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

20th November 2017

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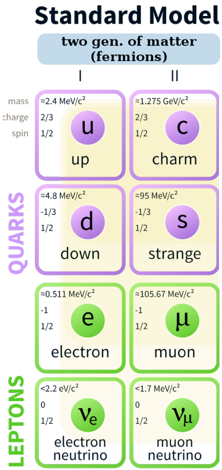
Section 1

Introduction

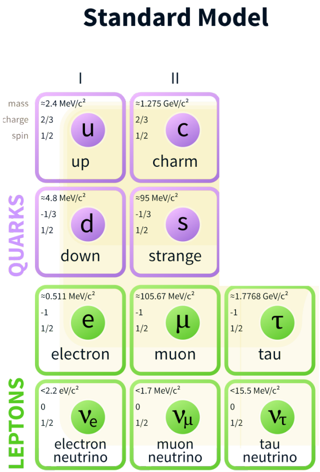
Introduction

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



Introduction

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



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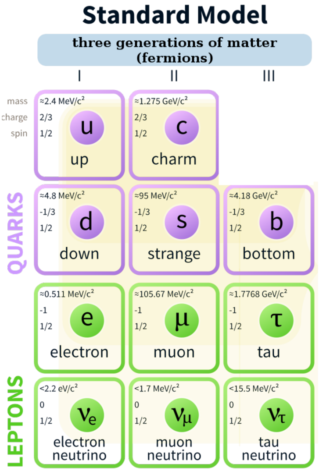
- postulation of a sixth quark



Introduction

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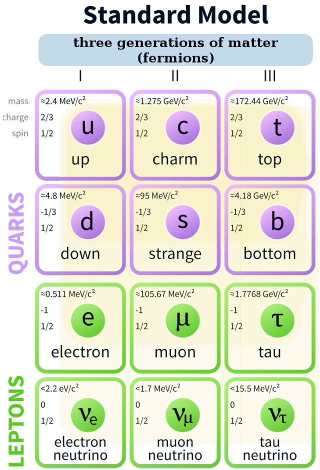
- in 1973 6-plet proposed by Kobayashi and Maskawa to describe CP violation
- in 1975 Perl et al. discovered τ-lepton and its neutrino
- indiction of another pair of quarks
- in 1977 discovery of the bottom (beauty) quark
- postulation of a sixth quark
- in 1995 discovery of the top (truth) quark
- complete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

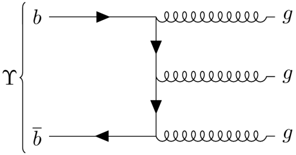


Section 2

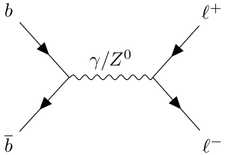
The Beauty Quark

The Υ-Meson

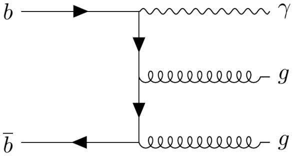
- bound state of $\mathbf{b\bar{b}}$
- decay channels:



(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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and

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(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.

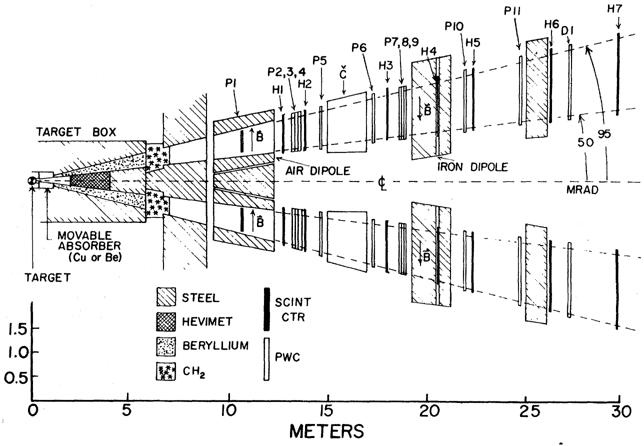
We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident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

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

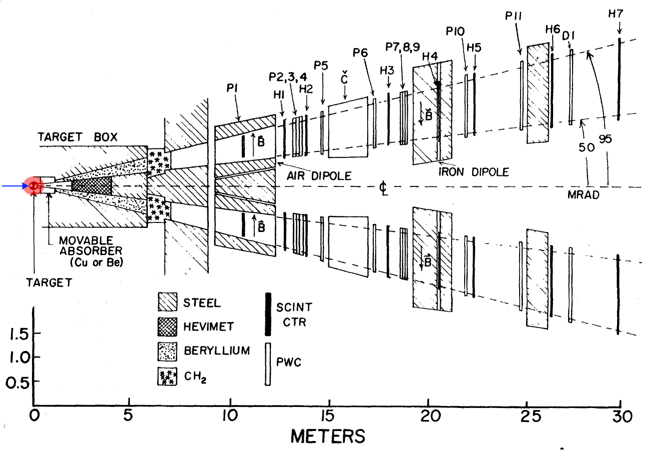
The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) $\approx 2\%$.

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

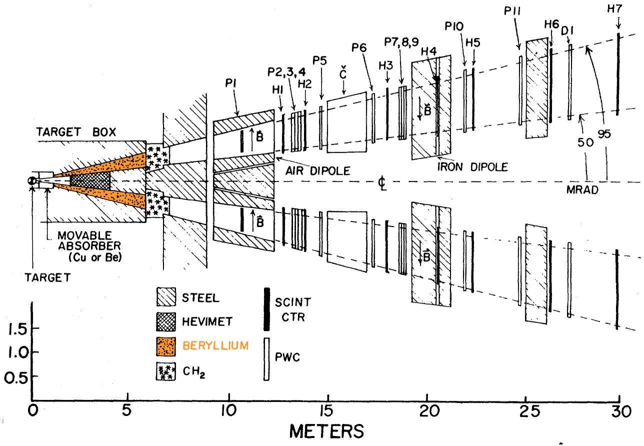

TARGET BOX
MOVABLE ABSORBER (Cu or Be)
TARGET
P1
H1
P2,3,4
H2
P5
Č
P6
H3
P7,8,9
H4
P10
H5
P11
H6
D1
H7
AIR DIPOLE
IRON DIPOLE
50
95
MRAD
STEEL
HEVIMET
BERYLLIUM
CH2
SCINT CTR
PWC
1.5
1.0
0.5
0
5
10
15
20
25
30
METERS

Setup



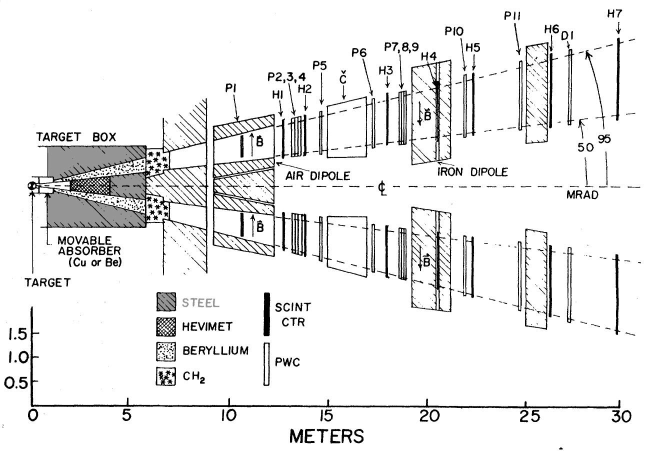
- 400 GeV proton beam shot on narrow target (Pt/Cu) with 30 % interaction length

Setup



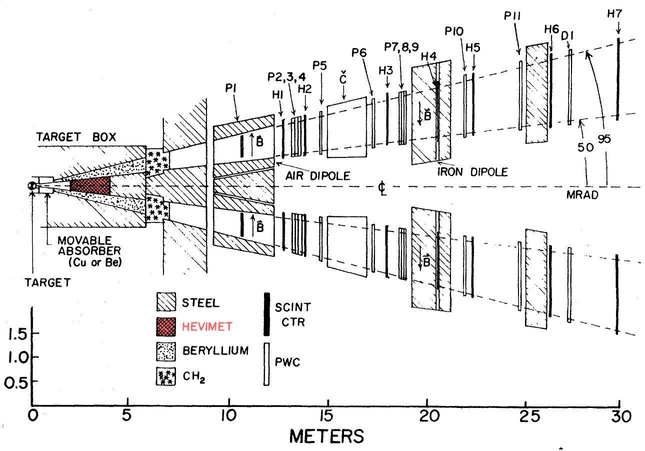
- hadron filter out of Be with 18 interaction length (3° to 5° horiz. and $\pm 0.5^\circ$ vert.)

Setup



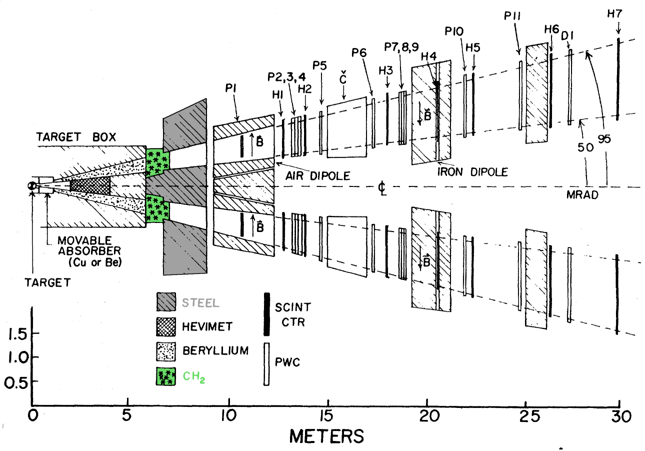
- heavy metal (Steel, W) shielding to minimise particle leakage

Setup



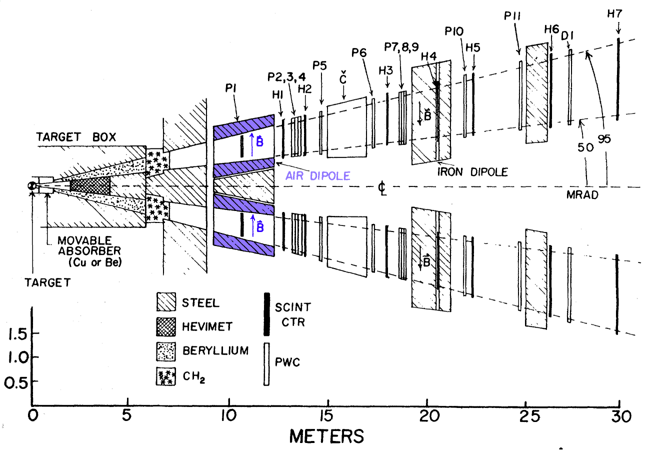
- tungsten beam dump

Setup



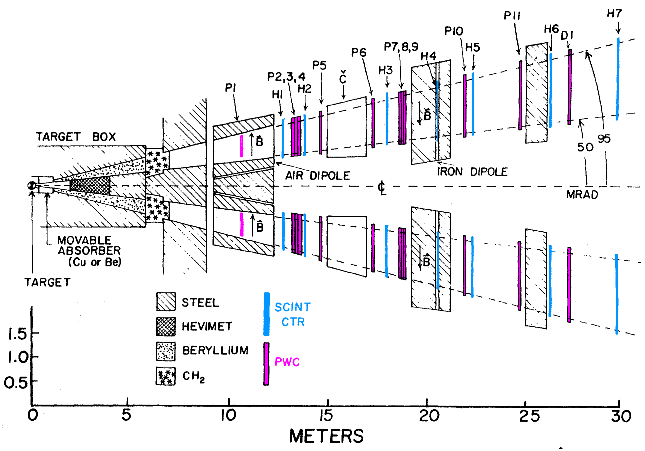
- additional shielding out of polyethylene and more steel

Setup



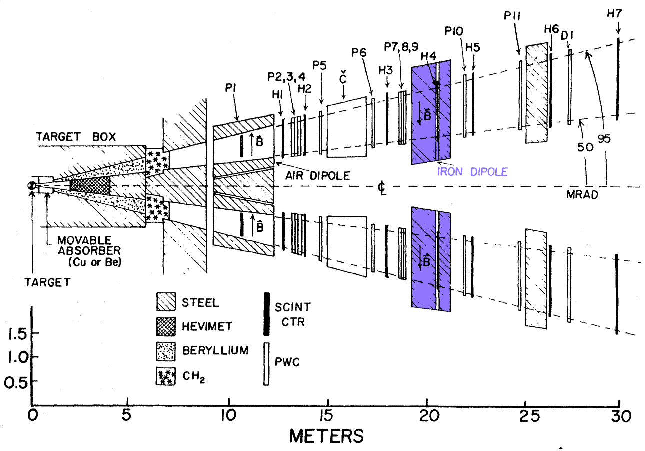
- spectrometer dipole magnets with horizontal field
- both arms are symmetric to drawing plane and detect μ^+ and μ^-

Setup



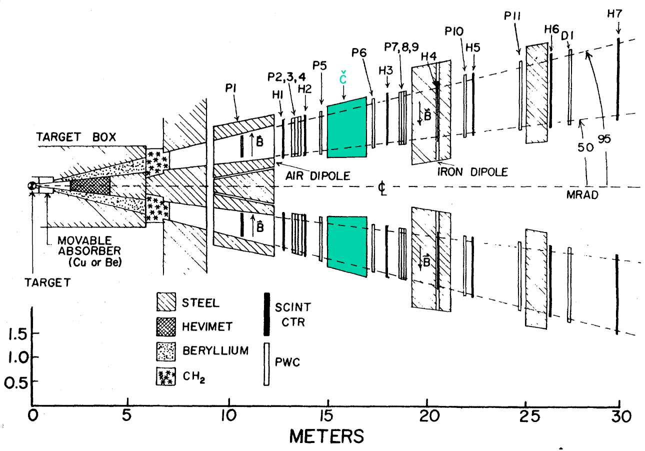
- scintillation hodometers and wire chambers for tracking (limit of 10×10^7 counts/s)

Setup



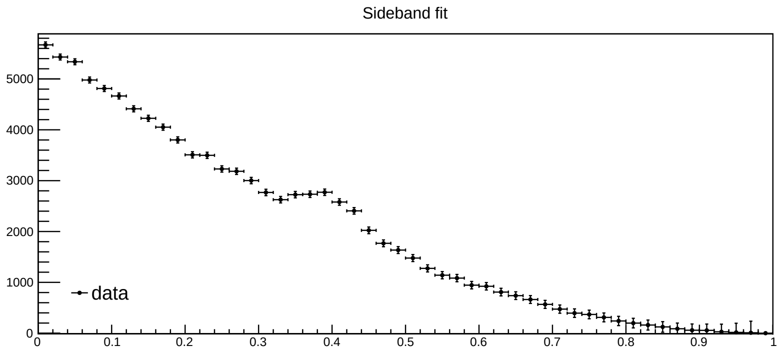
- solid iron magnet to partially refocus and redetermine muon momentum

Setup



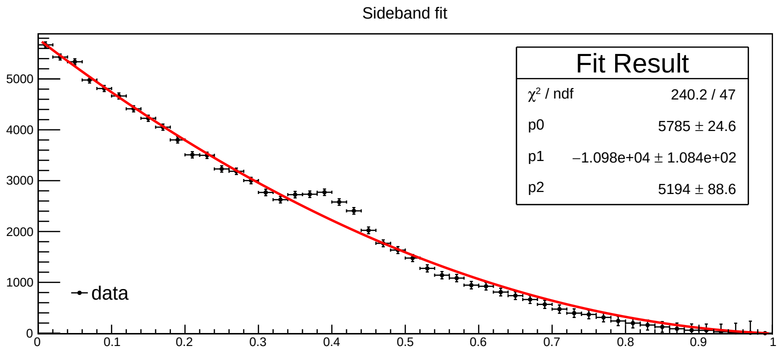
- Čerenkov counter to prevent low momentum muon triggers

Intermezzo: Sideband Fit



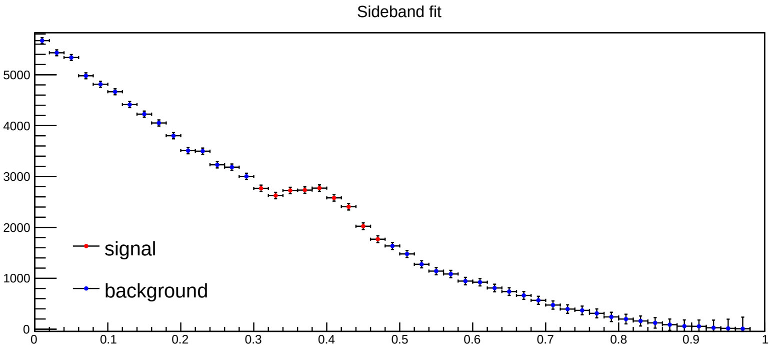
- typical shape of data in particle physics: continuous background with a small bump

Intermezzo: Sideband Fit



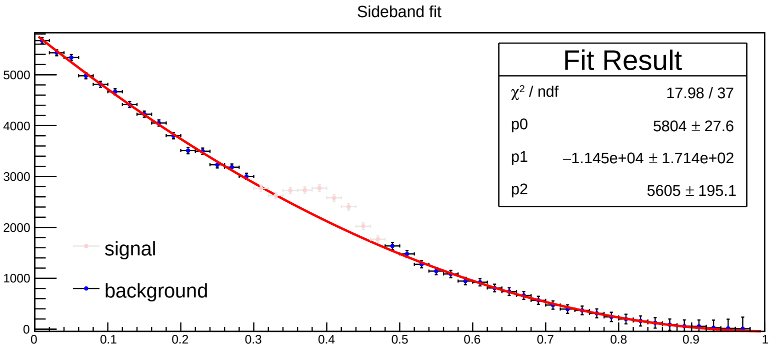
- background extraction with a fit of the whole set does not work well

Intermezzo: Sideband Fit



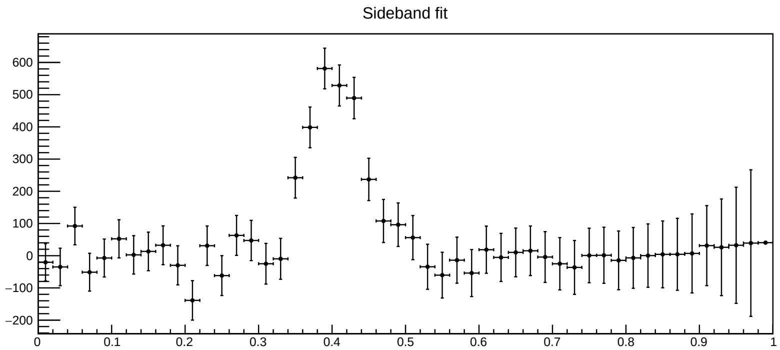
- divide the data set in a signal and two background parts ($\rightarrow$ side bands)

Intermezzo: Sideband Fit



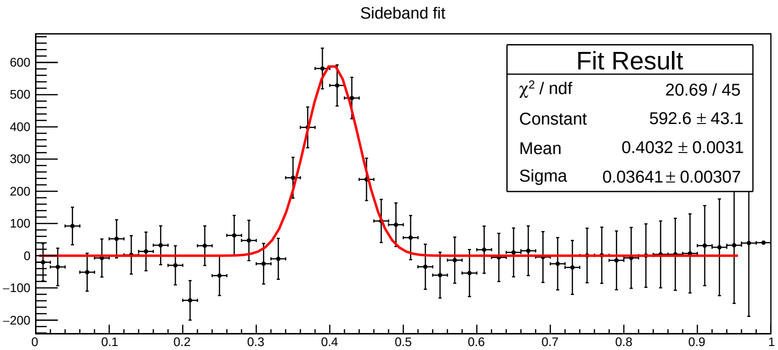
- fitting just the side bands yields a much better result

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

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

- fit expects 350 events in excluded region but 770 events in data
- bump wider than resolution of detector (FWHM: 0.5(1) GeV)
- simple Gaussian fit of background subtracted data yields:

$$\mathbf{m = 9.54(4)\,GeV}$$
$$\mathbf{FWHM = 1.16(9)\,GeV}$$

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

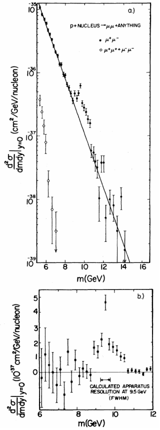
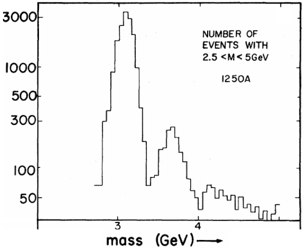


Figure: dimuon production cross section as a function of invariant mass

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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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,
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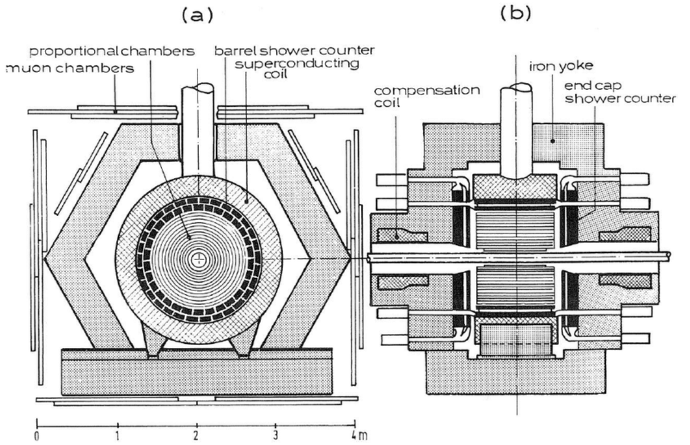
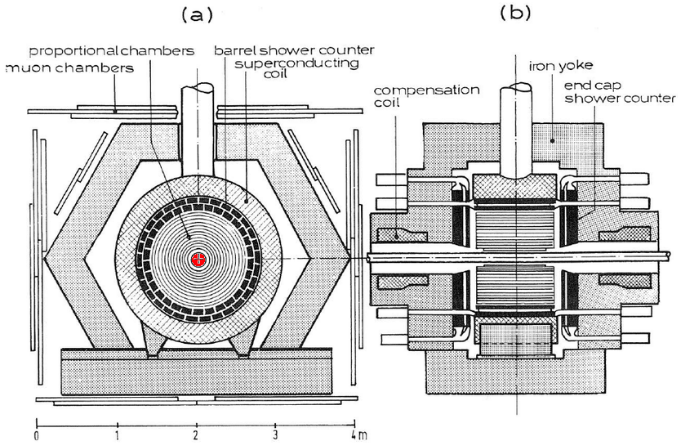
Received 9 May 1978

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 $\Gamma_{ee} = 1.3 \pm 0.4$ keV was obtained. In standard theoretical models, this favors a quark charge assignment of $-1/3$.

PLUTO Detector

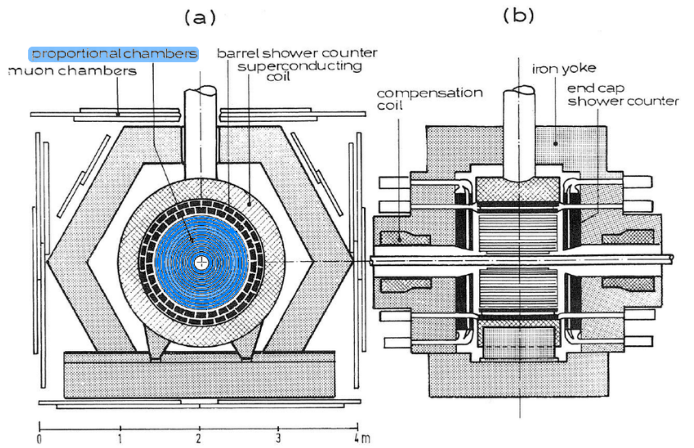


PLUTO Detector



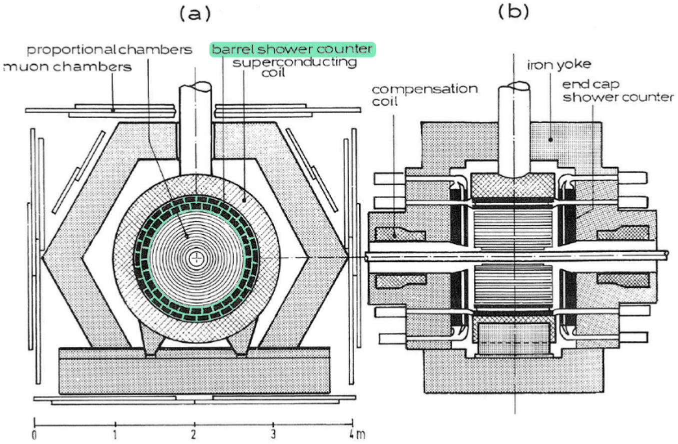
- up to 5 GeV electron beams collided in the centre

PLUTO Detector



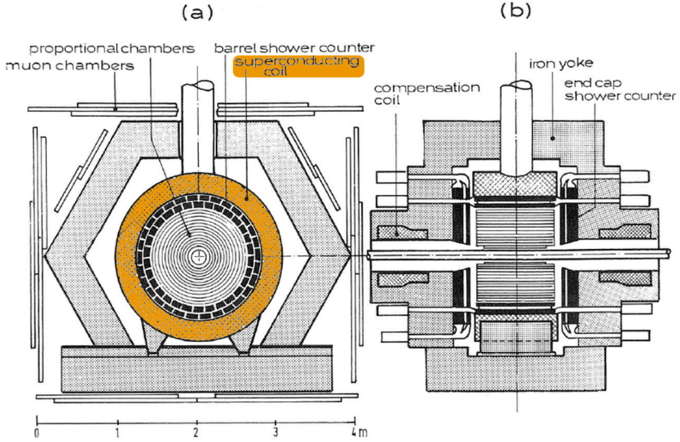
- cylindrical proportional wire chamber with 92 % coverage
- tracking and momentum measurement

PLUTO Detector



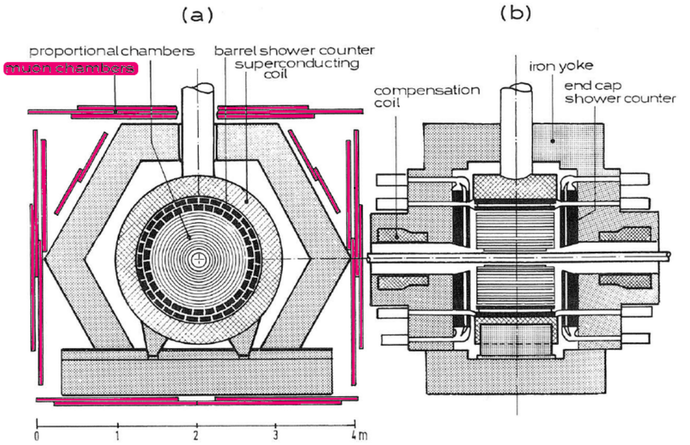
- cylindrical array of shower counters with 8.6 radiationlength and 94 % coverage
- calorimeter to measure the full energy

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)

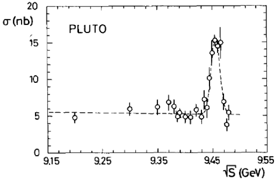


Figure: total cross section for hadron production

- 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:

$$\mathbf{m = 9.46(1)\,GeV}$$
$$\sigma_{\mathrm{Gauss}} = \mathbf{7.8(9)\,MeV}$$

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}

$$\Gamma_{ee} = 1.3(4)\,\mathrm{keV}$$

- theoretical predictions from the same model:

Decay Mode	Width [keV]	
	$e = \pm 1/3$	$e = \pm 2/3$
$\mu^+\mu^-$	0.70(9)	2.8(4)

- **implies charge of -1/3 for the bottom quark**

Section 3

The Truth Quark

Introduction

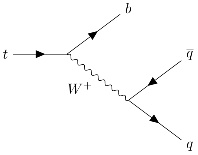
- in early 90s all SM particles except H and t-quark discovered
- beauty discovery $\rightarrow$ weak isospin partner was undoubted
- quark masses are fundamental parameters in the SM
- early estimates: $\mathrm{m_t} \approx 3\mathrm{m_b} \approx 15\,\mathrm{GeV}$
- many new accelerator could only push 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 $\rightarrow$ $^1/_2\mathrm{m_t}$
- hadron collider needed ($\rightarrow$ Tevatron)

Decay Channels (1)

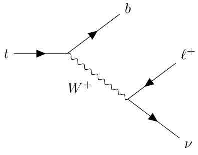
- estimate on m_t in 1994: $\sim$180 GeV
- prior to discovery: behaviour completely predicted by SM
- $m_t > m_W \rightarrow$ main decay channel ($\sim$95 %): $\mathbf{t \longrightarrow W^+ b}$

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

- width for the expected mass: $\sim$1 GeV $\rightarrow$ decay before hadronisation



(a) $\sim$60 %

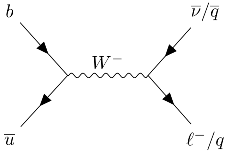


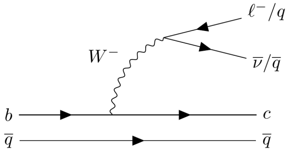
(b) $\sim$40 %

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

Decay Channels (2)

- top mostly pair produced via $q\bar{q} \longrightarrow t\bar{t}$ or gluon fusion: $gg \longrightarrow t\bar{t}$
- main decay of the top pair: $t\bar{t} \longrightarrow W^{+}bW^{-}\bar{b}$
- b decay:



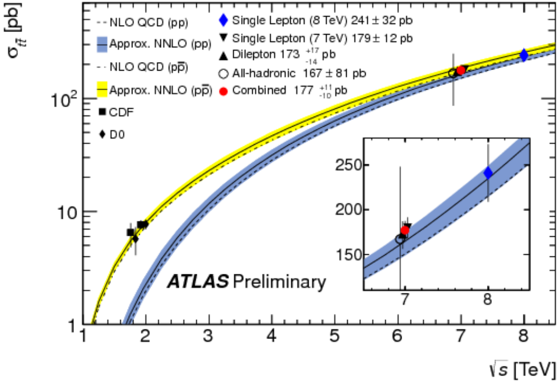


- typical signals:
  - 2 b-jets + dilepton (e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, μ^+e^-)
  - 2 b-jets + single lepton + two jets
  - 2 b-jets + 4 jets
- huge background on pure QCD process due to other more common QCD processes
- how to discriminate b-jets from other jets?

B-Tagging

- how to discriminate b-jets from other jets?

$t\bar{t}$ Cross Section



- cross section extracted from SM
- Tevatron Lumi in 1995: $10 \times 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

$$R_{t\bar{t}} = \sigma_{t\bar{t}}\mathscr{L} = 0.1\,\mathrm{Hz}$$

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

F. Abe,[14] H. Akimoto,[32] A. Akopian,[27] M. G. Albrow,[7] S. R. Amendolia,[24] D. Amidei,[17] J. Antos,[29] C. Anway-Wiese,[4]
S. Aota,[32] G. Apollinari,[27] T. Asakawa,[32] W. Ashmanskas,[15] M. Atac,[7] P. Auchincloss,[26] F. Azfar,[22]
P. Azzi-Bacchetta,[21] N. Bacchetta,[21] W. Badgett,[17] S. Bagdasarov,[27] M. W. Bailey,[19] J. Bao,[35] P. de Barbaro,[26]
A. Barbaro-Galtieri,[15] V. E. Barnes,[25] B. A. Barnett,[13] P. Bartalini,[24] G. Bauer,[16] T. Baumann,[9] F. Bedeschi,[24]
S. Behrends,[3] S. Belforte,[24] G. Bellettini,[24] J. Bellinger,[34] D. Benjamin,[31] J. Benlloch,[16] J. Bensinger,[3] D. Benton,[22]
A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[27] K. Biery,[12] M. Binkley,[7] D. Bisello,[21] R. E. Blair,[1]
C. Blocker,[3] A. Bodek,[26] W. Bokhari,[16] V. Bolognesi,[24] D. Bortoletto,[25] J. Boudreau,[23] G. Brandenburg,[9]
L. Breccia,[2] C. Bromberg,[18] E. Buckley-Geer,[7] H. S. Budd,[26] K. Burkett,[17] G. Busetto,[21] A. Byon-Wagner,[7]
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Discovery Paper (2)

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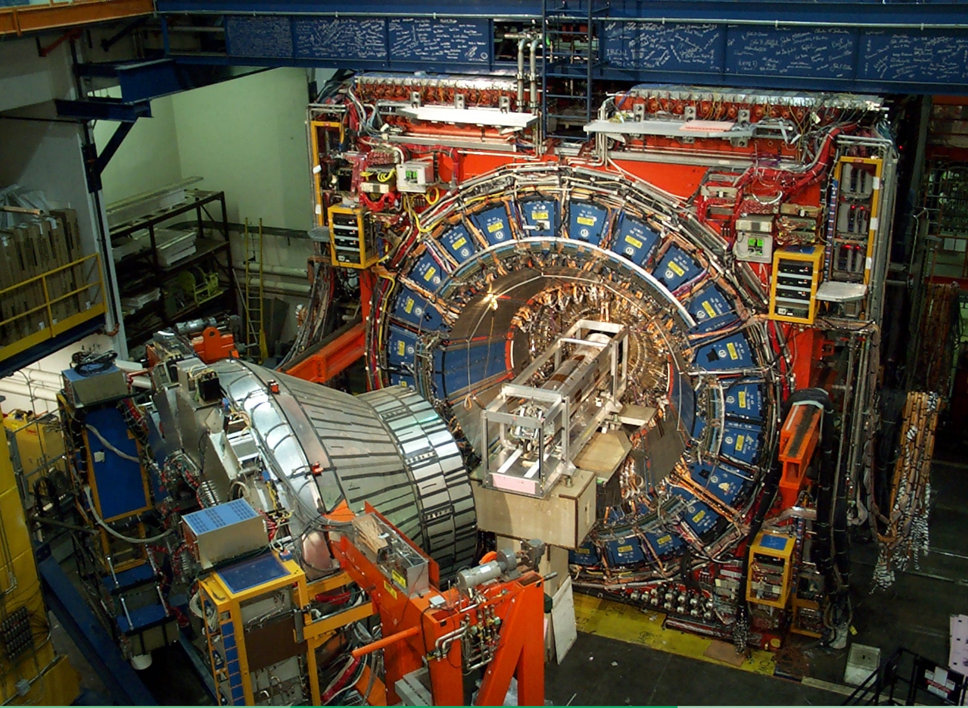
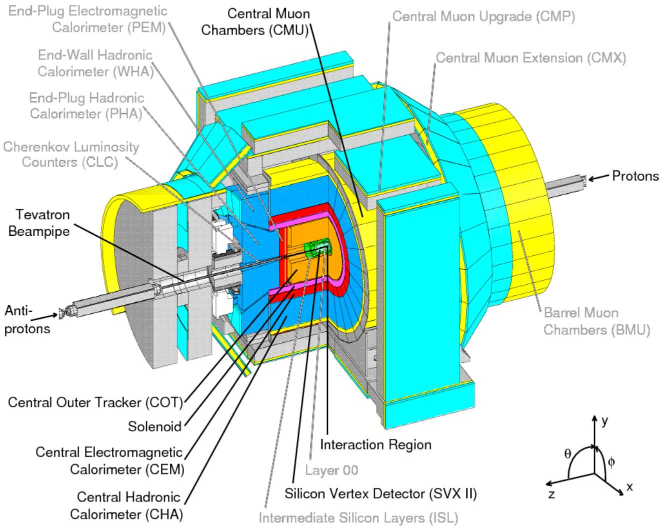
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, 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

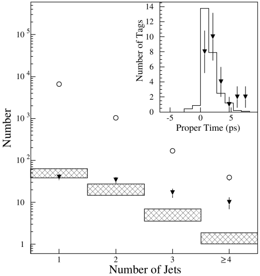
- paper from 1994 with estimate on mass and cross section
- using dataset of $19\,\mathrm{pb}^{-1} + 47\,\mathrm{pb}^{-1}$ ($\rightarrow \sim 400$ events)
- looking at two decay channels
  - dilepton
  - lepton + jets
- both data samples subsets of events with isolated leptons with high $P_T > 20\,\mathrm{GeV}$
- 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:

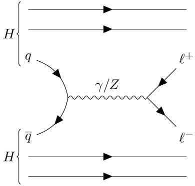
- search for secondary vertices with three ore more tracks
- then search for two ore more tracks with more stringed track and vertex quality
- efficiency estimated by e, μ samples with enriched b decays (96 % agreement to MC)
- tagging efficiency: 42(5) %

- backgrounds from recoil of heavy quark pairs against W and mistags
- for W+ $\geq$ 3 jets: observation of 27 tags with bg of 6.7(21) tags
- decay lifetime of SVX tags agrees well with MC



Dilepton Channel

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



Section 4

Conclusion

The Truth Quark

- empty
- moreempty
- moremoreempty