Celebrating 20 years of the discovery of the Top quark

Patrizia Azzi - INFN Padova& CERN

former member of the CDF collaboration

Many thanks to: G. Unal, R. Rose, G. Watts, K. Sliwa, J.Konigsberg, T. Dorigo, M. Narain, M. Cobal, B. Klima,… and so many more etc etc etc etc
much material taken from the « Top Turns Ten » celebration videos & posters

CDF Trailers being demolished

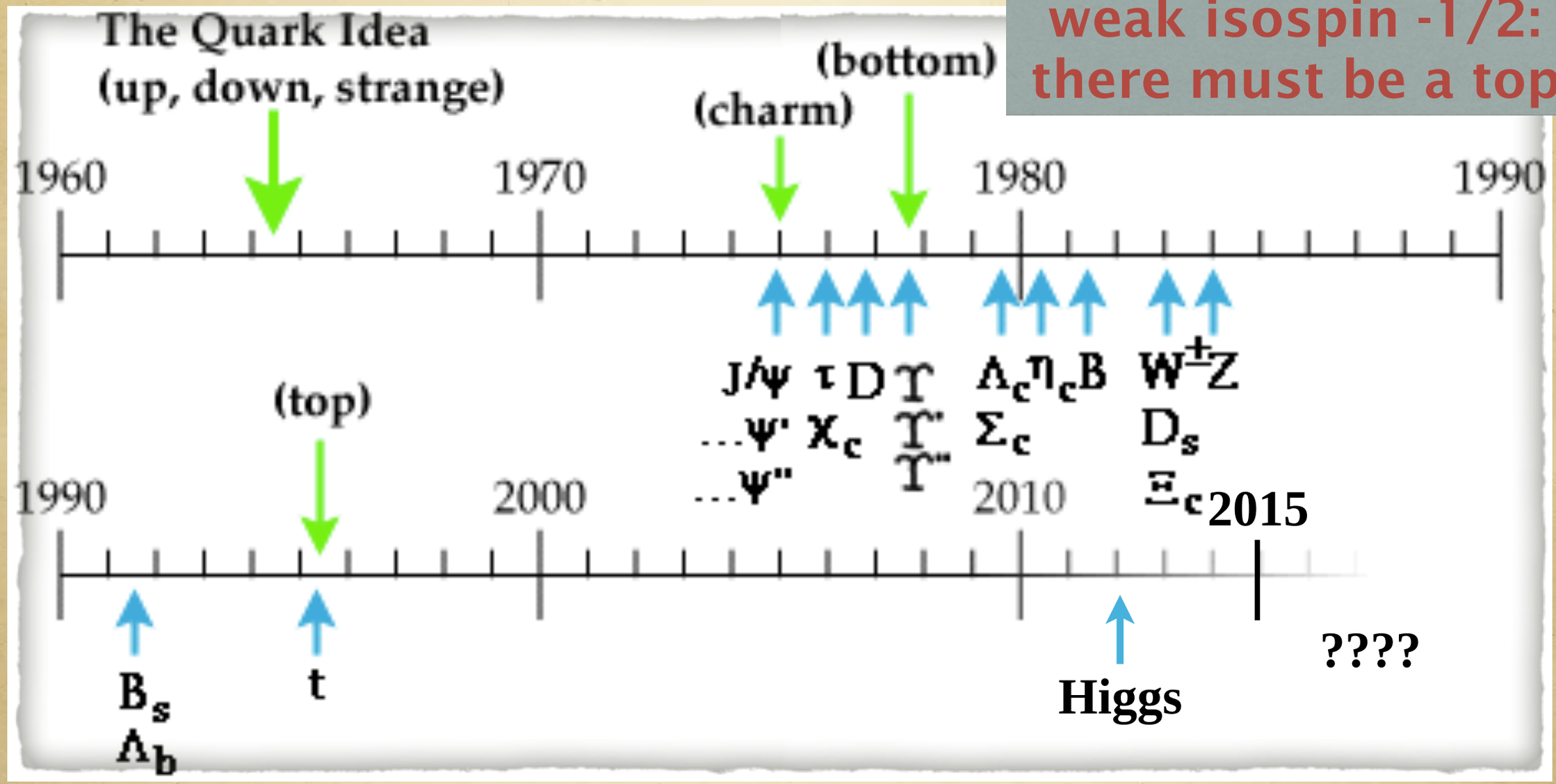
Think Back

- To the early 90's
- Ok – so you were all probably in grade school…
  - Before iPhones
  - Before laptops were commonplace
  - When physicists ran jobs on DEC VAX's and lived in their offices day and night
  - We programmed in FORTRAN, used PAW, and had to learn about ZEBRA – a memory management system
  - We thought we knew a lot back then…. BUT
- Silicon detectors had not been tried in a hadron collider environment

Keep Thinking Back

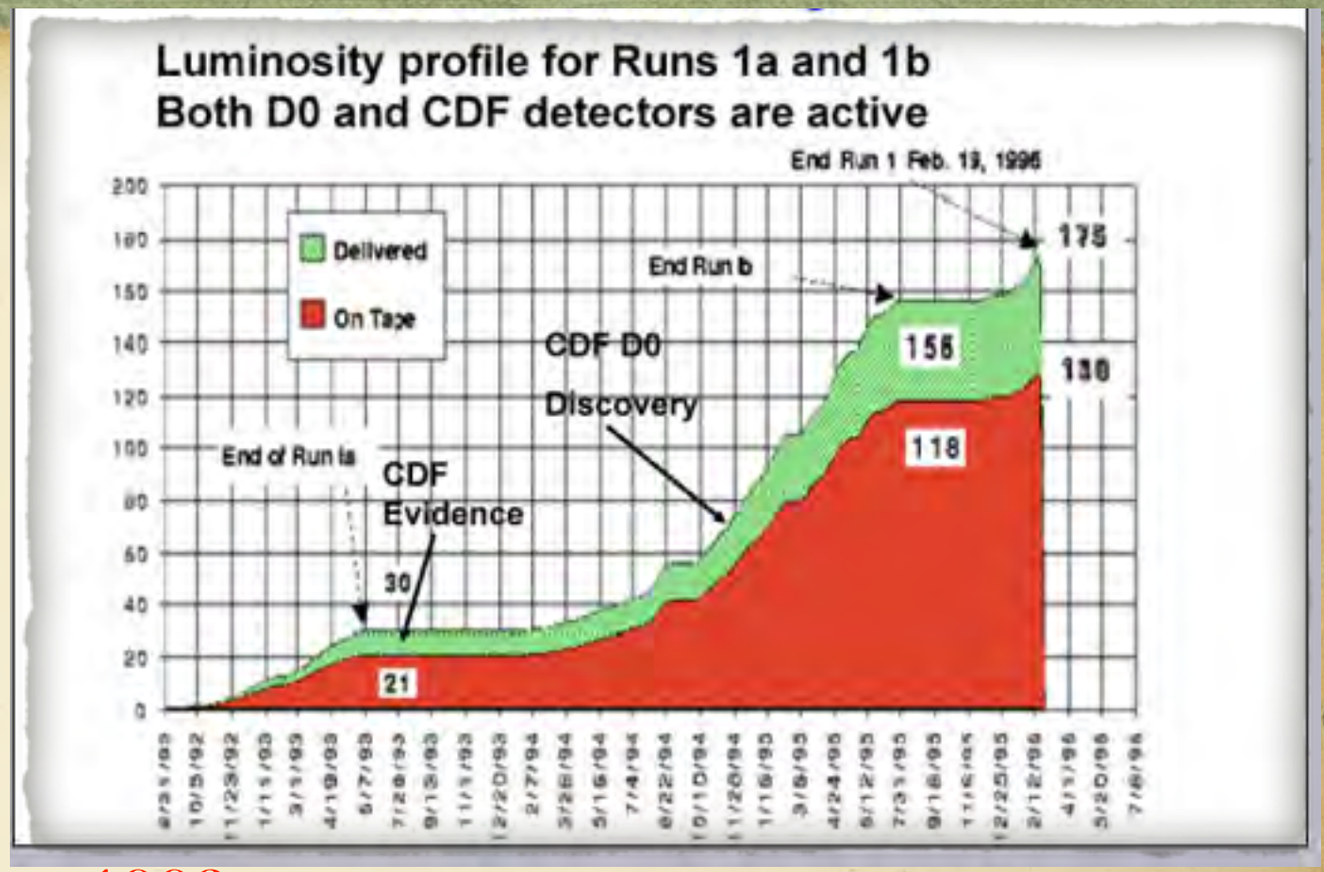
- Our MC did not differentiate b-quarks from light quarks (VECBOS)
- We did not know how to b-tag
- We did not even know if a silicon detector would work in a hadron collider environment?
- How long would it last before the accelerator put a hole in it?
- We did not know how to measure b-tagging efficiency
- It took us a year to collect 20 pb-1
- But we were motivated!!!

Particle Discoveries timeline



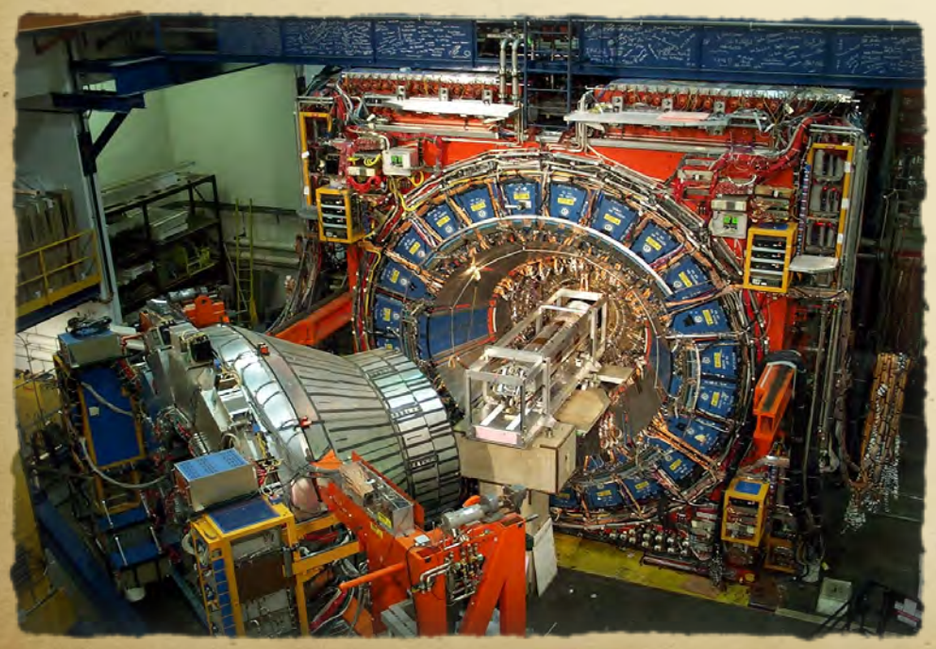
weak isospin -1/2: there must be a top!

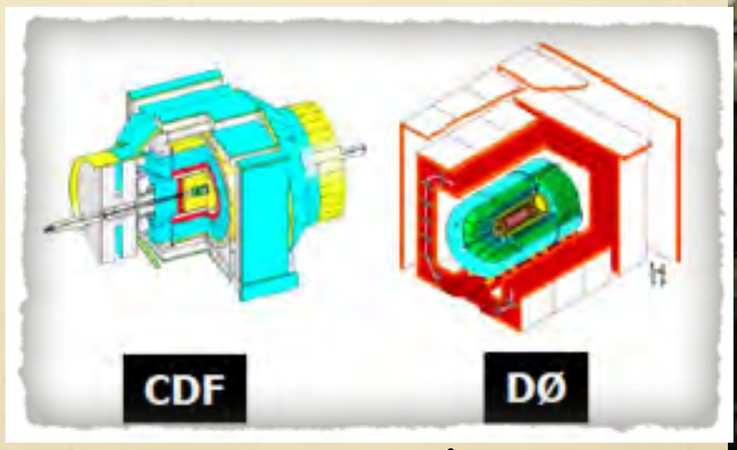
- Why was the top discovery so special ? some people say « you knew were to look » , « it was expected » , « it was obvious », they way it went was far from there…



1992

The Main Actors



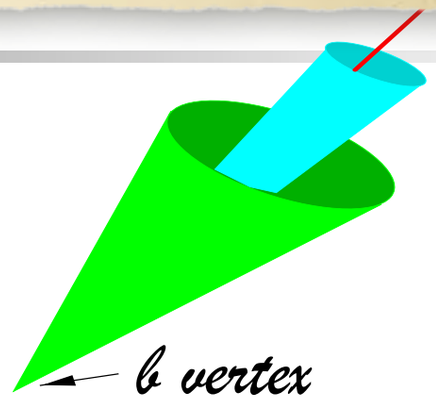


two experiment
confirmation
in case of discovery

Search in Run 0 of the Tevatron(88/89)

- Believe $M_{Top} < M_W$
  - Decay mode would be W -> tb with t -> blν
- Search strategies
  - Dilepton channel
    - ee, eμ, and μμ
  - L+jets channel
    - Added **SLT** tags
- Set limit $M_{Top} > 91$ GeV
- **CDF had no silicon yet!**

No D0 at the time!



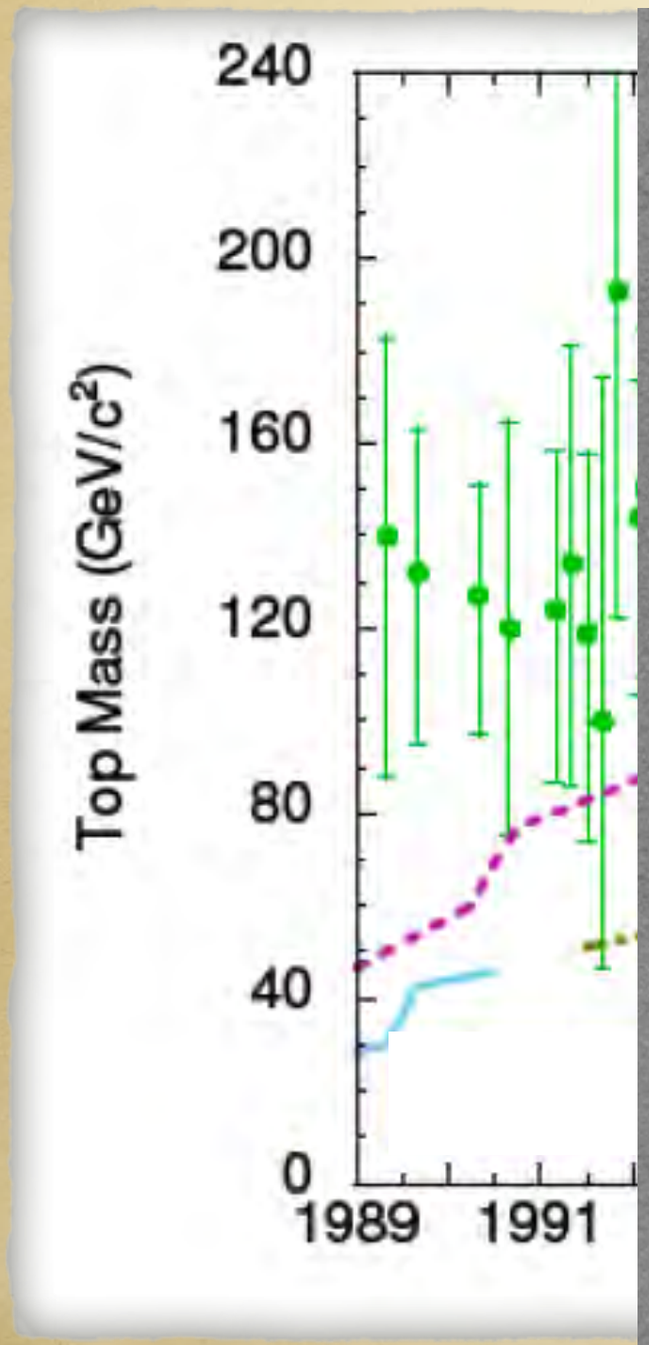
- Soft Lepton Tagging
- Identify semileptonic B decay

$$b \to l \ , \ b \to c \to l$$

- ε(SLT) ~ 20%

at this point CERN is out of the game…

The road to the Top from the EWK fits (the other side of the pond)



The EWK fits where hinting a « higher » mass ~130GeV nobody really listened, though. The direct search needed to cover all corners

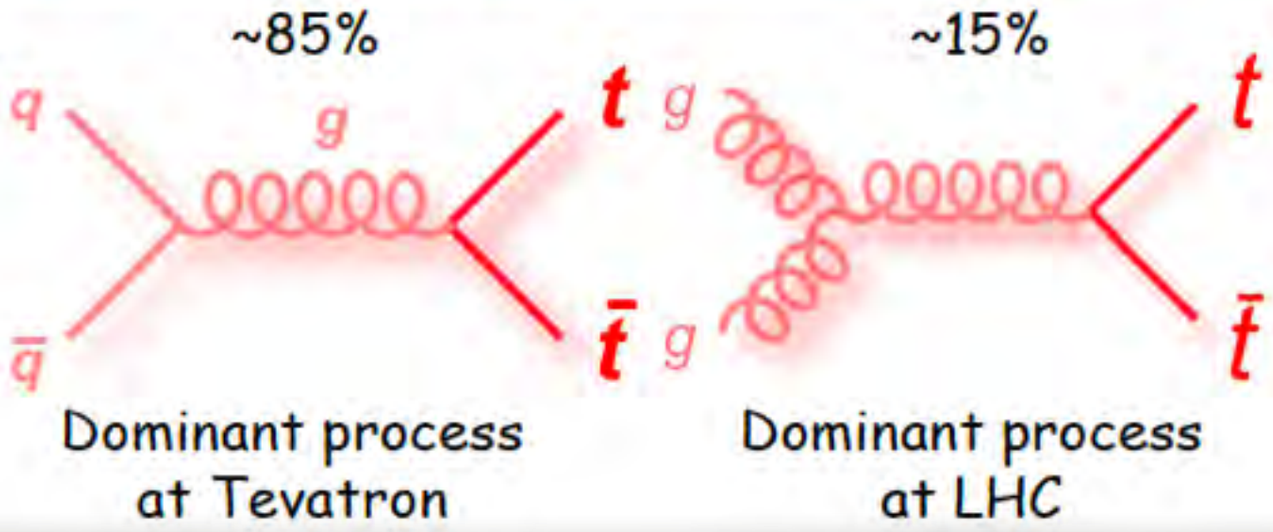
Top Quark Production at Tevatron

- QCD pair production

σ_{SM} = 7.35 pb

(for m_{Top} = 173.3 GeV)

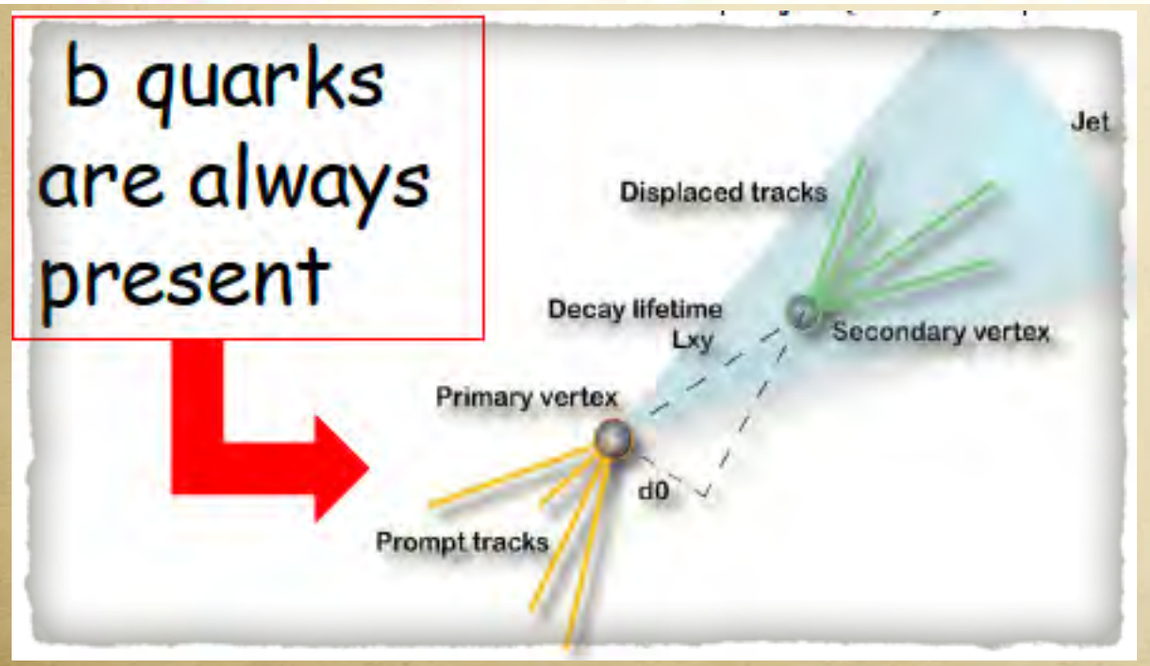
(arXiv:1303.6254)

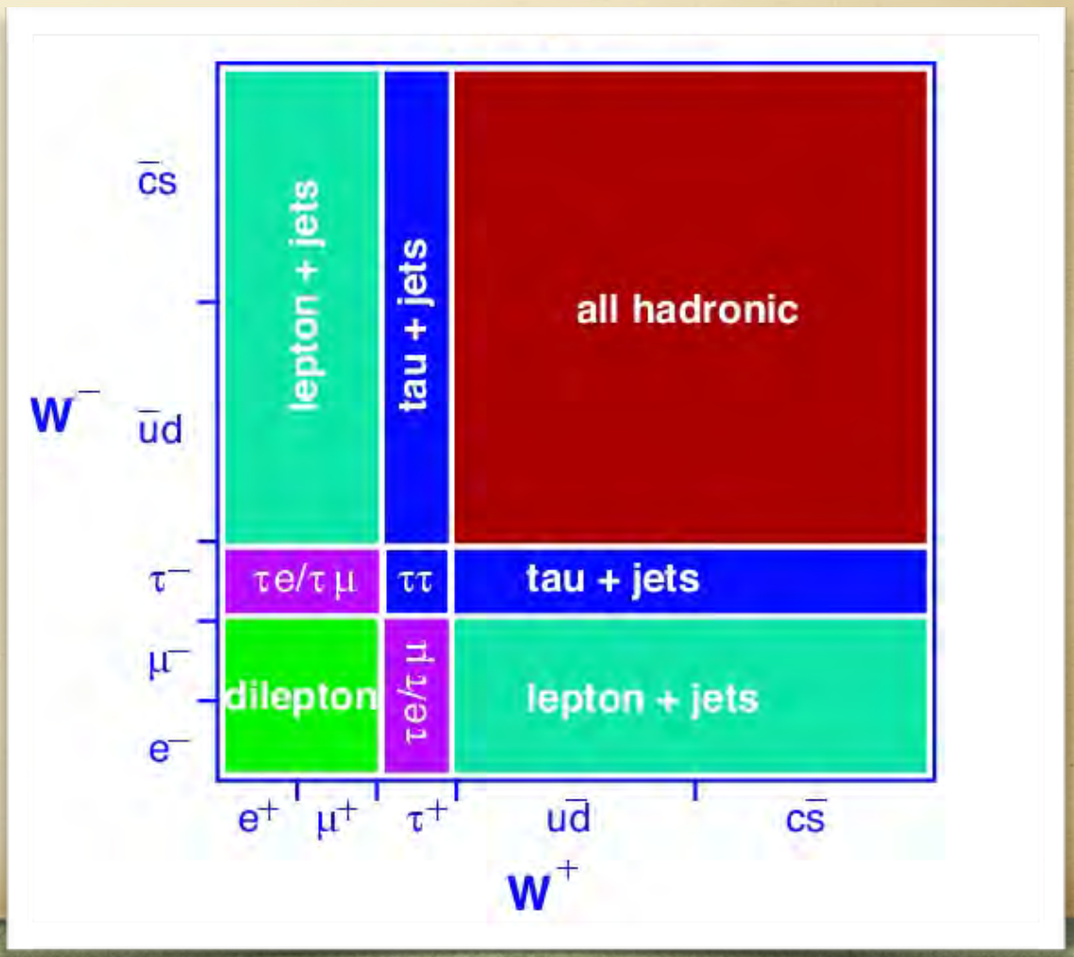


At Tevatron ~10 tt pairs/day (while at LHC ~1 tt pairs/second)

Top Quark Decay

b quarks are always present





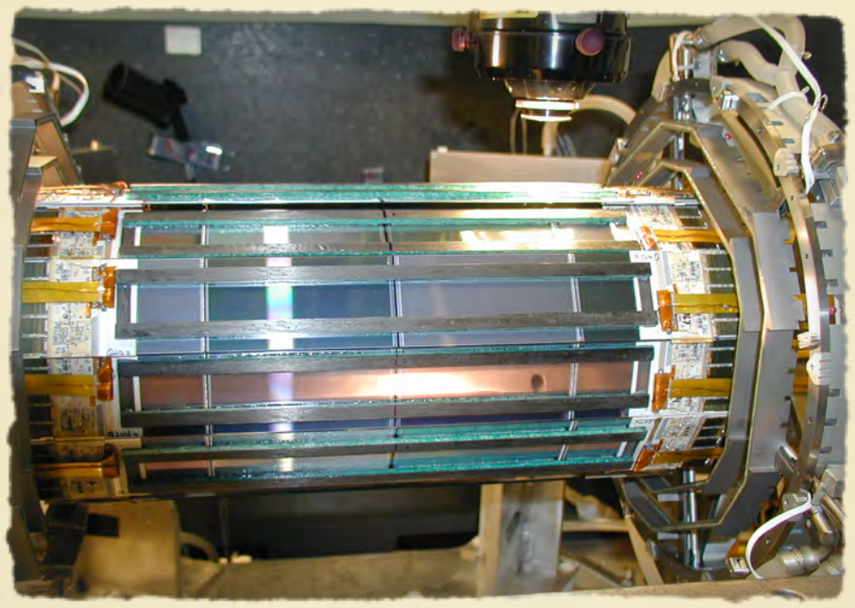
The SVX: the 1st silicon detector at a hadron collider

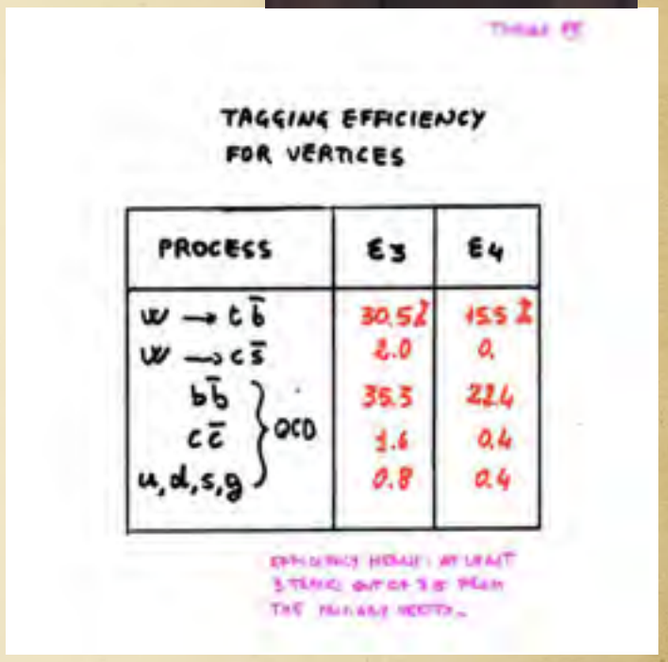
« Popularity vs time »

10 20 30 40 50 60 70 80 90 100 %

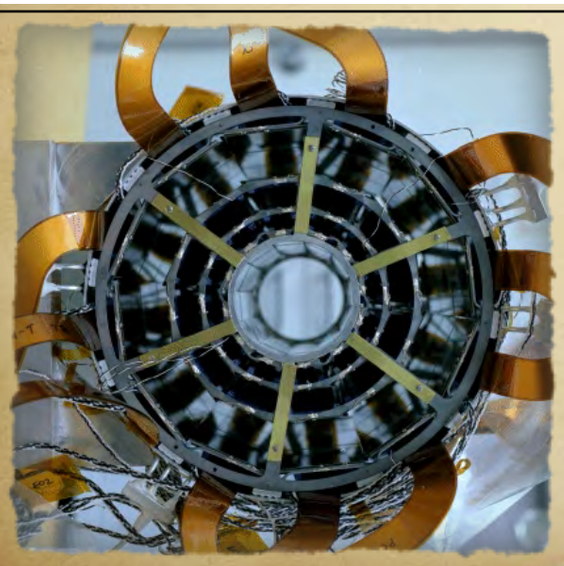
1980
1981 design report
1982
1983
1984
1985 first coll lbl tsuk
1986
1987
1988 run 0 test beam
1989 m o u
1990
1991 test beam
1992 run 1 start
1993 svx'
1994 top

…from an idea by Aldo Menzione in 1981





incredibly enough this is still very close to what we use now!



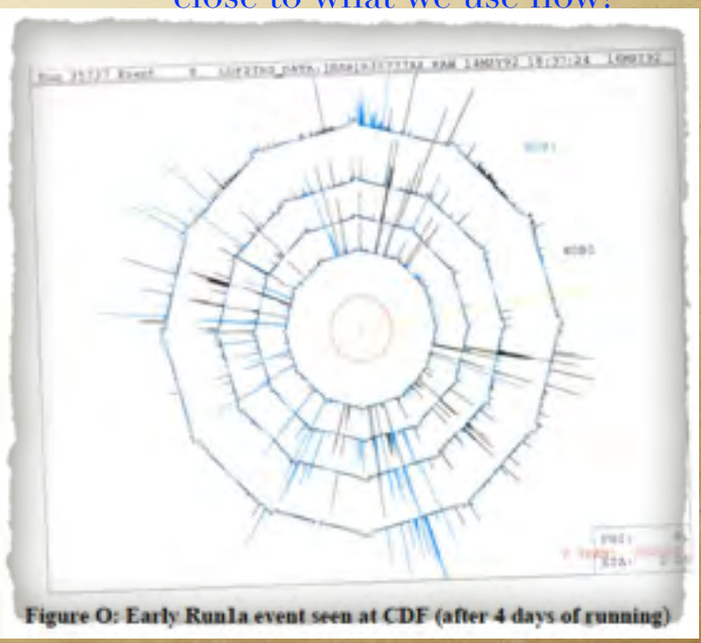
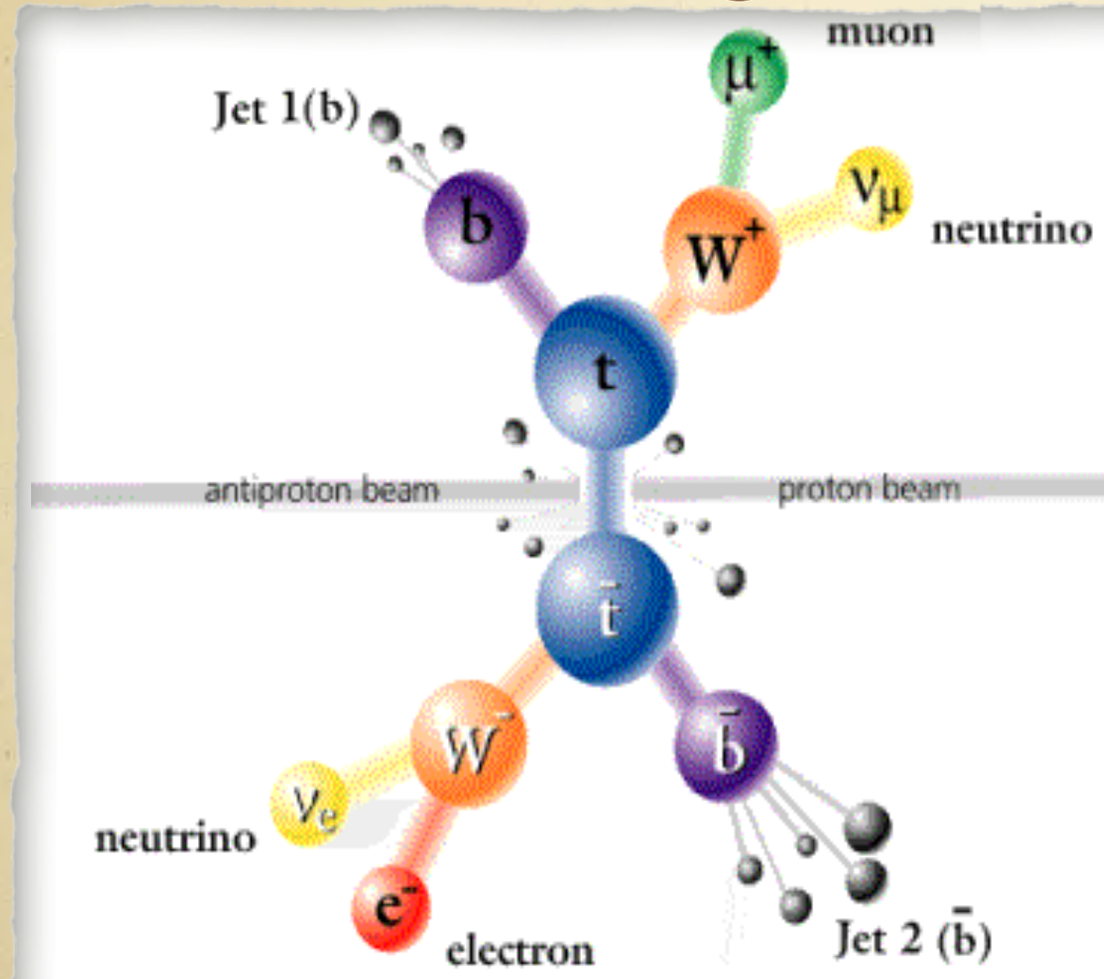


Figure O: Early Run1a event seen at CDF (after 4 days of running)

How Hard is it going to be?

- Tevatron was running at 900 GeV and colliding beam at 300,000 times/sec
- A ttbar event is created about once every 10 billion collisions
- So in Run 1A, about 1 trillion collisions
- For a top mass of 175, we made about 100 total!!! (not taking into account acceptance, trigger etc)

The search gets « organized »



DILEPTON

DIL - both W decay to leptons

Low rate, Very clean

LEPTON+JETS

SVX - one of the b-jets is identified using a displaced vertex tag

SVX detector (CDF only)

LEPTON+JETS

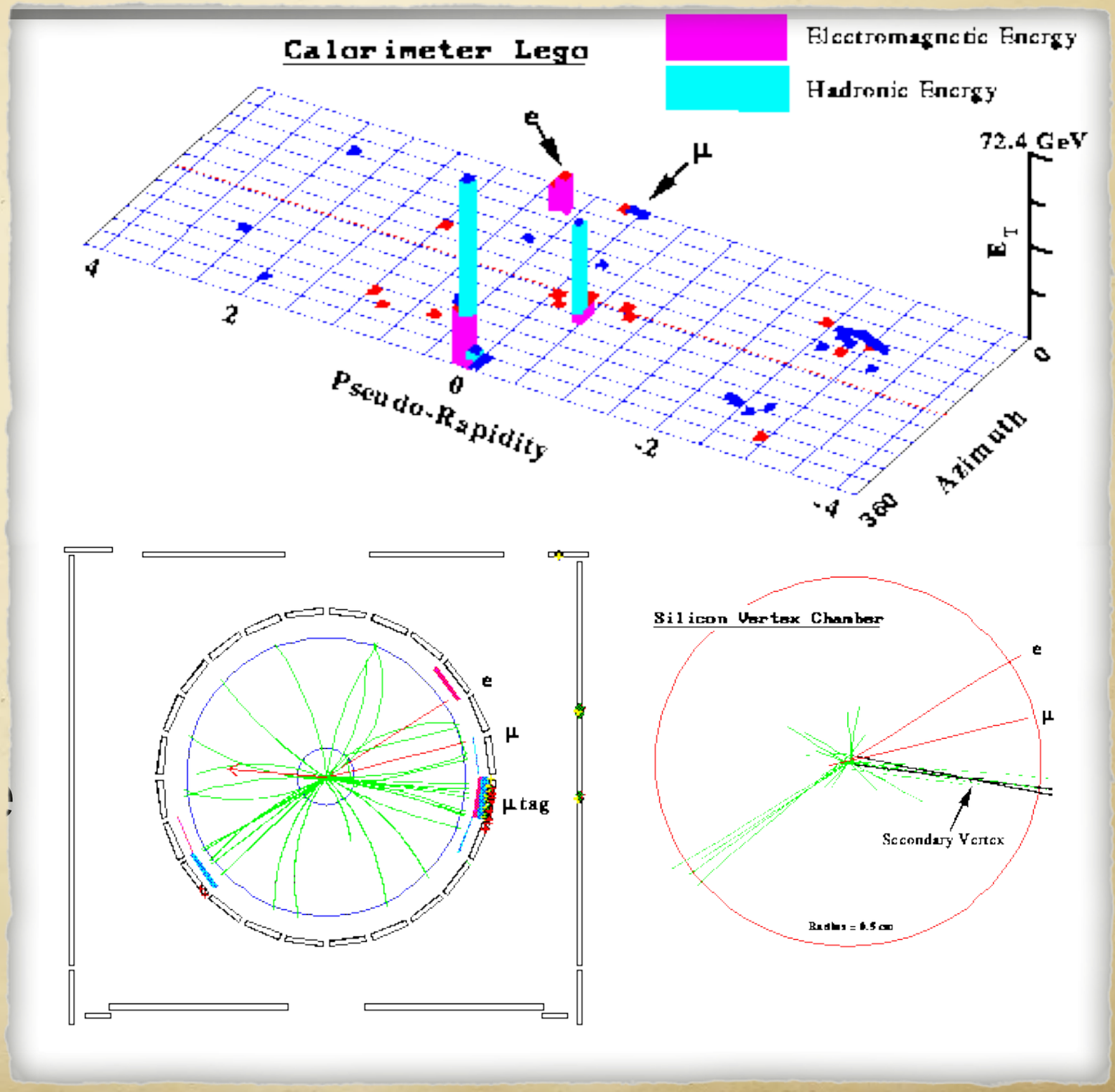
SLT - one of the b-jets is identified using a leptonic decay product

lepton I.D. in jets

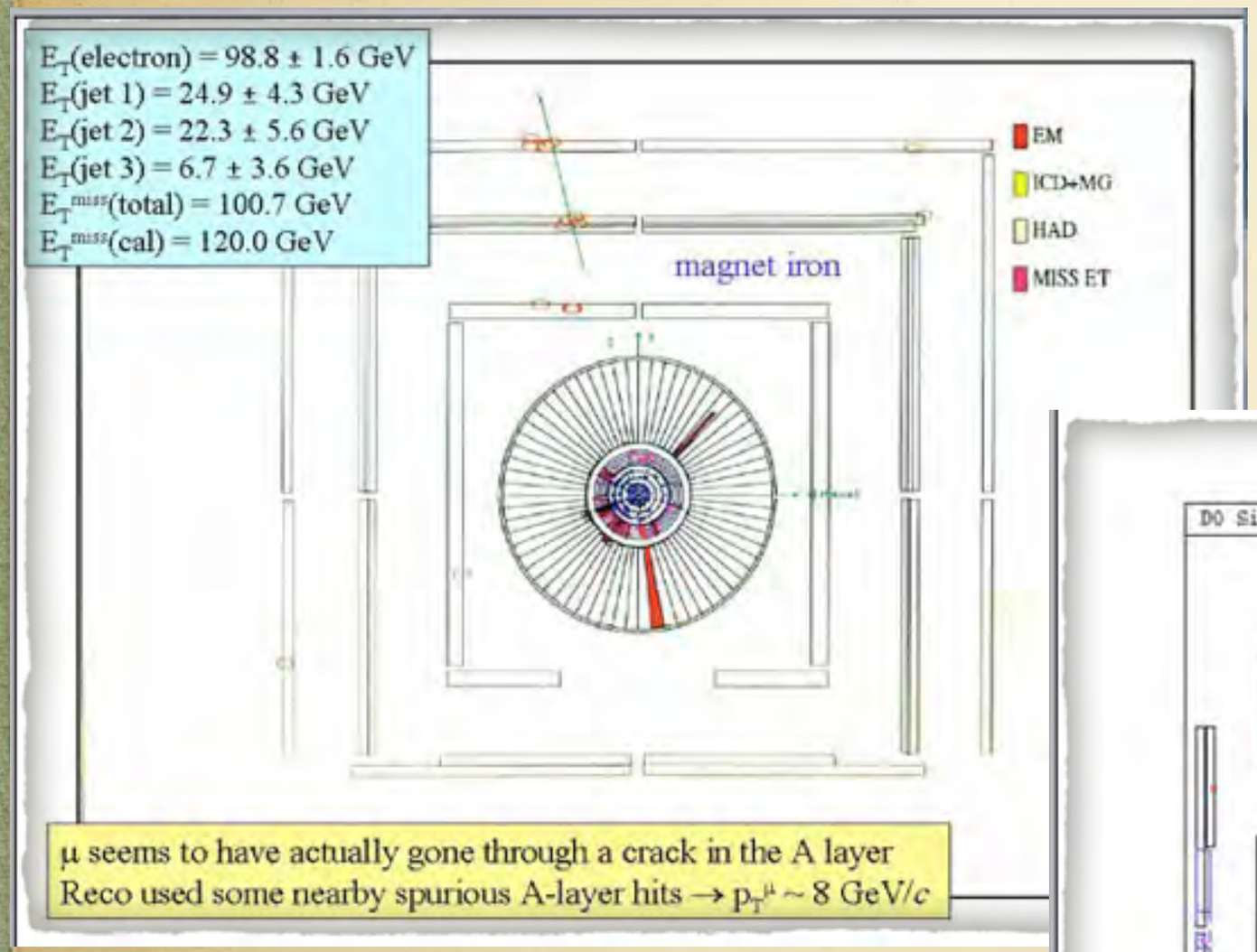
- Main analyses defined, but several other progressing in parallel as well with different method (Dalitz, Relative Likelyhood) and channels (all hadronic with double btag or kinematic)
- Common discussion and approvals in single big group !!!

CDF: the « DPF » event

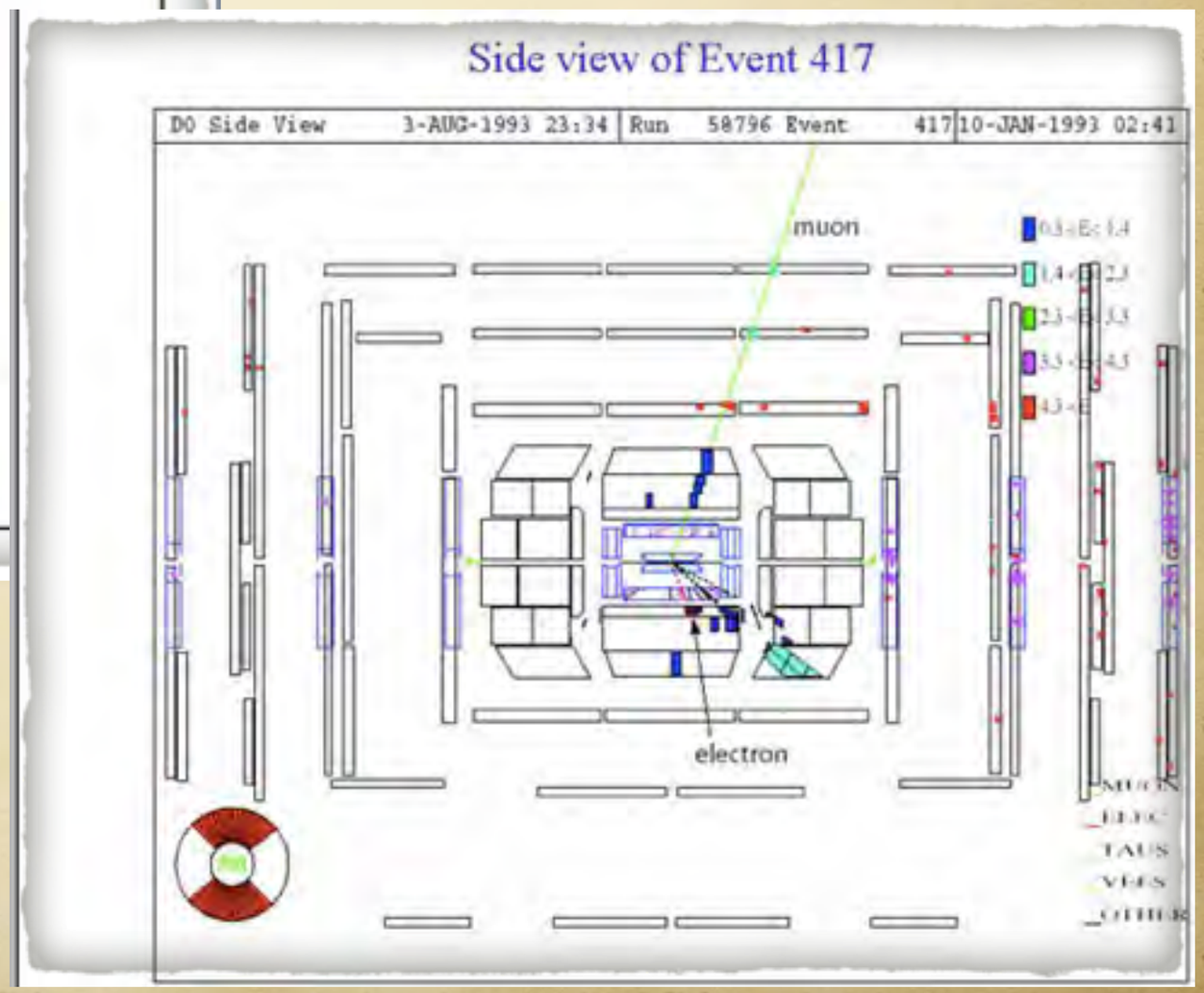
Oct 22, 1992
e-mu event
plus two jets,
one jet tagged
by both SVX
and SLT



D0 and the Event 417



- Another exceptional e-mu event!



D0 and event 417

M. Narain

- The year is 1993, the month is Jan…
  - An event with exceptional qualities has been found
  - The "excitement" generated by this event was so high, that until Oct – Nov 1993, it subsumed almost every meeting and every person "associated" with the top group.

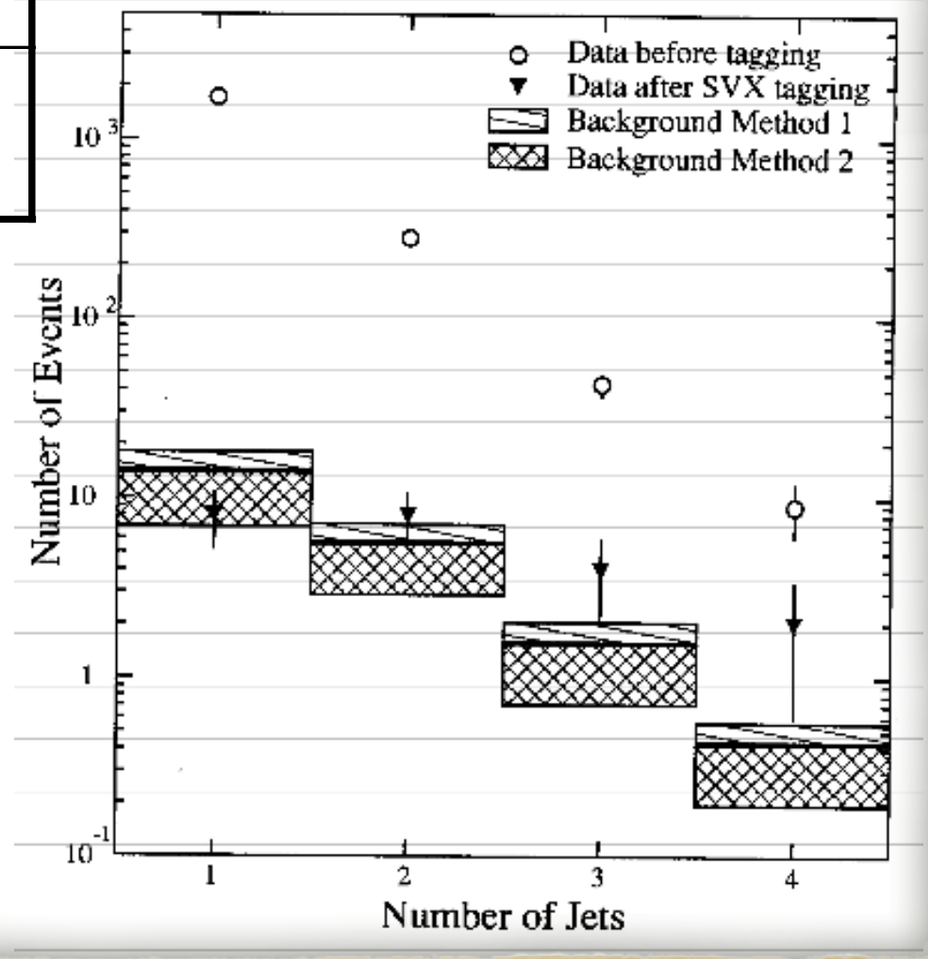
- Byproducts of this exceptional event are:
  - Both the muon and the central tracking reconstruction are revisited and made more robust.
  - Development of many techniques, including multivariate analyses to compute the probability that this event is inconsistent with background and is due to top quark production.
  - A couple of competing Dilepton mass analyses seem to develop almost overnight, and all indicate that the event is consistent with a top quark of mass between 145-200 GeV !

Reoptimizing the analysis for high top mass!!!

Results for Evidence Paper

Channel:	SVX	SLT	Dilepton
Expected Bkg.	2.3±0.3	3.1±0.3	0.56±0.25
Observed Events	6	7	2

- Combining all channels with 19 pb^{-1}
- Prob bkg fluctuate up to observed = 0.26% (2.8σ)
- Back then – we did not consider a Look Elsewhere Effect



the pre-history of blind analyses(1)

4. a-priori Vs. a-posteriori knowledge

What are we "allowed" to use?

2.8 sigma from counting exps

> Additional 2.3 sigma --> mass

> Not used,

because it was not in the “plan”

CDF measured:

(1994) Mtop = 174 +- 10 +- 13 GeV

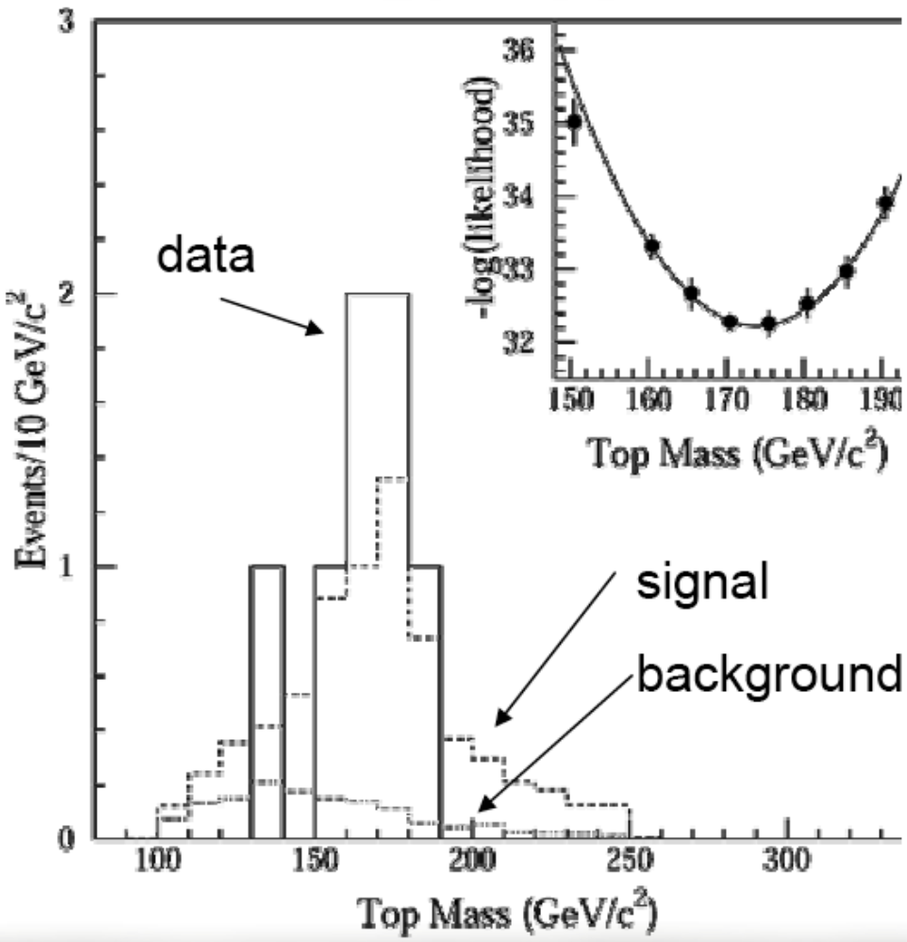
(1995) Mtop = 176 +- 8 +- 10 GeV

(2005) Mtop = 172 +- 3.7 GeV

World average, as of today:

172.7 +-2.9 GeV

CDF 1994



After a very long and exhausting meeting the « evidence » title was chosen.

MORIOND 1994

Abstract

The lepton and quark asymmetries measured at LEP are presented. The results of the Standard Model fits to the electoweak data presented at this conference are given. The top mass obtained from the fit to the LEP data is 172^{+13+18}_{-14-20} GeV; it is 177^{+11+18}_{-11-19} when also the collider, ν and A_{LR} data are included.

talk presented on the XXIXth Rencontres de Moriond
Méribel, March 12-19,1994

paper & talk
by Bolek Pietrzyk

			LEP + Collider and ν data + A_{LR} from SLC
		ν data	
M_t (GeV)	$172^{+13\ +18}_{-14\ -20}$	$170^{+12\ +18}_{-12\ -19}$	$177^{+11\ +18}_{-11\ -19}$
$\alpha_s(M_Z^2)$	$0.125 \pm 0.005\ \pm 0.002$	$0.125 \pm 0.005\ \pm 0.002$	$0.124 \pm 0.005\ \pm 0.002$
$\chi^2/(d.o.f.)$	11.4/9	11.5/11	19.1/12
$\sin^2\theta^{lept}_{eff}$	$0.2323 \pm 0.0002\ ^{+0.0001}_{-0.0002}$	$0.2324 \pm 0.0002\ ^{+0.0001}_{-0.0002}$	$0.2320 \pm 0.0003\ ^{+0.0001}_{-0.0002}$
$1 - M_W^2/M_Z^2$	$0.2251 \pm 0.0015\ ^{+0.0003}_{-0.0003}$	$0.2253 \pm 0.0013\ ^{+0.0003}_{-0.0002}$	$0.2243 \pm 0.0012\ ^{+0.0003}_{-0.0002}$
M_W (GeV)	$80.28 \pm 0.08\ ^{+0.01}_{-0.02}$	$80.26 \pm 0.07\ ^{+0.01}_{-0.01}$	$80.31 \pm 0.06\ ^{+0.01}_{-0.01}$

Evidence for top quark production in p^-p collisions at $\sqrt{s}$ =1.8 TeV

F. Abe *et al.*

Phys. Rev. D **50**, 2966 – Published 1 September

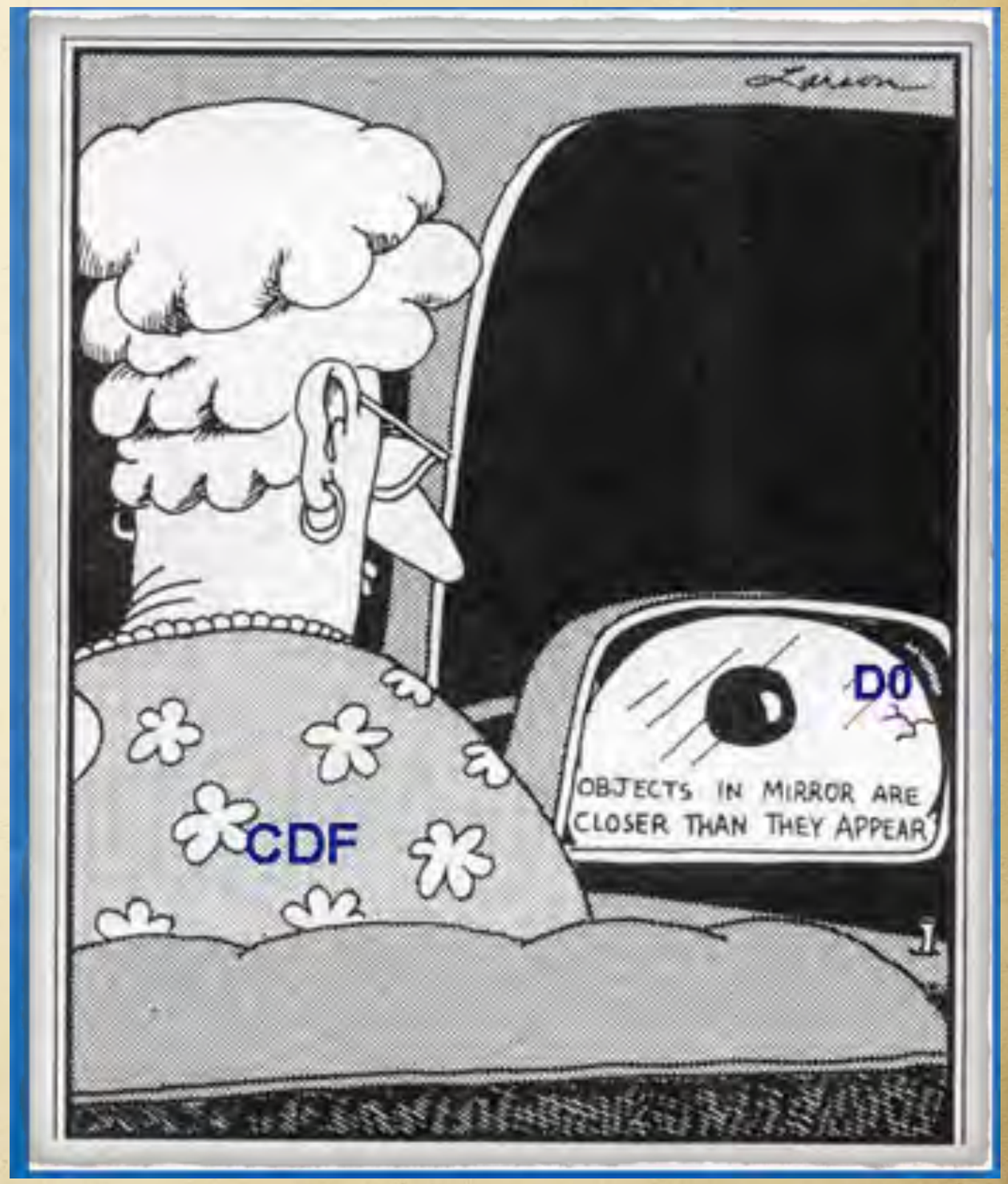
CDF EVIDENCE PAPER

estimated to be 0.26%. The statistics are too limited to firmly establish the existence of the top quark; however, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. We present several cross-checks. Some support this hypothesis; others do not. Under the assumption that the excess yield over background is due to $t\bar{t}$, constrained fitting on a subset of the events yields a mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2 for the top quark. The $t\bar{t}$ cross section, using this top quark mass to compute the acceptance, is measured to be $13.9^{+6.1}_{-4.8}$ pb.

Received 25 April 1994

Competition

- After the CDF paper the competition reached a new level
- New data were coming in!!!
  - analyses reorganized & reoptimized
  - <u>CHOICE OF CUTS FINALIZED A PRIORI!!!</u>
- ~9 months of discussion trying NOT to leak information on the « other side »
  - *few couples made by a CDF+D0 person had to swear to the spokesmen not to confess anything to their spouse!*
- draft papers hidden in directories with unusal names: QCD, POT…
- Still the discovery draft leaked even to CERN few days before…



From D0 Info

The fear of leaks

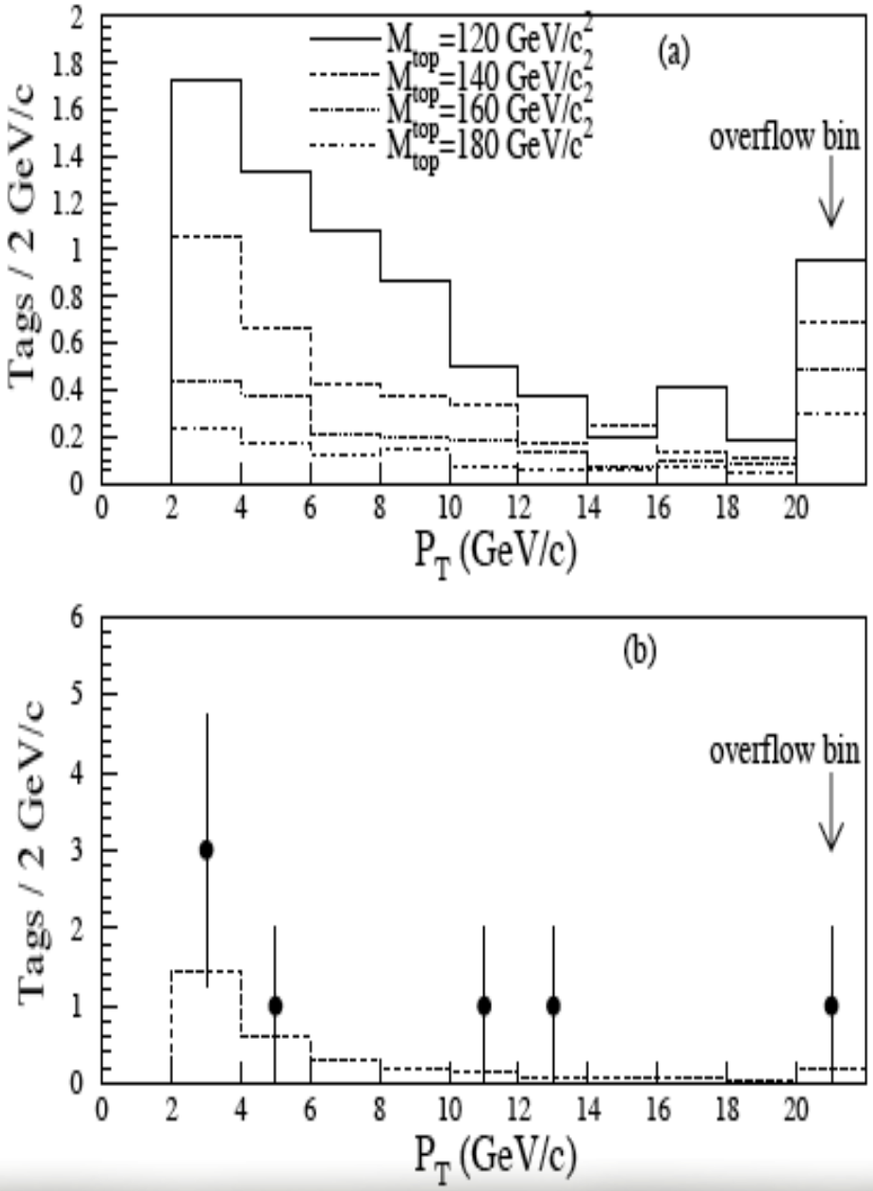
- Hide the paper in the QCD group project area.

```
From: D0SFT::JMBUTLER      "John M. Butler (708) 840-8705" 17-FEB-1995
Subj: paper location

                                                Fermilab, MS 357, 17-FEB-1995

     Paul,
In a crude attempt at subtlety, I've put the paper and "final" tables in
     PRJ$ROOT227:[QCD_3.CUCKOO]PAPER_V0-5.PS
     PRJ$ROOT227:[QCD_3.CUCKOO]TABLE_II.EPS
     PRJ$ROOT227:[QCD_3.CUCKOO]TABLE_IV.EPS
<..deleted text..>
                                        jb
```

- It still happened…
  - We also had their paper!
    - We have not yet figured out who our Karl Rove and Judith Miller are…

The Pre-history of blind analysis (2)

Blind analysis - what blind analysis? (part ii)



Example 2b. SLT P_T cut choice:

- Chosen to be 2 GeV at start of search (when top could have been anywhere between 120-200).
- After looking at the Pt spectrum of our tags, was obvious that a 4GeV cut will be slightly better…
- Painful, long arguments.
- Decided to stick to the "no changing cuts" rule

The Pre-history of blind analysis (3)

The Fallout from "blind" optimization

- The lost di-electron event due to standardization of the object-IDs across analyses…

  ⇒ a hole in the office door…

How was life during those months?

- **Physics Meetings:** they were different (can I say better than now?)
  - very few, sometimes very (very) (very) long (we brought lollipops!)
  - no video connection, no laptops (the CDF room for the btag meeting was named the « Black Hole »)
  - very well attended by young and seniors. Lots of discussion, very open, very constructive, lots of yelling too.
  - _BEING THERE_ made there difference
- **Data:** getting data was a struggle (oops?)
- **Governance:** few groups, very tight contact with convener and spokesmen, not very formal hierarchy
- **Analysis Strategy:** few chosen analysis priority, but many other on the side where brilliant. Maybe too original? CDF in particular has always been a bit too conservative…

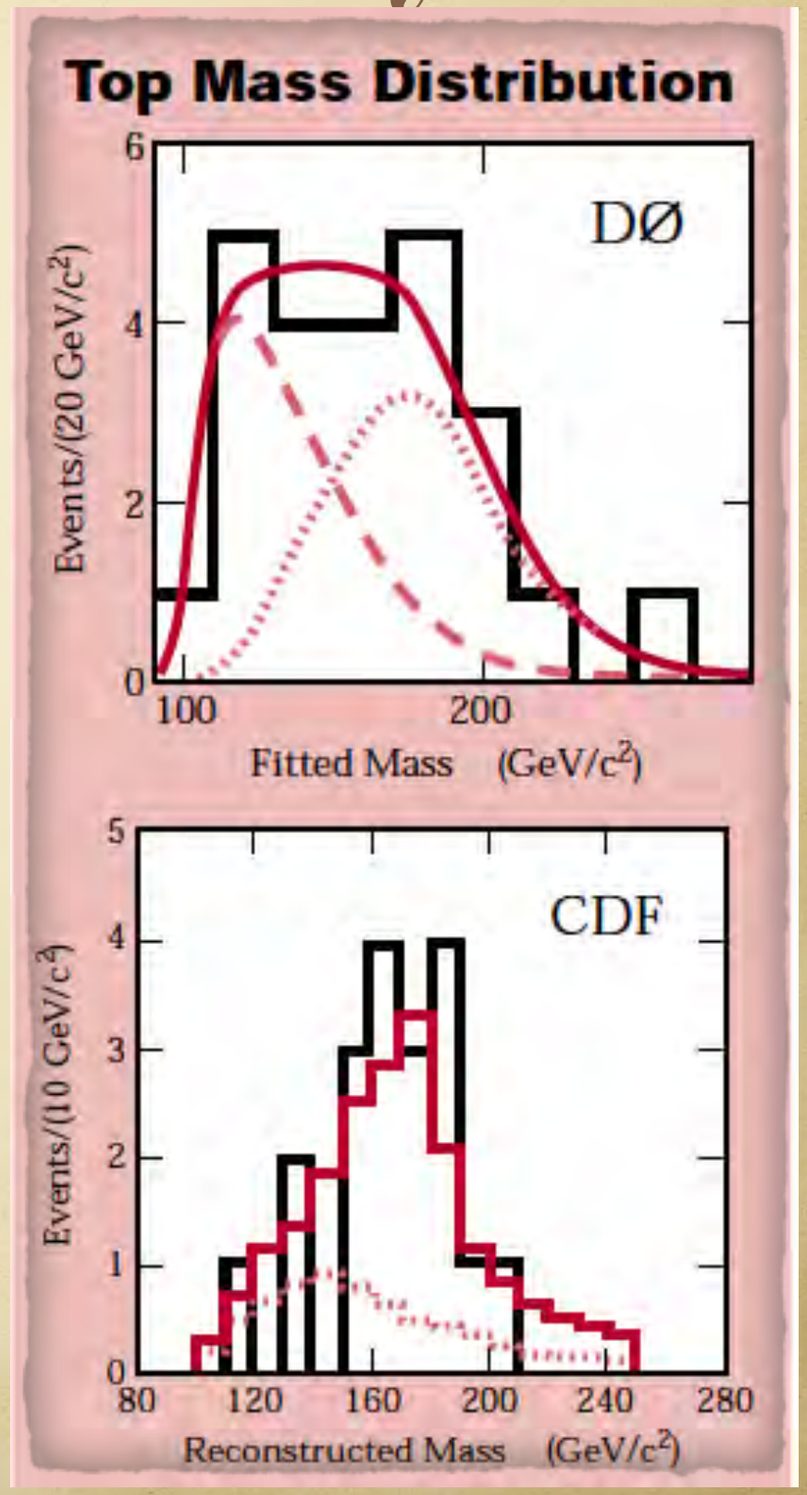
Finally: the Discovery

Observed: 17 events
Expected background: 3.8 ± 0.6 events.

Significance: 4.6 σ

D0

Probability for an upward fluctuation of the background to produce the observed signal is 2 x 10^{-6}



Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Exp. bkg	6.7±2.1	15.4±2.0	1.3±0.3
Probability	$2x10^{-5}$	$6x10^{-2}$	$3x10^{-3}$

- Using 67 pb-1 (includes Evidence data) combined Prob = $1x10^{-6}$ (4.8σ)
- If include mass distribution Prob = $3.7x10^{-7}$ (5.0σ)

CDF

It's official!

- Feb 24 1995, Friday, 11:00 a.m. papers submitted to PRL

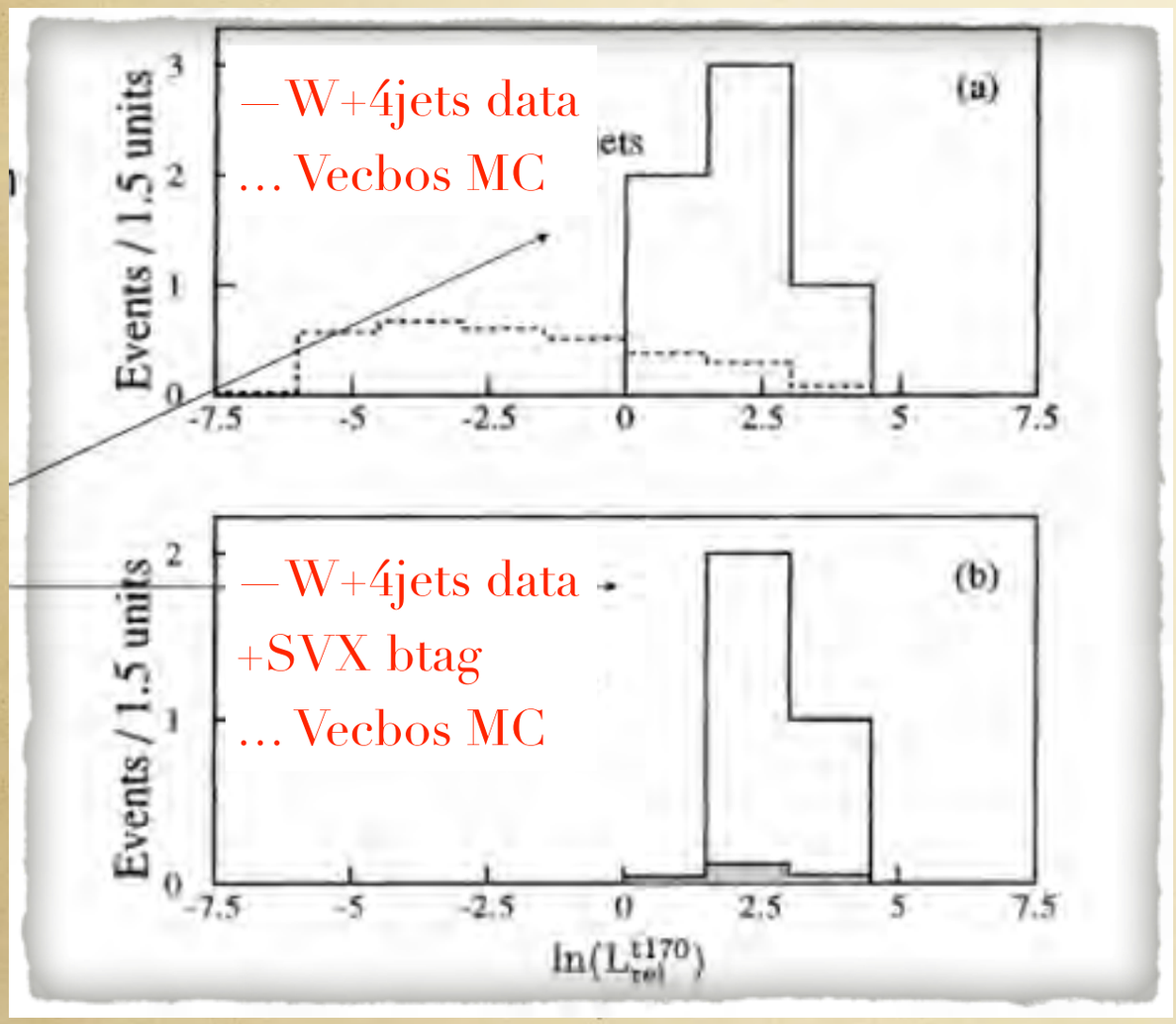
Georgio Bellettini, Paul Grannis, John Peoples, Hugh Montgomery and Bill Carithers at the top quark discovery and announcement seminar.

- Mar. 2, 1995, Thursday) Public announcement of top quark discovery

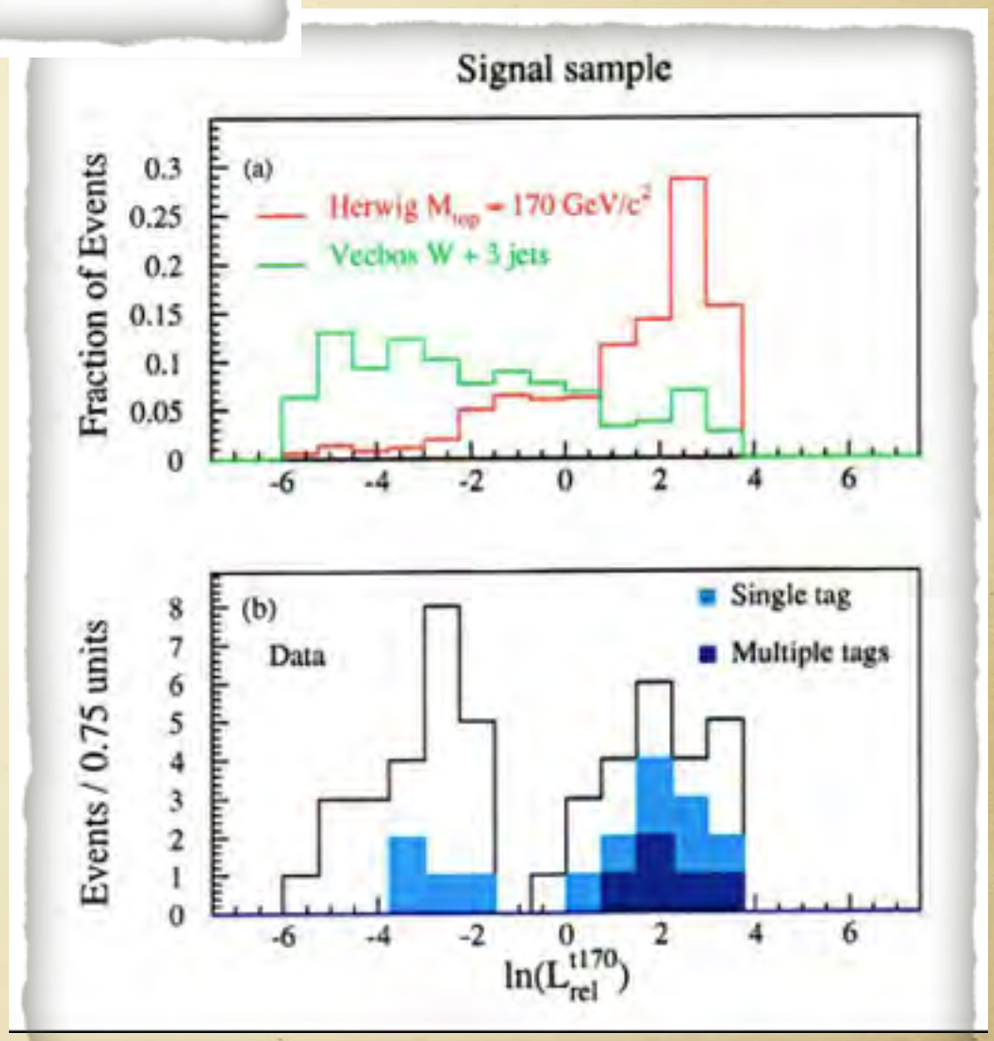
After official announcement: Relative Likelyhood Approach

Pre-Evidence for the top quark from the Event Structure

G. Bellettini, M. Cobal, H. Grassmann, S. Leone
INFN, Pisa



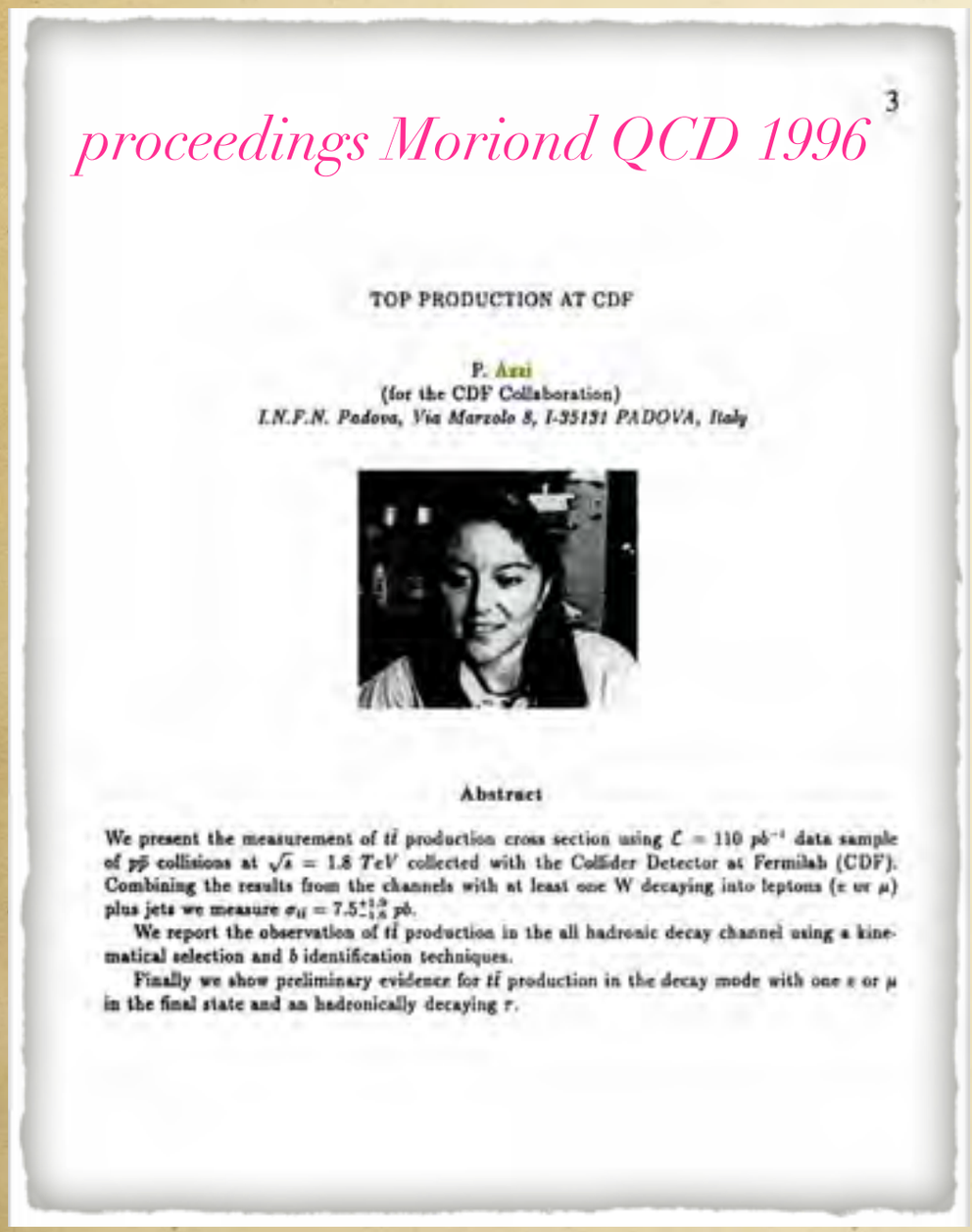
19pb^{-1} (thesis of M. Cobal 1994)



67pb-1 (PRD52 (1995)

After the official announcement of top discovery, CDF agreed to publish the findings of the Ln(Lrel) analysis. In 67 pb(-1) of data the top signal was huge.

After official announcement: First observation of top decays the all hadronic channel at CDF in 1996



proceedings Moriond QCD 1996

3

TOP PRODUCTION AT CDF

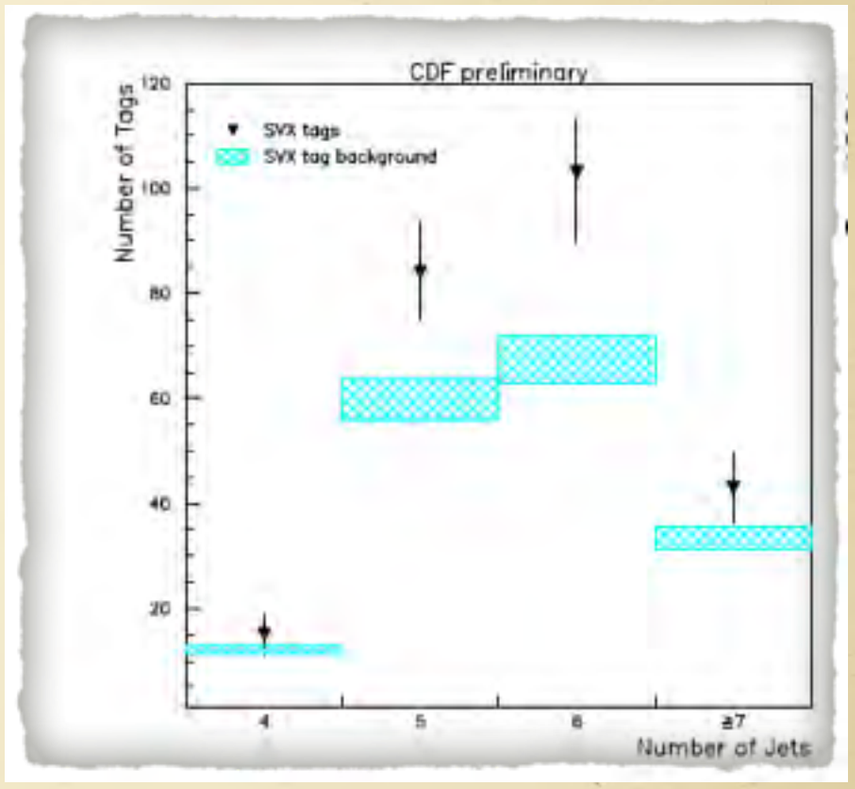
P. Azzi
(for the CDF Collaboration)
I.N.F.N. Padova, Via Marzolo 8, I-35131 PADOVA, Italy

Abstract

We present the measurement of $t\bar{t}$ production cross section using $\mathcal{L} = 110\ pb^{-1}$ data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.8\ TeV$ collected with the Collider Detector at Fermilab (CDF). Combining the results from the channels with at least one W decaying into leptons (e or μ) plus jets we measure $\sigma_{t\bar{t}} = 7.5^{+1.8}_{-1.5}\ pb$.

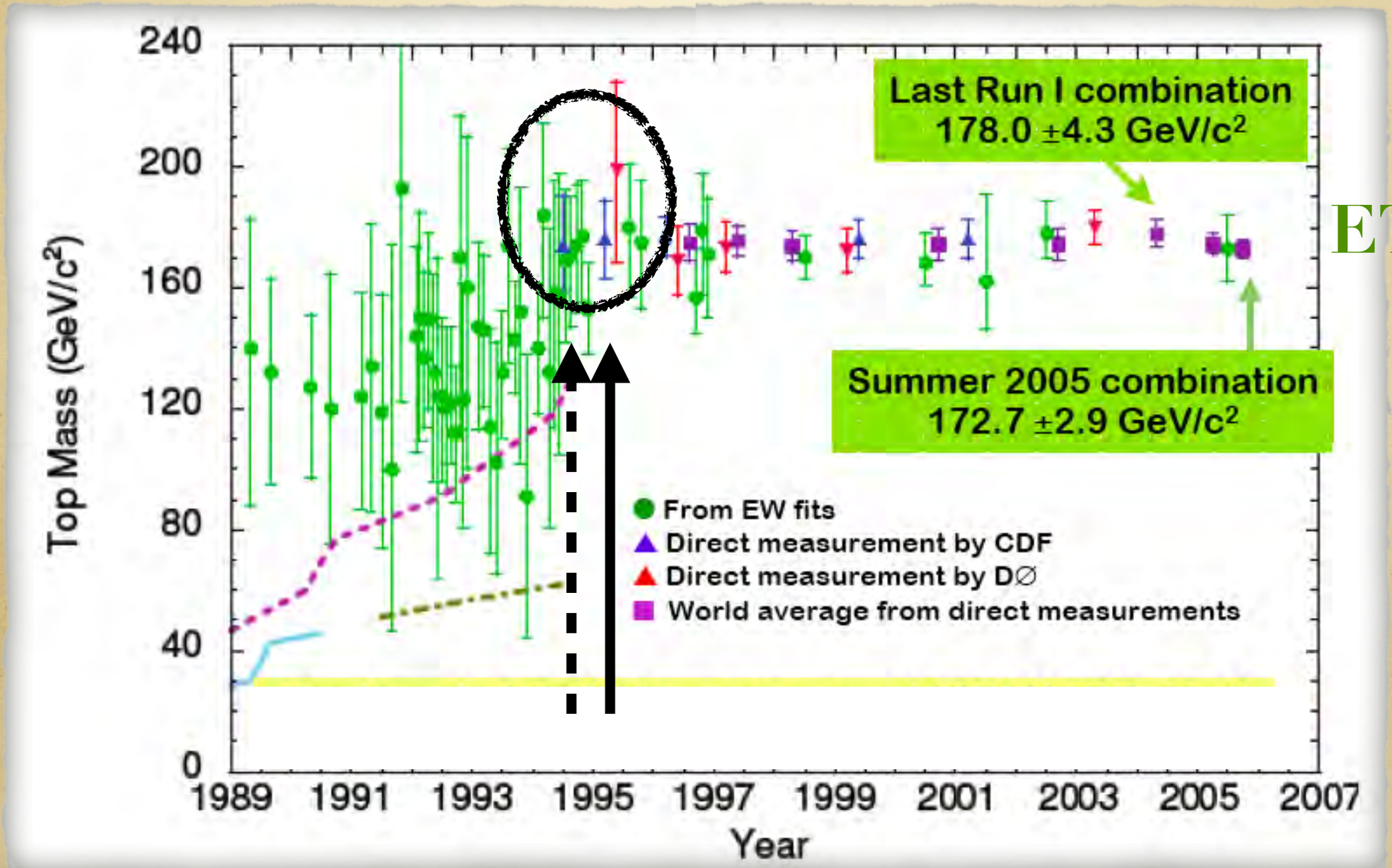
We report the observation of $t\bar{t}$ production in the all hadronic decay channel using a kinematical selection and b identification techniques.

Finally we show preliminary evidence for $t\bar{t}$ production in the decay mode with one e or μ in the final state and an hadronically decaying τ.



- Top hadronic channel not part of the first discovery paper, but final missing piece of the characterization of the properties of the new quark!

The road to the Top from the EWK fits (the other side of the pond)



ETC…

Taking the words from Boaz & Nick to their D0 team …

Boaz & Nick

You don't get to be part of a team which discovers a new elementary particle more than once!

Yeah, right…:-)

This was just a first step down memory lane…
more celebrations coming up at FNAL

« Top at Twenty », 9-10 Apr 2015,
Batavia, IL (United States)