What is Our World Made Of?

or

Searching for Quarks

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1. How We Understand Our World
2. The Building Blocks
3. The Forces
4. Searching for the Missing Pieces
5. What's Next?

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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!

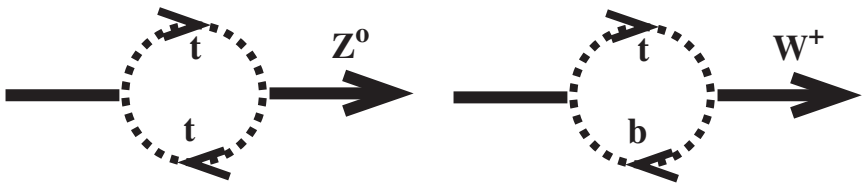
I'm going to focus on the most recent work

- search for the top quark

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 $e^+e^- \rightarrow b\bar{b}$

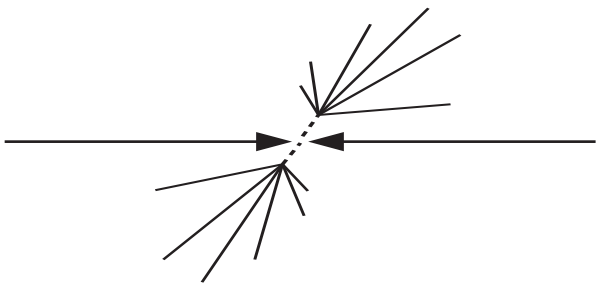
  - Not easy to modify SM to accomodate this

- b quark "mixing" could not occur

SM Top Quark Predictions

Searches at e^+e^- Colliders have ruled out "light" top

- data from LEP requires $M_{top} > 46$ GeV/c^2 at 95% CL
- Independent of how top decays



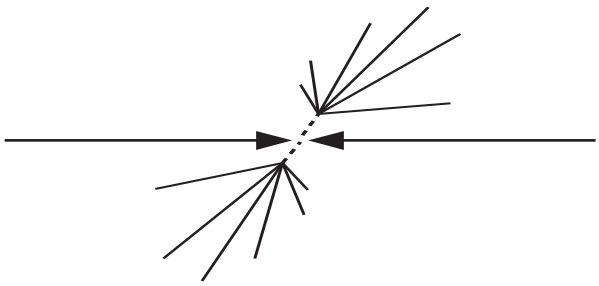
Searches at $p\bar{p}$ colliders at CERN and Fermilab

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

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})
- 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

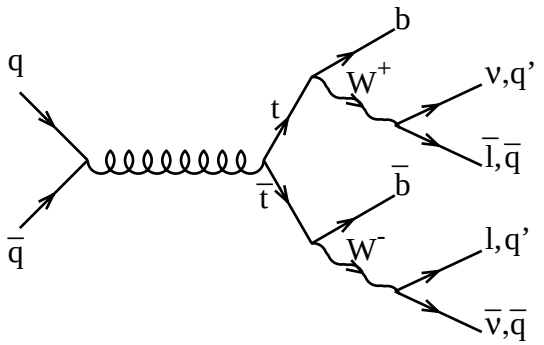
Top Quark Signatures

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

1992-93 Collider Run

Took data at the Tevatron Collider in 1992-93

- scanned $\sim 1 \times 10^{12}$ collisions
- Collected 16×10^{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 $\Rightarrow$ 160 produced $t\bar{t}$ events
  - expect to observe 1.3 dilepton events
  - expect to observe 3.5 lepton + jet events

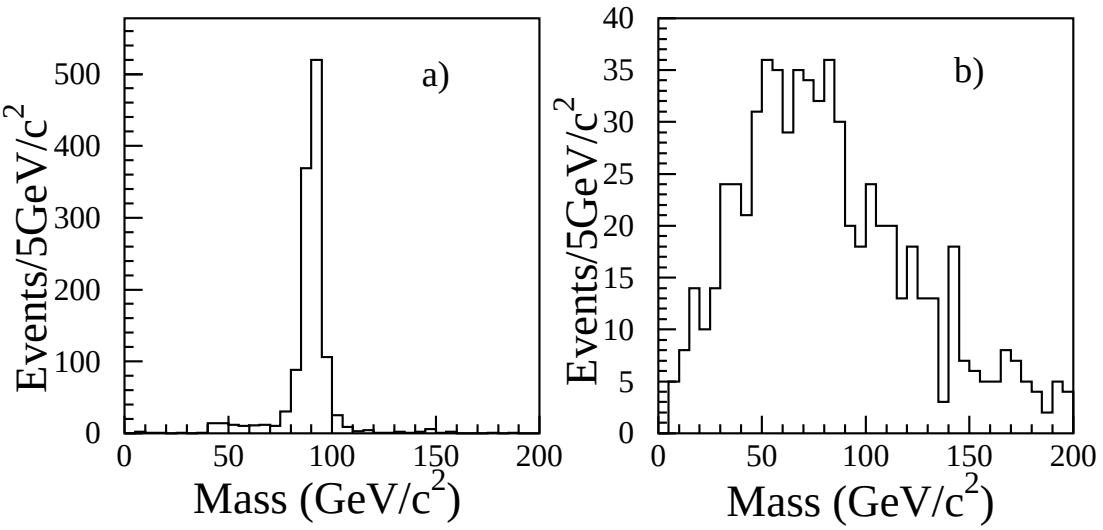
Dilepton Top Quark Search

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

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

Performed a search requiring

- Two "clean" lepton candidates with $P_T > 20$ GeV/c
- Missing transverse energy $\not\!\!E_T > 25$ GeV
- Require two jets with $E_T >$ 15 GeV and $|\eta| < 2.0$
- Reject specific backgrounds (e.g. Z°)



Backgrounds in Dilepton Channel

Have measured the rate of events from non-top sources

- Have used data to measure these rates
- Cross-checked using $Z^{\circ} \to e^{+}e^{-}$ and $Z^{\circ} \to \mu^{+}\mu^{-}$
- Consistent with theoretical calculations

Background	**eμ**	**ee, $\mu\mu$**
$Z \to \tau^{+}\tau^{-}$	0.07 ± 0.02	0.06 ± 0.02
One or both leptons fake	0.03 ± 0.03	0.04 ± 0.03
$b\bar{b}$	0.04 ± 0.03	0.05 ± 0.03
WW, WZ and ZZ	0.10 ± 0.04	0.06 ± 0.02
Drell-Yan		$0.10^{+0.23}_{-0.08}$
Total	0.24 ± 0.06	$0.31^{+0.24}_{-0.10}$

Expect $0.56^{+0.25}_{-0.13}$ background events

Observe **two** events in sample

- Both events have electron and muon candidates
- One has signature of b quark jet

Background sources are small

- Drell-Yan production $\Rightarrow$ 0.20 events
- WW, WZ production $\Rightarrow$ 0.16 events
- Total backgrounds are $0.56^{+0.25}_{-0.13}$ events

On the other hand, rate from top depends on top mass

M_{top} (GeV/c^2)	Number of events
120	3.7
140	2.2
160	1.3
180	0.7

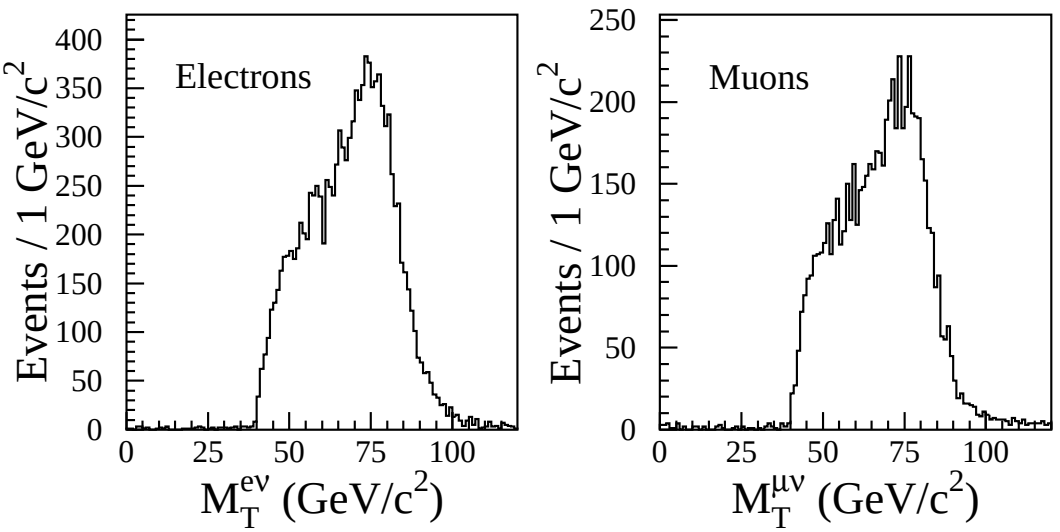
Probability 0.56 events fluctuates to ≥ 2 events is 12%

$\Rightarrow$ Not statistically significant

Lepton + Jets + B Tag Search

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

- About 30% of $t\bar{t}$ events decay this way
- Look for one high P_T lepton
- Require $\not\!\!E_T >$ 25 GeV
- Have 11,900 $e\nu_e$ and 7,000 $\mu\nu_\mu$ candidates



W + Jet Sample

Require 3 or more jets (from other W & b quarks)

- $E_T > 15$ GeV and $|\eta| < 2.0$
- Find 52 events with these criteria

We have estimated various background sources:

Background	Number of Events
Fake leptons and $b\bar{b}$	5.2 ± 2.6
WW, WZ and ZZ	2.6 ± 1.2
$Z \rightarrow \tau\tau$, ee, $\mu\mu$	4.4 ± 0.9
Total	12.2 ± 3.1

Would expect from $t\bar{t}$ and QCD W+jets

M_{top} (GeV/c^2)	Number of Events
120	39 ± 6
140	22 ± 3
160	12 ± 2
180	6.6 ± 0.7
W+jets	50^{+16}_{-8}

The W+jets remain single largest background

B Tagging Techniques

We use two properties of b quarks to identify them

1. "Long" b lifetime – $c\tau \sim 450$ microns
   - Use the Silicon Vertex Detector to identify jets with a secondary vertex
   - We call these "SVX" tags
   - Expect 20% of $t\bar{t}$ events to have at least one SVX tag

2. About 20% of b's decay via

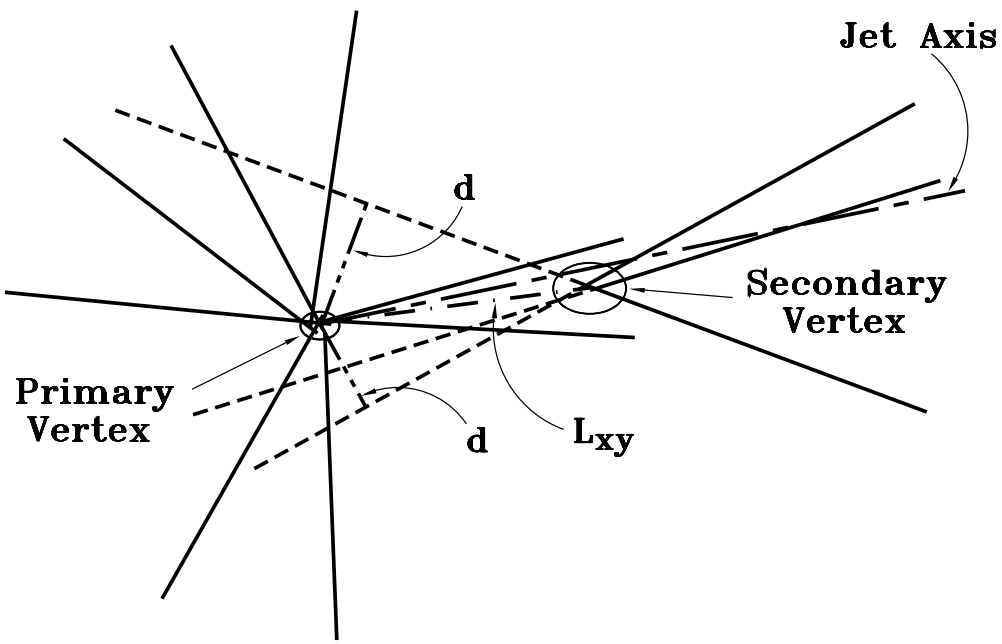
$$b \rightarrow e^{-}\nu_e X \quad \text{and} \quad b \rightarrow \mu^{-}\nu_\mu X$$

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

SVX B Tags

SVX tag requirements are

- at least 2 tracks with impact parameter $d > 3\sigma$
- track $P_T > 2$ GeV/c
- the tracks are consistent with coming from a common vertex



Used control samples to measure the tagging efficiency and fake rate

- inclusive electrons enriched in $b \to e^{+} \nu_e X$ decays
- $B \to J/\psi X, \quad J/\psi K^{\pm}, \quad J/\psi K^{*}$ decays
- "generic" jet sample

Soft Lepton Tagging

Identify muon or electron from b hadron decay

- Require lepton $P_T > 2$ GeV/c
- Require electron to satisfy standard cuts
  - Use dEdx measurement in CTC to reject pions
  - Require muon candidate to have good quality muon stub

Studied SLT tagging using

- photon conversions for electrons ($\gamma \rightarrow e^+e^-$)
- $J/\psi \rightarrow \mu^+\mu^-$ decays
- generic jets to obtain fake rates

Measured efficiency and fake rates

- Efficiency is 0.152 ± 0.023 for $M_{top} = 160$ GeV/c^2
- "Fake" tagging rate is $\sim 0.005 - 0.010$ tags/track

b Quark Tagging in W+Jet Events

Applied these tagging techniques to W+jet events

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

Sample	SVX bkg	SVX tags	SLT bkg	SLT tags
W+1 jet	15.8 ± 2.1	8	34.1 ± 3.3	33
W+2 jet	6.3 ± 0.8	8	9.9 ± 1.0	12
W+$\geq$ 3 jet	2.30 ± 0.29	6	3.1 ± 0.3	7

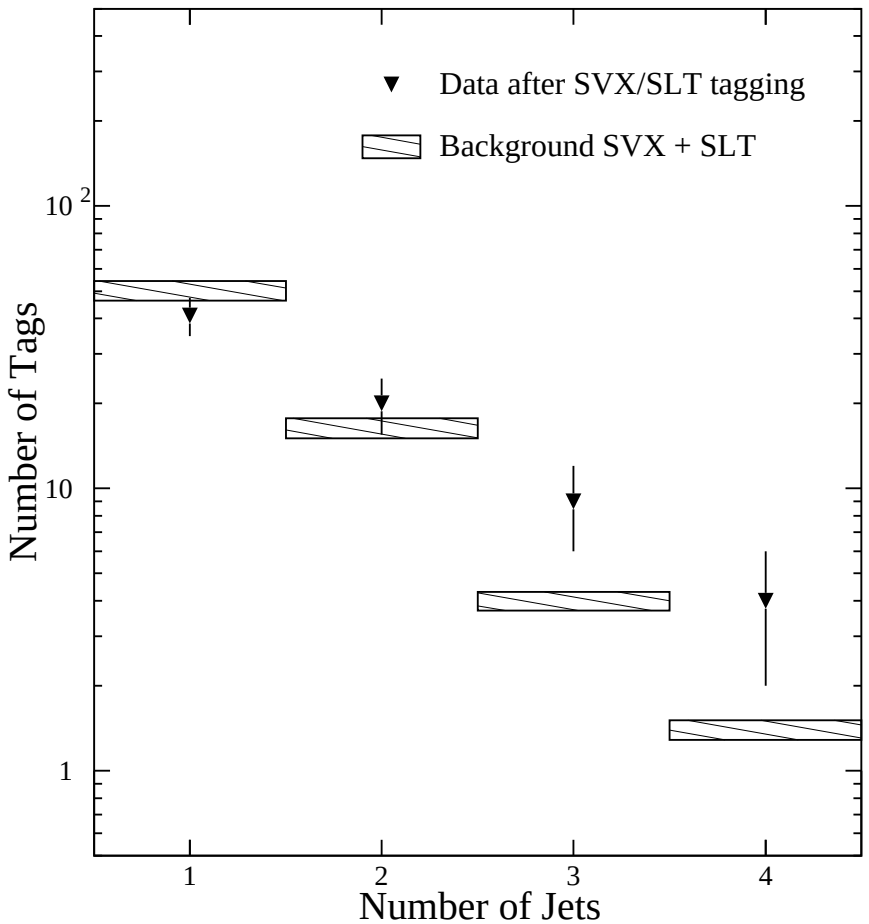
Observe 13 tags in 10 events

- 3 events that are double-tagged
- Expected to see 5.4 ± 0.4 background events

Summary of Jet Counting Experiment

We combine the SLT and SVX tagged data

- Compare with background estimates
- Observe 13 tags when we expect 5.4 ± 0.4 background



Features of Tagged Samples

Find that 3 events are "double tagged"

- 2 of these 3 have 2 different jets tagged
- Probability of 2 fake tags is very low
- Expect only 1.3 double-tagged events from background

One dilepton event has jet tagged as an SLT and SVX

- Expect only 0.13 events from purely background
- Expect 0.7 double tags if both events are $t\bar{t}$

Statistical Significance

Observe 12 events in total

- 2 dilepton events when we expect $0.56^{+0.25}_{-0.13}$
- 13 tags when we expect 5.4 ± 0.4
- 3 double-tagged events

Evaluated the probability of this assuming no top

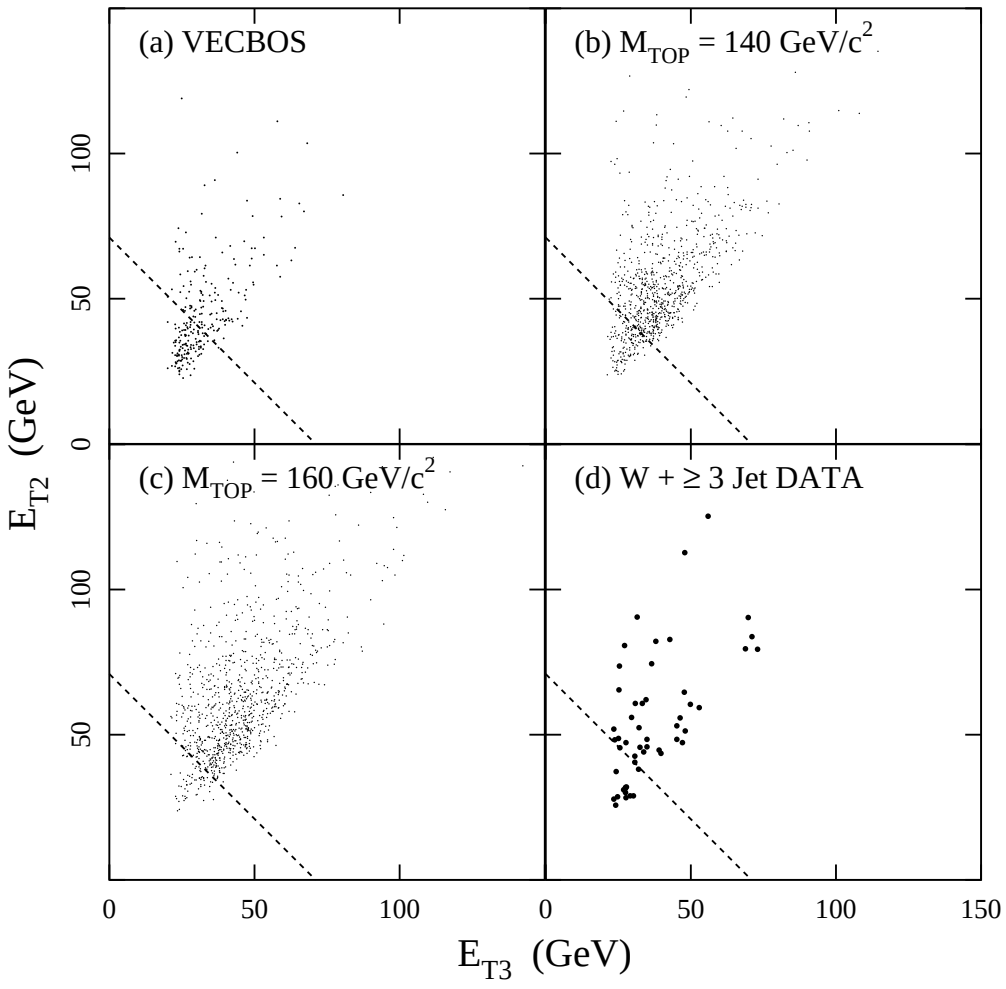
- Estimate the number of tags from the background sources
- Simulate our experiment assuming no top
- Count how often we would see at least the number of tags

Sample	Probability
6 SVX tags	0.032
7 SLT tags	0.038
13 tags + 2 Dilepton events	0.0026

Kinematic Features of Events

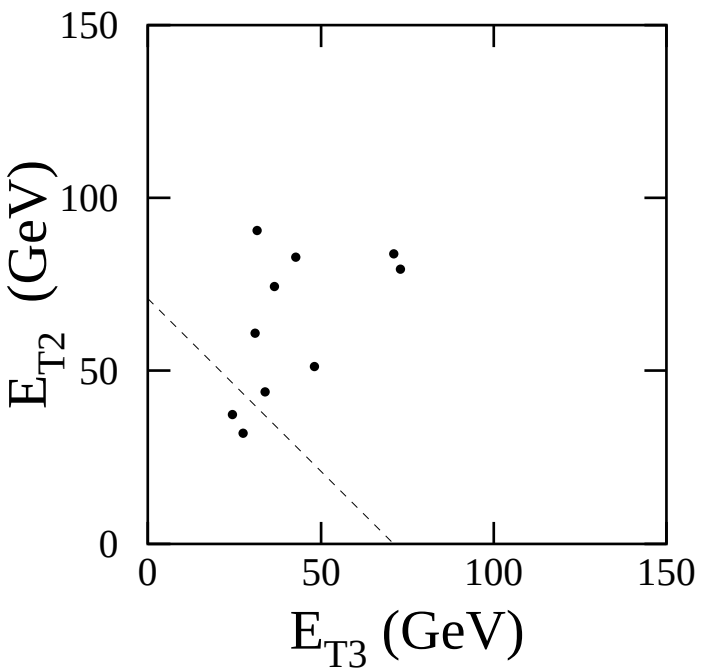
Examined the kinematics of these events

- Are there other features of data that indicate top?
- Good example are energies of second and third jet
- Need to trust MC calculations for W+jet and $t\bar{t}$ production



Kinematics suggest that of the 52 $W+ \geq 3$ jet events

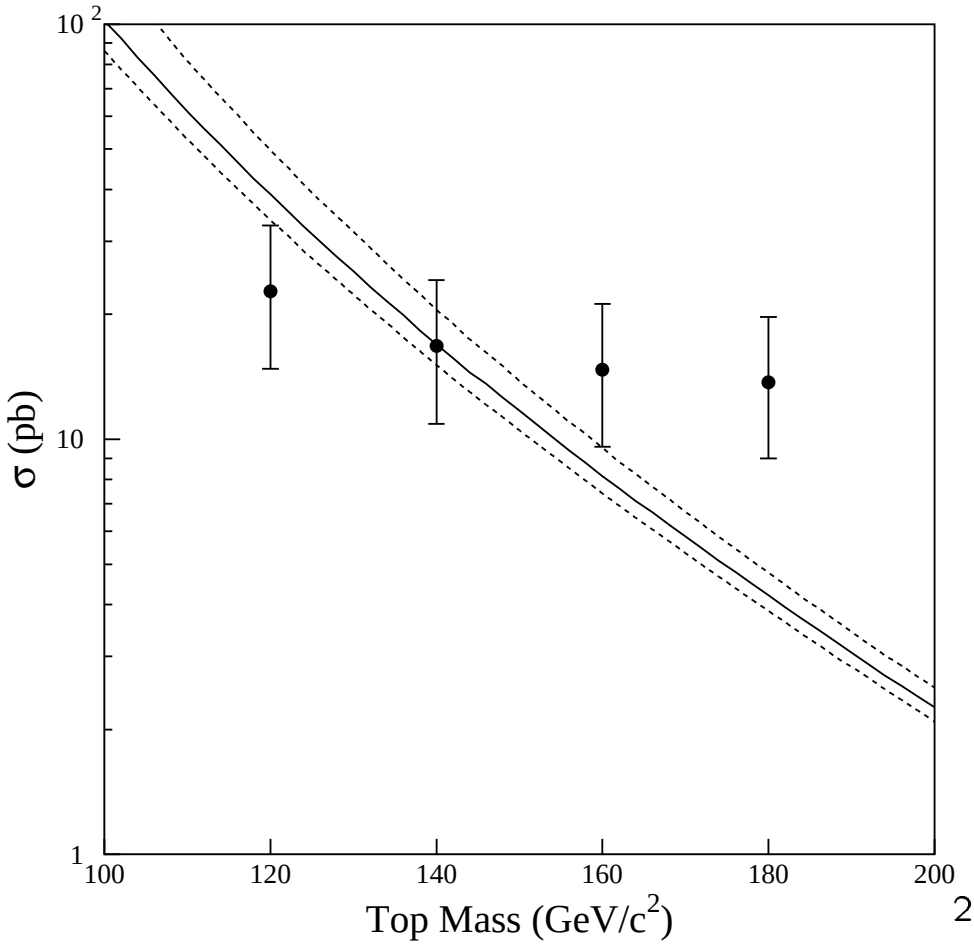
- $\sim$ 20 events from $t\bar{t}$ production
- remainder mostly QCD $W+$ jets
- Confirmed by looking at E_{T2} versus E_{T3} for tagged sample



Cross Section for Top Production

Can use our data to estimate top quark cross section

- Subtract the expected backgrounds
  - 1.6 ± 0.7 and 1.5 ± 0.7 SVX and SLT background tags
- Perform a maximum likelihood fit to estimate $\sigma_{t\bar{t}}$



Measurement of Top Mass

We can use event kinematics to estimate top quark mass

- Require events to have a fourth jet
- Combine all possible jet pairs to form $W \rightarrow q\bar{q}$
- Use b-tag information to identify b quark jet
- Fit events requiring kinematic constraints

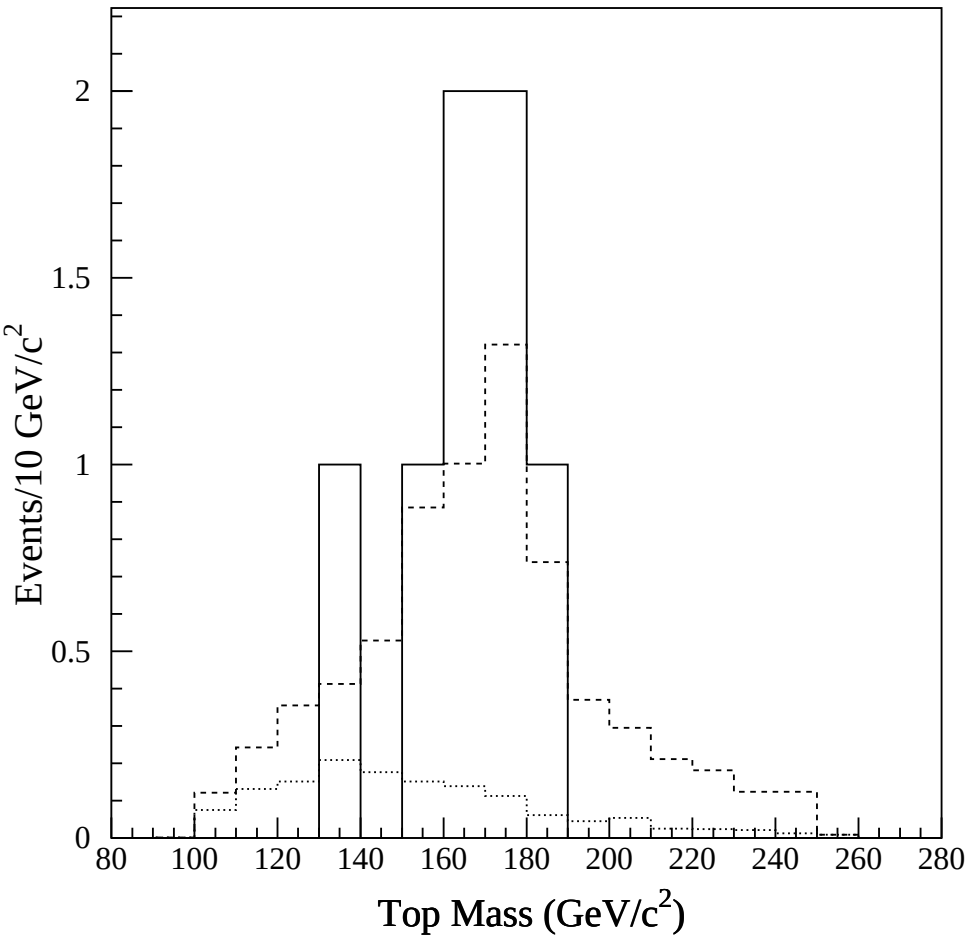
This selection leaves us with 7 tagged events

- Estimate background to be $1.4^{+2.0}_{-1.1}$ events
  - Primarily QCD W+jet

Procedure is dependent on theory predictions

Result of Mass Fits

The fitted mass for the 7 events is consistent with $t\bar{t}$

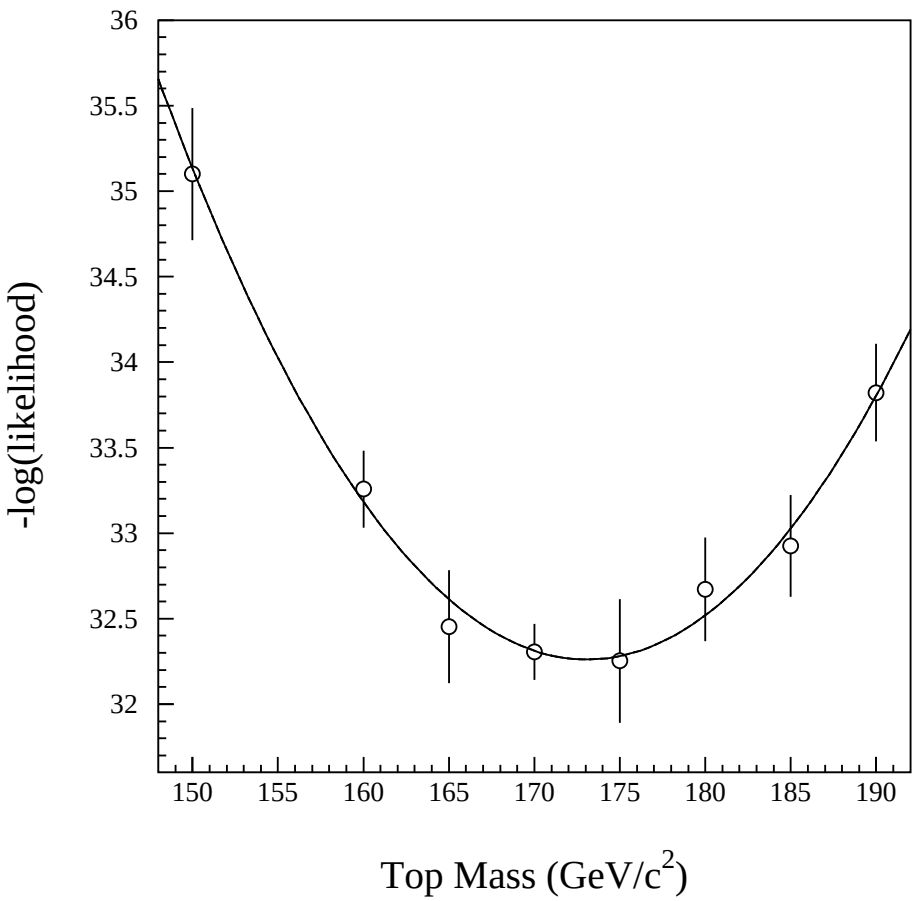


Fit the mass distribution to obtain

$$M_{top} = 174 \pm 10^{+13}_{-12} \quad \text{GeV/c}^2$$

Systematic error is dominated by uncertainties in

- Gluon radiation in $t\bar{t}$ production (4.4 GeV/c^2)
- Different background shapes ($\sim$ 5 GeV/c^2)



Are There Other Hypotheses?

We have considered a number of alternative hypothese

1. Are we seeing a b'?
   - Cross section would be too large
2. Are we seeing the Higgs boson?
   - Only expect to see ~ 0.2 events at best
3. Could be something VERY exotic (eg. H^+)
   - Will simply need more data

"Best" interpretation is that we are seeing SM top

So Is This a Top Discovery?

Statistically marginal signal

- probability of background fluctuation 0.26%
- Really would like to have $\times 2$ more data

Two consistency checks raise some concerns

1. Predicted rate of QCD W+4 jet events too large

Process	Observed Events
Predicted QCD W+4 jet rate	$8 \pm 3^{+6}_{-2}$
Estimated rate from $t\bar{t}$	$11.6^{+5.6}_{-4.5}$
Observed W+4 jet rate	9

2. Observe an apparent excess of $Z + 4$ jet events
   - Observe 3 Z° + 3 jet events and 2 Z° + 4 jet events
   - Both Z° + 4 jet events have b tags!
     - Expect 0.64 ± 0.06 background tags

Both observations are statistics-limited

- Cannot rule out statistical fluctuation
- But cannot rationalise these two observations away either

But More Data is Coming!

Tevatron began colliding in January 1994

- Run Ib will continue through end of 1995
- Maximum luminosity now 1.5×10^{31} cm^{-2}s^{-1}
- Goal is for CDF/D0 to collect ~ 100 pb^{-1}

This will allow us to confirm the "top" signal

- After ~ 25 pb^{-1} have a new $e^{-}\mu^{+}$ event
- Are working on repeating Run 1a analysis
- Hope to have preliminary results by spring 1995

Conclusions

We have now seen evidence for the sixth type of matter

- 2 Dilepton events
- 13 W+jet events with b quark tags

Best estimate of top quark mass is

$$M_{top} = 174 \pm 10^{+13}_{-12} \quad \text{GeV/c}^2$$

But there are still caveats

- Statistical significance needs to be improved
- Need more data

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!