The discovery of the top quark at the Tevatron by CDF and D0

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Disclaimer

Like Thomas, I was on CDF

This is going to be a little bit CDF-centric

The "race for the top" at the Tevatron almost ended before it had a chance to get started…..

news **search & discovery**

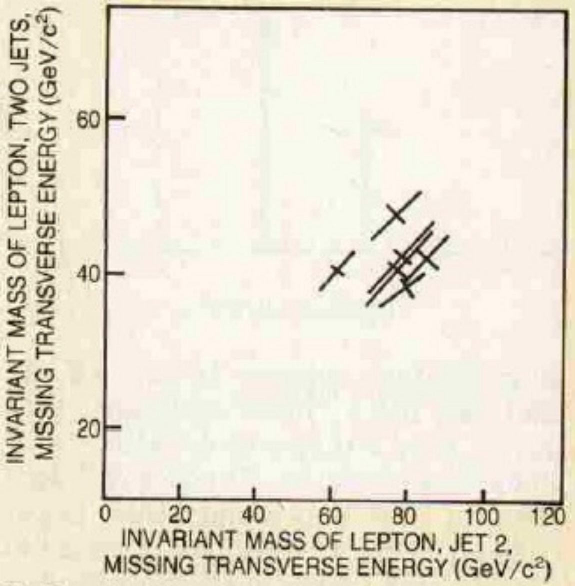
UA1 at CERN says it has candidates for sixth quark, top

Early in July the UA1 detector group working at the CERN proton–antiproton collider announced that they have found six candidate events suggesting the top quark. According to the standard model, quark flavors come in pairs—up and down, strange and charmed, bottom and top. The fifth quark, the bottom b, whose mass is about 5.2 GeV, was needed to explain the upsilon meson, found in 1977. But the missing sixth quark could not be found. If the mass of the top t had been less than 22 GeV, experiments at PETRA (at the DESY laboratory in Hamburg) with 22-GeV electrons colliding with 22-GeV positrons would have produced t and $\bar{t}$ from the 44-GeV center-of-mass energy available.

The UA1 candidate events indicate the top quark mass is somewhere in the range 30–50 GeV (and is essentially the same for the free top quark, not obser-

the t then decayed semileptonically into a positively charged lepton, a neutrino and a b quark. Similarly, there were some indications that a W^- was decaying into $\bar{t}b$ and then that $\bar{t}$ decayed into a negatively charged lepton, a neutrino and a $\bar{b}$ quark. The heart of the problem was to establish the identity of the lepton above background processes. When the electron channel was examined, five candidate events were found; then the muon channel was analyzed. UA1 reported on their top evidence at two June meetings, first a conference in Lund, then the Neutrinos '84 conference in Dortmund, each time making a somewhat stronger claim.

At a CERN seminar on 3 July, Michel Della Negra (CERN and Annecy) of the UA1 group presented six candidate events indicating the top



Evidence for top quark from UA1 group assumes the W decays into $t\bar{b}$, that the $\bar{b}$ produces jet 1, and that t decays into a lepton, a neutrino and a b, which decays into jet 2. The peak at 70–80 GeV suggests W decay and the peak at 40–45 GeV suggests

Meanwhile, at Fermilab…

Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

May 25, 1984

1. CDF has run out of money.

Meanwhile at Fermilab…

Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

May 25, 1984

1. CDF has run out of money.

Not to worry though….six months later…

Fermilab

MINUTES OF THE COLLIDER DETECTOR MEETING

November 9, 1984

1. There will be a workshop to discuss upgrades to the CDF detector in early January.

Many things were very different back then…

Fermilab

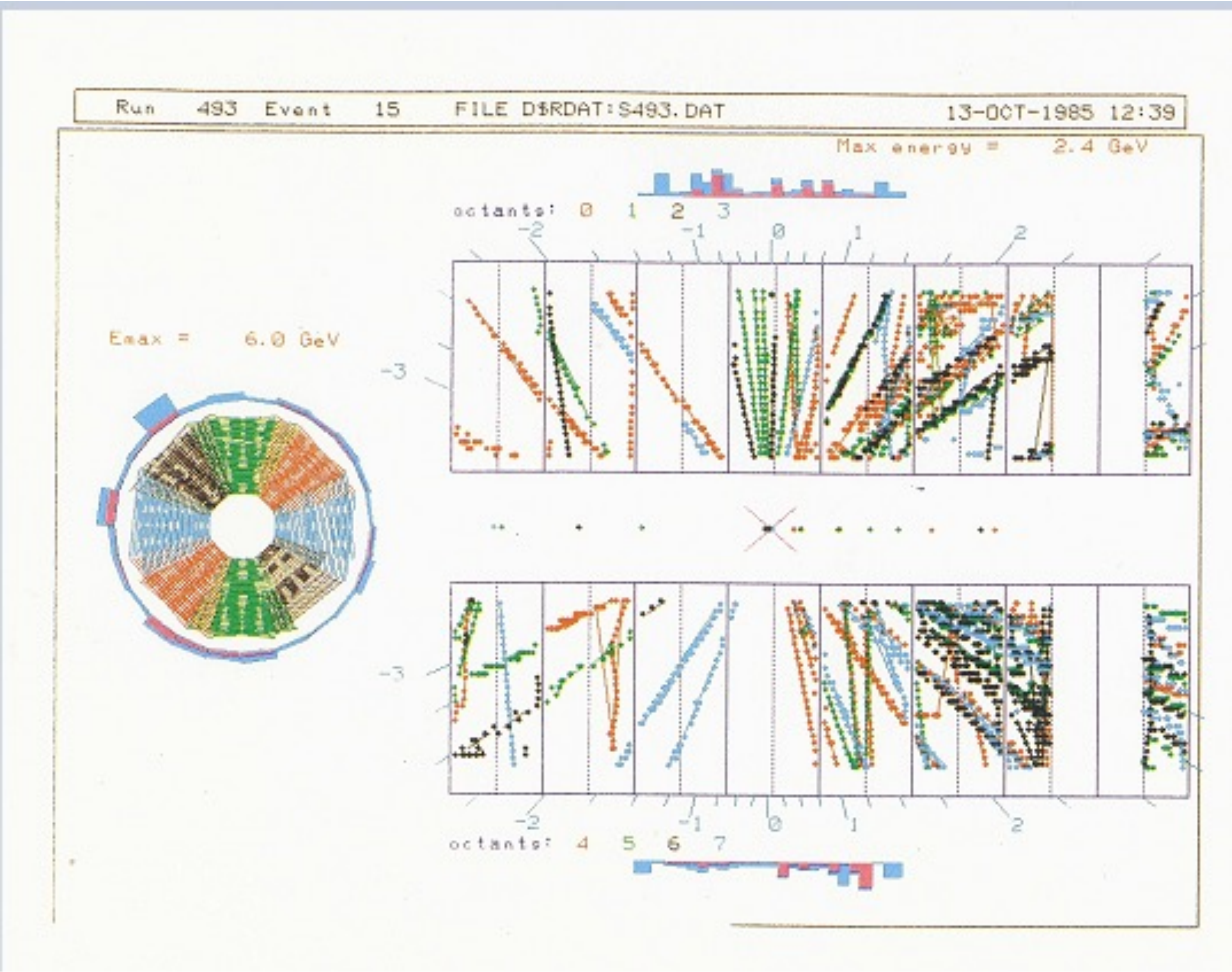
MINUTES OF THE COLLIDER DETECTOR MEETING

December 7, 1984

1. While in BO people should watch out for falling objects. More formal safety procedures are under consideration.

Tevatron experiments timeline towards top discovery

- October 1985, a few CDF collisions
  - First PhD thesis, Teruki Kamon



Tevatron experiments timeline towards top discovery

- October 1985, a few CDF collisions
  - First PhD thesis
- Run -1, 1987, CDF 25 nb^{-1}
  - 22 W→eν events
  - Tevatron enters the hadron collider game

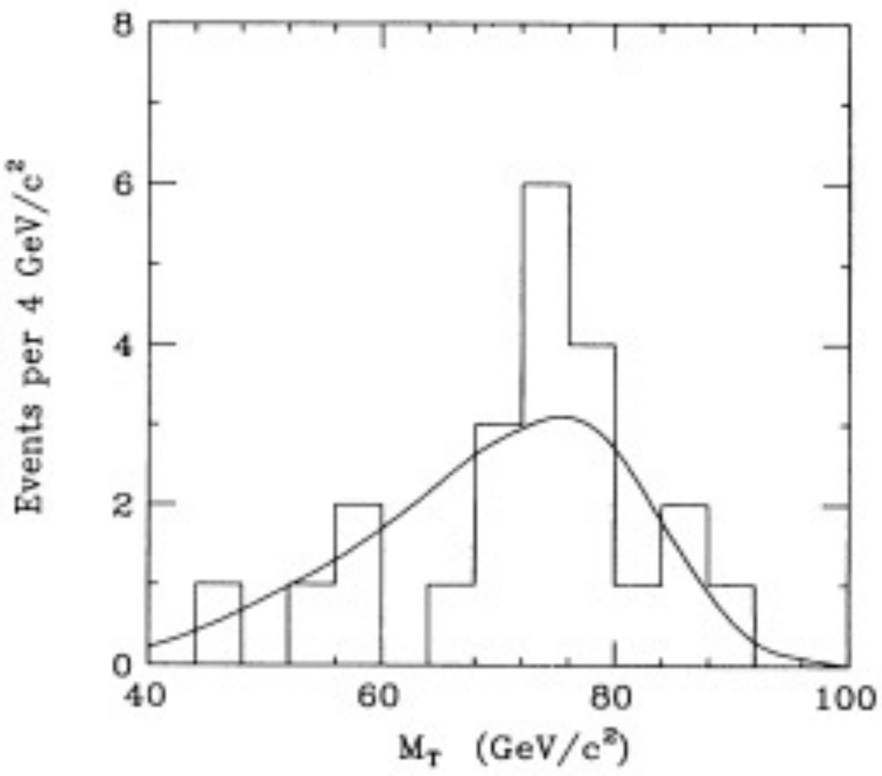


FIG. 2. The distribution in transverse mass for the *W* candidate events. The curve is an ISAJET (Ref. 10) prediction for a *W* mass of 80 GeV/c^2.

Tevatron experiments timeline towards top discovery

- October 1985, a few CDF collisions
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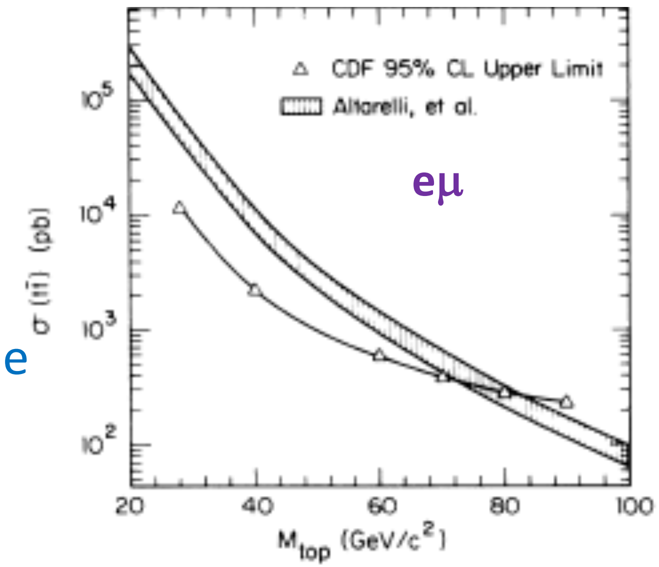
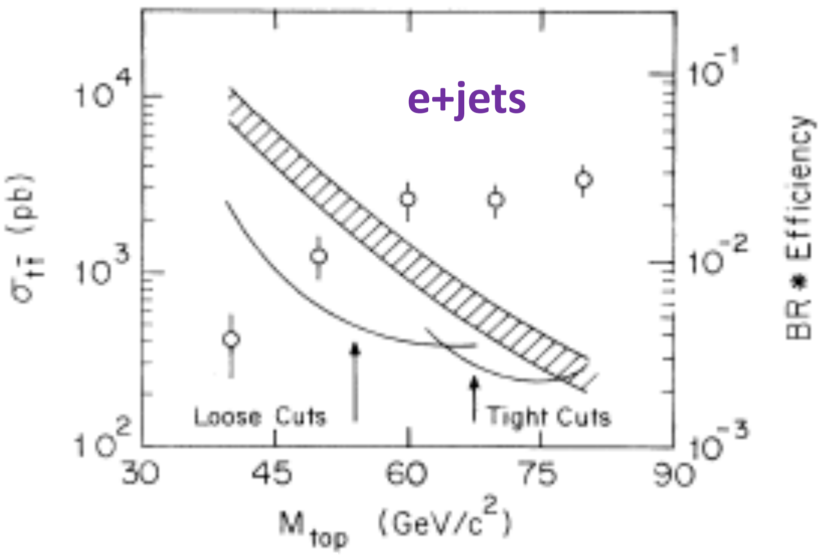
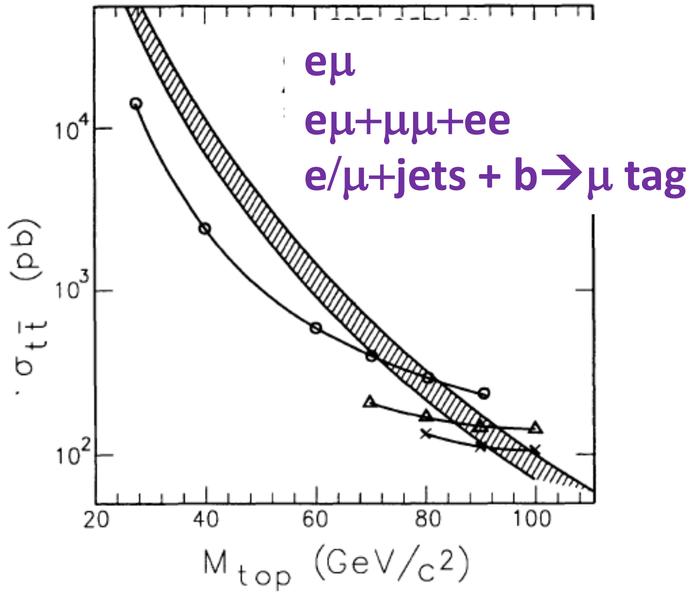
- Run -1, 1987, CDF 25 nb^{-1}
  - 22 W→eν events
  - Tevatron enters the hadron collider game
- Run 0, 1988-89, CDF 4.4 pb^{-1}
  - M > 72 → 77 → 91 GeV
  - Focus moves from SppS to Tevatron







Tevatron experiments timeline towards top discovery

- October 1985, a few CDF collisions
  - First PhD thesis
- Run -1, 1987, CDF 25 nb^{-1}
  - 22 $W \rightarrow e\nu$ events
  - Tevatron enters the hadron collider game
- Run 0, 1988-89, CDF 4.4 pb^{-1}
  - $M > 72 \rightarrow 77 \rightarrow 91$ GeV
  - Focus moves from SppS to Tevatron
- Run 1a, 1992-93 19 pb^{-1}
  - D0 enters the game
  - CDF Silicon Vertex Tracker (SVX)
  - CDF Evidence

VOLUME 73, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JULY 1994

Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s}$ = 1.8 TeV

counts from background alone. We find $\mathcal{P}_{combined}$ =0.26%. This corresponds to a 2.8σ excess for a Gaussian probability function.

CDF

VOLUME 74, NUMBER 13 PHYSICAL REVIEW LETTERS 27 MARCH 1995

Search for High Mass Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

[12]. Our measurement, although consistent with the CDF result [3] and of comparable sensitivity, does not demonstrate the existence of the top quark.

D0

Tevatron experiments timeline towards top discovery

- October 1985, a few CDF collisions
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- Run -1, 1987, CDF 25 nb^{-1}
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- Run 1a, 1992-93 19 pb^{-1}
  - D0 enters the game
  - CDF Silicon Vertex Tracker (SVX)
  - Evidence
- Run 1a + 1b 1992-94 67 pb^{-1}
  - Observation

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

Observation of Top Quark Production in $\bar{p}p$ Collisions with the Collider Detector at Fermilab

CDF

(Received 24 February 1995)

We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be $176 \pm 8(\text{stat}) \pm 10(\text{syst})$ GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

VOLUME 74, NUMBER 14 PHYSICAL REVIEW LETTERS 3 APRIL 1995

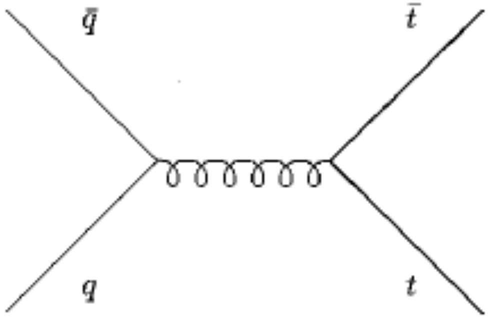
Observation of the Top Quark

D0

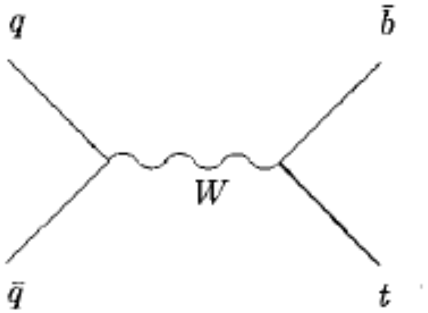
The D0 Collaboration reports on a search for the standard model top quark in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV at the Fermilab Tevatron with an integrated luminosity of approximately 50 pb^{-1}. We have searched for $t\bar{t}$ production in the dilepton and single-lepton decay channels with and without tagging of b-quark jets. We observed 17 events with an expected background of 3.8 ± 0.6 events. The probability for an upward fluctuation of the background to produce the observed signal is 2×10^{-6} (equivalent to 4.6 standard deviations). The kinematic properties of the excess events are consistent with top quark decay. We conclude that we have observed the top quark and measured its mass to be 199^{+19}_{-21} (stat) ± 22 (syst) GeV/c^2 and its production cross section to be 6.4 ± 2.2 pb.

Tevatron vs. SppS top production

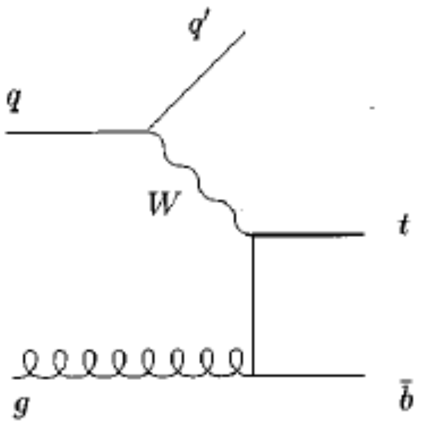
(a) $q\bar{q} \rightarrow t\bar{t}$
(gg init states also)

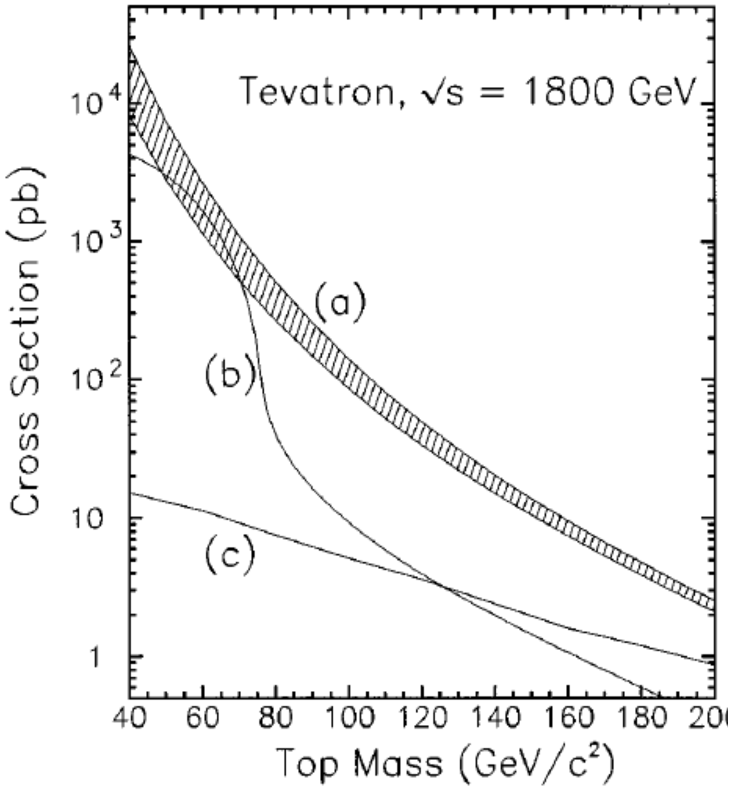


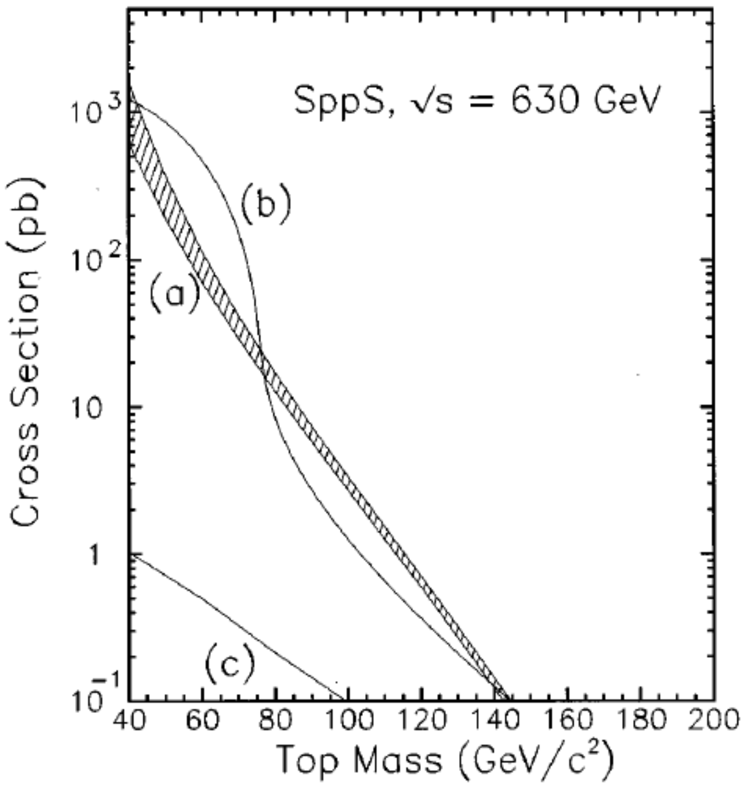
(b) $q\bar{q} \rightarrow W \rightarrow t\bar{b}$



(c) $q\bar{q} \rightarrow t\bar{b}q'$







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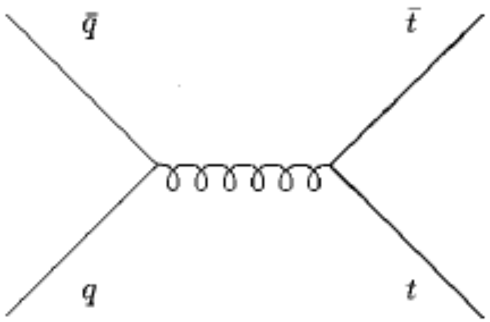

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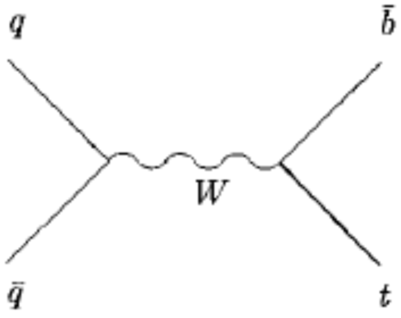

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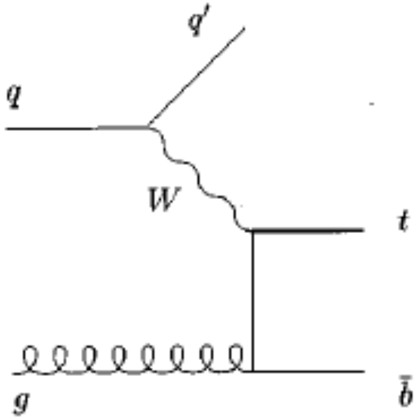
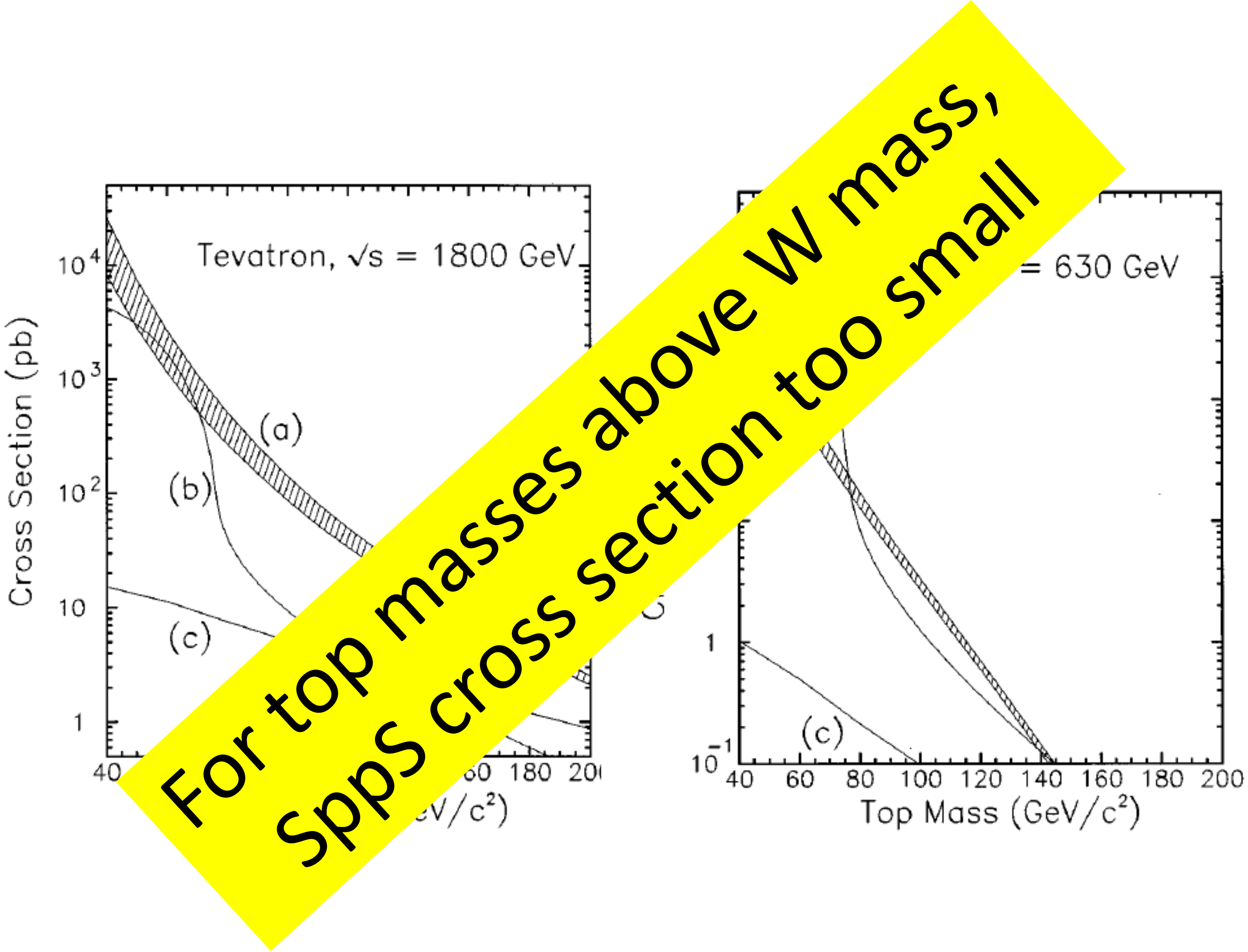
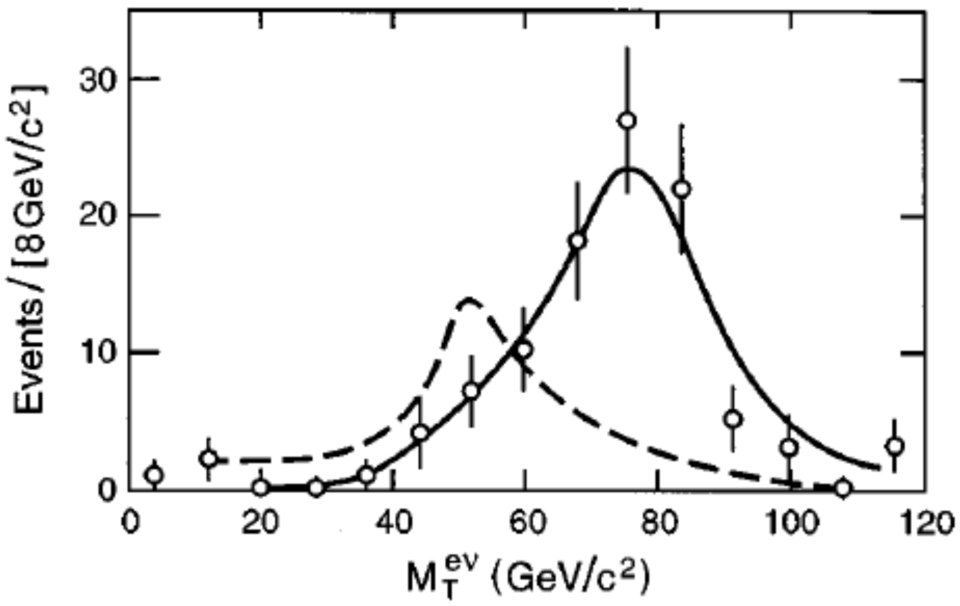




Run 0 CDF analysis, 4.4 pb^{-1}

- No real plan (eg, no yellow book, projections etc), very seat-of-the-pants
- Lepton+jets background was mostly W+jets
  - This is obvious now, but was not so clear at the time
  - W+jets calculations were in their infancy
    - Only up to 2 jets at matrix element
    - Matrix element → final state particle very primitive (Isajet independent fragmentation)
    - No matrix element to parton shower matching
- Very concerned about $b\bar{b}$, no real MC available
- Discriminating variable was transverse mass

e+jets
solid=Wjets, dashed=$t\bar{t}$ M=70 GeV



M < 77 GeV @ 95 C.L.

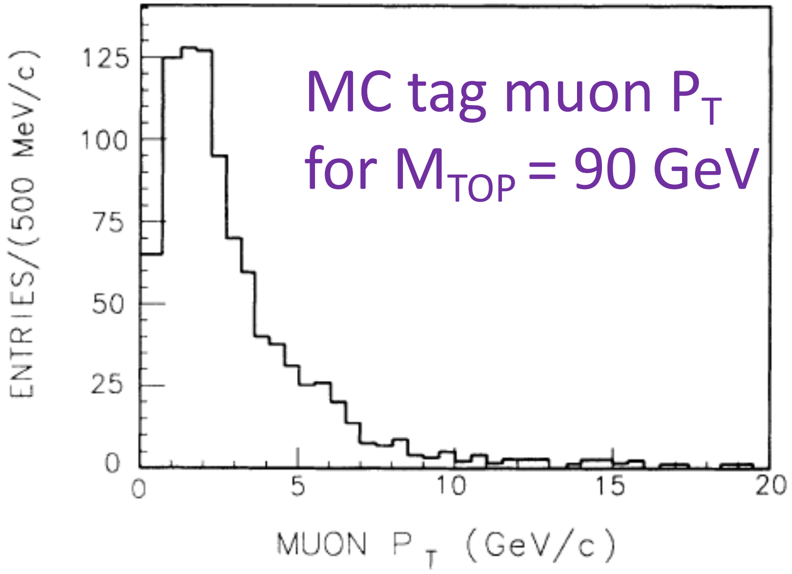
Run 0 CDF analysis, 4.4 pb^{-1}, crossing the M_W threshold

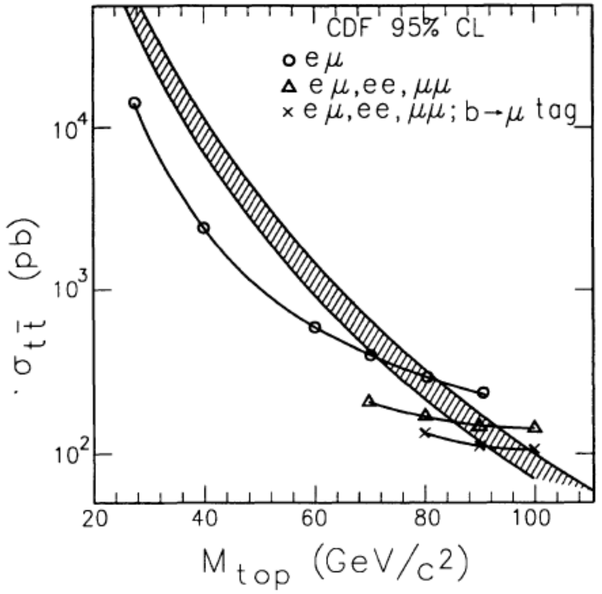
Dileptons + first attempt to b-tag in lepton+jets

- Tag = soft muon, down to 2 GeV (!)

Channel	Observed	BG predicted
eμ	1	1.2 ± 0.5
ee + μμ	0	1.5 ± 0.8
Lep+jets+tag	0	0.9 ± ??

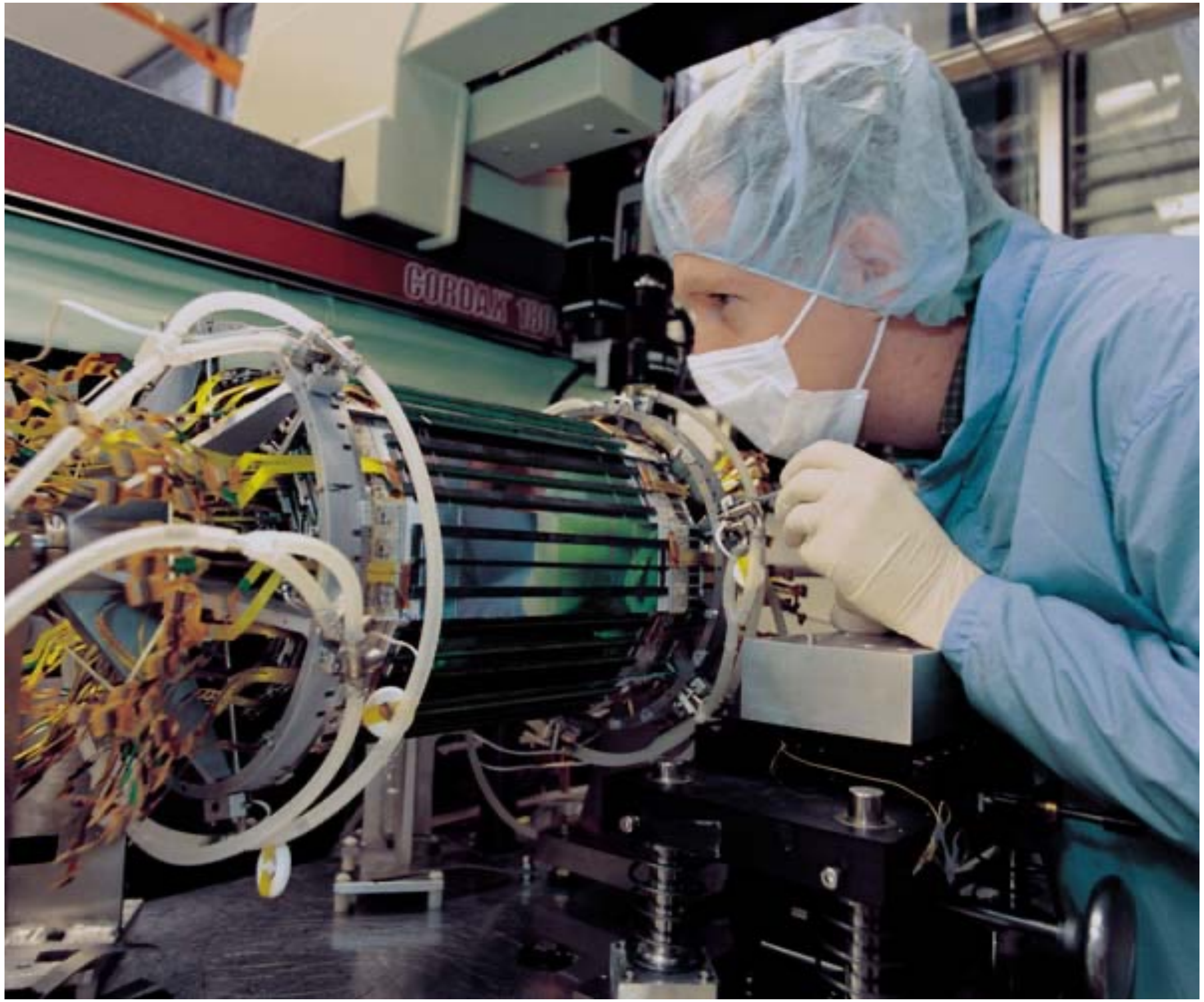
Counting experiment limit assuming observed is from top



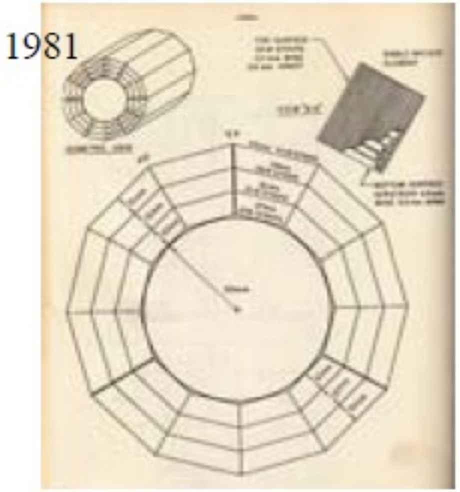


M > 91 GeV @ 95% C.L.

Run 1 CDF: Silicon Vertex Tagger (SVX)
A true game changer



Proposed by Aldo Menzione et al when CDF was barely in the womb



- 4 layers, DC coupled microstrips
- R = 3, 4.2, 5.7, 7.9 cm
- 51 cm long
- ~ 60% geometrical accept (beam spot σ=30 cm)

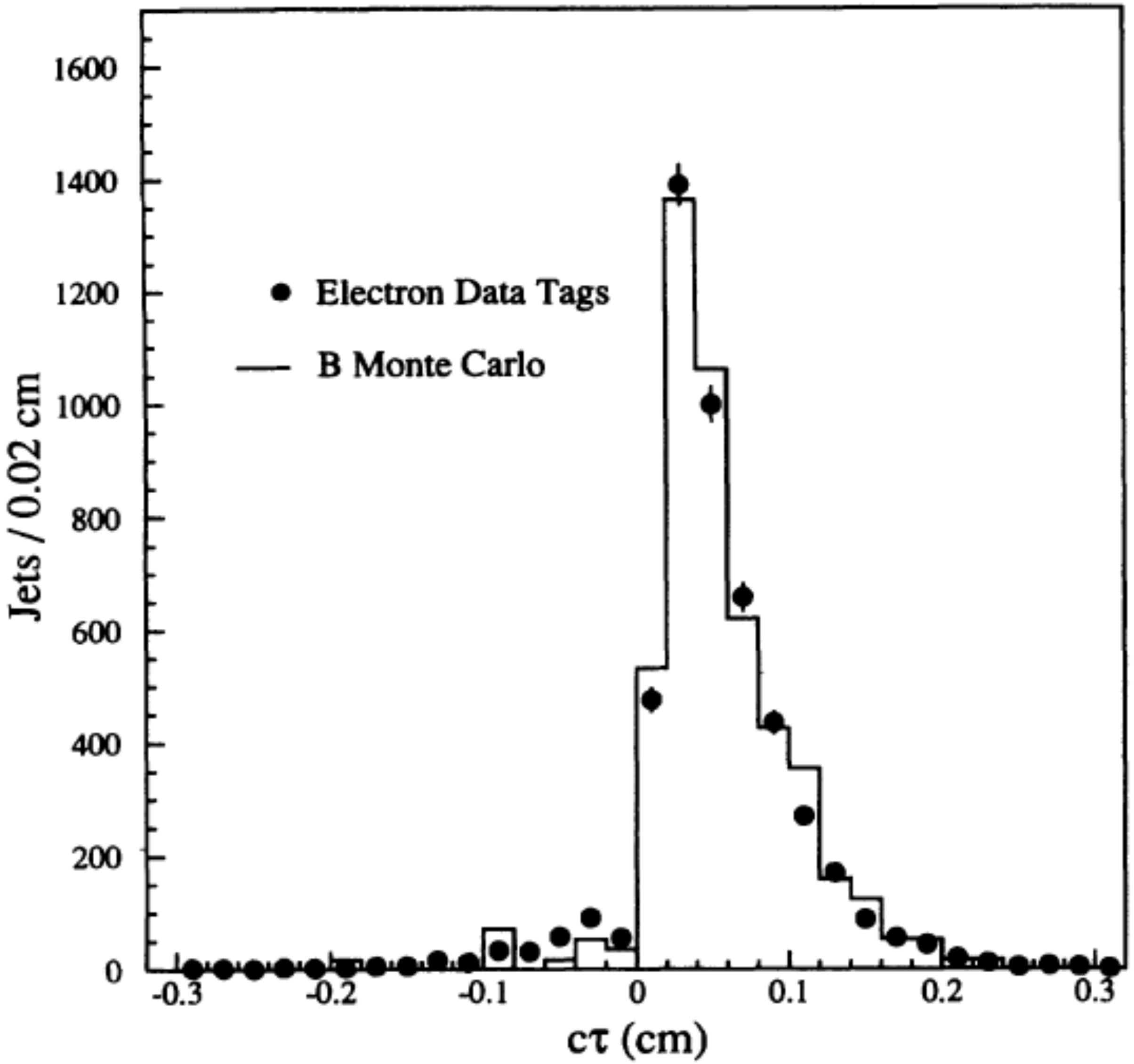
CDF tagging

<u>Secondary Vertex Tagging</u>

- Three separate algorithms
- Used for x-checks, but only one used for the results
  - Now we would put everything in one MVA and do much better
- Efficiency ~ 30% (semileptonic decays)
- Fake rate ~ 1 %

<u>Soft Lepton Tagging (SLT)</u>

- Now muons and electrons
- All the way down to 2 GeV (!)
- Lower efficiency, higher BG

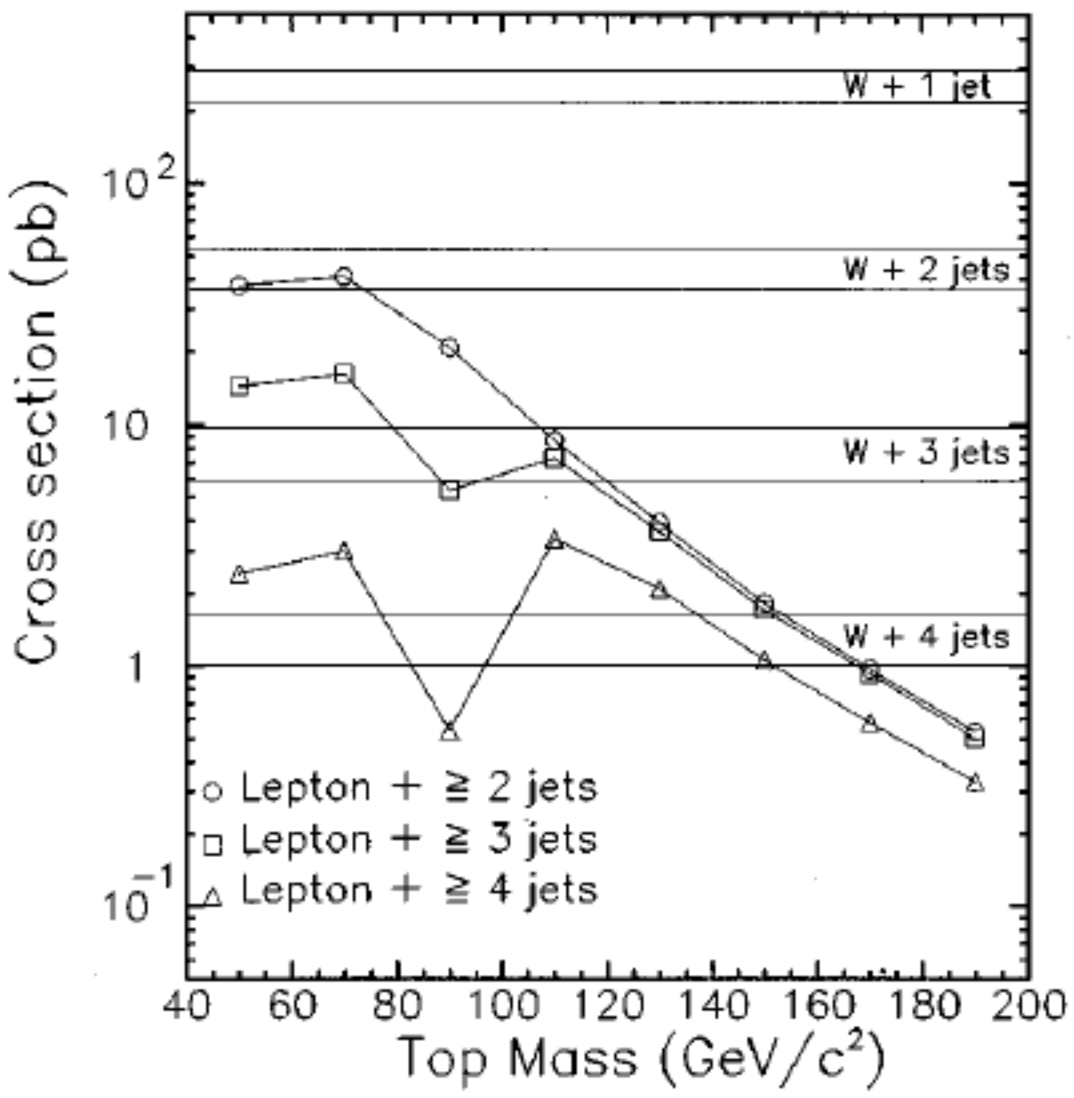


CDF Strategy

- Quantitatively ignore kinematical information (but of course look at it for qualitative confirmation)
  - e.g. HT difference, W+jets vs. $t\bar{t}$
  - Controversial
  - W+jets theory quite new, how to quantify theoretical uncertainties?

- Because of SVX power, base all results on counting tags (SVX or SLT) and dilepton events
  - Data driven conservative background estimates (“Method 1”)

Parton Level plot



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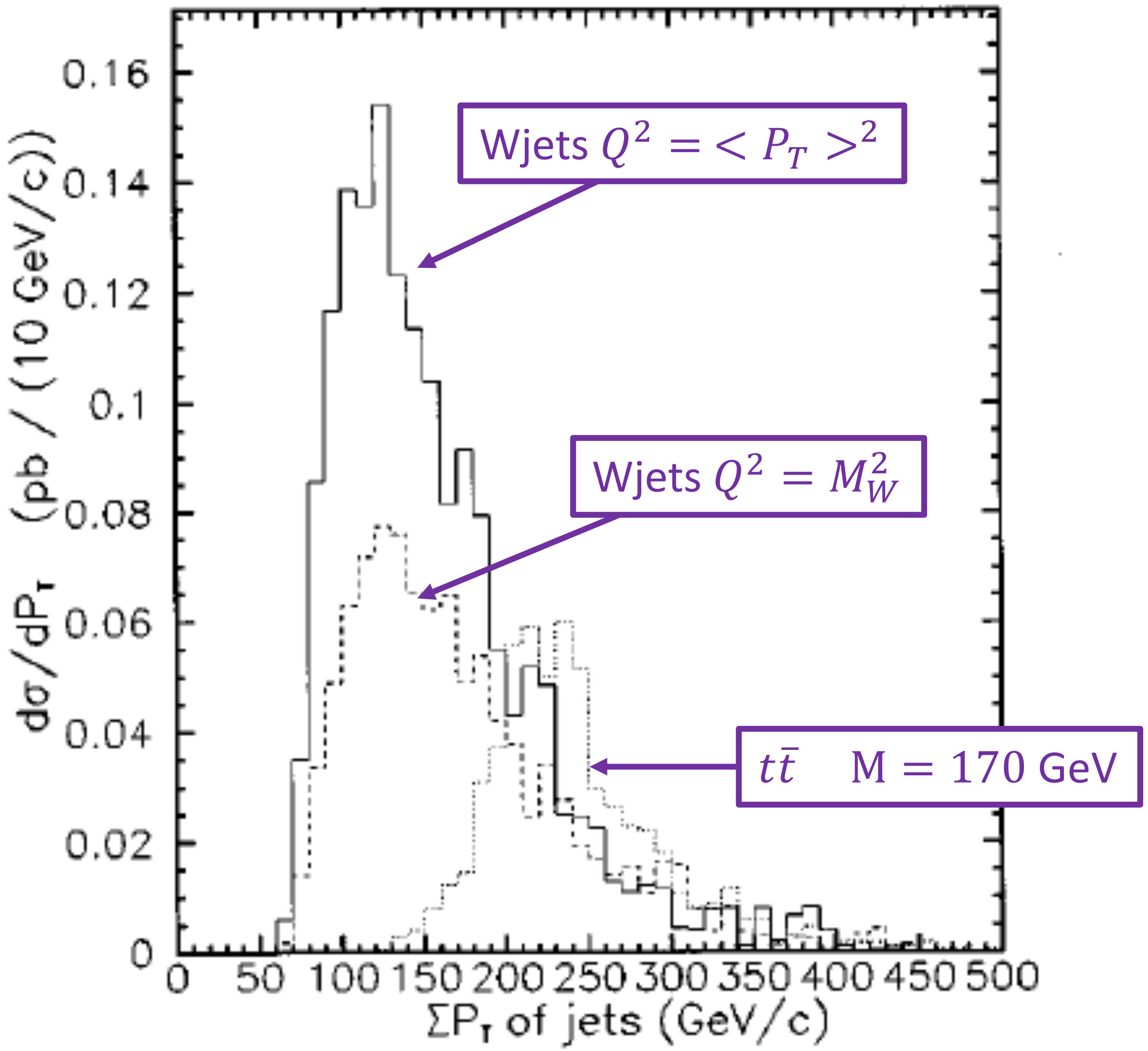
Parton Level plot, lepton + 4 jets

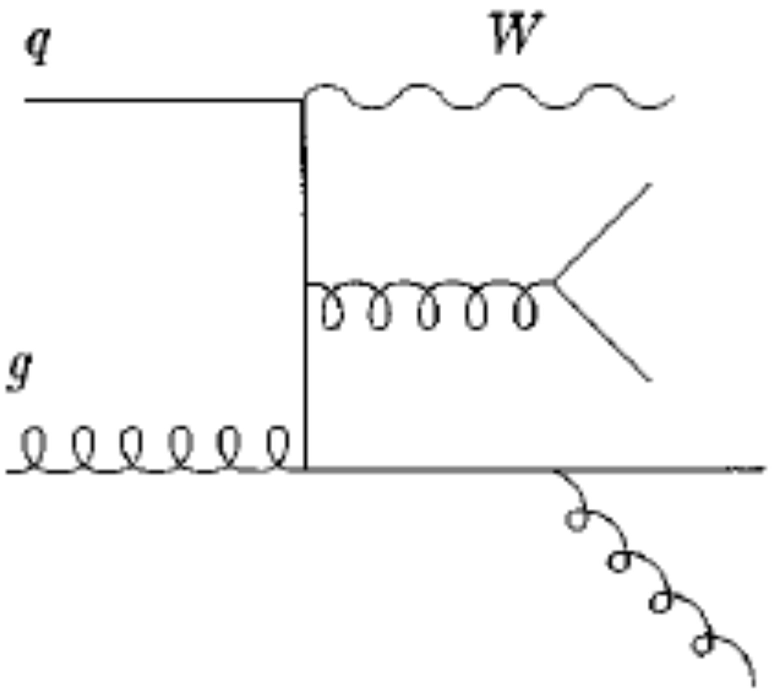


Lepton + jets tags, heavy flavor vs light flavor

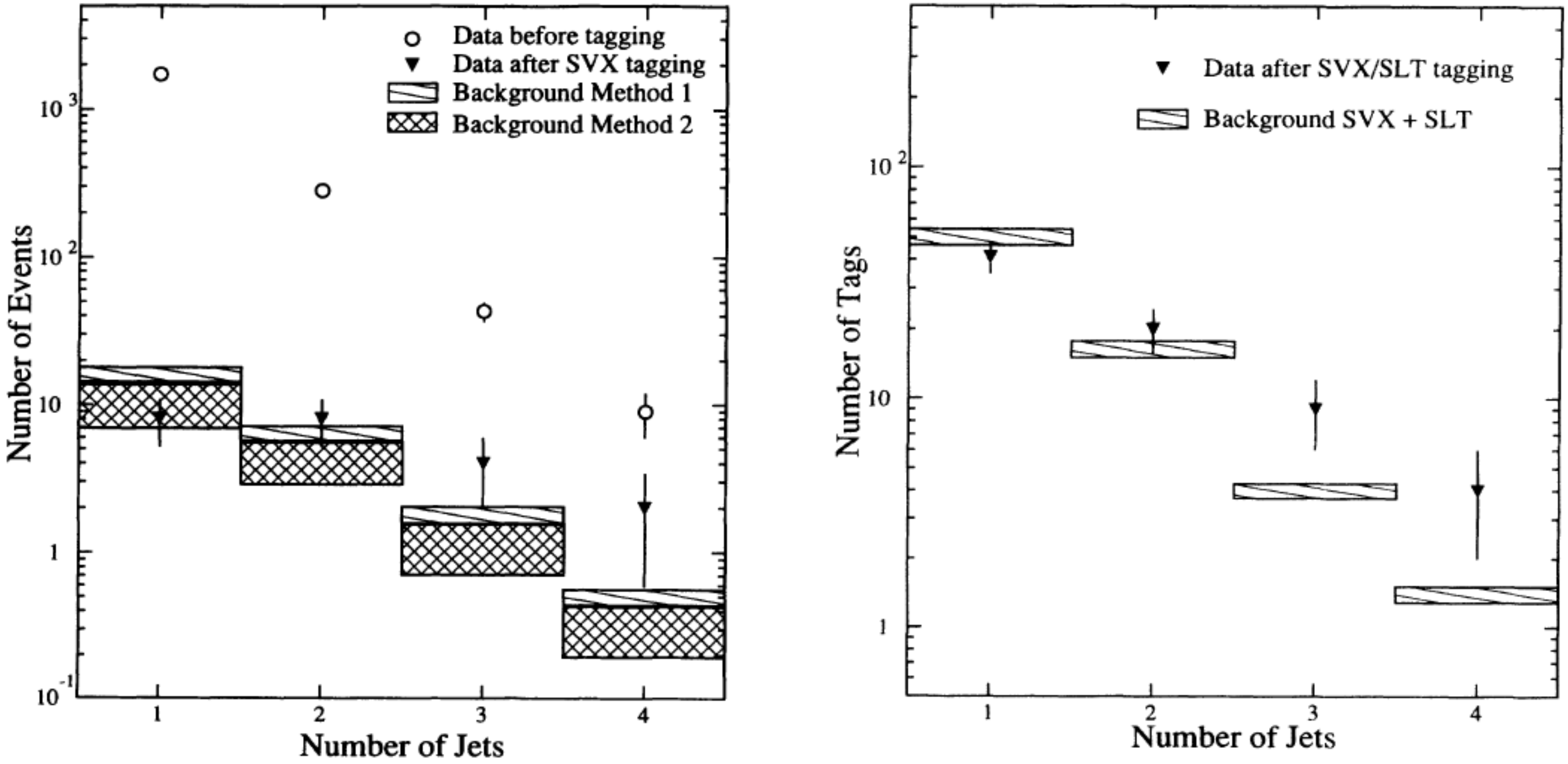
- Wjets = W+LF and W+HF
- Conservative Method 1 Assumption:
  - $\frac{p\bar{p} \rightarrow HF\ jets}{p\bar{p} \rightarrow all\ jets} = \frac{W + HF\ jets}{W + all\ jets}$
- "Generic jets" in $p\bar{p}$ mostly gluons
  - $g \rightarrow b\bar{b}$
- Jets in Wjets mixture of $g, q, \bar{q}$
- Measure tag rate in generic jets, apply to Wjets to obtain Wjets+tag background

- As the analysis progressed, very first calculations of W+ HF became available
- Method 2

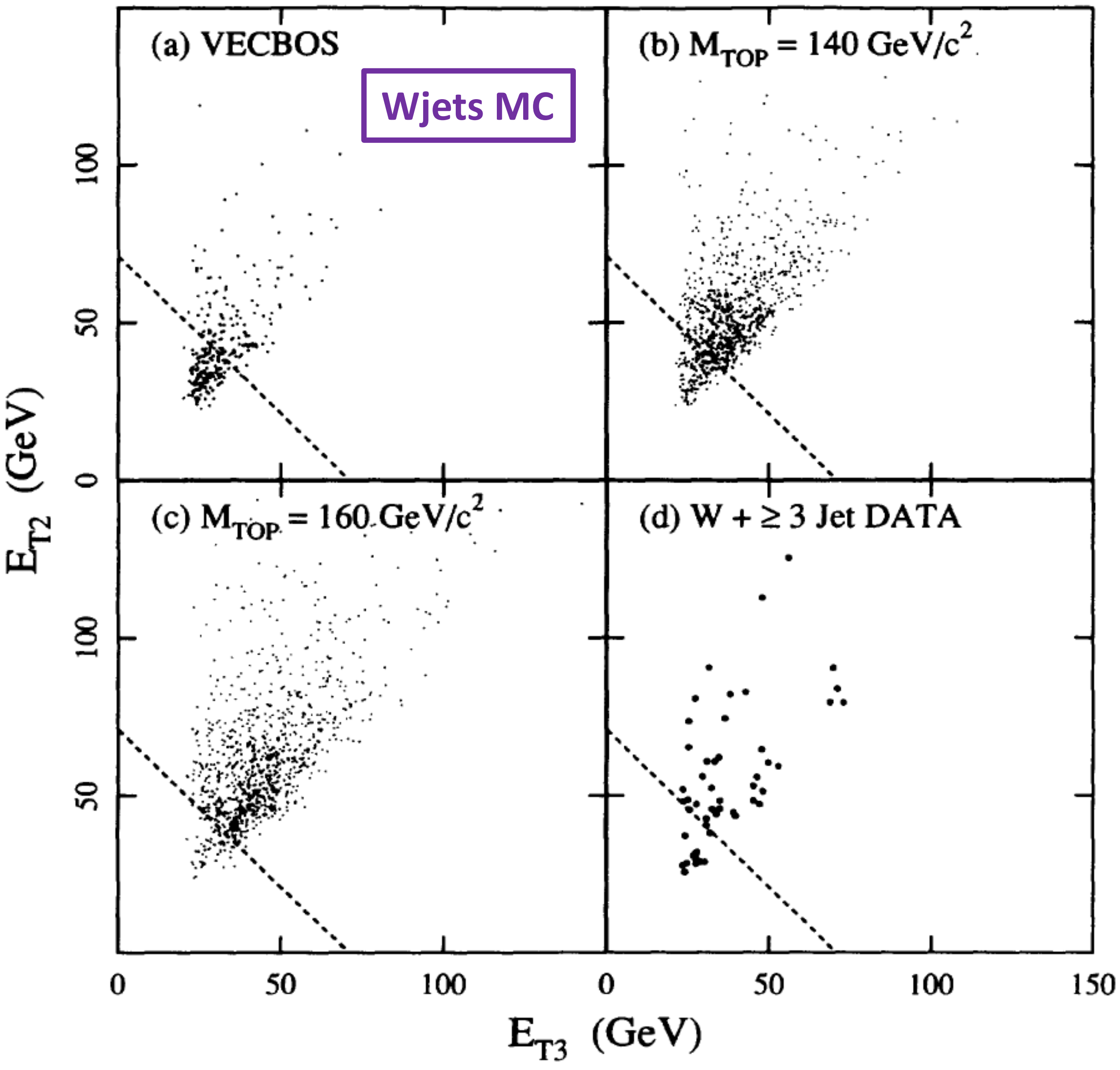
Sample W + 4 jets diagram



CDF Run 1a tags, signal region ≥ 3 jets



CDF Run 1a kinematical evidence in lepton+jets

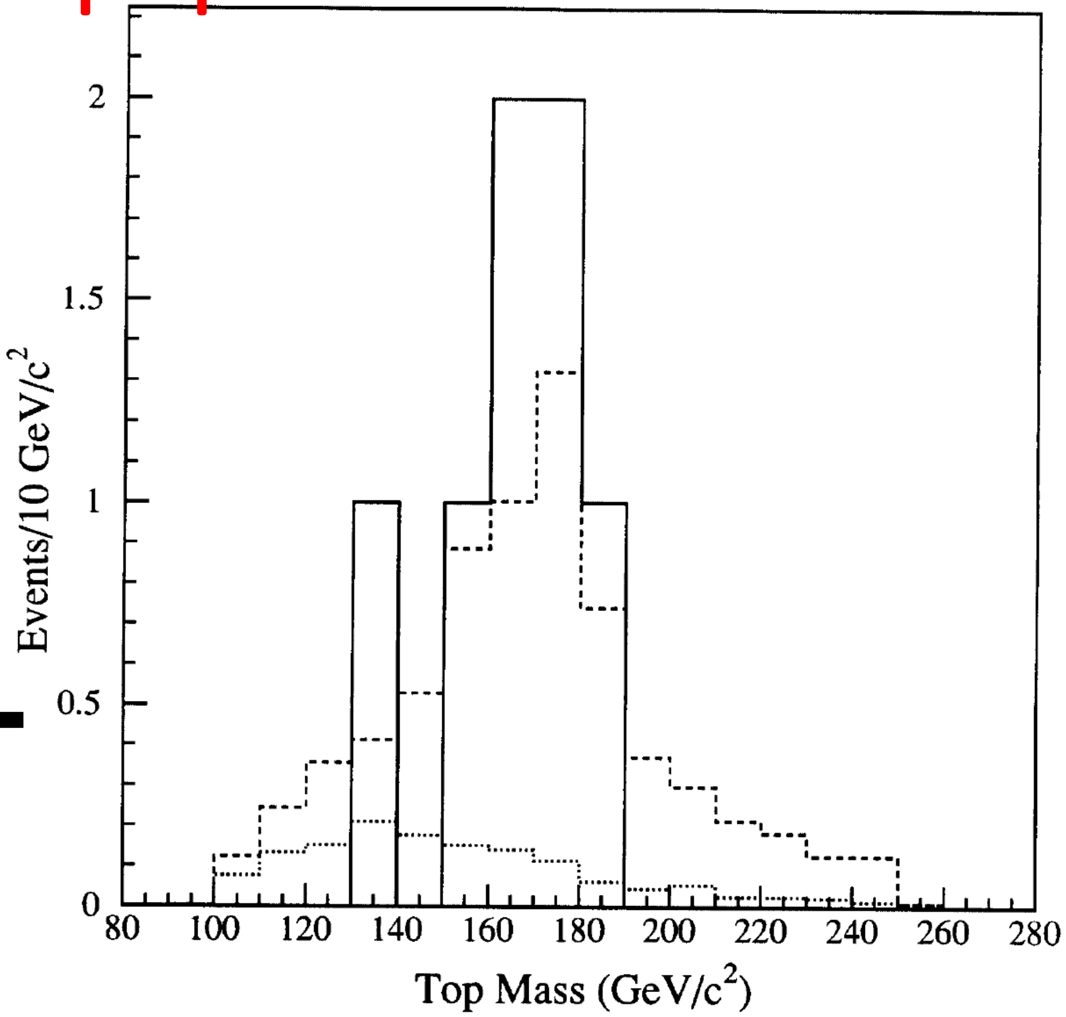


E_T of 2[nd] and 3[rd] most energetic jets

Not used quantitatively

CDF Run 1a "Evidence", 65-page paper

	Evidence
Integrated Luminosity	19.3 pb^{-1}
SVX tags (expected background)	6 (2.3 ± 0.3)
SLT tags (expected background)	7 (3.1 ± 0.3)
Dilepton events (expected background)	2 ($0.56^{+0.25}_{-0.13}$)
Production cross section	$13.9^{+6.1}_{-4.8}$ pb
Top mass	$174 \pm 10^{+13}_{-12}$ GeV/c^2
Significance	2.8σ



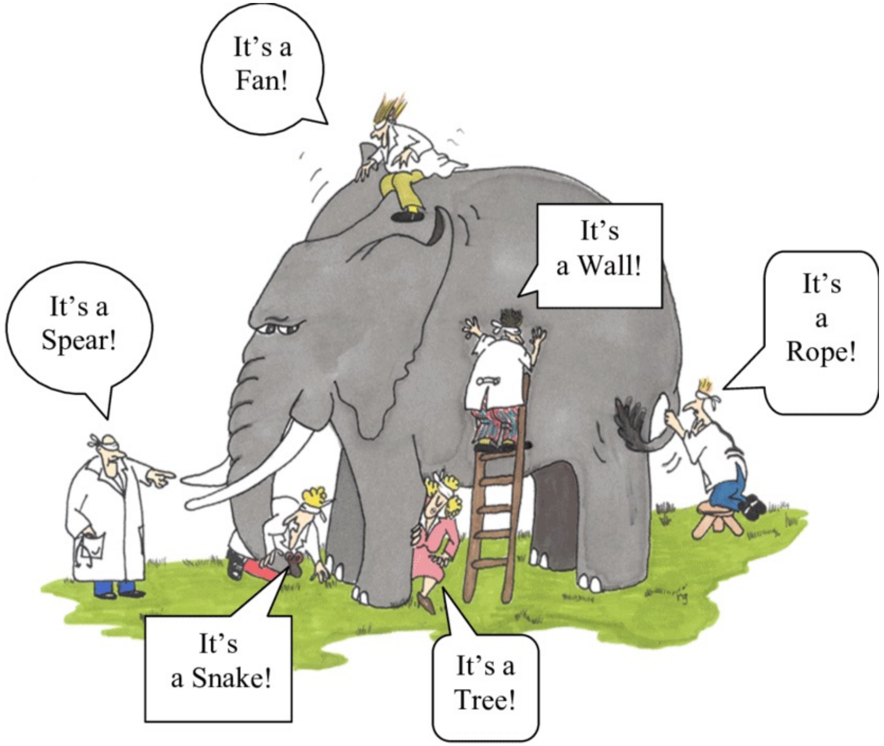
I witnessed the awkward first stage of CDF evidence, when four short draft papers were by compromise merged into a very long paper. I even promised CDF collaborators to read the thing and did, carefully, beginning to end, and found it a classic—a masterful exhibit of how science results should (but seldom do) get reported. – **BJ SLAC Beamline Vol 25, #3, Fall 1995**

PHYSICAL REVIEW D VOLUME 50, NUMBER 5 1 SEPTEMBER 1994

ARTICLES

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

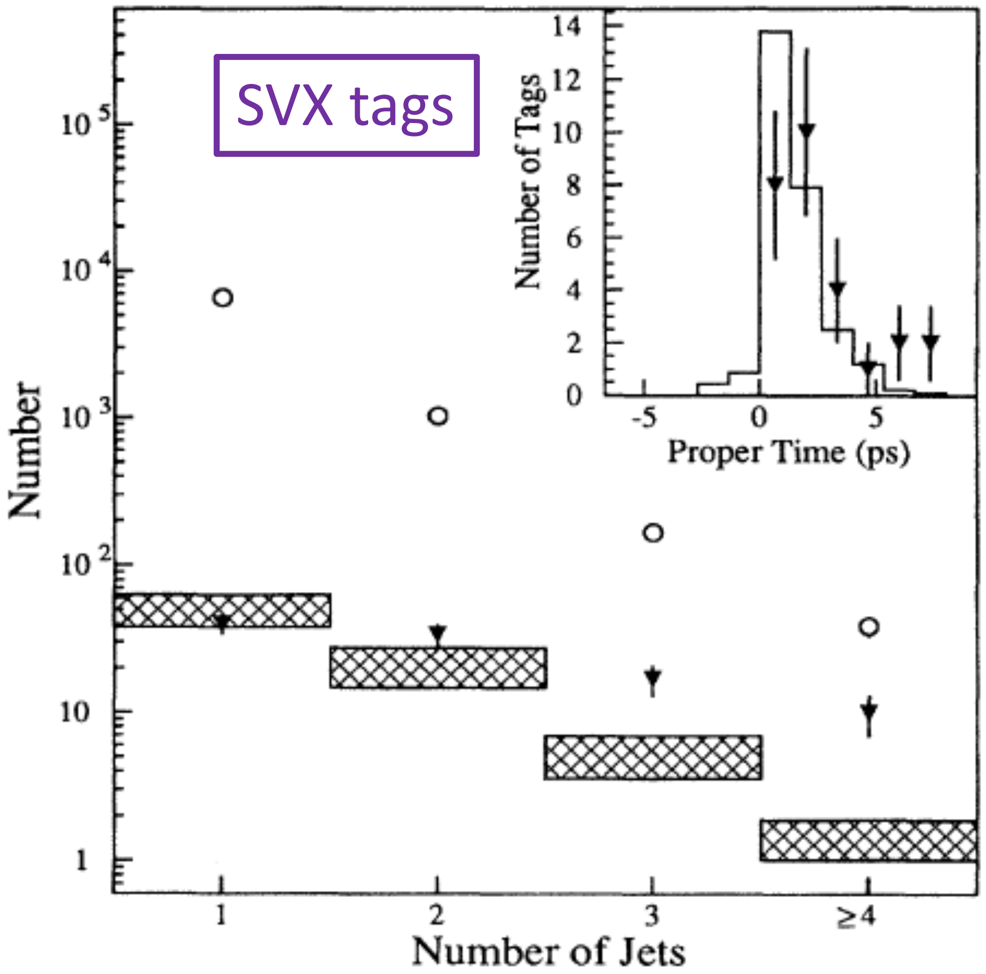
We present the results of a search for the top quark in 19.3 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. The data were collected at the Fermilab Tevatron collider using the Collider Detector at Fermilab (CDF). The search includes standard model $t\bar{t}$ decays to final states $ee\nu\bar{\nu}$, $e\mu\nu\bar{\nu}$, and $\mu\mu\nu\bar{\nu}$ as well as $e+\nu+$jets or $\mu+\nu+$jets. In the $(e,\mu)+\nu+$jets channel we search for b quarks from t decays via secondary vertex identification and via semileptonic decays of the b and cascade c quarks. In the dilepton final states we find two events with a background of $0.56^{+0.25}_{-0.13}$ events. In the $e,\mu+\nu+$jets channel with a b identified via a secondary vertex, we find six events with a background of 2.3±0.3. With a b identified via a semileptonic decay, we find seven events with a background of 3.1±0.3. The secondary vertex and semileptonic-decay samples have three events in common. The probability that the observed yield is consistent with the background is 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 $174\pm10^{+13}_{-12}$ 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.



Many qualitative x-check confirmed the $t\bar{t}$ hypothesis. But:
- There were some hints that the extracted x-section was ~1-2σ high (and it was)
- There were only two Z+4jets events, **and they were both b-tagged (???)**
  - This turned out to be a (scary) statistical fluctuation

CDF one year later, partial Run 1b, triple the stats, increased SLT muon coverage

	Observation	Evidence
Luminosity	48+19=67 pb^{-1}	19.3 pb^{-1}
SVX tags	27 (6.7 ± 2.1)	6 (2.3 ± 0.3)
SLT tags	23 (15.4 ± 2.0)	7 (3.1 ± 0.3)
Dilepton events	6 (1.3 ± 0.3)	2 $(0.56^{+0.25}_{-0.13})$
Cross section	$6.8^{+3.6}_{-2.4}$ pb	$13.9^{+6.1}_{-4.8}$ pb
Top mass	$176 \pm 8 \pm 10$ GeV/c^2	$174 \pm 10^{+13}_{-12}$ GeV/c^2
Significance	4.8σ	2.8σ



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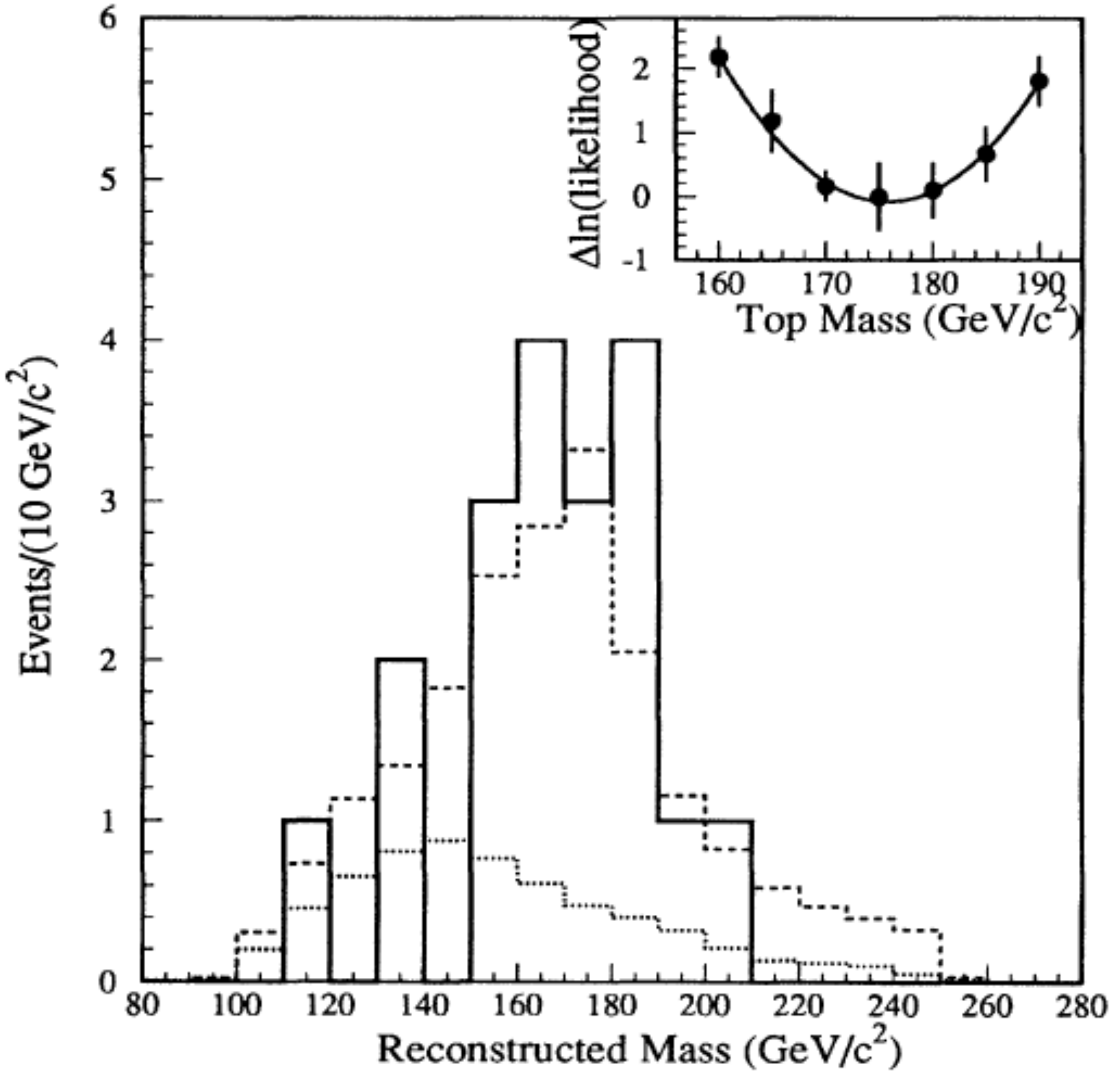
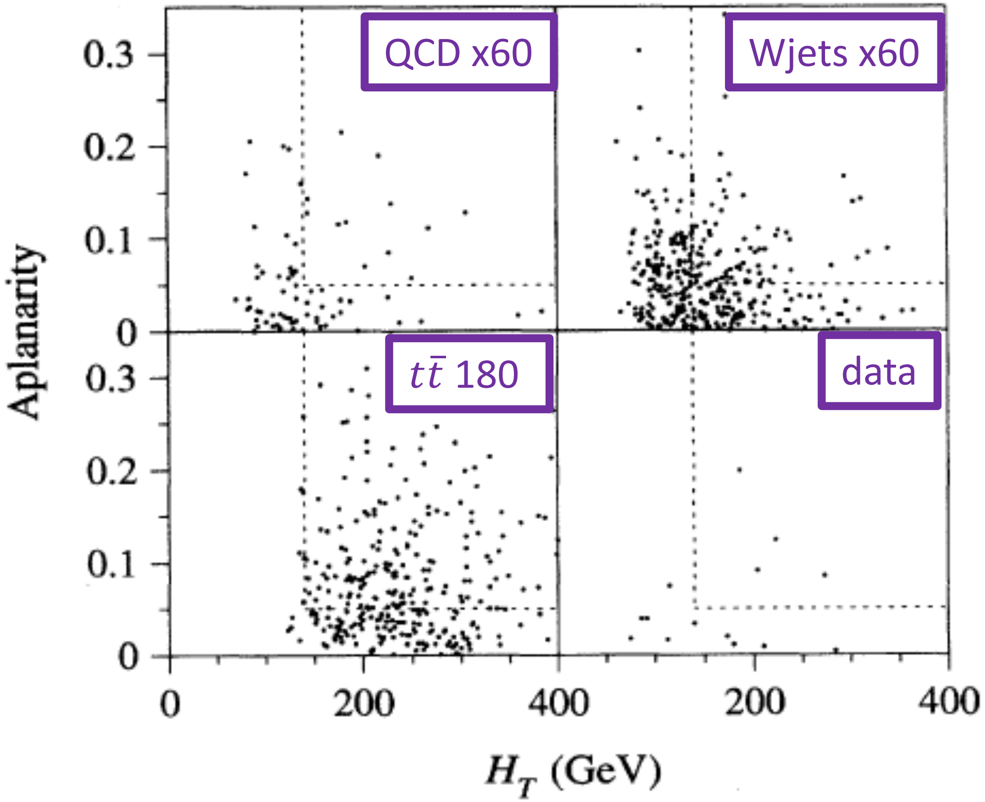
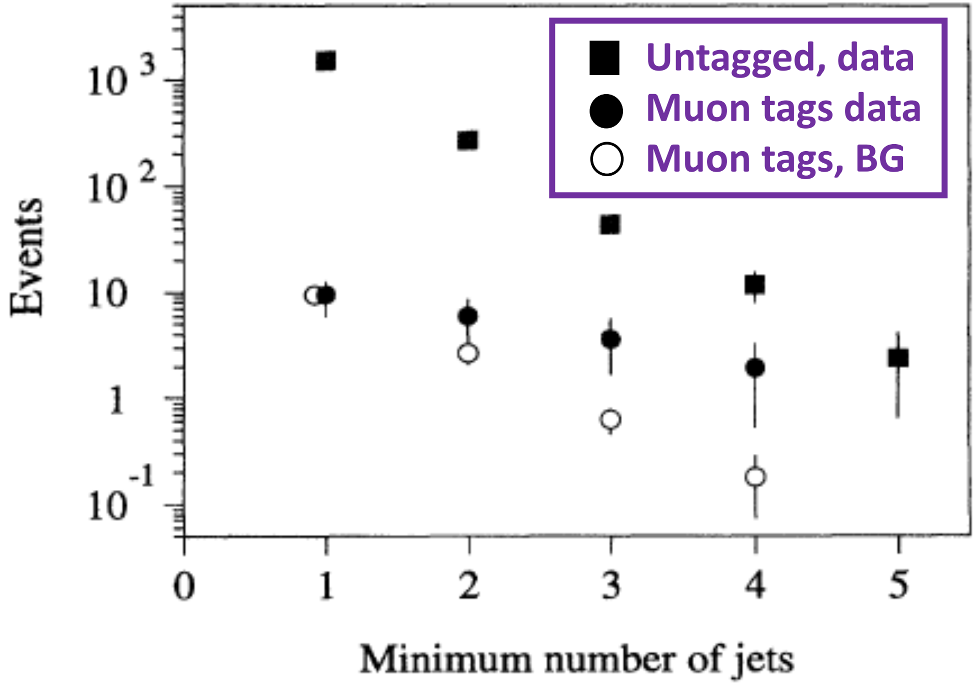


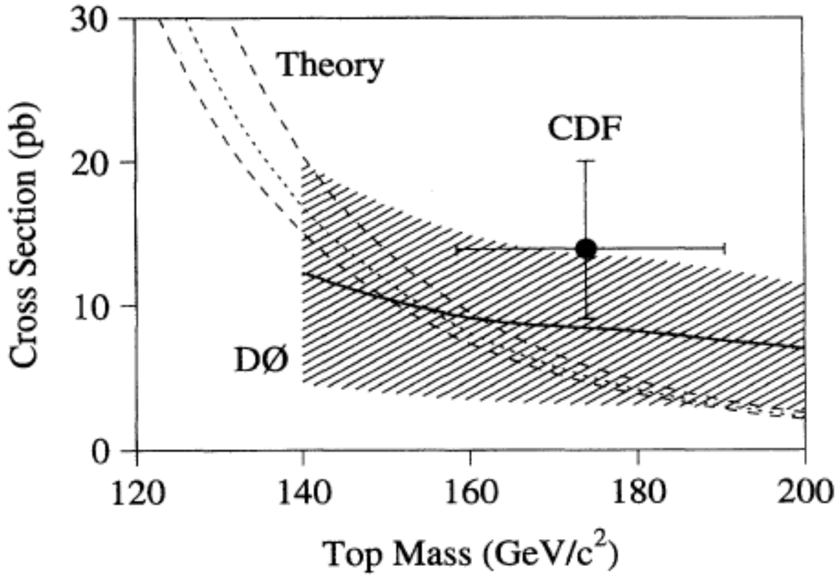
On the other side of the ring, D0

- Slightly lower luminosity
- No vertex detector
- No magnetic field: muon tags only, $P_T > 4$ GeV
- Lepton + jets search based on muon tags <u>and kinematical distributions</u>
- And of course, dileptons

D0 Run 1a



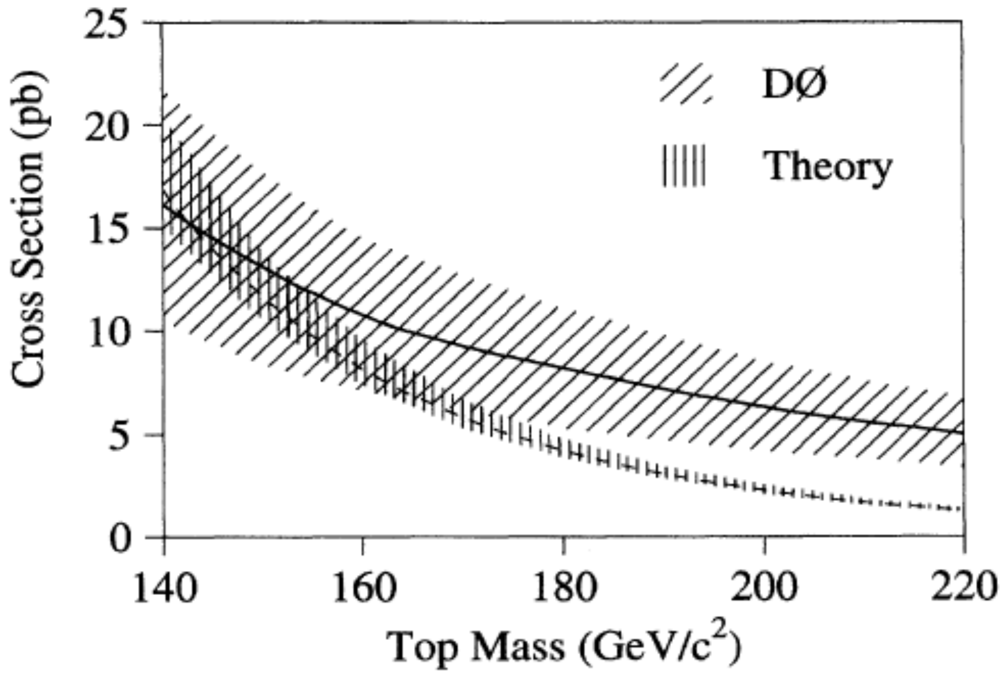


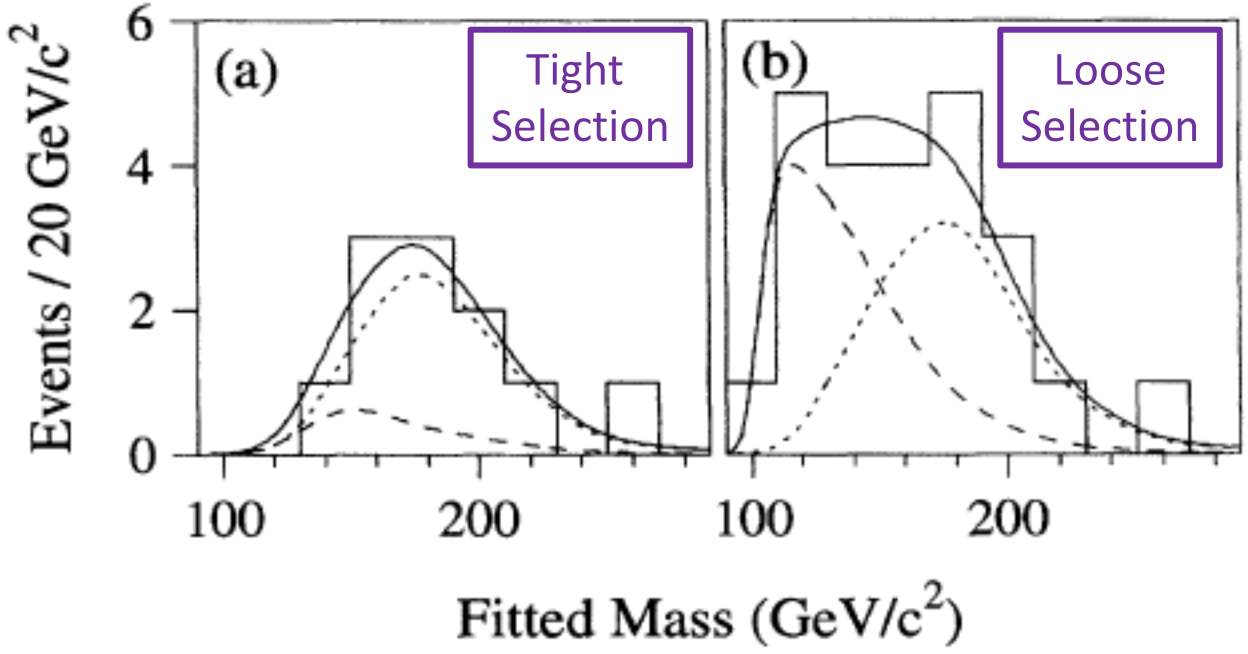


9 events on BG of 3.8 ± 0.9
Significance 1.9σ

D0 Run 1a + partial Run 1b, published simultaneously to CDF

- Tighten kinematical requirements
- 17 events (6 SLT + 11 lepton+jets) with a BG of 3.8 $\pm$ 0.6
- Significance 4.6σ
- M = $199^{+19}_{-21} \pm 22$ GeV/c^2





Final Comments. It was a different era…

- Much more "seat-of-the-pants"
  - Not a lot of advance planning. Figure it out as you go.
- Primitive tools
  - Most CDF MC was fast simulation
  - Key theoretical inputs (W+jets) very new and developed "in parallel"
  - Needed to be "creative" to make up for tool shortcoming
- Lively, open, sometime contentious, internal discussions in CDF
- CDF very conservative in minimizing reliance on theory/MC
- Many qualitative x-check to support $t\bar{t}$ hypothesis that did not enter "significance"
- No blind analyses
- No MVAs
- Statistics primitive by today's standards
  - Did you see any "Brazilian Flags" in this talk?
  - e.g. CDF "evidence" counting experiment added everything together, ignoring different signal/noise in different channels

It was very exciting and a lot of fun