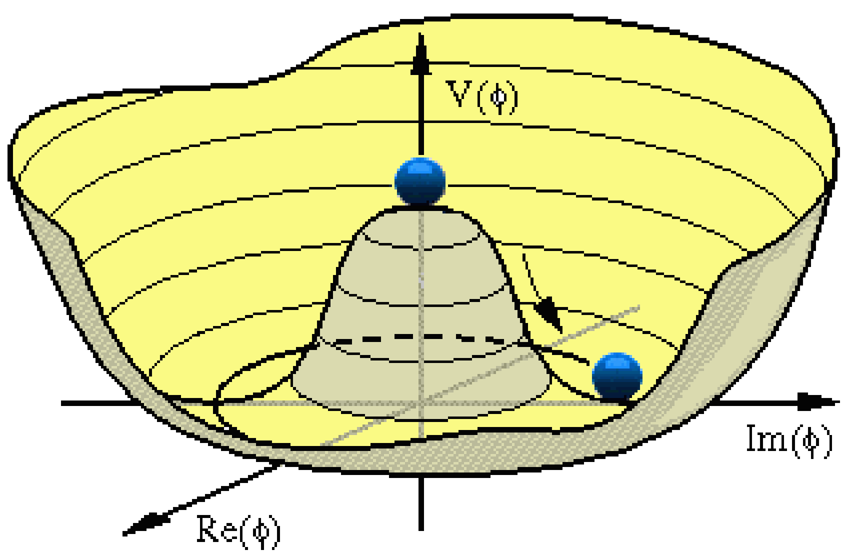
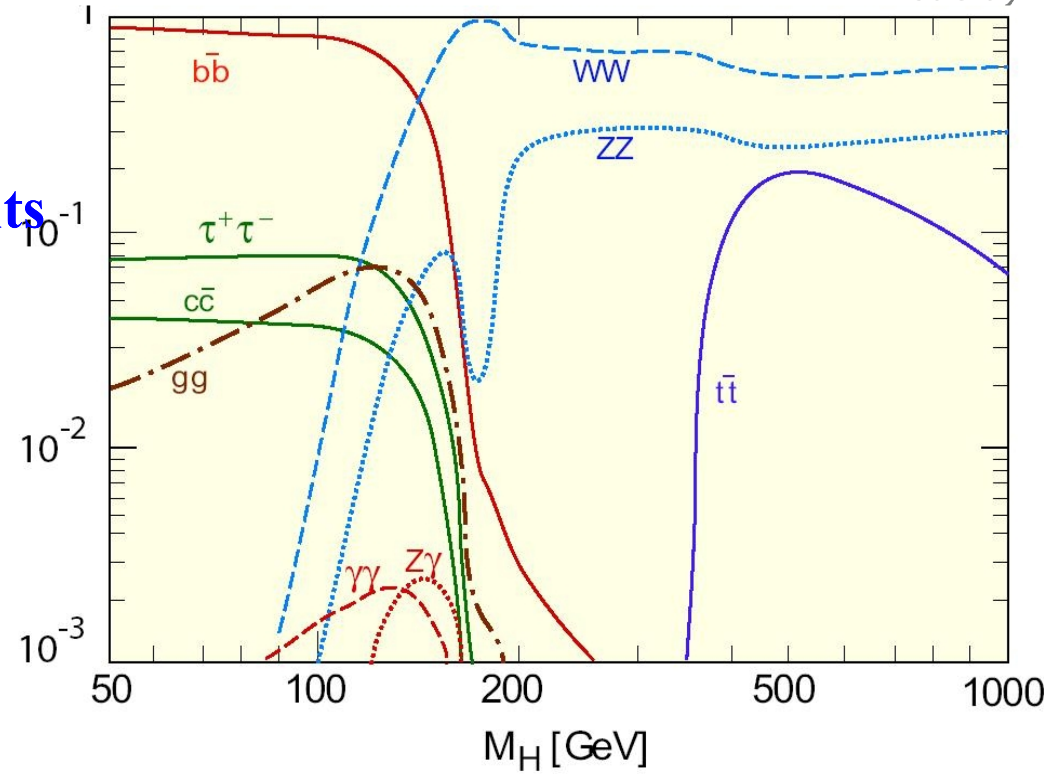
Role of the CMS electromagnetic calorimeter in the hunt for the Higgs boson through the two-gamma decay channel

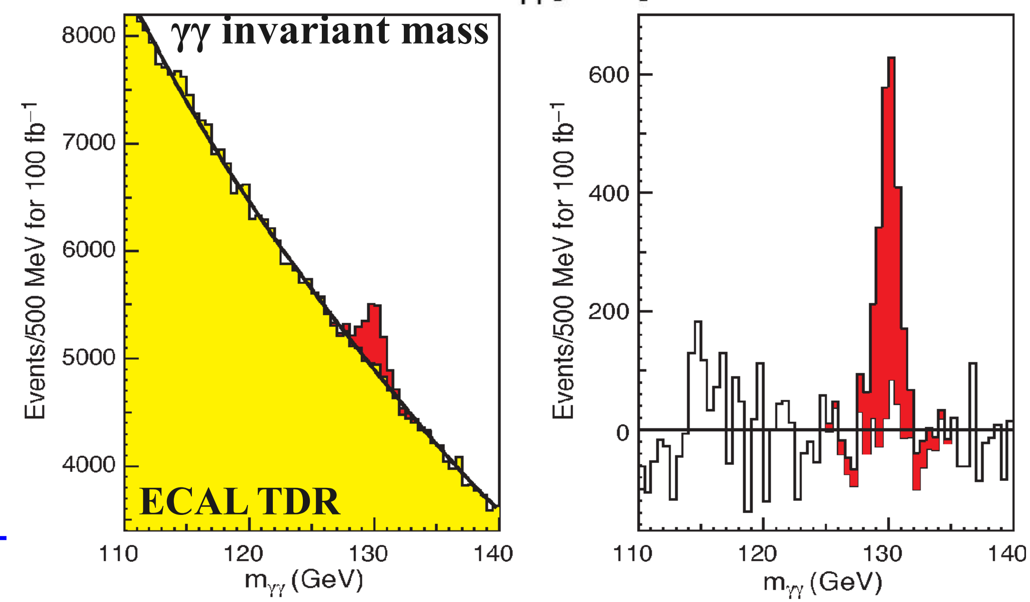


M. Déjardin, Irfu/SPP CEA-Saclay
On behalf of the CMS collaboration

Where to hunt ?

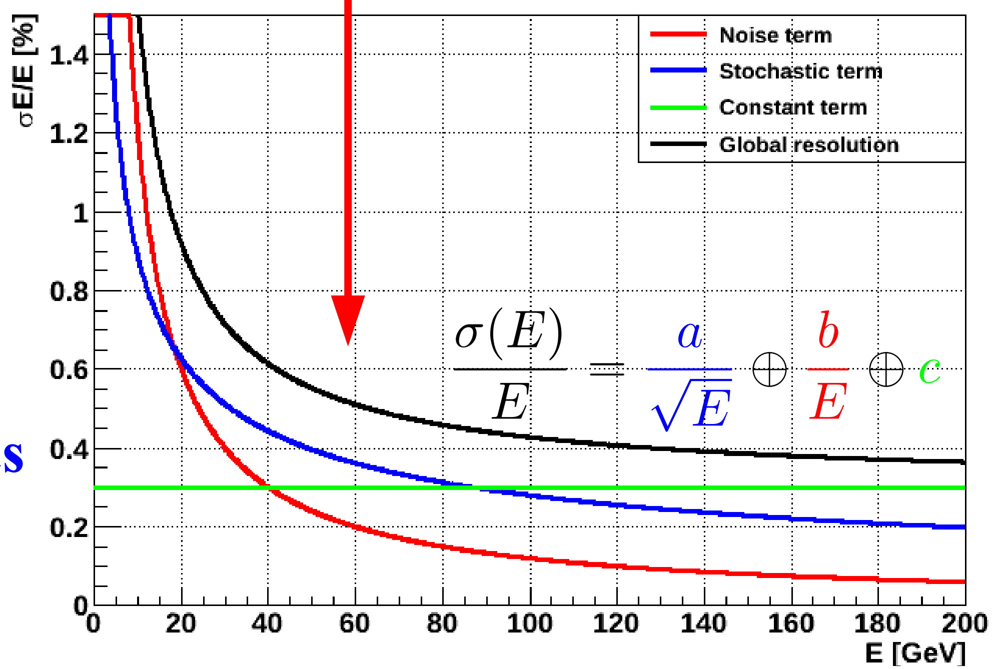
- Mid' 90s : Strong indication for low mass Higgs boson, if any...
  - Top and W masses + LEP constraints
  - DIS '95 : $m_H = 72^{+148}_{-48} GeV/c^2$
- Golden channels for low mass Higgs boson search:
  - $H \rightarrow ZZ$
    - ▶ e/μ final states
  - $H \rightarrow \gamma\gamma$
    - ▶ Small branching ratio but
    - ▶ Clean signature
- Drove the final choices for ECAL design





How to hunt ?

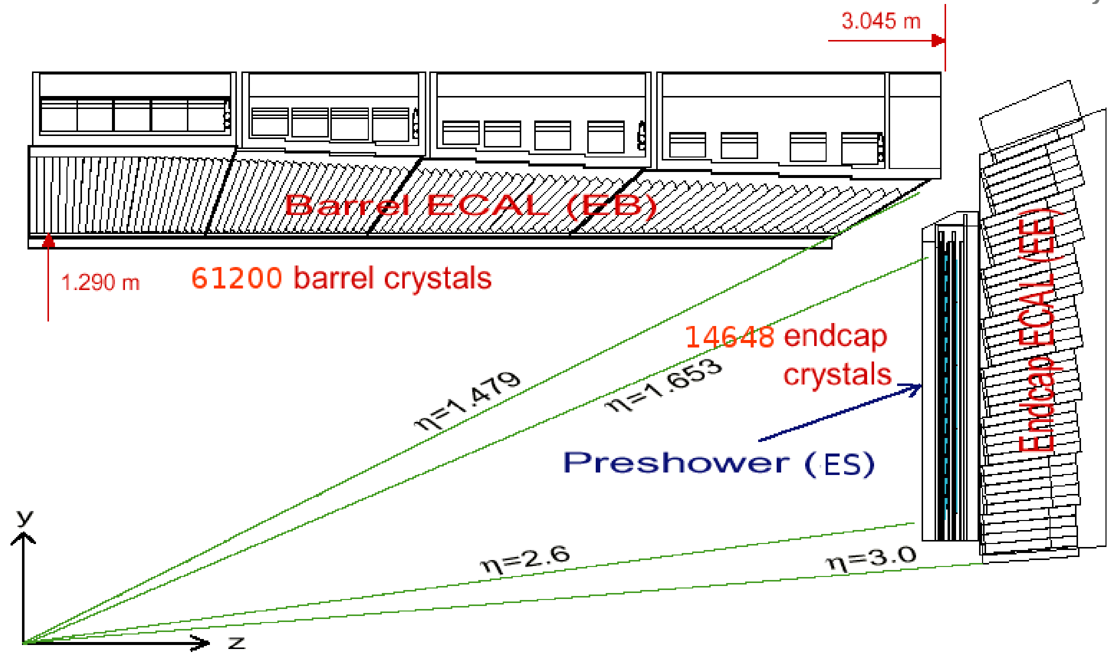
- Optimize the resolution for the Higgs boson search
  - $H \to \gamma\gamma$
    - $$\frac{\sigma_m}{m} = \frac{1}{2}\left(\frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_\theta}{tg(\frac{\theta}{2})}\right)$$
- The **stochastic** term
  - Quantifies effects of fluctuations
    - Homogeneous and deep calorimeter
- The **noise** term
  - Quantifies the noise due to electronics and/or pileup
    - Target : 40 MeV/channel
- The **constant** term
  - Quantifies the stability of the intercalibration of different channels

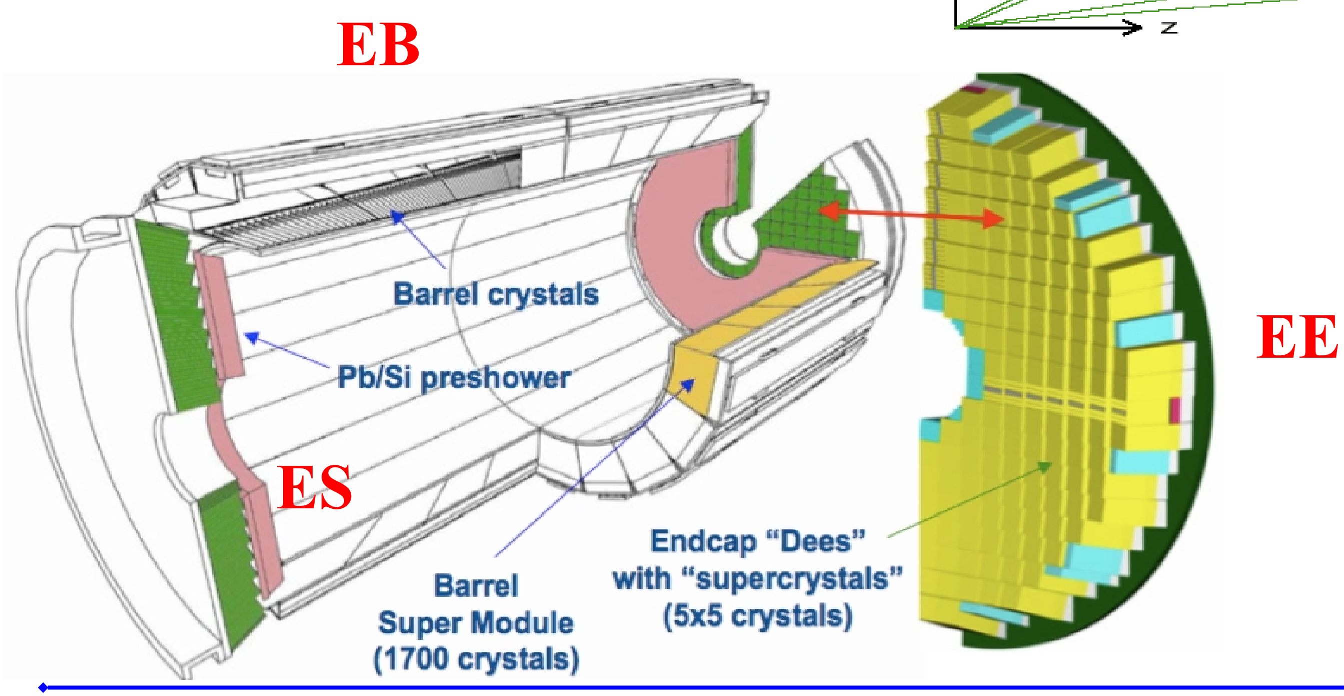


- Goal : $$\frac{\sigma(E)}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{150MeV}{E} \oplus 0.005$$ in Barrel
  $$= \frac{5.7\%}{\sqrt{E}} \oplus \frac{205MeV}{E} \oplus 0.005$$ in Endcap

The CMS electromagnetic calorimeter (ECAL)

- **Geometry optimized for photon detection**
  - **Off-pointing geometry**
  - **High granularity**
    - ▶ 2.2x2.2x23 cm³ in EB (26 X_0)
    - ▶ 3.0x3.0x22 cm³ in EE (25 X_0)

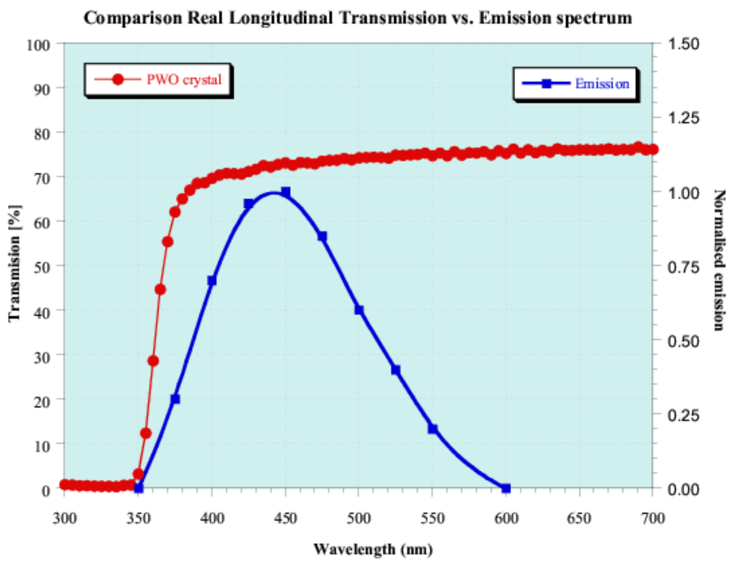


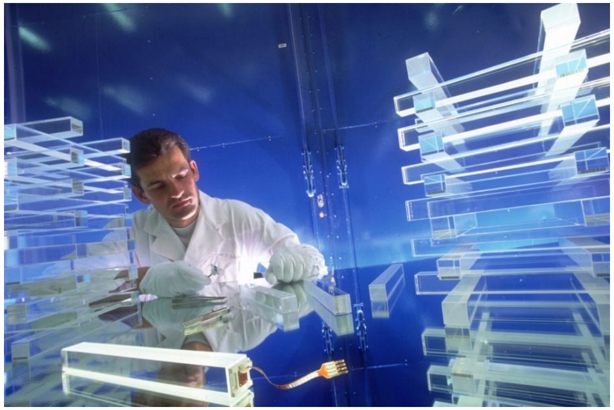


- **Barrel (EB)**
  36 supermodules x 1700 crystals
  |η|<1.48
- **Endcaps (EE)**
  2x7324 crystals, 1.48<|η|<3.0
- **Preshower (ES) (3X_0)**
  Lead-SiStrip calorimeter
  1.64<|η|<2.6

The stochastic term

- Quantifies the fluctuations
  - Sampling (lateral or longitudinal)
  - Preshower, etc.
- Optimization :
  - Homogeneous detector
    - ► Crystals





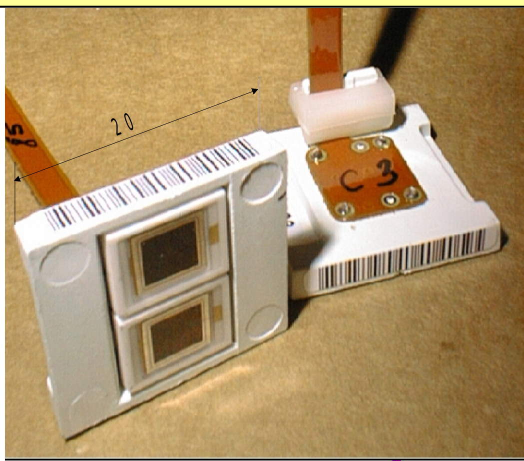
	PbWO4
Density [g/cm3]	8,28
X0 [cm]	0,89
Molière radius	2,19
Scintillation light decay time [ns]	5 (39%) 15 (60%) 100(1%)
Index	2,30
Emisison peak [nm]	420-440 nm
T dep. [%/°C]	-2
Optical yield (NaI=100 %)	1,3 = 100γ/MeV

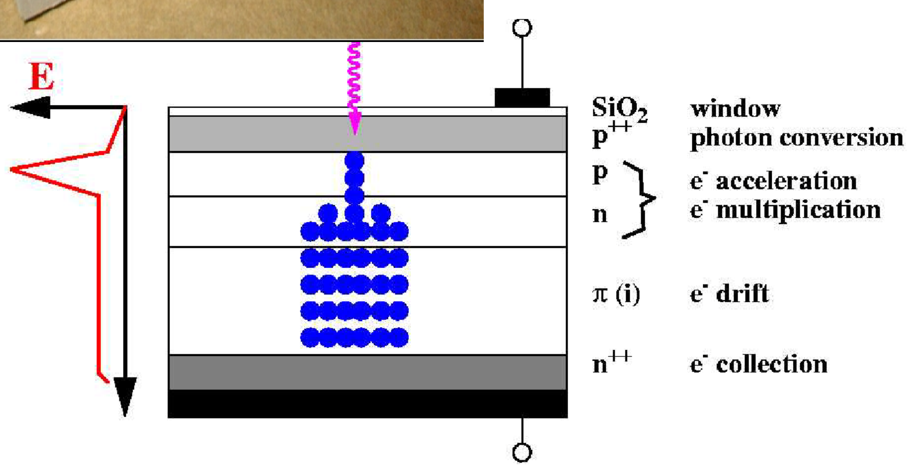
The photo-detectors

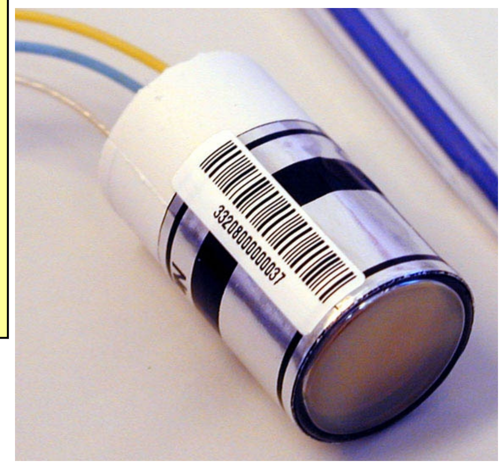
Barrel – Avalanche Photo-Diodes :

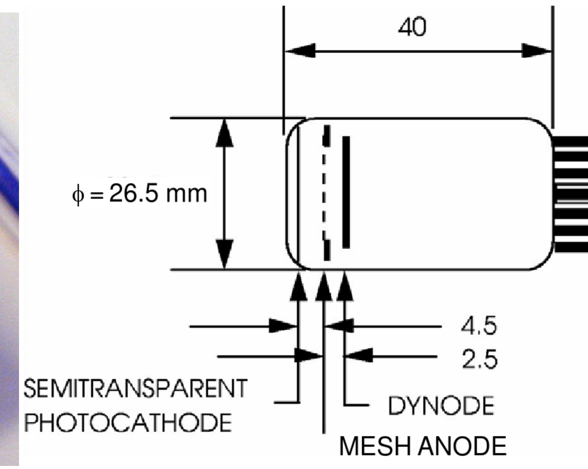
Twin 5x5 mm^2 APDs/crystal

- Gain: 50
- QE: ~75% @ 420 nm
- Temperature dependency: -2.4%/^{O}C









Endcaps - Vacuum Photo-Triodes:

B field direction more favorable to VPTs

(Axes : 8,5^{O} < |θ| < 25,5^{O} w/r to field)

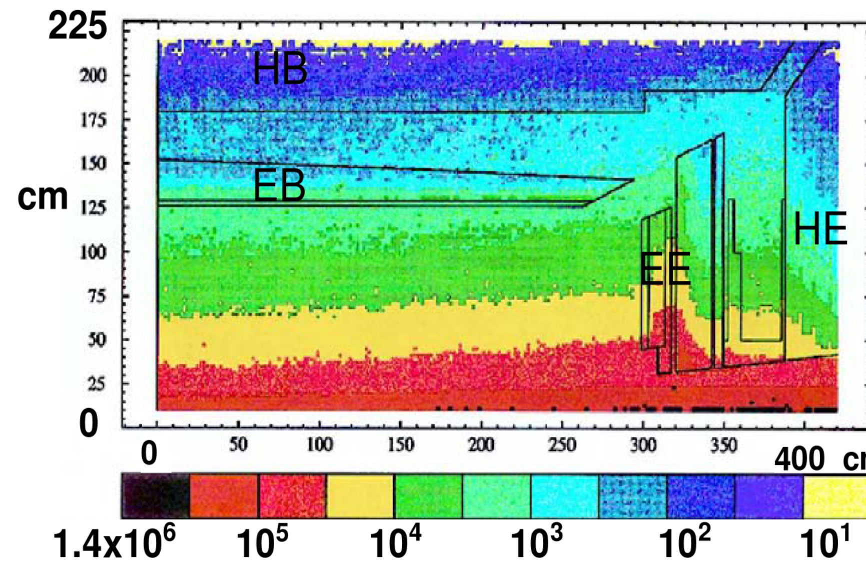
More rad-hard than Si diodes (with UV window)

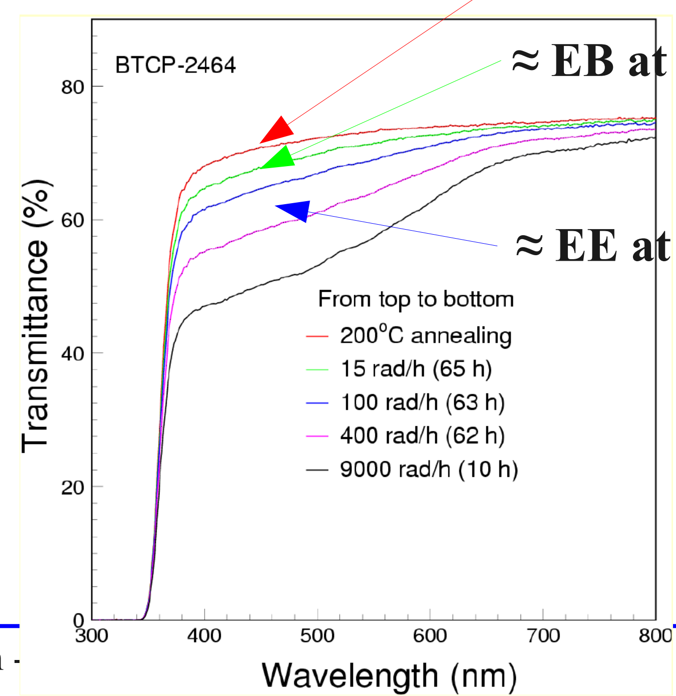
- Active area ~ 280 mm^2/crystal
- Gain 8 -10 @ B = 4 T
- Q.E. ~ 20% @ 420 nm
- Small temperature dependency

Radiation effects

- **Do NOT affect scintillation**
- **Affect transmission**
  - **Color centers creation**
    - **With some self-recovery**
    - **With saturation effect**
- **R&D 1995-2002**
  - **Minimize the transmission loss**
  - **Optimize the time constants**

- **Mandatory to measure the crystal transparency continuously !**

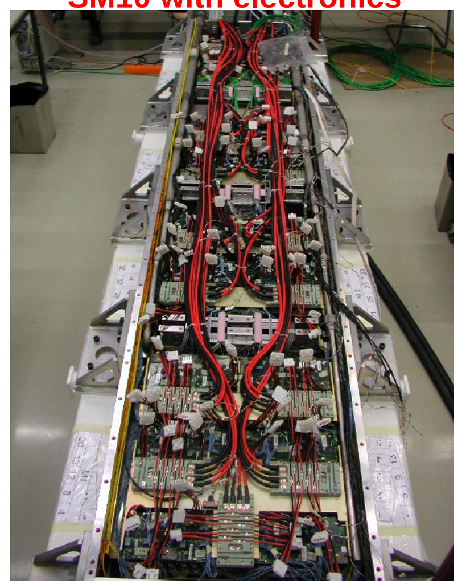




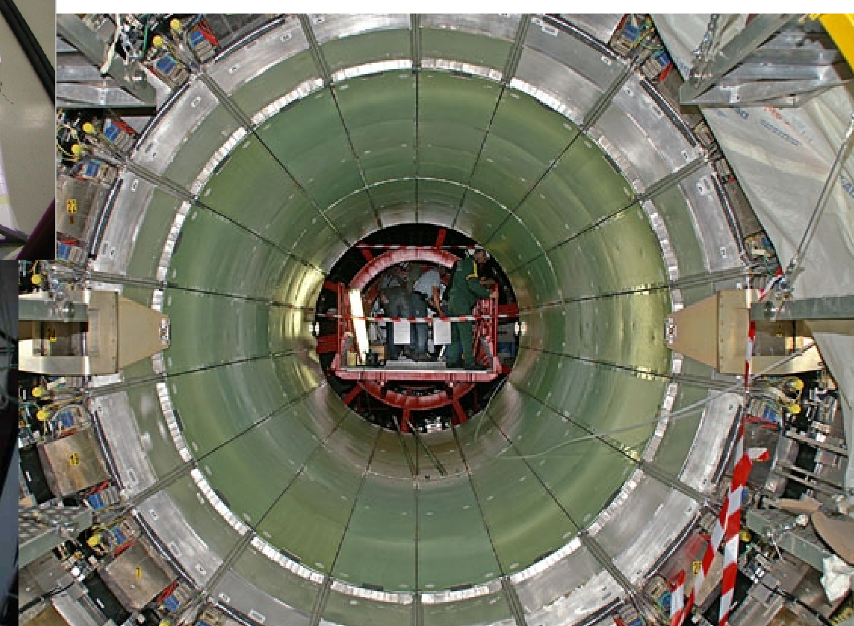
The noise term

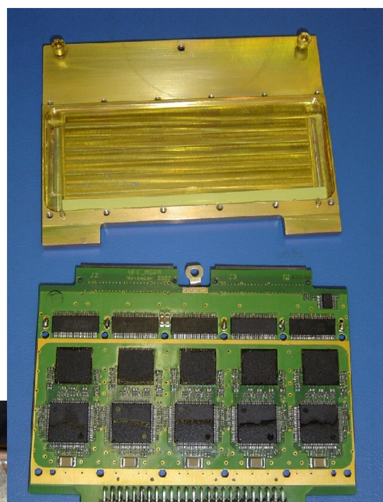
- **Electronics / EMC : σ(noise) ≈ 40 MeV (EB)**
  - **Maintain performances from single channel to full detector in situ**

SM10 with electronics

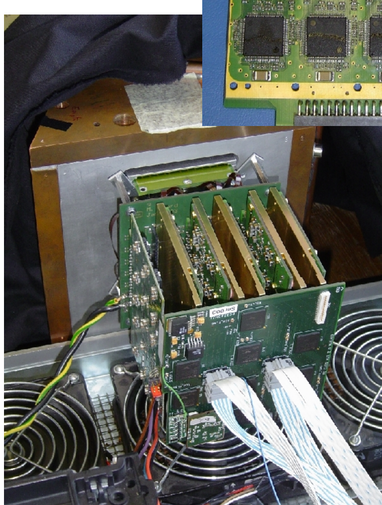


2007





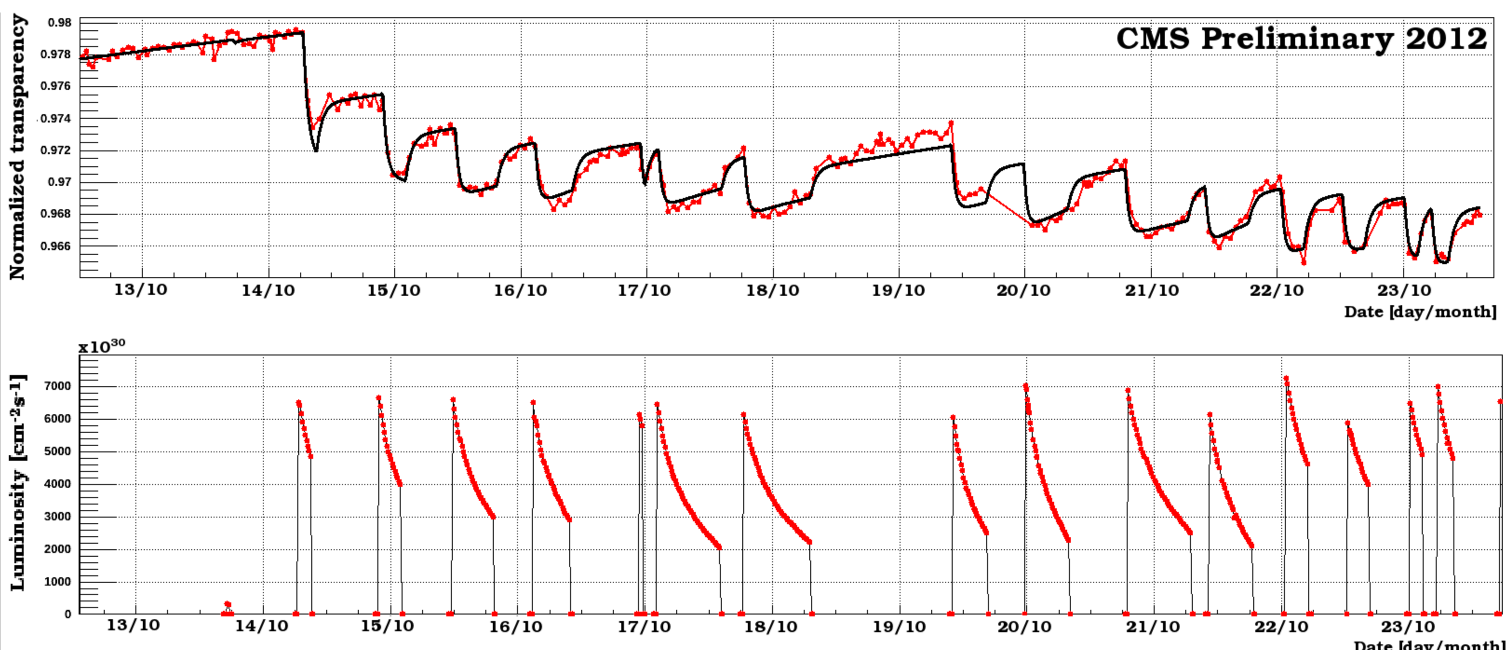
2001



2004

The constant term

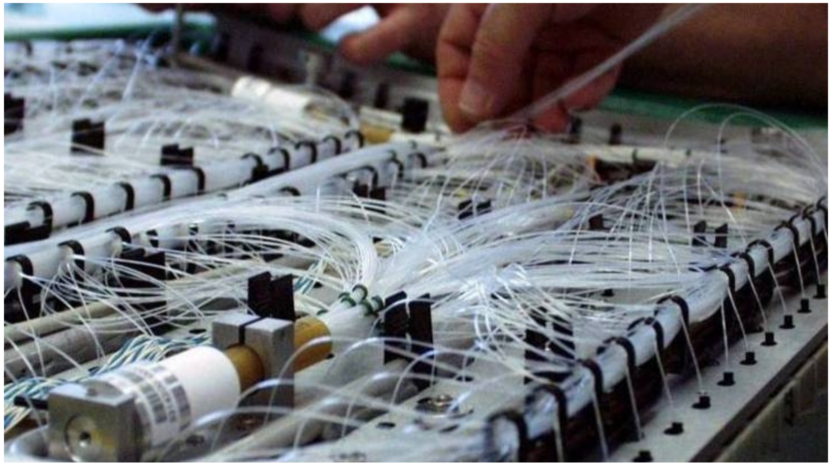
- **Limited by longitudinal non-uniformity of light collection**
- **Sensitive to channel inter-calibration**
  - ▶ Long term stability mandatory ! (few months)
  - ▶ 1 year period in 2011 and 4 periods in 2012
- **Radiation-tolerant crystals**
  - ▶ Measure and correct transparency in quasi real time

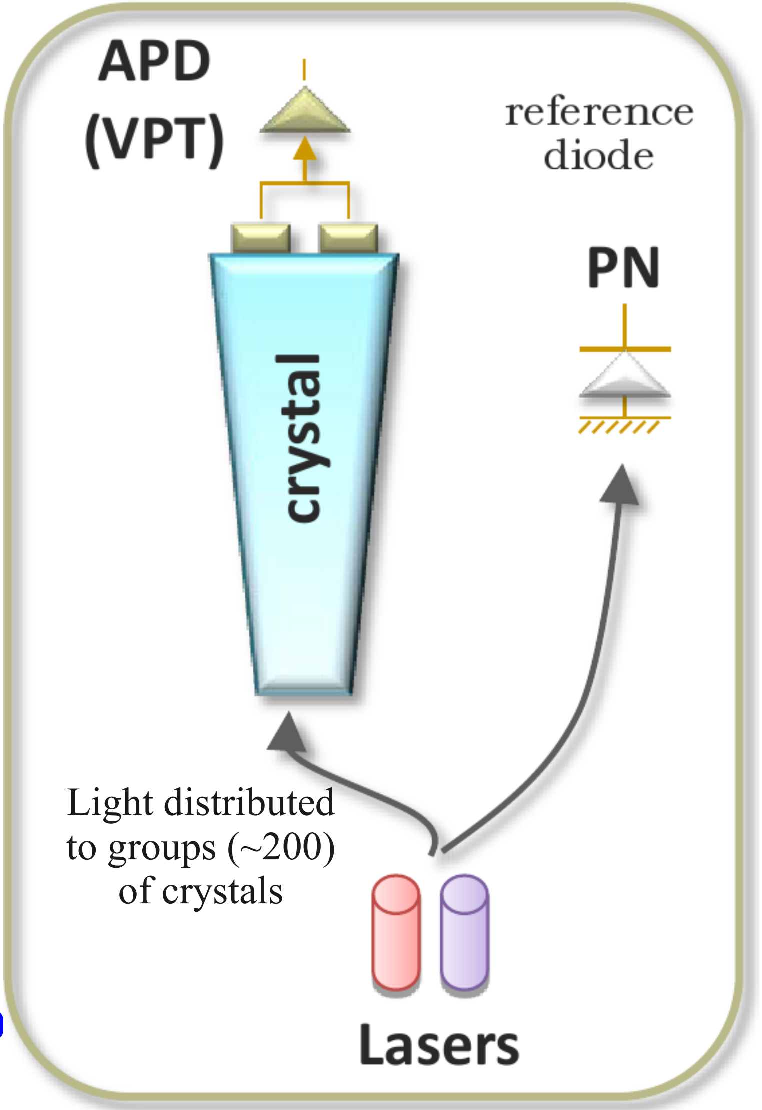


Good agreement between simple model of **Production/Recovery/Saturation** process with 2 types of defect and actual crystal behavior

The crystal transparency monitoring system

- Send light to each crystal
  - Measure the channel response
  - Normalize with reference PN diode response (APD or VPT/PN)



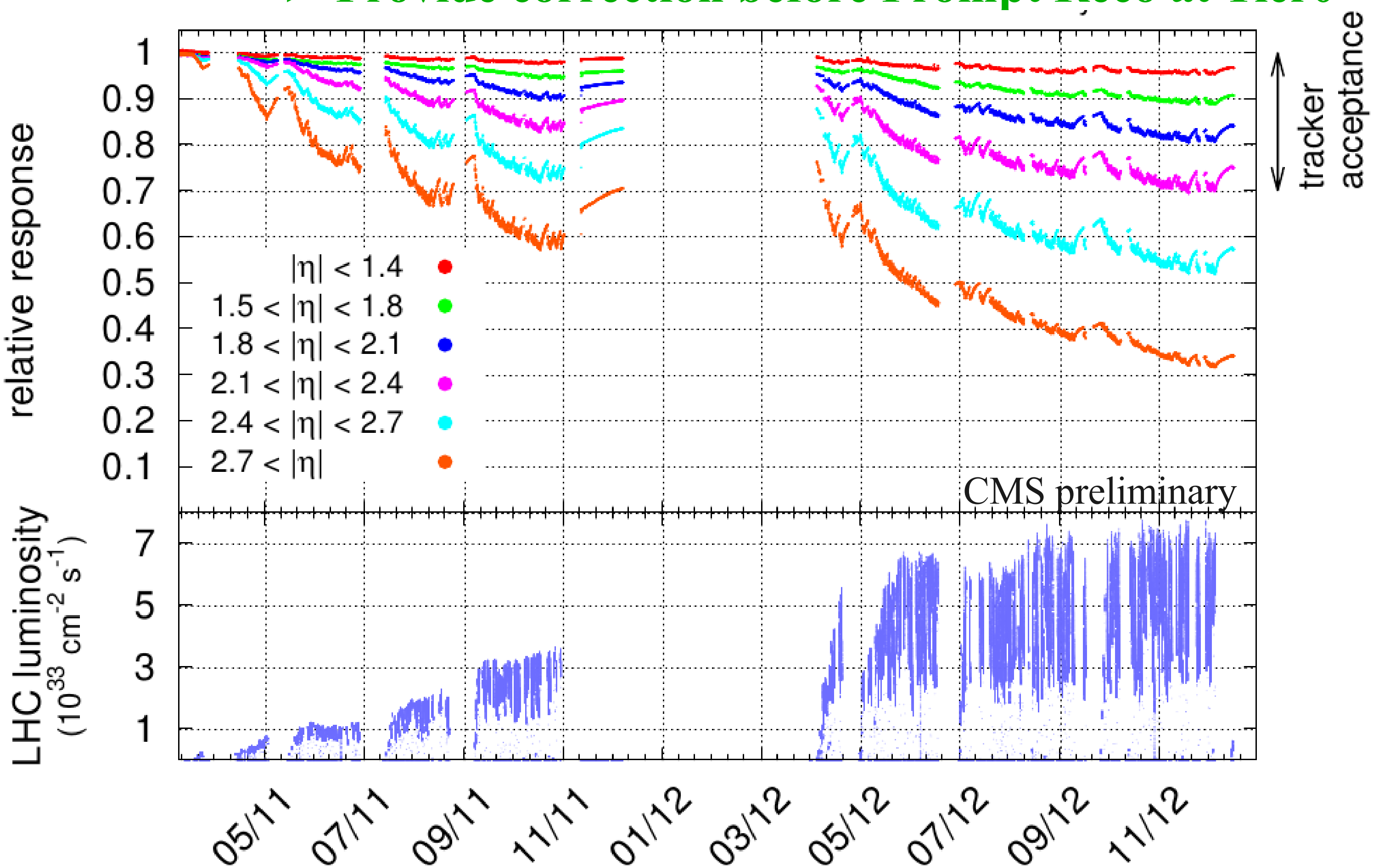


- Continuous process
  - 100 Hz laser firing during LHC abort gap
    - ►Full ECAL measurement every 40 mn

(92 regions, 600 laser pulses per region)

Measuring the transparency

- **Real time analysis of data**
  - **~24h/24, 7d/7**
    - ► **Data processing and validation**
    - ► **Provide correction before Prompt Reco at Tier0 → <48 h**



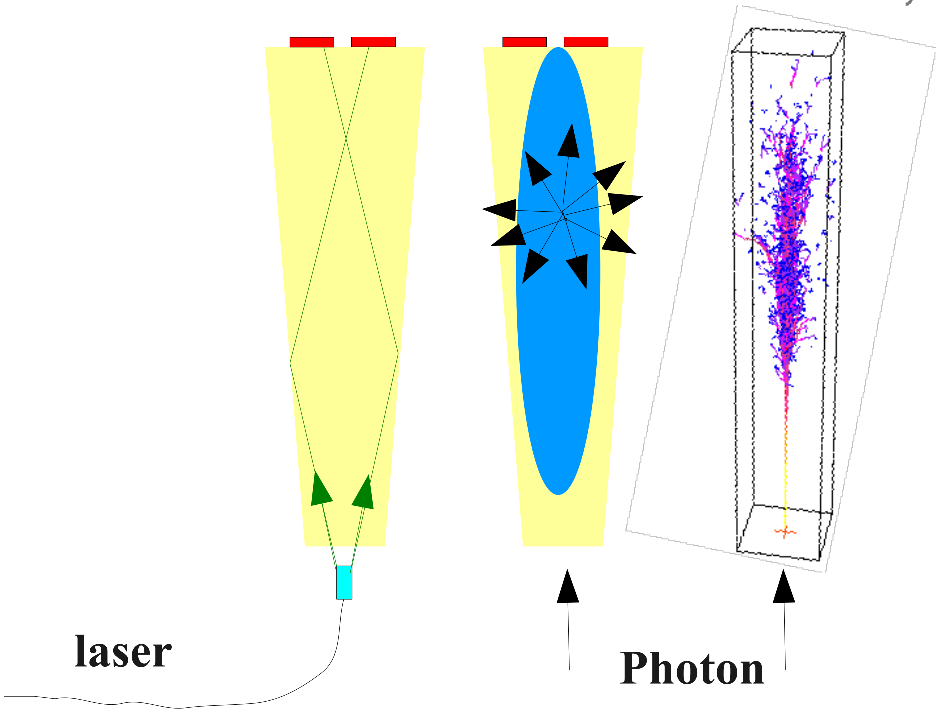
Loss after 25 fb^{-1}

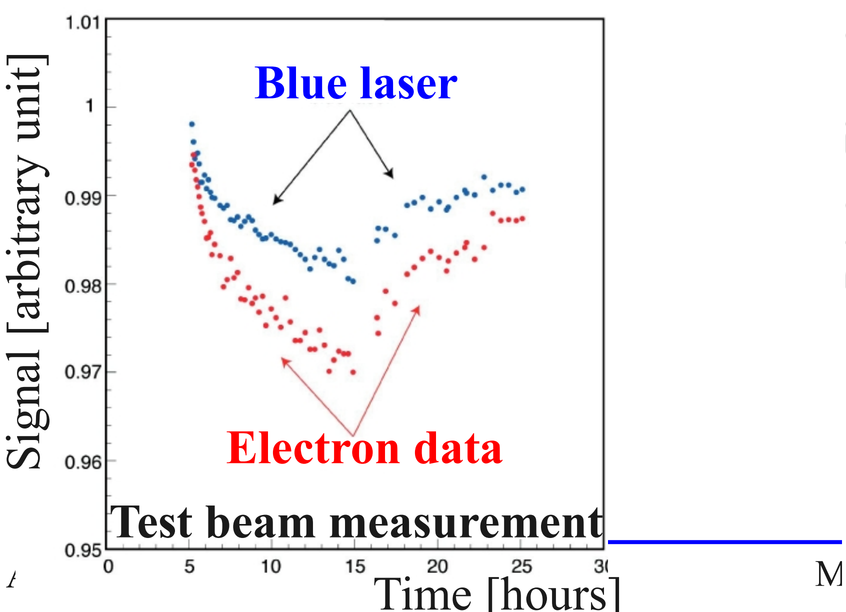
Barrel: loss ≈ 5%

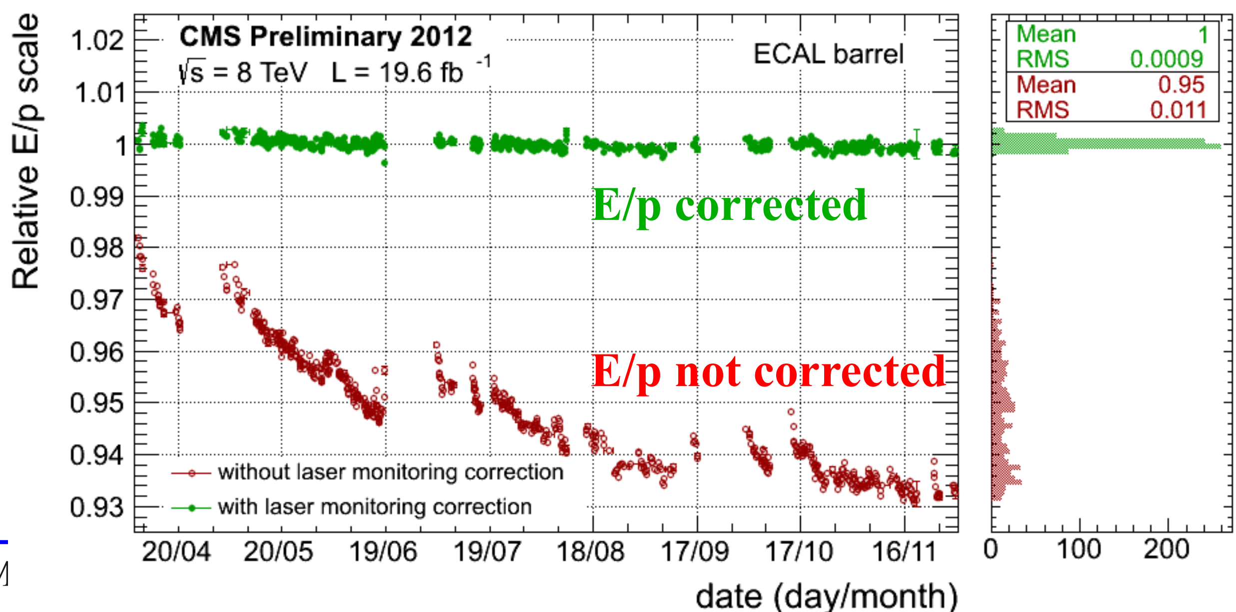
Endcap : loss ≈ 18%

From laser to scintillation

- Comparison
  - Different light paths in crystals
    - ▶ Different attenuation
- Which relationship?
  - $\frac{S(t)}{S_0} = \left(\frac{R(t)}{R_0}\right)^{\alpha}$
  - Tuned on data
    - ▶ $\alpha_{effective}$ = 1.52 in EB
    - ▶ $\alpha_{effective}$ = 1.16 in EE





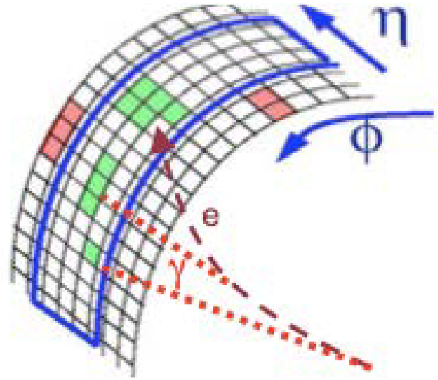


(Inter)Calibrating the calorimeter

- Use of physics events
  - φ-symmetry :
    - ► Short calibration periods ≈ 2 days
    - ► Frequent checks and controls
  - π^0/η
    - ► Average calibration periods ≈ weeks
  - E/p with electrons
    - ► Long calibration periods ≈ months
  - $Z^0 \rightarrow e^+e^-$
    - ► Long calibration periods ≈ months
    - ► ECAL absolute scale
- All details (and more) in M. Obertino's talk

Shower clustering and corrections

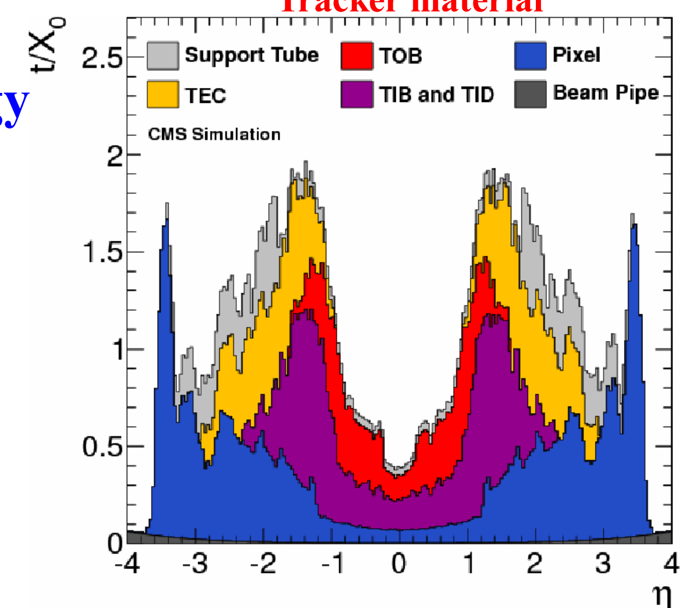
- **Dynamic clustering**
  - **Recover energy radiated upstream of ECAL**
  - **Bremstrahlung electron**
  - **Late converted photons**
    - ► Superclusters of clusters along φ
    - ► Use of preshower in endcaps

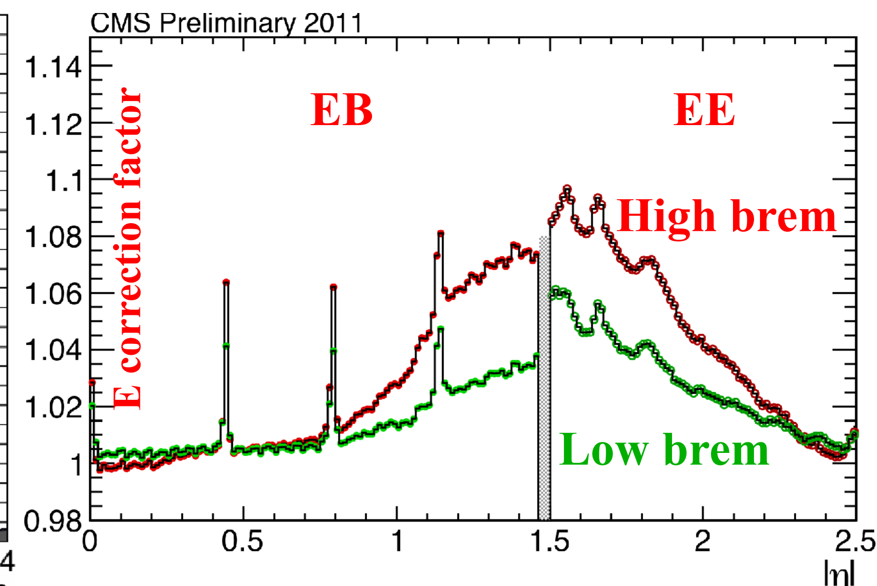


Shower shape parameter :
R9 = E(3x3)/E(SC)

- **Material effects**
  - **Correct for energy lost upstream of ECAL**

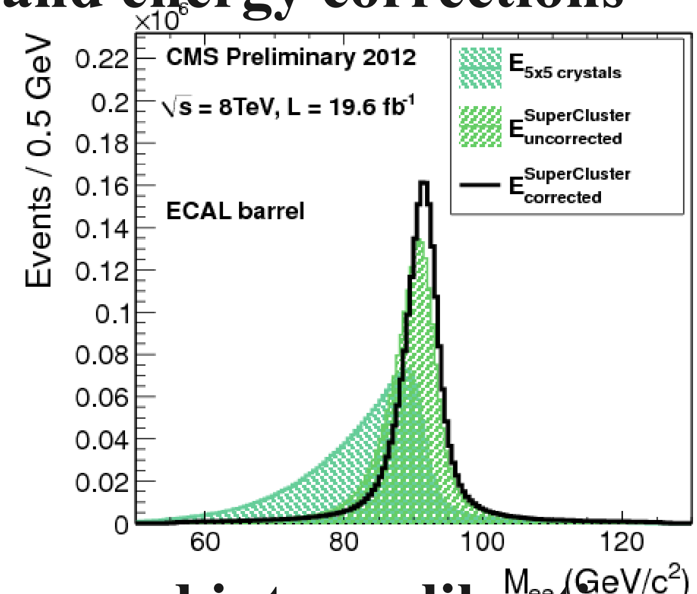
Tracker material

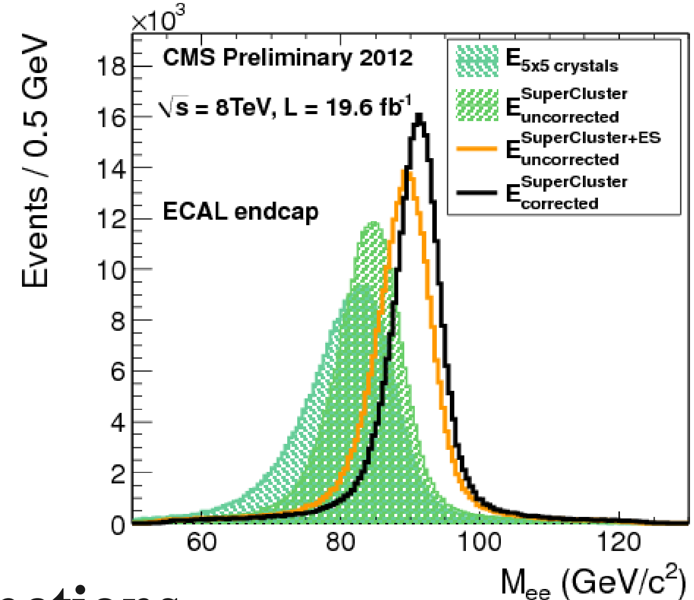




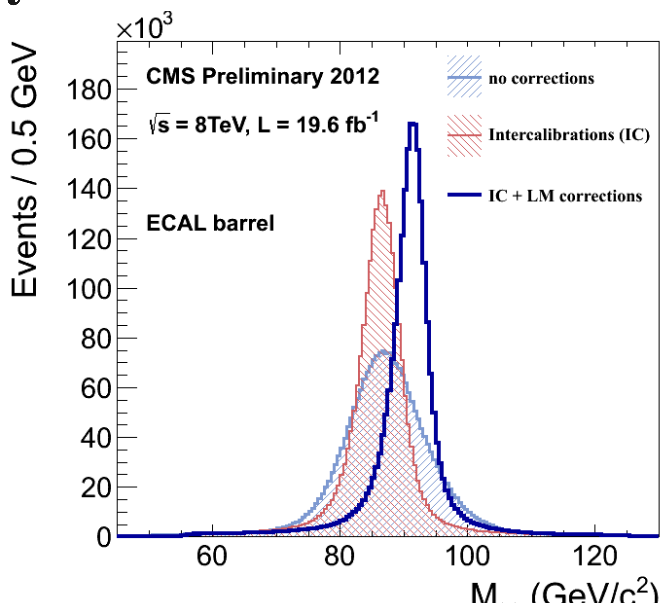
Effect of corrections: Z^0 mass peak

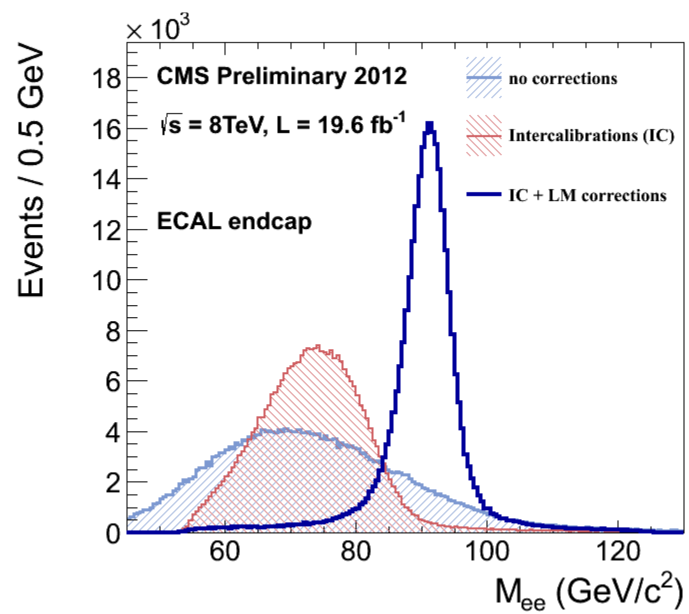
- Clustering and energy corrections



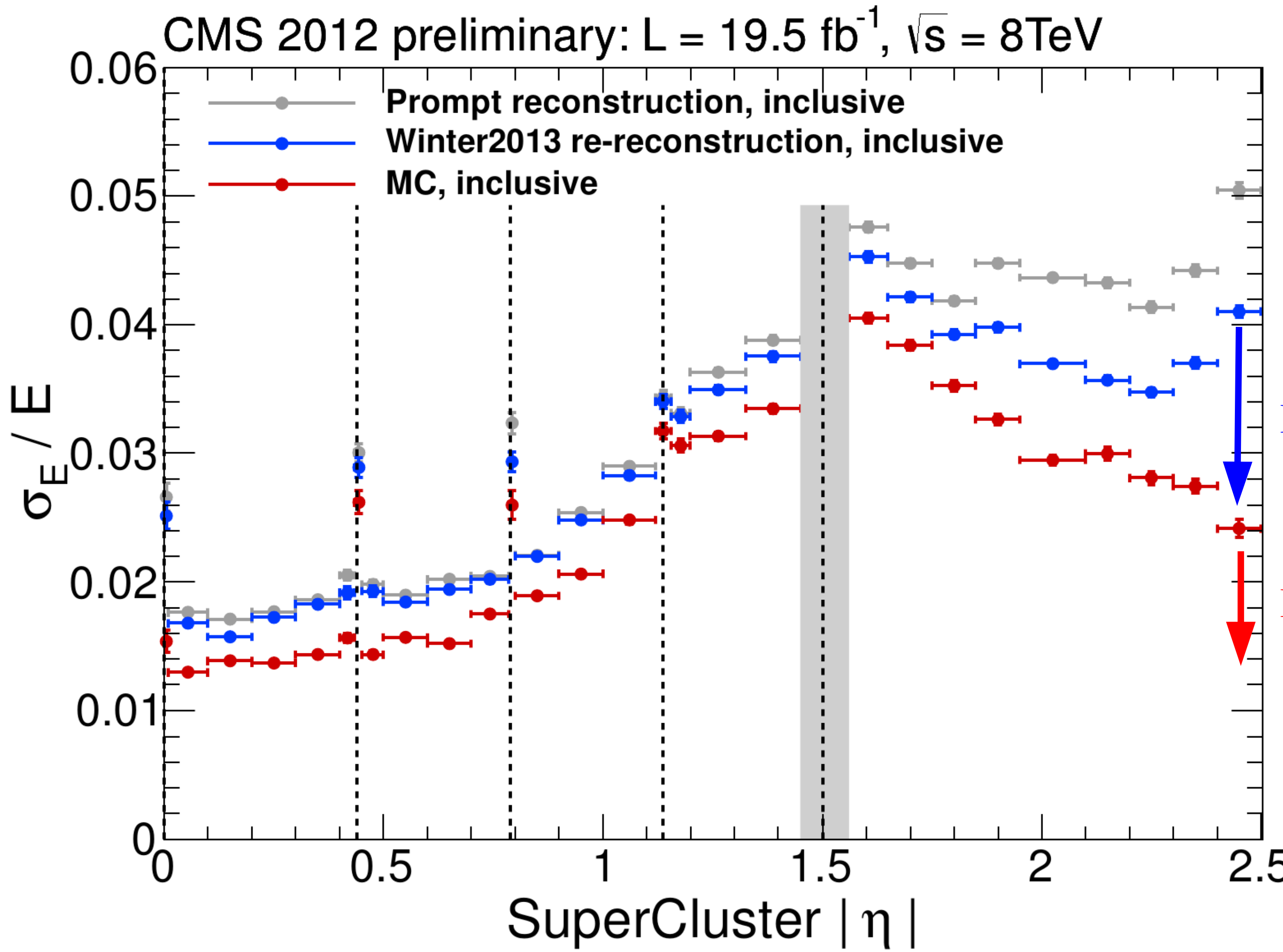


- Transparency and inter-calibration corrections





- Resolution of the energy measurement
  - Electrons from $Z^0 \rightarrow e^+e^-$



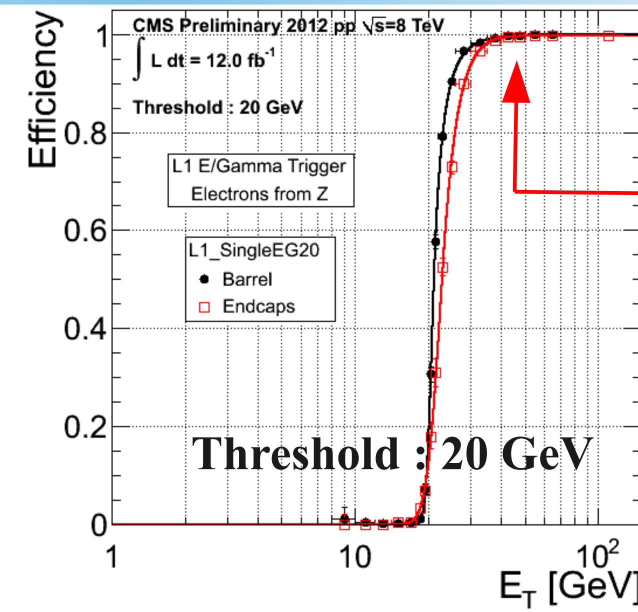
2013-2014 goals:

Put blue points over red points

Put red points lower

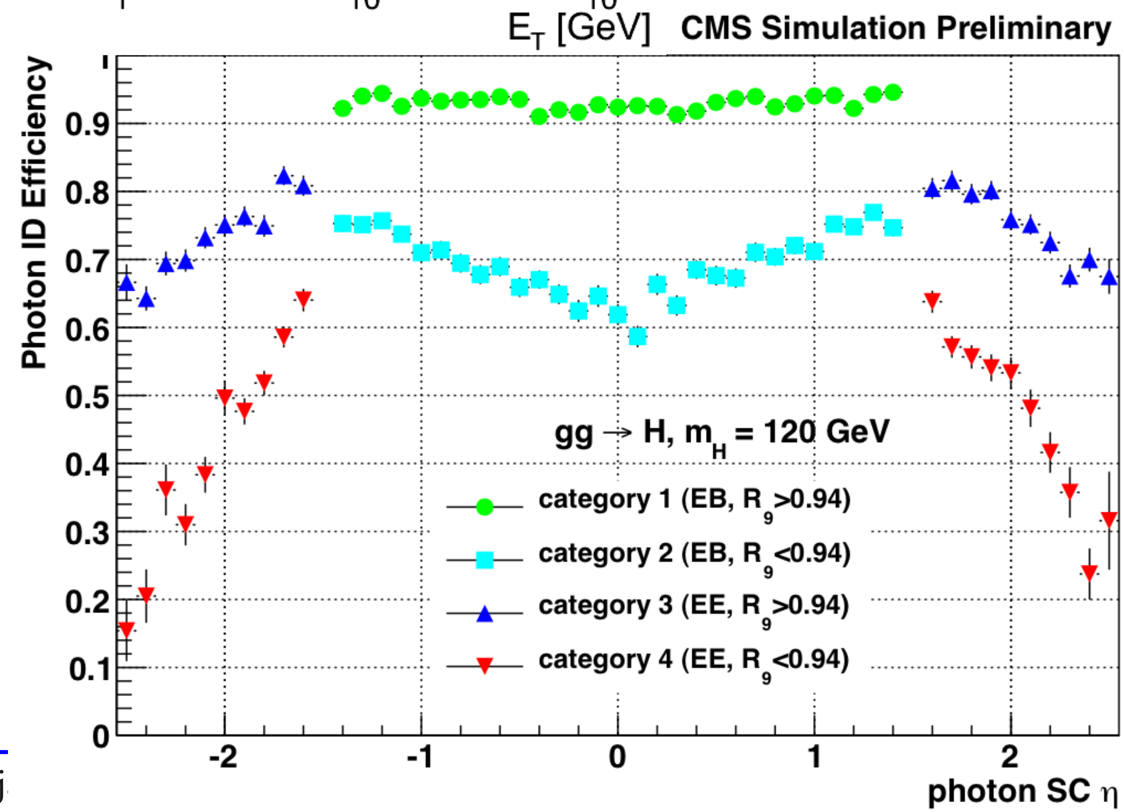
Identifying the photons

- **Online selection**
  - Trigger performances
    - ▶ See A. Zabi's talk



Photons from H→γγ

- **Offline selection tuned on 4 categories**
  - Barrel - Endcap
    Converted- Unconverted
    - ▶ Same S/B in all categories
    - ▶ MVA technique
  - Identification variables
    - ▶ Shower spread vs η
    - ▶ Isolation (pileup corrected)
    - ▶ H/E
    - ▶ Electron track veto

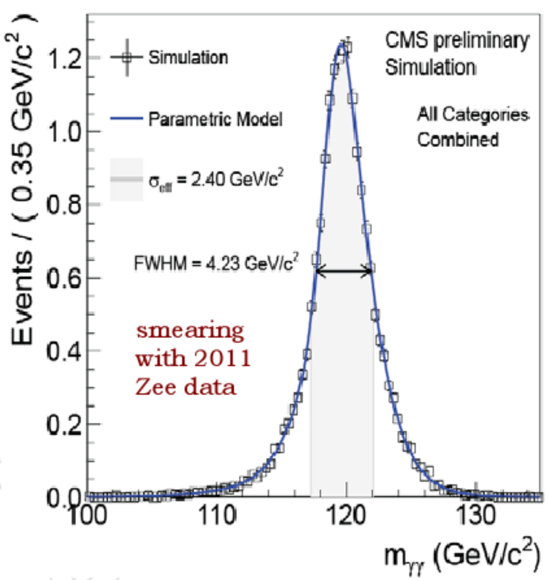


Application: Search for a narrow resonance

- **2 photons in the final state**
  - ▶ **γγ invariant mass resolution**

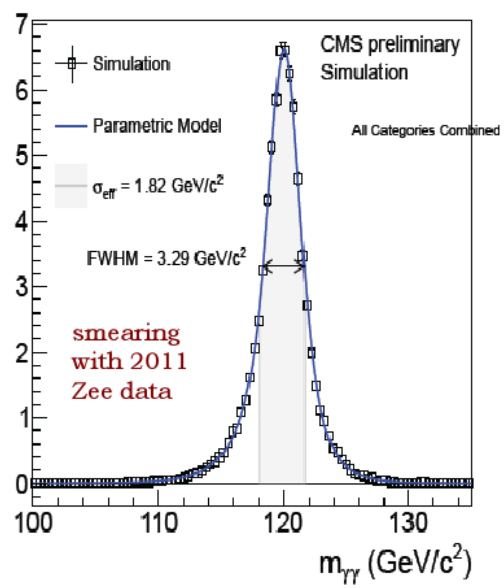
EPS
July 2011

FWHM/2.35 = 1.80 GeV (1.50 %)



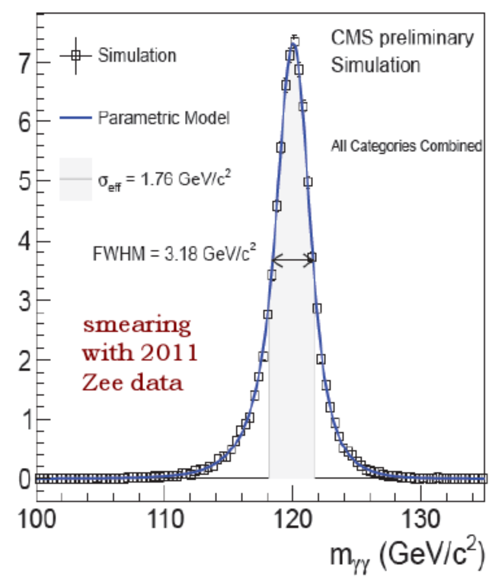
Moriond
March 2012

FWHM/2.35 = 1.40 GeV (1.17 %)



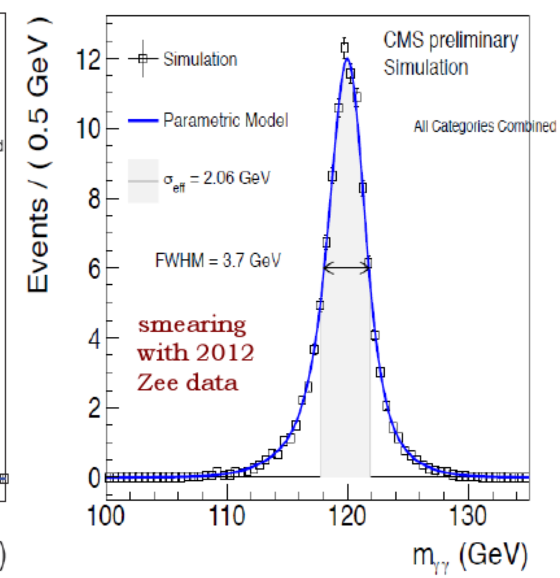
ICHEP
July 2012

FWHM/2.35 = 1.35 GeV (1,13 %)



ICHEP
July 2012

FWHM/2.35 = 1.57 GeV (1.31 %)

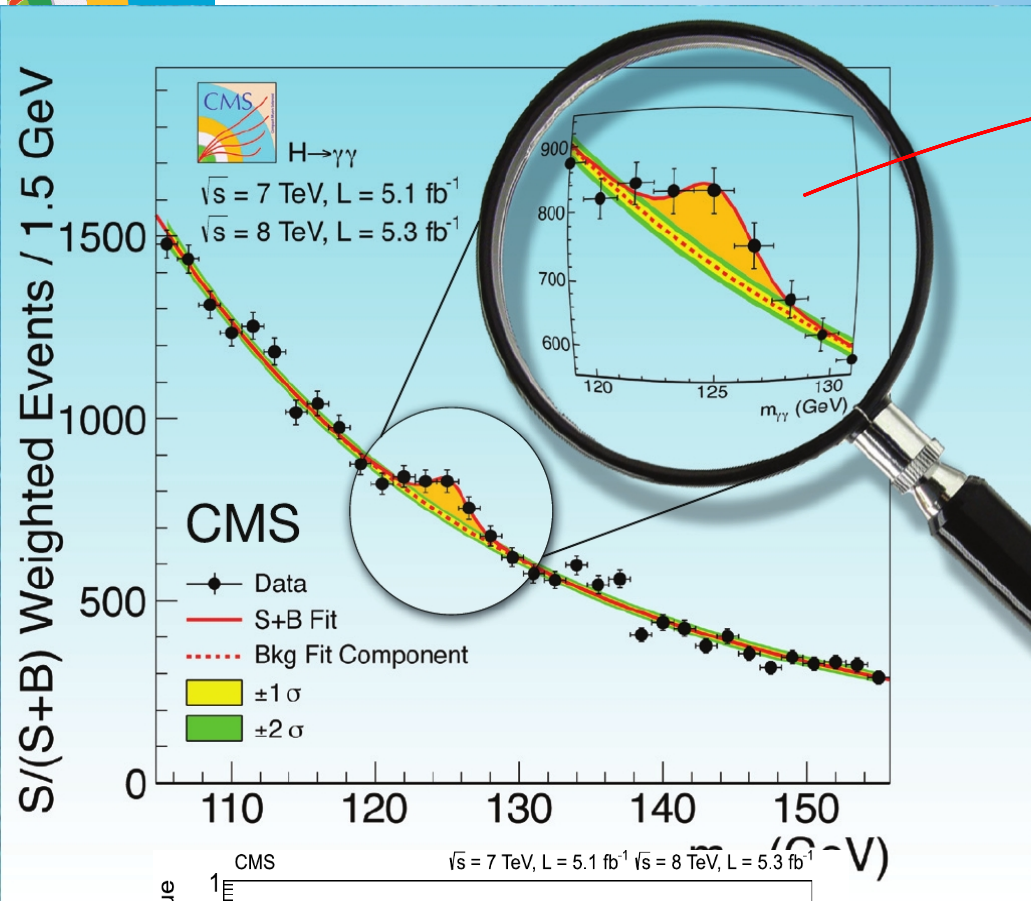


Improvements of ECAL calibration (2011 Zee data) →

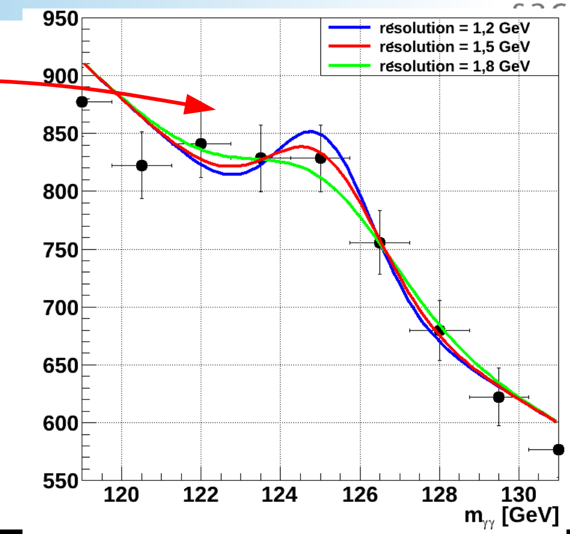
Prompt reco 2012

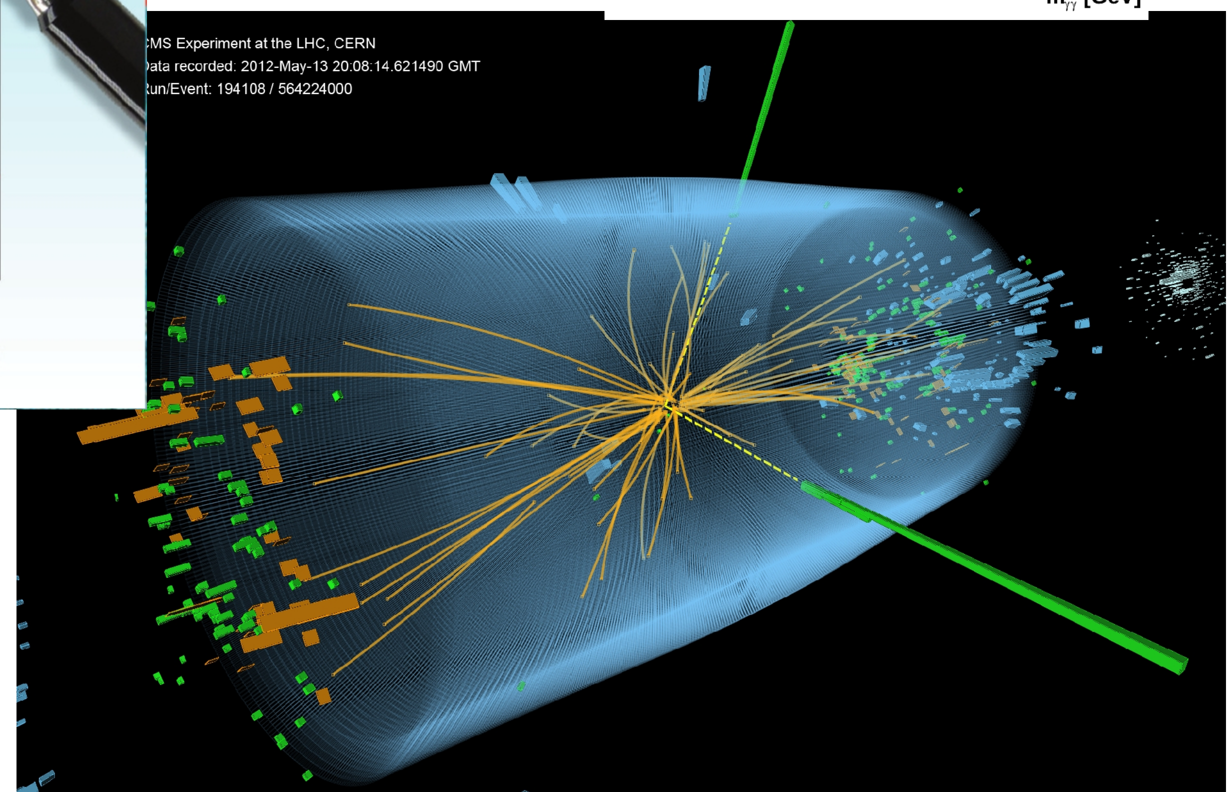
Best category (EB photons, not converted) : FWHM/2.35 = 1.04 GeV (0.87%)

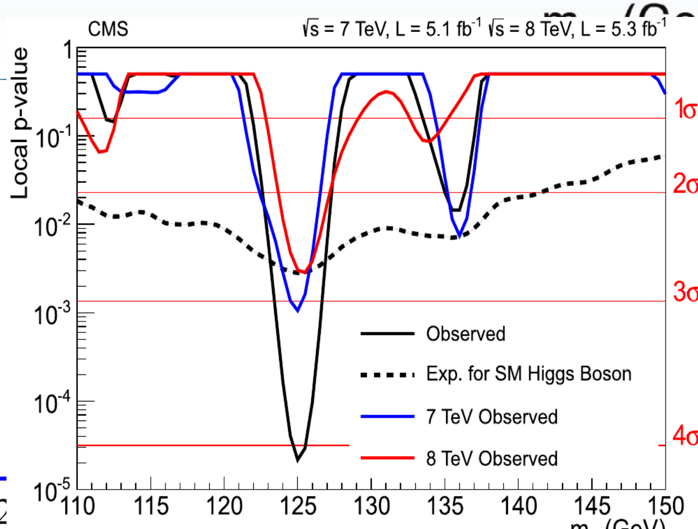
July 2012: The discovery



And what if ...

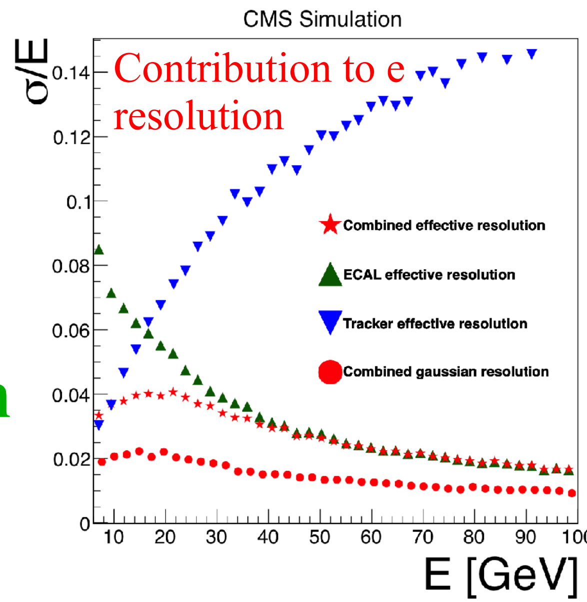


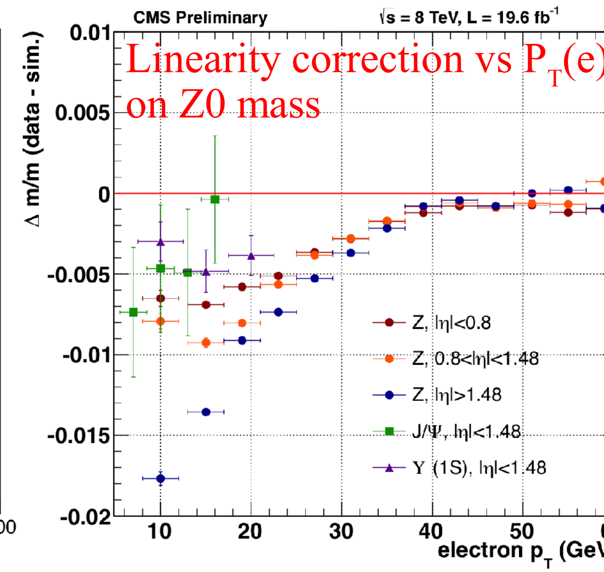


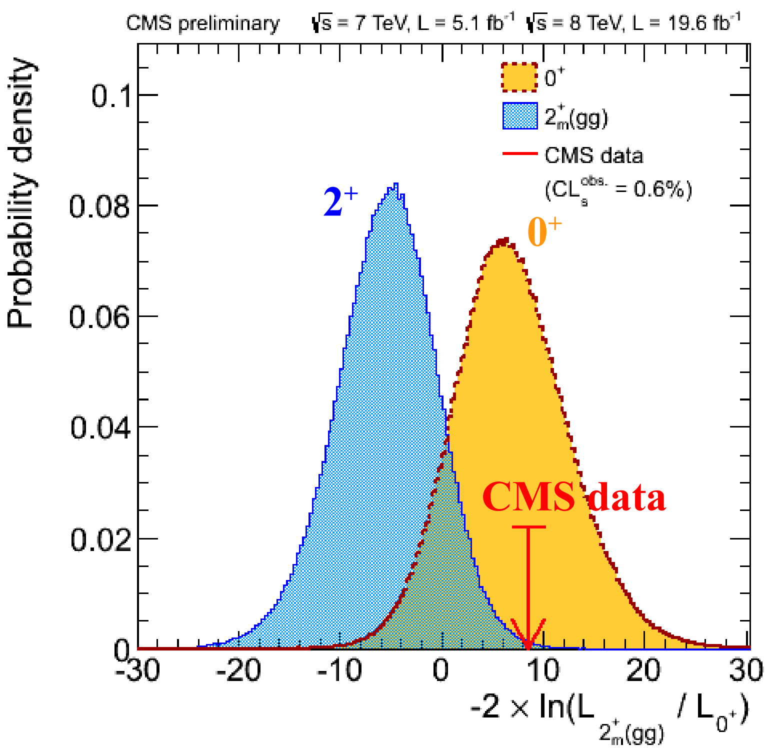


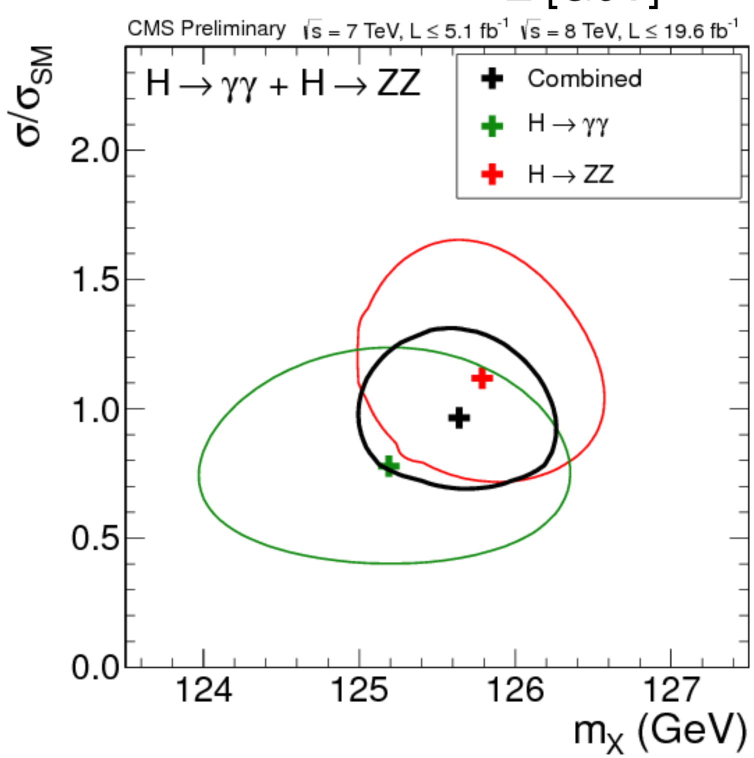
Moriond 2013: Full 2011-2012 result

- **Boson characterization**
  - **Mass measurement**
    - ▶ **Combine H→ZZ and H→γγ**
      - **ECAL role in both**
  - **Spin-Parity**









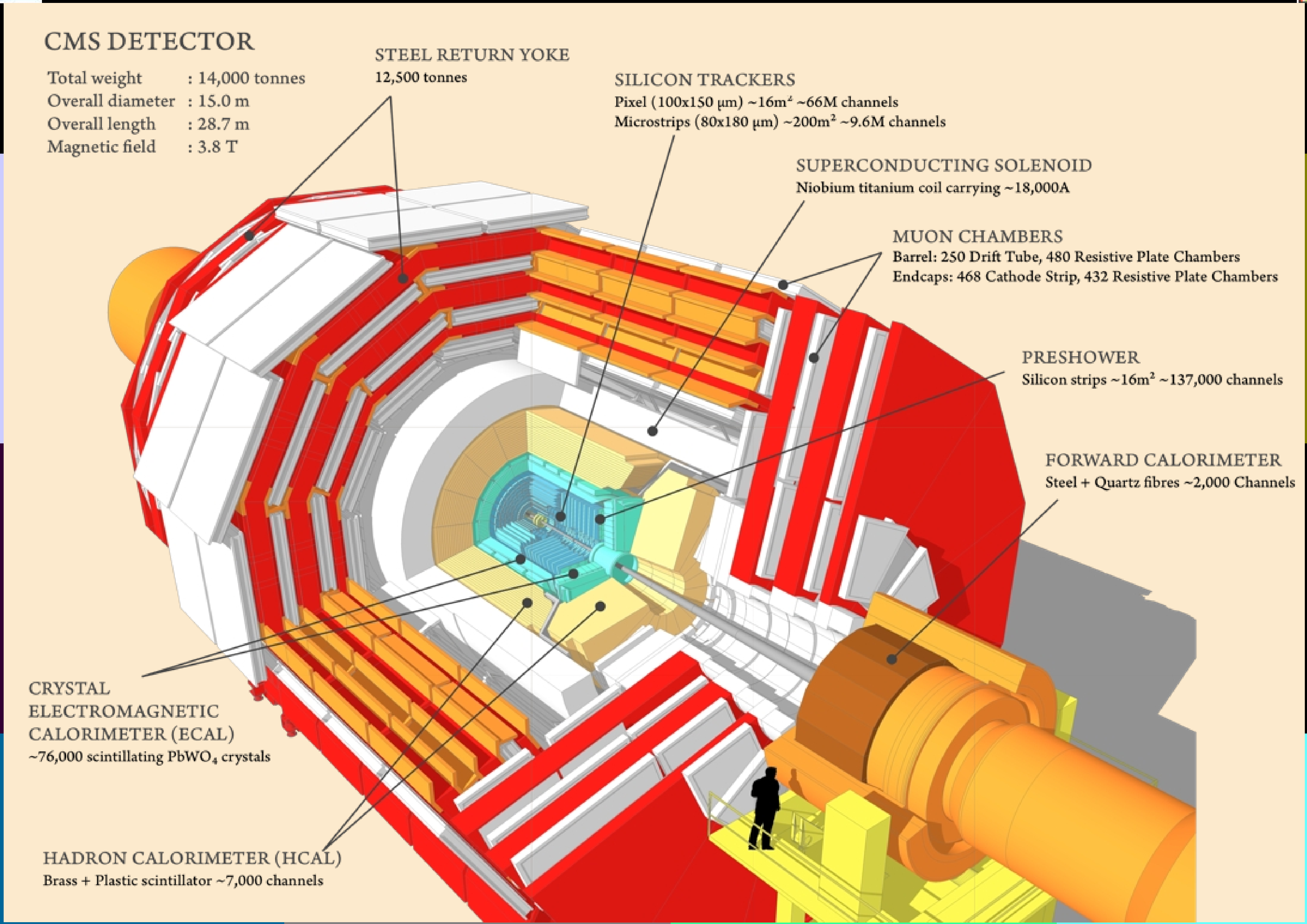
M_H=125.7±0.3(stat) ±0.3(syst) GeV

Conclusions

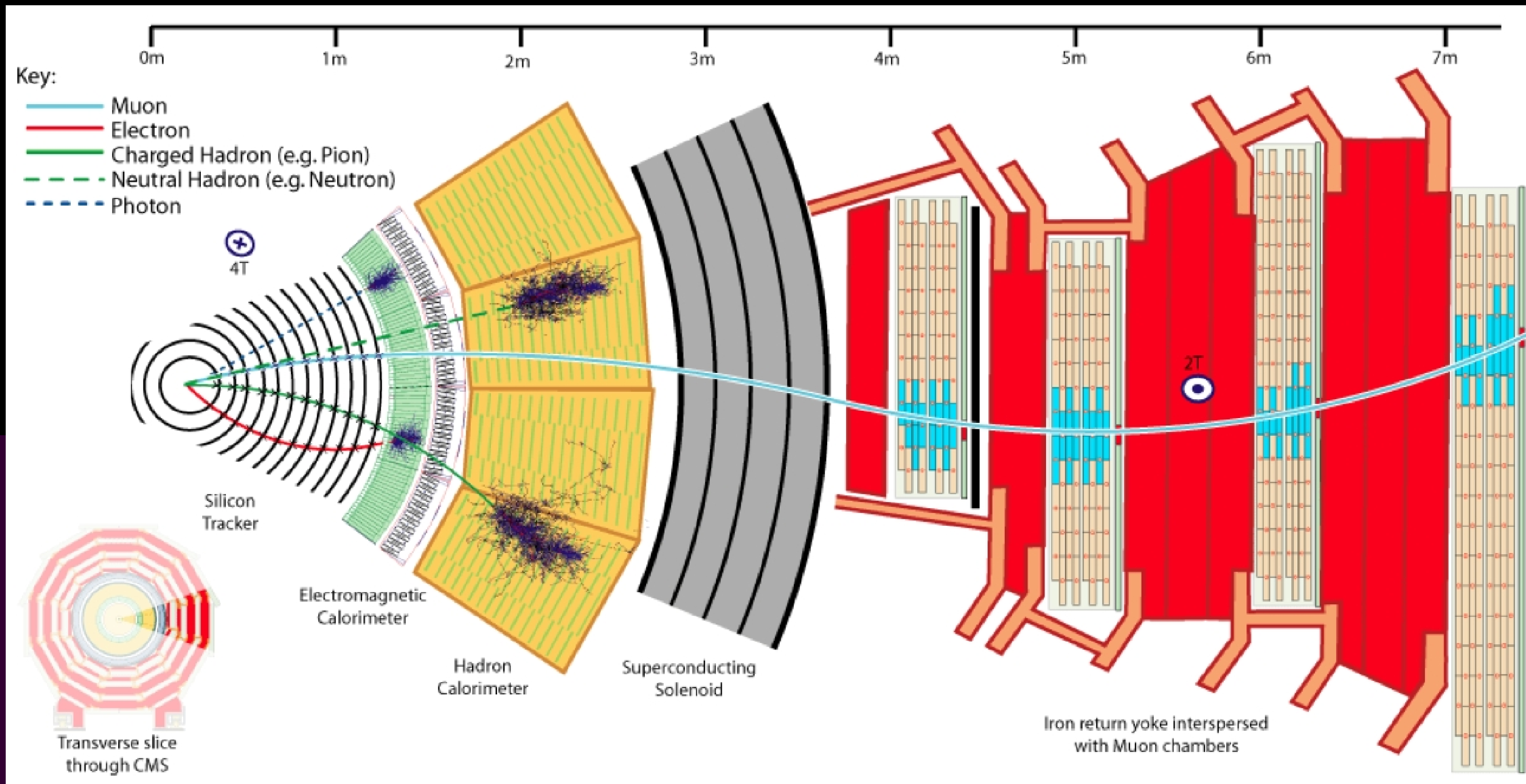
- **We succeeded in making our calorimeter work with outstanding performance for the discovery**
  - **First phase of the hunting is over:**
    - **We caught it !**
  - **And now, what do we do ?**
    - **$H \rightarrow \gamma\gamma$ is not only a discovery channel**
    - **Use it for coupling studies with associated production channels:**
      - **ttH : coupling with fermions**
      - **W/Z H : coupling with bosons**
      - **2017 ≈ same number of events for these channels as for the discovery...**
  - **Optimizing the ECAL response is critical for the next LHC runs !**
    - **Refine scintillation/laser relationship**
    - **Improve reconstruction tools**
    - **Include aging effects in simulation**
    - **Optimize tools for high pileup: in- and out-of-time**

No time for:

Compact Muon Solenoid detector

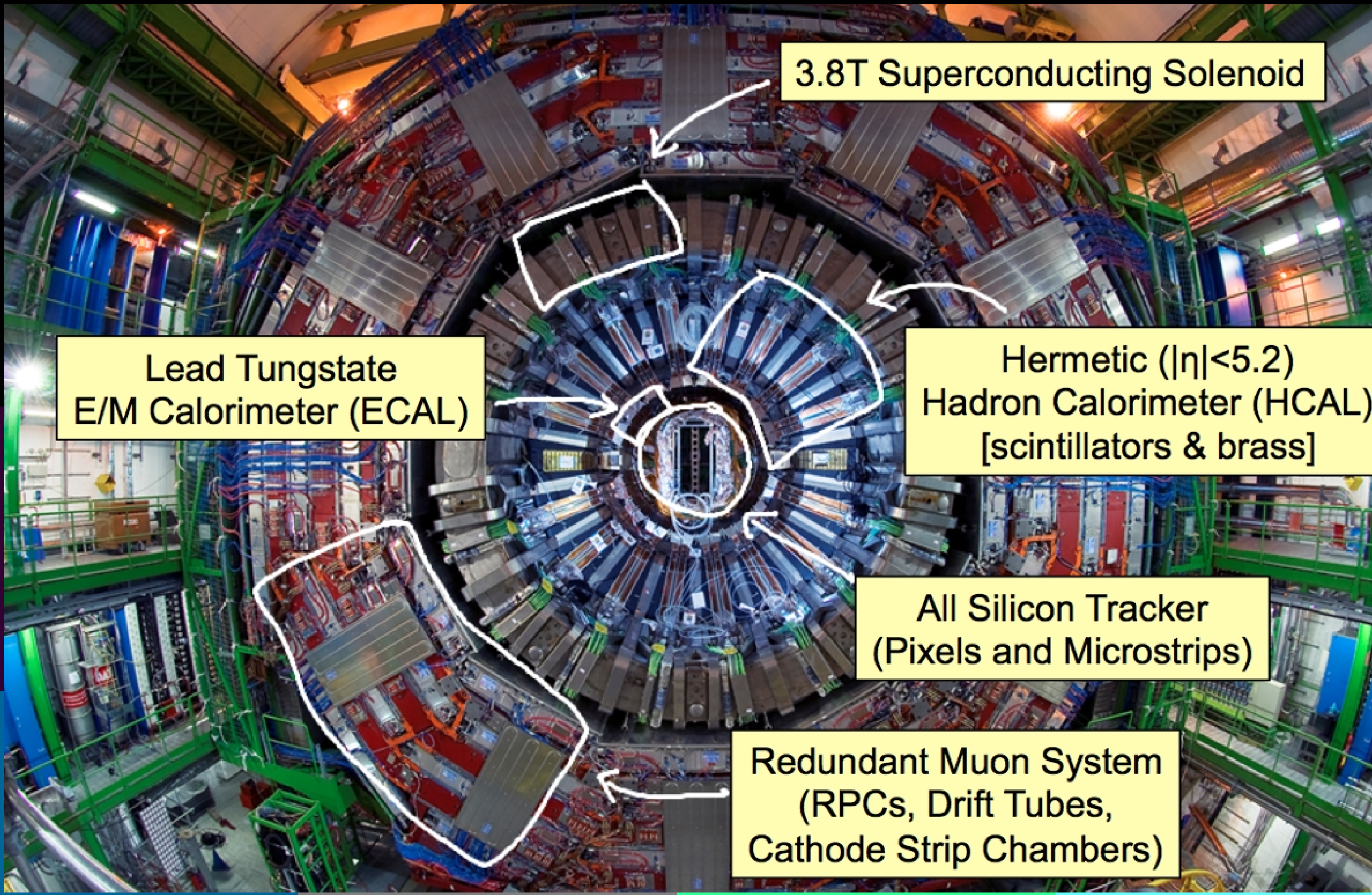


CMS slice

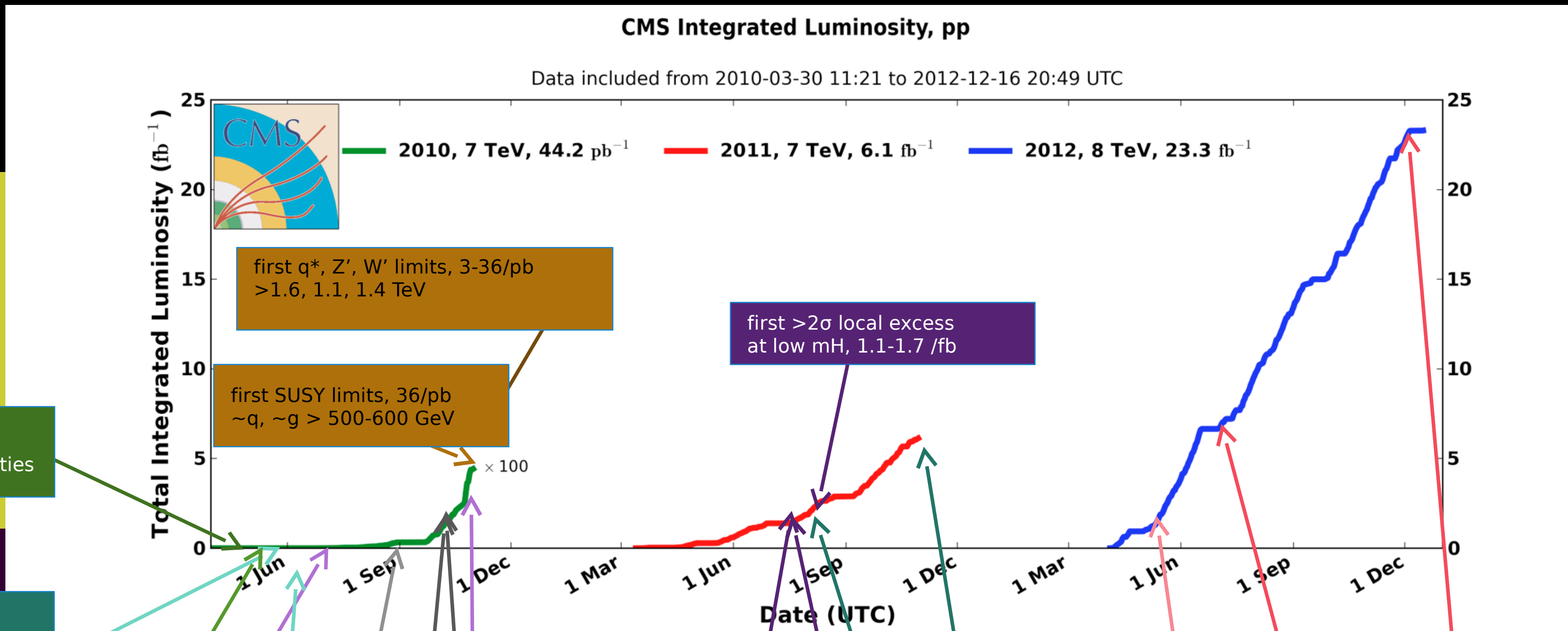


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

CMS View


3.8T Superconducting Solenoid
Lead Tungstate
E/M Calorimeter (ECAL)
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

Luminosity and CMS data taking



first q*, Z', W' limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb
~q, ~g > 500-600 GeV

first >2σ local excess
at low mH, 1.1-1.7 /fb

first MinBias / UE
studies, particle multiplicities

first incl. b x-section,
8/nb
δ ~ 15 %

first incl. jet x-section, PF jets
60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb
δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb
δ ~ 20%

first top xsec, 3/pb
δ ~ 40%

first single top
xsec,
t-chan., 36/pb
δ ~ 36%

first m top, 36/pb
Δ ~ 6.5 GeV

first WW xsec,
36/pb
δ ~ 40%
first limit on HWW

first ZZ xsec, 1.1 /fb
δ ~ 40%

going more differential,
e.g. Z/W + j,b,c

first significant limit on
Bs→μμ, BR<1.9x10-8

first particle discovered
by CMS: Ξb

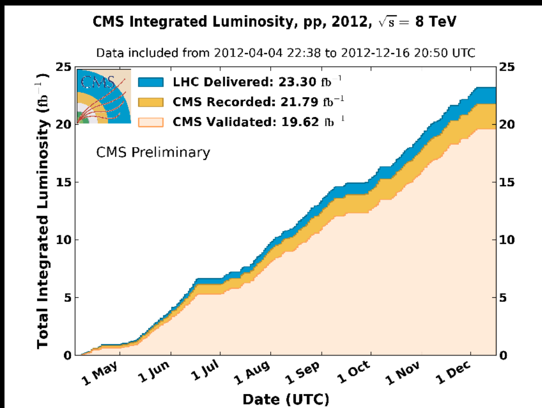
BSM searches
continue,
limits pushed

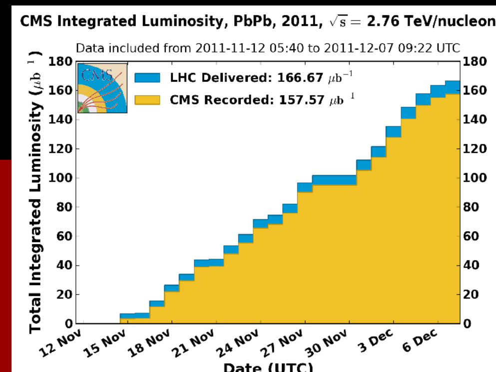
repeating the program
at 8 TeV

a new boson is
announced, 5 /fb

first spin parity
analysis of the boson,
17 /fb

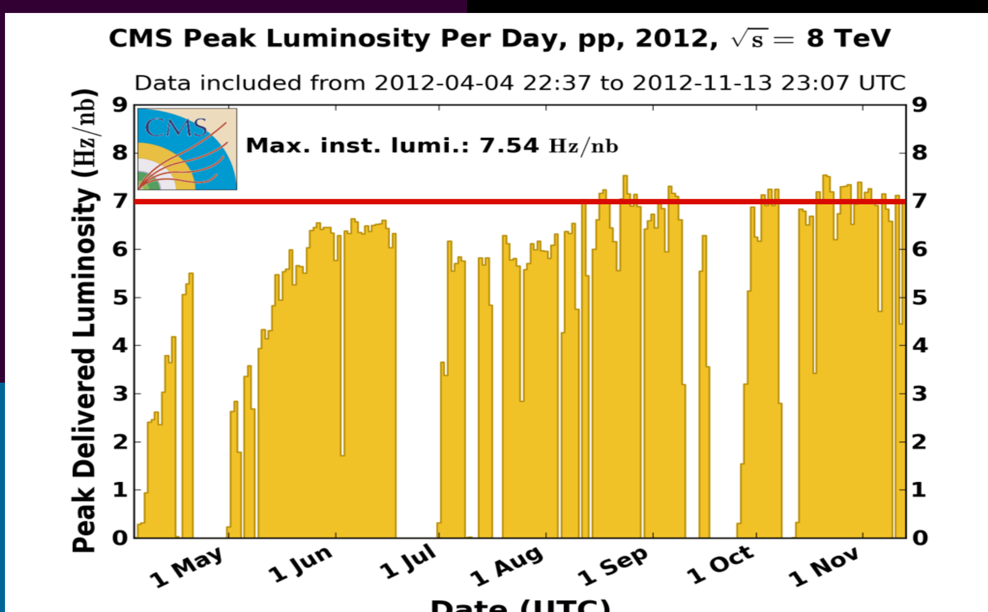
Luminosity Data taking 2012





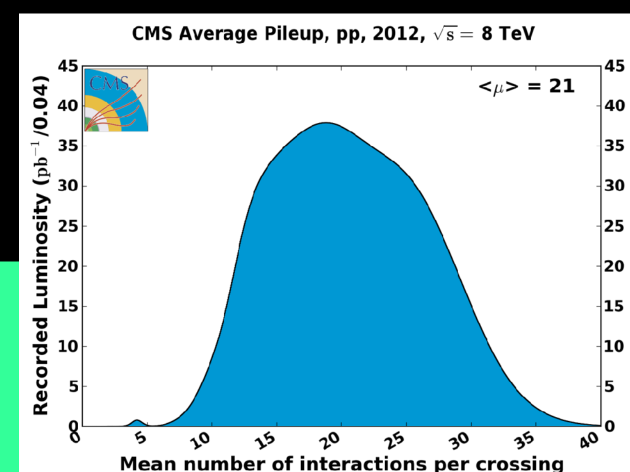
Period	√s [GeV]	Delivered luminosity [fb-1]	Data taking efficiency [%]	Data validated [%]
2010	7	0.044	92.2	88.6
2011	7	6.13	90.5	90.1
2012	8	23.20	93.5	90.0

Data taking efficiency Increased in 2012 due to development of automatic recovery procedures

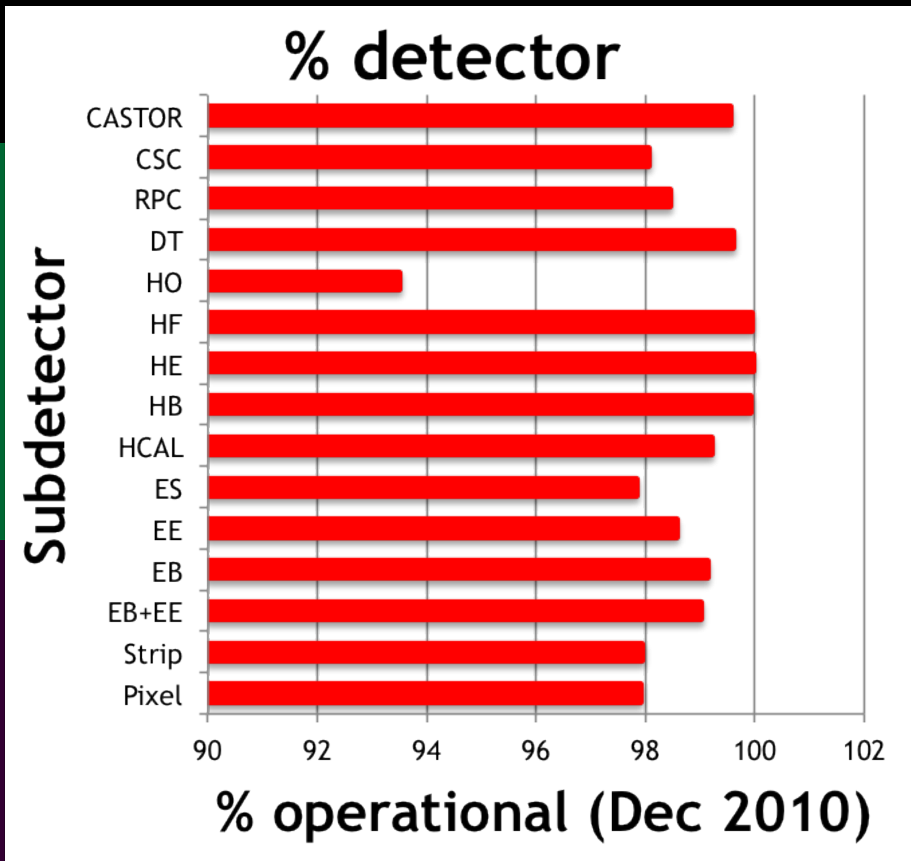


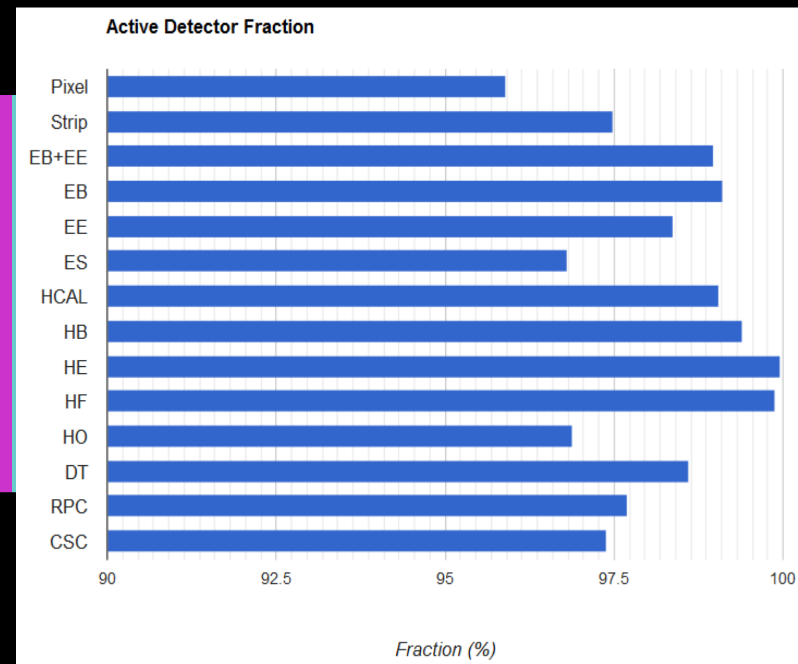
Almost at the design lumi, but at 50 ns running!

Pileup already larger than LHC design at 25ns (20)



Fraction of life channels 2010-2012

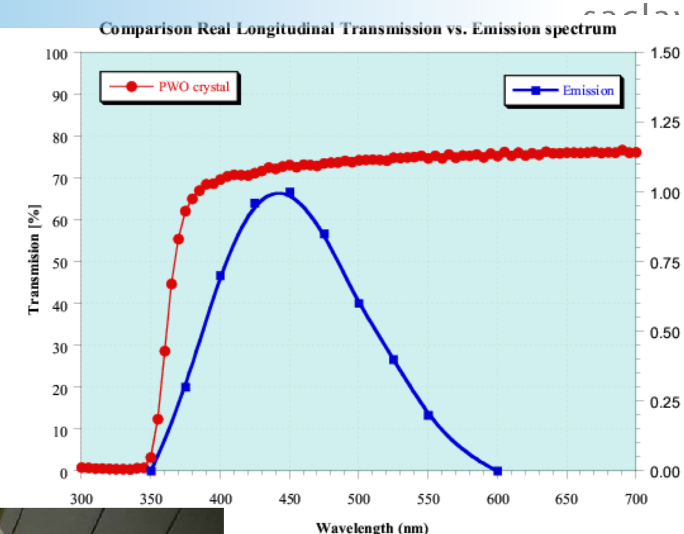




Dec 2012

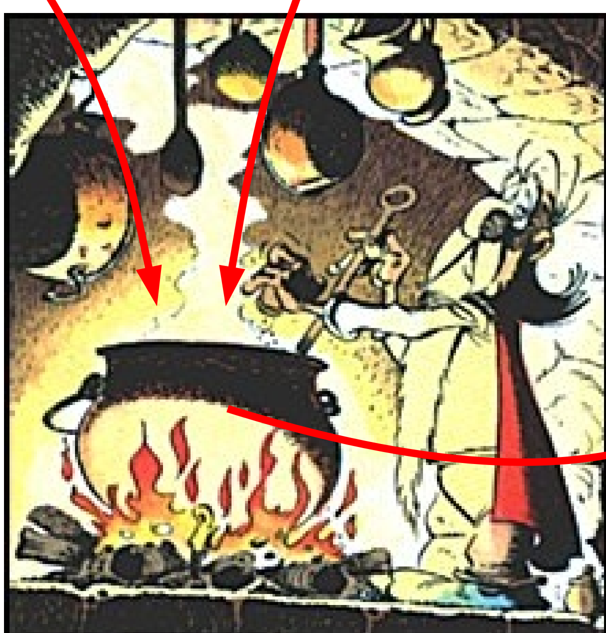
CMS looks like the first day after three years of operation

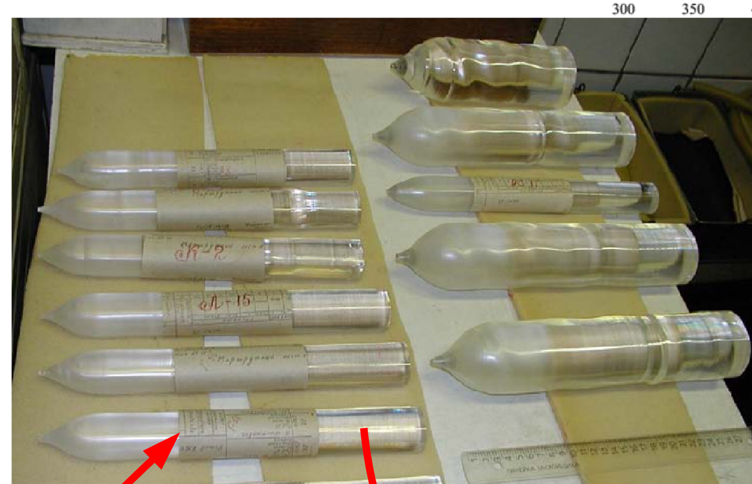
$PbWO_4$ crystals

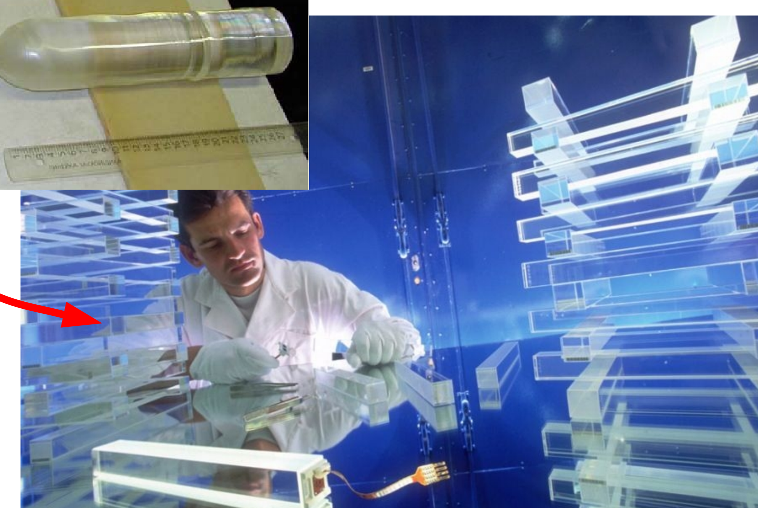


Pb

W

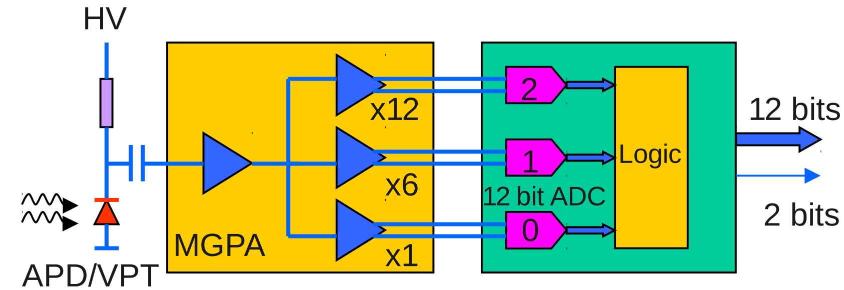




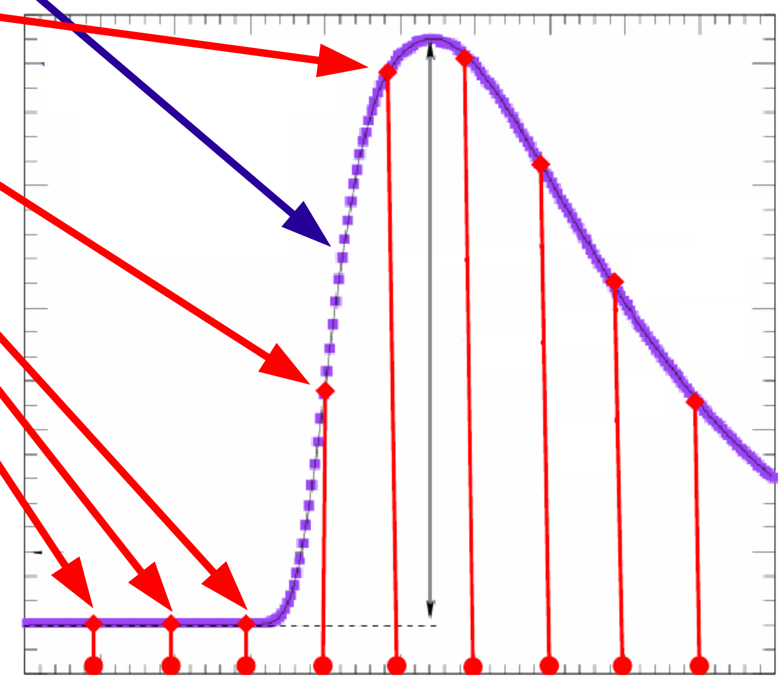


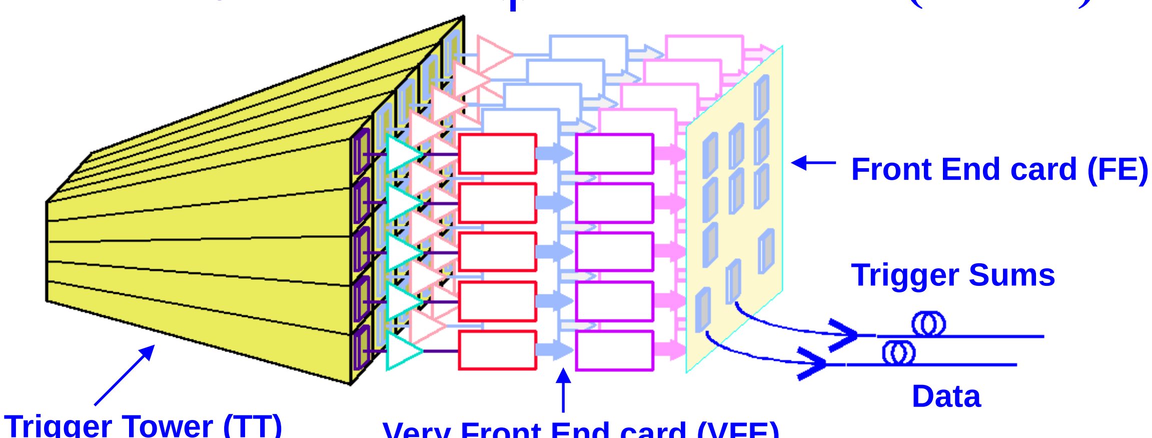
The read-out electronics

- Low noise preamplifier
  - 40 ns shaping time
  - 40 MeV noise/sample
- On-detector analog-to-digital conversion
  - 40 MHz sampling
  - 10 samples kept per trigger
- On-detector trigger primitives building
  - Sum of E_T on 5x5 matrix (barrel)



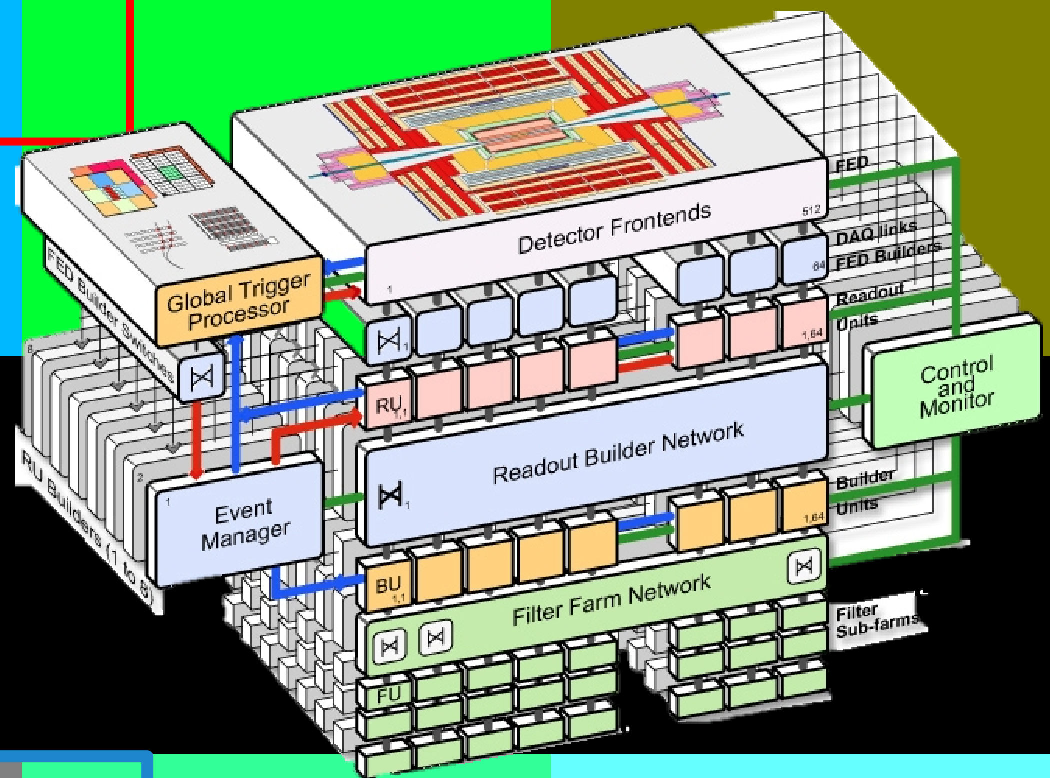
VFE architecture for single channel
0.25 μm IBM CMOS process





Trigger and DAQ architecture

- L1 Trigger: 40 MHz input from calorimeter and muon detectors,
  dead-time free, 100 kHz selected events

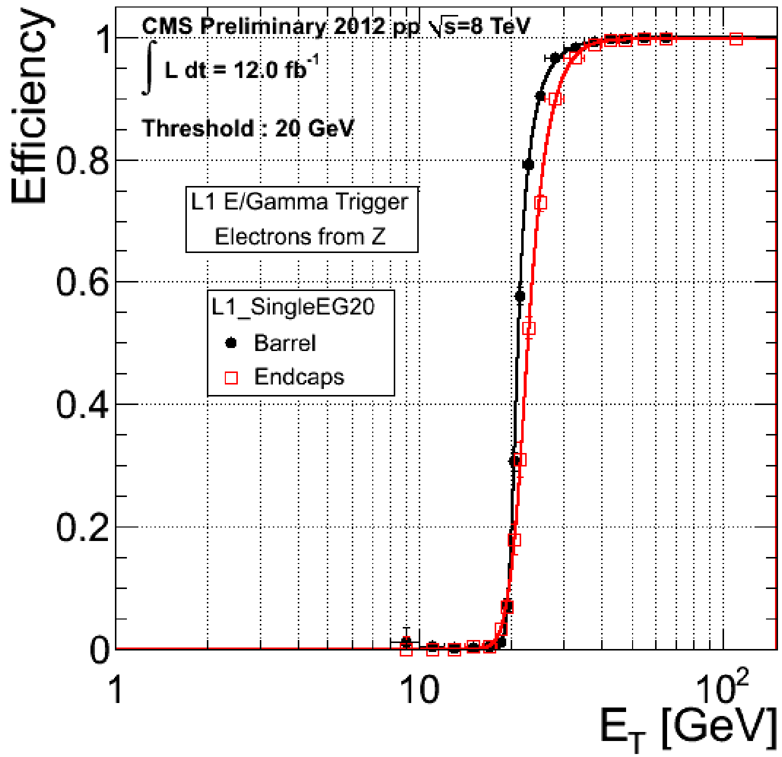


HLT: CPU farm for Event Building and filter algorithms. 1 kHz selected events (400 Hz “prompt-physics” + other)

Triggering on photons

- L1 trigger
  - Weekly recalibration of EE energy to account for transparency changes
  - EG20 trigger efficiency: (electron-photon > 20 GeV trigger)

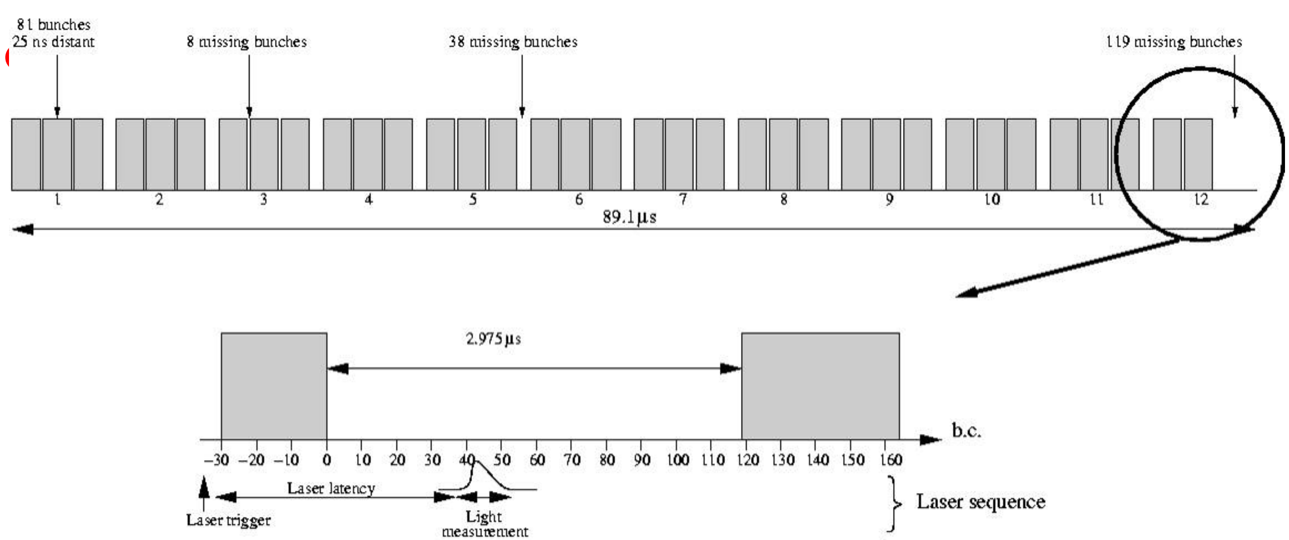
EG20	EB	EE
50%	21.2	22.8
95%	27.3	30.9
99%	35.7	38.5
100 GeV	99.96%	99.7%

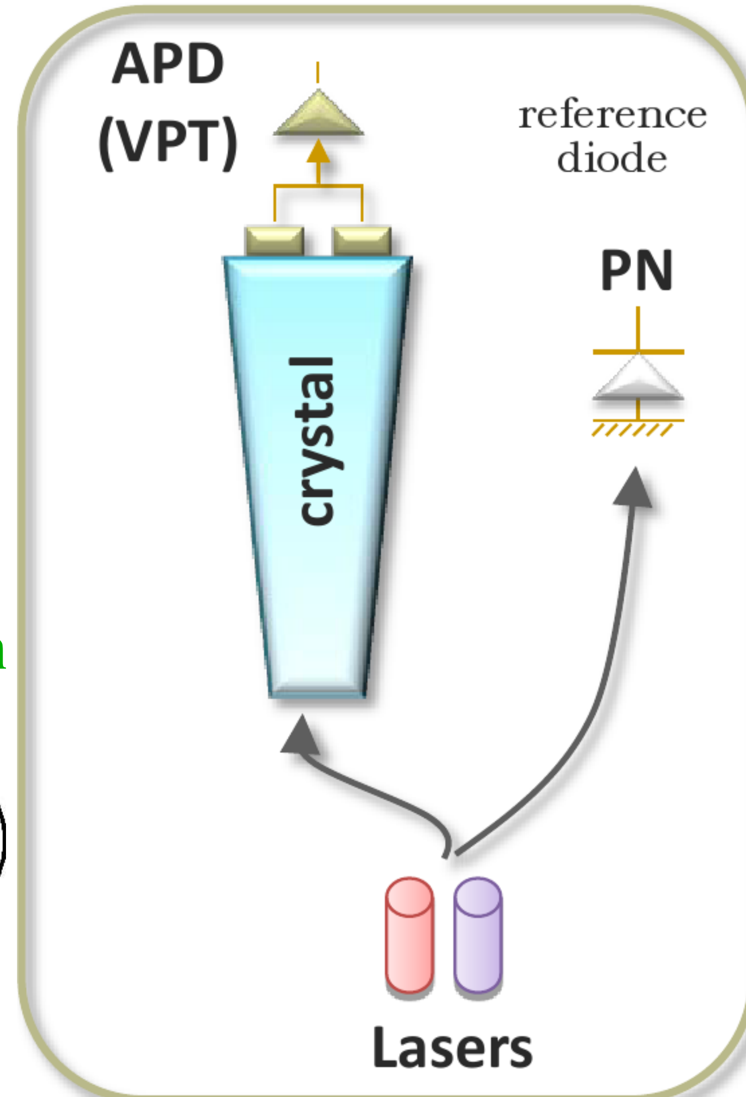


- All details (and more) in A. Zabi's talk

The crystal transparency monitoring system

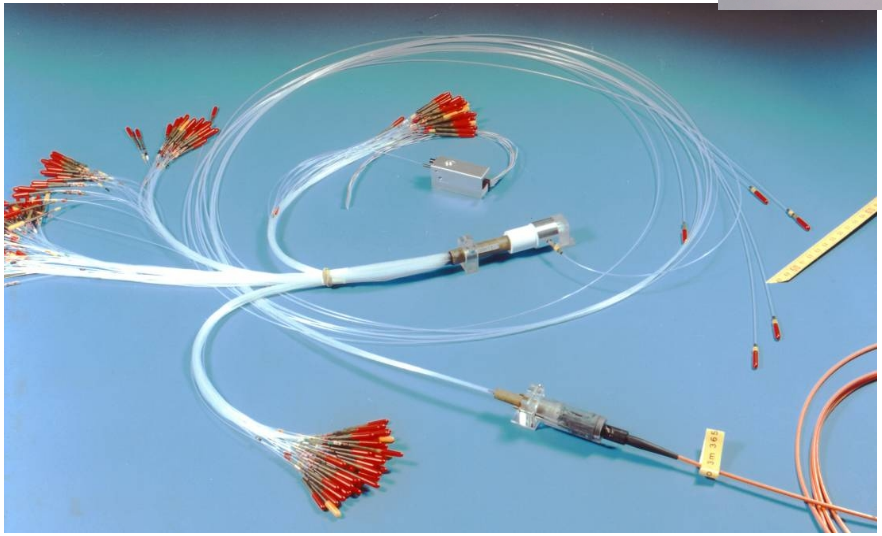
- Send light to each crystal
  - Measure the crystal response
  - Normalize with reference PN diode response (APD/PN)
- Statistical analysis
  - 600 laser pulses per measurement
  - 100 Hz firing
    - ►Full ECAL measurement every 40 mn

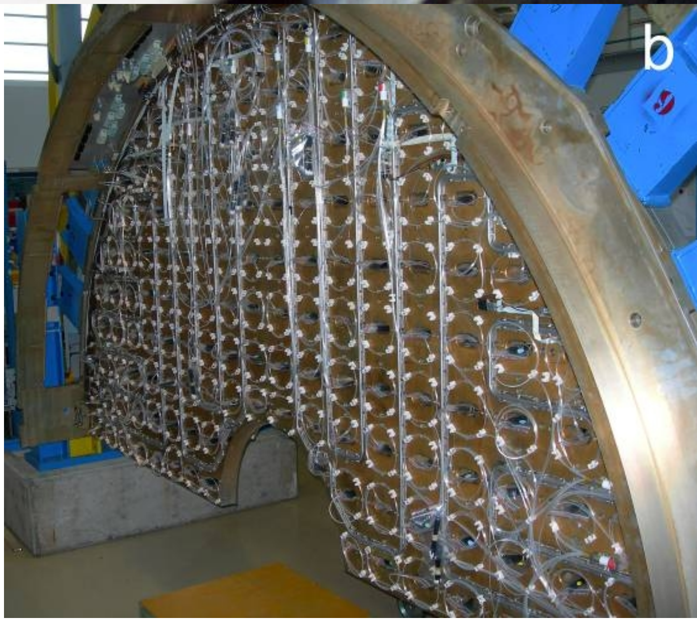




Light distribution system: lot of fibers ...

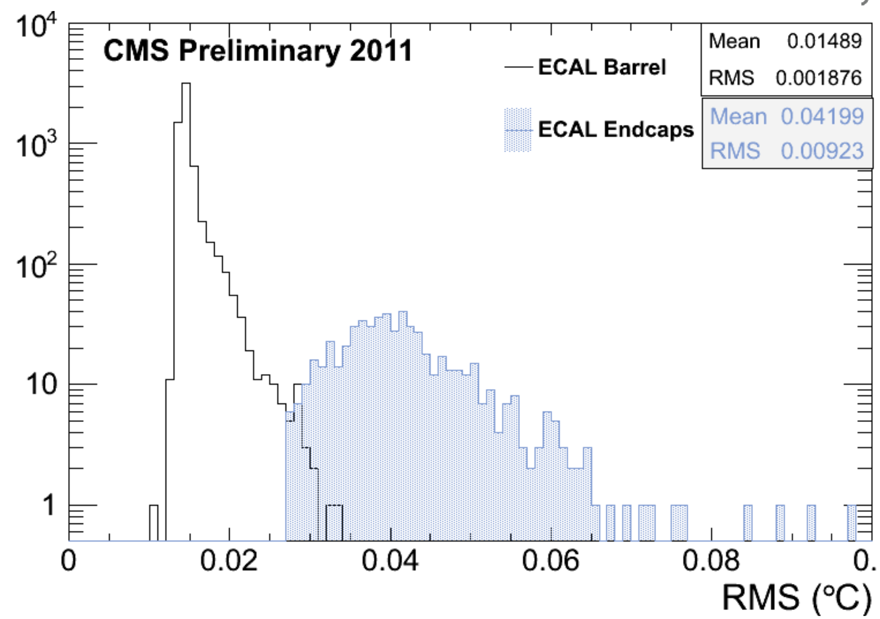
- **Key point:**
  - **Stability with respect to laser modes:**
    - ▶ **Break photons coherence**
    - ▶ **Diffusing spheres → dispersion**

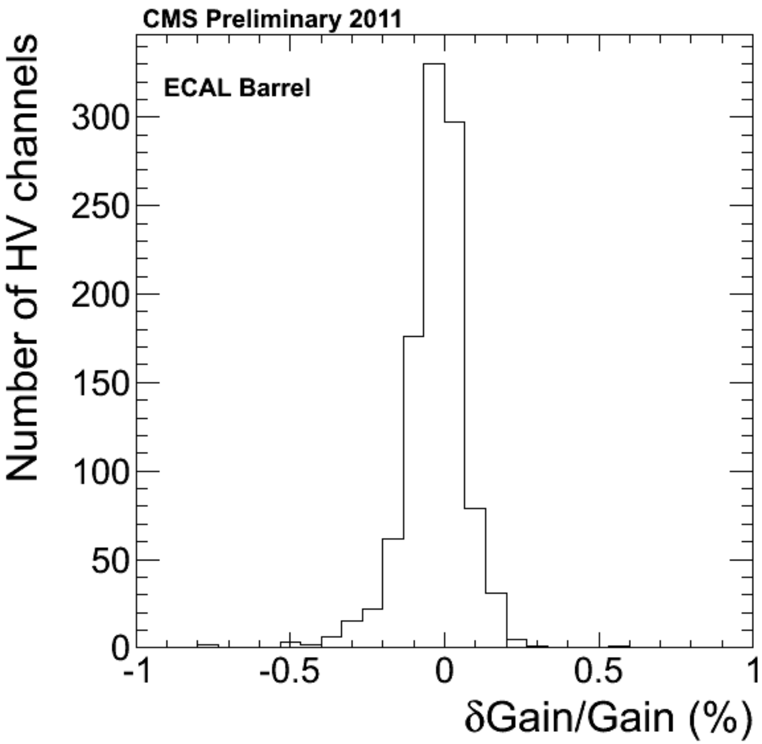




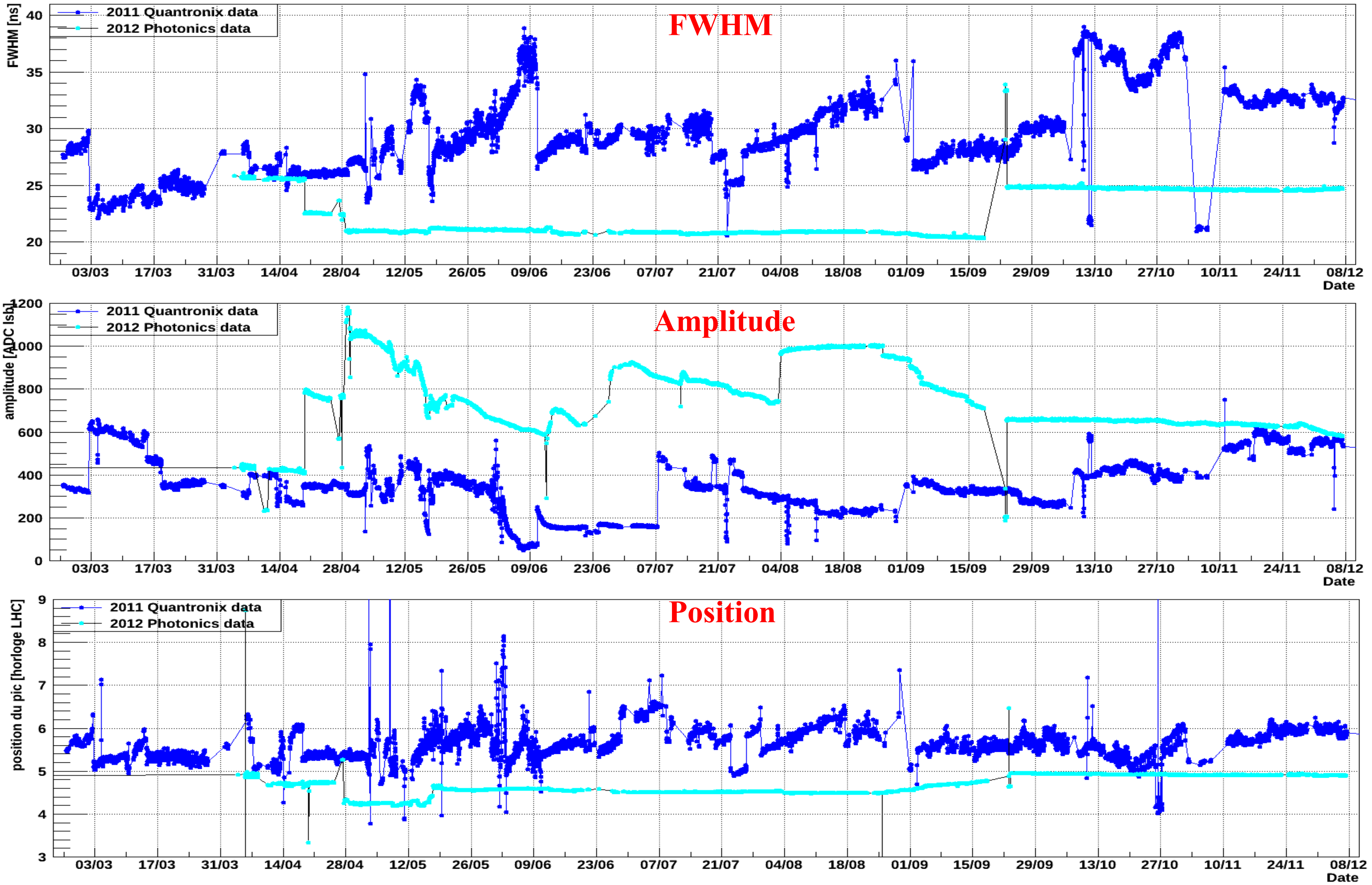
Mastering systematic effects

- Temperature (ΔG/G ≈ -2%/°C)
  - Stabilized to better than 0.1°C (EE) and better than 0.05°C (EB)
- HV (ΔG/G ≈ 3%/V)
  - Stabilized to better than 0.05 V
- Laser fluctuations
  - Amplitude
    - ▶ Electronic linearity calibrated
  - Pulse shape/position
    - ▶ Toolbox developed based on
      - SPR of electronics channels
      - Actual laser pulse shape



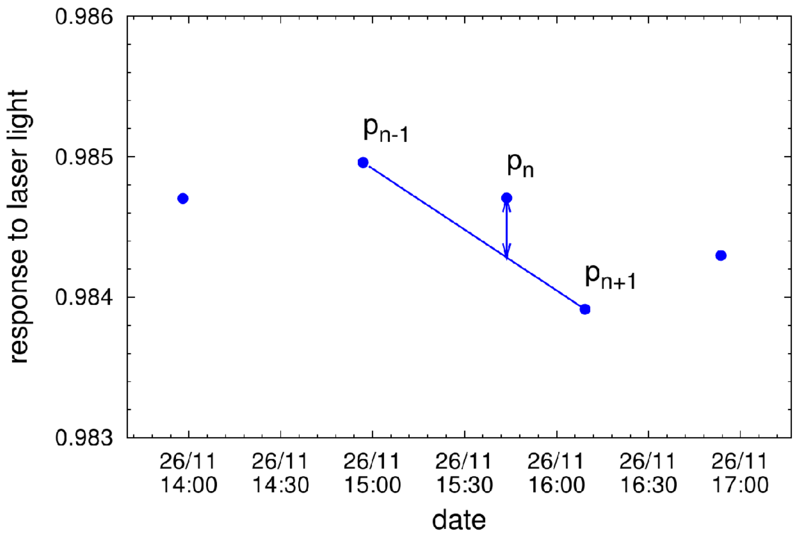


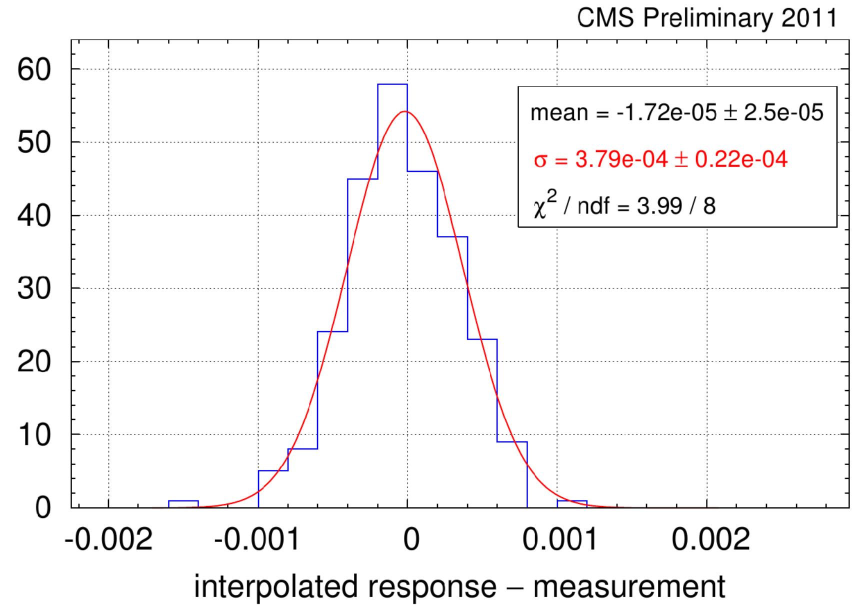
Laser parameters stability

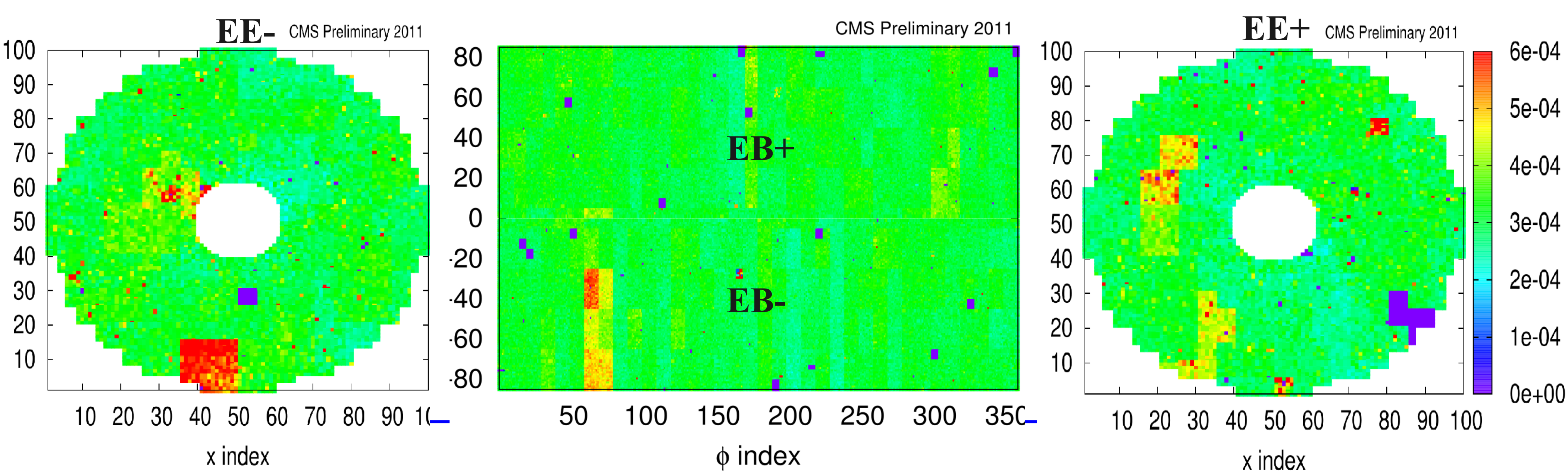


Estimating the stability

- During low irradiation period (HI runs)



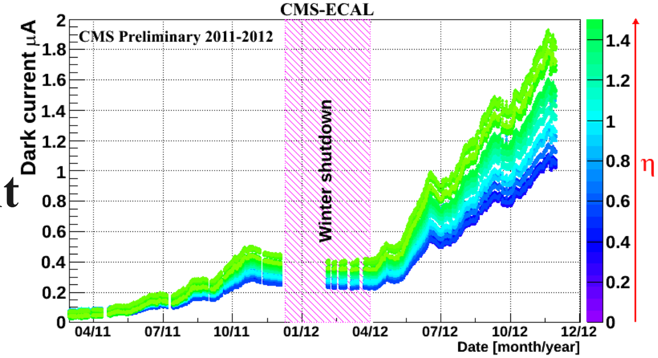




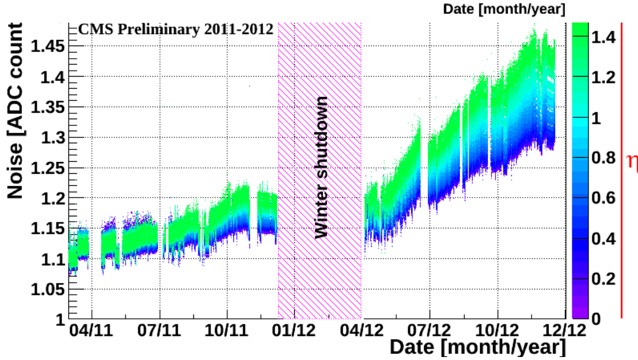
Radiation collateral victim: The noise term

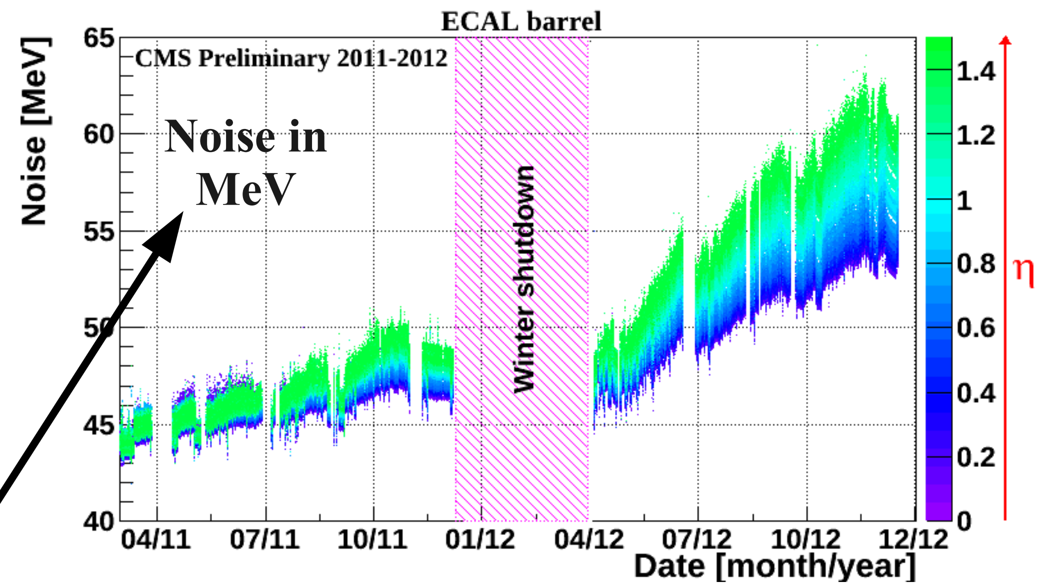
- **Barrel**

APD
dark current



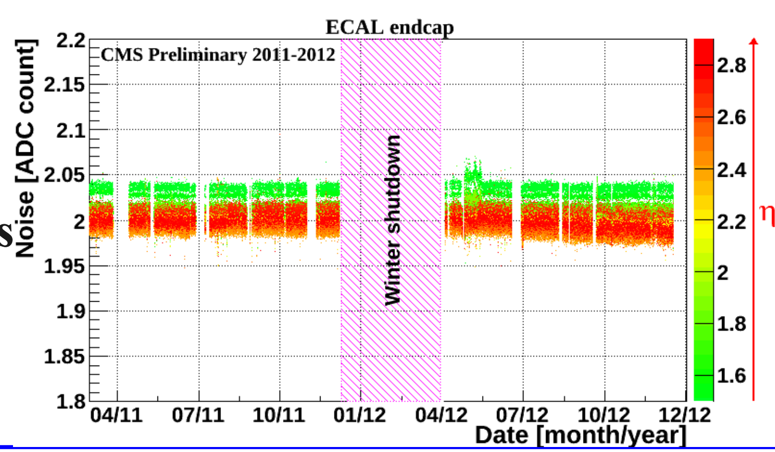
Noise in
ADC counts

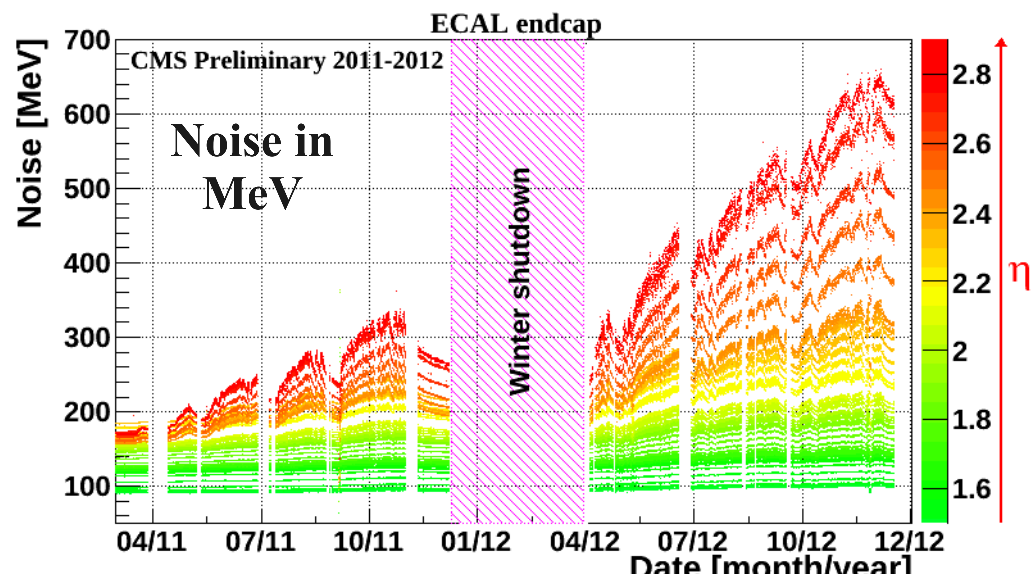




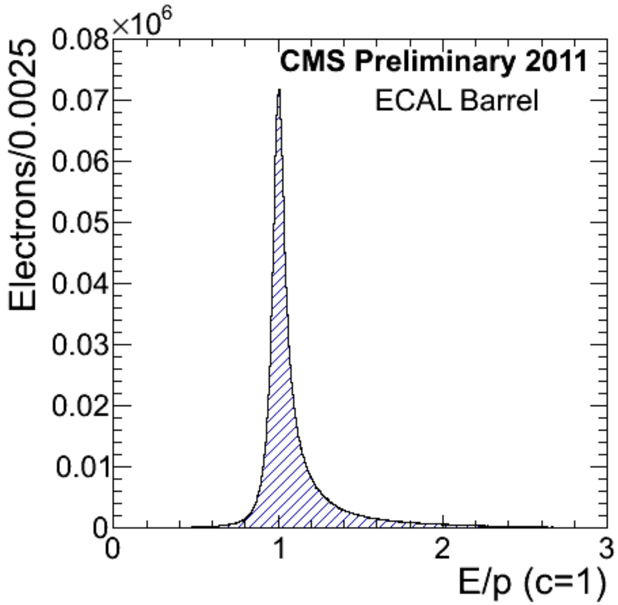
- **Endcaps**

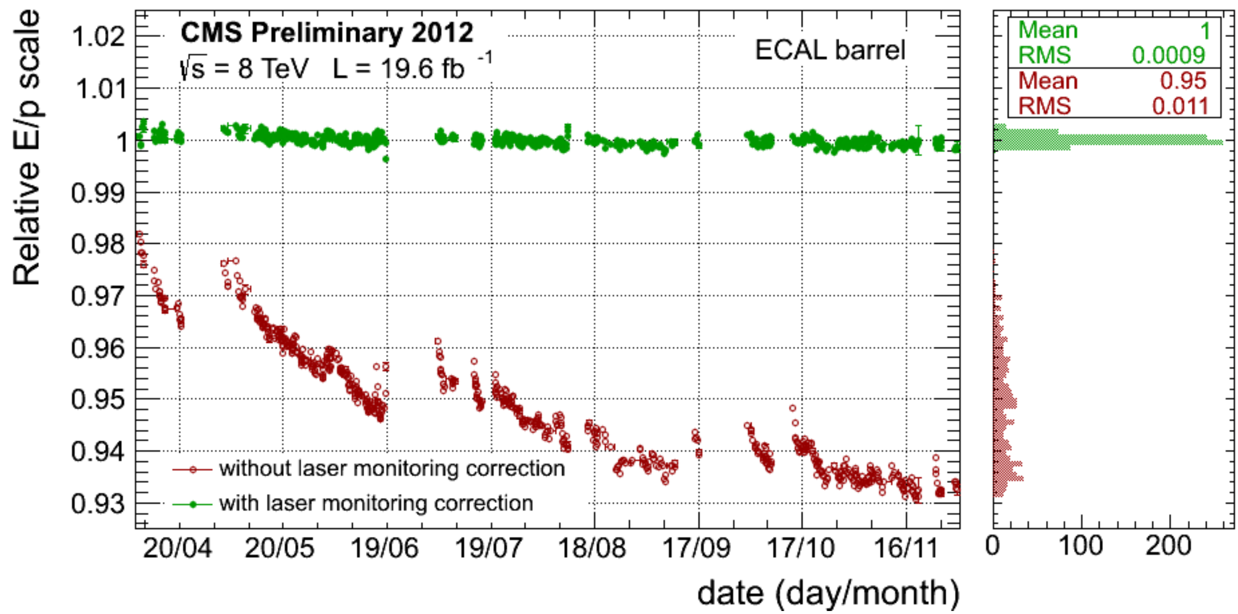
Noise in
ADC counts

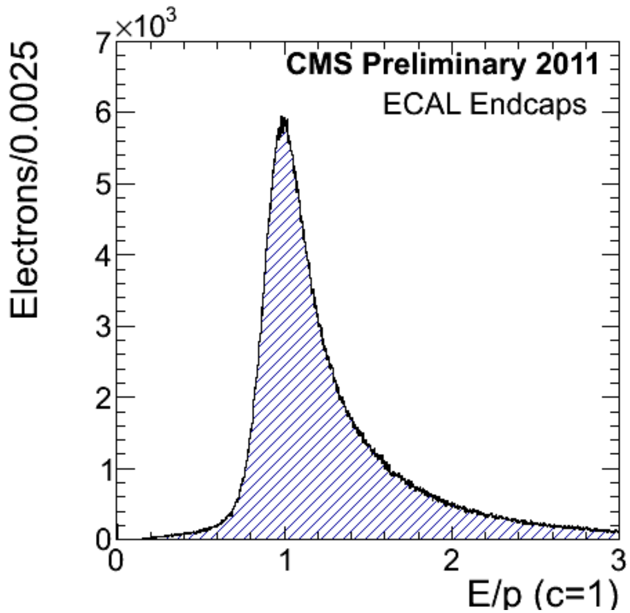


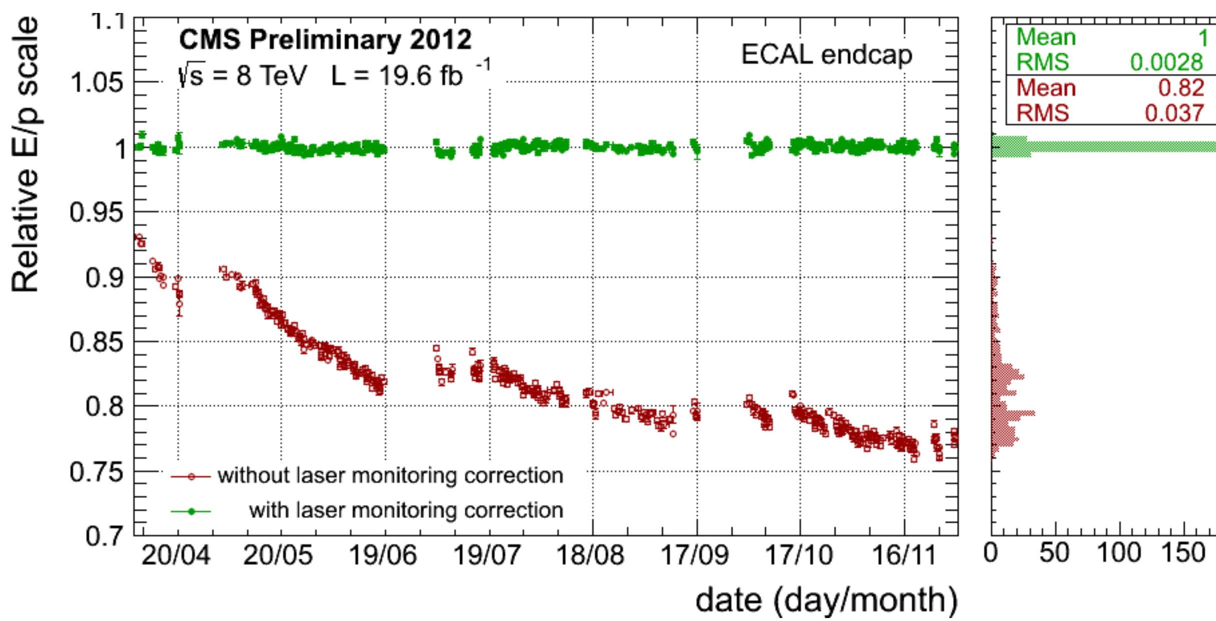


Controlling the corrections: E/p

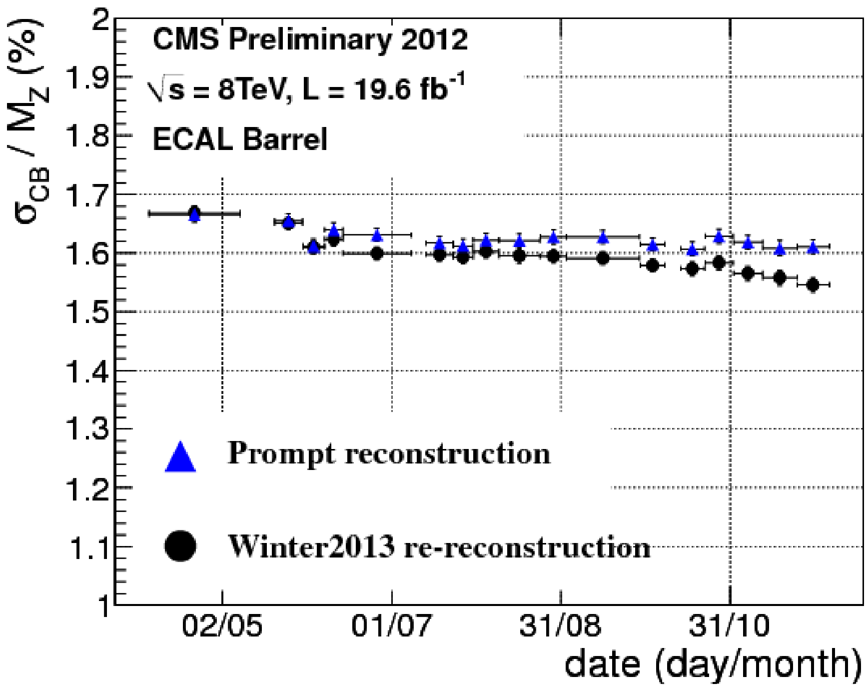


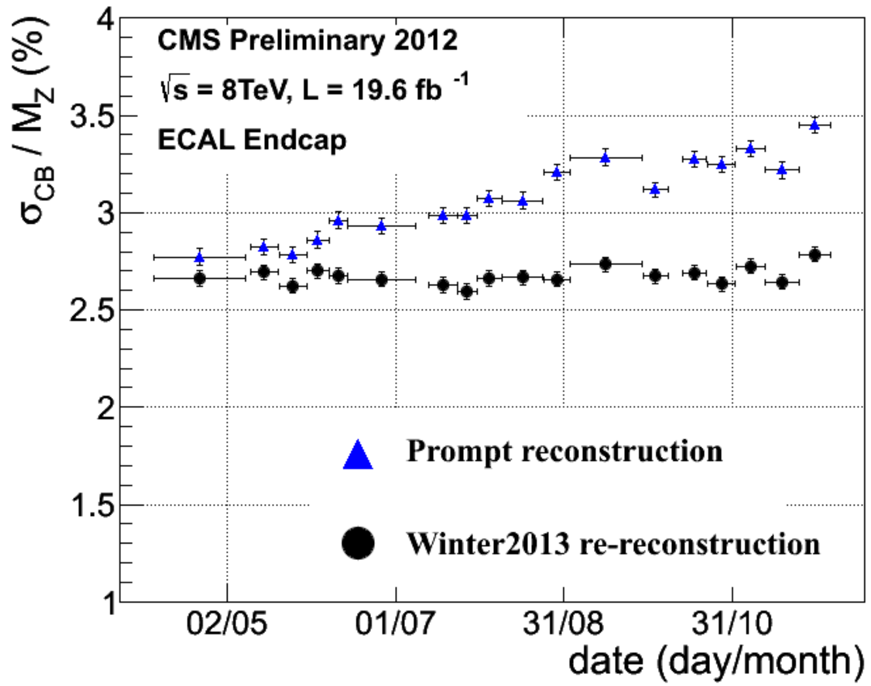






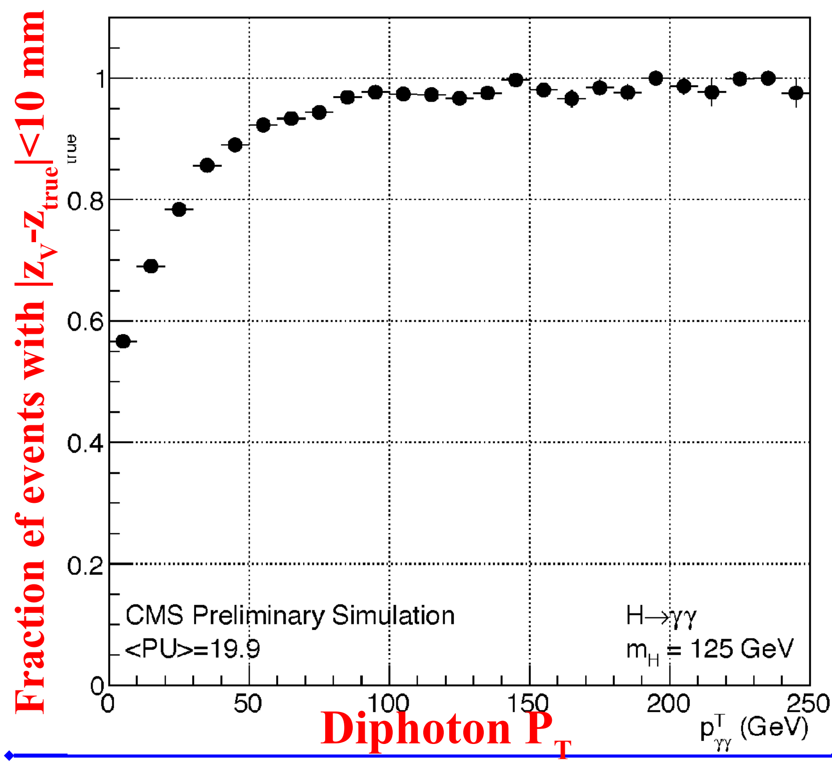
Controlling the performances : Z^0

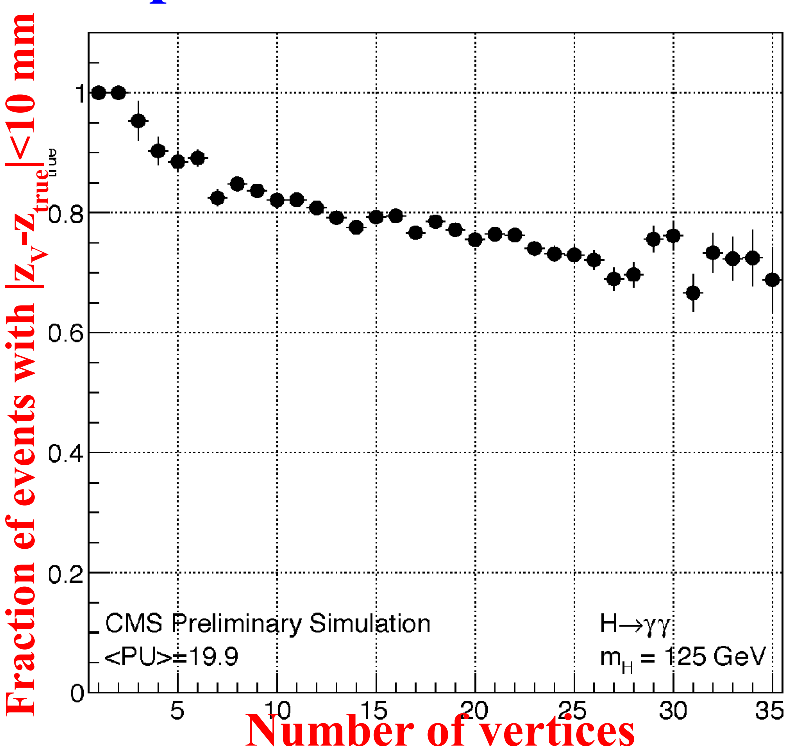




Identifying the vertex

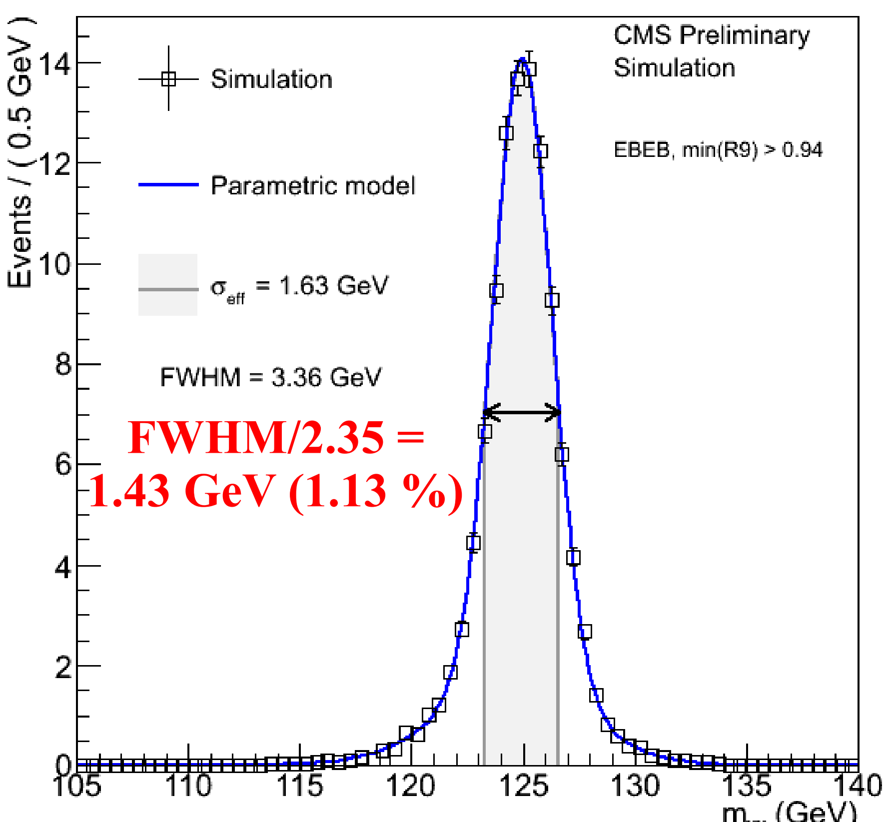
- No longitudinal segmentation of ECAL
  - No shower direction
- Vertex assignment
  - Based on tracks and di-photon system kinematics for non converted photons
  - Based on electron tracks for converted photons

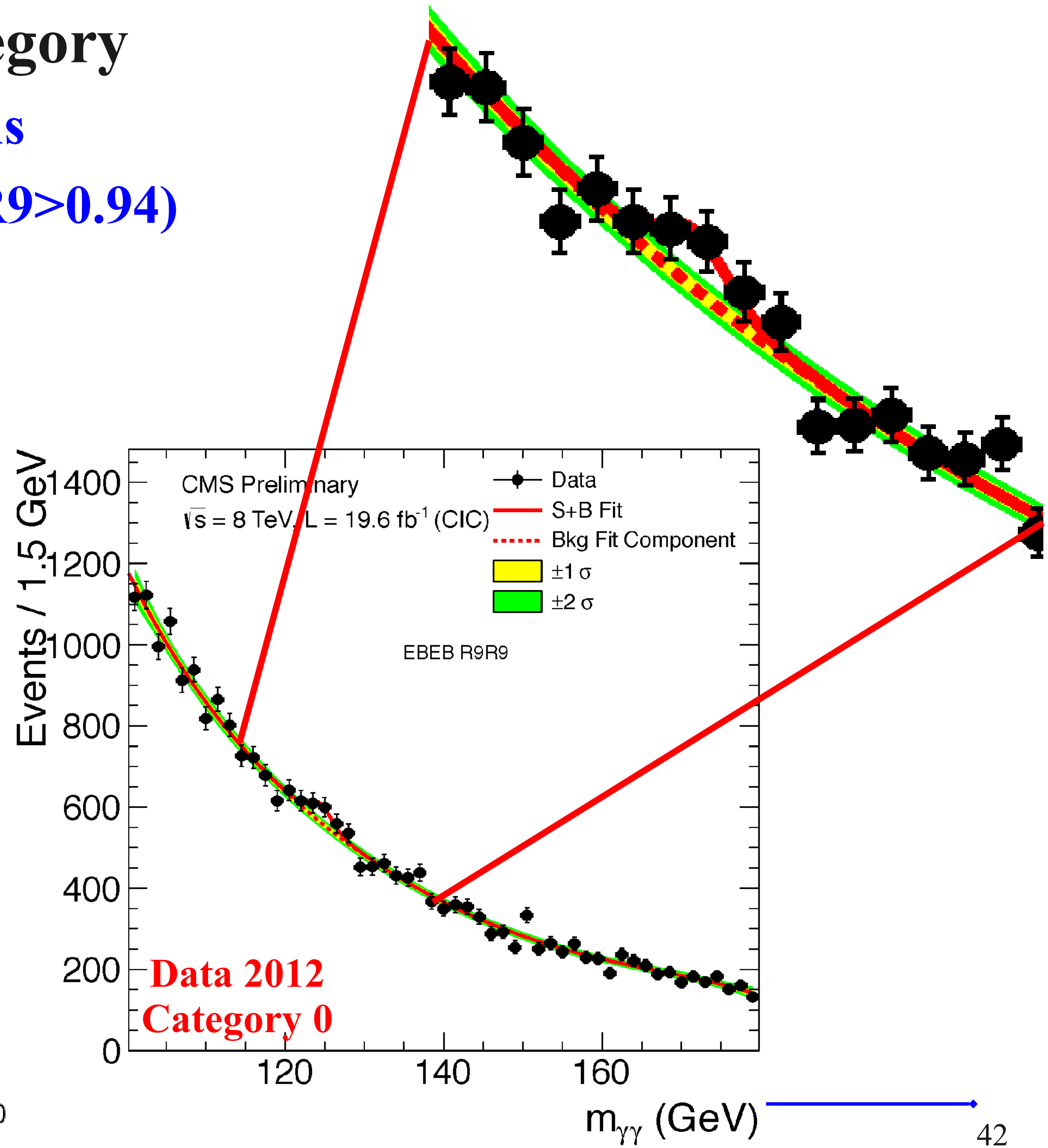




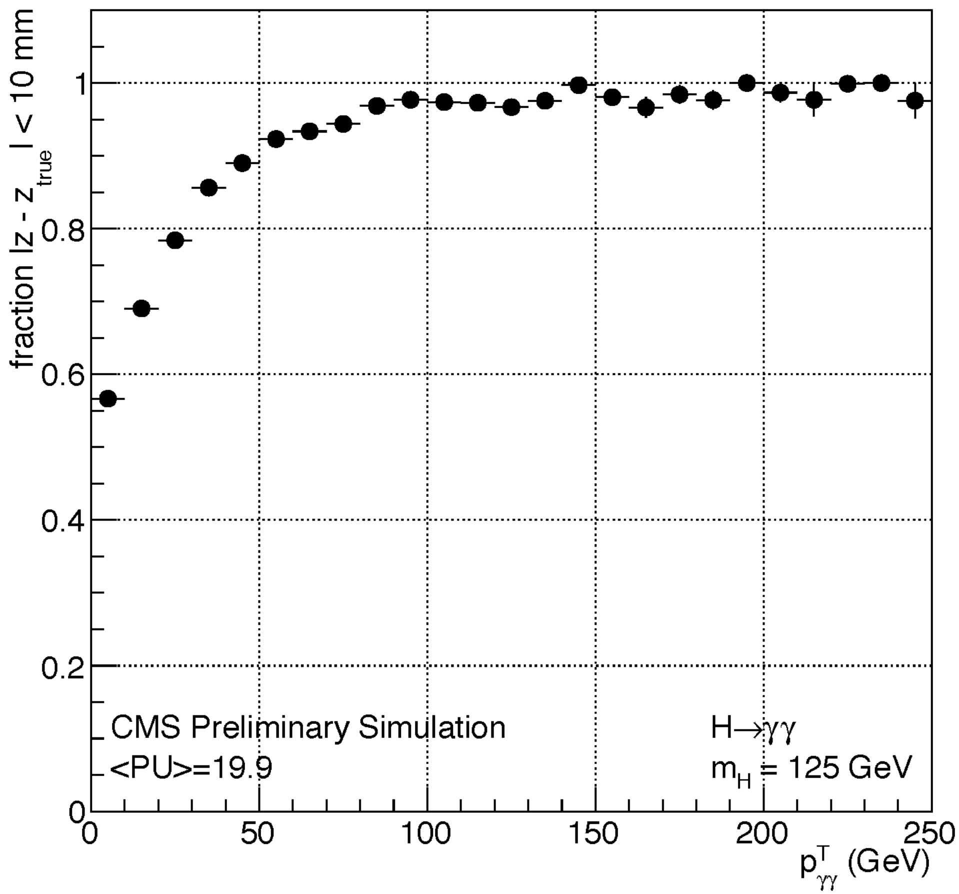
Higgs boson with ECAL only ?

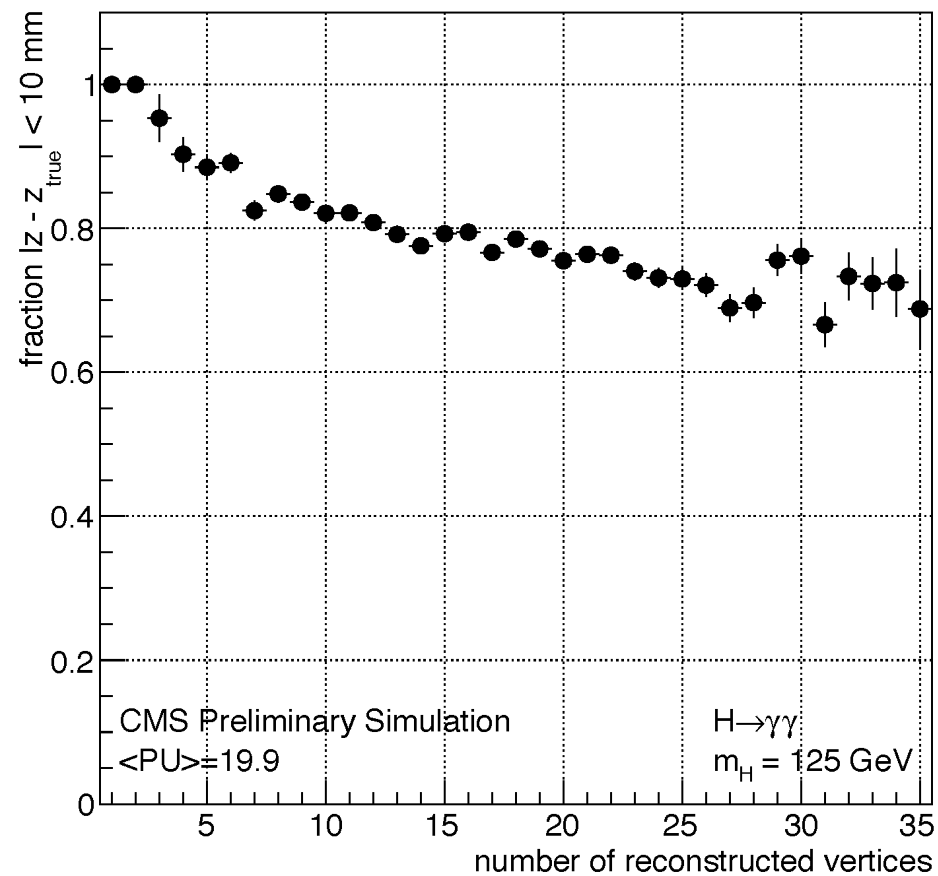
- Use of « golden » category
  - Not converted photons
  - Canonical showers (R9>0.94)
  - Photons in barrel



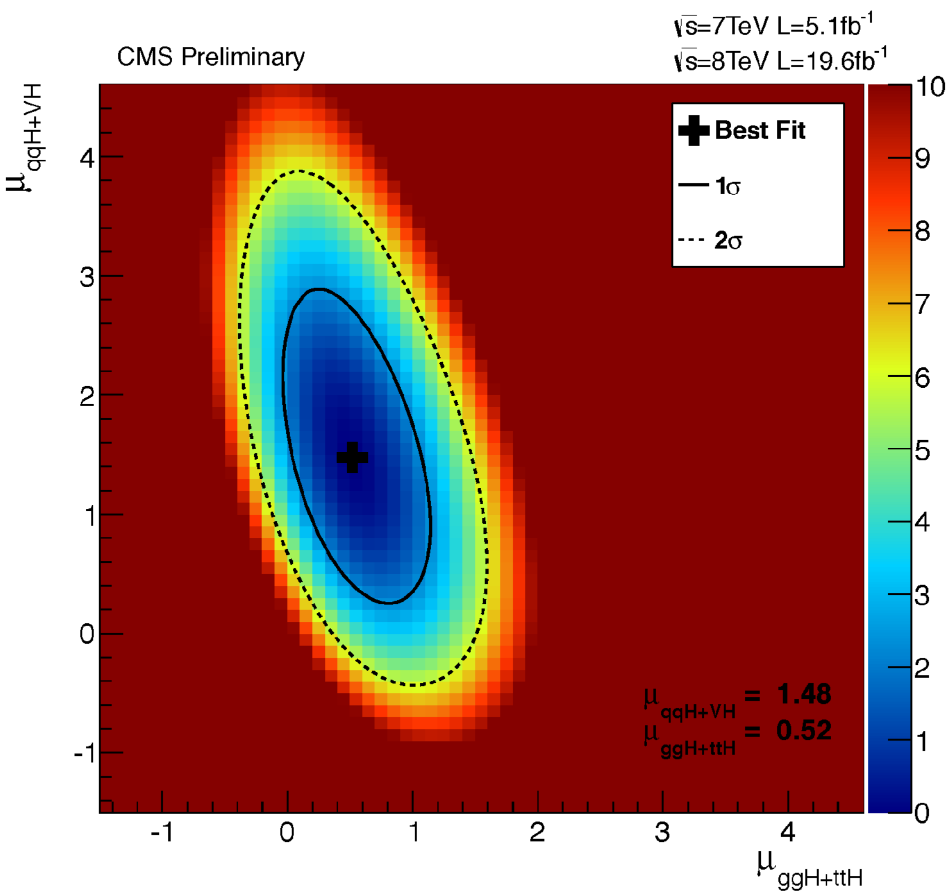


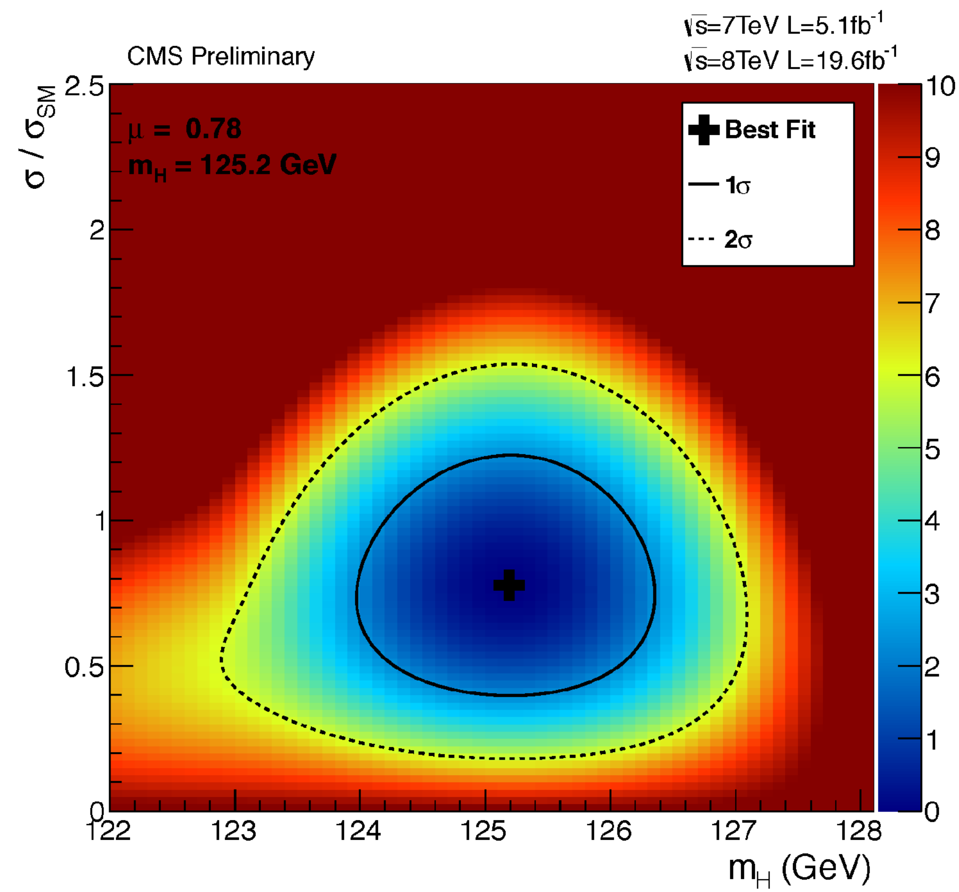
Hgg vertexing





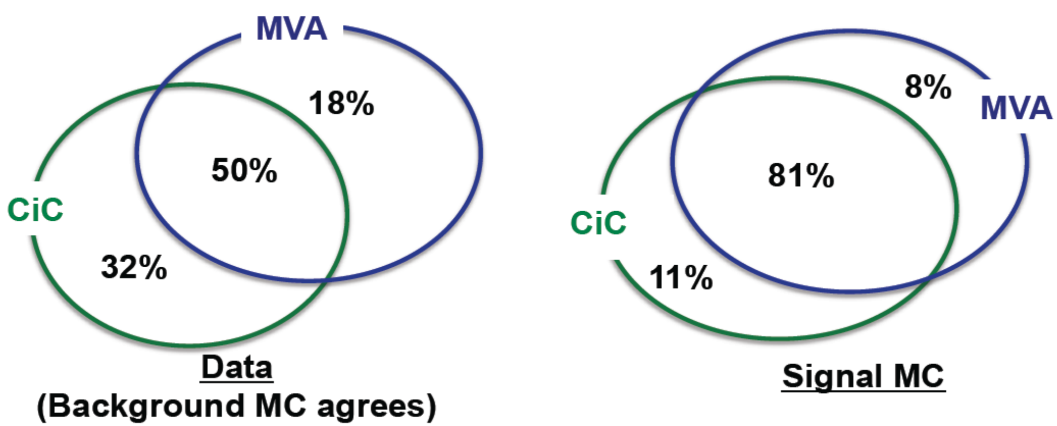
Mass, couplings and strength



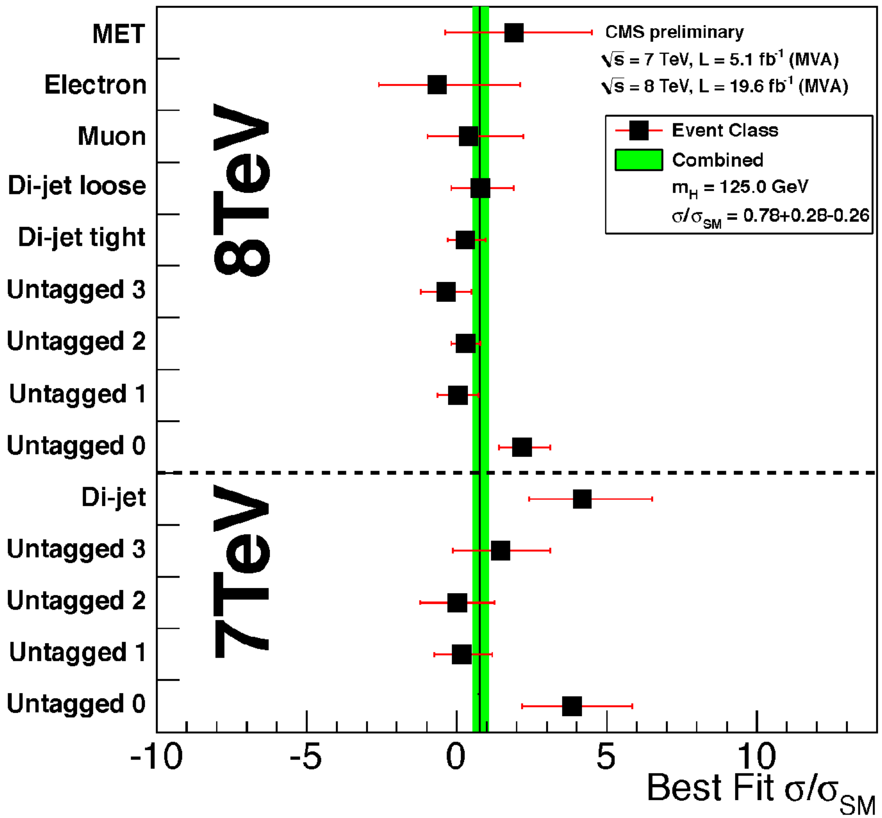


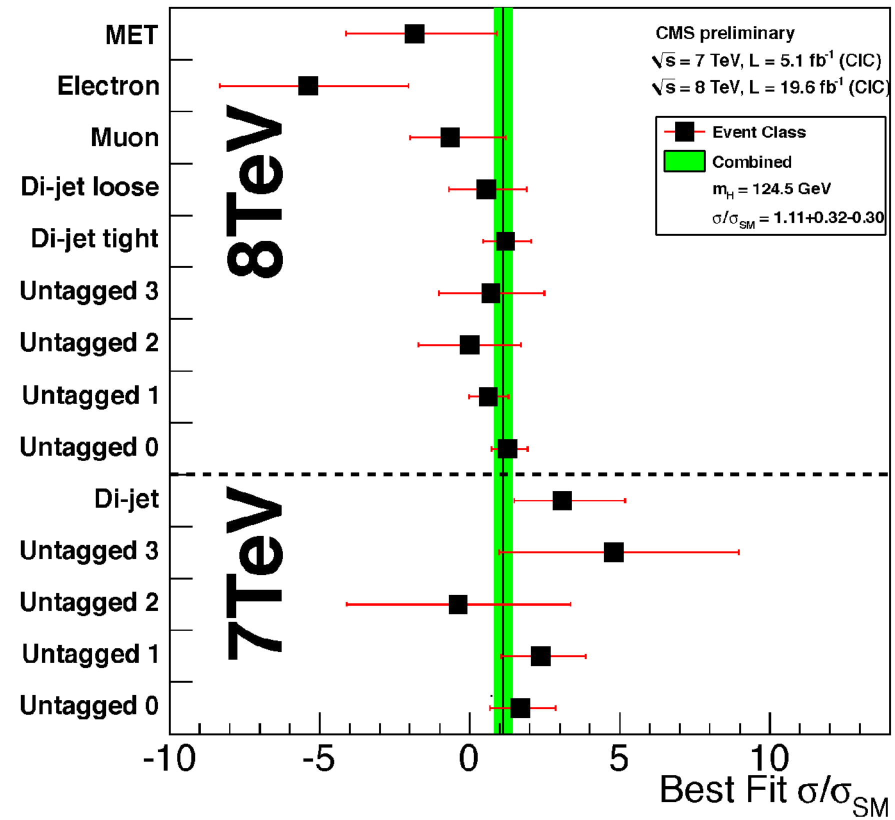
CiC vs MVA

	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	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

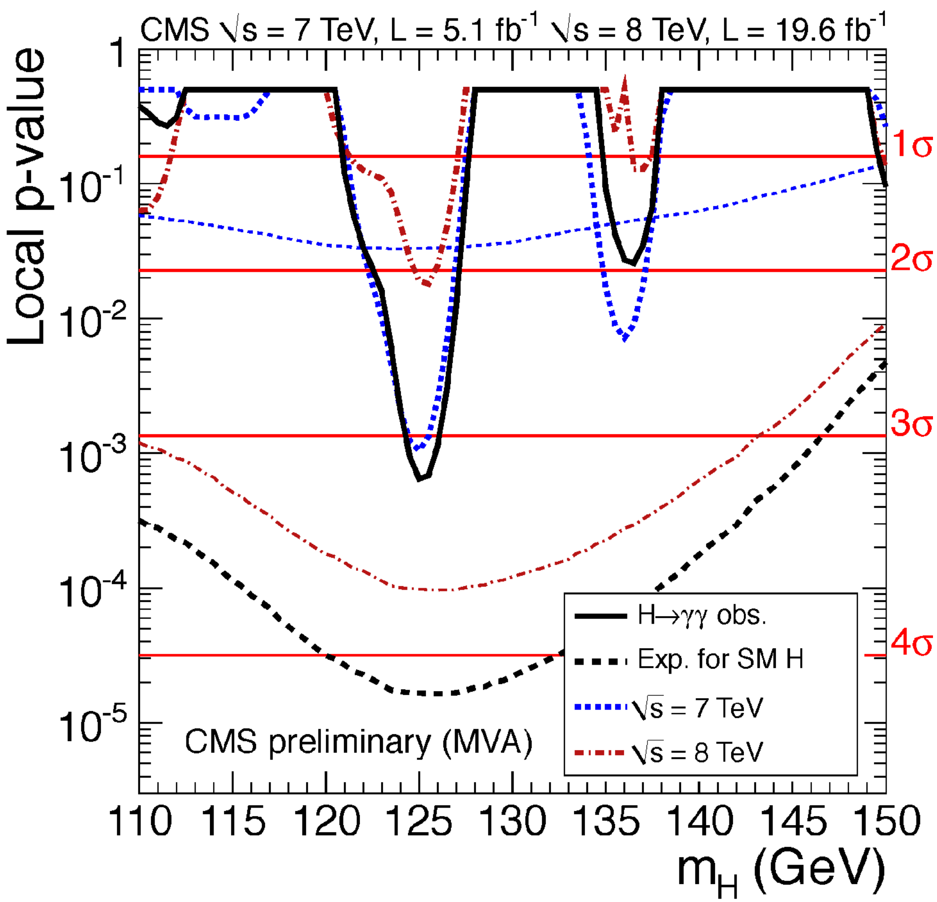


CiC vs MVA

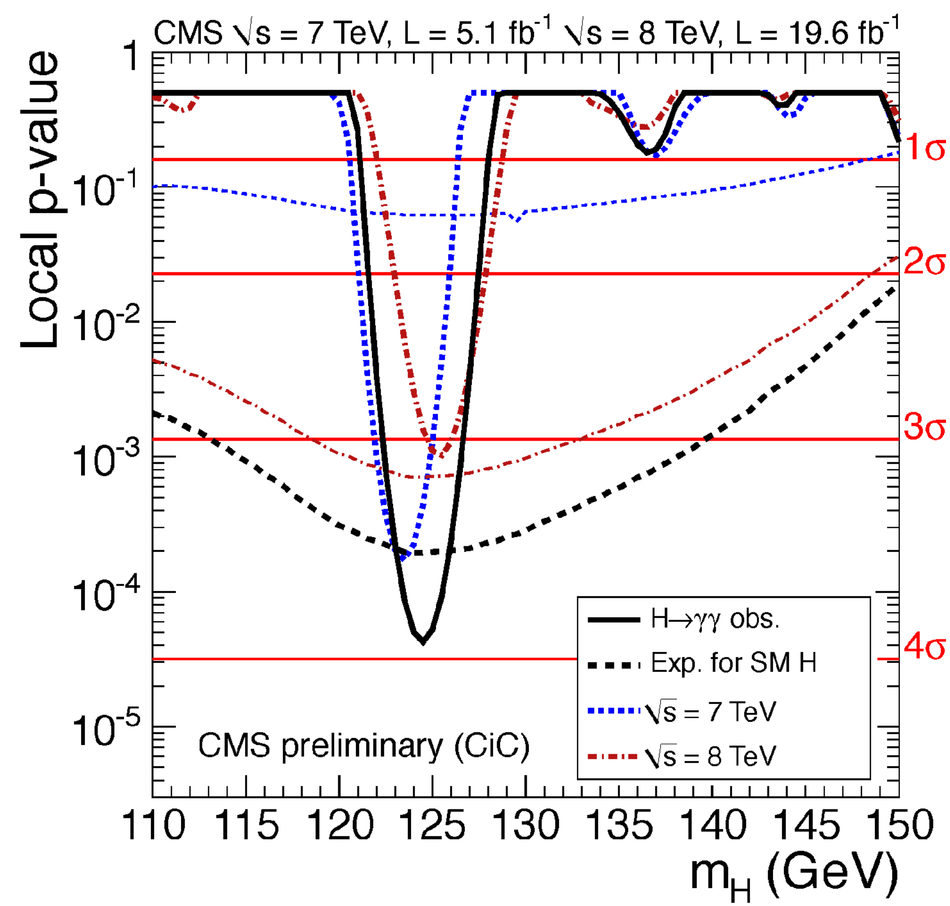

MET
Electron
Muon
Di-jet loose
Di-jet tight
Untagged 3
Untagged 2
Untagged 1
Untagged 0
Di-jet
Untagged 3
Untagged 2
Untagged 1
Untagged 0
8TeV
7TeV
CMS preliminary
√s = 7 TeV, L = 5.1 fb-1 (MVA)
√s = 8 TeV, L = 19.6 fb-1 (MVA)
Event Class
Combined
mH = 125.0 GeV
σ/σSM = 0.78+0.28-0.26
-10
-5
0
5
10
Best Fit σ/σSM


MET
Electron
Muon
Di-jet loose
Di-jet tight
Untagged 3
Untagged 2
Untagged 1
Untagged 0
Di-jet
Untagged 3
Untagged 2
Untagged 1
Untagged 0
8TeV
7TeV
CMS preliminary
√s = 7 TeV, L = 5.1 fb-1 (CIC)
√s = 8 TeV, L = 19.6 fb-1 (CIC)
Event Class
Combined
mH = 124.5 GeV
σ/σSM = 1.11+0.32-0.30
-10
-5
0
5
10
Best Fit σ/σSM

CiC vs MVA



CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 19.6 fb-1
Local p-value
1σ
2σ
3σ
4σ
H→γγ obs.
Exp. for SM H
√s = 7 TeV
√s = 8 TeV
CMS preliminary (MVA)
mH (GeV)



CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 19.6 fb-1
Local p-value
1σ
2σ
3σ
4σ
H→γγ obs.
Exp. for SM H
√s = 7 TeV
√s = 8 TeV
CMS preliminary (CiC)
mH (GeV)