The Top Quark
30 years later

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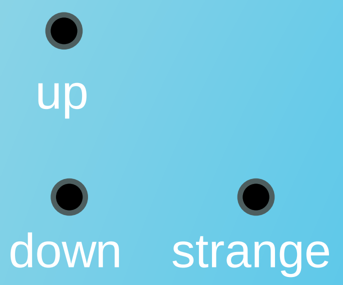
Outline

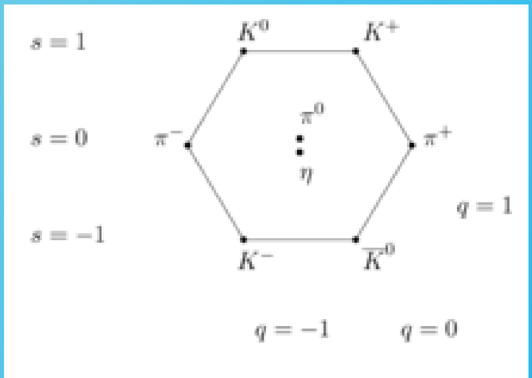
- **Pre-Tevatron**
- **Tevatron Collider**
  - **Early searches**
  - **Discovery**
  - **Final results**
- **What we know now about the top quark**

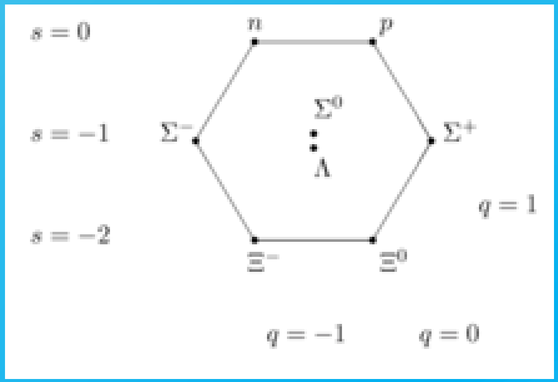
Late 1960's

The Eightfold Way and the Quark Model

- **The myriad of mesons and baryons, including non-strange and strange, discovered in the 1950s and 1960s could all be organized by an SU(3) flavor symmetry. This might imply elementary constituents, 3 types of quarks and their antiquarks.**







- **The existence of physical quarks was established in a series of deep inelastic lepton-nucleus scattering experiments.**

1974

With the discovery of the J/ψ:

quarks $\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$

leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$

The absence of flavor-changing neutral currents in *K* meson decay was explained (GIM mechanism).

1975-77

- **Observation of *τ* lepton in Mark I data (decay kinematics $\Rightarrow \nu_\tau$)**
- **Discovery at Fermilab of the *$\Upsilon \Rightarrow b$* quark**

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

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

  - ***b: non-SM? isosinglet? SM isodoublet?***

    1984 DESY measurement of $e^+e^- \rightarrow b\bar{b}$ FB asymmetry: (22.5±6.5)%

    c.f. 25.2% for SM isodoublet; 0% for isosinglet

- **If the SM were correct, there must be an isodoublet partner, the top quark.**
- **Mass = ? [*b/c/s* = 4.5/1.5/0.5 $\Rightarrow$ M_t = 15 GeV?]**

Searches in e^+e^- Collisions

PETRA could reach ~20 GeV (late ’70s)

- search for narrow toponium resonance
- look for an increase in R = (# of hadron events)/(# of $\mu^+\mu^-$ events)
- global event characteristics: look for spherical component
- negative results $\Rightarrow$ $M_{top} > 23$ GeV

TRISTAN built to study top quark (early ’80s)

- similar search techniques
- $M_{top} > 30$ GeV

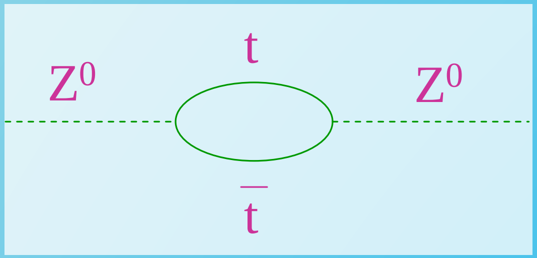
SLC/LEP

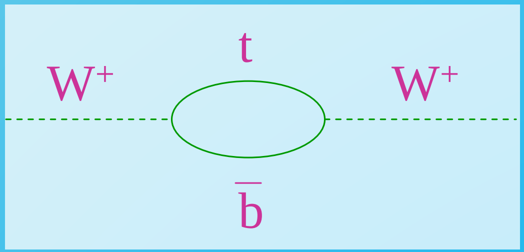
- look for $Z \rightarrow t\bar{t}$
- $M_{top} > 45$ GeV

That was the kinematic limit for direct search in e^+e^- collisions at that time.

Predictions from Z^0 Decay

In the Standard Model, various EWK measurables depend on the mass of the top quark.





EWK radiative corrections $\propto M_t^2$

Precision measurements of Z^0 decay $\Rightarrow$ predictions of M_{top}
(SM consistency)

Throughout the period 1990 – top discovery:

direct search lower limit > prediction lower limit

prediction upper limit < 200 – 225 GeV

Early Searches in Hadron Collisions

CERN Sp̄pS ($\sqrt{s}$ = 540 GeV) built to observe *W*, *Z*

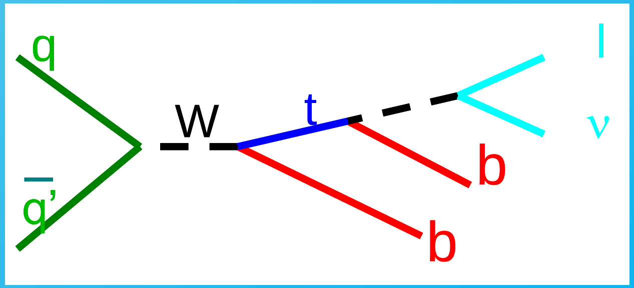
- **single ring ⇒ $\bar{p}$ production & cooling**

+: access to much higher mass

–: backgrounds are severe and/or event rates are very low

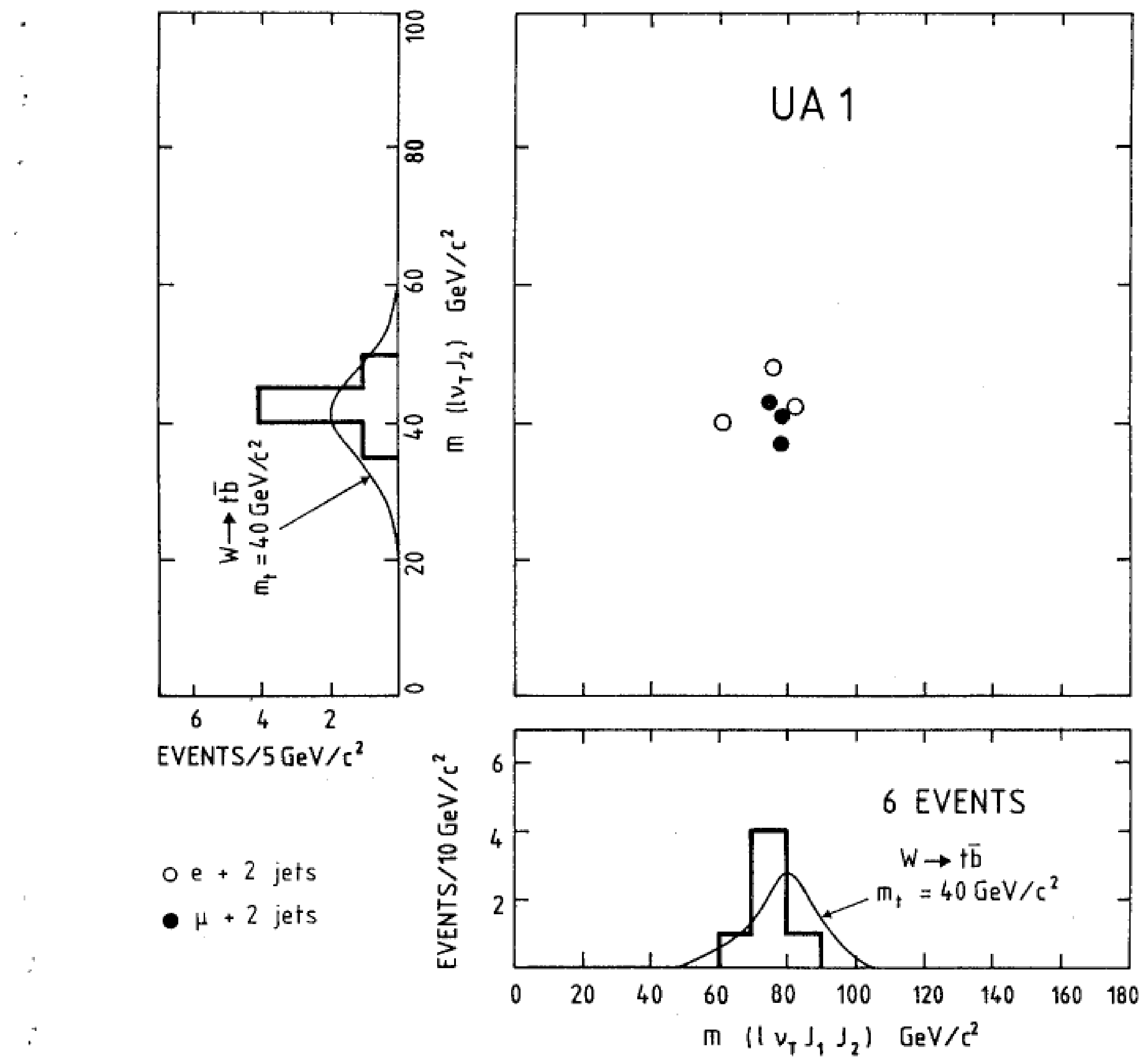
–: reconstruction difficult: jets

1984: UA1



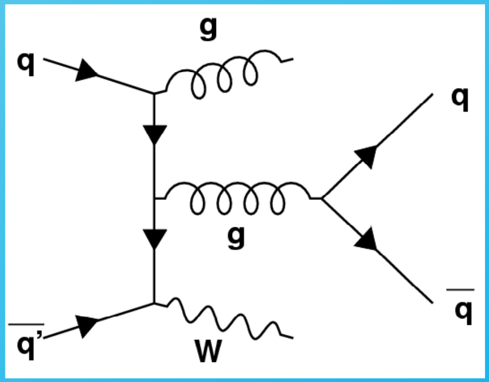
- **isolated high P_T lepton**
- **2 or 3 hadron jets**
- **Observe 5 events (*e* + >=2 jets); 4 events (μ + >=2 jets)**
- **Expected background: 0.2 events**
  - **fake leptons dominate**
  - ***b$\bar{b}$* & *c$\bar{c}$* production negligible**
- **Conclude: results consistent with M_{top} = 40 ±10 GeV.**

Stop just short of claiming discovery.


UA 1
EVENTS/5 GeV/c²
W → tb̄
m_t = 40 GeV/c²
m (lν_T J_2) GeV/c²
○ e + 2 jets
● μ + 2 jets
EVENTS/10 GeV/c²
6 EVENTS
W → tb̄
m_t = 40 GeV/c²
m (l ν_T J_1 J_2) GeV/c²

1988 UA1

- x6 data sample (600 nb^{-1})
- much better understanding of backgrounds
  - fake leptons
  - W + jets
  - DY, J/ψ, Y
  - $b\bar{b}$, $c\bar{c}$



channel	observed	expected background
$\mu + \geq 2$ jets	10 events	11.5 ± 1.5 events
$e + \geq 1$ jets	26 events	23.4 ± 2.8 events

(+ 23 expected if M_{top} = 40 GeV)

Conclude: $M_{top} > 44$ GeV

Fermilab's Path to Pbar-P Collisions at 2 TeV (John Peoples, 2020)

- **The Energy Doubler Project: The first successful large superconducting high energy proton synchrotron.**
  - **An R&D project from 1974-1982, culminating in installation and commissioning in 1983**
  - **An 800 GeV Fixed Target Proton synchrotron 1984-1997**
  - **A 2 TeV pbar-p collider 1987-2011**
  - **Dedicated as the Tevatron in 1984**
- **The "new" Tevatron 1 Project: "Re-Approved" by DOE in April 1982**
  - **An intense antiproton source (1987-1999)**
  - **Collider detector halls for CDF at B0 (1983) and for DZero at DO (1987)**
  - **Transformation of the Tevatron to a 2 TeV pbar-p collider**
  - **Completed and commissioned in 1987 with the 1987 Collider Run**

1988-89 Fermilab in the Hunt

At CERN, UA2 remains after detector upgrades.

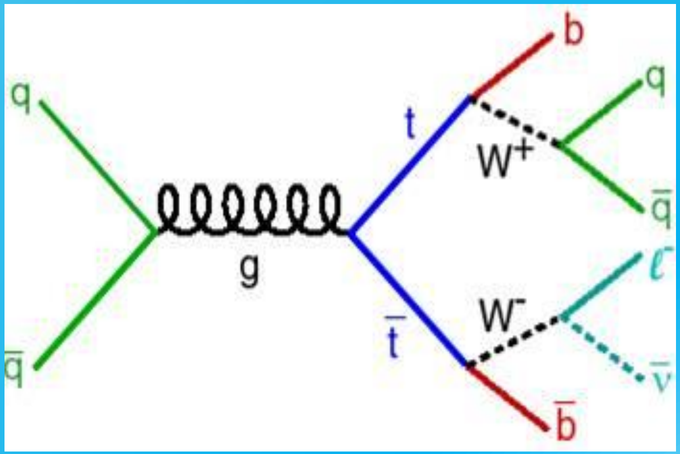
Fermilab: √s = 1.8 TeV vs. 0.63 @ CERN

⇒ much larger mass reach (75 GeV @ UA2)

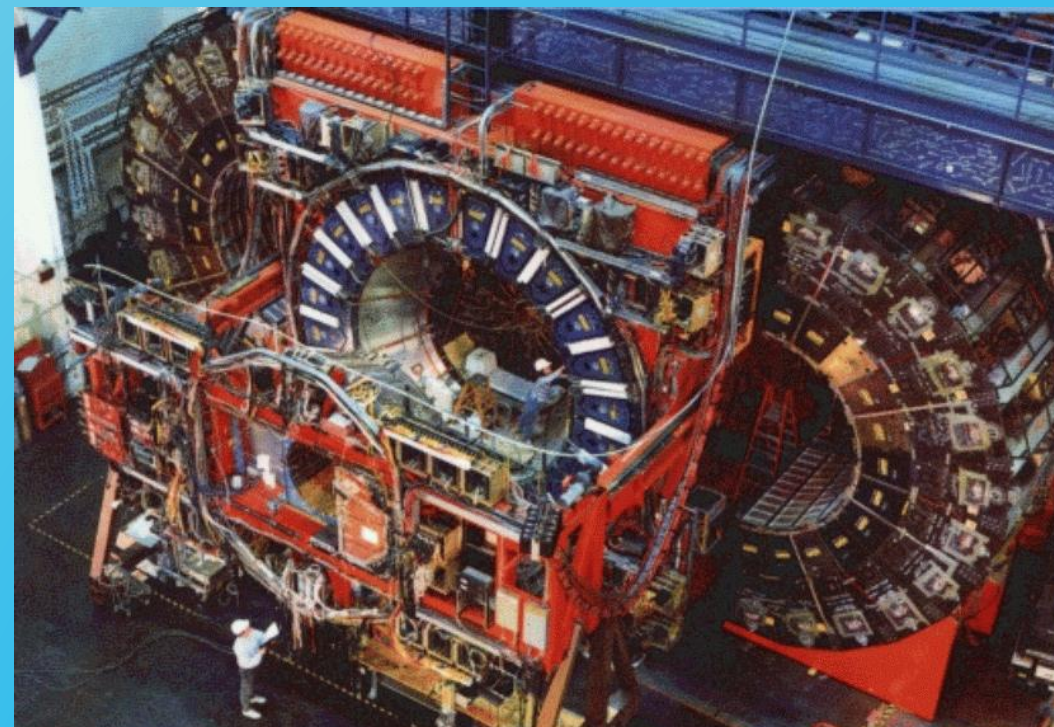
Competition! BBC, Nova: "The Race for the Top"

Pair production dominates at Fermilab: $t\bar{t} \rightarrow WbW\bar{b}$

%	$e\nu$	$\mu\nu$	$\tau\nu$	$q\bar{q}$
$e\nu$	1.2	2.5	2.5	14.8
$\mu\nu$		1.2	2.5	14.8
$\tau\nu$			1.2	14.8
$q\bar{q}$				44.4



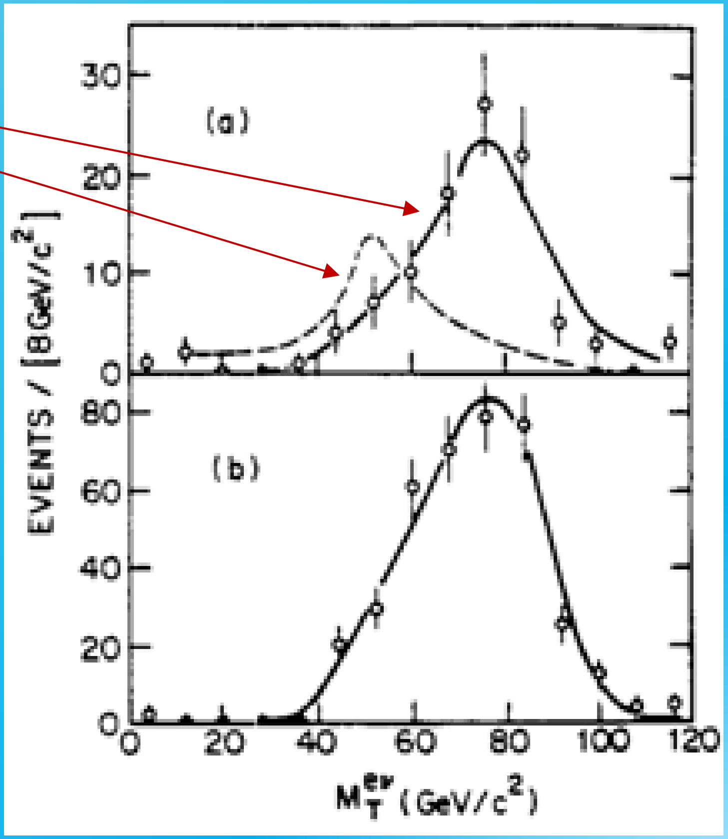
12 countries, 62 institutions
767 physicists



CDF (4 pb^{-1})

- $e\nu + \geq 2$ jets
  - **dominant background:** *W* + jet production
  - **discriminant:** $e\nu$ transverse mass
    - **background:** *W* on shell
    - **signal** (40-80 GeV top): *W* off shell
  - $M_{top} > 77$ GeV

[UA2 used a similar technique: > 69 GeV]

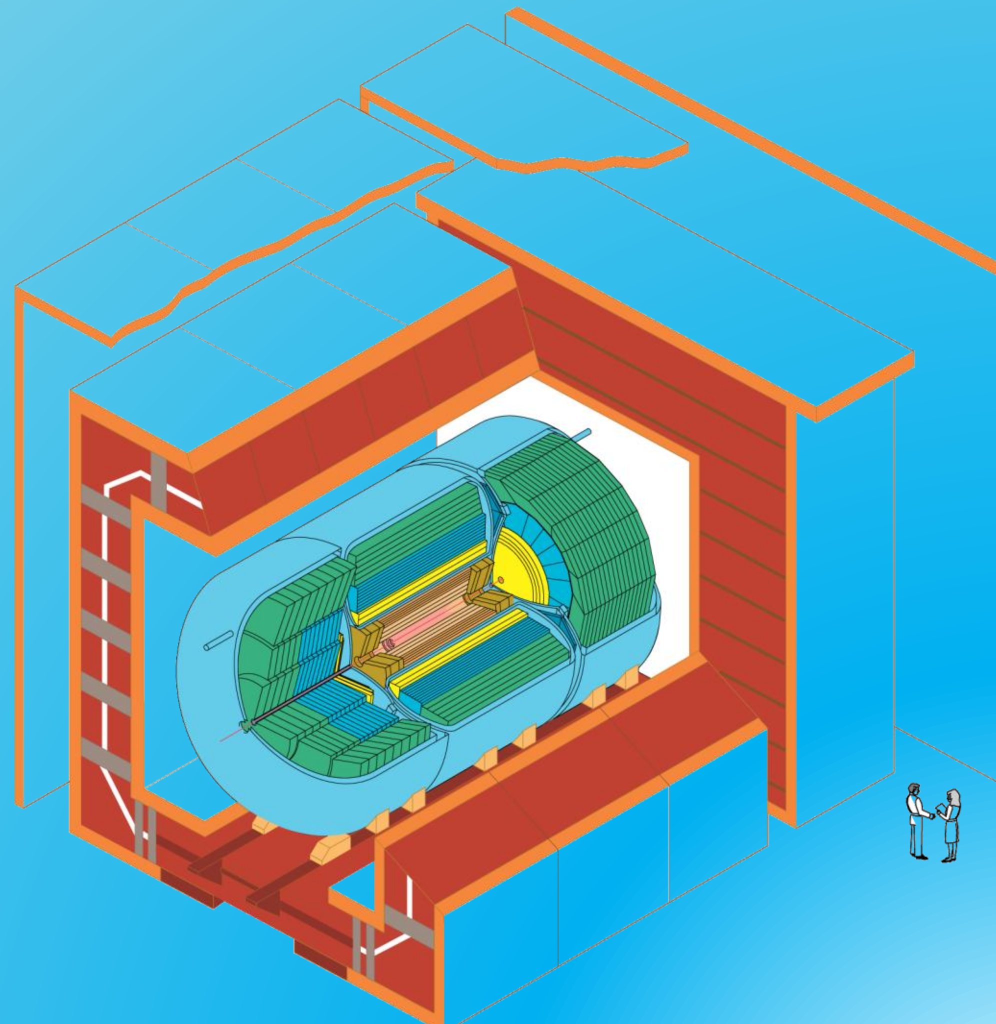


- $e\mu$
  - expected event rate much smaller since 2 x BR($W\to e\nu$)
  - Background is very small
    - no W + jets
    - no Drell-Yan
    - dominant background is $Z\to\tau\tau\to e\mu X$ (expect 1 event)
  - observe 1 event
  - M_{top} > 72 GeV (expect 7 events from 70 GeV top quark)

Strategy Change when $M_{top} > M_W + M_b$

- **top decays to on-shell W ⇒ no $M_T(l\nu)$ discriminant**
- **major difference:**
  - **background (~5 x N_{signal}): W + jets (largely light quarks & gluons)**
  - **signal (~10/yr for 175 GeV): W + jets (2 jets are *b*-jets)**
- **Last CDF top publication on '88-89 data**
  - **dilepton: include *ee*, $\mu\mu$ (missing E_T requirement, *Z* mass cut)**
  - **single lepton: require low P_T μ (semi-leptonic *b* decay)**
- **$M_{top} > 91$ GeV**

19 countries
83 institutions, 664 physicists



DØ Detector

D0 Joins the Hunt

Run I: 1992-95

- **Tevatron:** higher luminosity
- **D0:** excellent calorimetry, large solid angle μ coverage
- **CDF:** silicon vertex detector added to magnetic spectrometer

Run Ia:

D0 – optimized analysis strategy for 100 GeV mass

• $e\mu + \not{E}_T + \geq 1\,jet$	:	1 event	(background - 1.1 events)
• $ee + \not{E}_T + \geq 1\,jet$	:	1	(0.5)
• $e + \not{E}_T + \geq 4\,jets$	with aplanarity cut:	1	(2.7)
• $\mu + \not{E}_T + \geq 4\,jets$	with aplanarity cut:	0	(1.6)

M_{top} > 131 GeV @ 95% CL (15 pb^{-1})

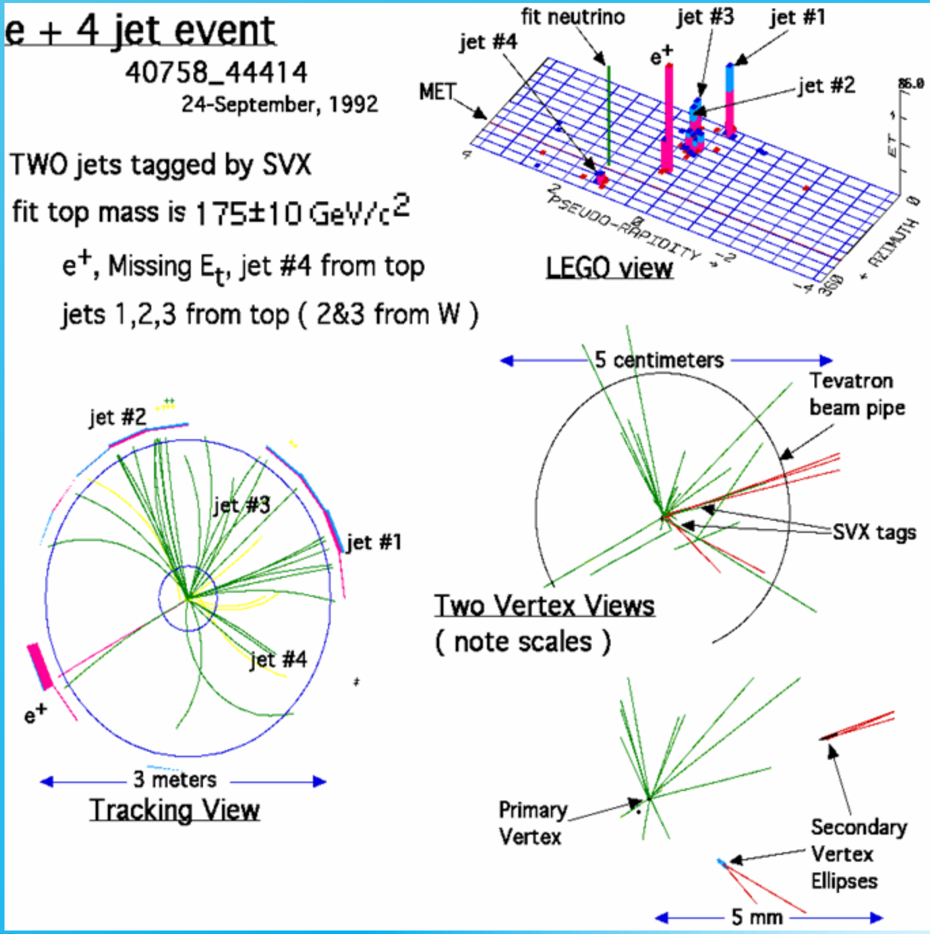
Establishing that the top quark is very heavy was important, since discovery would be more challenging if the top mass were only slightly above the sum of the *W* and *b* masses (produced close to rest).

CDF –different focus

New: SVX (40 μm impact parameter resolution)

⇒ **identify *b*-jets by secondary vertex**

powerful discriminant against background



Strategy:

- **dilepton: + 2 jets (Q value OK)**
- **single lepton: *b* tagging**
  - **soft *e* or μ (semi-leptonic *b* decay)**
  - **secondary vertex**

August, 1993 (19 pb^{-1})

Dilepton, secondary vertex, and soft lepton groups each report a small, not statistically significant excess.

	estimated background	observed
dilepton	0.6 events	2 events
1 lepton, vertex *b*-tag	2.3	6
1 lepton, lepton *b*-tag	3.1	7

3 events in common

- **In total, however, the numbers were becoming significant.**

background fluctuation probability: 1/400 (2.8σ)

Aside: big collaborations – monolith or competitive?

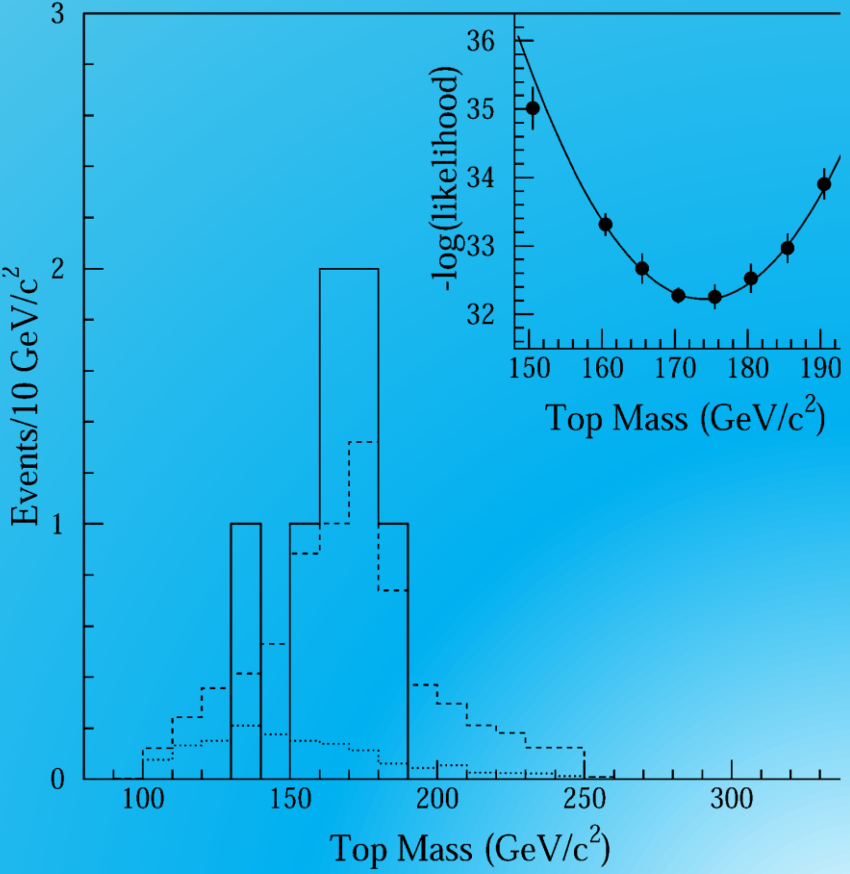
- **Many were skeptical, demanding additional studies, cross checks**
- **an additional 8 months before result submitted and made public**

- :

- **best single lepton + *b*-tag control sample: *Z* + ≥ 3 jets**
  - **expect 0.6 events, see 2 events**
  - **worrisome even if not statistically significant (higher stat. tests OK)**
- **# of $l\nu$ + 4-jet events (pre-tag) smaller than expected from signal plus background (1.5-2 σ)**

+ :

- **various kinematic distributions supported $t\bar{t}$**
- **mass distribution favored signal + background (2.3 σ)**



Final issue: Publication title: Search, Evidence, or Observation?

- counting experiment: 2.8 σ excess
- few checks with some discrepancy – none major
- other checks consistent with a signal
- mass distribution – looks (too) good

Counting was the *a priori* technique ⇒ "Evidence" in PRL & large PRD

$$\sigma_{t\bar{t}} = 13.9^{+6.1}_{-4.8}\ \text{pb}$$ ⟵ lucky

$$M_t = 174 \pm 10^{+13}_{-12}\ \text{GeV}$$

D0: more data & re-optimized for heavy top (single & di-lepton)

- Observed 7 events; expected 4-6 from background
- ⇒ no independent evidence

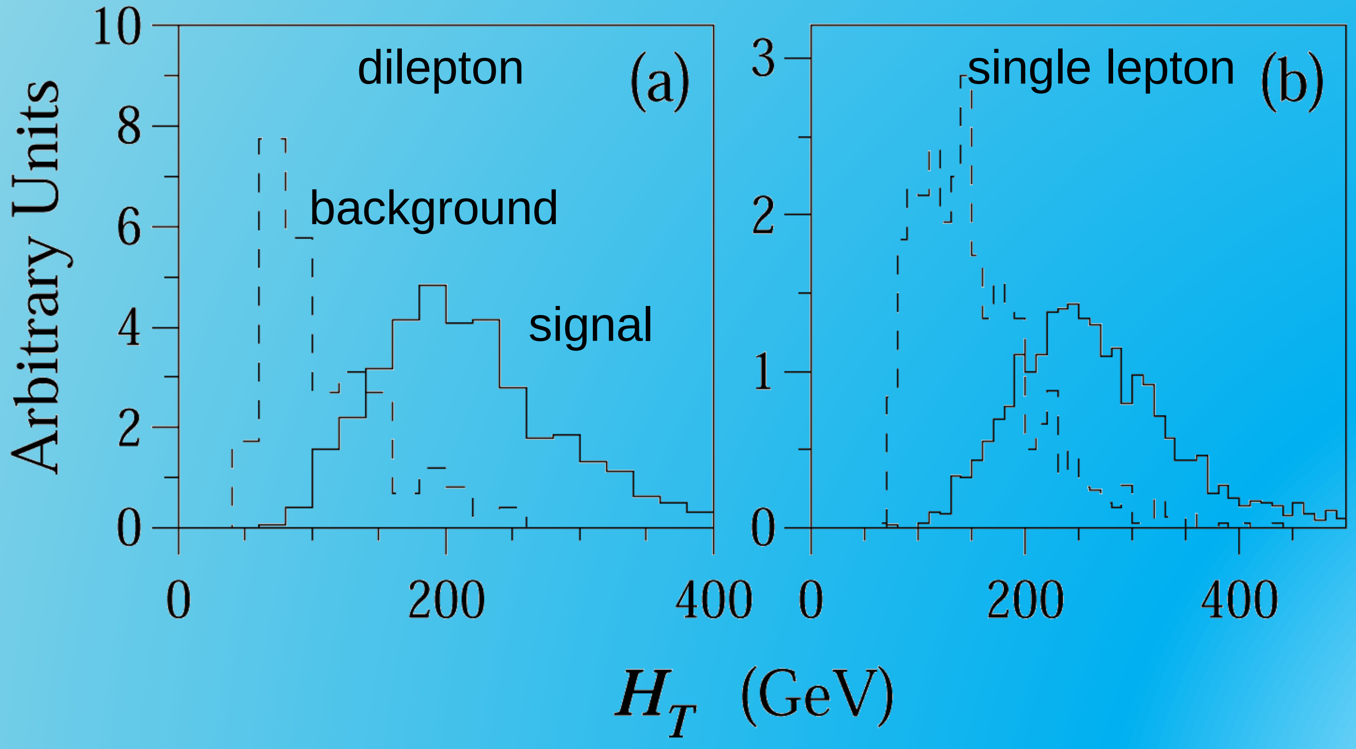
Discovery Papers

By early 1995 (Run Ia+b), analyzed x3.5 data sample.

D0: further optimized for high mass top quark; (50 pb^{-1})

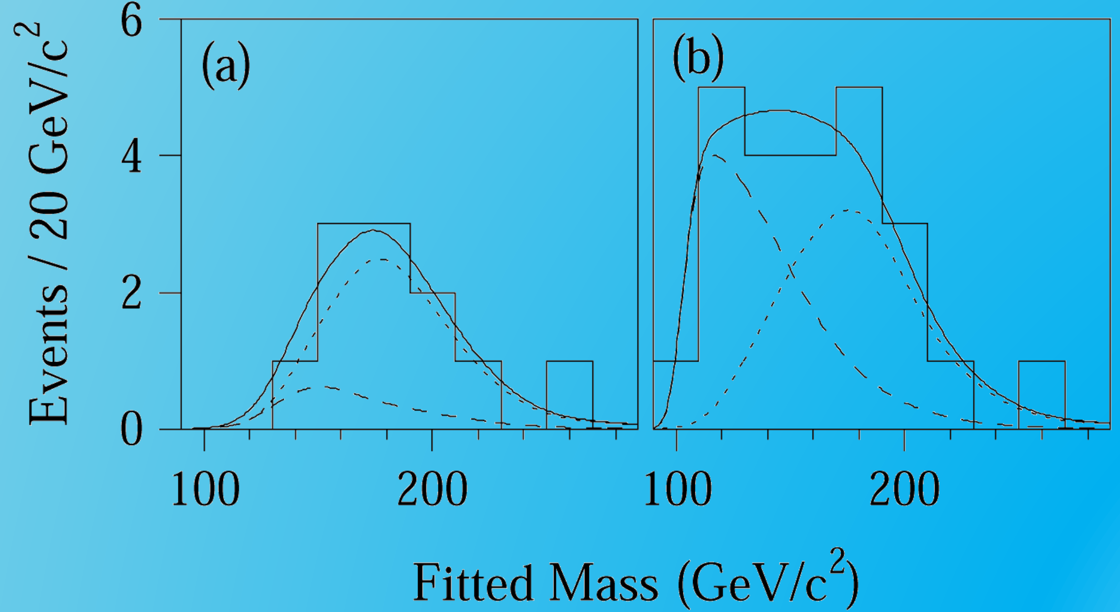
- **Require large H_T (ΣE_T of objects) to suppress background.**

  improves S/B by ~ x2.5



	estimated background	observed
dilepton	0.65 events	3 events
1 lepton, untagged	1.9	8
1 lepton, tagged	1.2	6
TOTAL	3.8	17

4.7σ excess



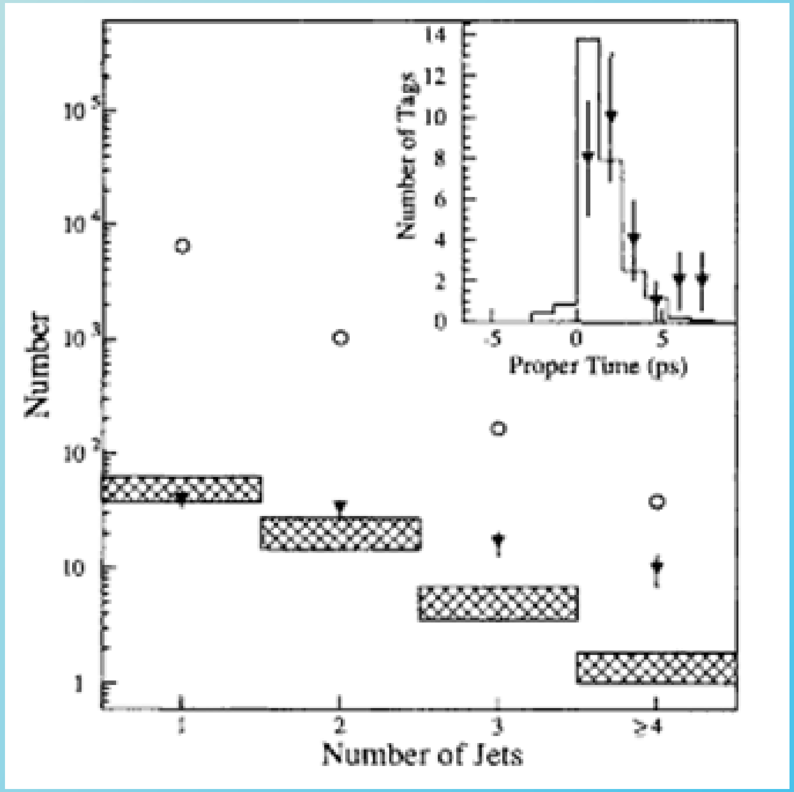
M_{top} = 199±30 GeV

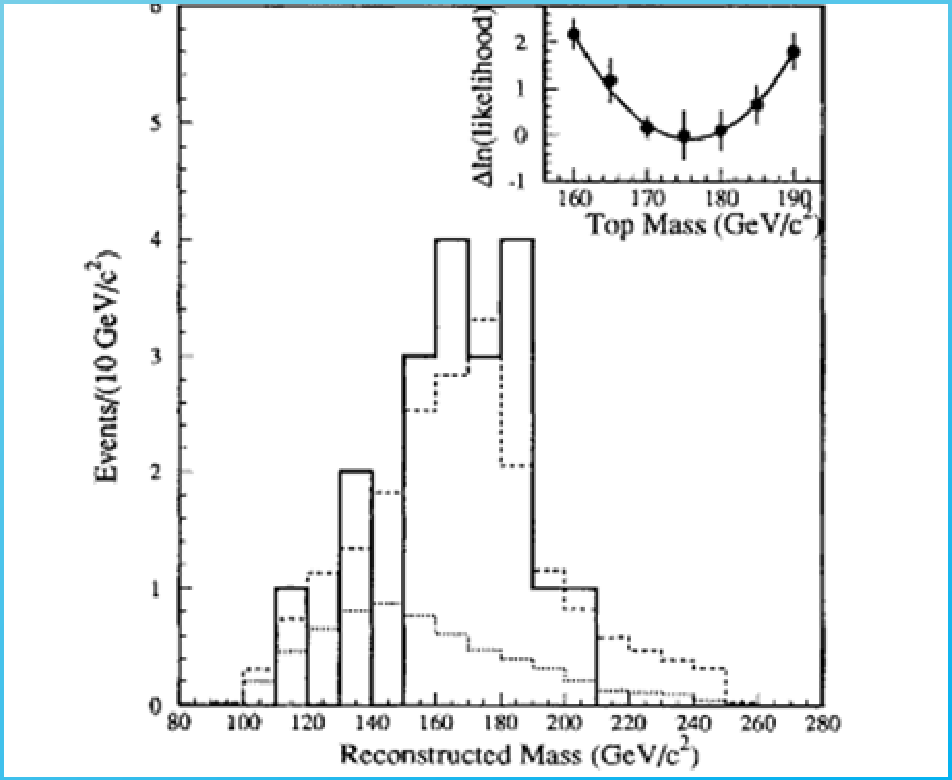
CDF: (67 pb^{-1})

- new improved SVX ⇒ x2 *b*-tag efficiency
- > 50% probability to tag at least 1 jet in a $t\bar{t}$ event
- previous "–" now OK with larger statistics

	estimated background	observed
dilepton	1.3 events	6 events
1 lepton, vertex b-tag	6.7	27
1 lepton, lepton *b*-tag	15.4	23

4.8σ excess





M_{top} = 176 ± 8 ± 10 GeV

- **CDF & D0 papers submitted simultaneously.**
- **This might be more than just the existence of another quark. In the Standard Model, a quark of this mass has a coupling to the Higgs boson of almost exactly 1, perhaps indicating a special role in Electroweak symmetry breaking.**

March 2, 1995: Joint seminar at Fermilab

Note

There were several other analyses in both D0 and CDF beyond the traditional cut-and-count method. These included:

- **multivariate techniques such as neural networks**
- **difference in expected jet E_T spectra for signal & background**
- **matrix element techniques**

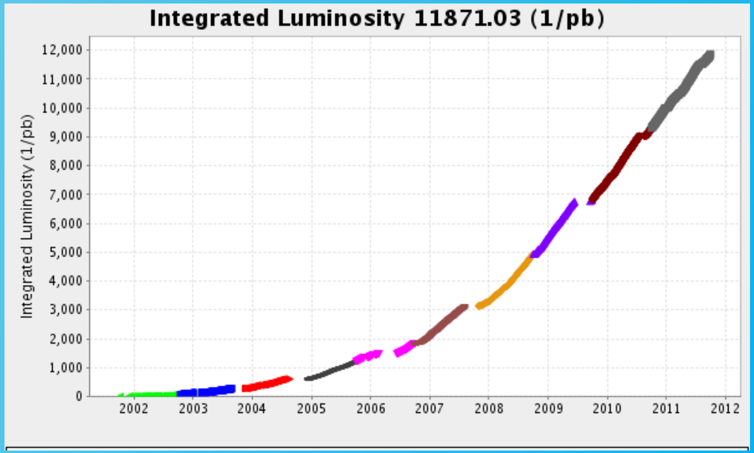
These were not used in the first publications. The collaborations were conservative, feeling that for discovering a new elementary particle they should rely on established techniques they believed the community would trust.

Of course, multivariate techniques soon became part of the standard toolkit for studying top quark properties, and, at the LHC, they are essential to almost all analyses.

Fermilab Final Results

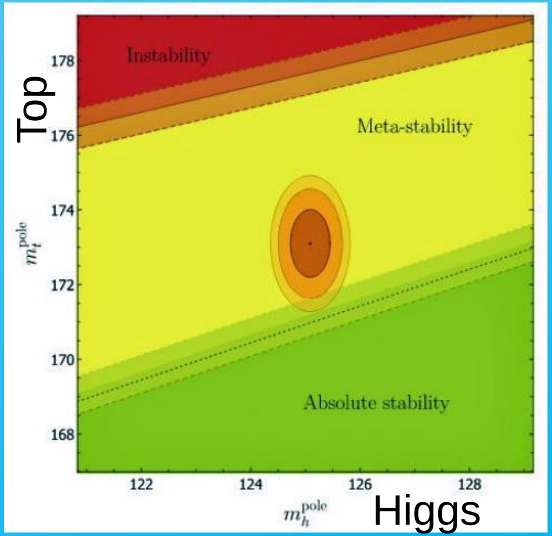
Throughout Run II and beyond, CDF and D0 continued to study the top quark with larger data sets and more powerful analysis techniques. Such studies can test the Standard Model and potentially find indications of physics beyond the Standard Model.

The integrated luminosity provided by the Accelerator Division during run II was 100 times larger than in Run I. Most top quark papers used 5-10 fb^{-1}.



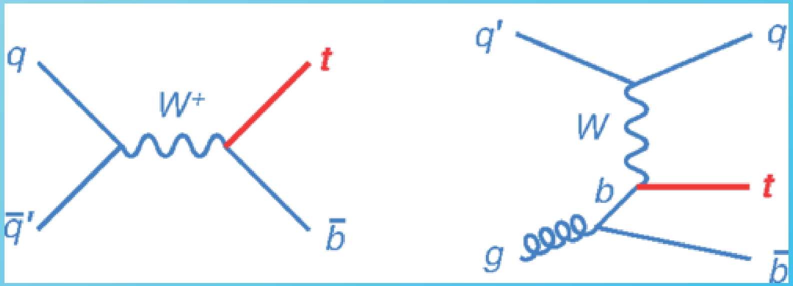
Top Mass

- **Precision knowledge of the top quark mass is important**
  - **Tests of the Standard Model**
  - **Yukawa coupling near 1**
  - **Question of stability of the universe**



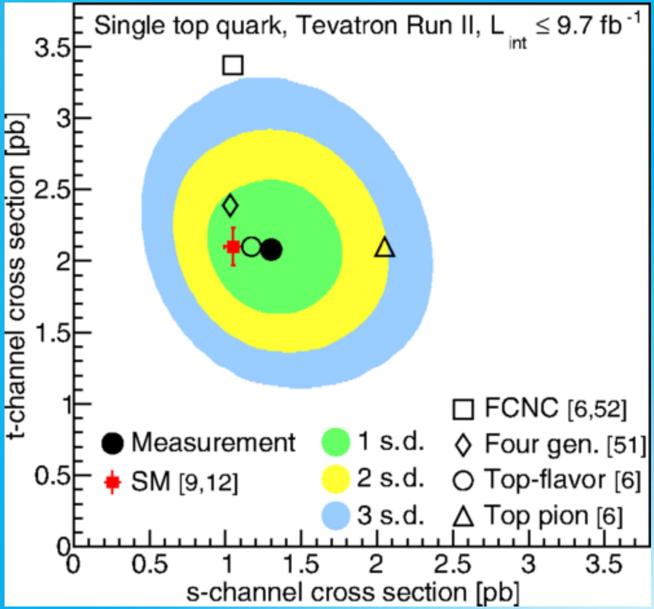
- **CDF/D0 combination of 12 measurements**
  - **173.18 ± 0.94 GeV (2012)**
- **D0 result with full Run II luminosity**
  - **174.95 ± 0.75 GeV (2017)**
- **The mass can also be determined from a comparison of the measured & predicted production cross sections.**
  - **172.8 ± 1.1 (theory) ± 3.2 (exp)**
- **The direct and indirect mass measurements each have theoretical challenges to convert them to the pole mass. (More later)**

Single Top Cross Section (V_{tb})



s channel t channel

- **Single-top production has a smaller production cross section than pair production and fewer handles for background rejection.**
- **The s-channel is more easily measured at the Tevatron than the LHC because of the $\bar{p}p$ initial state.**
- **D0 & CDF published a combined paper**
  - **s-channel and t-channel separated**

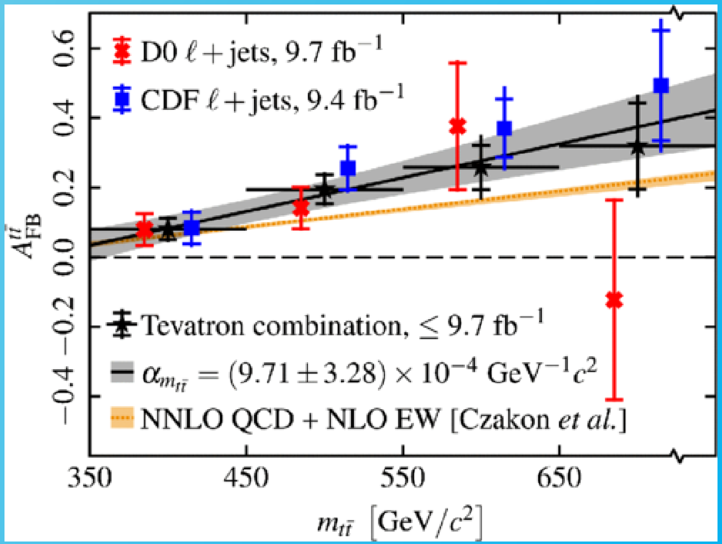


$$\left|V_{tb}\right| = 1.02^{+0.06}_{-0.05}$$

$$\left|V_{tb}\right| > 0.92$$

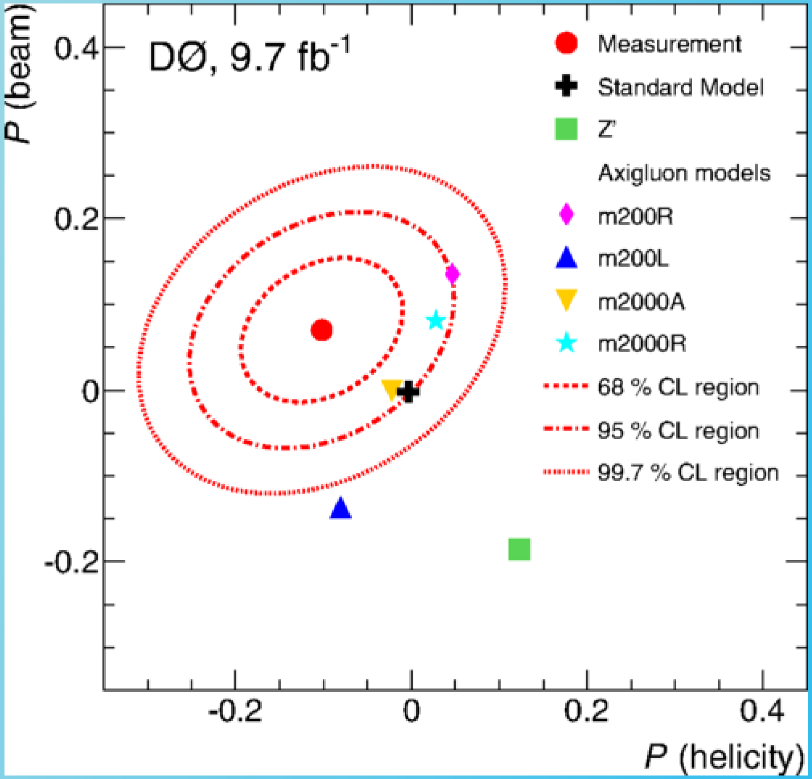
Forward-Backward Asymmetry

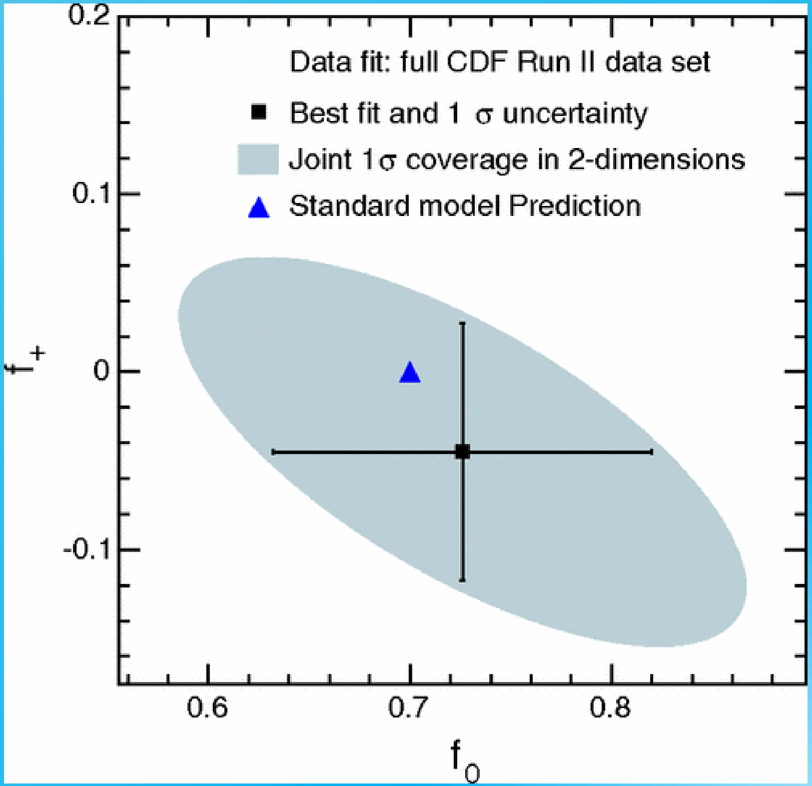
- Due to the asymmetric initial state at the Tevatron ($\bar{p}p$), there can be a forward-backward asymmetry in the produced top quark compared to the top antiquark.
- In the Standard Model, there is no asymmetry at leading order. An asymmetry does arise at higher order.
- The combined CDF & D0 result $A_{FB}^{t\bar{t}} = 0.128 \pm 0.025$ is consistent with the Standard Model. Differential asymmetries are within 1.5σ of Standard Model predictions.



Polarization

- D0 measured the top quark polarization along several axes.
- CDF measured the polarization of the daughter *W* boson.
- Results were consistent with the Standard Model predictions.



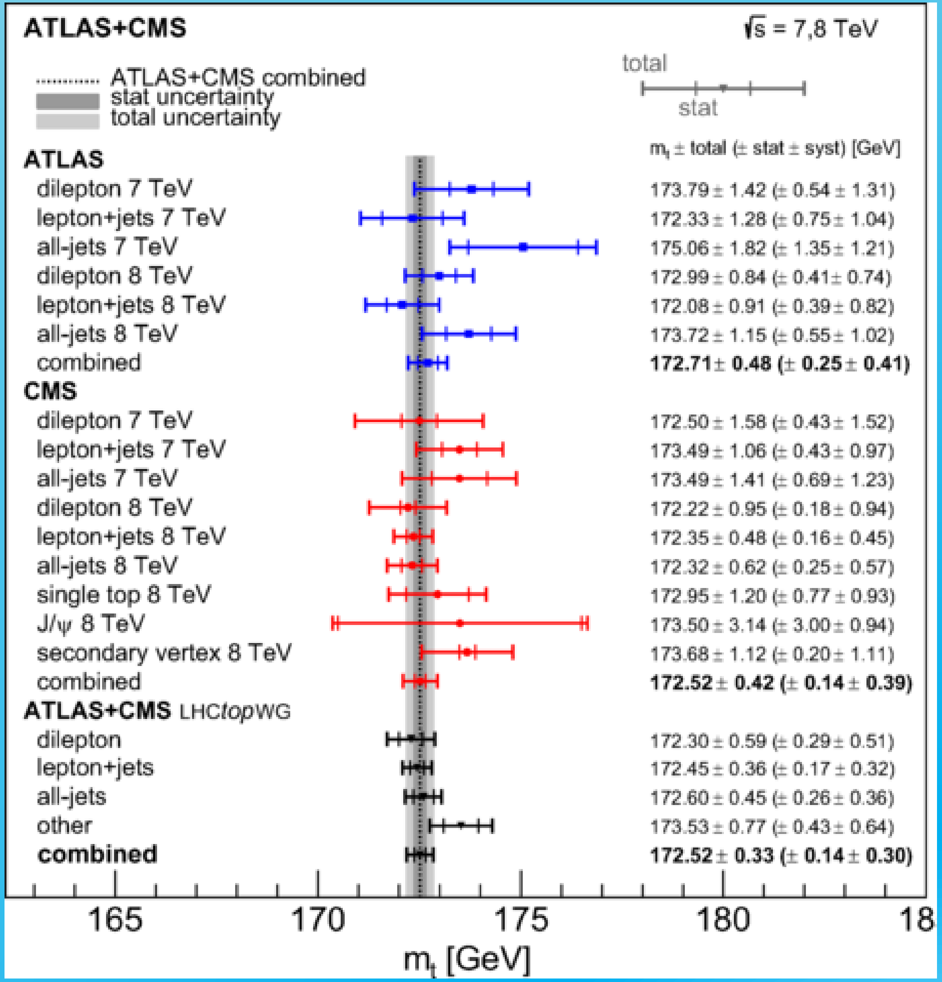


The Top Quark Today

- $\sigma_{LHC}(t\bar{t}) \sim 100 \times \sigma_{Tevatron}(t\bar{t})$
  - Tevatron analysis: ~ 1000 signal events
  - LHC analysis: ~ 100,000 signal events (with much more to come)
- **Machine learning techniques**
  - In their infancy at the time of the top quark discovery
  - Enormous development in the science and computing communities
  - Sophisticated ML provides more sensitivity/event

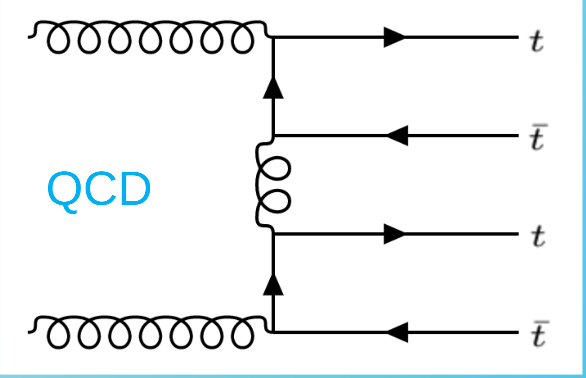
Top Quark Mass

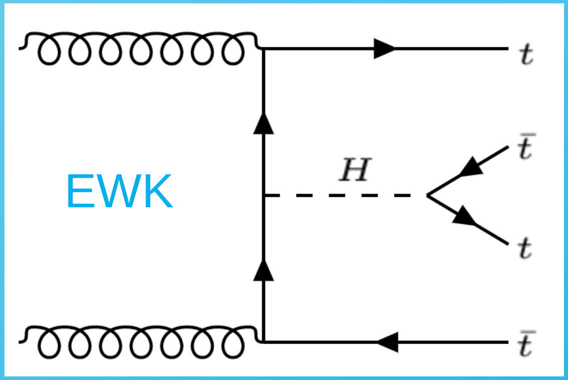
- **Direct mass measurements**
  (Monte Carlo mass)
  - **Traditional (7,8 TeV):**
    $$m_t = 172.52 \pm 0.33 \text{ GeV}$$
    (Similar 13 TeV uncertainty)
  - **High p_T boosted top (ATLAS):**
    $$m_t = 172.95 \pm 0.53 \text{ GeV}$$
- **Indirect mass measurements (via the cross section)**
  - **Pole mass, ~1 GeV uncertainty**



- **Each of these have different experimental systematics**
- **Different challenges to the theoretical mass**
- **Projections to the HL-LHC: few hundred MeV, exp. & theory**
- **If achieved, discriminate metastable & stable universe.**

4 Tops
(if 2 are good, 4 are better)

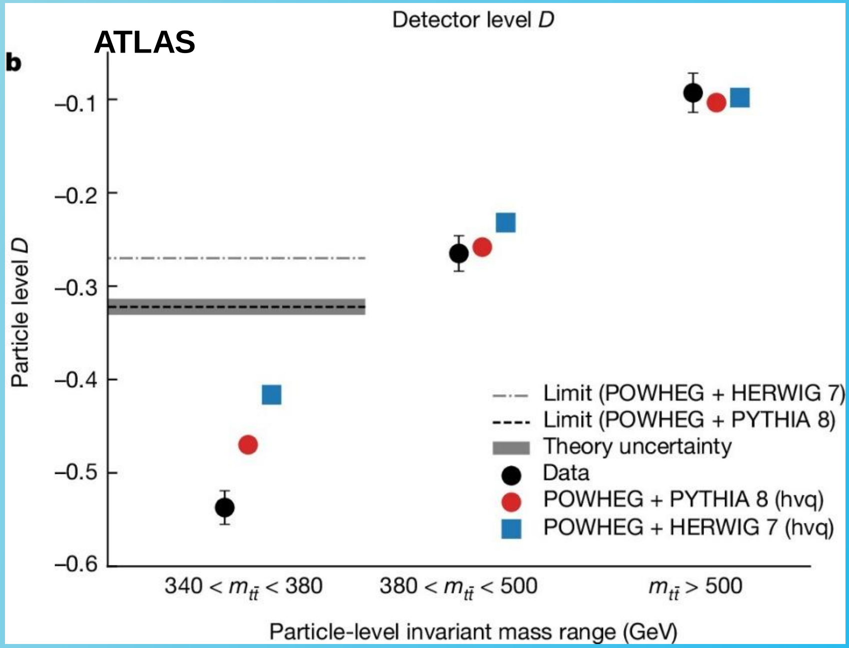


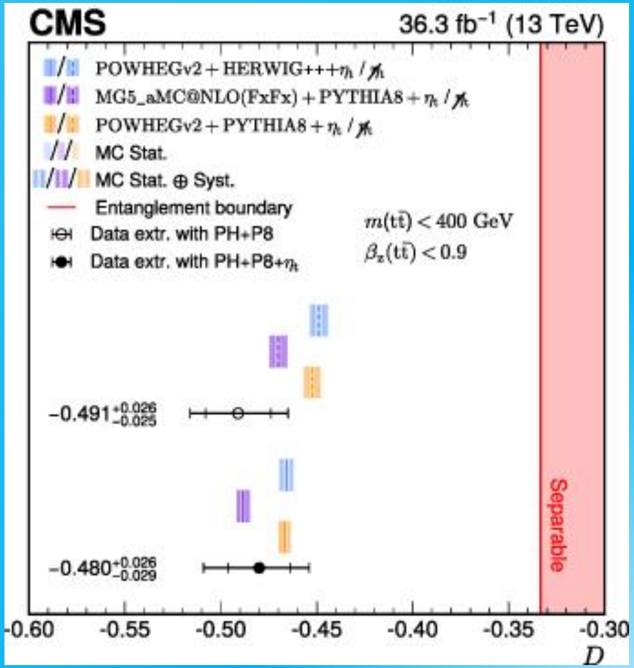


- **Study QCD, off-shell Higgs, and possible new resonances**
- $\sigma_{SM}(t\bar{t}t\bar{t}) = 13.4^{+1.0}_{-1.8}$ fb
  $\sigma_{CMS}(t\bar{t}t\bar{t}) = 17.7^{+4.4}_{-4.0}$ fb $\sigma_{ATLAS}(t\bar{t}t\bar{t}) = 22.5^{+6.6}_{-5.5}$ fb
- **New limits on heavy scalar bosons**
- **A measurement of the Higgs width by combining this process (off-shell H) with on-shell Higgs production**

Quantum Entanglement

- An element of standard quantum mechanics that is essential for quantum computing, cryptography, etc.
- Can it be seen at high energy in relativistic processes?
- $t\bar{t}$ spin correlations can be measured from the daughters.
- *D* is a measure of the angle between the leptons in the top rest frames. Entangled state if $D < -1/3$.





Conclusions

- **The search for the top quark began almost 50 years ago.**
- **The culmination occurred in this building 30 years ago this month when the discovery of the top quark was announced.**
  - **It represented the work of many in the Accelerator Division and the CDF and D0 collaborations, especially the very talented young faculty, staff, postdocs, and students.**
- **Through the remainder of Tevatron running and long beyond, studying top quark properties was a high priority.**
- **At the LHC, the top quark has become a tool for studying the Higgs boson and searching for new phenomena.**
- **As often happens with discoveries, today's sensation is tomorrow's background: suppress, measure, subtract!**