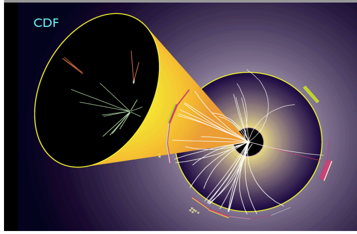

Discovery of the Top Quark
Silver Jubilee



SPEAKERS

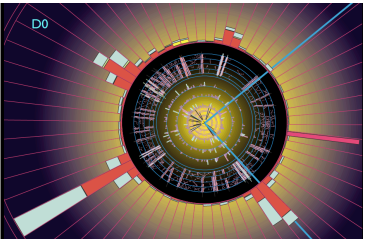
John Peoples,
Former Fermilab Director

Giorgio Bellettini, CDF/INFN/FNAL
(Bill Carithers, CDF/LBNL)

Paul Grannis, D0/Stony Brook

Hugh Montgomery, D0/FNAL/JLAB

Mel Shochet, CDF/UChicago



Moderator: Pushpa Bhat, D0/FNAL

Top Quark Silver Jubilee

Evolution of the Tevatron to 1995

John Peoples

Fermilab’s Path to Pbar-P Collisions at 2 TeV

- 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
- Two superb detectors CDF (1987) and D0 (1992)

1987 Collider Run peak luminosity 10^{29} cm^{-2} s^{-1} More luminosity needed

- CDF observed a comparable number of W and Z at 1.6 TeV cm in their 1987 run data as UA-1 and UA-2 had observed at .54 TeV at CERN between 1983 (their discovery year) and 1987.
- The only path open for a discovery was through much more luminosity. The SSC was designated to be the US high energy collider (40 TeV) of the future.
- The higher luminosity 1988-89 Collider run ($2x10^{30}$) yielded more W and Z than UA-1 and UA-2 would observe; But no discovery.
- Fermilab developed a plan for substantially higher luminosity in two phases.

Phase 1 provided the luminosity that led to a discovery

1988-89 Collider Run Goals and Achievements

	Goals	Achieved
Beam Energy [GeV]	900	900
Number of bunches/beam	3	6
Number of beam crossings	6	12
Peak Luminosity[cm^{-2} s^{-1}]	10^{30}	$2x10^{30}$
Initial Lifetime [hr]	12	12

Phase I Collider Upgrades

The phase I Collider Upgrade for run Ia consisted of:

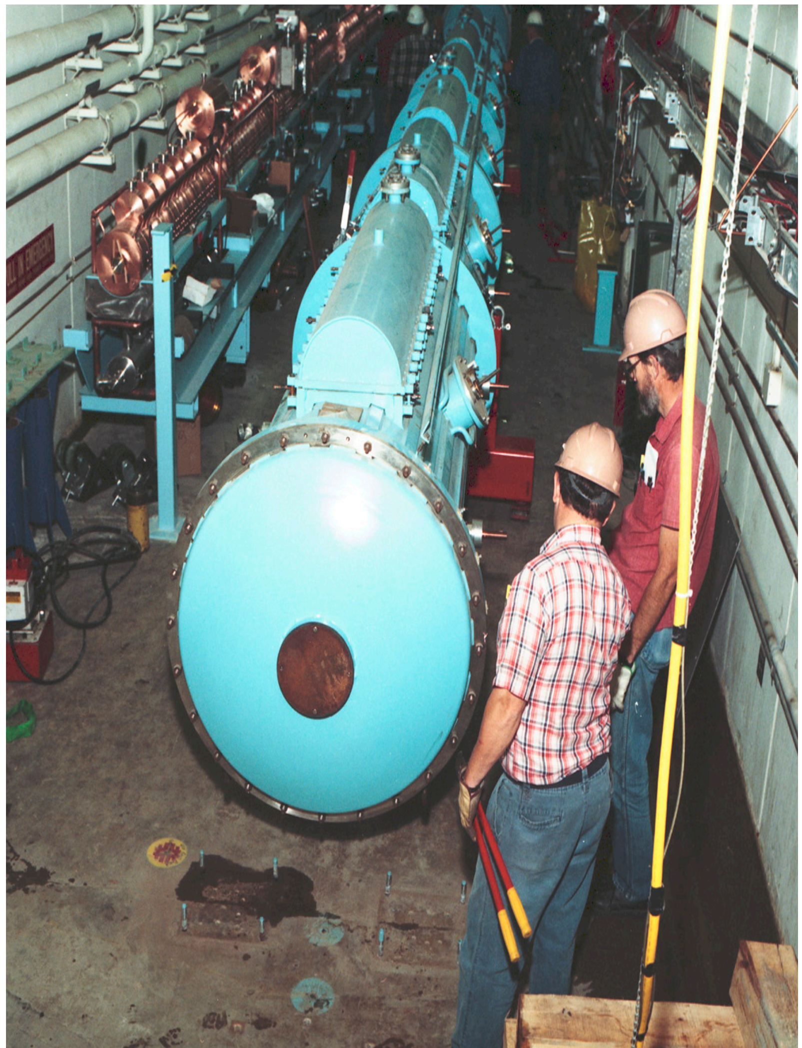
- Matched low beta insertions for CDF (B0) and D0
- Electrostatic separators to create helical orbits that reduce the number of beam-crossings from 12 to 2 (CDF and D0)

The phase I Collider Upgrade for run Ib consisted of:

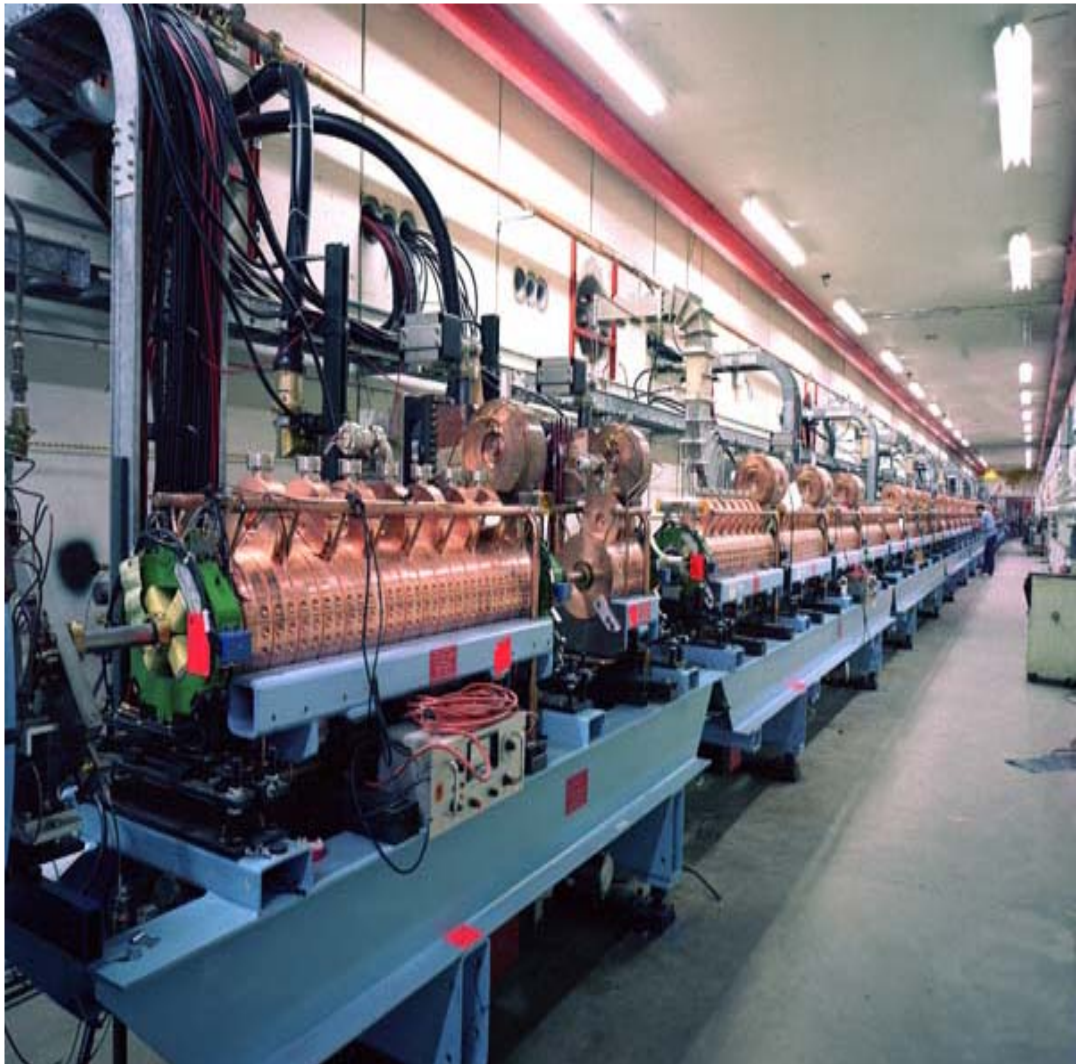
- Linac energy upgrade from 200 MeV to 400 MeV

CDF and D0 detectors installed and ready for collisions at the start of Run Ia

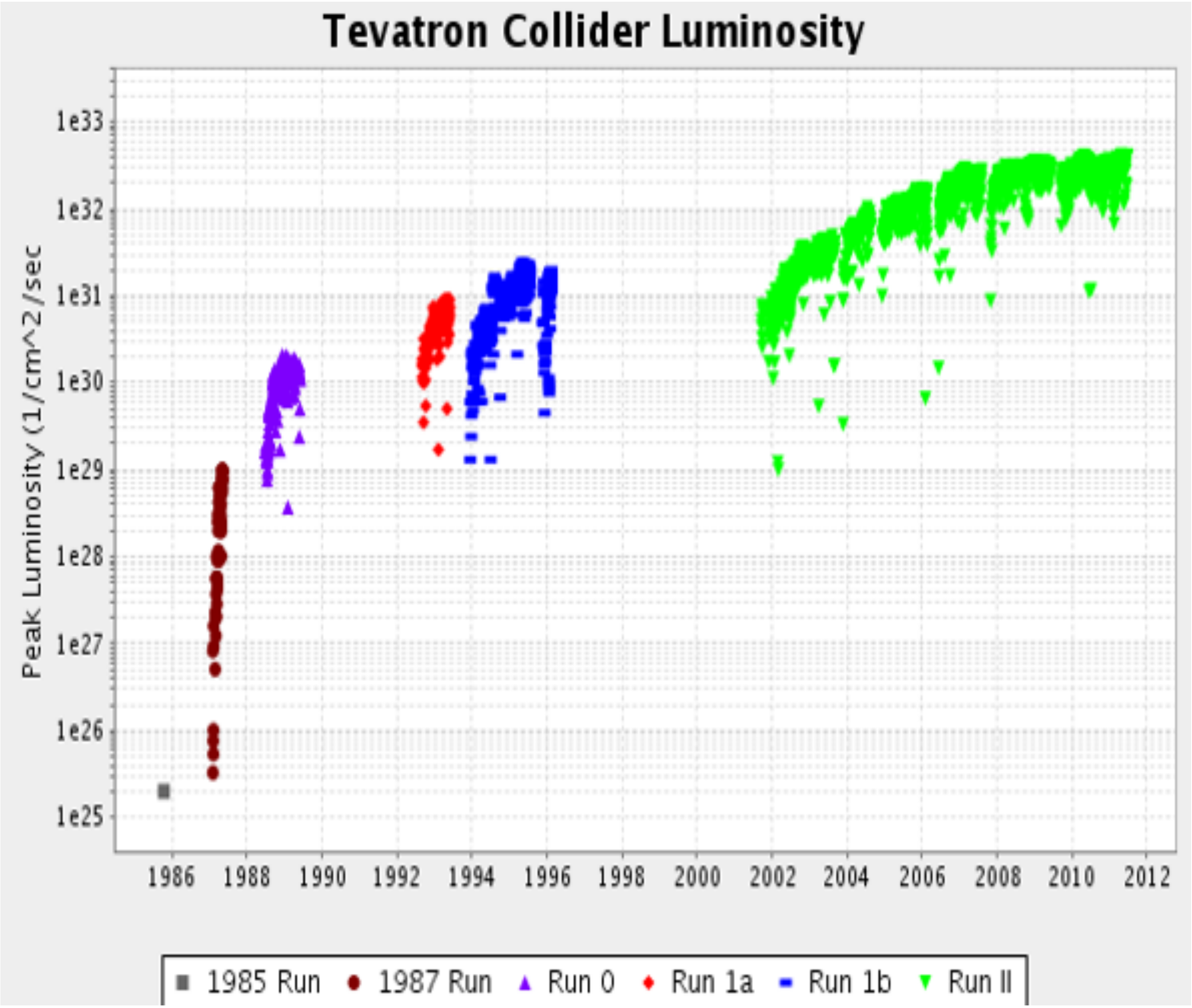
200 MeV Drift Tube Tanks ready to come out



400 MeV Linac Upgrade in place




The Last Magnet Installed
In The Energy Saver
March 18 1983


Tevatron Collider Luminosity
Peak Luminosity (1/cm^2/sec
1e33
1e32
1e31
1e30
1e29
1e28
1e27
1e26
1e25
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
1985 Run
1987 Run
Run 0
Run 1a
Run 1b
Run II

Run I Performance Statistics

	Run Ia	Run Ib
Duration	August 1992-June 1993	November 1993-February 1996
Peak Luminosity	9.2×10^{30} cm^{-2} sec^{-1}	2.5×10^{31} cm^{-2} sec^{-1}
Typical Luminosity	5×10^{30} cm^{-2} sec^{-1}	1.6×10^{31} cm^{-2} sec^{-1}
Stacking Rate	4.85×10^{10} hr^{-1}	7.02×10^{10} hr^{-1}
Maximum Stack Size	150×10^{10} $\overline{p}$'s	221×10^{10} $\overline{p}$'s
Delivered Integrated Luminosity	31.7 pb^{-1}	147 pb^{-1}

The CDF search for the top quark

Giorgio Bellettini

Also on behalf of William Carithers

Fermilab 2020 Users Meeting

The Pisa-Stony Brook R801 detector at the ISR

An ancestor of CDF at the CERN ISR.

The Italians had in mind to build a similar detector at the Tevatron where particle energies would also be measured

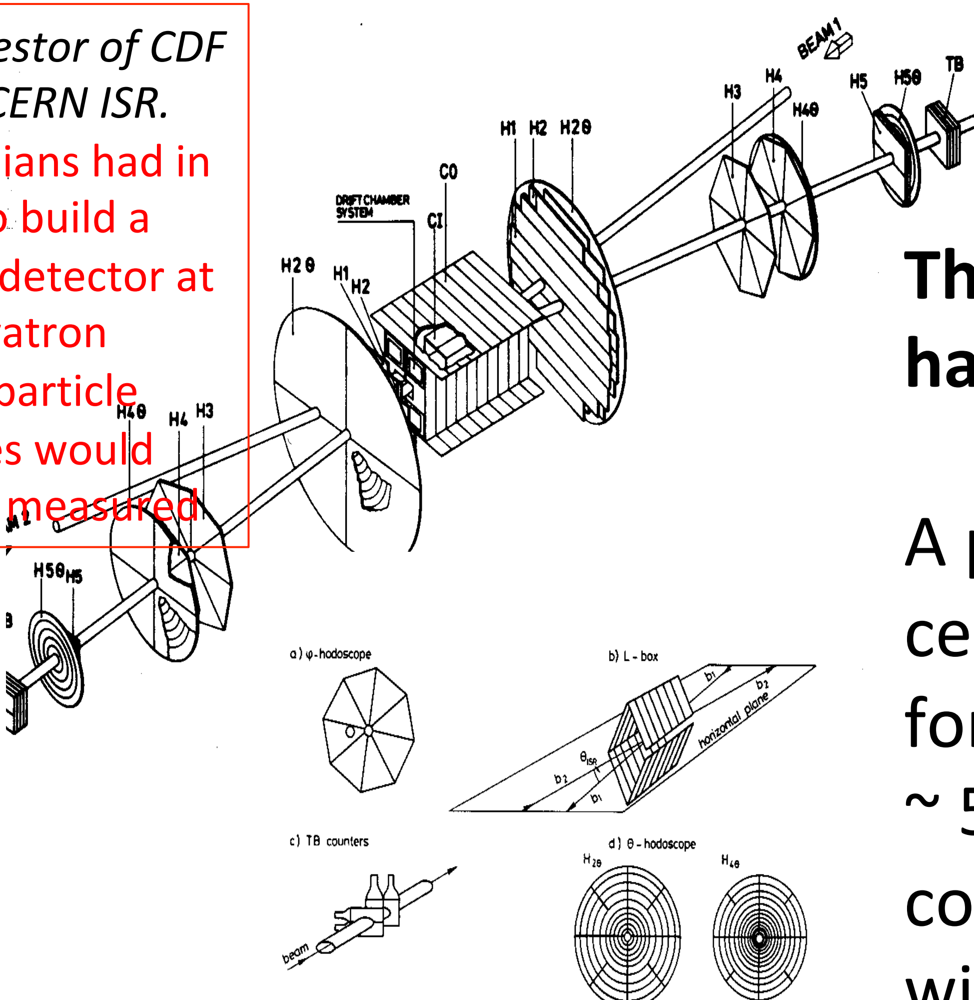


Fig. 2. Schematic drawing of hodoscope counters. a) H_1 hodoscope. Hodoscope H_2 is similar, but the ϕ-bins are rotated by $\pi/16$. Hodoscopes H_3 and H_4 are like H_1, H_2, but with no off-centre hole. b) L-box. Only the first layer is shown. The second layer is behind it, with a lead plate in between. c) TB counters. d) θ-hodoscopes. The outer rings are split into octants, the inner rings into quadrants.

120

The first 4π detector at a hadron collider

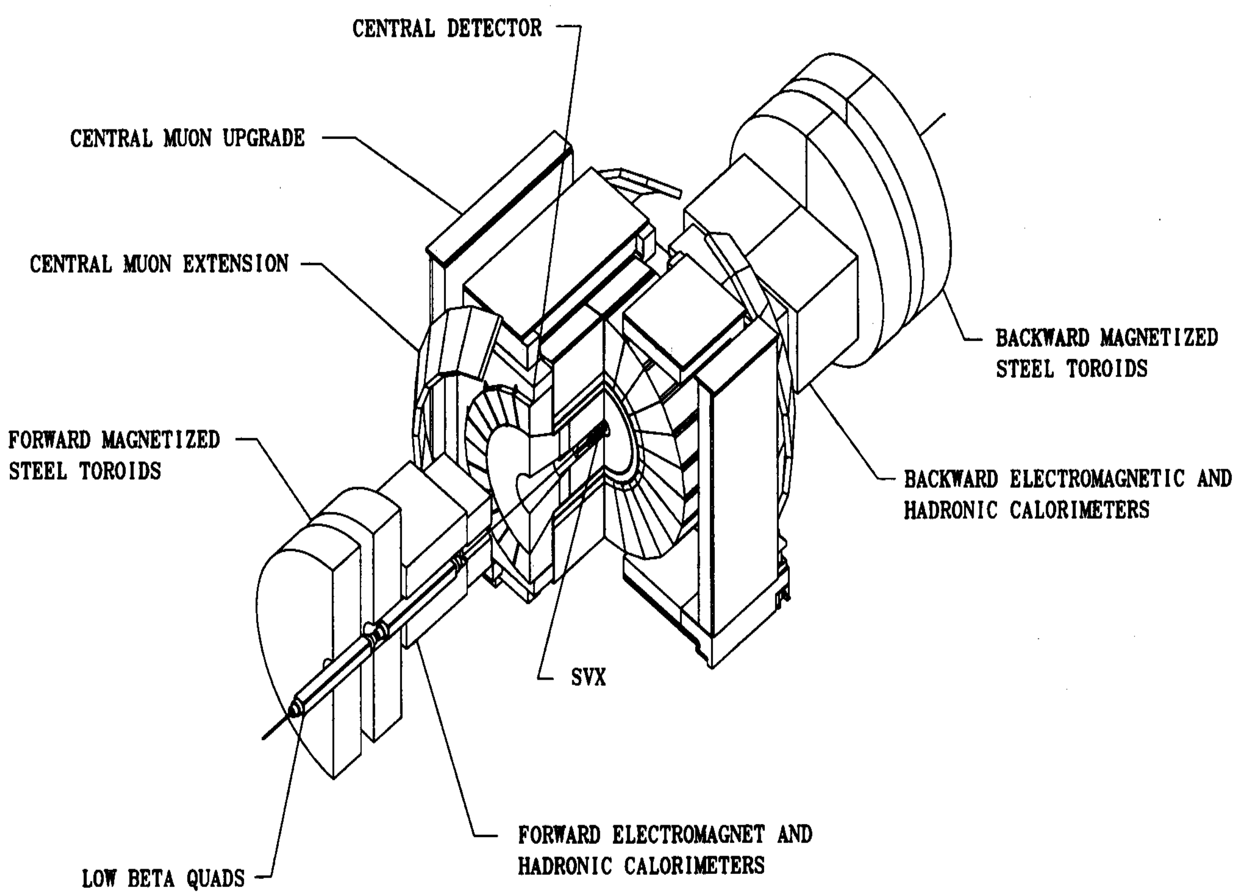
A plastic scintillator central box and two forward cones split into ~ 500 ϕ, θ bins with ~ constant pseudorapidity width

1981: CDF1 Design Report

CDF was a USA-Japan-Italy Collaboration

57 American, 15 Japanese,
15 Italian authors

CDF1 layout (1985-1995)



A calorimetric version of R801.

Particle energies were measured in projective towers in a central barrel and two forward calorimeter cones with ~ constant pseudorapidity width.

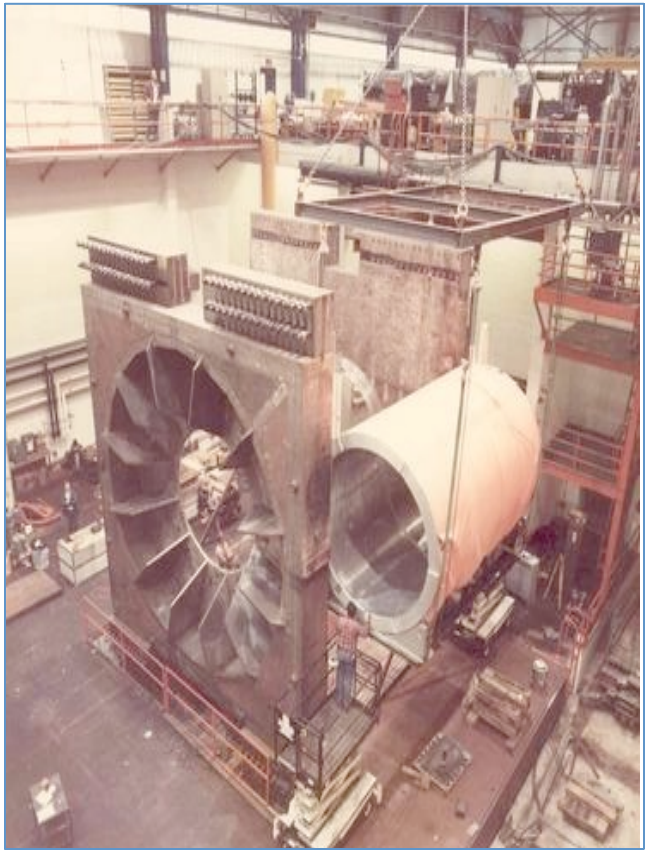
The solenoid yoke in 1985

The superconducting coil came from Japan

USA

Jap
an

Italy

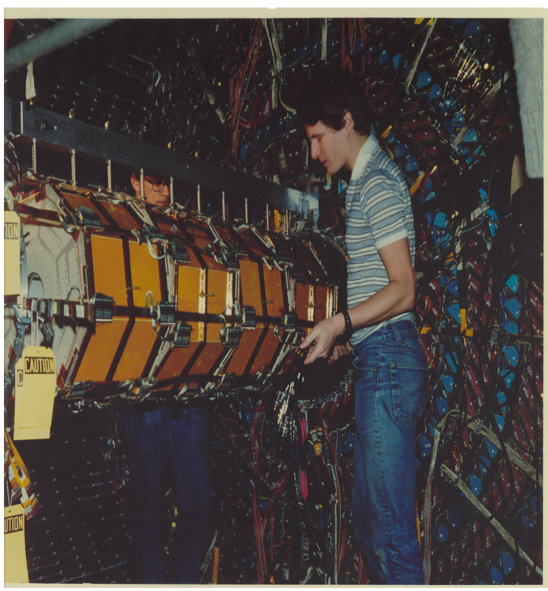


Solenoid was 6 m. long and 3 m. in diameter

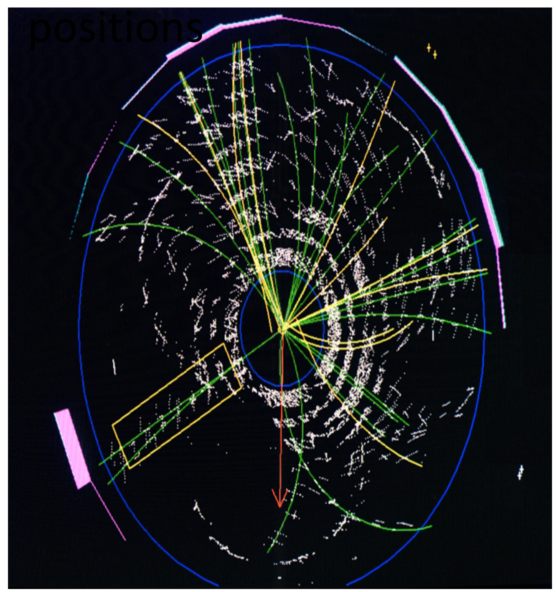
1,4 Tesla axial magnetic field

Some major components of CDF1

The vertex time projection chamber VTPC detected the charged prongs just outside the beam vacuum pipe



Outside the VTPC the central tracking chamber measured the bending of charged tracks in 84 radial positions

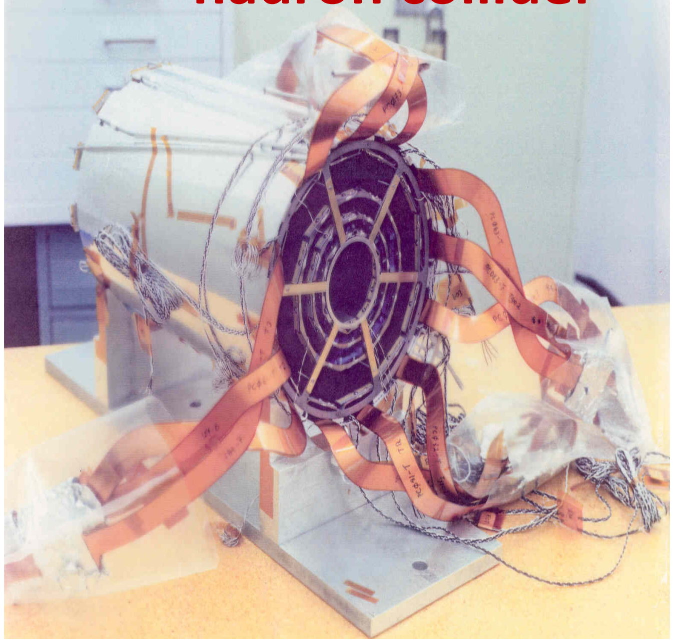


Outside the coil 48 scintillator calorimeter wedges were split into towers projecting to the detector center

The silicon vertex detector SVX1

Installed in 1991

The first silicon vertex detector at a hadron collider



½ of SVX1 in the Pisa university archive.

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Top-pair events if $M_{top} > M_W$

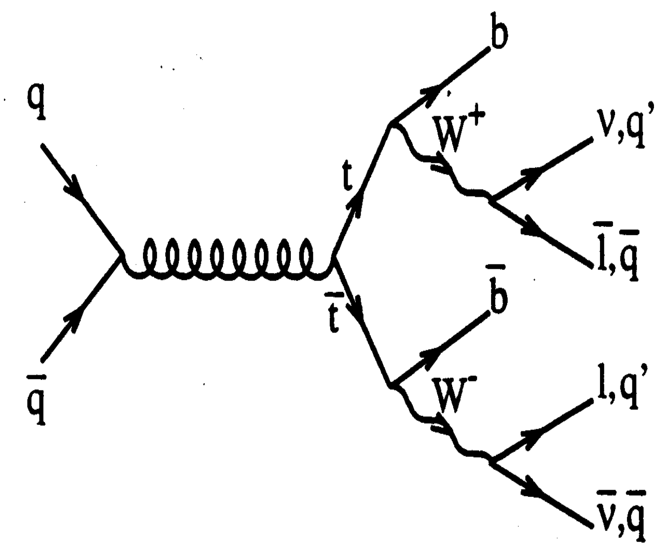


Figure 28: Tree level top quark production by $q\bar{q}$ annihilation followed by the Standard Model top quark decay chain.

Final states will depend on how the W`s decay:

1-Dilepton

2-Single lepton

3-All hadronic

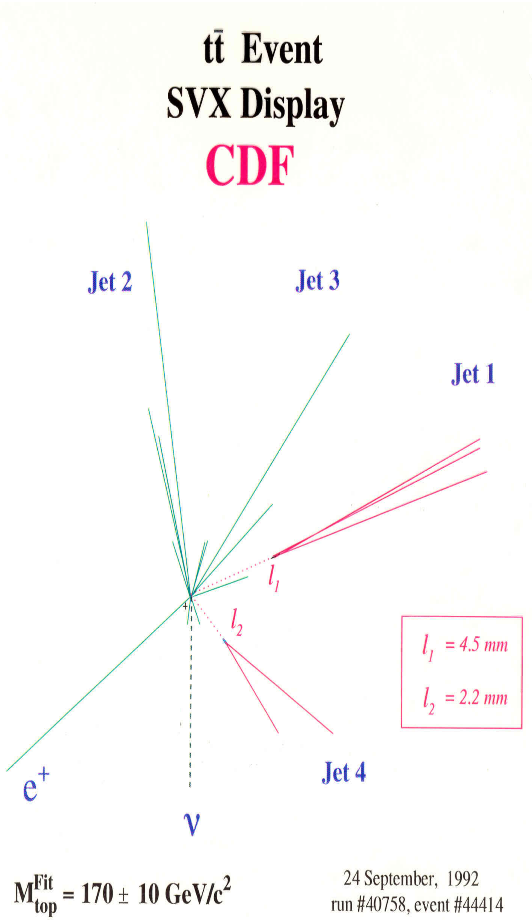
Approaching the discovery-1
1992. The excess of large Et central jets

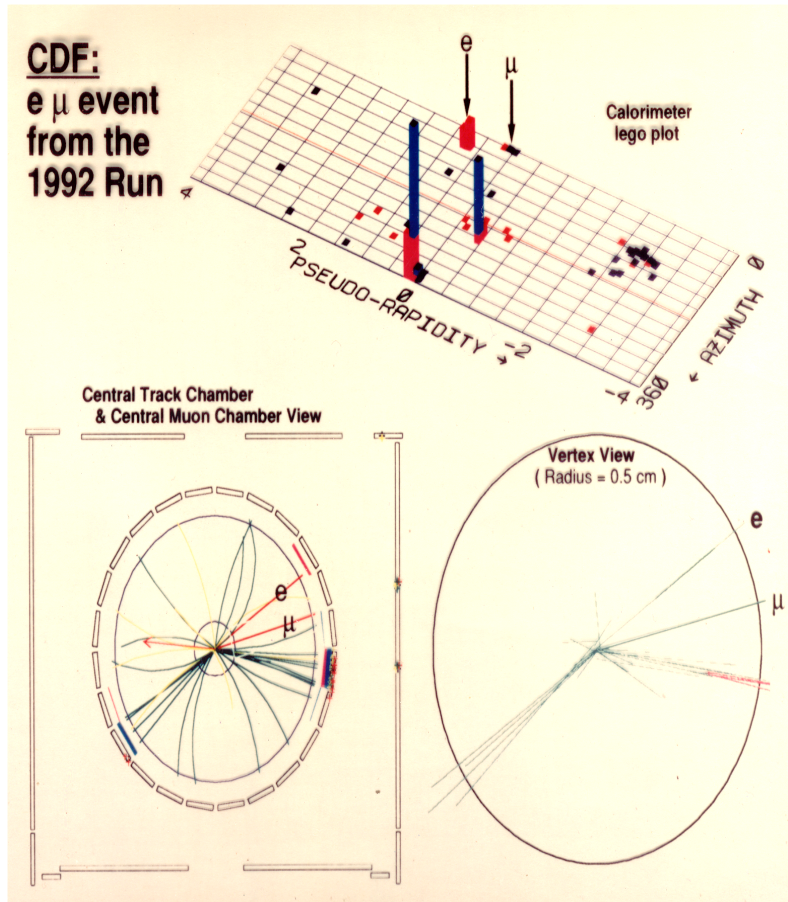
F. Abe et al Phys. Rev. 51D, 4623 (1995)

Many more jets with large transverse energy were found at large angles than expected from QCD background

Simulations showed that this was as expected if jets were coming from top decays

Approaching the discovery-2
1992. Some beautiful Top pair candidates





The projective calorimeter and the SVX provided some fascinating pictures of events

July 1994, Evidence paper from 19.3 pb^{-1}

F. Abe et al., Phys. Rev. Letters 73, 225 (1994)

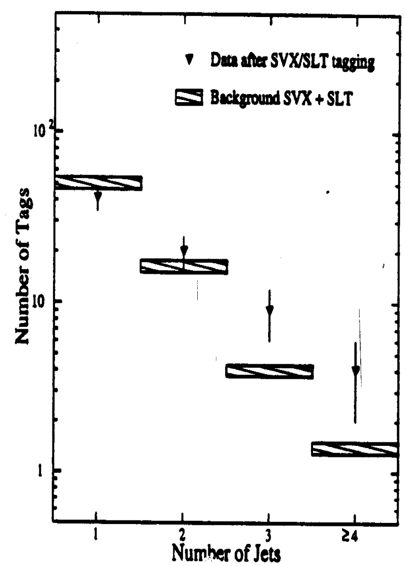


Figure 34: The sum of CDF SVX and soft lepton tags observed in W + jets data compared with background estimates. The three-jet and four-jet bins are the $t\bar{t}$ signal region.

2 eμ dilepton events observed, 0.56 expected

13 b-tagged jets observed in single lepton candidates, 5.4 expected

Overall probability of the 15 tag excess p = 0.26 %

Rate of b-tags > expectation in single lepton events with ≥ 3 jets

July 1994, Evidence paper

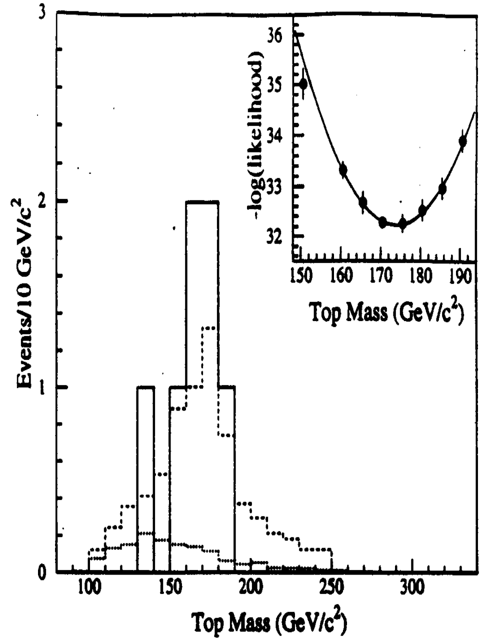


Figure 35: CDF top mass distribution (solid histogram) compared with the W + jets background prediction (dots) and the predicted signal+background distribution normalized to the data for $m_t = 175$ GeV (dashed). The inset shows the likelihood fit results.

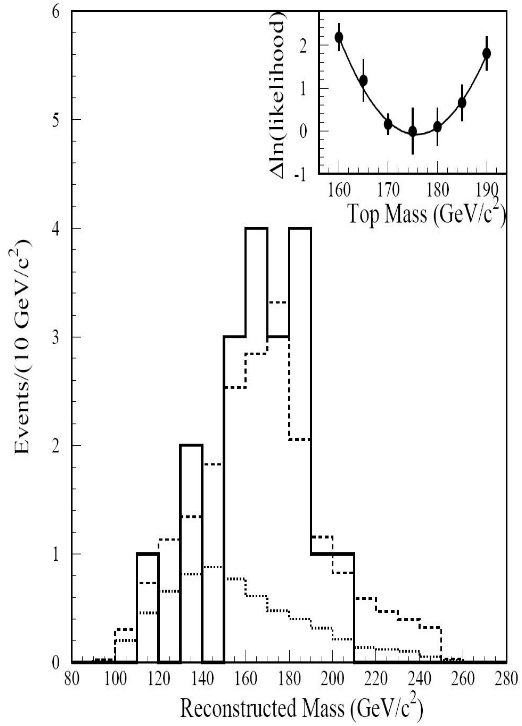
Fitted mass

$M_t = 174 \pm 17\ \mathrm{GeV}/c^2$.

Top quark mass from 7 single lepton events

April **1995: Discovery paper from 67 pb^{-1} of data**

F. Abe et al Phys. Rev. Letters 74, 2626 (1995)



Mass from 9 single lepton events

50 b-tagged jets in single lepton events
+ 6 dilepton events.
Overall probability of the excesses **p ≈ 10^{-6}**

Fitted mass

M_t = 176 ± 13 GeV/c^2

43 Japanese, 63 Italian out of 436 authors in the discovery paper

Concluding comment

In Run2 from 2001 to 2011 the upgraded CDF collected data with ≈ 10 fb^{-1} at √s = 1,98 TeV

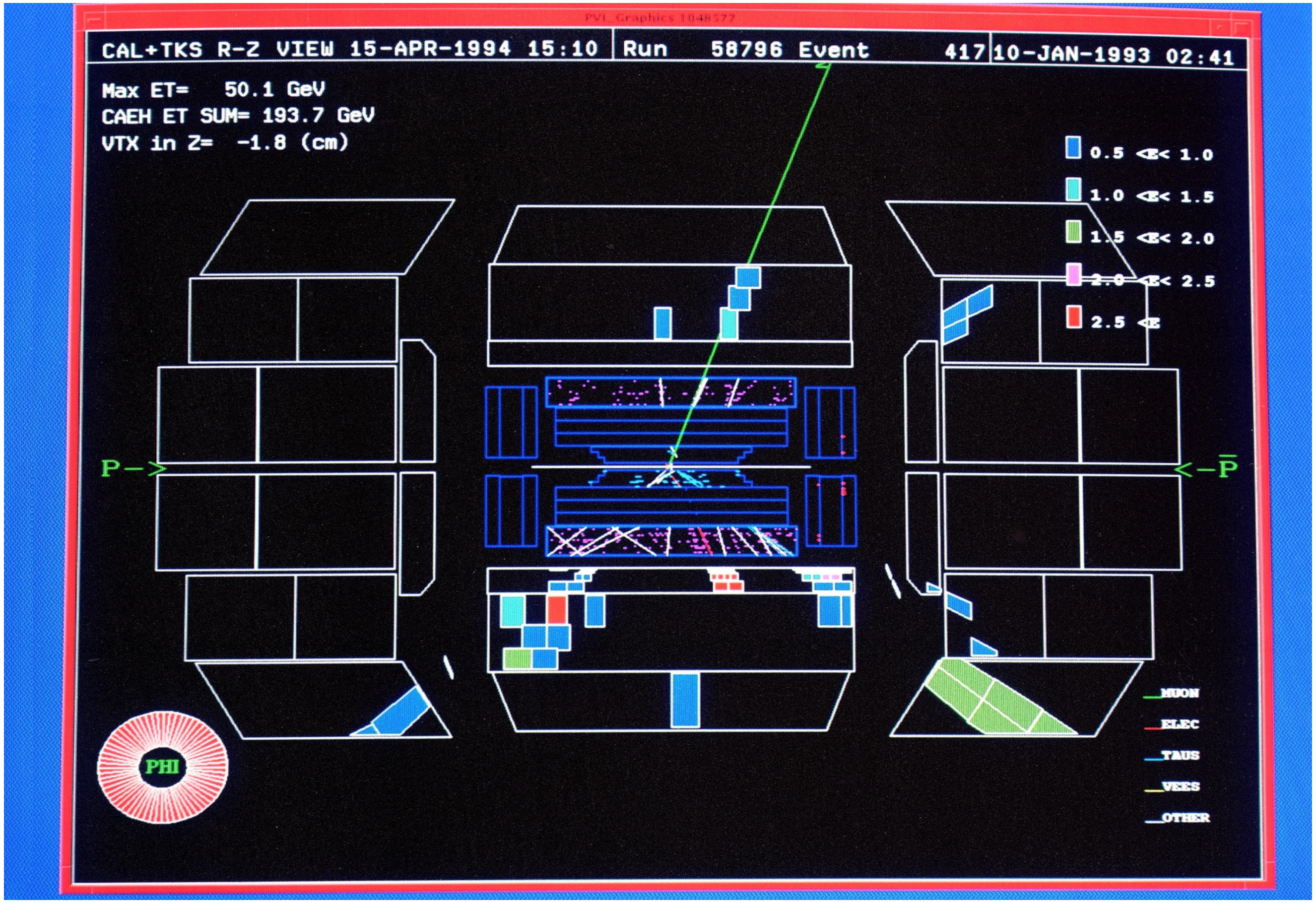
The top discovery was the highlight of Run1, but the the Run2 physics campaign of the USA-Japan-Italy CDF Collaboration produced a harvest of major results spanning most fields of HEP

The Top Quark Discovery
as seen from D0

Paul Grannis
Hugh Montgomery

Fermilab Users Meeting
August 12, 2020

A DZero Top Quark?

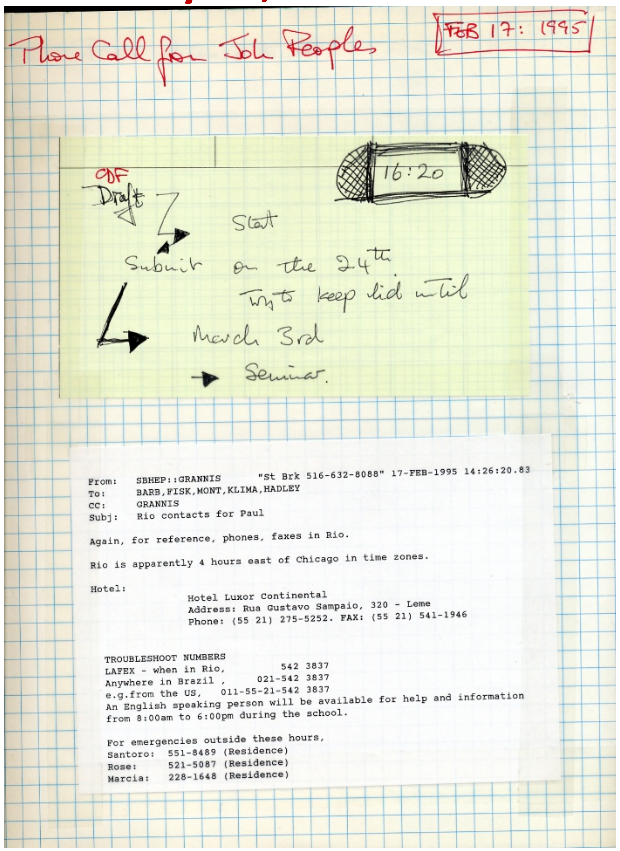


100 GeV electron; 200 GeV muon; 100 GeV MET; 25 and 22 GeV jets

$t\bar{t} \to W^+b\ W^-b \to (e^+\nu)\ b\ (\mu^-\nu\ b)$ candidate with very low background

Agreed process in action

February 17, 1995 Phone Call from John Peoples


Phone Call from John Peoples

FEB 17: 1995

16:20

Draft

Start

Submit on the 24th

Try to keep lid until

March 3rd

Seminar

From: SBHEP::GRANNIS "St Brk 516-632-8088" 17-FEB-1995 14:26:20.83
To: BARB,FISK,MONT,KLIMA,HADLEY
CC: GRANNIS
Subj: Rio contacts for Paul

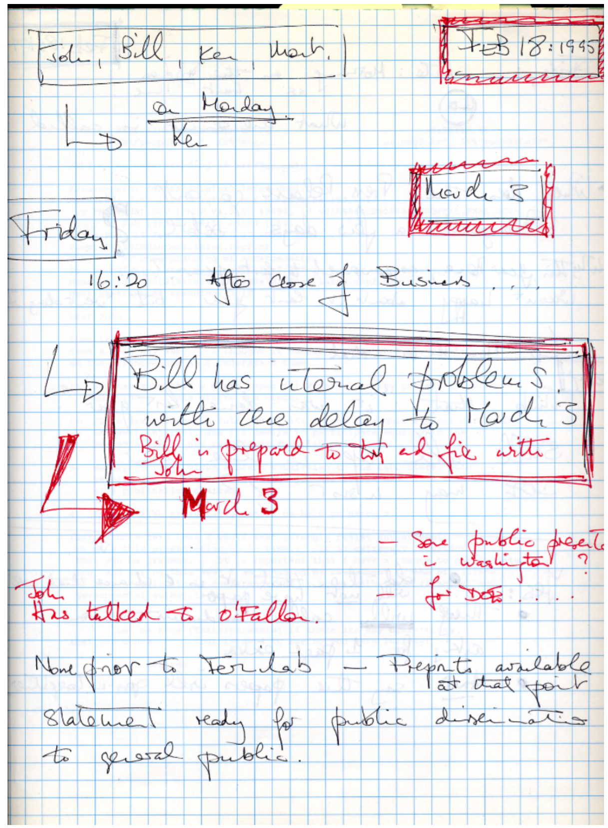
Again, for reference, phones, faxes in Rio.

Rio is apparently 4 hours east of Chicago in time zones.

Hotel:
Hotel Luxor Continental
Address: Rua Gustavo Sampaio, 320 - Leme
Phone: (55 21) 275-5252. FAX: (55 21) 541-1946

TROUBLESHOOT NUMBERS
LAFEX - when in Rio, 542 3837
Anywhere in Brazil , 021-542 3837
e.g.from the US, 011-55-21-542 3837
An English speaking person will be available for help and information from 8:00am to 6:00pm during the school.

For emergencies outside these hours,
Santoro: 551-8489 (Residence)
Rose: 521-5087 (Residence)
Marcia: 228-1648 (Residence)


John, Bill, Ken, Mark

FEB 18: 1995

on Monday Ken

March 3

Friday

16:20 After close of Business . . .

Bill has internal problems with the delay to March 3

Bill is prepared to live with

March 3

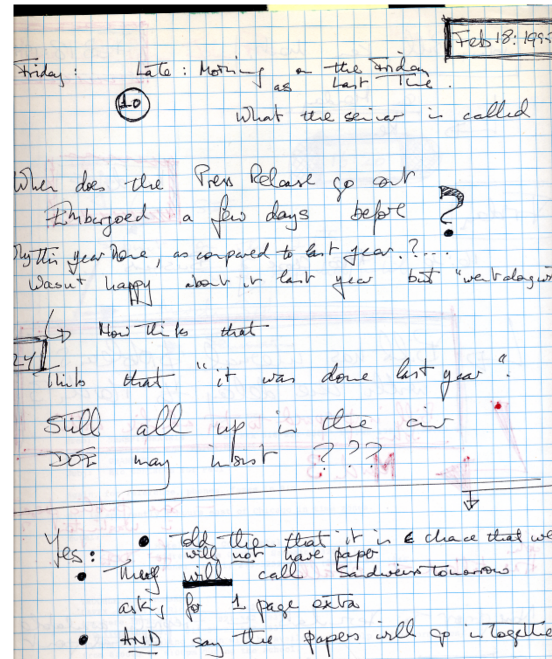
— Some public presentation in Washington?

— for DOE . . .

John Has talked to O'Fallon.

None prior to Fermilab — Preprints available at that point

Statement ready for public dissemination to general public.


Feb 18: 1995

When does the Press Release go out?

Embargoed a few days before

Still all up in the air

Yes: • Told them that it is a chance that we will not have paper

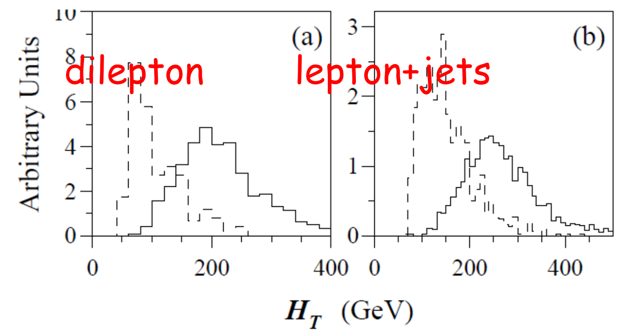
• They will call Sandweiss tomorrow asking for 1 page extra

• AND say the papers will go in together.

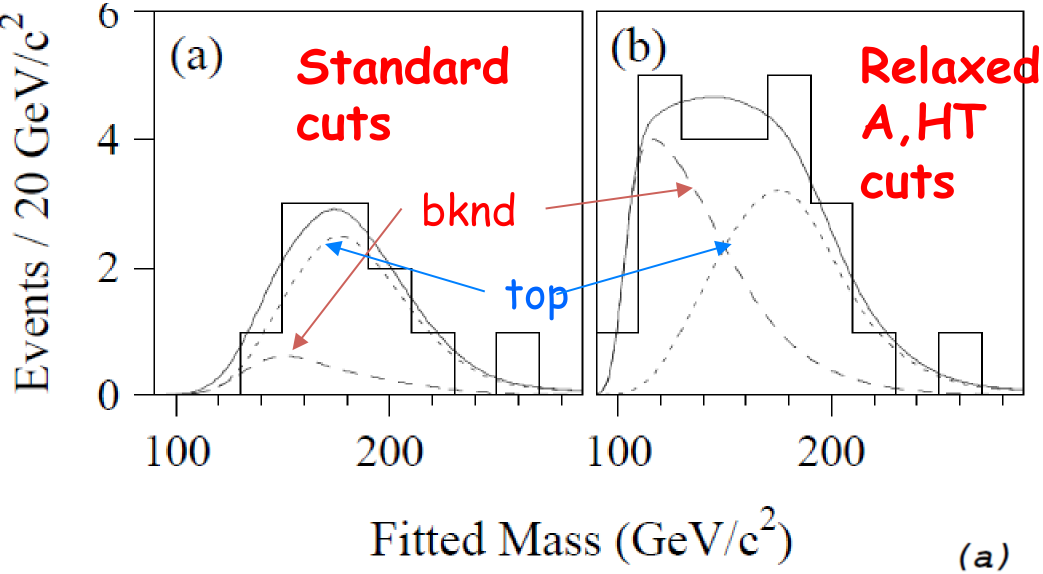
“Observation of the Top Quark” Submitted- February 24, 1995

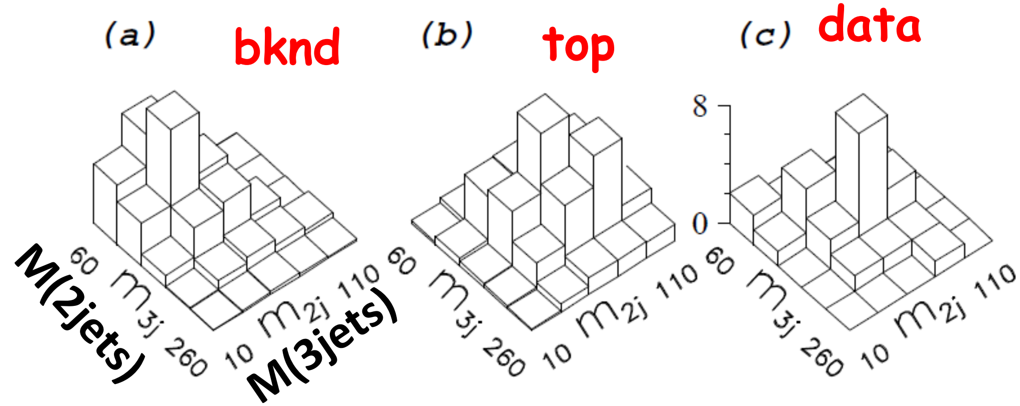
Top Quark Observation PRL 74. 2632 (1995)

D0 had no Si Vtx detector; relied on topological variables to reject bknd: Aplanaraity and $H_T = \Sigma E_T$(jets)



H_T distributions for signal and background





2 * 10^{-6} chance that the signal is background

List of Institutions on Dzero at time of discovery

THE DØ COLLABORATION

Universidad de los Andes, Bogota, Colombia
University of Arizona
Brookhaven National Laboratory
Brown University
University of California, Davis
University of California, Irvine
University of California, Riverside
LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
CINVESTAV, Mexico City, Mexico
Columbia University
Delhi University, Delhi, India
Fermi National Accelerator Laboratory
Florida State University
University of Hawaii
University of Illinois, Chicago
Indiana University
Iowa State University
Korea University, Seoul, Korea
Kyungsung University, Pusan, Korea
Institute of Nuclear Physics, Kraków, Poland
Lawrence Berkeley Laboratory
University of Maryland
University of Michigan
Michigan State University
Moscow State University, Russia
University of Nebraska
New York University
Northeastern University
Northern Illinois University
Northwestern University
University of Notre Dame
University of Oklahoma
Panjab University, Chandigarh, India
Institute for High Energy Physics, Protvino, Russia
Purdue University
Rice University
University of Rochester
DAPNIA/SPP-CE Saclay, Gif-sur-Yvette, France
Seoul National University, Seoul, Korea
State University of New York, Stony Brook
Superconducting Supercollider Laboratory
Tata Institute of Fundamental Research, Bombay, India
University of Texas, Arlington
Texas A&M University

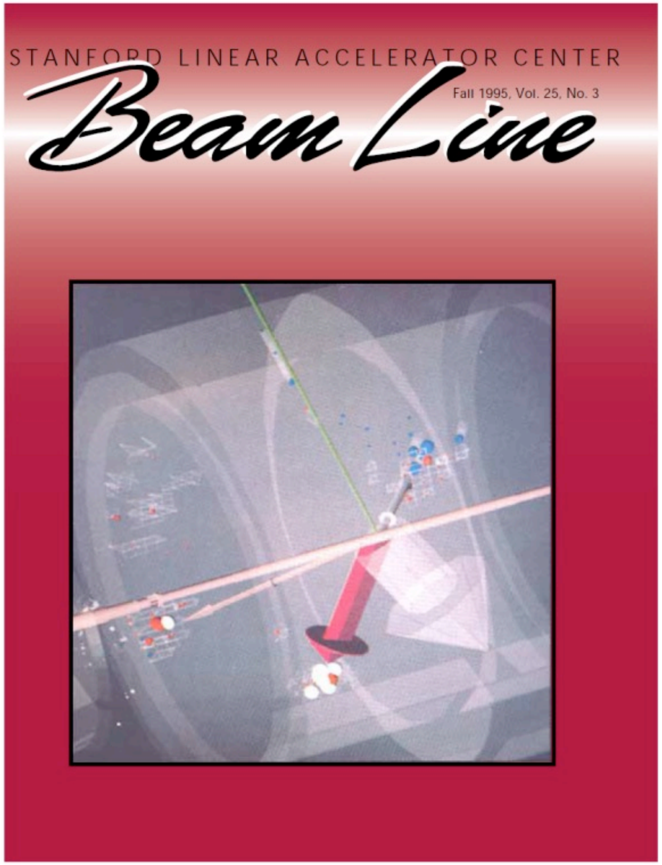
44 Institutions

Brazil
Colombia
France
India
Korea
Mexico
Poland
Russia
USA

Some of the D0 Collaboration

Some of
The Students

Bjorken on Top in <u>Beam Line</u>



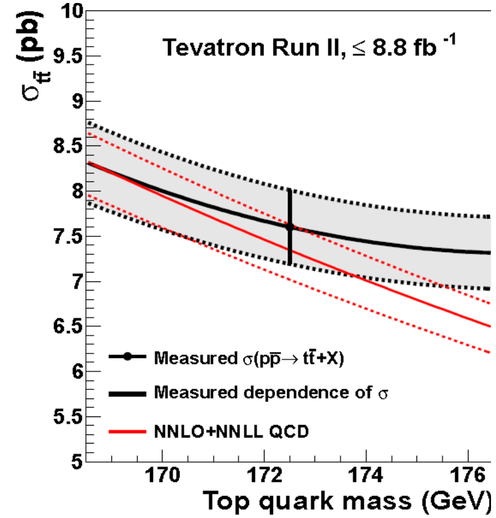
"The history of physics is full of near simultaneous discoveries by separate individuals or groups, and with that often has come acrimony and controversy, from Newton and Leibnitz to Richter and Ting, and down to the present time. There has been competition between CDF and DØ as well. In fact, it was built in from the beginning by then-director Leon Lederman … And the ensuing CDF/DØ competition has served for constructive purposes; I have never seen this competitiveness to be corrosive. … This piece of competition has been a class act."

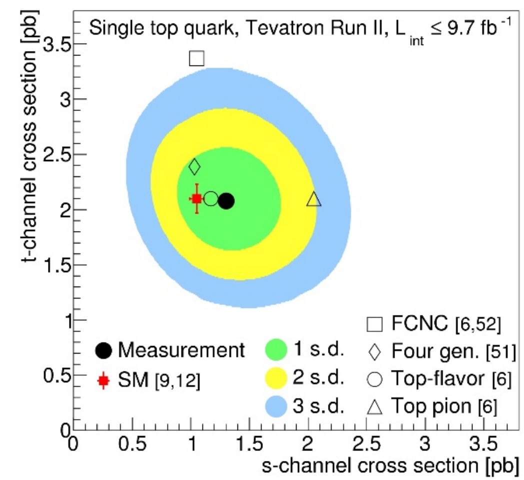
But is it the SM top?

~120 D0 papers address that question

- $t\bar{t}$ cross section and branching ratios agree with SM NNLO QCD + NLO EW for observed m_t
- Decay W helicity states as predicted
- Top quarks are unpolarized and spin correlations are as expected
- Charge 2/3 (not -4/3)
- Single top quark production via EW interaction observed at predicted rate
- CKM matrix element $V_{tb} \approx 1$
- Only (V-A) tWb couplings

CDF & D0





It quacks like a quark, so …

But its mass is 40 times larger than the b quark. Its lifetime ($t \approx 3\text{x}10^{-25}$ s) is so short it decays before hadronization.

European Physical Society Prize 2019

European Physical Society
PRIZE

The 2019 High Energy and Particle Physics Prize of the EPS
for an outstanding contribution to High Energy Physics

is awarded to

the CDF and D0 Collaborations

for the discovery of the top quark and the detailed measurement of its properties.

Petra Rudolf
President
European Physical Society

Barbara Erazmus
Chair
EPS High Energy and Particle Physics Division


D.Claus

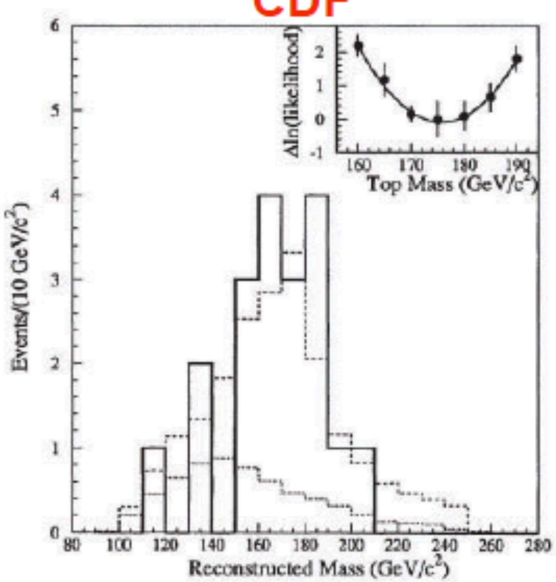
The Top Quark Now

Mel Shochet
University of Chicago

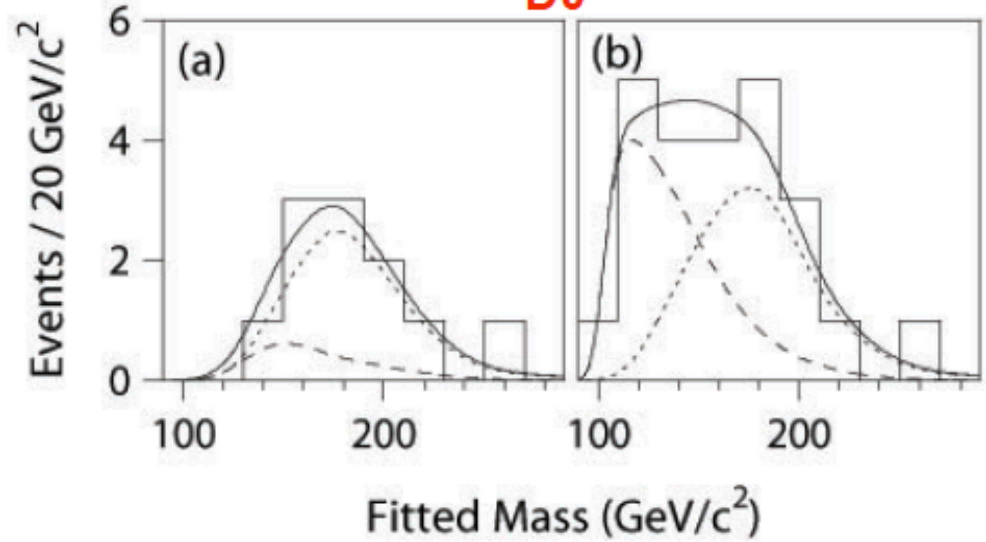
What a quarter century can do

- **At the time of the discovery, statistics were very limited (note the vertical scale on the plots below). We used what we had to check the properties expected of the top quark.**
  - number and type of charged leptons
  - number of *b* jets
  - a mass peak
  - kinematic properties

CDF



D0



- **Since then, especially at the LHC, the size of the samples has become very large, allowing in-depth studies of top properties and using the top to search for even more massive objects.**
  - **Millions of tt events in the signal regions. with about 80% purity.**
  - **Top is now the dominant background for many searches!**
- **To fully make use of the statistics, modern analysis techniques have become essential.**
  - **The search for very massive objects that decay into highly Lorentz boosted top quarks is now possible due to the development of sophisticated jet substructure techniques that allow the top to be identified and reconstructed even when the decay products are all in a single jet cone.**
  - **New machine learning techniques have greatly improved sensitivity by increasing signal-to-background and improving resolution.**

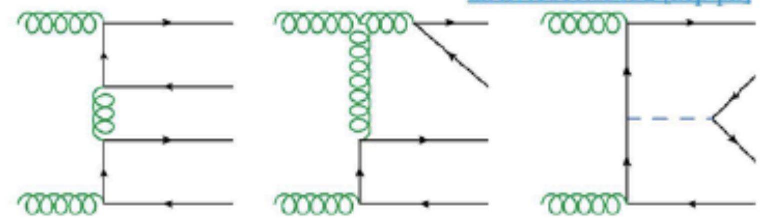
- **Illustrate this with results from last week's ICHEP meeting.**
  - **Top properties and SM couplings (implicit search for beyond the SM)**
    - ***tH*** **coupling, ttX and tX, inclusive and differential production cross sections, spin correlations, charge asymmetry, decay width, mass**
  - **Top in explicit searches for new phenomena**
    - **stop/sbottom, tt resonances, heavy Higgs, dark matter, EFT analysis of ttX and tX, 3rd-generation leptoquarks**

ATLAS – 4 tops

- **Very complicated process**
  - at LO 72 gg+12 qq' initiated diagrams

- **Sensitive to top-Yukawa coupling (y_t)**
  - non-SM value of y_t can change dramatically the production via an off-shell Higgs

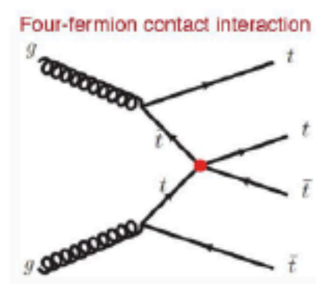
arXiv:1611.05032 [hep-ph]

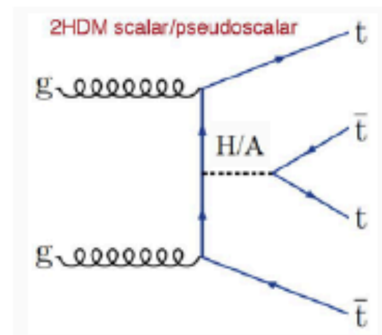


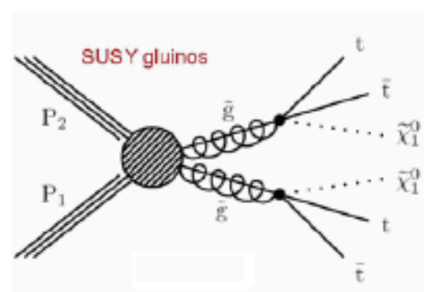
Leading: $O(\alpha_S^4)$

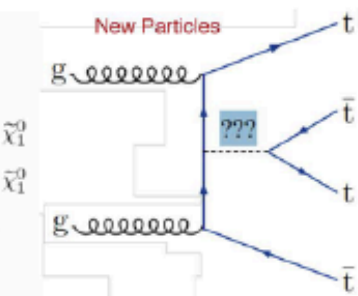
Sub-Leading: $O(\alpha_S^2 y_t^4)$, $O(\alpha_S^2 \alpha^2)$

- **Extremely high energy scale production makes it naturally sensitive to many BSM models**
  - EFTs, including four-fermion contact interaction
  - Higgs physics: 2HDM scalar/ pseudoscalar
  - SUSY: gluinos, sgluons
  - New particles coupling to top quark









| ICHEP | Nedaa Alexandra Asbah, 30.07.2020

2

2ℓSS/3ℓ Channel: Results

- The tttt production cross section is measured via a binned likelihood fit of the BDT score distribution in the signal region and of the discriminating variables in the four control regions ***(b* tagging, lepton and jet kinematics)**
- The measured tttt signal strength is found to be:

$$\mu = 2.0[^{+0.4}_{-0.4}(stat)\ \ ^{+0.7}_{-0.5}(syst)]\ = 2.0^{+0.8}_{-0.6}$$

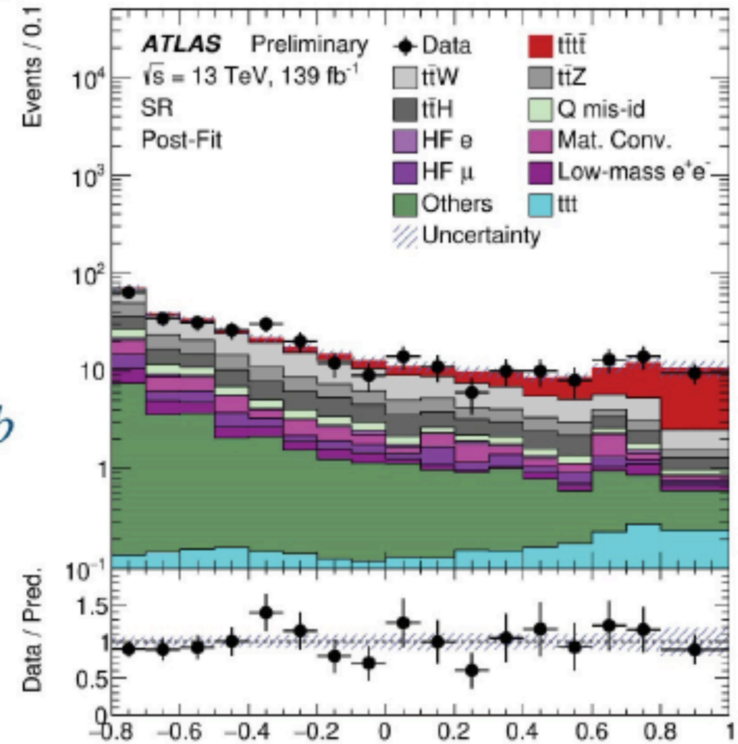
- Cross section:

$$\sigma(t\bar{t}t\bar{t}) = 24^{+5}_{-5}(stat)\ \ ^{+5}_{-4}(syst)\, fb = 24^{+7}_{-6}\ fb$$

- Compared to the theoretical predication of

$$\sigma(t\bar{t}t\bar{t}) = 12 \pm 2\ fb$$

- **Strong 4.3σ (2.4σ expected) evidence**
  - Consistent to 1.7σ with the Standard Model



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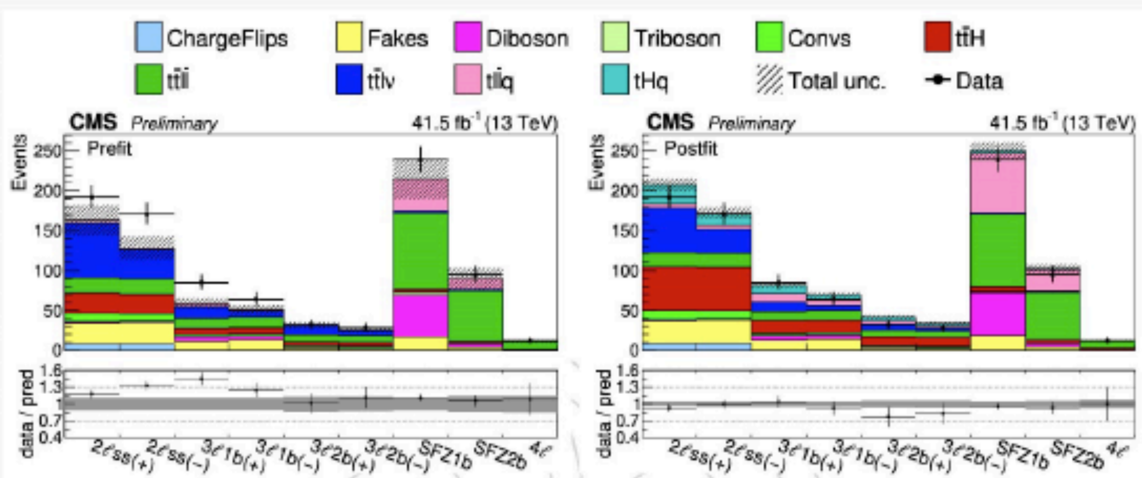
- Several tests were done to check the stability & consistency of the result

Novel EFT Approach with $t\bar{t} + X \rightarrow$ multilepton (1/3)

- **CMS PAS TOP-19-001:** new result!
- Analysis targets single top and $t\bar{t}$ production in association with W, Z, or H, requiring b-jets and multiple leptons: 2l (SS), 3l and 4l in final states.
- **Novel approach to EFT:** rather than search for specific processes, parametrize predicted event yields for *all* relevant processes in terms of *all* relevant WCs.
  - Examine event yields as a function of N_{leptons}, N_{jets}, and $N_{\text{b-jets}}$: different composition of underlying physics processes in each category $\Longrightarrow$ sensitivity to a wide range of EFT operators!



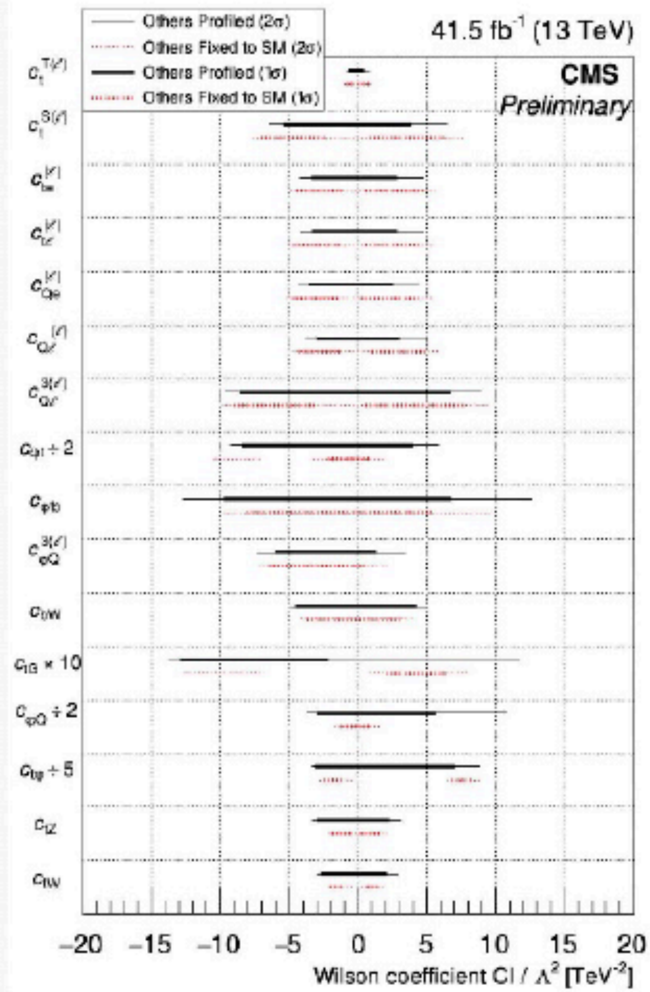
Samuel May (UCSD) **FCNC and EFT interpretations in top quark events at CMS** (July 29, 2020) 11

Novel EFT Approach with $t\bar{t} + X \to$ multilepton (2/3)

- **CMS PAS TOP-19-001:** new result!
- EFT Parametrization: yields for processes with prompt leptons taken from simulation & parametrized as a function of WCs for all relevant EFT operators for that process. Processes with non-prompt leptons predicted with extrapolation from control regions.
- Can express matrix element as sum of SM and BSM contributions:

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}, \qquad (2)$$

- and this can be translated to predicted event yields for each category which are a function of the 16 relevant WCs: $N = N(\vec{c}/\Lambda^2)$.



- **These a few examples of the enormous progress that has been made over the past 25 years in the study of and use of the top quark.**
- **However a major question still remains. With a mass 40 times the next heaviest elementary fermion and a Yukawa coupling very close to 1.0, does the top quark play a central role in electroweak symmetry breaking and perhaps beyond the Standard Model? We are still looking for the answer.**


Thank you all!

Thank You All!