Experiencing Discovery

Hadron Collider Physics Summer School

Fermilab

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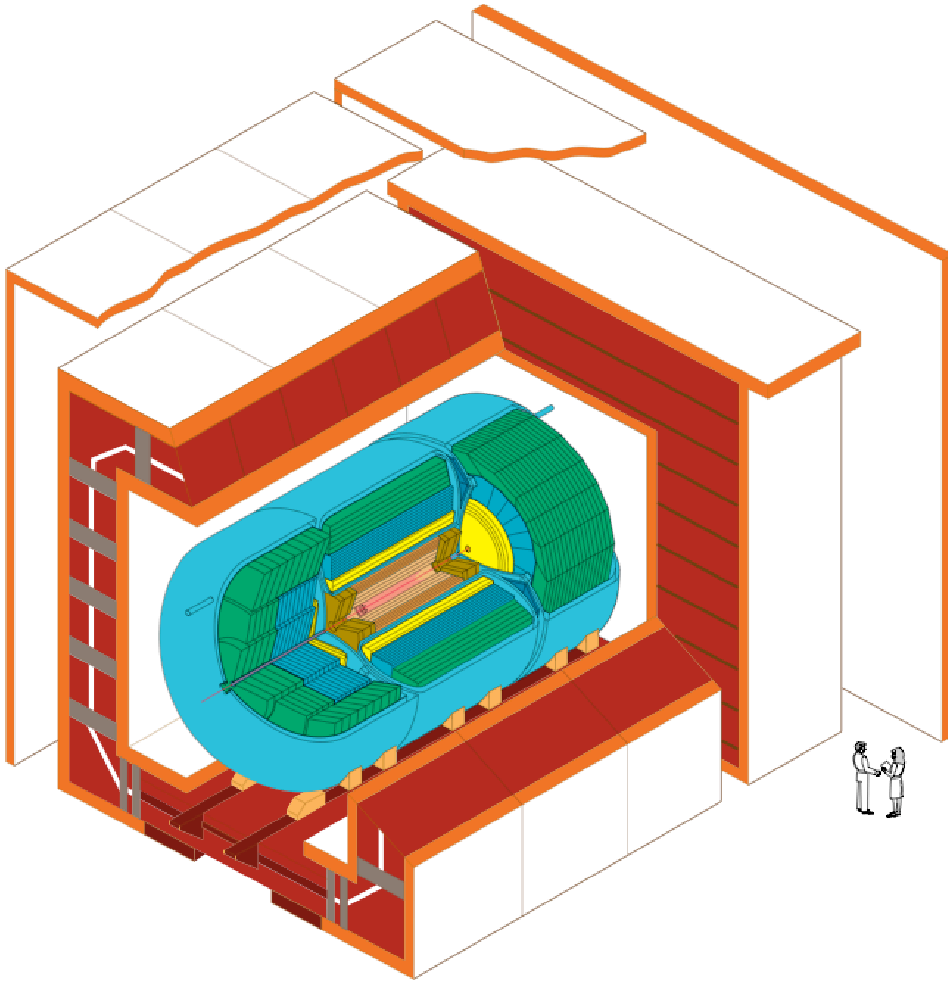
Who was I?

- Two very exciting things happened in Fall of 1992:
  1. DØ began collecting physics-quality data
  2. I started grad school at UC Berkeley
- From then until Summer of 1993, the following happened
  - Teams of physicists began the hunt for the top quark
  - I tried to solve *@#!@ Jackson problems
- By Summer 1993 I had decided to go into experimental HEP for my thesis
- By the time I was done with classes and able to go into research full-time it was spring of 1994
  - hints of top were already appearing by then
- So I’m reporting on work done almost entirely by others
  - I’ll mention my role when it comes up…

Expectation of Top

- Even before the Tevatron turned on, the top quark was widely anticipated
  - the *b* quark had been shown to have isospin -1/2 -- therefore it had to have a partner!
- Even the mass of the top was constrained in the SM context
  - but those limits had been creeping up, “staying ahead” of the experimentally-excluded value
- So the situation was analogous to the Higgs boson today
  - if anything, I would argue that the top was even more of a “sure thing”

The Run I DØ Detector



Unique features:

- no *B* field in central region
- Finely segmented calorimeter covering out to $|\eta| \sim 4$
- Toroidal iron magnet for muon spectrometer
- Two accelerators
  - that's not a plus..

Comparing the Detectors

- The Tevatron was clearly the only place where the top quark might show up in the 1990's
- So, which of the two detectors would see it first?
- Though broadly similar, they did have significant differences
  - the advantages were as follows:

	CDF	DØ
Electron ID	✓	
Electron Energy		✓
Muon ID		✓
Muon Momentum	✓	
Jet Energy		✓
Missing E_T		✓
b Jet Tagging	✓ ✓	

The Backgrounds

- For every set of final-state objects produced in a $t\bar{t}$ event, there are other SM processes that produce the same objects. These backgrounds are:
- All-hadronic mode: QCD multijet production (HUGE)
- Lepton+jets mode: $W + \geq 4$ jet production
- Dilepton modes: Z, WW or $WZ + \geq 2$ jet production
- Note that the jets in the background tend to arise from gluon radiation
  - rate calculations were leading-order $\rightarrow$ large uncertainties for high jet multiplicities
  - better to calculate background rates from data whenever possible

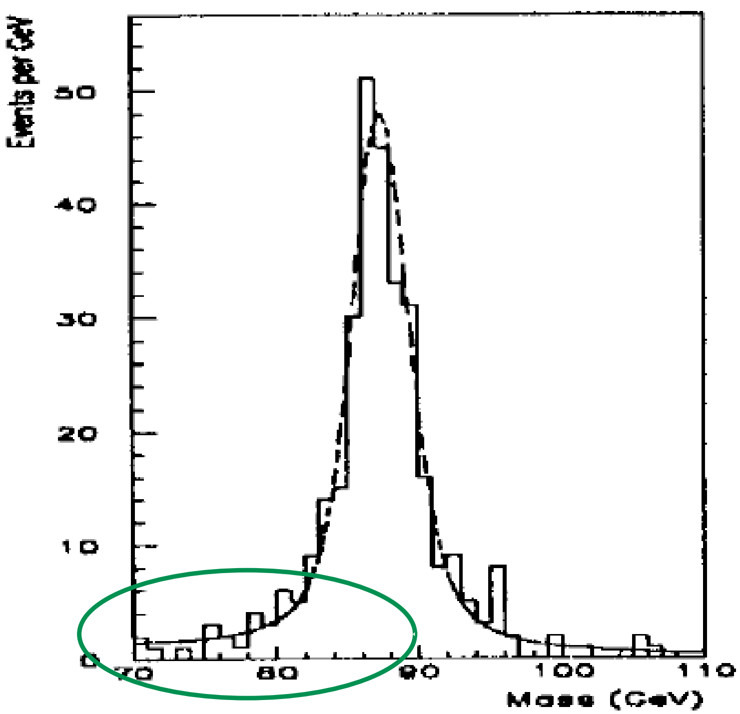
Detector Backgrounds

- In addition to the physics backgrounds on the previous slide, there are also detector backgrounds
  - a jet that appears to be a lepton
  - missing E_T coming from mismeasured jet or muon energies
- These can be studied in data directly
  - i.e. by looking at events where a jet satisfies some, but not all of the lepton ID requirements
- For the signal and physics backgrounds one needs to understand:
  - the kinematic distributions of leptons, quarks and gluons produced (theoretical model)
  - the response of DØ to those objects (calibration)

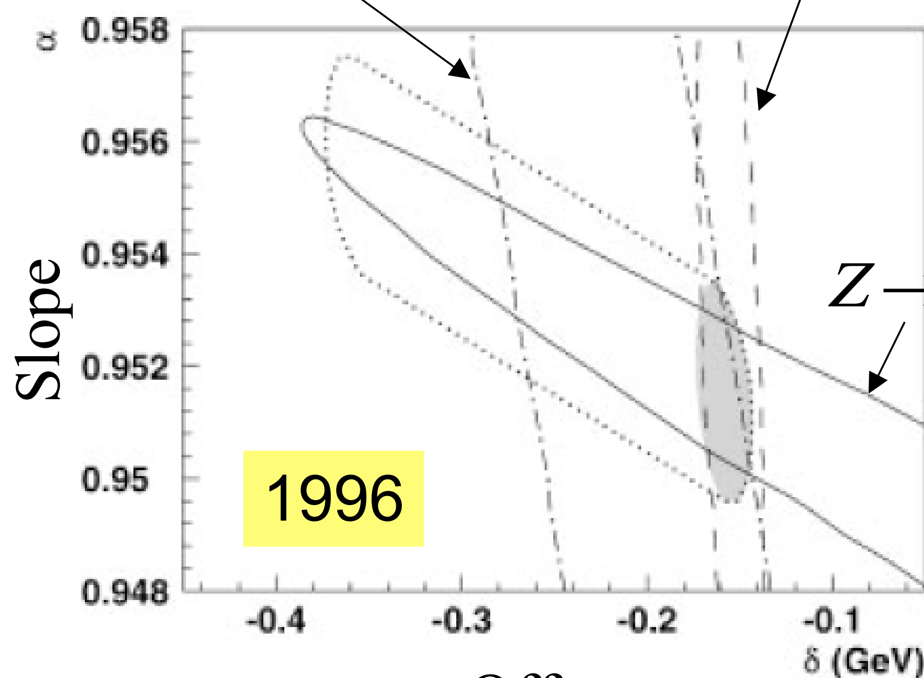
Calibrating (Leptons)

- Based on known resonance masses
  - Z, J/ψ, π^0

$Z \rightarrow e^+e^-$

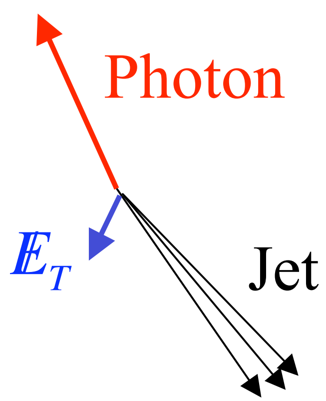


No tail from brems



Calibrating (Jets)

- No resonances to help out here
  - later in Run I tried to observe $W \to qq$, but no luck
- So, tie the jet calibration to the EM energy scale
  - use events with a photon recoiling against a jet
  - if calibration were perfect, would have $E_T^{\gamma} = E_T^{\text{jet}}$, $\not{E}_T = 0$
  - in real life, one sees something like:



- Hadronic response R given by:

$$R = 1 + \frac{\not{E}_T \cdot E_T^{\gamma}}{E_T^{\gamma\,2}}$$

- But R is only part of the story:

Energy from electronics noise, radioactive decay, random particles

Energy of particles belonging to jet within jet cone. NOT the energy of the parton that produced the jet

$$E_{true} = \frac{E_{meas} - U}{(1 - C)R}$$

Energy leaking out of (or into) the jet cone

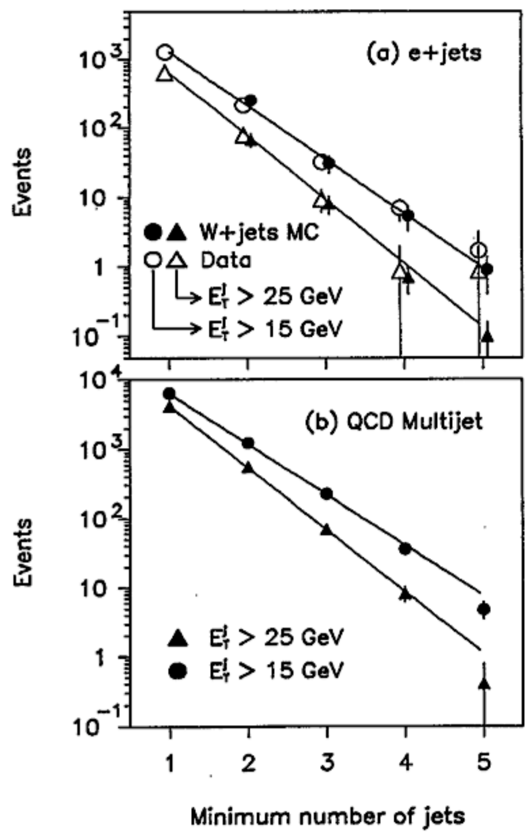
- Hadronic calibration was (and is!) one of the more complex facets of top quark measurements

Estimating the Background From Data

- "Berends scaling"

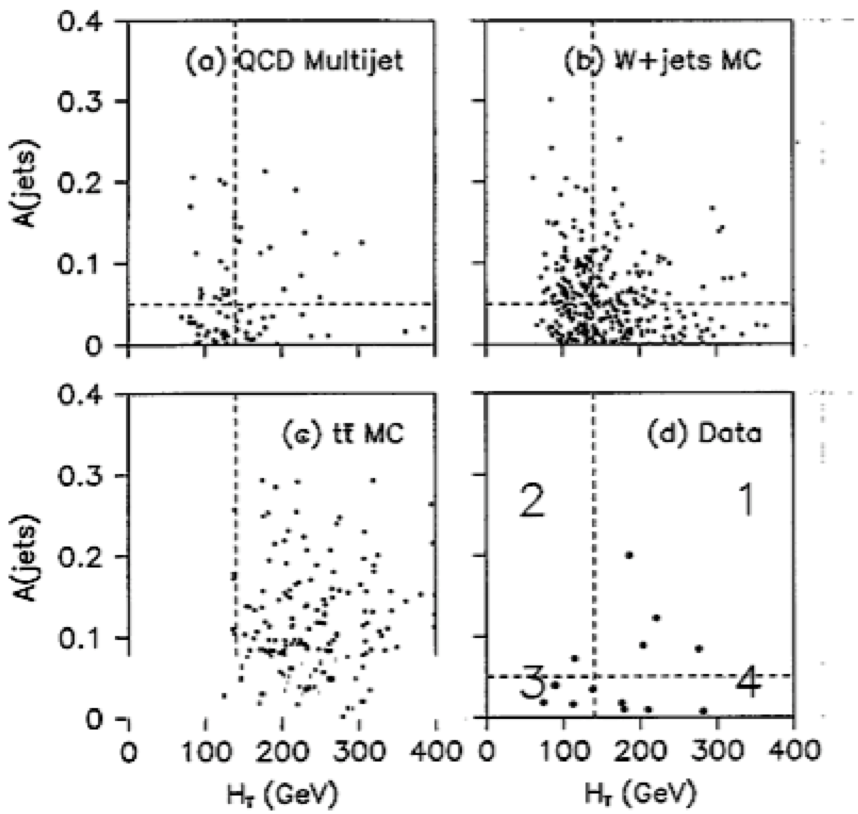
$$\text{In theory: } \frac{W+(n-1)\text{ jets}}{W+n\text{ jets}} = \frac{W+(n-2)\text{ jets}}{W+(n-1)\text{ jets}} \equiv \alpha$$

- Data agrees well with this expectation
  - for both of the major background sources in l+jets channel



Using Kinematics

- One can also look at how events are distributed in total jet energy (H_T) and aplanarity:



- *Both* methods rely on input from theory
  - Scaling rule in 1st case
  - Kinematic distributions for background in 2nd case*
- But these are two different aspects of the theory
- Results should be consistent between the two methods
  - and they were!

- Average of the two was taken as the background estimate

*EWV contributed to studies here

The First Look at DØ

- DØ's first in-depth search for the top quark was done on about 15pb^{-1} of data from 1992 and 1993
  – we get more in a good week nowadays!
- From CDF's previous search, we knew that the mass was somewhere above 91 GeV
  – means *W* can't decay to top, and *W* in top decay is on-shell
- But where? Needed a selection that was efficient across the entire mass range
  – i.e. loose kinematic cuts
  – used aplanarity to distinguish "spherical" $t\bar{t}$ events from "jet-like" backgrounds

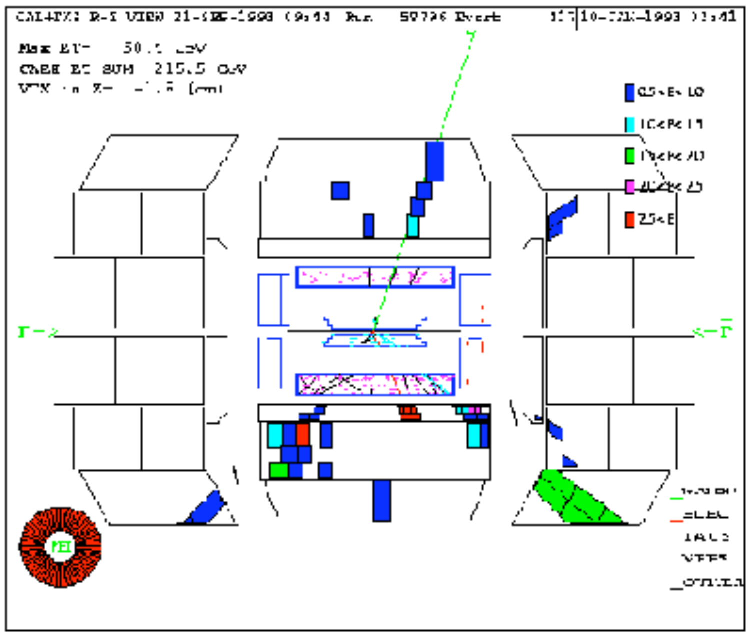
Results of the Initial Search

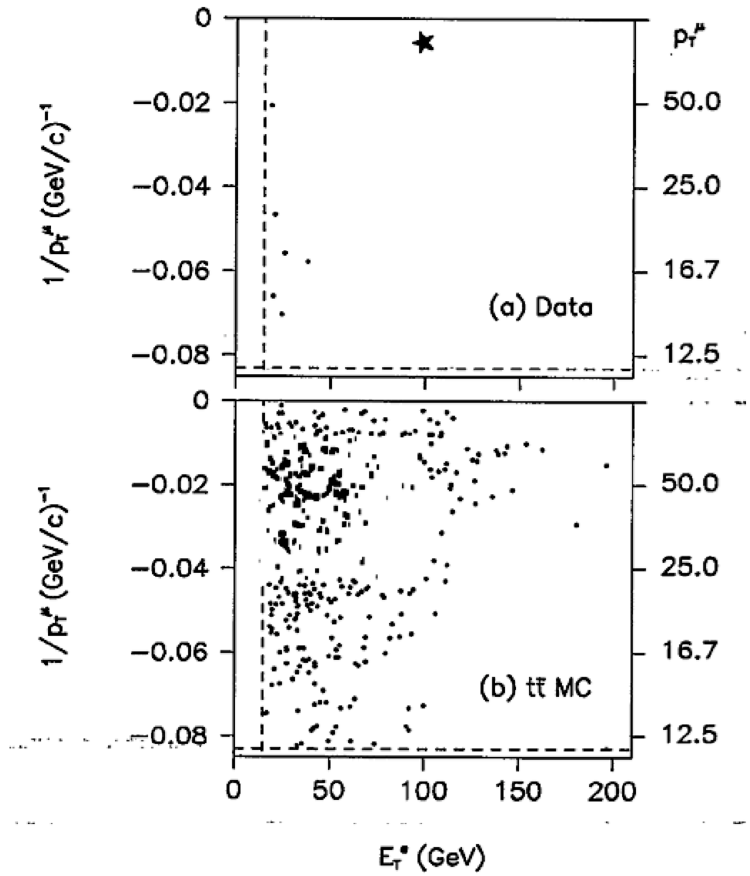
m_t (GeV/c^2)		$e\mu$	ee	$e+$jets	$\mu+$jets	All
90	$\varepsilon \times B(\%)$	0.39 ± 0.10	0.16 ± 0.02	0.28 ± 0.08	0.15 ± 0.07	22.9 ± 3.6
	$\langle N \rangle$	9.4 ± 2.6	4.0 ± 0.8	6.8 ± 2.1	2.7 ± 1.3	
100	$\varepsilon \times B(\%)$	0.46 ± 0.11	0.20 ± 0.03	0.44 ± 0.12	0.19 ± 0.08	17.0 ± 2.7
	$\langle N \rangle$	6.3 ± 1.7	2.8 ± 0.5	6.0 ± 1.8	1.9 ± 0.9	
120	$\varepsilon \times B(\%)$	0.49 ± 0.12	0.26 ± 0.04	1.13 ± 0.22	0.61 ± 0.20	12.3 ± 1.7
	$\langle N \rangle$	2.6 ± 0.7	1.4 ± 0.3	5.9 ± 1.3	2.4 ± 0.8	
140	$\varepsilon \times B(\%)$	0.54 ± 0.13	0.28 ± 0.04	1.45 ± 0.19	0.90 ± 0.27	6.7 ± 0.8
	$\langle N \rangle$	1.2 ± 0.3	0.6 ± 0.1	3.3 ± 0.6	1.6 ± 0.5	
160	$\varepsilon \times B(\%)$	0.56 ± 0.14	0.29 ± 0.04	1.69 ± 0.18	0.85 ± 0.24	3.5 ± 0.4
	$\langle N \rangle$	0.6 ± 0.2	0.3 ± 0.1	1.9 ± 0.3	0.7 ± 0.2	
Physics background		0.5 ± 0.2	0.2 ± 0.1	2.1 ± 1.1	1.1 ± 0.7	3.9 ± 1.3
Fake background		0.6 ± 0.3	0.3 ± 0.1	0.3 ± 0.3	0.3 ± 0.1	1.5 ± 0.4
Total background		1.1 ± 0.4	0.5 ± 0.2	2.4 ± 1.3	1.4 ± 0.9	5.4 ± 1.4
$\int \mathcal{L}dt$ (pb^{-1})		13.5 ± 1.6	13.5 ± 1.6	13.5 ± 1.6	9.8 ± 1.2	
Data		1	1	1	0	3

- Not even a hint of top
  - Masses less than 128 GeV ruled out at 95% C.L.
- Well, maybe there was *one* hint of top…

Event 417

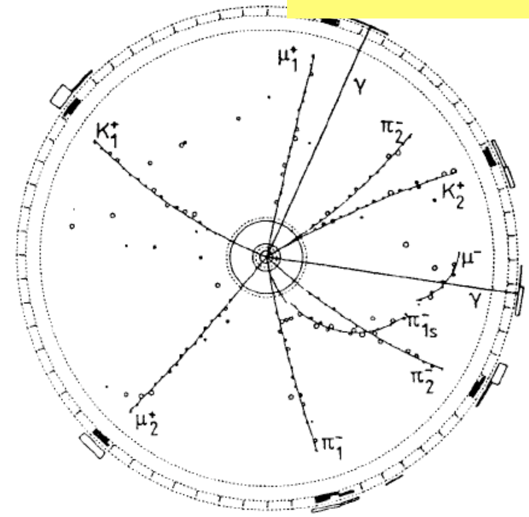
- Candidate in the $e\mu$ channel with large electron and muon energies, and large missing E_T





How Do We Discover?

ARGUS



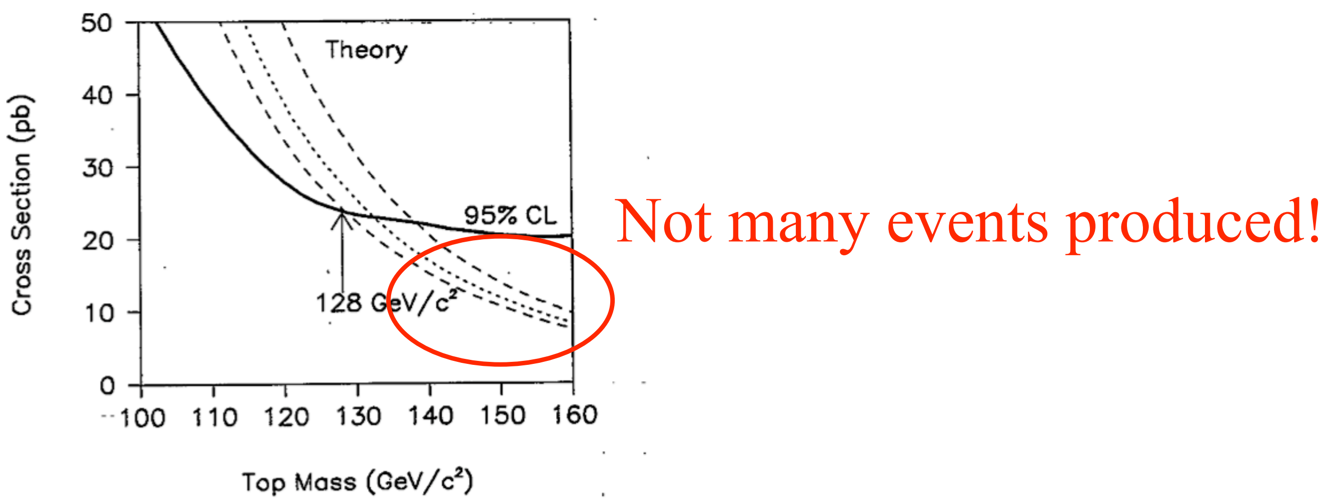
- Many discoveries in particle physics have arisen from a single spectacular event
  - *B* meson mixing, for example
- Was Event 417 spectacular enough?
  - intense discussion within DØ
  - the event couldn't arise from the most common background

$$Z + \text{jets} \to \tau\tau\text{+jets} \to e\mu\text{+jets+}\not\!\!E_T$$

  - but maybe WW + jets $\to e\mu$+jets+$\not\!\!E_T$…
- In the end, decided not to make any claims from this event
- Need to collect a set of events that collectively is very unlikely to arise from background
  - where very unlikely means $O(10^{-6})$ probability

Moving to Higher Mass

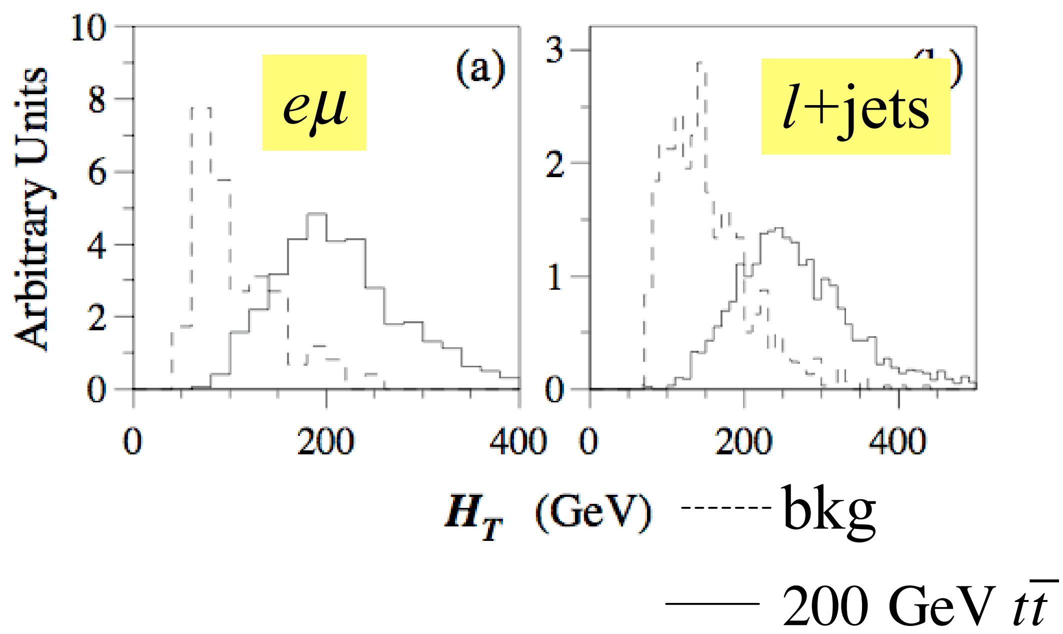
- We now knew the top wasn't less than 130 GeV
- That's a problem:



- But also an opportunity
  - the heavier the top is, the easier it is to distinguish from background
- So selection was re-optimized to look for high-mass top

How To Explore Higher Masses

- A higher top mass means that higher $\sqrt{\hat{s}}$ is required
  - more energy in $t\bar{t}$ events
  - typically shows up as higher jet transverse energies
- So the transition to searching at high mass meant requiring that either individual jet E_T's be higher, or that their sum (H_T) be higher
  - H_T turned out to be an excellent variable
  - we could trade a modest amount of $t\bar{t}$ efficiency for a large reduction in background

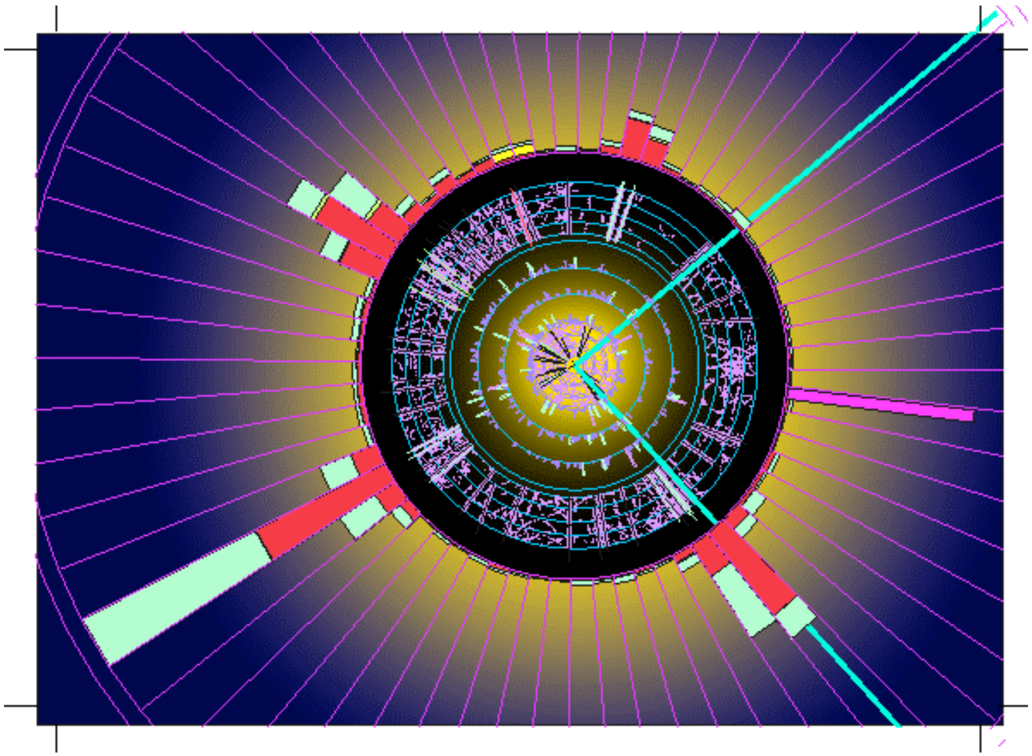


Adding More Channels

- We also increased our sensitivity to top by looking in three more decay channels:
  - Dimuon
    - Here the main challenge is limiting the Z background with poor muon momentum resolution
    - Cut on difference in dimuon momentum and missing E_T directions
  - b-tagged e+jets and μ+jets
    - But DØ didn't have a silicon tracker…

Tagging *b*'s Without a Vertex Detector

- While DØ couldn't see the displaced *b* decay vertices, it could find muons from semileptonic *b* decay



- Thick calorimeter and muon toroid made it essentially impossible for other charged particles to mimic this signature
- But only ~20% of *b*'s have a muon in their decay
- Means that we could tag, at most, ~40% of events
  – with detector efficiency, down to ~20%
  – but reduced background allows one to open up the kinematic selection

The Evidence Mounts

- With the new selection, we find (same $15 pb^{-1}$ data set):

m_t (GeV/c^2)		$e\mu$ + jets	ee + jets	$\mu\mu$ + jets	e + jets	μ + jets	e + jets/μ	μ + jets/μ	All
140	$\varepsilon \times B(\%)$	0.31 ± 0.04	0.18 ± 0.02	0.15 ± 0.02	1.1 ± 0.3	0.8 ± 0.2	0.6 ± 0.2	0.4 ± 0.1	
	$\langle N \rangle$	0.72 ± 0.12	0.41 ± 0.07	0.25 ± 0.04	2.5 ± 0.7	1.3 ± 0.4	1.4 ± 0.5	0.7 ± 0.2	7.2 ± 1.3
160	$\varepsilon \times B(\%)$	0.36 ± 0.05	0.20 ± 0.03	0.15 ± 0.02	1.5 ± 0.3	1.1 ± 0.3	0.9 ± 0.2	0.5 ± 0.1	
	$\langle N \rangle$	0.40 ± 0.08	0.22 ± 0.04	0.12 ± 0.02	1.7 ± 0.5	0.9 ± 0.3	1.0 ± 0.3	0.4 ± 0.1	4.7 ± 0.8
180	$\varepsilon \times B(\%)$	0.39 ± 0.05	0.21 ± 0.03	0.14 ± 0.02	1.6 ± 0.3	1.1 ± 0.3	1.1 ± 0.2	0.7 ± 0.1	
	$\langle N \rangle$	0.23 ± 0.04	0.12 ± 0.02	0.06 ± 0.01	0.9 ± 0.3	0.5 ± 0.1	0.6 ± 0.1	0.3 ± 0.1	2.7 ± 0.4
200	$\varepsilon \times B(\%)$	0.40 ± 0.05	0.30 ± 0.04	0.14 ± 0.02	1.8 ± 0.4	1.3 ± 0.3	1.4 ± 0.1	0.8 ± 0.2	
	$\langle N \rangle$	0.12 ± 0.02	0.09 ± 0.02	0.03 ± 0.01	0.5 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	1.7 ± 0.3
Background		0.27 ± 0.14	0.15 ± 0.11	0.33 ± 0.06	1.3 ± 0.7	0.7 ± 0.5	0.6 ± 0.2	0.4 ± 0.1	3.8 ± 0.9
$\int \mathcal{L} dt$ (pb^{-1})		13.5 ± 1.6	13.5 ± 1.6	9.8 ± 1.2	13.5 ± 1.6	9.8 ± 1.2	13.5 ± 1.6	9.8 ± 1.2	
Data		1	0	0	2	2	2	2	9

- More events than in “all-mass” search?
- Due to lowering aplanarity cut from 0.10 to 0.05 (2 events) and lowering muon p_T cut from 15 to 12 GeV
  - so these just missed being seen in the initial search

The 50pb^{-1} Sample

- Now we had:
  - calibrated the detector
  - developed event selections for seven different decay channels
  - demonstrated sensitivity to top production
  - seen an intriguing excess of events in the "high-mass" analysis
- Time to look at the next chunk of data!
  - total of ~50pb^{-1}
- Further optimization of selection (applying H_T in all channels, raising cut value in channels where already used) reduced background rate by nearly 4x
  - while retaining about 70% of 180 GeV top
  - cuts chosen to give best *expected* significance for top -- i.e. only look at MC when making the decision

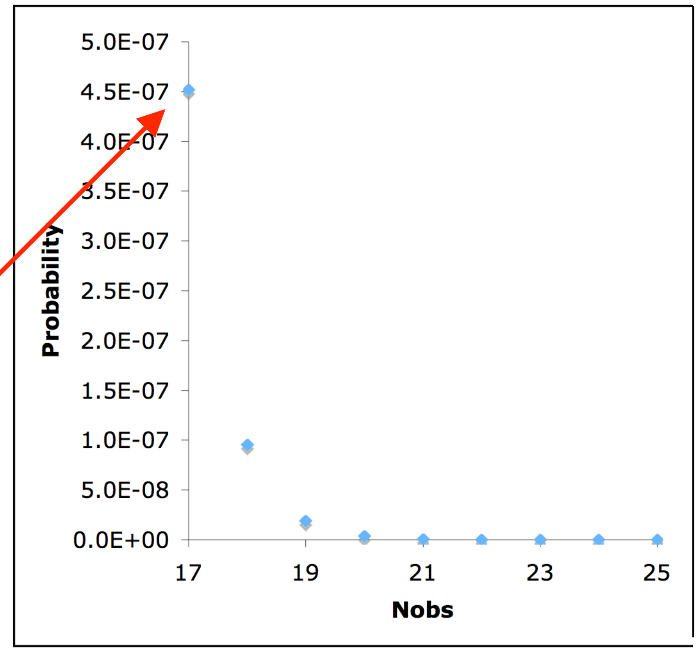
- This time, we found:

m_t (GeV/c^2)	$e\mu$ + jets	ee + jets	$\mu\mu$ + jets	e + jets	μ + jets	e + jets/μ	μ + jets/μ	All
140 $\varepsilon \times \mathcal{B}$ (%)	0.17 ± 0.02	0.11 ± 0.02	0.06 ± 0.01	0.50 ± 0.10	0.33 ± 0.08	0.36 ± 0.07	0.20 ± 0.05	
$\langle N \rangle$	1.36 ± 0.21	1.04 ± 0.19	0.46 ± 0.08	4.05 ± 0.94	2.47 ± 0.68	2.93 ± 0.68	1.48 ± 0.42	13.80 ± 2.07
160 $\varepsilon \times \mathcal{B}$ (%)	0.24 ± 0.02	0.15 ± 0.02	0.09 ± 0.02	0.80 ± 0.10	0.57 ± 0.13	0.50 ± 0.08	0.25 ± 0.06	
$\langle N \rangle$	0.94 ± 0.13	0.69 ± 0.12	0.34 ± 0.07	3.13 ± 0.54	2.04 ± 0.53	1.95 ± 0.39	0.92 ± 0.24	10.01 ± 1.41
180 $\varepsilon \times \mathcal{B}$ (%)	0.28 ± 0.02	0.17 ± 0.02	0.10 ± 0.02	1.20 ± 0.30	0.76 ± 0.17	0.56 ± 0.09	0.35 ± 0.08	
$\langle N \rangle$	0.57 ± 0.07	0.40 ± 0.07	0.19 ± 0.04	2.42 ± 0.67	1.41 ± 0.36	1.14 ± 0.22	0.64 ± 0.16	6.77 ± 1.09
200 $\varepsilon \times \mathcal{B}$ (%)	0.31 ± 0.02	0.20 ± 0.03	0.11 ± 0.02	1.70 ± 0.20	0.96 ± 0.21	0.74 ± 0.11	0.41 ± 0.08	
$\langle N \rangle$	0.34 ± 0.04	0.25 ± 0.05	0.11 ± 0.02	1.84 ± 0.31	0.95 ± 0.24	0.81 ± 0.16	0.41 ± 0.10	4.71 ± 0.66
Background	0.12 ± 0.03	0.28 ± 0.14	0.25 ± 0.04	1.22 ± 0.42	0.71 ± 0.28	0.85 ± 0.14	0.36 ± 0.08	3.79 ± 0.55
$\int \mathcal{L}\, dt$ (pb^{-1})	47.9 ± 5.7	55.7 ± 6.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	47.9 ± 5.7	44.2 ± 5.3	
Data	2	0	1	5	3	3	3	17

- Excess over background in almost every channel

Significance

- So there's clearly an excess over background
  - and it appears unlikely to be a fluctuation
  - but *how* unlikely?
- Easy to find the Poisson probability for the 3.8 expected background events to fluctuate to 17: 4.5×10^{-7}!
- Probability of 3.8 fluctuating to 17 *or more* is 5.7×10^{-7}



- But there's more
  - there's also the uncertainty on the expected background to consider
  - almost entirely a systematic uncertainty

Systematics

- Understanding the systematics is the major component of any analysis
- We had to deal with at least three major classes:

1. What does background look like?
   - theoretical understanding of object kinematics
   - vary parameters in MC
   - cross-check with data when possible

2. How does DØ respond?
   - trigger efficiency
   - jet energy scale and resolution
   - lepton ID efficiencies
   - missing E_T

3. How much data is there?
   - luminosity uncertainty

- By discovery paper, total uncertainty was at 15% level

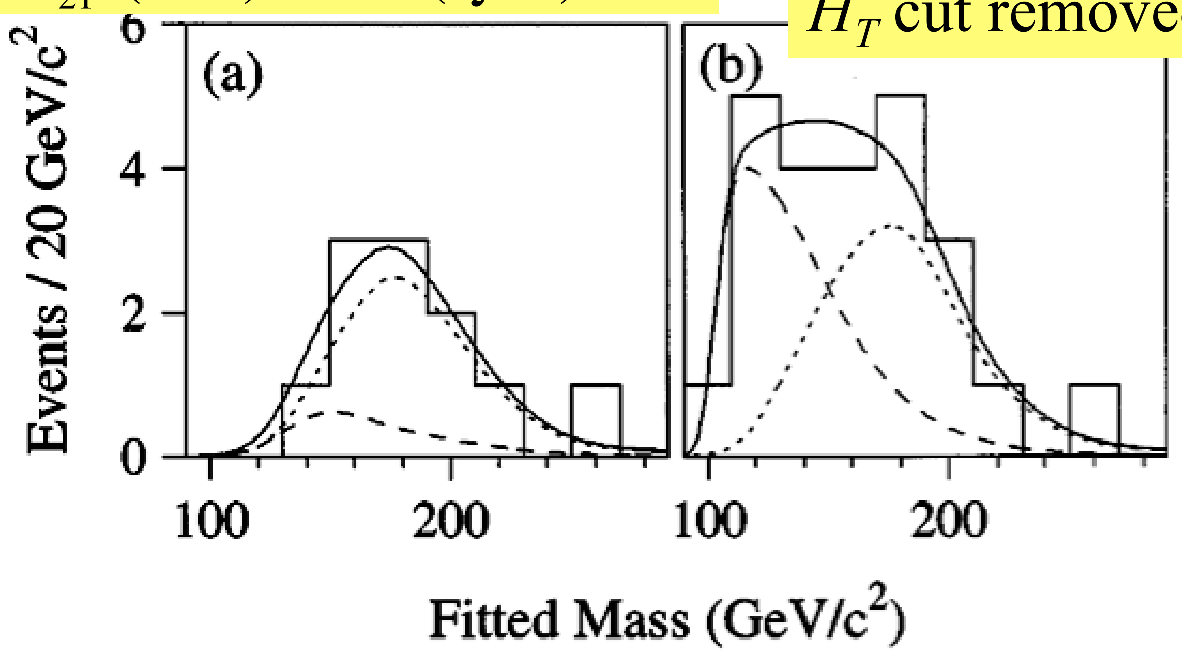
Accounting for the Systematics

- Solution: MC simulation of the background fluctuations
  - throw a Gaussian random number centered at 3.8 with width 0.6 to get expected background
  - then throw a Poisson-distributed random number based on expected background
  - count fraction of tries that result in 17 or more observed events
- Answer is 2×10^{-6} -- Discovery!
- Note that this assumes that all the uncertainties in the background estimate are Gaussian
  - fine for statistical component
  - not as obvious for systematics
- That's the real reason we don't trust signal probabilities until they get down to the 10^{-6} range

Circumstantial Evidence

- Beyond merely counting events, one can also look at the kinematics of the events
- The reconstructed mass in l+jets events is the most interesting single quantity*:

199^{+19}_{-21} (stat.) ± 22 (syst.) GeV

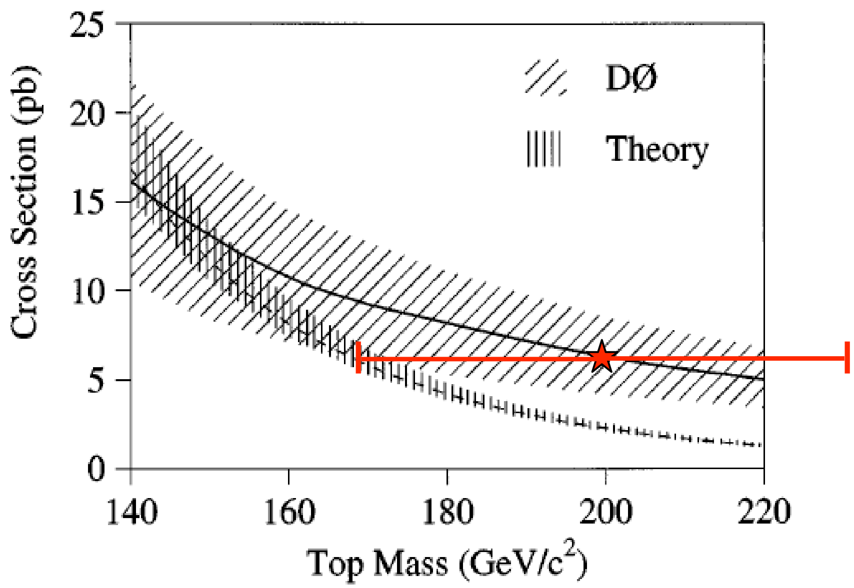


- Data looks like sum of background and $t\bar{t}$
- Not obvious how to incorporate this into overall significance

- In the end, this was taken as additional reassurance that we had top quarks in our sample

*EWV looked into mass value for dilepton events. Methods not sufficiently developed to say anything meaningful

- Best-fit top mass value was 199^{+19}_{-21} (stat.) ± 22 (syst.) GeV
- Above the previous limits, but also an indication that luck played a role in the discovery:



- More events than expected from top across range consistent with mass value

- Also looked at distribution of events across decay channels
  – highly consistent with expectation from top

Summary

- Discovering the top quark required
  - a well-calibrated detector
  - innovative methods of separating signal from background
  - combination of results from many decay channels
    - no one channel would have done it
  - committed effort from a large group of physicists
  - and a bit of luck to see it in 50 pb^{-1}
- Provided me a through (and intense) introduction to what's required to do a physics analysis
- Seeing something no one has seen before is definitely exciting
- But it would be even better to find something unexpected