ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ETH Institute for Particle Physics

Beauty

Truth

The Discovery of the Heavy Quarks

Experimental Foundations of Particle Physics

Michael Reichmann

21st November 2017

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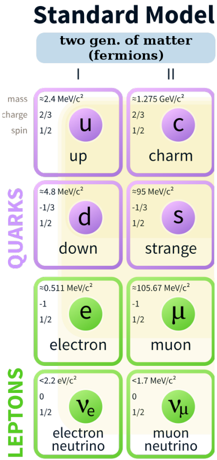
Section 1

Introduction

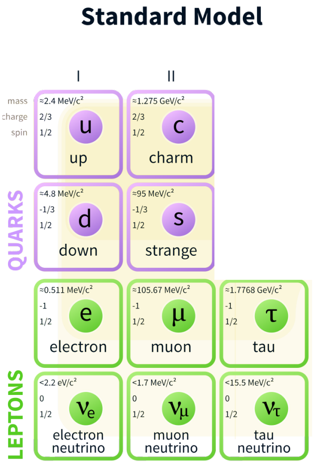
Introduction

- in 1974 (with J/ψ) 4 leptons and 4 quarks discovered



Introduction

- in 1974 (with J/ψ) 4 leptons and 4 quarks discovered
- in 1975 Perl et al. discovered τ-lepton and its neutrino
- in 1973 6-plet proposed by Kobayashi and Maskawa to describe CP violation
- indiction of another pair of quarks



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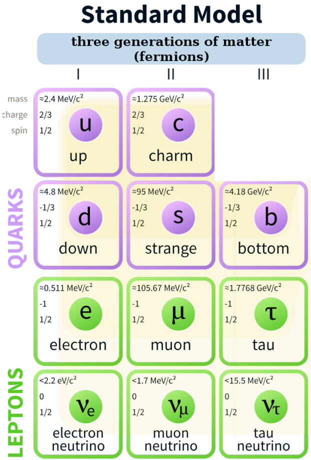
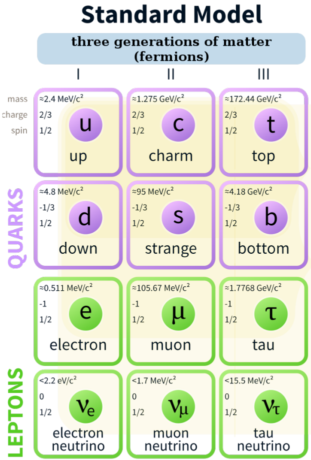
- postulation of a sixth quark



Introduction

- in 1974 (with J/ψ) 4 leptons and 4 quarks discovered
- in 1975 Perl et al. discovered τ-lepton and its neutrino
- in 1973 6-plet proposed by Kobayashi and Maskawa to describe CP violation
- indiction of another pair of quarks
- in 1977 discovery of the bottom (beauty) quark
- postulation of a sixth quark
- in 1995 discovery of the top (truth) quark
- complete set of fermions until now



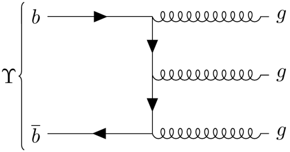
Section 2

The Beauty Quark

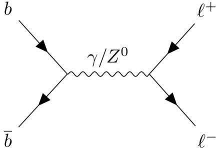
The Υ-Meson

- bound state of $\mathbf{b\bar{b}}$

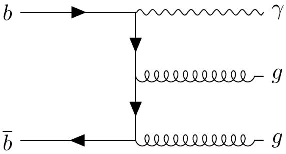
- decay channels:



(a) 82 %



(b) 9 %



(c) 2 %

- mostly decay into gluons which hadronise → signals mostly caused by hadrons
- leptonic decay splits up into 2.5 % to 3 % for each e, μ and τ

Discovery Paper

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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Columbia University, New York, New York 10027

and

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Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

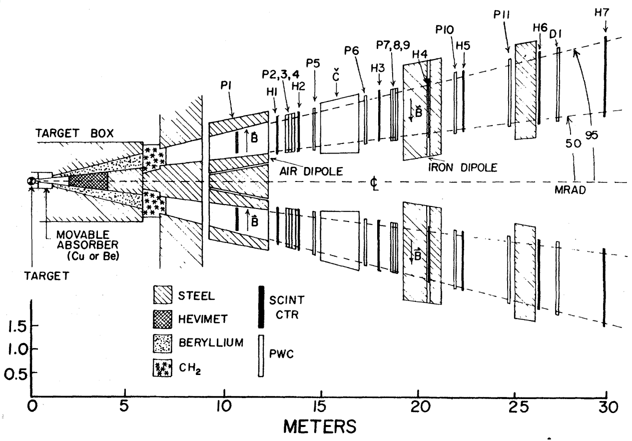
We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

$$p + (\mathrm{Cu, Pt}) \to \mu^+ + \mu^- + \text{anything}.$$

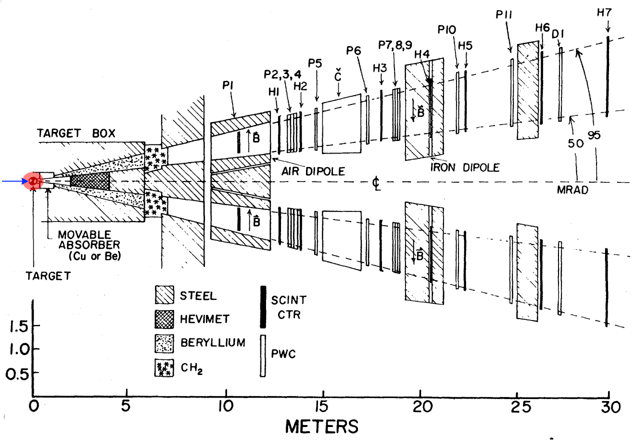
The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) $\approx 2\%$.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.[1-3] Narrow targets (~0.7 mm) with lengths corresponding to 30% of an interaction length are employed.

Setup

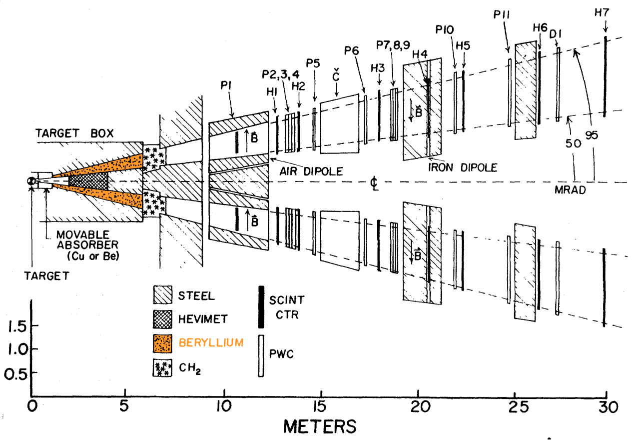

TARGET BOX
MOVABLE ABSORBER (Cu or Be)
TARGET
P1
P2,3,4
H1
H2
P5
Č
P6
H3
P7,8,9
H4
P10
H5
P11
H6
D1
H7
AIR DIPOLE
IRON DIPOLE
MRAD
50
95
STEEL
HEVIMET
BERYLLIUM
CH2
SCINT CTR
PWC
METERS

Setup



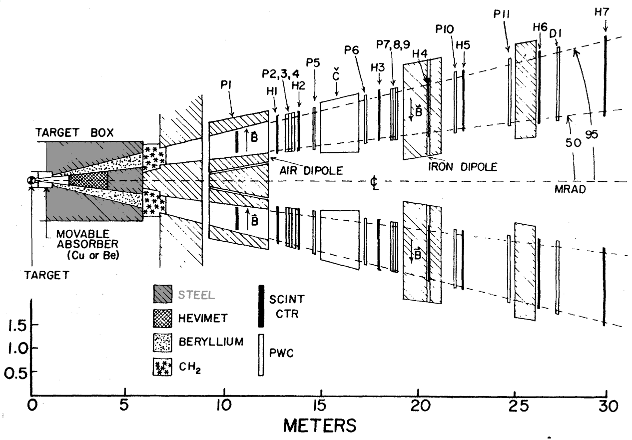
- 400 GeV proton beam shot on narrow target (Pt/Cu) with 30 % interaction length

Setup



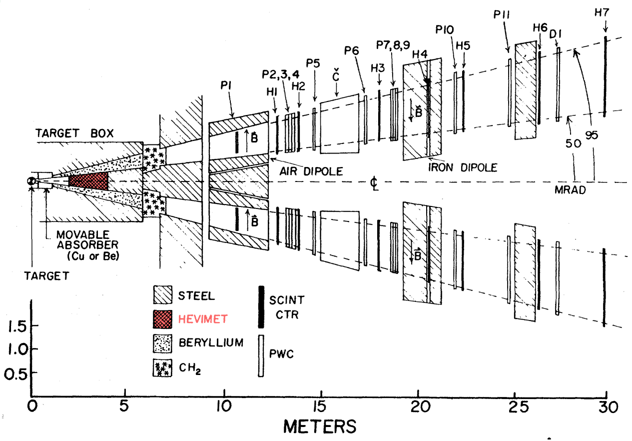
- hadron filter out of Be with 18 interaction length (3° to 5° horiz. and $\pm 0.5^\circ$ vert.)

Setup



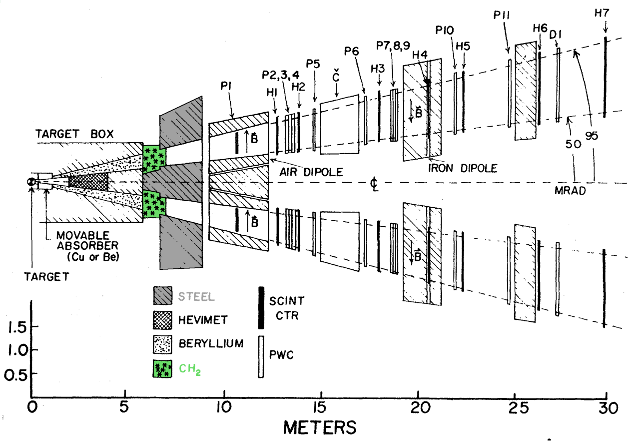
- heavy metal (Steel, W) shielding to minimise particle leakage

Setup



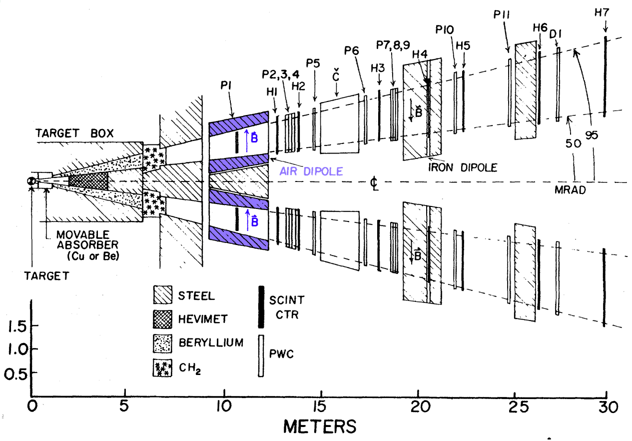
- tungsten beam dump

Setup



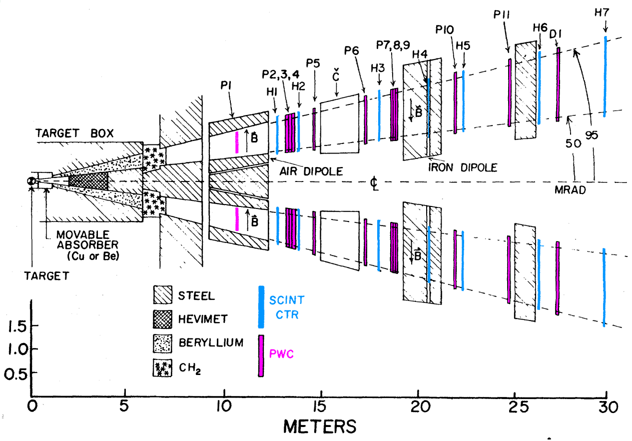
- additional shielding out of polyethylene and more steel

Setup



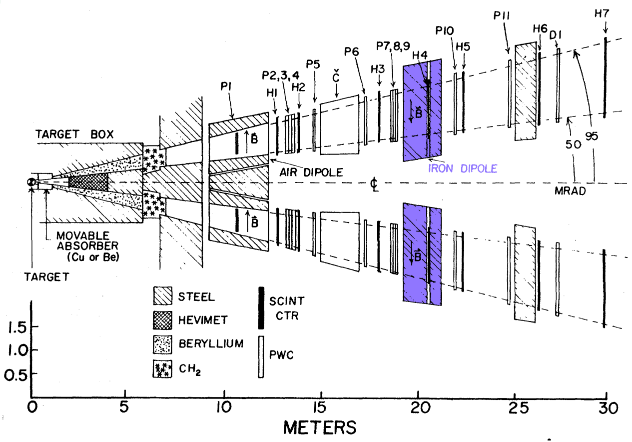
- spectrometer dipole magnets with horizontal field
- both arms are symmetric to drawing plane and detect μ^+ and μ^-

Setup



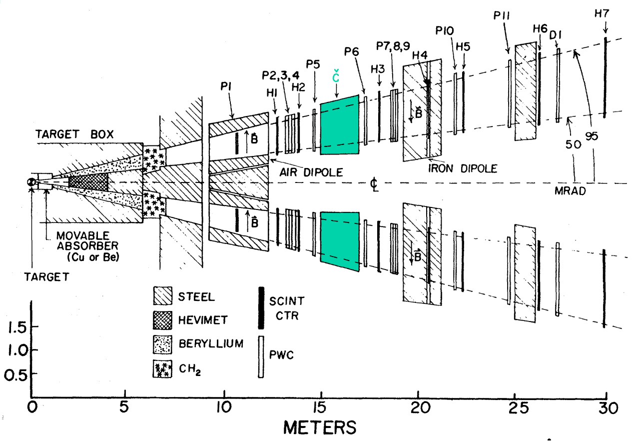
- scintillation hodometers and wire chambers for tracking (limit of 10×10^7 counts/s)

Setup



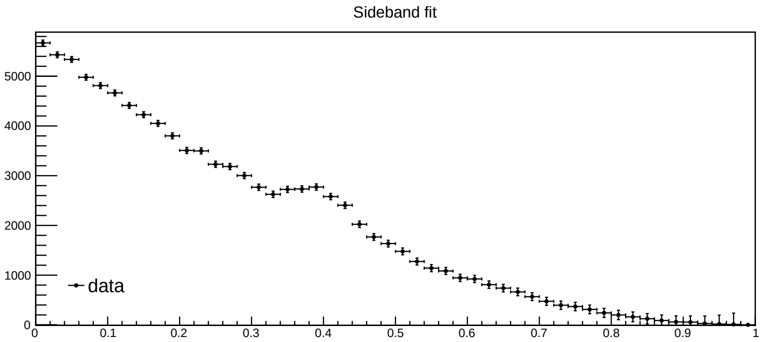
- solid iron magnet to partially refocus and redetermine muon momentum

Setup



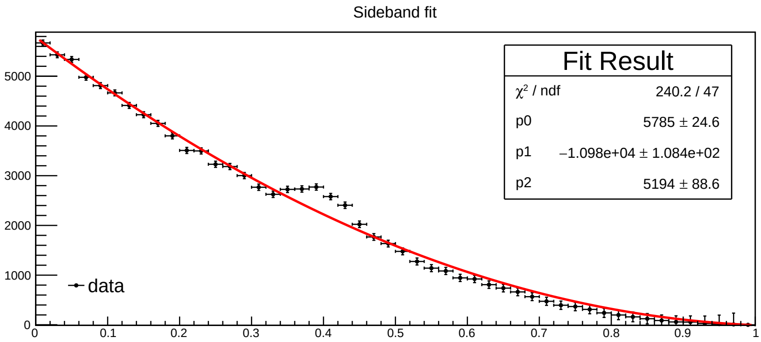
- Čerenkov counter to prevent low momentum muon triggers

Intermezzo: Sideband Fit



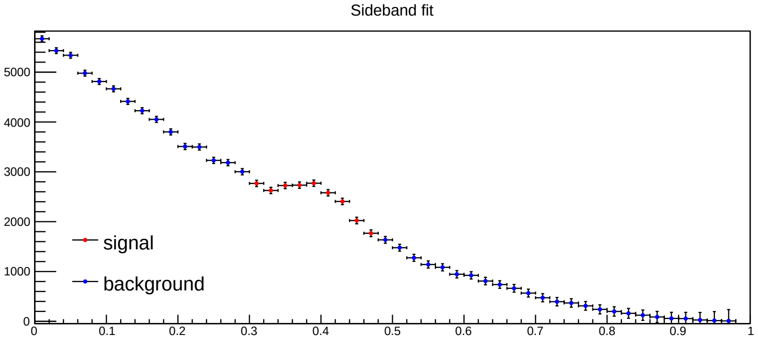
- typical shape of data in particle physics: continuous background with a small bump

Intermezzo: Sideband Fit



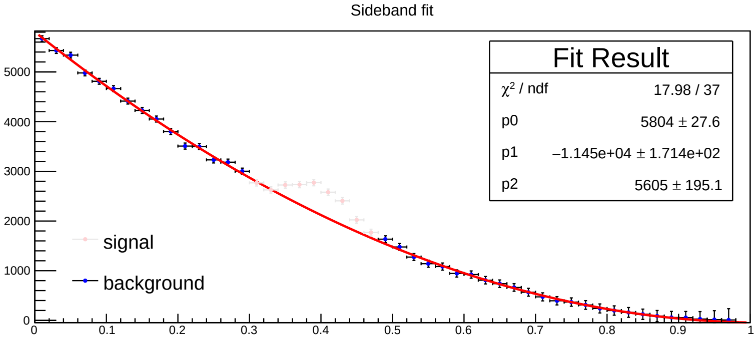
- background extraction with a fit of the whole set does not work well

Intermezzo: Sideband Fit



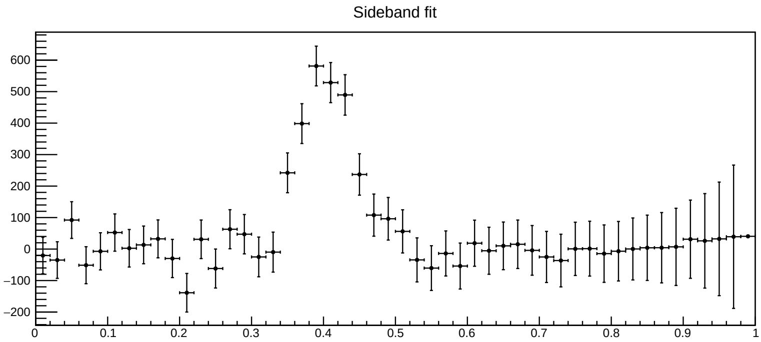
- divide the data set in a signal and two background parts ($\rightarrow$ side bands)

Intermezzo: Sideband Fit



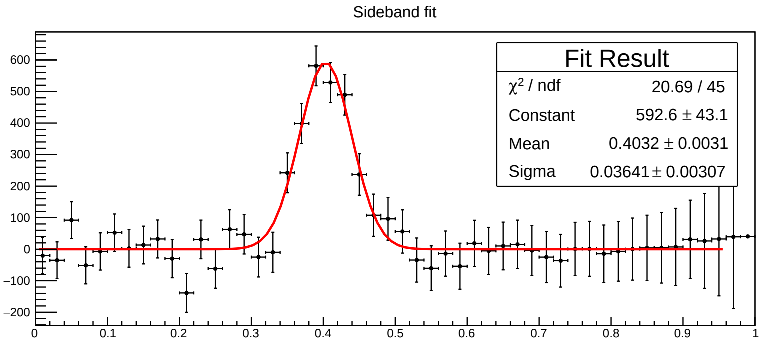
- fitting just the side bands yields a much better result

Intermezzo: Sideband Fit



- getting the signal distribution by subtracting the full data set by the fit

Intermezzo: Sideband Fit



- get width and position of the signal by a fit

Results

- statistically significant enhancement at 9.5 GeV $\mu^+\mu^-$ mass
- solid line background fit using side band method

$$\frac{d^2\sigma}{dmdy} = Ae^{-bm}$$

- fit expects 350 events in excluded region but 770 events in data
- bump wider than resolution of detector (FWHM: (0.5 ± 0.1) GeV)
- simple Gaussian fit of background subtracted data yields:

$$\mathbf{m = (9.54 \pm 0.04)\,GeV}$$
$$\mathbf{FWHM = (1.16 \pm 0.09)\,GeV}$$

- same goodness of fit with two Gaussians with fixed with of detector resolution $\rightarrow$ later Υ and Υ'

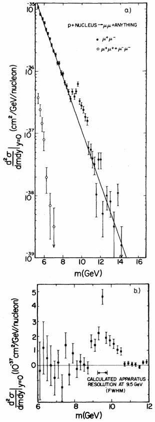
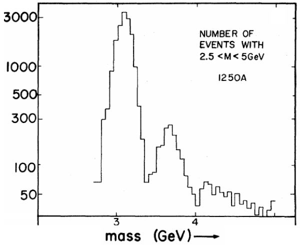


Figure: dimuon production cross section as a function of invariant mass

Verification

- same sign dimuon spectrum ($\mu^+\mu^+$ and $\mu^-\mu^-$)
  - upper limit on combined effects of accidental coincidences and hadronic decays
- re-measurement of the muon momentum by the second magnet and by PCW at the centre of the first magnet
  - avoid misidentified $\psi \longrightarrow \mu^+ + \mu^-$ at high mass
  - confirmed by clear separation of the ψ and ψ' in the Figure
- study of various subsets of the data with different magnetic fields
  - check for apparatus bias
- study of data with and without target
  - rule out signal created from beam dump



PLUTO Collaboration Paper

OBSERVATION OF A NARROW RESONANCE FORMED IN e^+e^- ANNIHILATION AT 9.46 GeV

PLUTO Collaboration

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I. Physikalisches Institut der RWTH Aachen, FRG

G. ALEXANDER [1], L. CRIEGEE, H.C. DEHNE, K. DERIKUM, R. DEVENISH, G. FLÜGGE, G. FRANKE
Ch. GERKE, E. HACKMACK, P. HARMS, G. HORLITZ, Th. KAHL [2], G. KNIES, E. LEHMANN,
B. NEUMANN, R.L. THOMPSON [3], U. TIMM, P. WALOSCHEK, G.G. WINTER,
S. WOLFF, W. ZIMMERMANN
Deutsches Elektronen-Synchrotron DESY, Hamburg, FRG

O. ACHTERBERG, V. BLOBEL, L. BOESTEN, H. DAUMANN, A.F. GARFINKEL [4], H. KAPITZA,
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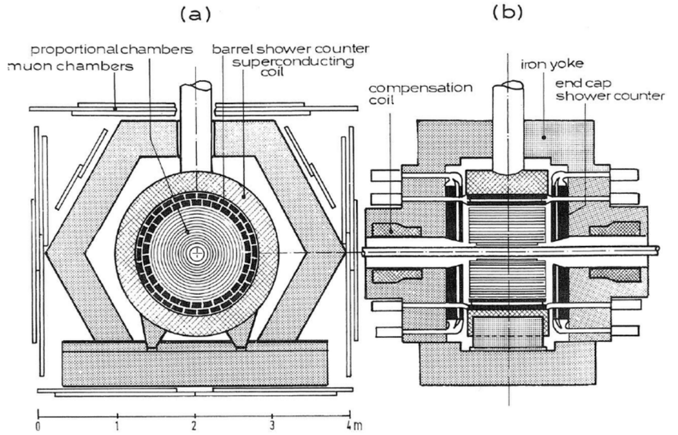
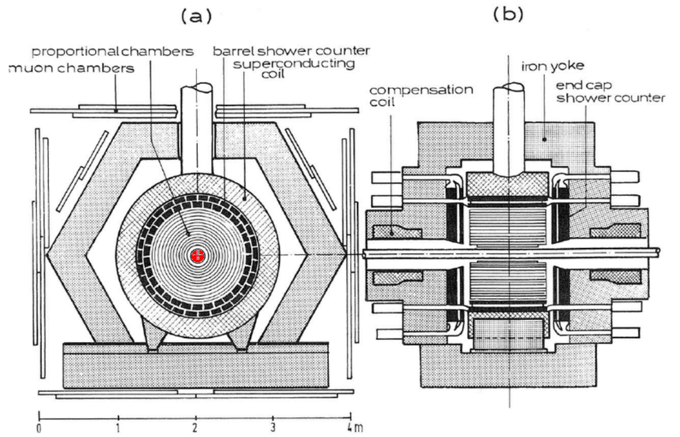
Received 9 May 1978

An experiment using the PLUTO detector has observed the formation of a narrow, high mass, resonance in e^+e^- annihilations at the DORIS storage ring. The mass is determined to be 9.46 ± 0.01 GeV which is consistent with that of the Upsilon. The gaussian width σ is observed as 8 ± 1 MeV and is equal to the DORIS energy resolution. This suggests that the resonance is a bound state of a new heavy quark-antiquark pair. An electronic width Γ_{ee} = 1.3 ± 0.4 keV was obtained. In standard theoretical models, this favors a quark charge assignment of −1/3.

PLUTO Detector

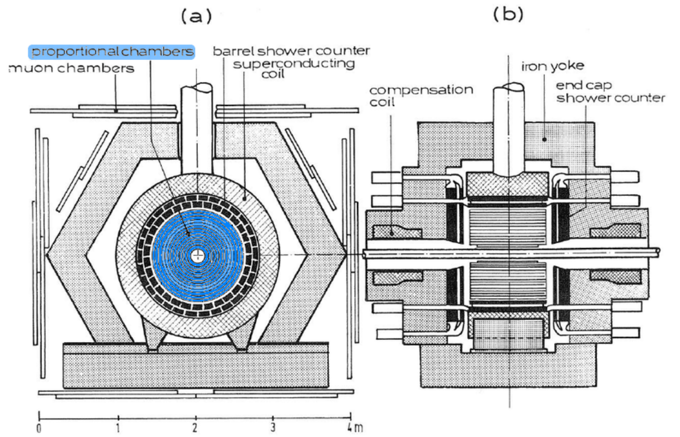


PLUTO Detector



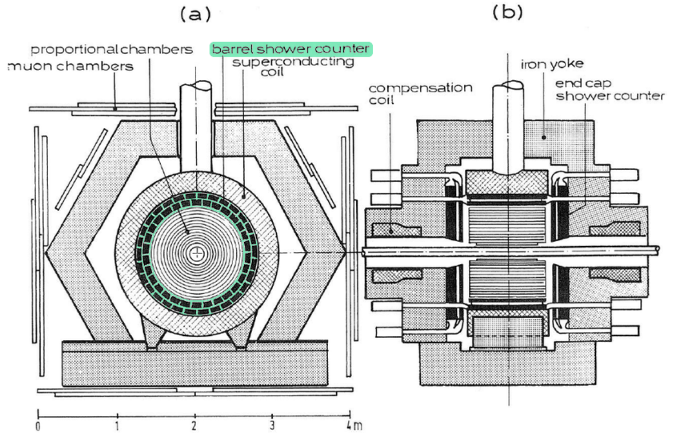
- up to 5 GeV electron beams collided in the centre

PLUTO Detector



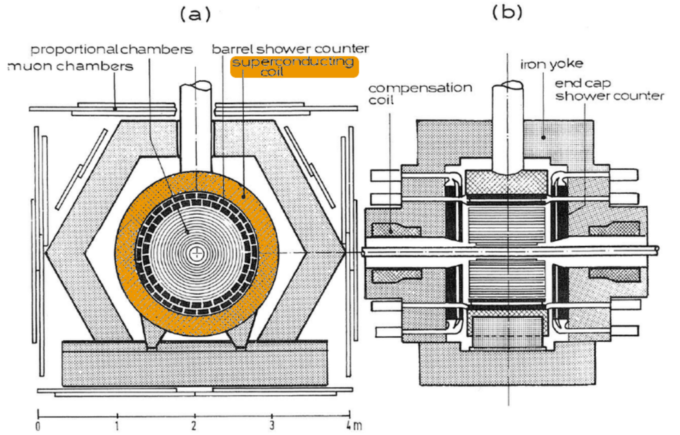
- cylindrical proportional wire chamber with 92 % coverage
- tracking and momentum measurement

PLUTO Detector



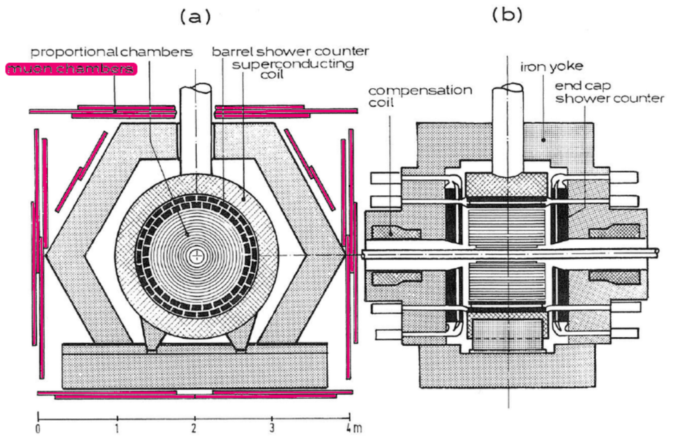
- cylindrical array of shower counters with 8.6 radiationlength and 94 % coverage
- calorimeter to measure the full energy

PLUTO Detector



- magnet with 1.69 T

PLUTO Detector



- muon chambers

Results

- acquiring cross section by scanning $\sqrt{s}$ in steps of either 5 GeV or 10 GeV
- only considering hadronic decay products
- remove $1/s$ background
- reduce cosmic ray background by use of bunch crossing time (bunched beam structure vs continuous background)

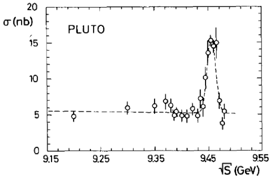


Figure: total cross section for hadron production

- remove QED events with coplanarity cut and shower recognition
- remove beam gas interaction by cuts on visible energy and missing mass
- fitting data with Gaussian yields:

$$\mathbf{m = (9.46 \pm 0.01)\,GeV}$$
$$\sigma_{\text{Gauss}} = \mathbf{(7.8 \pm 0.9)\,MeV}$$

Charge

- relation of total hadronic cross section to resonance mass and the resonance width

$$\int \sigma_h dM = \frac{6\pi^2}{{M_R}^2} \frac{\Gamma_{ee}\Gamma_h}{\Gamma_{tot}}$$

- standard assumption: $\Gamma_{tot} \approx \Gamma_h \rightarrow$ direct measurement of Γ_{ee}

$$\Gamma_{ee} = (1.3 \pm 0.4)\,\mathrm{keV}$$

- theoretical predictions from the same model:

Decay Mode	Width [keV]	
	$e = \pm^1/_3$	$e = \pm^2/_3$
$\mu^+\mu^-$	0.70 ± 0.09	2.8 ± 0.4

- **implies charge of -⅓ for the bottom quark**

Section 3

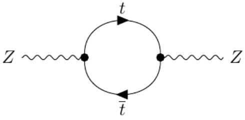
The Truth Quark

Introduction

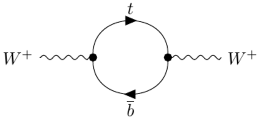
- in early 90s all SM particles except H and t-quark discovered
- beauty discovery $\rightarrow$ weak isospin partner was undoubted
- quark masses are fundamental parameters in the SM
- early estimates: $\mathrm{m_t} \approx 3\mathrm{m_b} \approx 15\,\mathrm{GeV}$
- many new accelerator could only push limits higher:
- TRISTAN (e^+e^-) at KEK (Tsukuba, Japan) with $\sqrt{s} = 61.4\,\mathrm{GeV} \rightarrow 30.2\,\mathrm{GeV}$
- Sp$\bar{\mathrm{p}}$S at CERN with $\sqrt{s} = 630\,\mathrm{GeV} \rightarrow 69\,\mathrm{GeV}$
- SLC (e^+e^-) at Stanford and LEP (e^+e^-) at CERN $\rightarrow$ $^1/_2\mathrm{m_Z}$ (not seen in $\mathrm{Z} \longrightarrow \mathrm{t\bar{t}}$)
- hadron collider needed ($\rightarrow$ Tevatron)

Estimated Mass

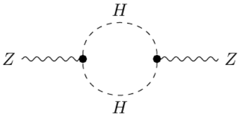
- using radiative corrections of the W, Z bosons:



(a) $\sim m_t^2$

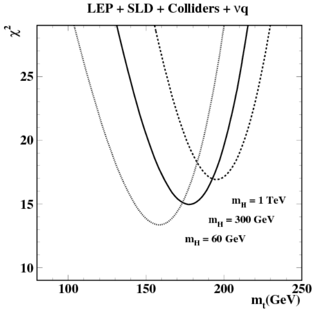


(b) $\sim m_t^2$



(c) $\sim \ln\left(m_H^2\right)$

- weak dependence on m_H
- get estimate on m_t by measuring the m_W and m_Z
- fit all available electroweak data
- estimate in 1994: $\sim$180 GeV

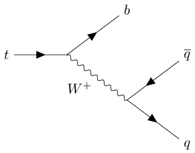


Decay Channels (1)

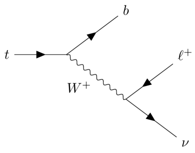
- prior to discovery: behaviour completely predicted by SM
- $m_t > m_W \rightarrow$ main decay channel (~96 %): $\mathbf{t \longrightarrow W^+ b}$

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right)$$

- width for the expected mass: ~1 GeV → decay before hadronisation



(a) ~67 %

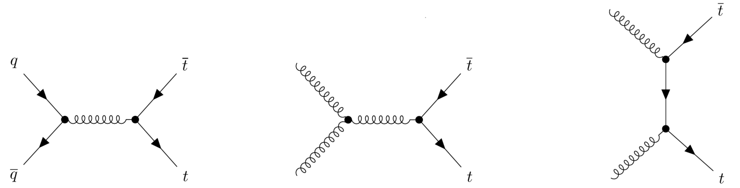


(b) ~33 %

- leptonic decay equally splits up into e, μ and τ

Top Production

- top mostly pair produced via two processes:
  - $\mathrm{q\bar{q}} \longrightarrow \mathrm{t\bar{t}}$
  - gluon fusion: $\mathrm{gg} \longrightarrow \mathrm{t\bar{t}}$

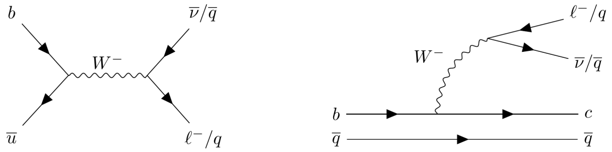


(a) $\mathrm{q\bar{q}}$ (b) gluon fusion (c) gluon fusion

- at Tevatron mostly $\mathrm{q\bar{q}} \longrightarrow \mathrm{t\bar{t}}$ ($\rightarrow \mathrm{p\bar{p}}$ collider)
- at LHC gluon fusion dominant

Decay Channels (2)

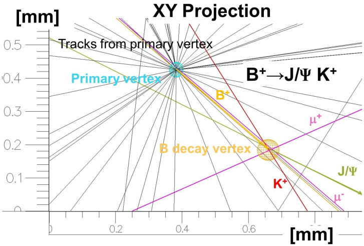
- main decay of the top pair: $\mathrm{t\bar{t}} \longrightarrow \mathrm{W^+bW^-\bar{b}}$
- b decay:



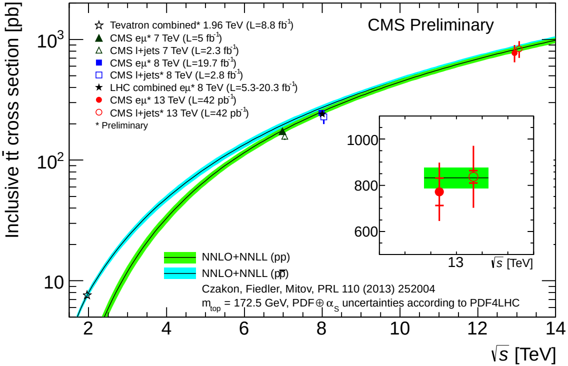
- typical signals:
  - 2 b-jets + dilepton (e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, μ^+e^-)
  - 2 b-jets + single lepton + two jets
  - 2 b-jets + 4 jets
- huge background on pure QCD process due to other more common QCD processes
- how to discriminate b-jets from other jets?

B-Tagging

- most jets from light partons (u,d,s) or gluons
- lower rates from c, and b quarks
- interesting physics from b $\rightarrow$ top, higgs, supersymmetry or new phenomena
- b longer lifetime than other partons ($\rightarrow$ range $\mathcal{O}\,(1\,\text{mm})$ depending on boost)
- look for secondary vertices (away from primary vertex $\rightarrow$ interaction point)
- first reconstruct primary vertex:
  - cluster all tracks together and determine likelihood they origin from common vertex
  - vertex with highest p_T = primary vertex
- background for secondary vertices (mostly from light flavoured jets)
  - K-short Meson
  - lambda Baryon
  - photon conversion



$t\bar{t}$ Cross Section



- cross section extracted from SM
- Tevatron Integrated Lumi from 1993 to 1995: $\sim 50\,\mathrm{pb}^{-1}$

$$R_{t\bar{t}} = \sigma_{t\bar{t}}\mathscr{L} = 5 \times 10^{-6}\,\mathrm{Hz} \approx 1 \text{ per day}$$

Discovery Paper (1)

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

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2626 0031-9007/95/74(14)/2626(6)$06.00

Discovery Paper (2)

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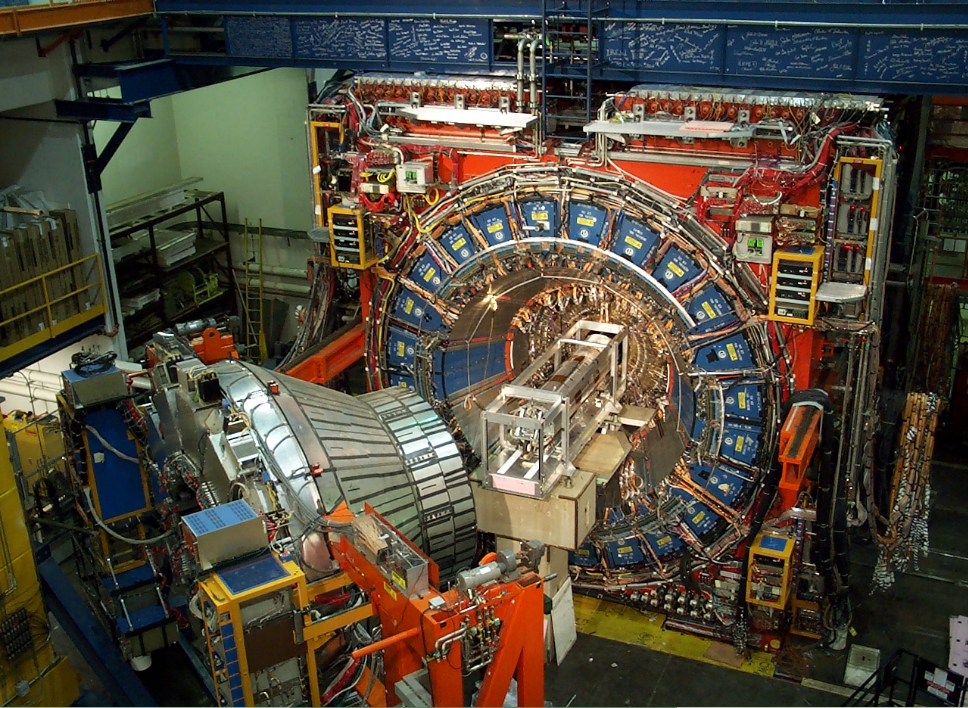
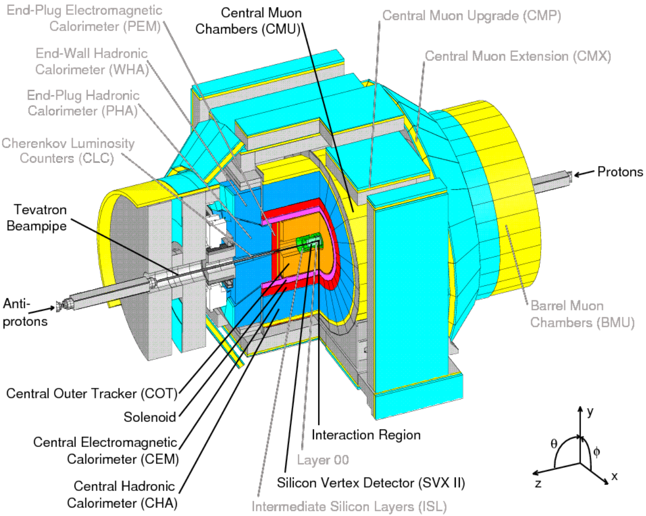
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, 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 $176 \pm 8(\mathrm{stat}) \pm 10(\mathrm{syst})\ \mathrm{GeV}/c^2$, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.



CDF Detector



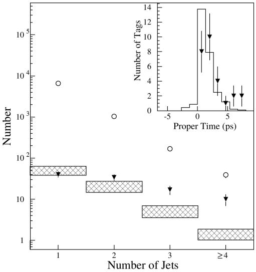
Introduction

- paper from 1994 with estimate on mass and cross section
- using dataset of $19\,\mathrm{pb}^{-1} + 47\,\mathrm{pb}^{-1}$ ($\rightarrow \sim 400$ events)
- looking at two decay channels
  - dilepton
  - lepton + jets
- both data samples subsets of events with isolated leptons with high $P_T > 20\,\mathrm{GeV}$
- cut on invariant mass of dilepton $75\,\mathrm{GeV} < \mathrm{m_l} < 105\,\mathrm{GeV} \rightarrow$ exclude Z events
- main background reduction by b-tagging
  - reconstruction of secondary vertices from b decay in SVX $\rightarrow$ SVX tag
  - finding additional leptons from b decay in ECAL $\rightarrow$ SLT tag

Lepton + Jets Channel

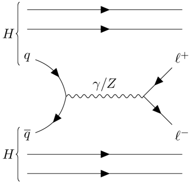
SVX tagging:

- search for secondary vertices with three ore more tracks
- then search for two ore more tracks with more stringed track and vertex quality
- efficiency estimated by e, μ samples with enriched b decays (96 % agreement to MC)
- tagging efficiency: $(42 \pm 5)\,\%$
- backgrounds:
  - recoil of heavy quark pairs against W
  - mistags
- for W+ ≥ 3 jets: observation of 27 tags with bg of (6.7 ± 2.1) tags
- decay lifetime of SVX tags agrees well with MC



Dilepton Channel

- major backgrounds:
  - Drall-Yan process
  - $Z \longrightarrow \tau\tau$
  - misidentified hadrons
  - WW, $b\overline{b}$



- first three bg calculated by data and last two by MC
- cuts:
  - $\not{E}_T \geq 10\,\text{GeV}$
  - number of jets ≥ 2
- reduces Drell-Yan bg (very little $\not{E}_T$)
- correct for jet energy mismeasurement

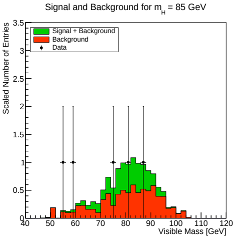
Results

Channel	**SVX**	**SLT**	**Dilepton**
Observed	27 tags	23 tags	6 events
Expected background	6.7 ± 2.1	15.4 ± 2.0	1.3 ± 0.3
Background probability	2×10^{-5}	6×10^{-2}	3×10^{-3}

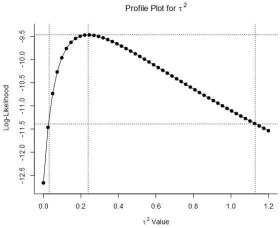
- combined likelihood of the background fluctuating up: 1×10^{-6} $(4.8\,\sigma)$

Intermezzo: The Profile Likelihood Method

- one dataset with signal and a background → unable to describe analytically
- MC simulation of both background and signal
- nuisance parameter → e.g. unknown top mass
- vary nuisance parameter → compare to data
- fit best result



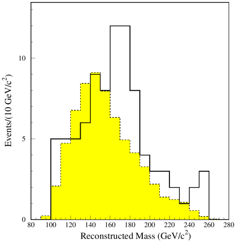
(a) data and MC



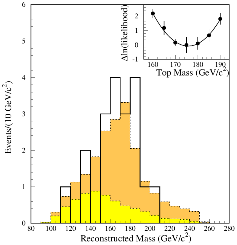
(b) likelihood fit

Mass Reconstruction

- kinematically mass reconstruction by use of single lepton + 4 jet events
- $t\bar{t} \longrightarrow WbW\bar{b} \longrightarrow q\bar{q}b\ell\nu\bar{b}$
- predicted mix of 30 % $t\bar{t}$ and 70 % W + jets bg (yellow)
- reducing bg by applying SVX and SLT tags
- get best top mass by using MC with W + jets bg and varying the top mass



(a) before b-tagging



(b) after b-tagging

Combined Results

- combined signal size and mass distribution
- probability for and upward fluctuation of the bg:

$$P_c = 3.7 \times 10^{-7} \ (5.0\,\sigma)$$

- reconstructed mass:

$$m_{top} = 176 \pm 8 \pm 10\,\mathrm{GeV/c^2}$$

- cross section:

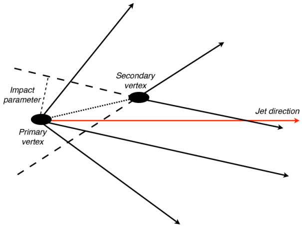
$$\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}\,\mathrm{pb}$$

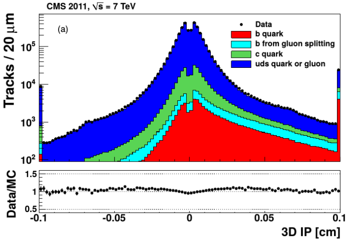
Introduction

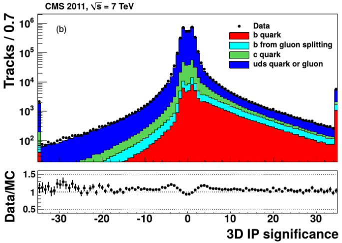
- variety of reconstructed objects (tracks, vertices, leptons) used as discriminator
- usually one observable for simple and robust algorithms
- combination of several for higher discrimination power
- discriminator thresholds in misidentification probability at p_T of 80 GeV/c:
  - loose ("L") - 10 %
  - medium ("M") - 1 %
  - tight ("T") - 0.1 %
- also first finding primary vertex
- requirement of well-reconstructed tracks of high purity

Identification by Track Impact Parameters (IP)

- IP: transverse and longitudinal distance of track from primary vertex
- IP calculated in 3D using good resolution from the pixel detector along z
- tracks from decay along jet-axis $\rightarrow$ tend to IP > 0
- strong dependence on p_T and η

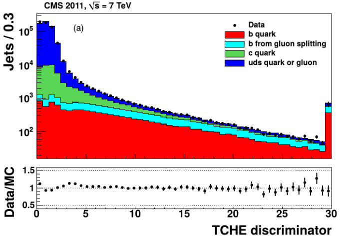


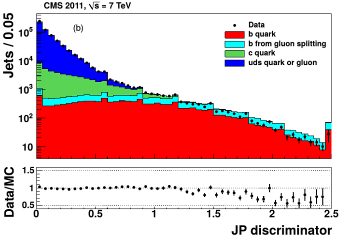




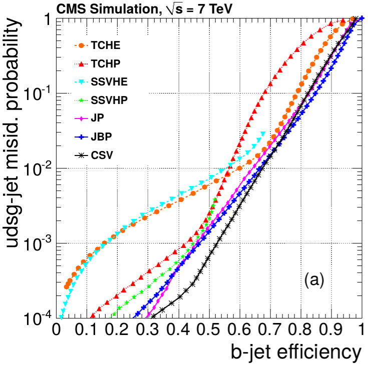
Track Counting Algorithm

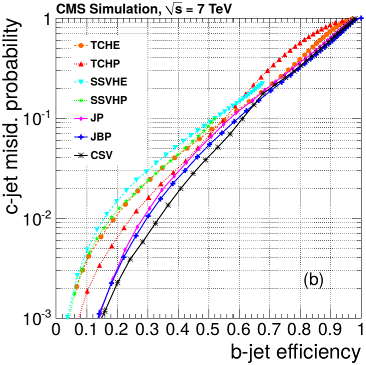
- IP by itself discriminating power between decay products of b and non-b jets
- sort tracks by IP significance (IP/Uncertainty)
- low probability to have several jets with high significance from light partons
- use sign. of 2. + 3. (1. biased) → *Track Counting High Efficiency* (TCHE)
- likelihood that all tracks from one jet cone come from primary vertex → *Jet Probability* (JP)





Performance





- for jets with $p_T > 60\,\text{GeV}/c$
- loose selection (10 %) → ∼80 % to 85 % efficiency
- tight selection (0.1 %) → ∼45 % to 55 % efficiency

Discovery Paper

Observation of the Top Quark

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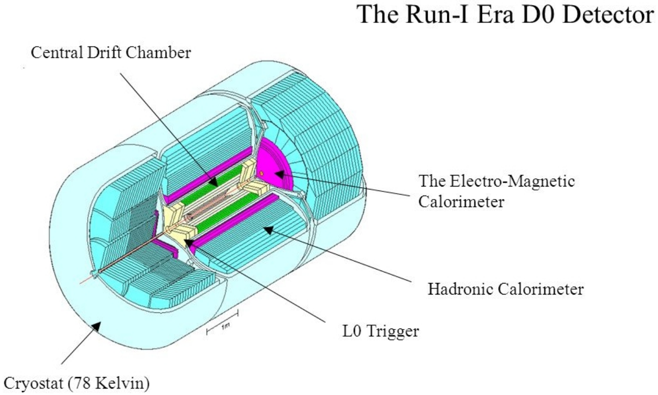
⋮

Abstract

The DØ 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 measure 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.

D0 Detector

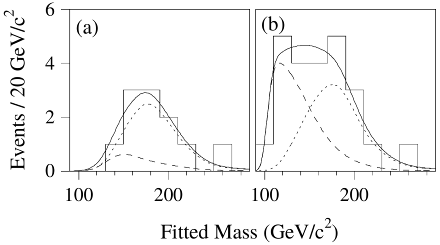


- no magnetic field
- no vertex detector, just drift chamber
- very good calorimeters

Results

- also dilepton and lepton + jets channels
- b-tagging by extra muon from b decay
- no vertexing → very good lepton identification
- bg reduction by using H_T - scalar sum of E_T of jets or leading electron + jets

$$\mathbf{P_c = 2.0 \times 10^{-6}\ (4.6\,\sigma)}$$
$$\mathbf{m_{top} = 199 \pm 20 \pm 22\,GeV/c^2}$$
$$\sigma_{t\bar{t}} = \mathbf{(6.4 \pm 2.2)\,pb}$$



Section 4

Conclusion

Conclusion

- **discovery of b-quark** in 1995 (Fermilab)

$$\mathbf{m} = (\mathbf{9.54} \pm \mathbf{0.04})\,\mathbf{GeV}$$
$$\Gamma_{\mathbf{ee}} = (\mathbf{1.3} \pm \mathbf{0.4})\,\mathbf{keV}$$
$$\mathbf{q} = -\tfrac{1}{3}$$

- sideband fitting
- **discovery of the t-quark** (Tevatron at Fermilab)

$$\mathbf{m} = \mathbf{176} \pm \mathbf{8} \pm \mathbf{10}\,\mathbf{GeV/c^2}$$
$$\sigma_{t\bar{t}} = \mathbf{6.8}^{+3.6}_{-2.4}\,\mathbf{pb}$$
$$\mathbf{q} = \tfrac{2}{3}$$

- b-tagging
- likelihood fit