History of collider physics in India

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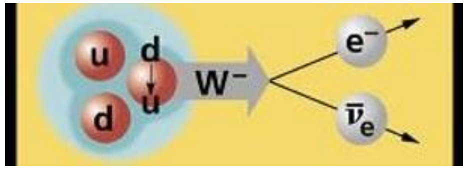
Outline

- Snapshot of particle physics in 1960's
- Indian participation in the 1st hadron *(p-p)* collider, the ISR at CERN
- The interim period 1970's towards next-gen collider involvement

- The L3 experiment at CERN
- The D0 experiment at FNAL
- Indian involvement in the LHC → Higgs discovery in 2012
- What does the future hold?

Snapshot of Particle Physics progress 1960's onward

- Many (10's) of particle "resonances" discovered in accelerator based experiments during 1950's – early 1960's
- To explain these, the Quark model was proposed by Gellman and Zweig, with 3 quarks (*u,d,s*) as constituents of all known particles till then.
- Baryons (p, n, Λ, Σ, etc) and mesons (π, η, ρ, … $K^{\pm,0}$, $K^{*\,\pm,0}$, etc)
- The "strange" particles (Λ, Σ, … $K^{\pm,0}$, $K^{*\,\pm,0}$) had one *s*-quark, the others had only combinations of *u*- and *d*-quarks, e.g. **proton** (*uud*), **neutron** (*ddu*), ….
- E.g., in the Quark Model:



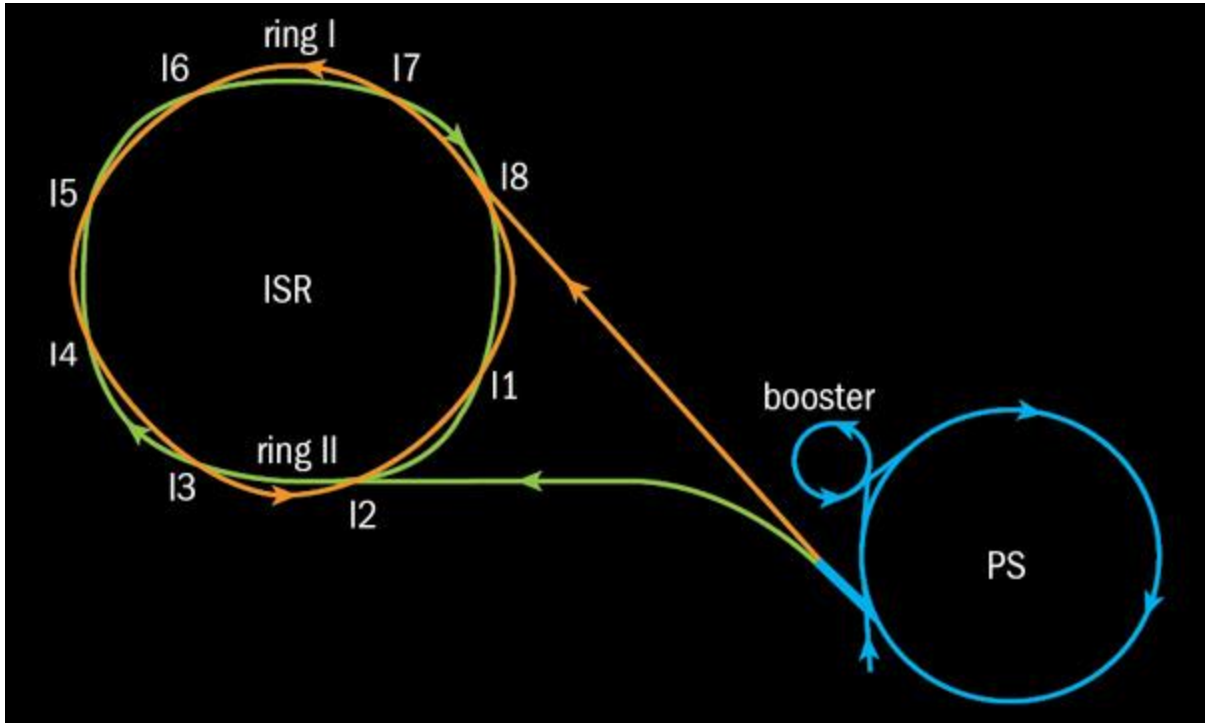
- In 1962 the second neutrino was discovered related to the muon, **$\mu \rightarrow e\ \nu_e\ \nu_\mu$**
- During the mid-late 60's the **theories of electromagnetism and weak decay were unified into the Electro-Weak theory (Weinberg, Salam).** Prediction → there should exist a neutral carrier of the weak force, **the Z^0**, in addition to the charged carriers $W^{\pm}$, responsible for the known weak decays, e.g., n → p + e^- + ν_e-bar

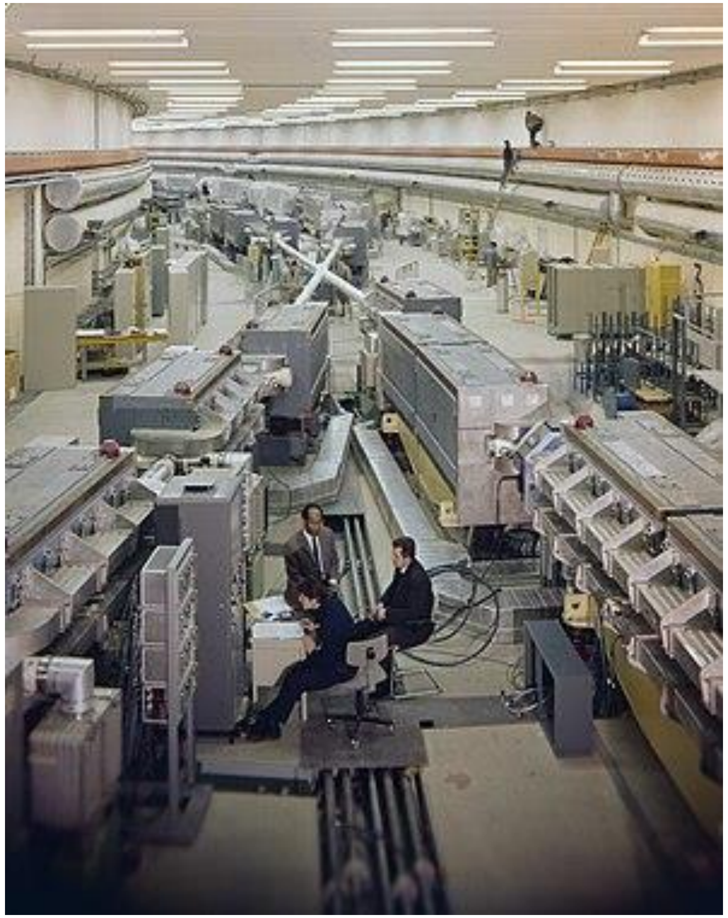
Indian participation in the 1st hadron *(p-p)* collider, the ISR, at CERN

- Colliders are built to maximize the c.m. energy available in particle interactions
- Problem: as one beam hits another, intensity is the problem to obtain good (useful) statistics
- Over the years techniques have been developed to squeeze beams to obtain high intensities (Luminosities) to enable useful physics
- The first to be build were e+e- colliders in the late 1950's – 60's, at Frascati (Italy), Stanford (USA) and Novosibirsk (USSR)
- In mid-1960's CERN designed the first *p-p* collider using its Proton Synchrotron beams of energy 20 – 30 GeV → E_{CM} = 40 – 60 GeV

The CERN Intersecting Storage Rings operational 1971 – 1984

- Two interlaced rings each with a diameter of 300 metres
- Protons injected in opposite directions from the PS





The TIFR Expt at the ISR, CERN

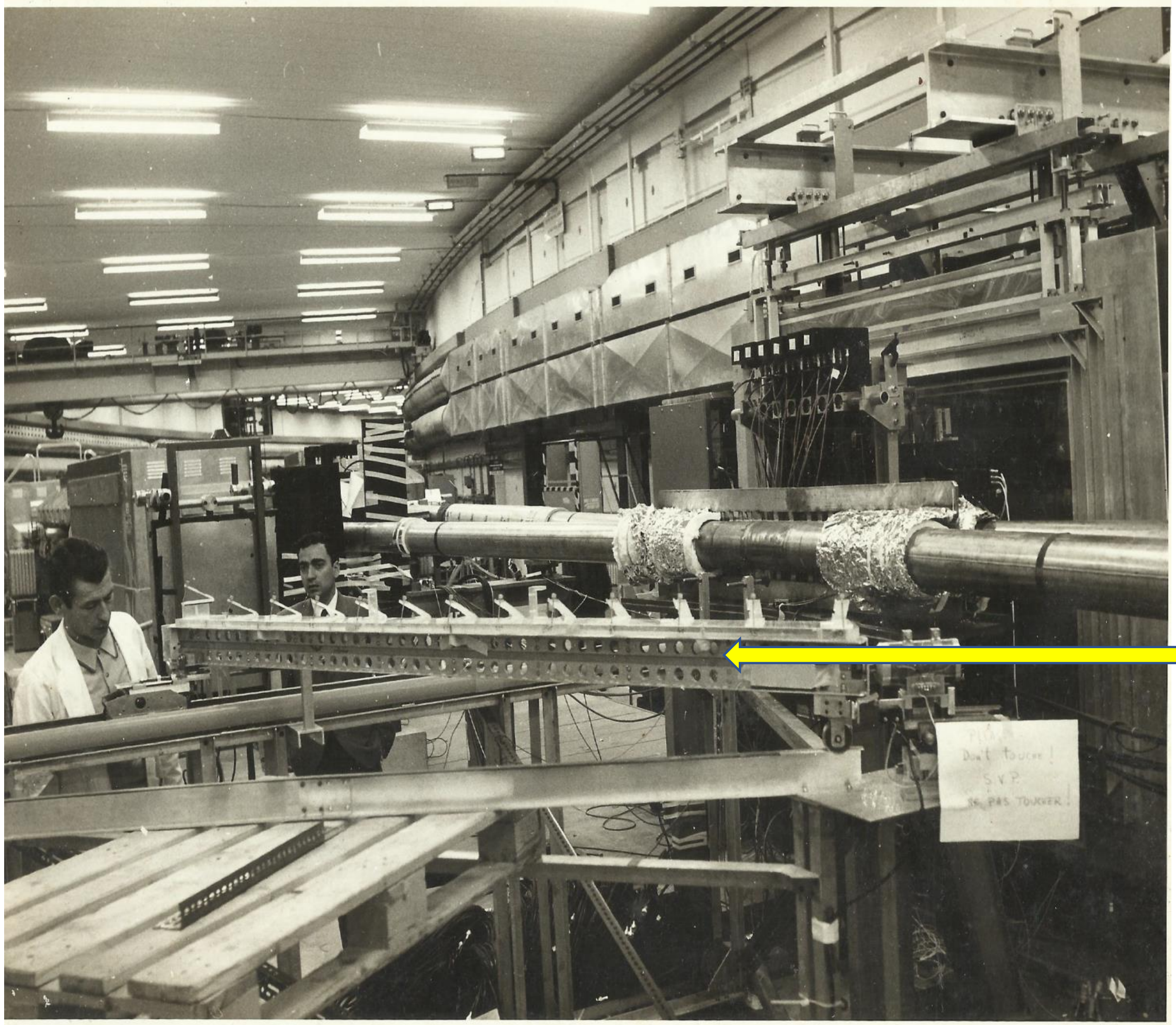
- R.R. Daniel, S.N. Ganguli & P.K. Malhotra of the Emulsion Section, TIFR proposed an experiment at the ISR. (I joined TIFR in Nov 1969 & became the 4th author.)

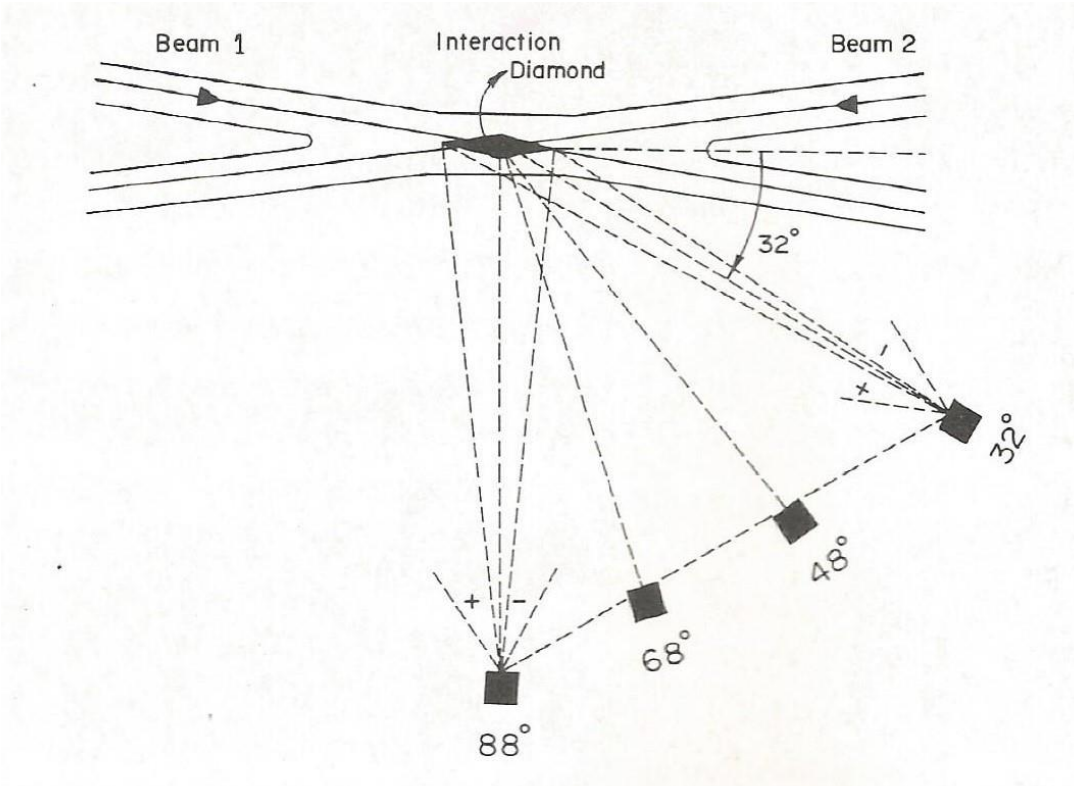
- **Objective:** To measure **γ-ray production** at various angles w.r.t. the beam axis and deduce the **multiplicity & angular distribution of π^0s** produced in p-p collisions at the then **highest available c.m. energy of 44.4 GeV.** (ISR would go on to 62 GeV c.m. energy)

- This was a unique experiment at the ISR with emulsions being used as detectors

- With an operational emulsion section at TIFR with many scanners, the idea was to have a fast turn around and obtain results quickly.

Experimental set-up at ISR, schematic & actual

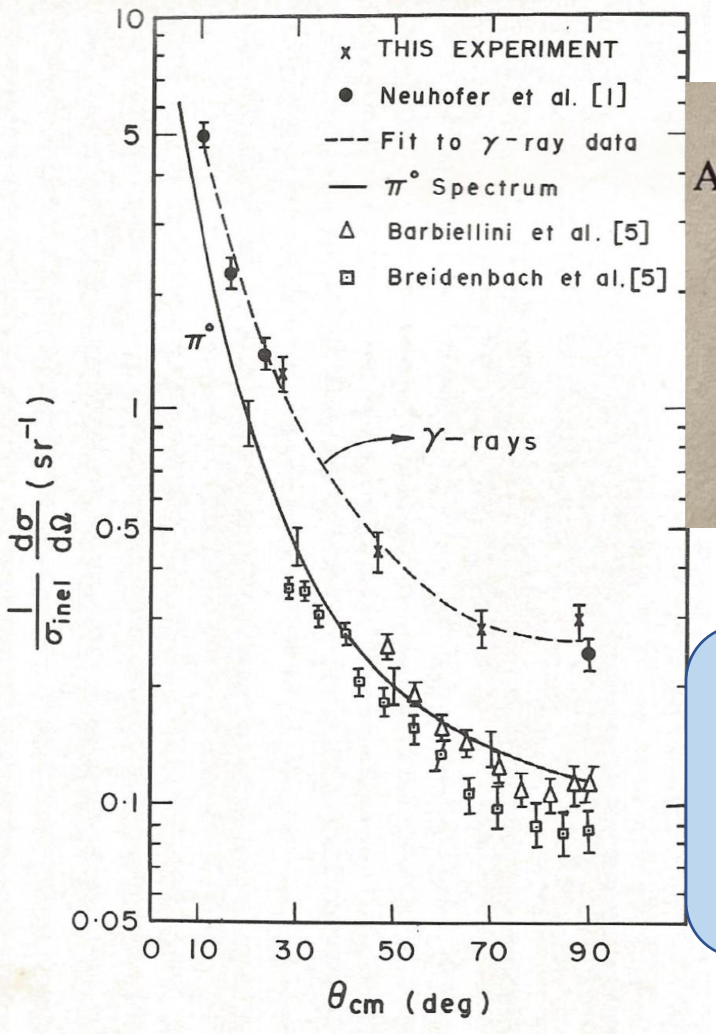




Aluminium bar on which emulsion stacks were affixed.

To avoid radiation damage to the emulsions, the whole bar was transported in-place just after stable beams

R.R.Daniel, S.N.Ganguli, A.Gurtu and P.K.Malhotra :
Nucl. Phys. **B63**, 45 (1973)



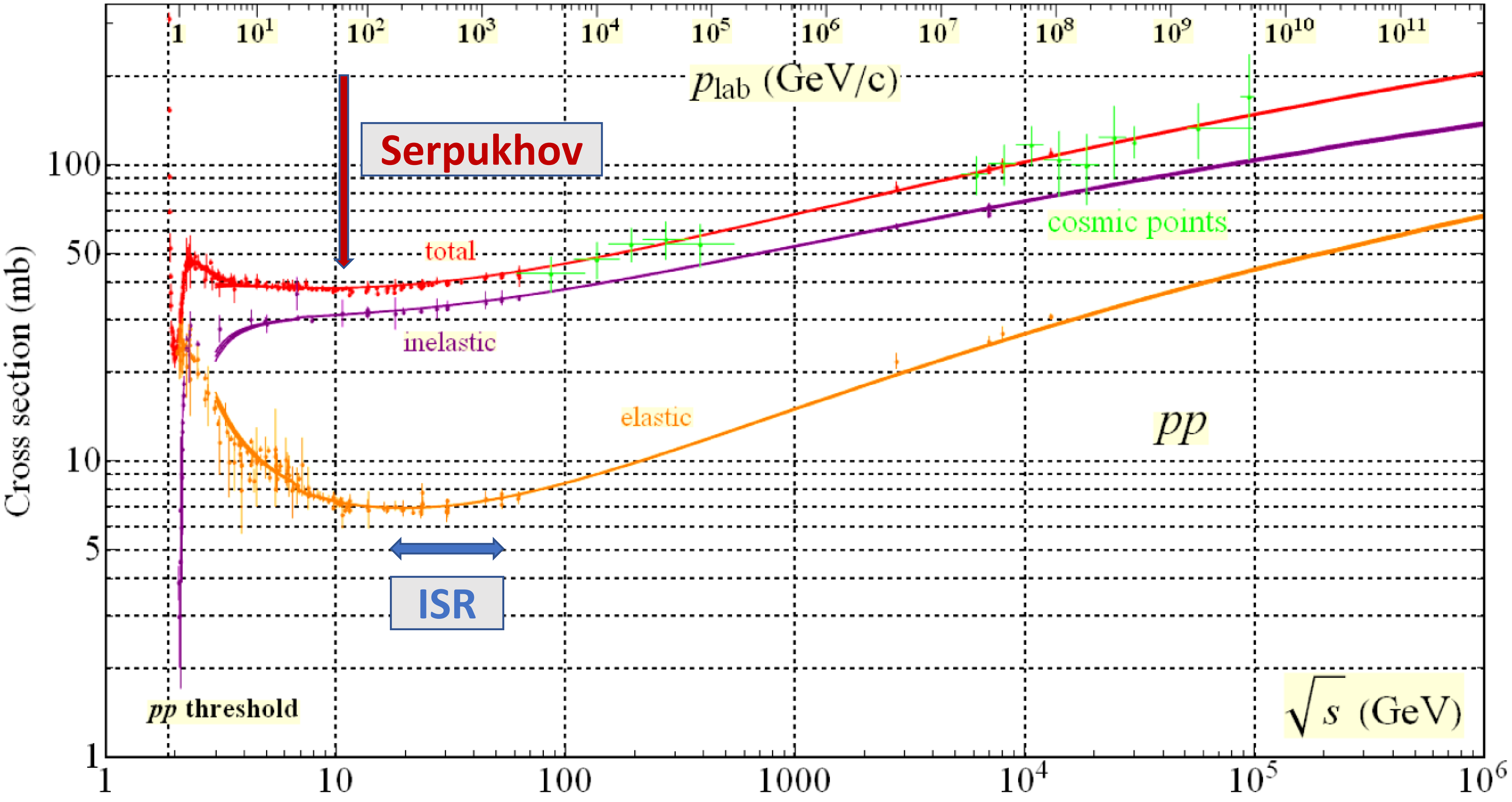
Abstract: The angular and momentum distributions of γ-rays, produced in pp collisions at the CERN ISR at a centre of mass energy of 44.4 GeV, have been measured using nuclear emulsions. This experiment covers an angular region $27° < \theta_{cm} < 88°$ which had not been covered in an earlier ISR experiment. Using the entire available γ-ray data, the π^0 angular distribution has been deduced. The average π^0 multiplicity is found to be $\langle N_{\pi^0} \rangle = 4.0 \pm 0.6$. Using this value, we deduce the average charged particle multiplicity to be $\langle N_{ch} \rangle = 10.6 \pm 1.4$.

Two other publications in collab with the Krakow-CERN group:

→The angular distribution of charged particles produced in pp collisions at the CERN Intersecting Storage Rings J.Babecki et al : Phys. Lett. 40B, 1972, 507

→Wide angle production of slow antiprotons at the CERN ISR B.Bogdan et al : Phys. Lett. 41B, 1972, 221

Lasting legacy of ISR: confirmation that interaction cross sections rise with energy, indicated at the 70 GeV Serpukhov machine

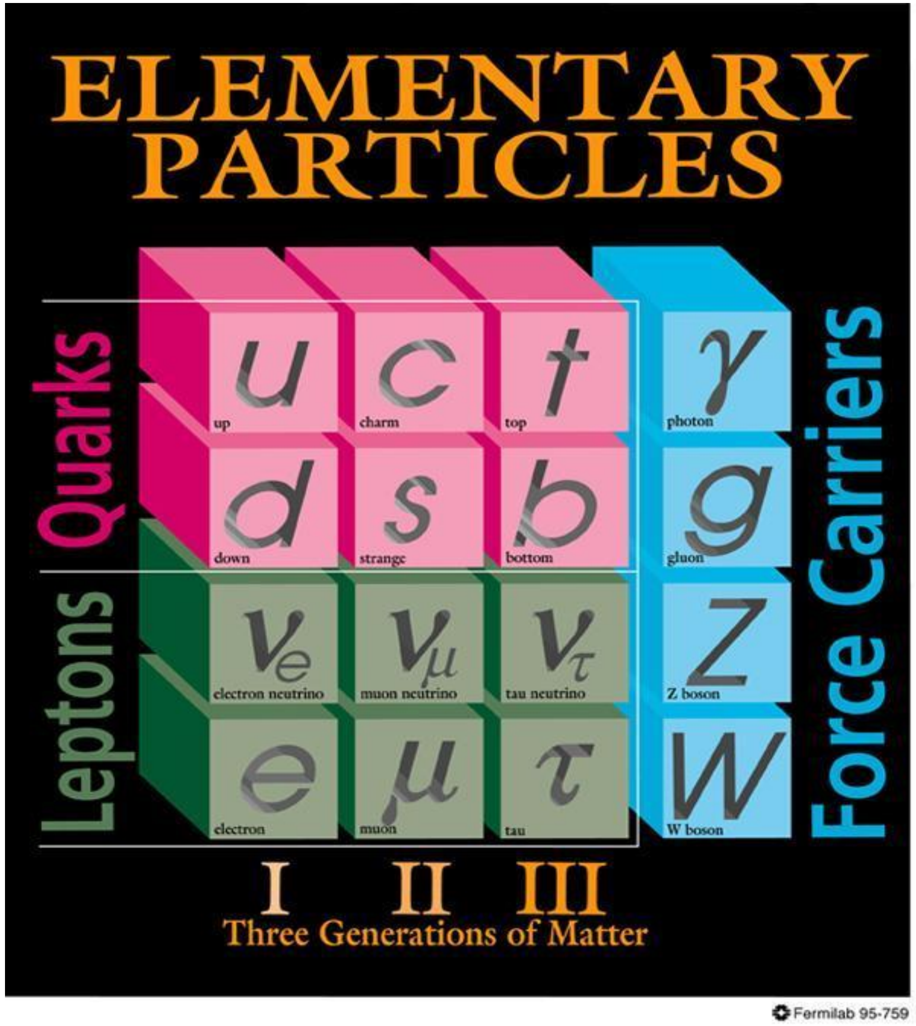


Particle physics discoveries/theoretical advances

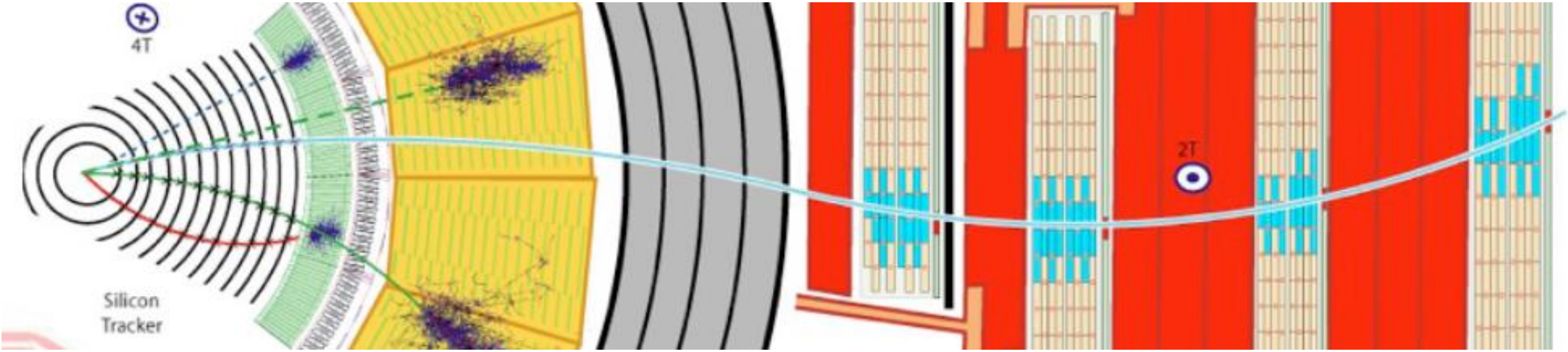
Year	Discovery
1960's	CP-violation, more resonances; Quark –parton model (u,d,s), EW unification → prediction of Z, prediction of 4th quark (u,d) (c,s)
1972	Kobayashi,Maskawa→ prediction of 3 quark doublets (+ 3 lepton doublets)
1973	Indirect discovery of Z at CERN
1974	Discovery of 4th charm quark at BNL, SLAC
1975	Tau lepton discovered (3rd generation)
1977	Discovery of *b* quark (3rd gen)
1979	Discovery of gluon at DESY

Year	Discovery
1970's	Development of Standard Model as we know it. Electroweak + QCD (Quantum Chromo Dynamics). Remaining: Direct discoveries of W, Z, Higgs, top quark, tau neutrino
1983/4	W, Z discovered at CERN
1989-2002	*Detailed study of Z at SLC & LEP and of W at LEP → consolidation of SM*
1995	*Discovery of top quark → quark doublets complete*
1998	Neutrino oscillations confirmed → non zero neutrino mass→ BSM
2000 *2012*	Tau neutrino discovered (DONUT) *Higgs discovered at LHC*

Particle Zoo in 2000



Modern Collider Physics (1980's onward)
Generic structure of ~4π detectors at Colliders



- Charged particles seen in tracker + momentum measurement
- Electrons and photons (also from π^0) absorbed in ECAL, electrons associated with a track
- Charged hadrons seen in tracker, energy deposits in ECAL, HCAL
- Neutral hadrons leave no track in tracker, interact in ECAL, HCAL
- Muons seen in tracker, min ionizing in ECAL, HCAL, tracked in muon chambers.
  Momentum from tracker + muon chambers

Large Electron-Positron (LEP) collider & Indian (TIFR) participation in L3

- EW and QCD theories & indirect observation of the Z^0 at CERN in 1973

→ necessary to verify their predictions and to discover $W^{\pm}$ & Z

- CERN constructed the anti-proton proton collider and UA1, UA2 collaborations discovered $W^{\pm}$ & Z in 1983-84.
- To study/verify other predictions of EW and QCD, CERN decided to build LEP.
- Phase I, LEP I would be a Z^0-factory with c.m. energy 88 – 94 GeV;
- LEP II would have c.m. energy 161 to ~200 GeV to study W^+W^- pair-production

- (**Imp. Note:** the size of LEP, 27 km, was designed to be able to accommodate a suitably large *p-p* collider in future… the LHC).

L3 (now ALICE)

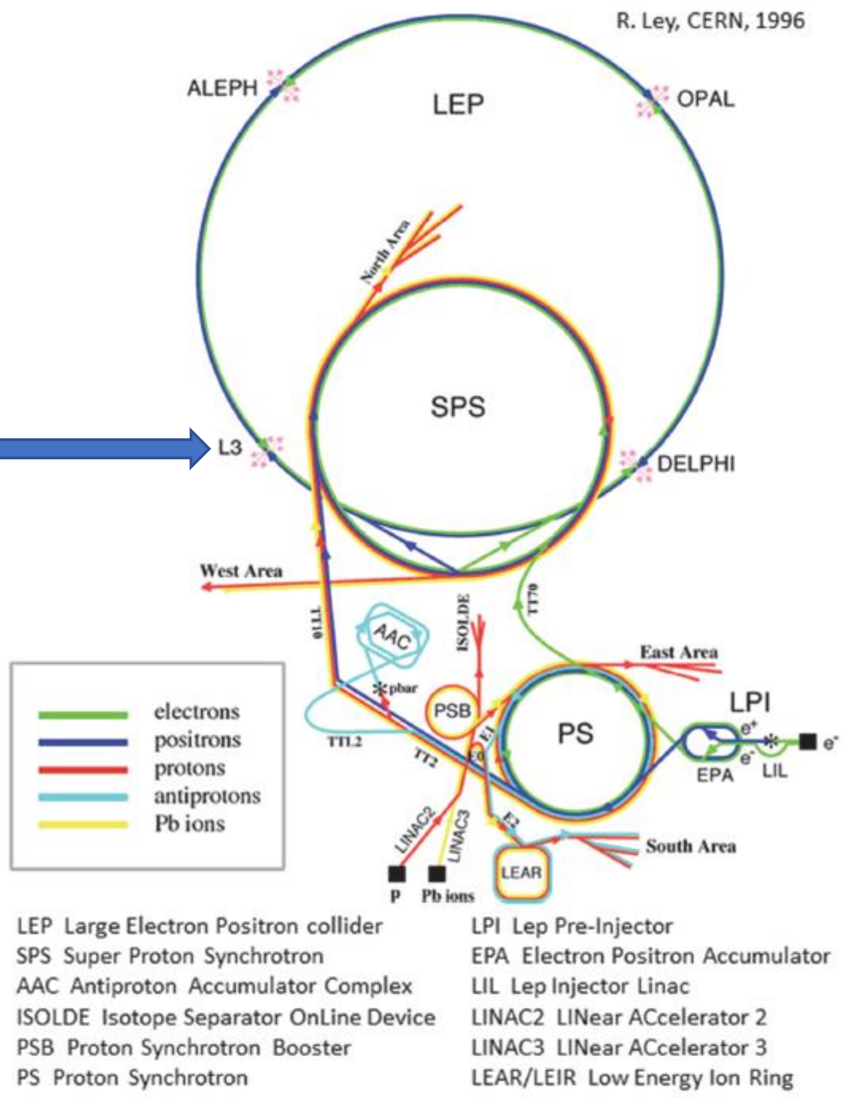
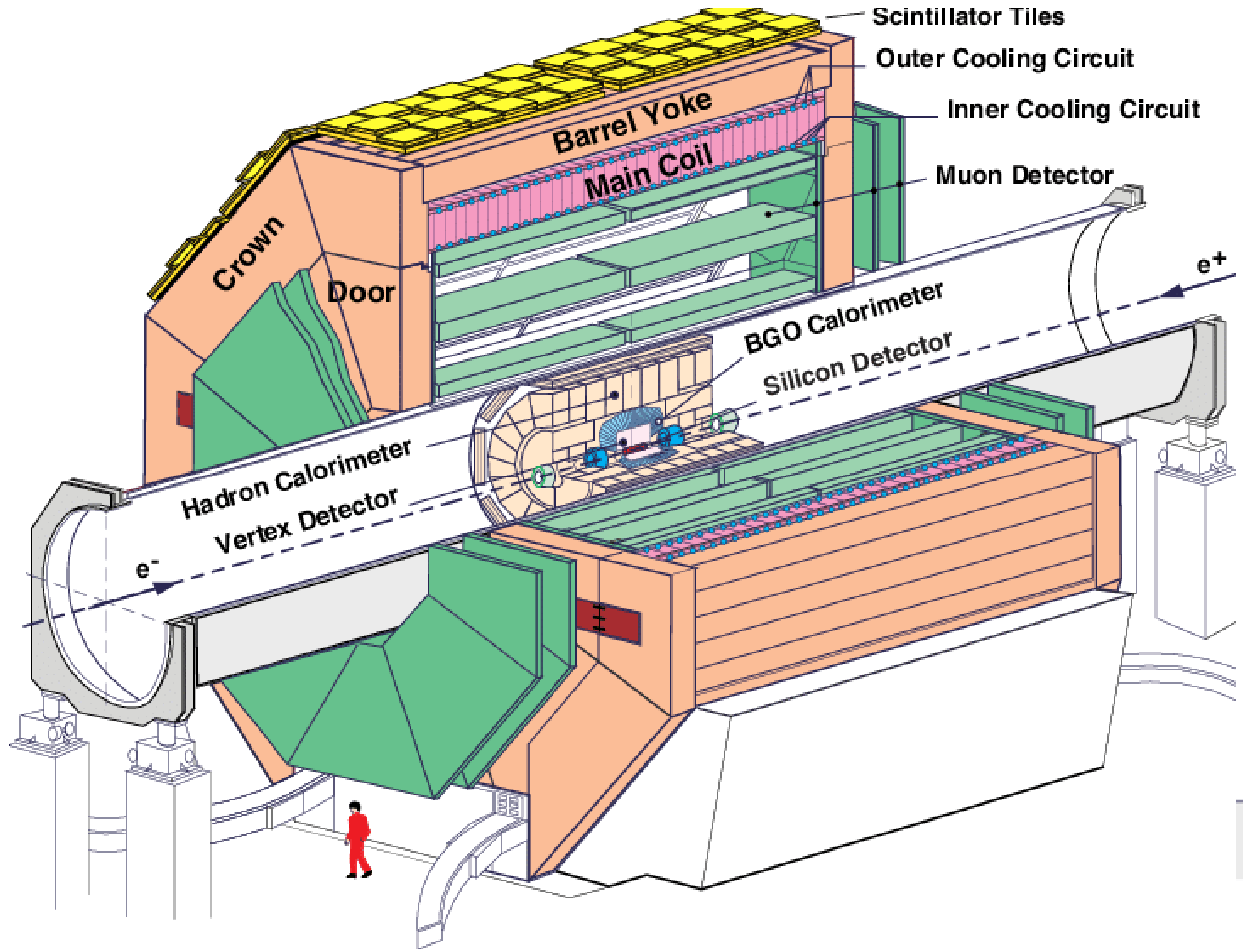
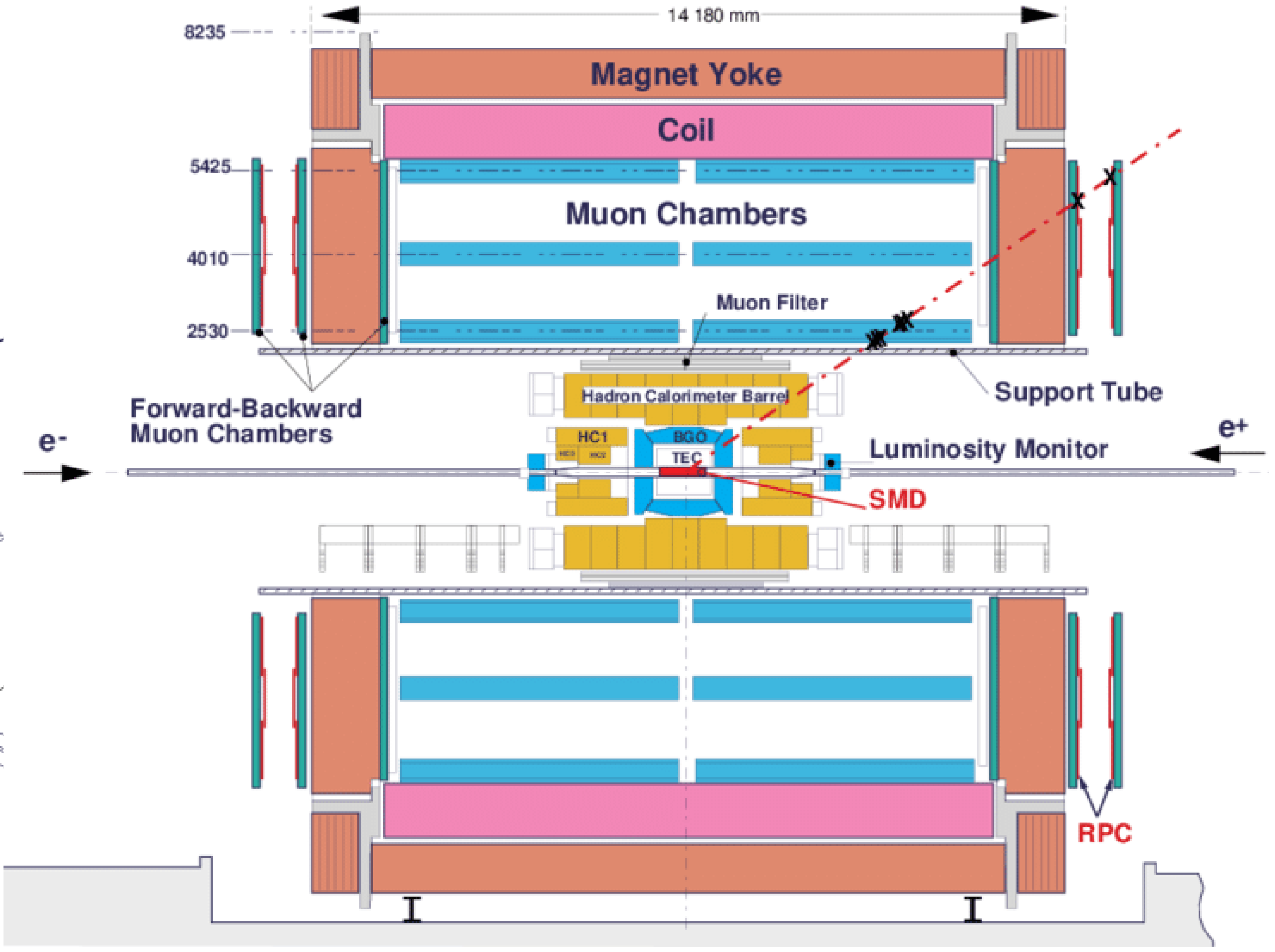


Fig. 7.1. Diagram showing the CERN accelerators at the time of LEP and how they were used to produce the high energy beams circulating in the collider.



Scintillator Tiles
Outer Cooling Circuit
Inner Cooling Circuit
Barrel Yoke
Main Coil
Muon Detector
Crown
Door
e+
BGO Calorimeter
Silicon Detector
Hadron Calorimeter
Vertex Detector
e-



14 180 mm
8235
Magnet Yoke
Coil
5425
Muon Chambers
4010
Muon Filter
2530
Support Tube
Forward-Backward
Muon Chambers
Hadron Calorimeter Barrel
HC1
BGO
TEC
e-
e+
Luminosity Monitor
SMD
RPC

TIFR-EHEP in L3 at LEP – brief summary

- **1983: TIFR-EHEP group joined the L3 collaboration**
  → fabricated brass tube proportional chambers for HCAL end-cap (with Aachen-I group)
  → Very significant role in core software development

- **LEP-I period: Responsible for L3 Z-lineshape fits and analysis**
  → precision determination of Z mass, widths, couplings, # of light neutrino species (mass < 0.5 x m_Z) …

- Strong contributions in
  -- b-physics (neural net)
  -- QCD (event shape, α_s determination)
  -- higgs searches

- **LEP-II: studied channels WW →qqqq, qqeν**
  W mass/width (threshold, reconstructed)
  QCD, 4-jets, b-physics, SUSY/higgs searches.

L3 hadron calorimeter (yellow); barrel and endcaps (HC1,2,3)

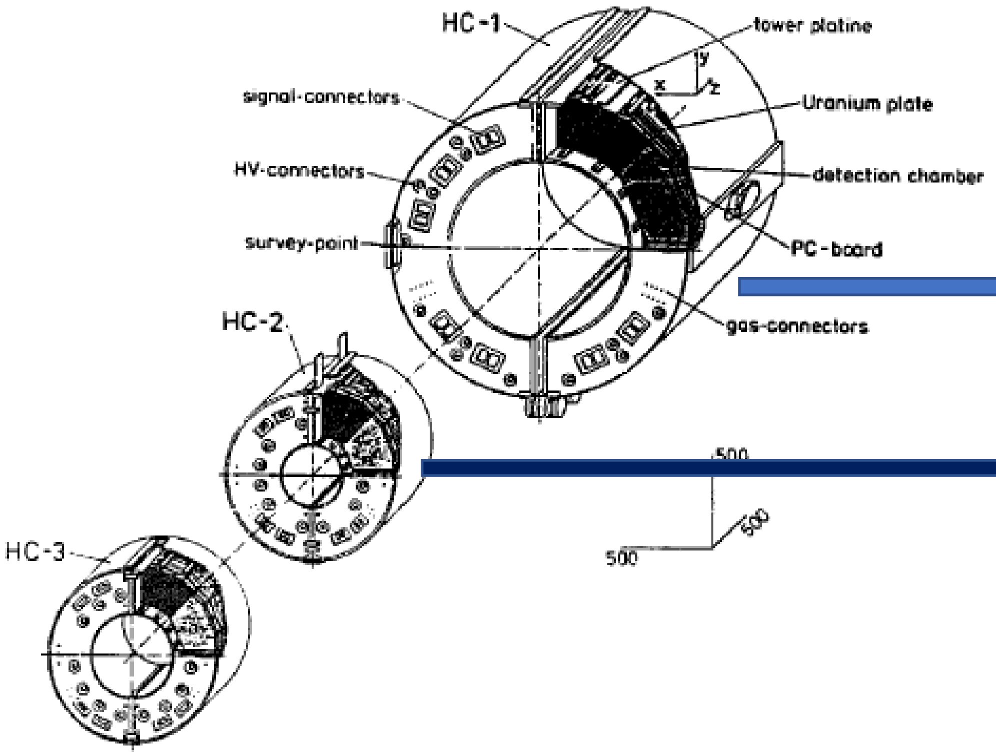
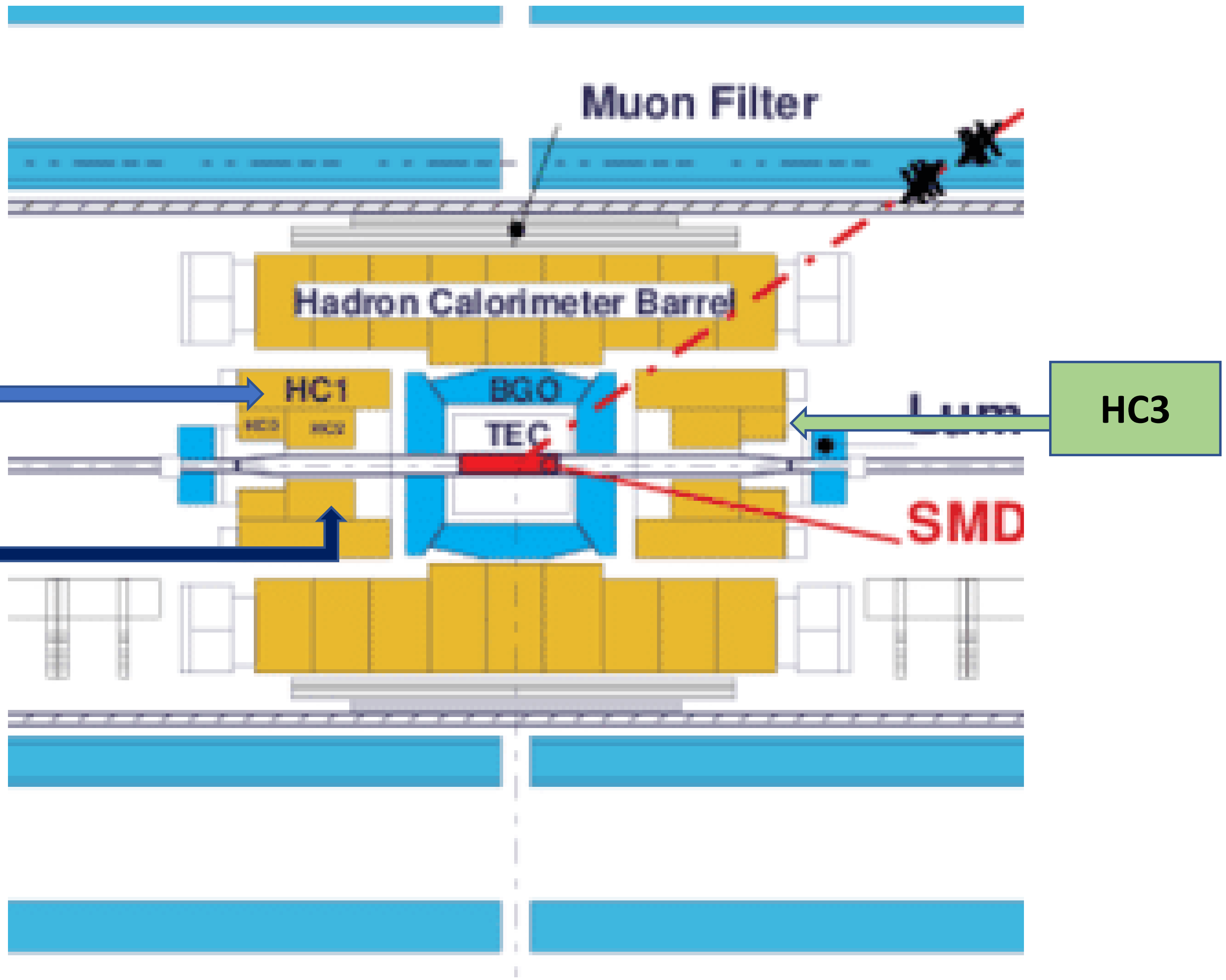


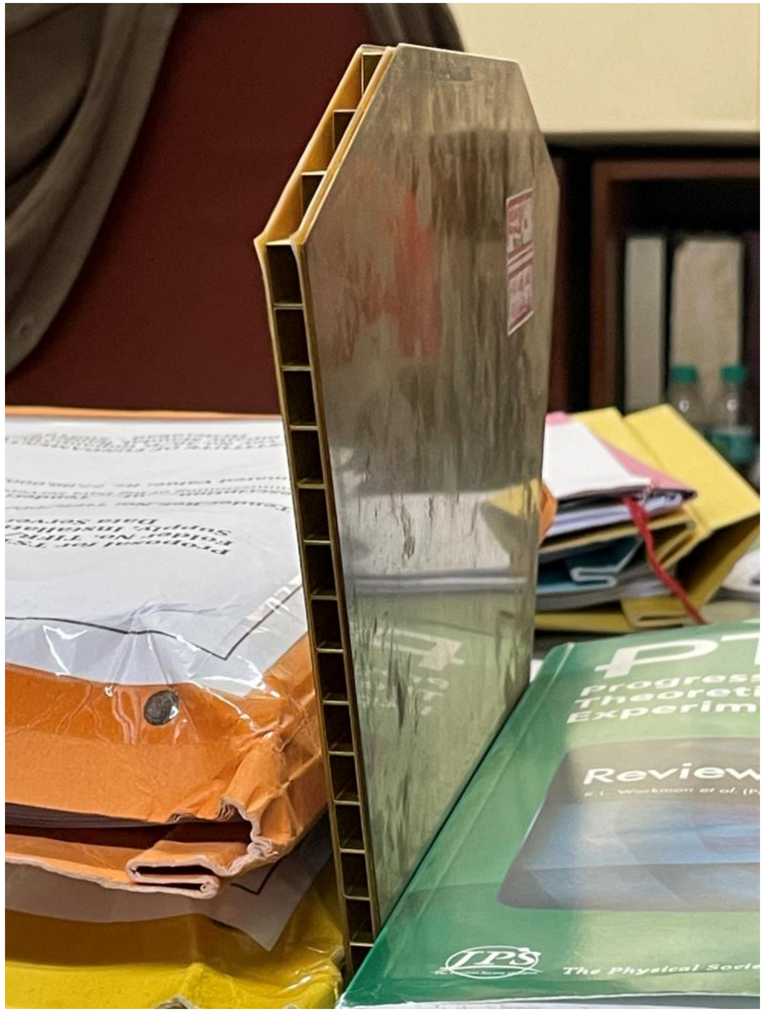
Fig. 65. Perspective view of the forward–backward hadron calorimeter.



Design of the HC detectors

(thanks to Gobinda Majumder for preserving these)

- The detector consisted of brass tube proportional chambers.
- Each 0.3mm thickness tube had a 10mm x 5mm inner cross-section and a 50µm gold-plated tungsten wire threaded through it's length & insulated from the tube.
- Tubes held together by gluing between 1mm thick brass plates which were insulated from the tubes by layers of insulating paper.
- A high voltage would be applied between the wire and the tube, so that passage of a charged particle through it generates an electric signal.
- **The strength of the summed up signals would measure the energy deposited.**

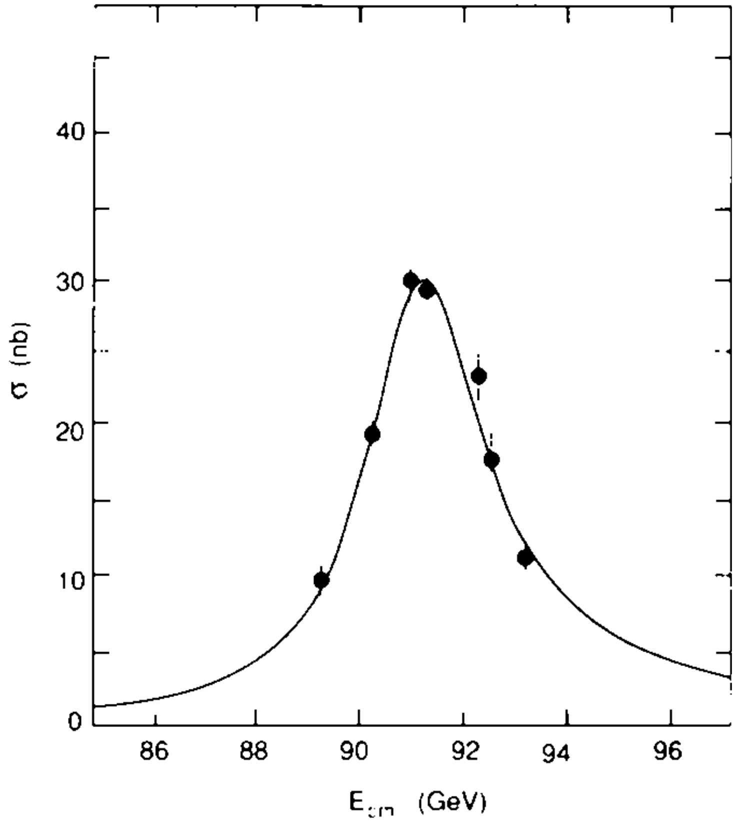


Details of the chambers

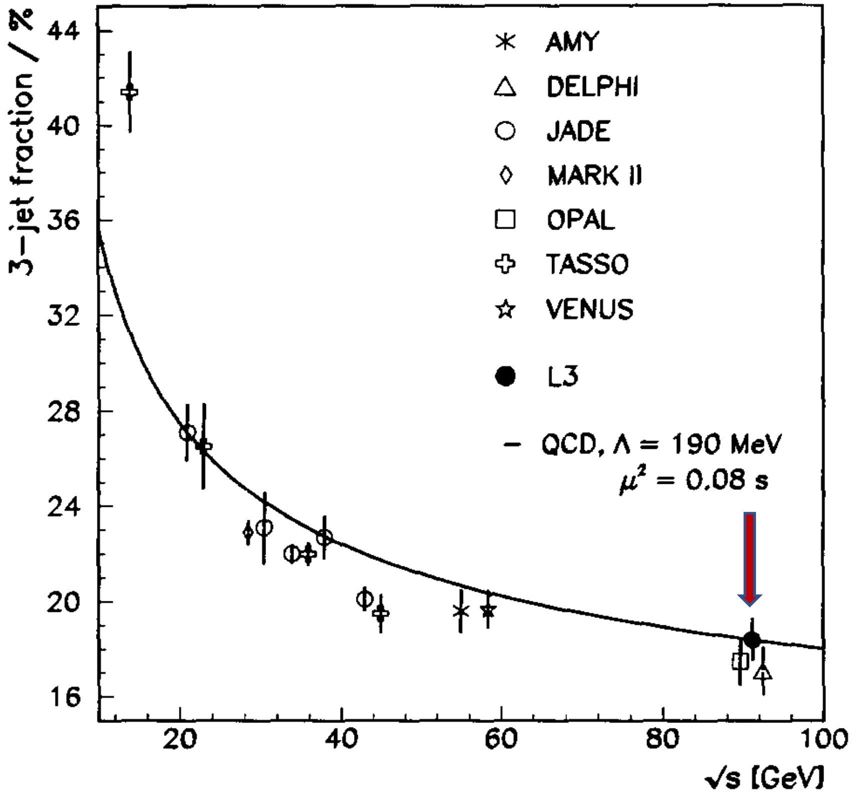
- Gas used: Ar-CO_2 (80-20) mixture. Small adjacent holes in the brass tubes enabled gas flow thru the chamber.
- HC2/HC3 → 27/23 layers of chambers
- Total chambers HC2/HC3 → 488/412
- Total no. of tubes (wires) HC2/HC3: 11712/ 7828
- Main absorber → depleted Uranium
- Weight of HC2/3: 2.45/1.92 tons
- Fabrication completed in 1988, shipped to CERN after complete testing, including using cosmic rays.
- Assembled within the L3 detector

LEP began operation in Aug 1989

First L3 papers on Z-Lineshape, QCD (running of α_s) & Z → *b bbar*



Phys. Lett. B231, 1989, 509



Phys. Lett. B248, 1990, 464

L3 $\alpha_S = 0.115 \pm 0.005_{-0.010}^{+0.012}$

Identified Z → *b bar* decays

Determined:

- Γ (Z → *b bar*) = 353 ±48 MeV
- neutral current vector coupling $g_v^2(b)$ = 0.095 ±0.047
- Forward-backward asymmetry *A*(*b bar*) = 13.3 ±9.9 %

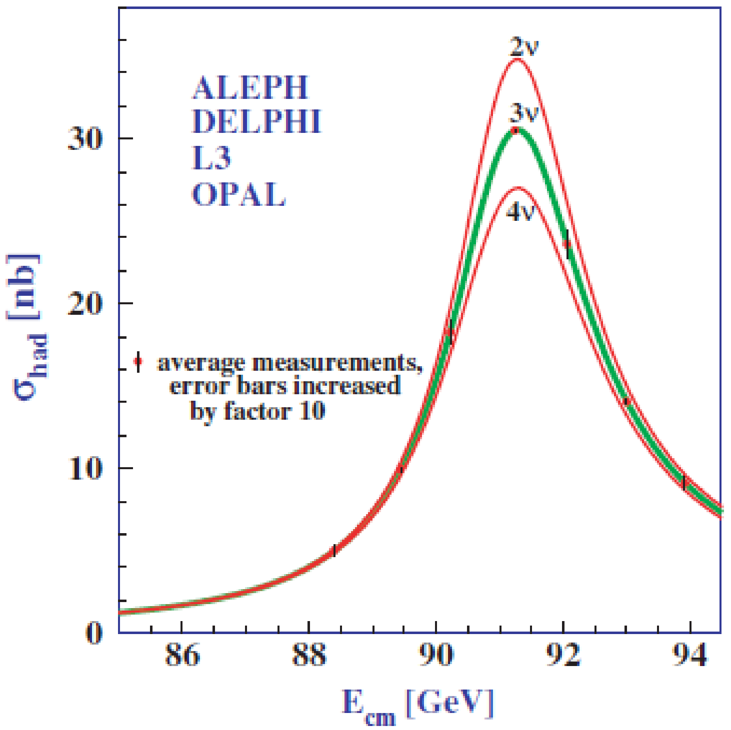
Phys. Lett. B241, 1990, 416

To cut a long story short: LEP I major results

- Combining results from 4 LEP expts (Aleph, Delphi, L3, Opal) including proper correlations…
- **Mass of Z = 91187.6 ± 2.1 MeV** Unprecedented precision (1 part in 45,000!)

  taking into account, among other **more normal** things
- Effect of **earth tides on diameter** of the LEP ring (few mm!)
- Effect of electric currents from **nearby passing trains**

  (the time-table was used!)



- **Total decay width = 2495.2 ± 2.3 MeV**
- **Partial decay widths to e+e-, μ+μ-, τ+τ-, hadrons**

  → invisible width (neutrinos) = 499.0 ± 1.5 MeV

- **Forward-backward decay asymmetries which test out the EW theory**
- **A_{FB} (b-bar), A_{FB}(l^+l^-) (Imp. SLC contribution, electron polarisation)**

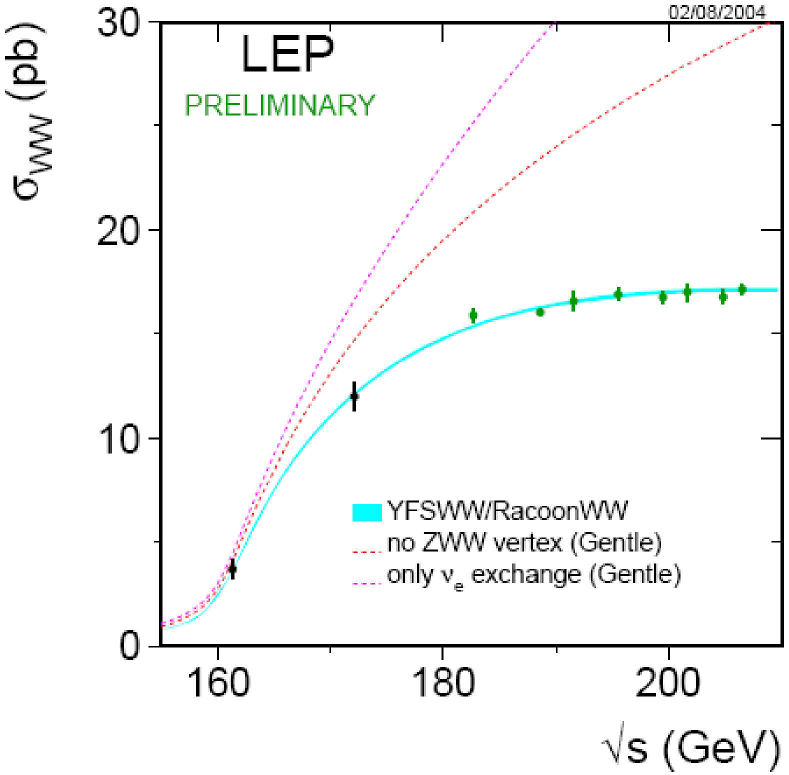
LEP II – most salient results (combining all expts)

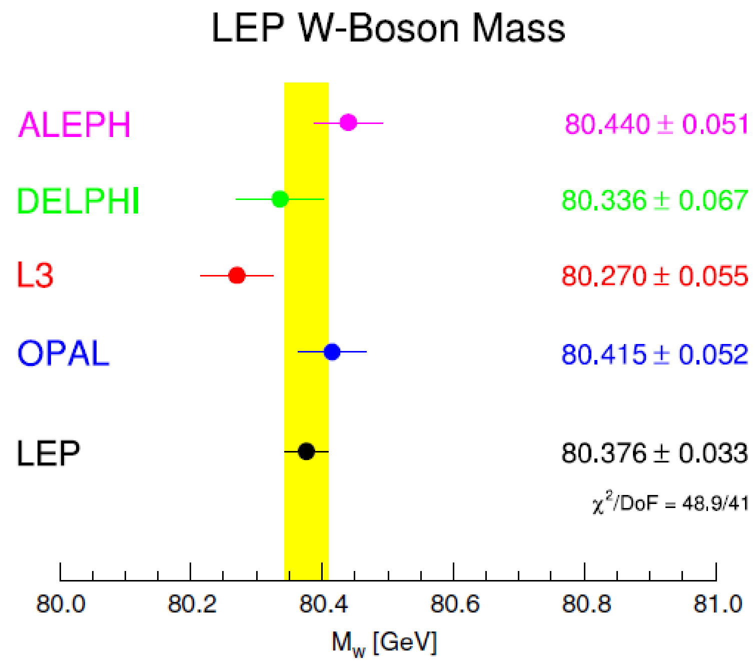
1. Determination of e+e- → W+W- cross section vs energy.

The energy dependence completely bears out the SM prediction

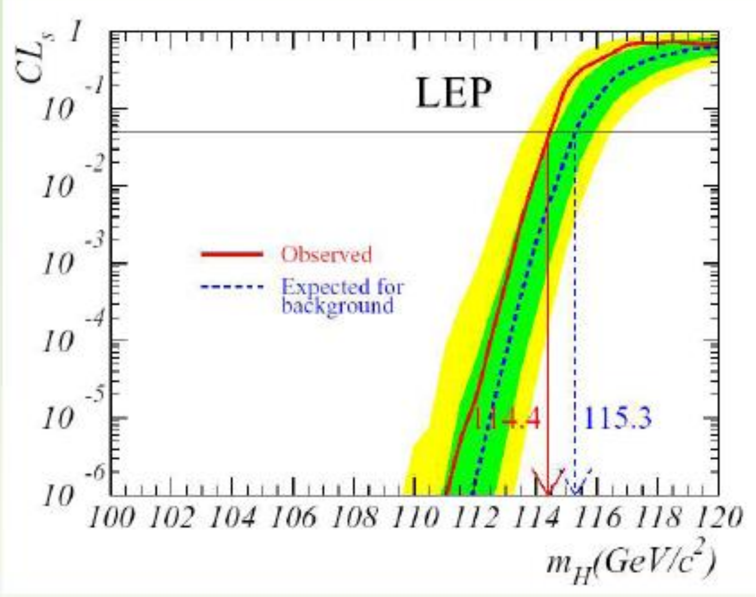
2. Determination W-mass

3. Lower limit on higgs mass….





Direct searches (only published LEP Higgs combination):



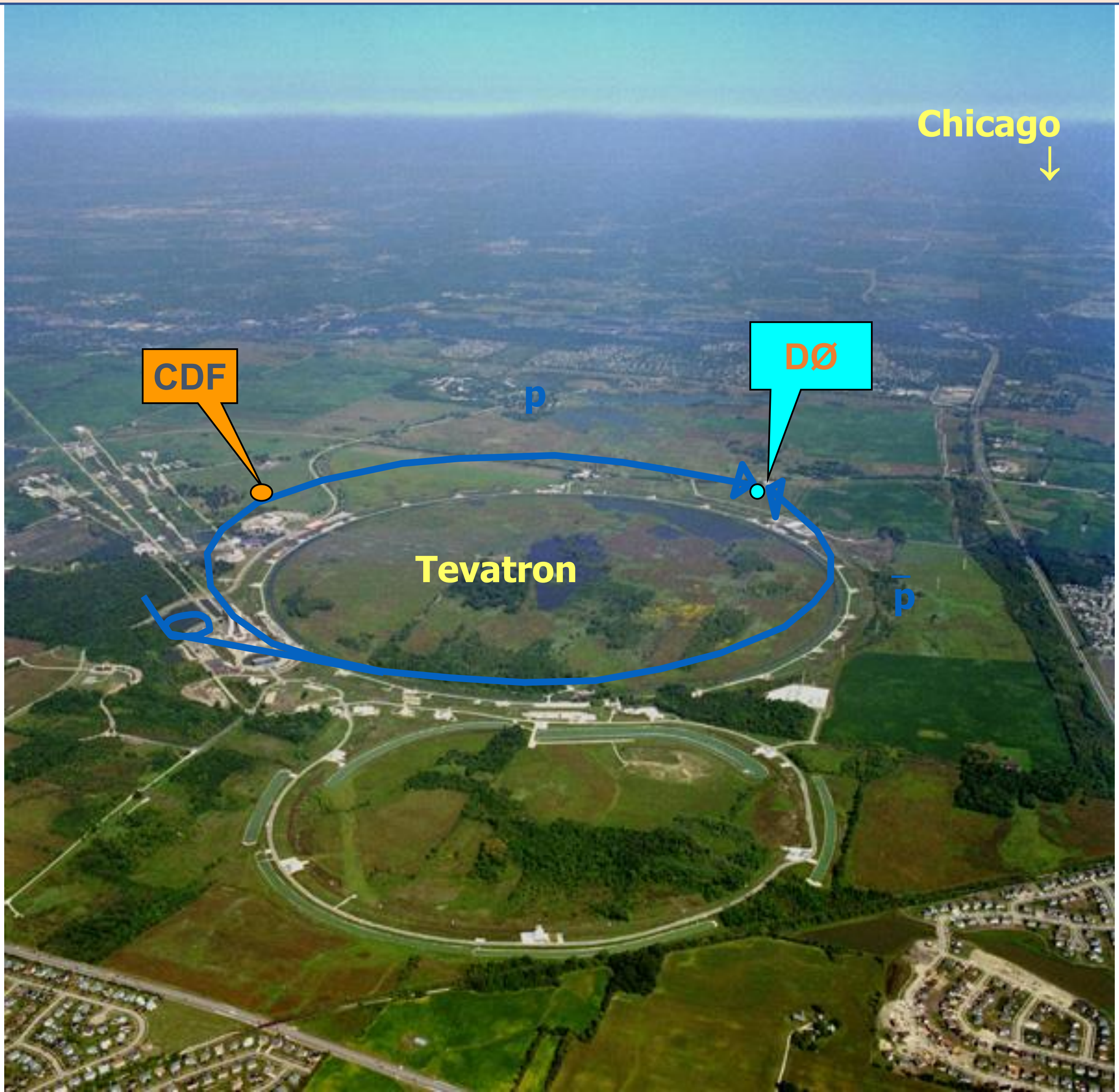
m_H>114.4 GeV(CL=95%)

Overall impact of LEP physics results

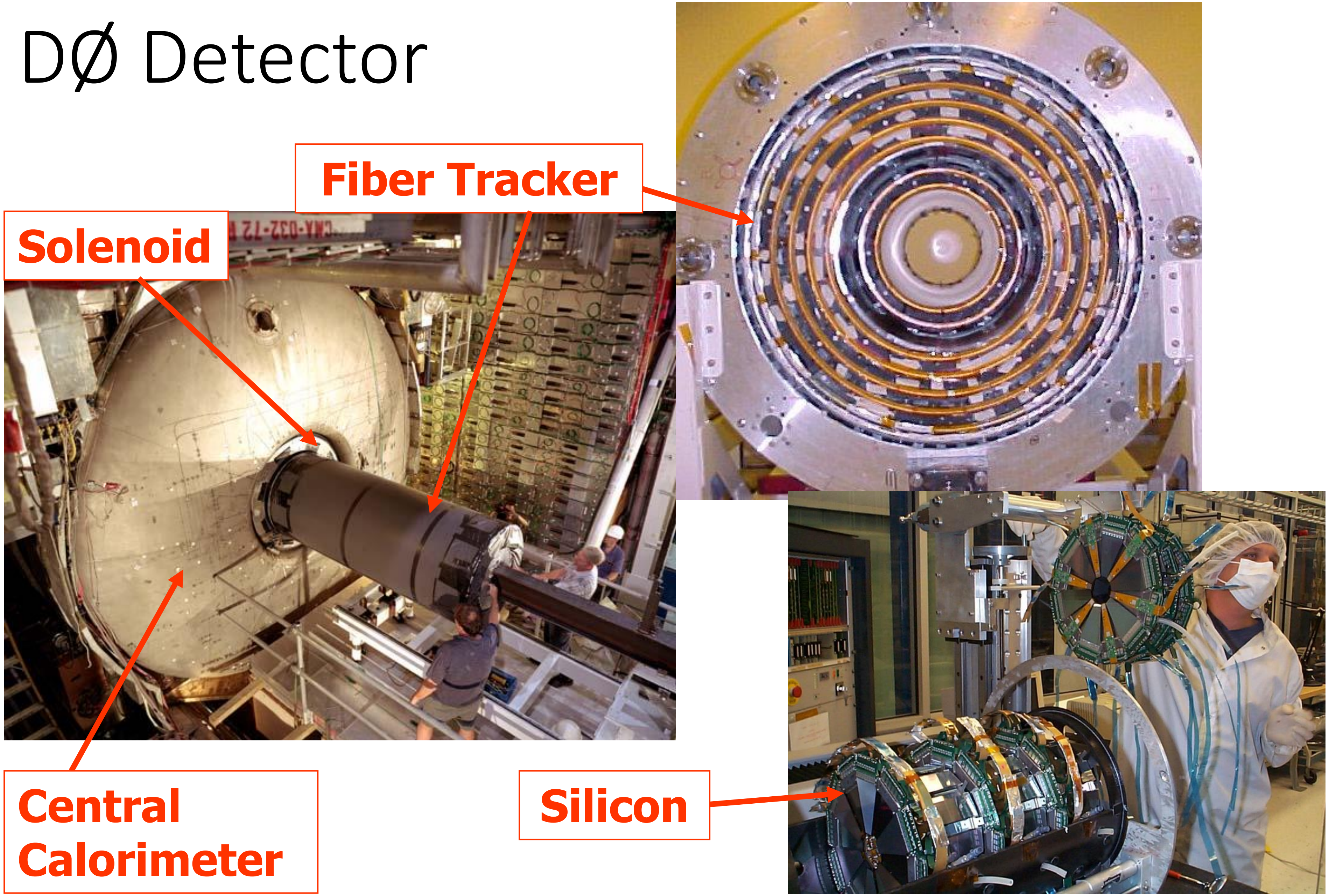
- The physics impact of the LEP physics program was vast
- It led to precision testing and vindication of the Standard Model (EW & QCD)
- It set a new lower limit on the higgs mass of 114.4 GeV.
- No new particles were discovered: the excluded parameter regions for predicted new particles (e.g., SUSY) was enlarged.

- **All in all, by the end of the LEP era the SM stood well entrenched!**

Indian Participation in the D0 experiment at the Tevatron, Fermilab



DØ Detector



Delhi U, Panjab U, TIFR-HECR in D0

- TIFR-HECR group contributed significantly towards hardware

- All 3 groups participated in running of the experiment, in data and physics analyses.

- Apart from extending study of $p\,\bar{p}$ interactions to highest energies, the major discovery that came out in 1994-95 was that of **the top quark.** Panjab U scientists and students were working on the top-quark search channels.
- Owing to much larger $W^{\pm}$ statistics available both D0 and CDF determined **the W-mass to much higher precision than LEP**

TIFR Group in DØ – Hardware contribution

- Joined in 1990.
- Participated in the design of the central muon scintillator detector.
- Fabrication of 120 + 44 muon scintillator detectors with fiber readout.
- Performance study for the pre-shower detector for electron identification.
- Online software for High Voltage Control.
- Development of fully automatic software dominated system to test muon fan-out cards.
- Calibration of scintillator PMTs using LED.
- Commissioning and testing of the central muon system.

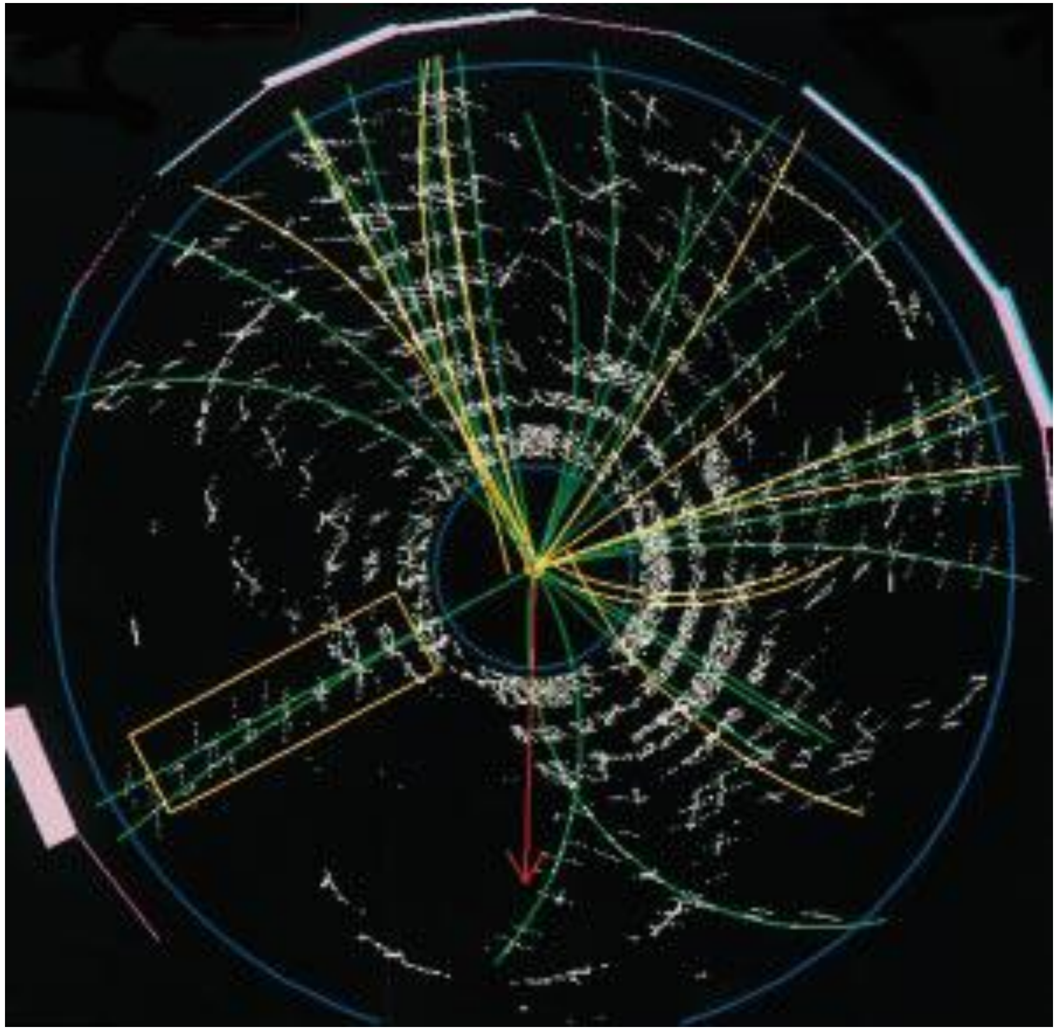
TIFR Detector Fabrication

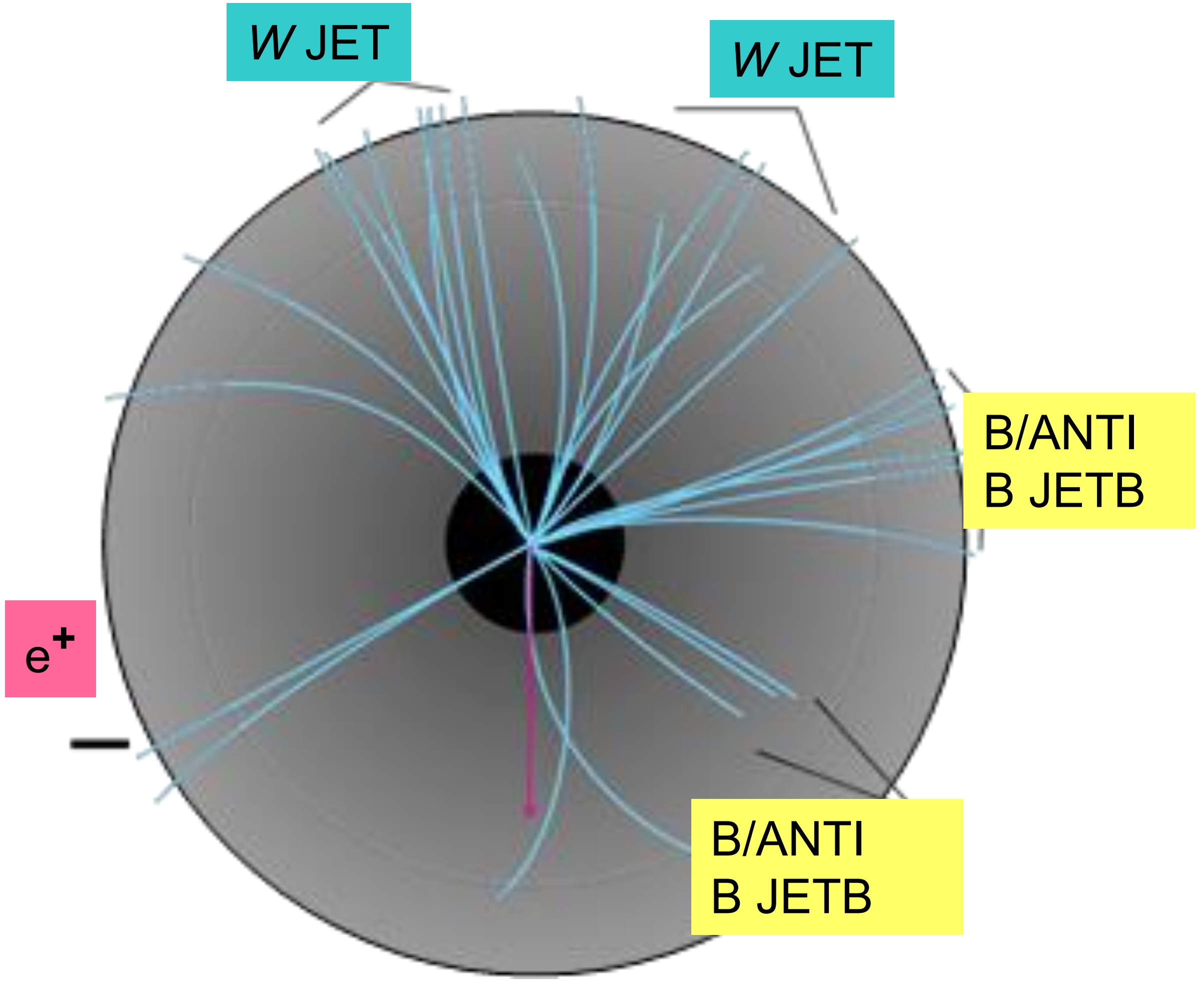
Participation in D0 Physics

- Top cross section measurement.
- B-Physics.
- Higgs search.
- Search for Compositeness & Extra Dimensions
- SUSY search.
- Searched particles decaying to $t\bar{t}$

Many students have completed their Ph.D. analysis work.

A Classic Top Event 1.96 TeV p $\bar{p}$ CDF expt at Tevatron, Fermilab





Explanation of the event: each t → W + b
each W → 2 q $\bar{q}$ jets

- A proton and an antiproton traveling in opposite directions collide at the center of the Collider Detector at Fermilab (CDF)
- Produce four distinct jets and a few other particles. **Two jets, identified by a silicon vertex detector, are from the decay of a bottom and an anti-bottom quark**, whereas **two are from the decay of a *W* into a quark and an antiquark**. An energetic positron is produced by another *W* decay, along with an invisible neutrino (*red arrow*).
- **Multiple jets, along with a positron, alert experimenters to the possible creation of a top**.
- The direction of curvature of tracks shows the sign of a particle's charge, and the extent reveals its momentum.
- Further, a calorimeter wraps around the beam line; it measures the energies of the emerging particles.
- **The combination of devices allows experimenters to reconstruct the original event with a high degree of confidence**. *—T.M.L. and P.L.T.*

D0 Top quark discovery paper 1995

- **Observation of the Top Quark**
- **S. Abachi *et al.* (D0 Collaboration)**

Phys. Rev. Lett. 74, 2632 – Published 3 April 1995

- **Used variable $H_T = \Sigma\, |E_T|$ of all jets**
- **Scalar sum of all energy going in TRANSVERSE direction to the beams.**
- **Excellent signature of *t-tbar* production**

- **Observed 17 events with "top quark" signature, expected background = 3.8 ±0.6**

  → 4.6σ signal
- **Mass = 199 +19 -21 (stat) ±22 GeV (syst)**

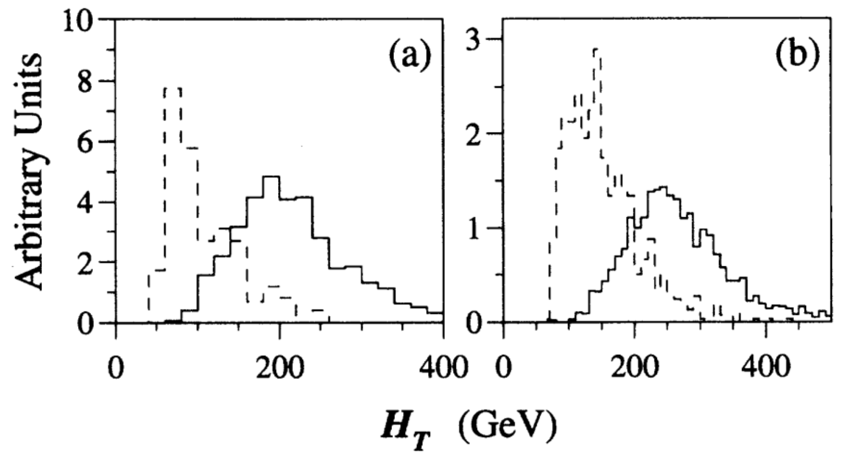


FIG. 1. Shape of H_T distributions expected for the principal backgrounds (dashed line) and 200 GeV$/c^2$ top quarks (solid line) for (a) $e\mu$ + jets and (b) untagged single-lepton + jets.

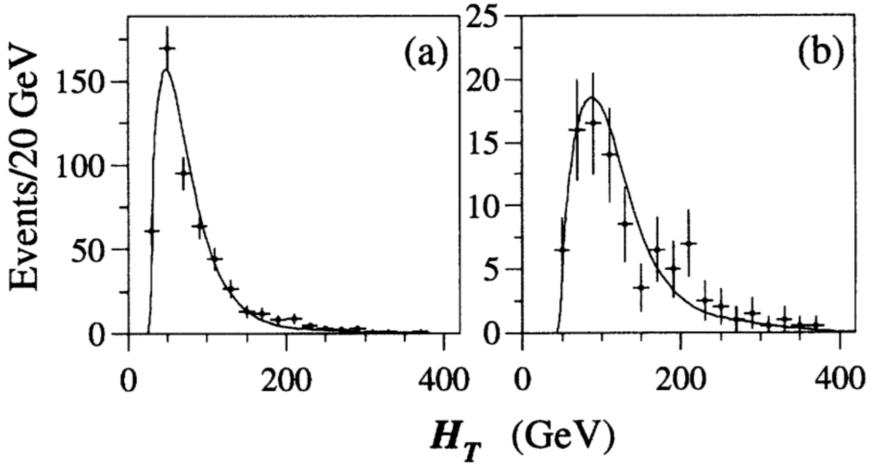


FIG. 2. Observed H_T distributions (points) compared to the distributions expected from background (line) for $\not{E}_T >$ 25 GeV$/c$ and (a) $e+ \geq 2$ jets and (b) $e+ \geq 3$ jets.

CDF discovery of the top quark & Constituent table

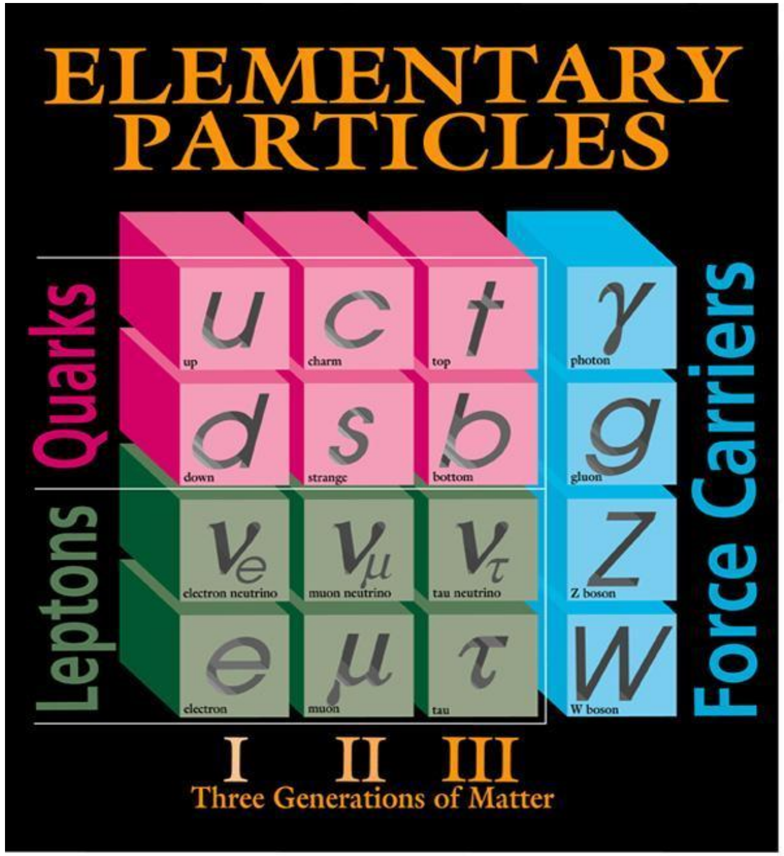
- **CDF, the other experiment at Fermilab, also discovered top at the same time**
- Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. 74, 2626 – Published 3 April 1995

Currently the best value of the top quark mass is: 172.69 ± 0.30 GeV (PDG 2022)

In the year 2000 the tau-neutrino was also discovered, leading to completion of the list of constituents and force particles.

The Higgs, the cornerstone of the SM still to be discovered… later at the LHC



Fermilab 95-759

W mass from the D0 & CDF at Fermilab

- LEP: mass of W = 80.376 ± 0.033 GeV based upon ~40,000 WW events among the 4 expts Aleph, Delphi, L3, Opal
- Advantage: being an e+e- collider, the initial state momentum and energy is KNOWN so one applies energy-momentum conservation to properly reconstruct the W-mass
- Each of D0 and CDF have much higher statistics of W production, BUT protons are **COMPOSITE OBJECTS (quarks + gluons).** Thus the energy-momentum of the collision is UNKNOWN. **So only TRANVERSE MOMENTUM & ENERGY can be used to deduce the W-mass.**
- This involves modelling and fitting of measured energy-momentum distributions in the transverse plane.

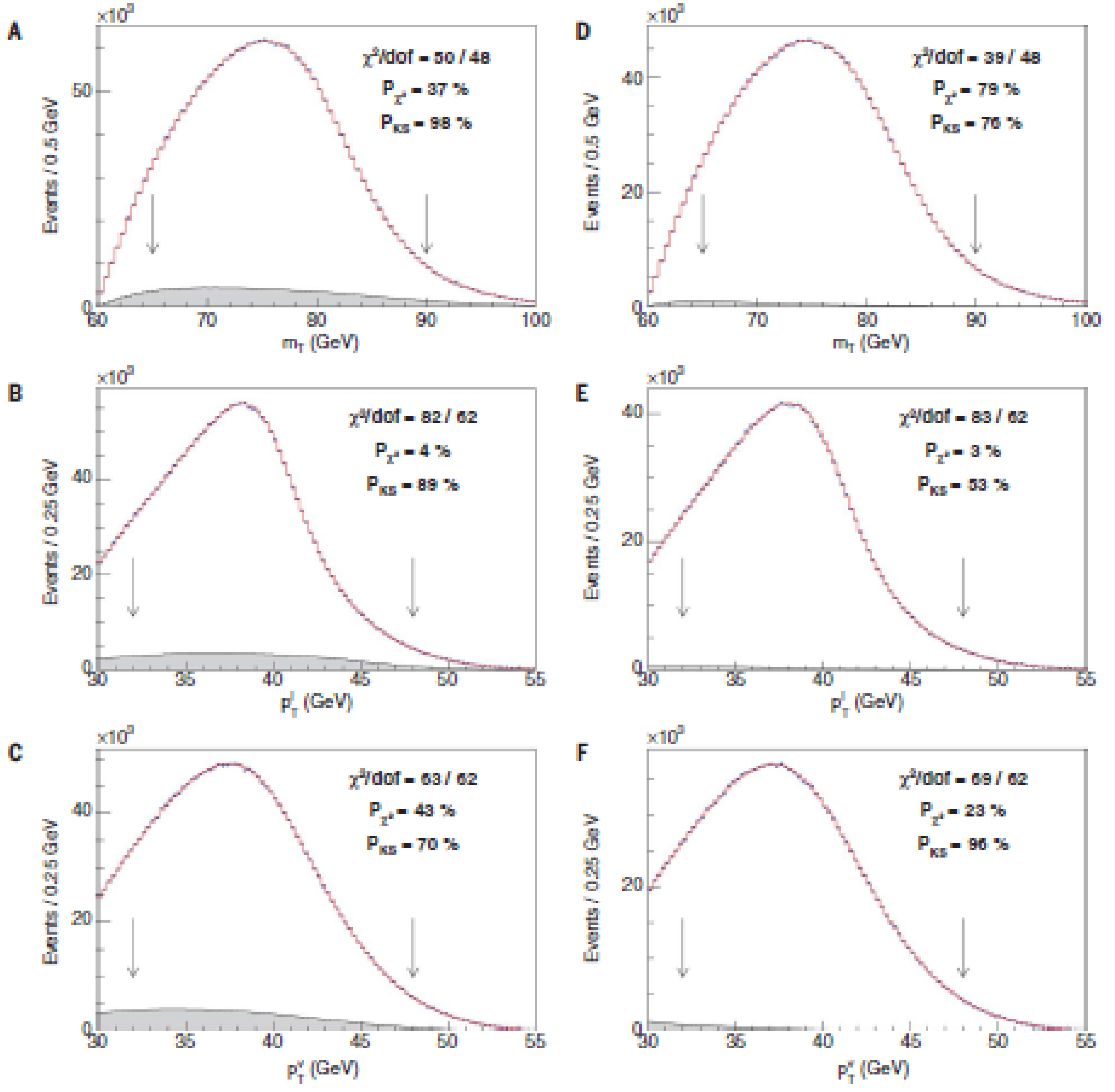
CDF Collab *et al.*, ***Science 376***, 170-176 (2022) 8 April 2022

Left: W → μν

m_T (W)

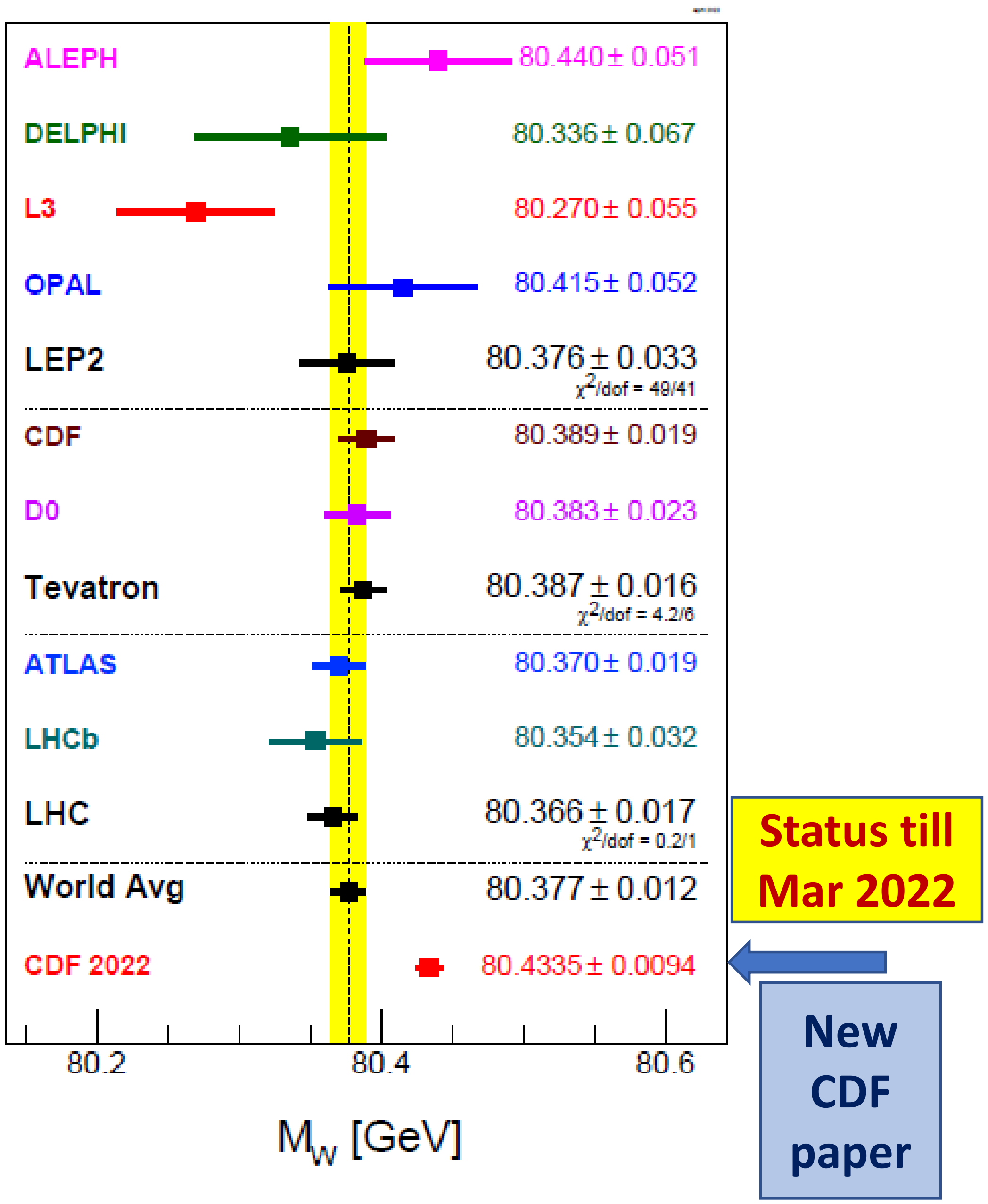
p_T (μ or e)

p_T (ν)



Right: W → eν

Fig. 4. Decay of the W boson. (**A** to **C**) Distributions for m_T (A), p_T^ℓ (B), and p_T^ν (C) for the muon channel. (**D** to **F**) Same as in (A) to (C) but for the electron channel. The data (points) and the best-fit simulation template (histogram) including backgrounds (shaded regions) are shown. The arrows indicate the fitting range.



New CDF paper in Apr 2022 using full 4M W's.

80.4335 ±0.0094

Completely disagrees with the earlier world data as well as SM predictions!

Very small error!

How to combine such **discrepant** data?

A "combination group" of physicists from CDF, CMS, D0, ATLAS, LHCb is trying to go over the various inputs that go into their W mass determinations and trying to figure out the issues.

Searches for new particles at the Tevatron
Summary: no evidence for any (predicted or unpredicted)

- MSSM (Minimal Supersymmetric extension of the SM):
- 2 Higgs doublets, with mixing angle $\tan\beta$ → 5 higgs particles

  $H^{\pm}$, CP-even scalars H^0, h^0, CP-odd A^0.

- Abazov et al, PRL 95, 151801, 2005

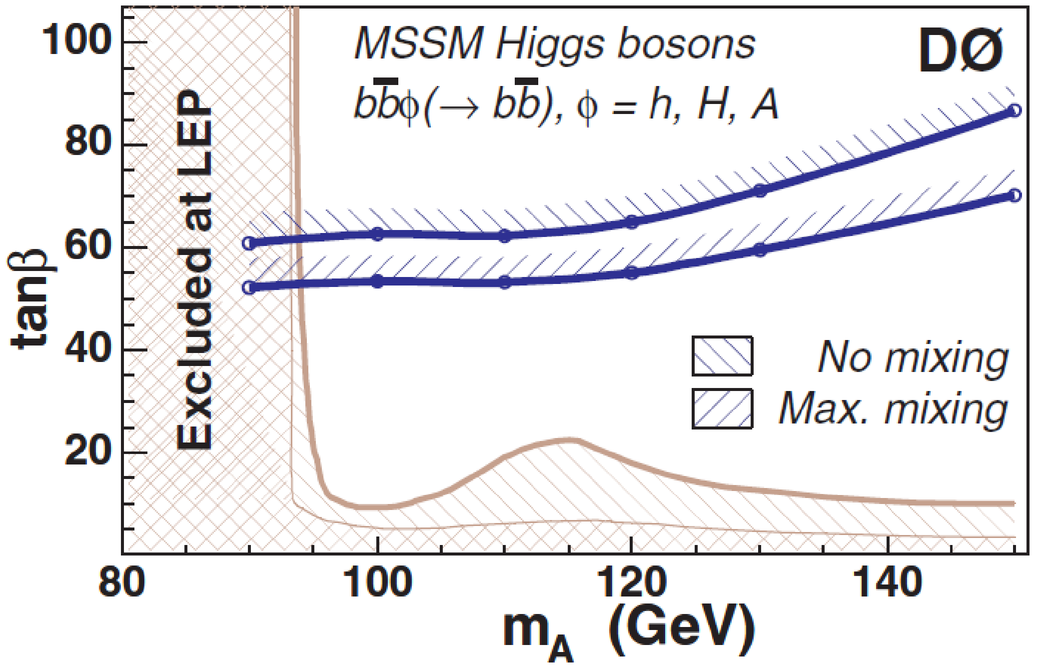


FIG. 5 (color online). The 95% C.L. upper limit on $\tan\beta$ as a function of m_A for two scenarios of the MSSM, "no mixing" and "maximal mixing." Also shown are the limits obtained by the LEP experiments for the same two scenarios of the MSSM [3].

- Search for **squarks & gluinos** in single photon events with jets & large missing E_T: B.Abbot et al, PRL 82, 29, 1999

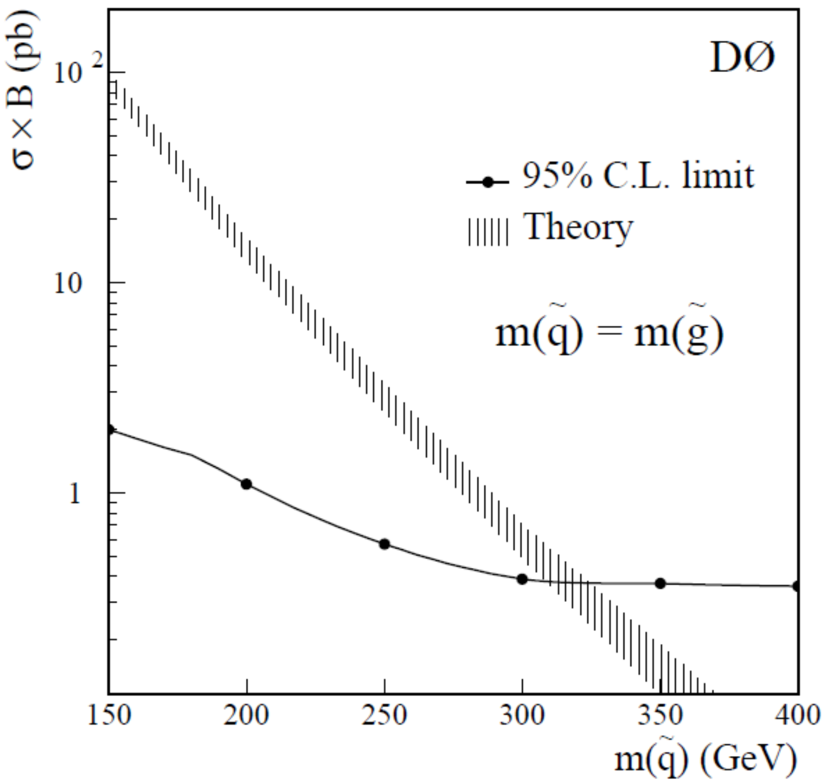


FIG. 3. The 95% C.L. upper limit on $\sigma \times B$ as a function of $m_{\tilde{q}/\tilde{g}}$, assuming equal $\tilde{q}$ and $\tilde{g}$ masses. The hatched band represents the range of expected cross sections for different sets of MSSM parameters; see text. The inflection below 200 GeV in the limit curve is the intersection of the two curves using the two sets of optimized cutoffs discussed in the text.

- Second generation **Leptoquark** search in p-pbar collisions at 1.8 TeV: S. Abachi et al, PRL 75, 3618, 1995
- Limit is set at mass > 89 GeV
- (LEP limit was 45 GeV)

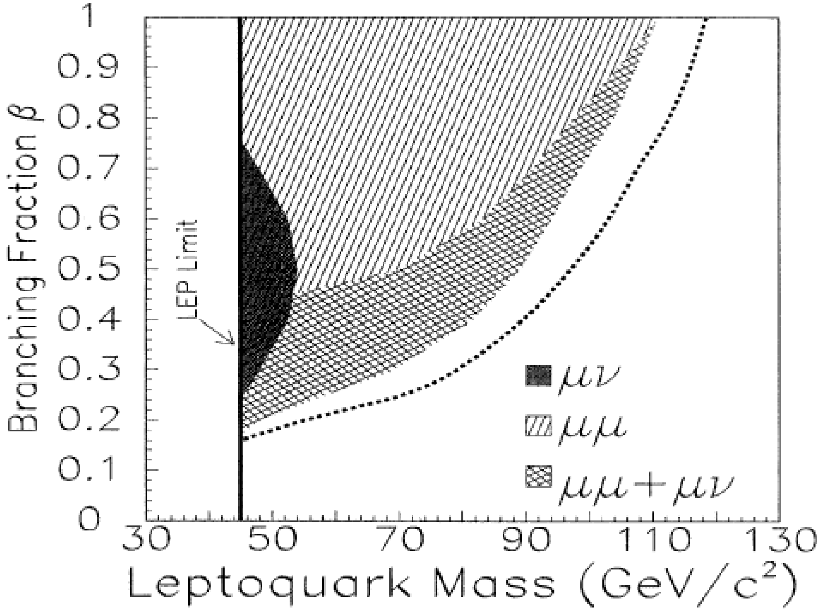


FIG. 3. The 95% C.L. excluded regions for the dimuon, single muon, and combined signatures. The dashed line is the combined limit using cross sections from ISAJET V7.06 with CTEQ2pM from Ref. [14].

LHC

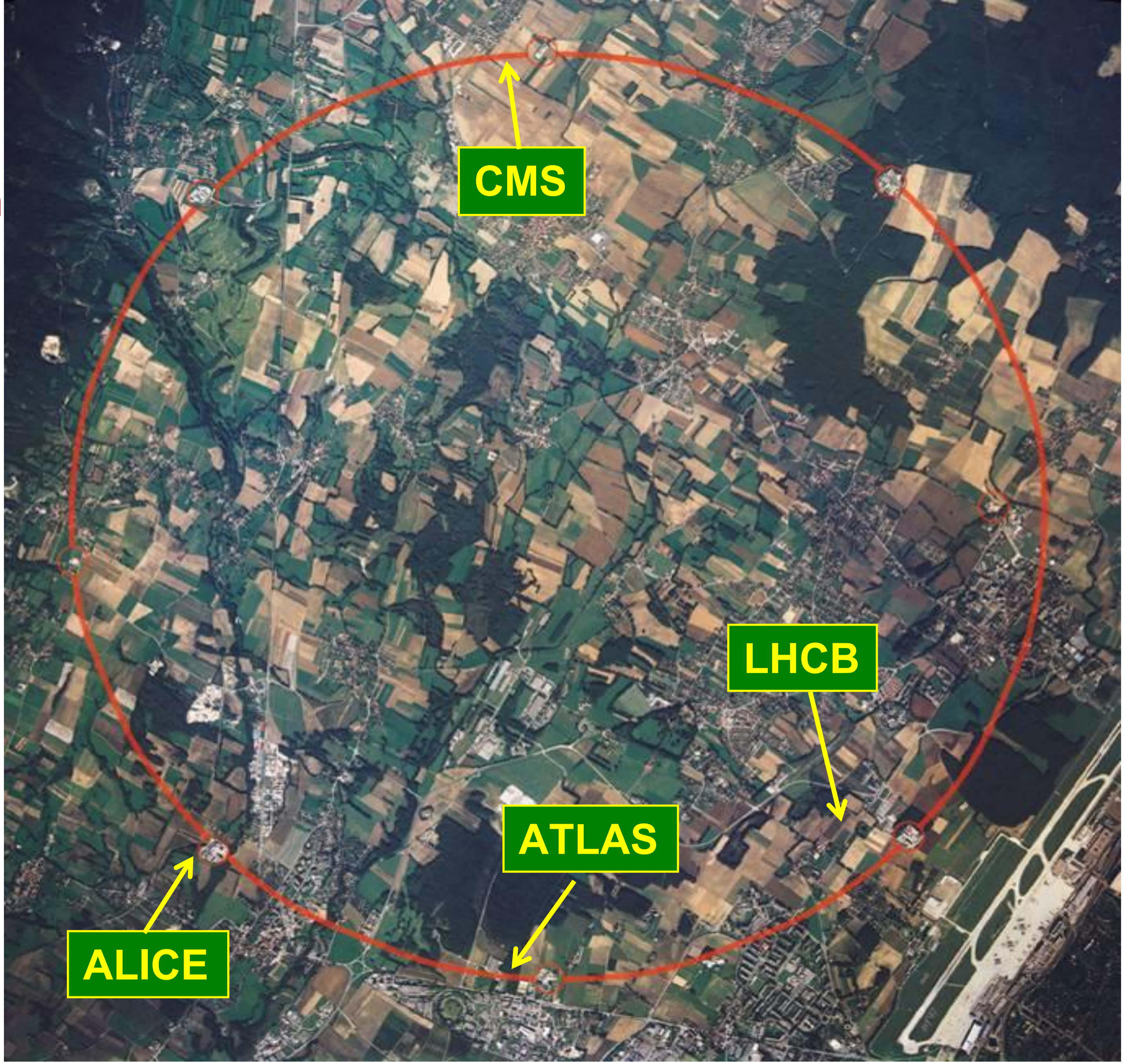
- Post-2000, the only SM particle remaining to be discovered was **the higgs**
- Additionally, there were indications that some new particle(s) should be discovered in the ~TeV mass range.
- In particular, the SUSY conjecture and theory developed around it was very attractive.
- Conjecture: that for every particle in the SM, there should exist another set of particles differing by ½ spin.
- quarks/leptons (1/2 integer spin) ←→ squarks/sleptons (integer spin) etc…
- **A great plus point was it had the potential of accounting for the "dark matter" discovered in the totally unrelated experimental field of experimental astronomy!**

LHC : 2008-2035+
circumference 26.7 km

- proton-proton & ion-ion collider
- 4+ experiments
- Design energy: 7 TeV per beam (total 14 TeV)
- Till 2013 operated at 3.5 → 4 TeV/beam

- 2015 → Operational at 6.5 TeV/beam. Total energy = 13 TeV.

- 2022 → 6.8 TeV/beam. Total 13.6 TeV



LHC: technological marvel

- To accelerate and store these beams the insides of these pipes are

- the **coldest place in the universe(!)** being maintained at 1.9 degree Kelvin (outer space is at 2.7 degree)

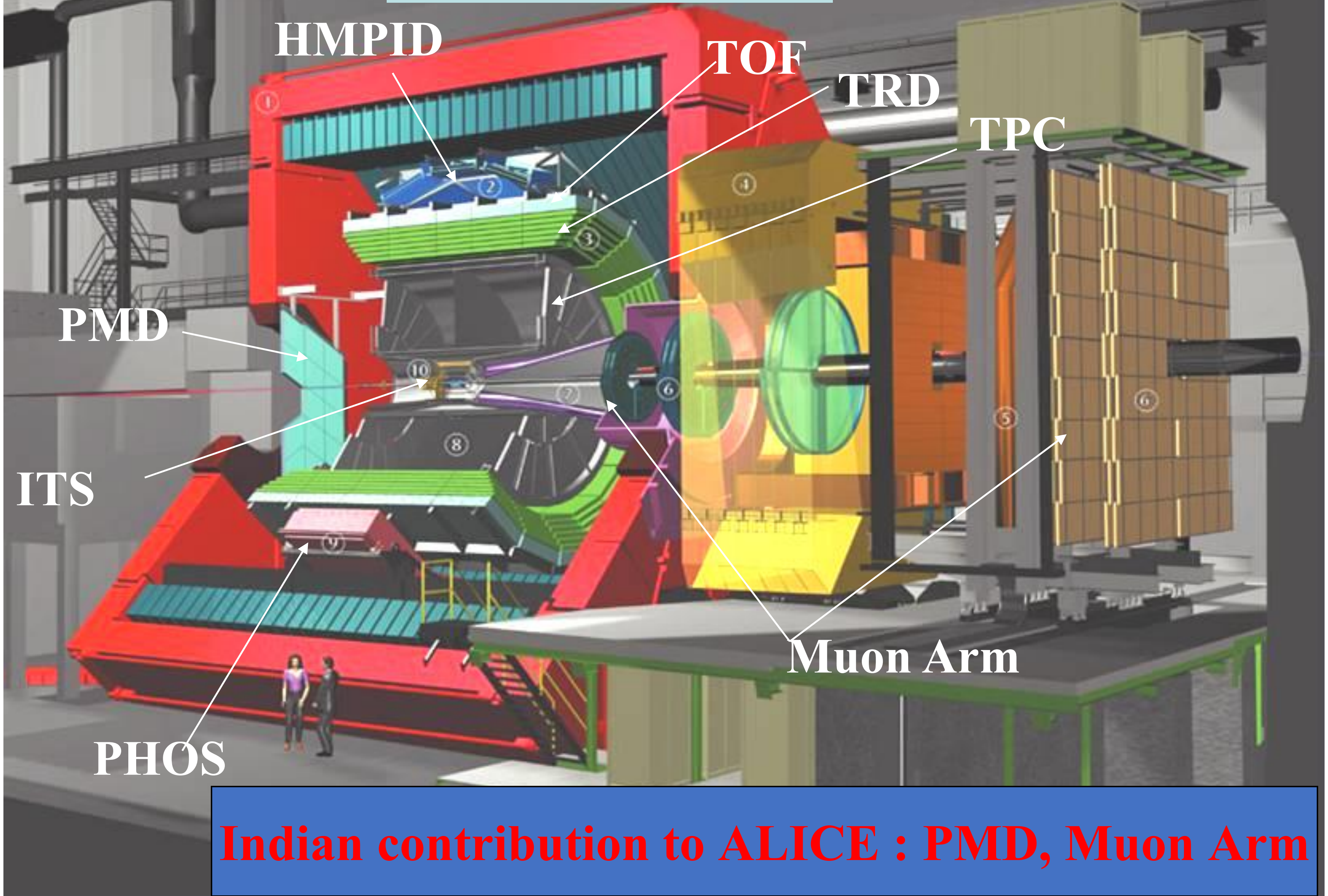
- the **most empty place in the galaxy,** with extremely high vacuum so the beams don’t dissipate.

India in LHC - experiments

- Indian groups participating in 2 LHC experiments: CMS and ALICE

- CMS is one of the two general purpose experiments at LHC (ATLAS is the other).
- ALICE is a specialized experiment for studying nucleus-nucleus (Pb-Pb) collisions in search for quark gluon plasma.
- India-CMS has TIFR, Mumbai as its nodal institution
- India-ALICE has VECC, Kolkata as its nodal institution

ALICE Setup



Indian contribution to ALICE : PMD, Muon Arm

Indian groups in ALICE

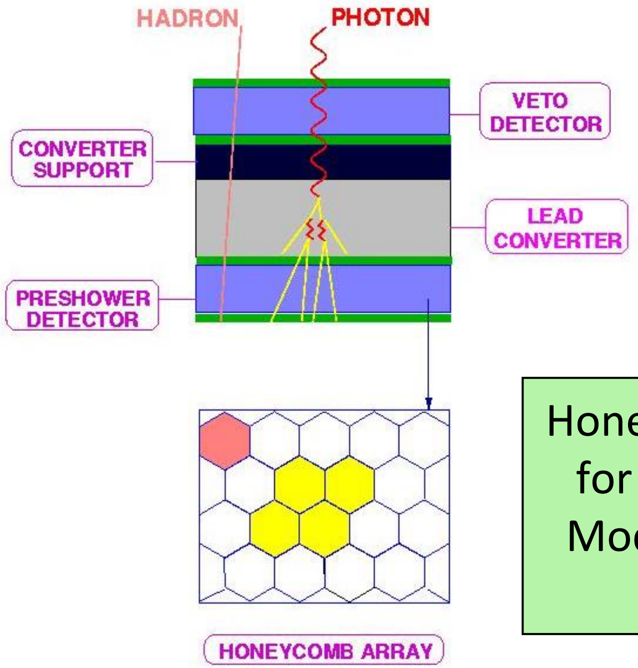
PMD

- **Bhubaneswar**, Institute of Physics
- **Chandigarh**, Panjab University
- **Jaipur**, University of Rajasthan
- **Jammu**, University of Jammu
- **Kolkata**, Variable Energy Cyclotron Centre
- **Mumbai**, Bhabha Atomic Research Centre
- **Mumbai**, Indian Institute of Technology

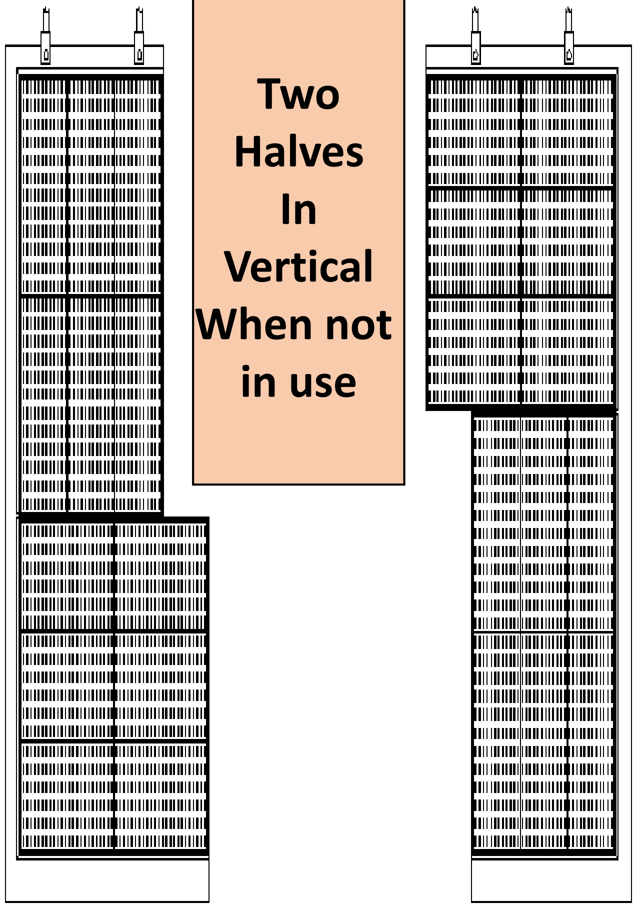
Muon Arm

- **Aligarh**, Aligarh Muslim University
- **Kolkata**, Saha Institute of Nuclear Physics

ALICE PMD (η=2.3 – 3.5)



Honeycomb counters for ALICE PMD are Modified edition of STAR PMD

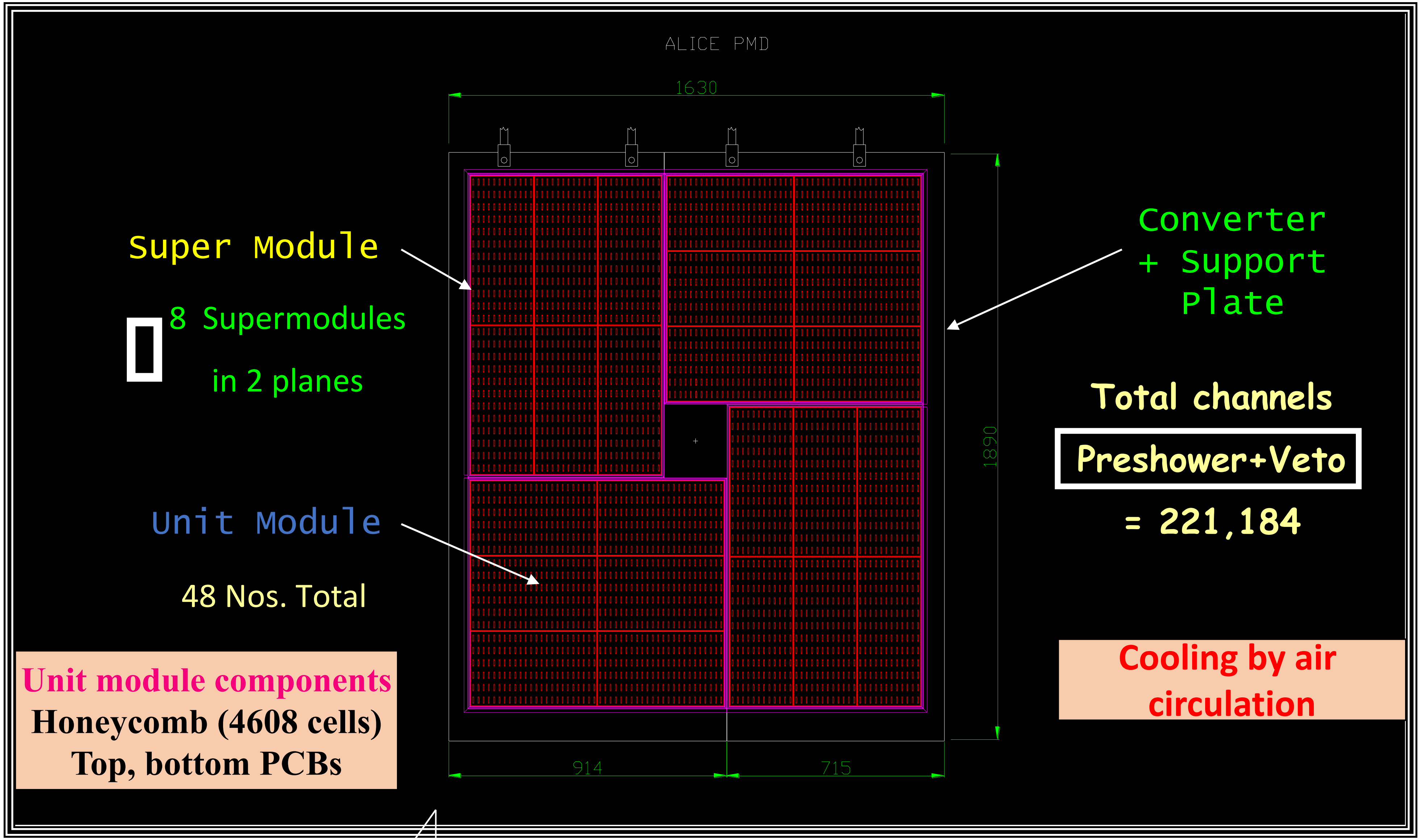


Two Halves In Vertical When not in use

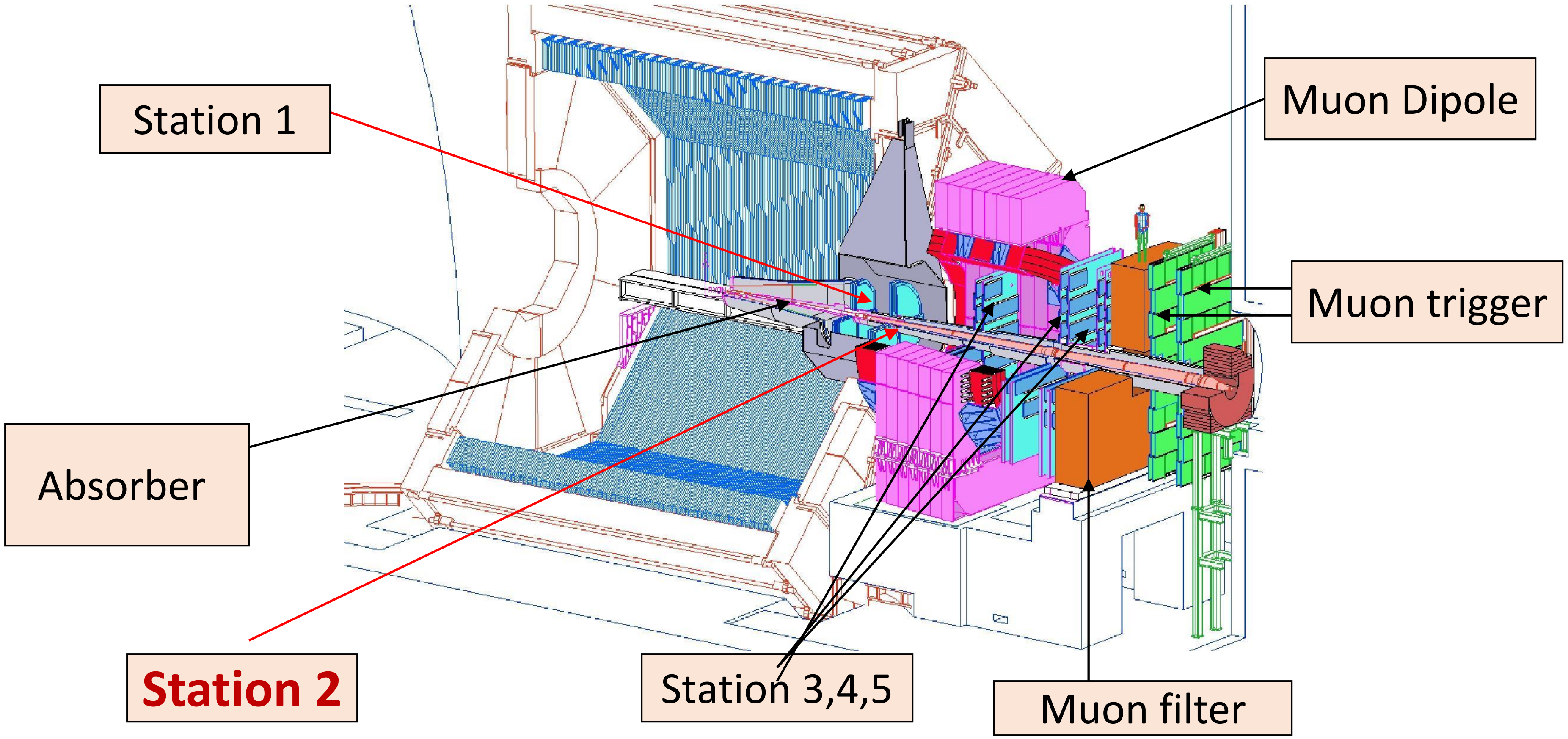
Two planes of honeycomb proportional counters
3 X_0 thick lead converter
Arranged in two halves in vertical plane
Installed at z=360 cm from I.P.

PMD in ALICE : Fully Indian Contribution

ALICE PMD Layout (Data taking position)

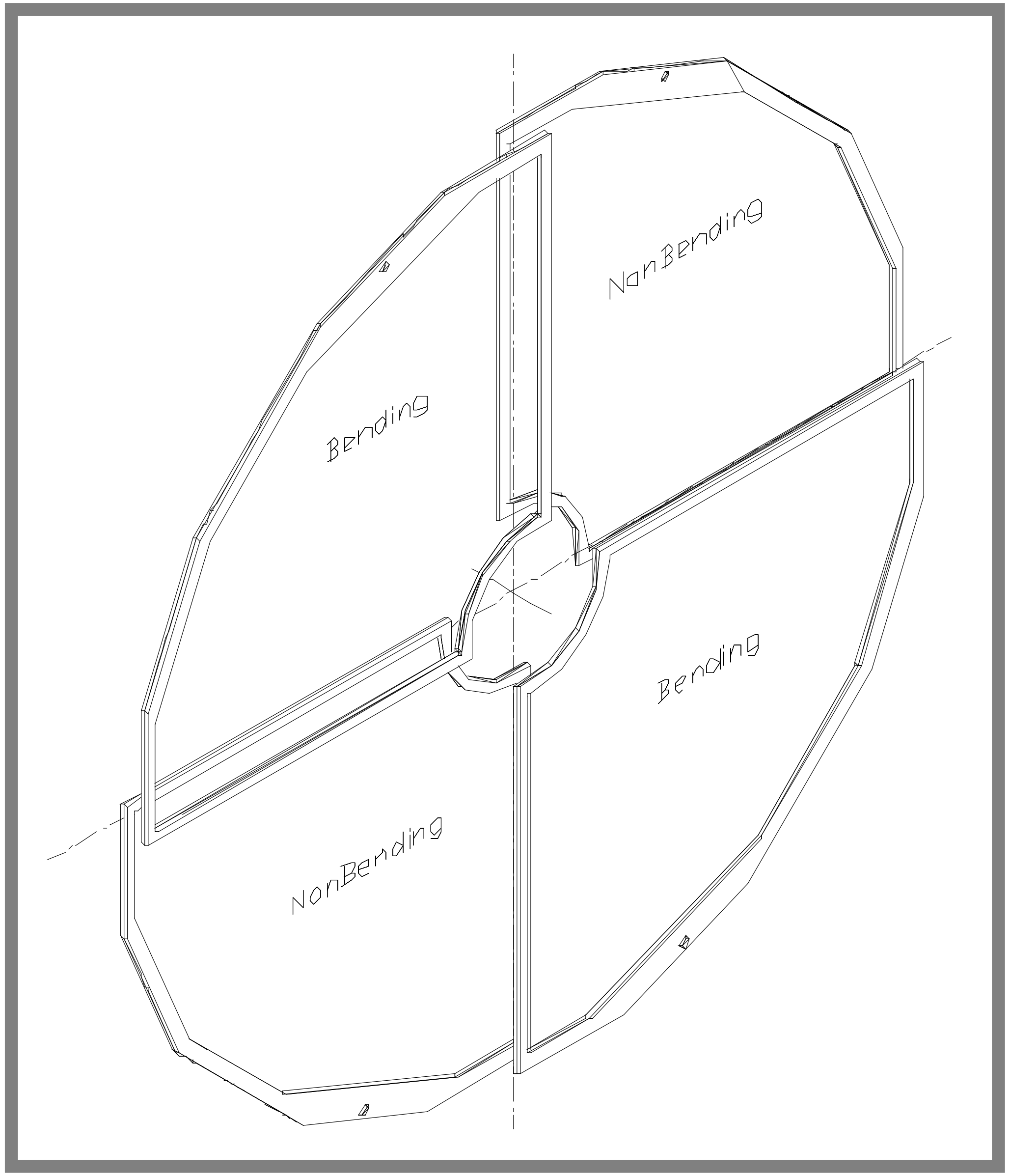


Forward MUON Spectrometer of ALICE



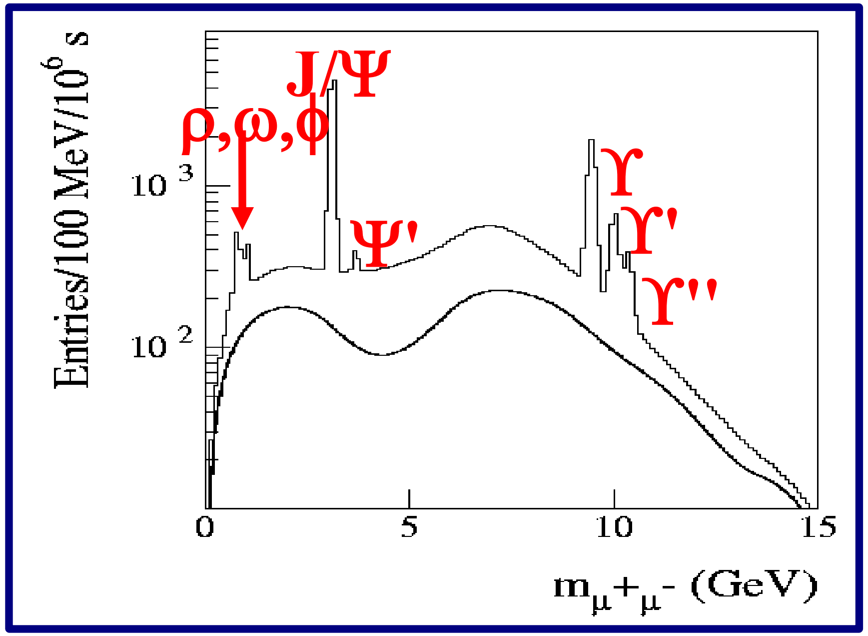
Tracking Station 2, part of absorber and MANAS for 1M channels from India

MUON Chambers

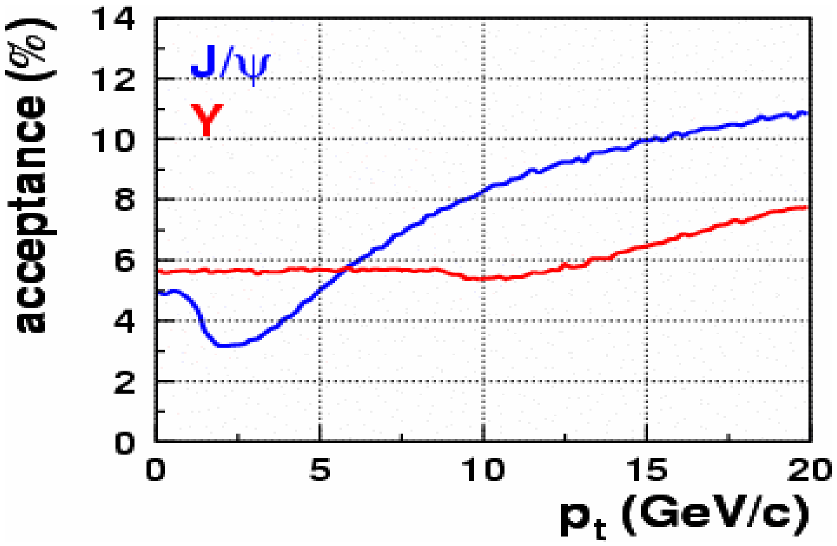


Physics of Heavy Quark Resonances

- **Study of the Quark Gluon Plasma in heavy ion collisions at LHC energies via muon production.**
- **Observables:**
  - Quarkonia production: J/Psi, Psi', Upsilon family via their muon decay (5%, 1%, 2% BR)
  - Open Charm and beauty: D^{+-0}, D*, D^{+-}_{s} and B^{+-0}, B^{0}_{s} B^{+-}_{c} via their semi-muonic decay (12% & 15% BR)
  - Vector mesons ρ, ω, φ.



- **Invariant Mass Analysis**
  - **Separation of Upsilon resonances (s<100 MeV)**
  - **Combinatorial and correlated background subtraction.**
  - **Measurement of bottonium**
  - **Recombination versus Debye screening @ LHC**



Front-end Absorber components

SS cone, permeability less than 1.005, 2.5 m dia, 80 cm high

Graphite cone 1.8 m dia, 1.2 meter long, 2.8 tonnes,

Intregration completed

ALICE@LHC : Summary

R&D for a special honeycomb proportional counter with zero cross-talk for charged particle detection

Large scale gaseous detectors, with hundreds of thousands of channels, made for ALICE PMD and muon tracking stations

Low noise analogue signal processing ASIC designed and fabricated in large number in India, supplied to a major international collaboration, for the first time by an Indian group

India-CMS Collaboration

- **Panjab U, Delhi U, BARC, TIFR , NISER (Bhubaneswar), Visva-Bharati U, IITB (Mumbai), SINP (Kolkata),**

  IISER (Pune), IITM (Chennai), Shoolini (H.P.), IIT, NISER Bhubaneswar, IISc (Bangalore),… total of 14 groups now…

- **Initial Hardware responsibilities (2000 – 2006):**

  - TIFR, PU: Outer hadron calorimeter.

  Physics necessity: ensure more hermetic detector to look for missing energy signals of SUSY/ other new physics. SUSY → DARK MATTER CANDIDATE

  - BARC, DU: Silicon Pre-shower Detector.

  Physics necessity: discriminate between γ/π^0 to detect the Higgs → $\gamma\gamma$ decay mode (for low mass Higgs favored by existing data)

Later Hardware responsibility (2011 – 13)

- Owing to time and funding constraints some CMS detectors were not fabricated and installed initially.

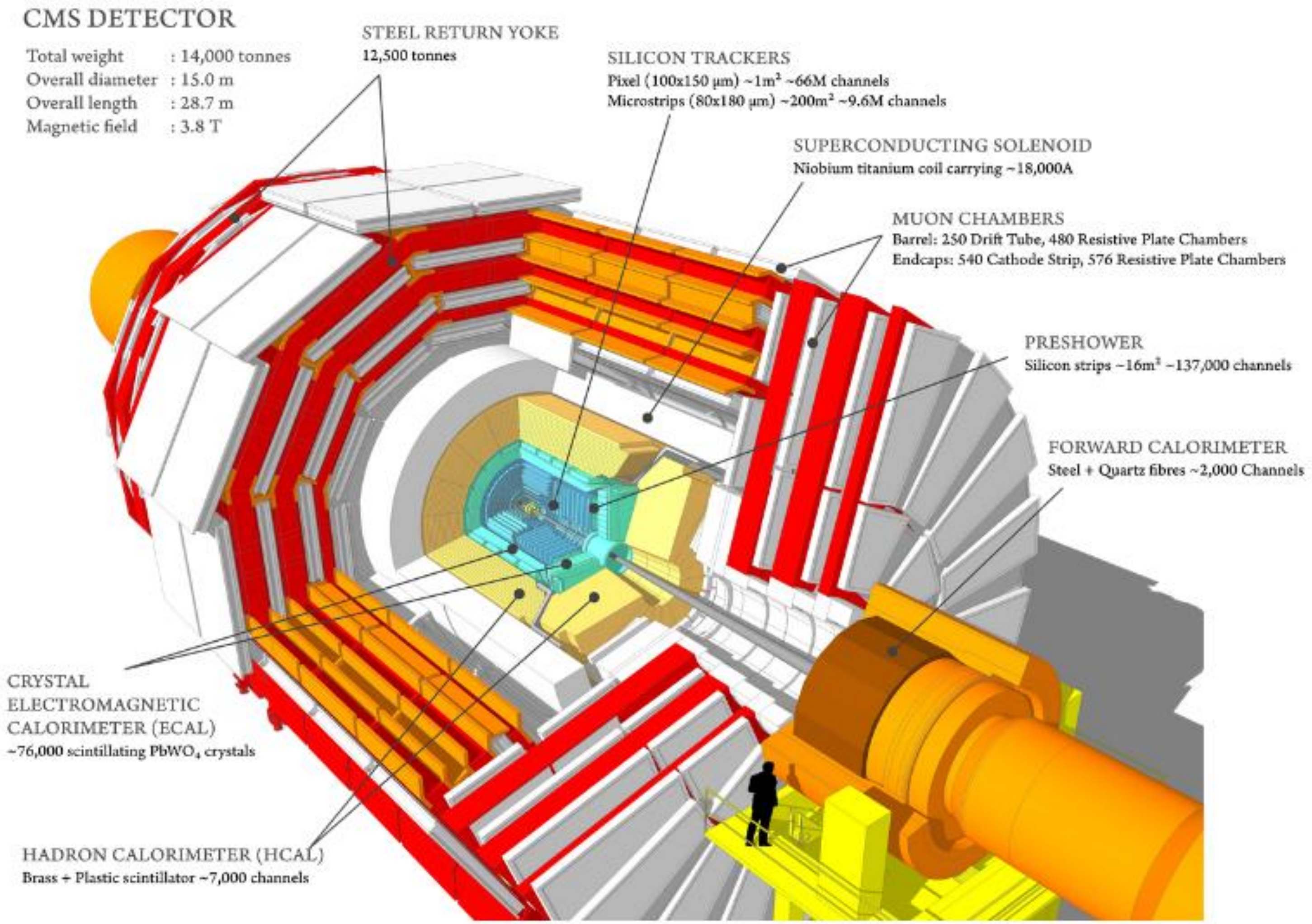
- **Forward-backward RPCs (Resistive Plate Chambers)** which help very much in muon detection and more accurate reconstruction.

- **BARC and Panjab U** contributed to this effort in 2011-13 and these chambers were successfully installed in the CMS detector during the 2013-15 shut down.

How CMS Works

The 14,000-tonne detector gets its name from the fact that:

- at 15 metres high and 21 metres long, it really is quite **compact** for all the detector material it contains;
- it is designed to detect particles known as **muons** very accurately; and
- it has the most powerful **solenoid** magnet ever made.



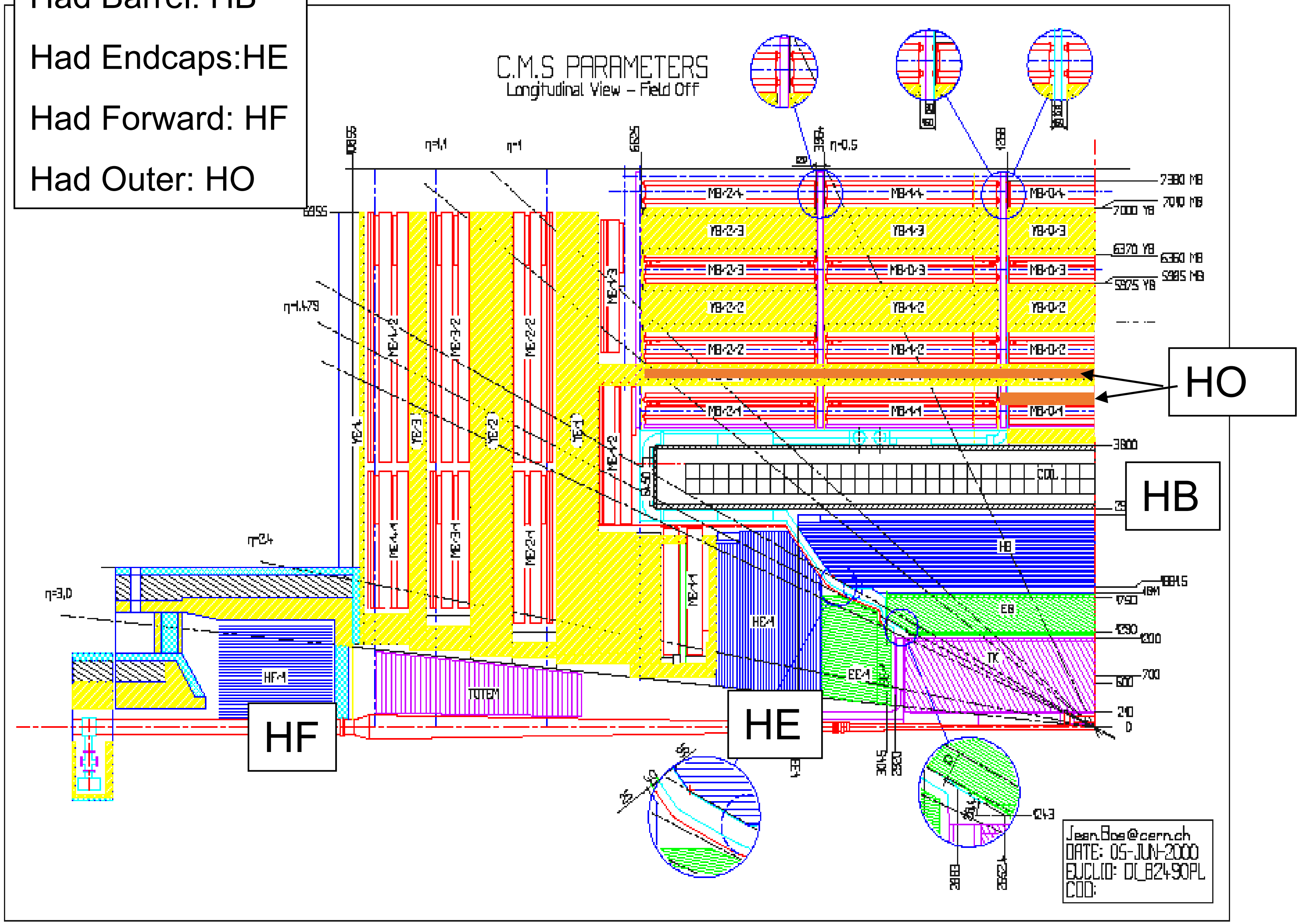
Hadronic Calorimeter: HCAL; HO essential for greater absorption of hadrons in central region

Had Barrel: HB

Had Endcaps:HE

Had Forward: HF

Had Outer: HO

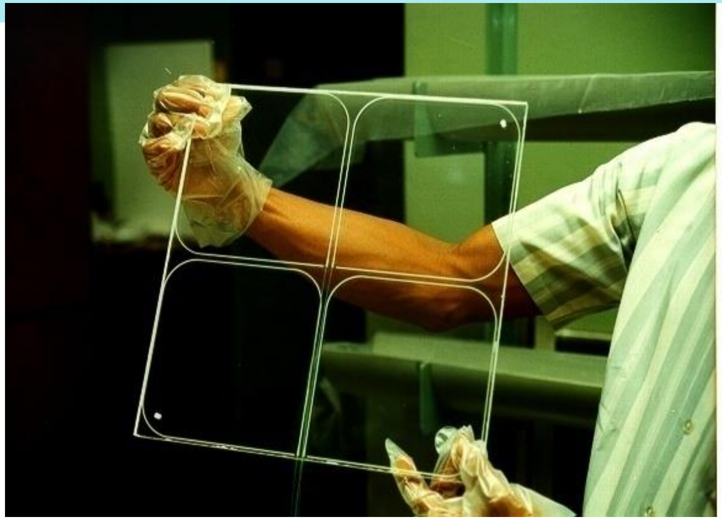


HO basic design

- Detector element is a plastic scintillator tile which produces light when charged particles pass through it
- This light is collected by embedded WLS fibers (4 sigma grooves/tile)
- Light is transported to HPD detector via clear optical fibers spliced to WLS fibers

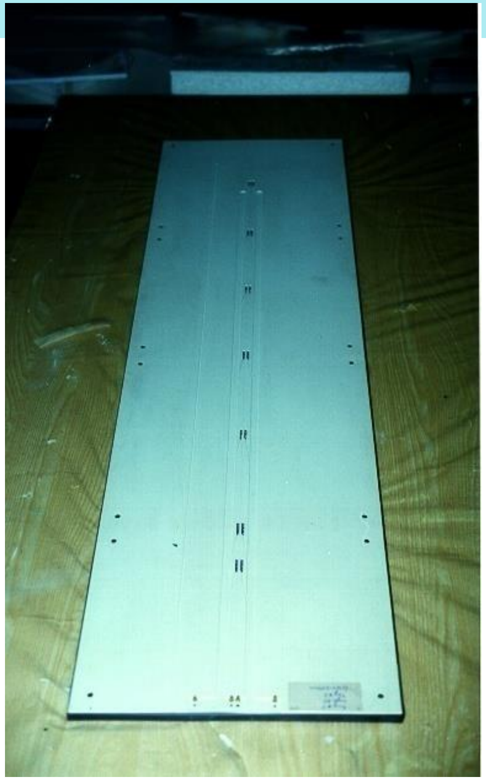
- Size and placement of the tiles is matched to geometric towers in the CMS calorimeters
- Tiles are grouped together and packed in “trays” for ease of handling, and 6 trays in each phi sector are in turn inserted inside aluminum honeycomb housings.

HO Tile, Tray (one of 432 trays)



⇑

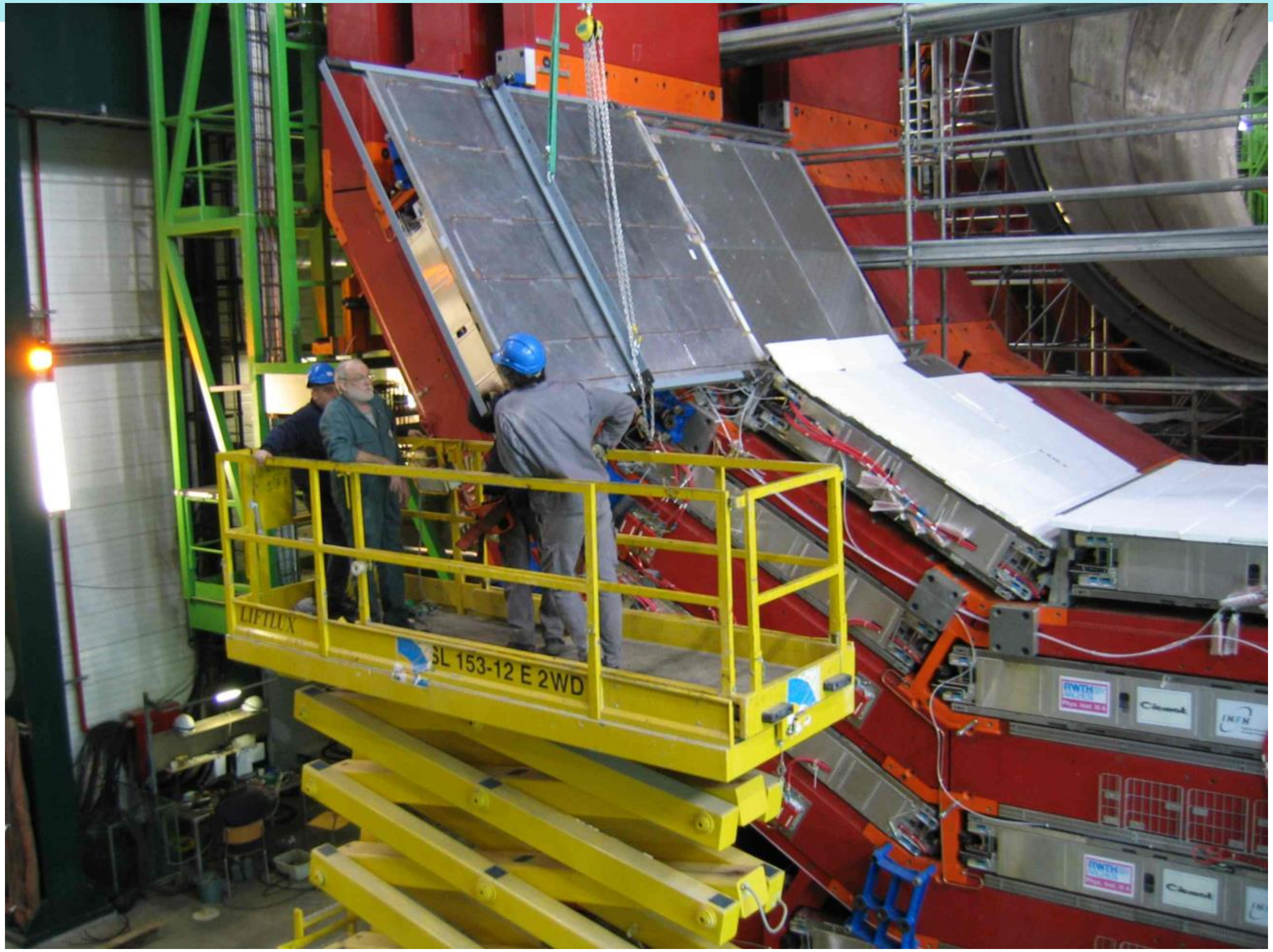
PPP tile with 4 σ grooves visible



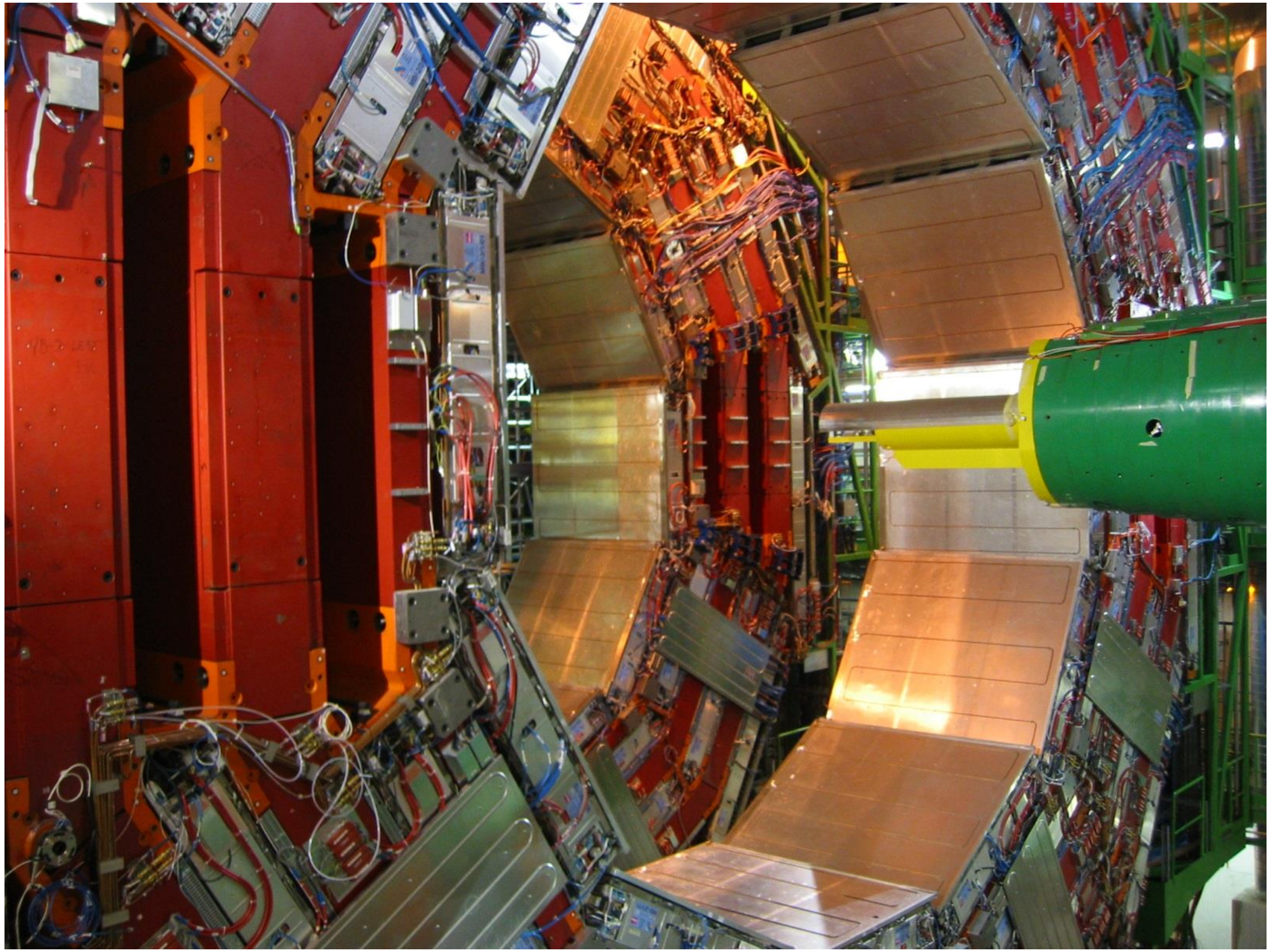
⇐ **Finished Tray**

⇐ **Pigtail with connector**

Installation of one HO housing containing 6 trays in CMS magnet

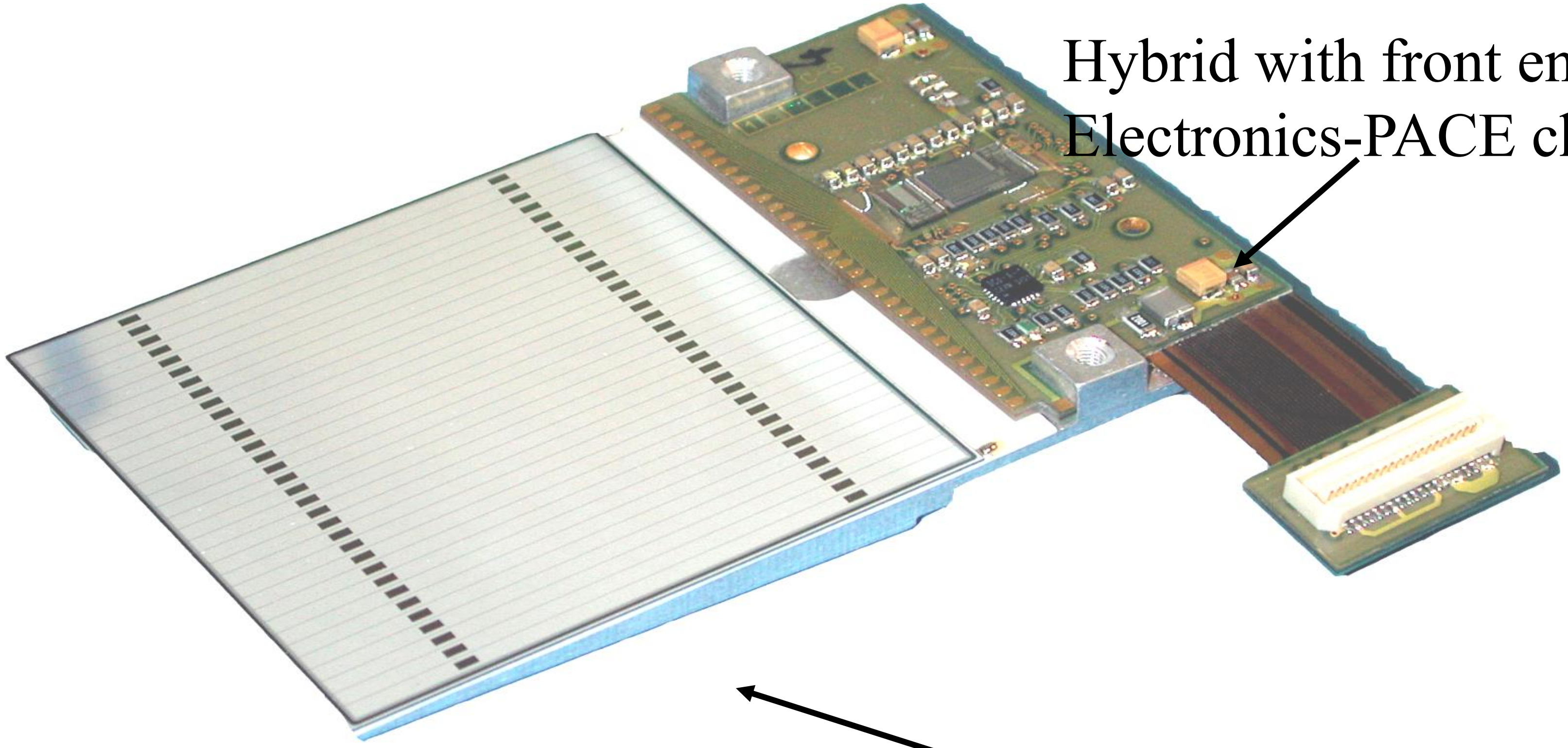


In Underground Pit



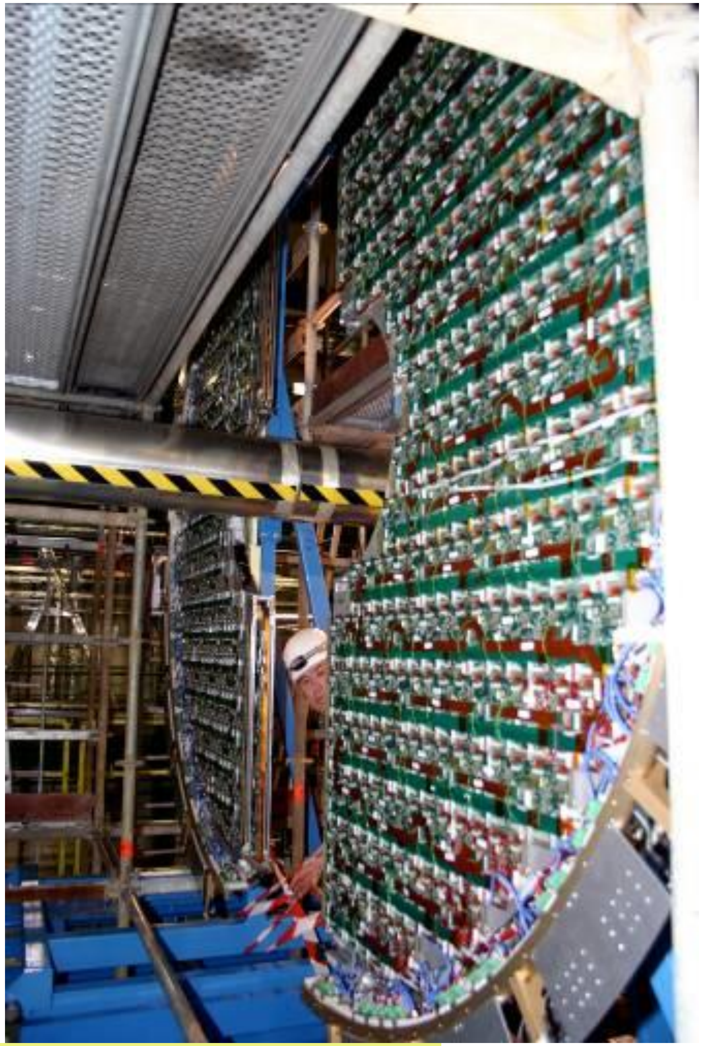
Silicon detector made in BEL, Bangalore, on micro-module made at CERN

Hybrid with front end Electronics-PACE chip



Detector mounted on ceramic & Al tile

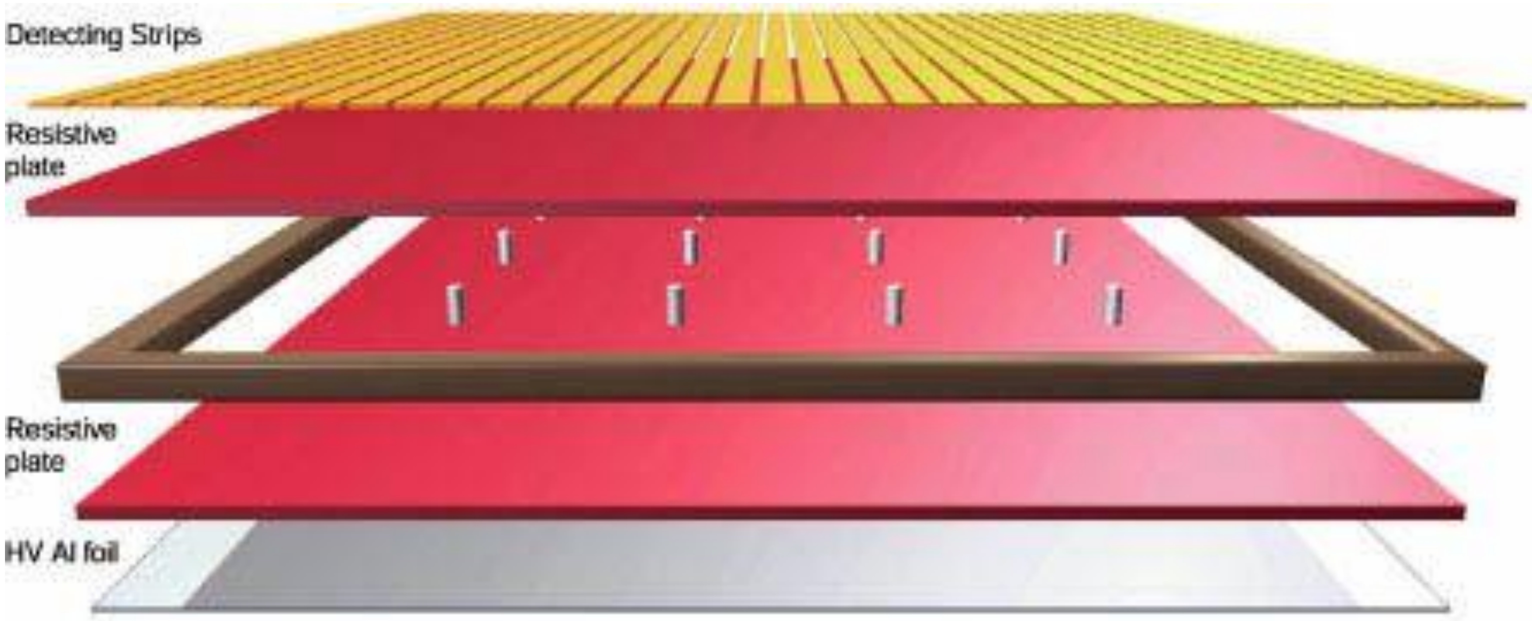
Assembly/mounting at CERN



The two separate ES Dees

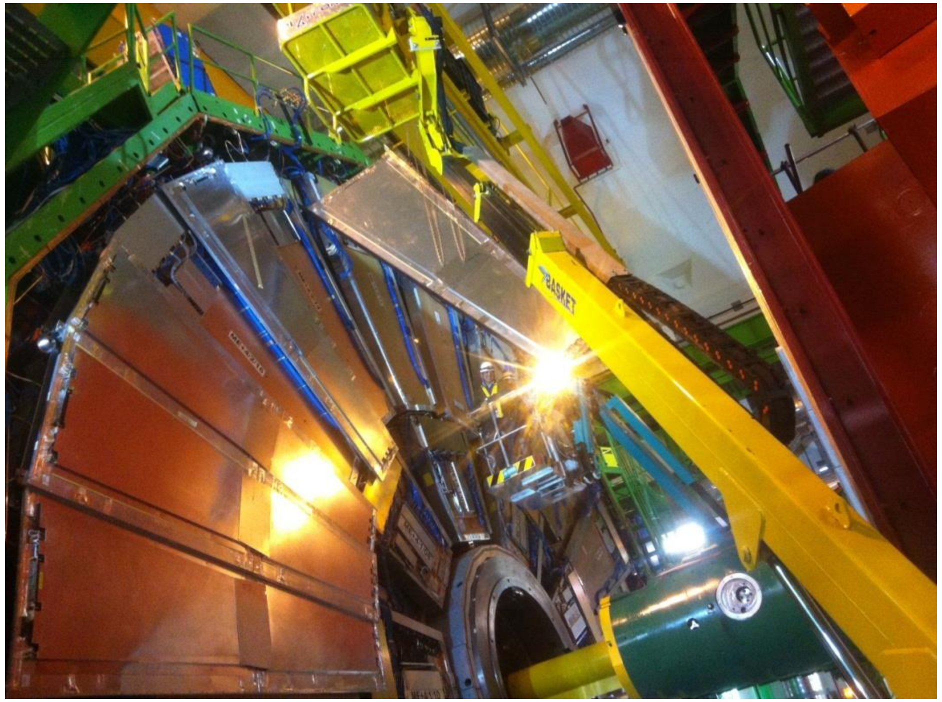
CMS RPCs

Two parallel resistive plates (2mm thick bakelite,1-2x10^{10} ohm-cm) with 2 mm gap using spacers. The gap is filled with UV photon absorbing gas (95% $C_2H_2F_4$ + 5% i- C_4H_{10}) at atmospheric pressure. Backs of the plates are low resistivity and 8.5-9 kV is applied between them. A charged particle passing through produces ionization which is collected on strips on one or both sides. There are 2 gaps in one RPC.



RPC Upgrade for the CMS : Assembly and characterization of RPCs at NPD-BARC

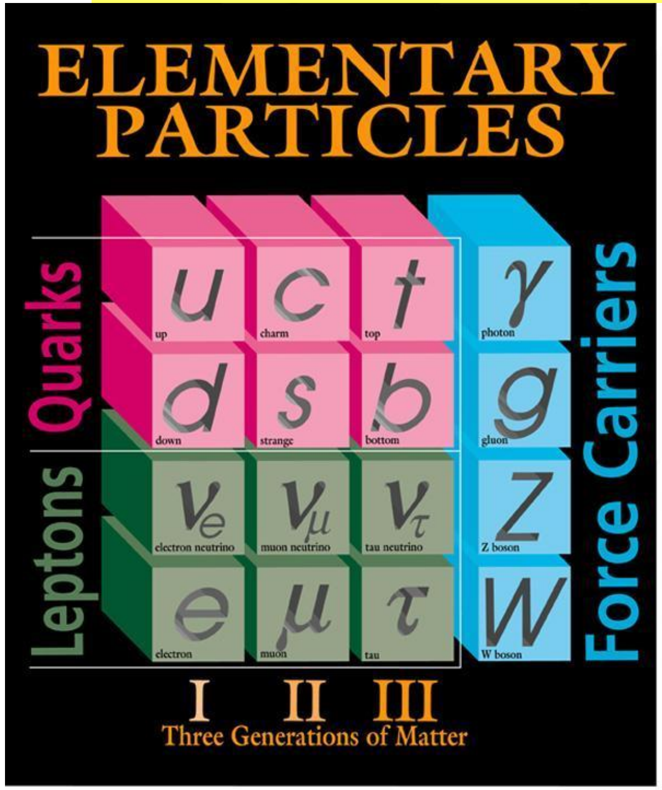
RPC Installation



How was the Higgs actually discovered?

- One detects the decay products and "reconstructs" the mass of the decayed particle.

Possible decay products:

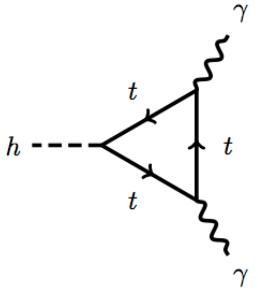


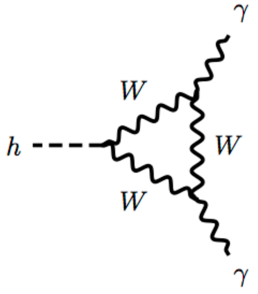
Fermilab 95-759

H → $u\bar{u}$, mass = few MeV
$d\bar{d}$, few MeV
$s\bar{s}$, ~ 100 MeV
$c\bar{c}$, ~ 1.3 GeV
$b\bar{b}$, ~ 4.2 GeV
$t\bar{t}$, ~ 173 GeV

H → $W^+ W^-$ ~ 80 GeV
H → $Z Z^*$ ~ 91 GeV
H → γγ = zero

BUT indirectly is possible
Most important.
EASILY IDENTIFIED





How does one get the Higgs mass?

- OK, so we have detected 2 gamma's with energies E_1 & E_2 and with angle θ between them…

- Then if we think these gammas have come from the decay of one particle, the mass of that particle would be

$$M = \sqrt{[2 E_1 E_2 (1 - \text{cosine } \theta)]}$$

(YES! Its as simple as that!!)

- **Of course, gammas can from other sources also (background).**
- **Thus if we plot M one will see a continuous distribution of masses (background), and if a Higgs is present, one will see a superimposed peak.**

2012: Discovery of the Higgs → ZZ → γγ

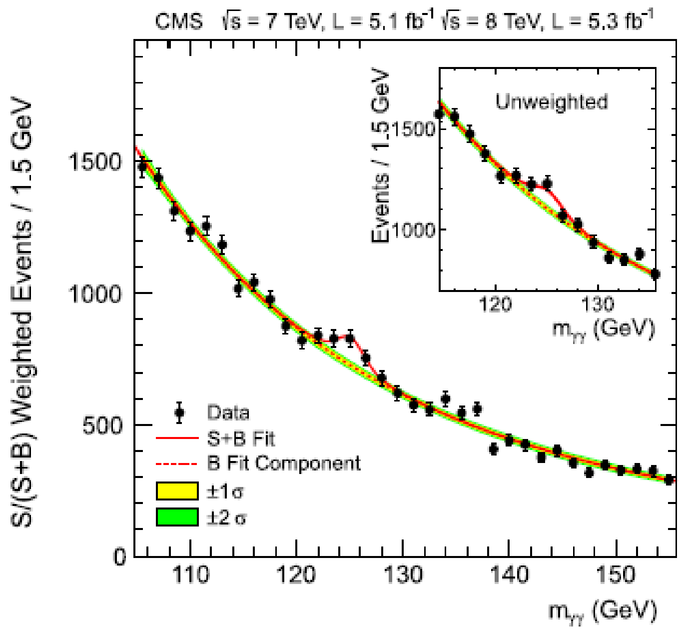
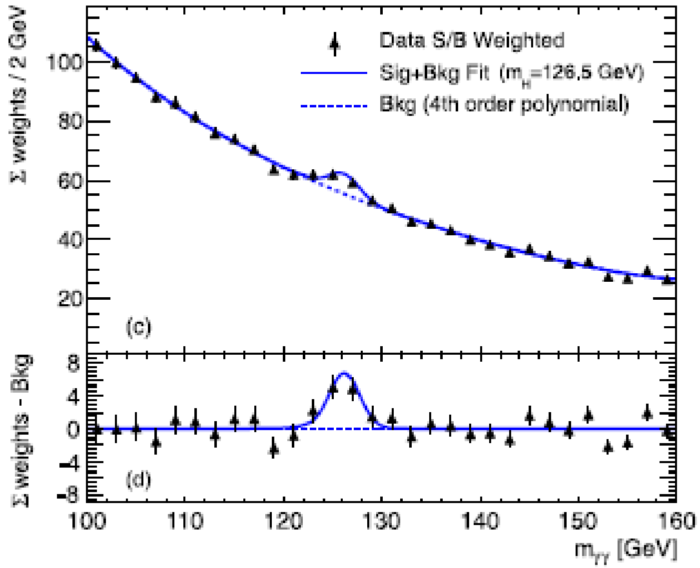


Fig. 3. The diphoton invariant mass distribution with each event weighted by the $S/(S+B)$ value of its category. The lines represent the fitted background and signal, and the coloured bands represent the ±1 and ±2 standard deviation uncertainties in the background estimate. The inset shows the central part of the unweighted invariant mass distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)



ATLAS: Phys. Lett. B716, p1-29
CMS: Phys. Lett. B716, p30-61

2012: Discovery of the Higgs → ZZ → 4l

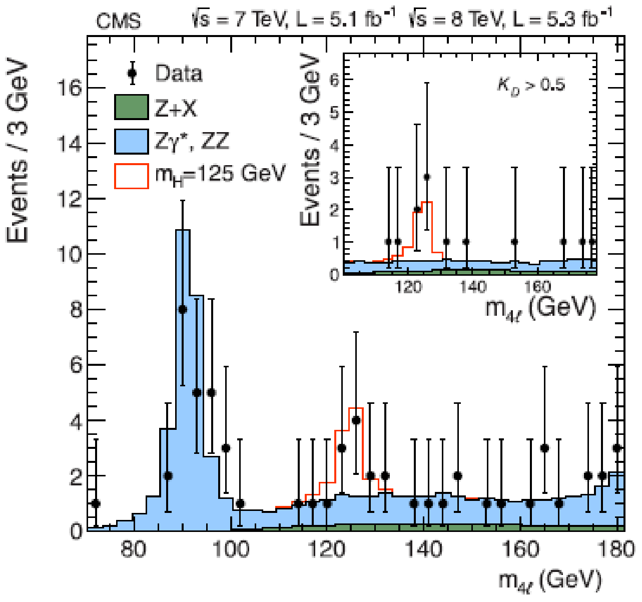


Fig. 4. Distribution of the four-lepton invariant mass for the $ZZ \to 4\ell$ analysis. The points represent the data, the filled histograms represent the background, and the open histogram shows the signal expectation for a Higgs boson of mass $m_H = 125$ GeV, added to the background expectation. The inset shows the $m_{4\ell}$ distribution after selection of events with $K_D > 0.5$, as described in the text.

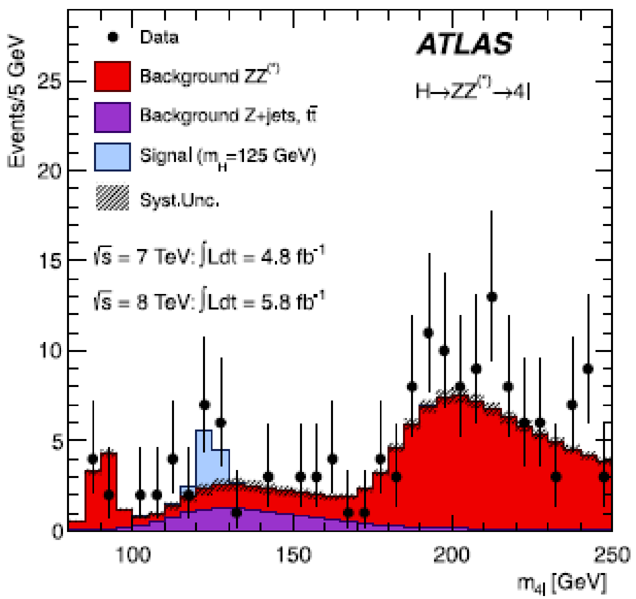
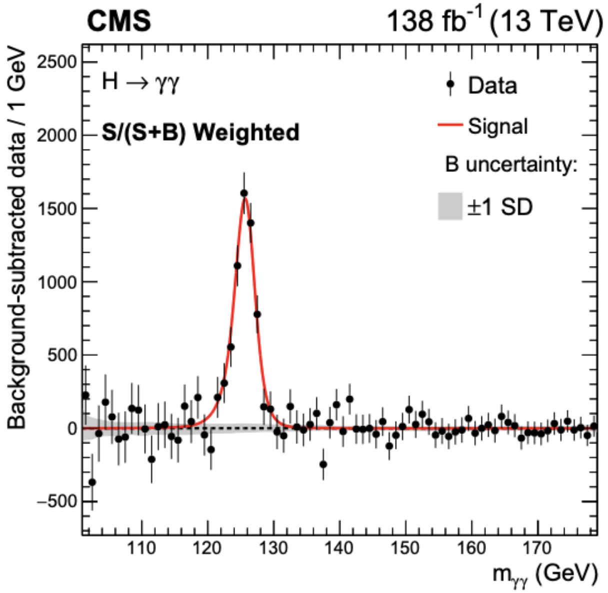
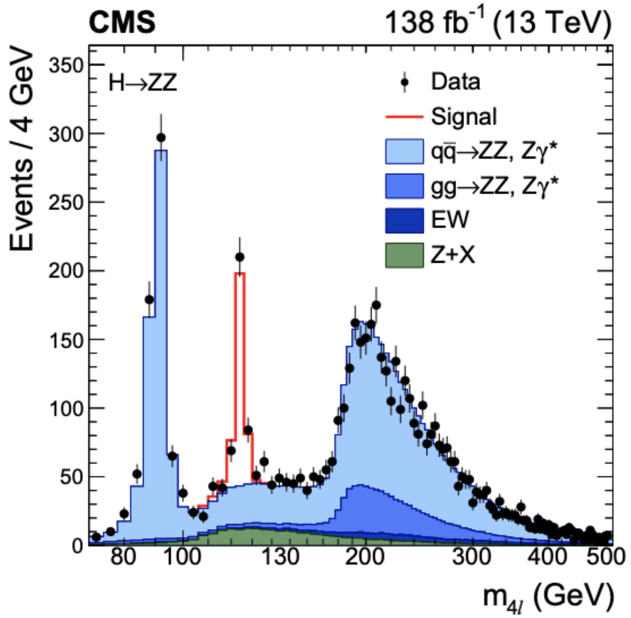
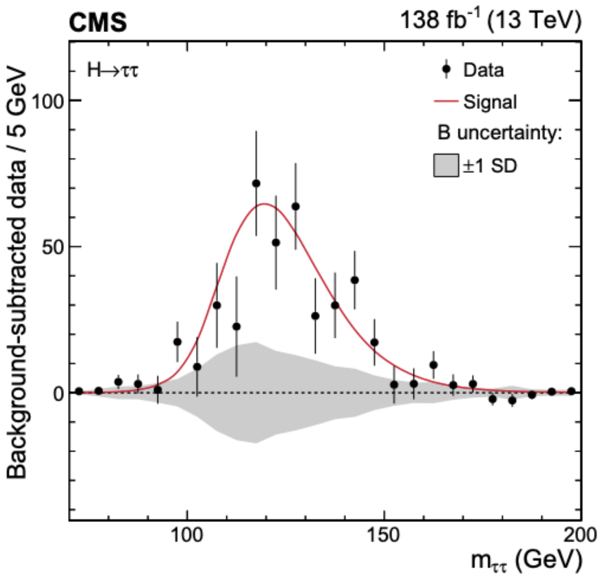


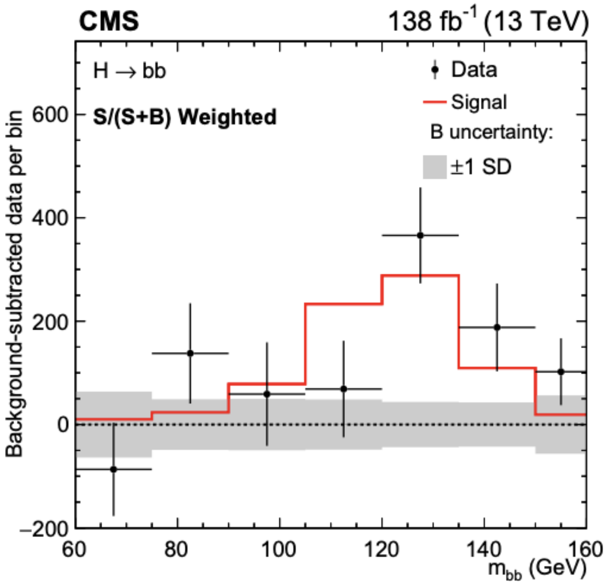
Fig. 2. The distribution of the four-lepton invariant mass, $m_{4\ell}$, for the selected candidates, compared to the background expectation in the 80–250 GeV mass range, for the combination of the $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV data. The signal expectation for a SM Higgs with $m_H = 125$ GeV is also shown.

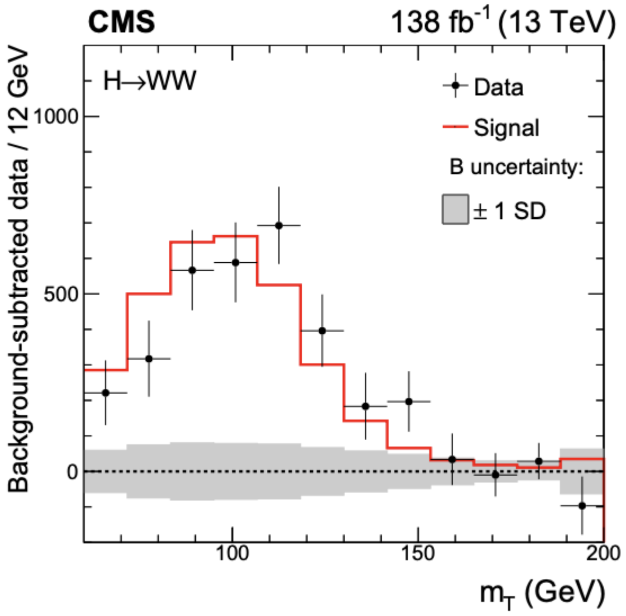
Bosonic channels (2022) Fermionic channels

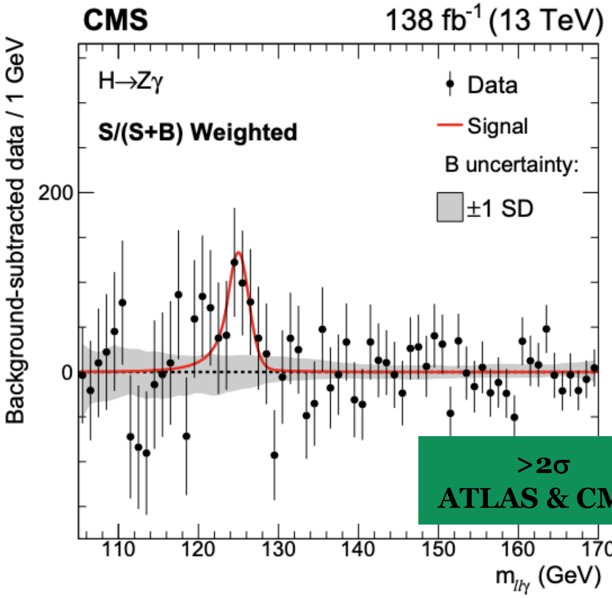




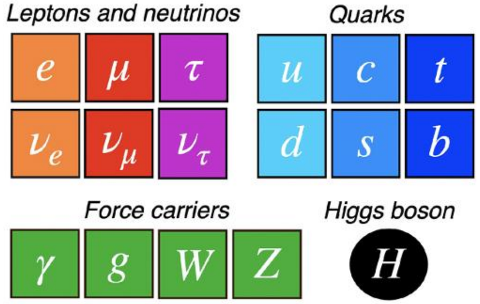


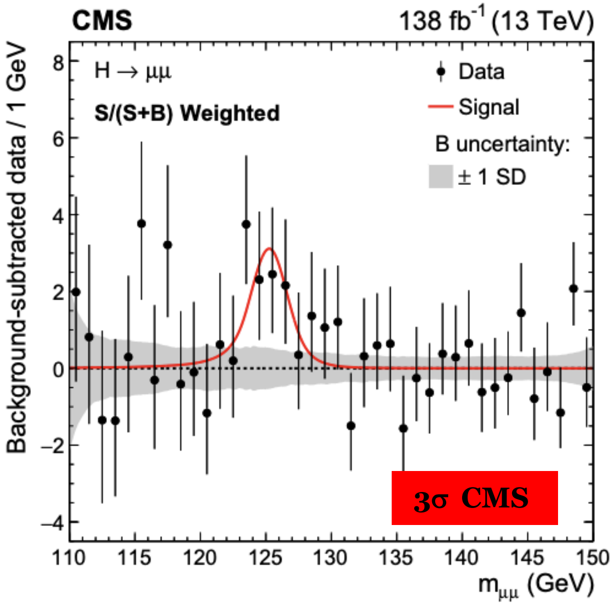






>2σ
ATLAS & CMS





3σ CMS

Nature 607, 60-68 (2022)

The Higgs mass from $\gamma\gamma$ and 4l decay channels

Once the mass is known all other properties are precisely defined.

$\gamma\gamma$

$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{12})$$

Choice of the primary vertex

Energy calibration

4 leptons: mass measurement performed with a 3D fit

- four –lepton invariant mass $\mathbf{m_{4l}}$
- associated per-event mass uncertainty $\delta \mathbf{m_{4l}}$
- kinematic discriminant MELA/NN

→ lepton momentum scale

ATLAS+CMS Run1 125.09 ± 0.24 (± 0.21 stat ± 0.11 syst) GeV

CMS Run1 + 2016 125.38 ± 0.14 (± 0.11 stat ± 0.08 syst) GeV

ATLAS Run1 + *4l* Run2 124.94 ± 0.17 (± 0.17 stat ± 0.03 syst) GeV

1 per mille precision

Present & future in Collider Physics

- NO NEW PHYSICS beyond SM has been discovered either as new particle(s) or deviation from it's predictions
- LHC will continue till ~2035 with successively increasing luminosity
- But NO INCREASE in energy is envisaged → any deviation from the SM will have to be discovered via high statistics studies of various processes
- UNIQUE situation in particle physics where every prediction within the SM has been found to be true.
- → outstanding problems: Expt: Dark Matter, non-zero neutrino masses
- Theory: SM doesn't seem to be a fundamental theory; too many arbitrary parameters, e.g., no. of generations, masses of constituents, etc…
- EXPERIMENT HAS TO LEAD THE WAY TO FIND SIGNIFICANT DEVIATIONS
- Possible future accelerators: ILC, FCC, CEPC,…… & extensive study of neutrino physics