Celebrating 20 years of the discovery of the Top quark

Patrizia Azzì - 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!!!
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…
The Main Actors

1992

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 $W \rightarrow tb$ with $t \rightarrow b\nu$

- Search strategies
  - Dilepton channel
    - $ee, e\mu$, and $\mu\mu$
  - L+jets channel
    - Added SLT tags

- Set limit $M_{Top} > 91$ GeV

- CDF had no silicon yet!

No D0 at the time!

![b vertex]

- Soft Lepton Tagging
- Identify semileptonic B decay
  - $b \rightarrow l$, $b \rightarrow c \rightarrow l$
- $\varepsilon(SLT) \sim 20\%$

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**
  \[ \sigma_{SM} = 7.35 \text{ pb} \]
  (for \( m_{Top} = 173.3 \text{ GeV} \))
  (arXiv:1303.6254)

- Dominant process at Tevatron: \( \sim 85\% \)
- Dominant process at LHC: \( \sim 15\% \)

At Tevatron: \( \sim 10 \text{ } \bar{t}t \) pairs/day (while at LHC: \( \sim 1 \text{ } \bar{t}t \) pairs/second)

Top Quark Decay

- b quarks are always present

Diagrams showing decay modes and signatures.
The SVX: the 1st silicon detector at a hadron collider

...from an idea by Aldo Menzione in 1981

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

- 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 !!!
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!

\[ E_T(electron) = 98.8 \pm 1.6 \text{ GeV} \]
\[ E_T(jet 1) = 24.9 \pm 4.3 \text{ GeV} \]
\[ E_T(jet 2) = 22.3 \pm 5.6 \text{ GeV} \]
\[ E_T(jet 3) = 6.7 \pm 3.6 \text{ GeV} \]
\[ E_T^{\text{miss}}(\text{total}) = 100.7 \text{ GeV} \]
\[ E_T^{\text{miss}}(\text{cal}) = 120.0 \text{ GeV} \]

\( \mu \) seems to have actually gone through a crack in the A layer
Reco used some nearby spurious A-layer hits \( \rightarrow p_\mu \sim 8 \text{ GeV/c} \)
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!!!
Combining all channels with 19 pb$^{-1}$

Prob bkg fluctuate up to observed = 0.26% (2.8$\sigma$)

Back then – we did not consider a Look Elsewhere Effect
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) $M_{\text{top}} = 174 \pm 10 \pm 13 \text{ GeV}$
(1995) $M_{\text{top}} = 176 \pm 8 \pm 10 \text{ GeV}$
(2005) $M_{\text{top}} = 172 \pm 3.7 \text{ GeV}$

World average, as of today:
$172.7 \pm 2.9 \text{ GeV}$

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

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

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

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 $tt^*$ 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 $tt^*$, constrained fitting on a subset of the events yields a mass of $174^{+13}_{-12}$ GeV/$c^2$ for the top quark. The $tt^*$ 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
After the CDF paper the competition reached a new level

New data were coming in!!!

analyses reorganized & reoptimized

**CHOICE OF CUTS FINALIZED A PRIORI!!!**

~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 unusual names: QCD, POT…

Still the discovery draft leaked even to CERN few days before…
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 sublety, I've put the paper and "final" tables in

PRJSGROOT227:[QCD_3.CUCKOO] PAPER_V0-5.PS
PRJSGROOT227:[QCD_3.CUCKOO] TABLE_T1.EPS
PRJSGROOT227:[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...
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 $P_T$ 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: $3.8 \pm 0.6$ events.

Significance: $4.6 \sigma$

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

Using 67 pb-1 (includes Evidence data) combined Prob = $1 \times 10^{-6}$ ($4.8\sigma$)

If include mass distribution
Prob = $3.7 \times 10^{-7}$ ($5.0\sigma$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>SVX</th>
<th>SLT</th>
<th>Dilepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>27 tags</td>
<td>23 tags</td>
<td>6 events</td>
</tr>
<tr>
<td>Exp. bkg</td>
<td>$6.7\pm2.1$</td>
<td>$15.4\pm2.0$</td>
<td>$1.3\pm0.3$</td>
</tr>
<tr>
<td>Probability</td>
<td>$2\times10^{-5}$</td>
<td>$6\times10^{-2}$</td>
<td>$3\times10^{-3}$</td>
</tr>
</tbody>
</table>
It’s official!

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

- Mar. 2, 1995, Thursday Public announcement of top quark discovery
Relative Likelihood Approach

After official announcement:

- $W+4\text{jets data}$
  - Vecbos MC

- $W+4\text{jets data}$
  + SVX btag
  - Vecbos MC

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

67pb$^{-1}$ (PRD52 (1995))
After official announcement: First observation of top decays the all hadronic channel at CDF in 1996

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)

- Last Run I combination: $178.0 \pm 4.3 \text{ GeV/c}^2$
- Summer 2005 combination: $172.7 \pm 2.9 \text{ GeV/c}^2$

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)