How did D-Zero discover the top quark without a silicon vertex detector?

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Hermeticity and Electron Identification

- The silicon vertex detector is acknowledged to be the "sine qua non" of the CDF top quark discovery. Without it, the "QCD fake" background events would have overwhelmed the CDF signal.
- D0 had no silicon vertex detector. Yet it managed to discover the top quark. How?
- The answer lies in D0's Hermeticity and its electron identification algorithms.
- With the original non-hermetic design, the QCD background would have been higher by a factor of ~3 in the e+jets and the μ+jets channels in D0.
- D0 used a sophisticated multivariate electron Id tool, the H-Matrix. Without it, (D0 had no magnetic field to do Energy/Momentum matching) the QCD fake background would have been higher by another factor of ~3 in the e+ jets channel.
- The D0 discovery paper had 17 events with a background of 3.8 events. This background would have increased to ~15 events, making the discovery impossible.
- In this poster, I explore the events that made the Hermeticity and the H-Matrix a reality in D0 by means of a series of vignettes.

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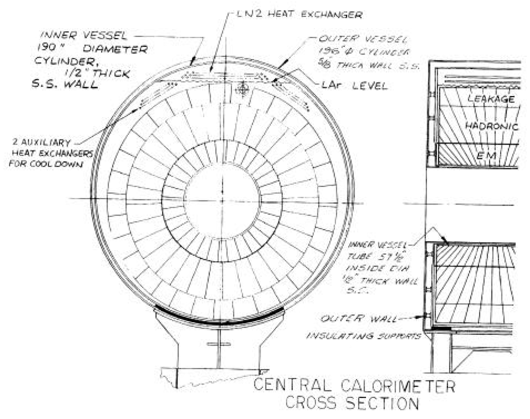
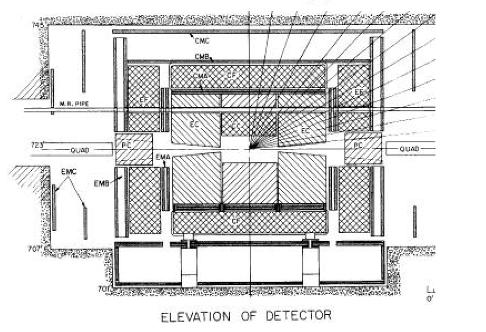
Hermeticity

- The D0 calorimeter design was initially highly non-hermetic. The design report shows the following.
- The central calorimeter had 32 phi-segments in each of its layers.
- There was a forward cone ala CDF run I, which was supposed to measure the E_T of forward particles better.
- No attention was paid in the design report on the Central/End Cap transition region.
- In short, hermeticity did not seem high on the list of design goals.





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Hermeticity-Adoption of Geant3

We decided in 1985 to adopt Geant3 as the simulation package. I was strongly in favor of this. Others supported D0SYM, a parametrized Monte Carlo. Geant3 permitted detailed hermeticity studies. D0SYM did not.

I fed the D0 calorimeter Geometry into Geant with careful attention to dead material and cracks.

Geant3 was a slow program and 16 MIP's those days had to be obtained using 16 microvax nodes. One could not simulate large numbers of 2-Jet events to study the effects of inhomogeneities. One had to do something better.

Minutes of the Monte Carlo Meeting
Held at Brookhaven on October 23, 1985

Present

Bruce Gibbard, Dave Hedin, Alan Jonckheere, Steve Kahn, S. Kunori, Jim Linnemann, Rajendran Raja, Serban Protopopescu, T. Trippe.

After some initial discussion of the DØSYM/GEANT3 Committee report, it as decided to adopt GEANT3 as the Monte Carlo Package for simulating the DØ experiment.

In order to facilitate a rapid implementation of GEANT3 for DØ simulation, a Monte Carlo working group was formed. The initial members of this group are:

A. Jonckheere, S. Kunori, S. Linn, R. Raja, and A. Zieminski

R. Raja was asked to coordinate this group. This group may be enlarged as need be.

The quality factor technique was the result. We could estimate the effects of calorimeter inhomogeneities using single particle responses, assuming an overall minimum-bias distribution of single particles.

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DEAD MATERIAL HERMITICITY STUDIES IN THE D0 CALORIMETER

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October 1986

D0 Note 461

Dead Material	Quality Factor.
I)CC/EC Transition region.	~200
II)Central Calorimeter EM crack.	8.59
III)Insert Plug/Middle Fine Hadronic crack.	5.43
IV)Crack between CC Fine Hadronic Modules	3.73
V)Crack between CC coarse Hadronic modules	3.47
VI)Crack between Middle Fine Hadronic End Cap modules.	2.56
VII)Crack between EC Middle Fine Hadronic and Outer Coarse hadronic modules	1.83
VIII)Crack between EC Outer Coarse hadronic modules.	0.98

Table 1: Ordered list of Quality Factors for the D0 detector

The definition of the Quality Factor

$$< E_T >= \frac{1}{2\pi\sigma_{incl}} \int gh(p_T^2) p_T dp_T^2 \int\int \frac{\Delta E(\eta,\phi)}{E} d\eta d\phi$$

The first term depends on the physics and is constant over the various dead materials, and the second term contains the properties of the dead materials. This second term, which we introduce here, we christen the Quality factor QF.

$$QF \equiv \int\int \frac{\Delta E(\eta,\phi)}{E} d\eta d\phi$$

Using this technique, we showed that the biggest hermeticity problem was due to the cryostat material in the Central/Endcap transition region.

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Hermeticity-ICD, Calorimeter modules

In order to reduce the effect of the transition region we proposed changing the cryostat material from iron to Aluminum. Management threatened to resign, arguing that this will delay D0 turn-on by 6 months. At this point we expected to turn on in 1989! Aluminum cryostat was defeated. I persevered with the argument and succeeded in convincing people for the need for an inter-cryostat scintillator detector (ICD) to measure the amount of energy lost in the cryostat in this region. I had the support of Walter Selove in these arguments and little else from the rest of the collaboration. The ICD was adopted and was built by Andy White, Kaushik De et al.

I was also unhappy about the 32 cracks in all the layers of the CC and EC. I managed, after vehement arguments to get the design for the hadronic layers in the CC and EC to have 16 cracks. It was deemed too late to change the CC EM calorimeter design, since it was deemed too advanced. I argued for the End Cap hadronic module closest to the beam to be monolithic and have the largest possible radius. In this I was successful.

Typical Management Response:- "Raja, You are paranoid about cracks. Cracks are not important".

One of the few D0 collaborators who strongly supported these design changes was Pier Oddone, who was in D0 at that time.

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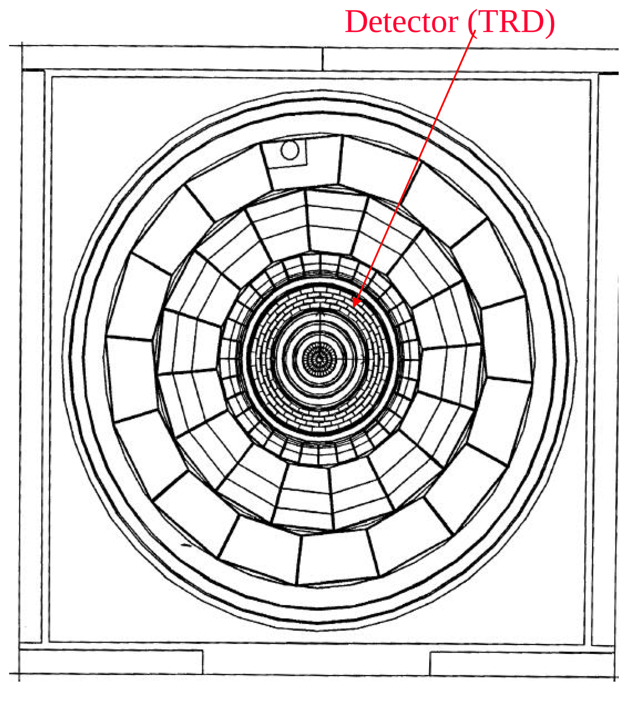
Hermeticity- Elimination of the forward cone

- Using Geant3 showers, we also showed that the forward cone followed by a distant end plug was a bad idea. The showers start on the cryostat walls and the forward going particles will strike the end plug at a different point resulting in a mis-measurement of the E_T. (A.Jonckheere did these calculations). I argued for a monolithic end cap module with no cone and the cryostat walls to come as close the beam pipe as possible. This design paid dividends not only in the top quark discovery but also in the rapidity range over which QCD jets could be studied.

Transition Radiation Detector (TRD)



D0 Central Calorimeter as built

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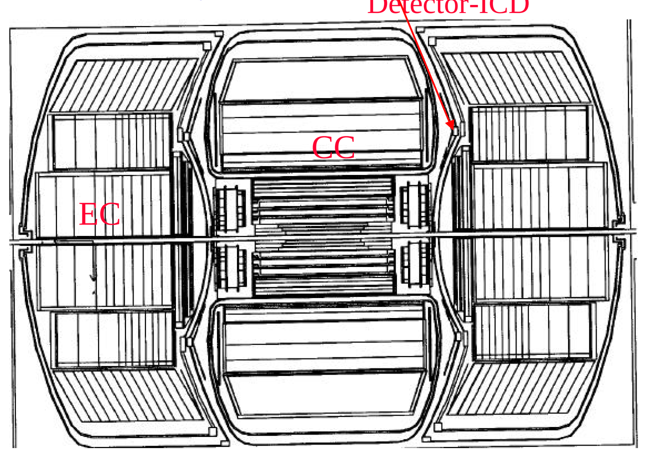
Hermeticity

The background to the top quark comes from "QCD fakes", where QCD processes fake a top-like topology. They simulate missing E_T by mis-measurement and in the case of e+jets, the electron is faked by a track overlapping a π^0 in the calorimeter. If the ICD was not present, it can readily be shown that the missing E_T resolution of QCD jets would be far worse and the number of events with missing E_T greater than 15 GeV (cut used in the top quark analysis) would go up by a factor of ~3.

If the forward cone were present, this would have been a far worse scenario still!

Inter Cryostat Detector-ICD



D0 Longitudinal section as built. No Forward Cone. Monolithic End Plug, ICD present.

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Electron Identification

- D0 had no magnetic field in Run I. Magnetic field plays a central role in electron identification since the matching of the momentum measured by the field to that of the energy measured in the calorimeter eliminates a large number of fake electrons caused by charge particle /π^0 overlaps. This loss in analysis power was supposed to have been compensated for by the Transition Radiation Detector (TRD) which in test beam data produced a rejection of ~50:1 against single charged pions.
- However, the TRD had three layers each with phi segmentation of 256 but no segmentation in pseudorapidity.
- I realized as early as 1987 that the TRD will not work as advertised since the number of tracks in a real collider event will ensure that more than one track occupied a phi cell on average.
- I said so at the 1987 Berkeley conference on SSC detectors in a talk on TRD's for a non-magnetic SSC detector given by Chris Fabjan. His response "You have no basis for saying this!"
- I went back to the D0 management with my concerns and tried to get them to change the design yet again and add a magnetic field in Run I. Response- "Raja, if you want to work in a detector with a magnetic field, go join CDF".

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Electron Identification– The H-Matrix

- As late as 1994, the paper, "The D0 detector" NIMA338, argued for the TRD," Pion rejections of approximately 50 are found for 90% efficiency for electrons in this analysis using the likelihood function. The rejection factors are better at non-normal incidence, in part because of the increased path length and in part due to space charge distortions at normal incidence induced by pile-up of all ionization along a particular track."
- I decided to work on the most sophisticated electron identification algorithm I could conceive of, to counteract what I perceived was a potentially fatal flaw in the D0 design. The result was the H-Matrix algorithm.
- As I had predicted, the TRD did not work during Run I due to the reasons mentioned and the H-Matrix came to the rescue.
- The main method in common use then for pattern recognition in HEP was to impose a series of cuts on well chosen variables. The cuts method in electron identification was flawed since the variables being cut on were highly correlated. There was significant loss of efficiency due to losses at each stage of cutting and the purity of the electrons was not high. A magnetic field would have considerably helped, but alas, we did not have one!

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Electron Identification– The H-Matrix

- The H-Matrix employs a multi-variate algorithm (aka Fisher discriminant). The correlation matrix M of the electron cluster was computed.

$$M_{ij} = \frac{1}{N}\sum_{n=1}^{n=N}(x_i^n - \bar{x}_i)(x_j^n - \bar{x}_j)$$

- Where M is a 41x41 matrix; x_i is a quantity of interest in the pattern recognition (fractional energies in layers 1,2,4 of calorimeter and a 6x6 transverse cells in layer 3, log(Energy of cluster) and primary vertex position). The matrix is evaluated using N Monte Carlo events.
- There were 37 matrices one for each eta cell of the calorimeter.
- We also had a longitudinal version of the above matrix (6x6).

Then the χ^2 of an EM cluster is computed by

$$c^2 = \sum_{i,j}^{41}(x_i - \bar{x}_i)H_{i,j}(x_j - \bar{x}_j)$$

$$H_{i,j} = M_{i,j}^{-1}$$

This uses the maximum information available in the shower and gives an additional factor of ~3 in rejection against $\pi^\pm/\pi^0$ overlaps that fake electrons.

Such was the initial distrust of this method by the collaboration that during our first reconstruction pass, a committee of wise men forbade us to cut on H-matrix χ^2 but only to compute it.

We (Prosper, Bhat, RR) applied this method to show that our eμ event (E417) was more top-like than any other hypothesis. This served as the beginning of the multivariate analysis boom in D0 (Neural Networks, Fisher discriminants) and other collaborations soon followed suit.

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The Software Support Group

- Other activities that contributed significantly to the success of D0 Run I are related to the software support group which was started in 1986 at my request, since I felt that D0 needed to buttress its software effort. We managed to build a strong group of physicists which contributed significantly to the success of Run I. We were charged with building the Alarms and Monitoring Software which enabled us to quickly debug the detector once we turned it on in 1992. This enabled the rapid turn-on of D0 in 1992. The group also made significant contributions to reconstruction software, graphics software and the top analysis.

•The productive members of the software support group who deserve special mention are Fritz Bartlett, Mike Diesburg,Stu Fuess,Al Jonckheere,Stan Kzywzinski, Lee Lueking, Wyatt Merritt, Nobu Oshima, Laura Paterno, and Harrison Prosper. We also had significant help from the accelerator controls group under Peter Lucas.

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Top Quark Physics group 1990-1994

- In 1990, Serban Protopopescu and I were asked to be conveners of the top quark physics group in D0. This we did till 1994. During this period, we laid the ground work of all the analyses of all the sub-channels that contribute to the top quark. The group generated the Monte Carlo events (Geant3) , worked out the entire analyses in all the channels and analyzed data.
- e+jets(Serban, RR, Chopra, Dhiman)
  μ_+jets(J.Hobbs,J.Thompson,T.Rock well)
- ee (R.Kehoe,M.Narain)
- eμ (J.Cochran.W.Cobau,H.Greenlee)
  $\mu\mu$(R.Hall)
- Muon tagging -T.Diehl, D.Wood et al helped by making the muon system work!
- Mass Analysis(RR+Students)

By 1994, we had set the top quark limit to 132 GeV/c^2 and analyzed the Event 417 to show that it was top like. Multivariate analyses were beginning to be made. The difference in analysis between 1994 and the discovery paper in 1995 was merely in optimizing a few cuts to be sensitive to higher mass top quarks and adding more data.

Respectfully submitted

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Convener Monte Carlo Group(1986-1997)

Head, Software Support Group(1986-1993)

Head, Calorimeter Reconstruction(1987-1990)

Head, Electron Id(1989-1994)

Convenor, Top quark physics group(1990-1994)

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