Higgs Boson – Have we seen it?

Outline

- The excitement!!
- What led to this?
  - The challenge and the effort
- Have we found something new?
- What the Indians did if any?

May 2013
IOP, Bhubanswar

Sunanda Banerjee

July 4, 2012

- Physicists get excited at times – for what?
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne,

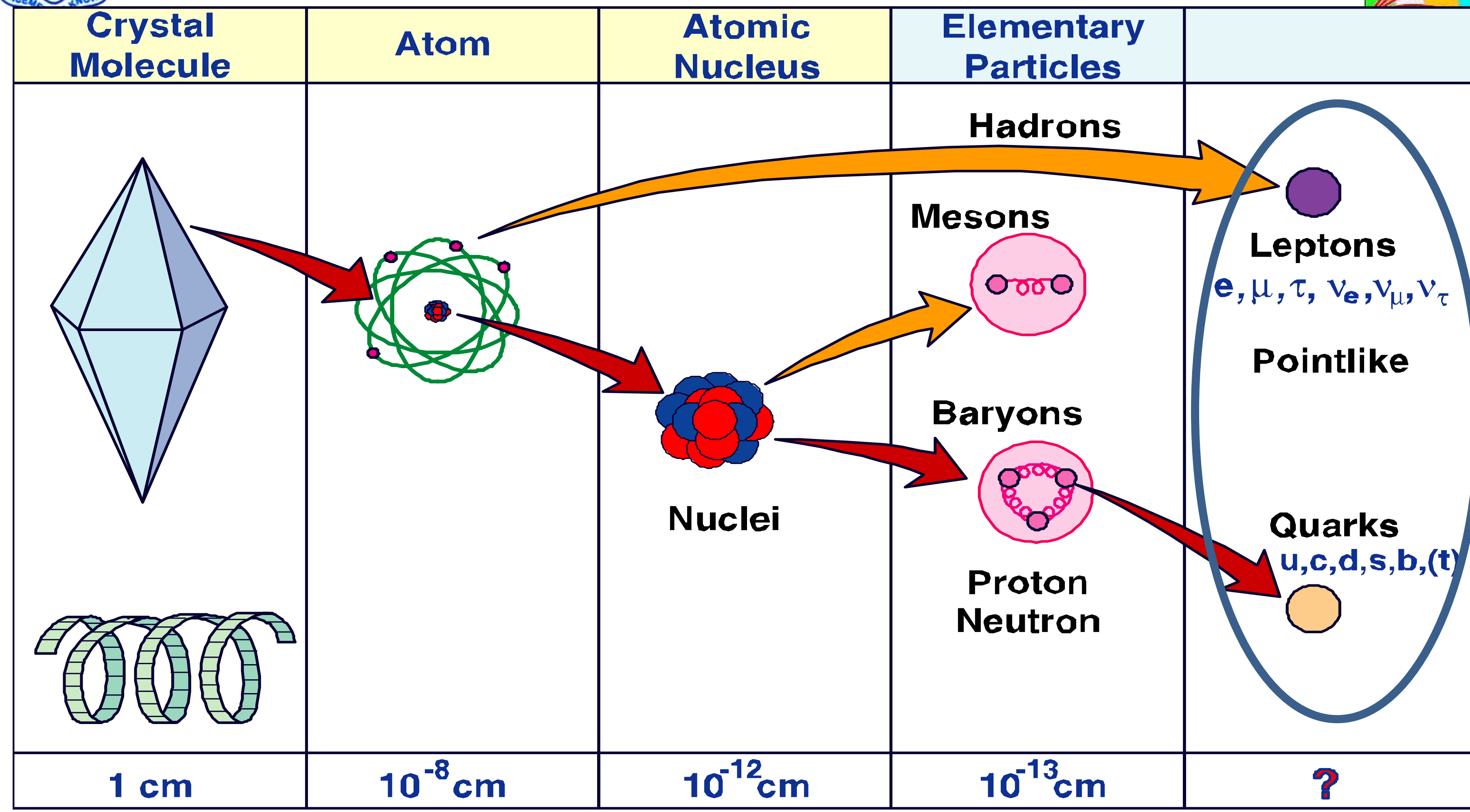
he Large Hadron Collid

Media gets excited as well

July 4th 2012

The discovery of a new particle

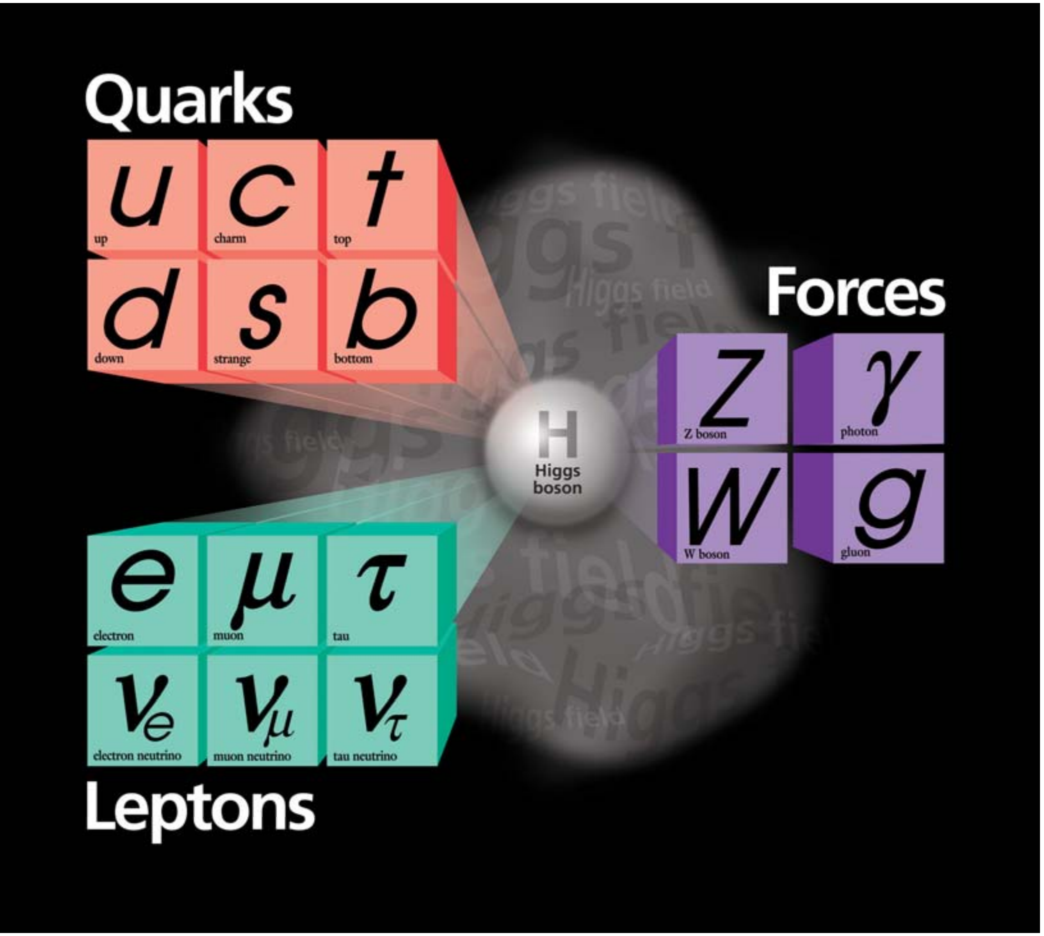
Constituents of matter



y1101

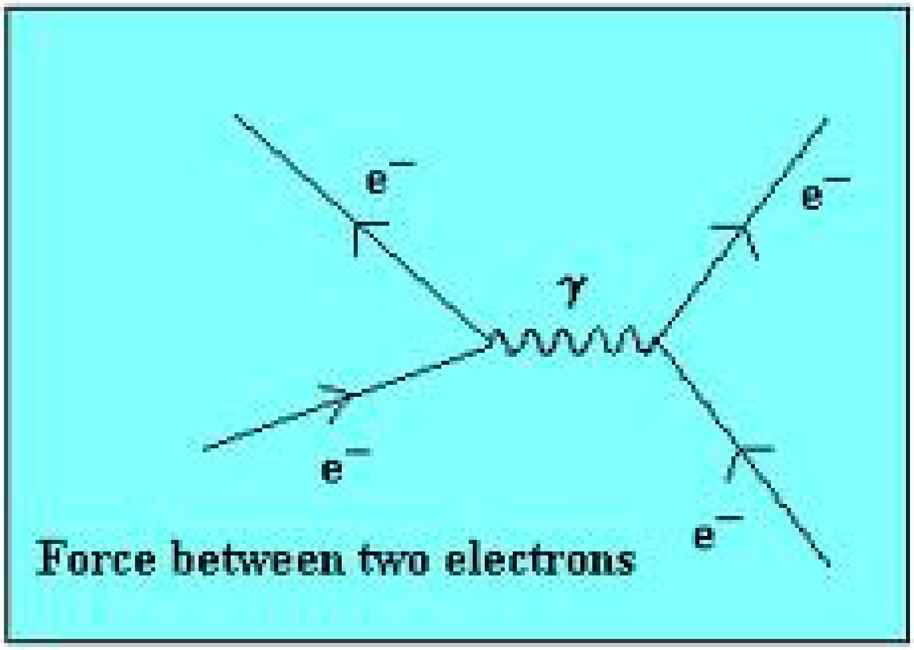
	Thomson	Rutherford	Chadwick	SLAC
	1897	1909	1932	1968

Finding so far



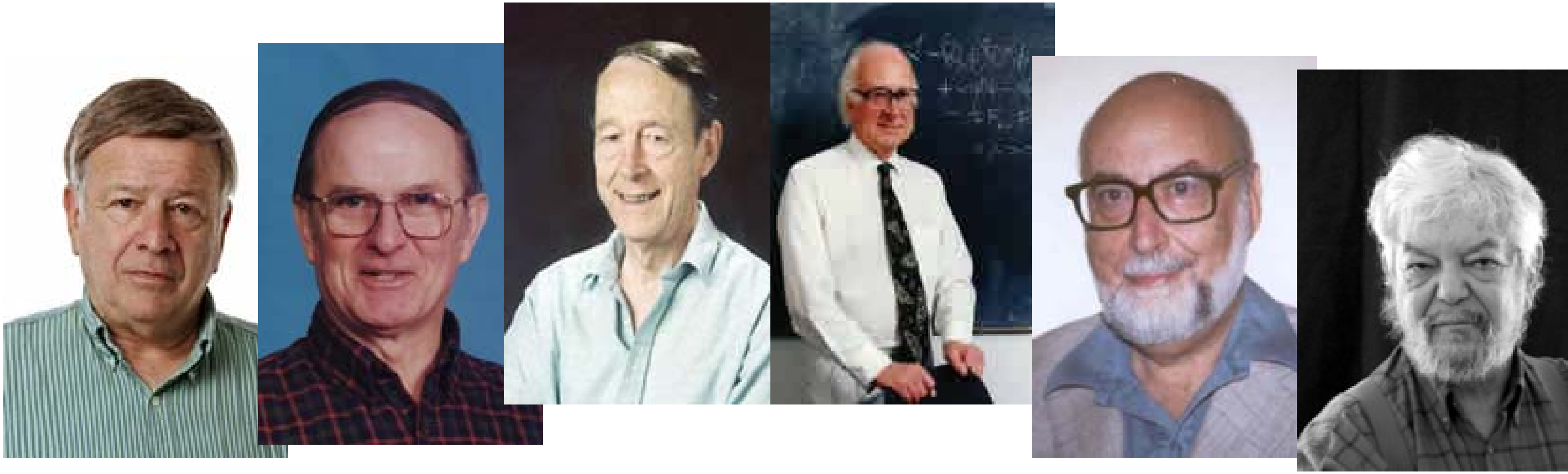
- So far we have probed to a scale of 10^{-19} m
- Basic constituents of matters are all spin ½ objects (fermions)
- The six basic types of quarks and leptons are arranged in 3 families
- There are 4 types of interactions. We consider only 3: EM, weak & strong
- These interactions are mediated through exchange of spin 1 objects (vector bosons)

Evolution of Theory



- Interaction is explained by exchange of a carrier of force
- Theory of electromagnetic interaction reformulated during 40's by Feynman, Schwinger and Tomonaga - gauge theory
- Exchange particle has zero mass ⇒ photons
- Try to apply gauge theory to other interactions – weak, strong
- These interactions are short range – weak interaction needs exchange of massive particles; but mass cannot be easily included in theories satisfying gauge invariance

The Guralnik-Hagen-Kibble-Higgs-Englert-Brout mechansim…

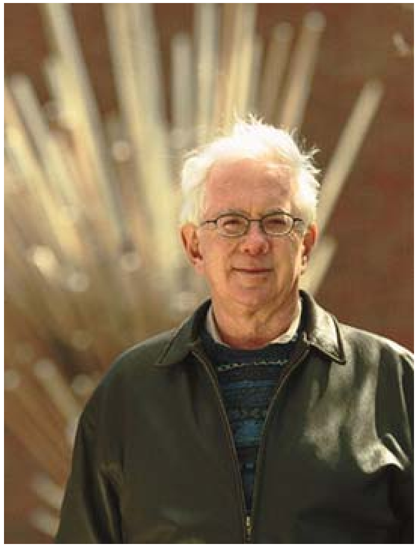


- These six gentlemen during early 60's came up with an idea which could rescue gauge theory approach to explain electroweak interactions..
  - They, as 3 independent groups, wrote in the same 1964 volume of Physical Review Letters about a mechanism, which gives mass to particles, from different perspectives and each paper made a distinct contribution
- Physical Review Letters volume 13 (1964):
  - Guralnik, Hagen, Kibble, "Global Conservation Laws and Massless Particles"
  - Higgs, "Broken Symmetries and the Masses of Gauge Bosons"
  - Englert, Brout, "Broken Symmetry and the Mass of Gauge Vector Mesons"

The Standard Model

- This idea is incorporated in unifying the theory of electromagnetic and weak interactions by Glashow, Weinberg and Salam
- Strong interaction is also explained in terms of gauge theory: Quantum Chromo Dynamics

⇒ The Standard Model of high energy physics



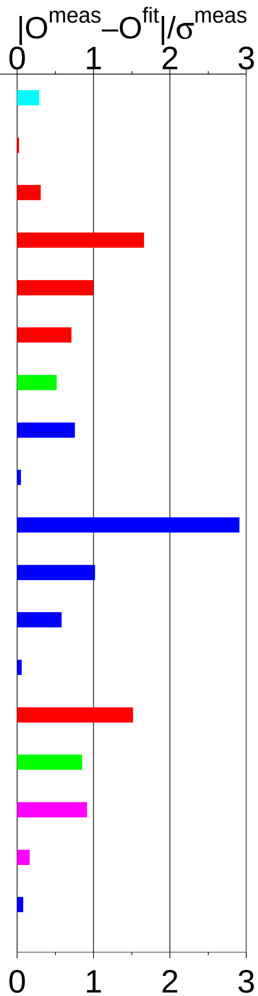
Sheldon Glashow

Steven Weinberg

Abdus Salam

The Standard Model vs experiments

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1039
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1482
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



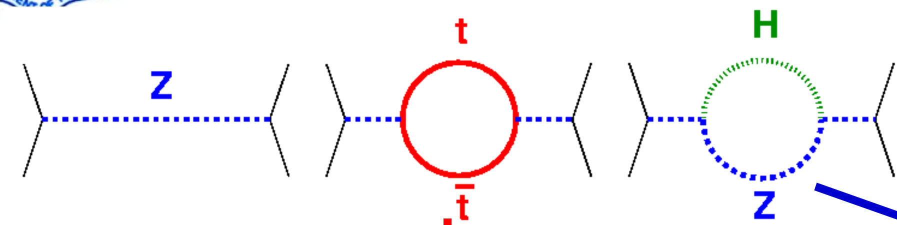
July 2011

- Earlier experiments (particularly the experiments done at the LEP, CERN and Tevatron, Fermilab) have tested the predictions of the Standard Model to a high level of accuracy
- All measurements agree with the predictions which start with a few unknown parameters

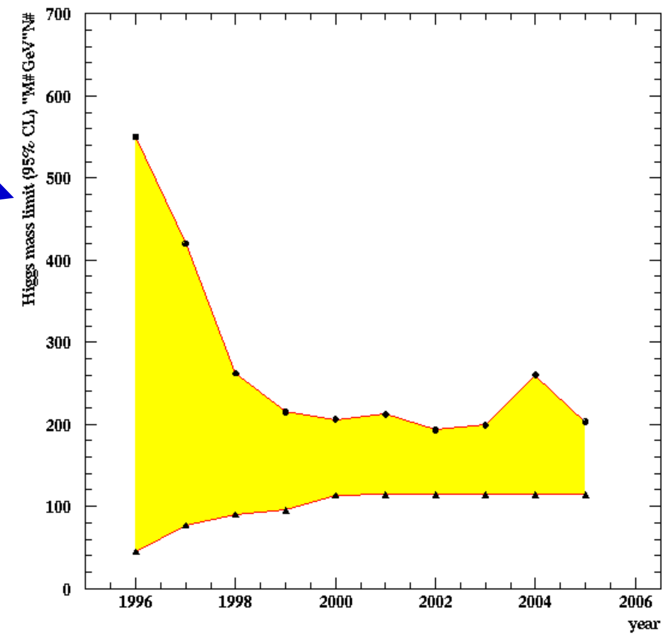
The Standard Model is a beautiful theory and arguably one that is most precisely tested

But where is Higgs boson?

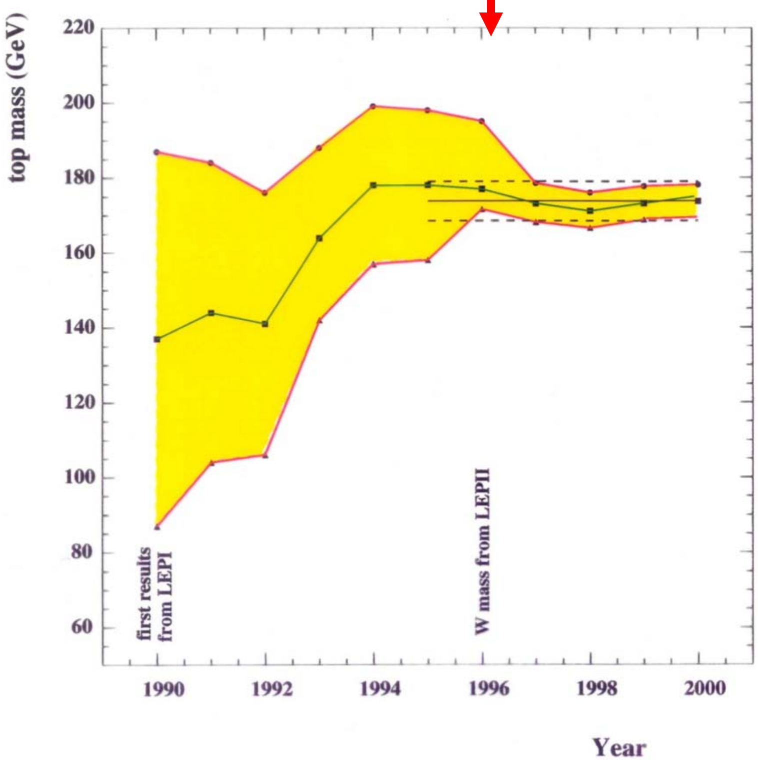
Indirect hints



Prediction for the Higgs mass



LEP: indirect determination of the top mass



Possible due to

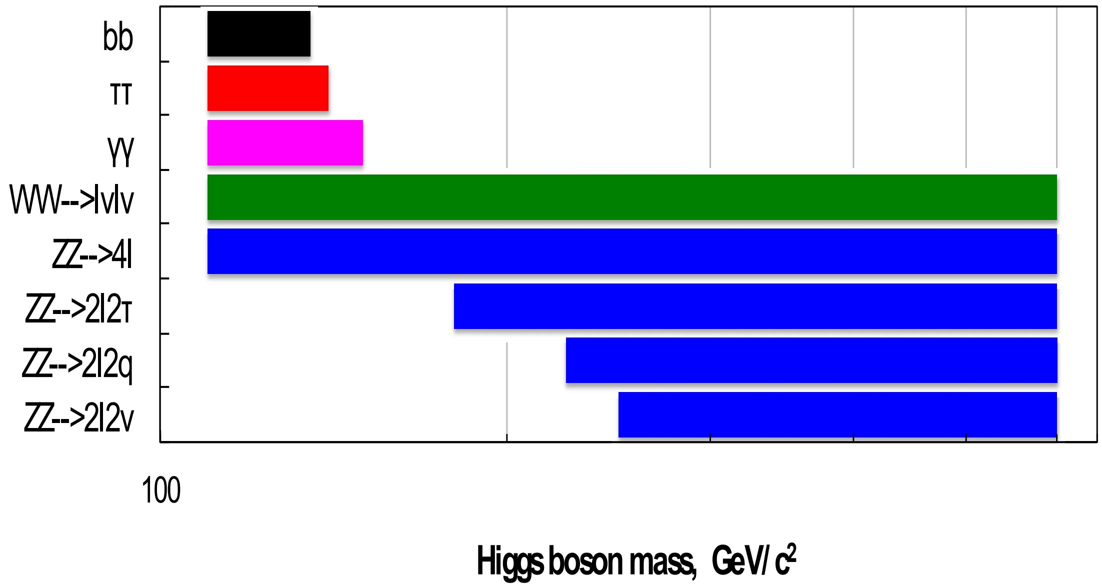
- precision measurements
- known higher order electroweak corrections

t' Hooft

Veltman

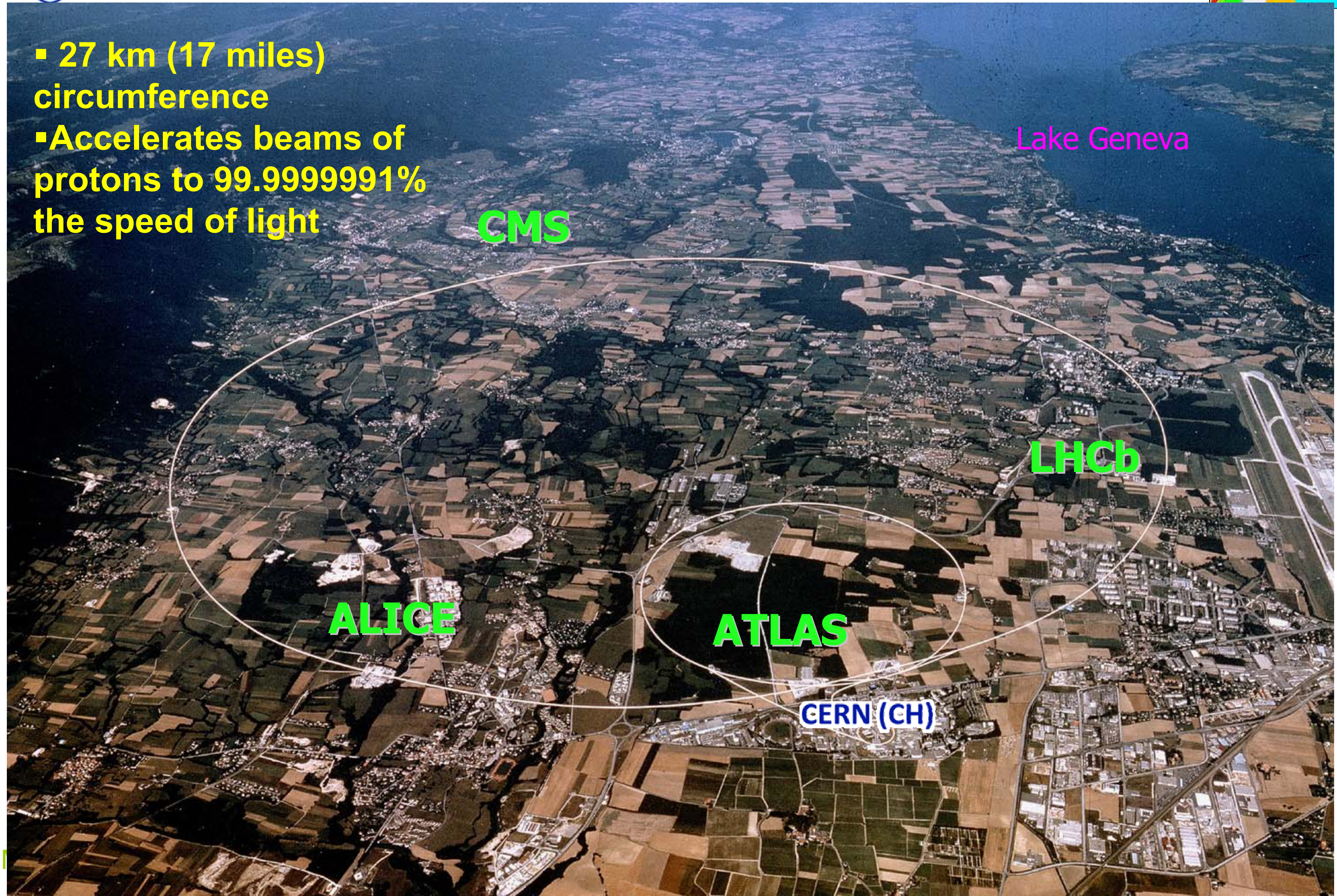
How to find Higgs boson?

- It has to be produced in interactions
  - Collide particles with sufficient high energy
  - Protons are good choice for the colliding particles
  - Probability of Higgs production is small → need a large number of interactions
- Higgs boson is unstable and will decay to other particles immediate after it is produced
  - Look at all possible signatures
  - Observation in multiple final state can only establish a new object

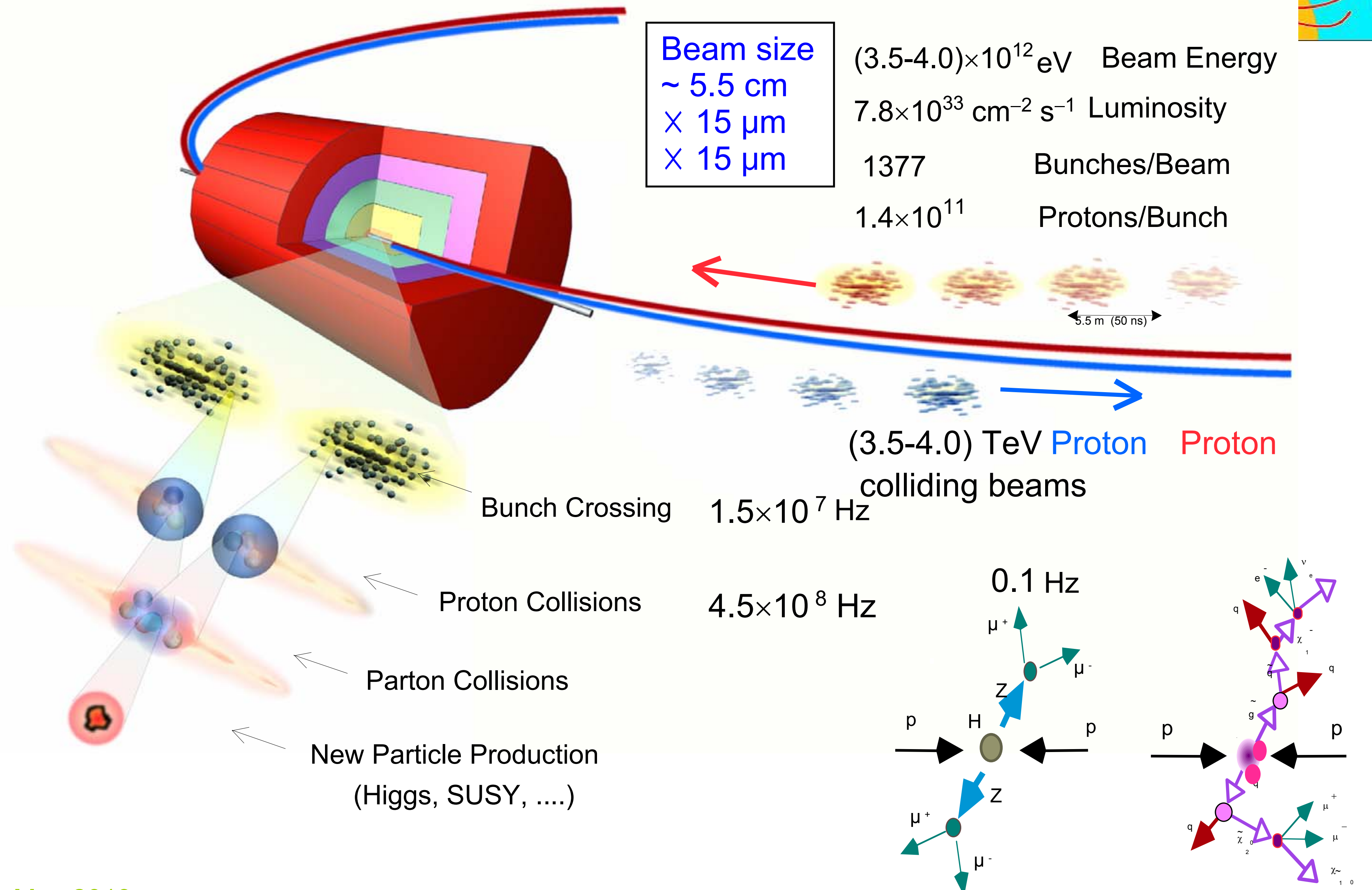


The Large Hadron Collider at CERN

- 27 km (17 miles) circumference
- Accelerates beams of protons to 99.9999991% the speed of light



Large Hadron Collider



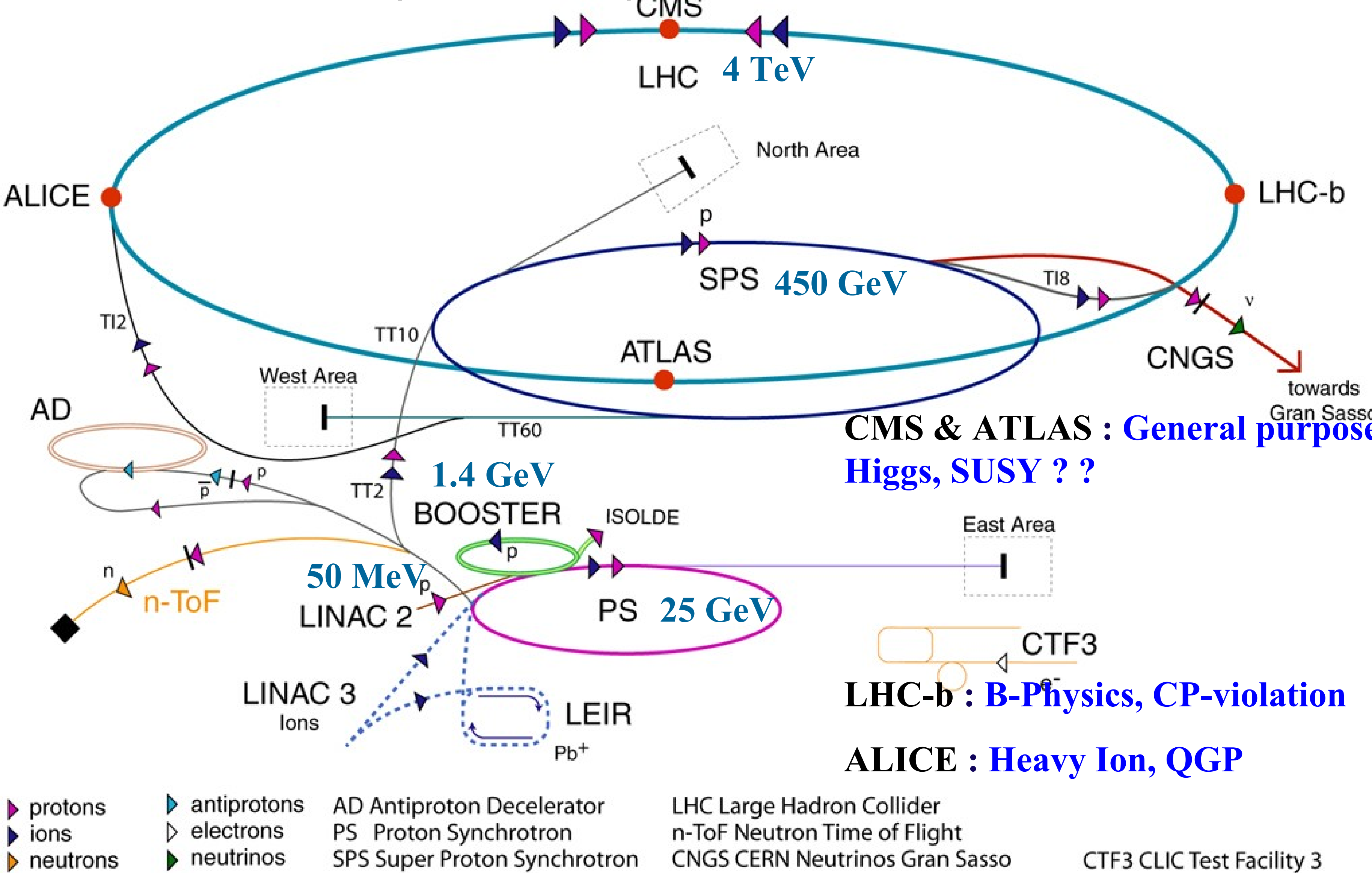
Facts about LHC

- Energy stored in magnets: 10 GJ = A380 at a cruise speed of 700 km/h. Can heat and melt 12 tons of copper!

- Energy stored in a single beam: 360MJ is equivalent to 90 kg of TNT or 15 Kg of chocolate
- The amount of liquid helium in the machine is 60 tons or 120 thousand gallons
- LHC is the coldest place within the solar system with the temperature of 1.9^{o}K
- It is also the emptiest place in the solar system with the vacuum in the pipe containing the beams at 10^{-13} atm.

CERN accelerator complex

(not to scale)



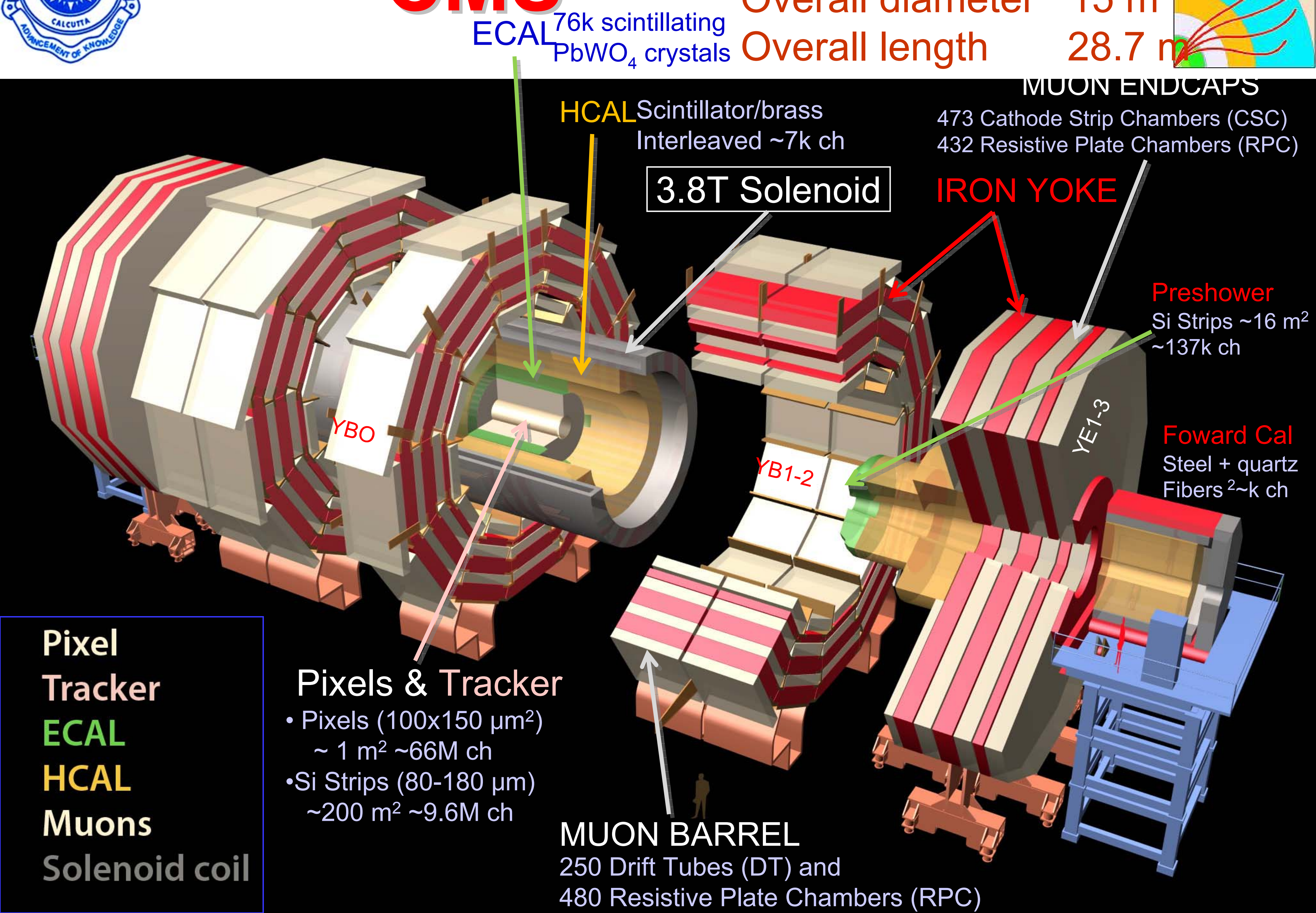
CMS & ATLAS : General purpose, Higgs, SUSY ? ?

LHC-b : B-Physics, CP-violation

ALICE : Heavy Ion, QGP

CMS

Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m



The CMS collaboration

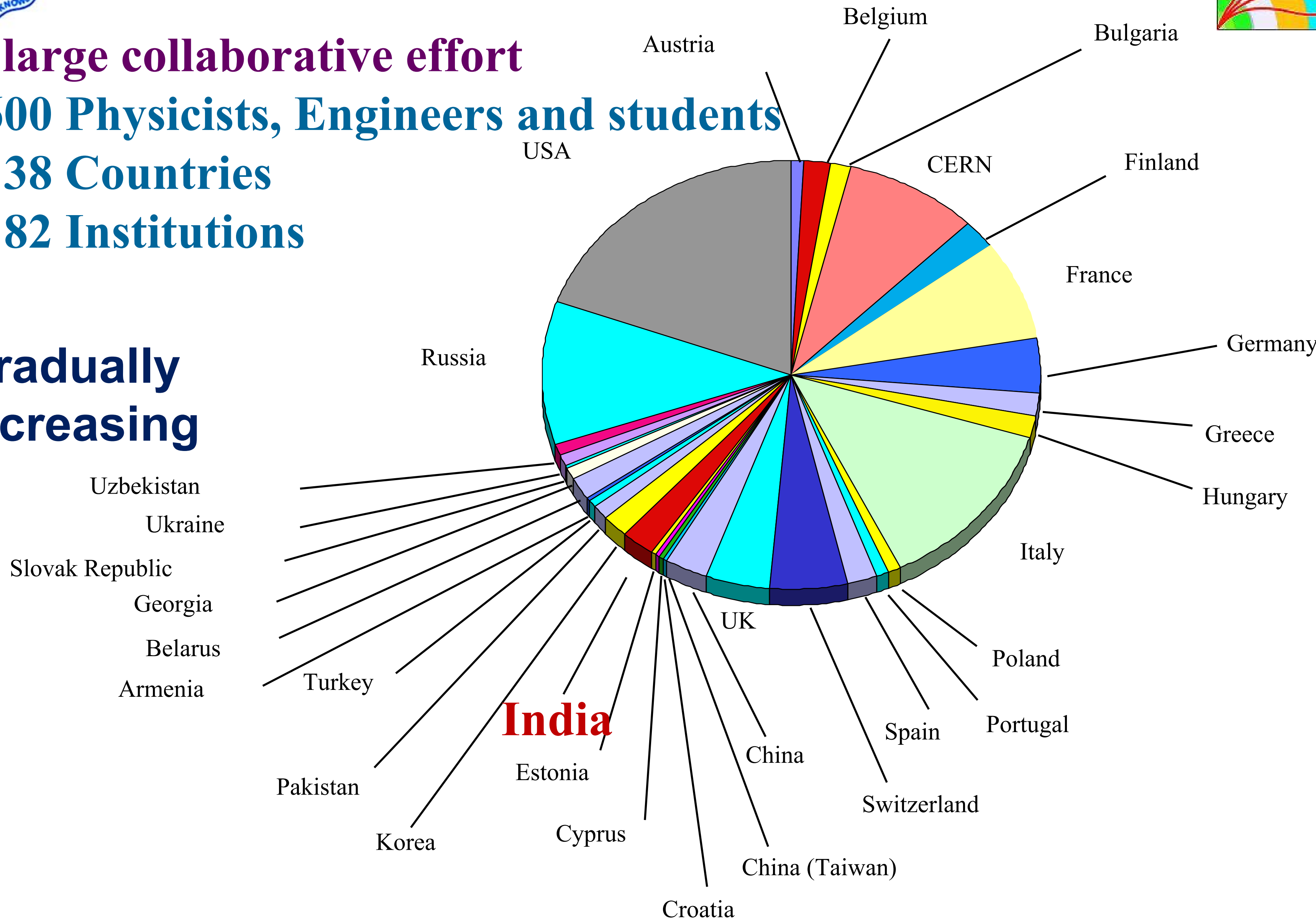
A large collaborative effort

3600 Physicists, Engineers and students

38 Countries

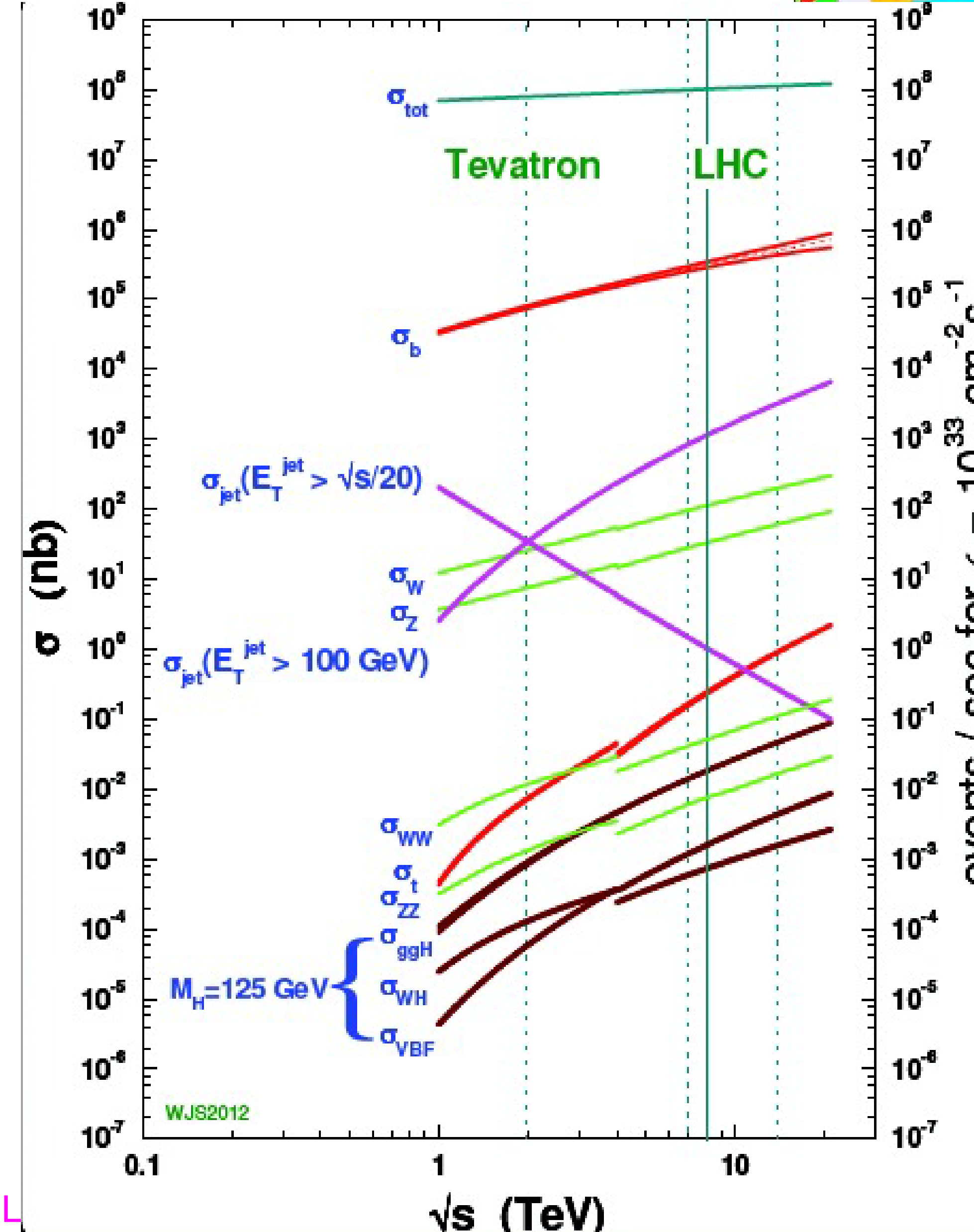
182 Institutions

Gradually increasing

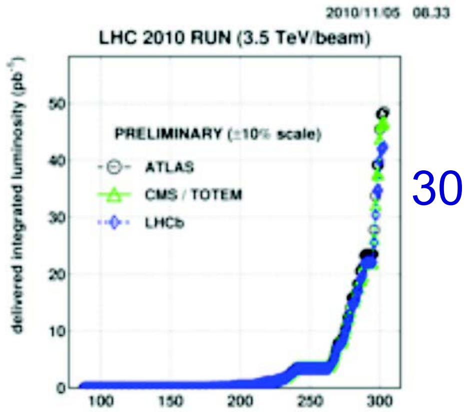


What may happen

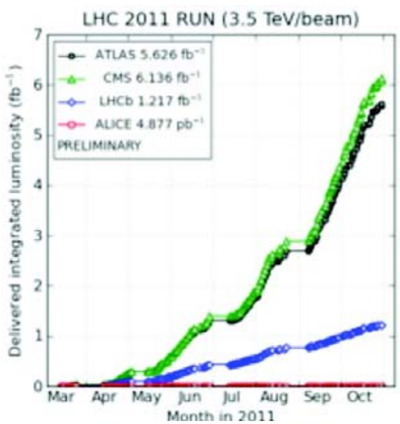
- ❑ Need a large number of interactions to probe at small cross section of the production process
- ❑ LHC was generous for that
  - Provided excess of ~4x10^14 interactions during 2011 at 7 TeV cm energy and even larger number at 8 TeV during the first half of 2012
  - The experiments collected the provided luminosity with very high efficiency
- ❑ However this will produce ~10^9 unwanted interactions for each Higgs boson



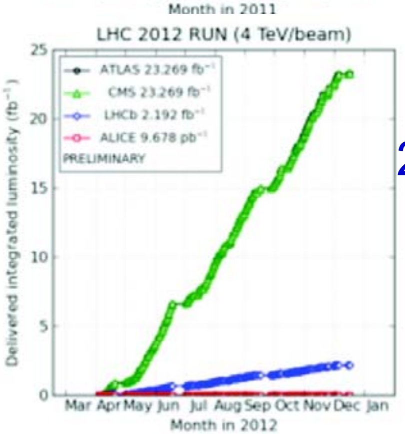
Success of LHC (Misery to Experiments)



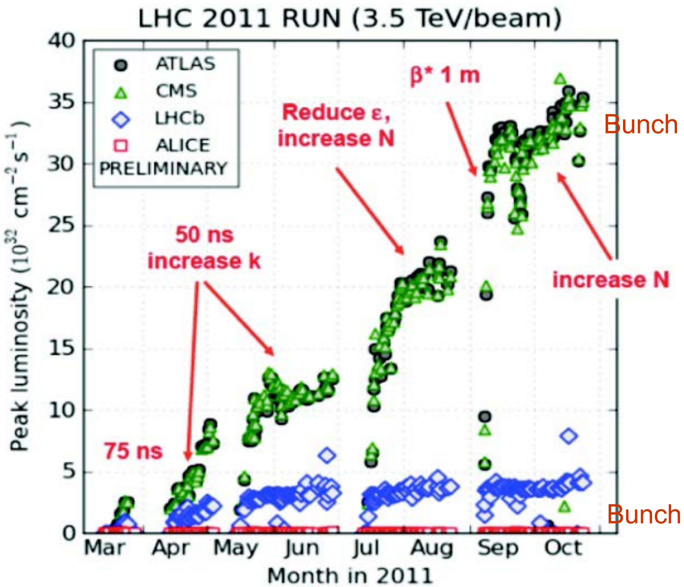
30 pb^{-1}



5.8 fb^{-1}



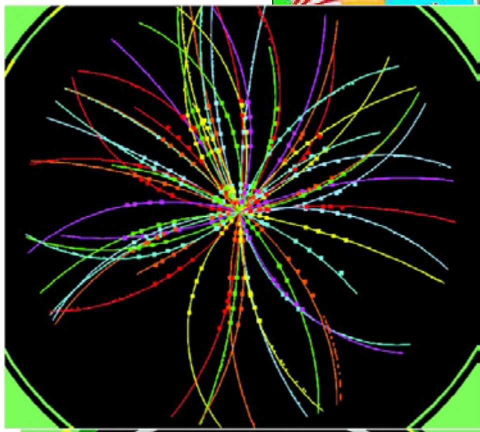
25 fb^{-1}



$$L = \frac{kN^2 f}{4\pi\sigma_x^*\sigma_y^*}F = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon}F$$

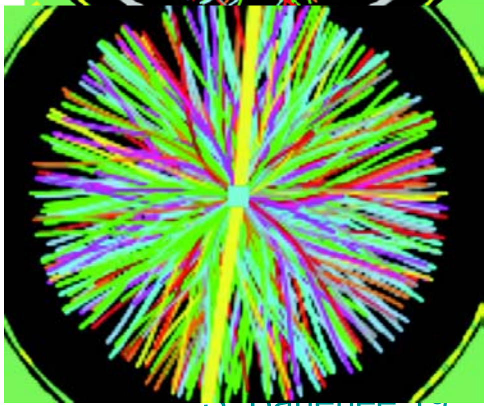
- k = # of bunches
- N = # of p's/bunch
- f = rev. frequency
- σ = beam size
- F = geometry loss factor
- ε = beam emittance
- β = betatron function

2010
O(2) PU
Bunch spacing 150 ns



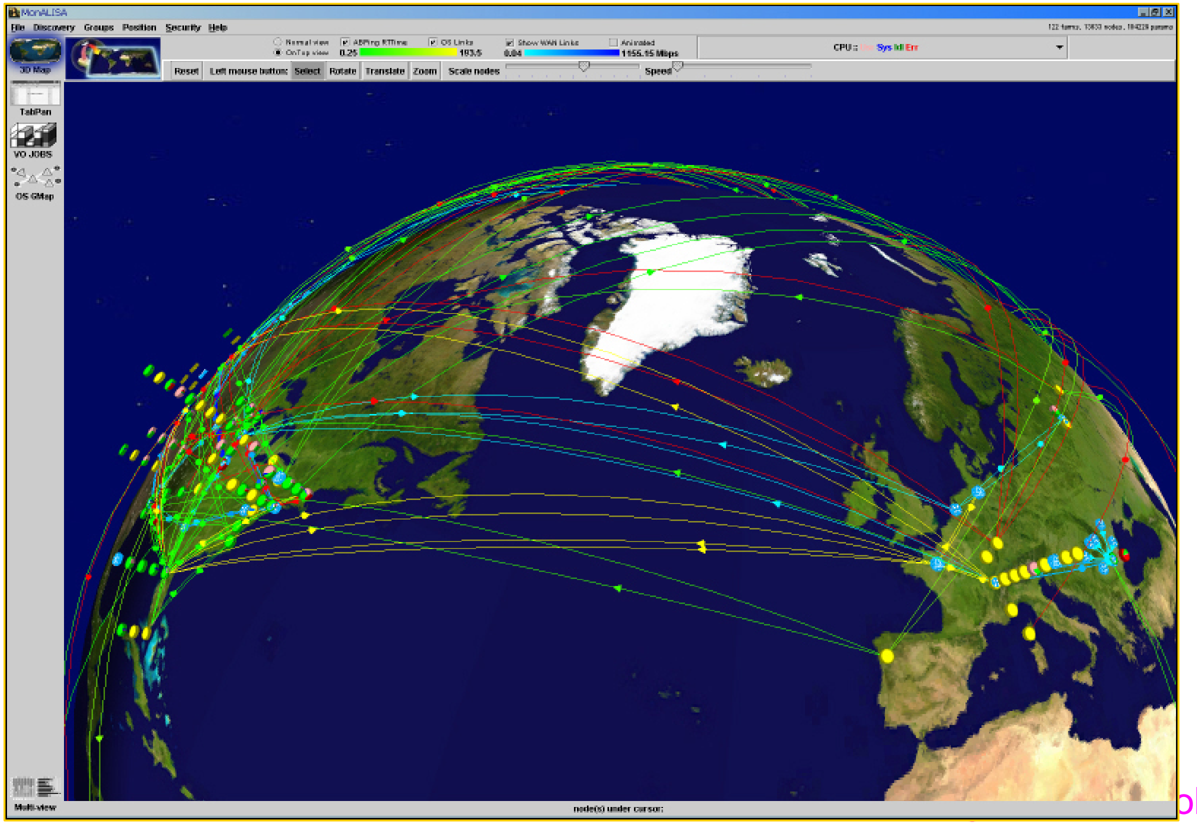
2011
O(10) PU
Bunch spacing 75-50 ns

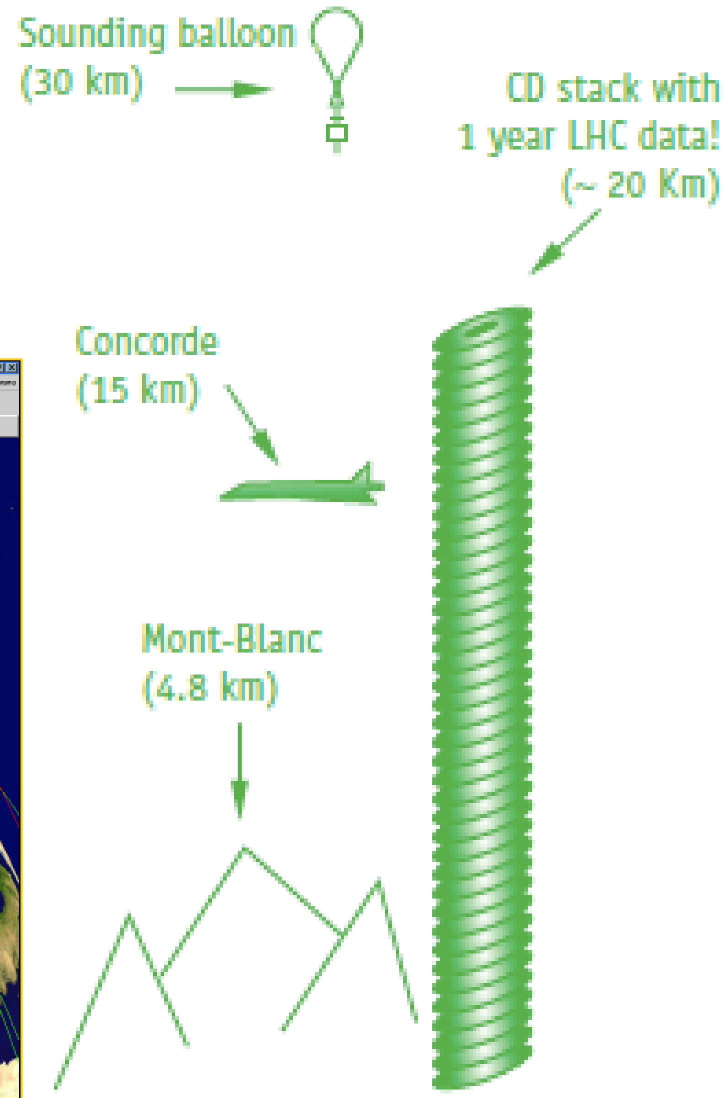
2012
O(20) PU
Bunch spacing 50 ns



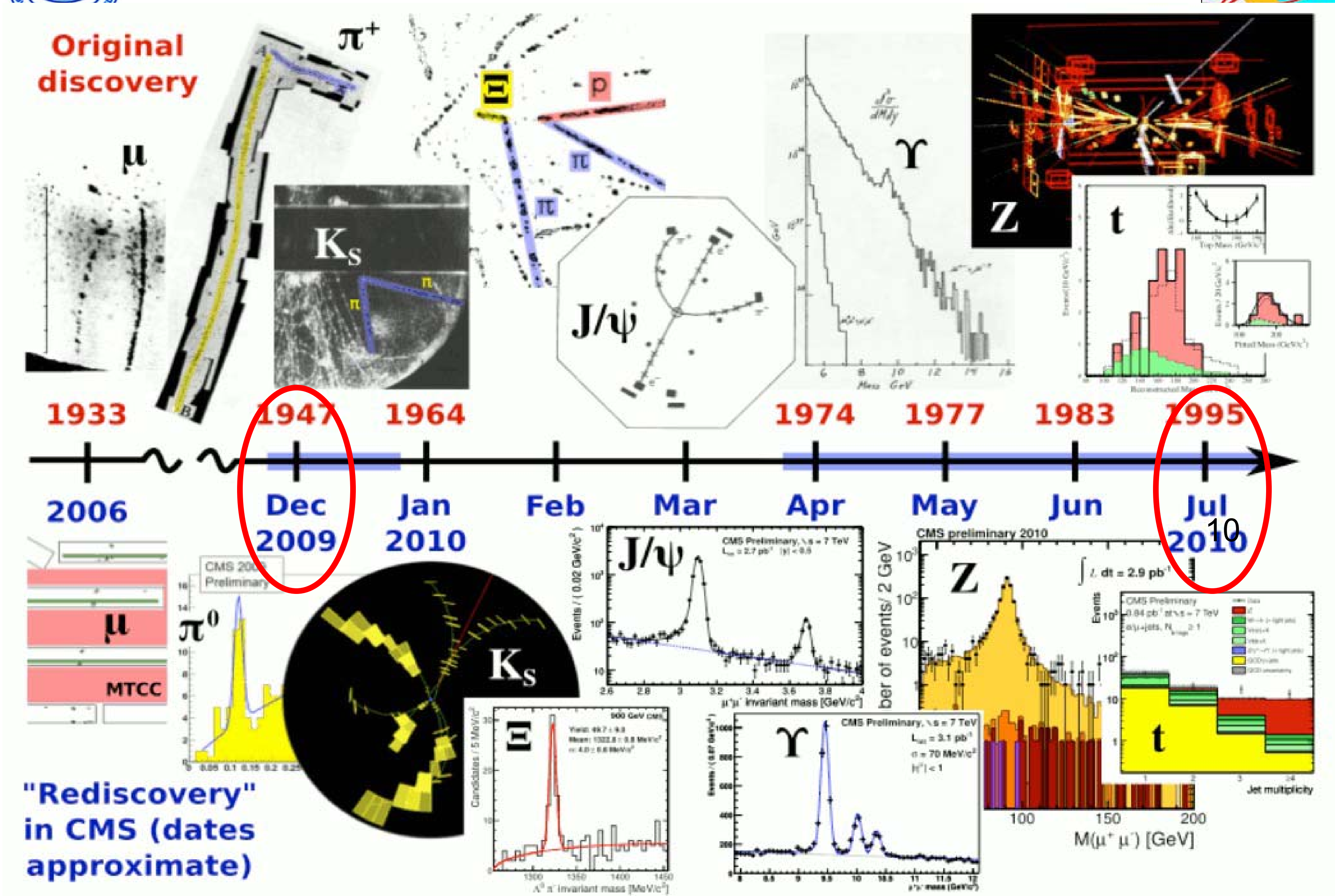
How much data is produced?

- ❑ Nearly 1 GB of data is recorded every second
  - 15,000 TB/year = 15 PB/year
  - It's like recording a DVD every 4 sec
  - Enough to fill your hard drive in 2 min
- ❑ Processed all around the world via LHC Computing Grid



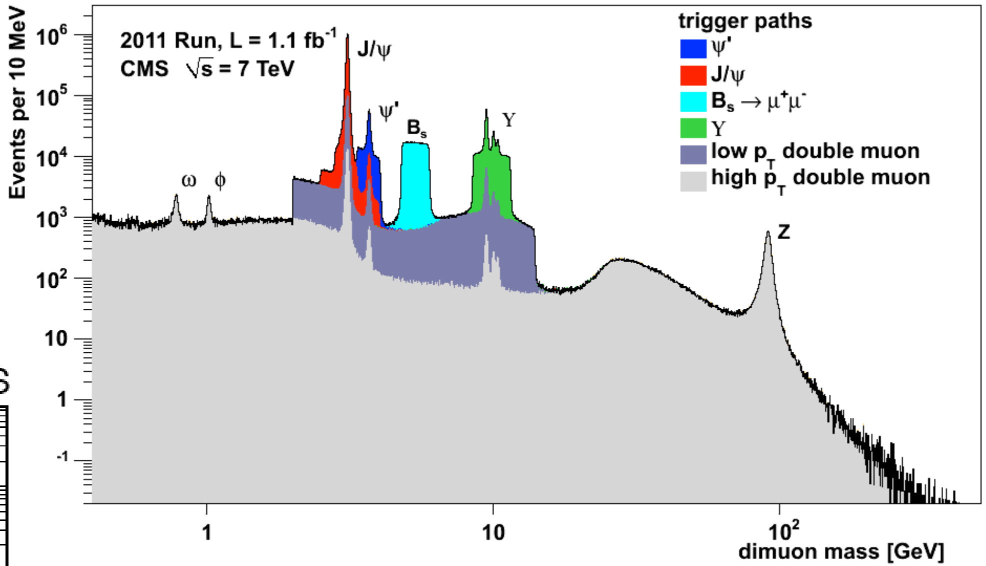


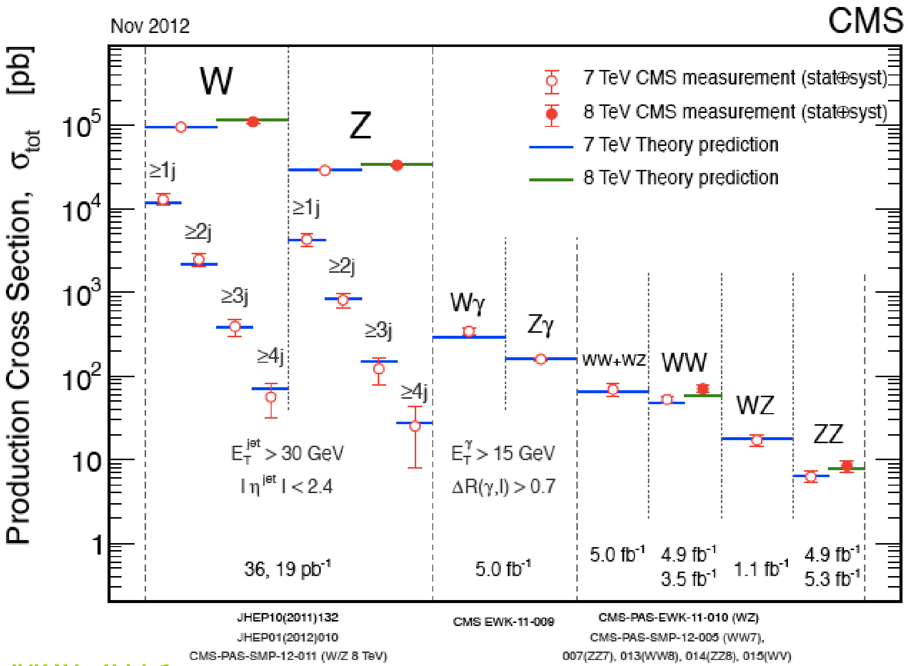
Understand the detector first



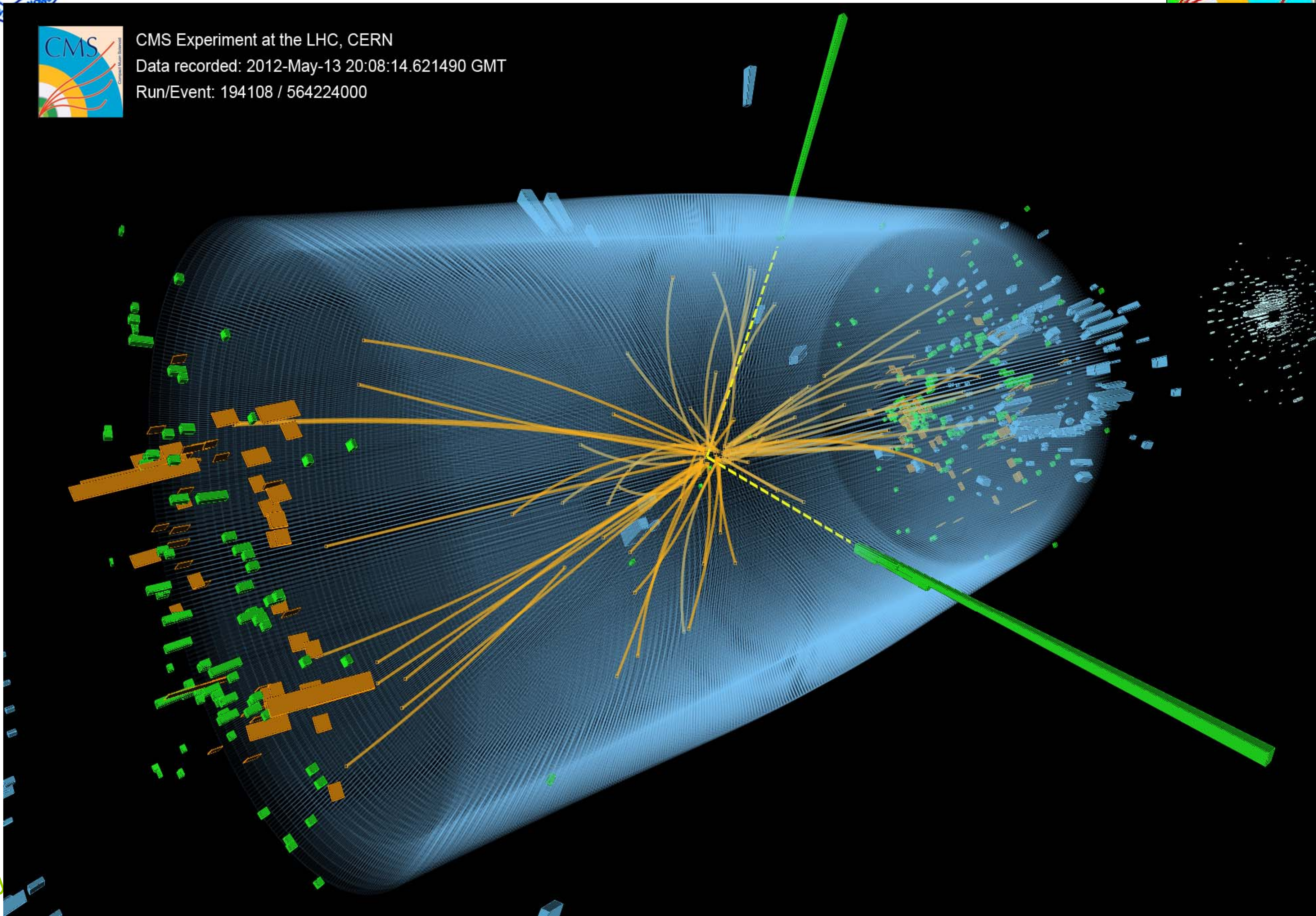
Standard Model Measurements

- Key point for any new discovery is to understand the backgrounds from SM processes and understanding the detector effects.

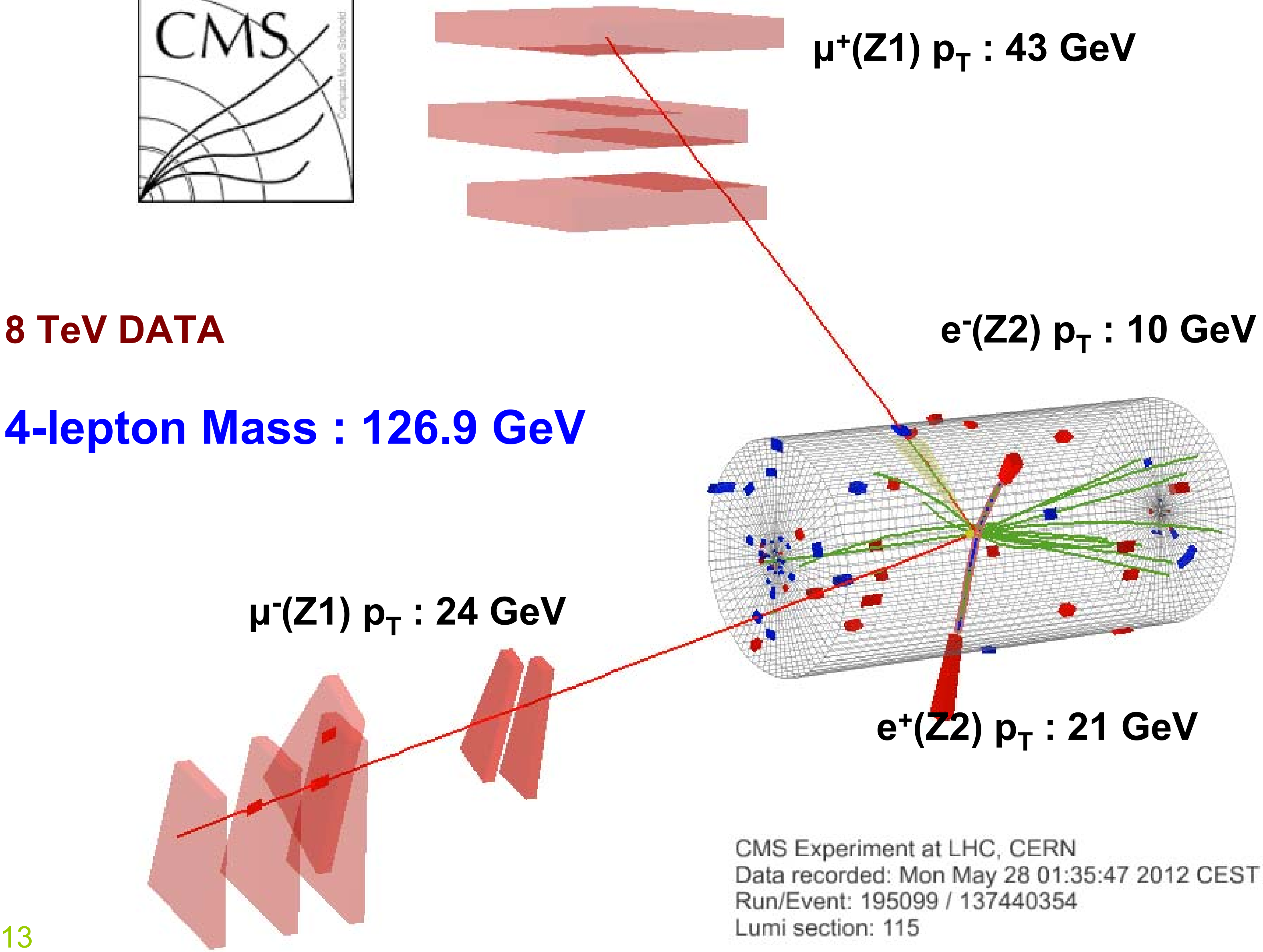




Candidate event (H→γγ)

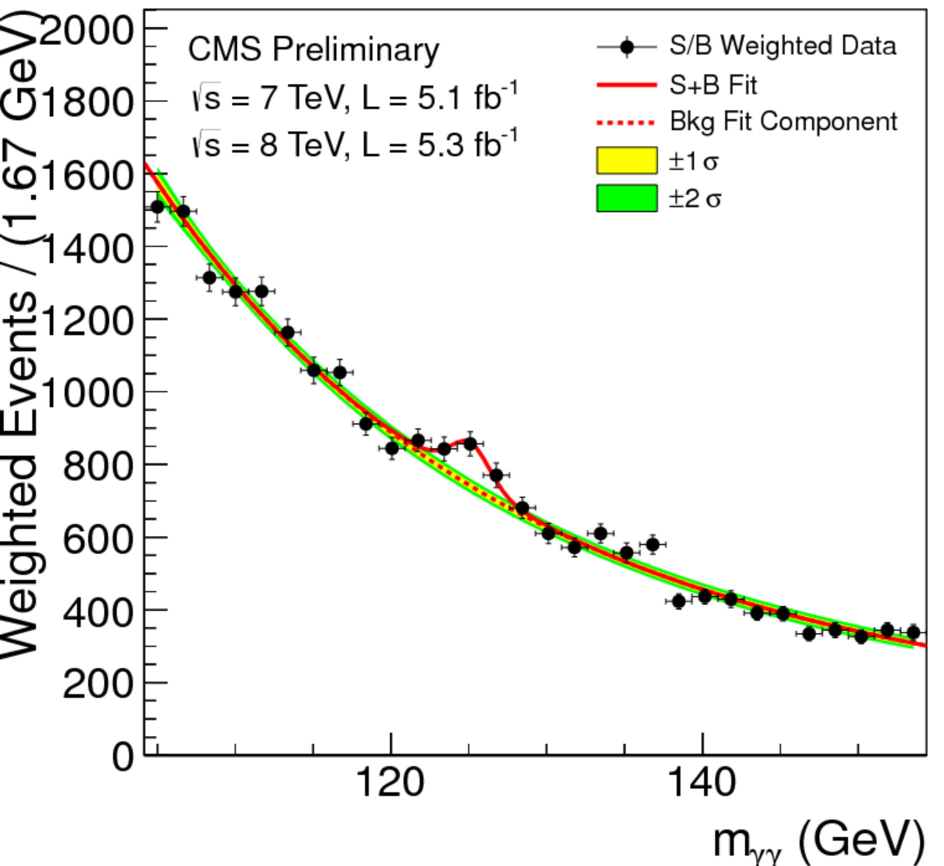


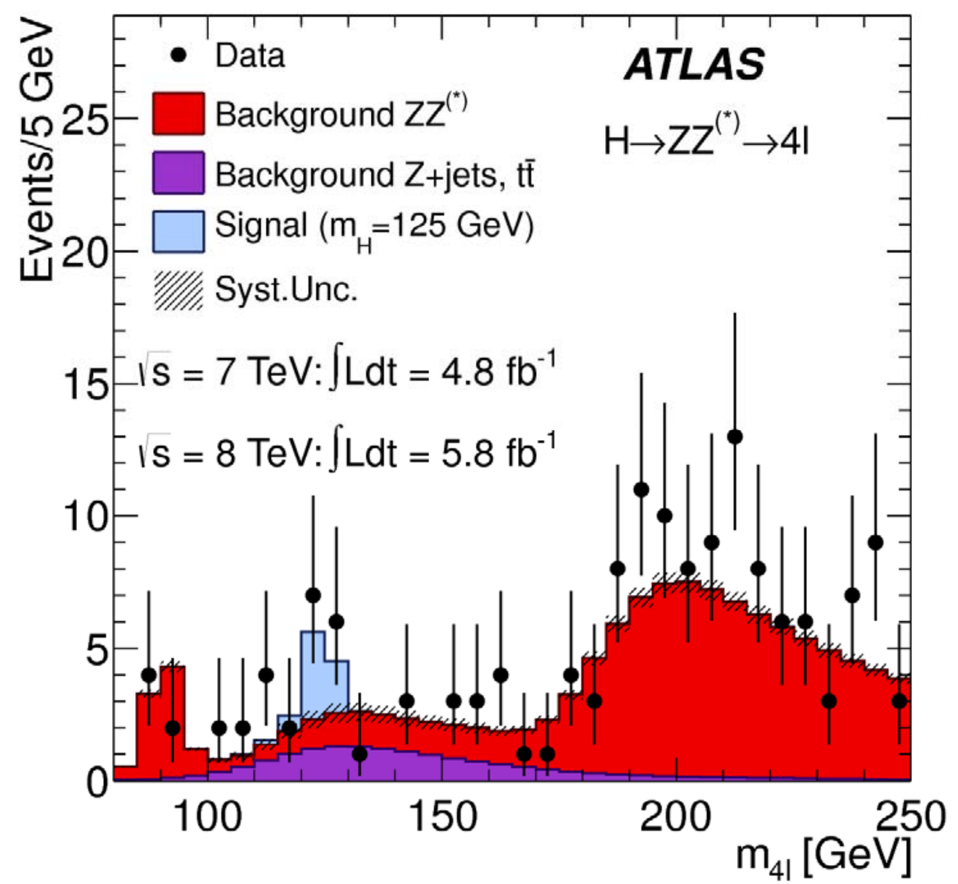
Candidate event (H→ZZ$^{(*)}$→2e+2μ)



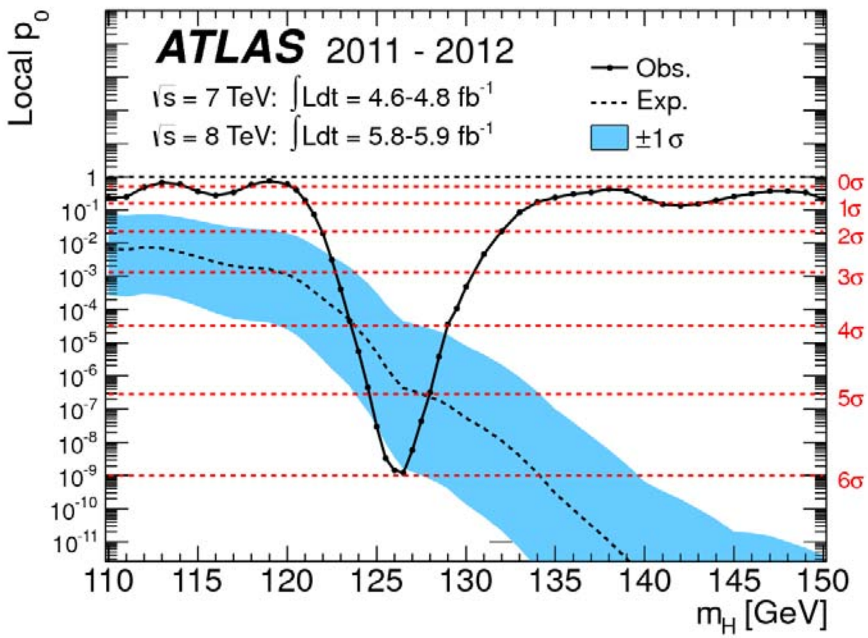
Search

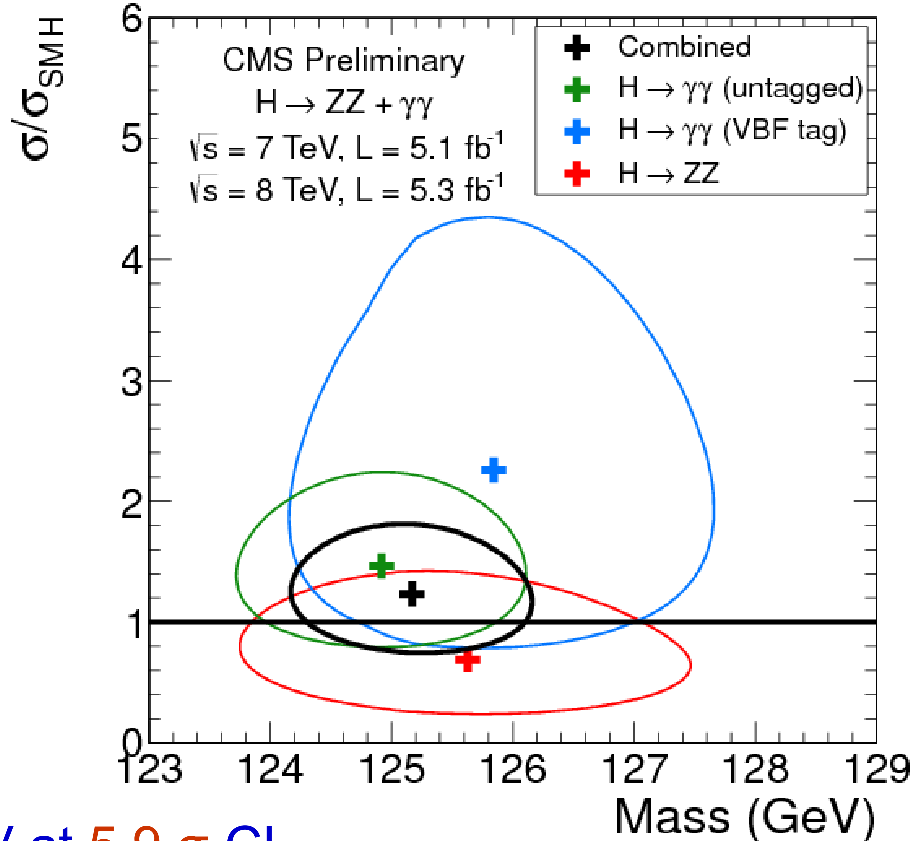
- There are other Standard Model process which may give events with similar signatures
- Evaluate how many such background events will be seen against possible signal events





Final Results

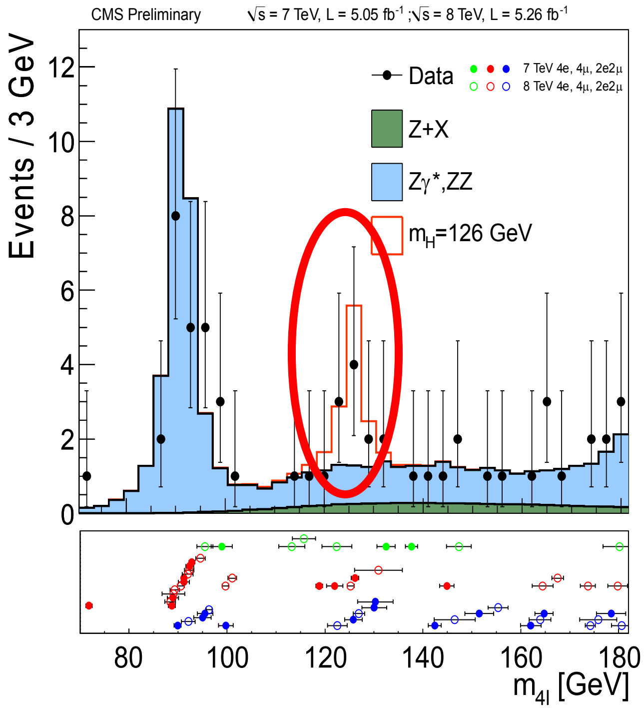


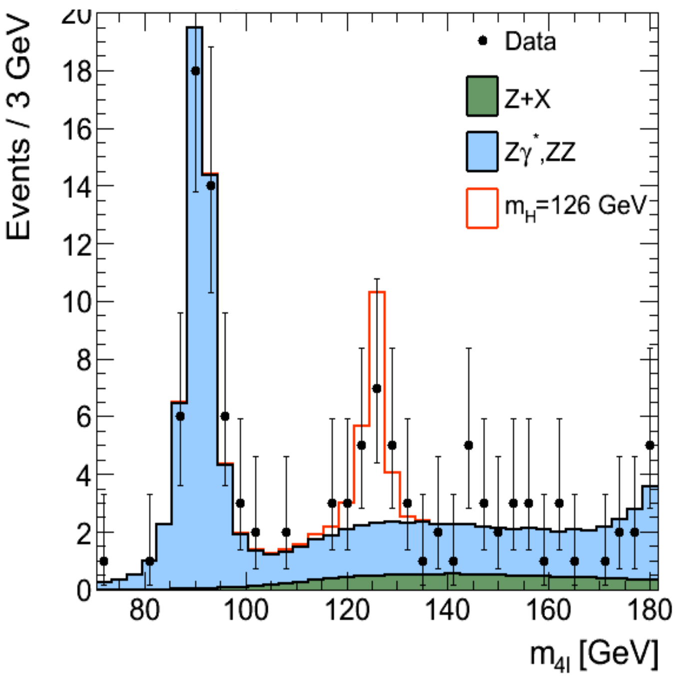


- ATLAS observes:
  - Maximum excess at 126.0 GeV at 5.9 σ CL
  - Probability of fluctuation 1.7×10^{-9}
- CMS observes:
  - Excess in 4 different channels at 125.3 GeV
  - Level of fluctuation at 5.0-5.1 σ CL (3×10^{-7})

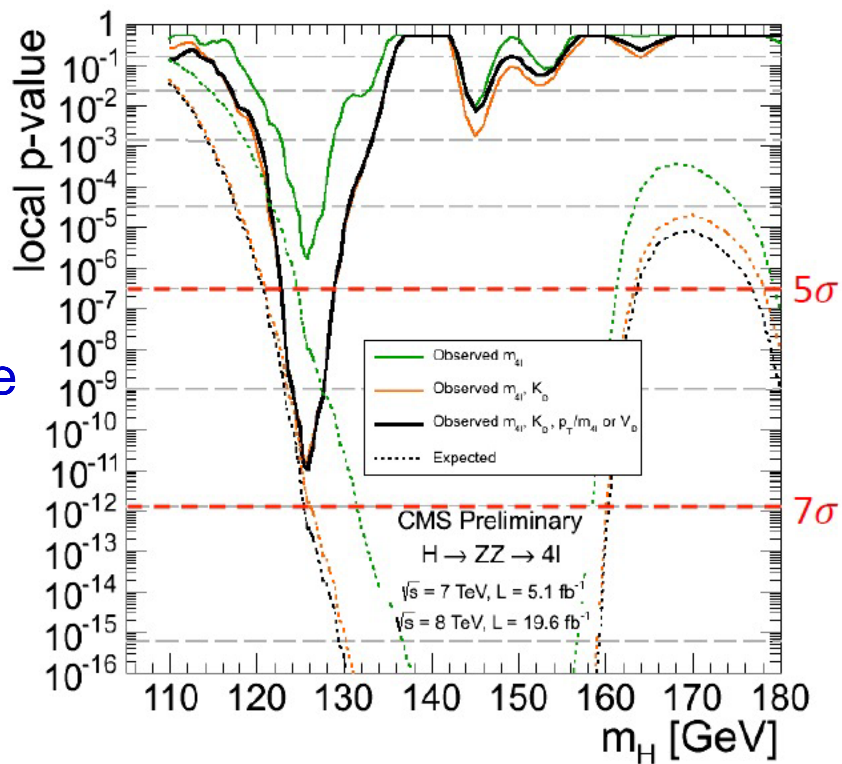
New Data from CMS

- ❑ Significance = 6.7 σ
- ❑ Expected separation $0^+/0^-$ ~ 2σ
  - – Scalar (0^+): consistent at ~ 0.5σ
  - – Pseudoscalar (0^-): inconsistent ~ 3.3σ
- ❑ Rule out 2^+ ~ 2.7 σ

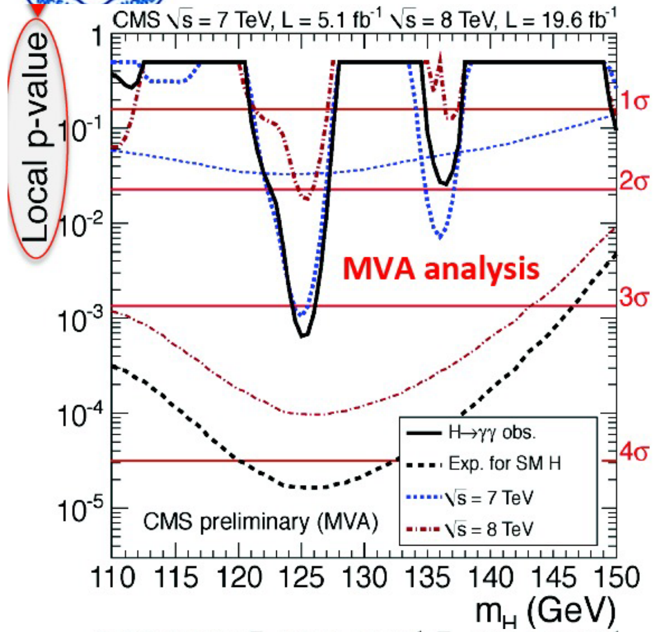


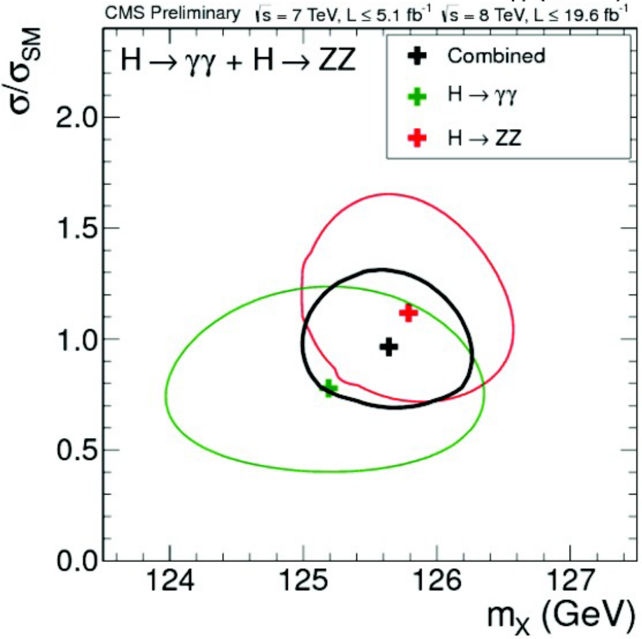


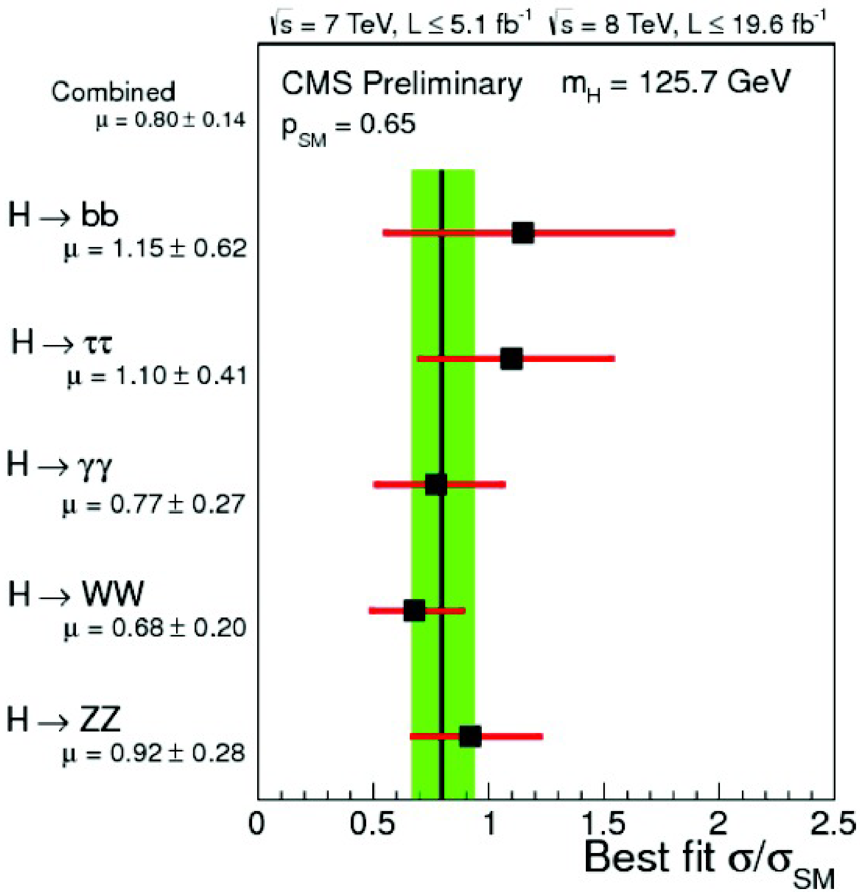
The new data adds more significance and also some of the empty regions get filled up



CMS Combined Results

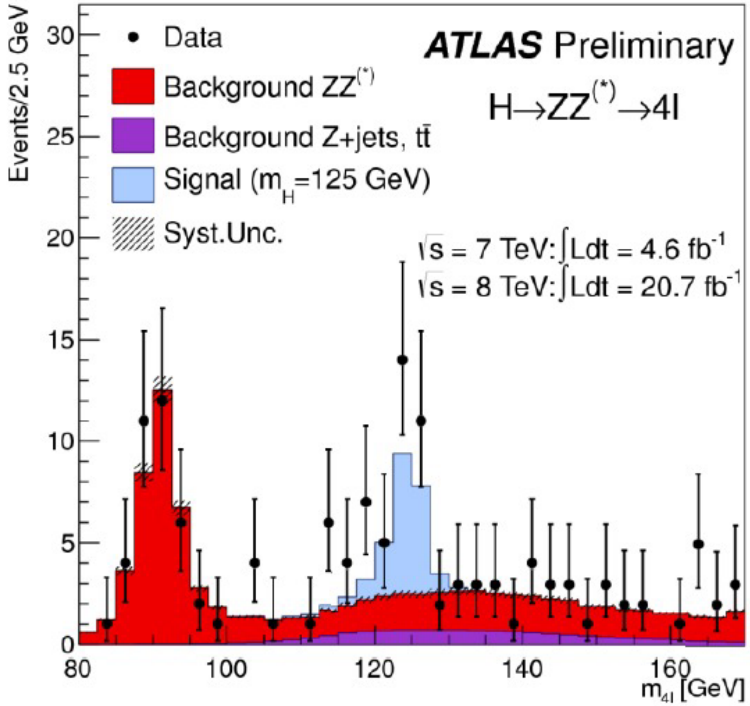


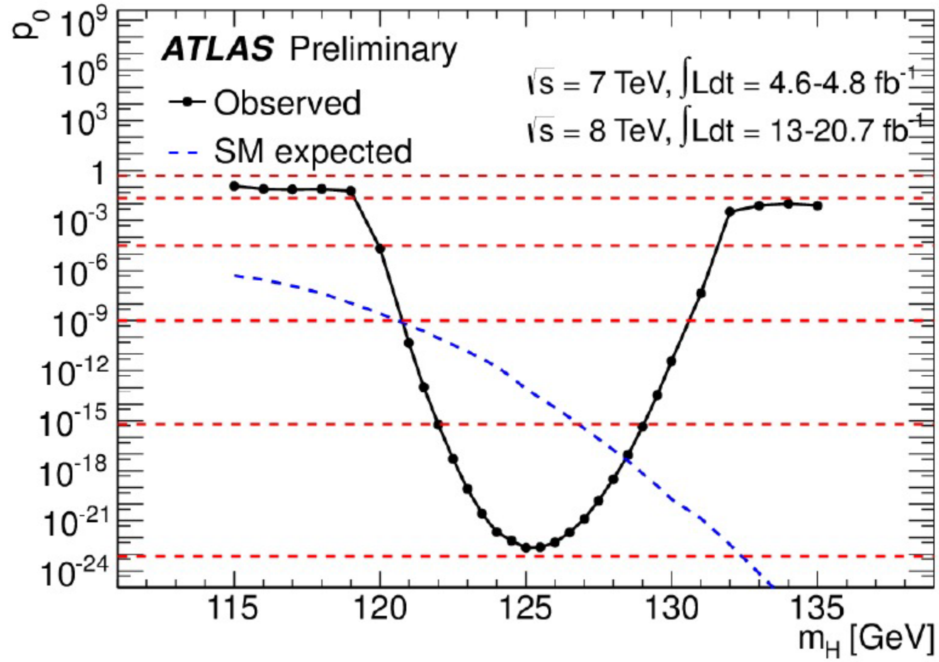


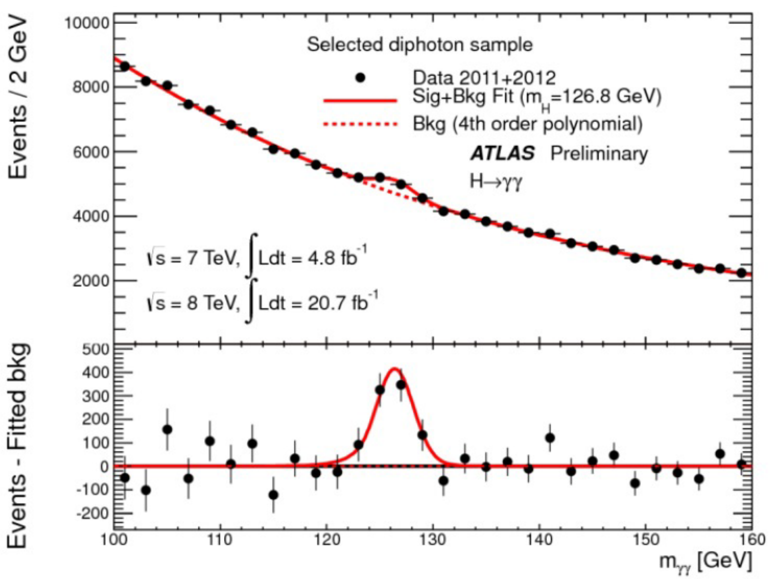


- Significance in $H\rightarrow\gamma\gamma$ is reduced to 3.5 σ expected: 3.9 σ
- signal strength: 0.80 ± 0.14
- Mass estimate: 125.7 ± 0.4 GeV

New data from ATLAS

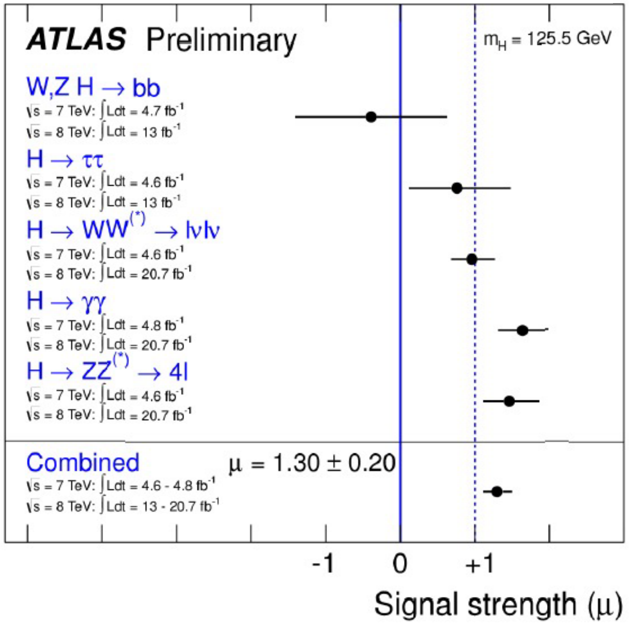




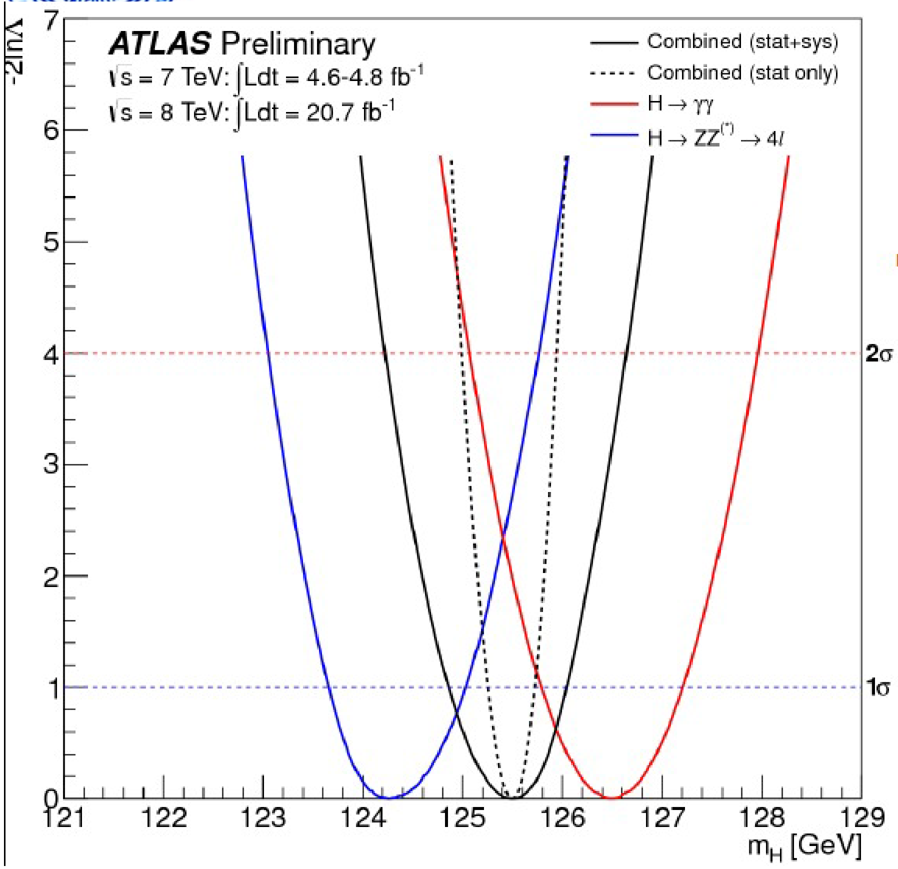


- Including ~21 fb^{-1} 8 TeV data
  - Observe ~ 10σ significance
- Mean signal strength:

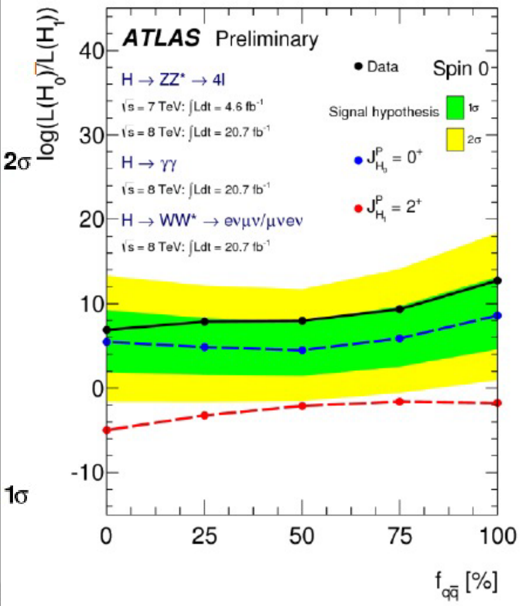
  μ = 1.30 ± 0.20



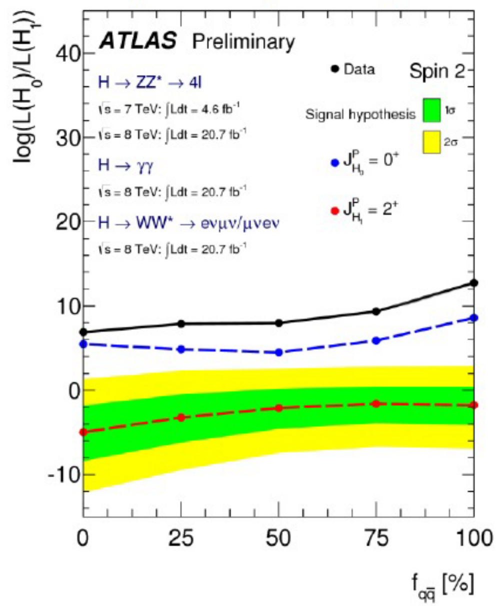
ATLAS Updates



Compatibility with spin 0

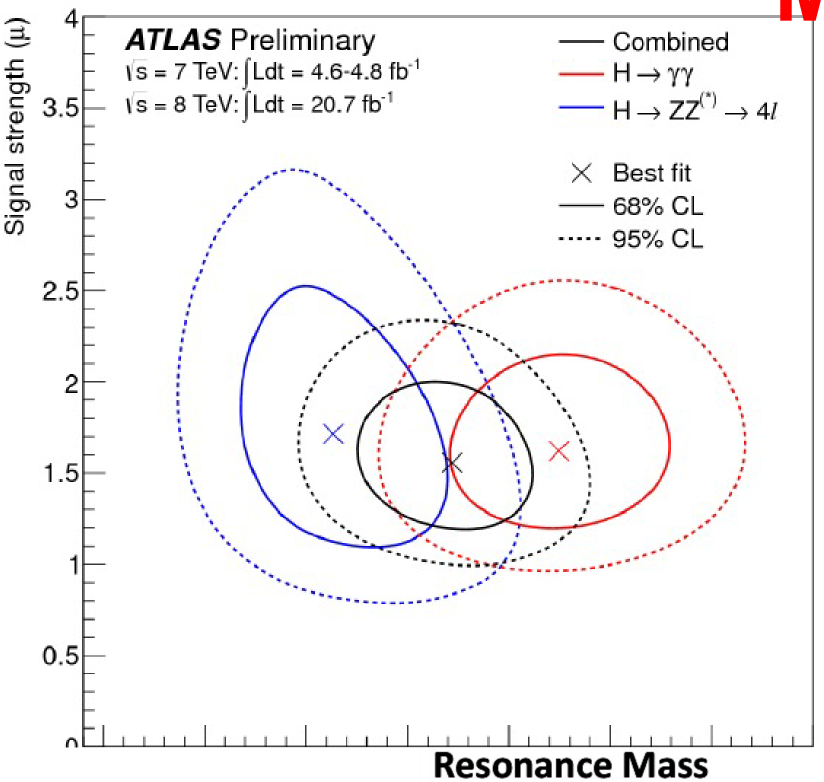


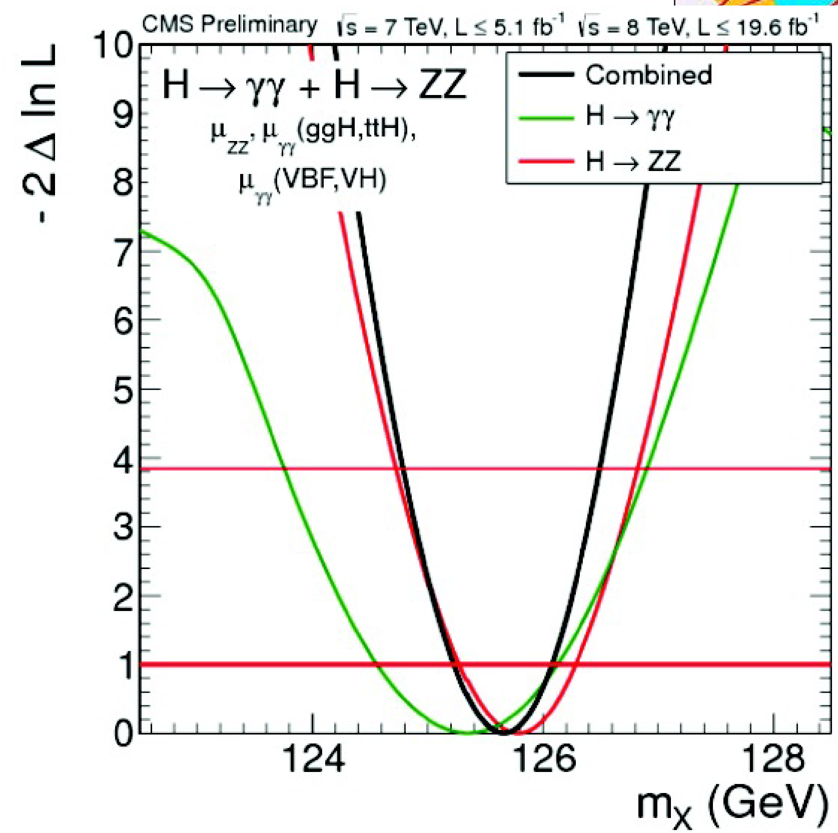
Compatibility with spin 2

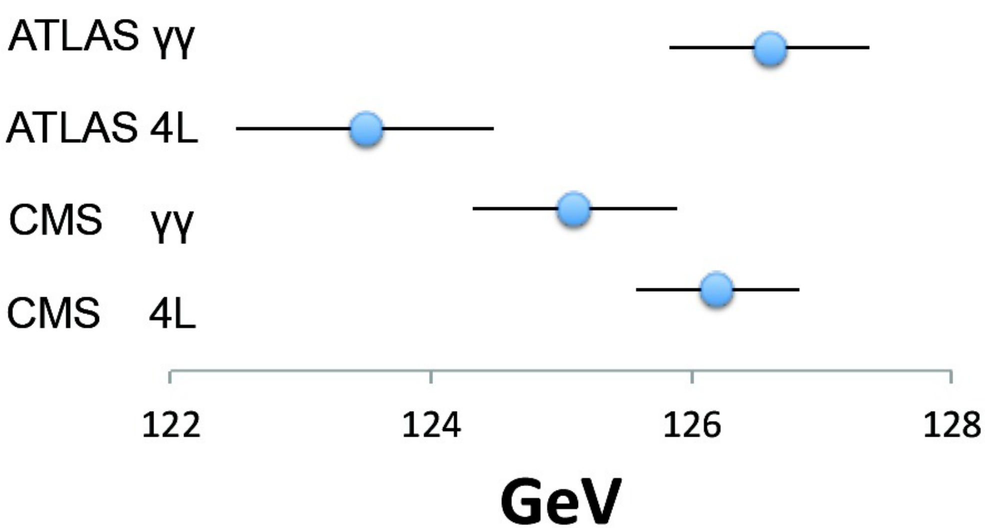


- Accurate mass measurement from ZZ and γγ channels:
  - M = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV
- Spin is analyzed in a model with unknown Higgs production mechanism (fraction of qq/gg being parameters)
  - Exclude 2^+ at 99.9% CL; other possibilities at > 95% CL

Mass of the Resonance







- Z peak into 2 electrons or 2 muons is the main tool for mass scale

Indian participation in CMS

- Participants: Universities of Chandigarh, Delhi + BARC (Mumbai), SINP (Kolkata), TIFR (Mumbai) (since 1993)
- Indian groups participated in
  - the design of the detectors,
  - building hardware components,
  - contributing to the software and detector performance studies
  - physics analysis leading to the papers for publication
- Early design work includes
  - choice of material for the electromagnetic calorimeter
  - detector granularity to balance resolution vs particle identification

TIFR/EHEP/94-12
CMS TN/94 - 238
August 31, 1994

Radiation Hardness Study of CeF_3, $PbWO_4$ Crystals and Heavy Glass to MeV Neutrons [1)]

S. Banerjee, S. Mangla, G. Mazumdar and R. Raghavan
Tata Institute of Fundamental Research, Bombay

TIFR–EHEP/94–15
CMS–TN/94–291
December 6, 1994

Neutral Pion Rejection and Position Resolution for Gammas as a Function of Granularity for a $PbWO_4$ Crystal Calorimeter

S. Banerjee, R. Raghavan
Tata Institute of Fundamental Research, Bombay

Early Studies

- Early studies also include
  - Design of the software system
  - Probing new observables from the detectors
  - First use of new techniques in analysis
  - Comprehensive analysis of finding the final reach of CMS

CMS TN/95-128

First Evaluation of the Curvature Sampling Pattern Recognition Algorithm in context of the CMS Inner Tracker

S.Banerjee, F.Bruyant
CERN/ECP

S.Piperov
Sofia University and INRNE - Sofia

24 November 1995

Available on CMS information server

CMS NOTE 1999/056

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

22 October 1999

Study of dE/dx Measurements with the CMS Tracker

S. Banerjee[a], A. Caner[b], S. Dutta[c], A. Khanov[b,d], F. Palla[c], G. Tonelli[c]

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CMS TN/ 96-023
February 23, 1996

Application of Neural Networks in Detecting Higgs at CMS.

S. Banerjee 1), A. Khan 2) 3)

Eur Phys J C **39**, s2, s41–s61 (2005)
Digital Object Identifier (DOI) 10.1140/epjcd/s2004-02-003-9

EPJ C direct
electronic only

Scientific Note

Summary of the CMS potential for the Higgs boson discovery

S. Abdullin[1,a], S. Banerjee[2], L. Bellucci[3], C. Charlot[4], D. Denegri[5,b], M. Dittmar[6], V. Drollinger[7], M.N. Dubinin[8], M. Dzelalija[9], D. Green[10], I. Iasvili[10], V.A. Ilyin[8], R. Kinnunen[11], S. Kunori[1] K. Lassila-Perini[11], S. Lehti[11], K. Mazumdar[2], F. Moortgat[12], Th. Muller[13], A. Nikitenko[14,a], I. Puljak[9], P. Salmi[11], C. Seez[14], S. Slabospitsky[15], N. Stepanov[5,a], R. Vidal[10], W. Wu[10], H.D. Yildiz[16], M. Zeyrek[16]

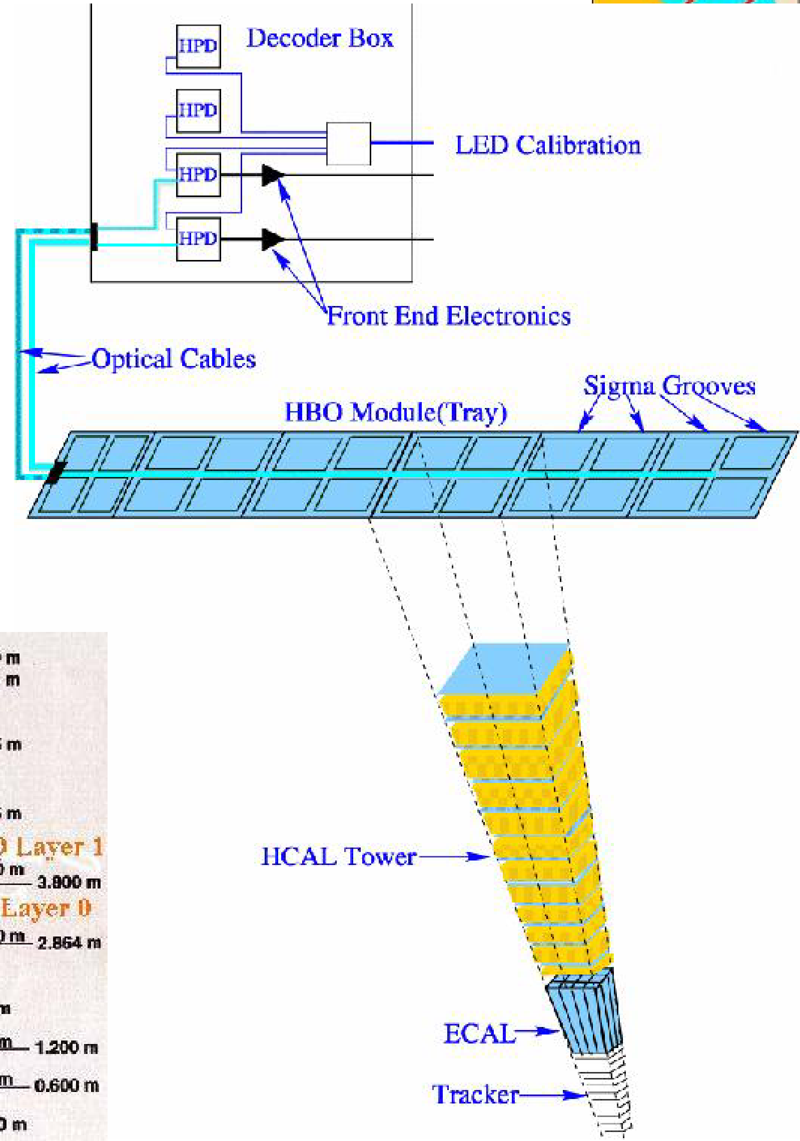
1 University of Maryland, College Park, Maryland, USA
2 Tata Institute of Fundamental Research, Mumbai, India

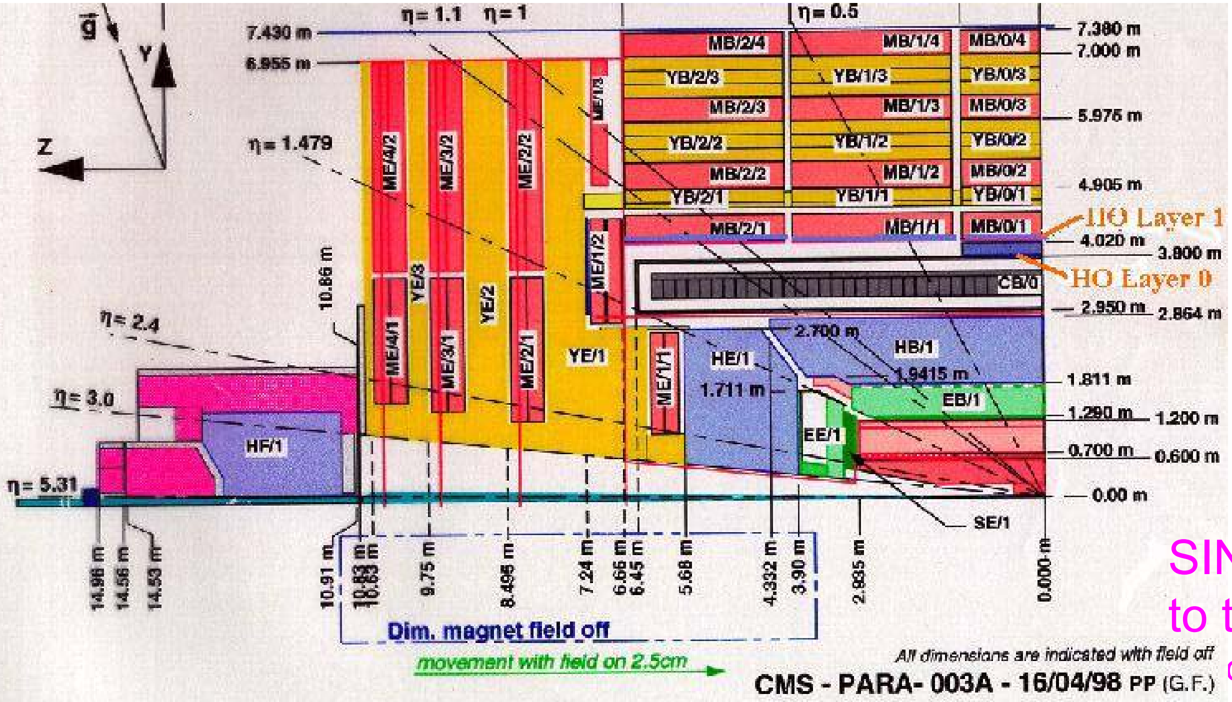
Hardware contribution

- TIFR, together with Panjab University constructed the outer hadron calorimeter
- HO covers central rapidity region |η|<1.3 occupied by the five muon rings to improve jet and MET resolution

Pseudorapidity, $\eta = -\log_e(\tan(\theta/2))$

- Basic detector element maps tower granularity of 0.0873 ×0.0873 in η×Φ
- 432 trays are built from 2730 tiles

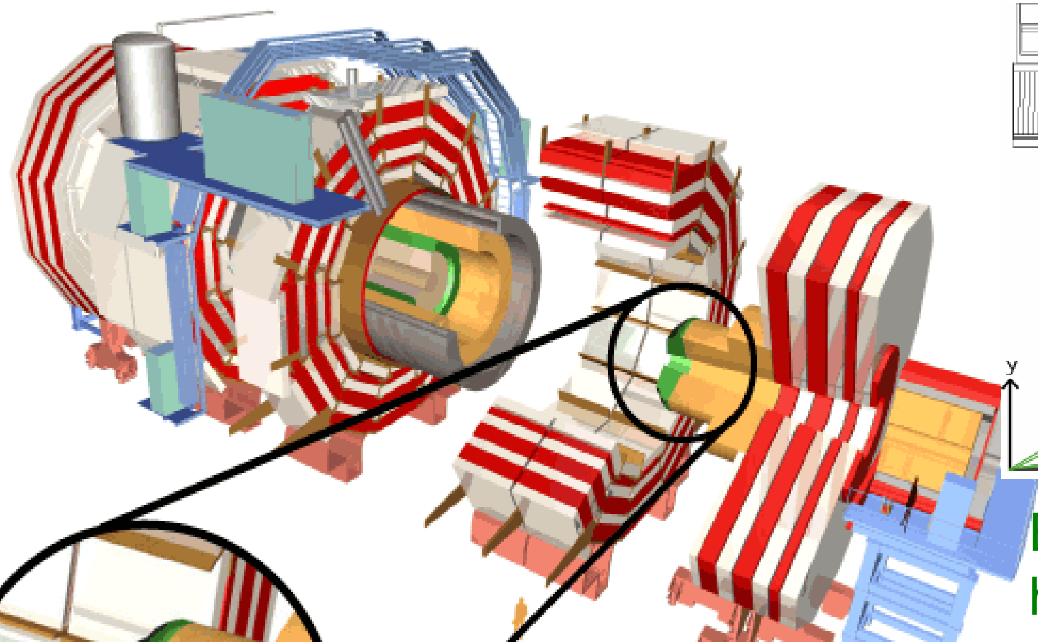


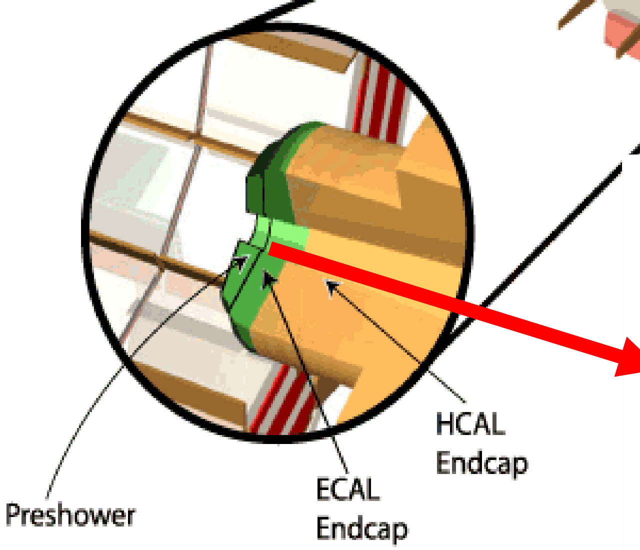


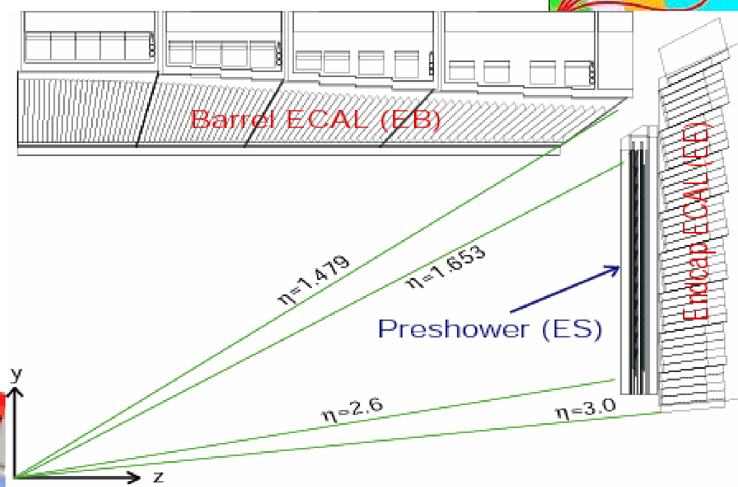
SINP, TIFR are now contributing to the upgrade effort of HCAL

der

CMS preshower detector

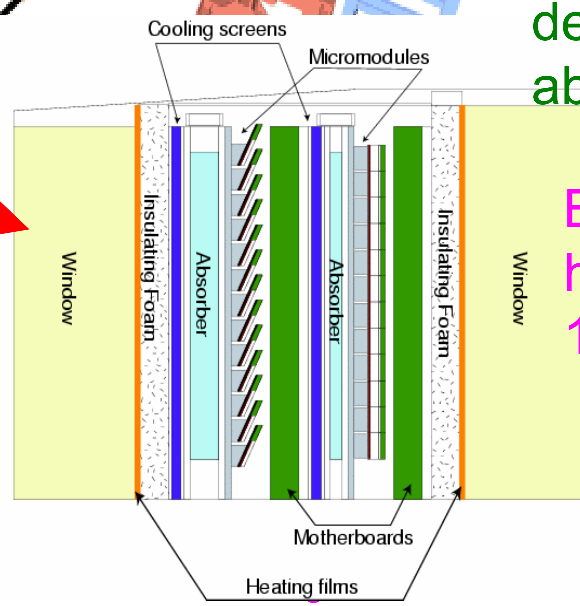






End caps of CMS detector have 4300 silicon strip detectors covering area of about 17 m^2

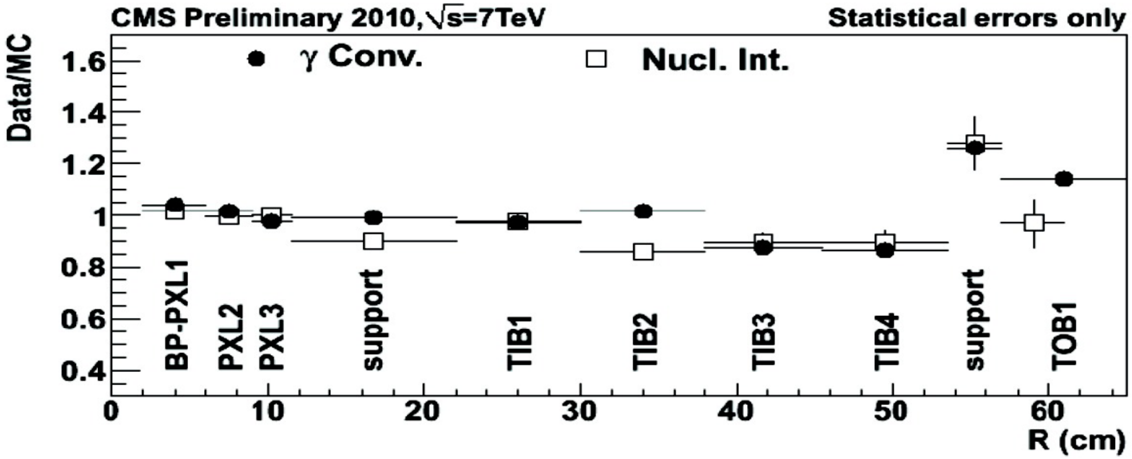
BARC and Delhi university have delivered more than 1000 detector modules



Higgs discovery : Good π^0 rejection for $H \rightarrow \gamma\gamma$ mode

Software contributions

- One of the main architects of the offline software project – starting from the very first version of simulation and reconstruction, graduating to object oriented software to the final version which is deployed from HLT to analysis. The first success of LHC experiments is how well and quickly the detectors are understood – largely due to work of a few task forces which were steered by Indian scientists.



- First designer of web based GUI (Graphical User Interface) for data quality monitoring and coordinating DQM activities of the tracker
- Prototyping the DAQ system with testing of various high speed switches
- Development of GRID monitoring tools for CMS
- Participation in calibration and overall performance of the hadron calorimeter system

Physics studies

- Carried out several analyses leading to public version of the analyses and a number of physics publications:
  - Single particle response in the calorimeter
  - Event shape distributions at a few CM energies
  - Studies of underlying events using jets reconstructed from tracks and using Drell-Yan events
  - Direct photon production and constraints on parton density function
  - Measurement of subjet multiplicity in dijet events
  - Test of QCD in inclusive jet and multi-jet production
  - Measurement of W charge asymmetry and Wγ production
  - Search of Standard Model Higgs boson in a number of channels involving leptons, τ's and ν's
  - Quarkonia production in heavy ion collisions
  - Search for excited lepton
  - Study of mono photon production in view of extra dimension
  - Search of Supersymmetry in all hadronic final state

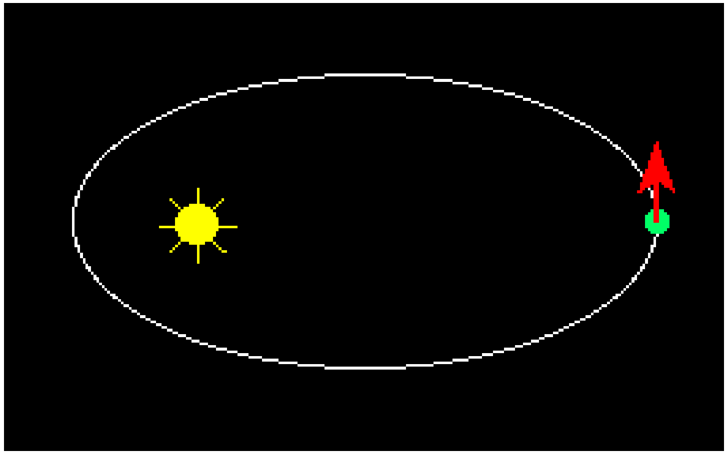
Last Word

- There is a very strong evidence of a new narrow boson of mass around 125-126 GeV
- The search criteria of this object is motivated by Higgs boson within the Standard Model
- Evidence is slowly growing toward a scalar boson with properties as expected from Higgs boson within the Standard Model
- This is achieved by international collaboration of thousands of people working over two decades
- We, the Indians, have been a part of this from very early days

Back Up

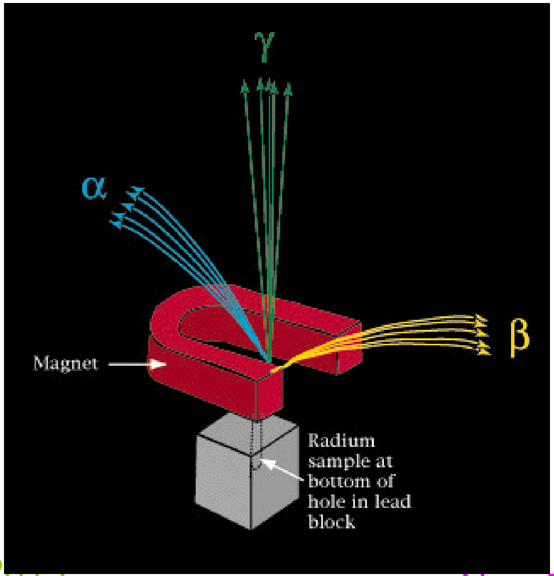
Nature of interactions

Gravitational → solar system

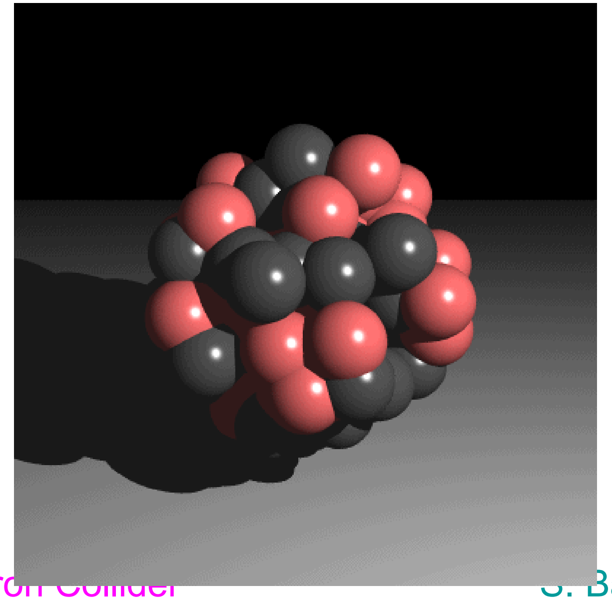


Electromagnetic → photon

Weak → radioactivity

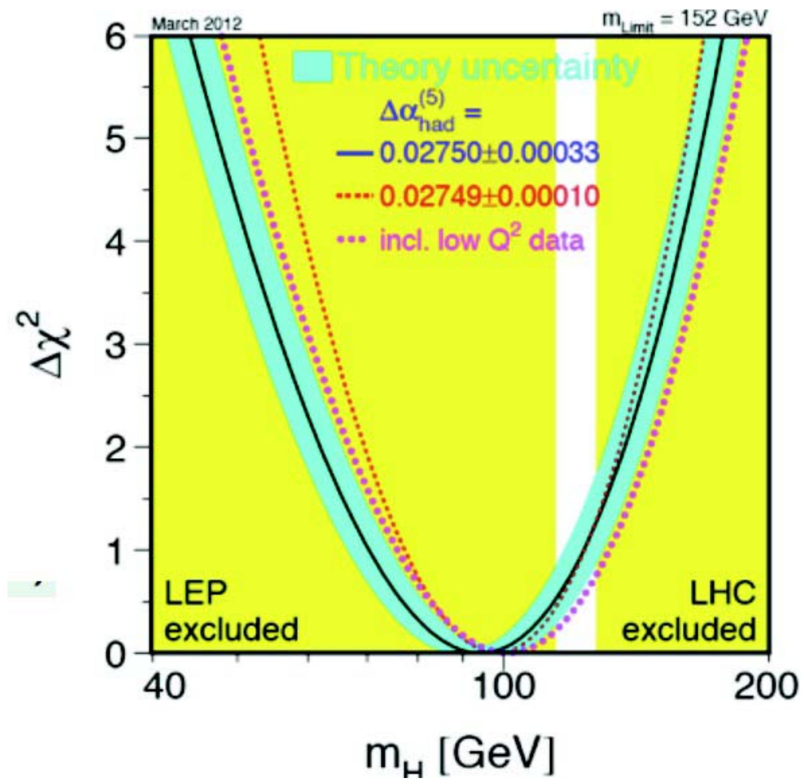


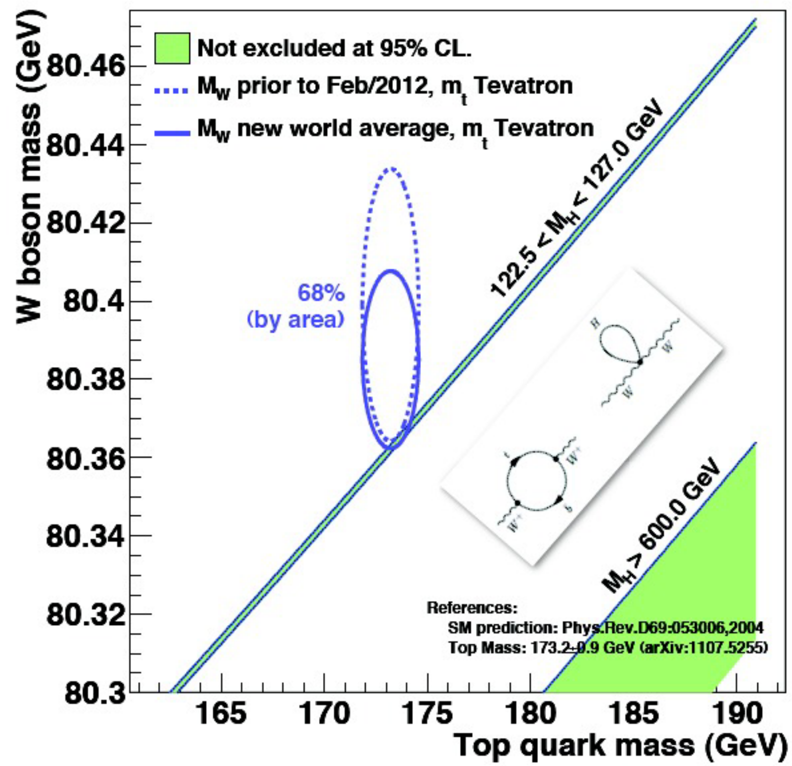
Strong → binding of nucleus



Indirect Measurement (Jan 2012)

- Use precision measurements from LEP/SLC/Tevatron measurements and carry out Standard Model fit





New (preliminary) indirect Higgs mass determination

$M_H = 94^{+29}_{-24}\, GeV$ (was $M_H = 92^{+34}_{-26}\, GeV$ before)