The CMS Road Map for the Discovery of the Higgs.

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Julius Wess Award Talk
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The standard model (SM) in the 80's

At the end of the years 1980 the UA1+UA2 community was prepared to jump to the next hadron collider to be installed in the existing LEP tunnel.

The SM was comforted by UA experiments:

- QCD : Jets abundantly produced and studied in gluon-gluon collisions
- EWK theory: W and Z discovered and properties studied.

Two fundamental pieces were missing:

- The Top:
  - $m_t < 200$ GeV (indirect LEP 1) ; $m_t > 77$ GeV (CDF)
- The Higgs:
  - $m_H > 44$ GeV (LEP 1); $m_H < 1$ TeV (Theory : WW scattering unitarity)

No lose theorem: A machine able to probe WW scattering up to 1 TeV will either find the Higgs or discover new strong forces beyond the SM.

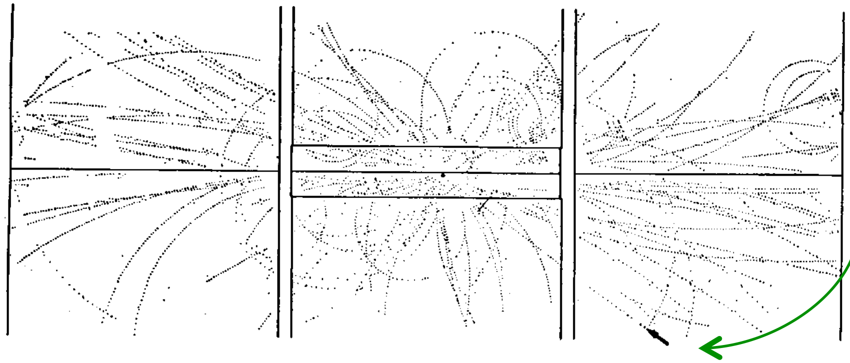
- The LHC project (16 GeV pp in LEP tunnel) was launched in the Aachen workshop in 1990 (Rubbia, Brianti). To compete with the SSC (40 TeV pp in Texas, USA) a very high luminosity (10^{34} $cm^{-2}s^{-1}$) was mandatory.
- First ideas on detectors able to work at 10^{34} were discussed in the Aachen workshop.

Lessons from UA1

•Discovering W$\rightarrow$ eν at UA1 (1981) was relatively easy:

Electron: electromagnetic calorimeter + magnetic tracking

Missing transverse energy: Hermetic Calorimeter



Electron E_T= 24 GeV well measured in em calorimeter + no visible jet on the away side (hadron calorimeter)

•Demonstrating W$\rightarrow$ $\mu\nu$ was a lot more difficult!

High p_T muons suffer from poor momentum resolution: B=0.7T (dipole)

$\pi\rightarrow\mu\nu$ decays can fake high p_T muons and induce fake missing transverse energy.

Low pT muons on the other hand have an advantage over electrons. They can be detected inside jets: B physics at hadron collider was pioneered by UA1.

First ideas for an LHC detector:

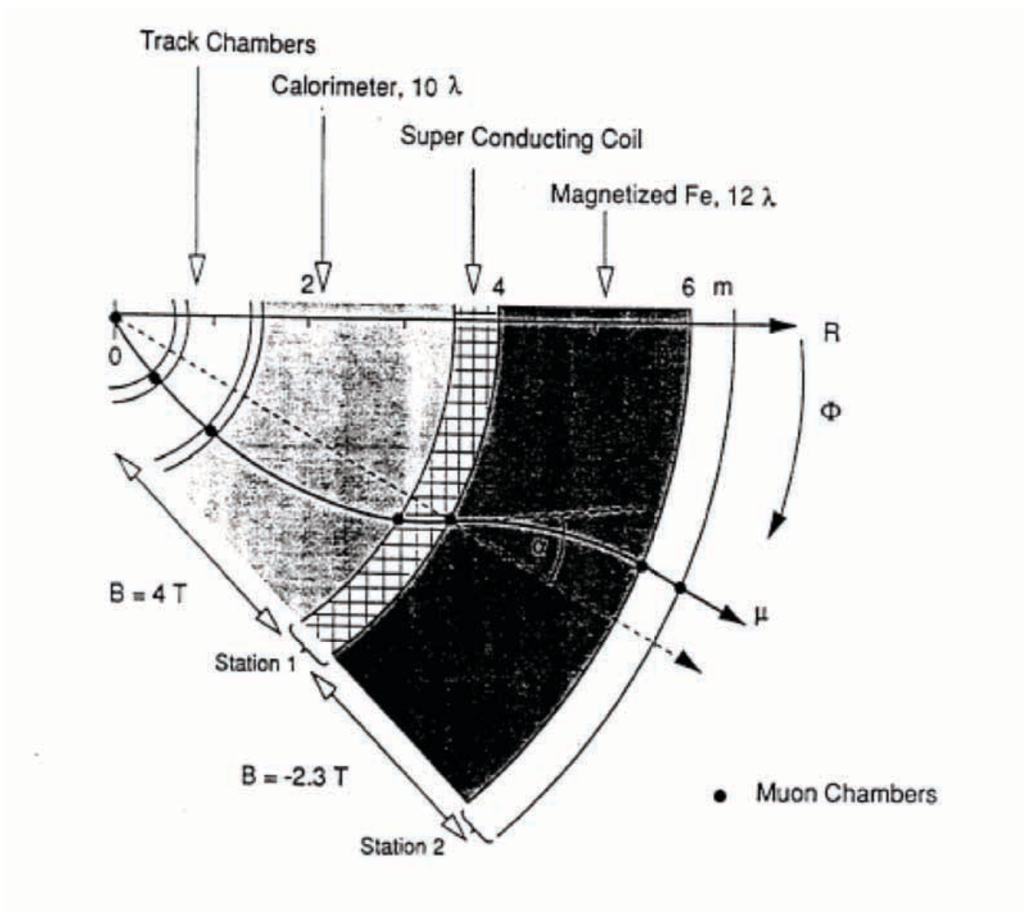
- A robust and redundant muon detector is a priority.
- Muon detection is guaranteed at any luminosity (Iron Ball).
- Need a strong magnetic field (momentum resolution).

Design Criteria for the CMS Experiment

First conceptual design of a “Compact Muon Solenoid” (CMS) was presented in Aachen (1990) based on a 4 Tesla solenoid.

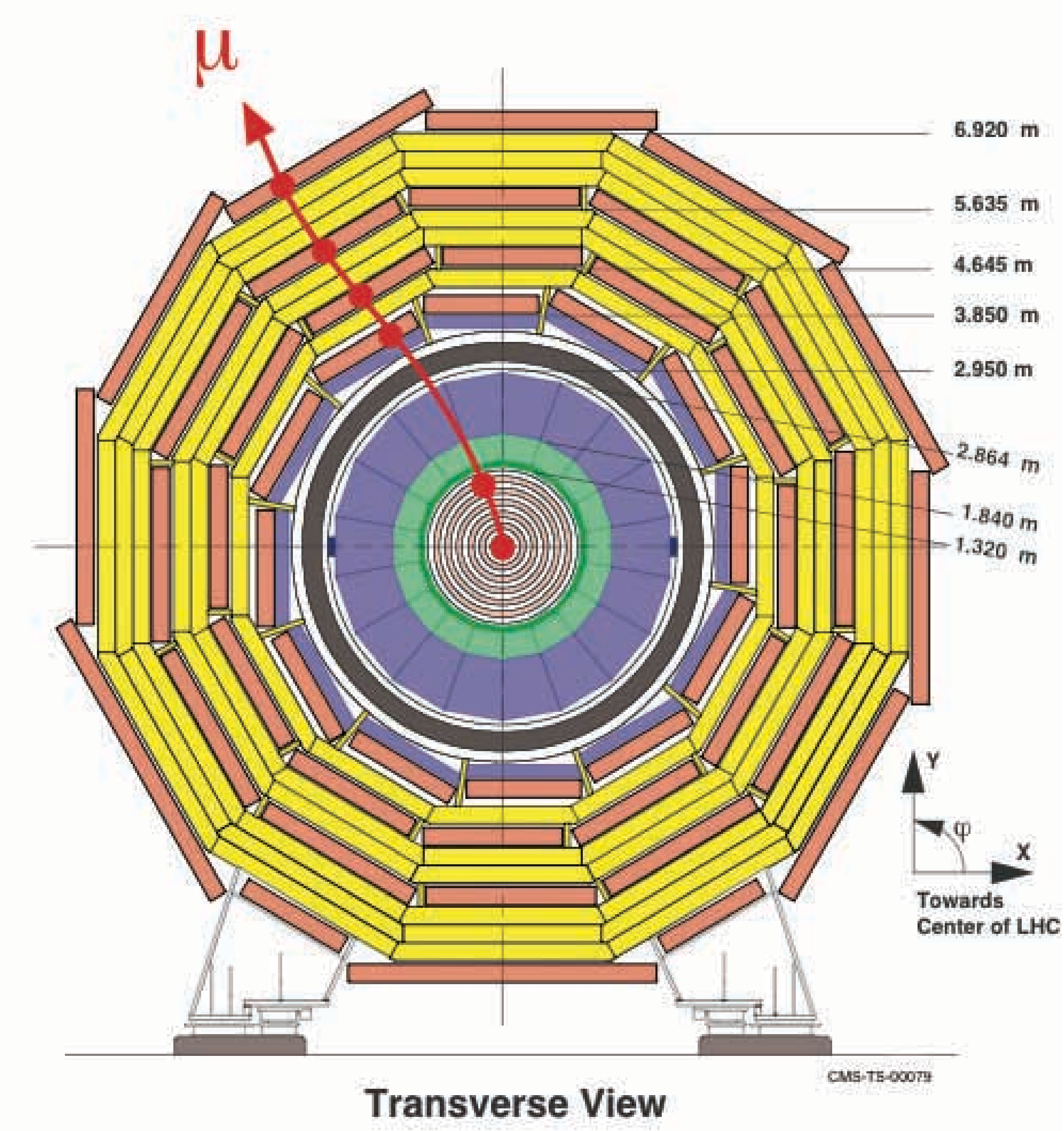
Compact Muon Solenoid

M. Della Negra, K. Eggert, M. Lanzagorta, M. Pimiä, F. Szoncso



- Very good muon identification and momentum measurement.
  $H \rightarrow ZZ$, with $Z \rightarrow \mu\mu$
- Most precise photon detector.
  $H \rightarrow \gamma\gamma$
- Powerful inner tracking systems for electron identification.
  $H \rightarrow ZZ$, with $Z \rightarrow ee$
- Hermetic calorimetry for missing E_T signatures.
  $H \rightarrow WW$, with $W \rightarrow \mu\nu$ or $e\nu$

Precise and Redundant Muon Detector



Strong Field 4T

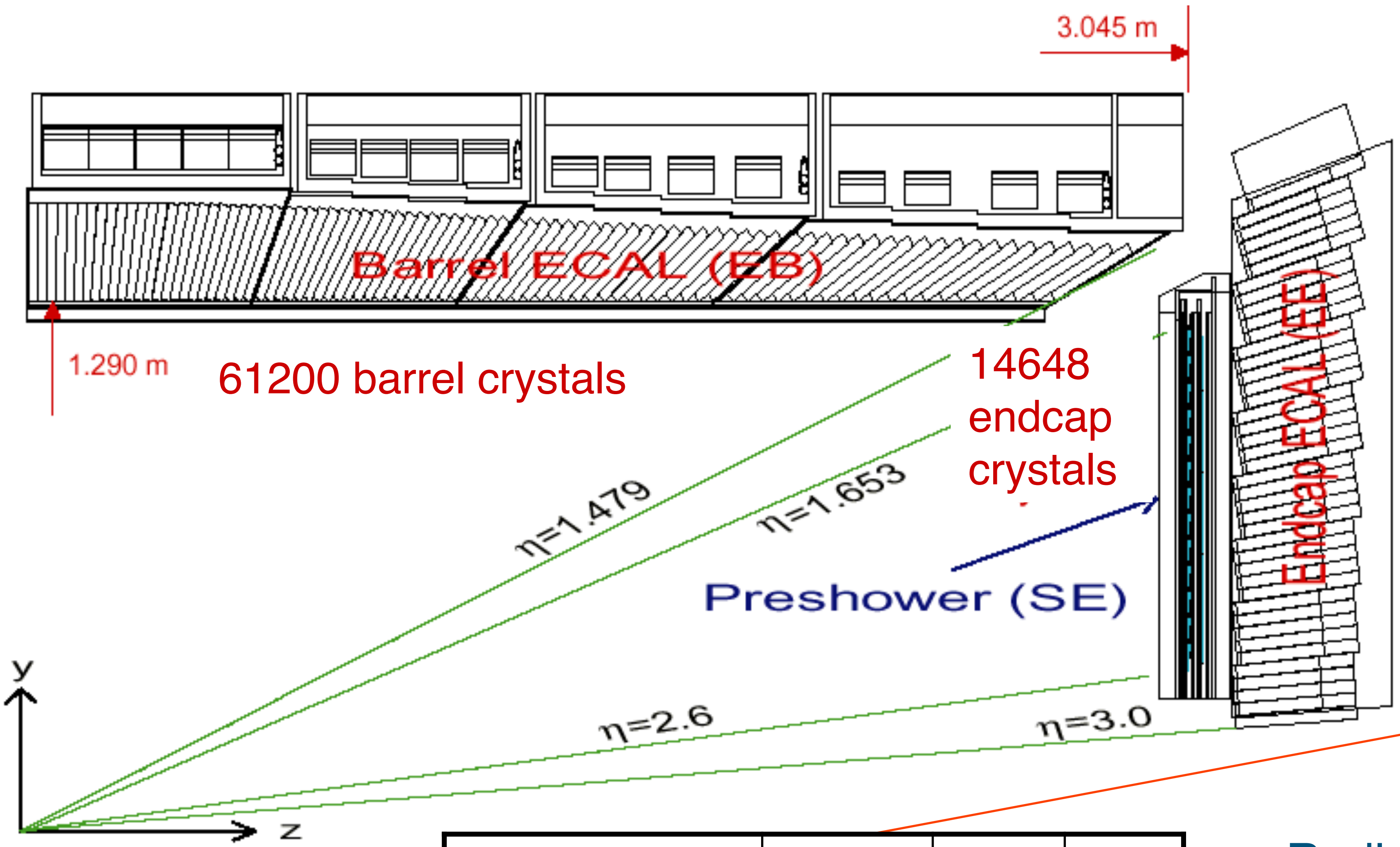
Compact design

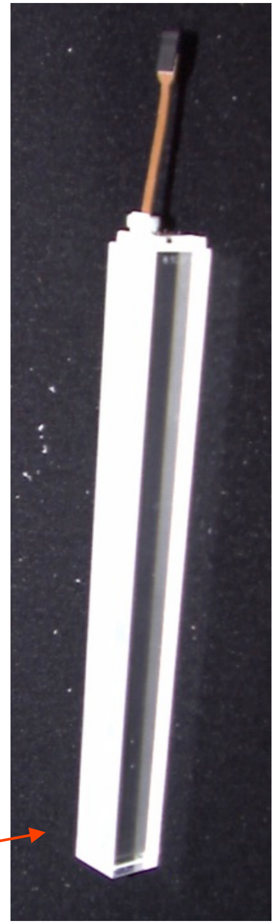
Solenoid for Muon P_t trigger in transverse plane

Redundancy: 4 muon stations with 32 r-phi measurements

$\Delta P_t/P_t \sim 5\%$ @1TeV for reasonable space resolution of muon chambers (200μm)

Precise Photon Detector: PbWO4 Crystal Calorimeter

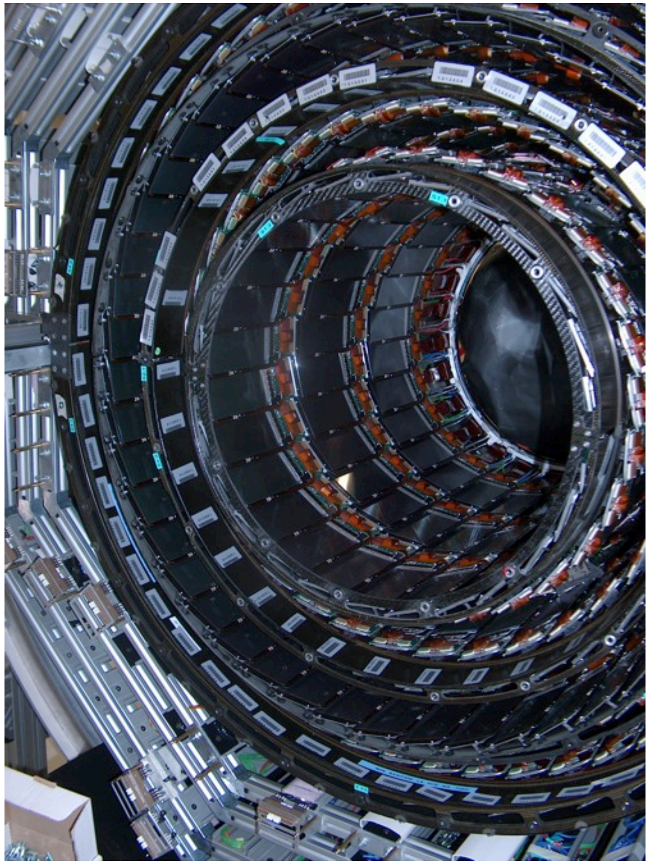


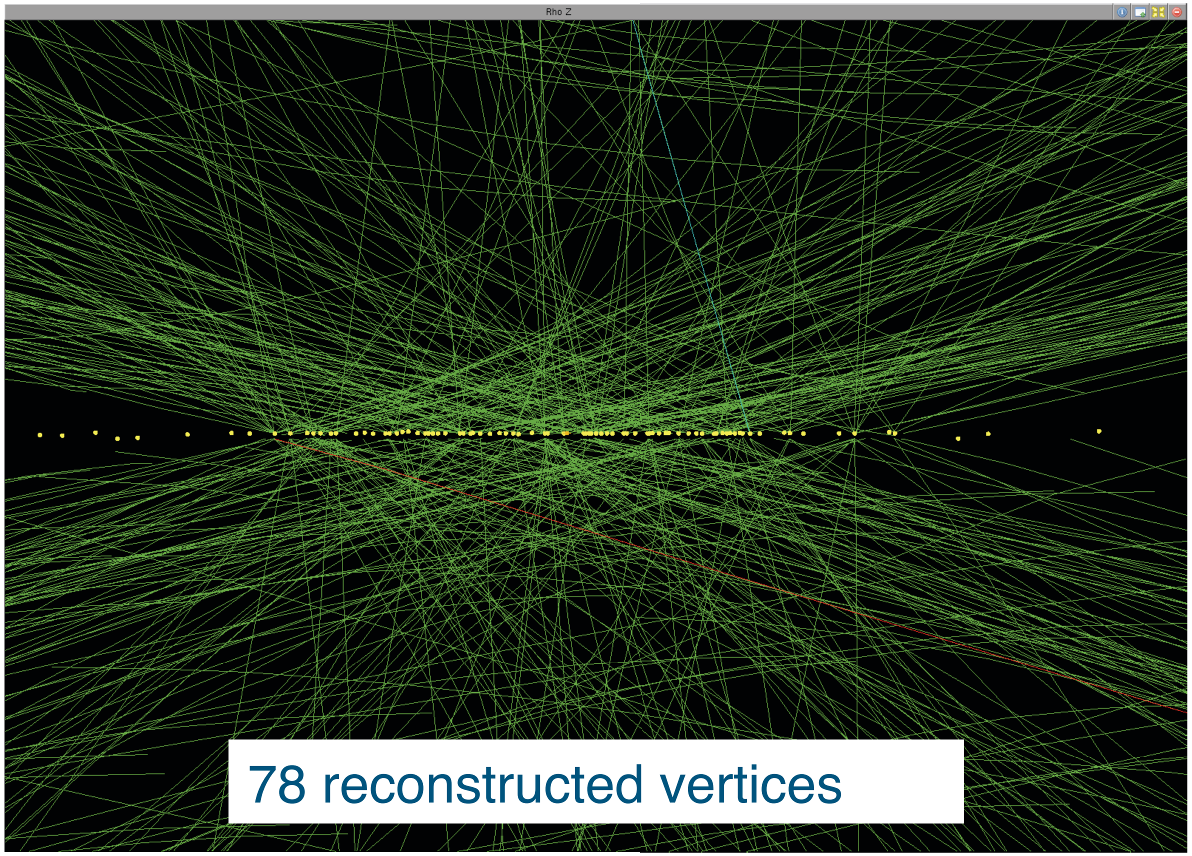


Material	$PbWO_4$	Pb	Fe
Density (g/cm^3)	8.3	11.3	7.9
X_0 (mm)	8.9	5.6	17.6

Radiation Hard:
10^5 Gy (10 Mrad).
Photodetector: APD
works in B = 4T

Tracking at LHC?





66 million silicon pixels: 100 × 150 μm^2

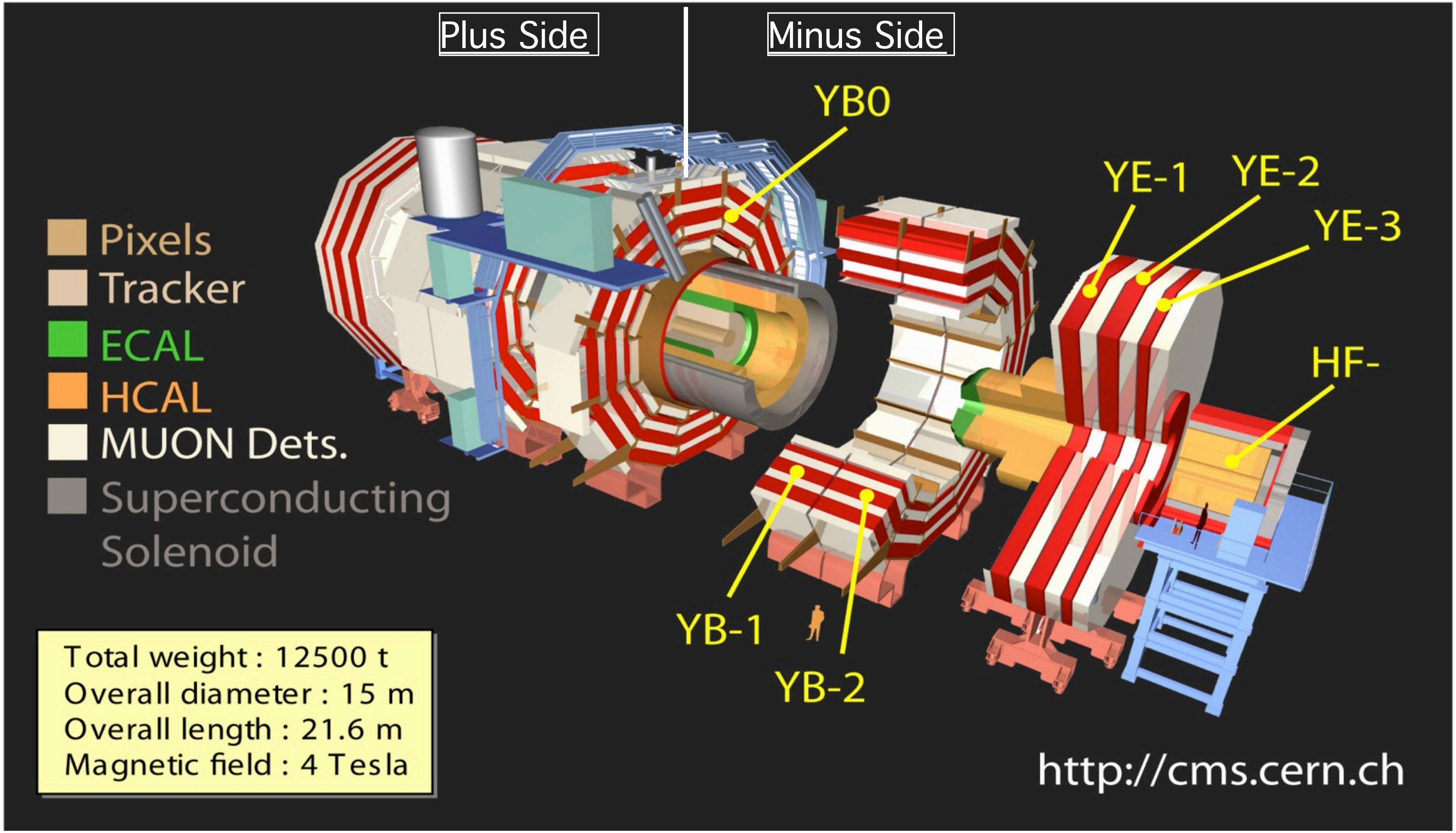
9.3 million silicon microstrips: 80μm - 180μm.

~200 m^2 of active silicon area (cf ~ 2m^2 in LEP detectors)

~13 precise position measurements (15 μm) per track.

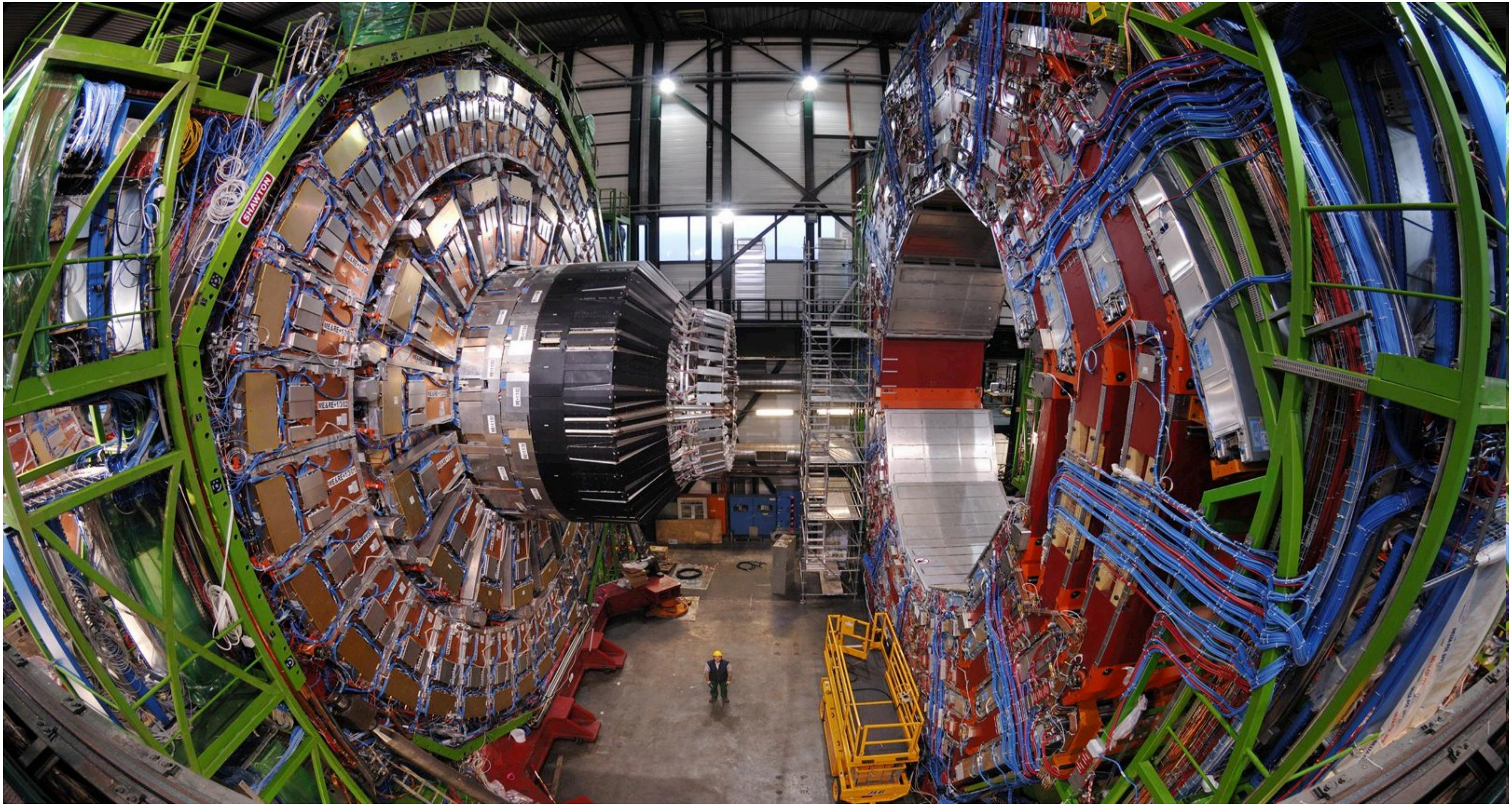
Modular Design of CMS (A. Hervé)

CMS is sectionned in 5 barrel wheels, 6 endcap disks and 2 forward calorimeters: 13 pieces

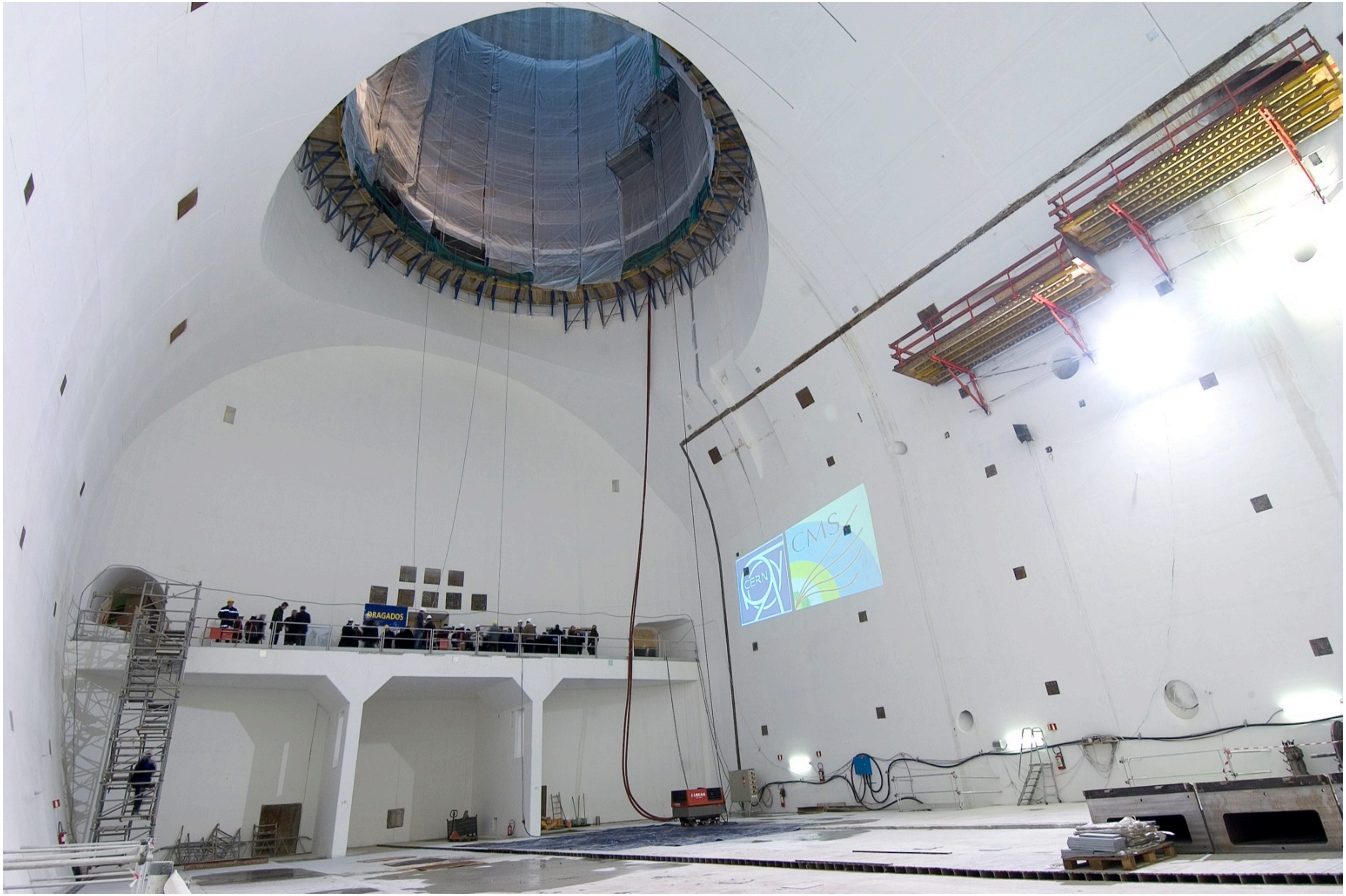


Assembly in the surface hall

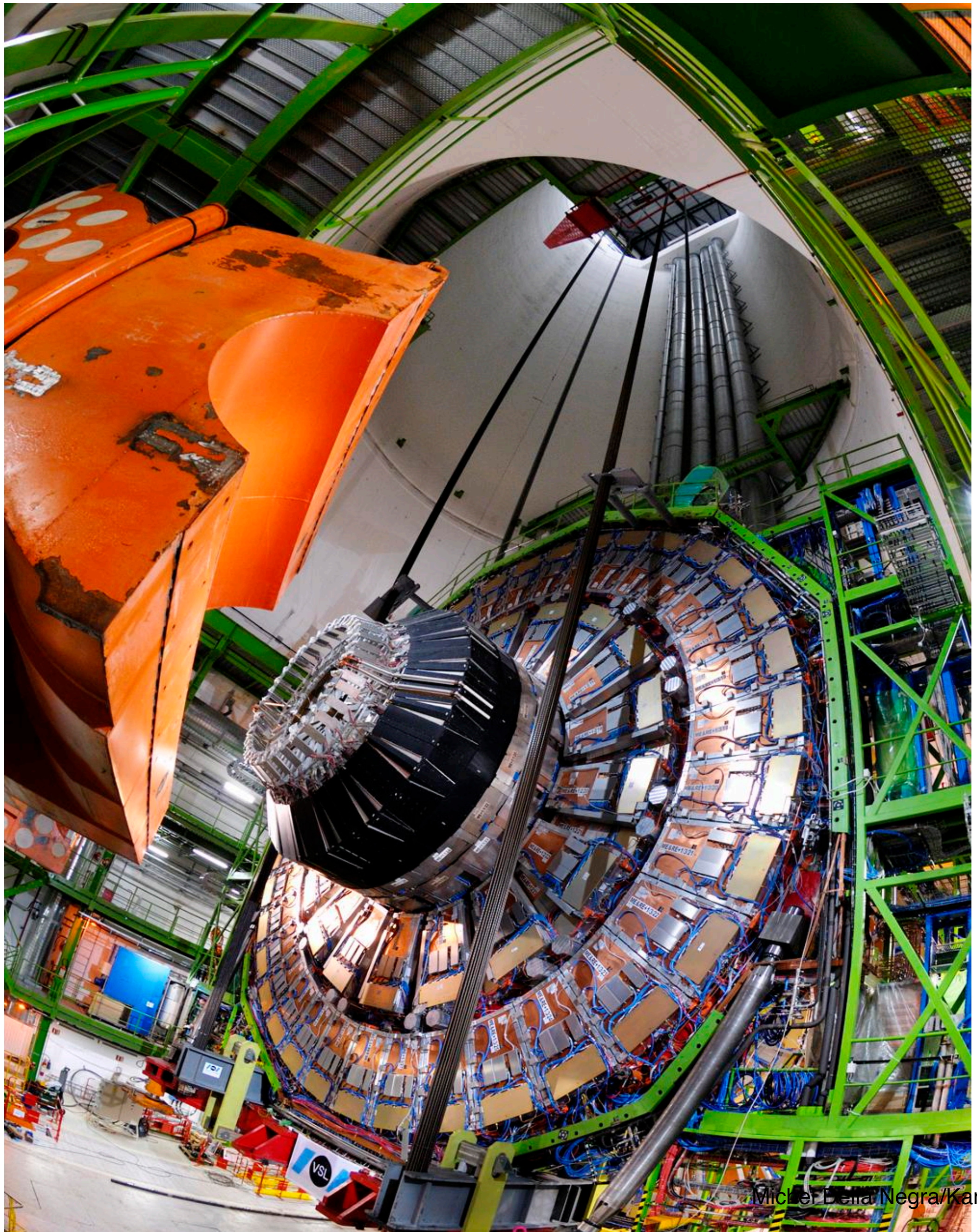
Waiting for the cavern to be ready

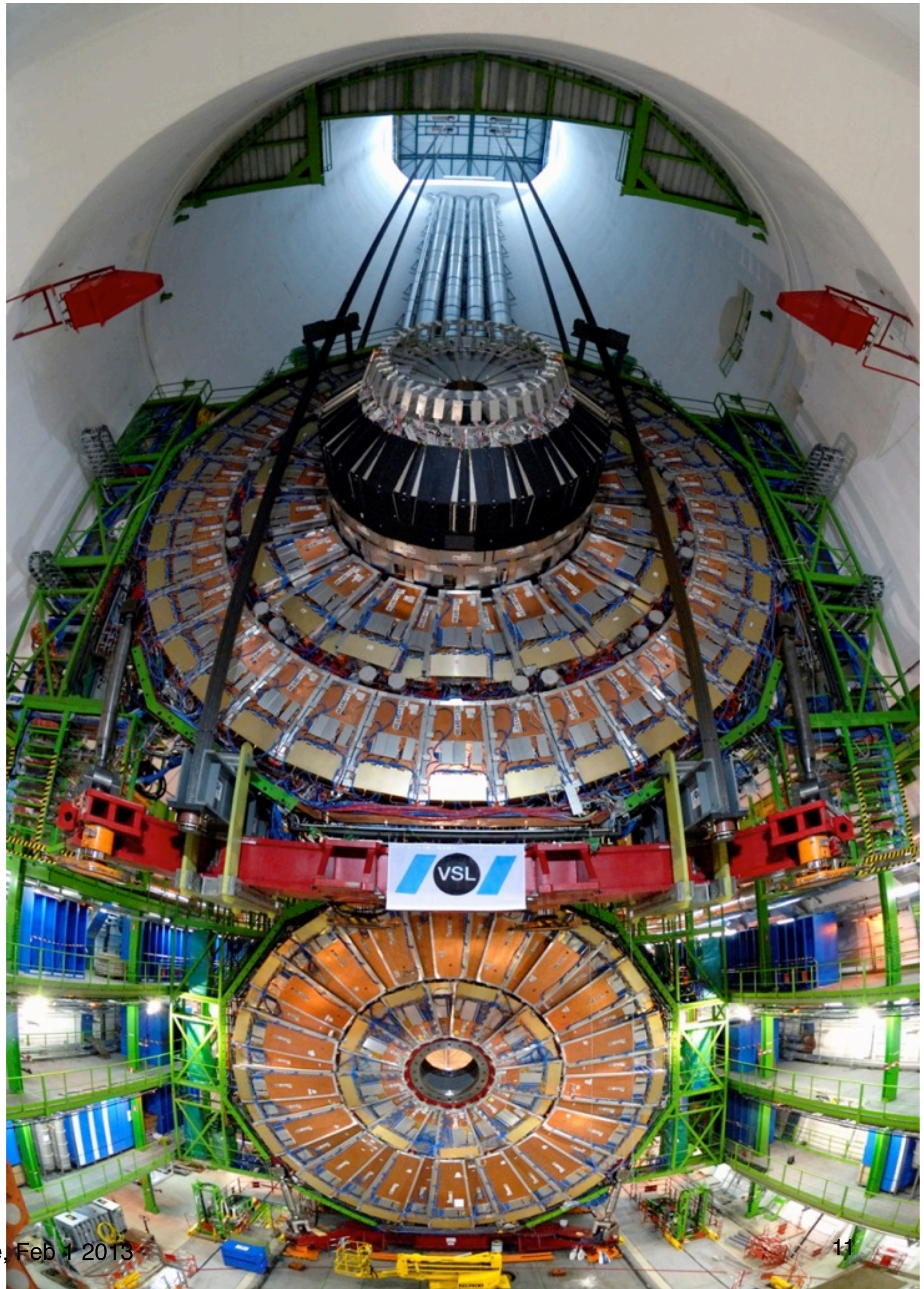


Empty Cavern ready: Feb 2005



Descent of the endcaps





Descent of the central wheel (2000 tons)

From Concept to Data Taking: 18 years

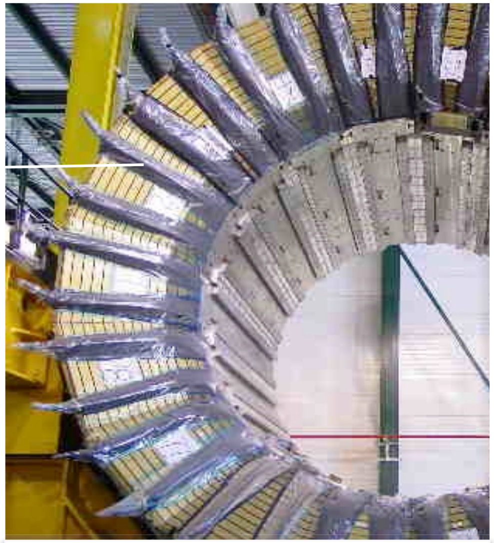
Letter of Intent (1992)
Technical Proposal (1995)
10 Technical Design Reports (1997-2006)
3000 scientists from 40 countries

Silicon Tracker

Muon Chambers

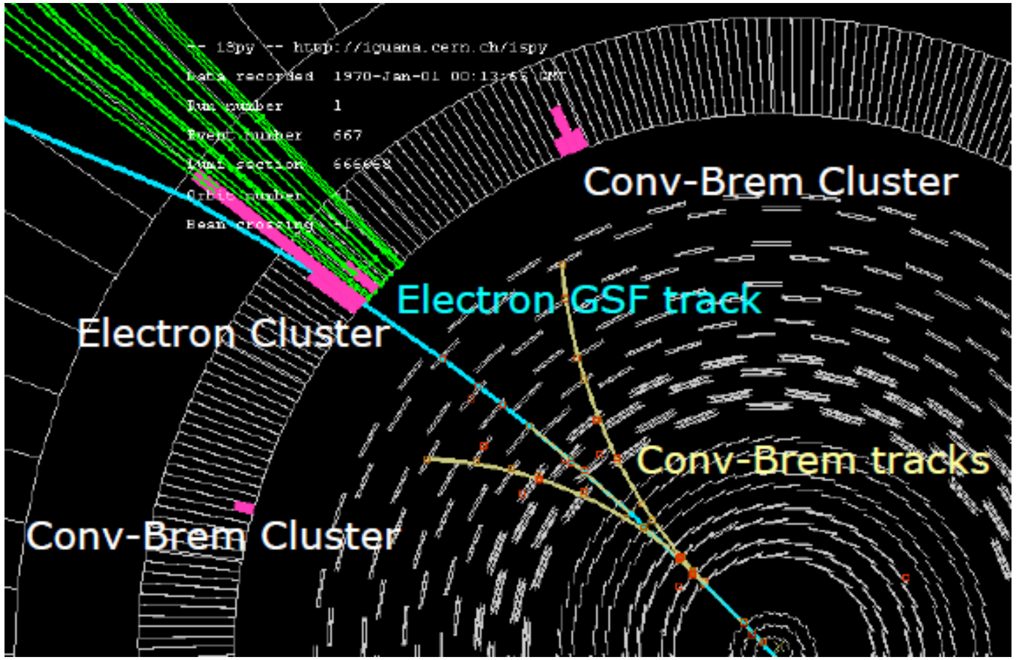
CMS cut in mid-plane

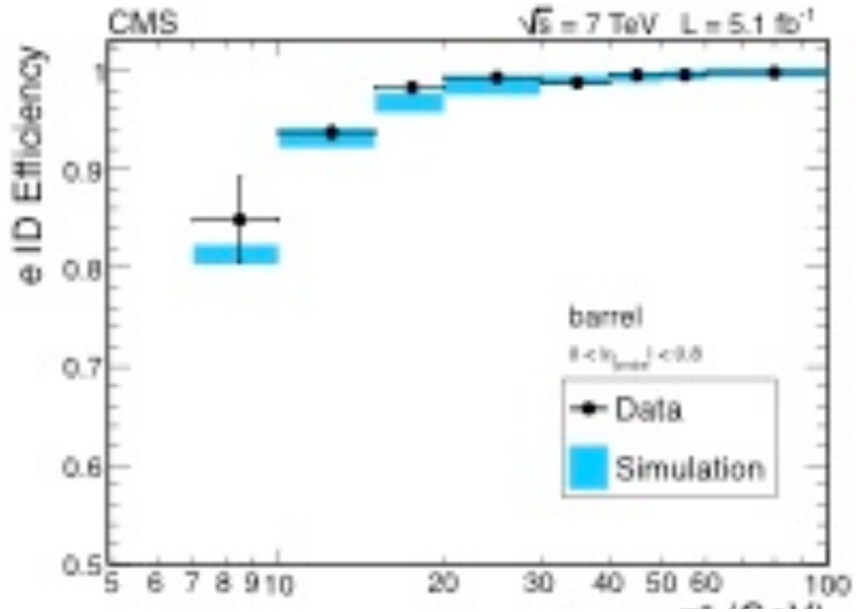
Scintillating Crystals

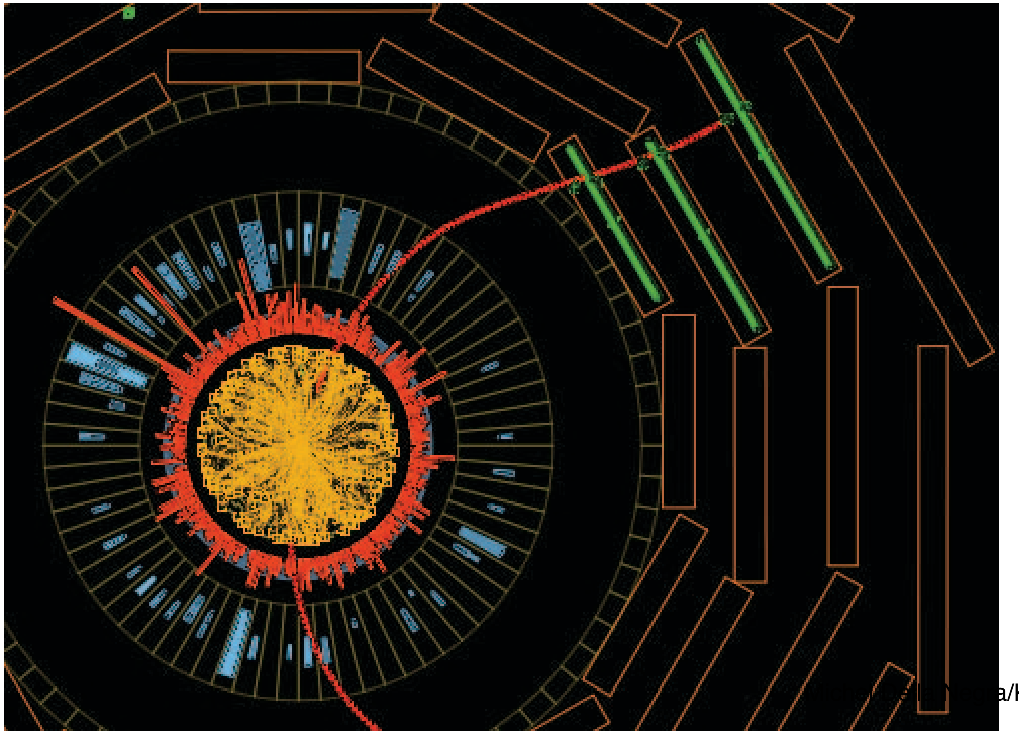


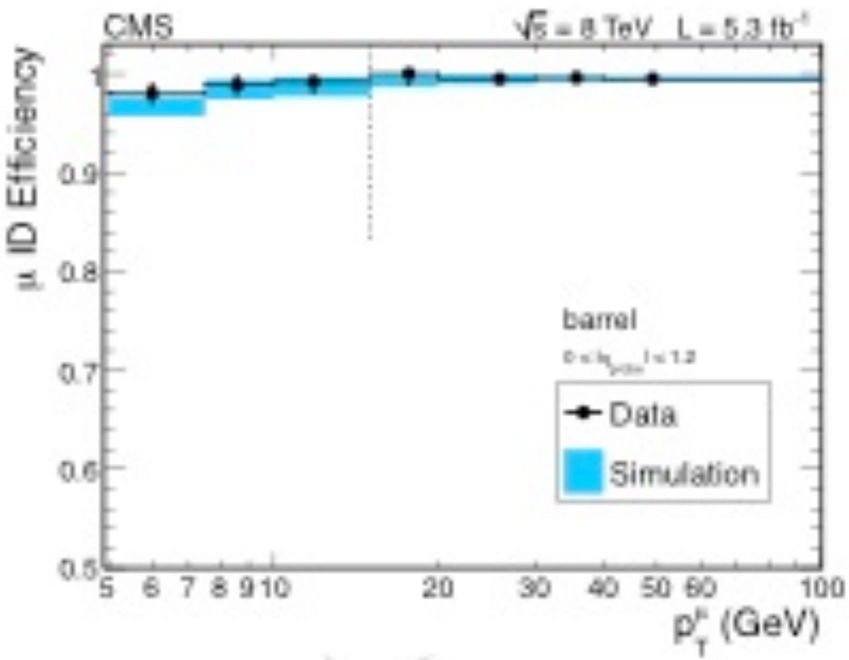
Hermetic Hadron Calorimeter: Brass plastic scintillator

Electrons and Muons

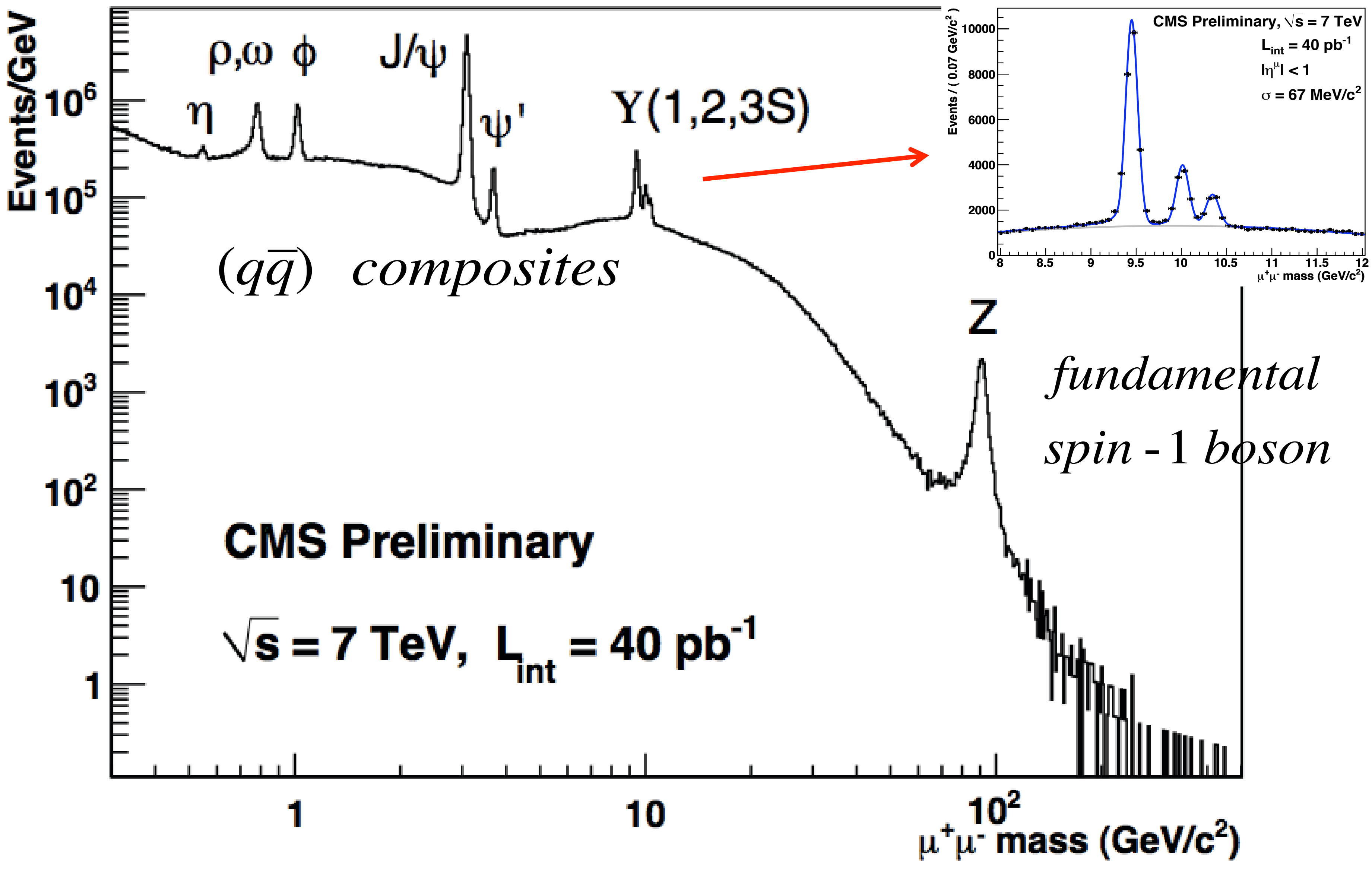




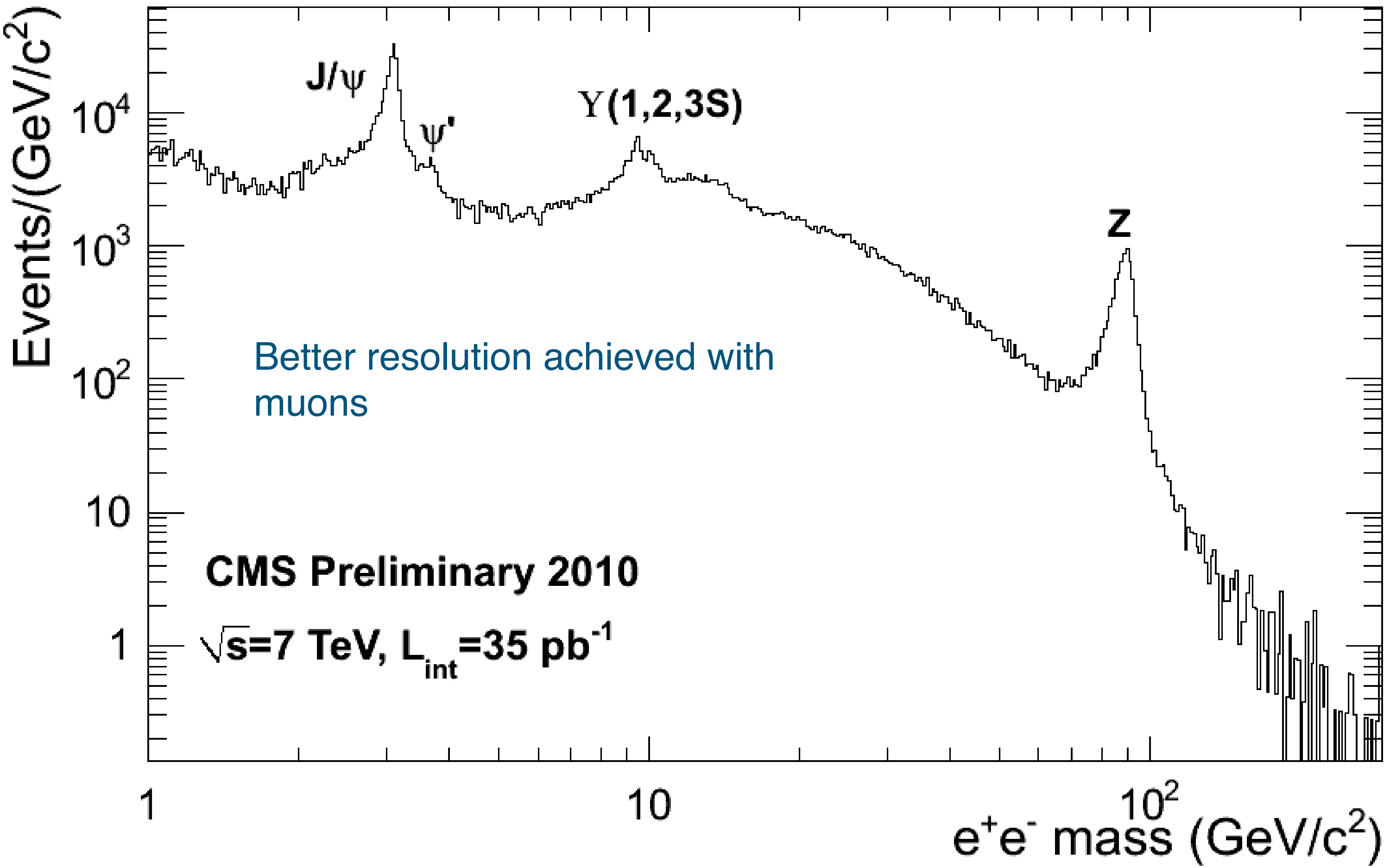




Dimuon mass resolution

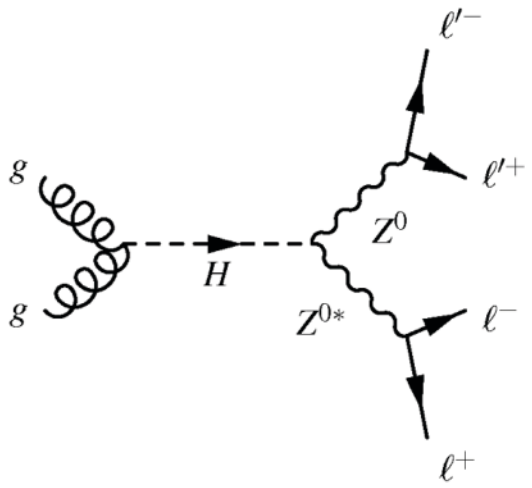


Dielectron mass resolution



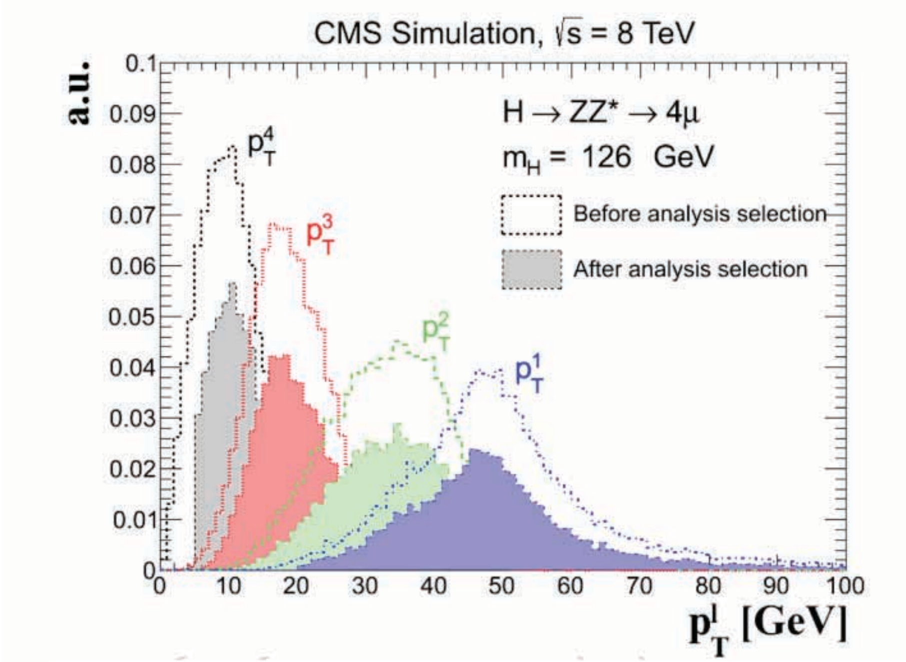
Better resolution achieved with muons

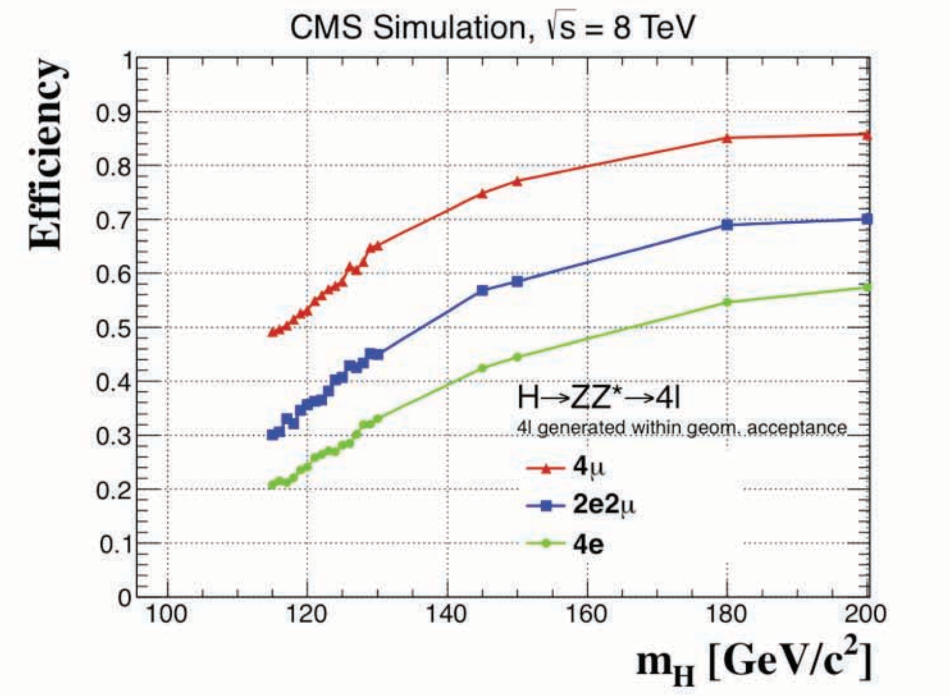
Searching for the Higgs in the four leptons final state

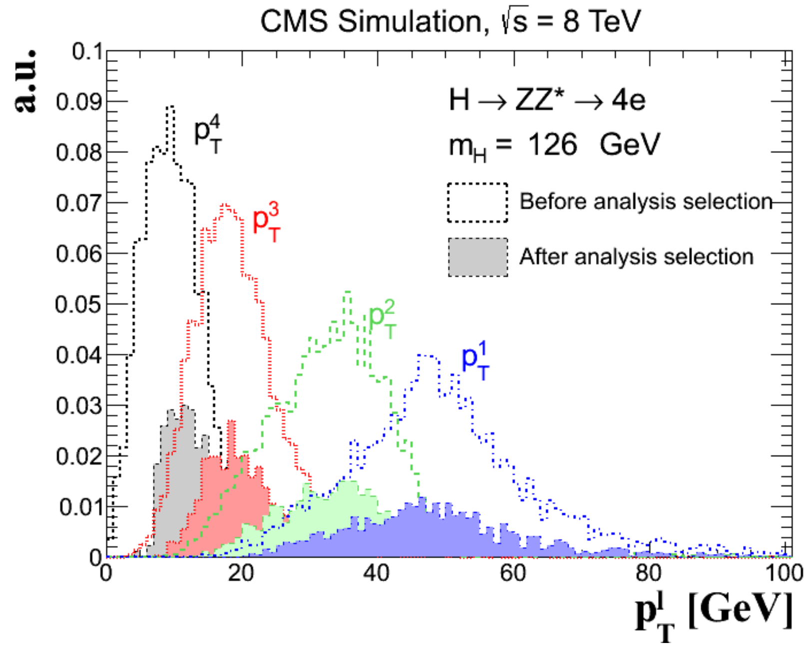


For a low mass Higgs the fourth lepton is soft.
Selection cuts:

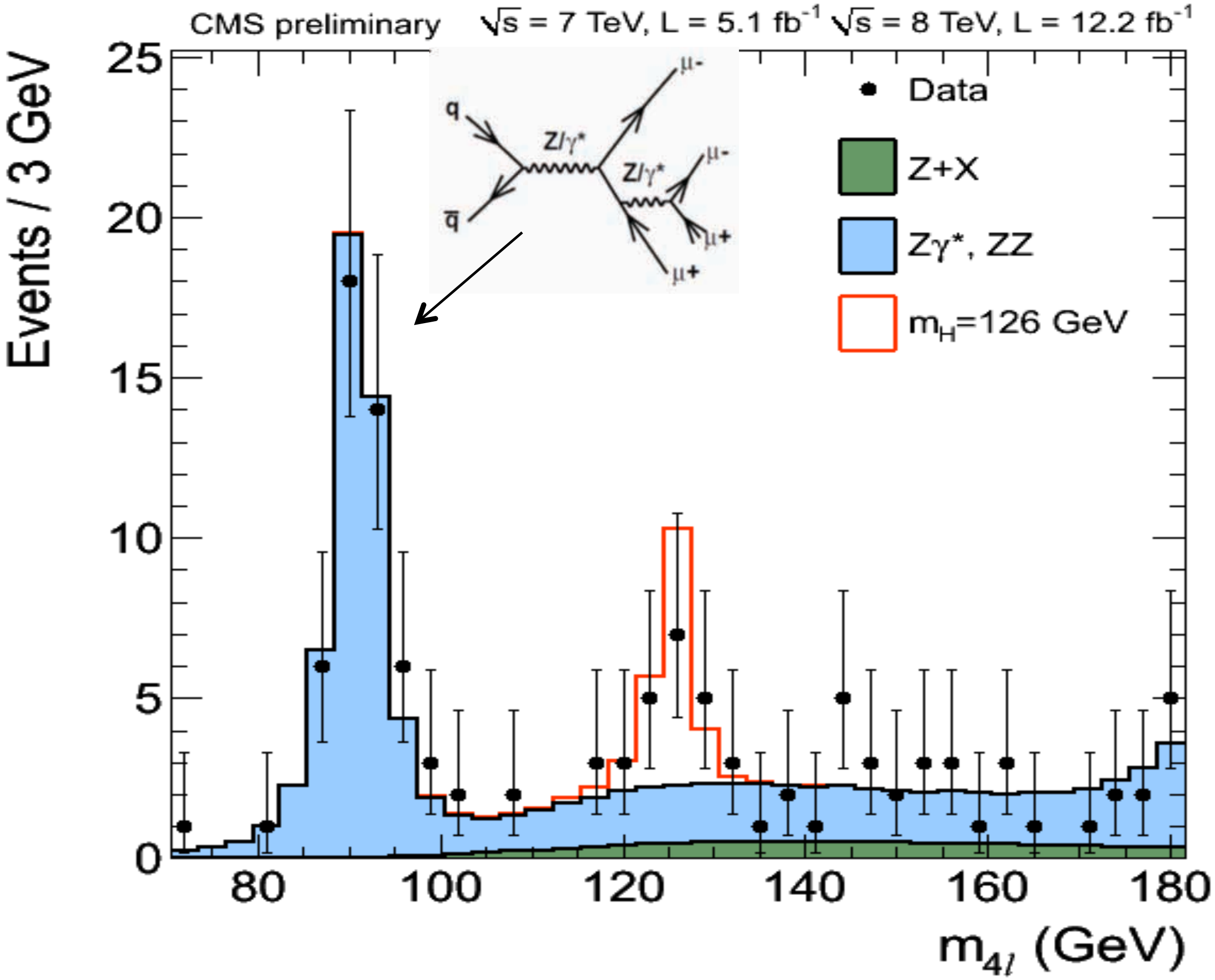
Electrons $p_T > 7$ GeV
Muons $p_T > 5$ GeV
40 GeV $< m_{12} <$ 120 GeV
$m_{34} > 12$ GeV

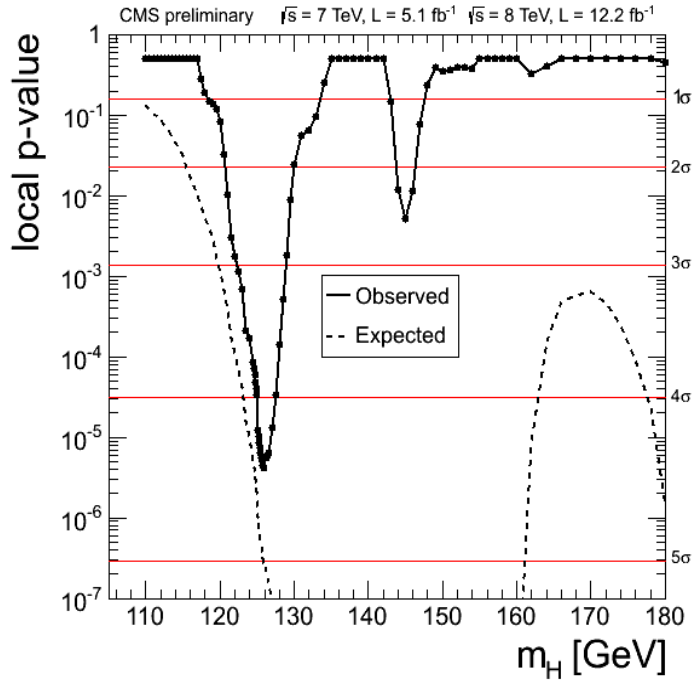


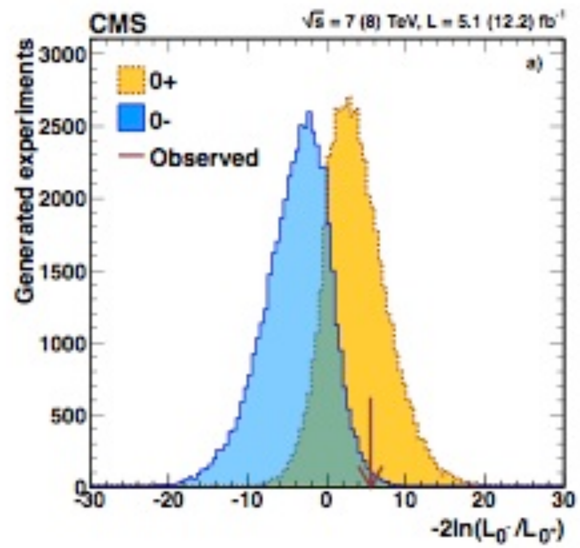




H→ZZ→ 4 leptons







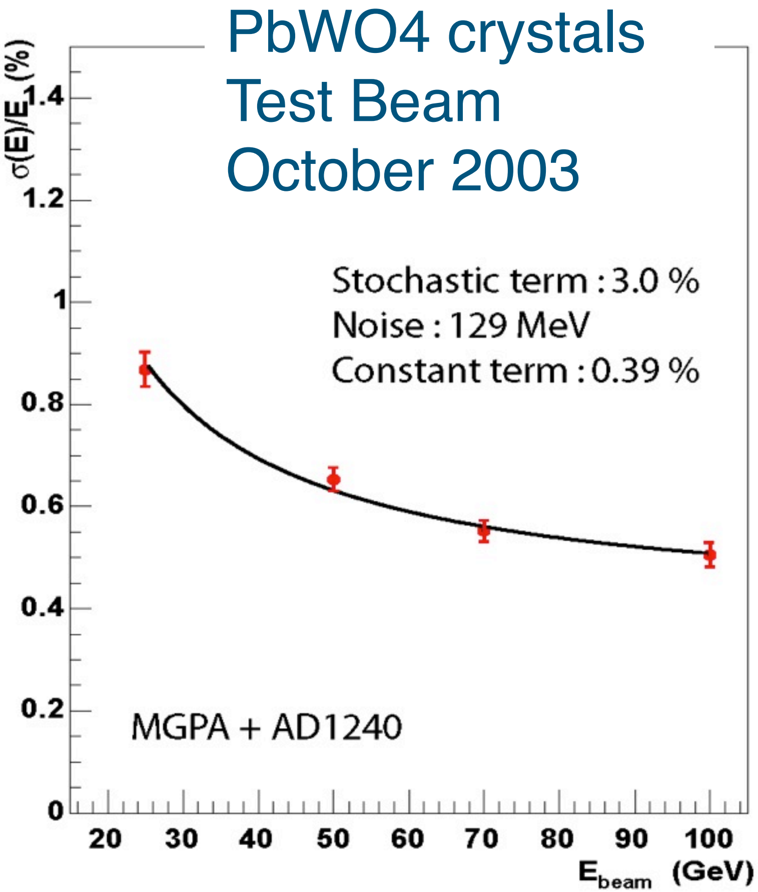
Significance $4.5\ \sigma$

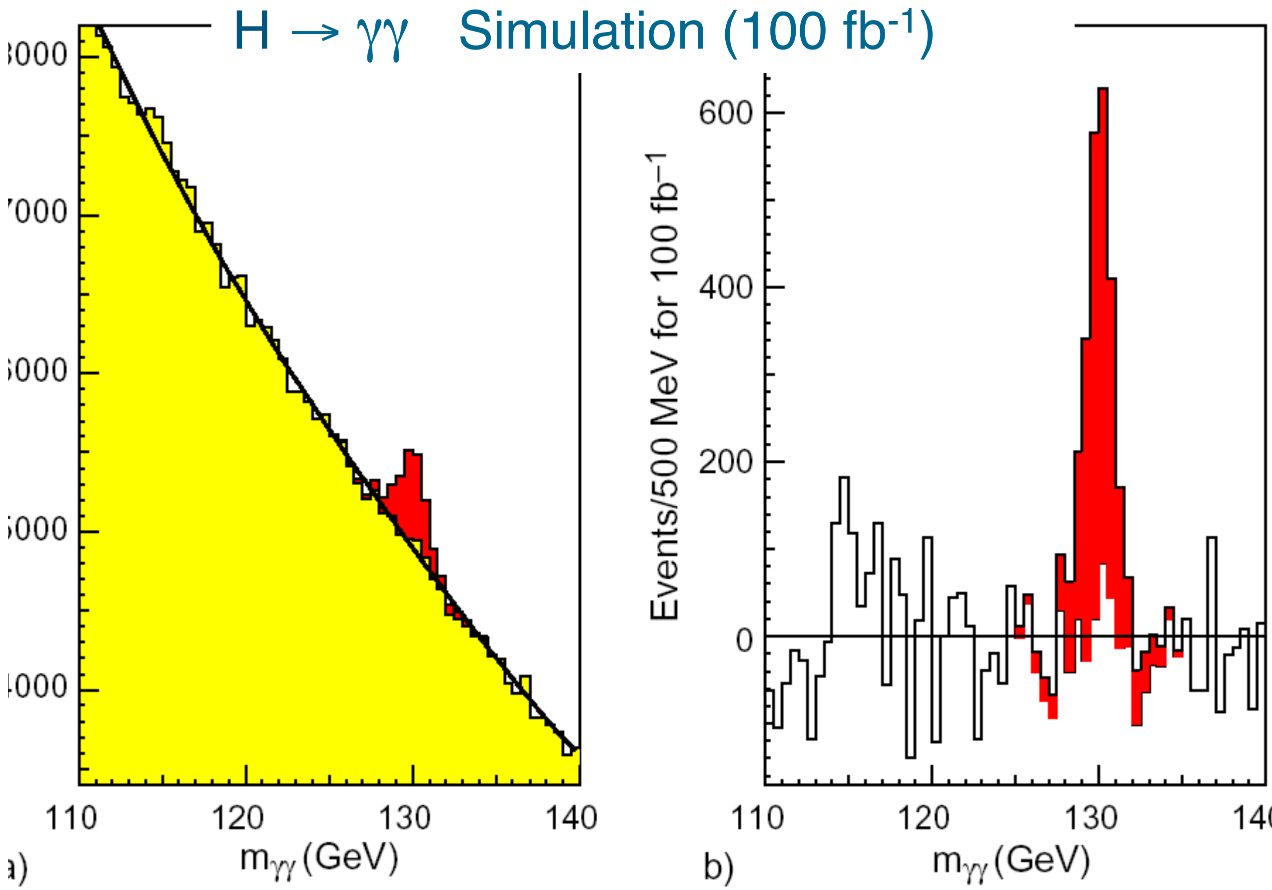
Mass 126.2 ± 0.6 (stat) ± 0.2 (syst) GeV

0^- excluded to > 95% CL

Search for the SM Higgs boson in the $\gamma\gamma$ channel

Mass resolution is the key for Higgs discovery in this channel





$$\frac{\sigma}{E} = \frac{3\%}{\sqrt{E}} \oplus 0.39\% \oplus \frac{129\,MeV}{E}$$

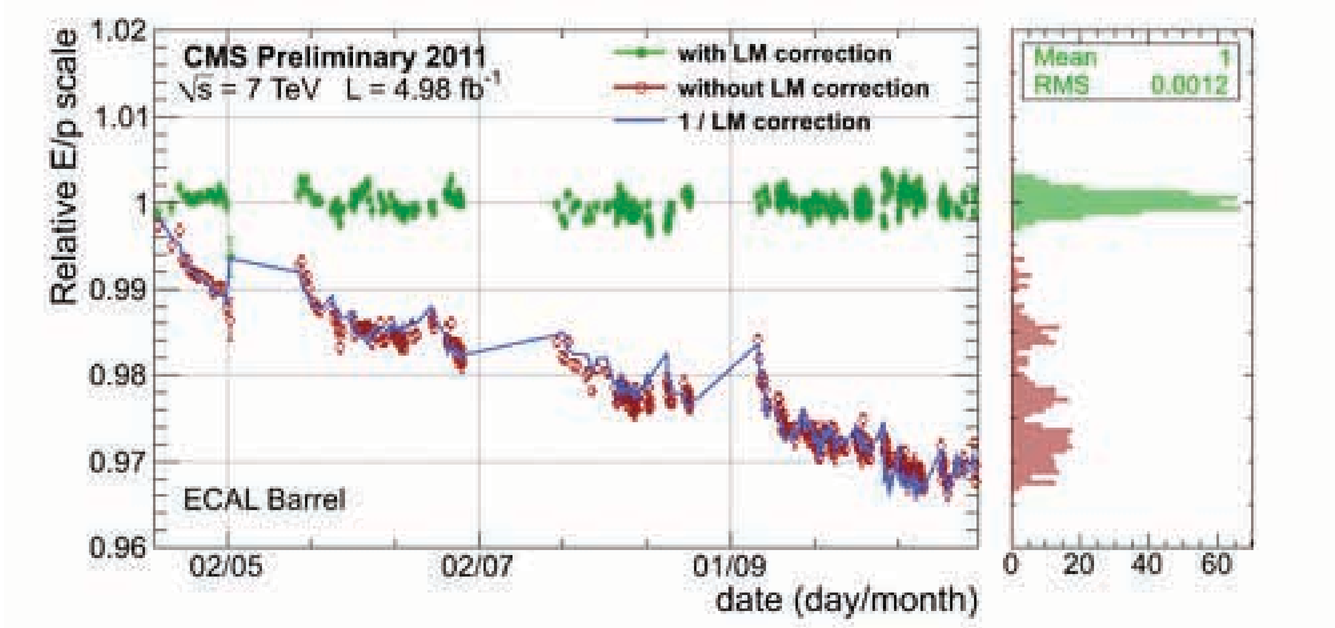
$$\sigma_m/m = 0.5\,[\sigma_{E1}/E_1 \oplus \sigma_{E2}/E_2 \oplus \cot(\theta/2)\Delta\theta]$$

Target for the intercalibration < 0.5%

Energy Resolution dominated by calibrations!

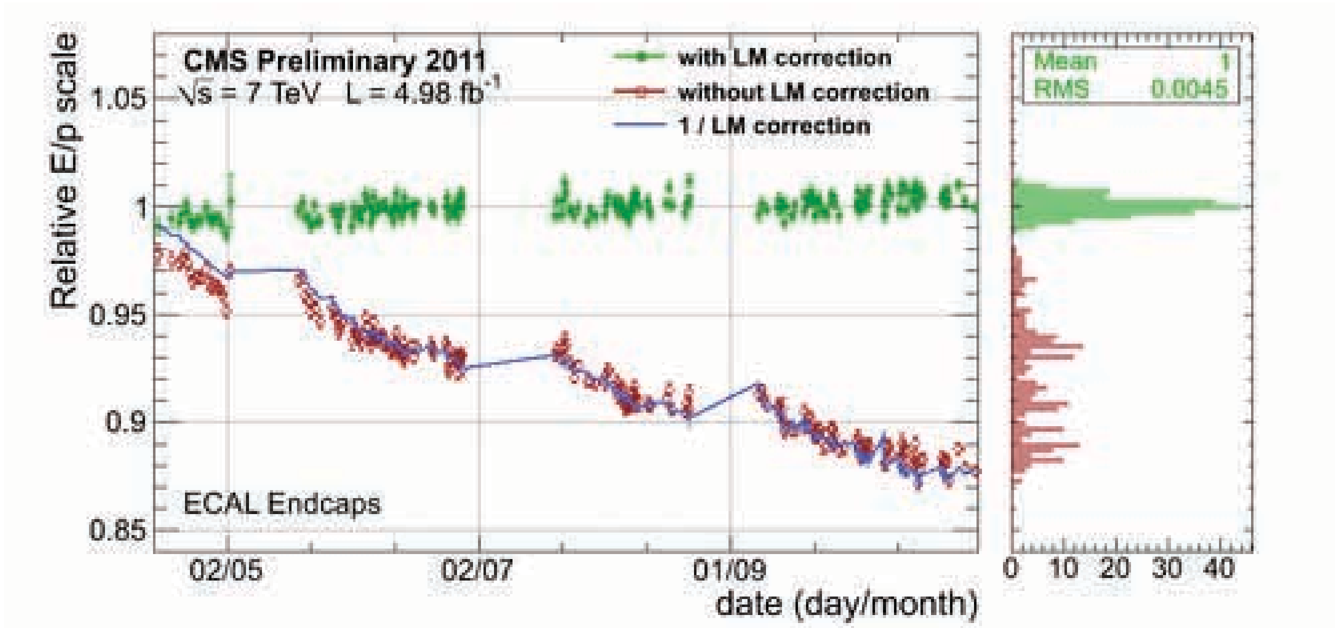
Calibration of the crystals:

- Crystal transparency correction (Laser monitoring)
- inter-crystal calibration: π^0, η

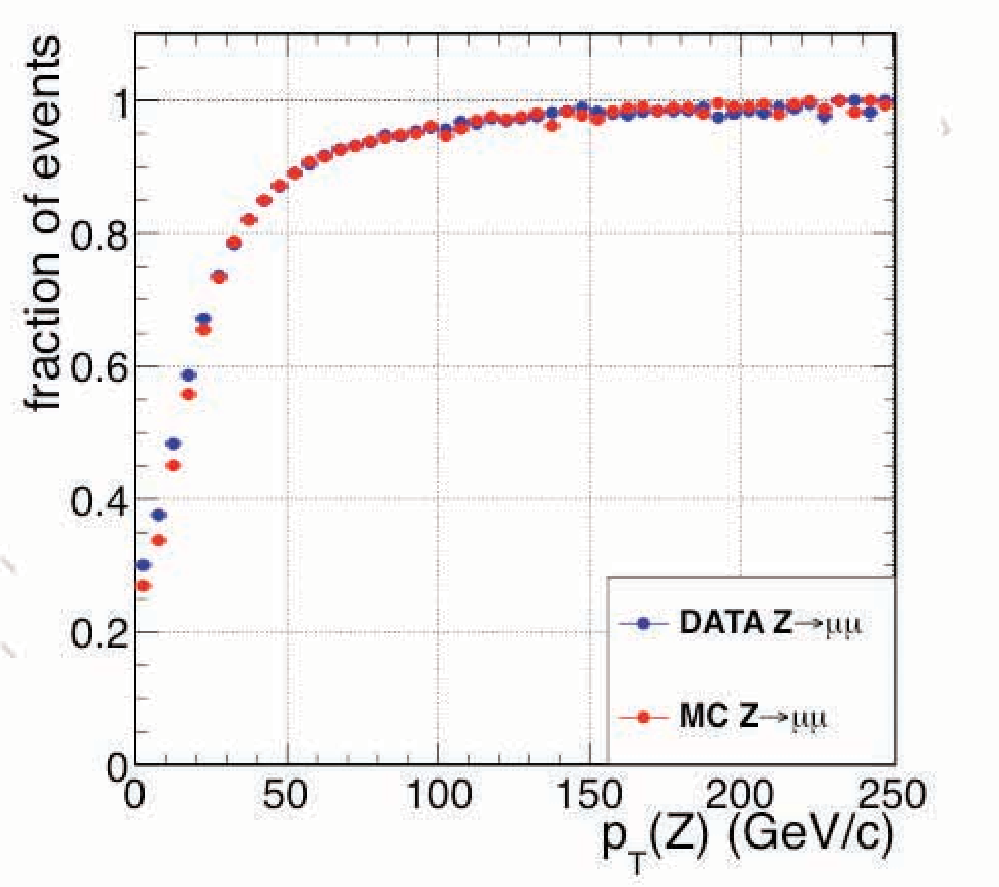


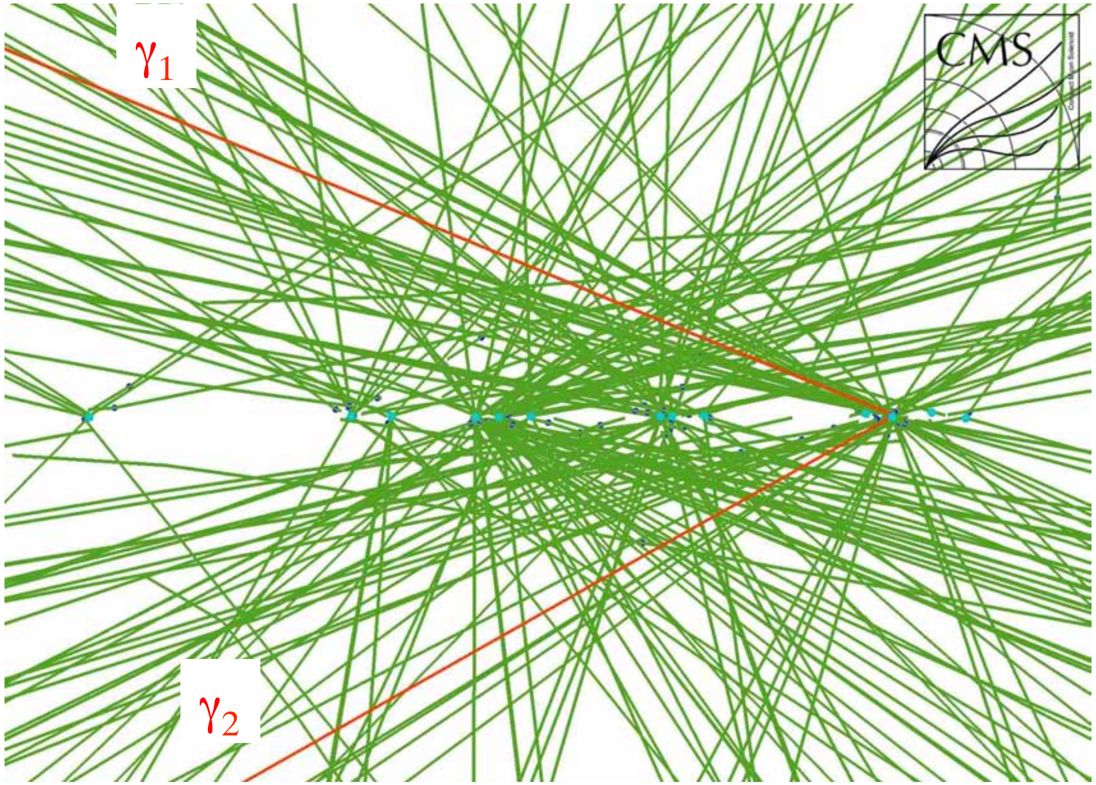
Energy scale stability
(after response correction)

- Barrel: 0.12% (2.5% loss)
- Endcap: 0.45% (10% loss)



Mass resolution of $\gamma\gamma$ system: Find the right vertex

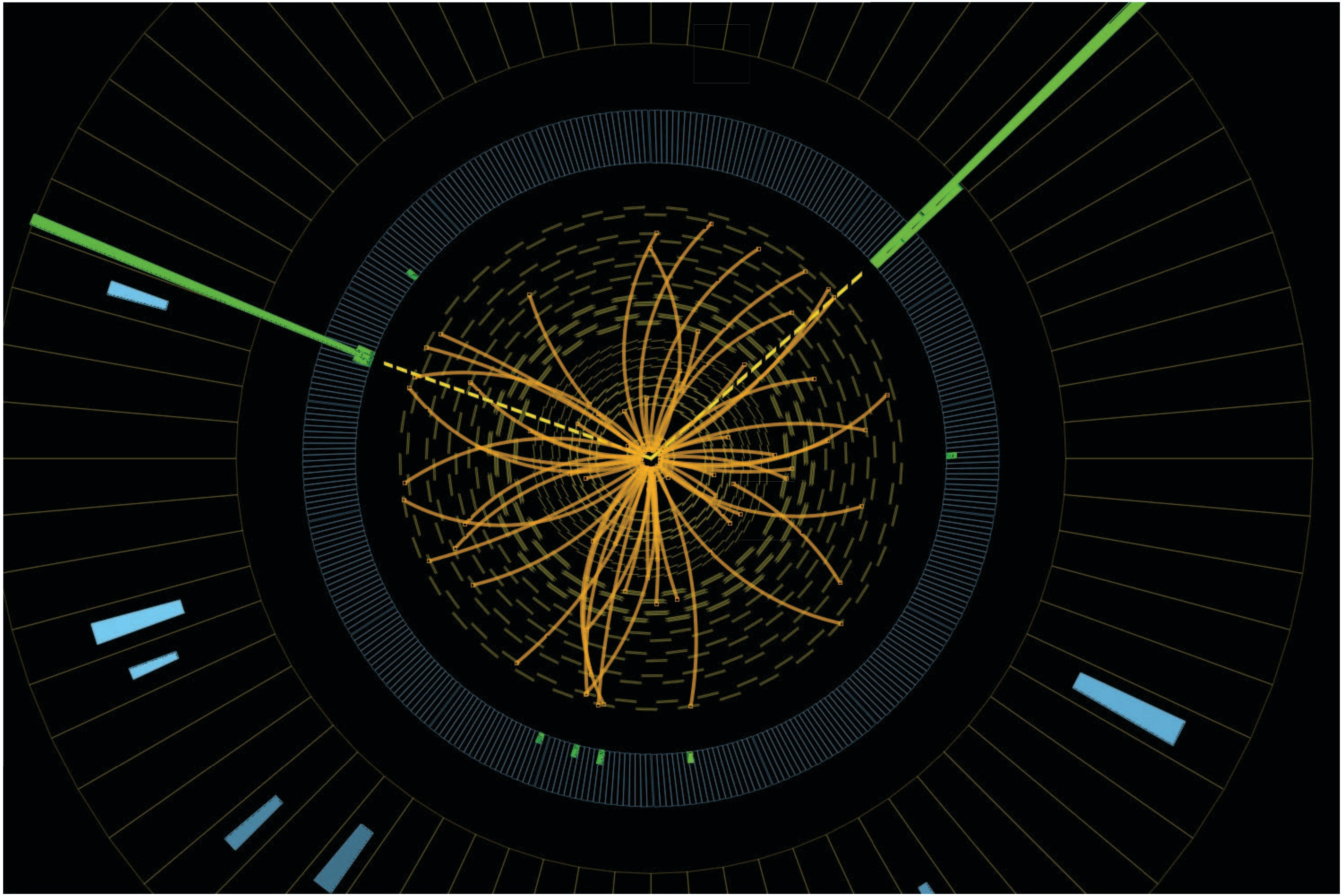




$\sigma_m/m = 0.5\ [\sigma_{E1}/E_1 \oplus \sigma_{E2}/E_2 \oplus \cot(\theta/2)\Delta\theta]$

- Algorithm to find the right vertex based on Σp_T^2 of tracks and $p_T^{\gamma\gamma}$ balance.
- Tested on $Z \to \mu\mu$ events
- Overall efficiency to find the right vertex for Higgs (m = 120 GeV) integrated over p_T spectrum: ~ 80%

Diphoton Candidate



Search in γγ channel: event classification

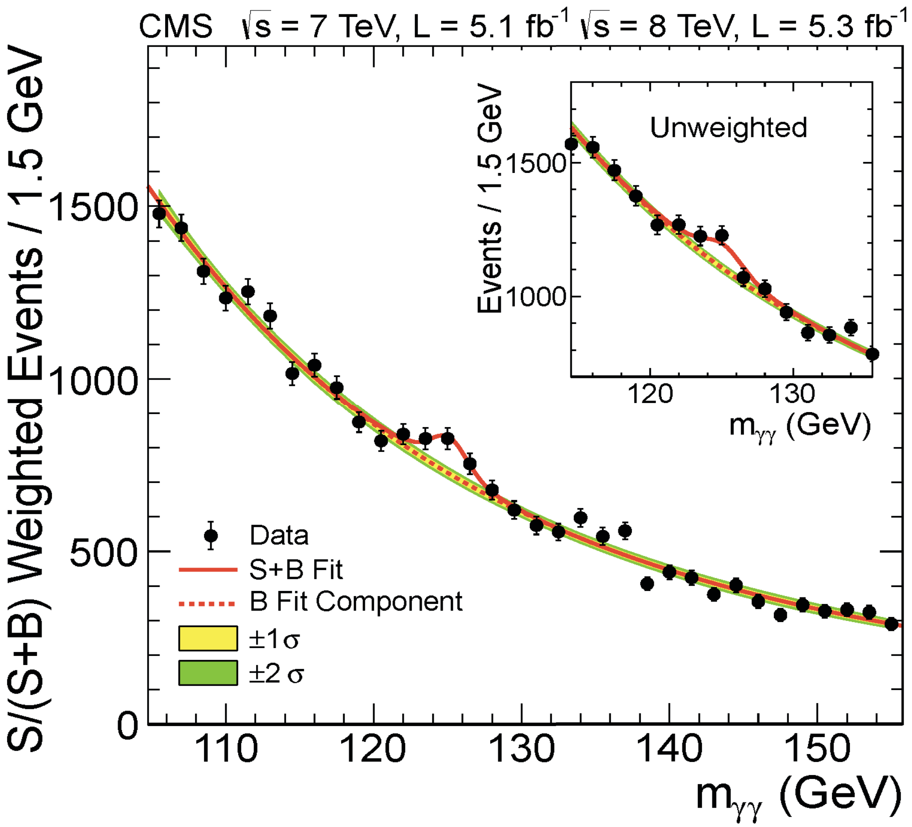
		Expected Higgs events at 125 GeV	Mass Resol. σ_m (GeV)	Background events/GeV	S/B
7 TeV, 5.1 fb^{-1}	BDT 0	3.2	1.14	3.3 ± 0.4	0.28
	BDT 1	16.3	1.08	37.5 ± 1.3	0.13
	BDT 2	21.5	1.32	74.8 ± 1.9	0.07
	BDT 3	32.8	2.07	193.6 ± 3.0	0.03
	Dijet tag	2.9	1.37	1.7 ± 0.2	0.42
8 TeV, 5.3 fb^{-1}	BDT 0	6.1	1.23	7.4 ± 0.6	0.22
	BDT 1	21.0	1.31	54.7 ± 1.5	0.10
	BDT 2	30.2	1.55	115.2 ± 2.3	0.05
	BDT 3	40.0	2.35	256.5 ± 3.4	0.02
	Dijet tight	2.6	1.57	1.3 ± 0.2	0.43
	Dijet loose	3.0	1.48	3.7 ± 0.4	0.18

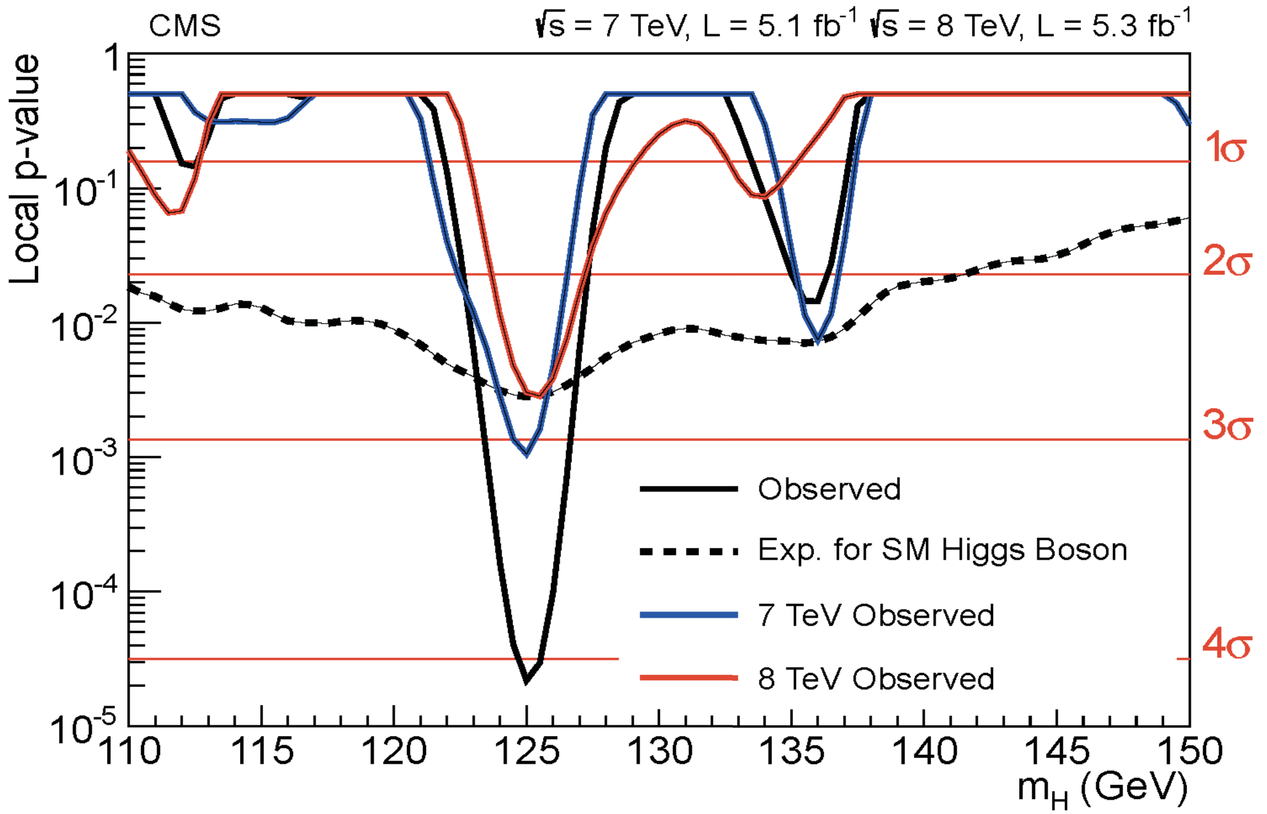
Diphoton events are separated into categories of different expected S/B ratios, based on properties of the reconstructed photons and the presence of jets. Likelihood fits are performed separately for each category and combined.

γγ Mass Distribution

Background is estimated from the data by a polynomial fit.

An excess is observed consistent with a narrow resonance around 125 GeV mass at 4.1 σ

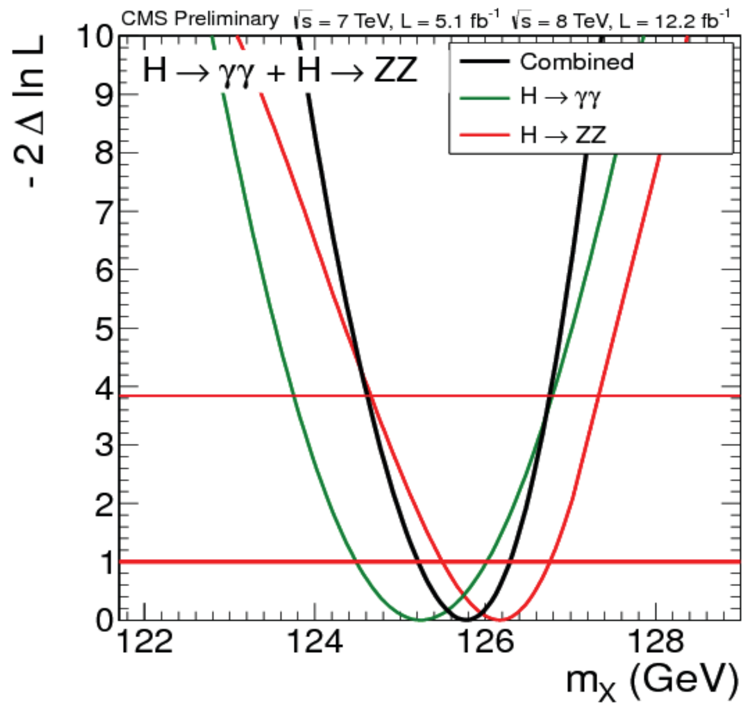


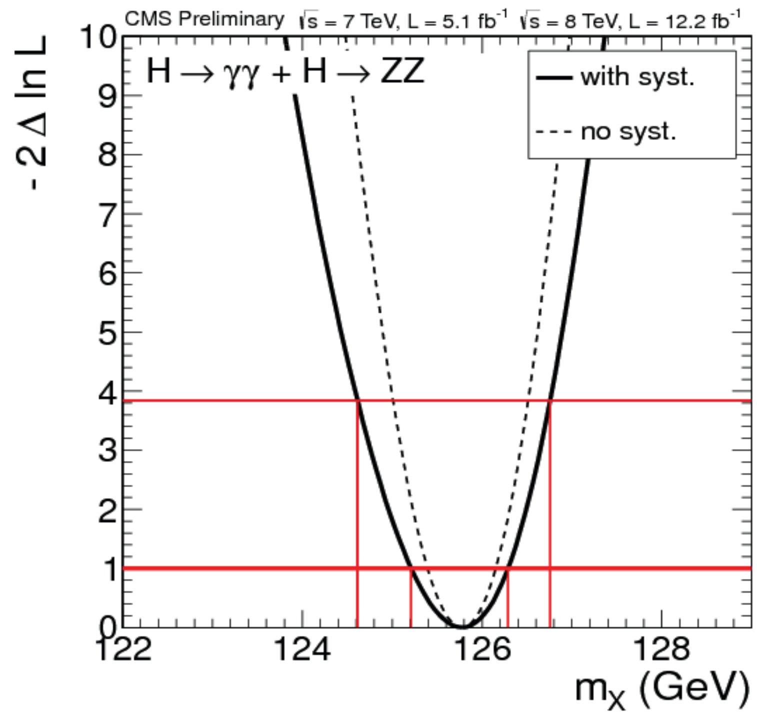


Mass measurement

- Combine information from the high resolution channels measurements, H→ZZ and H→γγ
- Signal cross section for the channels left floating independently in the fit

M=125.8 ±0.4 (stat) ± 0.4 (syst) GeV

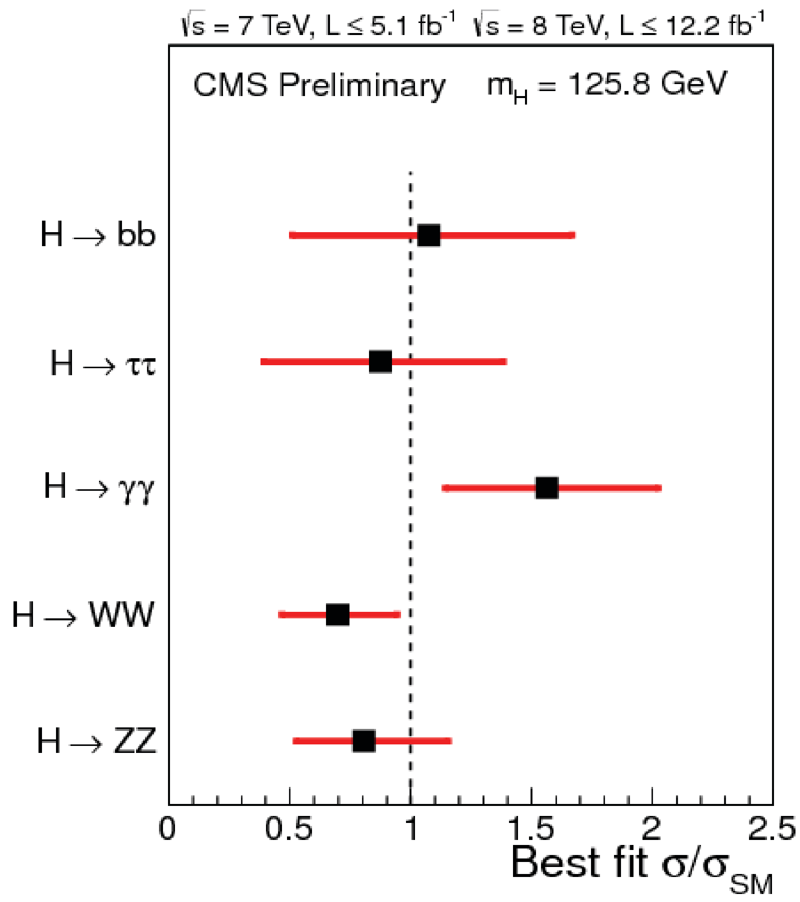




Other Channels

- Search for the Higgs in other decay modes : WW, bb and $\tau\tau$ has been performed.
- Combined significance at M_H=125.8 GeV: 6.9 σ
- Overall satisfactory level of compatibility of the individual channels to the SM cross section.
- Combined σ/σ_{SM}=0.88±0.21

MH=125.8 GeV	Expected (σ)	Observed (σ)
ZZ	5.0	4.5
$\gamma\gamma$	2.8	4.1
WW	4.3	3.0
bb	2.2	1.8
$\tau\tau$	2.5	1.5
Combination	7.8	6.9



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    - Alain Hervé
    - Jim Virdee
    - Sergio Cittolin
    - Peter Sharp†
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Muons:	Fabrizio Gasparini, Hans Reithler, Guenakh Mitselmakher, Pino Iaselli
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