Collider Experiments and India

January, 2019

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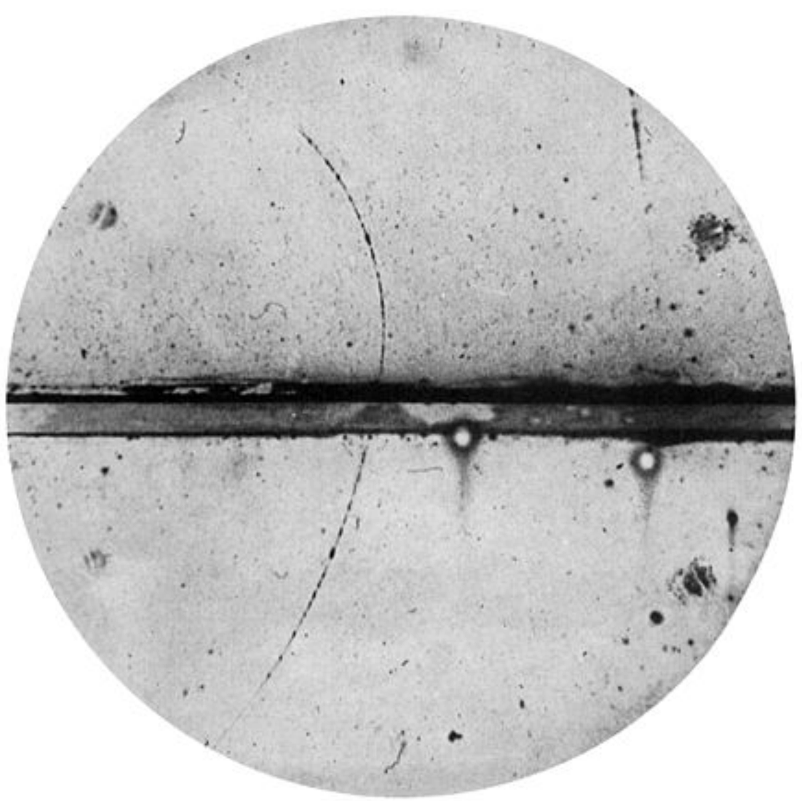
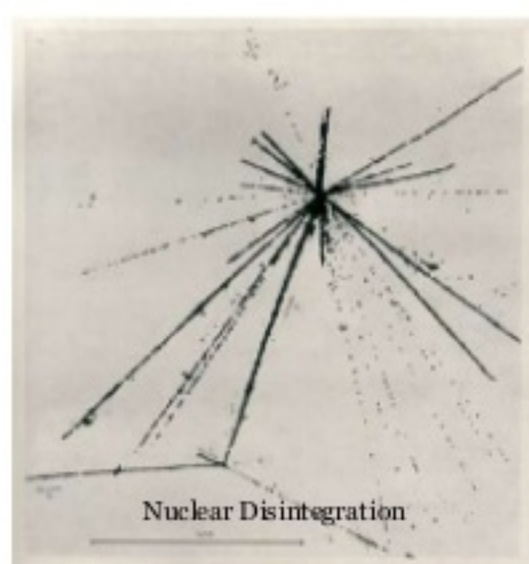
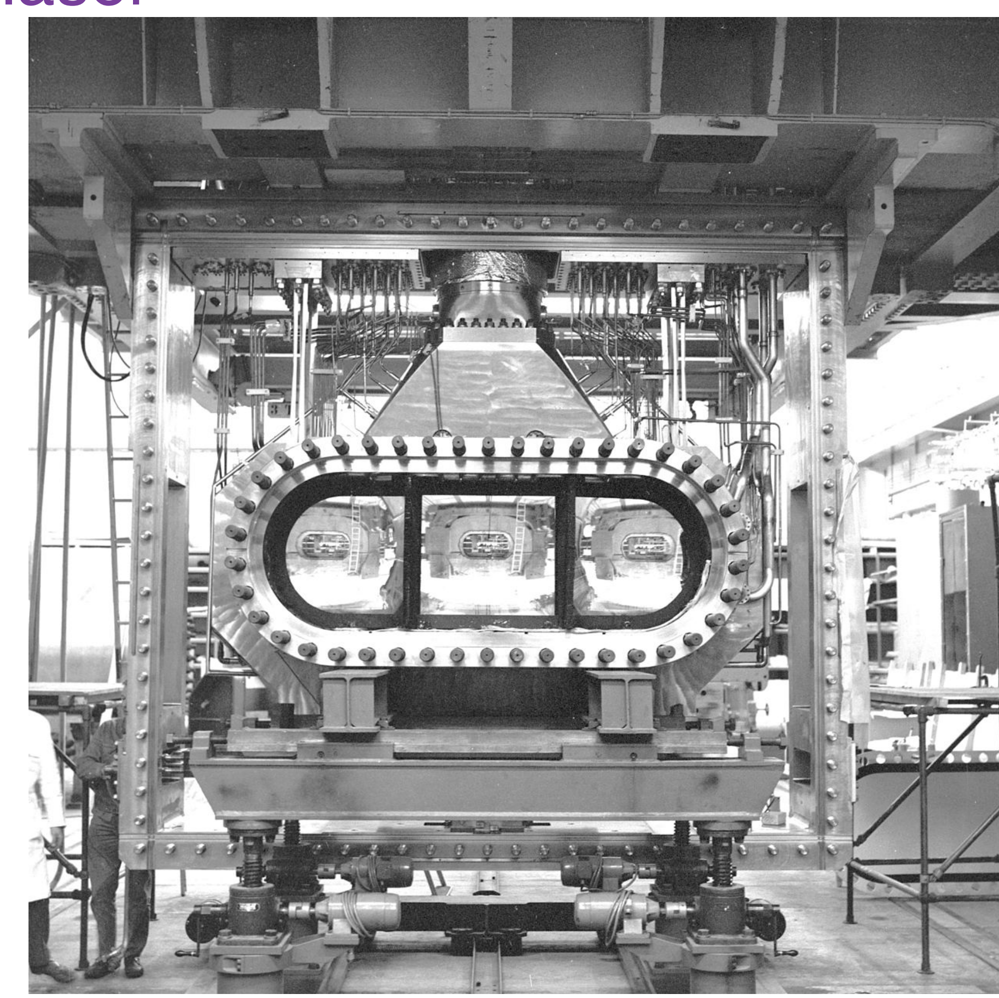
Experiments in High Energy Physics

- Particle physics experiments in the world started with
  - No accelerator
  - Visual detection technique
- In absence of accelerators what was the source?
  - Cosmic Rays
- What about visual techniques?
  - Cloud chambers as discovered by C.T.R.Wilson
  - Photographic plates (nuclear emulsion) developed by Marieta Blau
  - Bubble chamber as discovered by Donald Glaser







Startup in India

- India was not too far behind in those days
  - Cosmic Rays are as abundant in India as in Europe or USA
  - Indian scientists were trained to build Cloud chambers
- First cloud chamber was built in Calcutta by Debendra Mohan Bose. The next generation of cloud chamber was built at Ooty in the initiative of Homi Bhabha and Bernard Peters
- Instrumentation started in TIFR who built several field stations to study Cosmic Ray physics: Kolar, Ooty, (B.V.Sreekantan)
- Nuclear emulsion studies did not require too much instrumentations
  - Need emulsion development techniques and high precision microscopes which are commercially available
  - The famous Indian experiment was again done by Calcutta group (D.M.Bose and Biva Chowdhury) who saw evidence of meson trajectories in the Sandhakpo experiment
  - Several emulsion groups were built - at TIFR, in universities of Aligarh, Delhi, Jaipur, Chandigarh, Jammu and Jadavpur
- High energy experiments soon moved to accelerator labs
  - Expose nuclear emulsion stacks in those accelerators and study them in India
  - TIFR moved toward Bubble chamber film analysis (P.K.Malhotra, A.Subramanian). The technology was transferred to Chandigarh and Jammu.

Collider Experiments

- Collider experiments started in Europe during the 60’s
  - The first collider was ADA - an electron-positron collider built at Frascati during early 1960’s
  - The first hadron collider was ISR at CERN which started operating from 1971
- Indian groups did not think of joining such an activity for a long time
  - Collider experiment needs presence at the accelerator laboratory
  - It needs expertise in building equipments (detectors) and operating them
  - It also needs confidence and adequate expertise to participate in a front ranking experiment
- During early 80’s, the EHEP group of TIFR was brain-storming about their future endeavor
  - They have been participating in hybrid spectrometer experiment at CERN
  - They participated in a number of bubble chamber experiments at Rutherford Laboratory and CERN
  - Three possibilities arose
    - TRISTAN collider at KEK
    - Fermilab fixed target facility
    - LEP collider at CERN

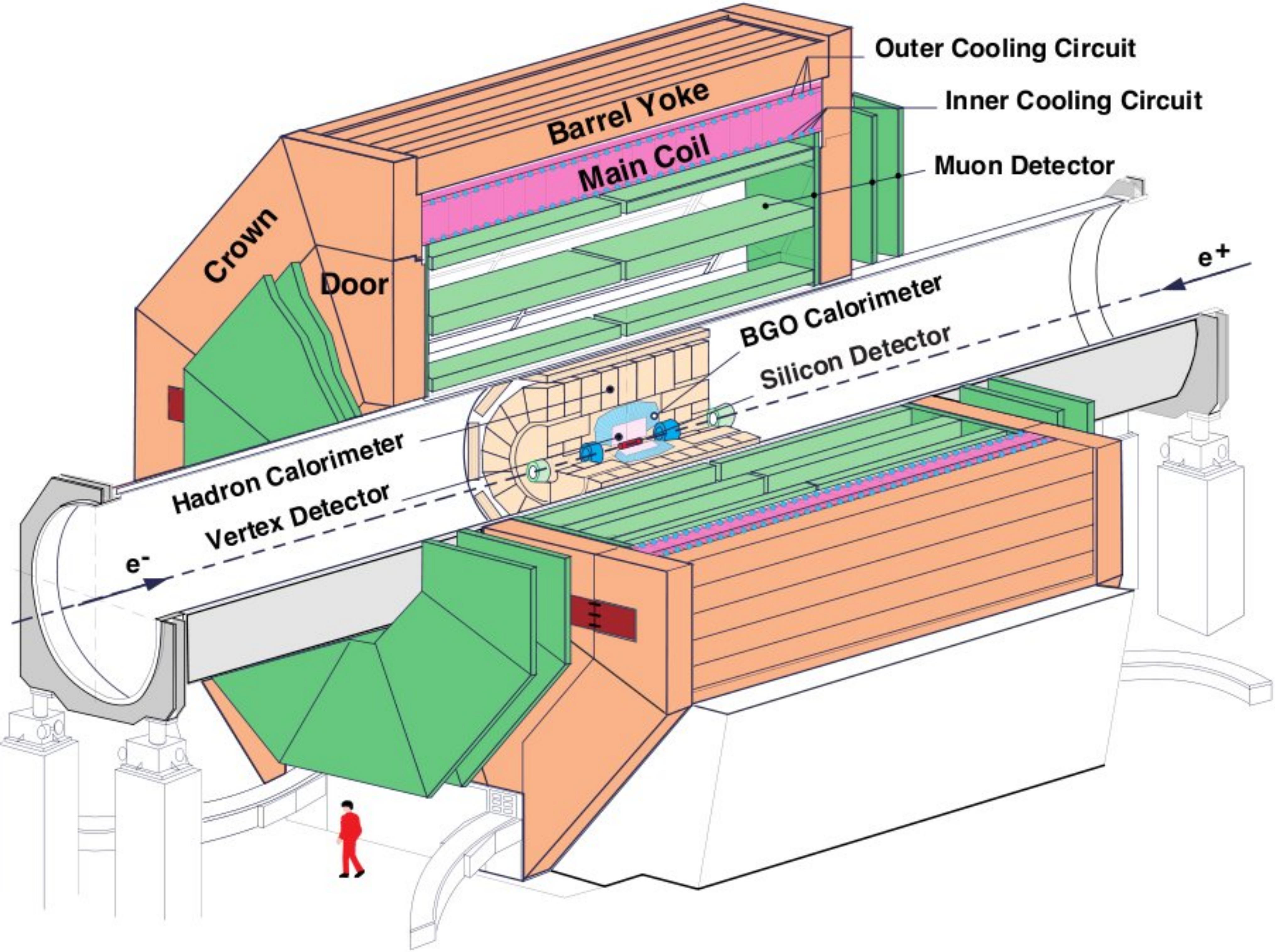
LEP Wins

- After several iterations in brainstorming sessions, decision went in favor of the L3 experiment at CERN
  - Several members had enough working experience at CERN
  - EHEP group's major mentor Lucien Montanet was a member of that experiment
  - Though major language was French, working language at CERN is English
- There were several handicaps to overcome
  - Convince the institute for participation in a foreign based experiment
  - With limited experience in building equipments try to build a part of the detector
  - Finance was very limited - nothing available for building detectors, participating in a foreign based experiment
- Youth was on the side of the group and so was the enthusiasm
  - 3 members in late 20's/early 30's
  - 1 member in mid 30's
  - 3 members in early 40's
  - 2 members in mid/late 40's

L3

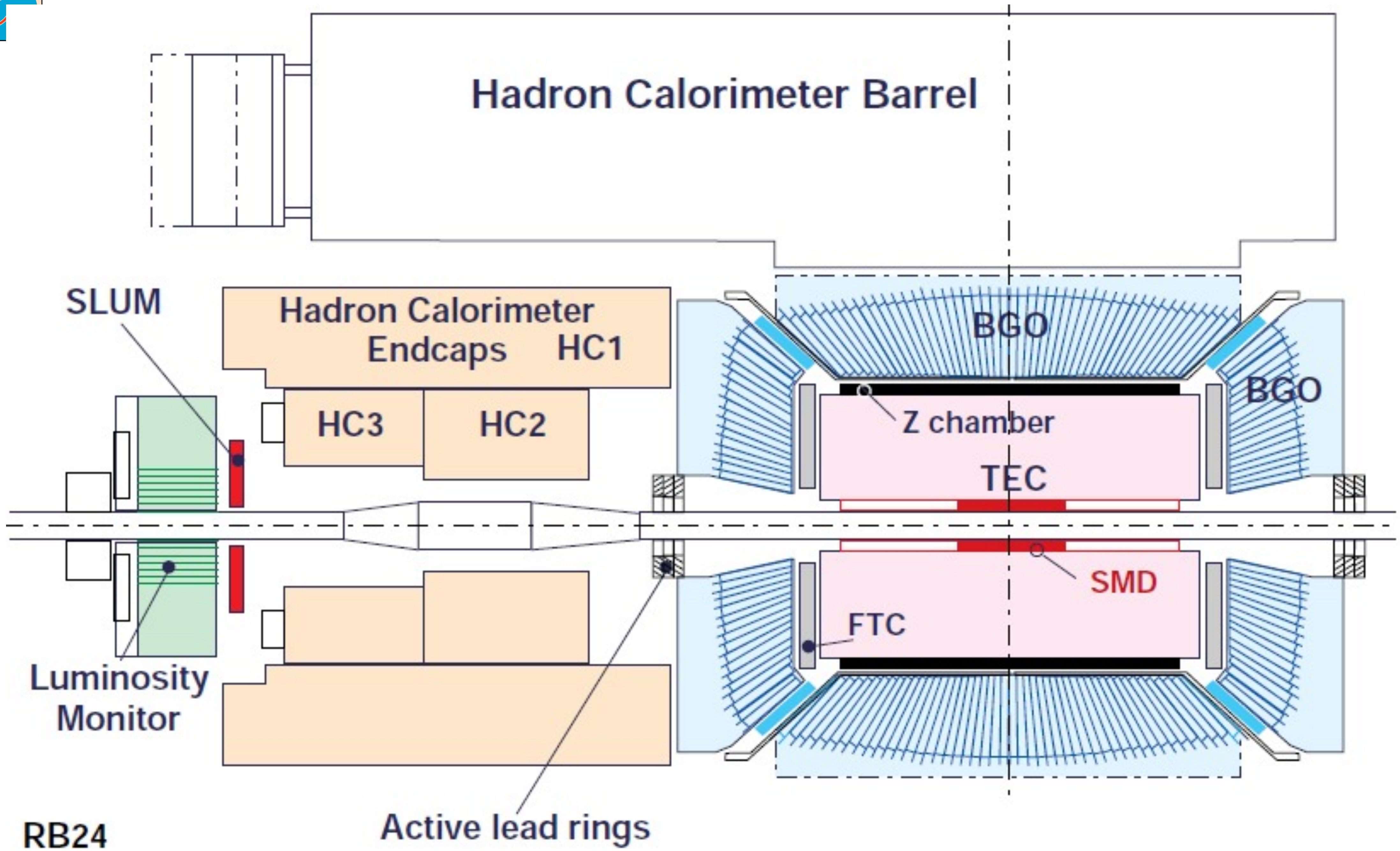
- Prince presented the case to TIFR
  - Very harsh criticism and concern if we could deliver
  - Almost no additional money could be provided
  - Thanks to the support of some of the theory colleagues, we could go ahead on an experimental basis
- Somnath presented the case to L3
  - Thanks to Lucien very well received by the L3 collaboration
  - Started probing how we can participate in the experiment
  - The design came as a brain child of Samuel Ting.
    - Focus on discovery - so key components on precision measurement of electrons, photons and muons
    - Jets are important but coarser resolution is acceptable
    - TIFR chose to participate in the construction of the hadron calorimeter
      - Found a wonderful collaborator who led the construction of the endcap hadron calorimeter and guided us in its construction (Klaus Lubelsmeyer of 1st Institute of RWTH Aachen and his very able engineer Rolf Siedling)
- A special instrumentation school was organized by Suresh Tonwar in Mahabaleswar where several experts (Fabio Sauli, Albert Walenta, David Jacobs, Klaus Lubelsmeyer, …) taught us about instrumentation and online software

L3 Detector



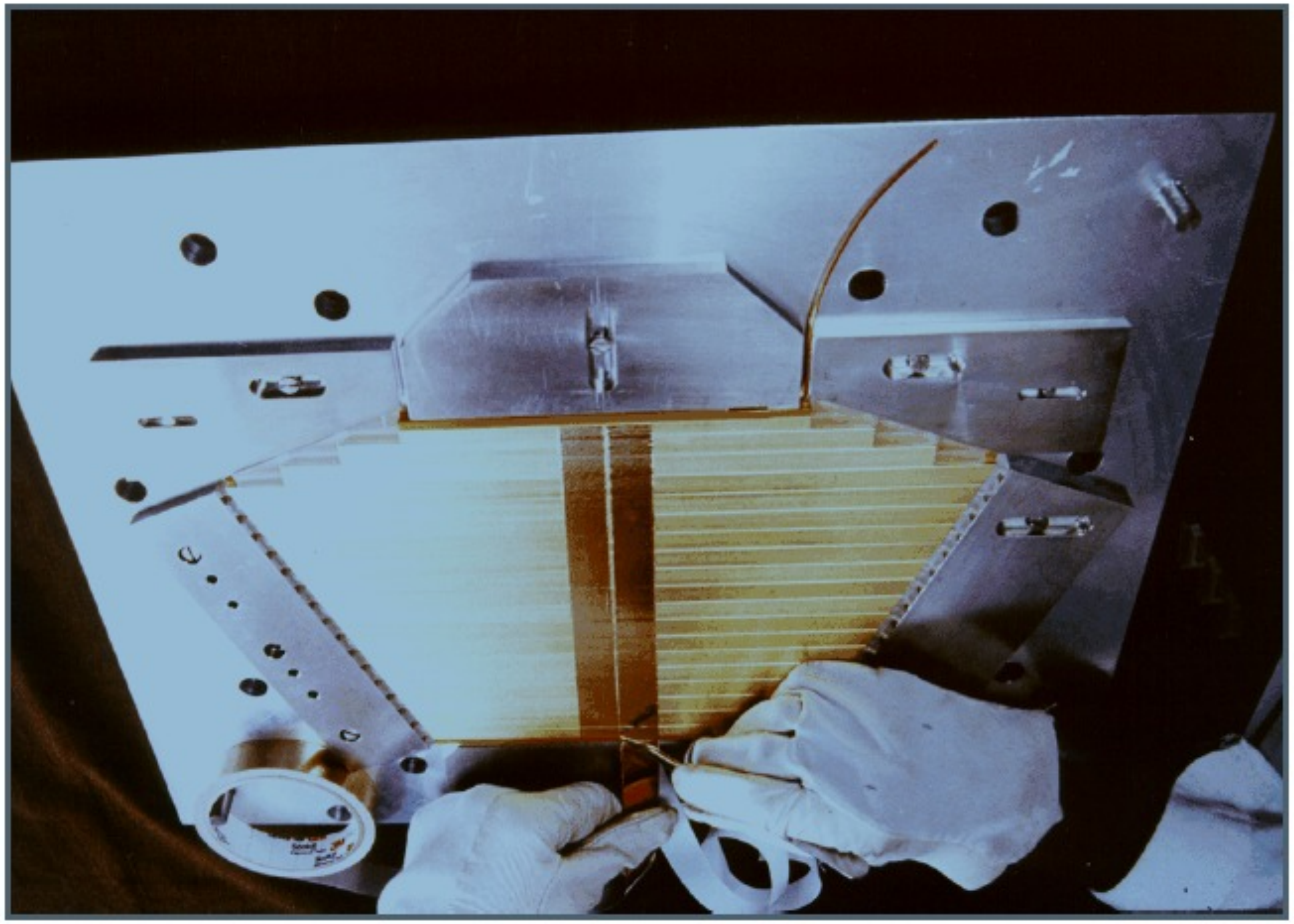
- L3 was the largest experiment at the LEP (in size as well as in author list)

L3 Endcap Hadron Calorimeter



- Sampling calorimeter with alternate layers of depleted uranium and brass tube proportional chambers
- The calorimeter is divided into 3 major parts: HC1 with 1000 larger chambers; HC2 and HC3 with another 1000 smaller chambers
- TIFR was assigned to build 1000 chambers of HC2 and HC3

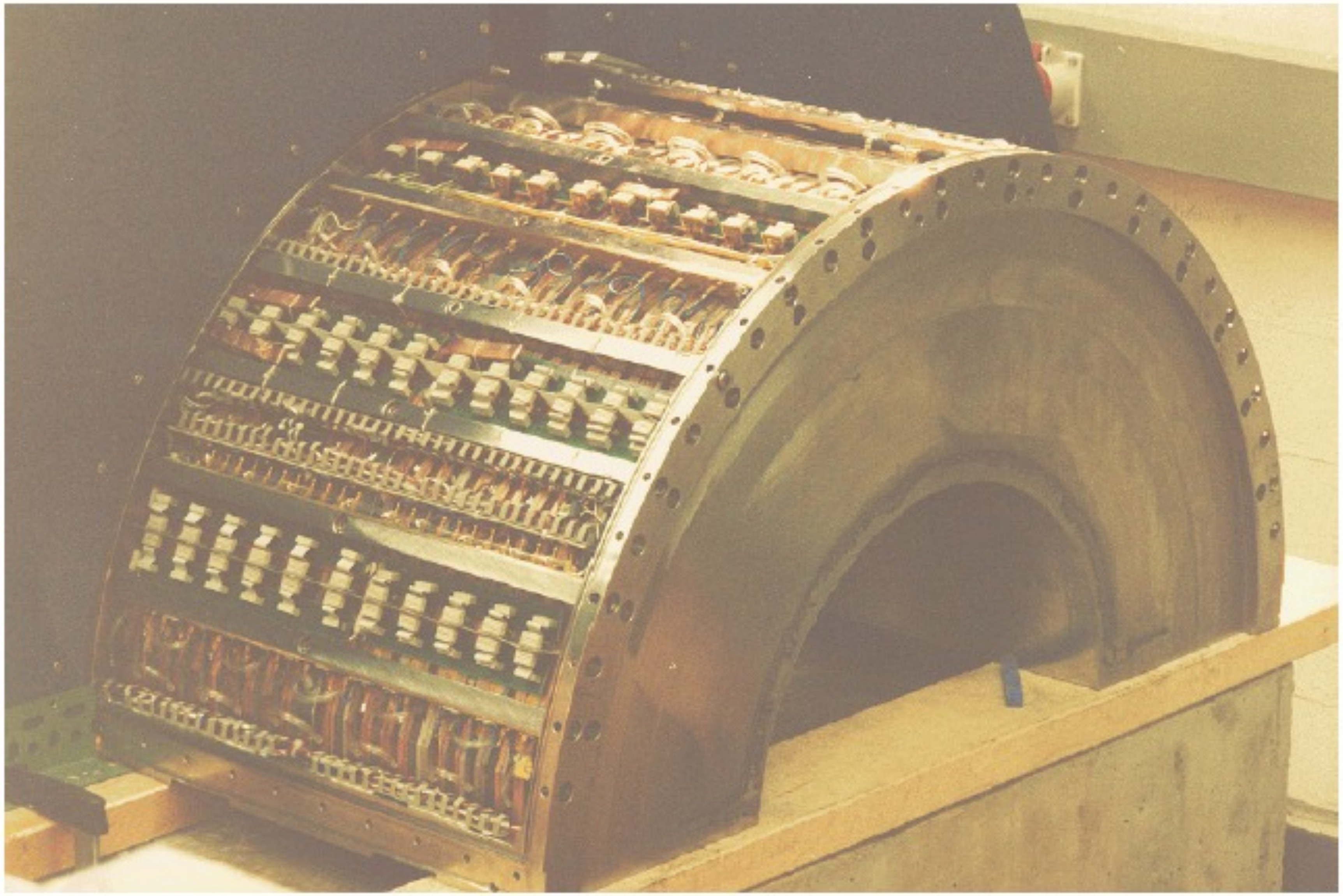
Construction of the Chambers



- Brass tubes (22 for HC2 and 19 for HC3) to be cut to right precision and edges at a very precise angle
- Brass plates (to be placed on either side) to be cut in the right shape with precision better than 50 micron
- Make assembly frames to put the tubes together with the glue sheets in between
- Need ovens for baking and arrange insertion and fixing of thin gold wires

- TIFR workshop was not so well equipped to meet the required precision
- Probed all local industries for precision tooling to make all components
- Also found industries to make the PCB's for readout system
- Chamber assembly was done in house with a team of technicians and engineers
- Wire tension was monitored by a home-made instrument

Construction of Housing



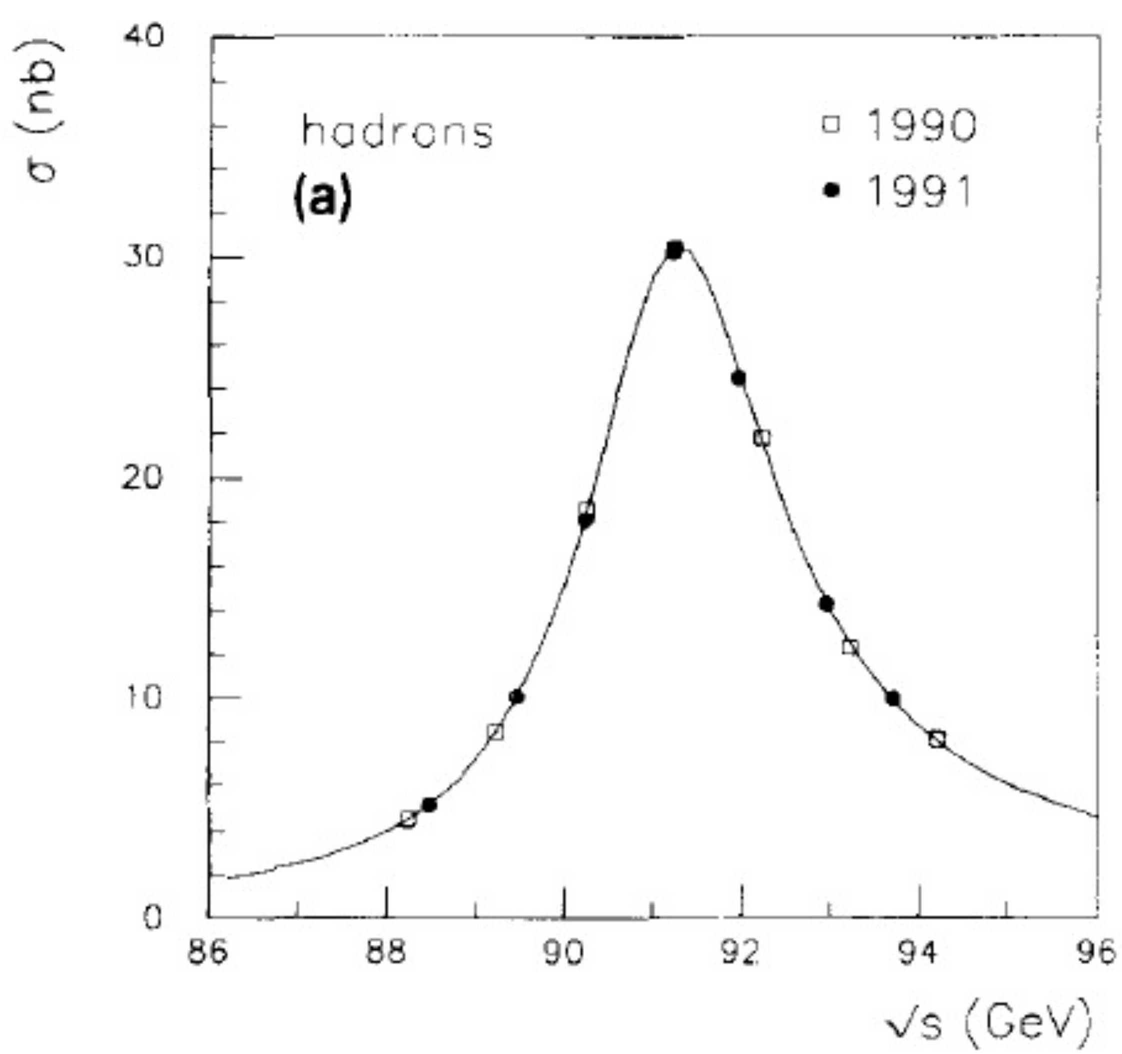
- Indian group also made the stainless steel housing
- Made out of 304L non-magnetic stainless steel
- High degree of precision was again required
- PPED (Nuclear Power Corporation) came to the rescue in providing the required steel plates
- BARC central workshop (Jayandrinath et.al.) rescued with the construction

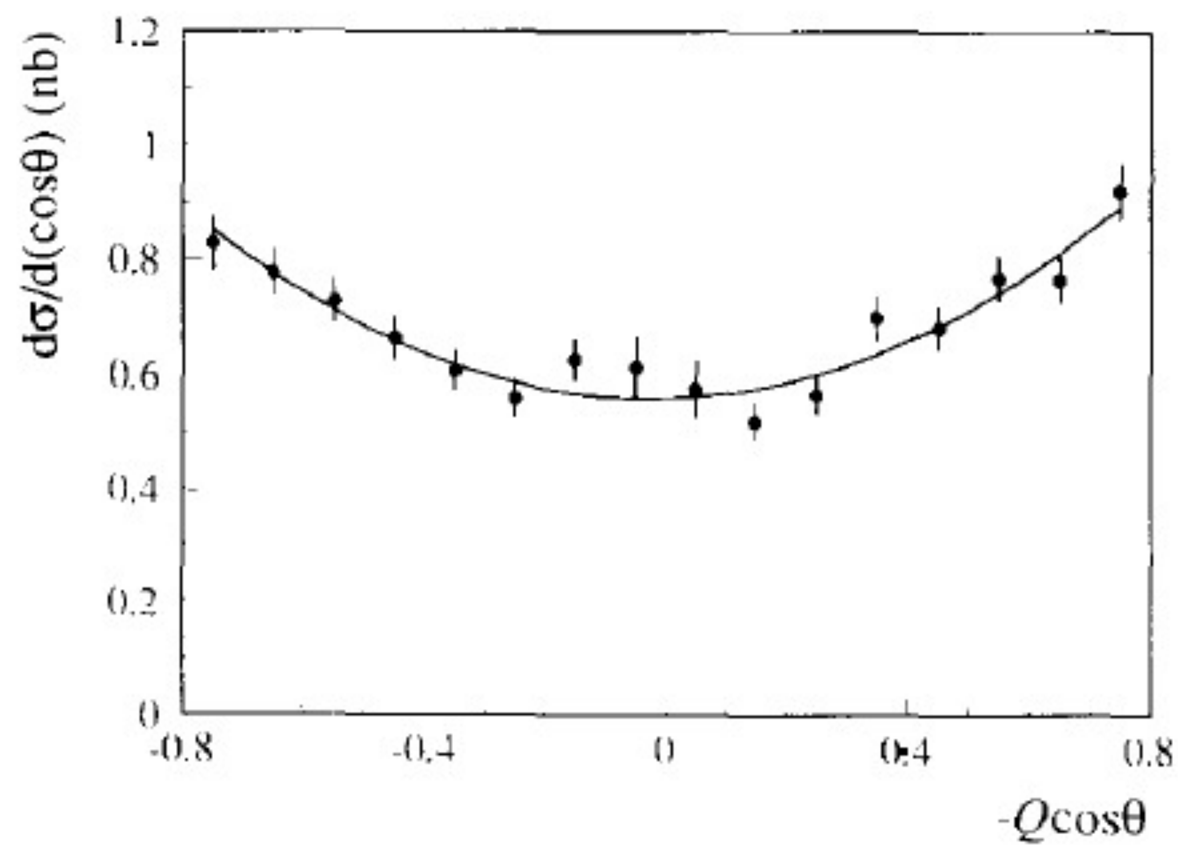
Also Software

- L3 priority was the hardware
- There was a small team at CERN led by Francis Bruyant who was investigating the software requirement of the experiment:
  - Simulation of the detector including extending the basic toolkit Geant3
  - Reconstruction of MC as well as real data including the basic data structure
  - Storage and retrieval of non-synchronous data (data base)
  - Visualization of the detector and the reconstructed objects (step to interactive reconstruction)
  - Production scheme keeping records of reconstruction, re-reconstruction (going back to the source code, calibration constants for a given reconstructed event; also avoid duplicate and the latest reconstructed events while doing analysis)
- Six months before LEP start-up Prof. Ting approached and asked Francis to explain his work giving an entire collaboration meeting time (1 full day). The task is to see if this work provides the software which L3 needs
  - Francis, Elmer and Sunanda divided the task and faced the entire L3 collaboration for criticism and possible rejection
  - Software effort was approved by Ting and his chief advisors

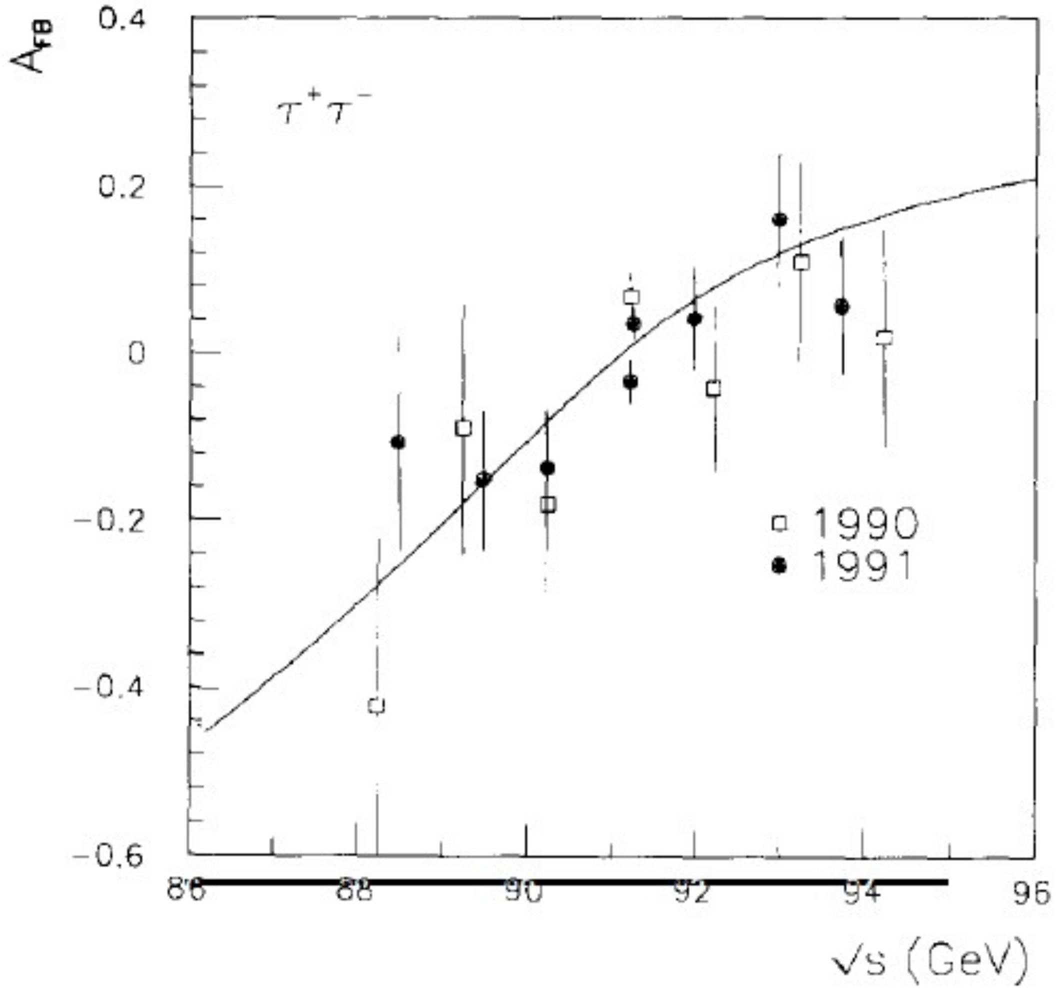
First Results

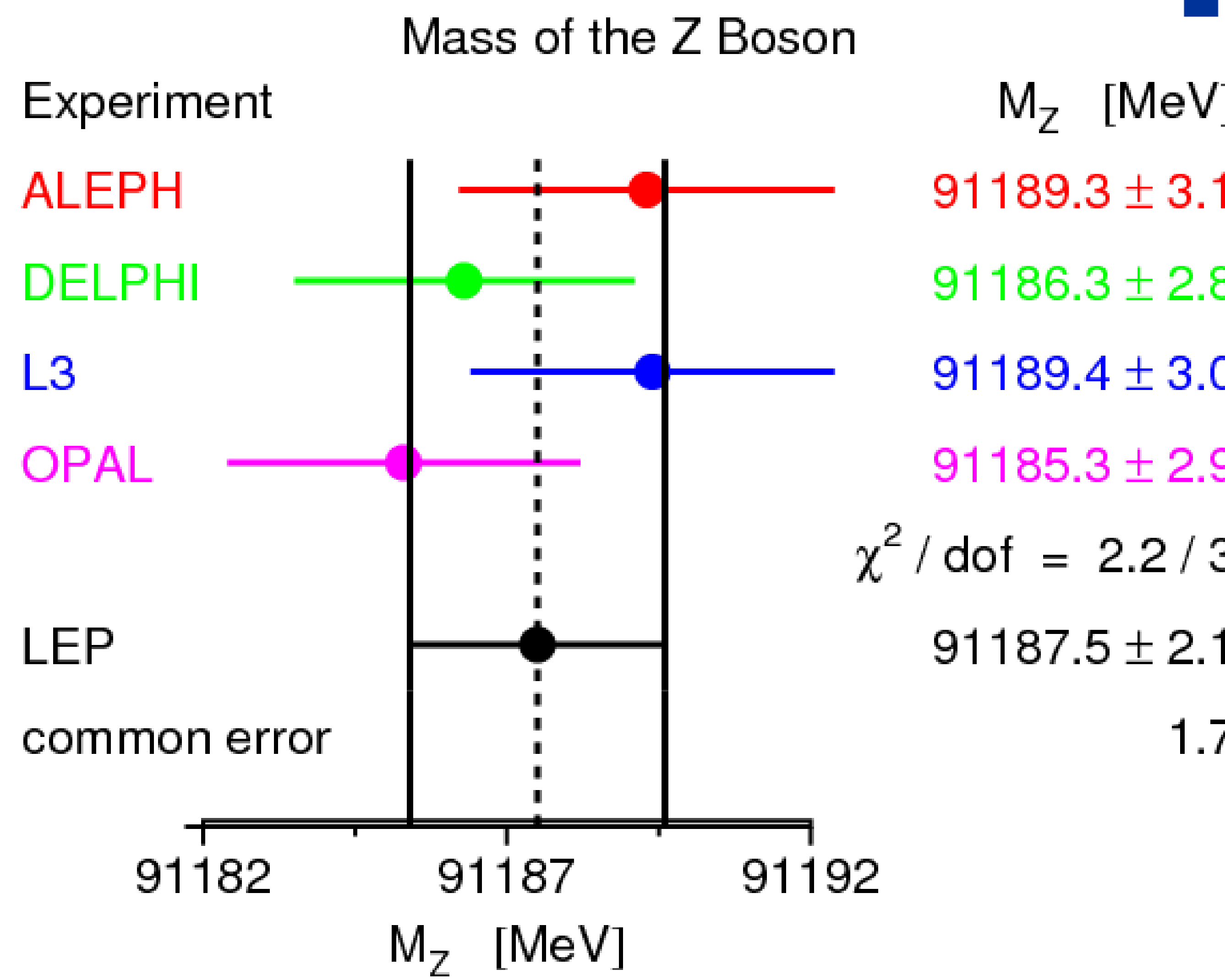
- The first phase of LEP was a scan around the Z-mass to measure the properties of Z with the greatest accuracy
- TIFR theory group (Probir Roy and Durga Prasad Roy) conducted the first WHEPP in Bombay during 1989
  - Guido Altareli was one of the participants and he inspired Somnath Ganguli & Atul Gurtu to become equipped with fitting Z line shape
  - Line shape team was formed with Somnath, Atul, Sunanda and two students Kajari+Suchandra





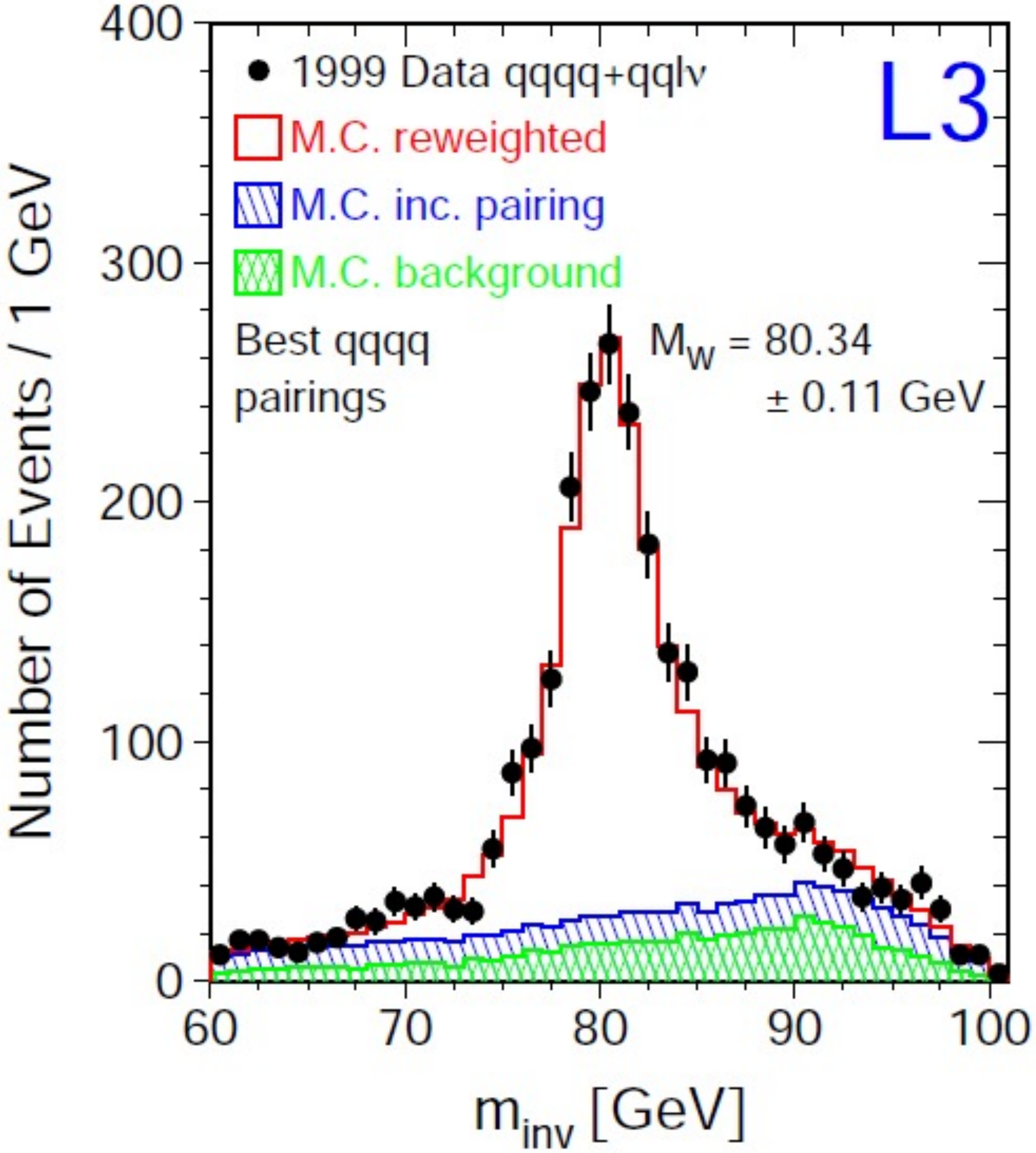
Line Shape

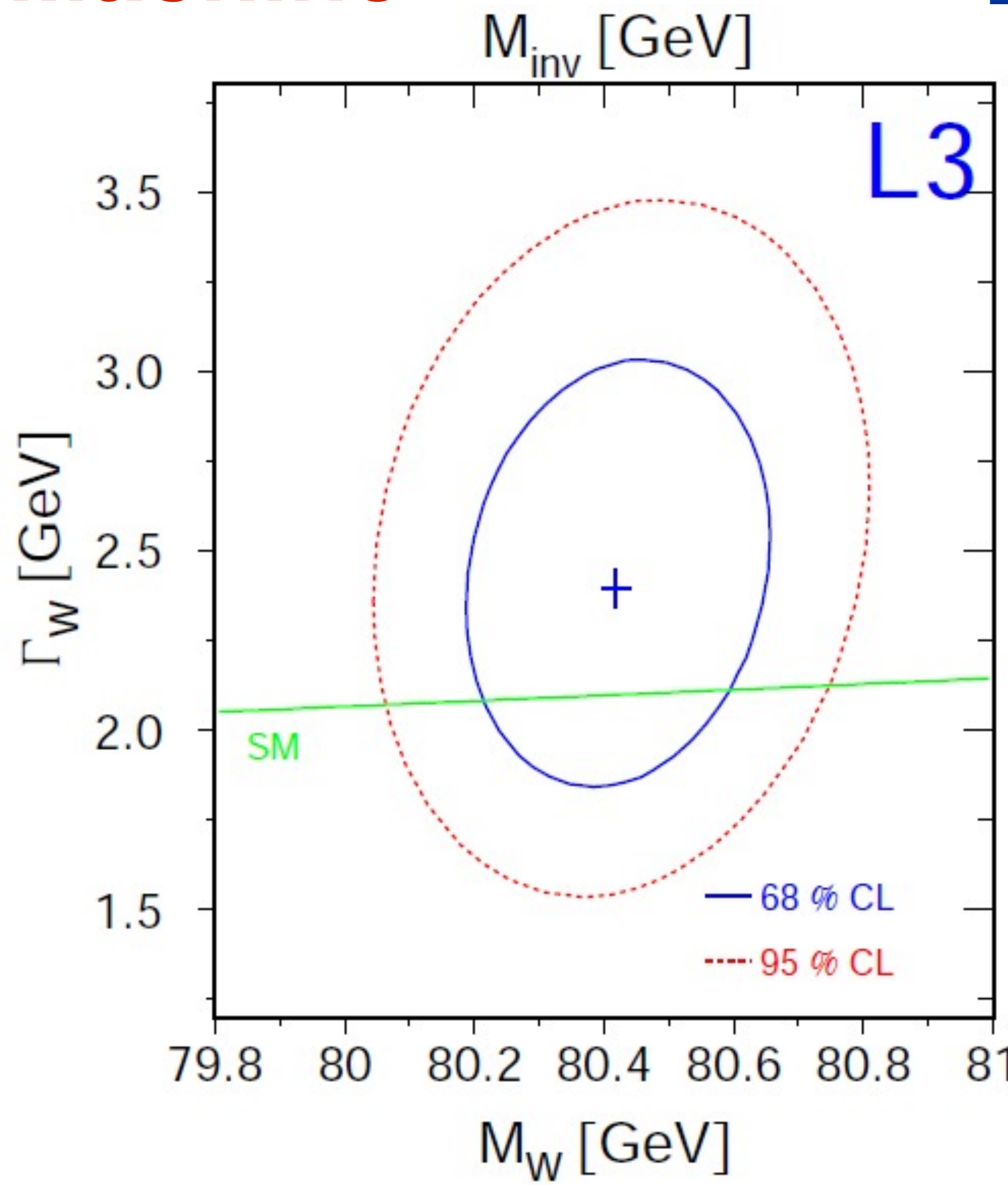




- The effort was enlarged to LEP wide EW group by Jack Steinberger which combined the results of the 4 LEP experiments
  - Better understanding of the systematic uncertainties
  - Improve statistics 4 folds
  - Later add on measurements from SLD, Tevatron and also some of the low energy experiments ($\sin^2\theta_W$)
  - Give prediction on top and Higgs mass in the framework of Standard Model

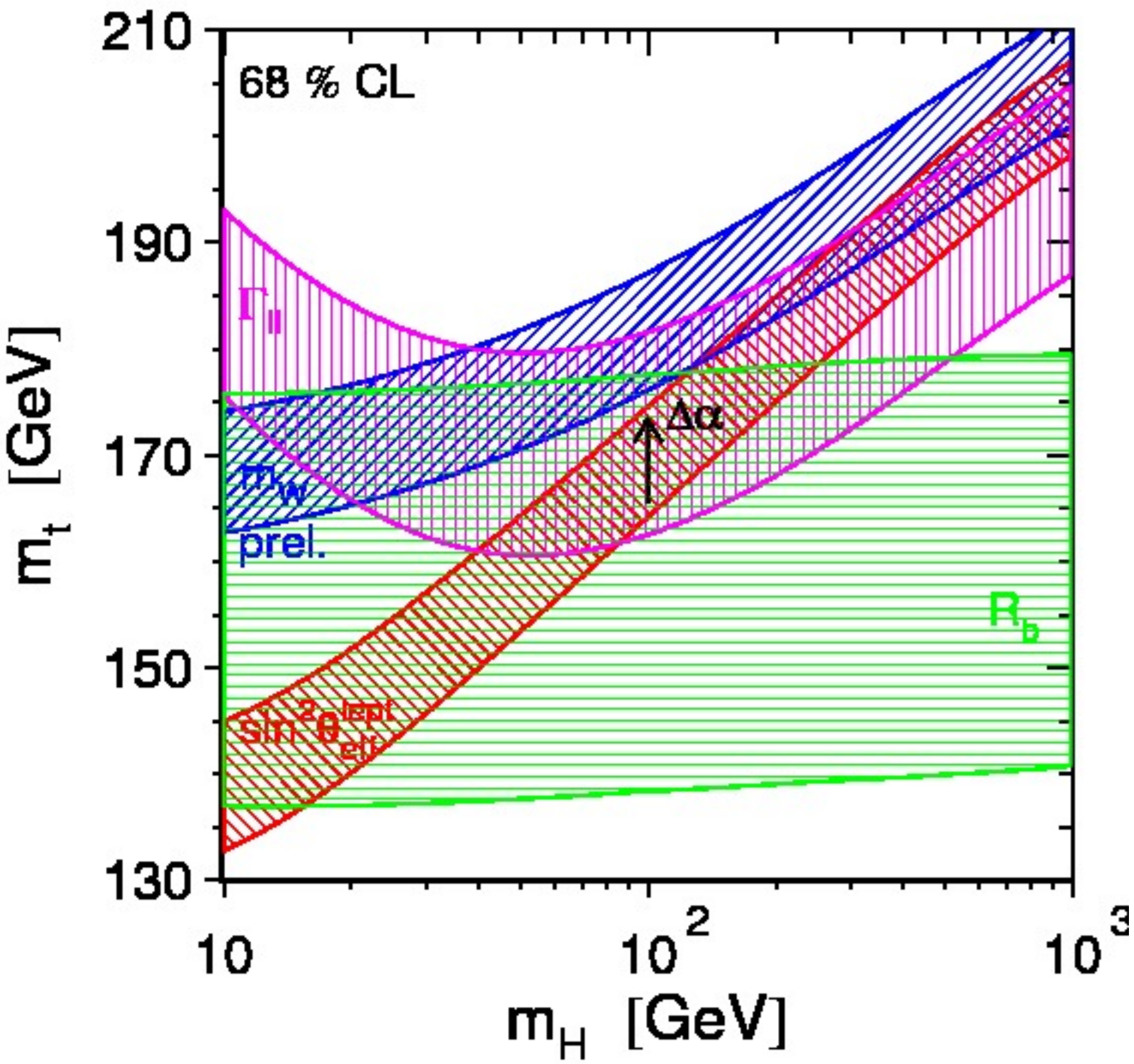
LEP as a EW Machine

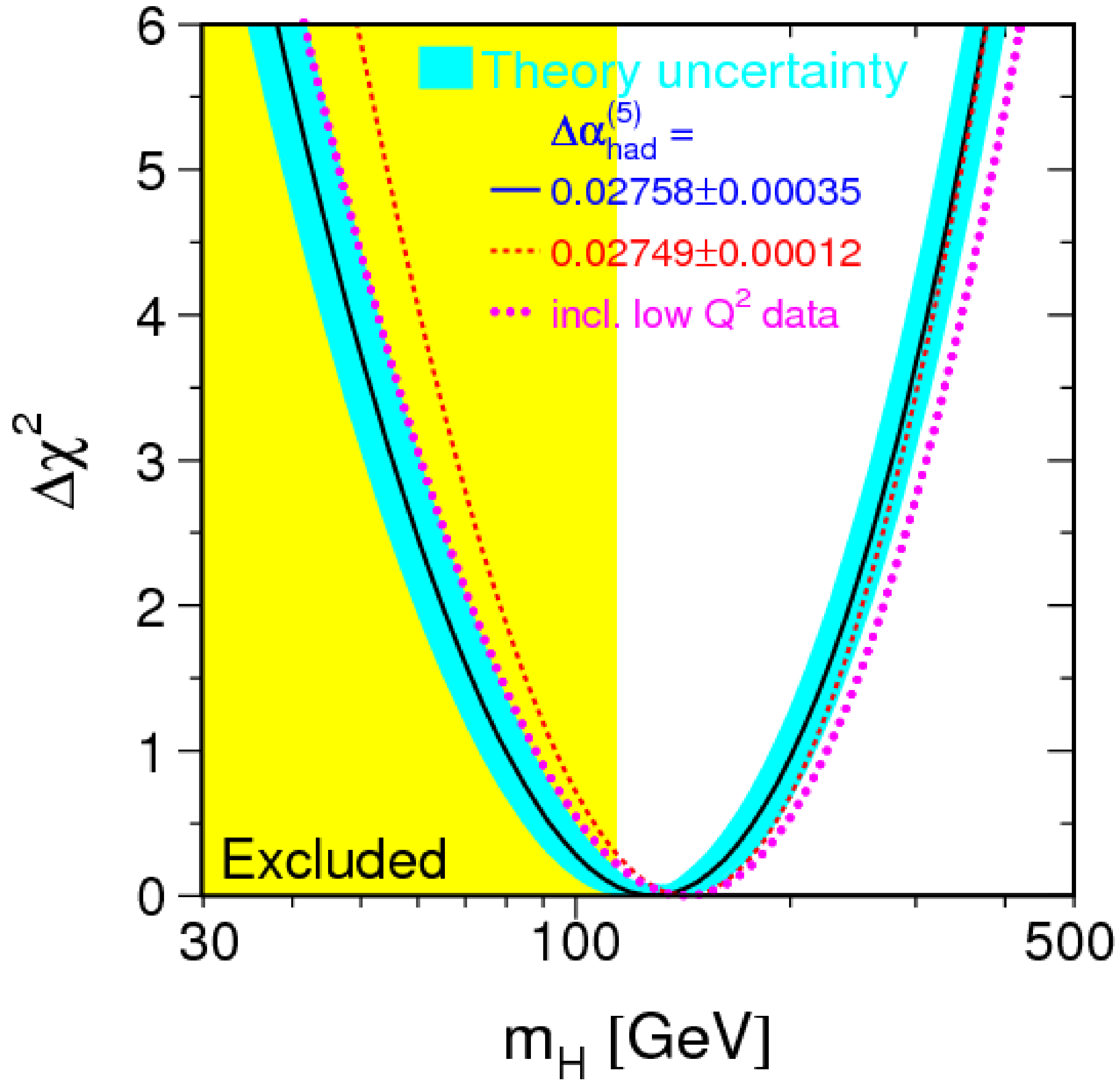




- After successful run around the Z-mass, LEP energy was increased to go above W-pair threshold.
- Identifying W-pair (and later Z-pair) were one of the tasks of the TIFR group
- This led to accurate determination of W-mass and its width as well as coupling of W's and Z's
- TIFR group also made use of ANN for the first time to extract physics results (partial width of Z to heavy flavor)

LEP EW

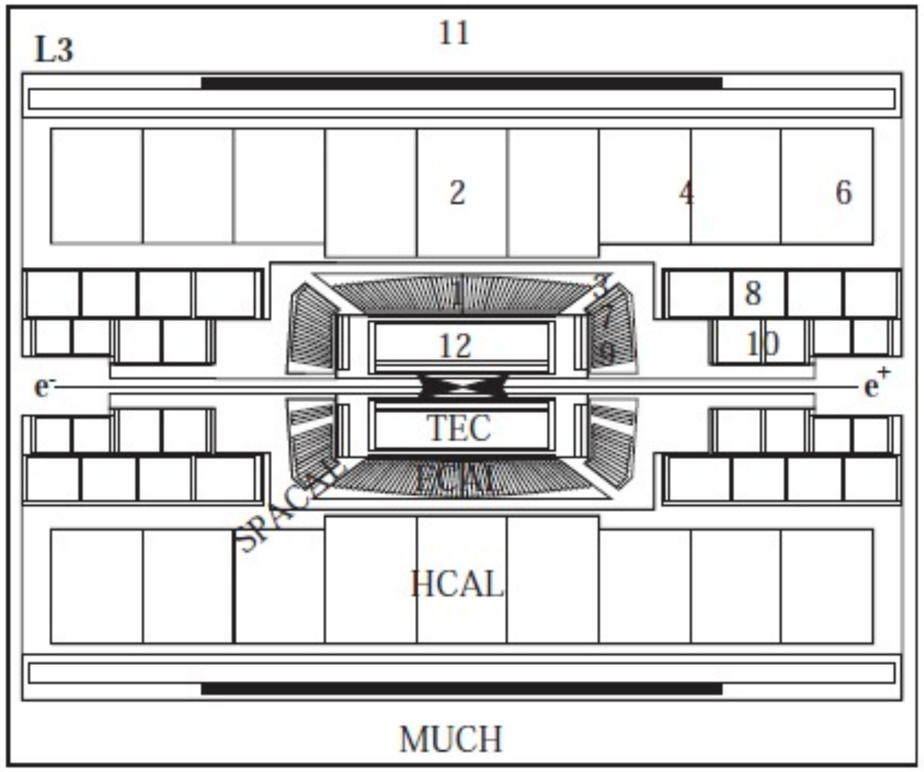




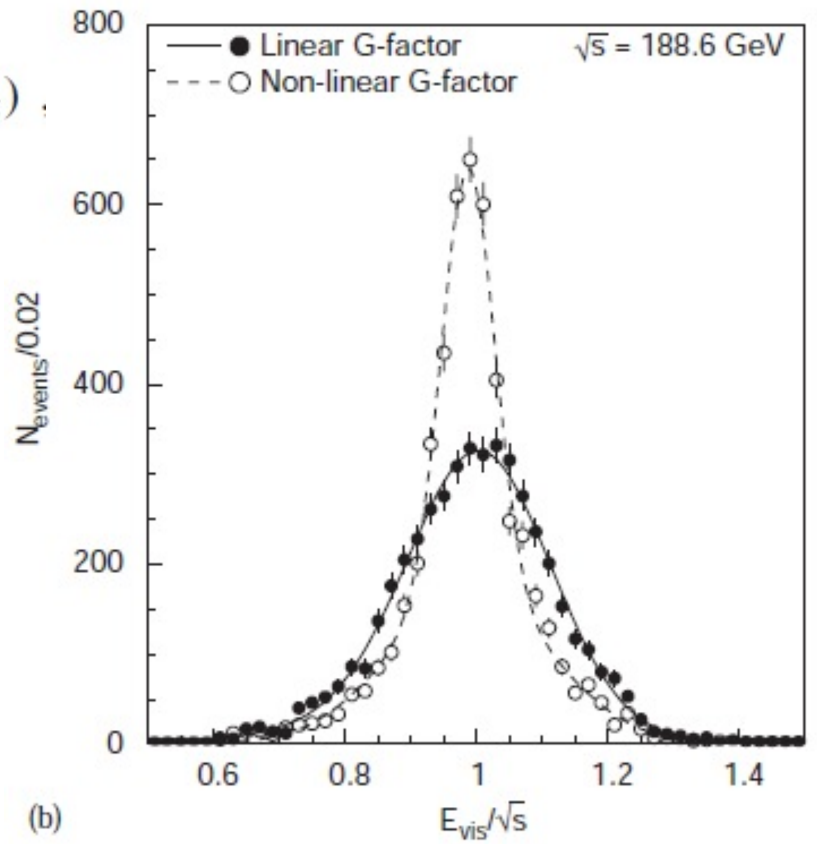
- LEP EW group kept on combining EW results from LEP, SLD and Tevatron and tried to predict mass ranges of top (before its discovery in 1994) and Higgs (before its discovery in 2012)

Influence of PETRA

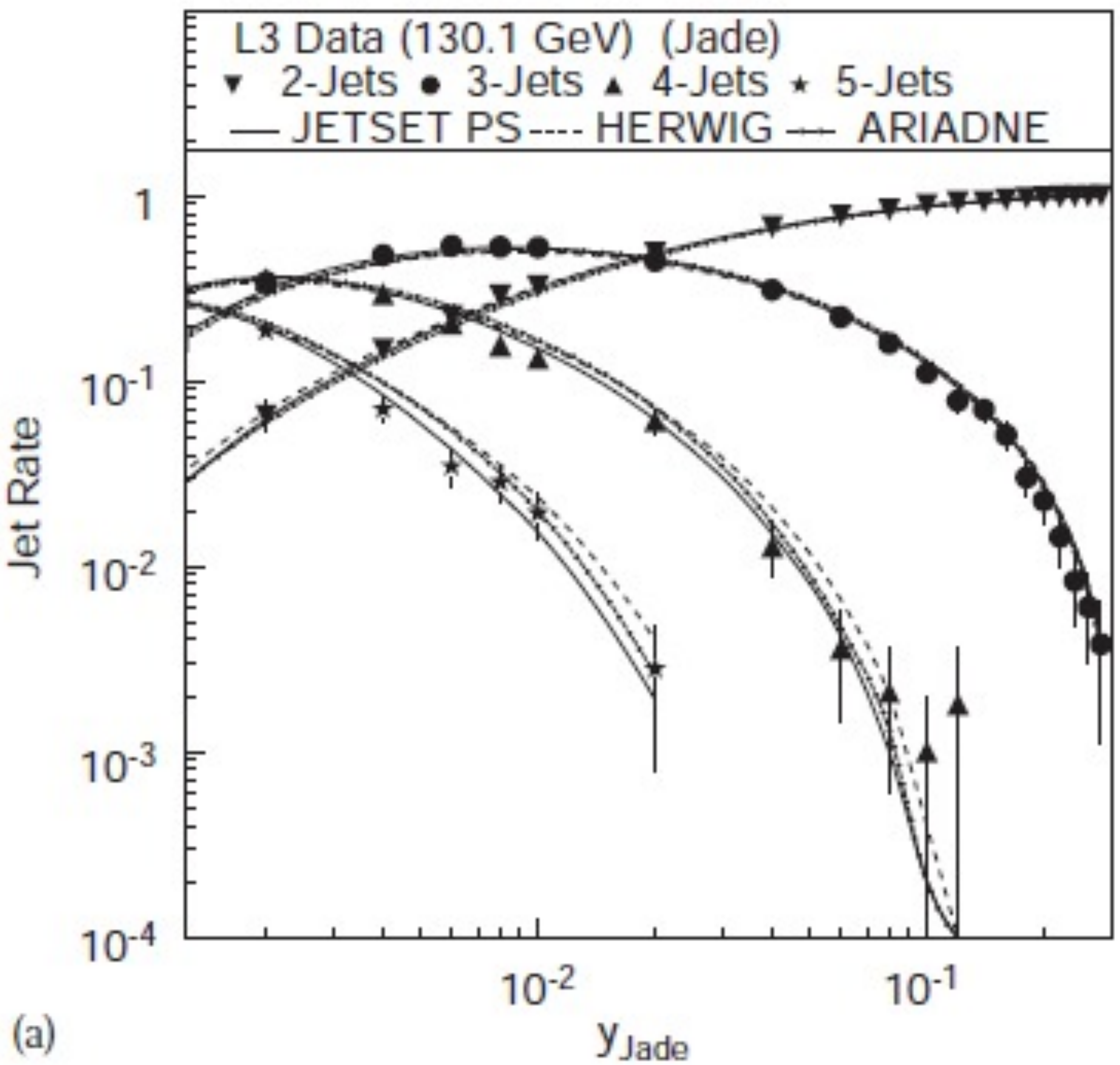
- PETRA was a preceding electron-positron machine which essentially had a few important results
  - Discovery of gluon
  - Evidence of γ -Z interference in lepton pair production
  - Usage of event generators for understanding EW as well as QCD
- Some of these experiences was brought over to L3
  - Better calibration method to improve energy resolution
  - Combining information from different detector components to get the best energy determination (precedent of Particle Flow)
  - Usage of event shape variables in classifying events
  - Development of jet algorithms (both theory as well as experiment motivated)

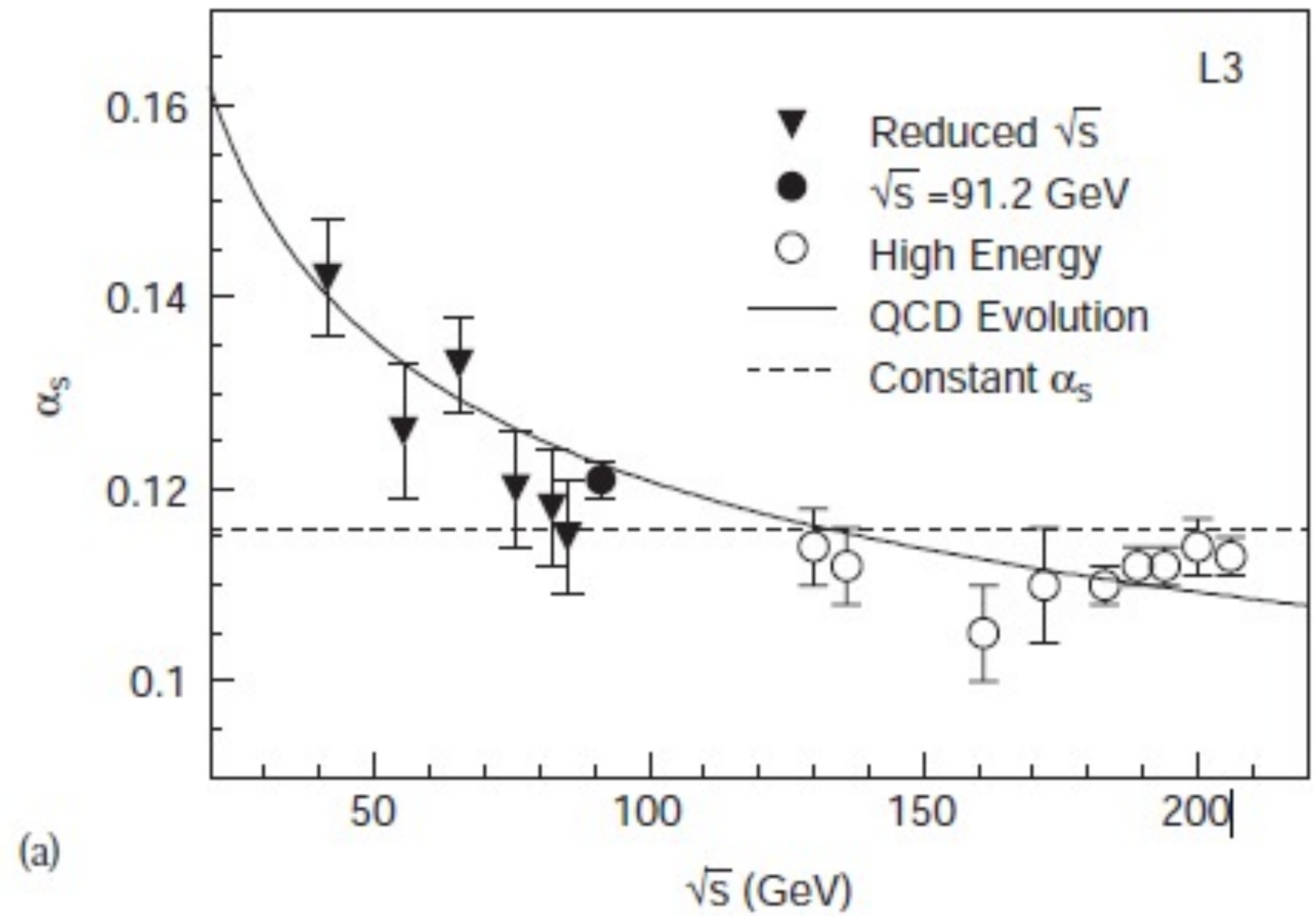


$$\widetilde{E}_\ell^{sc} = \sum_{i=1}^{12} \widetilde{G}_i^{NL} \cdot E_i + \sum_{j,k=1}^{12} \widetilde{A}_{jk}^{NL} \cdot C_\ell(E_j, E_k) \ ,$$



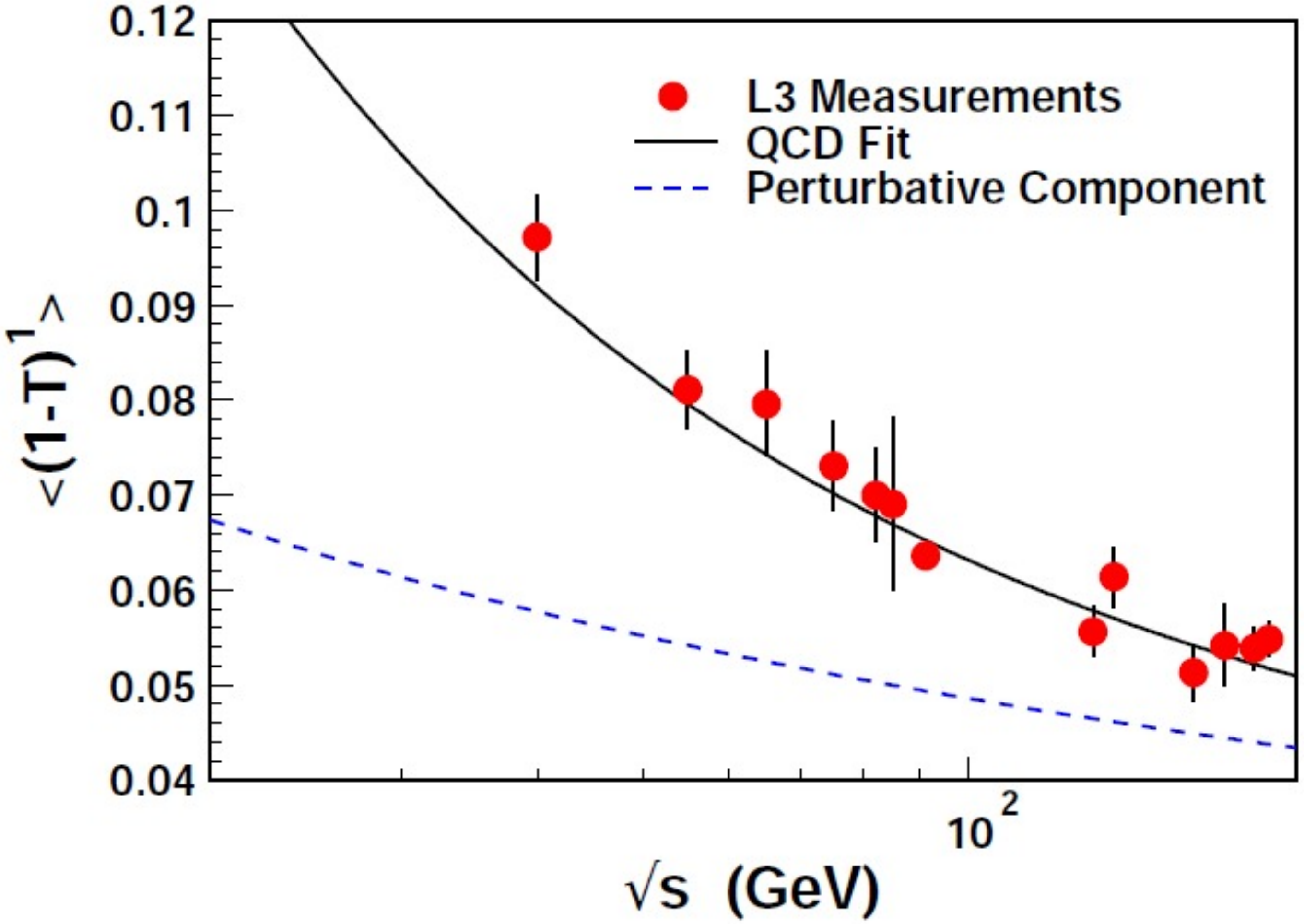
LEP as a QCD Machine

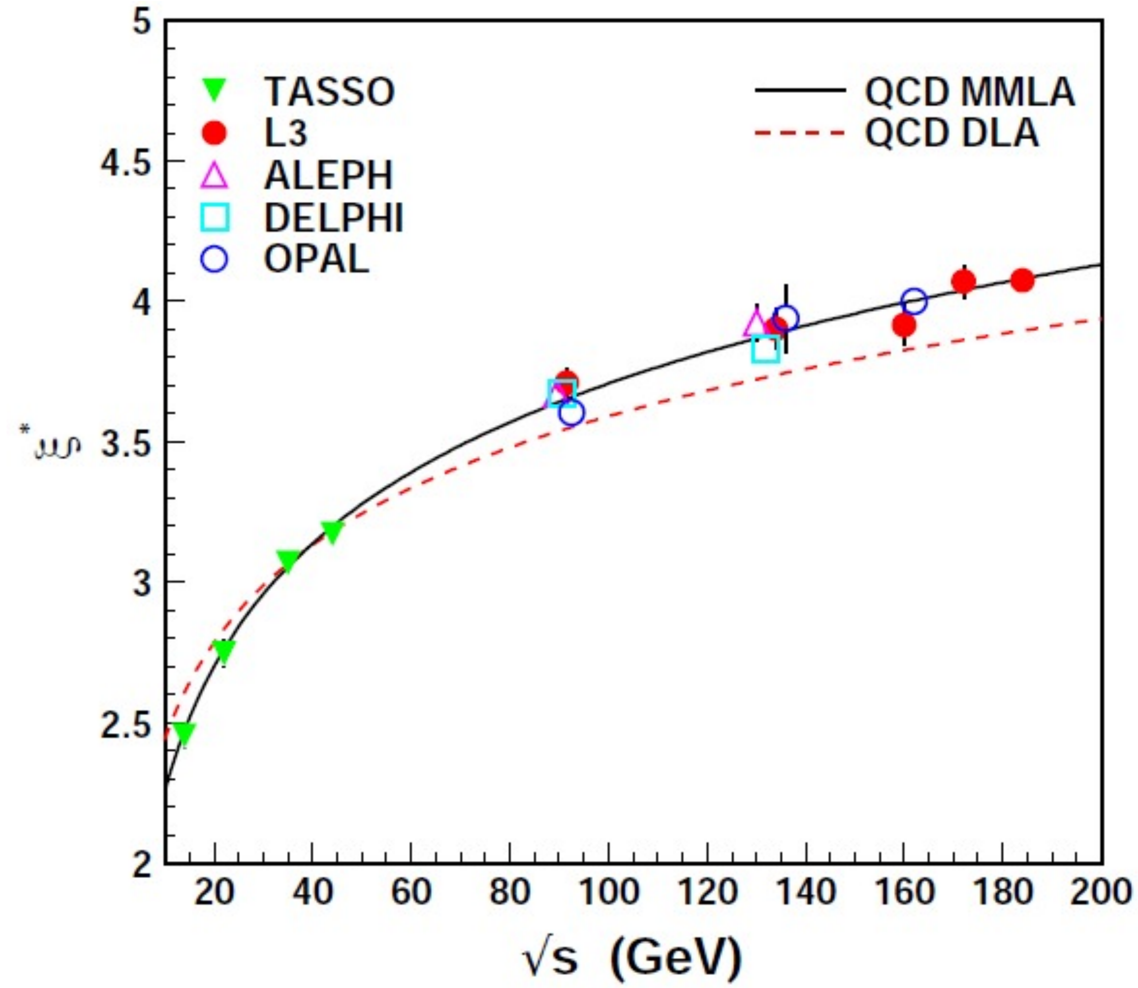




- Jet rate is a measure of the strong coupling constant α_s
- Also several event shape distributions can be fitted to a combination of complete second order QCD + Next to leading log terms to obtain α_s
- Used Z as well as high energy data (+ ISR/FSR data to get reduced CM energy) and from a single experiment obtain running of strong coupling constant

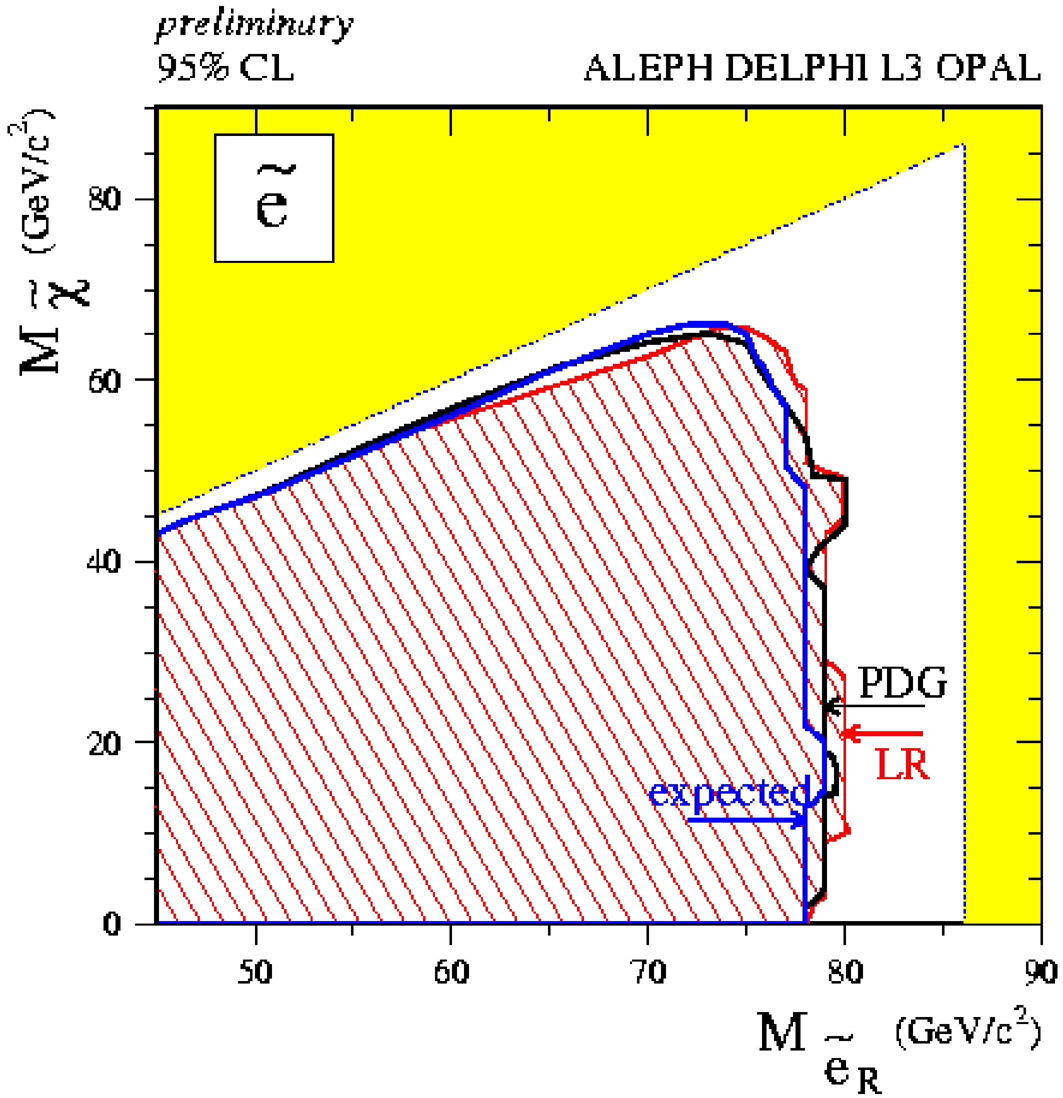
Further tests of QCD

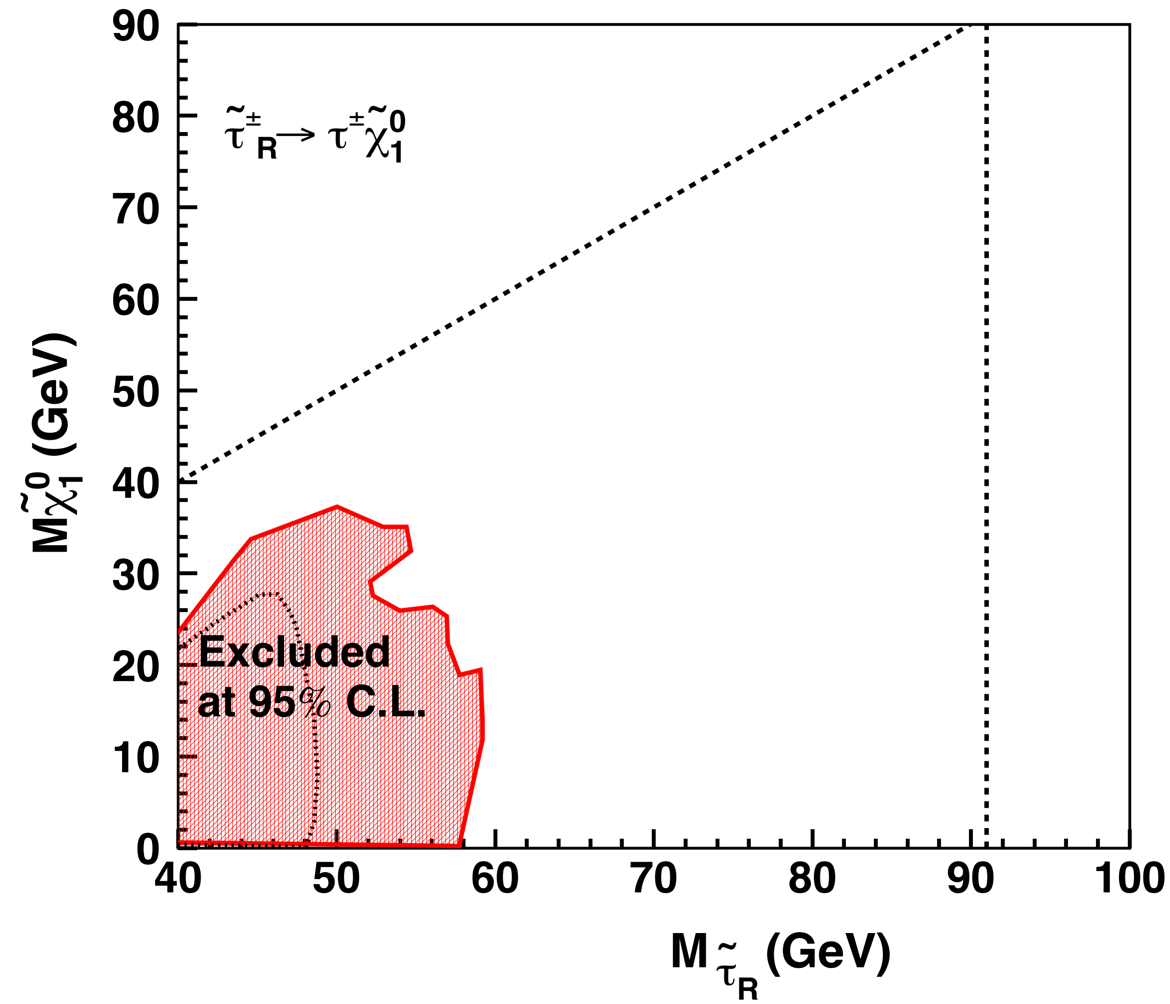




- Fit the first moments to certain event shape distributions to a sum of perturbative and non-perturbative part
  - Verification of QCD and extraction of α_s in a new method
- Study inclusive momentum distribution [$-\ln(2p/\sqrt{s})$] at each center of mass energy - fit to a function given by Fong and Weber and see the energy evolution of the peak position. Theory comes from soft gluon summation.
  - Provides evidence of soft QCD summation

LEP as a Search Machine





- LEP data were heavily used for search of new physics including Higgs and SUSY particles
- During LEP2 period the TIFR group also fell for such a dream (search for sleptons)
  - No evidence was found and only obtained exclusion limits

Second Collider Experiment

- Three groups from India joined the same experiment at Fermilab (DZero) following 3 different paths
  - Delhi university (R.K.Shivpuri, ..) after participating in a fixed target direct photon experiment
  - Panjab university (J.M.Kohli, …) after participating in some neutrino experiments with 15’ BC
  - TIFR (V.S.Narasimham, …) after finding continuation of home-based experiments needs new techniques which can be ported from accelerator based experiments

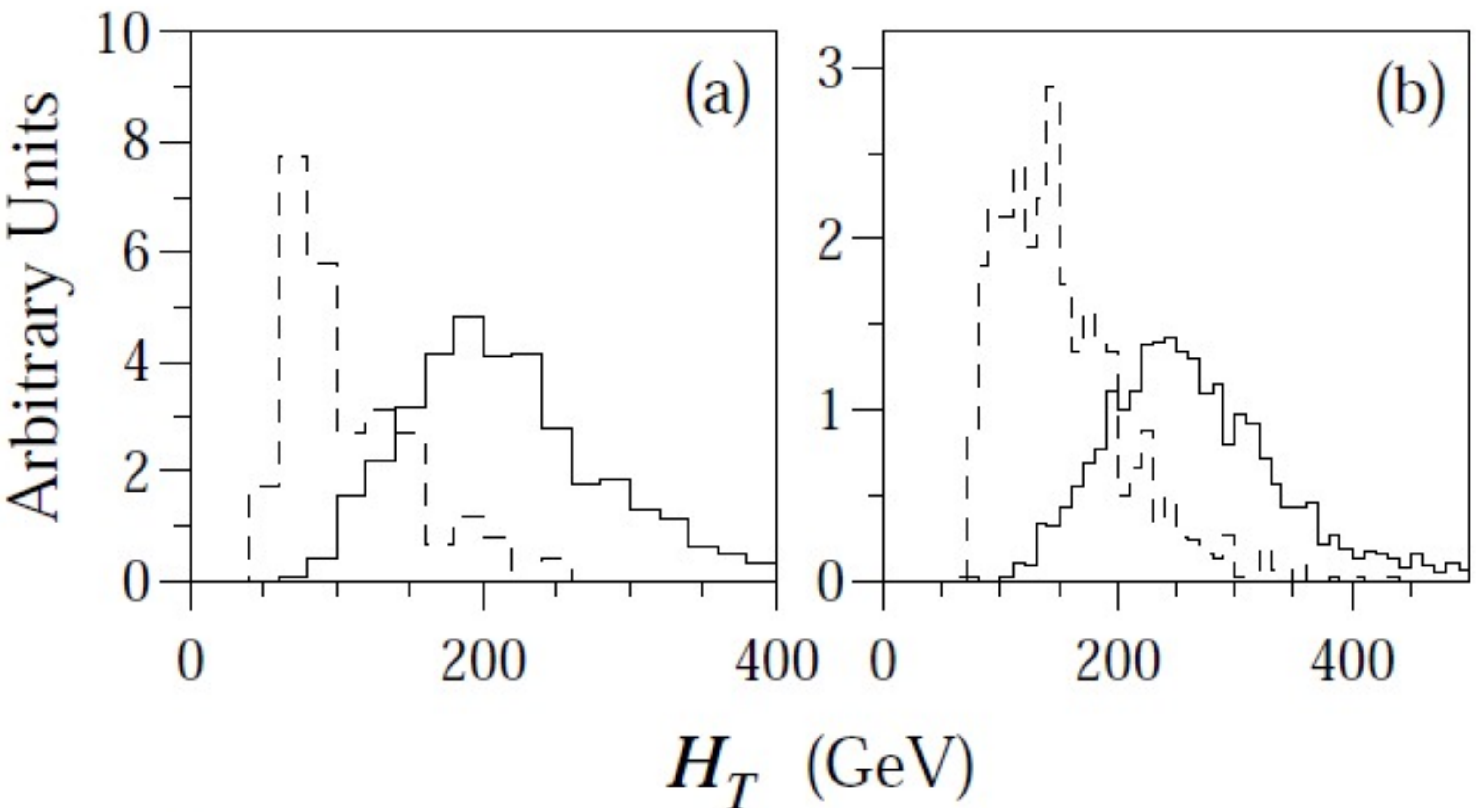
Hardware for Zero

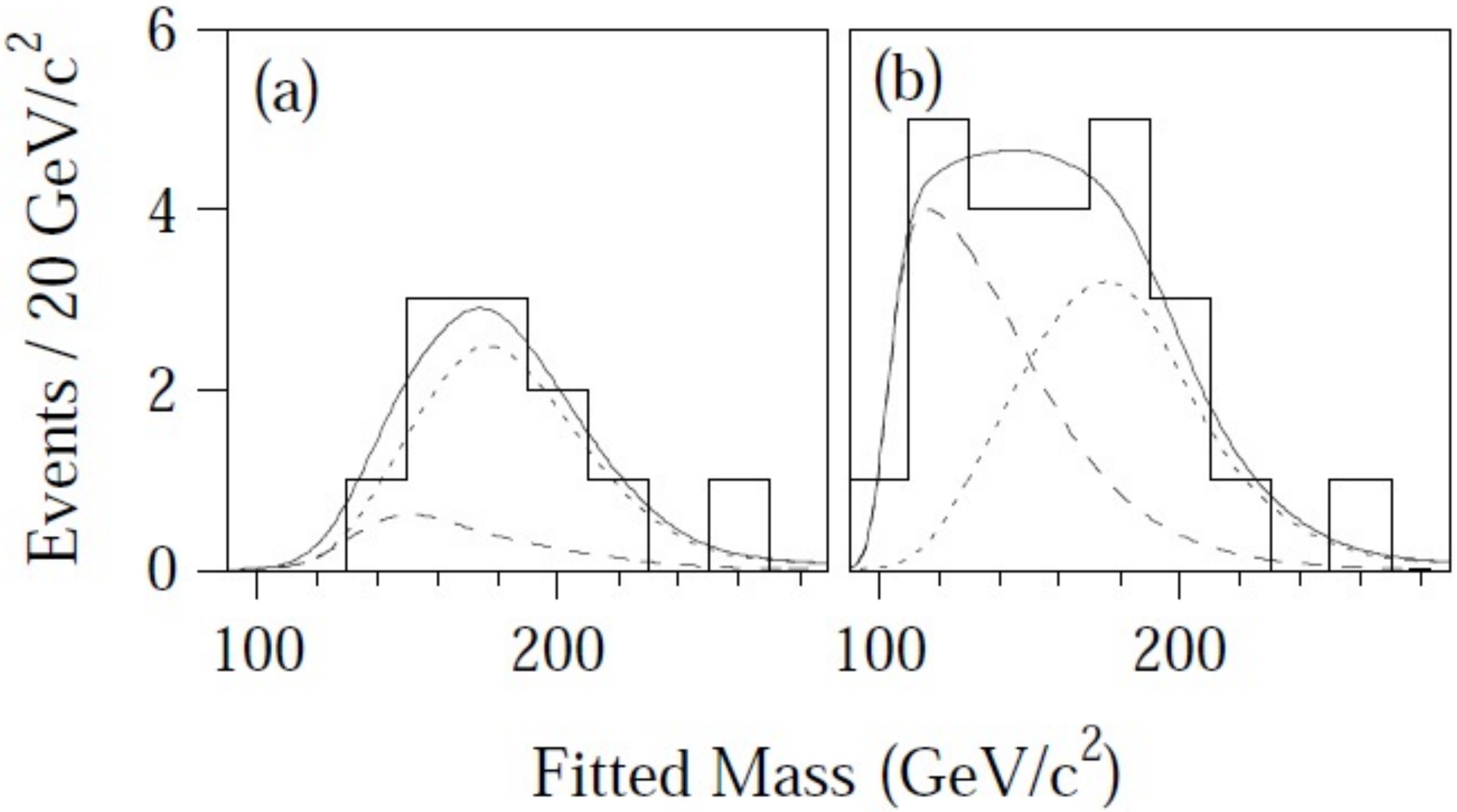
- The hardware contribution came from the TIFR group which built the veto detector for the muon system
- Large scintillator detector with embedded WLS fibers
  - completely built in-house and transported to USA

Indians in Dzero

- India's contribution was the most visible part of Dzero
- Also active participation in calibration and in the trigger system

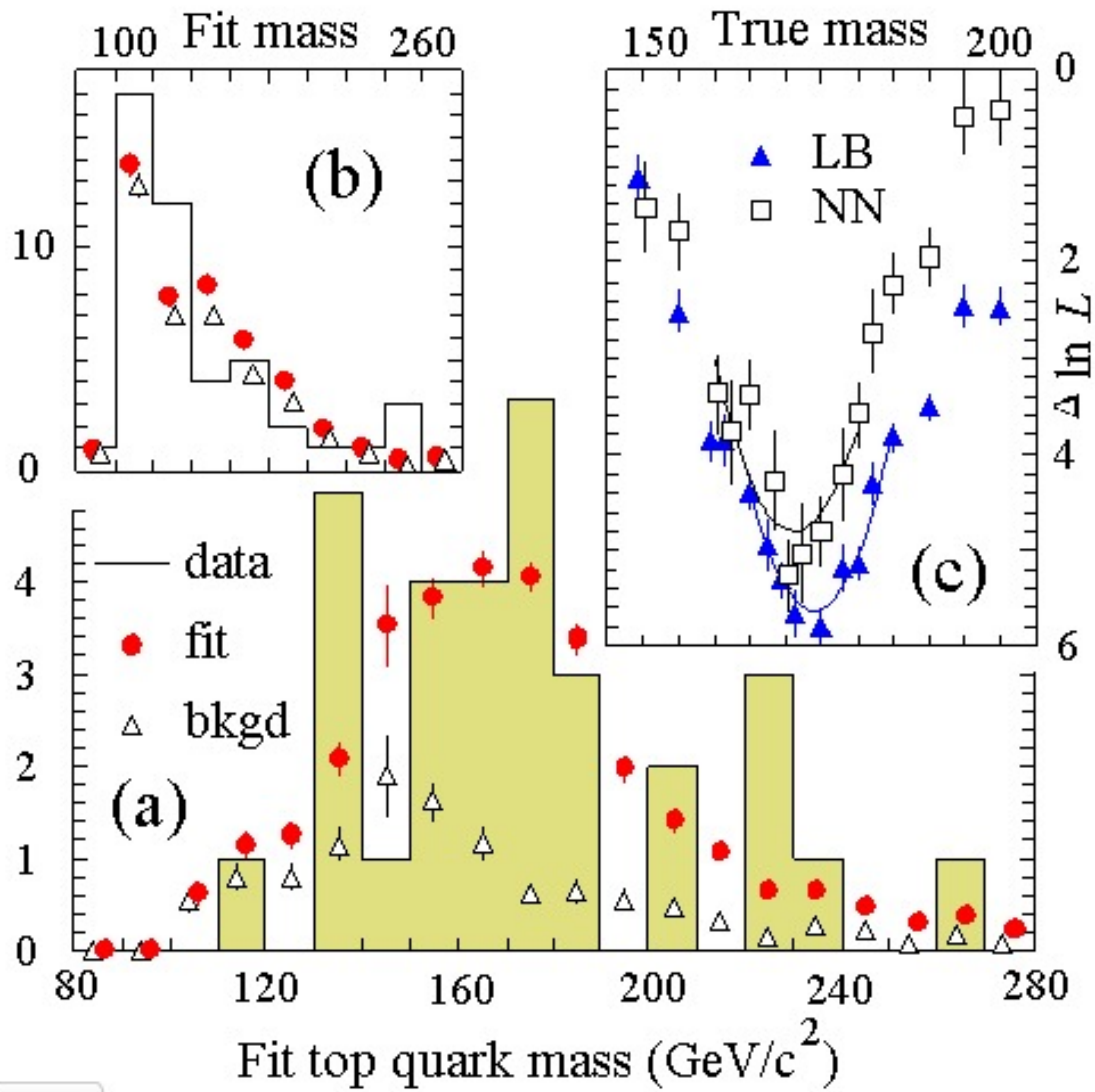
Dzero and Top Quark





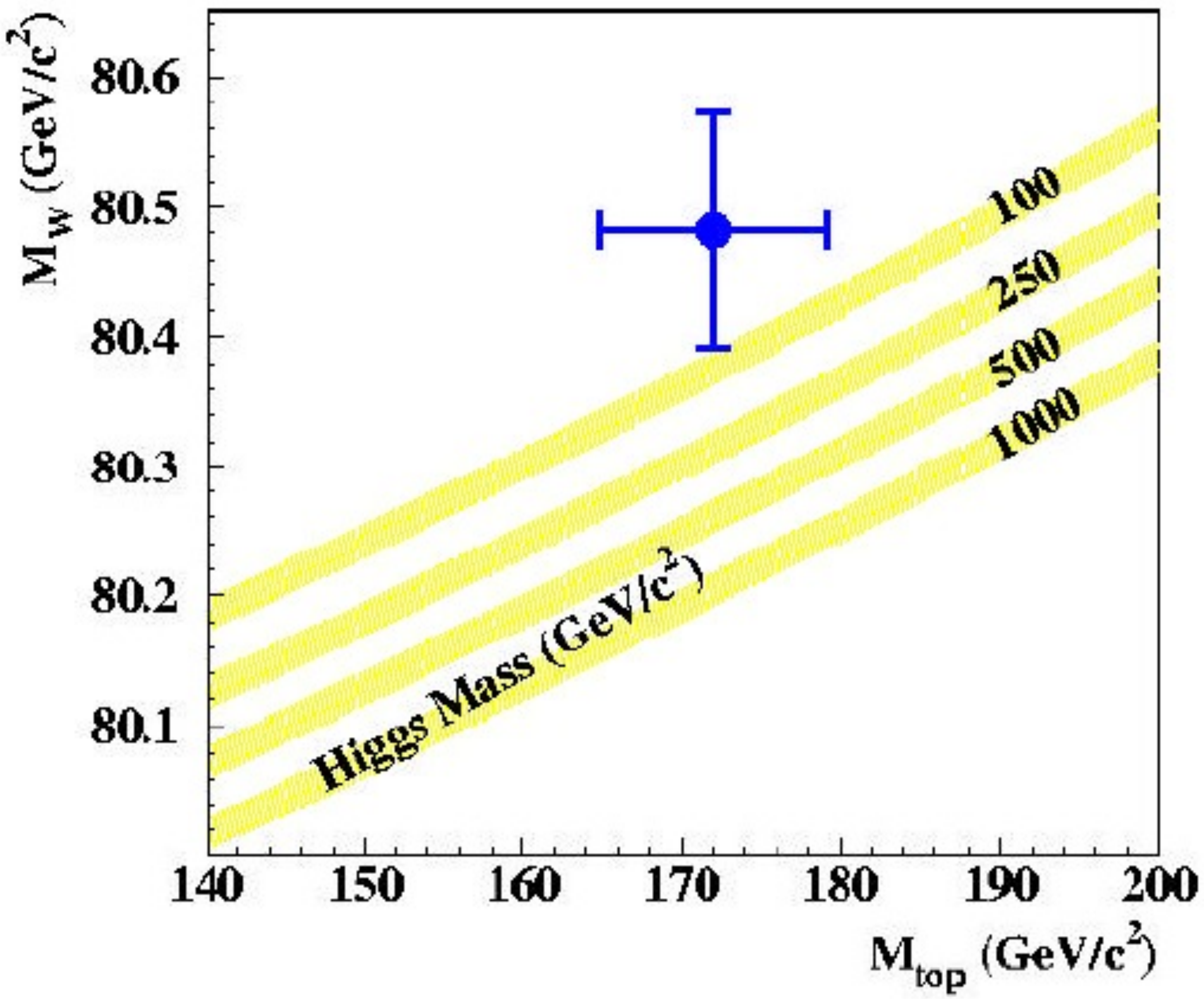
- Dzero during RunI was heavily dependent on calorimetric measurements
- So one way to look for heavy new quark was to look for special features in event shape variables
- Machine learning was a useful tool as well
- Discovery was announced in 1995 along with CDF
- Even with advanced techniques and best possible calorimeter, the first estimate of top quark mass was a bit on the higher side

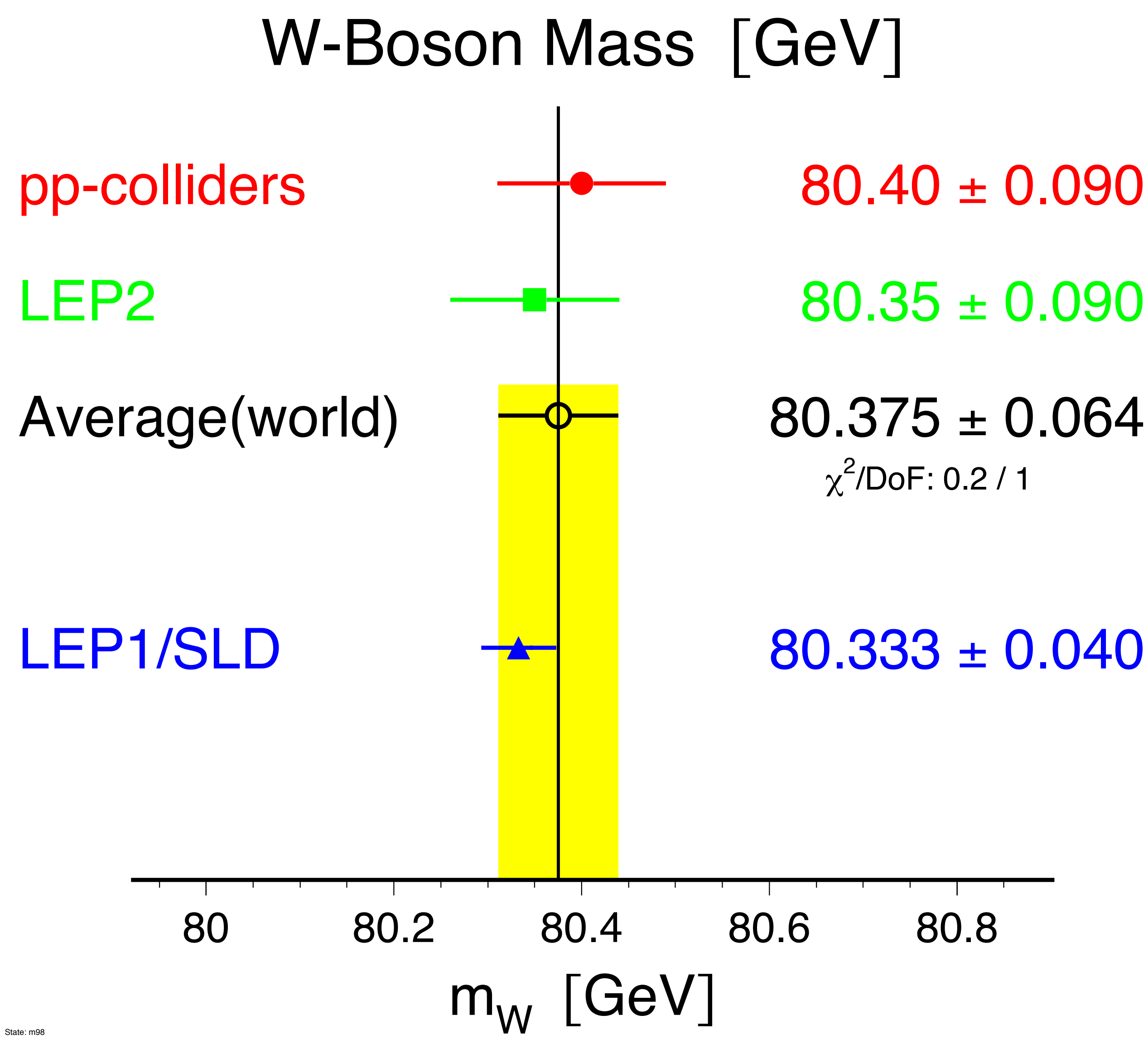
Dzero at Run2



- During Run2 the detector was modified to include a tracking detector and a solenoid to measure momenta of the charged particles
- Mass resolution was improved and the mass determination was accurate

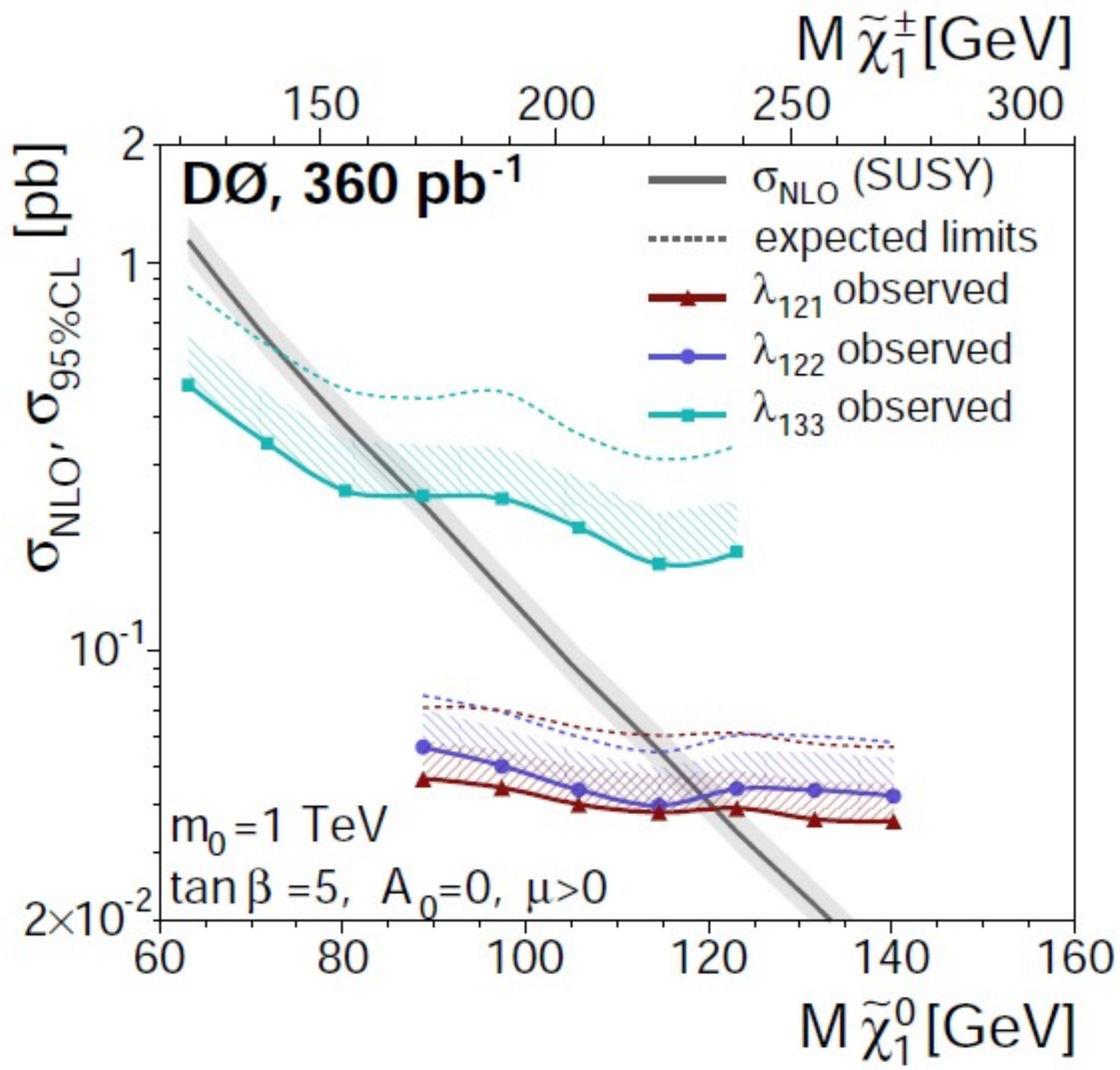
Precision EW Measurements

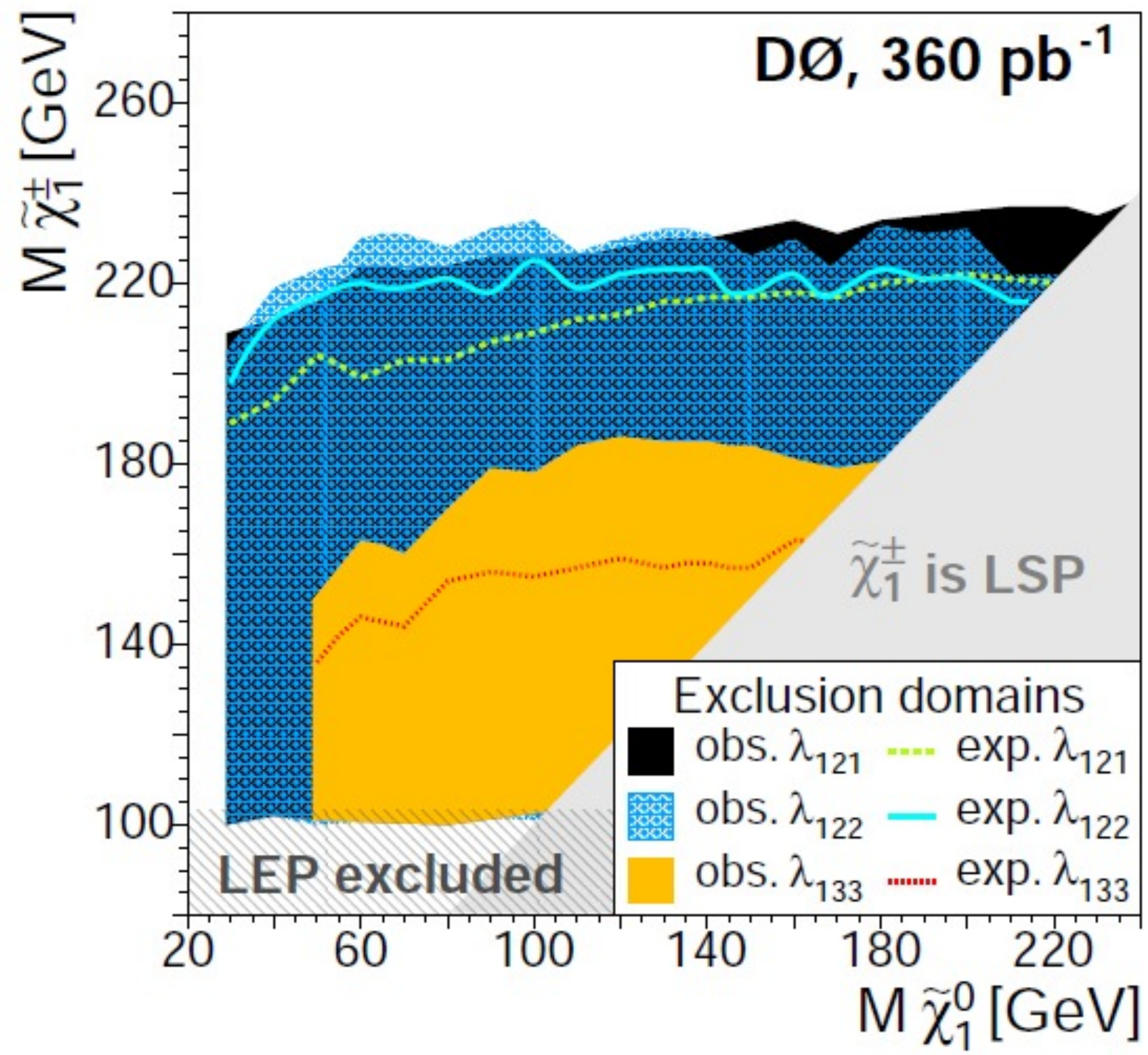




- Tevatron beat LEP in the determination of W-mass
- Together with top-quark mass they could predict a narrow region of Higgs mass in the Standard Model framework

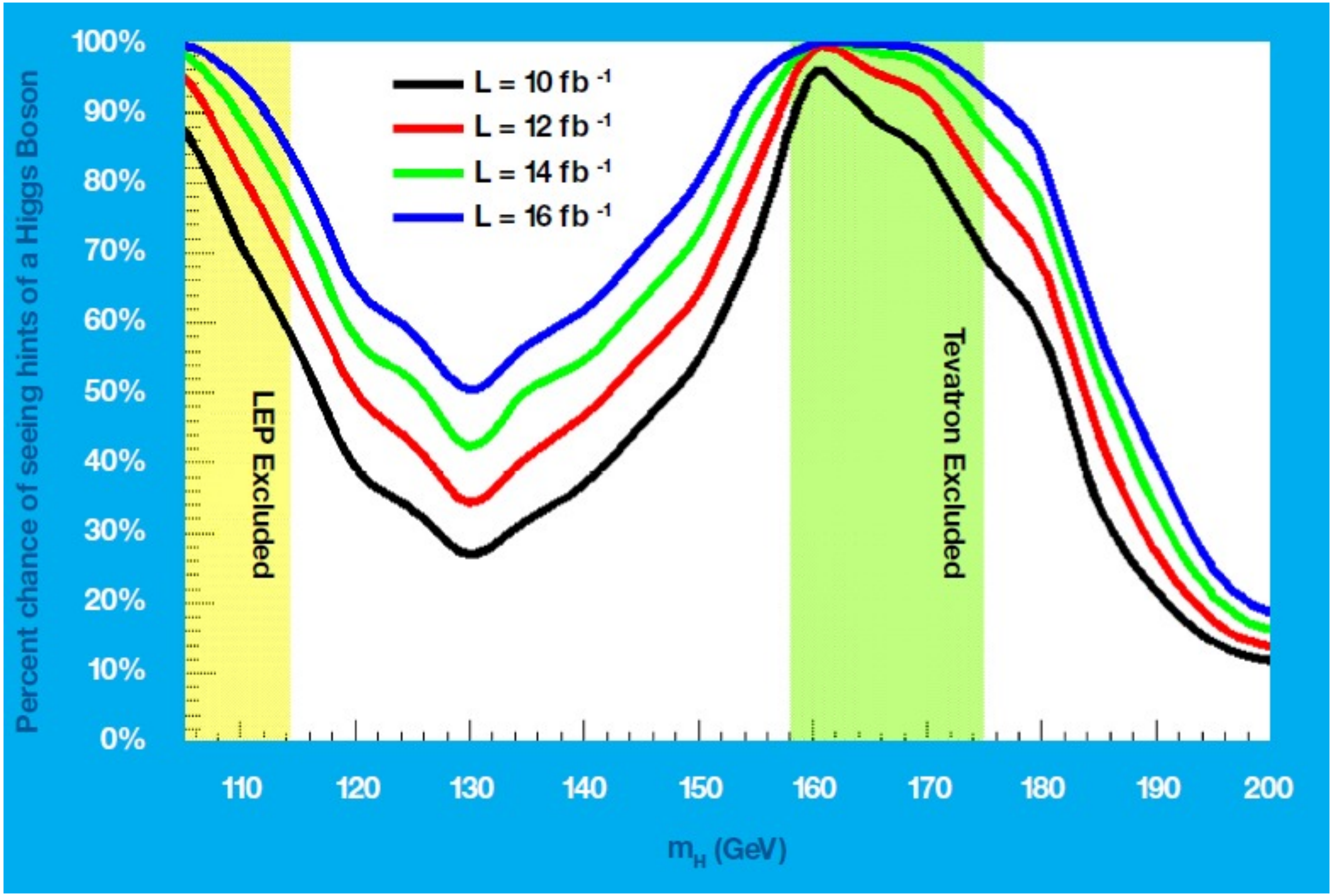
Searches at Dzero





- Like everywhere else search for SUSY was carried out both in R-parity conserving as well as R-parity violating scenario
- All these searches led to null results and provided upper bound to cross section or some exclusion region in the parameter space of some favorite model of theorists

Most Important Search from Dzero

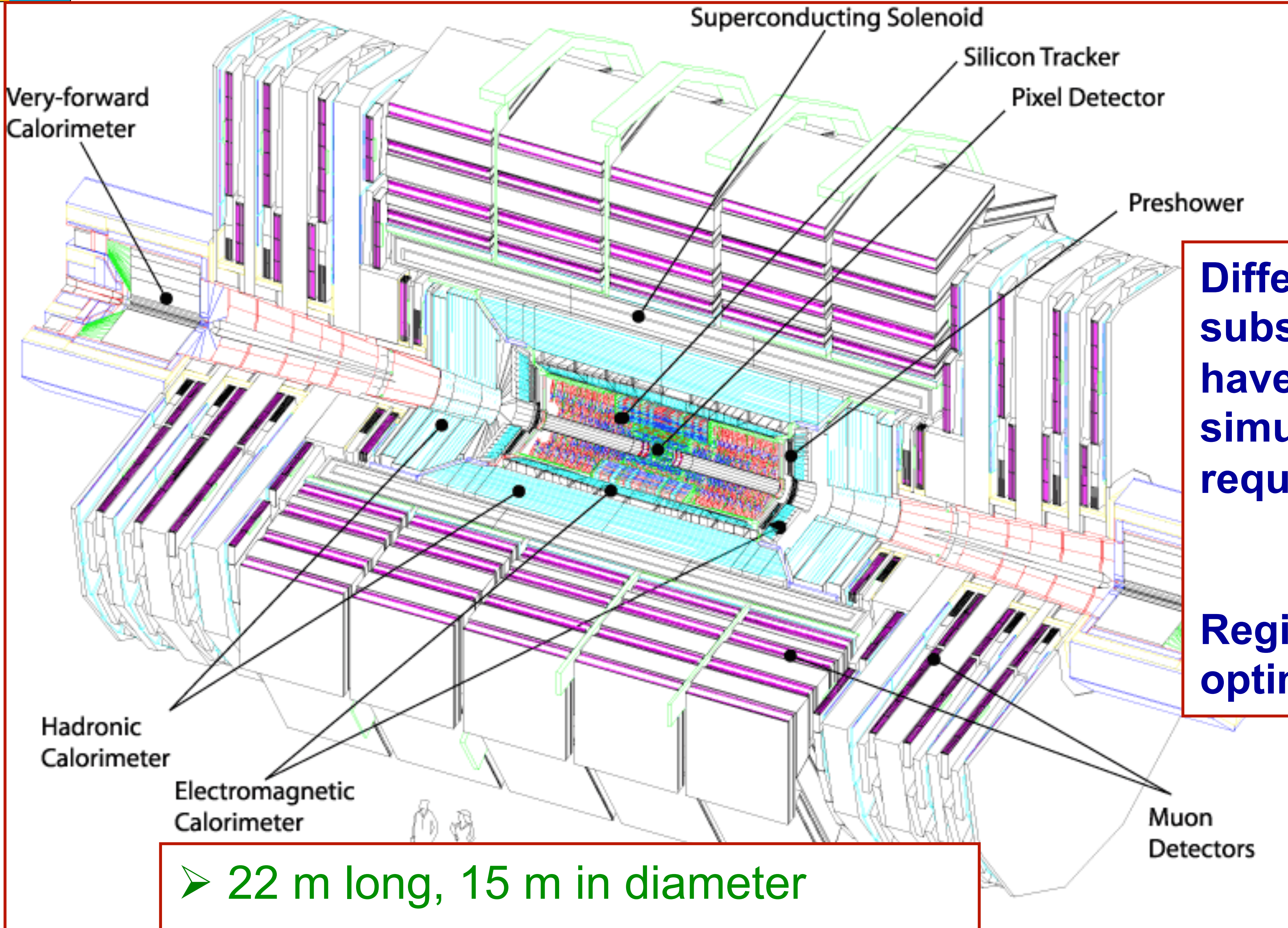


- Dzero (also CDF) looked for Higgs boson in associated production (along with a vector boson).
    - No luck and only some exclusion region

Third Collider Experiment

- High energy community moved toward high energy pp collider project by the end of 80's
  - Two proposals were in the market: SSC at Texas and LHC at CERN
- SSC received two major proposals
  - SDC with participation from many US institutions
  - LSTAR, a collaboration led by Ting
    - Emphasis was again on leptons and photons. India became a part of this proposal.
    - It was turned down by the committee in view of management structure. The same idea was moved to a new proposal GEM led by B. Barish
- LHC received four proposals for general purpose detectors
  - Two proposals used toroidal agents (EAGLE and ASCOT)
  - Two proposals (CMS and L3+1) used solenoids
  - Committee asked each pair to combine and provide 2 rather than 4 proposals
    - The first 2 combined to submit the ATLAS proposal
    - The second 2 could not be combined. L3+1 was dropped and some of the groups went to ATLAS and others to CMS
    - India became a part of CMS - the first group to join was EHEP group of TIFR; soon came HECR group of TIFR, Universities of Delhi and Panjab and finally BARC
      - These groups formed so called India-CMS team; first such national collaboration
      - The collaboration is enlarged with many groups from Calcutta, Bombay, Madras, Bangalore, Bhubaneswar, Pune, ……

CMS Detector



Different subsystems have different simulation requirements

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Region based optimization

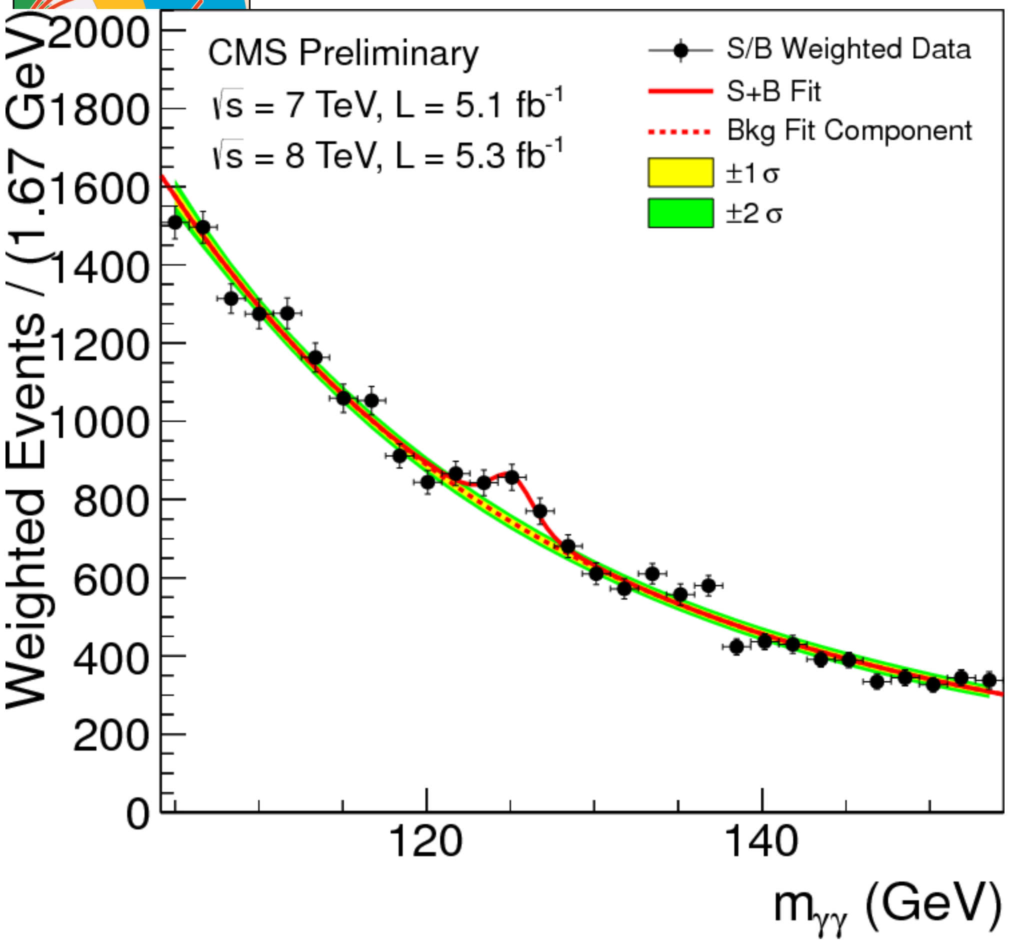
- 22 m long, 15 m in diameter
- Over a million geometrical volumes
- Many complex shapes

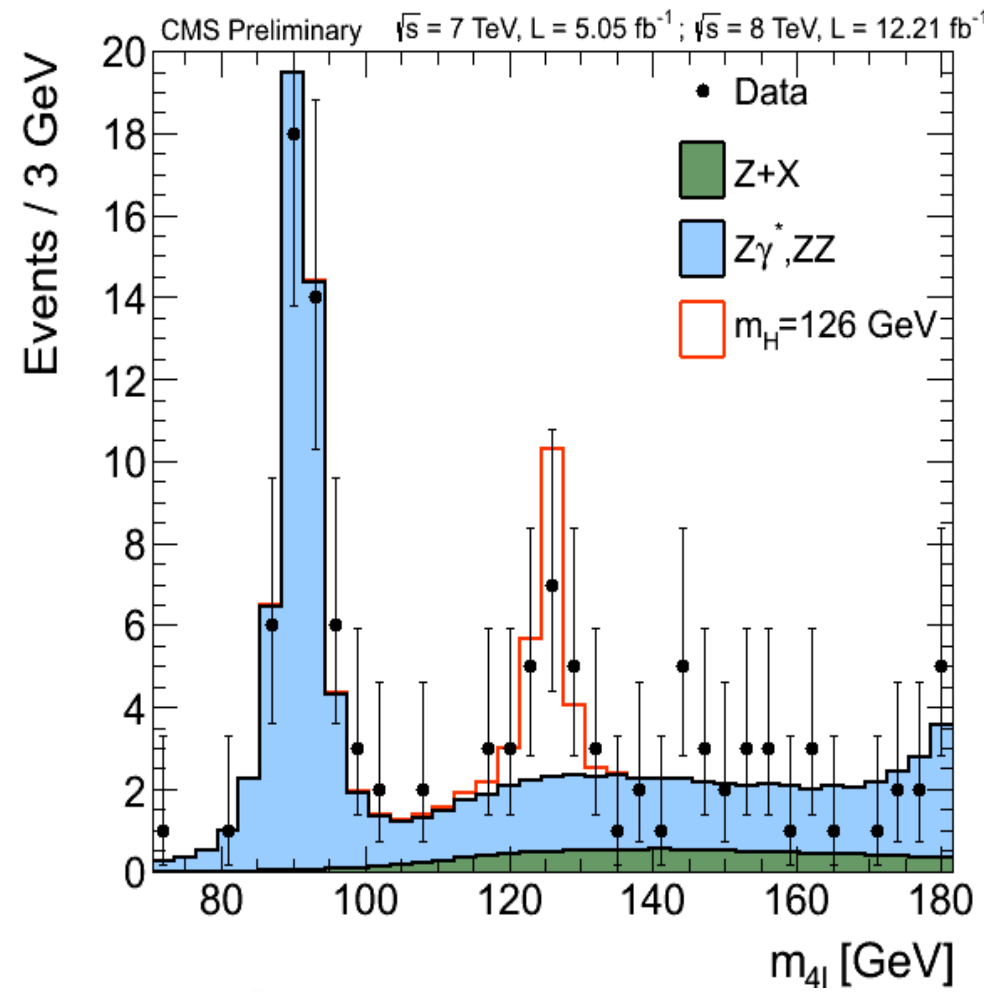
Indian Participation

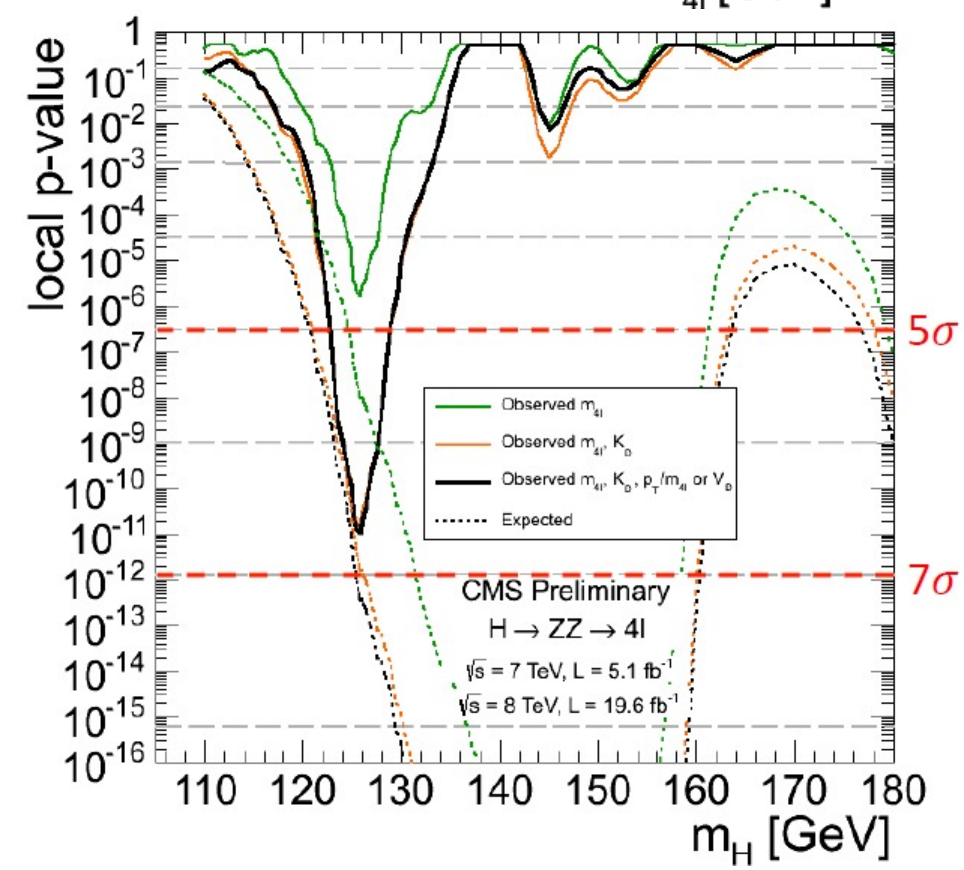
- Indian contribution in term of manpower as well as detector components increased with time
- For the Run 1 detector Indian groups participated in 2 major detector components
  - Outer hadron calorimeter: a scintillator detector just outside the magnet coil
  - Preshower detector: silicon strip detectors in front of the endcap electromagnetic calorimeter
    - A new endeavor by having a joint collaboration with local industry (Kataria)
  - Utilization of Apsara and gamma sources to study radiation hardness of crystals to be used for EM calorimeter
- Big contribution to the offline software and responsible for the current agreement between data and simulation (material content as well as quality of simulation)

- There was a major test beam activity with combined calorimeter system
  - Learnt many issues of the calorimeter system
    - Noise in the barrel calorimeter system due to glues in the APD
    - Noise in the forward calorimeter because of punch/sail through particles hitting PMT windows

Just One Achievement







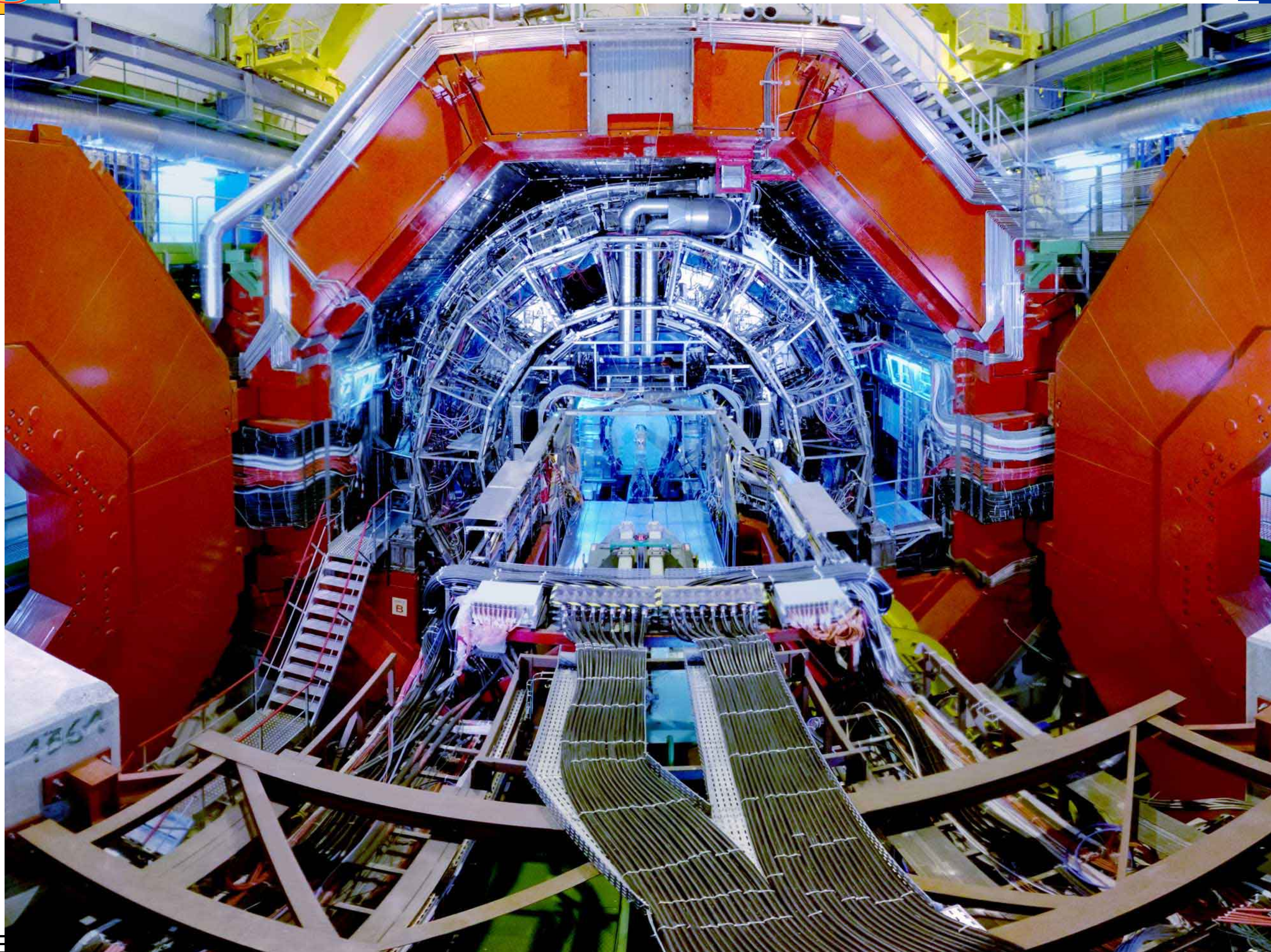
- During 2012, CMS along with ATLAS announced the discovery of a new particle. It has now been shown that this new particle has the properties of Standard Model Higgs boson
- Some members from India-CMS participated in this finding

Celebration Thereafter

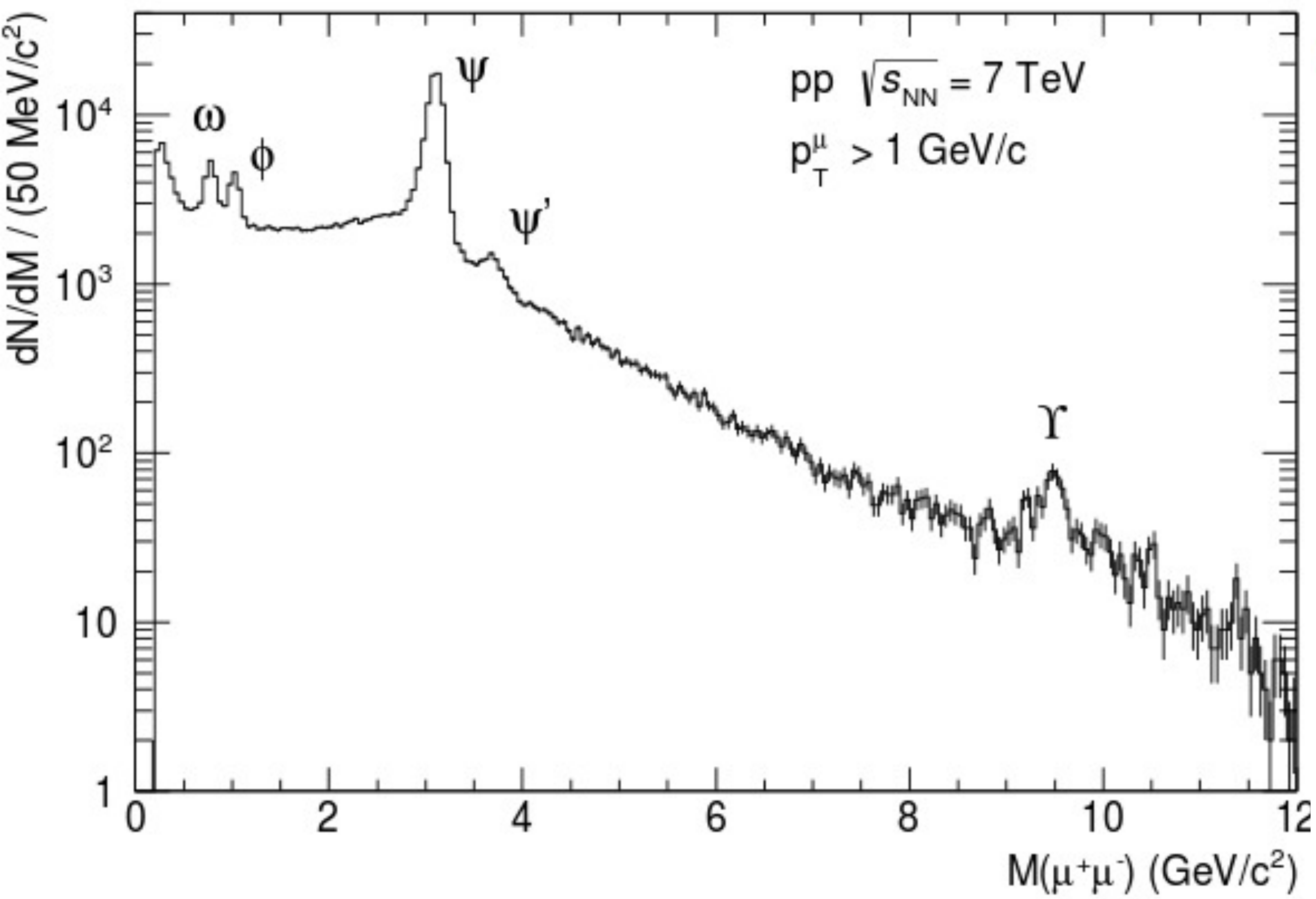
The Next Two Ventures

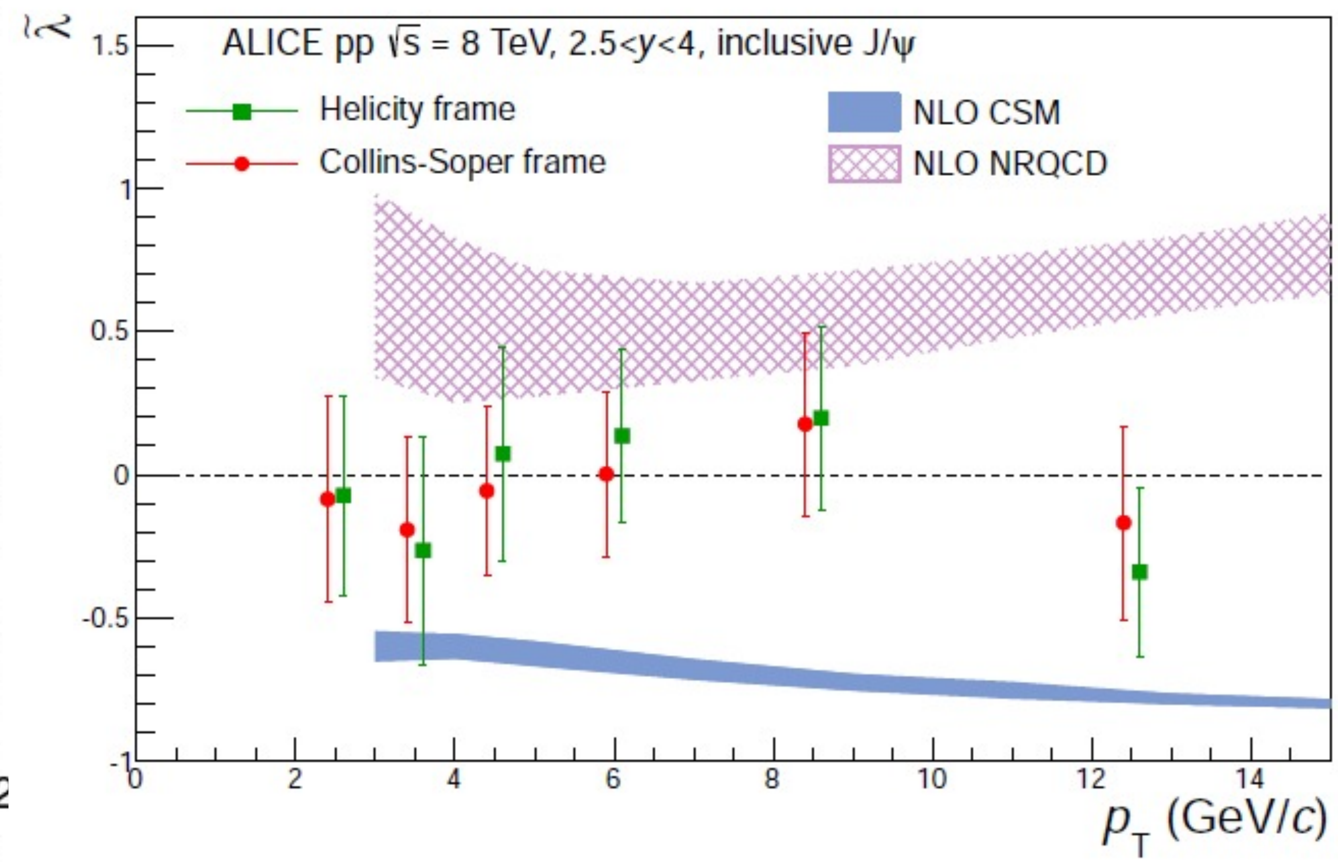
- VECC team under the leadership of Bikas Sinha approached CERN to participate in a heavy ion experiment
  - First participation (Y.P.Viyogi, …) was in a number of fixed target experiments (WA93, WA98)
  - Several groups joined this effort: IOP, Universities of Jammu, Jaipur, Panjab, …
- Soon this collaboration joined the heavy ion programs at the LHC and RHIC
  - ALICE collaboration like CMS is continuously taking data and have several groups from India: Aligarh, Bhubaneswar(IOP, NISER), Calcutta (Bose Institute, SINP, VECC), Chandigarh, Jammu, Jaipur, ……
  - STAR collaboration now have active participation from IOP, Jammu, NISER, VECC, ..
  - PHENIX collaboration was joined by BARC and BHU
- The major detector contributions for the first phase of the experiments:
  - Photon Multiplicity Detector (to both STAR and ALICE)
  - Forward Muon Spectrometer and the frontend readout chip ("MANAS")

ALICE



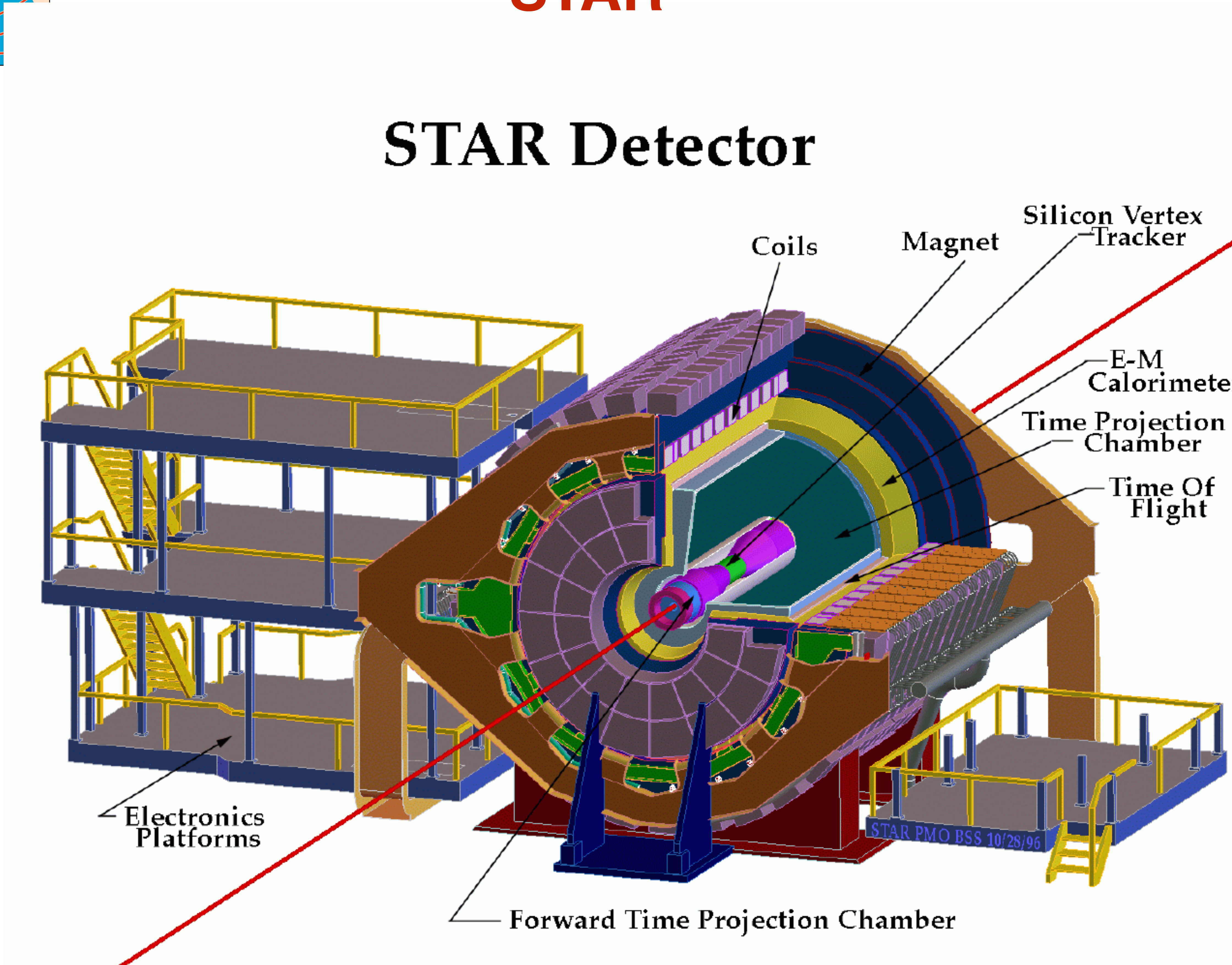
One Example from ALICE



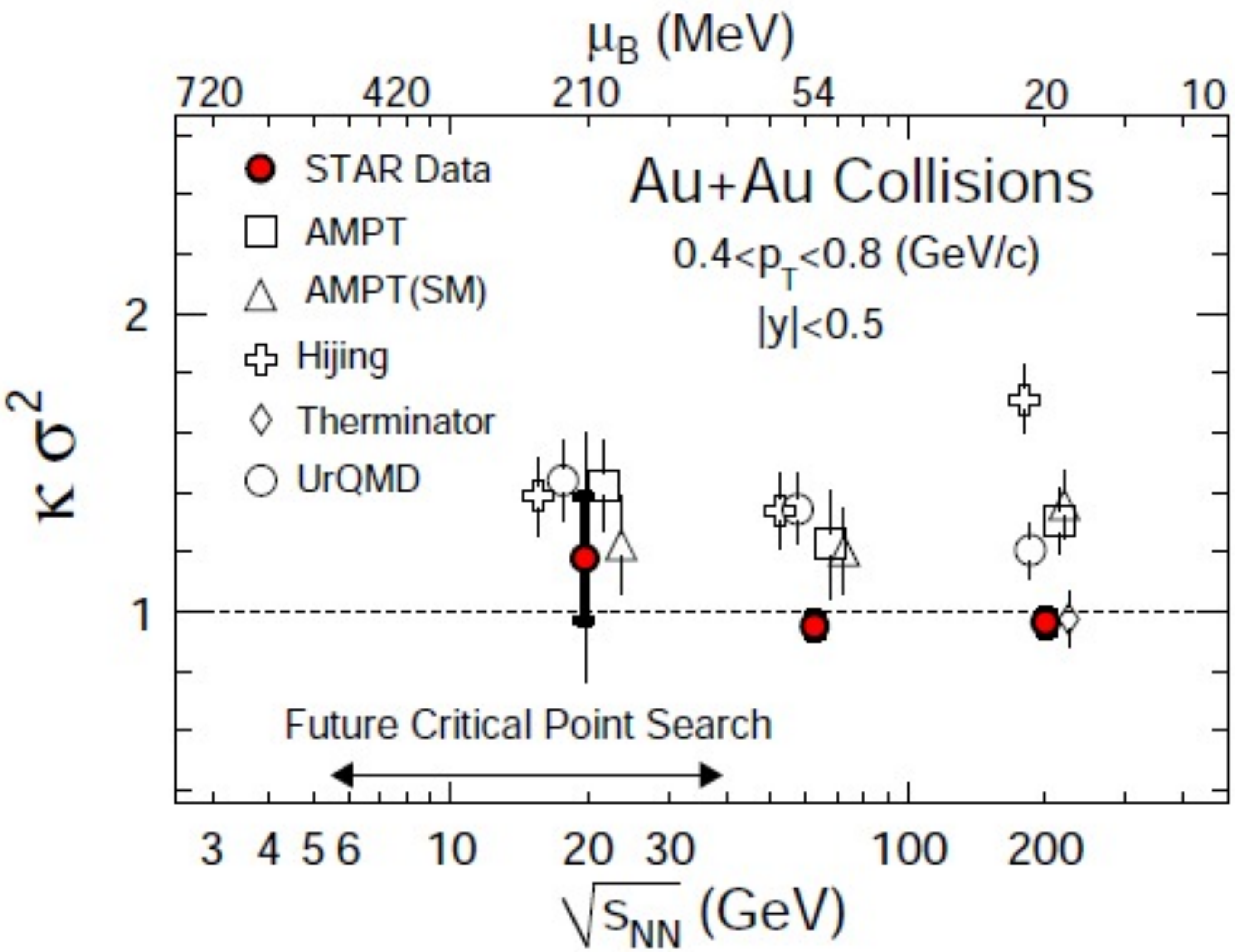


- ALICE can reconstruct J/ψ in the forward rapidity region
- Decay angular distribution of the muons provides a measurement of the polarization
  - No polarization is observed for the J/ψ system
  - Comparison with two theoretical models show that neither of these models provide agreement with the data

STAR

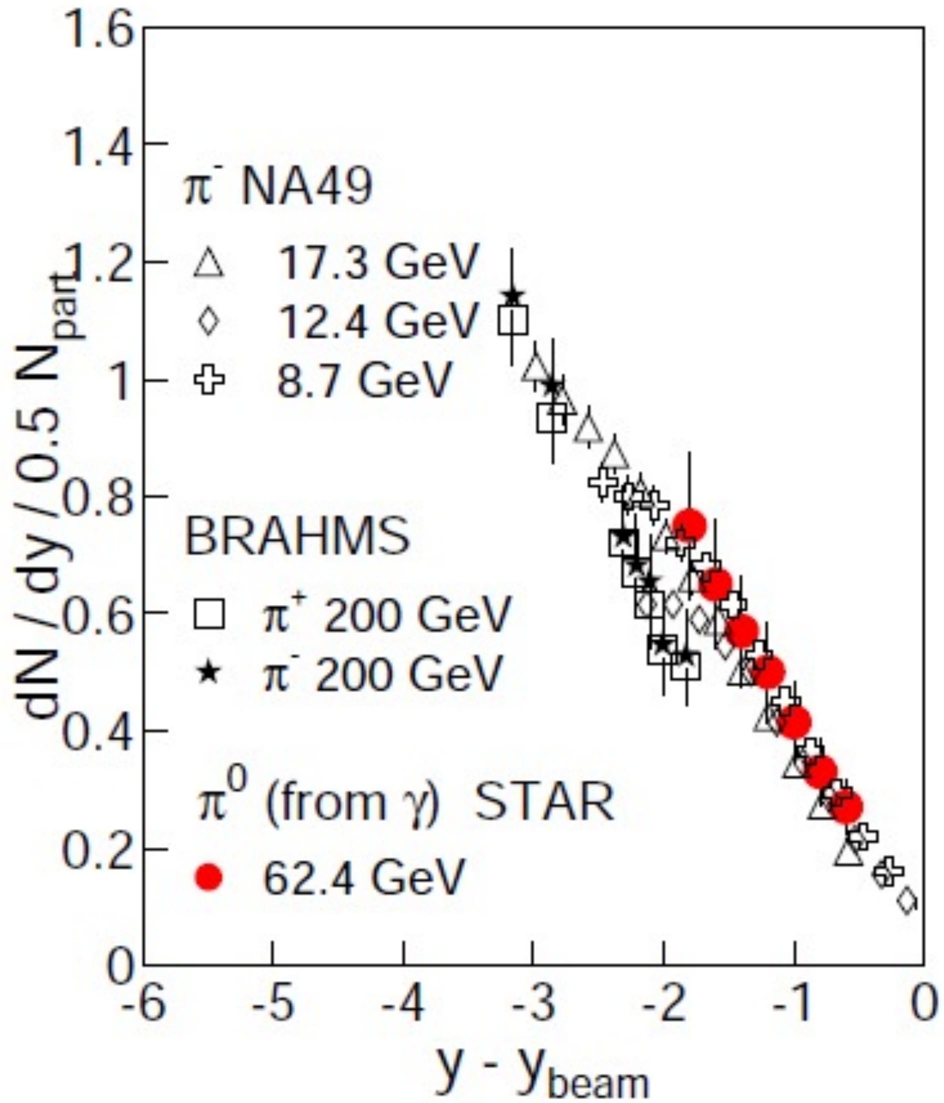

STAR Detector
Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
STAR PMO BSS 10/28/96

Net Proton Multiplicity



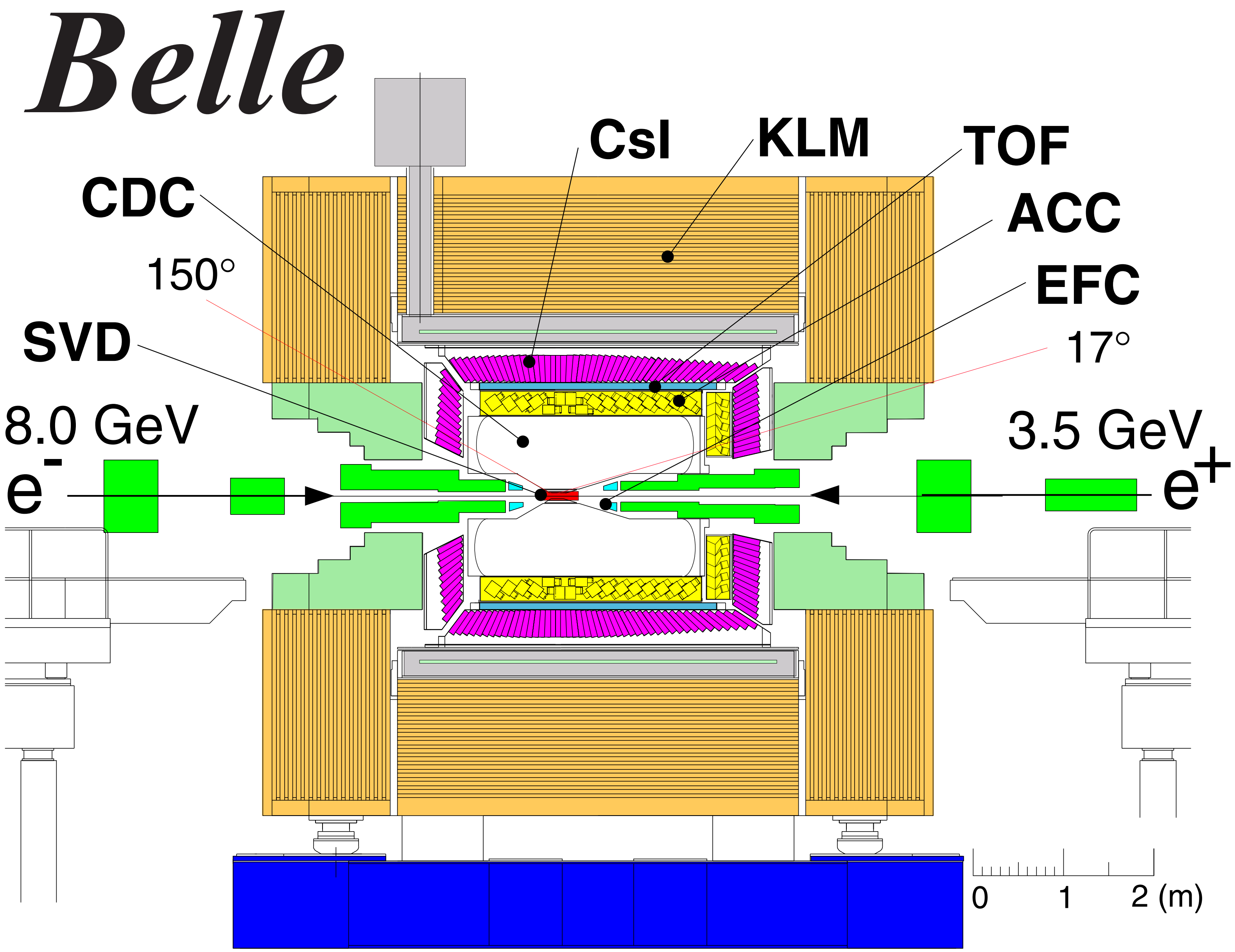
- Study evolution of centrality dependence of proton (+anti-proton) multiplicity moments in terms of the first 4 moments (mean, variance, skewness, kurtosis) in Au+Au collisions at 3 energies
- Data do not support any evidence that critical point (CP) in the QCD phase plane at baryon chemical potential (μ_B) is reached at RHIC beam energy

Photons in Au+Au Collisions



- Study photon multiplicity and pseudo-rapidity of photons for different centrality region in Au+Au collisions at effective nucleon-nucleon CM energy of 62.4 GeV
- Compare with charged pion rapidity density in Au+Au collisions and Pb+Pb collisions which shows that pion production in fragmentation region is independent of beam energy (limiting fragmentation picture)

The Latest Entry

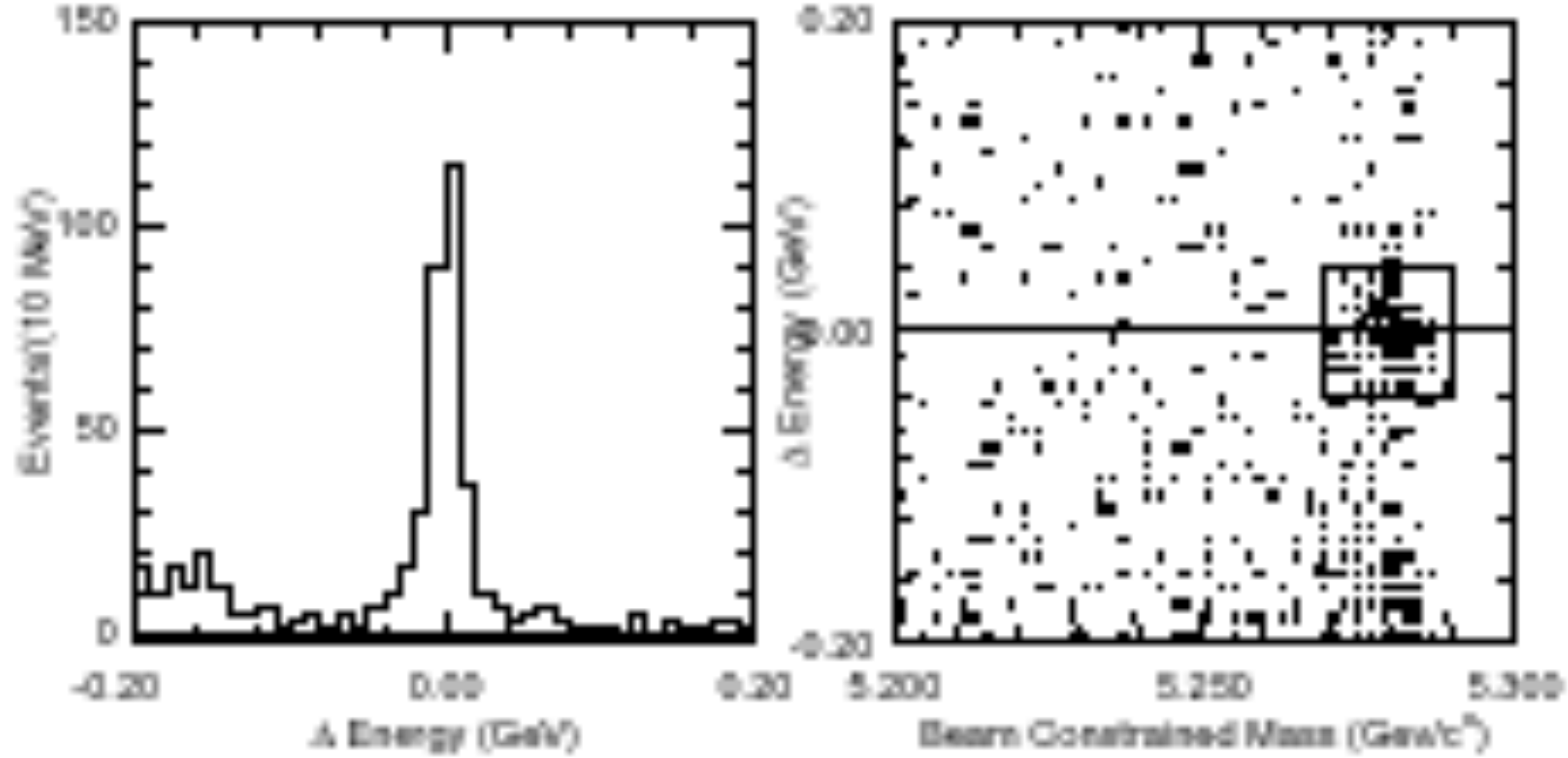


- Toward the end of 90's scientists from KEK encouraged Indian groups to participate in the experiment at KEK-B: Belle. Three groups joined initially
  - Utkal University (Mamta Satpathy + students)
  - Panjab University (Jasbir Singh + students)
  - TIFR (SB, Gobinda Majumder, Tariq Aziz, …)
- Scenario has changed significantly since then (IITM, IITG, IITBh, IISER-Mohali, …)

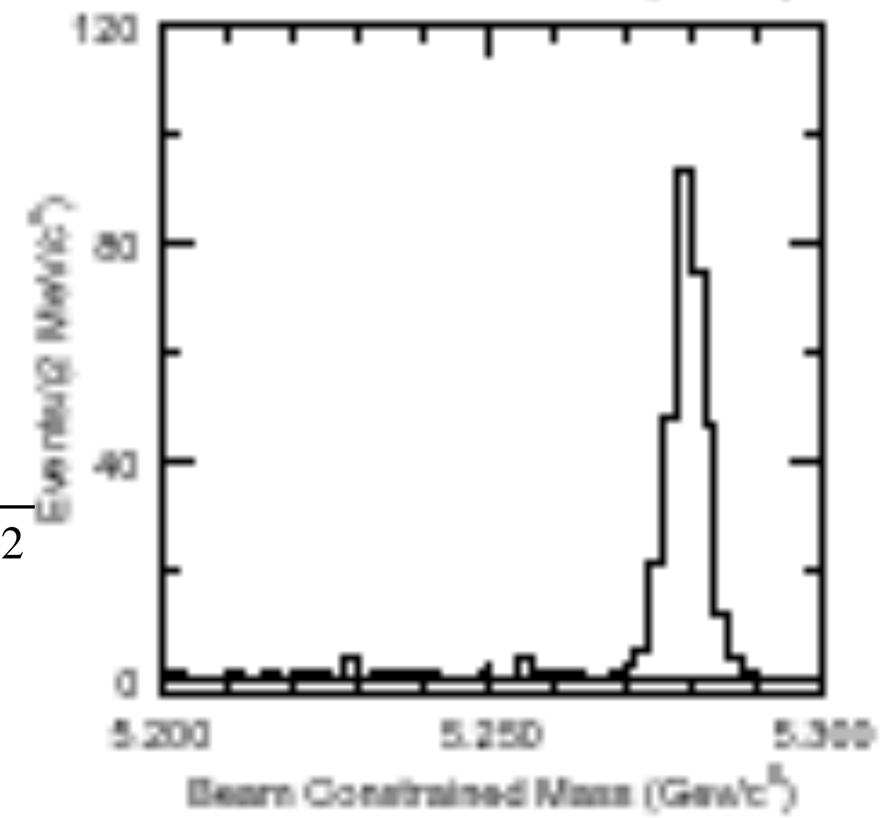
Contribution to Experiment

- When the Indian groups joined Belle-I, the detector was fully commissioned. So there was no question of hardware contribution. Also funding was almost non-existent
- Improve several reconstruction codes (even after the publication of the first papers on observation of CP violation)
  - Improve the performance of the KLM sub detector
    - improve direction resolution with optimum usage of hits
    - utilize radial information of the KLM hits
    - employ different algorithms in the barrel and endcap to improve signal to BG
  - Improve photon energy calibration
    - Use two different source of physics events to calibrate very low ($D^* \rightarrow D^0+\gamma$) and medium energy (radiative μ-pair) photons
  - Estimation of uncertainty in track finding algorithm
    - Use track embedding technique
  - Handling the effect of shower uncertainty in the electromagnetic calorimeter
    - Utilize the information of the Cerenkov and TOF detectors for early showering and of KLM for late showering
- In the Belle-II detector Indian groups are contributing to the silicon tracking detector

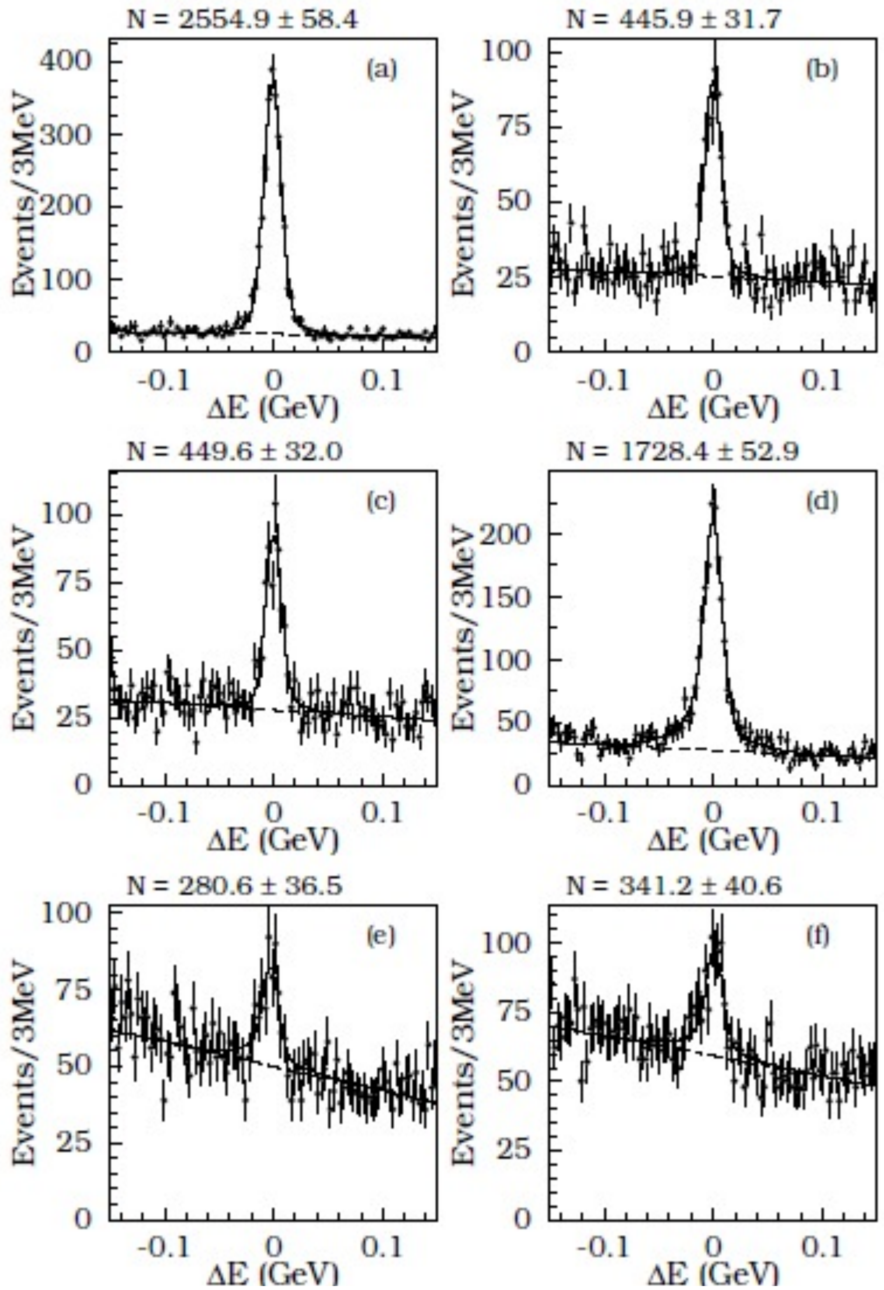
B-Meson Reconstruction



- Use two variables to select ev
  - Energy difference: $$\Delta E \equiv \sum E_i - E_{CM}/2$$
  - Beam constrained mass: $$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$



New Decay Modes of B Meson

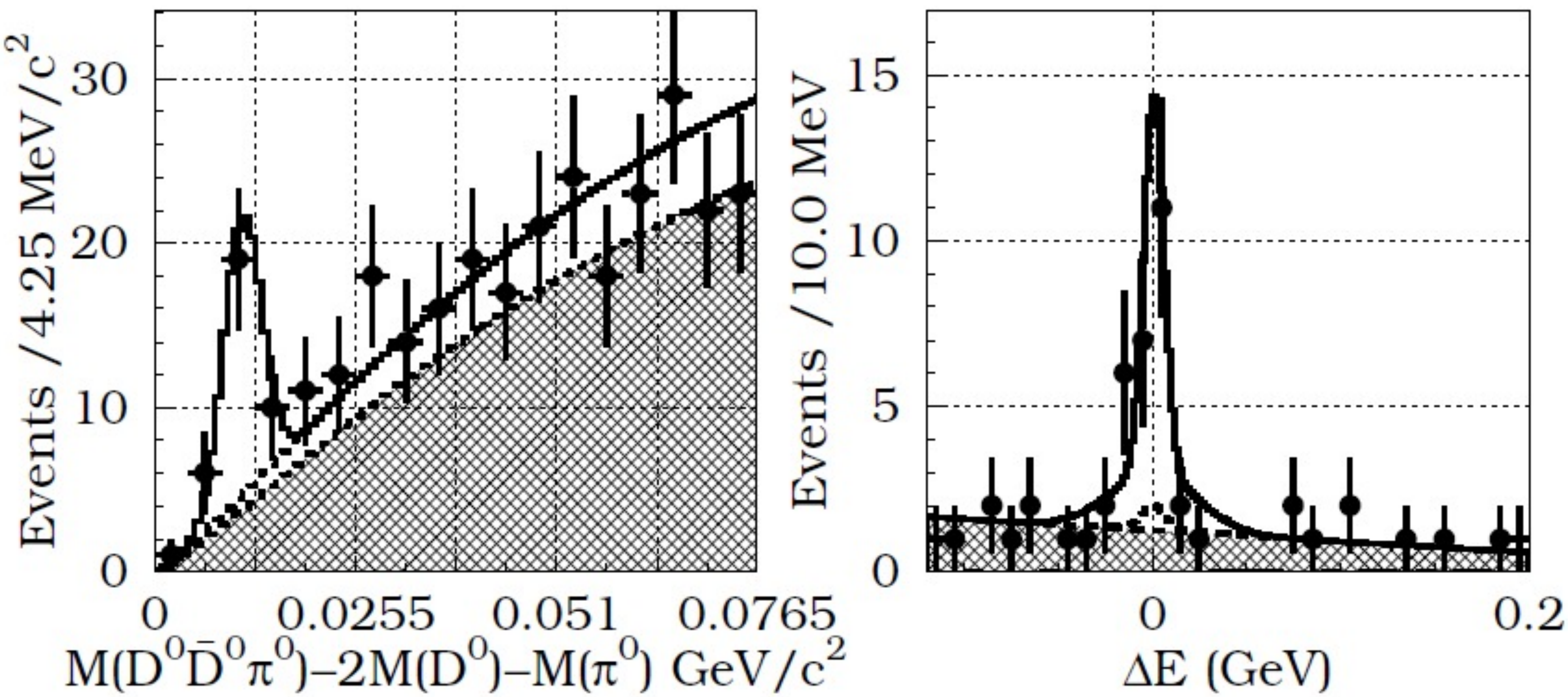


$$\Delta E = E_{D^*} + \sum_{i=1}^{n} E_{\pi_i} - E_{\text{beam}}$$

- Study several possible states with D* and nπ's with n = 3, 4, 5
- This led to the first observation of several new decay modes of B's and determination of their BR's

Channel	Signal yield			$\mathcal{B} \times 10^3$				
$B^0 \to D^{*-}(3\pi)^+$	2554.9	$\pm$	58.4	6.81	$\pm$	0.23	$\pm$	0.72
$B^+ \to D^{*-}(4\pi)^{++}$	445.9	$\pm$	31.7	2.56	$\pm$	0.26	$\pm$	0.33
$B^0 \to D^{*-}(5\pi)^+$	449.6	$\pm$	32.0	4.72	$\pm$	0.59	$\pm$	0.71
$B^+ \to \overline{D}^{*0}(3\pi)^+$	1728.4	$\pm$	52.9	10.55	$\pm$	0.47	$\pm$	1.29
$B^0 \to \overline{D}^{*0}(4\pi)^0$	280.6	$\pm$	36.5	2.60	$\pm$	0.47	$\pm$	0.37
$B^+ \to \overline{D}^{*0}(5\pi)^+$	341.2	$\pm$	40.6	5.67	$\pm$	0.91	$\pm$	0.85

New Decay Mode of X(3872)



- A new narrow resonance X(3872) was discovered in the Belle experiment
- A near threshold $D^0D^0\pi^0$ enhancement was observed at 3875.4 GeV which was 2σ above the world average value of X(3872) mass
  - Could be threshold effect
- This supports quantum number assignment of X(3872) to be $J^{PC} = 1^{++}$

Summary

- India has a history of 35 years in collider experiments
- Indians started hesitatingly in the new field with minimal support from the government or from peers around
- The first adventure was a success - with very large impact on all fronts: hardware, software and physics contributions
- India is now making a larger effort
  - Order of magnitude larger personnel
  - Many order of magnitude larger financial support
- Larger effort should bring larger impact in the field
  - Let us hope Indian participation in collider experiments bring more respect from all quarters

Additional Slides

consideration

History of Colliders

- Wideröe in 1953 made a German patent on construction of machines based on collision of similar (p-p) or dis-similar (e^+e^-) particles. This was a follow-up of an idea which Wideröe had in 1943 for collisions of non-relativistic particles

- From consideration of Fixed Field Alternating Gradient (FFAG) synchrotron, Kerst et al. gave a concrete proposal of making colliders during 1956

- O'Neil in 1956 gave first the idea of accelerator-storage ring complex in the CERN accelerator Conference

- Touschek built the first electron-positron storage ring AdA at Frascati in 1960, Budker at Novosibirsk (VEPP-1) and O'Neil/Panofsky made electron storage ring (Princeton-Stanford) at similar time

- The first high energy (> 2 GeV) physics results came in 1970 from the ADONE machine built in Italy using electron-positron beam

- The first hadron collider came at CERN with the ISR project approved in 1965, constructed under the leadership of Johnsen, with the experiments starting from 1971

- Possibility of using anti-proton came after the idea of cooling due to Budker (electron cooling) in 1966 and Van der Meer (stochastic cooling) in 1972