Higgs Results from CMS

Outline

- Introduction
- The preparation and the struggle
- Results from different channels:
  - 4 leptons
  - di-photon
  - W-pair
  - tau leptons
  - b-quark pair
- Did Indians do anything at all?

Jammu, September 2013
Triggering Discoveries in HEP

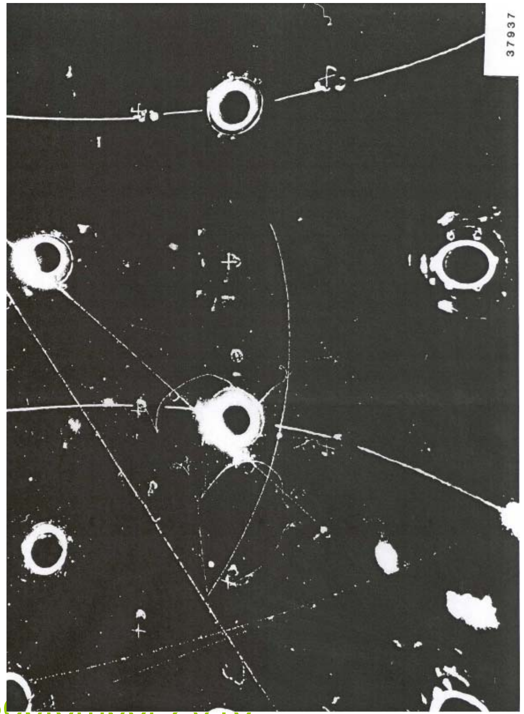
Sunanda Banerjee

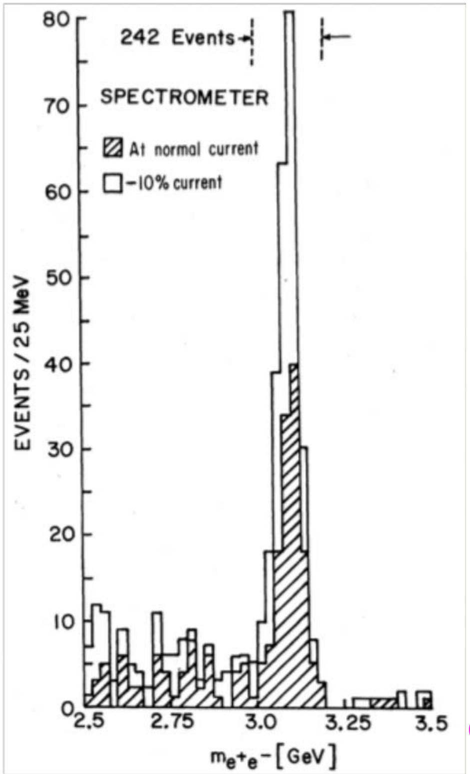
July 4, 2012

- Official announcement of the observation of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at ICHEP2012 in Melbourne, Australia

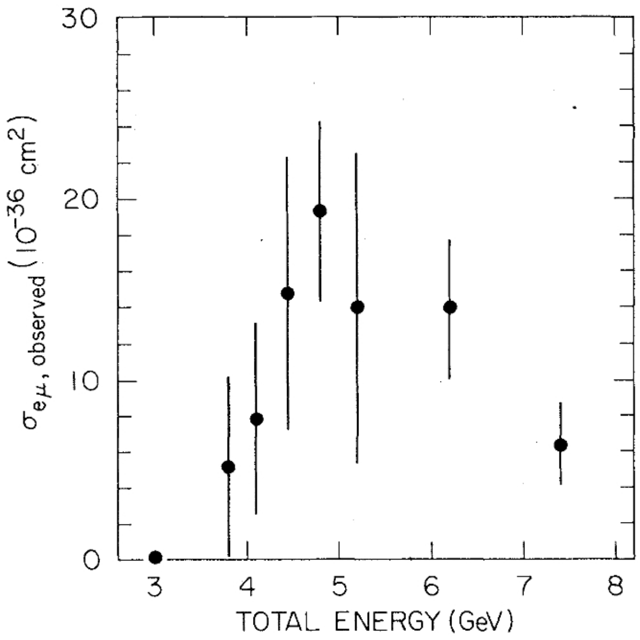
What is it about?

- During late 60's-early 70's, particle physics saw lots of excitements
  - Both experiments and theory saw many developments and discoveries
  - Experiments saw discovery of neutral current, discovery of charm, finding 3rd generation of lepton/quark, ….
  - Theory gave the birth of the Standard Model, explanation of CP violation, ideas about Supersymmetry, Grand Unification, …



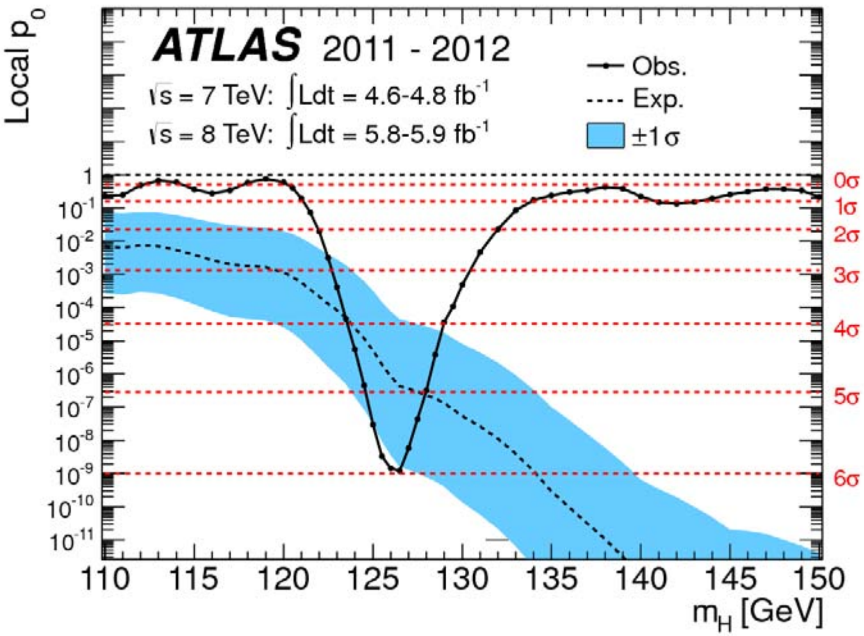


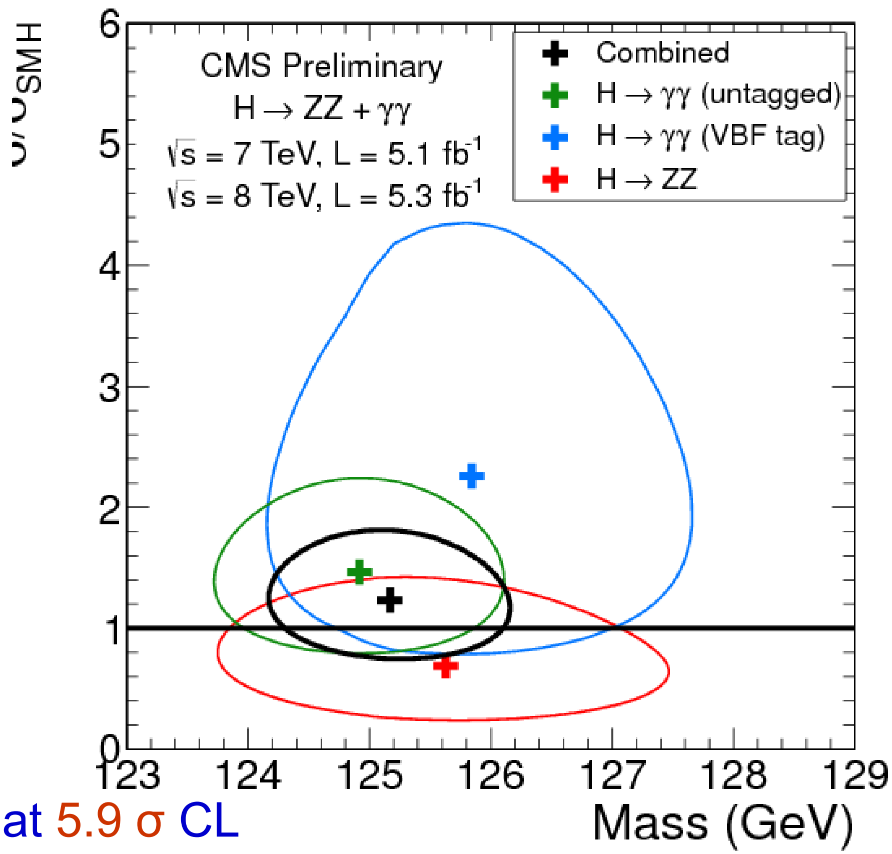
… but that was past



Results on July 4

Two experiments found evidence of some new boson – could be the elusive Higgs boson

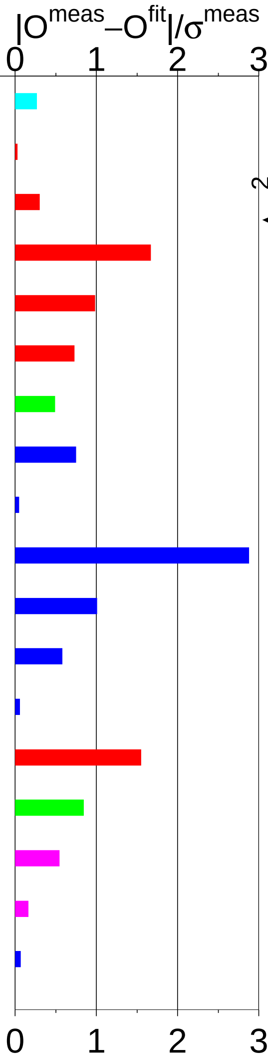




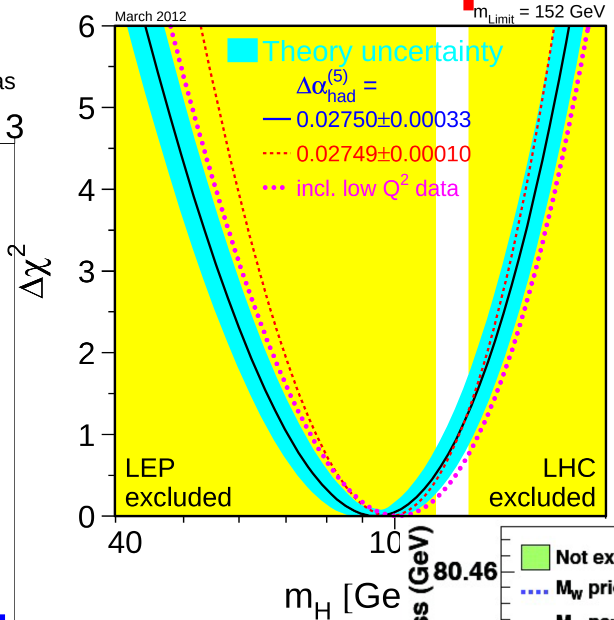
- ATLAS observes:
  - Maximum excess at 126.0 GeV at 5.9 σ CL
  - Probability of fluctuation of background to show the excess 1.7×10^{-9}
- CMS observes:
  - Excess in 4 different channels at 125.3 GeV
  - Level of fluctuation at 5.0-5.1 σ CL (3×10^{-7})

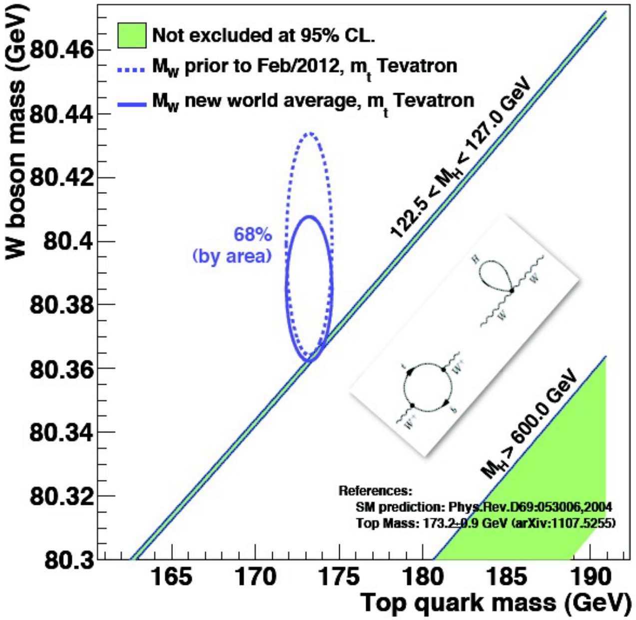
The Start: Standard Model vs Experiments

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	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_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

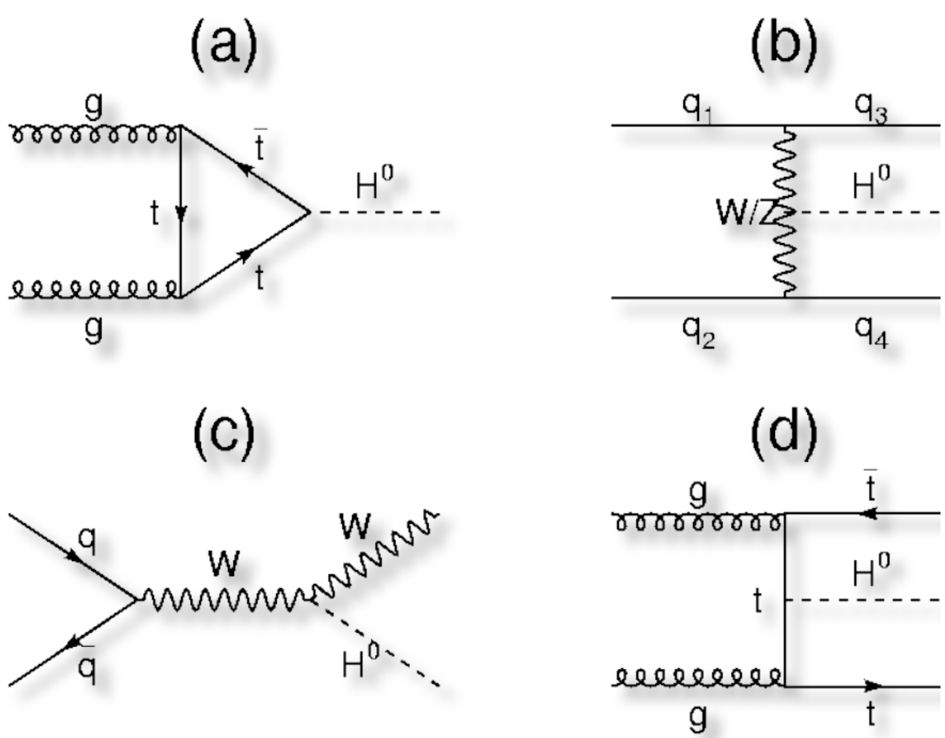


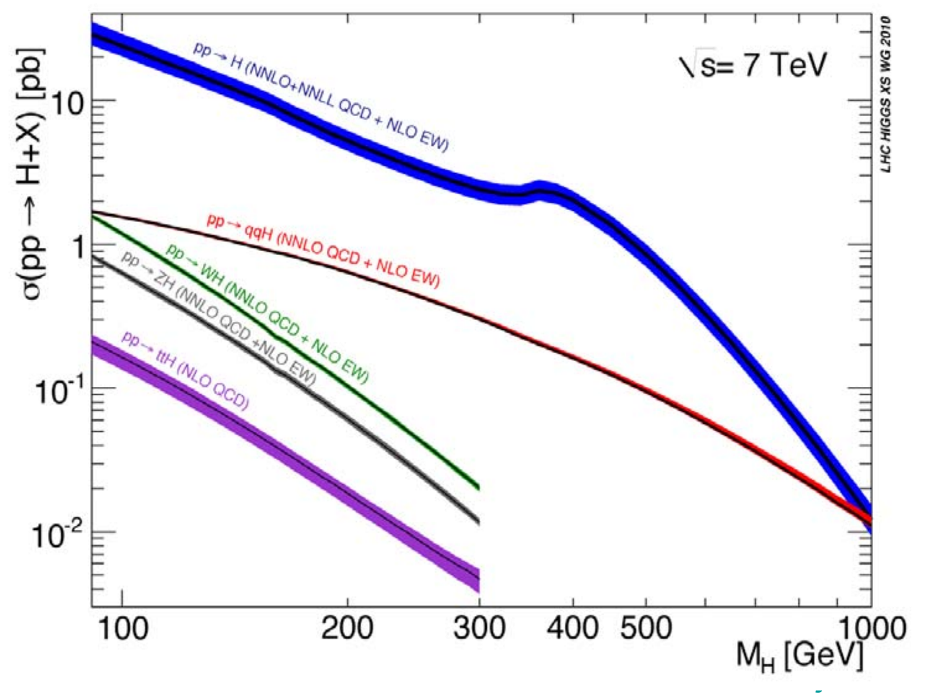


- Standard Model worked beautifully explaining all precision measurements
- The data suggests Higgs boson mass around 100 GeV

Production of Higgs boson

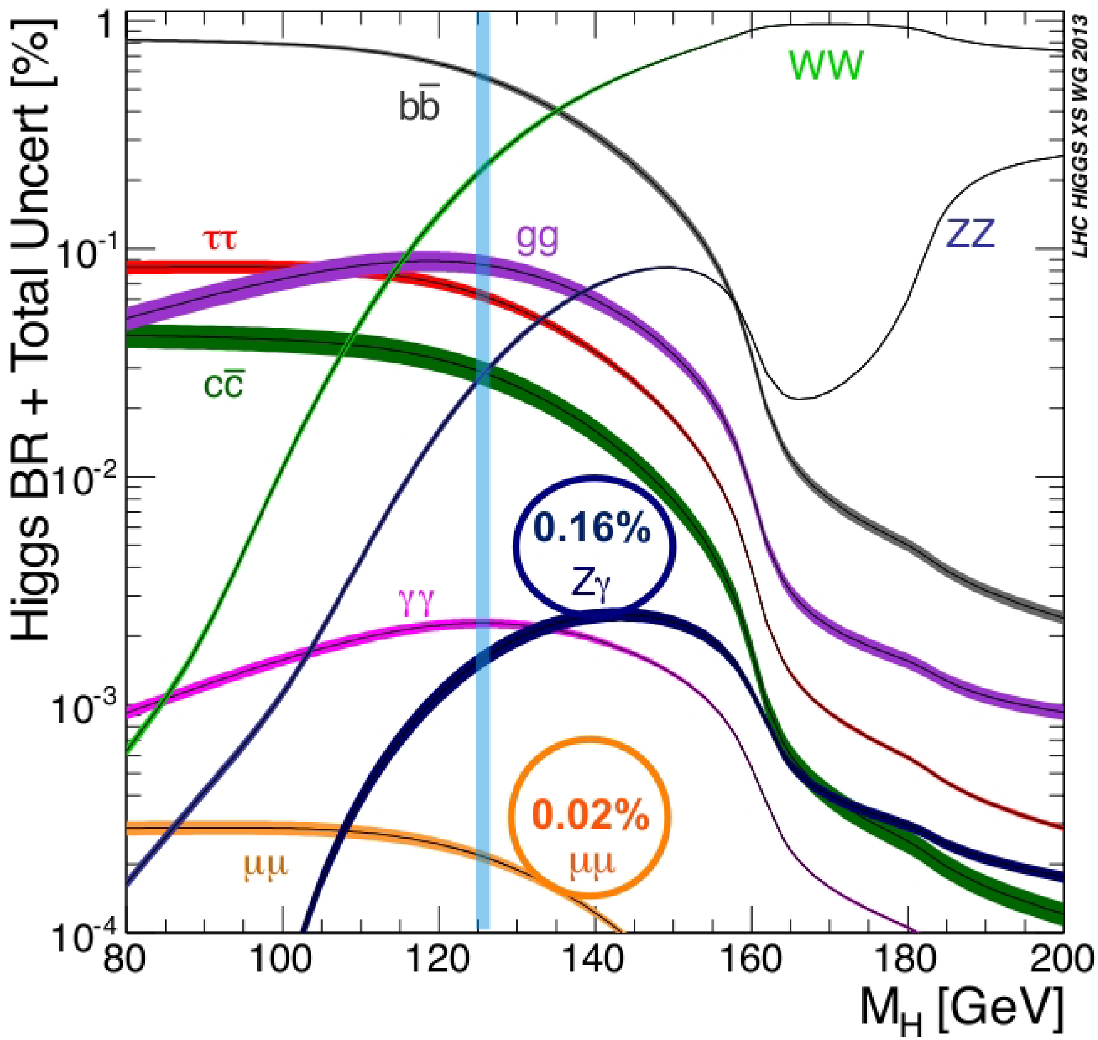
- Higgs boson can be produced from a number of mechanisms of which a few have been tested at the LHC
  - Gluon fusion (19pb at 8 TeV for SM Higgs)
  - Vector boson fusion (WW or ZZ)
  - Associated production with vector boson (VH)
  - Associated production with top quark (ttH)





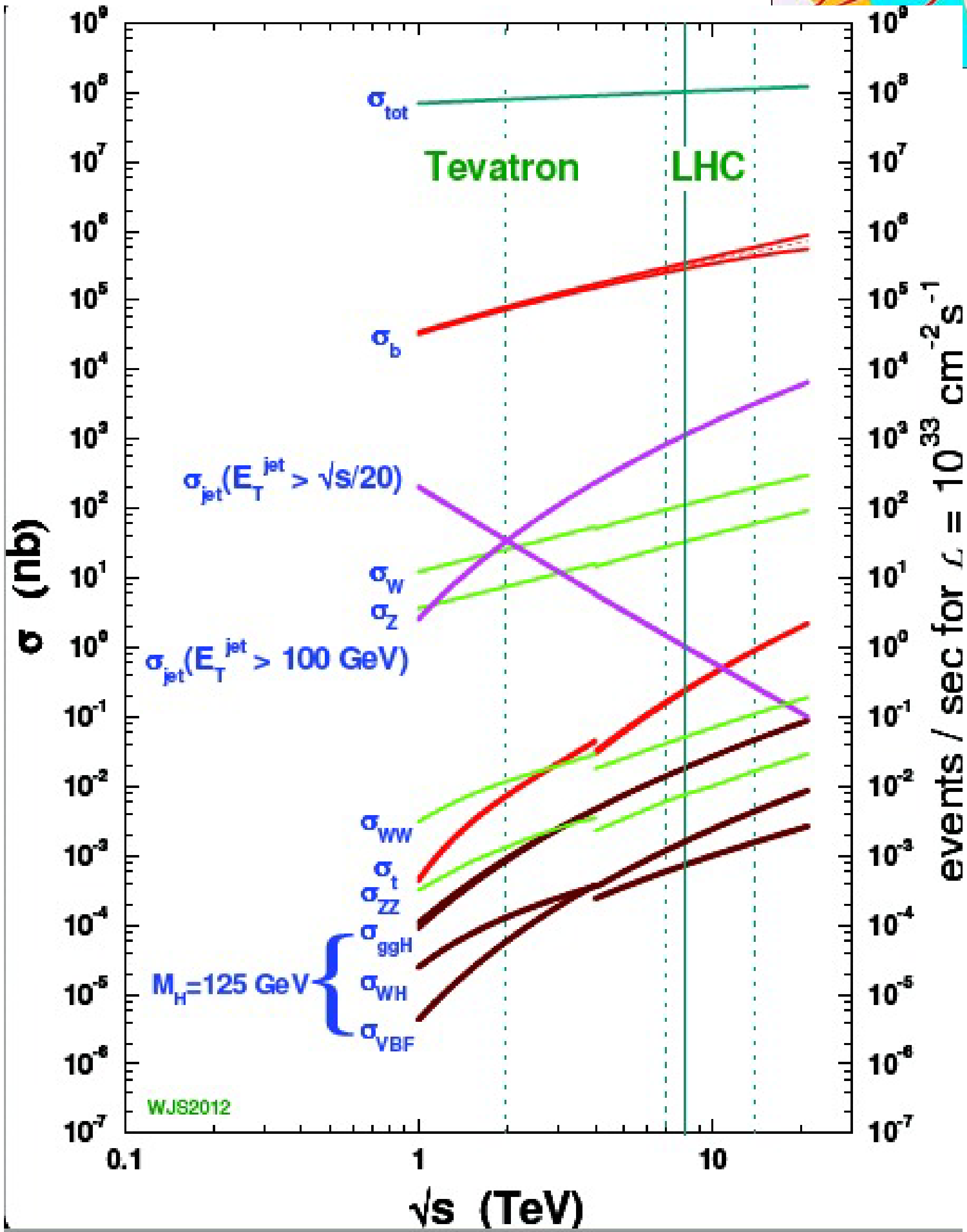
Higgs boson decays

- Higgs boson is unstable and will decay to other particles immediate after it is produced
  - Look at all possible signatures
  - At 125 GeV, Higgs boson can be seen in a number of final states:
    - H(bb) → 57%
    - H(WW) → 22%
    - H(ττ) → 6.2%
    - H(ZZ) → 2.8%
    - H(γγ) → 0.23%



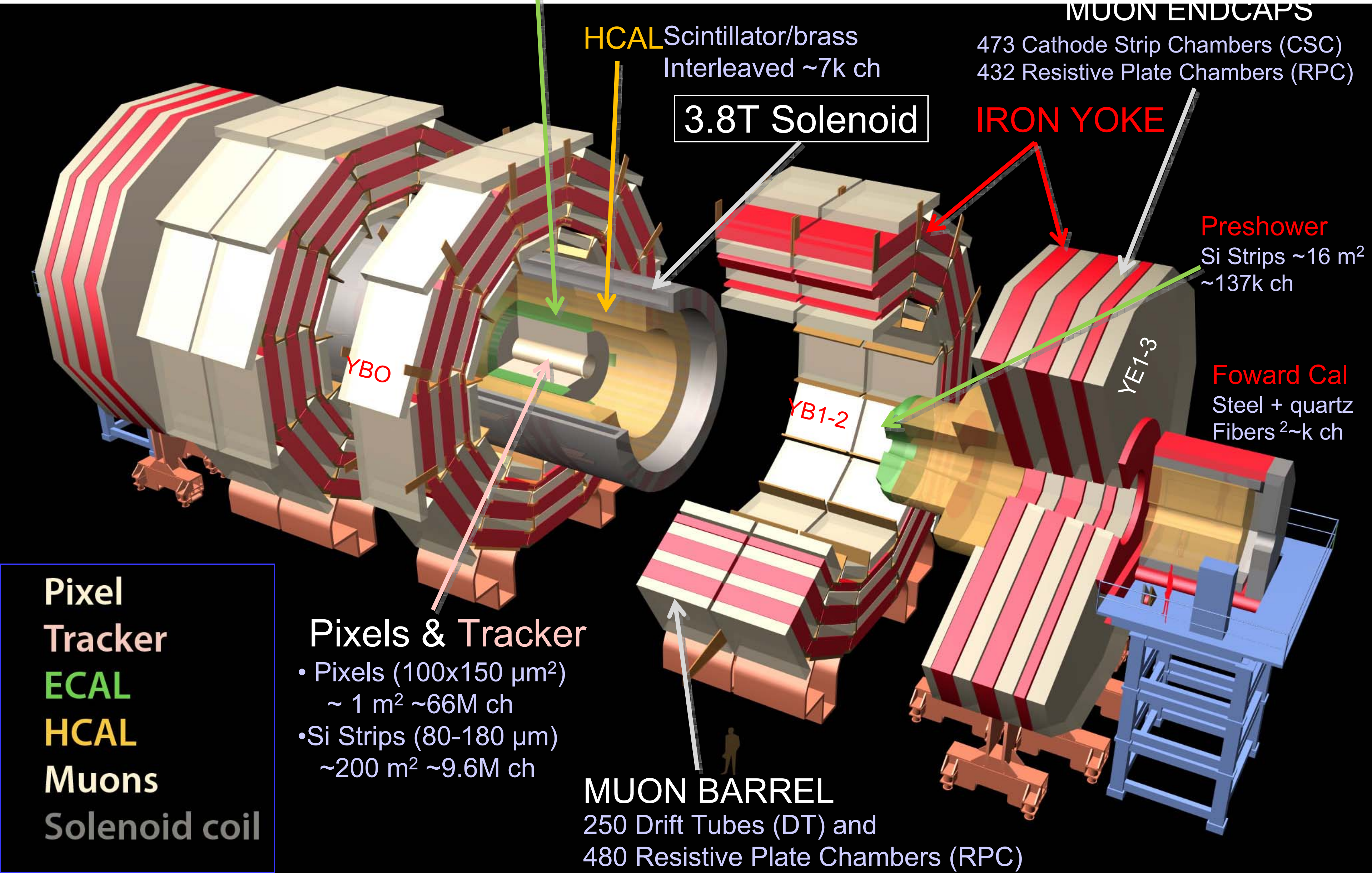
What happens at LHC

- LHC has been extremely generous:
  - Provided excess of ~4×10^{14} interactions during 2011 at 7 TeV cm energy and a factor of ~5 larger number at 8 TeV during 2012
  - CMS collected 95% of the provided luminosity and 90% of those are certified for physics publications
- However this will produce ~10^9 unwanted interactions for each Higgs boson

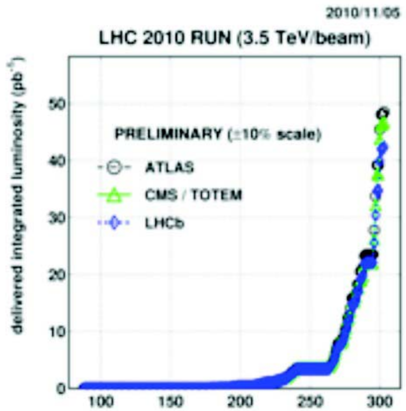


CMS

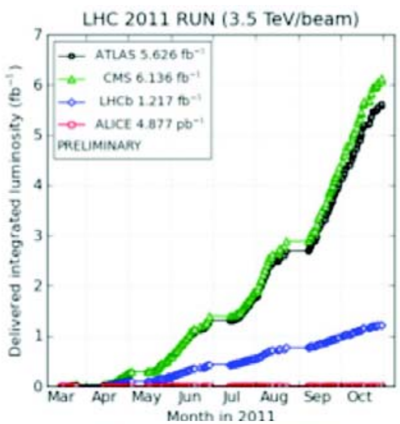
Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m



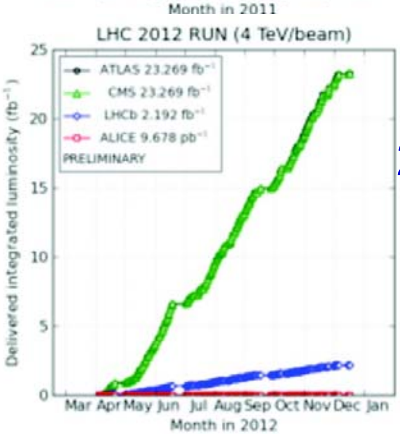
Success of LHC (Misery to Experiments)



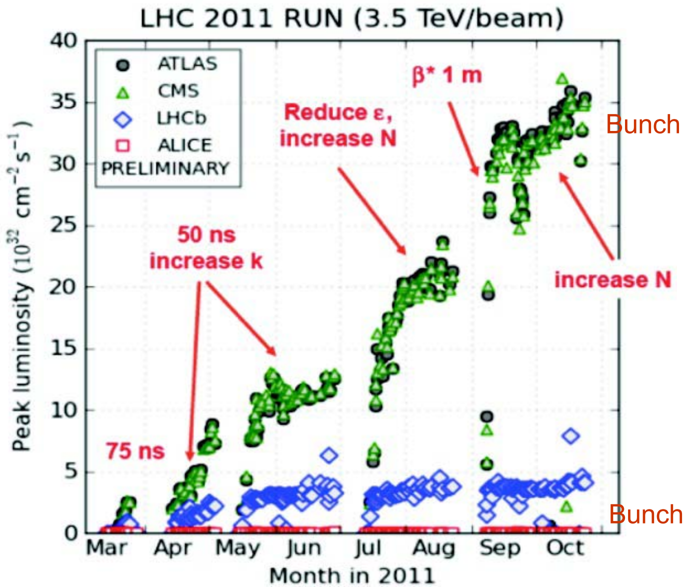
30 pb^{-1}



5.8 fb^{-1}



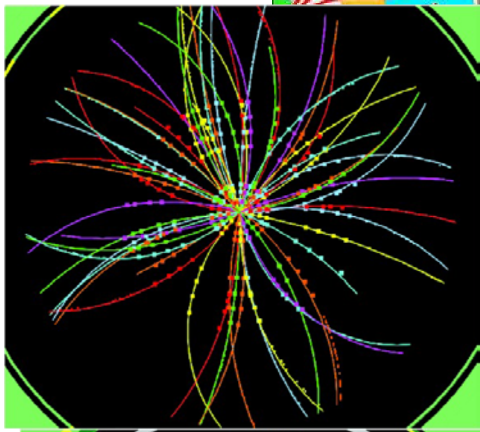
25 fb^{-1}



$$L = \frac{kN^2 f}{4\pi\sigma^*_x\sigma^*_y} F = \frac{kN^2 f\gamma}{4\pi\beta^*\varepsilon} F$$

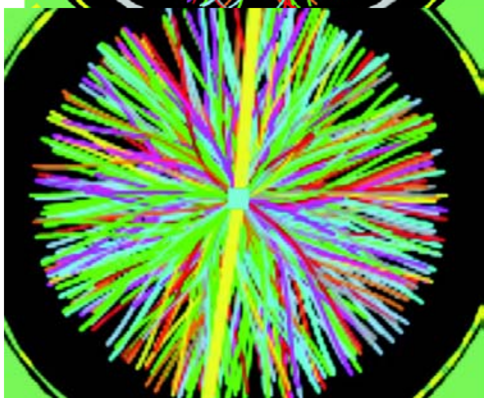
- k = # of bunches
- N = # of p's/bunch
- f = rev. frequency
- σ = beam size
- F = geometry loss factor
- ε = beam emittance
- β = betatron function

2010
O(2) PU
Bunch spacing 150 ns



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

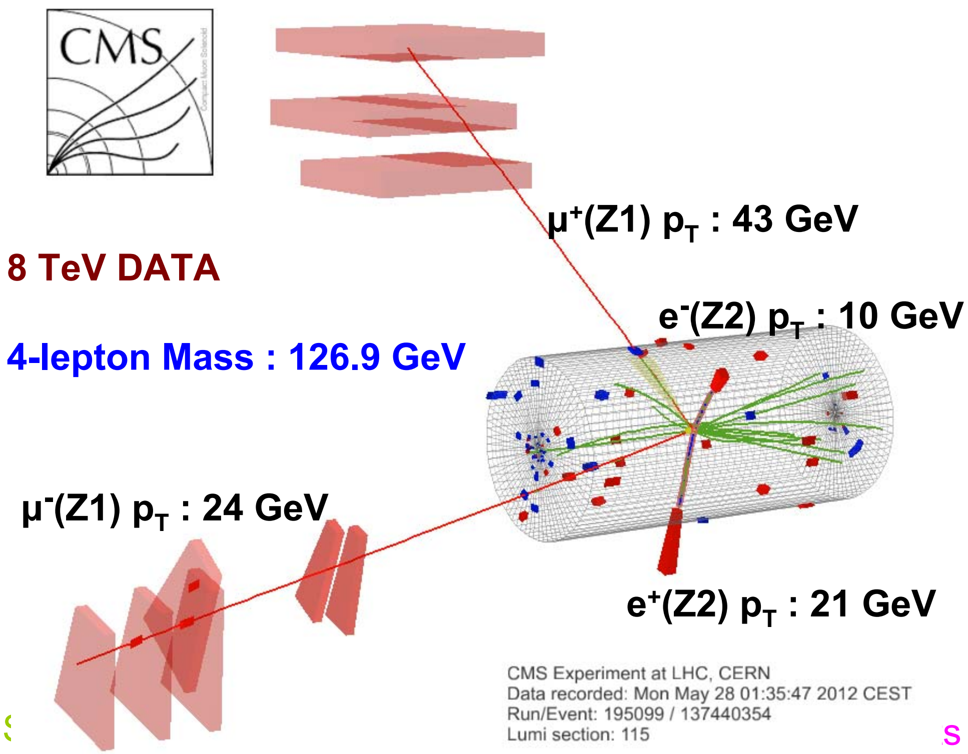
2012
O(20) PU
Bunch spacing 50 ns



Higgs Results from CMS

Search in the mode $H \rightarrow ZZ^{(*)} \rightarrow 4l(e/\mu)$

- This is the golden mode: trigger on single or two isolated leptons
- Offline selection demands 4 isolated leptons: 2 pair of oppositely charged same flavor leptons
- Each pair consistent with Z-decay (one close to Z-mass) and coming from the same production vertex



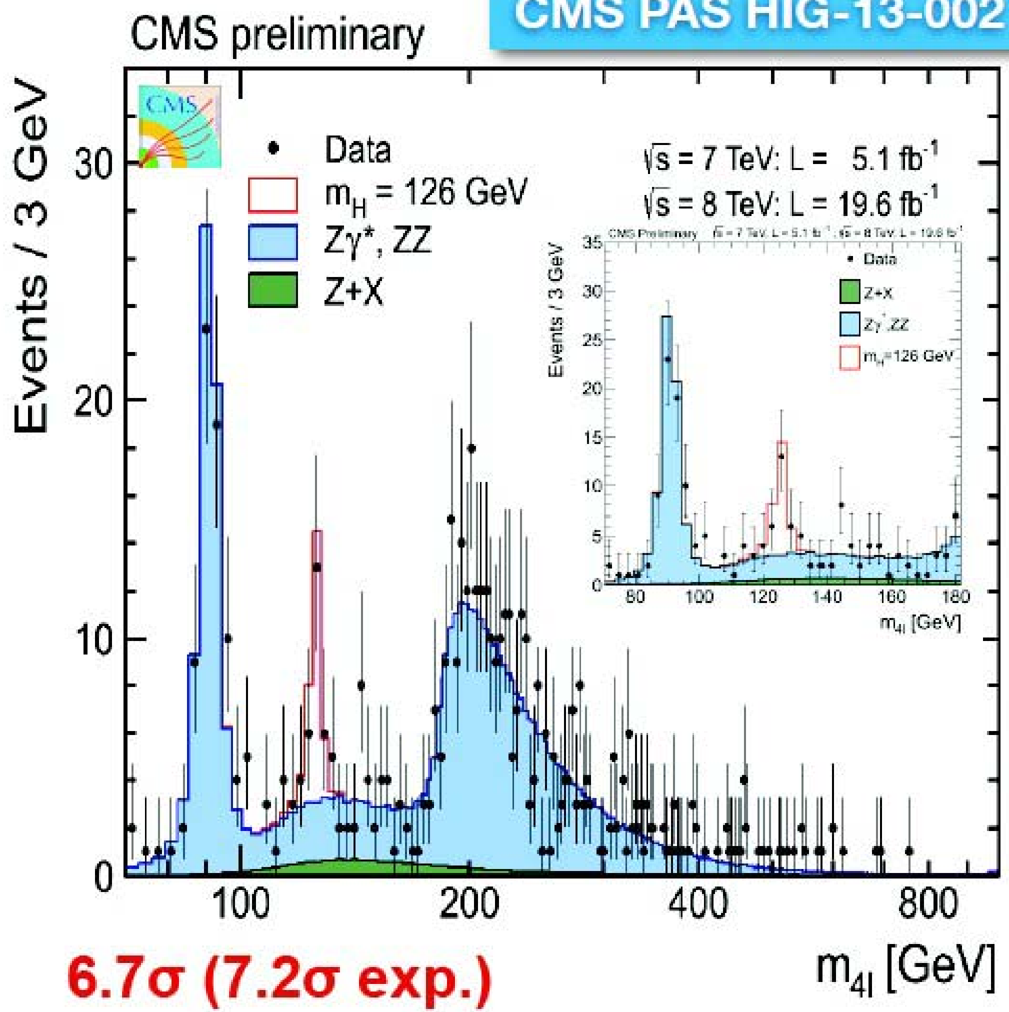
- Irreducible background is due to Z-pair production
- Reducible background is due to t-tbar, Zb-bbar and Z+jets. Additional leptons come from b-decays and greatly reduced using isolation and non-pointing criteria
- Signal and background shape modeled using Monte Carlo and using control regions from the data

s from CMS

Higgs to 4 Leptons

- Search for a narrow peak in the 4-lepton mass spectrum on top of a flat and small background
- Leptons are reconstructed and identified with high efficiency and precision in energy-momentum measurement has excellent
  - Mass resolution @125 GeV ~ 1/2%
- Events are categorized based on jet multiplicity
- Use additional help from kinematical discriminant based on angles between the leptons
- However the rate is small

CMS PAS HIG-13-002

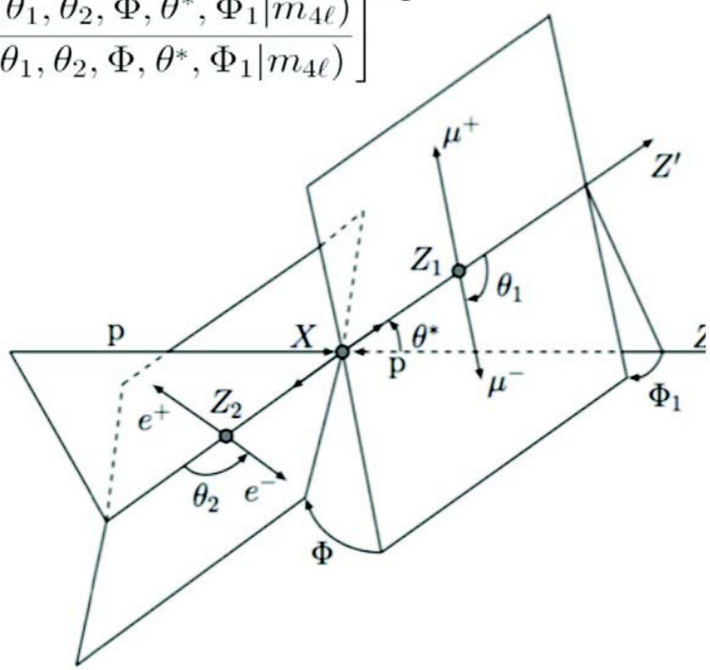


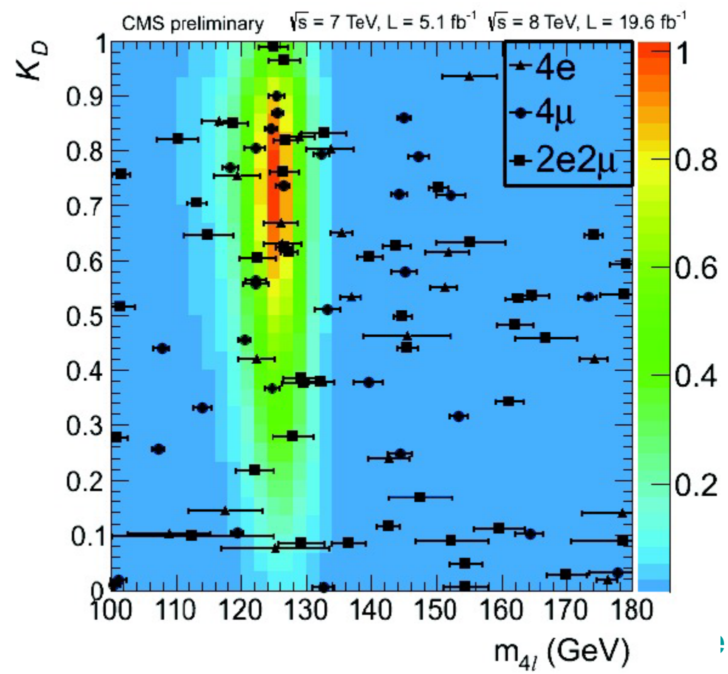
6.7σ (7.2σ exp.)

Higgs to 4 leptons

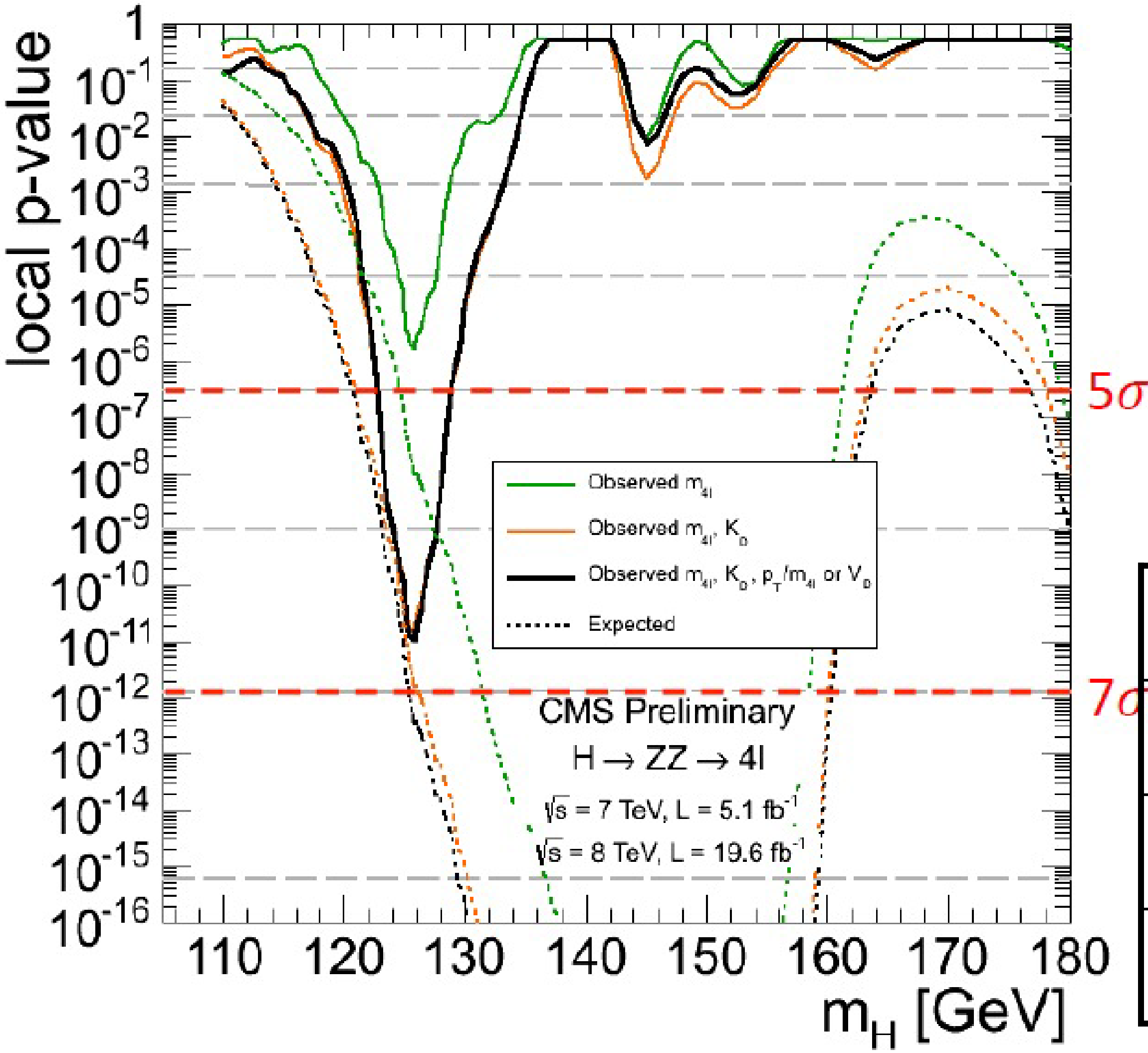
- Events split into 2 distinct categories:
  - Events with at least 2 jets of p_T > 30 GeV
    - ~20% of signal events are VBF ones
  - Untagged events (the remaining events)
    - < 5% of signal events are VBF
  - Use additional discriminants like di-jet mass, η-separation between the jets, etc.
- Also use kinematic discriminant based on dilepton mass and angles

$$\left[1 + \frac{\mathcal{P}_{\rm bkg}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\rm sig}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$





Higgs to 4 leptons

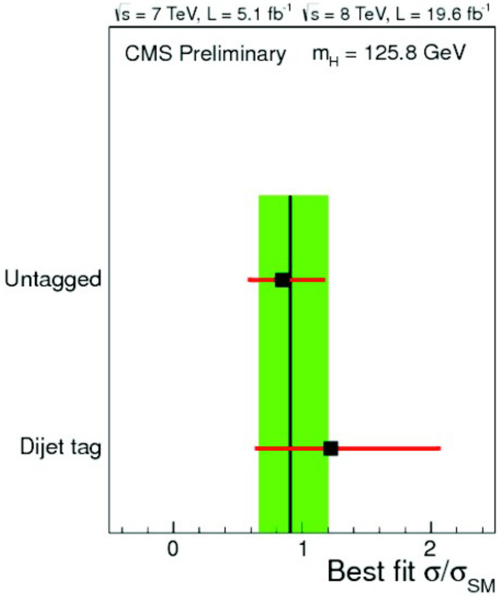


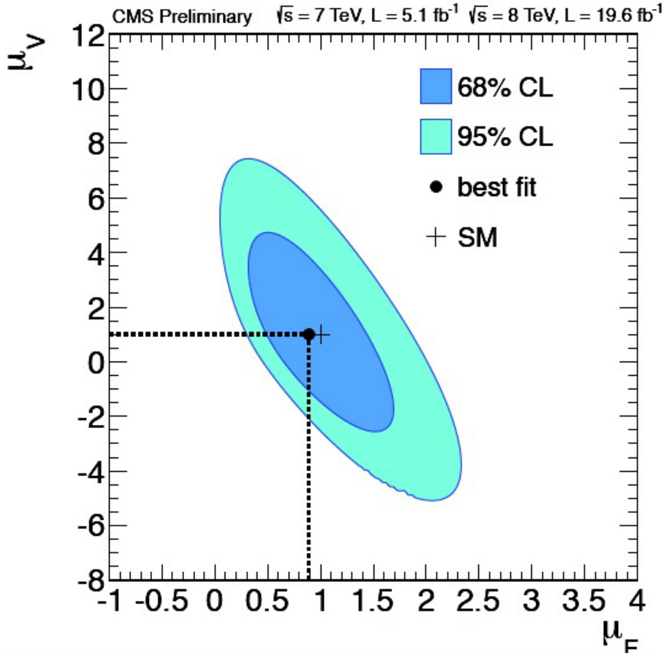
- Only excess seen at 125.8 GeV
- Extract information from 1D (M_{4L}), 2D (M_{4L}, K_D) or 3D (M_{4L}, K_D, p_T/M_{4L})

	Expected	Observed
3D	7.2σ	6.7σ
2D	6.9σ	6.6σ
1D	5.6σ	4.7σ

Higgs to 4 leptons

- Use information from untagged as well as di-jet tag analyses to probe production mechanism of Higgs boson





$\sigma/\sigma_{SM}(\mu) = 0.9^{+0.3}_{-0.2}$

μ_V (qqH, ZH, WH) = $1.0^{+2.4}_{-2.3}$

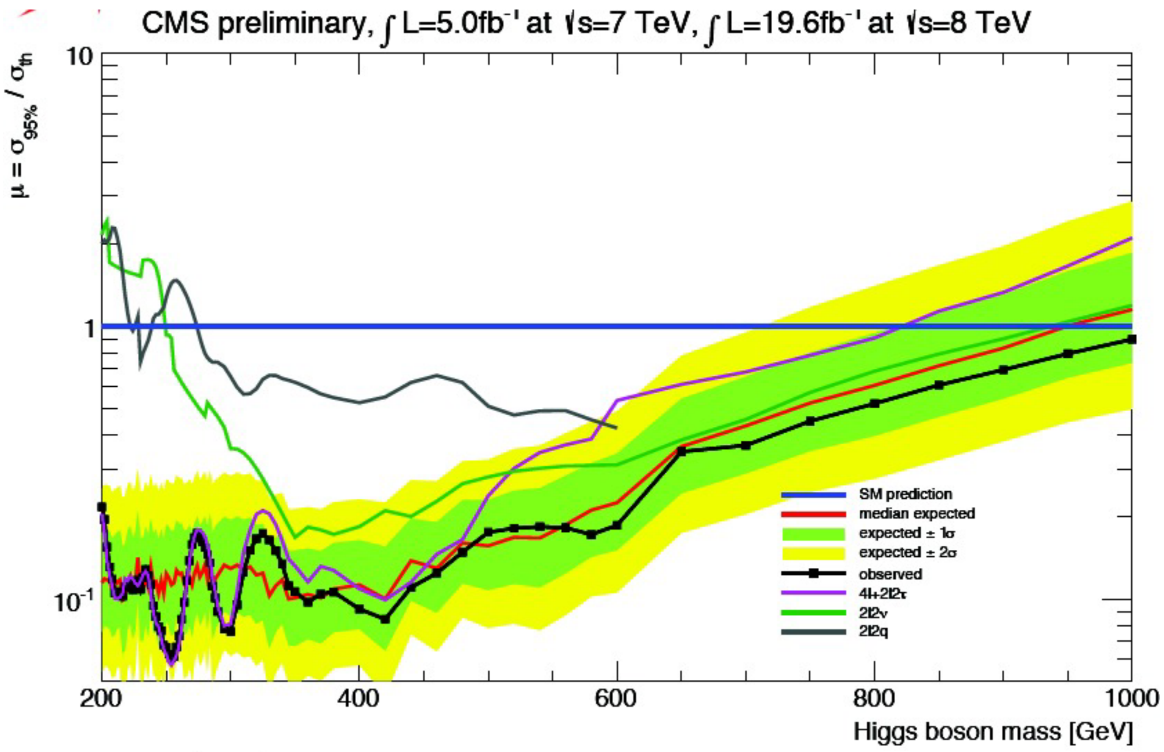
μ_F (gg->H, ttH) = $0.9^{+0.5}_{-0.4}$

- Mass measurement performed with a 3D fit using M_{4l}, ΔM_{4l}, K_D
  - 0.1-0;3% uncertainty due to energy scale
  - Mass resolution has 20% uncertainty

m_H = 125.8±0.5(stat)±0.2(syst) GeV

Higgs to ZZ$^{(*)}$

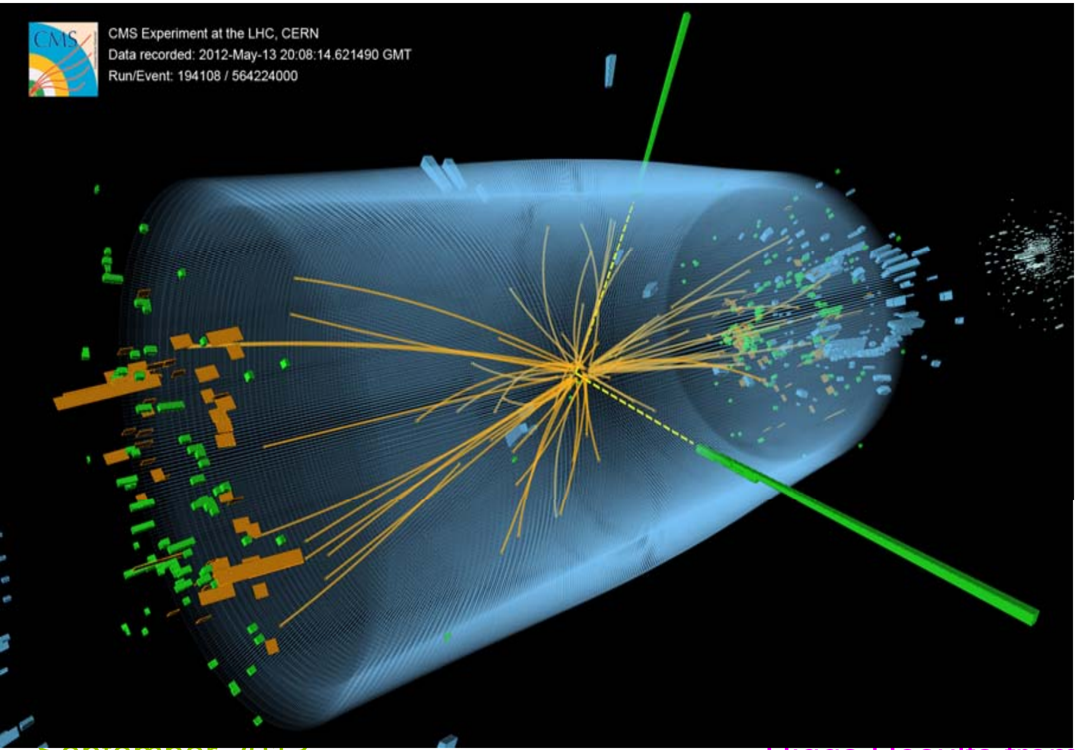
- Use dedicated searches for high mass Higgs boson in a number of channels: no other candidate with SM cross section
  - 4l + 2l2τ: exclude 130-827 (113.5-778) GeV observed (expected)
  - 2l2ν: exclude 248-930 (254-898) GeV observed (expected)
  - 2l2q: exclude 290-600 (266-600) GeV observed (expected)



Combined exclusion:
200-1000 GeV (obs)
200-950 GeV (exp)

Search in the mode $H \to \gamma\gamma$

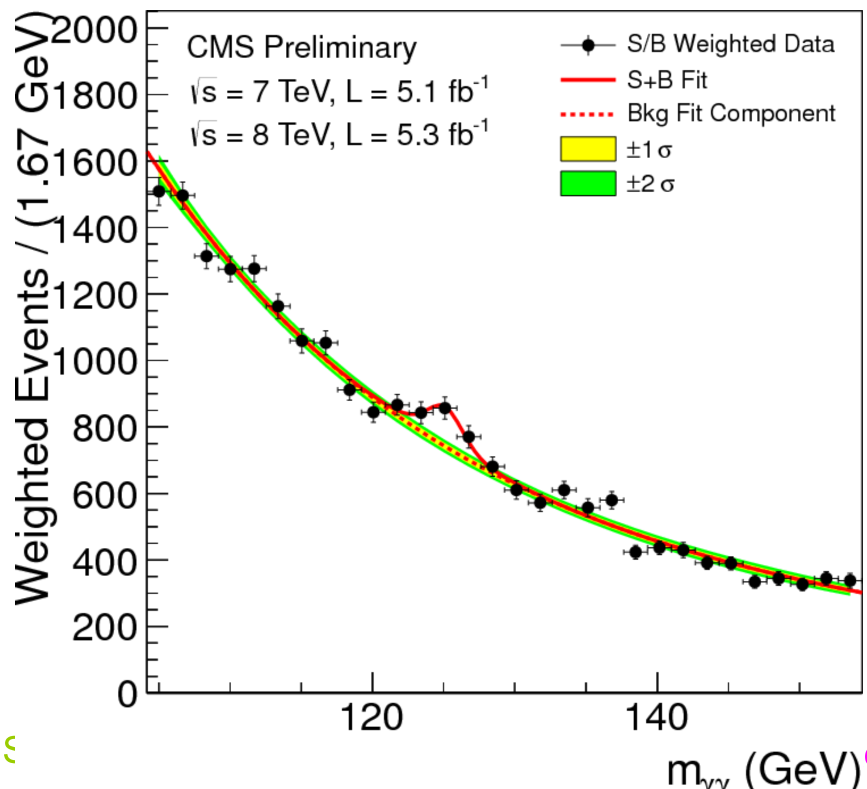
- Trigger on two high energy (p_T) EM objects
- Use shower shape variables and isolation criteria to select 2 high energy photons (minimize fakes)
- Low mass Higgs has very narrow width. Utilize this using the best possible resolution for photon energy and direction measurements.

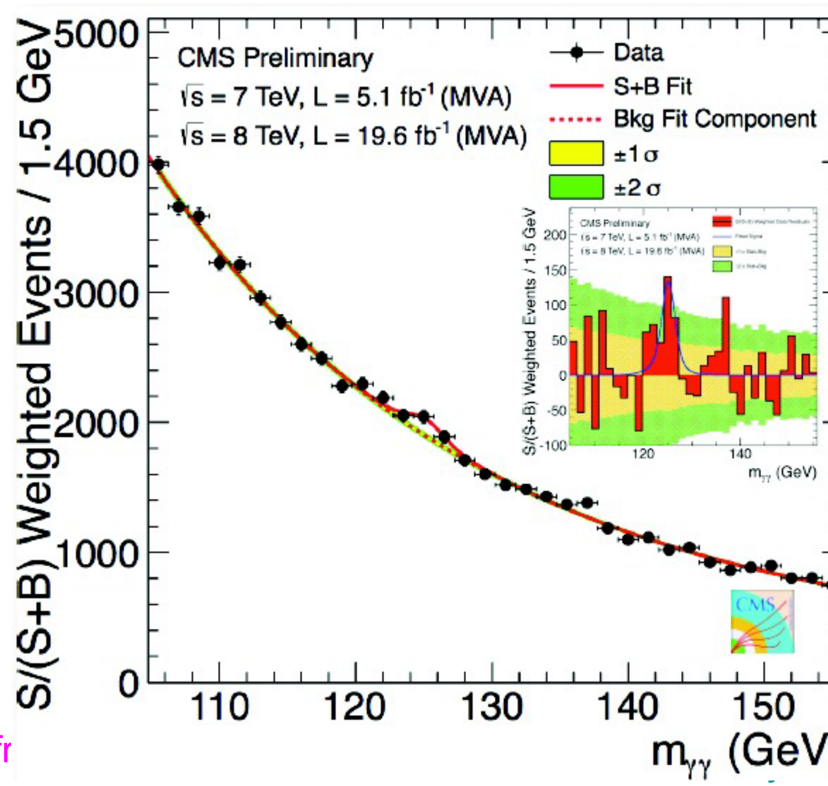


- There is a large irreducible background due to direct γ 's
- Key analysis feature is to improve energy resolution: continuous calibration
- Precise determination of di-photon mass requires precise location of the production vertex: use photon pointing whenever possible
- Reject fakes using optimized kinematics

Higgs to $\gamma\gamma$

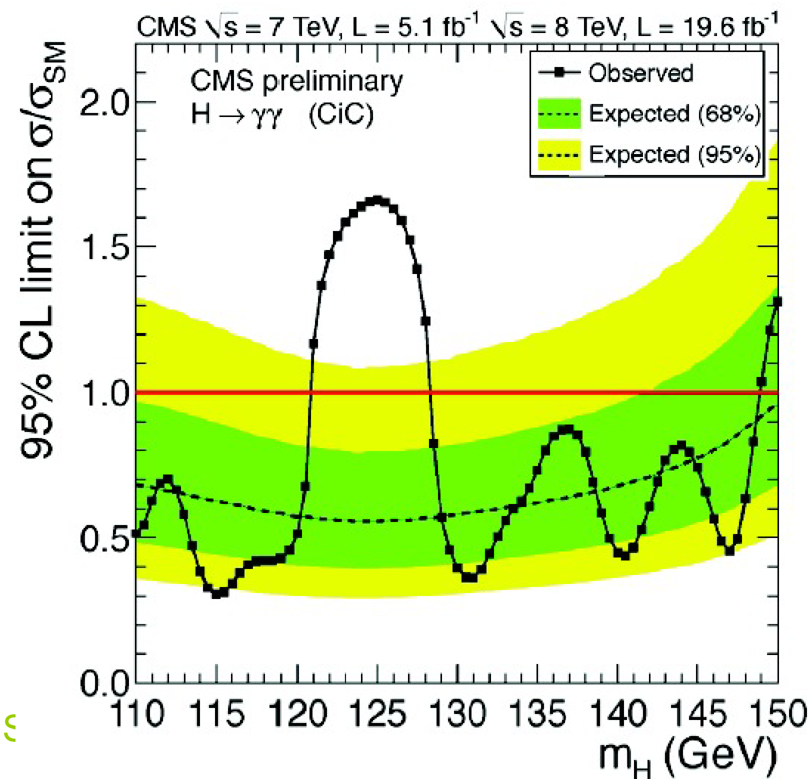
- Events are categorized according to signal to background ratio and energy resolution of the di-photon system
- Nice peak is observed over continuous background
- Signal and background shapes are modeled by analytic functions: came from a study of Monte Carlo samples and control regions
- Mass resolution achieved between 2-4 GeV for all categories and signal to background ratio can be as high as 0.2 for certain categories

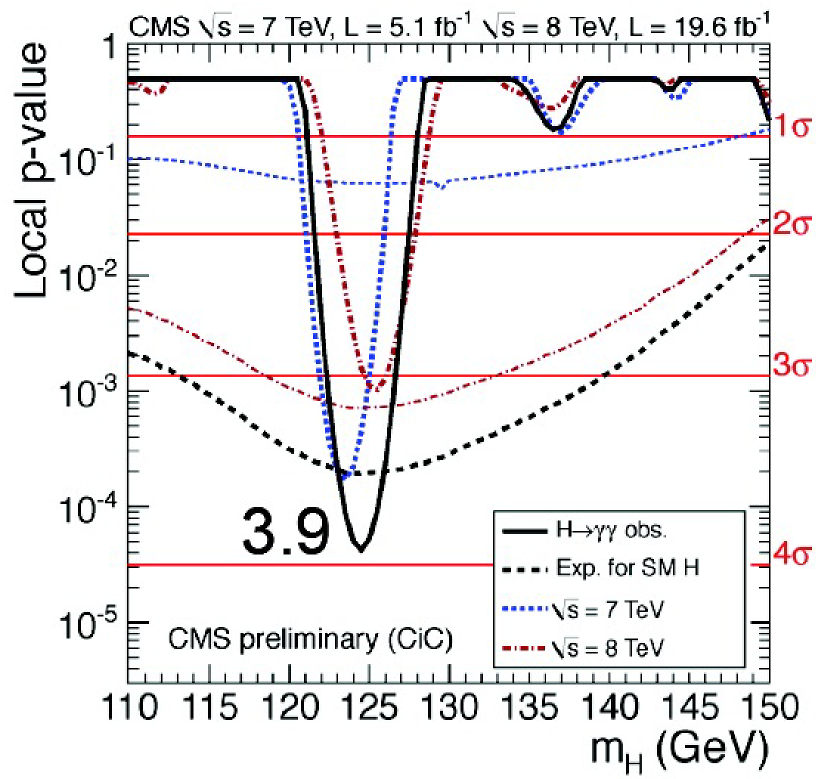




Higgs to $\gamma\gamma$

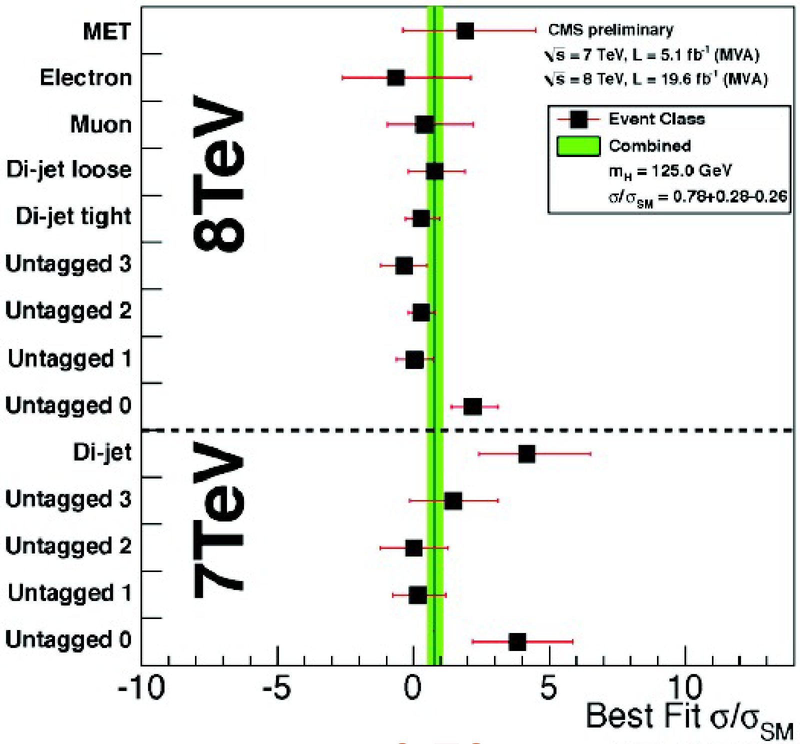
- Standard Model Higgs is expected to be excluded at 95% CL over a mass region between 110 and 148 GeV
- CMS has several independent selection procedure for the channel: (a) cut-based and (b) use of MVA
- Also there are several classifications depending on the tagging scheme: untagged, di-jet tag, lepton tags, MET tags
- Untagged data set shows largest statistics: MVA (3.2σ) and cut based (3.9σ) analyses give consistent results within 1.5σ



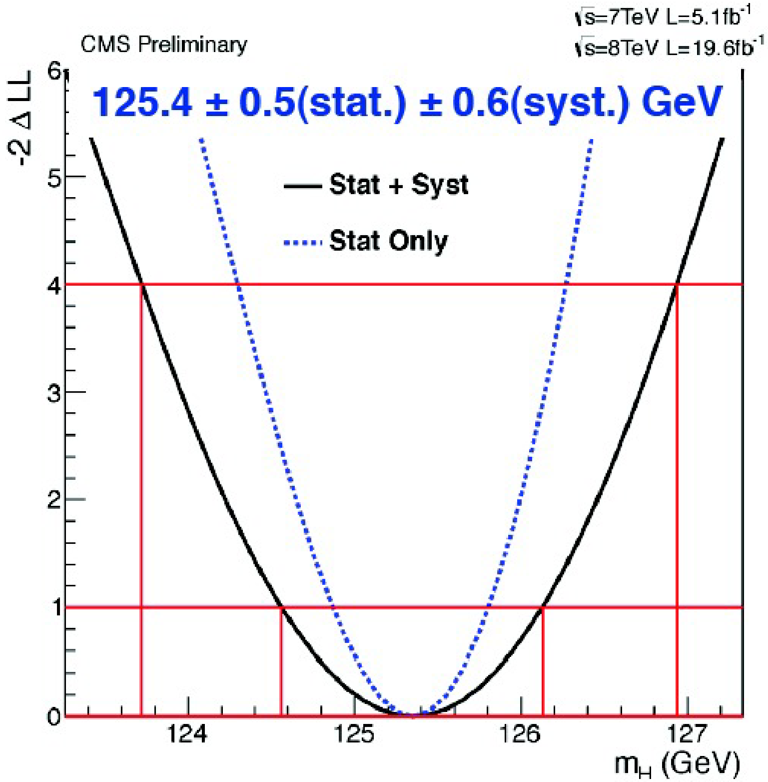


Higgs to γγ

- Divide the events into separate classes based on S/B and resolution to improve analysis sensitivity
  - High/low R9; barrel/endcap (4 categories)
- Also classify events by tags for associated production
  - Muon, electron, di-jet, MET, unassociated



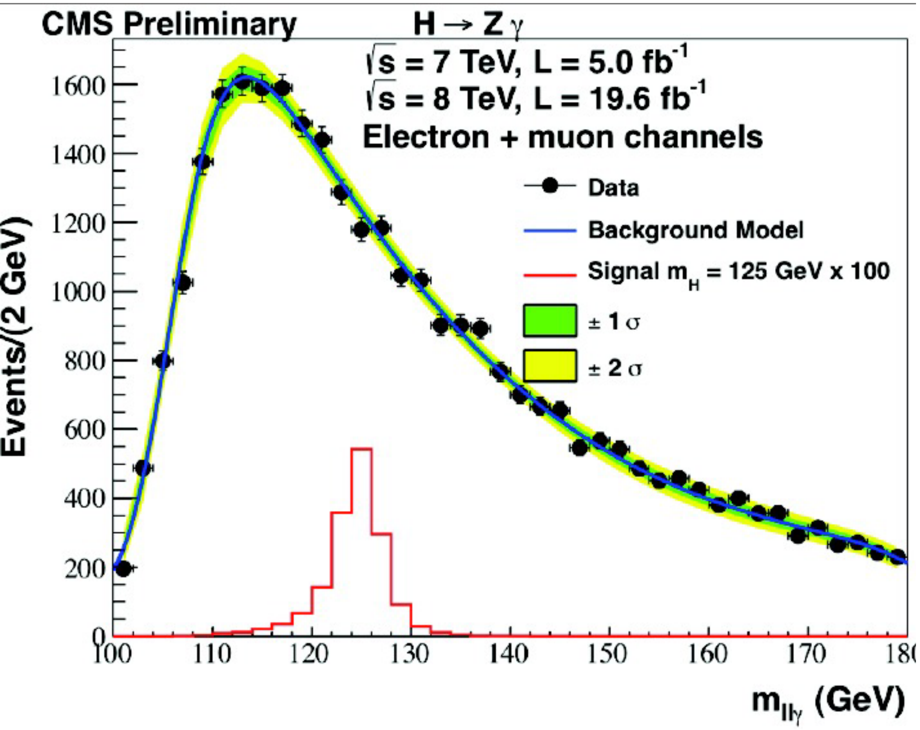
$\mu = 0.78$

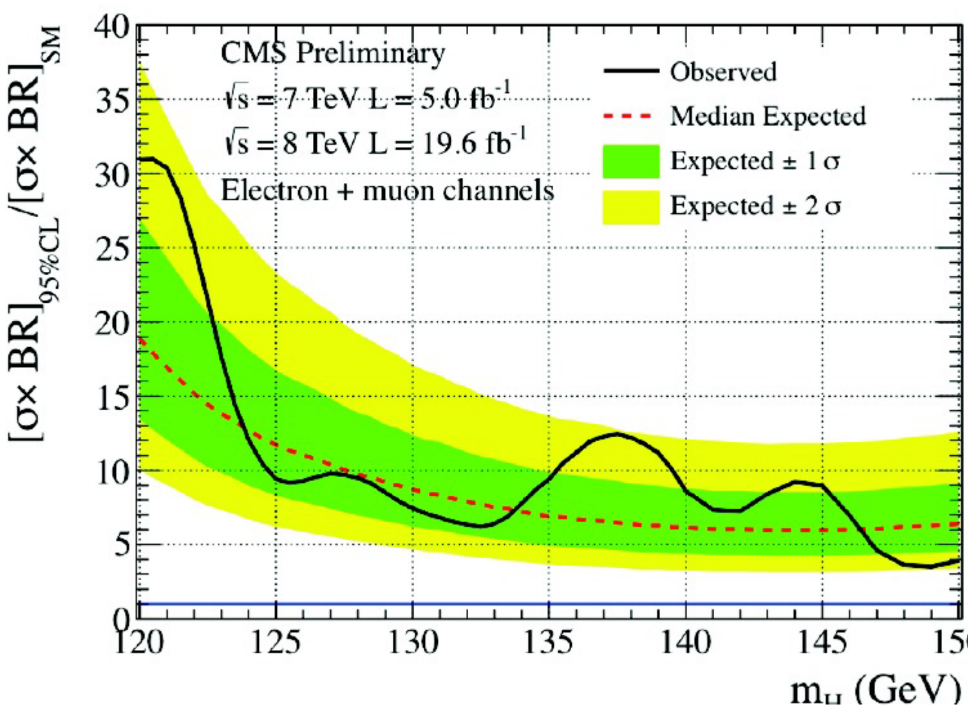


$\Gamma_H < 6.9$ GeV at 95% CL

Higgs to Zγ

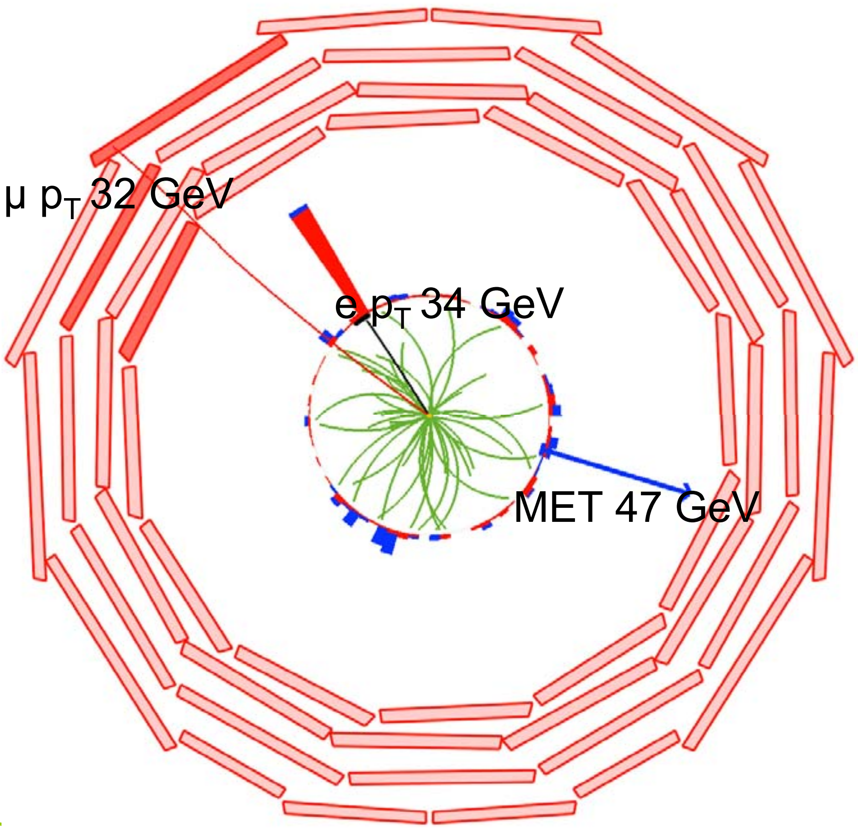
- Analysis strategy similar to H→γγ (signal/background modeling)
  - Use dilepton triggers
  - Classify in 4 categories based on lepton/photon η and high/low R_9





Searches in the mode $H \rightarrow WW^{(*)} \rightarrow 2l(e/\mu)2\nu$

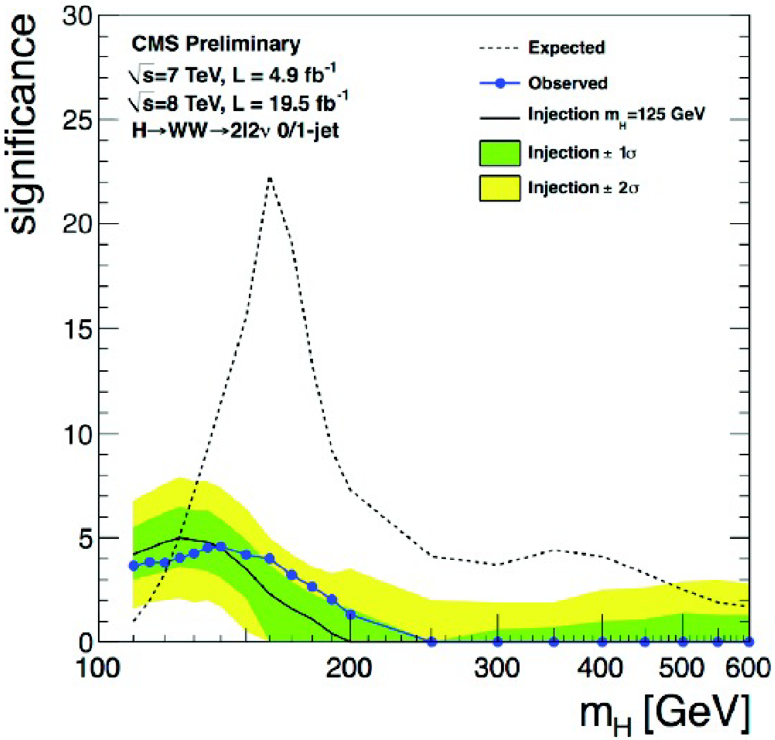
- Use single or di-lepton trigger
- Require 2 oppositely charged leptons (e/μ) and missing energy.
- Divide into different categories depending on number of jets
- Require the jets not to be b-jets

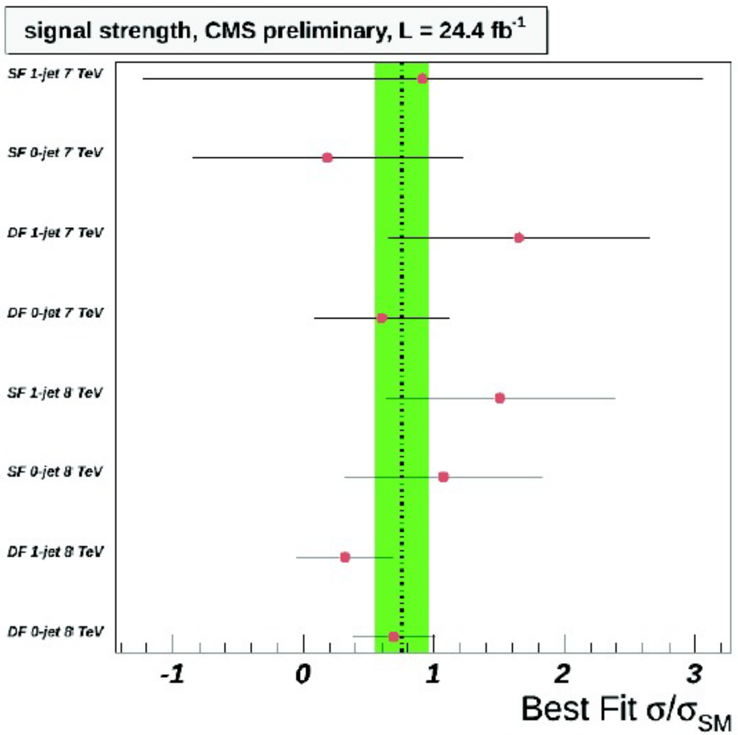


- Higgs being a scalar, the leptons will be close to each other
- Backgrounds are due to WW, W+jets, t-tbar, Drell-Yan
- Mixture of large backgrounds implies sensitivity dominated by uncertainties on backgrounds
- Analysis challenge lies in the understanding of the backgrounds and normalizing to control region
- Undetected neutrinos imply a broad neutrino signal

$H \to WW^{(*)} \to 2l(e/\mu)2\nu$

- CMS uses different as well as same flavour samples. Both these are divided into 3-categories: 0-, 1-, 2-jets (VBF)
- Shape analysis in $m_{\parallel}$-$m_{\perp}$ plane is also done for different flavour sample → improves sensitivity

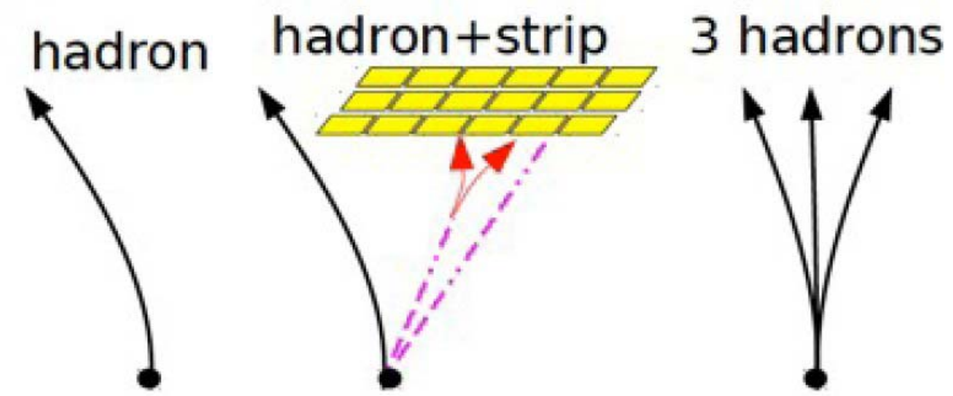




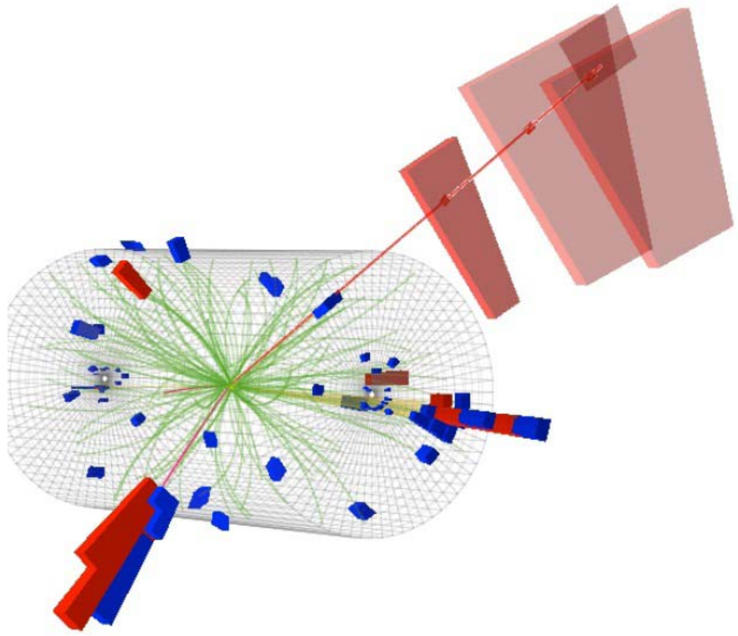
- There is a significant excess at low mass: observed (expected) excess: 4.0 (5.1) σ
- Measured signal strength at 125 GeV: 0.8±0.2

Searches in the mode $H \to \tau\tau$

- Special trigger developed for τ 's decaying to hadrons
- Identification of τ 's relies on multi-variate discriminants
- Divide into different categories depending on number of jets and p_T of the τ 's
- Also define categories depending on decay mode of τ 's: 0, 1 or 2 leptons (e/μ) in the final state



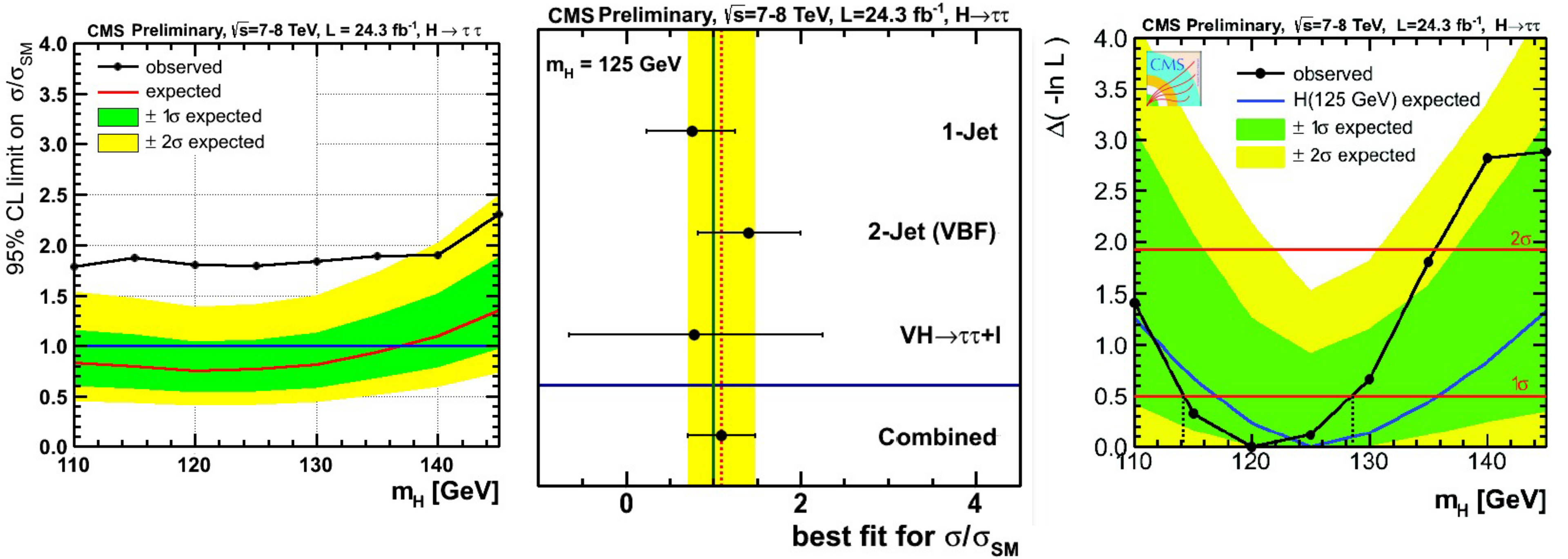
Identification of hadronic τ decays



$(\tau \to h)+(\tau \to \mu)$+2 Jets

Higgs to $\tau\tau$

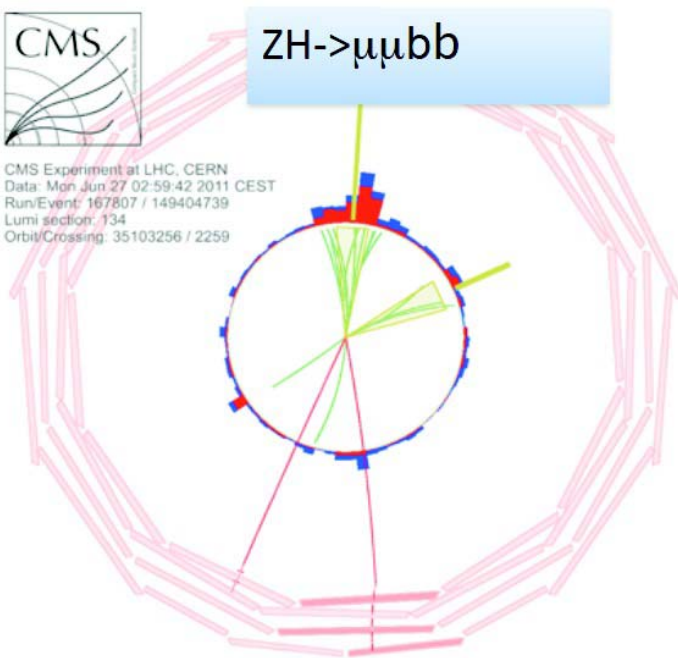
- Selects isolated leptons; restrict missing E_T and discriminate signal from background depending on the di-tau mass
- Background estimation is done depending on the background type: use shape from MC+normalization from sideband (di-boson+jet, t-tbar); pure data driven (QCD); MC+fake rate ($Z\to ee/\mu\mu$); use of $Z\to\mu\mu$ + replace μ with τ



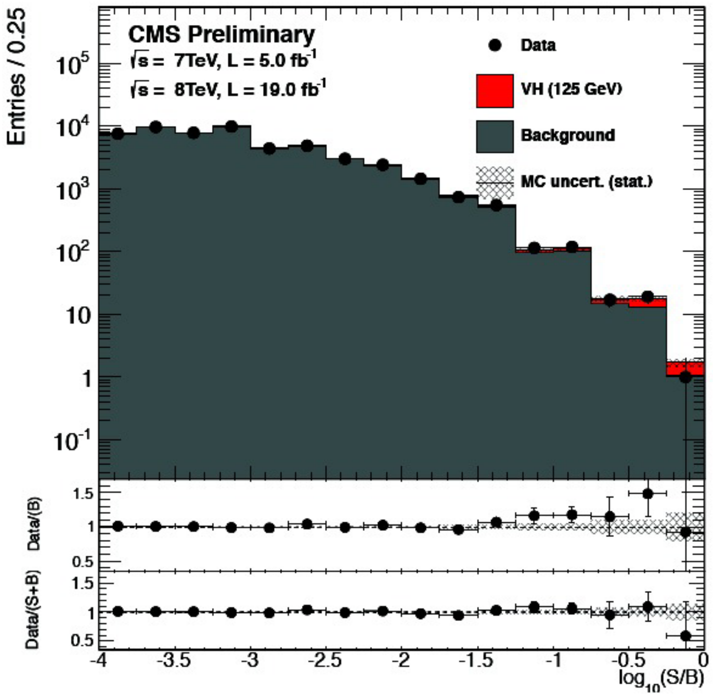
- Observed exclusion limit 1.81 x SM value: while 0.76 x SM expected
- Combined signal strength $\mu = 1.1 \pm 0.4$
- Most favoured mass of the observed excess $m_H = 120^{+9}_{-7}$ GeV

Searches in the mode VH with $H \rightarrow bb$

- This channel provides by far the largest number of Higgs decays – but it also provides the largest amount of background
- Trigger is based on isolated single leptons or large missing E_T
- b-jets are identified through displaced tracks. It is critical to reduce b-tag uncertainties. At high p_T this is achieved – also good for Higgs search
- Dominant background is due to W/Z+jets as well as t-tbar



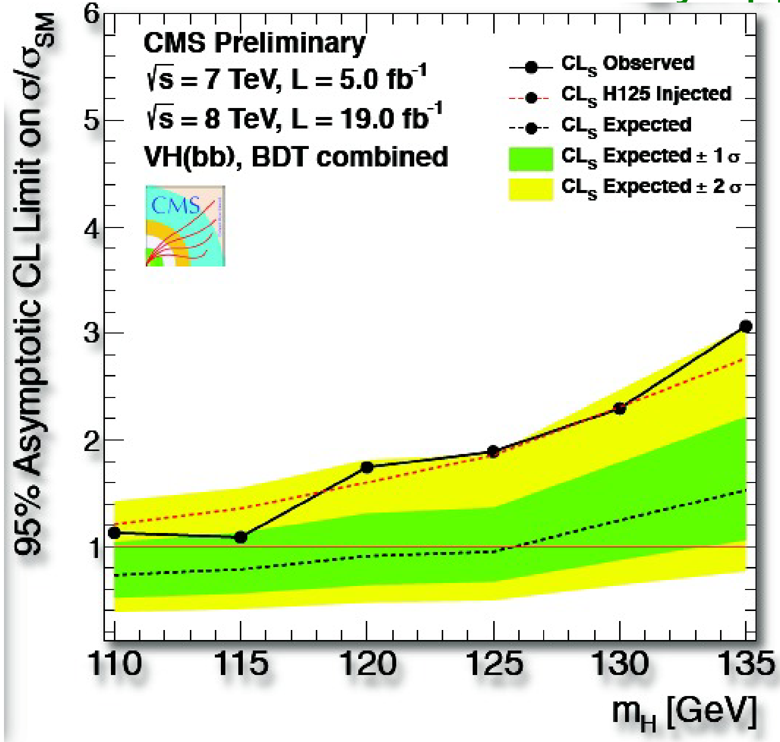
2 lepton event with moderate MET

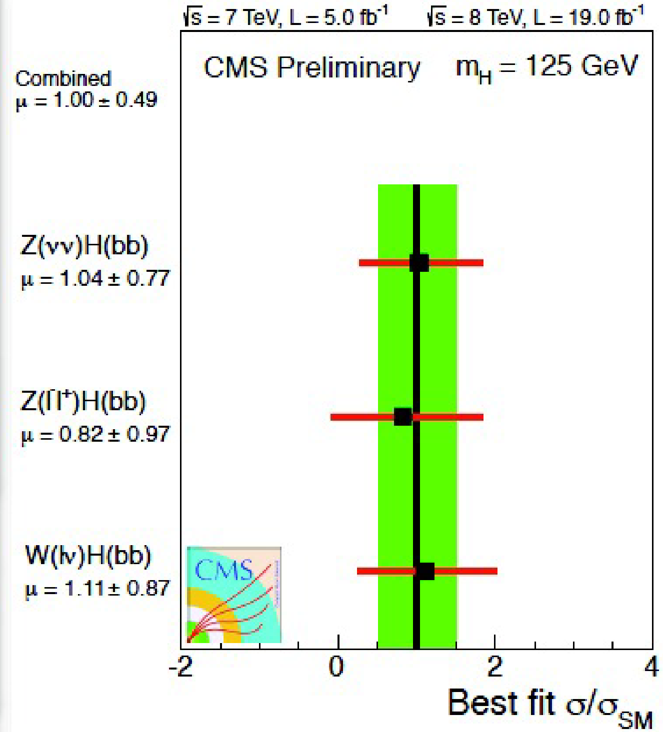


Small signal over large background

Higgs to bb

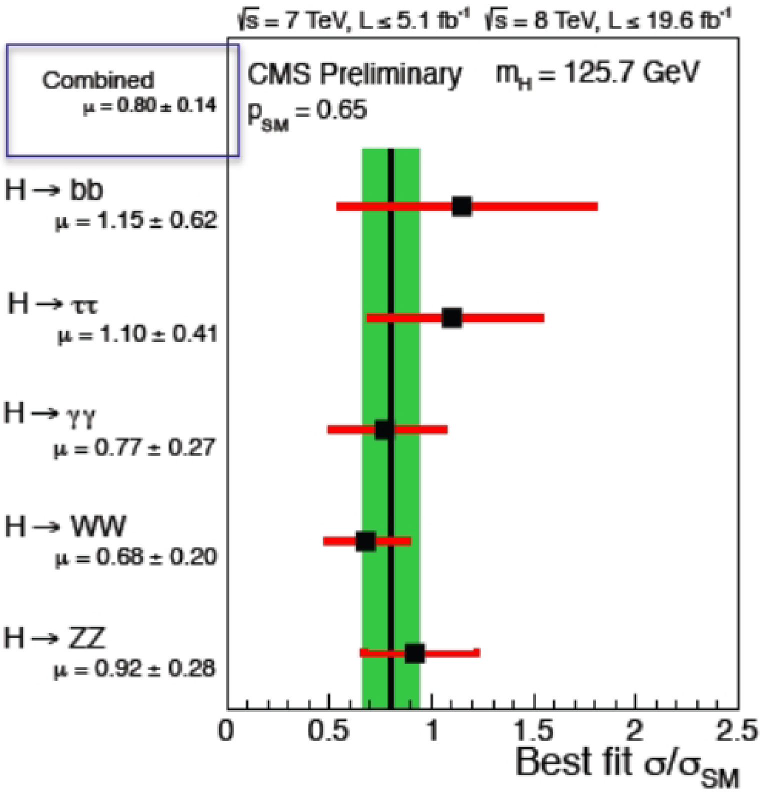
- Di-jet mass resolution is improved by regression technique to match b jet energy to the corresponding parton energy. Improves mass resolution by 15% using a specialized BDT algorithm,
- Backgrounds are estimated using data driven technique
- The methods are validated by applying it to other physics cases





- > 2σ excess which is compatible with Standard Model prediction
- Measured signal strength μ = 1.00 ± 0.49

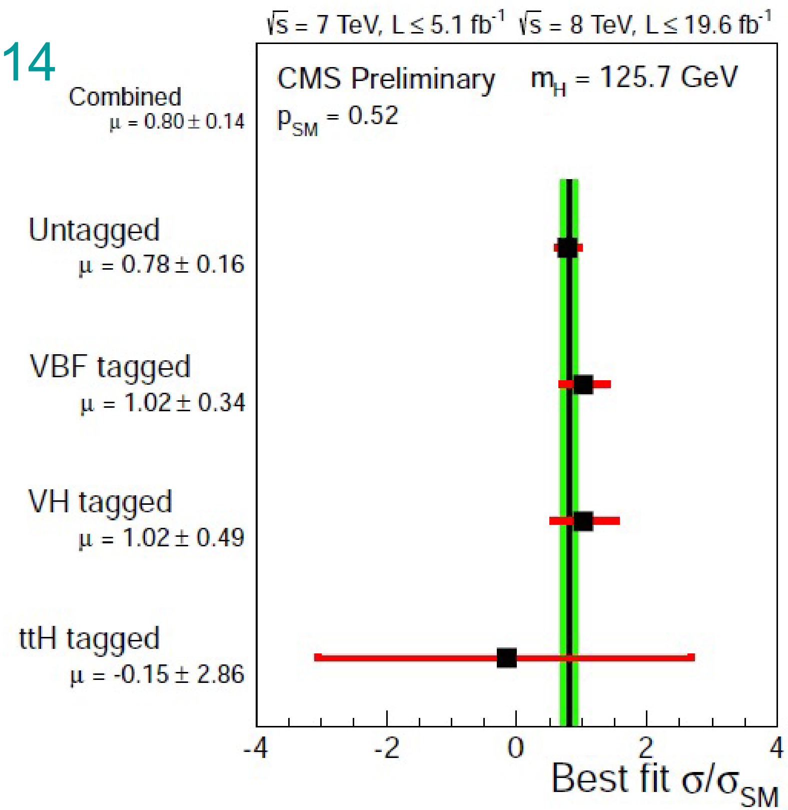
CMS Combined Results



Use tags:

Channel	Sub-channels
ZZ	Untagged, VBF
γγ	Untagged, VBF, VH
WW	Untagged, VBF, VH
bb	VH, ttH
ττ	Untageed, VBF, VH

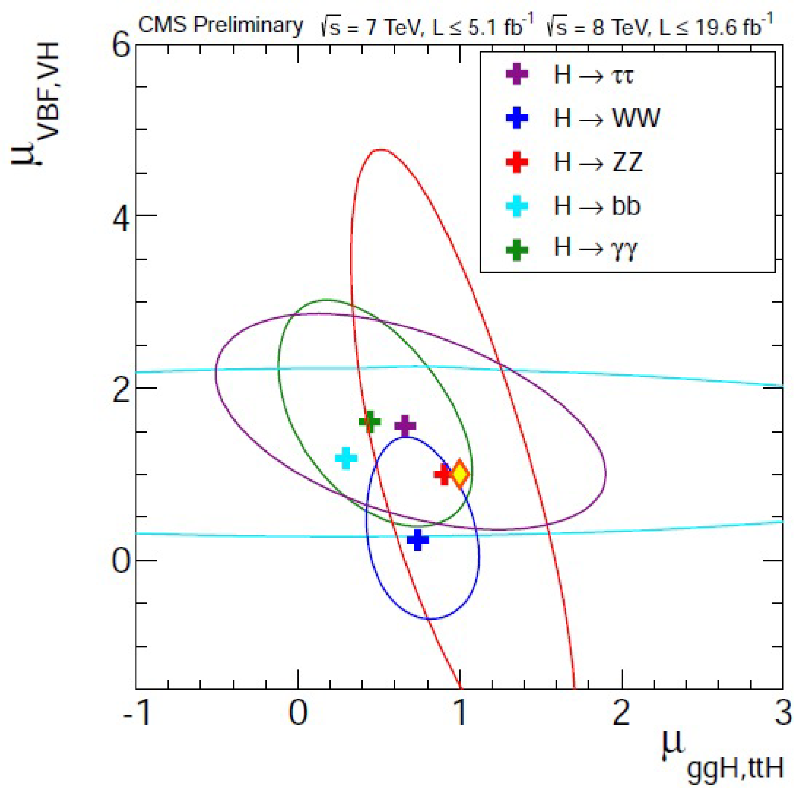
$\mu = 0.80 \pm 0.14$

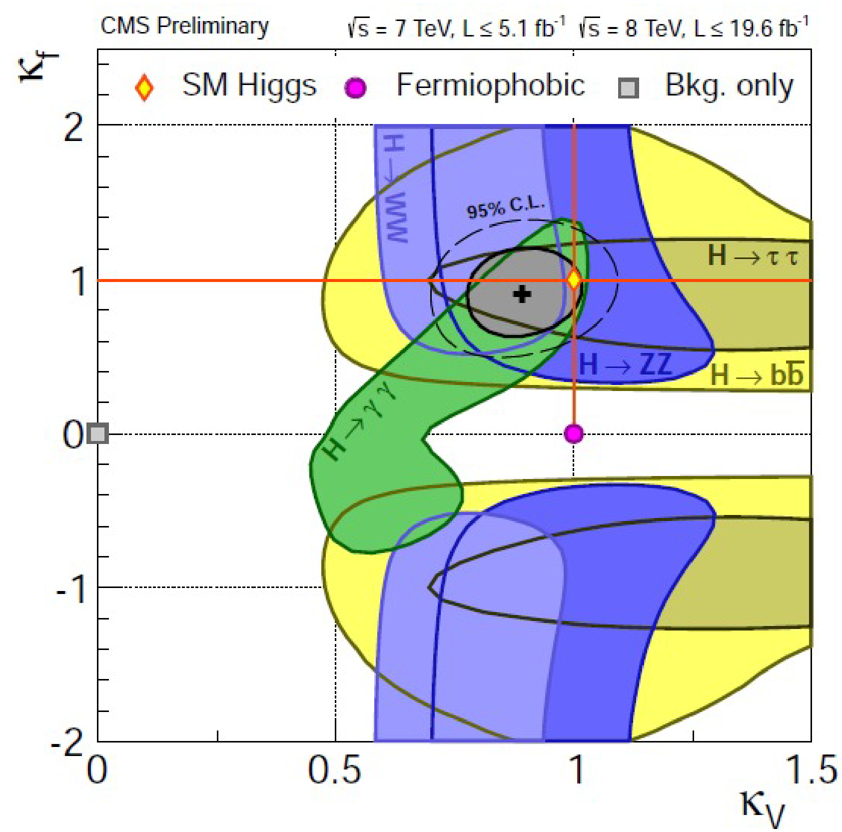


Channel	Expected	Observed
ZZ	7.1σ	6.7σ
γγ	3.9σ	3.2σ
WW	5.3σ	3.9σ
bb	2.2σ	2.0σ
ττ	2.6σ	2.8σ

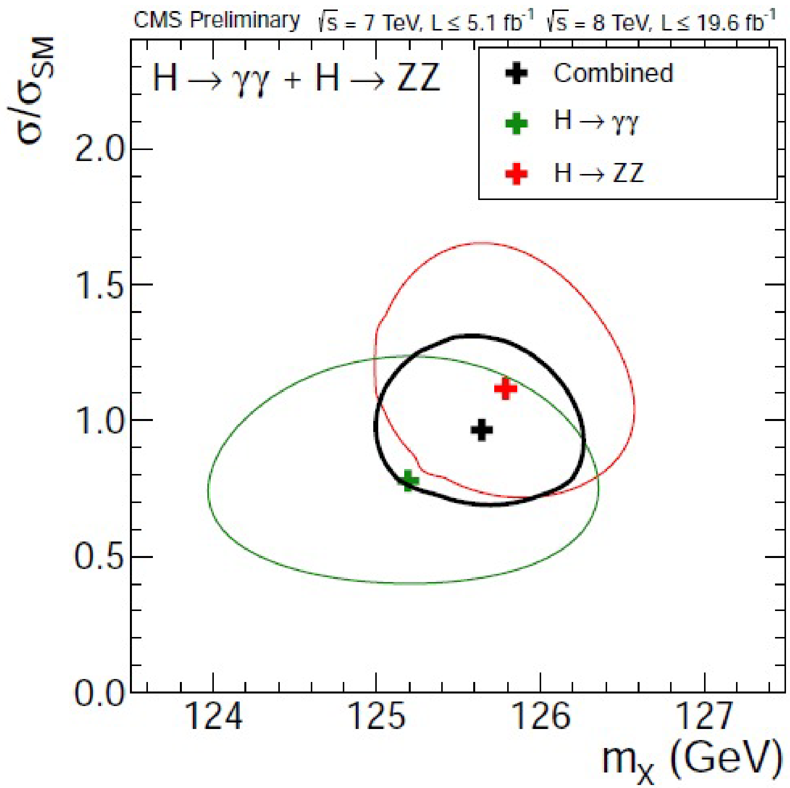
Production Mechanism

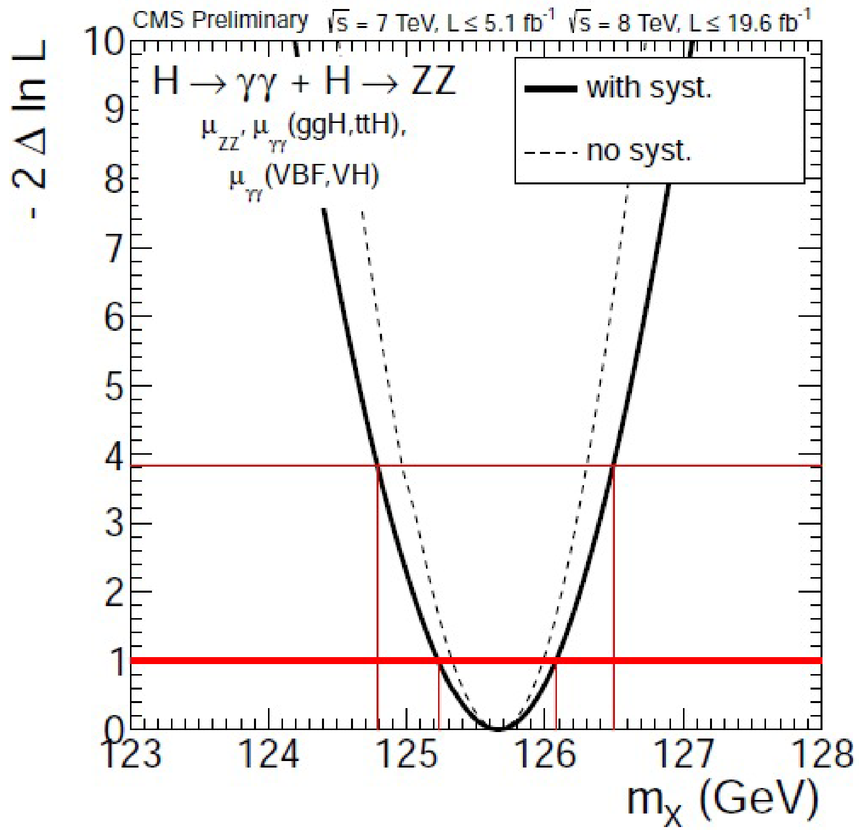
- Untagged channels dominated by gluon fusion
- Tagged channels sensitive to other production mechanisms
- Coupling fits are performed by introducing scale factors to SM LO Higgs couplings: κ_V, κ_f





Mass of the Resonance



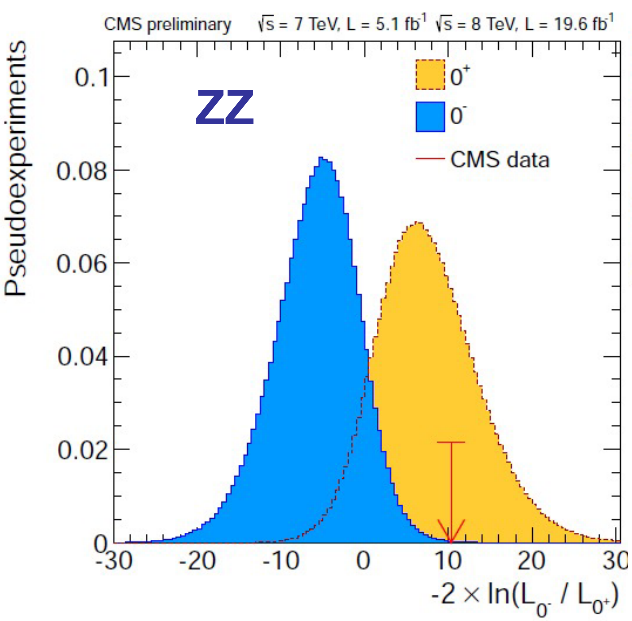


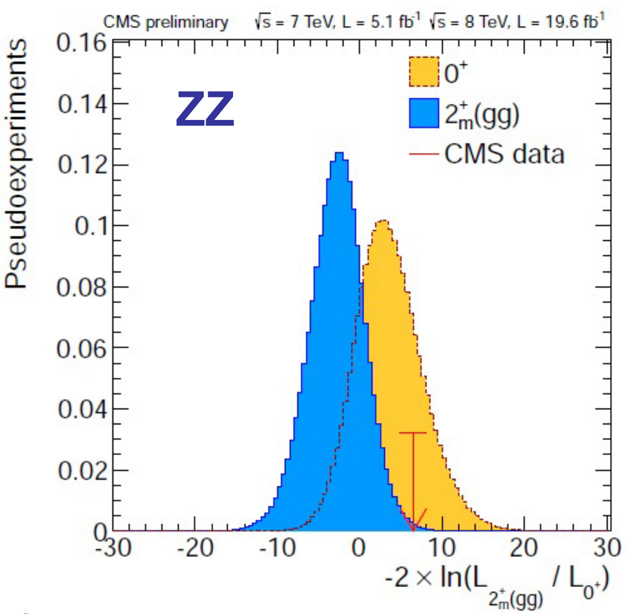
Use the channels with the best mass resolution

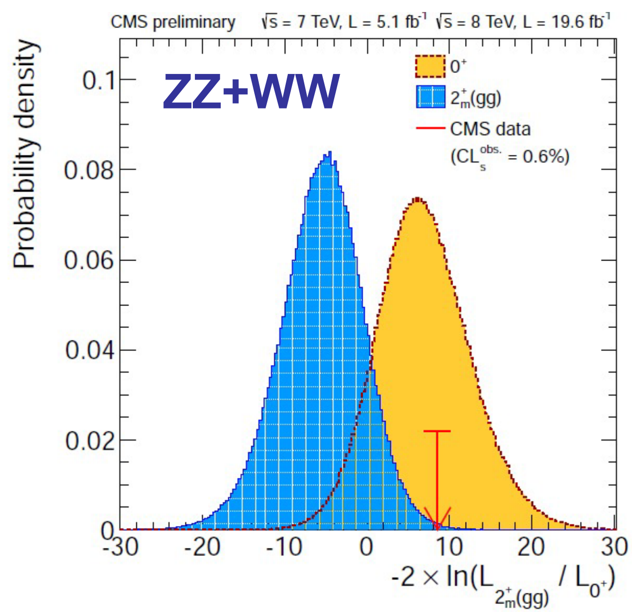
γ γ	m_H = 125.4 ± 0.5 ± 0.6 GeV
4 lepton	m_H = 125.8 ± 0.5 ± 0.2 GeV
Combined	m_H = 125.7 ± 0.3 ± 0.3 GeV

Spin-Parity

- Use angular distribution of photons in Collins-Soper plane in the $\gamma\gamma$ channel
- Use invariant masses and decay angles of leptons in the 4-lepton channel







So far the best measurements came from the 4 lepton channel

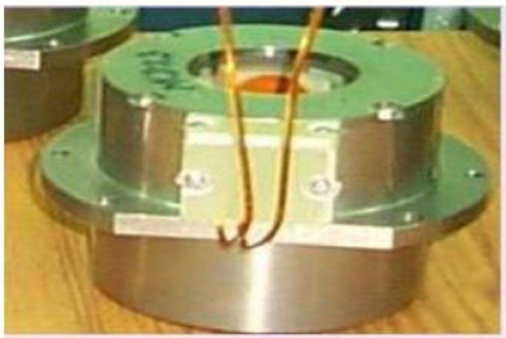
Exclude 2^+ hypothesis at 2.84σ by combining ZZ and WW channels

Pure 0^+ hypothesis is favored while a pure 0^- hypothesis excluded at 3.3σ

Indian contribution to the LHC machine

- RRCAT, BARC, VECC, IGCAR, ECIL, ATL, IGTR, BHEL contributed a number of critical components to LHC
- BARC, VECC, RRCAT contributed heavily to the GRID effort

Finished Decapole & Octupole SC corrector magnet assembly



Precision alignment Jacks were Designed & Developed by a RRCAT team for LHC Cryo-magnets.

- Each LHC cryo-magnets weighs ~32 Tons

6800 PMPS Jacks + 280 Motorizable & Higher Precision

Precision Magnet Positioning System (PMPS) Jacks

MCS & MCDO

Magnetic measurements teams- ~100 Man-years

Indian made PMPS Jacks being installed in LHC

The CMS collaboration

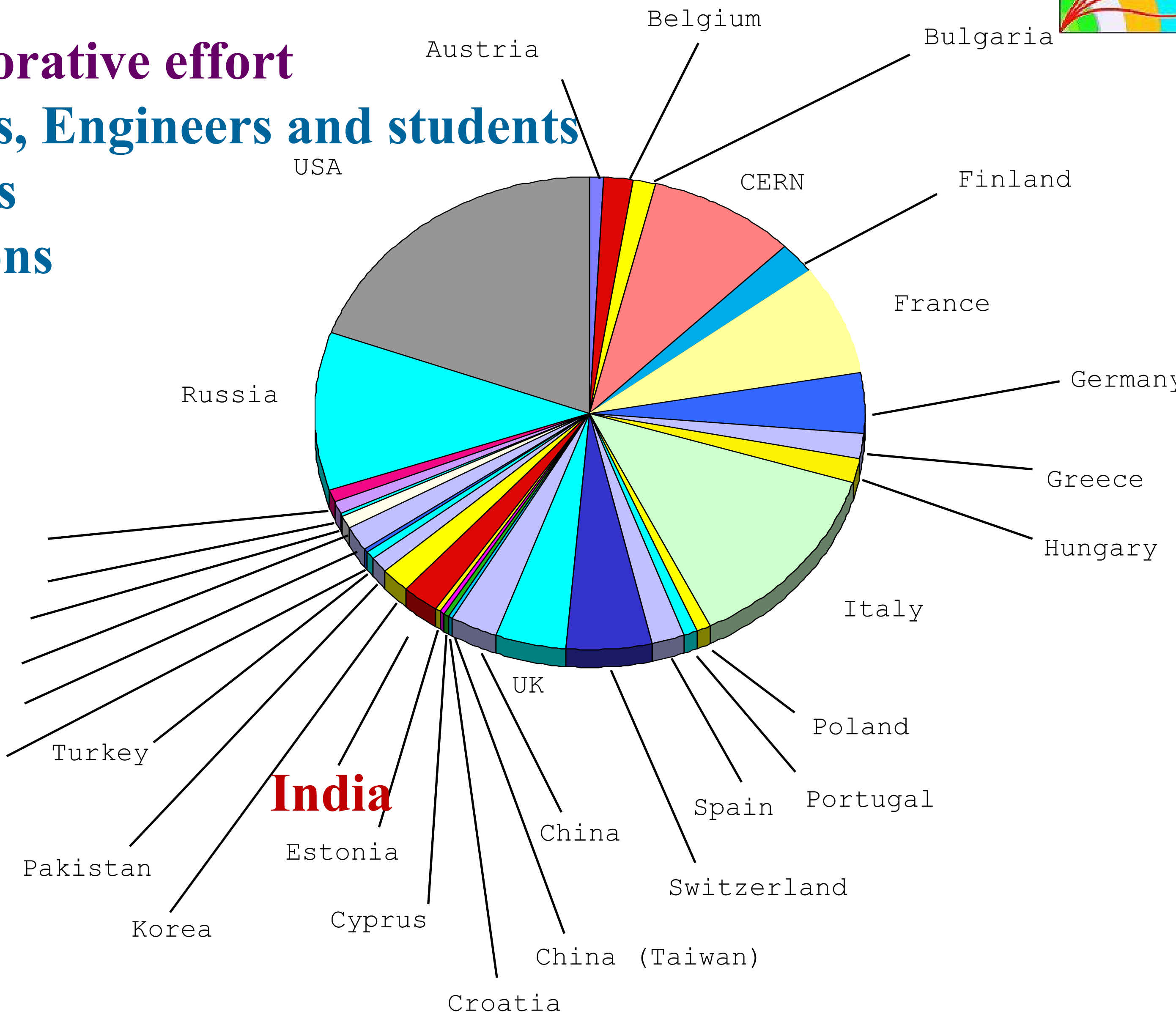
A large collaborative effort

3600 Physicists, Engineers and students

38 Countries

182 Institutions

Gradually increasing



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

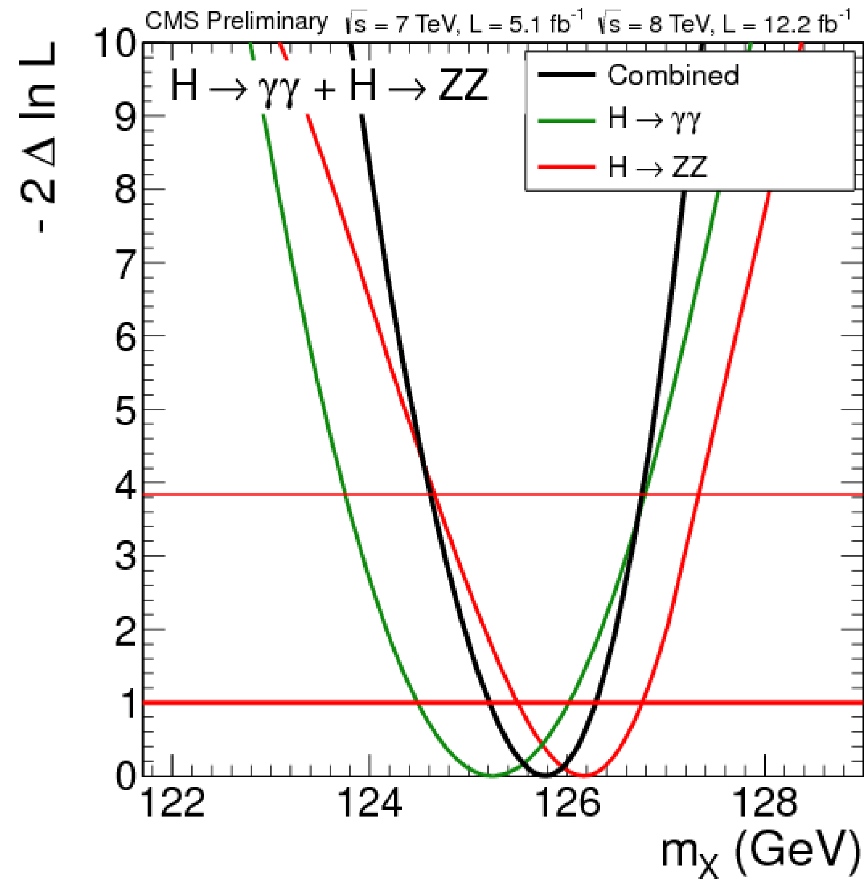
ults

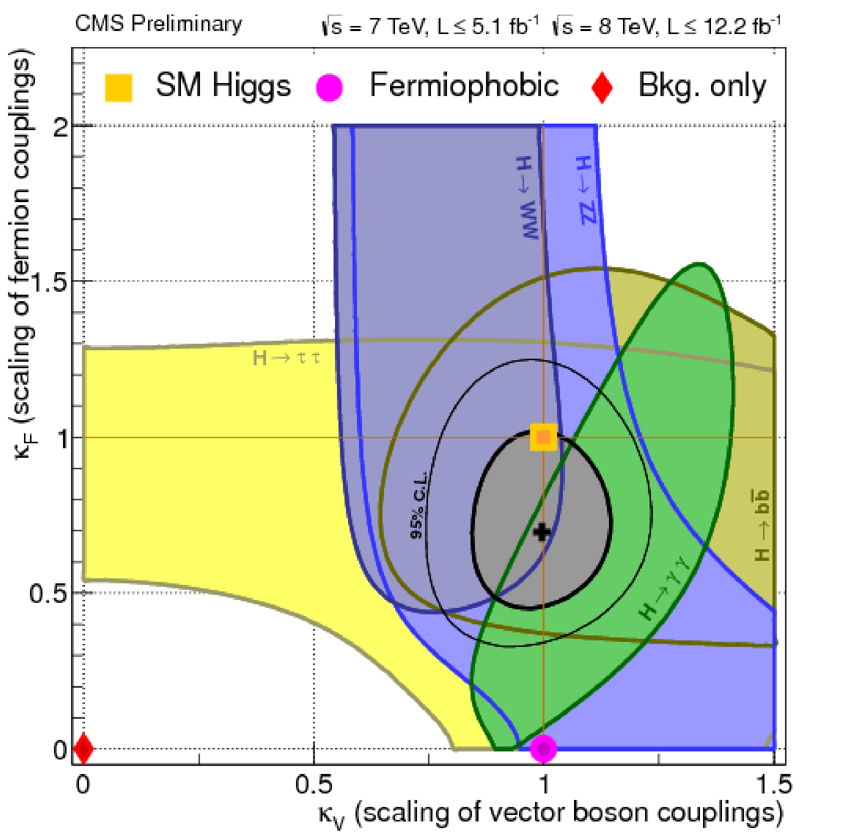
Last Word

- There is a very strong evidence of a scalar boson of mass around 125-126 GeV
- Observed properties of the Higgs boson are broadly consistent with the Standard Model predictions
- These studies have drawn attention of people from all quarters
- This discovery is achieved by international collaborations of thousands of people working over two decades
- The Indians have been a part of this from very early days

Back Up

Combination of Higgs Results





Mass and production strength

m_X = 125.8 ± 0.4(stat) ± 0.4 (syst) GeV

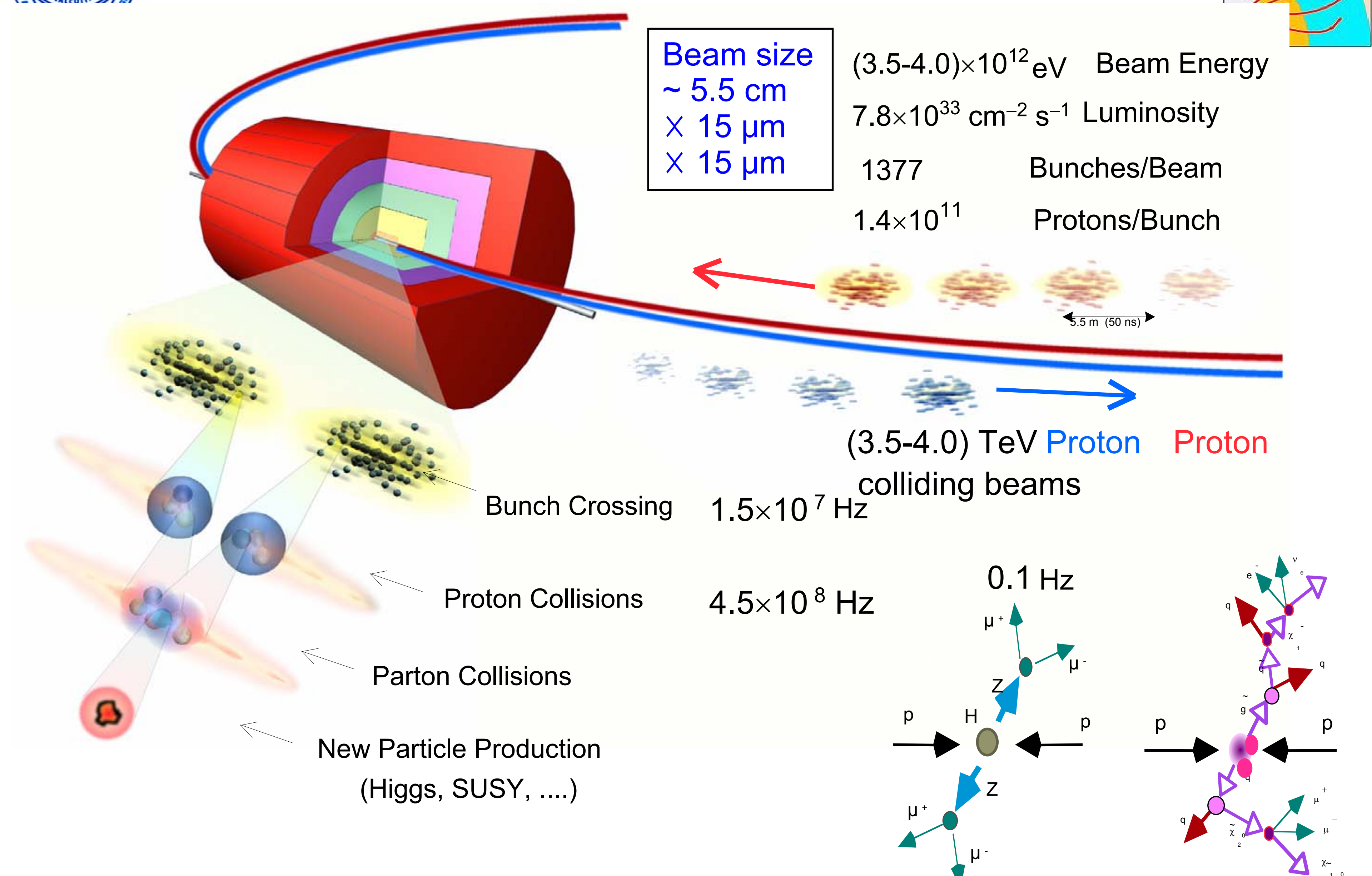
– Signal strengths consistent with each other and with SM

Couplings consistent

– Fermions versus vector bosons

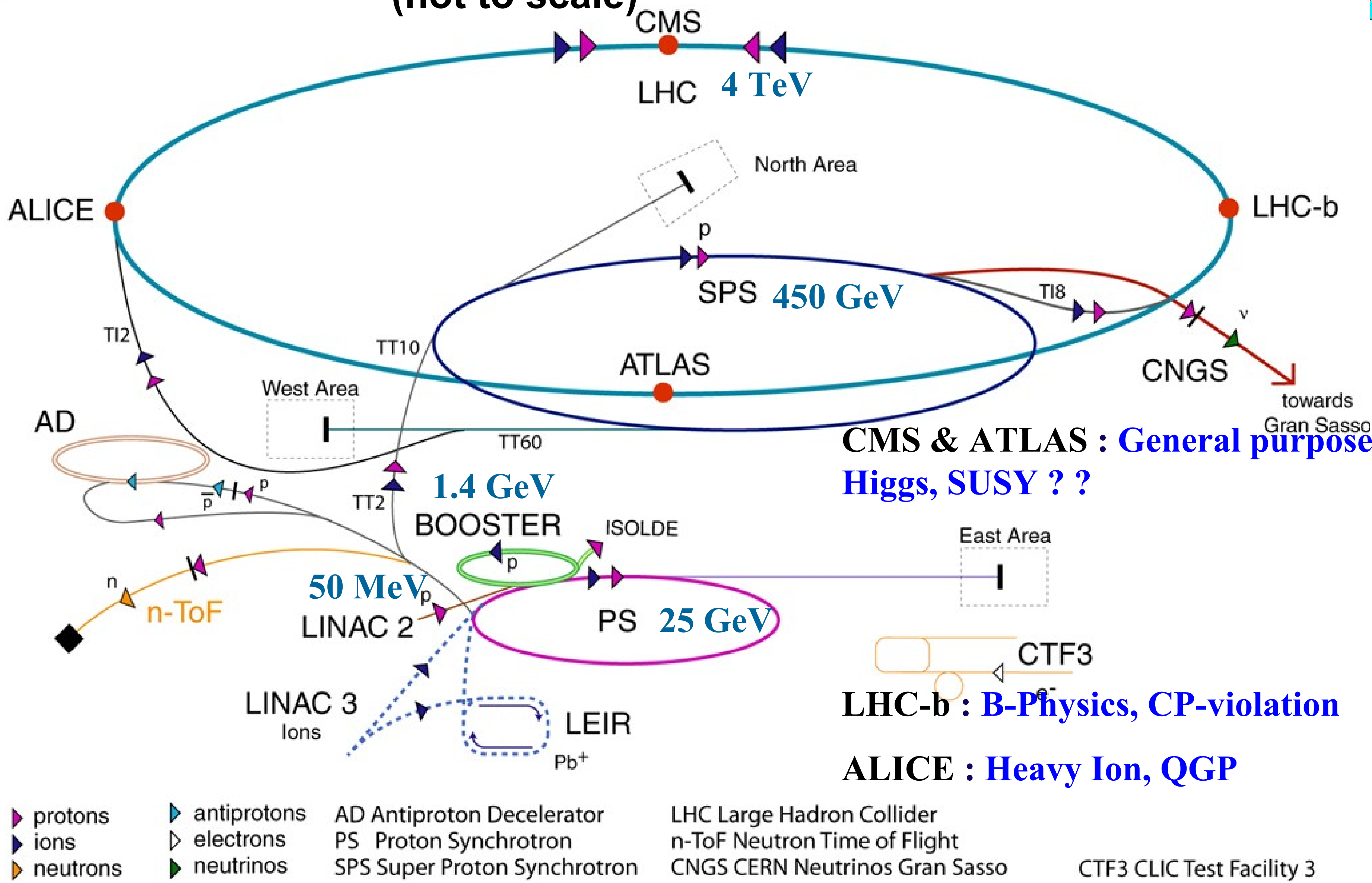
- Also effective gluon versus photon couplings (loops)

Large Hadron Collider



CERN accelerator complex

(not to scale)



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

LHC-b : B-Physics, CP-violation

ALICE : Heavy Ion, QGP

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

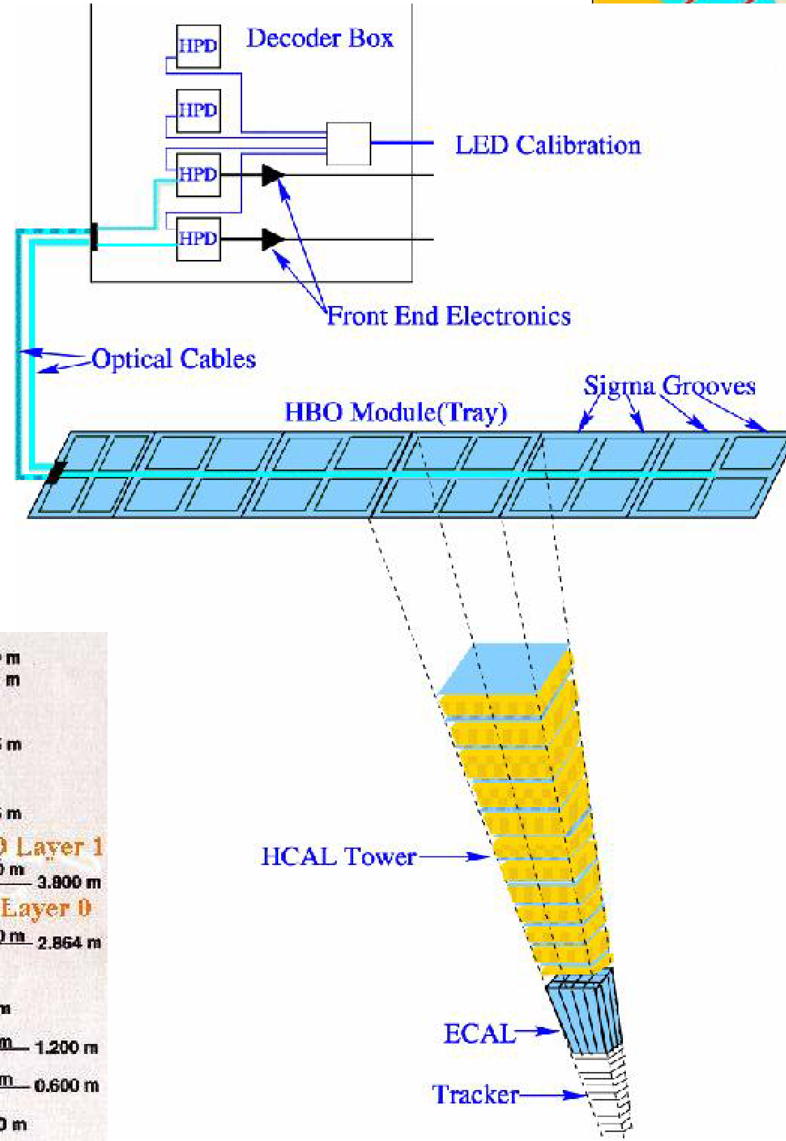
Summary of the CMS potential for the Higgs boson discovery

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

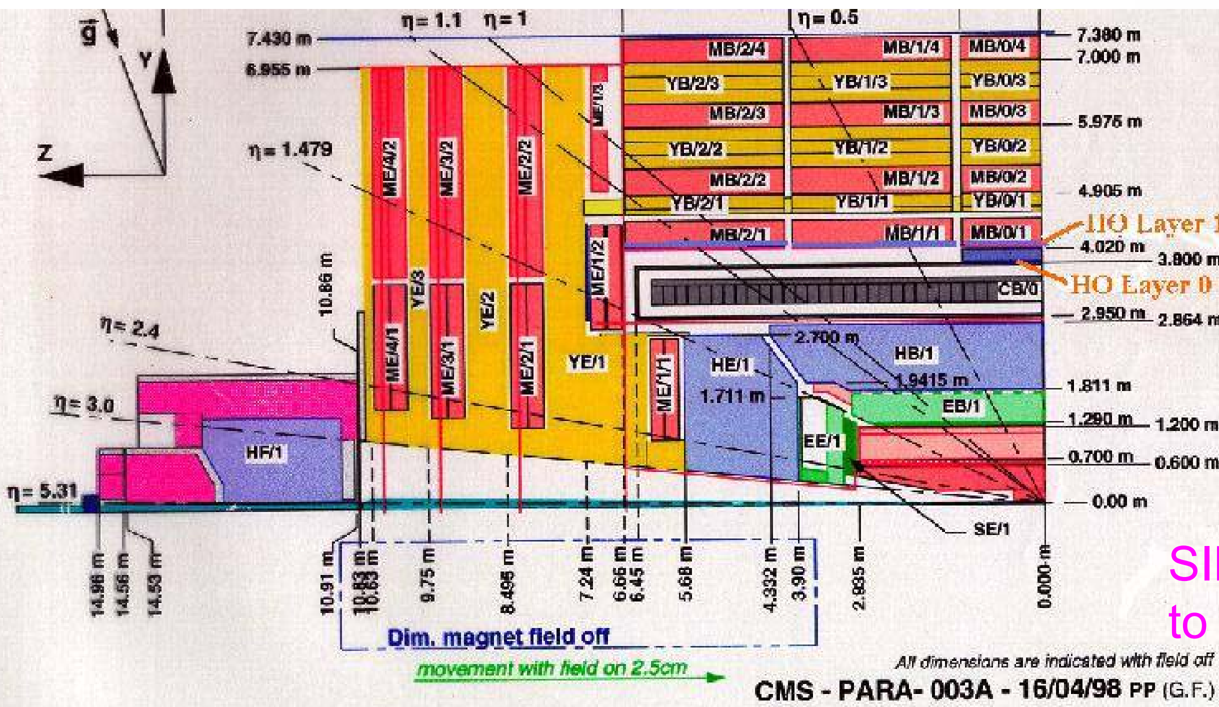
Hardware contribution

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



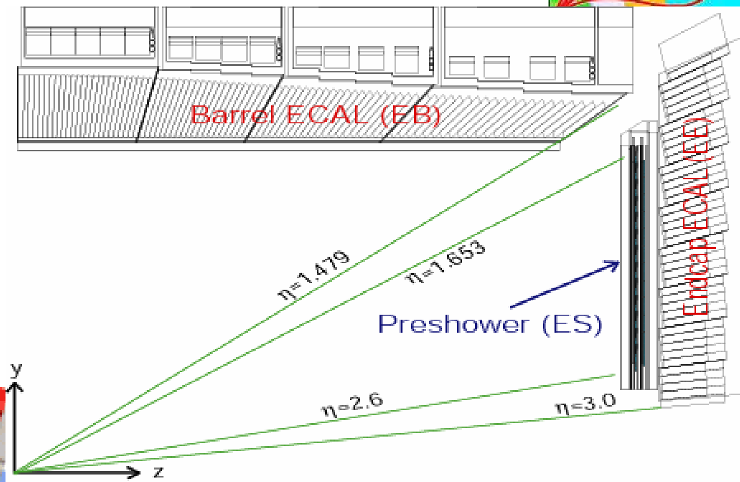
Pseudorapidity, $\eta = -\log_e(\tan(\theta/2))$

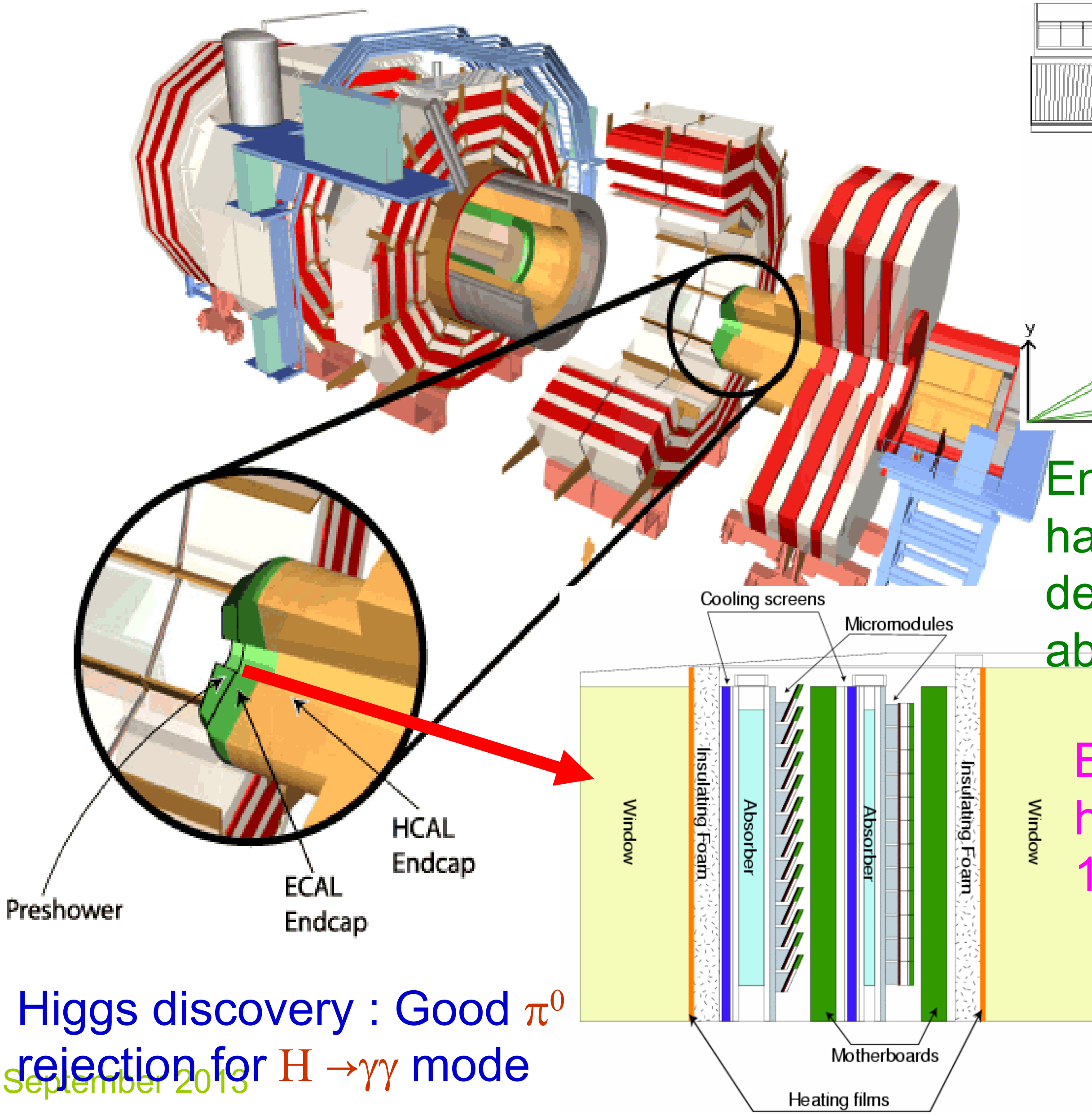
- Basic detector element maps tower granularity of 0.0873 ×0.0873 in η×Φ
- 432 trays are built from 2730 tiles



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

CMS preshower detector





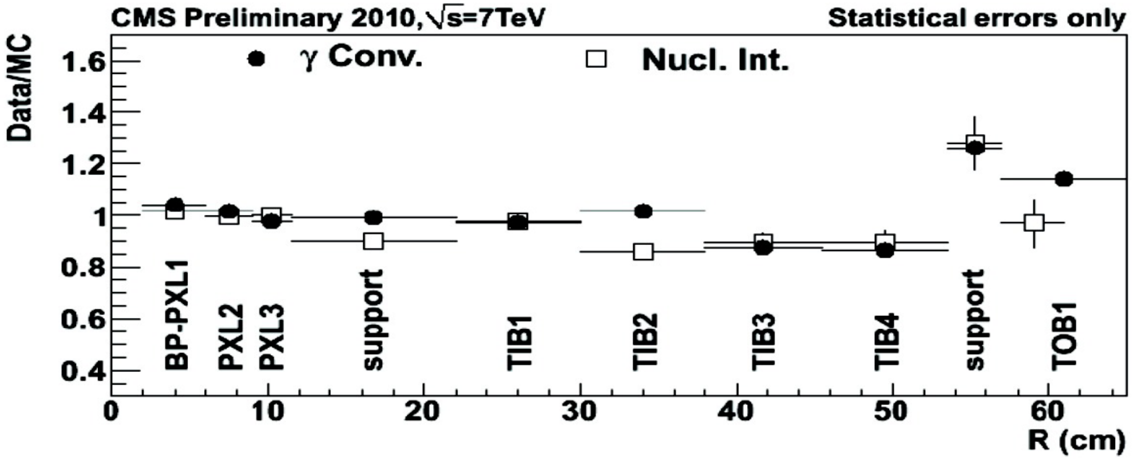
End caps of CMS detector have 4300 silicon strip detectors covering area of about 17 m^2

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