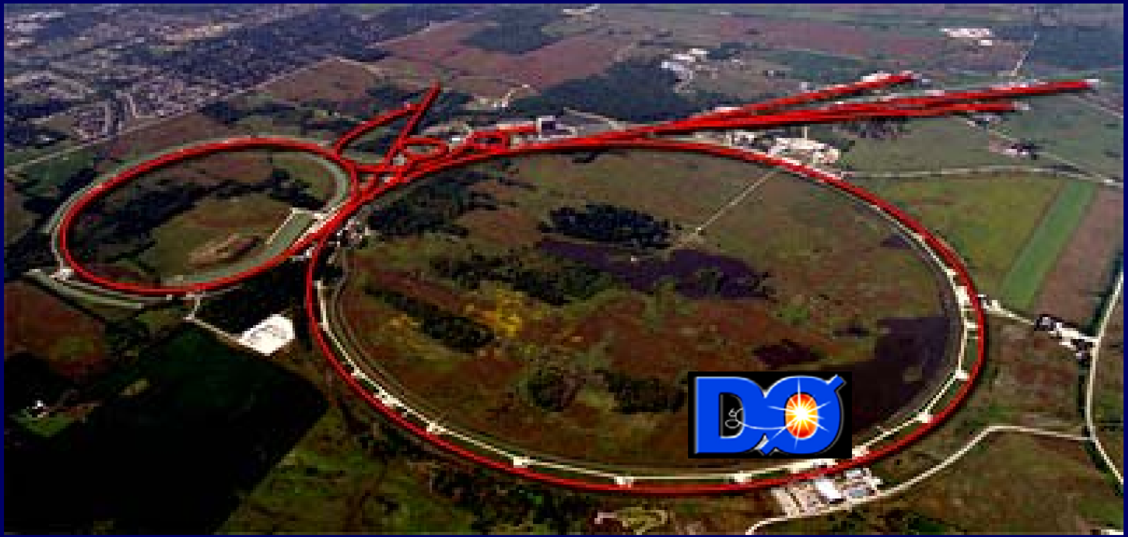
P. Grannis
Tevatron Symposium
June 11, 2012

The DØ Experiment

Its history and achievements



The Prehistory

- In 1981, Leon Lederman called for proposals for an experiment at DØ – something “small (to fit inside a 9m cube), simple, and clever” and moveable to and from the beam line (the fixed target beam extraction occurred in DØ).
- Expected to run in 1986 for about 2 years. Fermilab offered the princely contribution to the detector cost of up to $1M!
- 12 proposals were finally considered in the June 1983 PAC meeting, and all were disapproved – but carte blanche Stage I approval was given for a new consortium originally consisting of only one person. The emphasis was to be on high transverse energy physics, focusing on electrons, muons, jets and missing E_T – an experiment at least no worse than the proposed concepts.

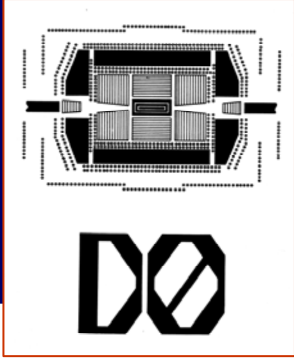
A collaboration formed from parts of the previous proposals in summer 1983. The first challenge was to find a name – GEM, BELLA, DØgbreath …

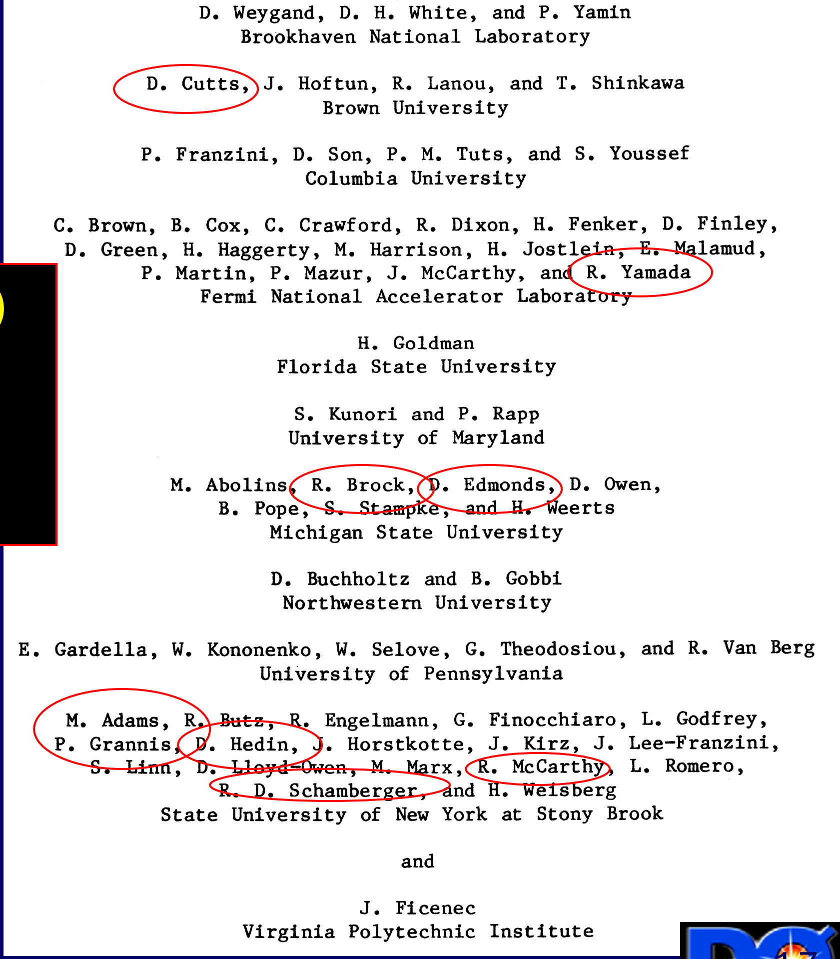
We failed utterly to agree and settled on the lowest common denominator “DØ”, our address in the Tevatron lattice.

The 1983 DØ Proposal

Our first idea was built around a calorimeter made of scintillating glass bars. In the "September '83 Revolution", this scheme was seen as too complex, and under-performing. We switched to liquid argon calorimetry with Uranium absorber (ensuring considerable delay while learning the LAr business). By December, a conceptual design was presented to the PAC and approved with a standing ovation (but no funds).

1983 Design Rept cover





B. Pifer
University of Arizona

L. Ahrens, S. Aronson, P. Connolly, B. Gibbard, H. Gordon, R. Johnson,
S. Kahn, M. Month, M. Murtagh, S. Protopopescu, S. Terada,
D. Weygand, D. H. White, and P. Yamin
Brookhaven National Laboratory

D. Cutts, J. Hoftun, R. Lanou, and T. Shinkawa
Brown University

P. Franzini, D. Son, P. M. Tuts, and S. Youssef
Columbia University

C. Brown, B. Cox, C. Crawford, R. Dixon, H. Fenker, D. Finley,
D. Green, H. Haggerty, M. Harrison, H. Jostlein, E. Malamud,
P. Martin, P. Mazur, J. McCarthy, and R. Yamada
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H. Goldman
Florida State University

S. Kunori and P. Rapp
University of Maryland

M. Abolins, R. Brock, D. Edmonds, D. Owen,
B. Pope, S. Stampke, and H. Weerts
Michigan State University

D. Buchholtz and B. Gobbi
Northwestern University

E. Gardella, W. Kononenko, W. Selove, G. Theodosiou, and R. Van Berg
University of Pennsylvania

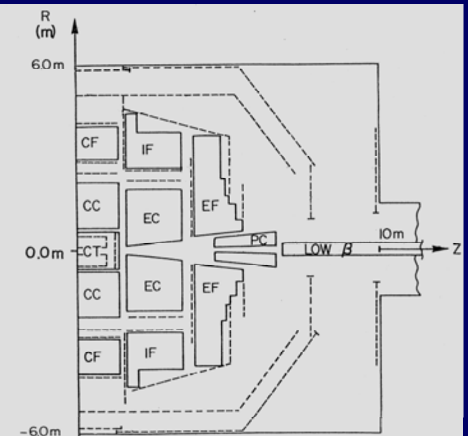
M. Adams, R. Butz, R. Engelmann, G. Finocchiaro, L. Godfrey,
P. Grannis, D. Hedin, J. Horstkotte, J. Kirz, J. Lee-Franzini,
S. Linn, D. Lloyd-Owen, M. Marx, R. McCarthy, L. Romero,
R. D. Schamberger, and H. Weisberg
State University of New York at Stony Brook

and

J. Ficenec
Virginia Polytechnic Institute

71 names on the 1983 proposal (9 still remain) from 12 institutions (all in the US).

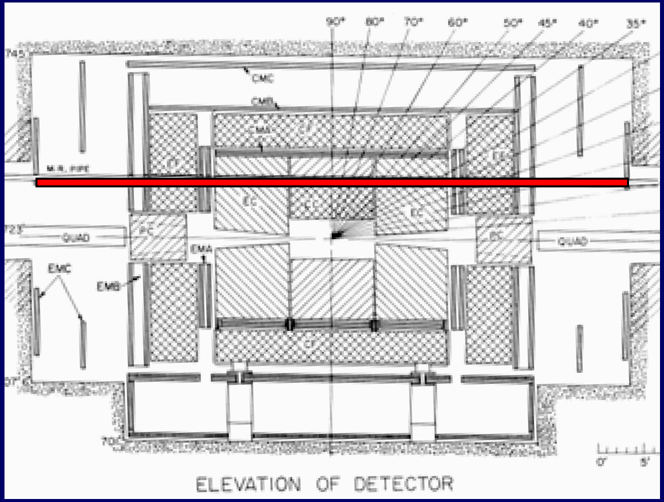
Today: ~400 authors (down from ~600 at peak) from 77 institutions in 18 countries

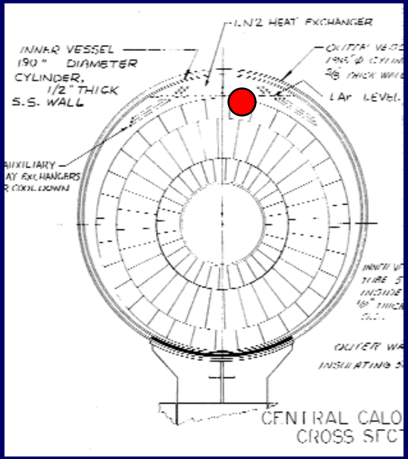


The design was rather baroque: 5 LAr cryostats; 5 iron toroids for muon ID; octagonal geometry – probably unworkable.

Fixing the design

1984: DOE did a baseline review (Temple+Lehman) of the design & cost.
DØ became an DOE approved project (but still with little money).



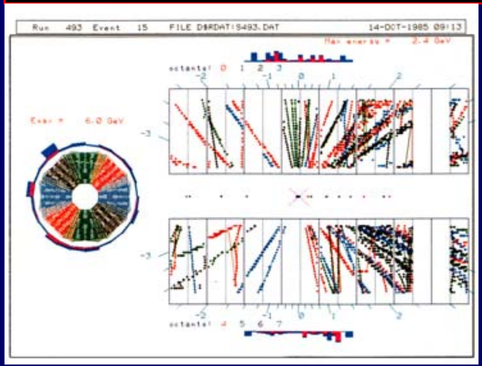


The 1984 design was essentially what we finally built.

(Note the Main Ring threading the calorimeter! No funds to build a bypass.)


First annual DØ workshop MSU July 1984

Getting into the game

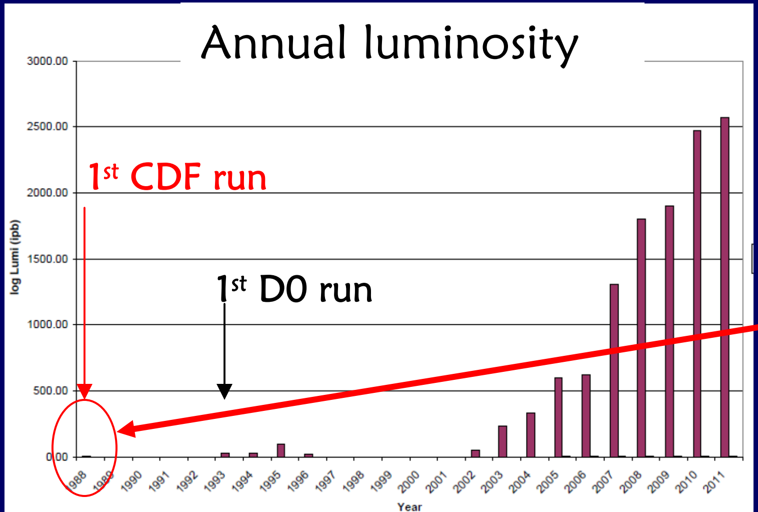


First Tevatron collisions were recorded on Oct. 14, 1985 in the (partially complete) CDF detector.

Oct. 15, 1985

DØ was still a hole in the ground.

How did DØ overcome the 4 year CDF head start? The answer lies in the performance of the Tevatron. The luminosity steadily grew, making the head start irrelevant!



Annual luminosity

1st CDF run

1st D0 run

Luminosity on linear scale

Run 1

Run 2

1 fb^{-1}/yr

1 pb^{-1}/yr

Lumi on log scale

Proving the concept

The biggest challenge was the U LAr calorimeter:

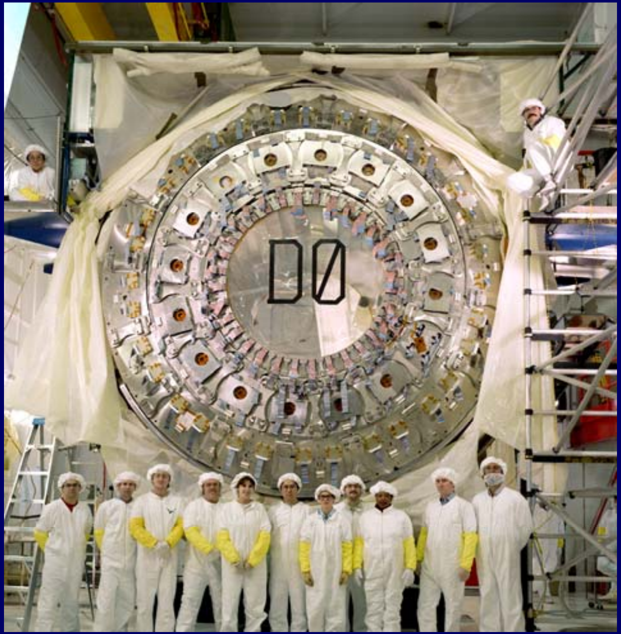
- 3 test beam runs with prototypes to learn the game
- Uranium oxidizes (quickly) – UO_2 flakes in 2.3 mm LAr gap cause shorts
- Ion buildup on oxide layer gives discharges
- How to attach HV connections? (can't weld)
- Assembled modules must made pristine: scrub, scrape, test, power vacuum
- Keep the Ar purity to <1 ppm O_2 (over 2 decades!)

scrub U plates

supersonic darts for HV connections

probe modules for defects

power vacuum



Seal it up never to see it again!

Run I begins

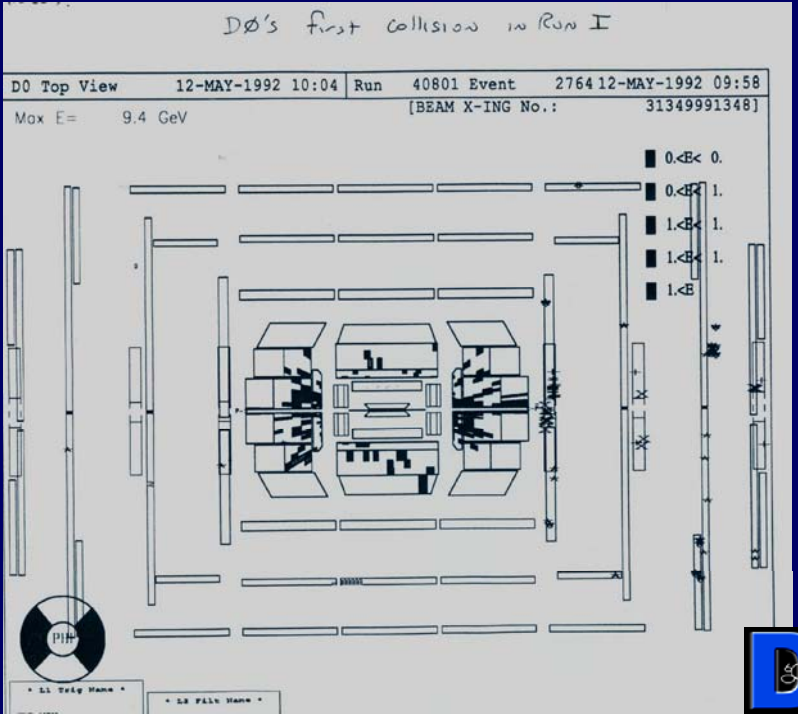
Feb. 14, 1992: DØ gathers to help push the detector into the collision hall

Feb. 15; at rest in collision hall
6 inches to spare under the lintel !

May 12, 1992: First $p\bar{p}$ collisions in DØ. Almost 9 years to form the collaboration, design, test, build, install and debug and ~$75M EQ funds (+R&D, operations)

The celebration had to wait until midnight due to the DOE Tiger Teams on site.

Run I continued to Jan. 1996 with 0.12 fb^{-1} luminosity delivered.



DØ's first collision in Run I

D0 Top View 12-MAY-1992 10:04 | Run 40801 Event 2764 12-MAY-1992 09:58

Max E= 9.4 GeV [BEAM X-ING No.: 31349991348]

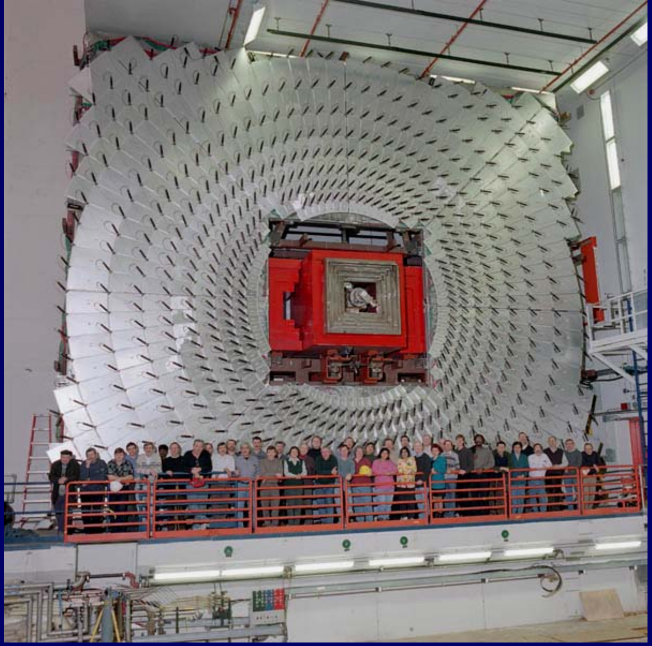
But the building continued …

Two years before its first collisions, DØ submitted a proposal to upgrade for Run 2:

Add a 2 T solenoid magnet, new silicon strip and scintillating fiber trackers, major upgrades to muon detector, triggers, calorimeter electronics …

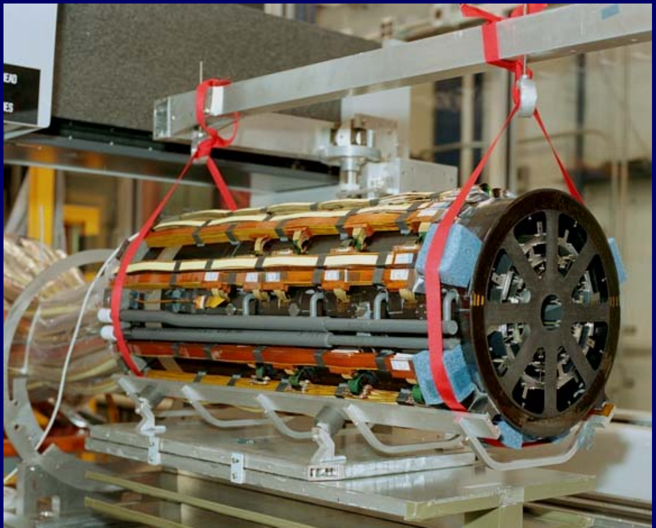
The Lab & PAC were skeptical … it took six years to get approval. But the major upgrade was complete in 2001 for Run 2 with a significant expansion of the international collaboration.

- 1st Run 2 collisions: Apr. 3, 2001

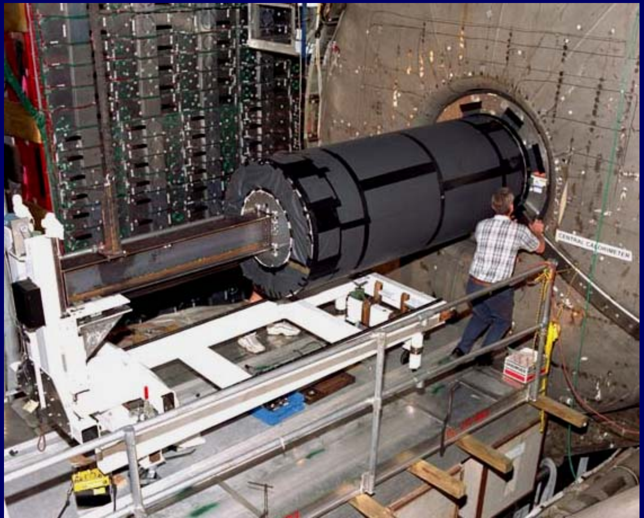


Muon pixel detectors

Silicon strip vertex detector



Scintillating fiber tracker inserted into solenoid



DØ physics legacy

DØ organizes its physics program into 6 major areas. Each has legacies for the textbooks that I will highlight.

But I will also feature another result that simply tickles my fancy.

QCD – the study of the strong force responsible for all of our collisions

b quarks (and c) – few appreciated the extent to which the Tevatron would expand our knowledge of heavy quark physics

Electroweak physics – the study of the W and Z bosons, the carriers of the of weak and EM forces

Top quark – the primary discovery legacy of the Tevatron. The top mass is 40 times that of the next heaviest quark – at the Electroweak symmetry breaking scale

Higgs boson search, the giver of mass and agent of EW symmetry breaking– discovery is tantalizingly close?

Search for non Standard Model physics. The Standard Model can't be the whole story

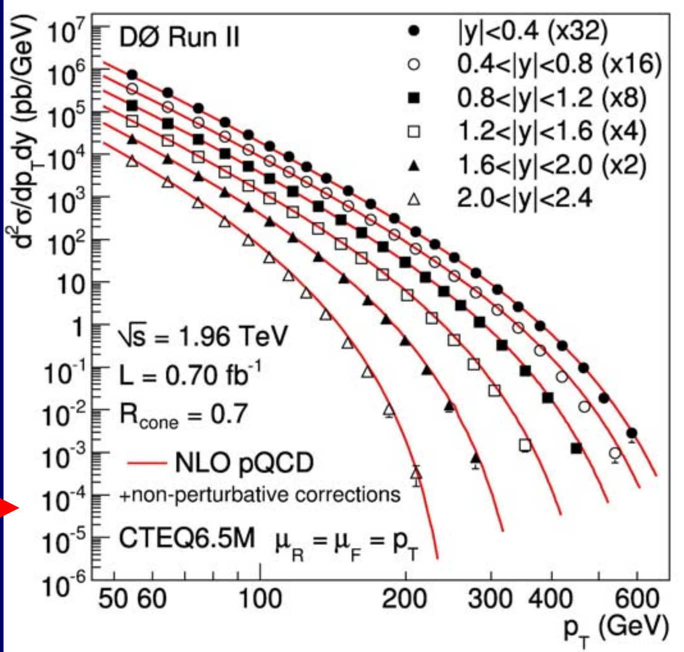
>400 papers published

~450 PhD's and ~ 70 still to come

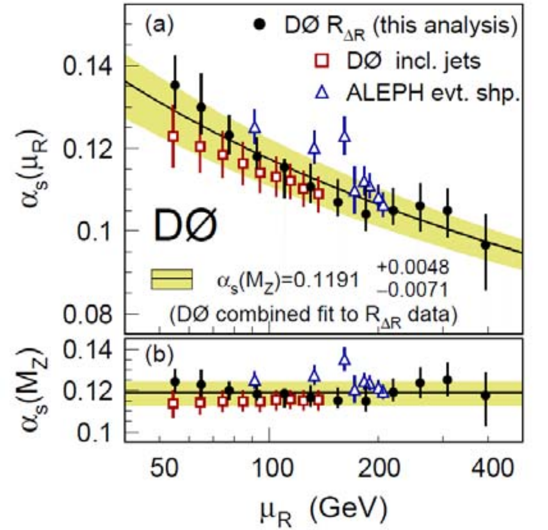
QCD

Protons are made of quarks and gluons. When these collide, the emerging jets, photons, or W/Z bosons, reveal the makeup of the proton, and probe the QCD strong force.

Quark/gluon scattering yields jets of collimated particles with up to 2/3 of the incoming proton momenta. Studies confirm QCD at the attometer (10^{-18} m) scale and refine our understanding of the proton's constituents.



(Measurements of W/Z bosons + jets have been essential for understanding backgrounds to rare processes)

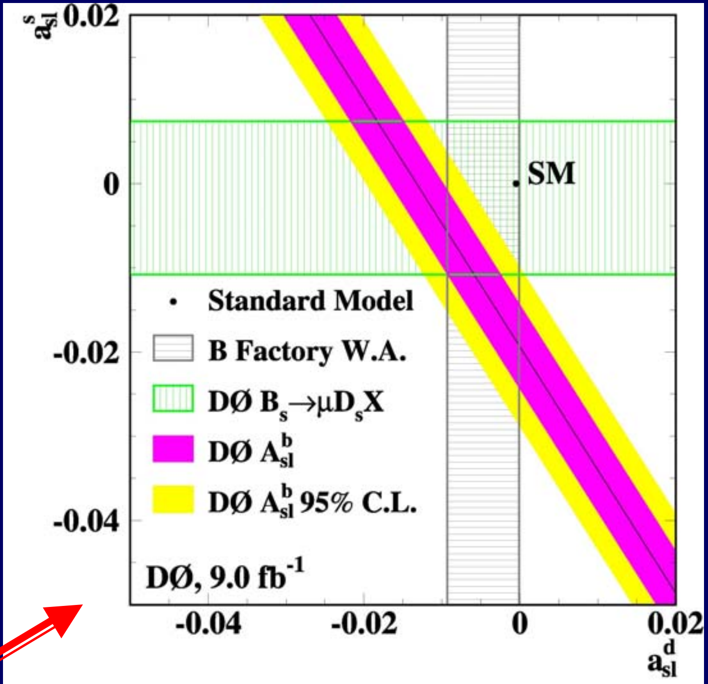


The angular separation of jets enables a measurement of the strong coupling 'constant' as a function of jet transverse momentum to p_T=400 GeV. This is a textbook plot confirming the central prediction of QCD

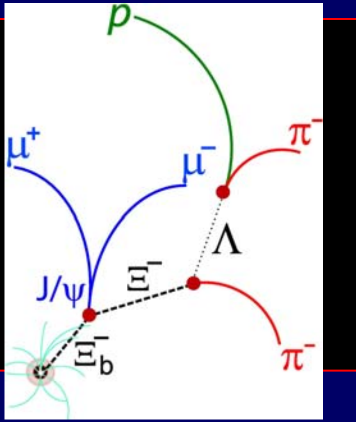
b Physics

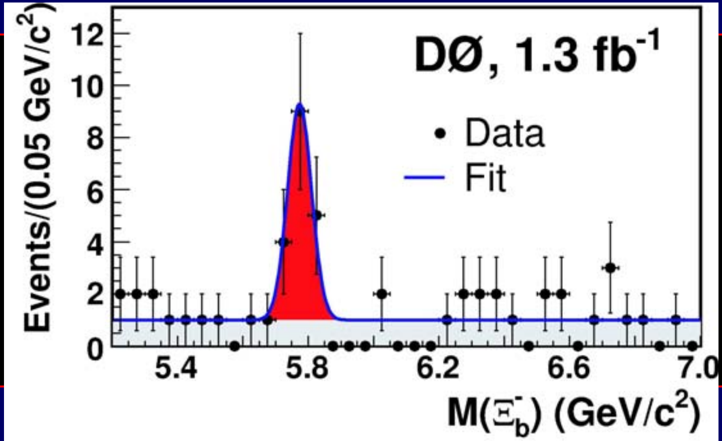
The e^+e^- B factories produced lovely results on the mesons composed of b and u/d quarks. But the Tevatron alone could study the B_s(bs) mesons and the b-baryons. The B_s system is fertile ground for studying the CP asymmetry seen in the universe but unexplained in the SM.

The DØ study of the asymmetry between $\mu^+\mu^+$ and $\mu^-\mu^-$ production is uniquely enabled by the ability to reduce instrumental asymmetries by reversing magnet polarities, and by the $p\bar{p}$ initial state.



The measurement A=–0.79±0.20 % (3.9σ away from the SM) shows a CP asymmetry favoring matter over antimatter. This saga will continue with further measurements.

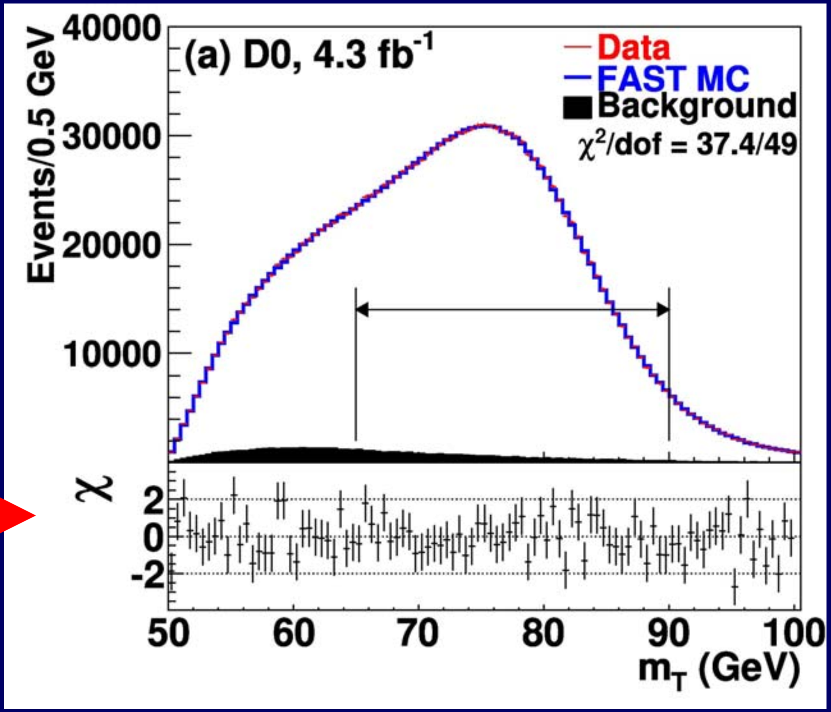


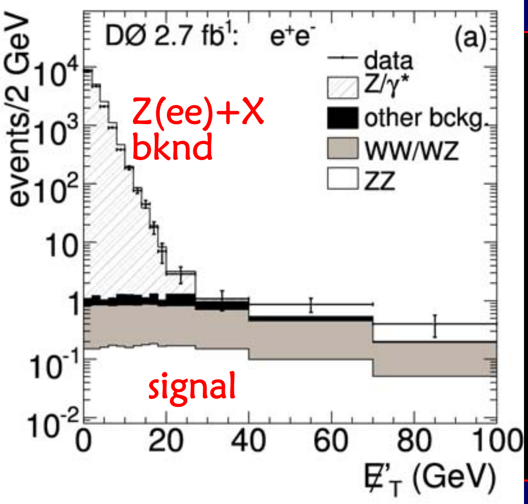


The "triple scoop" baryon – the Ξ_b^- composed of a quark flavor from each generation, first seen by DØ in a 3-stage weak decay.

Electroweak

The W boson mass is affected by the top quark and Higgs boson masses, so its measurement is a powerful constraint on the SM. The recent DØ measurement achieved a precision of better than 0.03% in the final state W→eν (and lots of hadronic debris) – an experimental *tour de force* for a hadron collider.



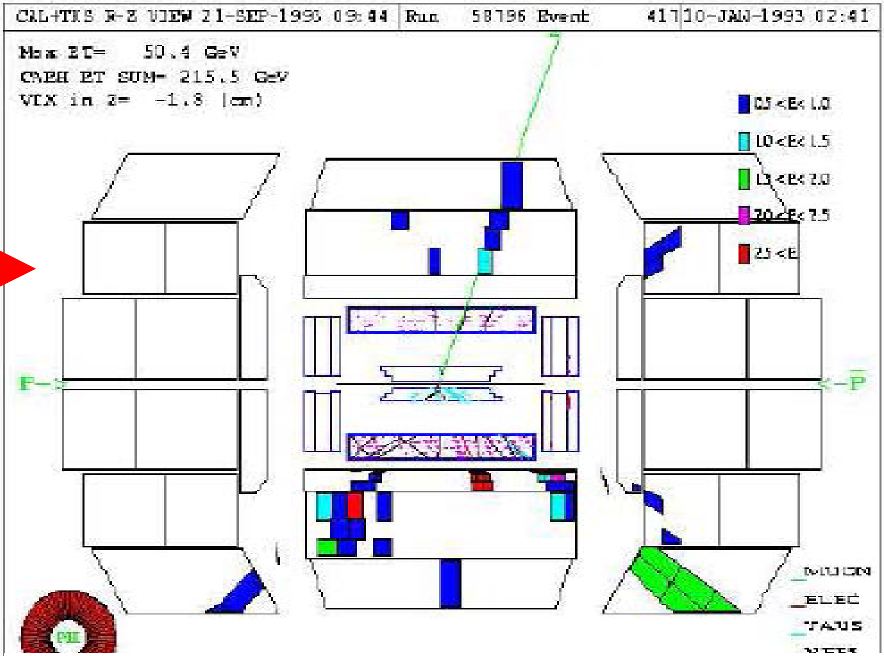


Production of pairs of gauge bosons (WW, Wγ, ZZ etc) are of interest as harbingers of new physics. The rarest of these (ZZ) has a cross section only 3 times that of the Higgs boson. DØ managed to see this process in the ee/μμ + νν channel, in the face of backgrounds from inclusive Z →*ℓℓ* of about 10^5 times the signal. The cross section agrees with that for the simpler four lepton final state.

Top quark

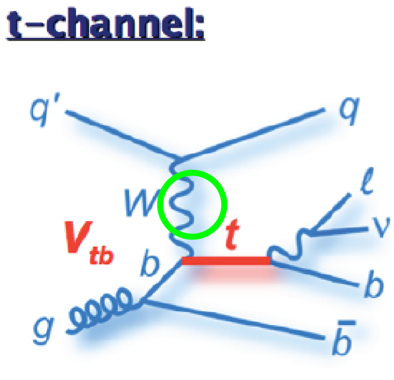
The top quark discovery was announced in this auditorium by CDF and DØ on Mar. 2 1995 to a packed house.

We now know the top mass to within 0.5%, and have measured its charge, quantum numbers & production properties. The heavy top mass ≈ EW symmetry scale might suggest new physics in top production, but the only hint is a tendency for a forward-backward asymmetry beyond that predicted by QCD.



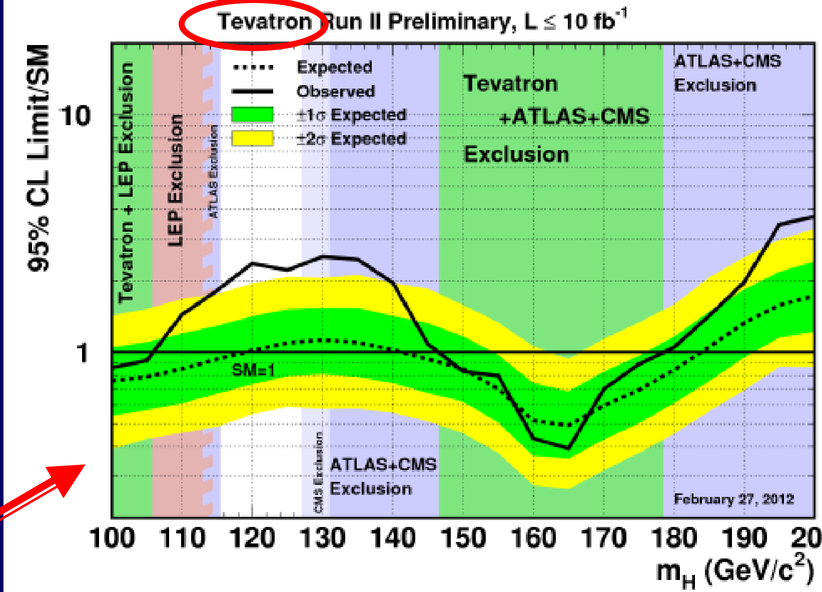
The first spectacular top event in 1993 – very high p_T e, μ, missing energy + 2 jets

Single top production by the EW interaction was observed by DØ and CDF in 2009 and allows sensitive probes of new physics.

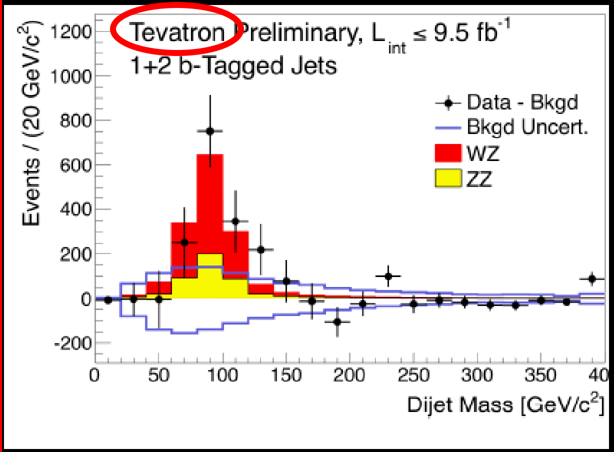


The t-channel single top cross section tells us the coupling of the Wtb vertex. The top pair production can be used to measure the branching ratio (t→Wb)/(t→W +any quark). The two measurements can be combined to measure the top quark lifetime to be 1/3 yoctosecond (3×10^{-25} s).

Higgs boson



The Higgs boson generates the EW symmetry breaking ($M_\gamma \neq M_Z$) and gives mass to all fundamental particles. We know the putative Higgs properties, but don't know if it exists, or its mass. Searches have been made for many Higgs production and decay channels (~100 separate analyses). The combined CDF & DØ searches exclude SM Higgs in the range (147, 179) GeV. There is an excess of events in the 115 – 140 GeV region with the background only hypothesis disfavored at 2.2σ , similar to that seen by ATLAS and CMS. The Tevatron result is important, as it is sensitive to the dominant bb decay in this mass region.

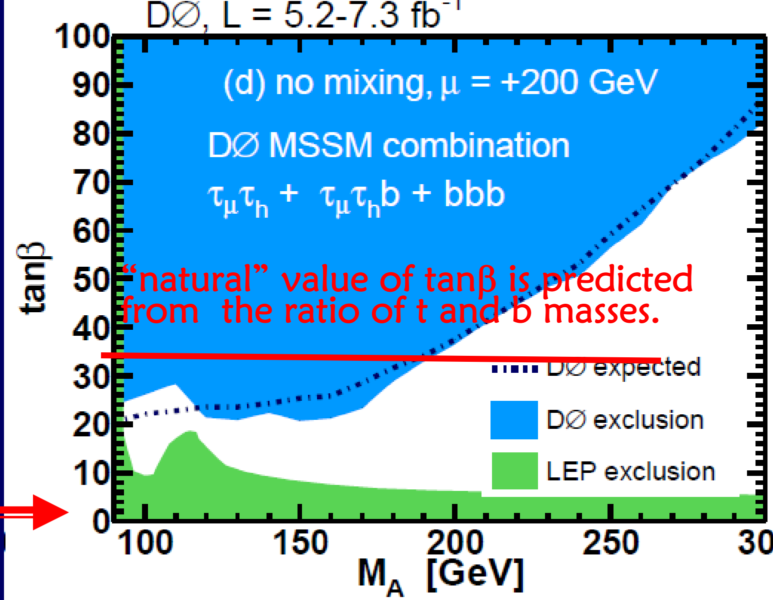


The Higgs analyses are extremely complex – neural networks for lepton & b-quark identification, multivariate discriminants to separate large backgrounds from small signals, and elaborate statistical modelling.

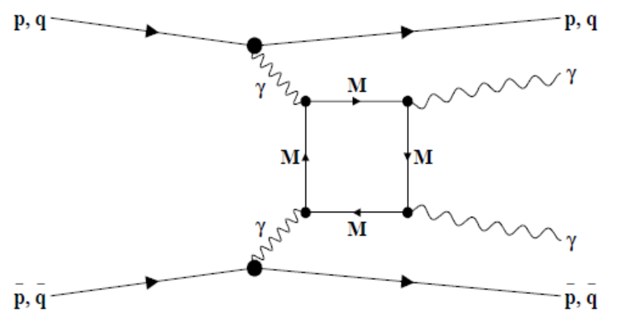
The exact same data sets and machinery were used to extract the WZ/ZZ production cross section to get a value in agreement with previous analyses in simpler channels and with the SM prediction, validating the Higgs methods.

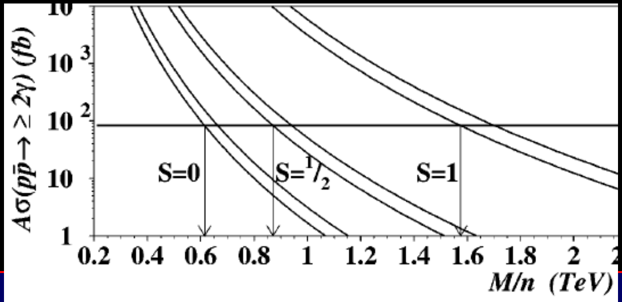
New phenomena

Our theoretical colleagues are ever inventive in proposing new models to explain the defects of the SM. About half of the DØ papers have been (unsuccessful) searches for such new phenomena. For example, Supersymmetry is widely admired as a way out of the SM dilemmas and we have pushed the limits on Susy extensively. The limits on supersymmetric Higgs in the bbb final state remain the best available, better than LHC.



"natural" value of tanβ is predicted from the ratio of t and b masses.



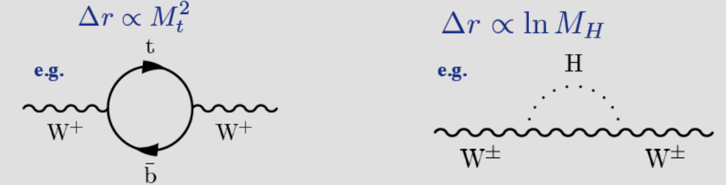


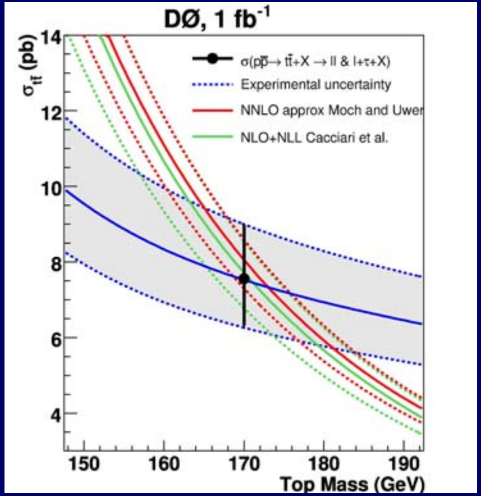
Magnetic monopoles are the natural analogs of electric charges and would symmetrize Maxwell's equations. Dirac showed that the monopole 'charge' **g** is quantized. The monopole coupling to photons would be large and would influence diphoton production. A search was made utilizing the ability of the DØ EM calorimeter to accurately 'point' the photons to a common interaction vertex. No spin ½ monopoles with mass < 1 TeV were seen.

Connectedness: ▲ ■ ⬟ ◯ ★ ⇛

The DØ physics areas are not islands; they connect in many ways.

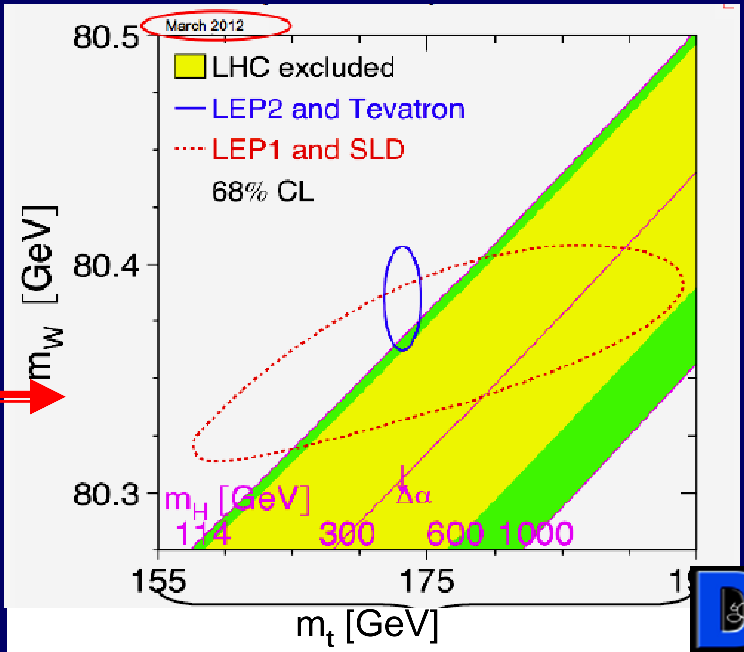
- The masses of the top quark and W boson are influenced by the Higgs boson, so the three masses are correlated.





- The $t\bar{t}$ production is governed by QCD, and the top mass can be inferred from the cross section. QCD processes are large backgrounds for both Higgs and top.
- Both top and Higgs decay dominantly to b-quarks, so well understood b-ID algorithms from heavy quark studies are essential.

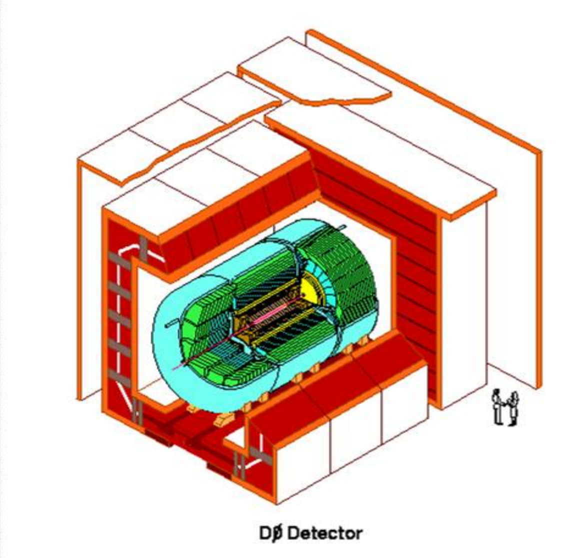
- The location of the experimental ellipse in M_t vs. M_W constrains the SM. A SM Higgs is now tenable only for masses below ~150 GeV, given the direct limits from LEP, Tevatron and LHC. If the ellipse were to shrink into the region above the diagonal Higgs bands, new physics like Supersymmetry would be indicated.



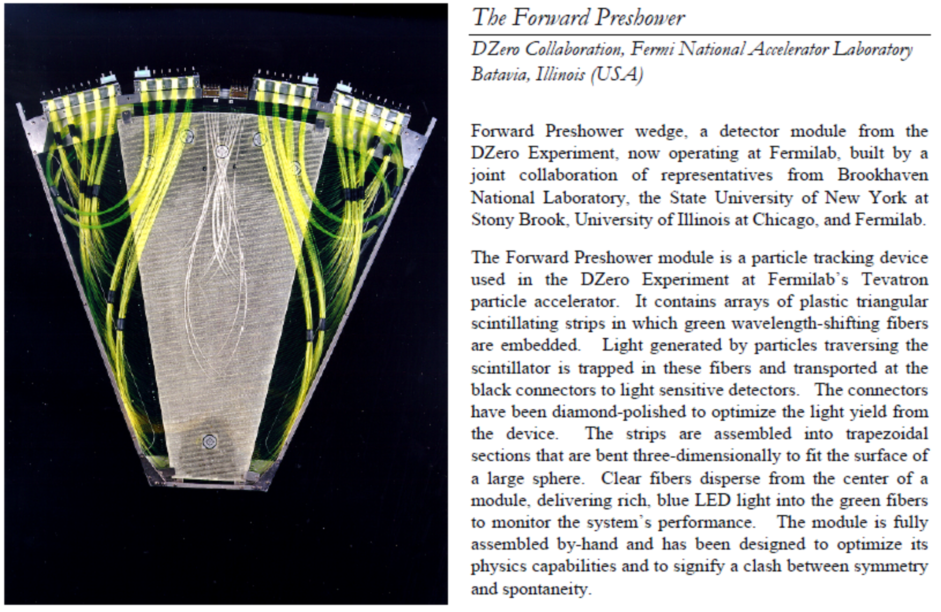
Aesthetics

Building an experiment is often grubby and detailed work – nuts, bolts, cables, safety regulations, cryogenics, software systems, computer disks …

But for those of us in the trenches, there are also enduring images that we treasure.



The DØ detector – one's children are always beautiful



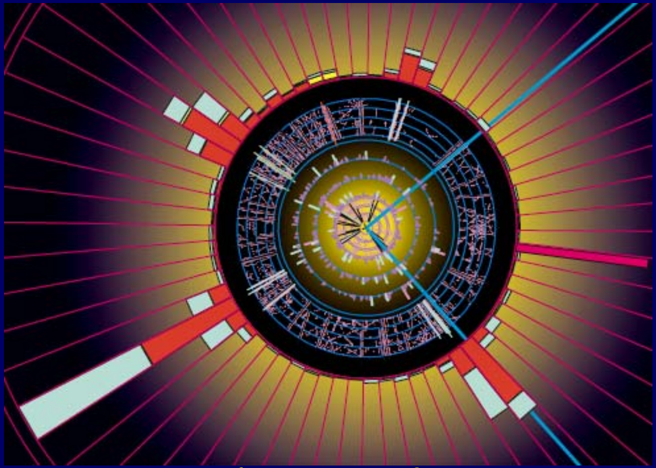
The Forward Preshower

DZero Collaboration, Fermi National Accelerator Laboratory
Batavia, Illinois (USA)

Forward Preshower wedge, a detector module from the DZero Experiment, now operating at Fermilab, built by a joint collaboration of representatives from Brookhaven National Laboratory, the State University of New York at Stony Brook, University of Illinois at Chicago, and Fermilab.

The Forward Preshower module is a particle tracking device used in the DZero Experiment at Fermilab's Tevatron particle accelerator. It contains arrays of plastic triangular scintillating strips in which green wavelength-shifting fibers are embedded. Light generated by particles traversing the scintillator is trapped in these fibers and transported at the black connectors to light sensitive detectors. The connectors have been diamond-polished to optimize the light yield from the device. The strips are assembled into trapezoidal sections that are bent three-dimensionally to fit the surface of a large sphere. Clear fibers disperse from the center of a module, delivering rich, blue LED light into the green fibers to monitor the system's performance. The module is fully assembled by-hand and has been designed to optimize its physics capabilities and to signify a clash between symmetry and spontaneity.

Forward Preshower module in Museum of Modern Art in New York



End view of a top quark pair event

People

The DØ Collaboration on Sept. 30, 2011, minutes before the Tevatron shut down.

1500 students and scientists worked on DØ in its 30 year lifetime. They built the detectors, wrote software, debugged electronics, took the shifts and conducted the analyses that led to >400 papers.

This may look like to you like just another large group photo, but to me it is a collection of friends and very talented people. Each made essential contributions.

The succession of DØ spokespersons on ‘les bateaux Parisiens’ in 2008 (and 2 more not there). These people led the collaboration through trials and tribulations, and are now leaders at the international level.

Acknowledgements

The achievements of the Tevatron experiments would not have been achieved without the outstanding contributions from the Particle Physics Division in building and operating the detector, from the Computing Division for providing the computing infrastructure and data analysis, and the Accelerator Division for steadily pumping out the protons and antiprotons at ever increasing rates.

The support of taxpayers – through the DOE, NSF in the US, and agencies in France, Russia, Brazil, India, Colombia, Mexico, Argentina, Ecuador, Korea, the Netherlands, the UK, Germany, the Czech Republic, Sweden, Ireland, Canada, China and the Ukraine – was essential. We appreciate that we live in societies that value the exploration of the universe.

Coda

It has been an honor and a great pleasure to have been a part of DØ since its inception, and to have had the chance to participate in a grand adventure.

The hard work of many has been repaid with a rich legacy of new understanding the fundamental particles and the forces acting between them.

Large collaborations like DØ, though self-organized outside established institutions, work well and command loyalty, often beyond that to one’s home institute. They take on personalities of their own.

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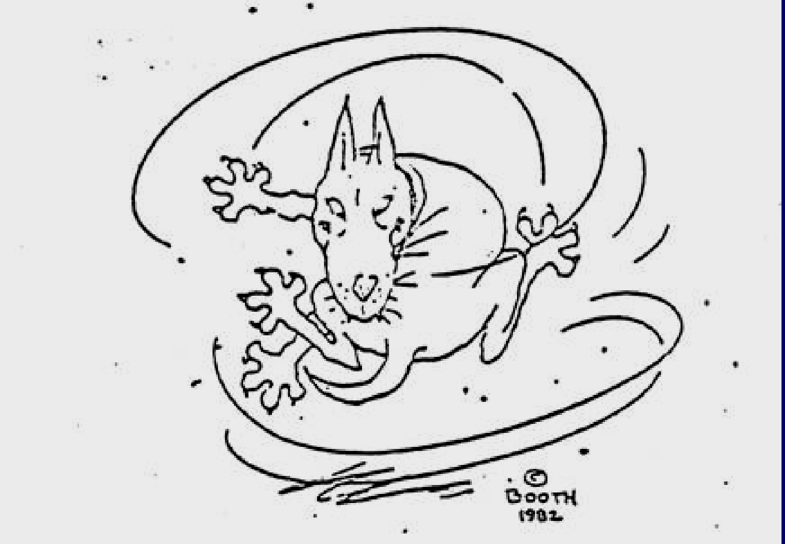

A lot of scratching those flea bites over the years … but it was worth it!