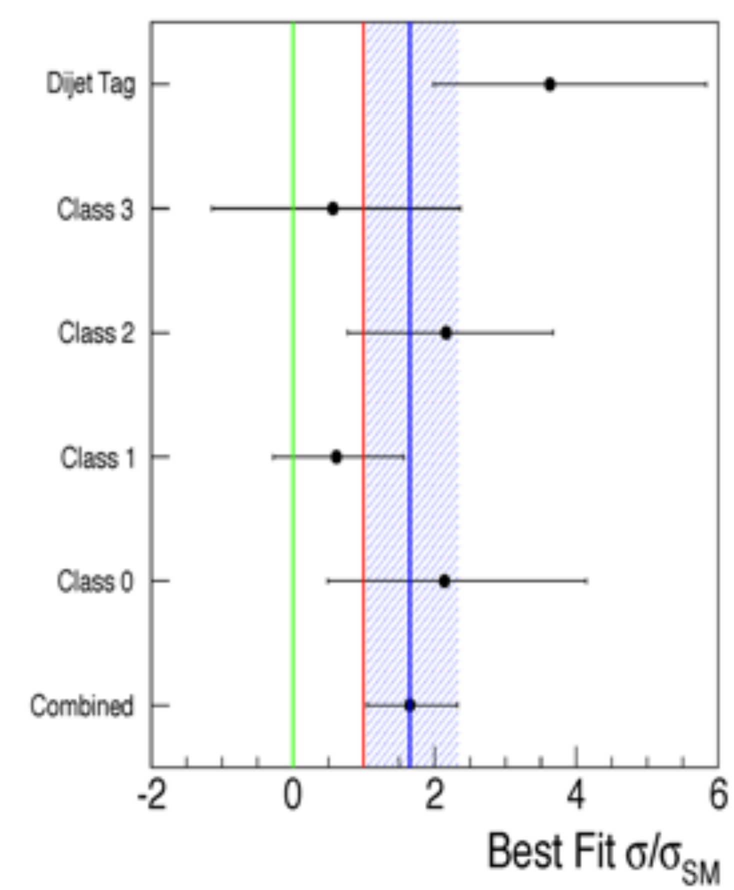
Source	CMS	ATLAS
	applicable to photons	
Photon identification efficiency	1.0% ÷ 2.6%	11%⊕5%(iso)⊕4%(PU)
Clus. shape	4.0% ÷ 6.5%	-
Energy resolution	0.2% ÷ 0.9% (on γ)	12% (on $m_{\gamma\gamma}$)
Energy scale	0.2% ÷ 0.9% (on γ)	-
Material	-	6%($e\to\gamma$) ⊕3%(PU)
	applicable to di-photons	
Integrated luminosity	4.5%	3.9%
Trigger efficiency	0.4%	1%
Vertex finding efficiency	0.4%	1%
pT>40GeV cut efficiency	-	8%
	cross sections and branching ratios	
Gluon-gluon cross section	+12.5%-8%(scale) ~7.8%(PDF)	
Other production modes (scale)	0.5%(VBF) 0.8%(WH) 1.6%(ZH)	
Other production modes (PDF)	2.5%(VBF) 4.2%(WH) 8.5%(ZH)	
	dijet category	
VBF (Gluglu) contribution	10%(70%)	-

Optimized CMS Analysis (Multivariate)

- **New analysis presented by CMS at Moriond**
  - **multivariate approach** for selecting photons and di-photon events
- Expected **limit improved by 20%** (1.2*SM at 120GeV)
  - equivalent to 50% more statistics
- **Similar structure in UL.** Excess slightly moved up (now at ~125GeV)



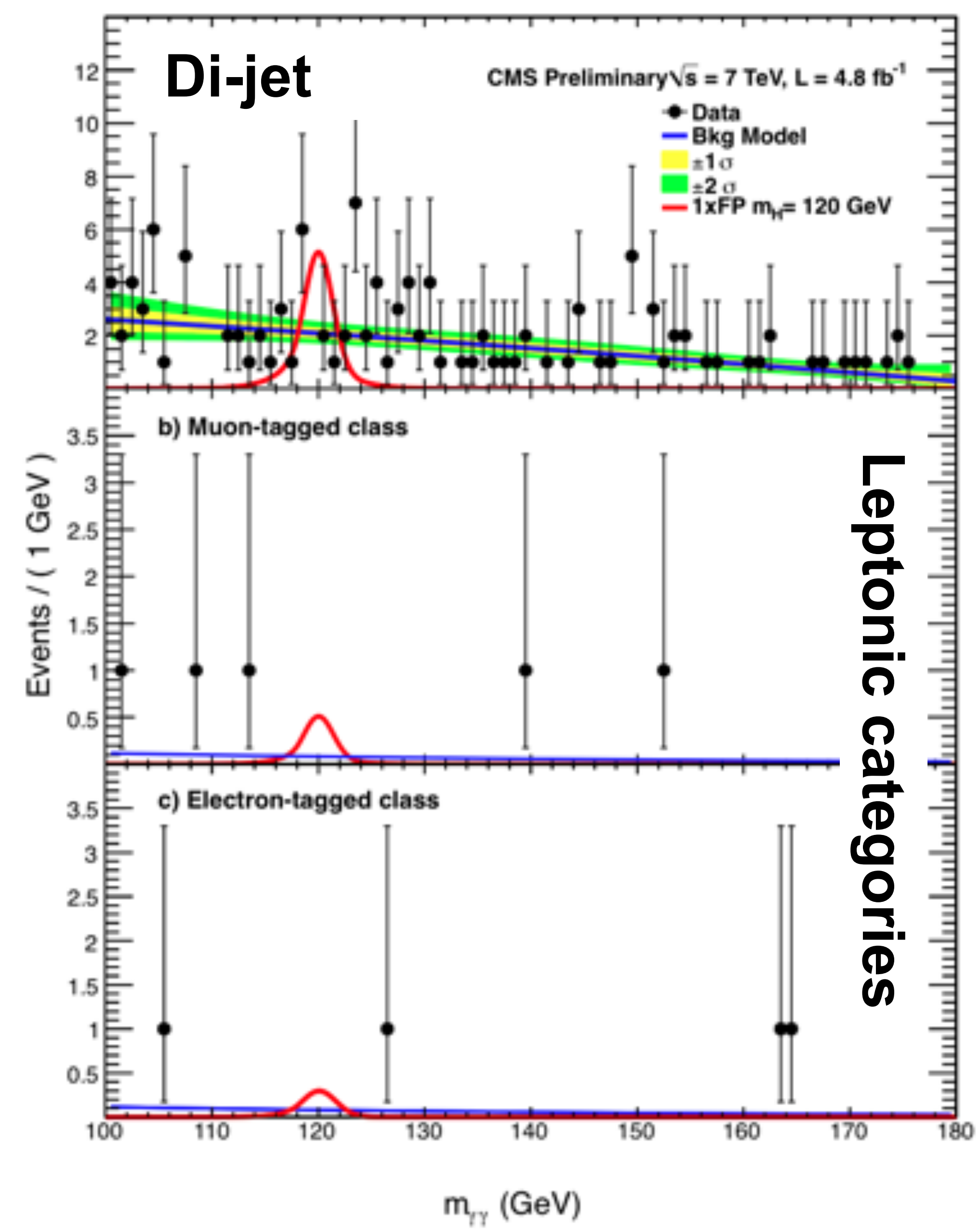




Fermiophobic Interpretation

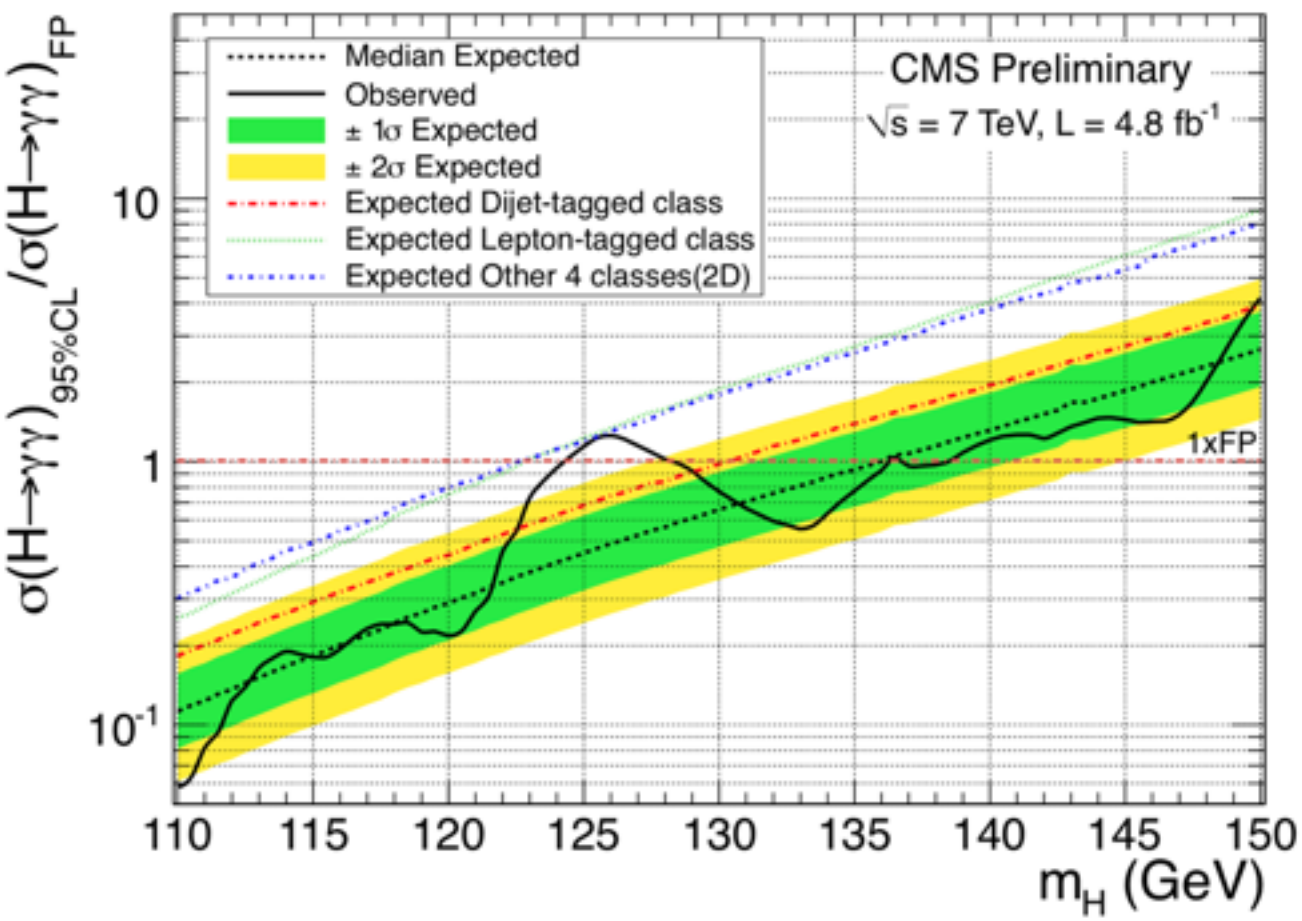
- $H \to \gamma\gamma$ analysis can be **interpreted in scenarios different from SM**
- **Fermiophobic (FP) scenario**
  - Higgs does not couple to fermions
  - only VBF and VH production modes allowed
  - BR($H \to \gamma\gamma$) highly enhanced (~10*SM at 120GeV)
  - Higgs is more boosted (harder p_T spectrum)
- **ATLAS**: sensitive to FP thanks to p_T categories
- **CMS**: dedicated analysis
  - 2D fit: m(γγ) and π_T ($\pi_T = p_T\gamma\gamma/m\gamma\gamma$)
  - additional exclusive categories (dijet tagged for VBF and leptonic for associated prod.)

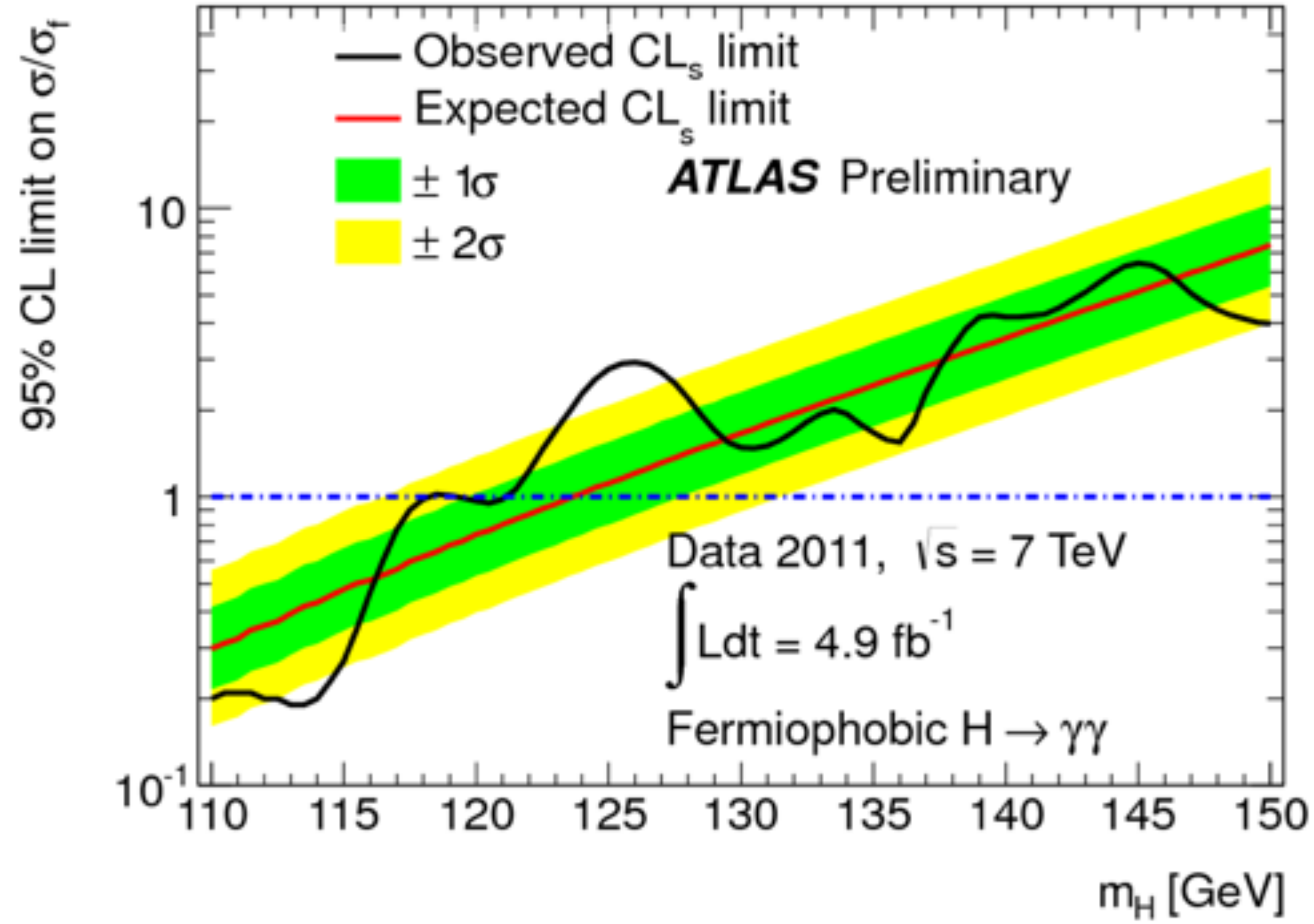
CMS exclusive categories



FERMIOPHOBIC: RESULTS

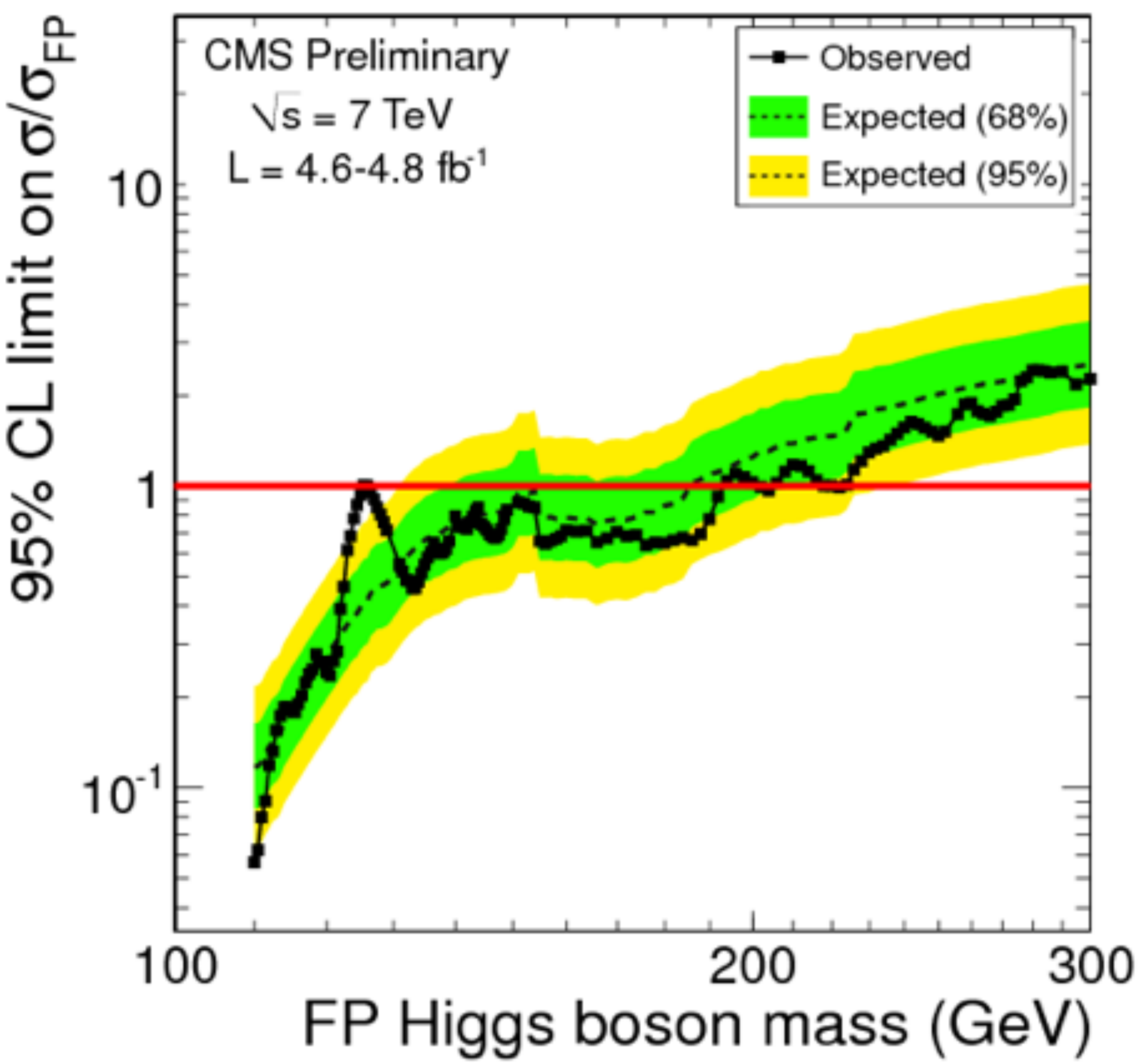
- **FP Higgs hypothesis** (with the SM couplings to vector bosons) **not favored**
  - difference in sensitivity comes mainly from addition of exclusive modes by CMS

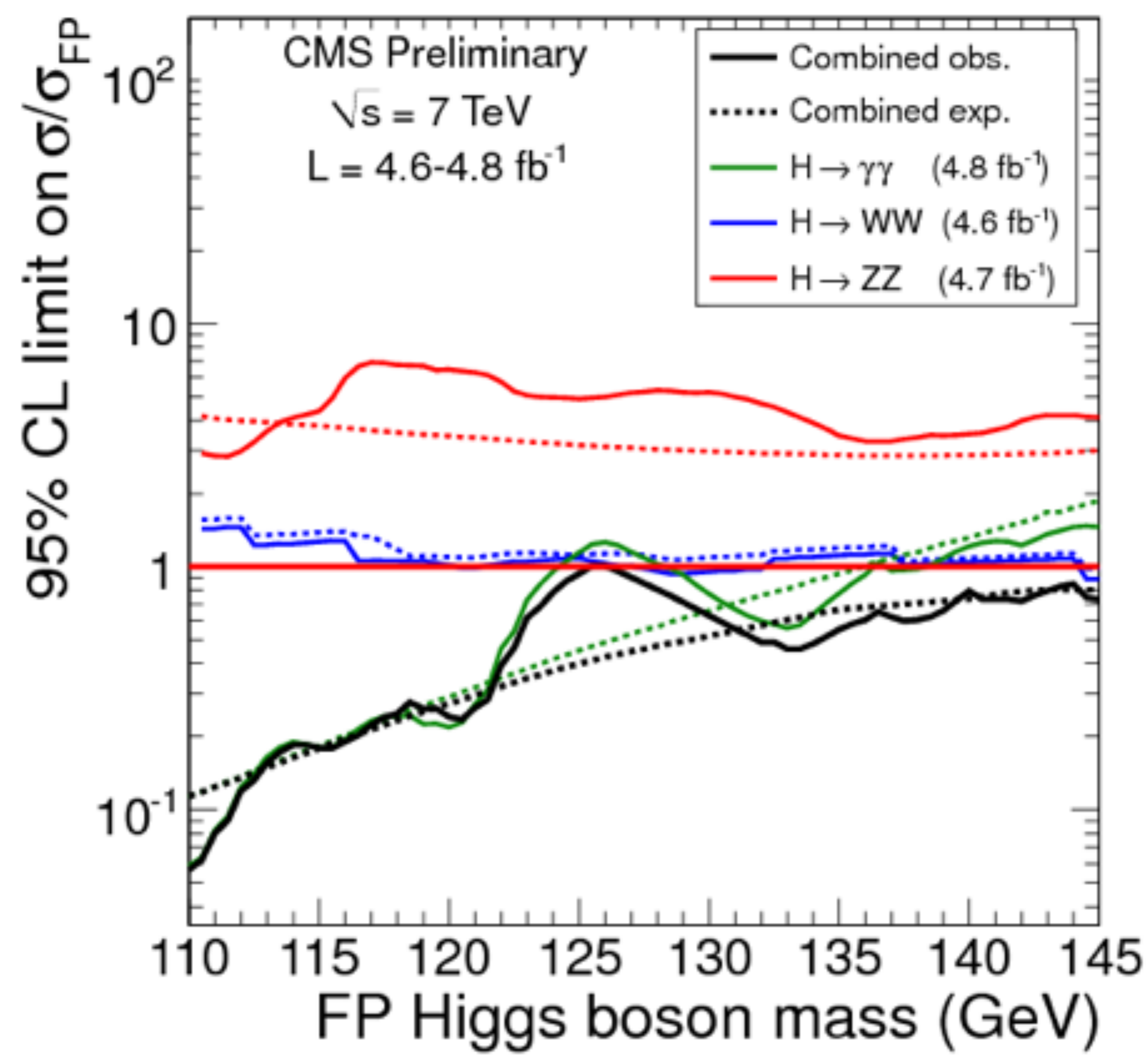




Fermiophobic: CMS Combination

- **Combination of different Higgs modes in FP scenario by CMS**
  - **FP hypothesis** (with the SM couplings to vector bosons) **excluded up 190 GeV**





CONCLUSIONS

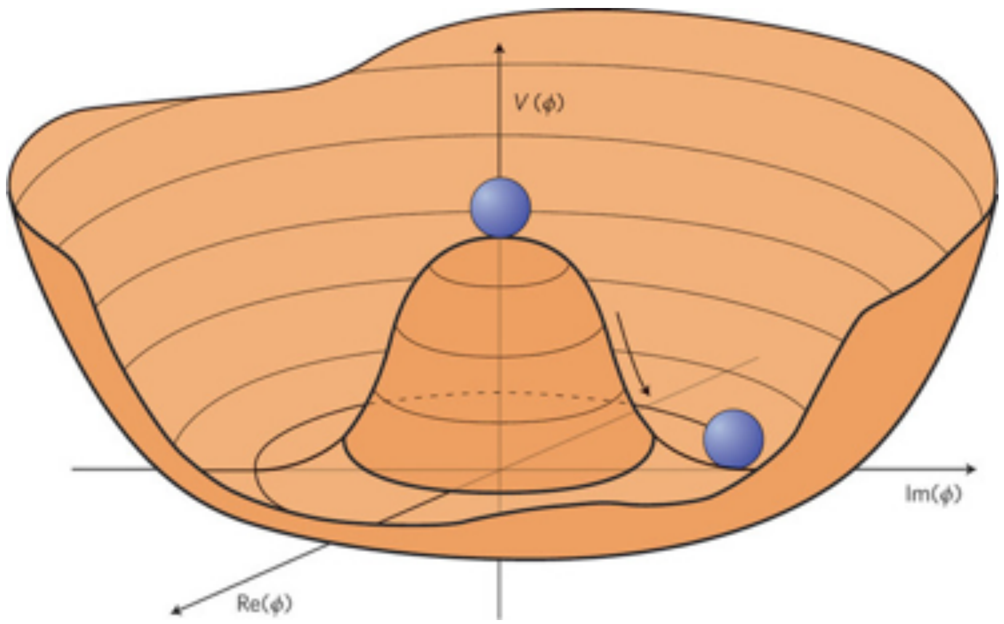
- **H→γγ search** performed **with ~5 fb^{-1} in both ATLAS and CMS**
- **Exclusion limits (@95% CL)**
  - **sensitivity** close to **SM cross section in range 110GeV<mH<150GeV**
  - **observed exclusions:** CMS: 128GeV<m_H<132GeV and ATLAS: 113GeV<m_H<115GeV, 134.5GeV<m_H<136GeV
- **Excess at 124-126 GeV:**
  - ~3σ (local) ~2σ (global) significant in both experiment
- **More data** needed to confirm excess and **ascertain its origin**
  - **Summer** (+5fb^{-1} @ 8TeV) maybe enough
  - **End of 2012** (+10÷15fb^{-1} @ 8TeV) very likely enough
- **Started excluding alternative scenarios** (e.g. Fermiophobic)

BACKUP

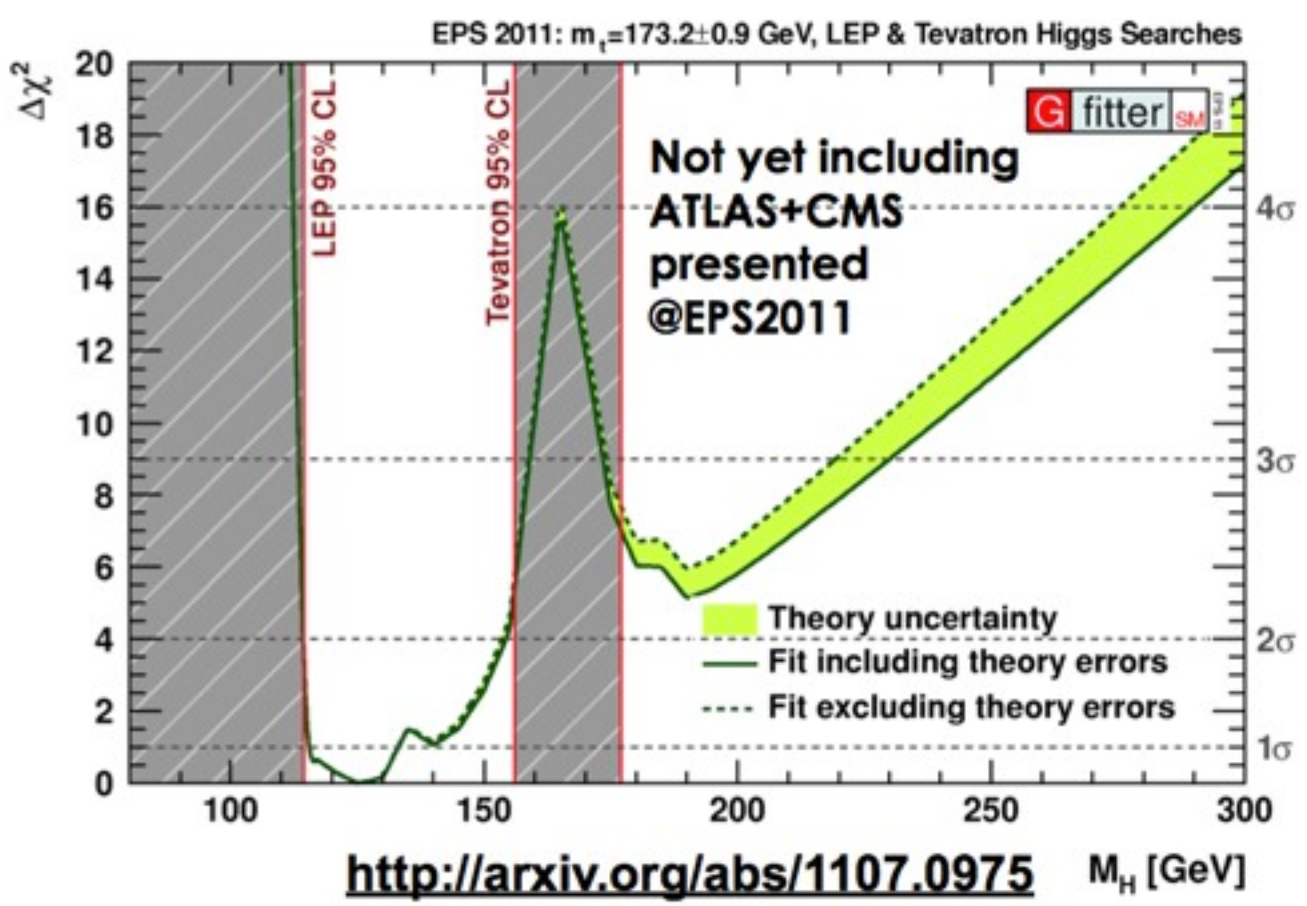
HUNTING THE HIGGS

- in SM **electroweak symmetry broken via the Higgs mechanism**

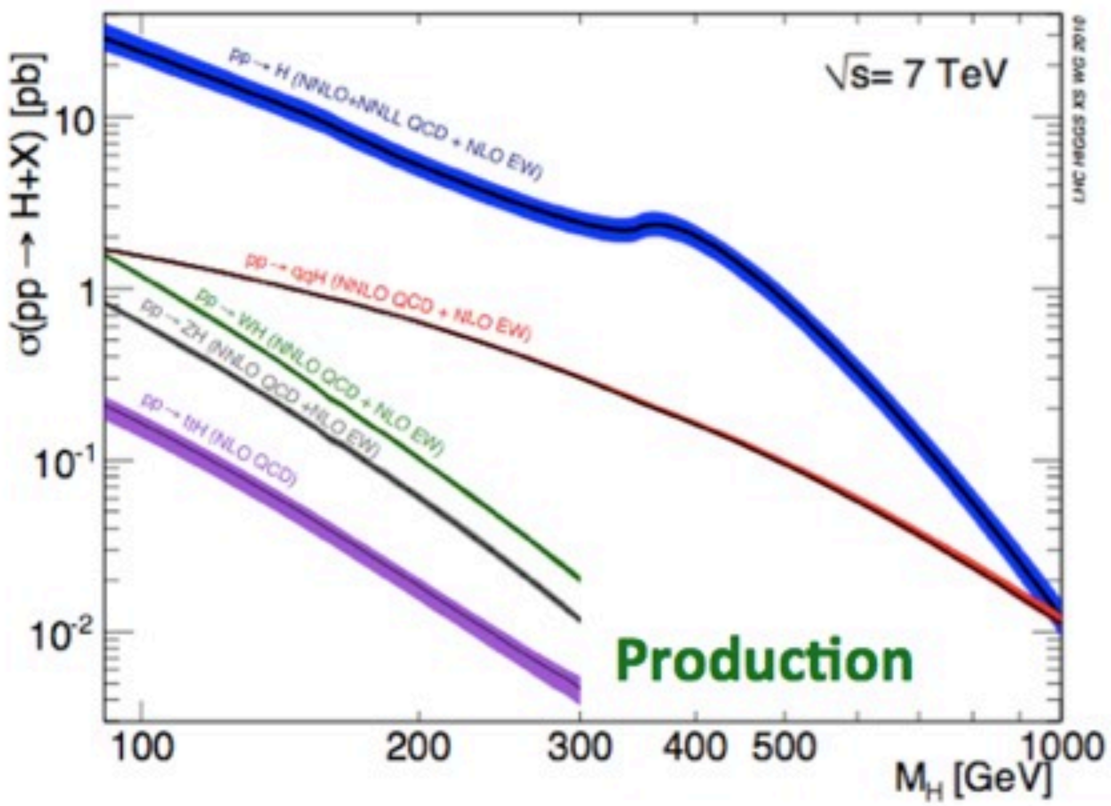
$$V(|\phi|) = \mu|\phi|^2 + \lambda|\phi|^4$$

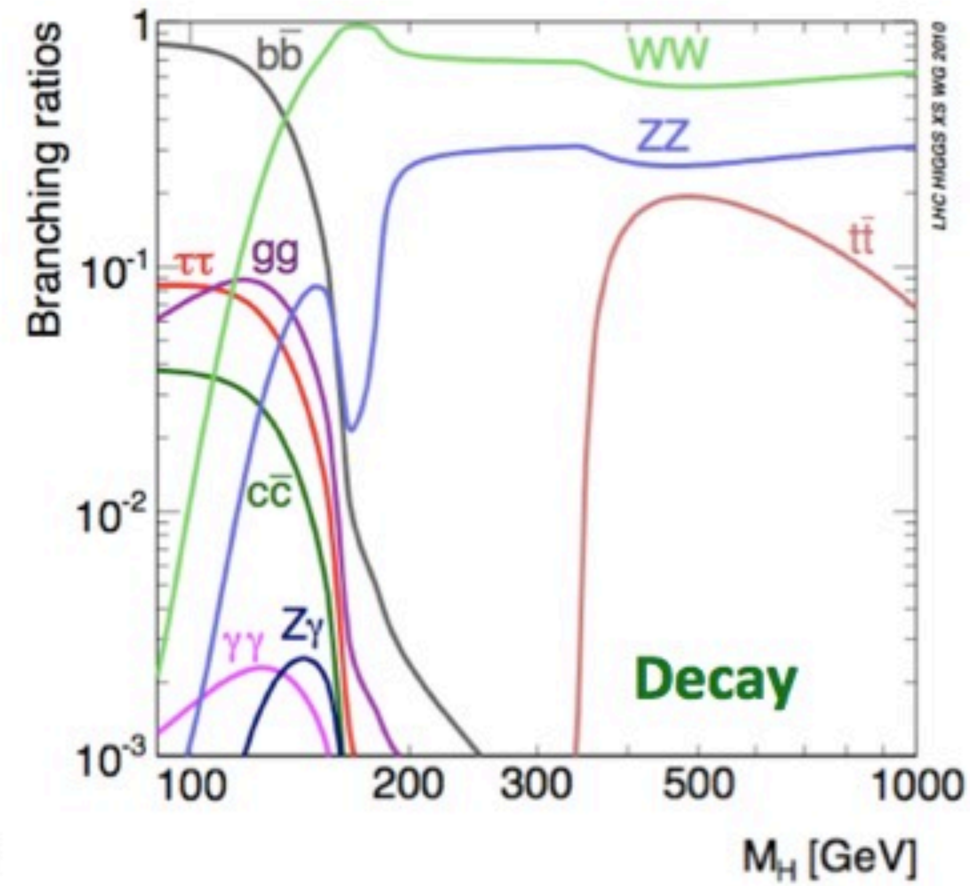


- **W and Z bosons acquire mass, photon** remains **massless**
- **Higgs not yet seen**
- **limits** for the Higgs bosons from **direct searches and global EW fits**

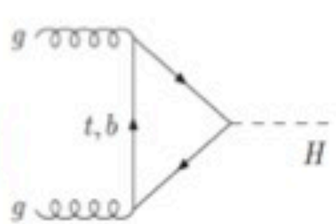


HIGGS CROSS SECTION AND BR

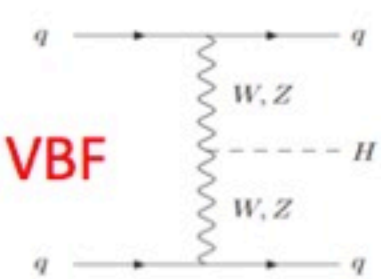




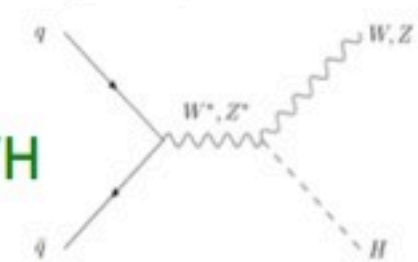
ggH



VBF



VH



Cross sections and BR
from the LHC cross section working group:

Photon-based Categories

- **Event categories** to
  - maximize statistical power
  - exploit differences in kinematics between signal and backgrounds
  - identify regions of the detector with very different performance
- **CMS: 4 photon-based categories**

2 η categories

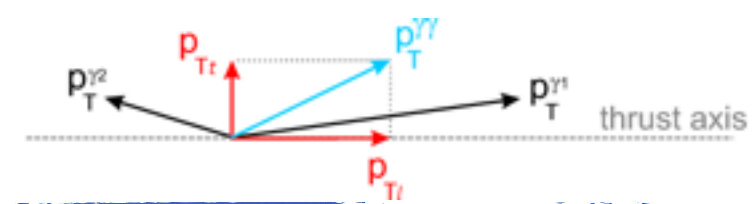
(1)1γ,2γ in barrel
(2) remainder

⊗

2 cluster shape categories

(1) R9(1γ,2γ)>0.94
(2) remainder

- **ATLAS: 9 photon-based categories**



2/3 η categories

(1) 1γ,2γ |η|<0.75
(2) 1γ in 1.3<|η|<1.75 (only converted)
(3) remainder

⊗

2 categories with conversions

(1) at least 1γ converted
(2) remainder

⊗

2 p_T categories

(except for conversions in transition region)

(1) $p_{Tt}(\gamma\gamma)$<40GeV
(2) $p_{Tt}(\gamma\gamma)$>40GeV

VERTEX ID: VARIABLES

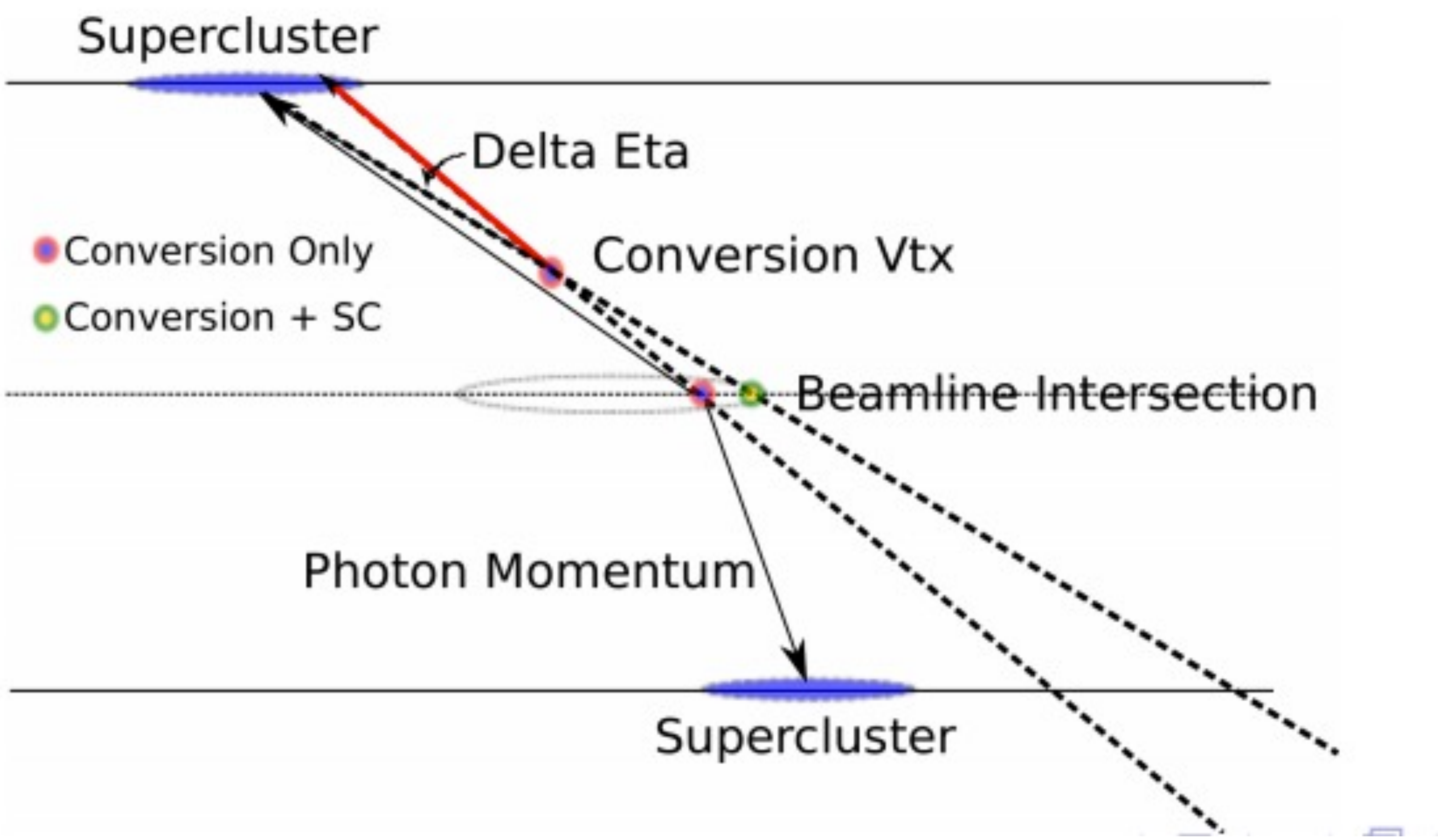
- **Sum p_T^2 =** $\sum_{tracks} p_T^2$

- **p_T^{asym} =** $\left(\sum_{tracks} p_T - p_T^{\gamma\gamma}\right) / \left(\sum_{tracks} p_T + p_T^{\gamma\gamma}\right)$

- **p_T^{bal} =** $-\sum_{tracks} \left(\overline{p}_T^{track} \cdot \frac{\overline{p}_T^{\gamma\gamma}}{\left|\overline{p}_T^{\gamma\gamma}\right|} \right)$

VERTEX ID: CONVERSIONS

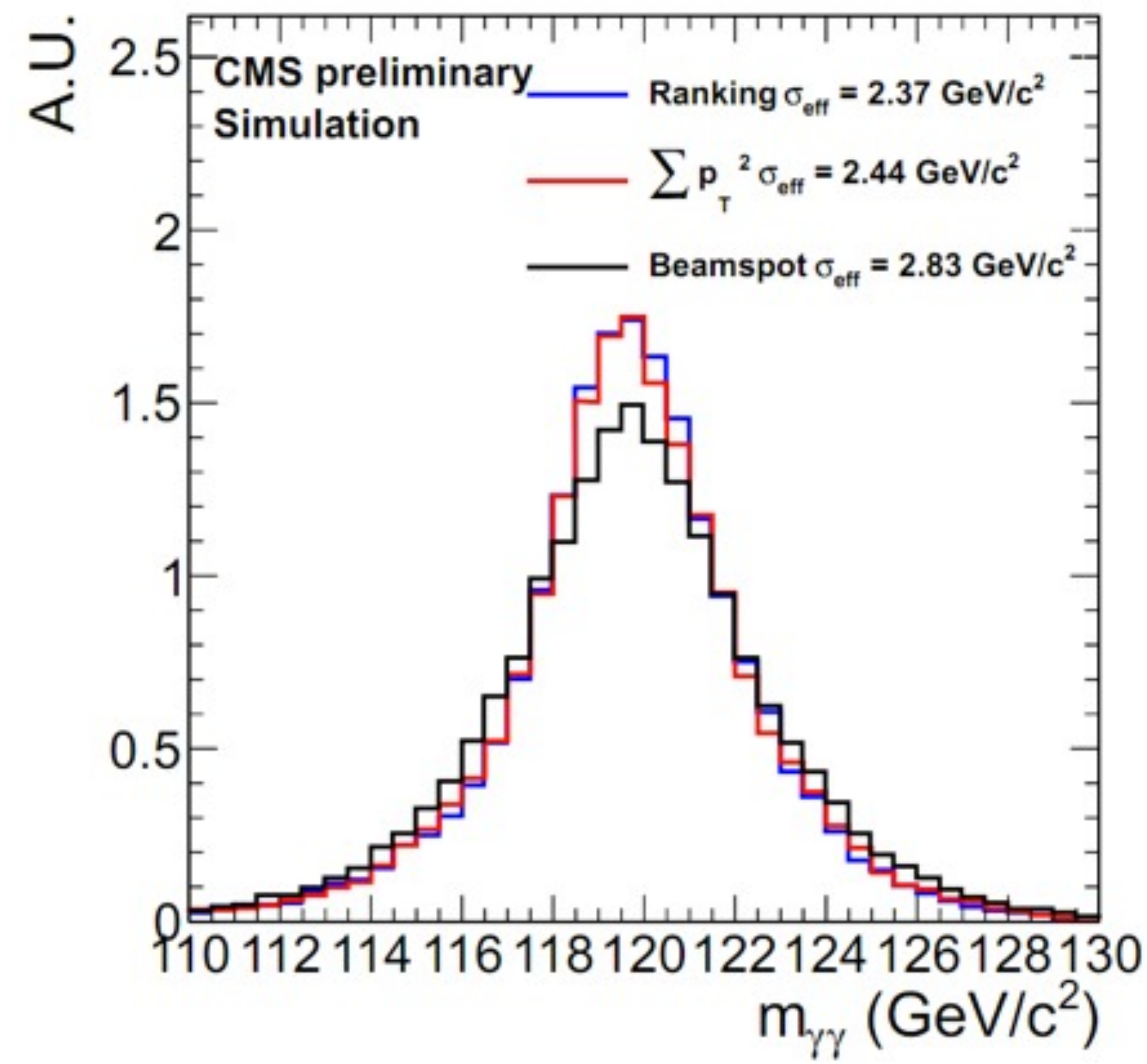
- about **40% of photons converts** in Tracker Volume
- measure photon direction using c**onversion vertex position and cluster barycenter**



VERTEX ID: PERFORMANCE

Overall performance integrated over Higgs P_T spectrum (from data):

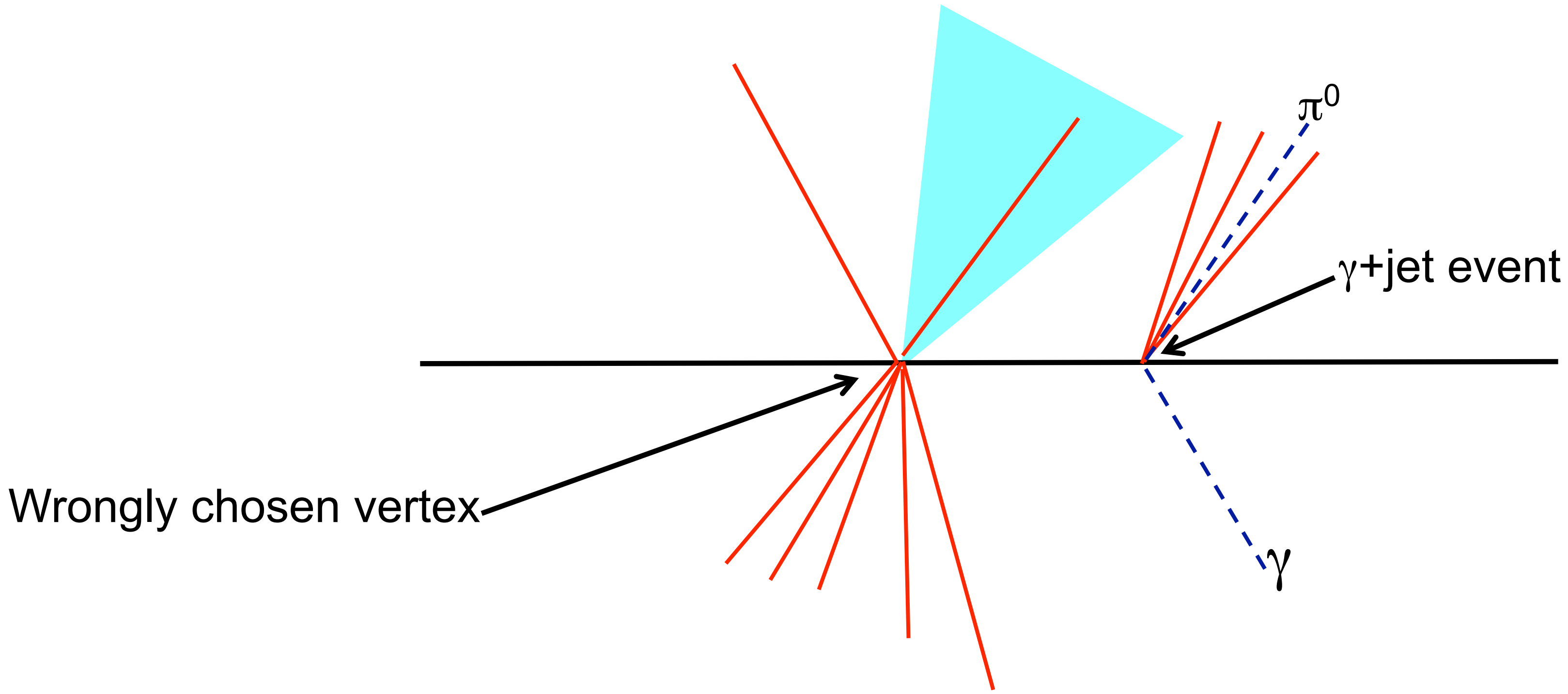
$$83.1\% \pm 0.2\%(\text{stat}) \pm 0.5\%(\text{syst})$$



Photon Isolation And PU

Multiple interactions pose additional challenges in this area:

- **additional energy in isolation cones (ECAL and HCAL)**
  - addressed using **FastJet** ρ subtraction
- **for track isolation cut on Δz to reject PU tracks**, but need to protect against incorrect vertex assignment
  - additional cut on track isolation computed wrt vertex giving highest track isolation sum for a given photon



Background Normalization

- **DiPhoton bkg** divided in different categories defined by experimental origin: **k-factors** derived x category as product of (K_{NLO}/K_{LO})* (K_{DATA}/K_{NLO})

  prompt-prompt 1.3±0.2 CMS QCD-10-035
  prompt-fake 1.3±0.25 CMS gamma-jet QCD-10-037
  fake-fake 1±0.5
  DY: CMS measurements in EWK-10-005

SETTING LIMITS

- CL_s Frequentist method is used with “LHC-type” test statistics

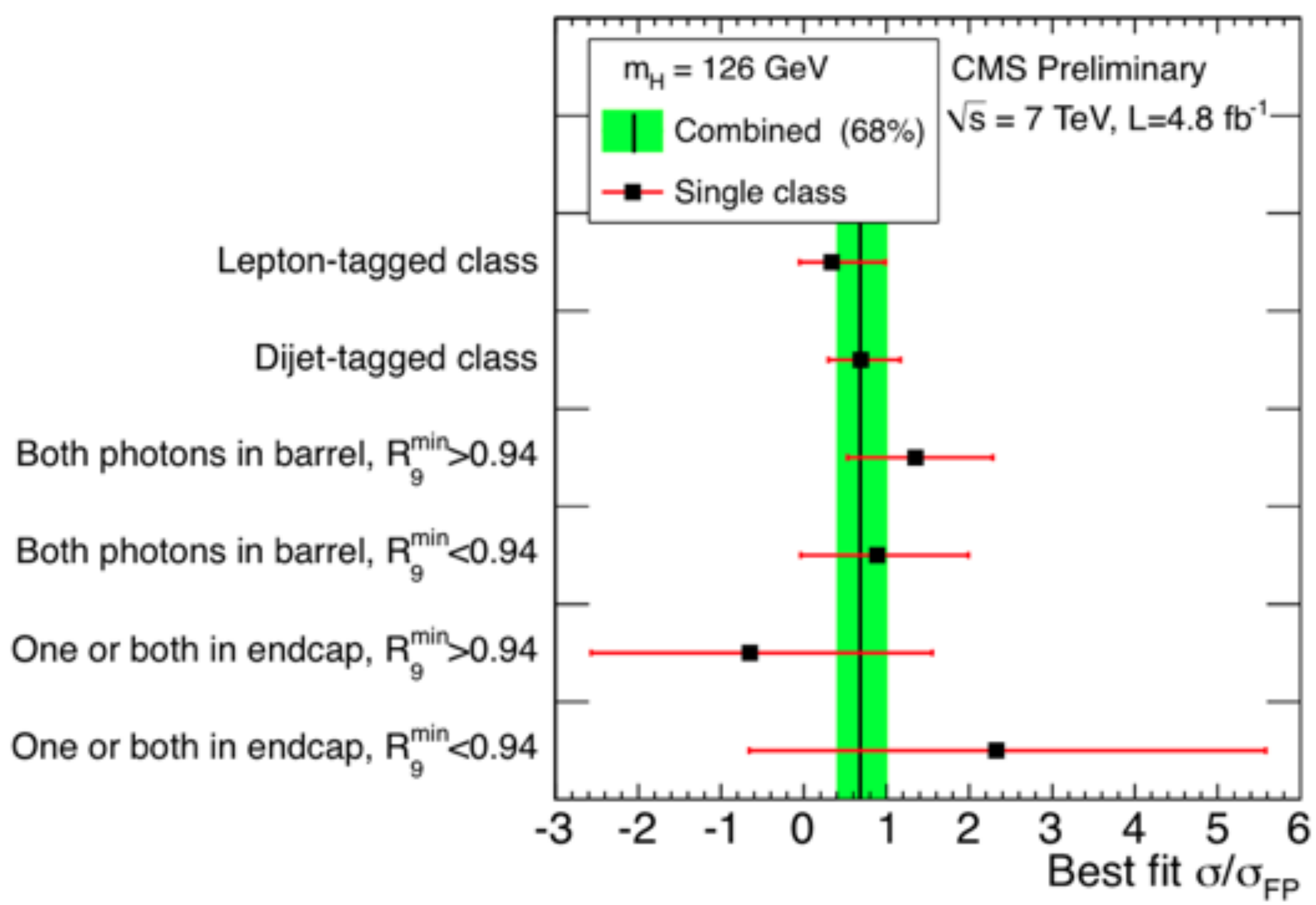
CLs "LHC-type" test statistic: $Q = -\ln \frac{\mathcal{L}(data|b(\hat{\theta}_b)+\mu s(\hat{\theta}_s))}{\mathcal{L}(data|b(\hat{\theta}_b)+\hat{\mu} s(\hat{\theta}_s))}$

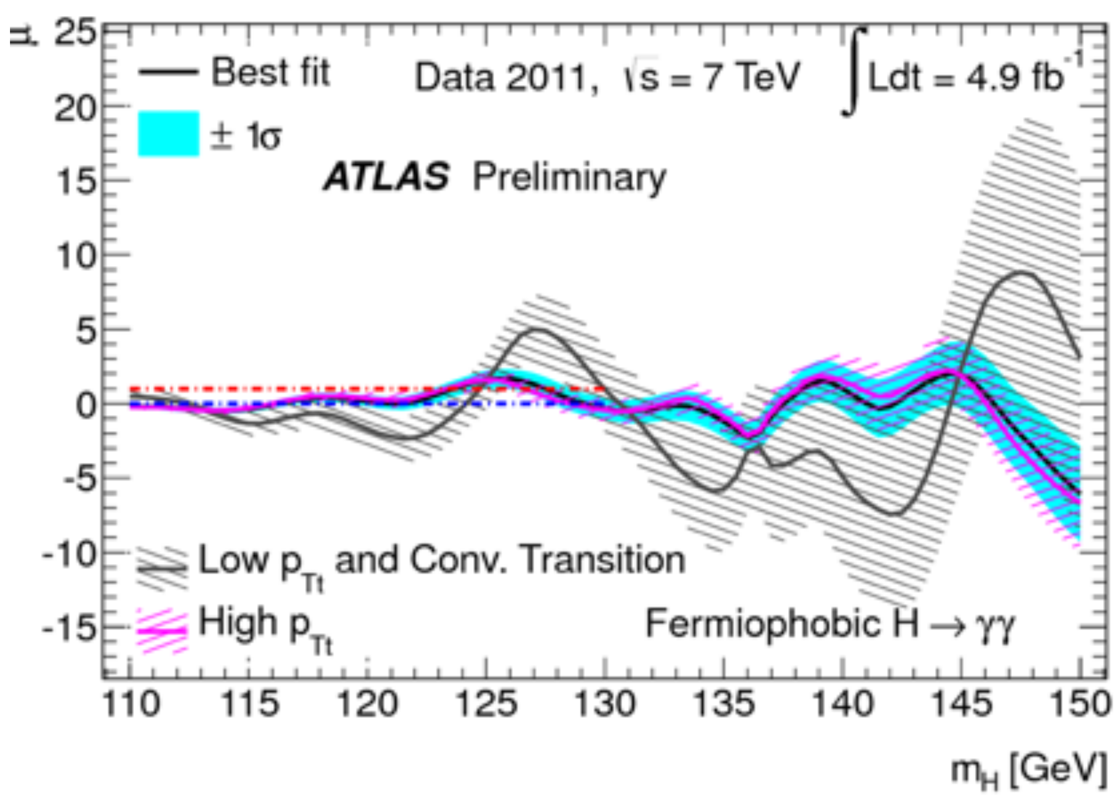
(constrain $0 \leq \hat{\mu} \leq \mu$, and add external constraints for signal nuisances)

- Limits are given in Higgs mass range 110-150 in 0.5 GeV/c^2 mass steps

- Bayesian limit is compared with CL_s results

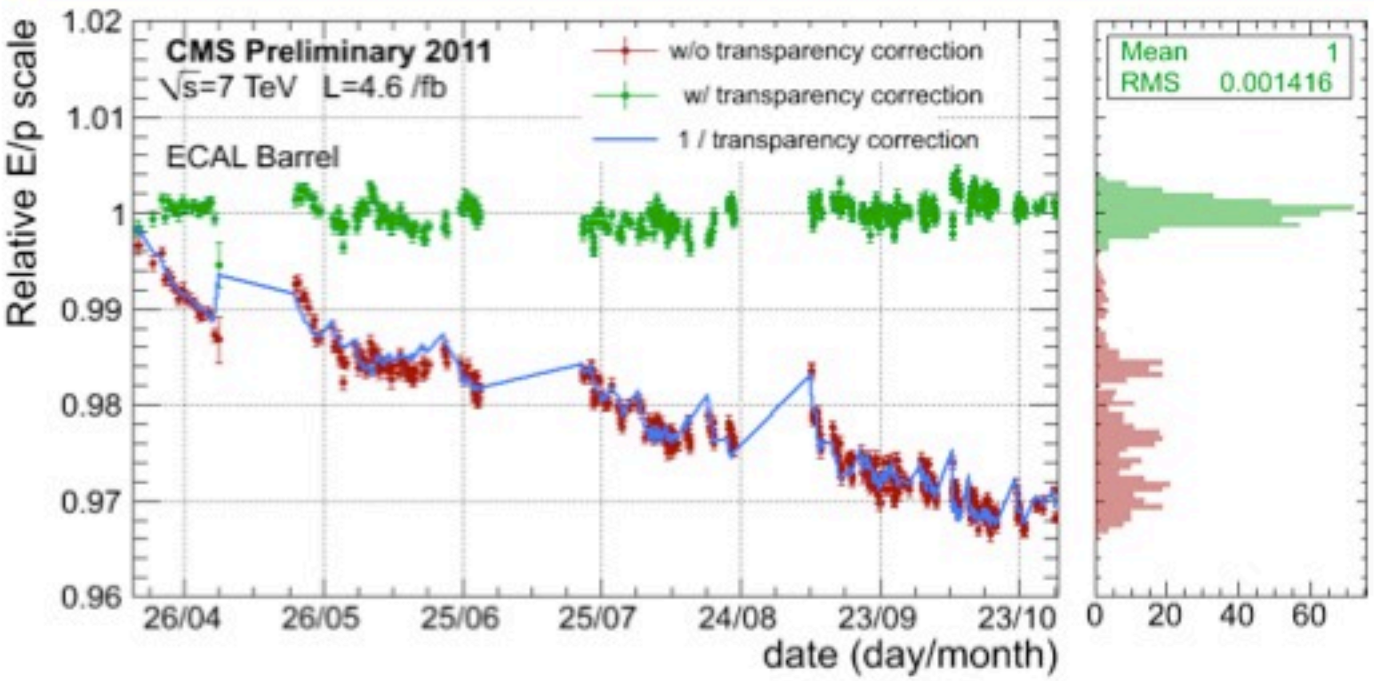
FERMIOPHOBIC: RESULTS

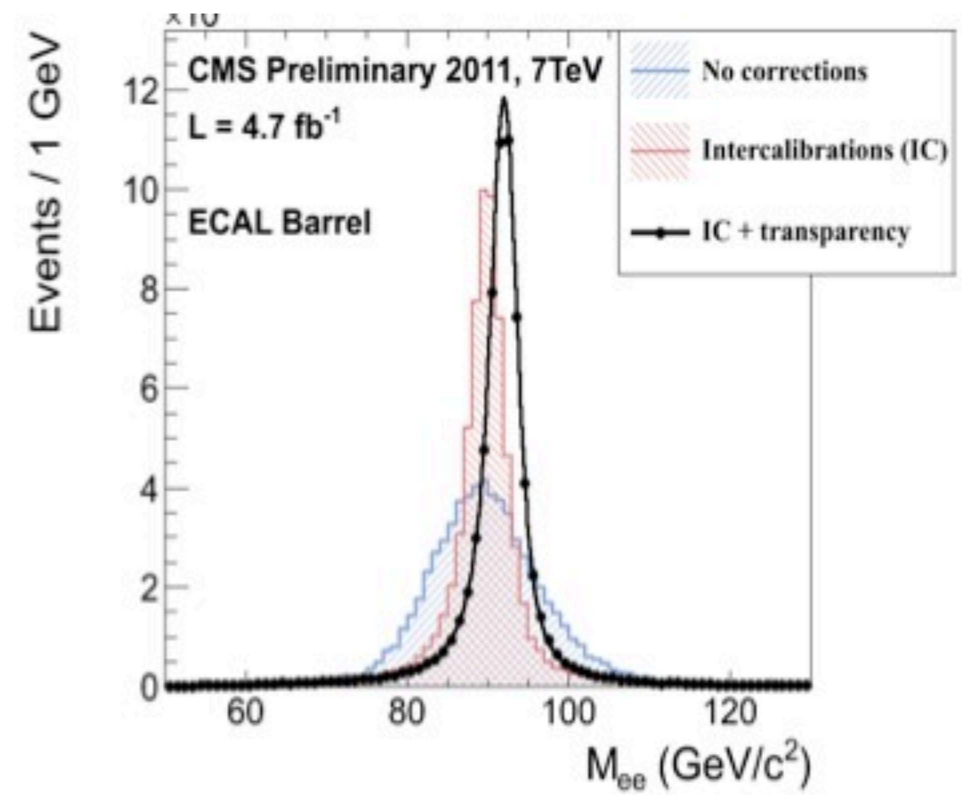




STABILITY OF CMS ECAL RESPONSE

Effect of new laser corrections and intercalibration on barrel-barrel Z→ee
Resolution in data improves typically by 10%, EB, |η|>1, R9>0.94
Instrumental contribution to the mass resolution in the best EB category is 0.99 ±0.01 GeV





Energy scale for W→eν and Z→ee stable throughout 2011 at the level of 0.1 GeV.

EB inter-calibration and transparency correction fully understood for EB for the entire 2011 data set.