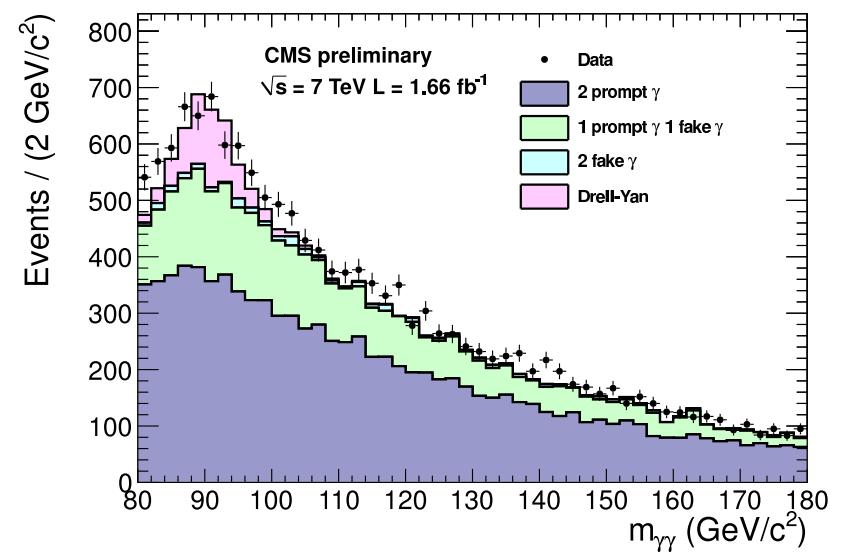
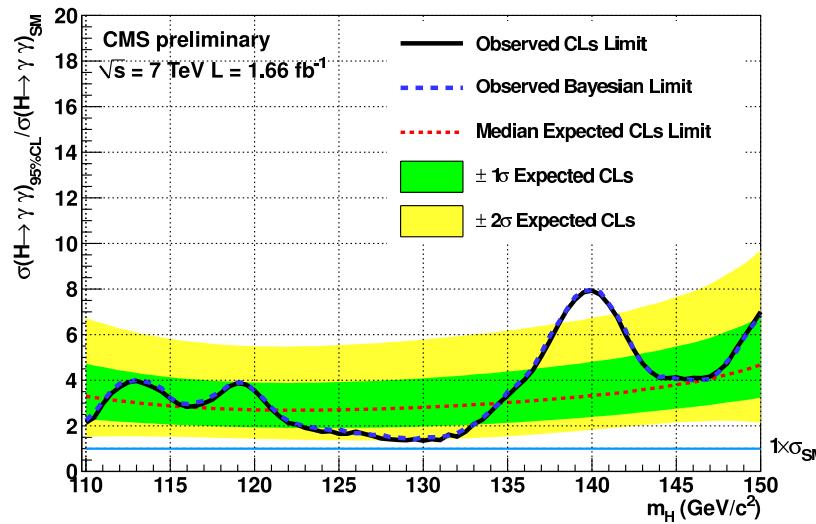


# Search for the Higgs Boson Decaying into Diphotons with Data Recorded by the CMS Detector at the LHC

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On behalf of CMS-Saclay Group



*Journée de l'Irfu sur la physique du Higgs*  
*November 02, 2011*

☞  $H \rightarrow \gamma\gamma$  becomes as a discovery channel at masses above LEP limit ( $114.4 \text{ GeV}/c^2$ ) and LHC exclusion ( $145 \text{ GeV}/c^2$ )

⇒ low signal rate  $\mathcal{B} \sim 10^{-3}$

→ decay involves  $q, W$  loops;

⇒ clean signature (contrarily to  $H \rightarrow b\bar{b}$ );

⇒ identified as a narrow peak on the top of continuous background

☞ CMS focuses on two model approaches:

⇒ Standard Model (SM)  $h \rightarrow \gamma\gamma$

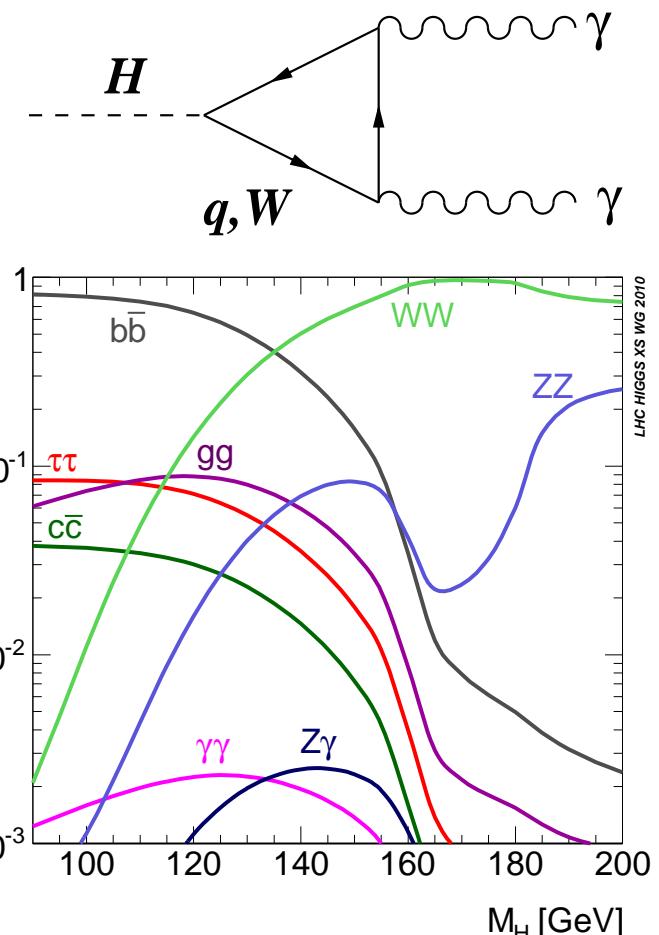
→ most likely scenario after first LHC results

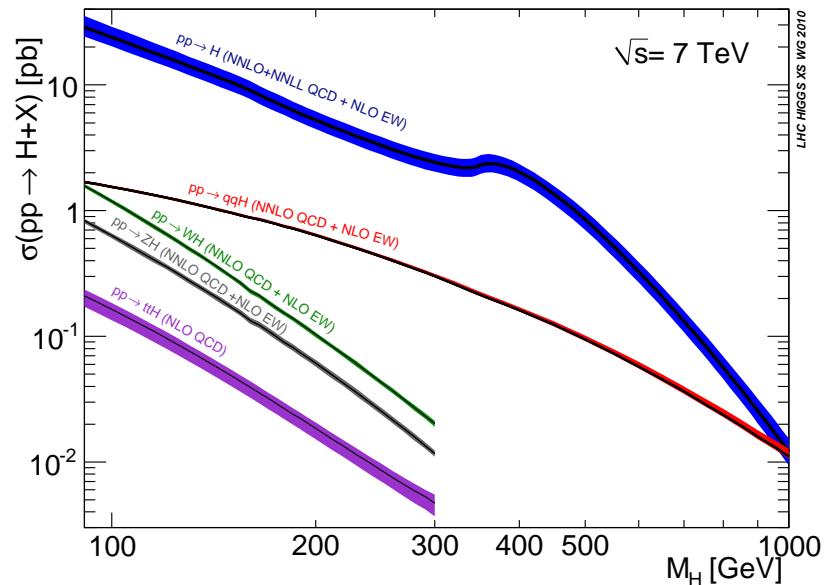
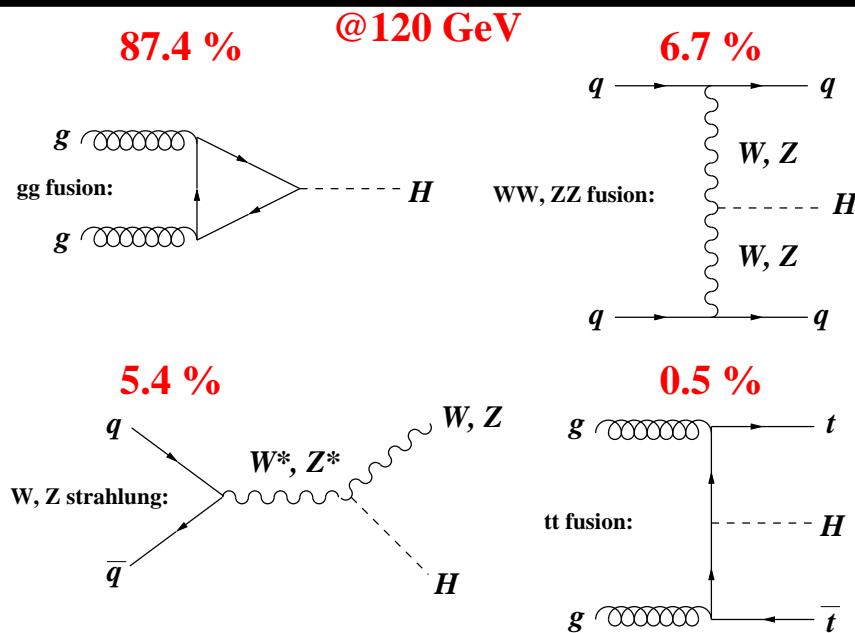
⇒ Fermiophobic (FP)  $h_f \rightarrow \gamma\gamma$

→ has particular interest for beyond the SM scenario of EWSB (2 HDM)

→ sensitive to new physics effects

→ no fermion couplings ⇒ enhance  $\mathcal{B}(h_f \rightarrow \gamma\gamma)$

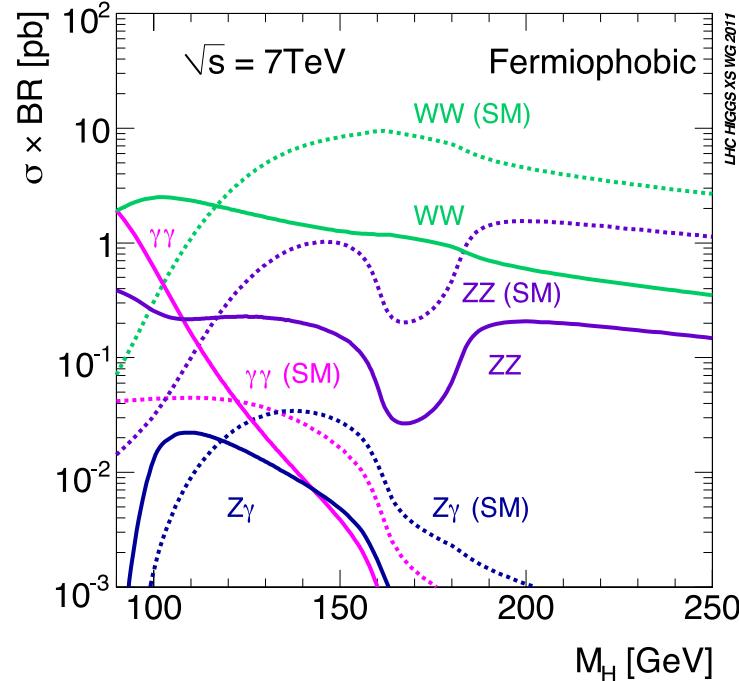
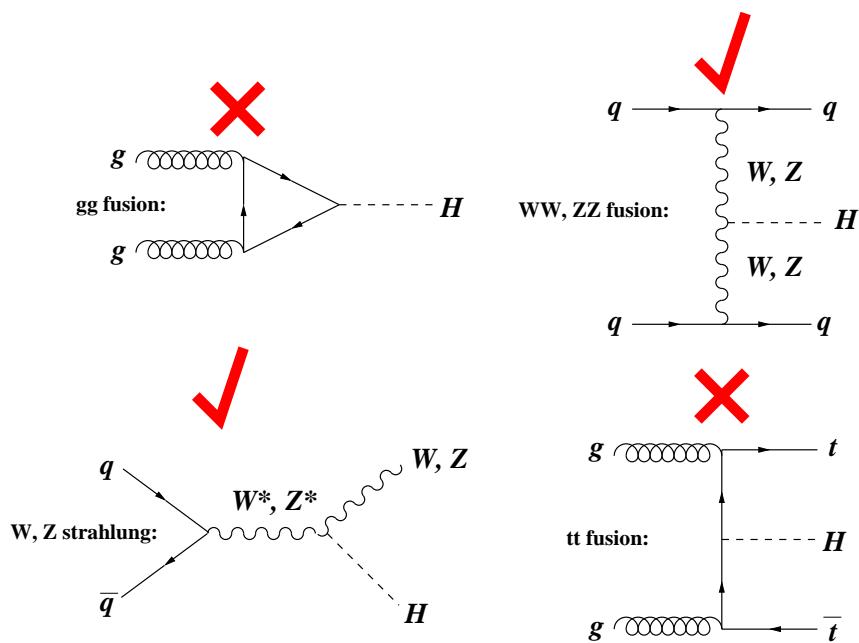




NNLO cross sections and branching ratios (SM)

- ☞ **ggH production is dominant**
- ➡ associated jets are emerged due to soft gluon radiation at NLO
- ➡ high k-factor ( $\sim 2$ )
- ➡ large theoretical uncertainty

$M_h$ (GeV)	110	115	120	130	140	150
$\sigma ggH$ (pb)	19.8	18.1	16.6	14.1	12.1	10.5
$\sigma VBF$ (pb)	1.40	1.33	1.27	1.15	1.05	0.96
$\sigma WH$ (pb)	0.88	0.75	0.66	0.50	0.39	0.30
$\sigma ZH$ (pb)	0.47	0.41	0.36	0.28	0.22	0.17
$\sigma t\bar{t}H$ (pb)	0.13	0.11	0.10	0.08	0.06	0.05
Total $\sigma$ (pb)	22.7	20.7	19.0	16.1	13.8	12.0
$\mathcal{B}(h \rightarrow \gamma\gamma)$ , %	0.20	0.21	0.23	0.23	0.19	0.14
$\sigma \times \mathcal{B}$ (fb)	44.7	43.5	43.7	37.0	26.2	16.8



- ☞ Driven by VBF and VH only
  - ➡ jets and leptons are at LO
  - ➡ low k-factor ( $\sim 1.1$ )
  - ➡ low theory uncertainty
- ☞ SM and FP signal rates become to be similar at  $125 \text{ GeV}/c^2$

## NNLO cross sections and branching ratios (FP)

$M_{hf} (\text{GeV})$	90	100	110	120	130	140	150
$\sigma \text{ VBF (pb)}$	1.71	1.55	1.40	1.27	1.15	1.05	0.96
$\sigma \text{ WH (pb)}$	1.64	1.19	0.88	0.66	0.50	0.39	0.30
$\sigma \text{ ZH (pb)}$	0.86	0.63	0.47	0.36	0.28	0.22	0.17
Total $\sigma$ (pb)	4.21	3.37	2.75	2.29	1.93	1.66	1.43
$\mathcal{B}(h_f \rightarrow \gamma\gamma), \%$	41.0	18.0	6.2	2.8	1.9	0.61	0.20
$\sigma \times \mathcal{B}$ (fb)	1726	607	170.5	64.1	36.7	10.1	2.9

## ☞ Irreducible backgrounds

➡ born, box and isolated bremsstrahlung;

➡ diff. rates at 120 GeV

$$d\sigma/dm_{\gamma\gamma} \sim 100 \text{ fb}/\text{GeV}/c^2$$

➡ required mass resolution:

$$\Delta M_{\gamma\gamma} \sim 1 \text{ GeV}/c^2$$

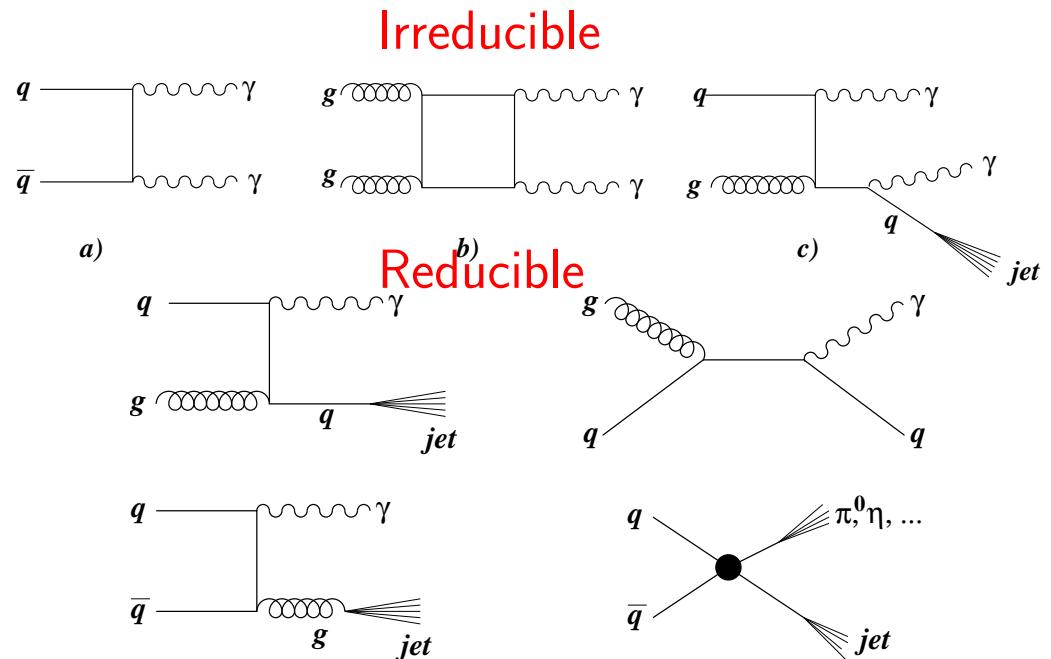
## ☞ Reducible backgrounds

➡ QCD high  $p_T$  jet processes;

➡ neutral hadrons ( $\pi^0, \eta$ ) may lead to the fake photons;

➡ required jet suppression

$$\epsilon_{jets} \sim 10^{-3} \div 10^{-4}$$

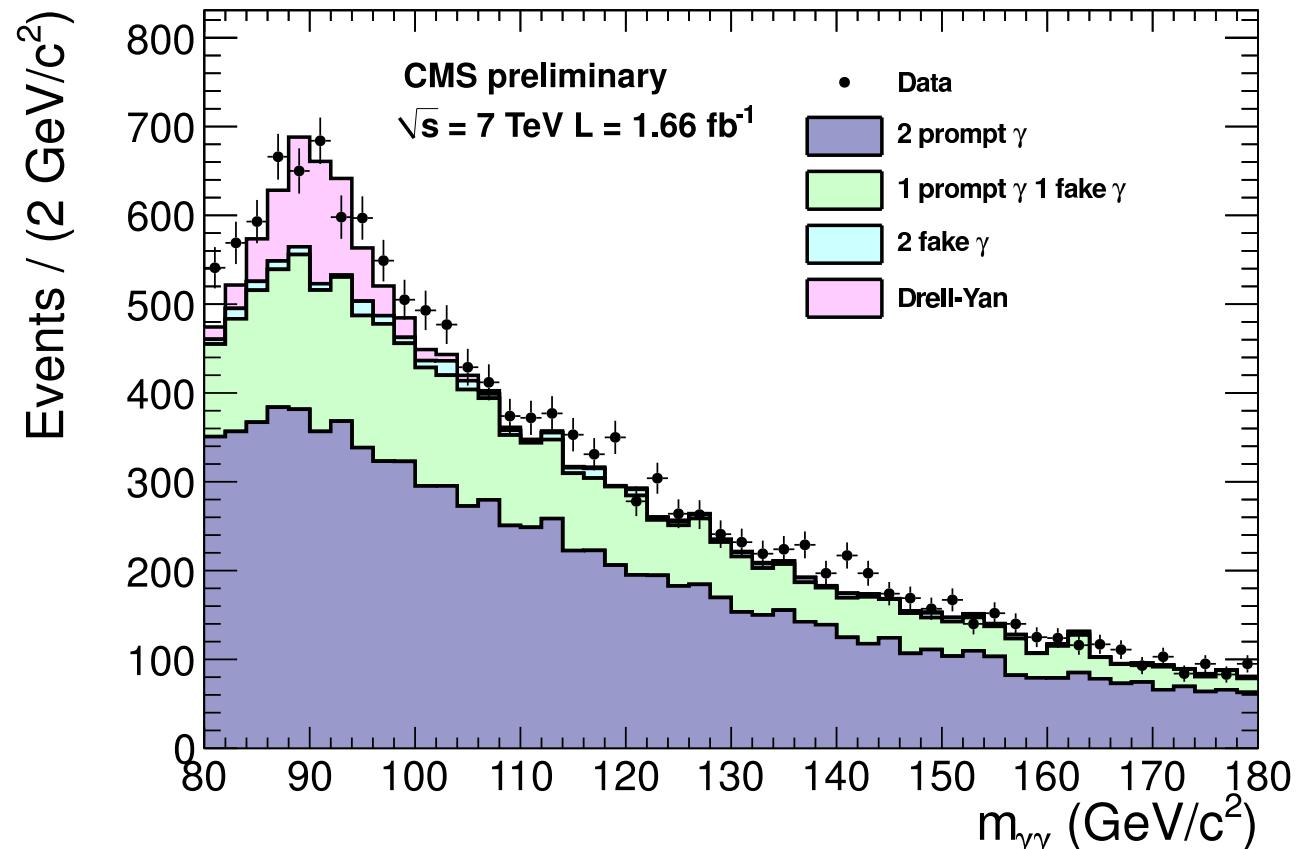


Process	$p_T$ ( GeV/ $c$ )	$\sigma_{\text{LO}}$ ( pb)
$H \rightarrow \gamma\gamma$ (120 GeV/ $c^2$ )	—	0.044 (NNLO)
$\text{pp} \rightarrow \gamma\gamma$ (Born)	> 25	22.4
$\text{pp} \rightarrow \gamma\gamma$ (Box)	> 25	12.4
$\text{pp} \rightarrow \gamma+\text{jet}$	> 30	$2.0 \times 10^4$
$\text{pp} \rightarrow \text{jets}$	> 30	$6.0 \times 10^7$
Drell Yan ee	—	$3 \times 10^3$

Search for  $H \rightarrow \gamma\gamma$  is the flagship analysis for the CMS-Saclay group

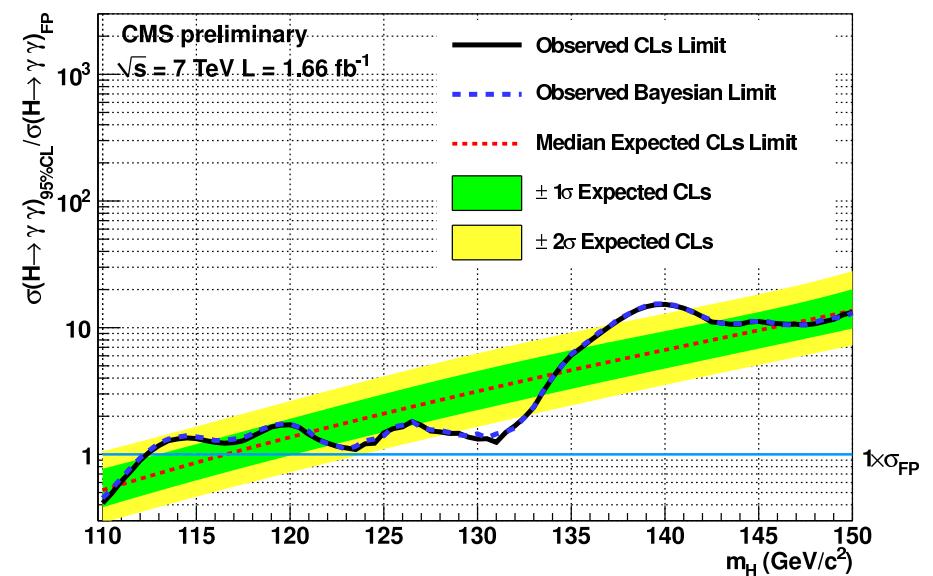
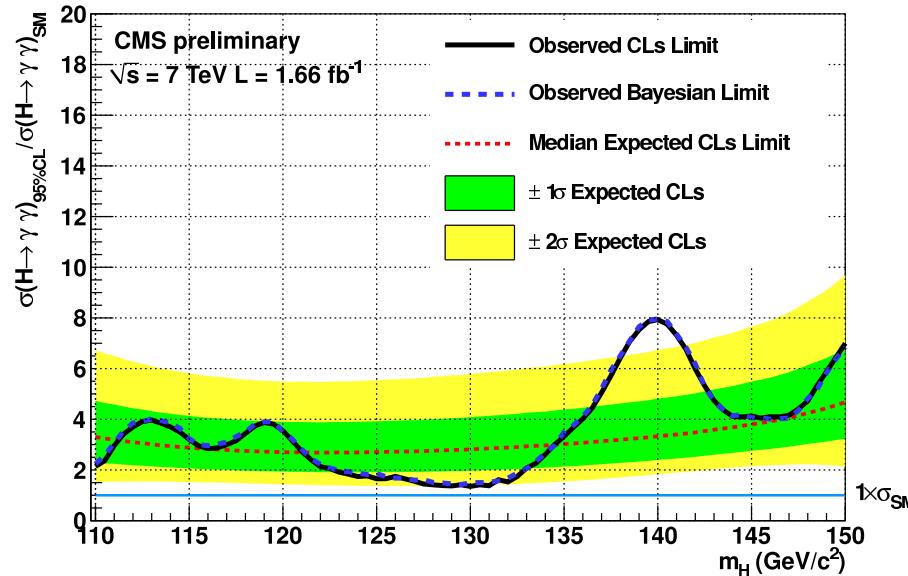
- ☞ Leading group in photon physics at CMS
  - ➡ photon reco and id
  - ➡ inclusive photons
  - ➡ diphotons
  - ➡ ECAL calibration (laser monitoring)

This talk is aimed to phenomenological aspects and common analysis issues



CMS-HIG-11-010 (EPS), CMS-HIG-11-021 (LP)

# Current Exclusion Limits



## Standard Model (SM) approach

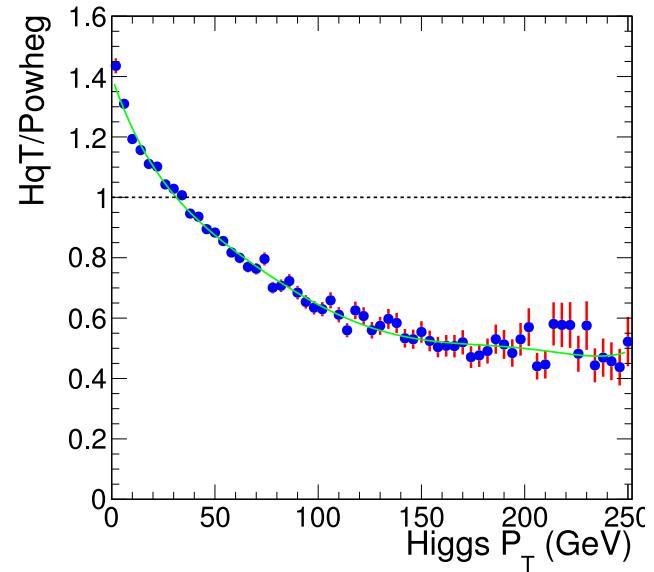
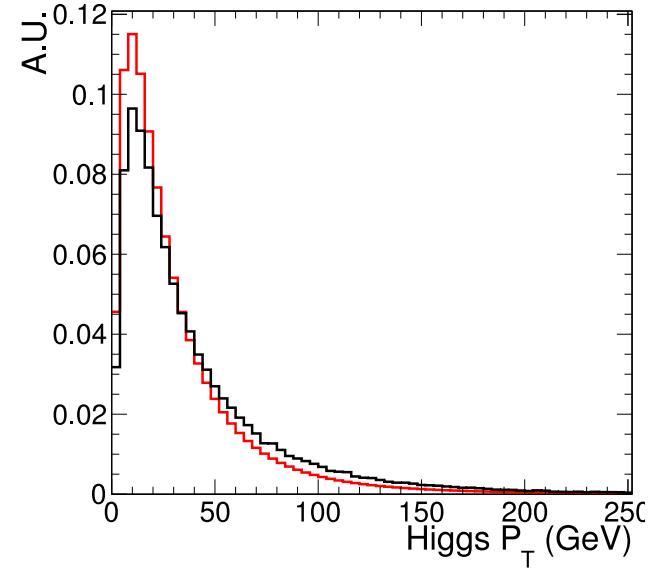
- ➡ gluon fusion is dominant;
- ➡ Higgs is produced almost at rest
- ➡ **exclusion 95% C.L. between 2.7 and 4.7 times SM cross section**

## Fermiophobic benchmark (FP) model

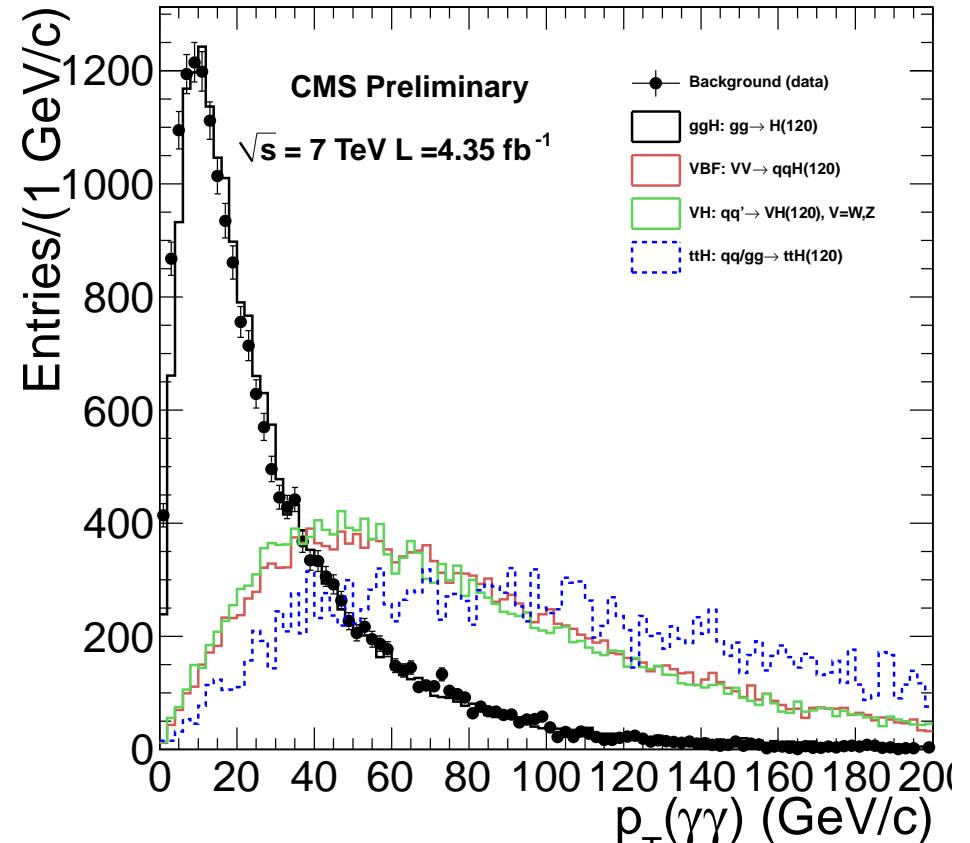
- ➡ large enhancement in  $\mathcal{B}(H \rightarrow \gamma\gamma)$ ;
- ➡ VBF and VH only (boosted Higgs)
- ➡ exploit  $p_T$  kinematics
- ➡ **exclude 110-112 GeV/ $c^2$  at 95% C.L.**

Process	Generator	# events
ggH: $gg \rightarrow H$	POWHEG	110k
VBF: $VV \rightarrow H$	POWHEG	110k
VH: $q\bar{q}' \rightarrow VH, V = W, Z$	PYTHIA	100k
ttH: $q\bar{q}/gg \rightarrow t\bar{t}H$	PYTHIA	22k

- ☞ Signal MC data sets normalised at NNLO XS
  - ➡ mass points: [90-160] GeV with 5 GeV step
  - ➡ generate main production mechanisms ggH and VBF with NLO generator POWHEG
  - ➡ ggH: MC@NLO for cross check
- ☞ Use  $HqT$  NNLO to reweight  $p_T$  for ggH
  - ➡ driven by soft gluon radiation (NLO jets);
  - ➡ important for studies with kinematics ( $p_T$ ) and semi-exclusive signature like  $gg \rightarrow H + nj$
- ☞ VH, ttH: k-factor  $\leq 1.1$



- ☞ Difference in the signal and background kinematics is a room for improvement:
  - ➡ exploit Higgs kinematical properties
  - ➡ include recoil objects in signature
- ☞ Current study use two  $p_T$  categories  $p_T(\gamma\gamma) < (>)40$  GeV
  - ➡ NNLO  $p_T$  spectrum for ggH is similar to background
  - marginal improvement (6% category migration systematic)
  - ➡  $p_T(\gamma\gamma) > 40$  GeV enhances VBF and VH for FP scenario



ggH spectrum was reweighted with HqT  
NNLO prediction

Understanding of theoretical uncertainties is a cornerstone

☞ Energy scale ( $\Delta E$ ) and mass resolution ( $\sigma_m$ ) are dominant systematics

⇒ mass scale is equivalent to energy scale:  $\Delta m \equiv \Delta E$

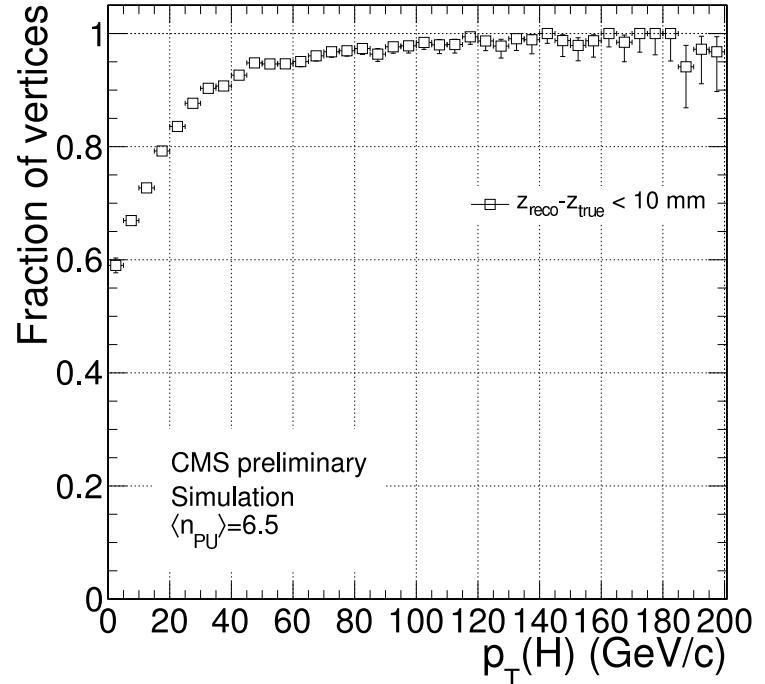
$$m^2 = 2E_1 E_2 (1 - \cos \theta)$$

⇒  $\sigma_m$  depends on energy ( $\sigma_E$ ) and angular ( $\sigma_\theta$ ) resolutions

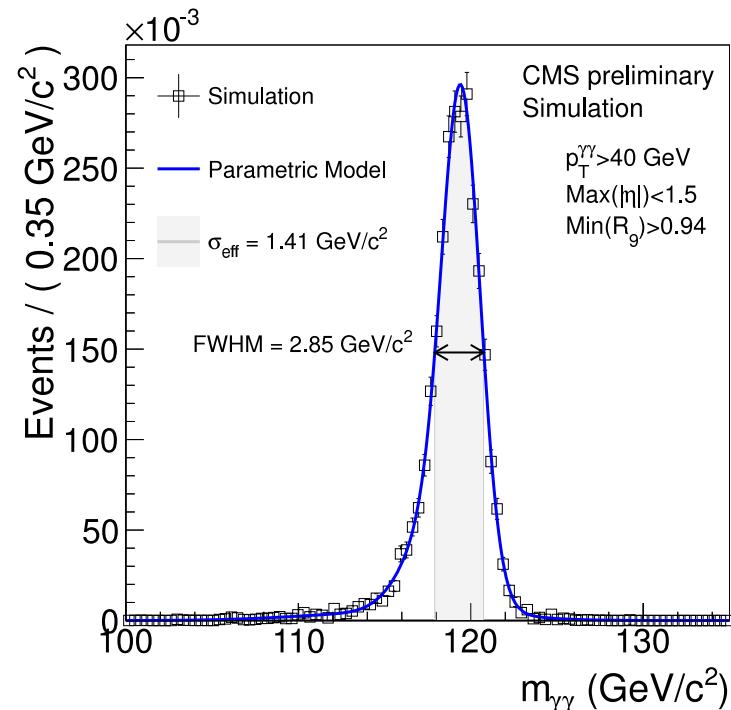
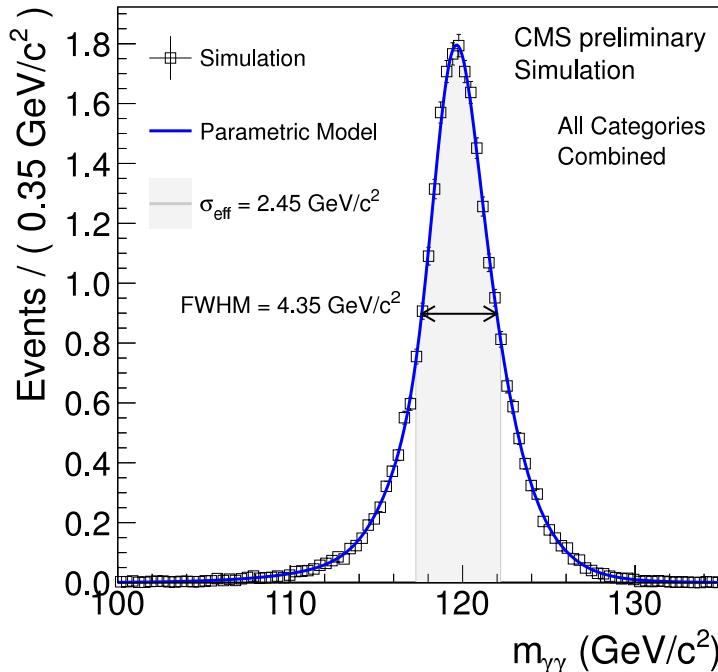
$$\frac{\sigma_m}{m} = \frac{1}{2} \left( \frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_\theta}{\tan \theta / 2} \right)$$

☞ Misvertexing has a small effect (PU)

⇒ angular term is negligible once Higgs is emerged at rest  
 ⇒ high efficiency due to presence of recoil objects for the boosted Higgs



☞ Higgs is produced in association with tracks from  
 ⇒ underlying events;  
 ⇒ initial state gluon radiation;  
 ⇒ associative particles  $qqH^0$ ,  $VH^0$ ;  
 ⇒ photon conversion;



👉 Use sum of Gaussians for LP

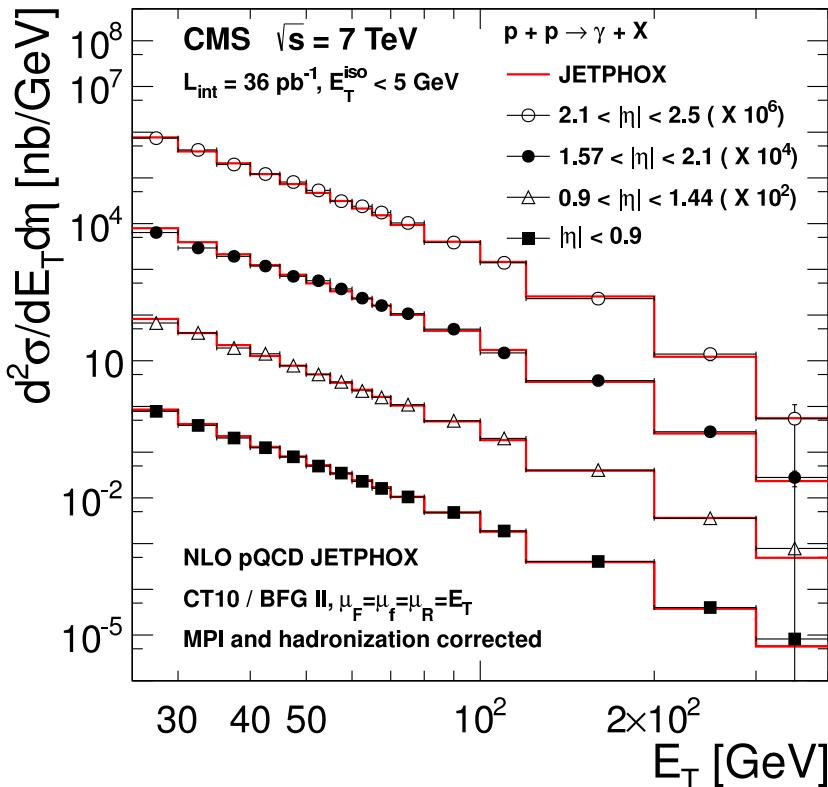
➡ it is foreseen **Crystal Ball plus Gaussian outliers** for the winter update

$$f(x) = N \cdot \begin{cases} \exp\left(-\frac{(x-m_0)^2}{2\sigma_{CB}^2}\right) & ; (x - m_0)/\sigma > -\alpha \\ A \times \left(B - \frac{x-m_0}{\sigma}\right)^{-n} & ; (x - m_0)/\sigma \leq -\alpha \end{cases}$$

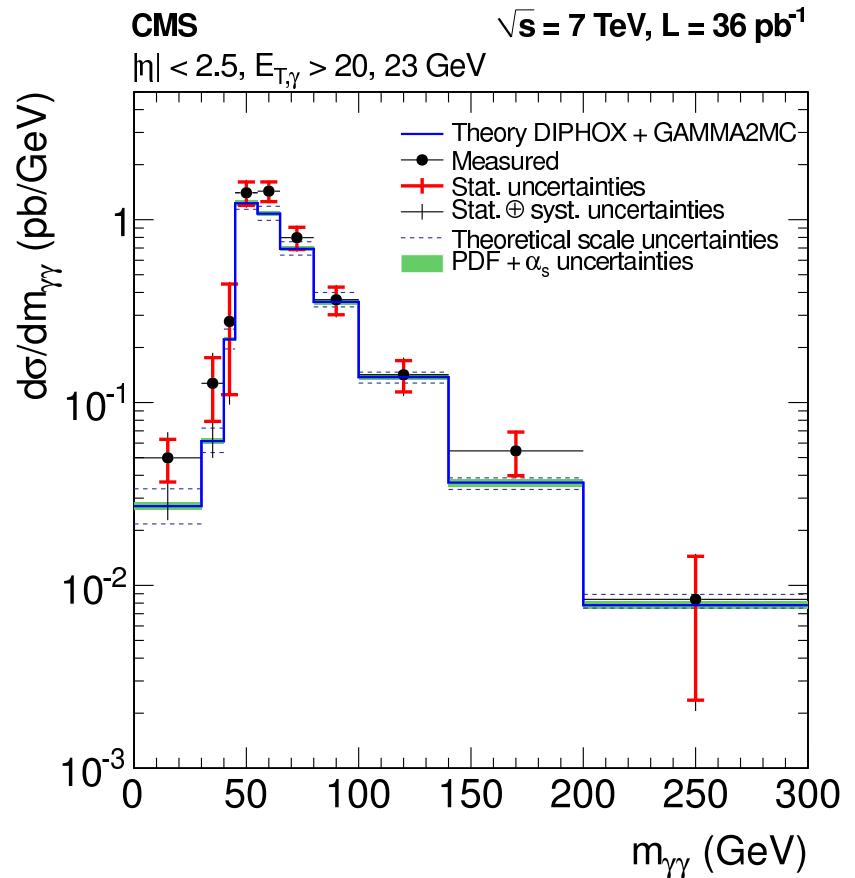
$$A \equiv \left(\frac{n}{|\alpha|}\right)^n \times \exp(-|\alpha|^2/2), B \equiv \frac{n}{|\alpha|} - |\alpha|$$

$$\sigma_{eff} \sim 1.4 \div 3.6 \text{ GeV}/c^2$$

- 👉 Significant improvement in mass resolution is expected for the winter update
- ➡ new energy correction schema;  
➡ improved ECAL calibration



Measurement of the Differential Cross Section for Isolated Prompt Photon Production in  $pp$  Collisions at 7 TeV  
Phys. Rev. Lett. **106**, 082001 (2011),  
Phys. Rev. **D84**, 052011 (2011)



Measurement of the Production Cross Section for Pairs of Isolated Photons in  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$   
CMS-QCD-10-035 on track of submission

- ☞ Background estimation and modeling is a fully data driven approach
- ☞ Decomposition of background components in MC is needed only to optimise selections

## “Irreducible” and Drell-Yan

Dataset	Generator	$\hat{p}_T/H_t$	$\sigma$ (pb)	# events	$L$ ( pb $^{-1}$ )
$q\bar{q}/qg \rightarrow \gamma\gamma$ (Born & Brem)	MADGRAPH	$> 10, m(\gamma\gamma) > 40$	154	$1.1 \cdot 10^6$	7143
$q\bar{q} \rightarrow \gamma\gamma$ (Born)	PYTHIA	10 – 25	236.4	$5.0 \cdot 10^5$	2115
$q\bar{q} \rightarrow \gamma\gamma$ (Born)	PYTHIA	25 – 250	22.37	$5.0 \cdot 10^5$	22351
$q\bar{q} \rightarrow \gamma\gamma$ (Born)	PYTHIA	$> 250$	$8.07 \cdot 10^{-3}$	$5.0 \cdot 10^5$	$6.2 \cdot 10^7$
$gg \rightarrow \gamma\gamma$ (Box)	PYTHIA	10 – 25	358.2	$5.0 \cdot 10^5$	1396
$gg \rightarrow \gamma\gamma$ (Box)	PYTHIA	25 – 250	12.37	$7.8 \cdot 10^5$	62056
$gg \rightarrow \gamma\gamma$ (Box)	PYTHIA	$> 250$	$2.08 \cdot 10^{-4}$	$5.0 \cdot 10^5$	$2.4 \cdot 10^9$
$Z^0 + \text{jets}$	MADGRAPH		3048	$5.26 \cdot 10^6$	1726

## “Reducible”

Dataset	$\hat{p}_T$	$\sigma$ (pb)	$\epsilon_{filter}$	# events	$L$ ( pb $^{-1}$ )
$\gamma + \text{jet(EMenriched)}$	$> 20$	$7.71 \cdot 10^4$	$6.4 \cdot 10^{-3}$	$1.2 \cdot 10^6$	2432
QCD(EMenriched)	30 – 40	$4.18 \cdot 10^7$	$2.3 \cdot 10^{-4}$	$3.6 \cdot 10^6$	374
QCD(EMenriched)	$> 40$	$1.87 \cdot 10^7$	$2.16 \cdot 10^{-3}$	$21.3 \cdot 10^6$	527

☞ Derive k-factors for 4 background components by comparing Pythia and Madgraph MC with

➡ full-NLO calculations (DIPHOX, gamma2MC)

➡ existing data measurements

→ diphoton (2 prompt);

→  $\gamma$ +jet (prompt-fake);

→ jet-jet (fake-fake);

→ Drell-Yan  $Z^0$  ( $e^+e^-$ ) (electroweak)

Process	k-factor	
	PYTHIA	MADGRAPH
$pp \rightarrow \gamma\gamma$ (born & brem)	1.3	1.15
$pp \rightarrow \gamma\gamma$ (box )	1.3	1.15
	PYTHIA	PYTHIA
$pp \rightarrow \gamma + \text{jet}$ (2 prompt)	1.3	-
$pp \rightarrow \gamma + \text{jet}$ (1 prompt)	1.3	1.3
$pp \rightarrow \text{jets}$ (2 prompt)	1.3	-
$pp \rightarrow \text{jets}$ (1 prompt)	1.3	1.3
$pp \rightarrow \text{jets}$ (0 prompt)	1	1
	PYTHIA	MADGRAPH
Drell-Yan	-	1.15

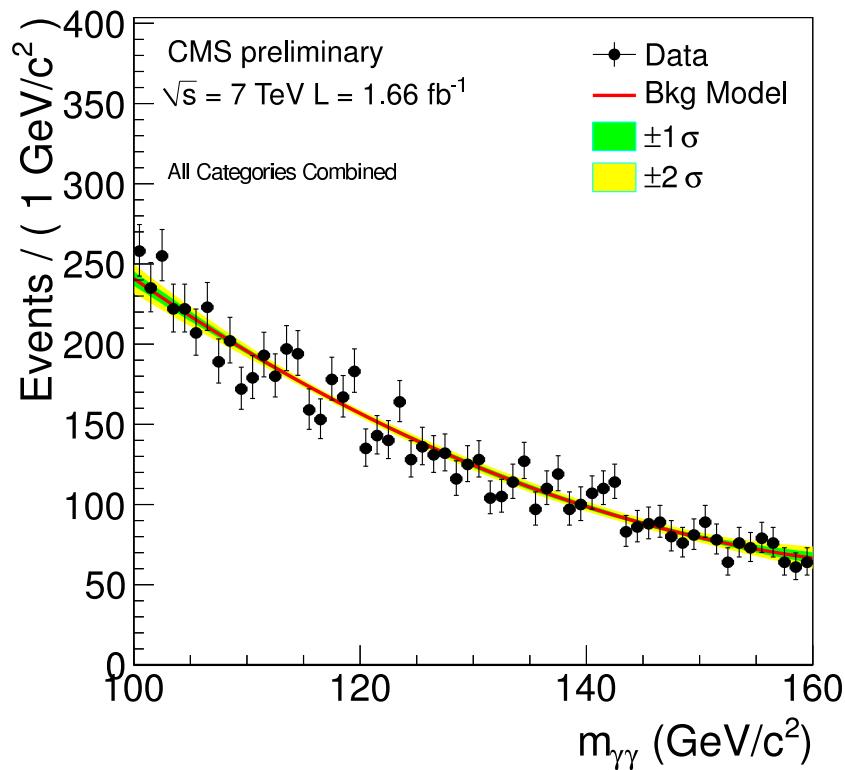
☞ Madgraph(Born & Brem) includes

➡  $q\bar{q}/qg \rightarrow \gamma\gamma + \text{n jets}$  (n=0,1,2)

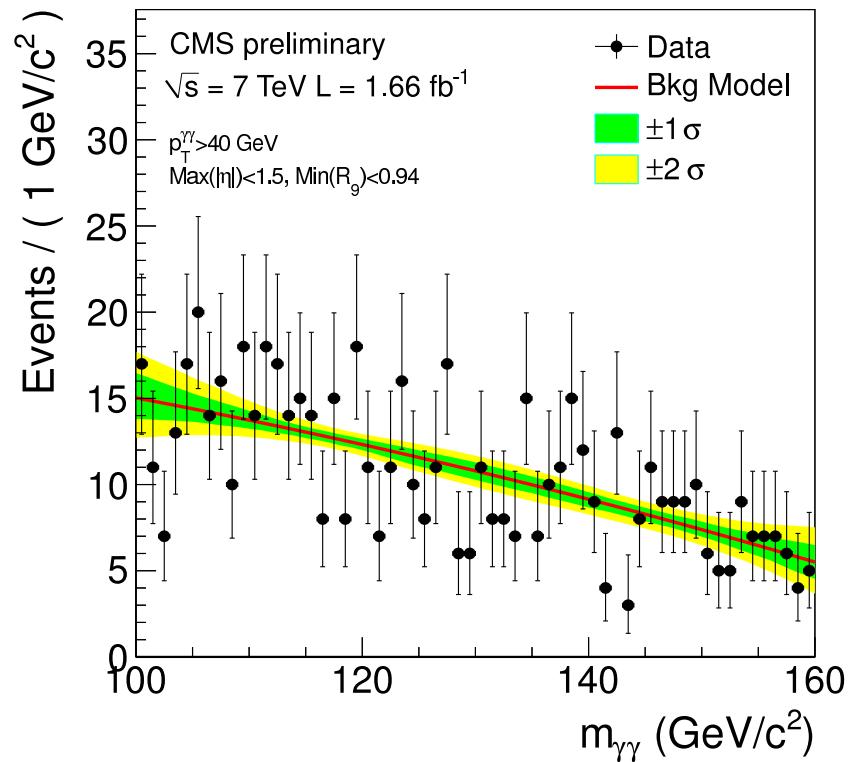
➡ most of NLO real emissions, not virtual emissions

➡ 1 FSR/ISR ( $\gamma$ +jet) and 2 FSR/ISR (di-jets)

☞ Use Pythia Born as a cross check only



☞ 3rd order polynomial positively defined in entire mass region (Bernstein)



☞ Decision is driven by high  $p_T$  categories where spectrum is shifted towards high mass region

## Signal

- ➡ luminosity;
- ➡ theory;
- ➡ efficiency;
- ➡ resolution;
- ➡ energy scale;

## Background

- ➡ slope;
- ➡ normalization;

☞ Implemented into a likelihood model via penalty term:

$$-\log \mathcal{L} - \log g(\theta_s) = NLL_0 + NLL_P$$

	Source	Uncertainty
<b>Standard Model</b>	gg cross section (scale)	12.5%
	gg cross section (PDF)	7.9%
<b>fermiophobic model</b>	VBF cross section (scale)	0.5%
	WH cross section (scale)	0.8%
	ZH cross section (scale)	1.6%
	VBF + VH cross section (PDF)	3.1%
	fermiophobic $H^0 \rightarrow \gamma\gamma$ BR	5%

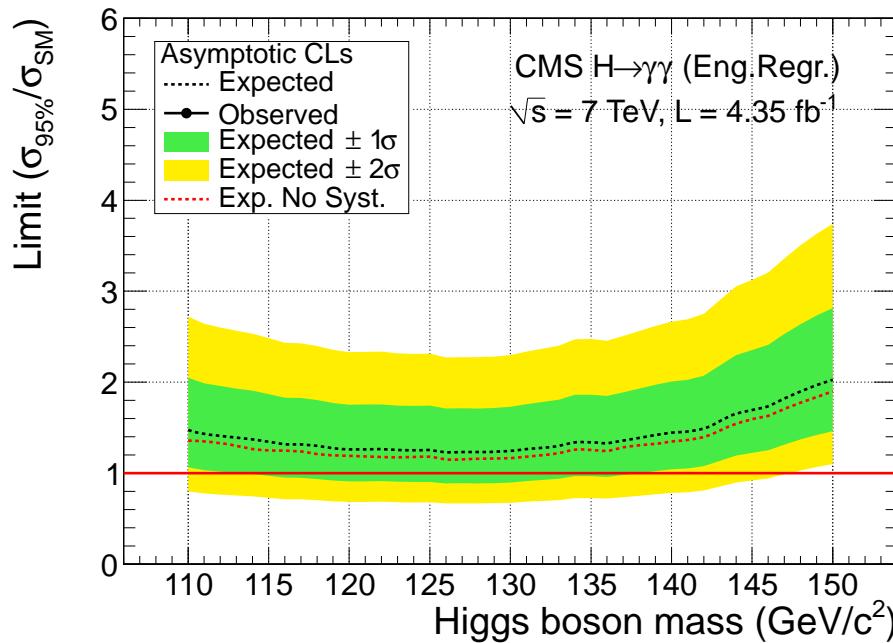
Source	Uncertainty	
Photon identification efficiency barrel endcap	1.0%	
	2.5%	
$R_9 > 0.94$ efficiency (results in class migration) barrel endcap	4%	
	6.5%	
Energy resolution ( $\Delta\sigma/E_{MC}$ ) barrel endcap	$R_9 > 0.94$	$R_9 < 0.94$
	0.2%	0.4%
Energy scale ( $(E_{data} - E_{MC})/E_{MC}$ ) barrel endcap	0.5%	0.4%
	0.1%	0.4%
	0.3%	0.4%

Source	Uncertainty
Integrated luminosity	4.5%
Trigger efficiency both photons in barrel one or more photon in endcap	1.0%
	1.0%
Vertex finding efficiency	0.5%
$p_T^H > 40 \text{ GeV}/c$ in gluon fusion (class migration)	6%

## GGAnalyzer team

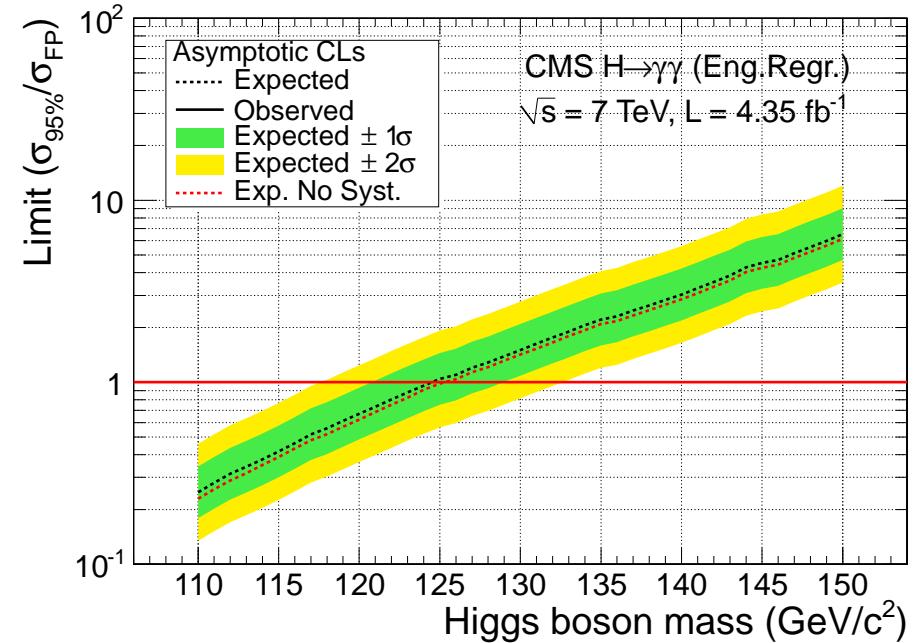
M. Déjardin, S. Ganjour, I. Tecker, et.al.

Saclay/NCU/NTU/FNAL/KSU/Minnesota/Rutgers



### ☞ Standard Model (SM) approach

- ➡ expected limit r=1.2
- ➡ include improved resolution

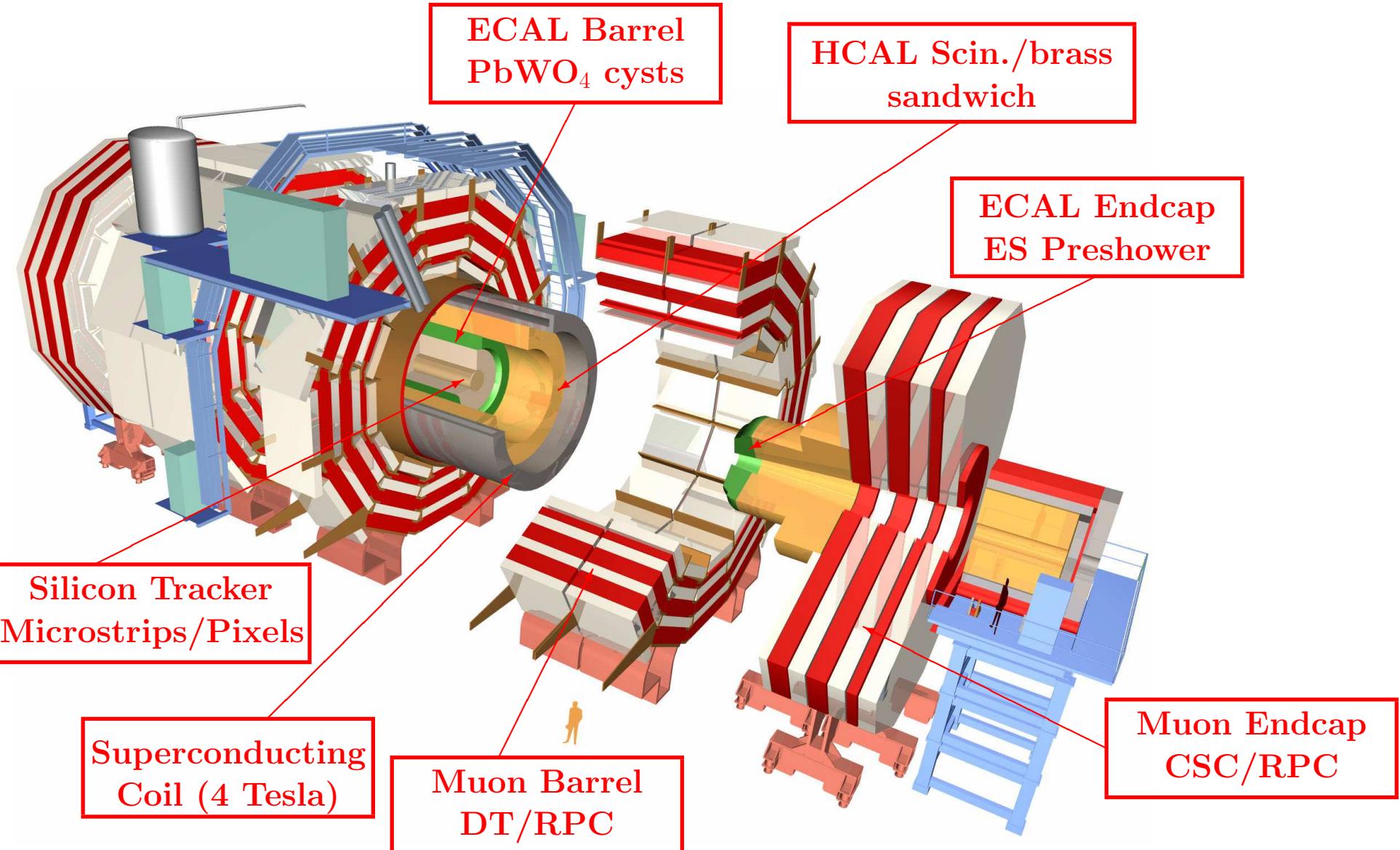


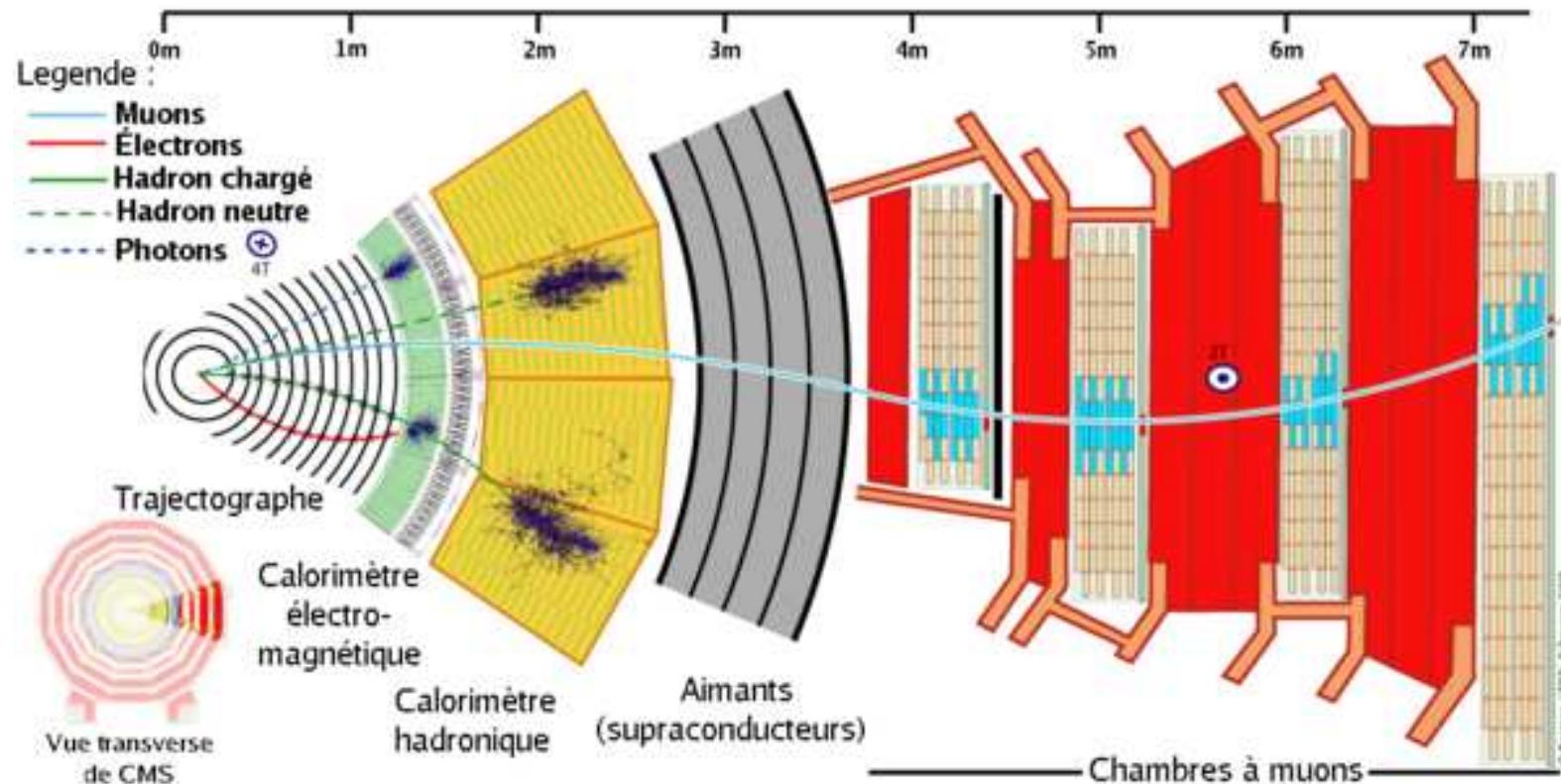
### ☞ Fermiophobic benchmark (FP) model

- ➡ expected exclusion 125 GeV
- ➡ include improved resolution

- ☞ CMS reported SM and FP Higgs boson searches using  $1.7 \text{ fb}^{-1}$  of recorded data
  - ➡ expected exclusion limit at 95% C.L. is between 2.7 and 4.7 times SM cross section
  - ➡ expected limit exclude fermiophobic model in the mass range  $110\text{-}116.5 \text{ GeV}/c^2$ , while data excludes  $110\text{-}112 \text{ GeV}/c^2$
- ☞ Significant improvement in the sensitivity is expected for this winter
  - ➡ exclusion limit at 95% C.L. is between at least 1.2 and 2.0 times SM cross section
  - ➡ exclude fermiophobic model below at least  $125 \text{ GeV}/c^2$  mass
  - ➡ expect low mass range exclusion for the SM Higgs in combined CMS and ATLAS
- ☞ Besides detector performances obvious analysis improvements rely on
  - ➡ including kinematical properties;
  - ➡ exploration of complementary signatures;
  - ➡ understanding of the theoretical uncertainties;
- ☞ Common analysis issues will be discussed on Higgs XS Workshop Nov. 21-22, Orsay

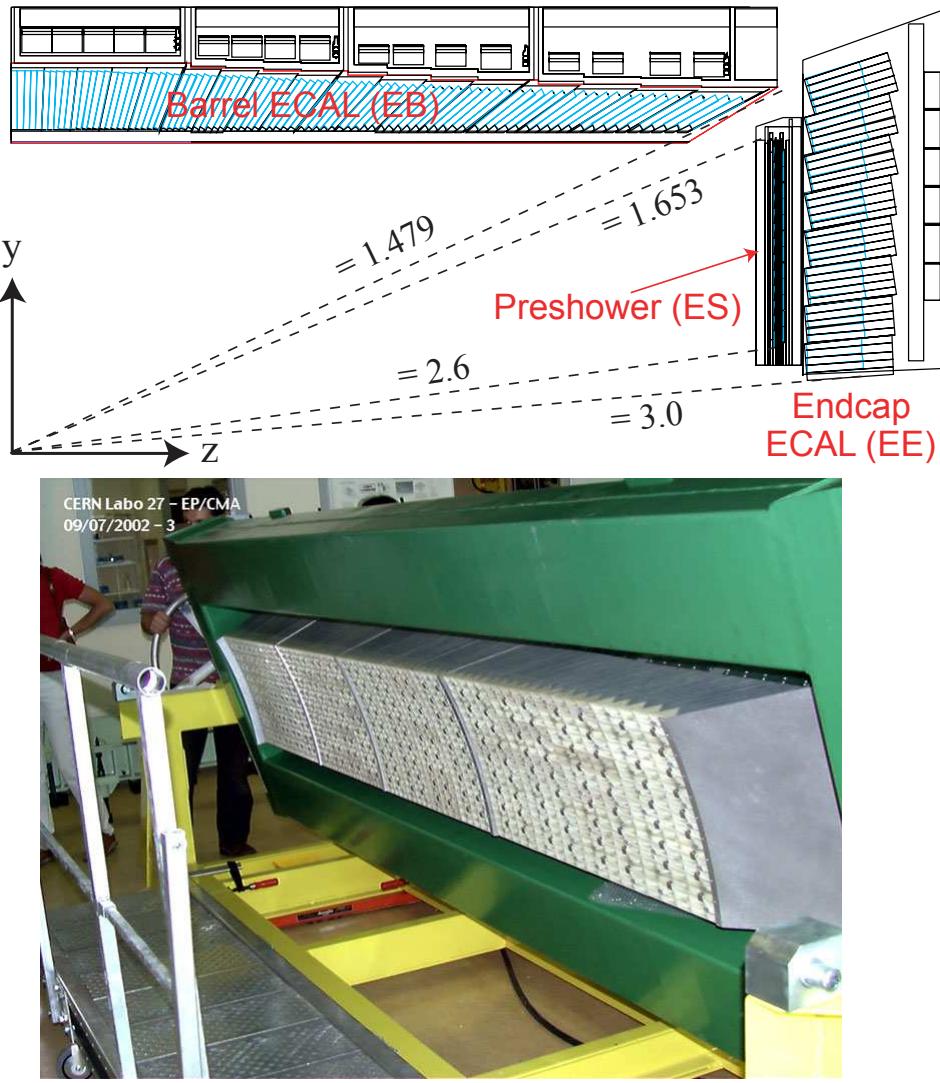
Backup slides





Compact, modular  
 Weight: 12500 t  
 Diameter: 15 m  
 Length: 21.6 m

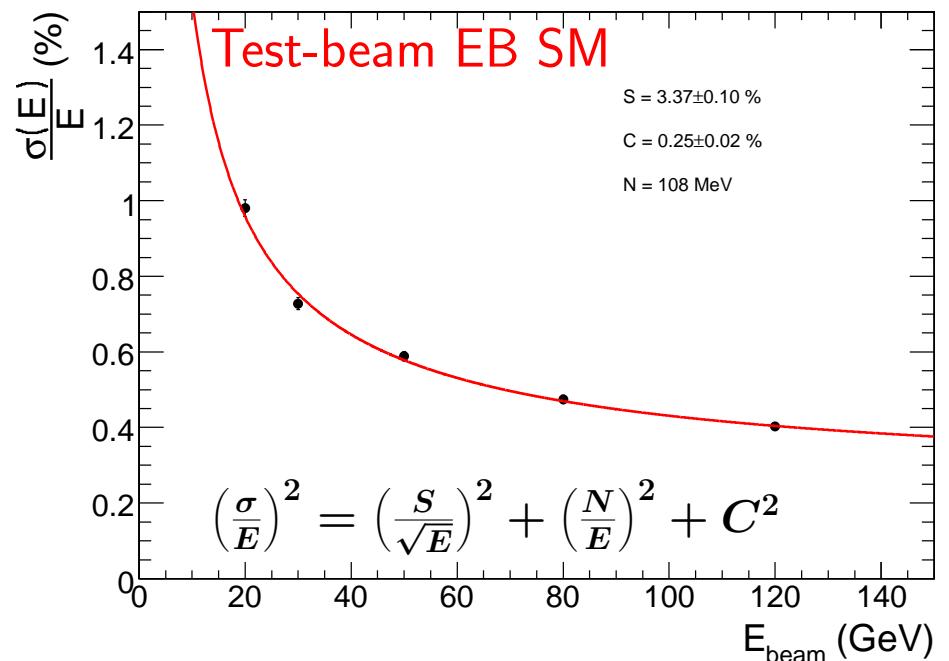
# Electromagnetic Calorimeter (ECAL)



EB Supermodule (SM)

$\text{PWO}_4$ crystal properties	
$X_0$	0.89 cm
$R_M$	2.19 cm
Front face	$2.2 \times 2.2 \text{ cm}^2$
Rare face	$2.6 \times 2.6 \text{ cm}^2$
Length	23 cm ( $25.8X_0$ )

☞ APD (VPT) photodetectors for EB (EE)



☞ Estimated energy in the ECAL:

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

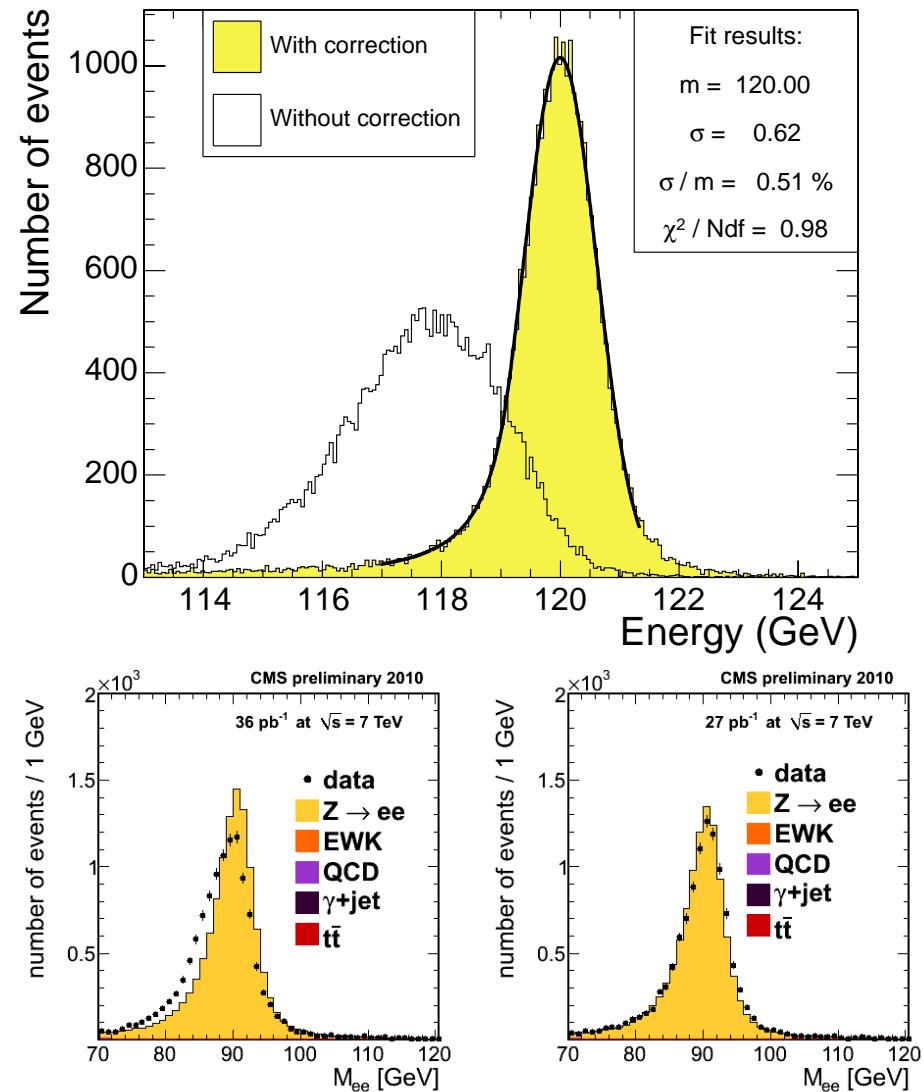
*Corrections*                    *Calibration*

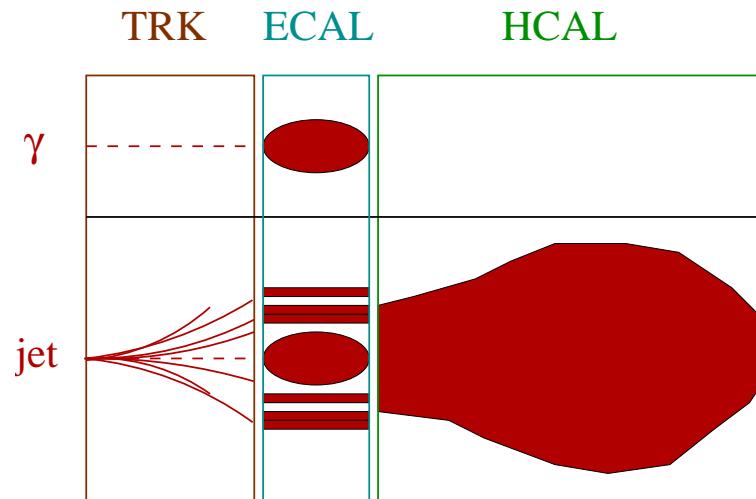
☞ Energy correction scheme

- ⇒  $F = 1$  for 5x5 crystal sum for the energy of unconverted photons;
- ⇒ overall containment factor;
- ⇒ local containment and boundaries;
- ⇒ correct for the bremsstrahlung;
- ⇒ crystal transparency (laser monitoring)

☞ Calibration with data

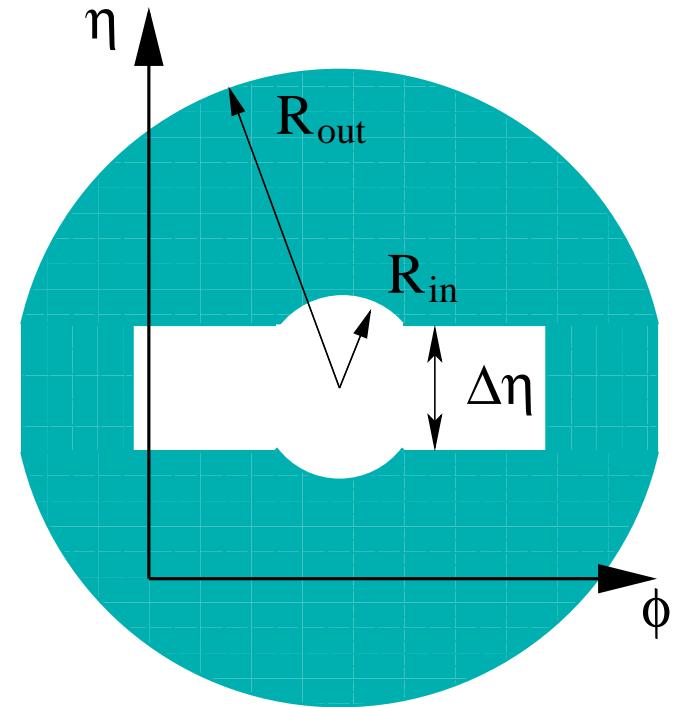
- ⇒  $Z^0 \rightarrow e^+ e^-$ ,  $Z^0 \rightarrow \mu\mu\gamma$  events
- ⇒  $\pi^0$  inter-calibration





- ☞  $\pi^0$  accompanied by other particles
- ☞ Isolation  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ 
  - ➡  $\text{Iso}_{\text{TRK}} = \sum p_T$  in tracker
  - ➡  $\text{Iso}_{\text{ECAL}} = \sum E_T$  in ECAL
  - ➡  $\text{Iso}_{\text{HCAL}} = \sum E_T$  in HCAL
- ☞ Low value of H/E identifies photons
- ☞ Suited for use as an electron control sample

Variable	$R_{\text{out}}$	$R_{\text{in}}$	$\Delta\eta$
$\text{Iso}_{\text{TRK}}$	0.4	0.04	0.015
$\text{Iso}_{\text{ECAL}}$	0.4	3.5 crystals	2.5 crystals
$\text{Iso}_{\text{HCAL}}$	0.4	0.15	-
H/E	0.15	-	-

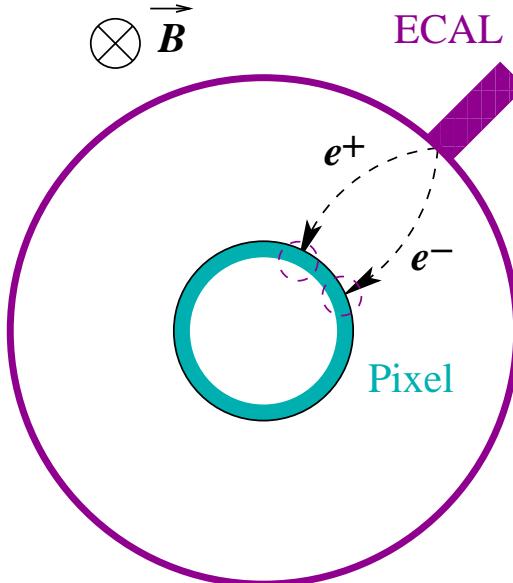
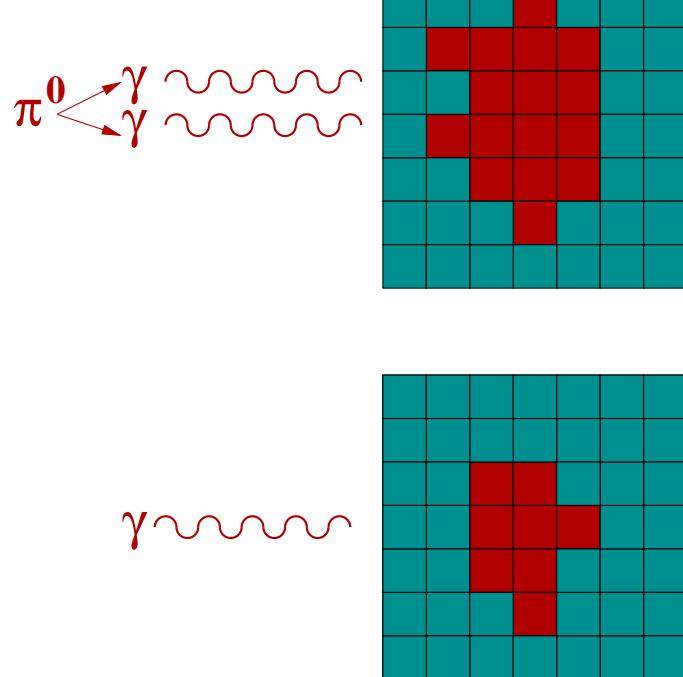


# Photon Identification

☞  $\pi^0 \rightarrow \gamma\gamma$  has wider transverse shower profile

$$\Rightarrow \sigma_{in in}^2 = \frac{\sum_{i=1}^{5 \times 5} w_i (\eta_i - \bar{\eta}_{5 \times 5})^2}{\sum_{i=1}^{5 \times 5} w_i},$$

$$w_i = \max(0, 4.7 + \ln \frac{E_i}{E_{5 \times 5}})$$



☞ **Reject electrons:** do not match pixel hits consistent with  $e^+$  or  $e^-$  track from interaction region

	Both photons in barrel		One or more in endcap	
	$\min(R_9) > 0.94$	$\min(R_9) < 0.94$	$\min(R_9) > 0.94$	$\min(R_9) < 0.94$
$p_T^{\gamma\gamma} < 40 \text{ GeV}/c$				
Signal	20.9%	27.1%	9.4%	11.6%
Background	16.7%	26.3%	12.9%	20.3%
Signal $\sigma_{eff}$ ( $\text{GeV}/c^2$ )	1.64	2.43	3.16	3.59
$p_T^{\gamma\gamma} > 40 \text{ GeV}/c$				
Signal	10.2%	12.2%	3.5%	5.1%
Background	4.3%	7.9%	4.3%	7.4%
Signal $\sigma_{eff}$ ( $\text{GeV}/c^2$ )	1.41	2.10	2.96	3.41

- ☞ High value of  $R_9 = E_{3\times 3}/E_{SC}$  readily identifies nonconverted photons
  - ➡ automatically selects against  $\pi^0$ ;
  - ➡ converted category remains background enriched;

- ☞ Classify events according to  $R_9, \eta$ 
  - ➡ S/B varies with  $\eta$ ;
  - ➡ different resolution for EB and EE;
  - ➡ conversion degrades resolution and raises background
- ☞ In addition use  $p_T^{\gamma\gamma}$  classes