Reaching the Top

Pekka K. Sinervo
University of Toronto

1. What is Our World Made Of
2. Missing Pieces
3. How Do We Find Them?
4. The Search for Top
5. Some Novel Stuff
6. What's Next?

North Toronto High School
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Where We Stand....

Always been fascination with how the world is put together

- Greeks proposed four constituents
- Various natural scientists came up with theories

When I was an Ontario high school student....

- taught that atoms existed
  - consisted of a nucleus (protons & neutrons)
  - cloud of electrons
- atoms were put together to form molecules
  - VESPR theory
  - gave you all the chemistry you wanted

But Scientific American told me much more...

How It All Worked (circa 1980)

The Standard Model of Elementary Particle Physics

- Three "generations" of quarks and leptons

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

  Come in "pairs" because of the way forces acted on them

- Forces carried by bosons

Electromagnetic force	γ
Strong force	eight gluons
Weak force	$W^{\pm}, Z^{\circ}$ bosons
Gravity	gravitons

What's Missing

But not all the pieces of this puzzle are there

1. "Unification" of forces hasn't panned out
   - don't have a clue as to how to understand gravity
   - only have hints that forces are unified
2. Don't understand mass at all
   - Enter the "Higgs" boson.....
3. Missing the last quark

But the rest of it works extremely well!

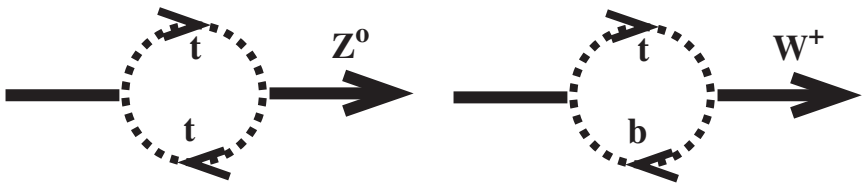
To learn more, have to "test" the theory

- $\Rightarrow$ search for the missing pieces

Why MUST the Top Quark Exist?

If top doesn't exist, the SM is in deep, deep trouble

- Masses of the $W^{\pm}$ and Z° bosons cannot be explained



  - Measurements of the Z boson require

$$M_{top} = 166^{+17+19}_{-19-22}\ \text{GeV/c}^2$$

- Behaviour of the bottom quark implies that it must have a partner

  - Weak force predicts asymmetry in $e^+e^- \rightarrow b\bar{b}$

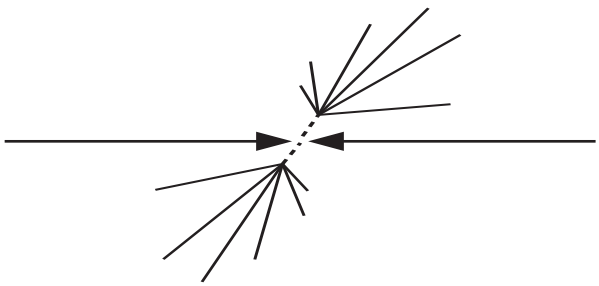
  - Not easy to modify SM to accomodate this

- b quark "mixing" could not occur

SM Top Quark Predictions

Should be produced in matter-antimatter collisions

- Searches at e^+e^- Colliders ruled out "light" top
  - data from LEP requires $M_{top} > 46$ GeV/c^2 at 95% CL
  - Independent of how top decays



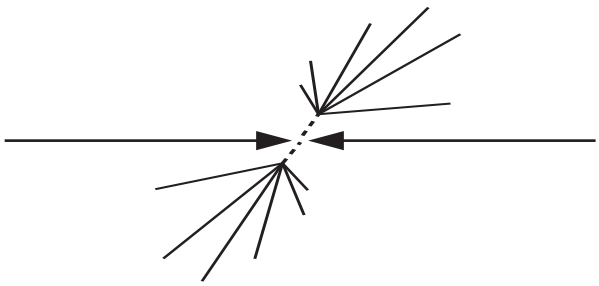
Searches at $p\bar{p}$ colliders at CERN and Fermilab

- searched for a "Standard Model" top
- $M_{top} > 131$ GeV/c^2 at 95% CL (D0 Collab).
  - makes it heavier than Silver atom

Searching for Top

A heavy quark can be pair-produced in collisions

- Require high collision energies
- Need tons of data (they are rare events)



$p\bar{p}$ Collider at Fermilab is the "only" choice

- High luminosities ($\mathcal{L} \sim 16 \times 10^{30}$ cm^{-2}s^{-1})
  - compare to radiation through this room $\mathcal{L} \sim 2 \times 10^{-2}$ cm^{-2}s^{-1})
- Highest energies ($\sqrt{s} = 1800$ GeV)

Why are Heavy Quarks Hard to Find

Hard to produce

- Must sift through lots of matter-antimatter collisions
- Happens about 1 in every billion collisions?

They Decay!

- A top quark decays via the weak force into a bottom quark
- The bottom quark then decays into lighter quarks

Ya can't see free quarks

- Quarks are "not allowed" to appear unescorted in public
- Have to "dress" themselves up around other quarks
- Result in "jets" of particles

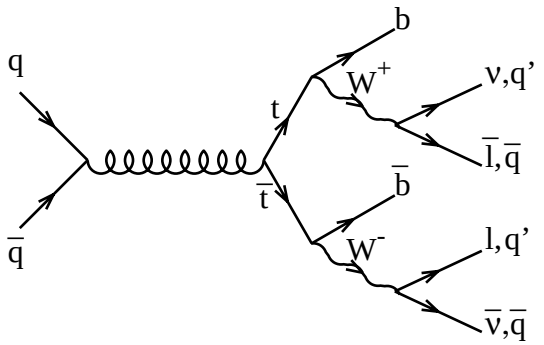
Top Quark Signatures

SM top quarks only decay via the weak force

$$t \rightarrow W^{+} b$$

$$\hookrightarrow u\bar{d} \text{ or } c\bar{s}$$

$$\hookrightarrow e^{+}\nu_e \text{ or } \mu^{+}\nu_\mu \text{ or } \tau^{+}\nu_\tau$$



This results in two, potential signatures

- Dilepton events with two, energetic $e^{\pm}$ and $\mu^{\mp}$
- Lepton + Jet events with at least one b quark

The CDF Experiment

CDF is detector designed to study $\overline{p}\,p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Large 5000 ton detector

Collaboration consists of

- 35 institutions from US, Japan, Italy, Canada and Taiwan
- 440 physicists

The Canadian IPP Group consists of

	McGill University	**University of Toronto**
Faculty	Ken Ragan	Pekka Sinervo
RA	Kurt Biery Klaus Strahl	Andreas Hölscher
Grad Students	Yunling Ye Kostas Kordas	George Sganos Andreas Warburton Hyunsoo Kim Wendy Taylor

1992-94 Collider Run

Took data at the Tevatron Collider starting in 1992

- scanned $\sim 5 \times 10^{12}$ collisions
- Collected 50×10^{6} events on tape

Most sensitive dataset acquired to date

- If top exists with a mass of 160 GeV/c^2
  - cross section of 8.2 pb $\Rightarrow$ 5000 produced $t\bar{t}$ events
  - expect to observe 5 dilepton events
  - expect to observe 10 lepton + jet events

Dilepton Top Quark Search

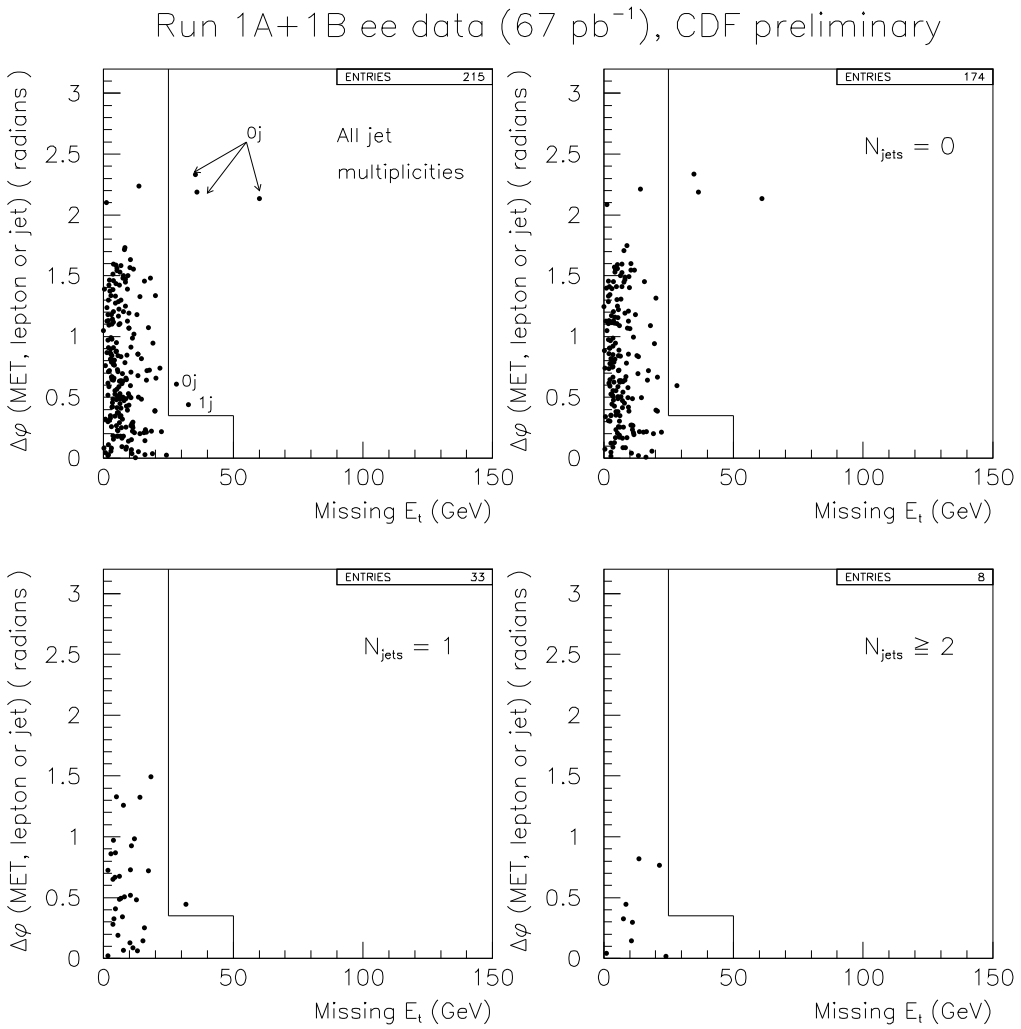
$t\bar{t}$ decaying into 2 leptons create unique signature

- Two charged leptons from $W^{\pm}$ decay
- Imbalance in total energy due to undetected neutrinos
- Two jets from bottom quarks

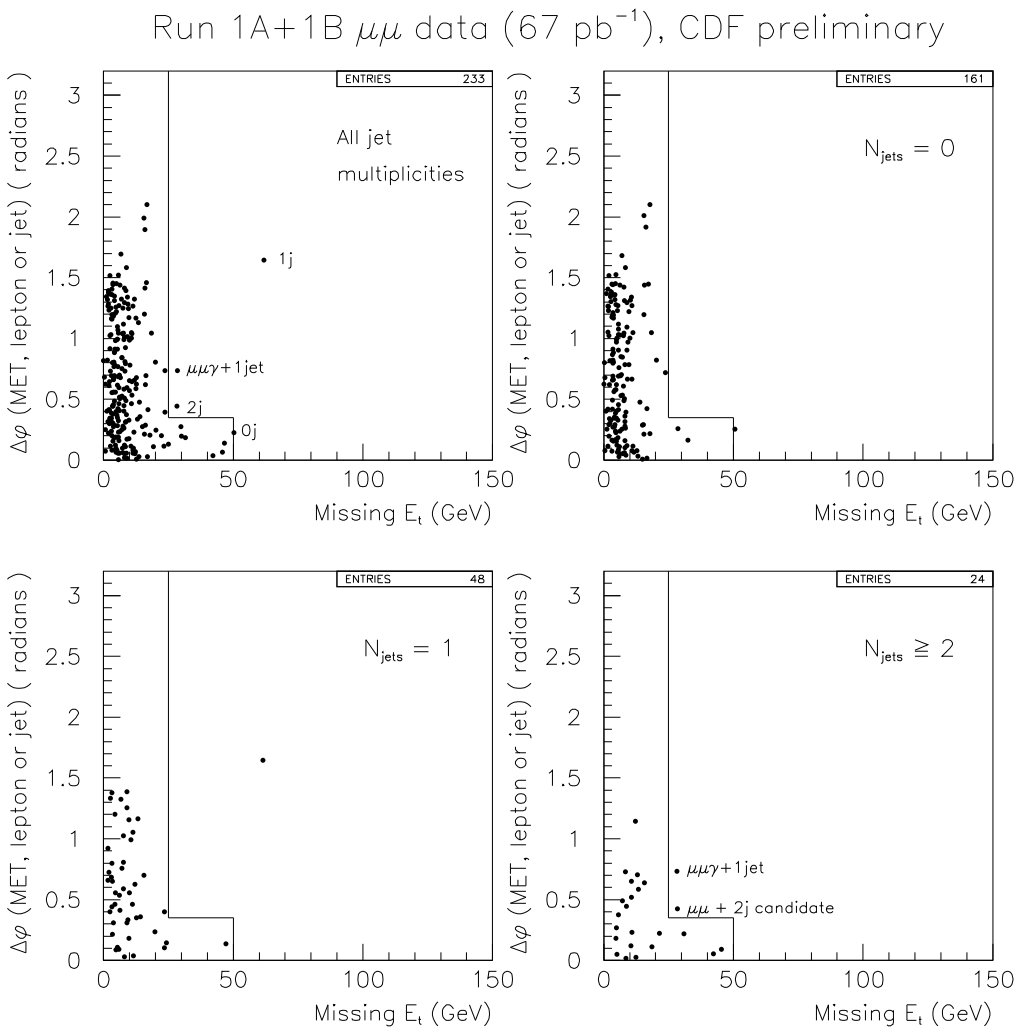
CDF performed a search requiring

- Two clean, high P_T lepton candidates
- Missing transverse energy $\not\!\!E_T > 25$ GeV
- Require two jets with $E_T >$ 10 GeV and $|\eta| < 2.0$
- Reject specific backgrounds (e.g. Z°)

Dielectron Data for Run 1A and 1B

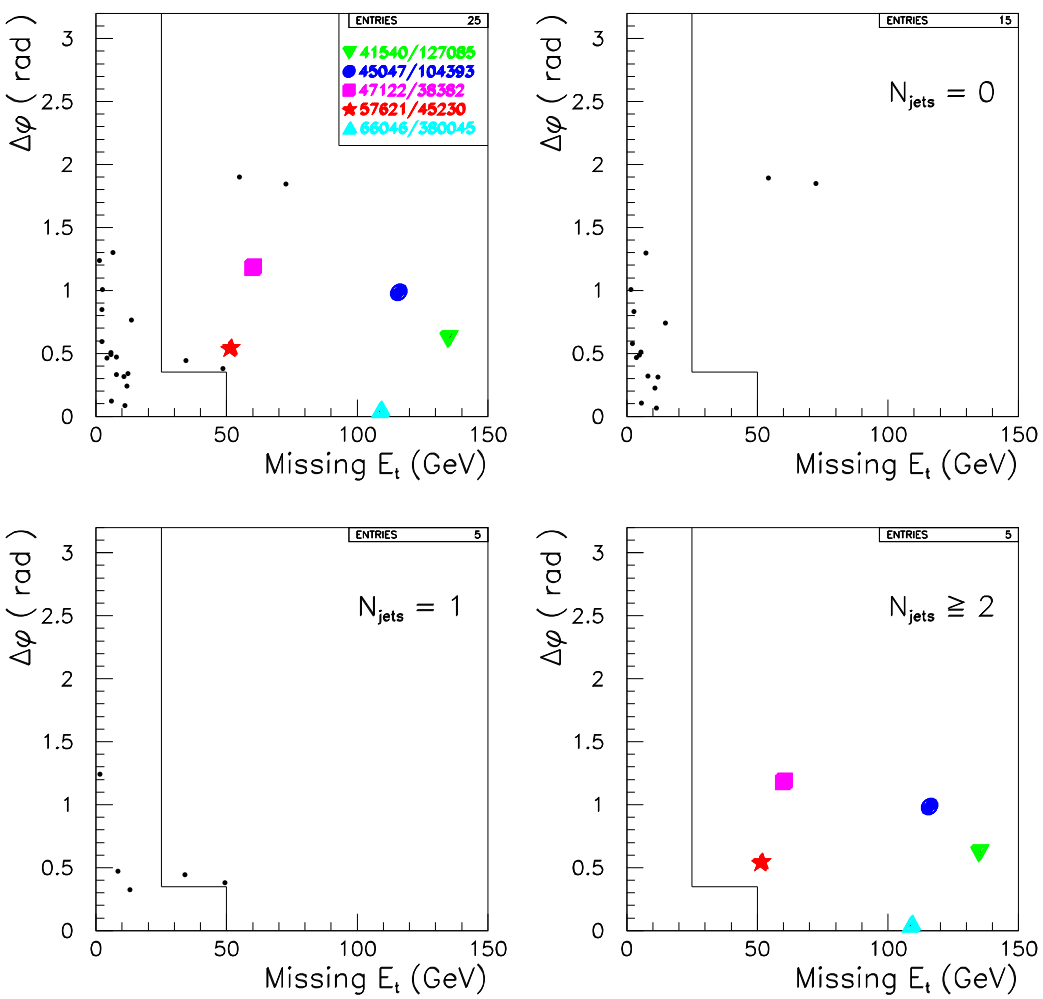


DiMuon Data for Run 1A and 1B



Electron-Muon Data for Run 1A and 1B

eμ data: Δφ (MET, lepton or jet) vs Missing E_t



Summary of Dilepton Search

Observe a total of 6 candidate events

- Observe 1 $\mu^+\mu^-$ event and 5 $e\mu$ events
- Expect 1.3 ± 0.3 events from background

Background	Expected Background Rate
$Z \to \tau^+\tau^-$	0.38 ± 0.07
One or both leptons fake	0.23 ± 0.15
$b\bar{b}$	0.03 ± 0.02
WW, WZ and ZZ	0.21 ± 0.07
Drell-Yan	0.44 ± 0.28
Total	1.3 ± 0.3

Probability of background fluctuation is 3.3×10^{-3}

Lepton + Jets Search Philosophy

Decay mode with the greatest sensitivity is "lepton+jets"

- About 30% of $t\bar{t}$ events decay this way
- Look for $W \to l\nu_l$ decay
- Require two jets from $W \to q\bar{q}$ decay
- Require at least one more jet from b quarks
  - must "tag" at least one b quark jet

Selection of W candidates straightforward

- Require high P_T isolated lepton candidate
- Require significant $\not\!\!E_T$
- Require three or more high P_T jets

Have now quadrupled our sample of $W+ \geq 3$ jet events

- Have 203 events before b tagging
- Expect ~ 30 to come from $t\bar{t}$ production

B Tagging Techniques

Use two properties of b quarks to identify them

1. About 20% of b's decay via

$$b \to e^- \nu_e X \quad \text{and} \quad b \to \mu^- \nu_\mu X$$

   - Look for jets with "soft" leptons in them
   - Call these soft-lepton tags (SLT's)
   - Expect 15% of $t\bar{t}$ events to have at least one SLT tag

2. "Long" b lifetime – $c\tau \sim 450$ microns

   - CDF uses Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 42% of $t\bar{t}$ events to have at least one SVX tag

Idea is to just "count" number of tagged events

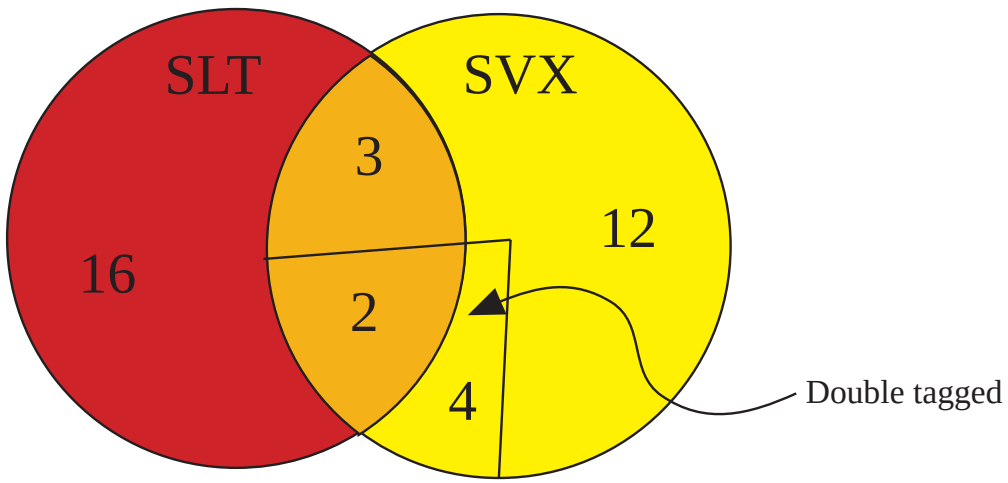
b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

- The $W + 1$ and $W + 2$ jet samples are control samples
  - Don't expect significant top contribution
  - Theory predicts low b hadron content

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+1 jet	50 ± 12	40	159 ± 25	163
W+2 jet	21 ± 7	34	46 ± 7	55
W+$\geq$ 3 jet	6.7 ± 2.1	27	15.4 ± 2.3	23

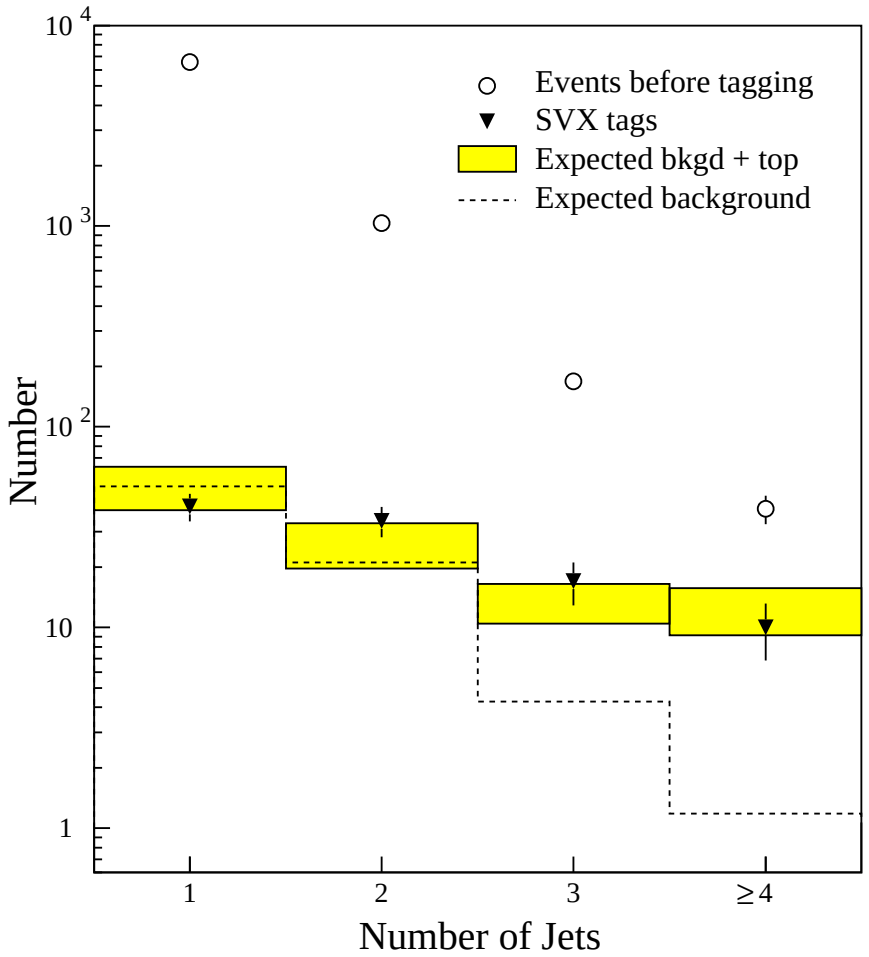
- Probability of background fluctuation is 1×10^{-6}
  - Combining SVX, SLT and DIL channels
- Agrees well with expected rate from $t\bar{t}$ production



SVX Tagging Results

The SVX tagged sample is single most significant observation

- Observe 27 tags when we expect 6.7 ± 2.1 background
- Probability of background fluctuation 2×10^{-5}



Measurement of Top Mass

We use event kinematics to estimate top quark mass

- Require events to have a fourth jet
  - Require $E_T >$ 8 and $|\eta| <$ 2.4 for 4rth jet
  - High efficiency ($\sim$ 85% for $t\bar{t}$)
- Combine all possible jet pairs to form $W \to q\bar{q}$
  - Choose one with best χ^2
  - Require $\chi^2 <$ 10
- Use b-tag information to identify b quark jet
- Fit events requiring kinematic constraints

This selection leaves us with 19 tagged events

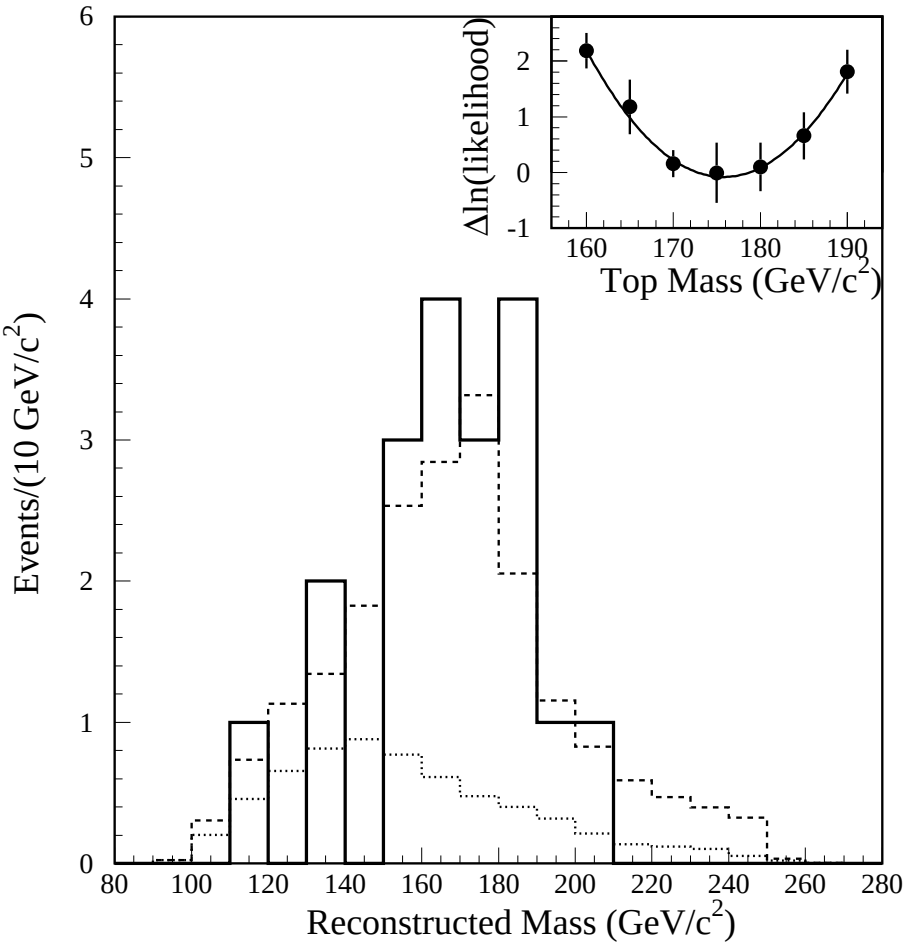
- Estimate background to be $6.9^{+2.5}_{-1.9}$ events
  - Primarily QCD W+jet

Procedure is dependent on theory predictions

Result of Mass Fits

The fitted mass for the 19 events is consistent with $t\bar{t}$

- Probability that background would fluctuate to give peak with similar significance is $< 2 \times 10^{-2}$



$$M_{top} = 176 \pm 8 \pm 10 \quad \text{GeV/c}^2$$

So Is This a Top Discovery?

You bet!

- probability of "being wrong" extremely low

Checked the data in lots of ways

- Everything points to the same conclusion
- Another experiment has also looked and agree with us

What Next?

Continuing to take data and get a larger sample of top quarks

- measure its properties
  - mass
  - how it decays
  - how it gets produced
- All provide additional tests of the Standard Model

Will this lead to a "better mousetrap?"

- No, but that's not what we're all about
- Important to understand how our world works
  - But for those who don't like this answer....
  - the following resulted from "basic research"
    1. nuclear medicine (and warfare...sigh)
    2. the transistor
    3. gene research
    4. antibiotic drugs

Conclusions

We have now seen evidence for the sixth type of matter

- the Top Quark does live (sometimes, at least)
- the "Standard Model" still works

Best estimate of top quark mass is

$$M_{top} = 176 \pm 9 \pm 10 \quad \text{GeV/c}^2$$

So now there is only one missing piece – Higgs Boson

- Quest for that is now beginning
- Building a new proton-proton collider in Geneva
  - Large Hadron Collider
  - 7 times more energetic than Fermilab Tevatron
  - 100 times higher collision rate
  - experimental teams have over 1000 scientists
- But don't hold your breath
  - Turn-on scheduled for 2003!