



Eidgenössische Technische Hochschule Zürich  
Swiss Federal Institute of Technology Zurich



**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  $J/\psi$ ) 4 leptons and 4 quarks discovered

## Standard Model

two gen. of matter  
(fermions)

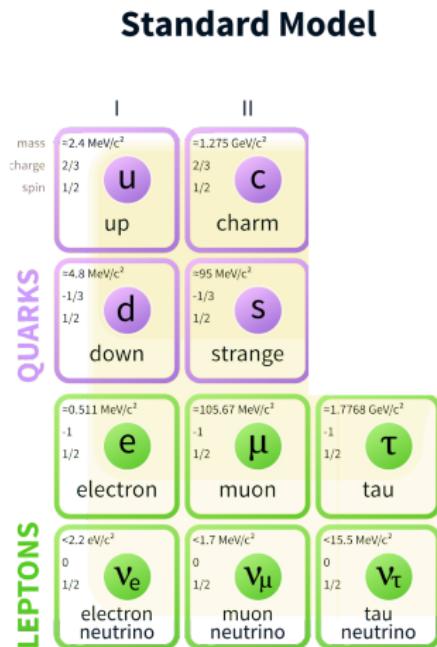
	I	II
mass	$\approx 2.4 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$
charge	2/3	2/3
spin	1/2	1/2
	u	c
	up	charm
mass	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$
charge	-1/3	-1/3
spin	1/2	1/2
	d	s
	down	strange
mass	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.67 \text{ MeV}/c^2$
charge	-1	-1
spin	1/2	1/2
	e	$\mu$
	electron	muon
mass	$< 2.2 \text{ eV}/c^2$	$< 1.7 \text{ MeV}/c^2$
charge	0	0
spin	1/2	1/2
	$\nu_e$	$\nu_\mu$
	electron neutrino	muon neutrino

QUARKS

LEPTONS

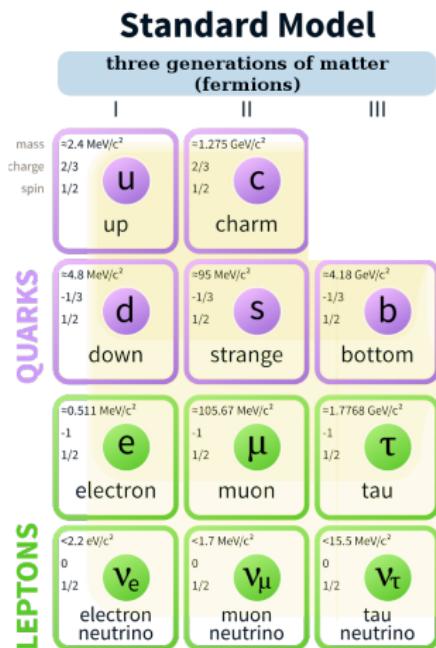
# Introduction

- in 1974 (with  $J/\psi$ ) 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  $\tau$ -lepton and its neutrino
- indiction of another pair of quarks



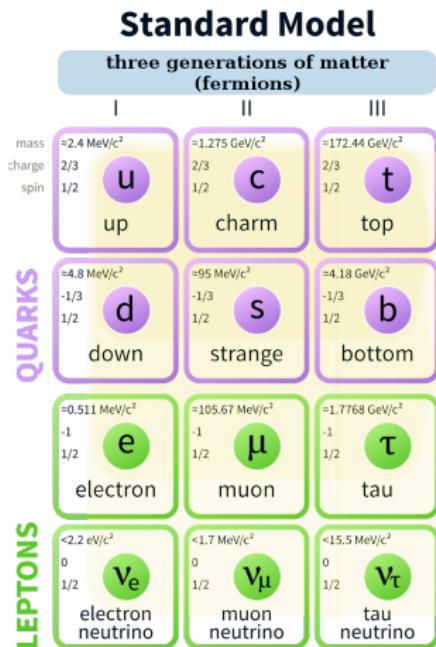
# Introduction

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- in 1977 discovery of the bottom (beauty) quark
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# Introduction

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- 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



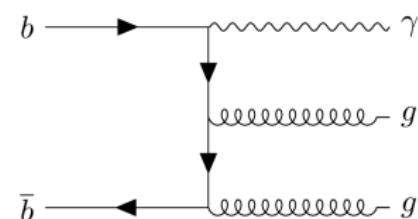
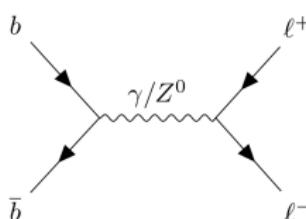
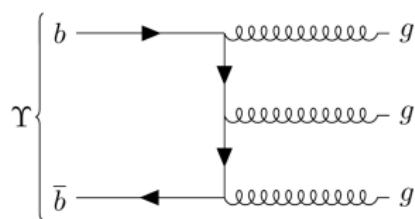


## Section 2

### The Beauty Quark

## The $\Upsilon$ -Meson

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



- mostly decay into gluons which hadronise  $\rightarrow$  signals mostly caused by hadrons
- leptonic decay splits up into 2.5 % to 3 % for each e,  $\mu$  and  $\tau$



## Discovery

## Discovery Paper

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

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,<sup>(a)</sup> H. D. Snyder, and J. K. Yoh  
*Columbia University, New York, New York 10027*

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi  
*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.

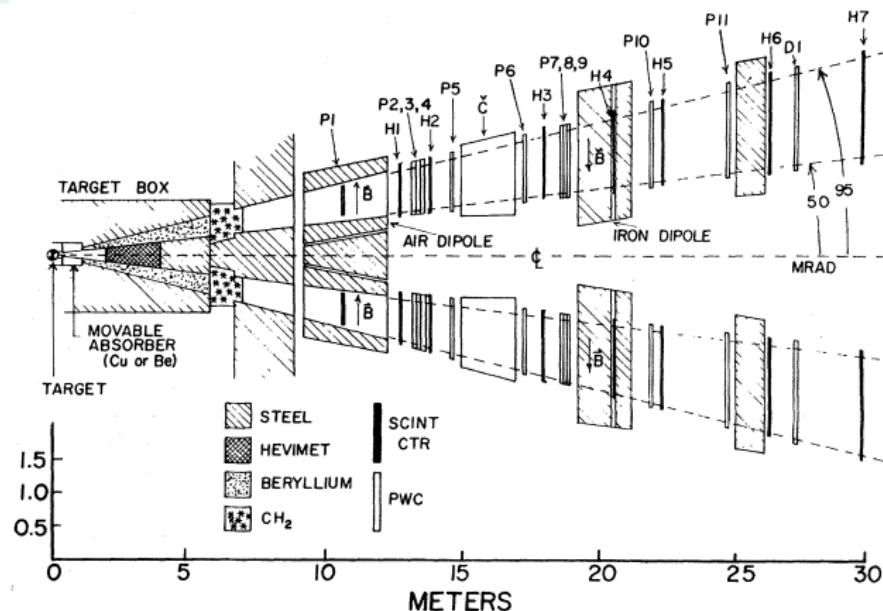
We have observed a **strong enhancement at 9.5 GeV** in the mass spectrum of dimuons produced in **400-GeV proton-nucleus collisions**. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass  $m_{\mu^+\mu^-}$  greater than 5 GeV corresponding to  $1.6 \times 10^{16}$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

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

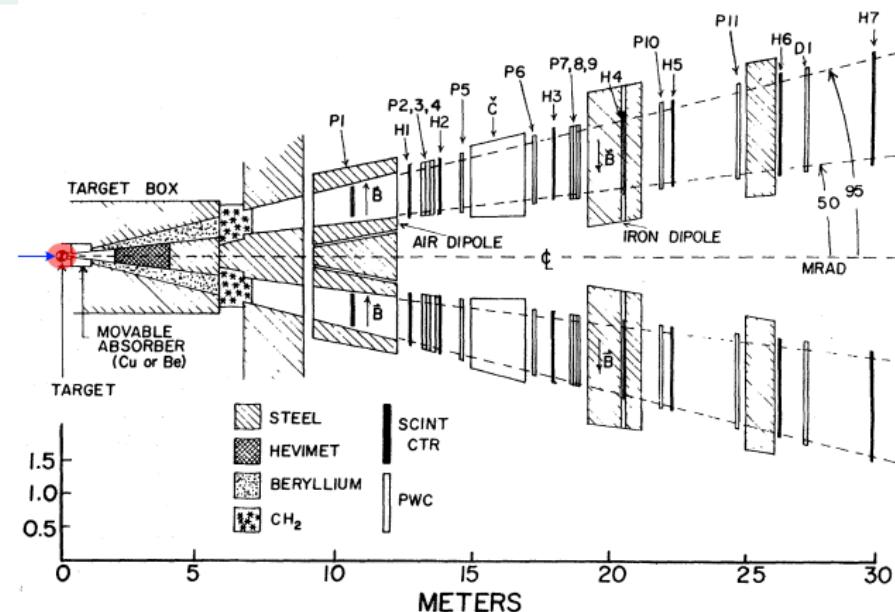
The produced muons are analyzed in a **double-arm magnetic-spectrometer system** with a mass resolution  $\Delta m/m$  (rms)  $\approx 2\%$ .

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.<sup>1-3</sup> Narrow targets ( $\sim 0.7$  mm) with lengths corresponding to 30% of an interaction length are employed.

# Setup

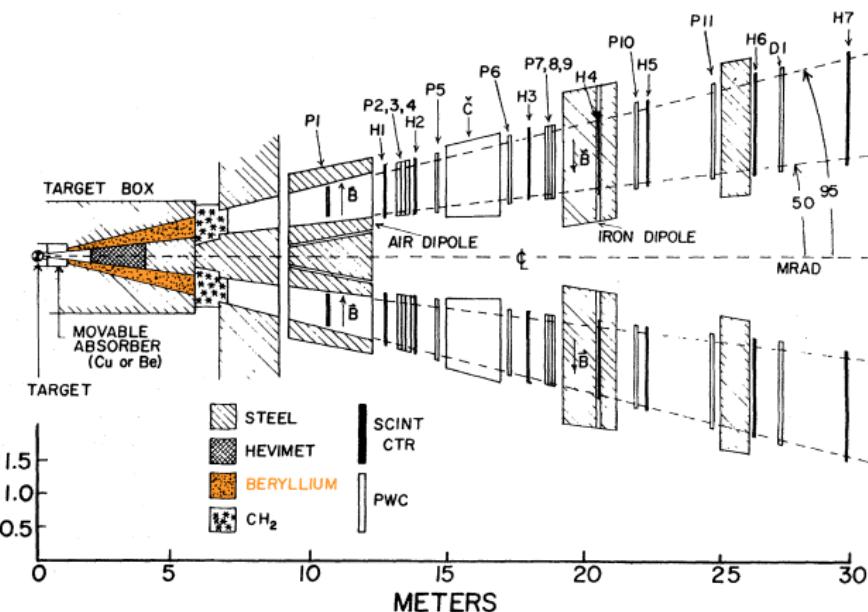


# Setup



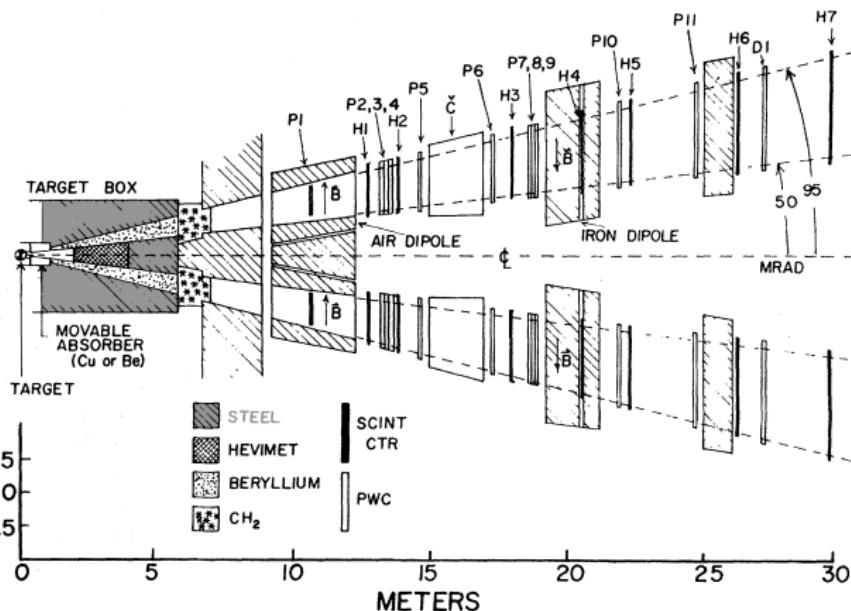
- 400 GeV proton beam shot on narrow target (Pt/Cu) with 30 % interaction length

# Setup



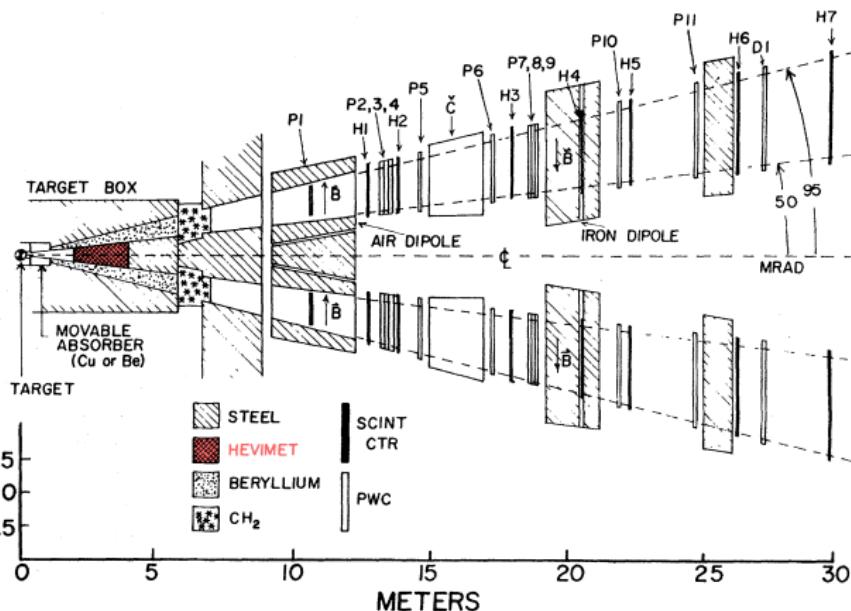
- hadron filter out of Be with 18 interaction length ( $3^\circ$  to  $5^\circ$  horiz. and  $\pm 0.5^\circ$  vert.)

## Setup



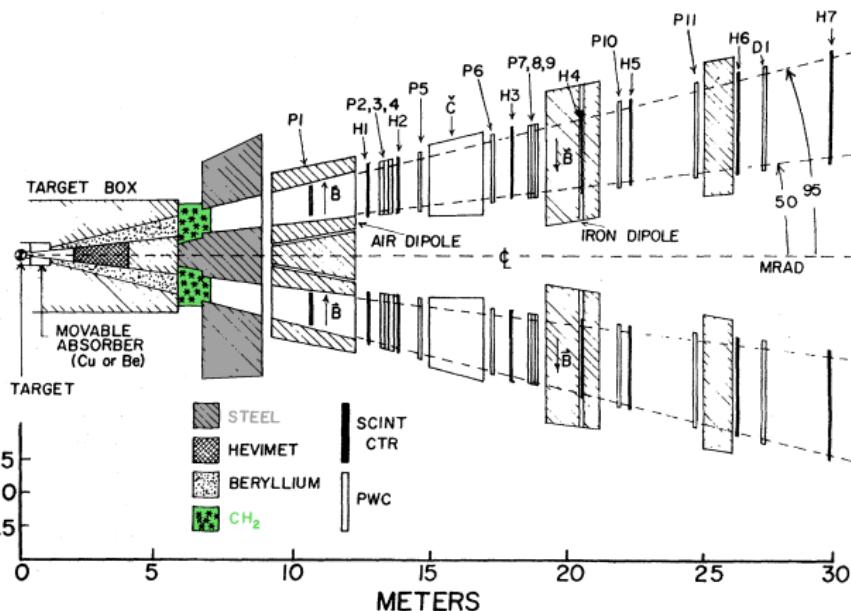
- heavy metal (Steel, W) shielding to minimise particle leakage

# Setup



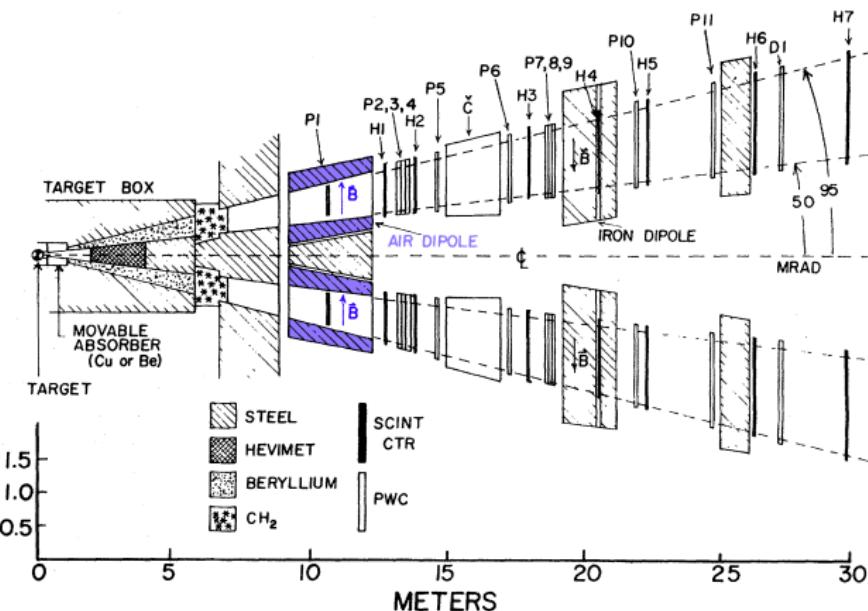
- tungsten beam dump

# Setup



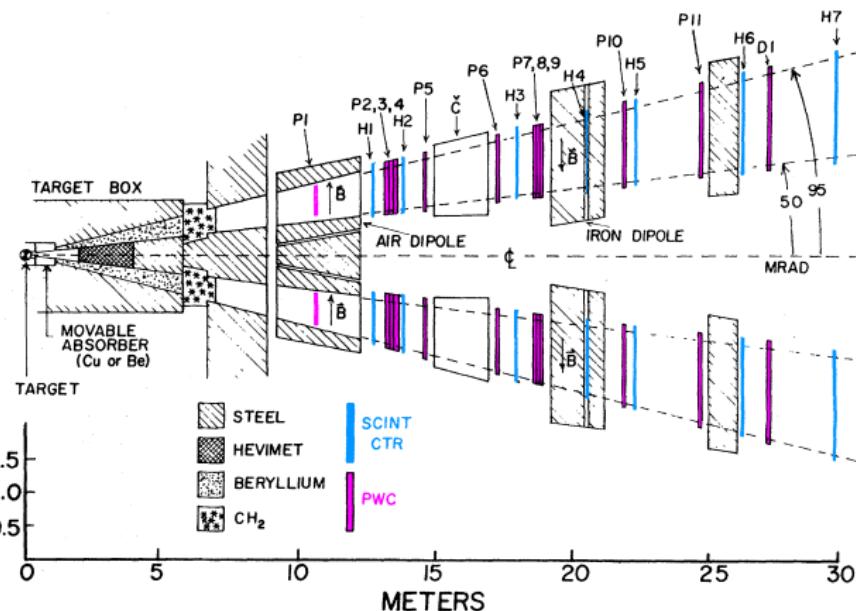
- additional shielding out of polyethylene and more steel

# Setup



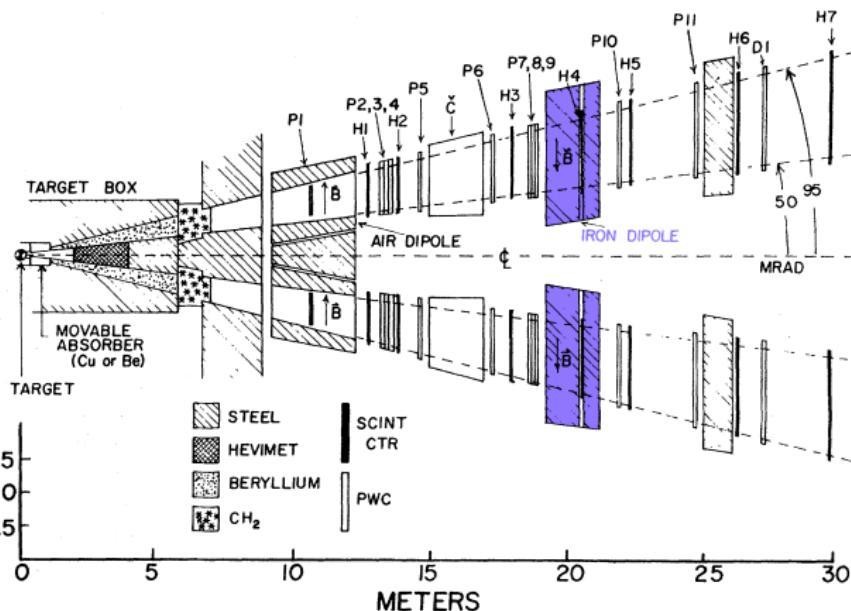
- spectrometer dipole magnets with horizontal field
- both arms are symmetric to drawing plane and detect  $\mu^+$  and  $\mu^-$

# Setup



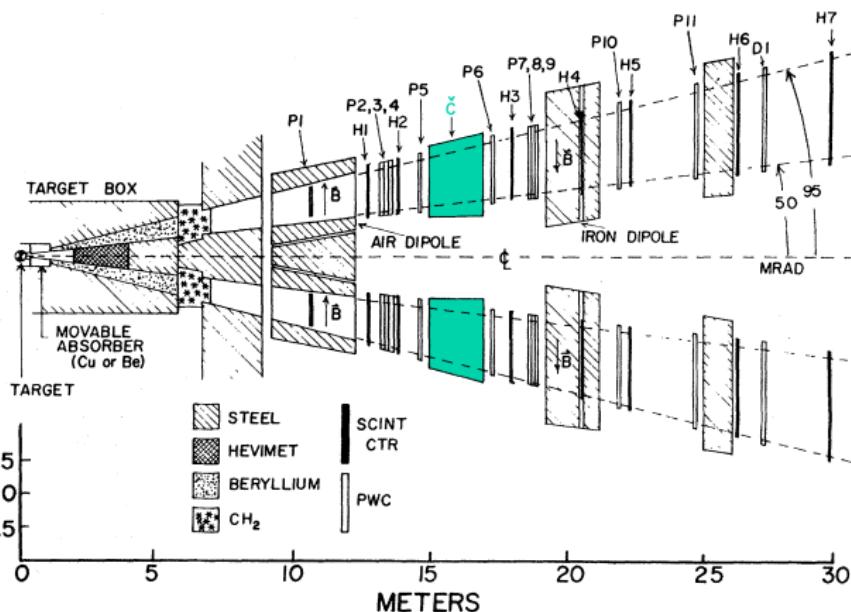
- scintillation hodoscopes and wire chambers for tracking (limit of  $10 \times 10^7$  counts/s)

## Setup



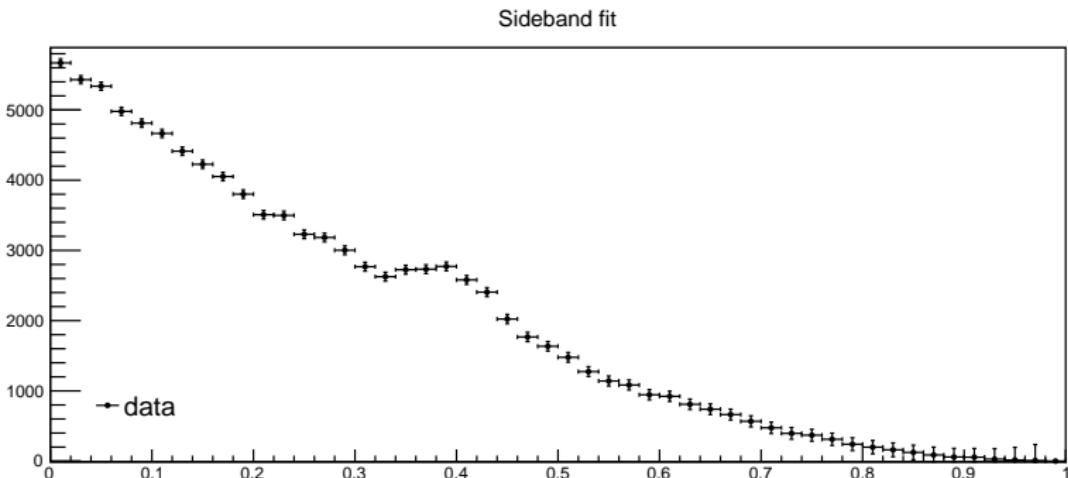
- solid iron magnet to partially refocus and redetermine muon momentum

## Setup



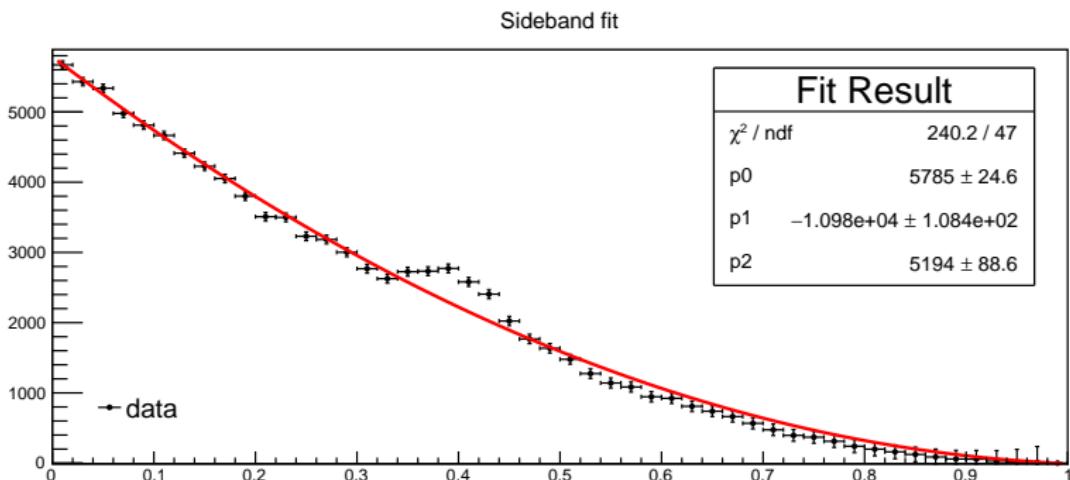
- Čerenkov counter to prevent low momentum muon triggers

## Intermezzo: Sideband Fit



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

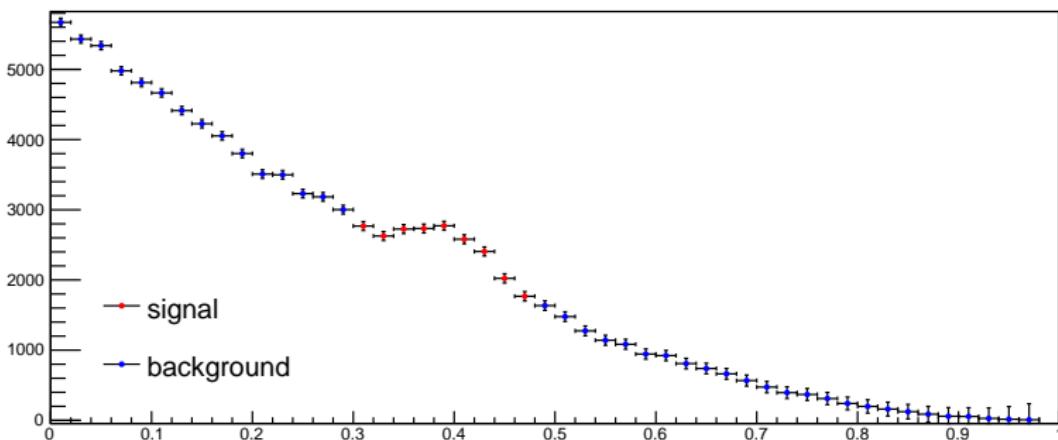
## Intermezzo: Sideband Fit



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

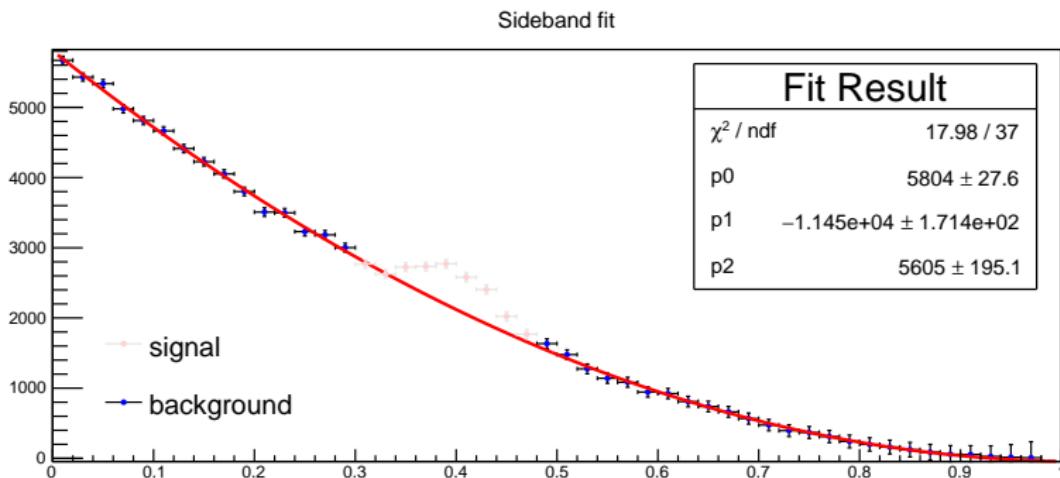
## Intermezzo: Sideband Fit

Sideband fit



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

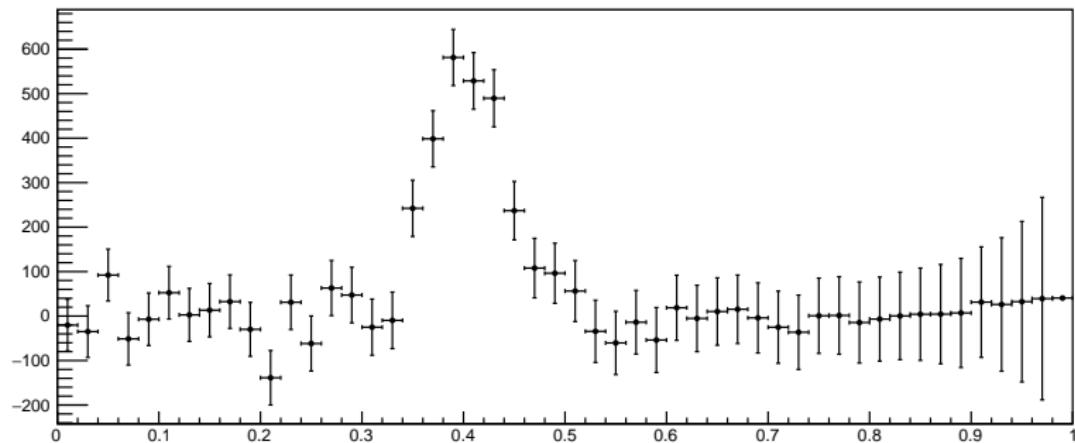
## Intermezzo: Sideband Fit



- fitting just the side bands yields a much better result

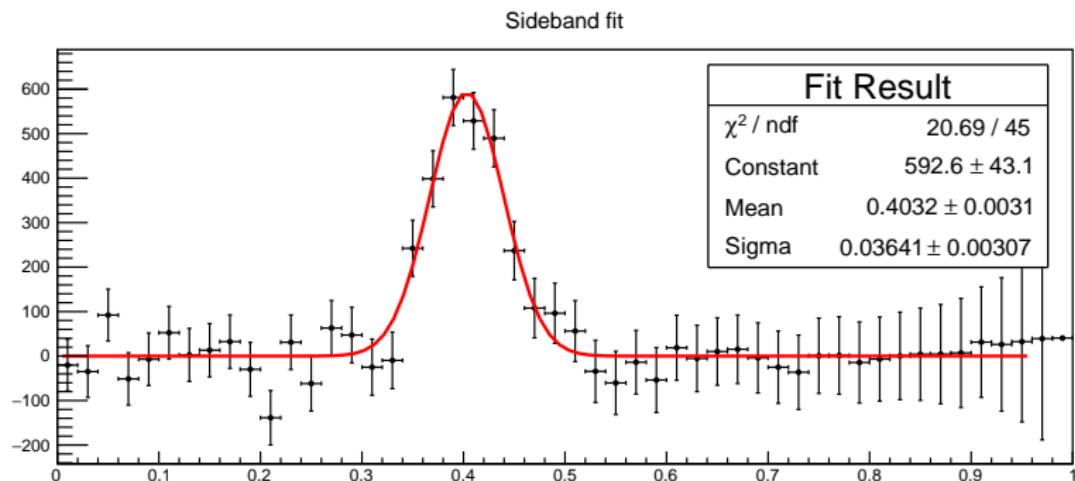
## Intermezzo: Sideband Fit

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



## Discovery

## Results

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

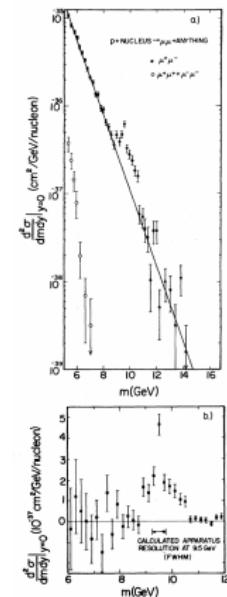
$$\frac{d^2\sigma}{dm dy} = Ae^{-bm}$$

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

$$m = (9.54 \pm 0.04) \text{ GeV}$$

$$\text{FWHM} = (1.16 \pm 0.09) \text{ GeV}$$

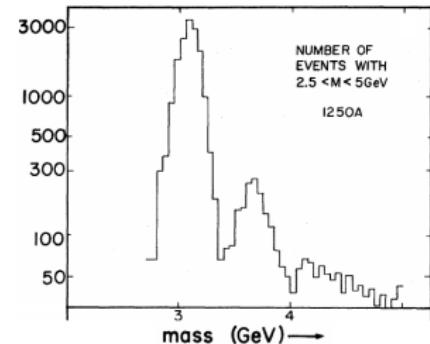
- same goodness of fit with two Gaussians with fixed width of detector resolution  $\rightarrow$  later  $\Upsilon$  and  $\Upsilon'$



**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  $\psi \rightarrow \mu^+\mu^-$  at high mass
  - ▶ confirmed by clear separation of the  $\psi$  and  $\psi'$  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





## Further Experiments

## PLUTO Collaboration Paper

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

PLUTO Collaboration

Ch. BERGER, W. LACKAS, F. RAUPACH, W. WAGNER

*I. Physikalisches Institut der RWTH Aachen, FRG*G. ALEXANDER<sup>1</sup>, L. CRIEGEE, H.C. DEHNE, K. DERIKUM, R. DEVENISH, G. FLÜGGE, G. FRANKECh. GERKE, E. HACKMACK, P. HARMS, G. HORLITZ, Th. KAHL<sup>2</sup>, G. KNIES, E. LEHMANN,B. NEUMANN, R.L. THOMPSON<sup>3</sup>, 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<sup>4</sup>, H. KAPITZA,

B. KOPPITZ, W. LÜHRSEN, R. MASCHUW, H. SPITZER, R. van STAAL, G. WETJEN

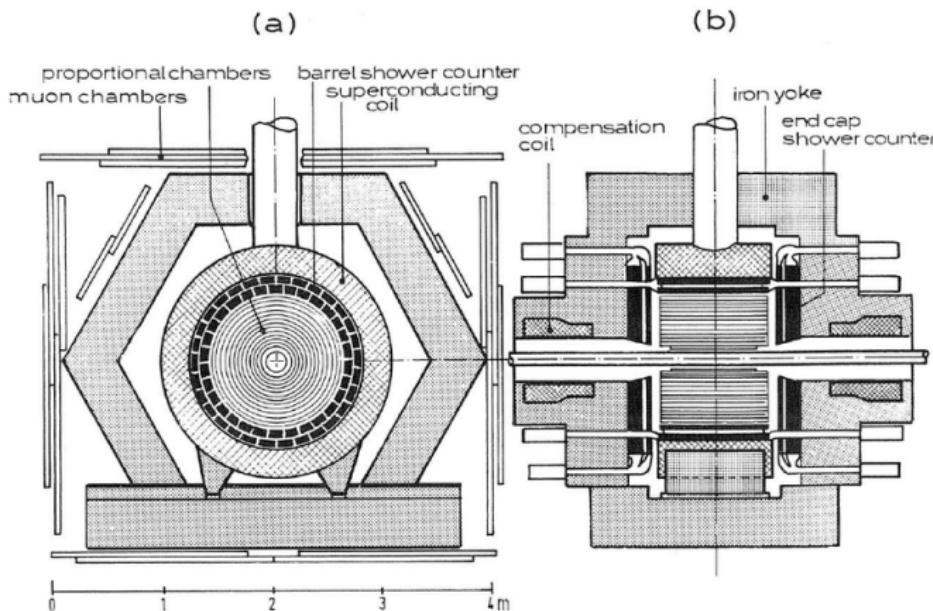
*II. Institut für Experimentalphysik der Universität Hamburg, FRG*

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  $9.46 \pm 0.01$  GeV which is consistent with that of the Upsilon. The gaussian width  $\sigma$  is observed as  $8 \pm 1$  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.

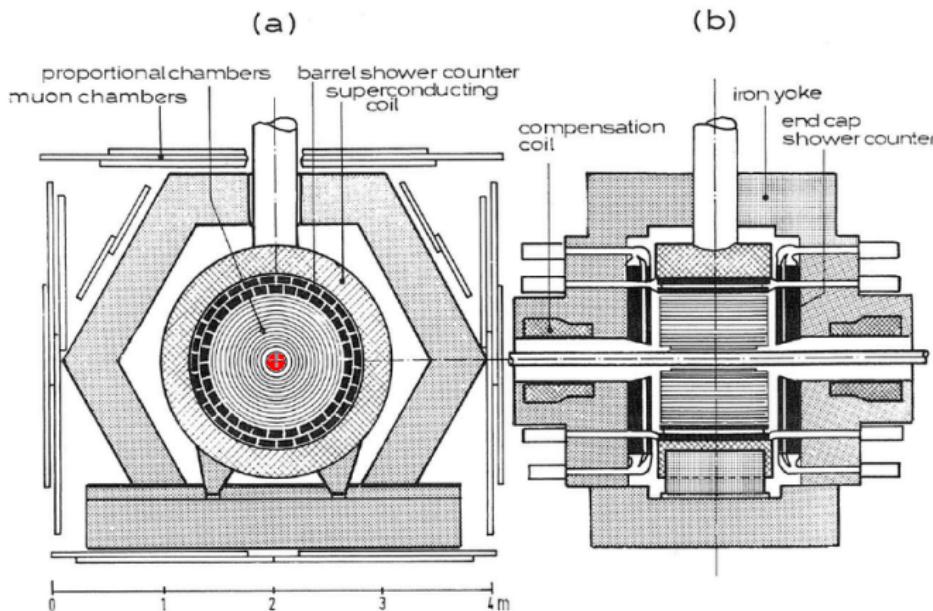
## Further Experiments

## PLUTO Detector



## Further Experiments

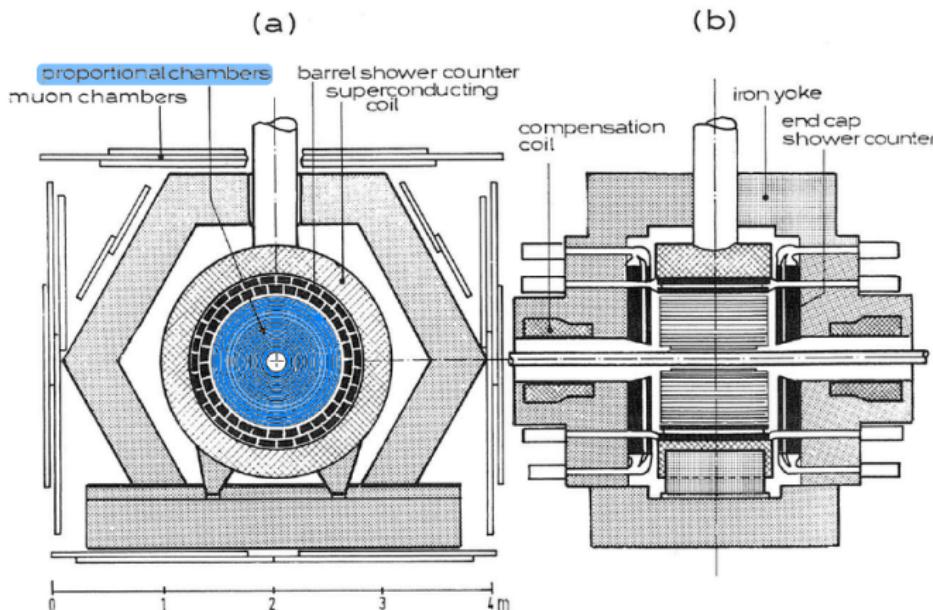
## PLUTO Detector



- up to 5 GeV electron beams collided in the centre

## Further Experiments

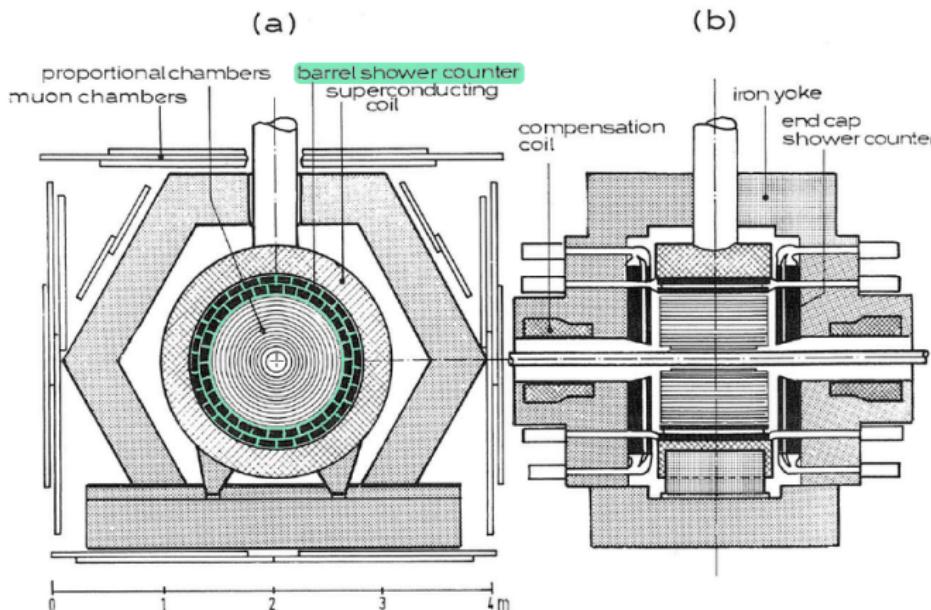
## PLUTO Detector



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

## Further Experiments

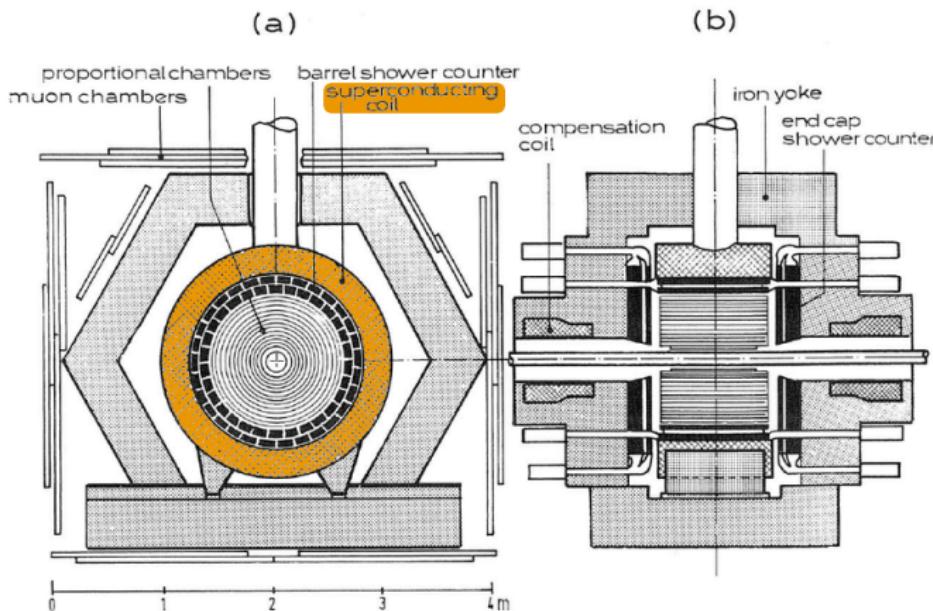
## PLUTO Detector



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

## Further Experiments

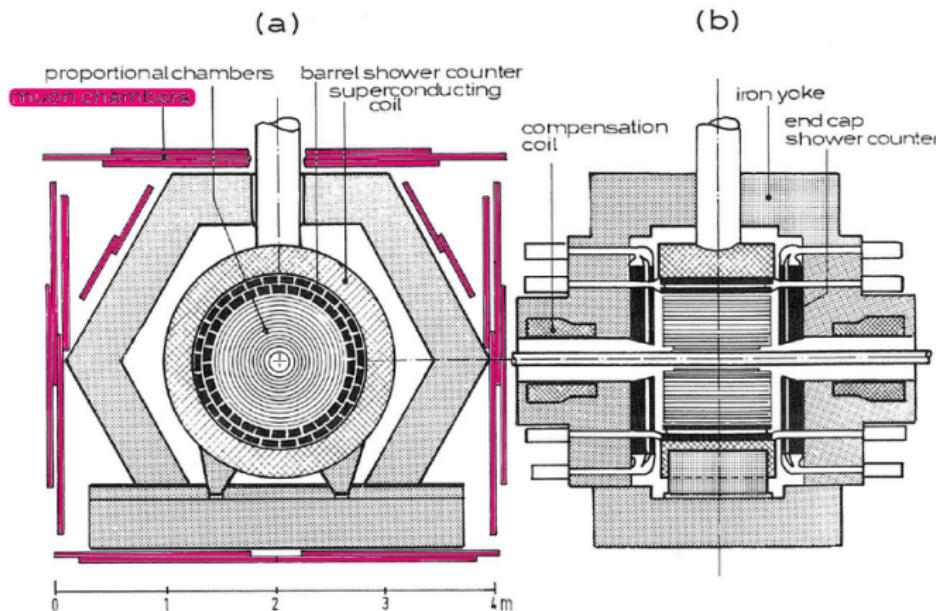
## PLUTO Detector



- magnet with 1.69 T

## Further Experiments

## PLUTO Detector



- muon chambers



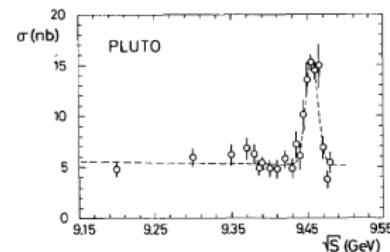
## Further Experiments

## 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)
- 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:

$$\mathbf{m = (9.46 \pm 0.01) \text{ GeV}}$$

$$\sigma_{\text{Gauss}} = (7.8 \pm 0.9) \text{ MeV}$$



**Figure:** total cross section for hadron production



## 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  $\Gamma_{ee}$

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

- theoretical predictions from the same model:

Decay Mode	Width [keV]	
	$e = \pm 1/3$	$e = \pm 2/3$
$\mu^+ \mu^-$	$0.70 \pm 0.09$	$2.8 \pm 0.4$

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



## Section 3

### The Truth Quark

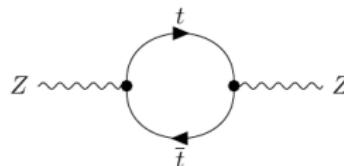
## Introduction

- in early 90s all SM particles except H and t-quark discovered
- beauty discovery → weak isospin partner was undoubted
- quark masses are fundamental parameters in the SM
- early estimates:  $m_t \approx 3m_b \approx 15 \text{ GeV}$
- many new accelerator could only push limits higher:
- TRISTAN ( $e^+ e^-$ ) at KEK (Tsukuba, Japan) with  $\sqrt{s} = 61.4 \text{ GeV} \rightarrow 30.2 \text{ GeV}$
- Sp $\bar{p}$ S at CERN with  $\sqrt{s} = 630 \text{ GeV} \rightarrow 69 \text{ GeV}$
- SLC ( $e^+ e^-$ ) at Stanford and LEP ( $e^+ e^-$ ) at CERN  $\rightarrow 1/2 m_Z$  (not seen in  $Z \rightarrow t\bar{t}$ )
- hadron collider needed ( $\rightarrow$  Tevatron)

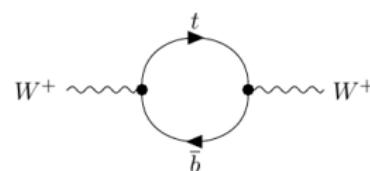


## Estimated Mass

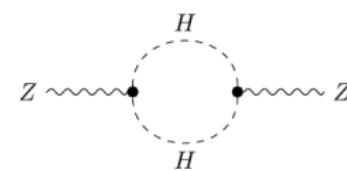
- using radiative corrections of the  $W$ ,  $Z$  bosons:



$$(a) \sim m_t^2$$



$$(b) \sim m_t^2$$



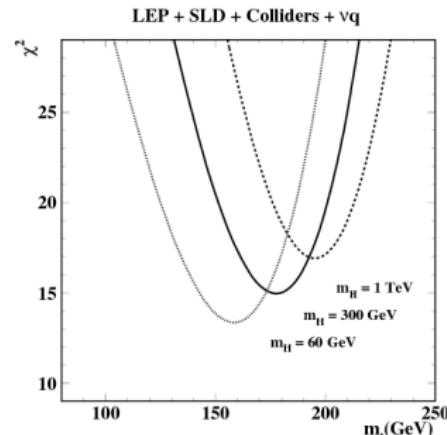
$$(c) \sim \ln(m_H^2)$$

- 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

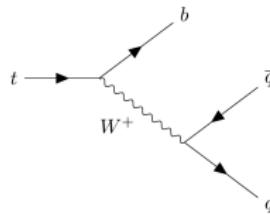


## Decay Channels (1)

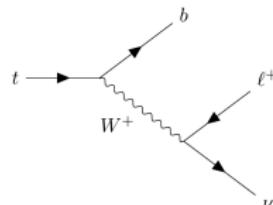
- prior to discovery: behaviour completely predicted by SM
- $m_t > m_W \rightarrow$  main decay channel ( $\sim 96\%$ ):  $t \rightarrow W^+ b$

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

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



(a)  $\sim 67\%$

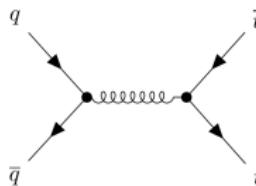
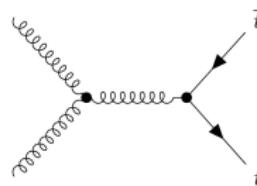


(b)  $\sim 33\%$

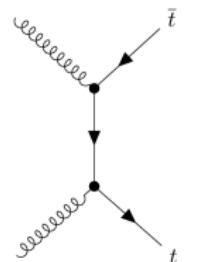
- leptonic decay equally splits up into  $e$ ,  $\mu$  and  $\tau$

## Top Production

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

(a)  $q\bar{q}$ 

(b) gluon fusion

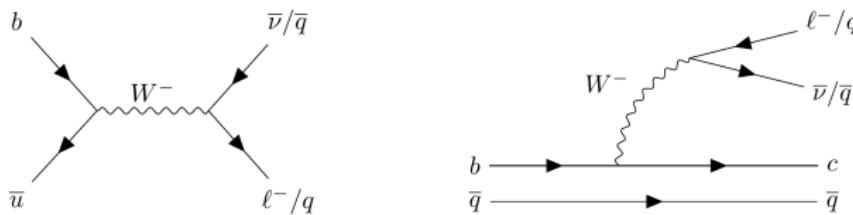


(c) gluon fusion

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

## Decay Channels (2)

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

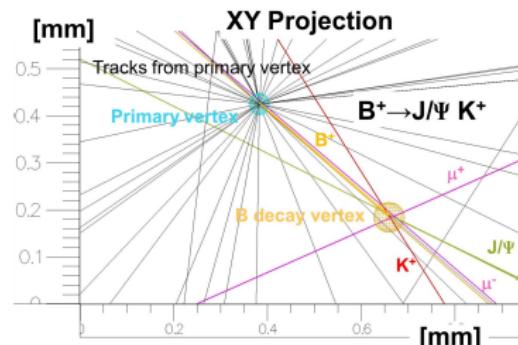


- typical signals:
  - 2 b-jets + dilepton ( $e^+ e^-$ ,  $\mu^+ \mu^-$ ,  $e^+ \mu^-$ ,  $\mu^+ e^-$ )
  - 2 b-jets + single lepton + two jets
  - 2 b-jets + 4 jets
- huge background on pure QCD process due to other more common QCD processes
- how to discriminate b-jets from other jets?

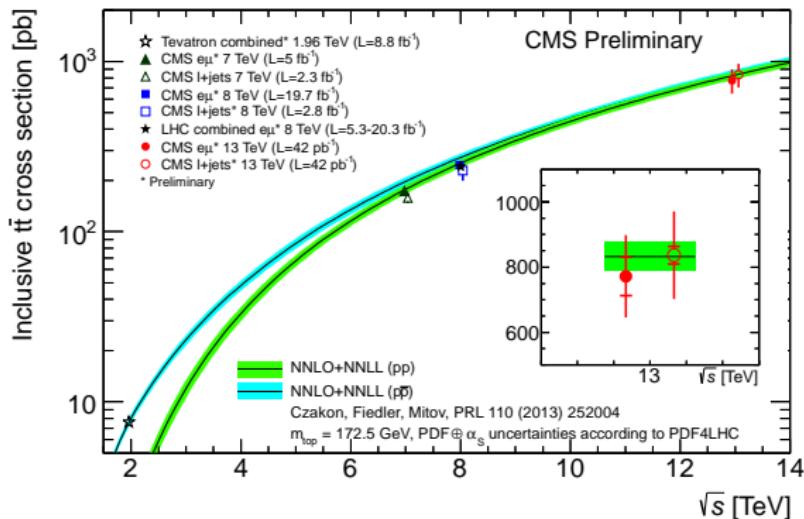
## B-Tagging

- 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



## t̄t Cross Section



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

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

## Discovery at CDF

## Discovery Paper (1)

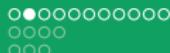
VOLUME 74, NUMBER 14

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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Williams,<sup>27</sup> P. Wilson,<sup>27</sup> B.L. Winer,<sup>27</sup> D. Wolinski,<sup>27</sup> X. Wu,<sup>24</sup> J. Wyss,<sup>27</sup> A. Yagli,<sup>27</sup> W. Yao,<sup>15</sup>



## Discovery at CDF

## Discovery Paper (2)

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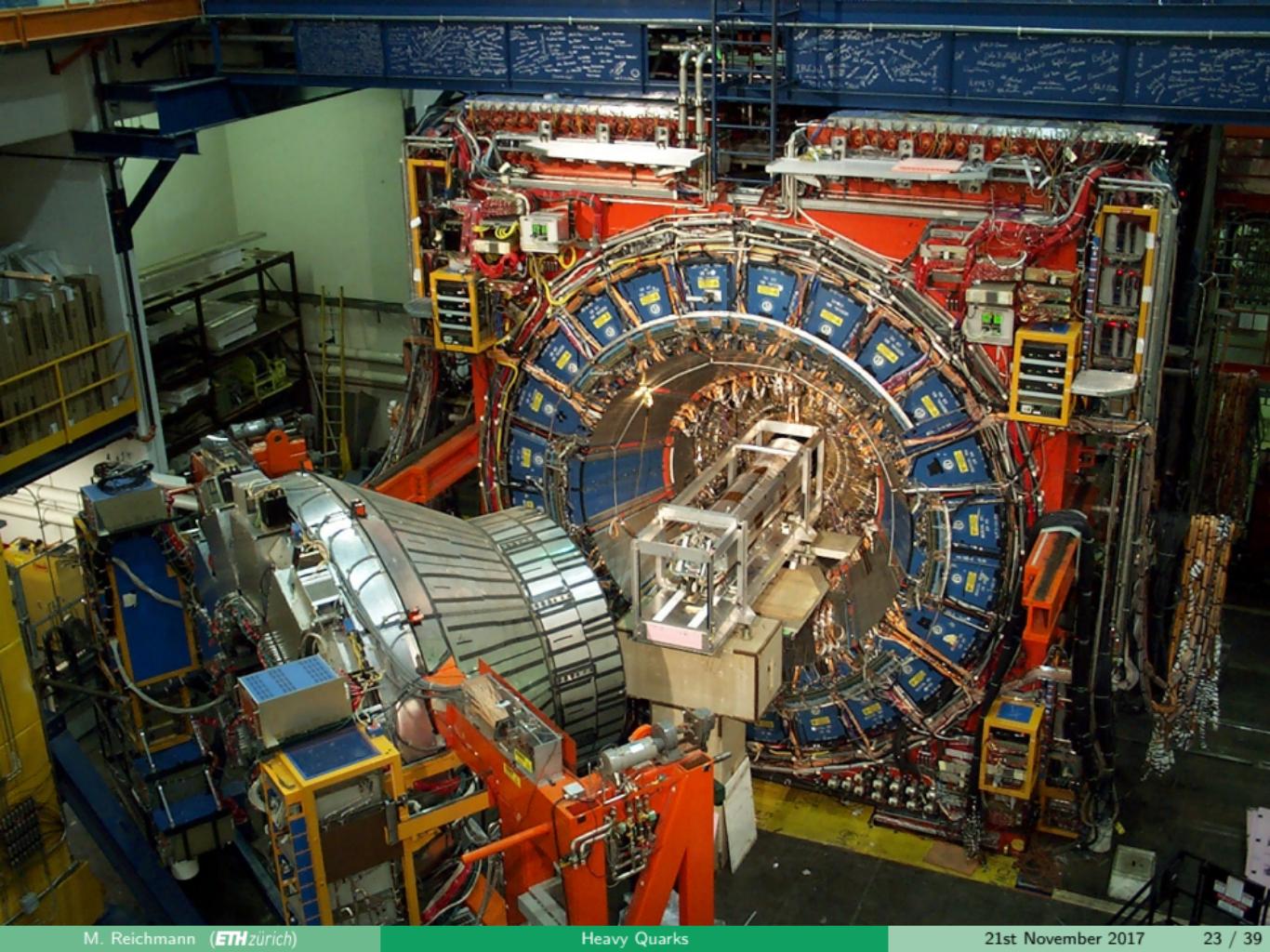
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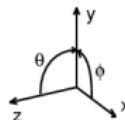
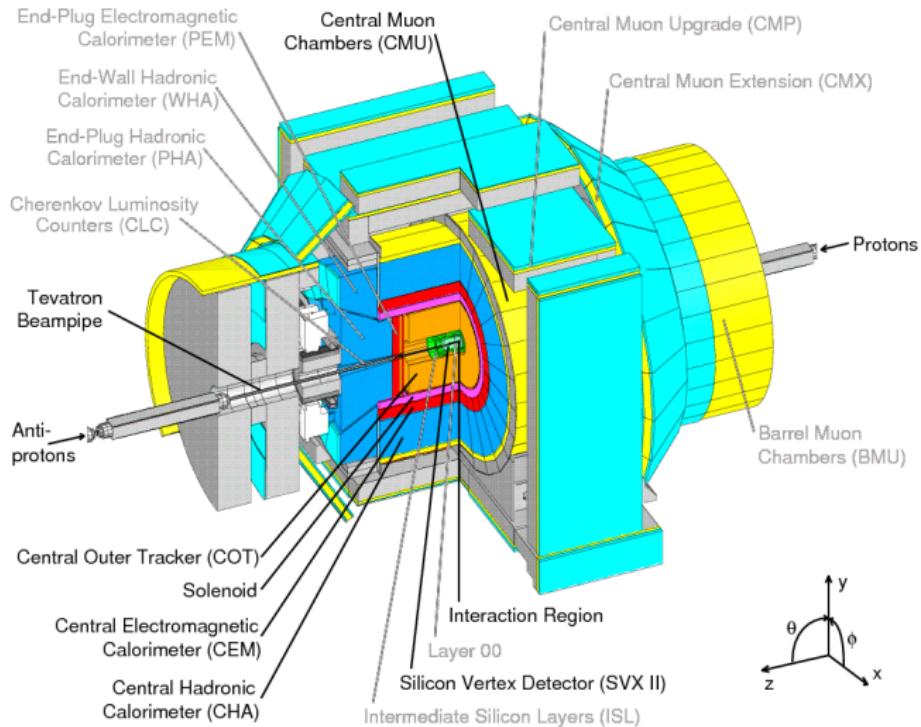
(Received 24 February 1995)

We establish the existence of the top quark using a  $67 \text{ pb}^{-1}$  data sample of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  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  $4.8\sigma$ . Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be  $176 \pm 8(\text{stat}) \pm 10(\text{sys}) \text{ GeV}/c^2$ , and the  $t\bar{t}$  production cross section to be  $6.8^{+1.6}_{-2.4} \text{ pb}$ .



## Discovery at CDF

## CDF Detector



## Discovery at CDF

## Introduction

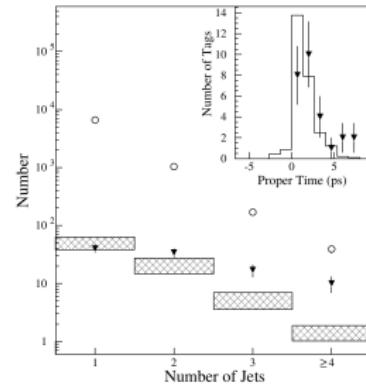
- paper from 1994 with estimate on mass and cross section
- using dataset of  $19 \text{ pb}^{-1} + 47 \text{ pb}^{-1}$  ( $\rightarrow \sim 400$  events)
- looking at two decay channels
  - ▶ dilepton
  - ▶ lepton + jets
- both data samples subsets of events with isolated leptons with high  $P_T > 20 \text{ GeV}$
- cut on invariant mass of dilepton  $75 \text{ GeV} < m_l < 105 \text{ GeV} \rightarrow$  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

## Discovery at CDF

## Lepton + Jets Channel

SVX tagging:

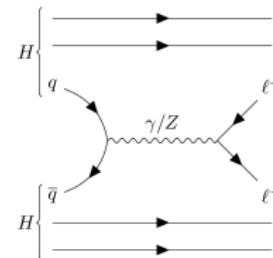
- search for secondary vertices with three or more tracks
- then search for two or more tracks with more stringent track and vertex quality
- efficiency estimated by  $e, \mu$  samples with enriched b decays (96 % agreement to MC)
- tagging efficiency:  $(42 \pm 5) \%$
- backgrounds:
  - ▶ recoil of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



## Discovery at CDF

## Dilepton Channel

- major backgrounds:
  - ▶ Drell-Yan process
  - ▶  $Z \rightarrow \tau\tau$
  - ▶ misidentified hadrons
  - ▶  $WW, bb$
- first three bg calculated by data and last two by MC
- cuts:
  - ▶  $E_T \geq 10 \text{ GeV}$
  - ▶ number of jets  $\geq 2$
- reduces Drell-Yan bg (very little  $E_T$ )
- correct for jet energy mismeasurement



## Results

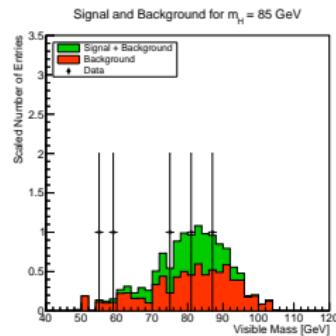
Channel	SVX	SLT	Dilepton
Observed	27 tags	23 tags	6 events
Expected background	$6.7 \pm 2.1$	$15.4 \pm 2.0$	$1.3 \pm 0.3$
Background probability	$2 \times 10^{-5}$	$6 \times 10^{-2}$	$3 \times 10^{-3}$

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

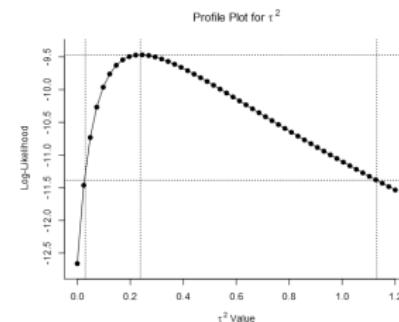
## Discovery at CDF

## 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

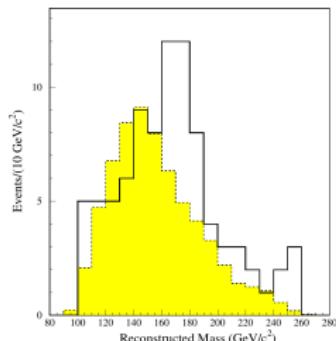


(b) likelihood fit

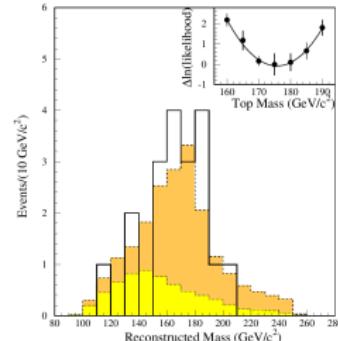
## Discovery at CDF

## Mass Reconstruction

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



(a) before b-tagging



(b) after b-tagging

## Discovery at CDF

## Combined Results

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

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

- reconstructed mass:

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

- cross section:

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

B Tagging at CMS at  $\sqrt{s}$  of 7 TeV

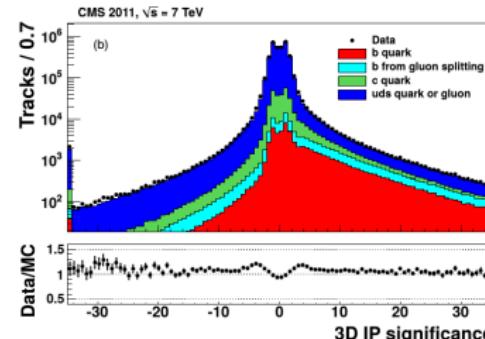
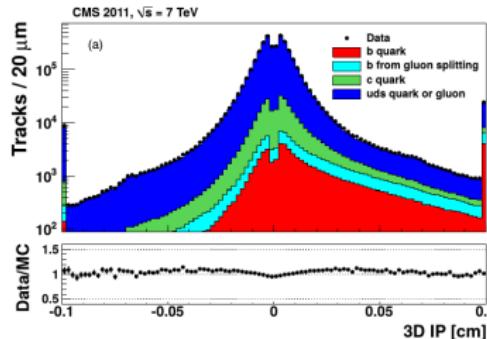
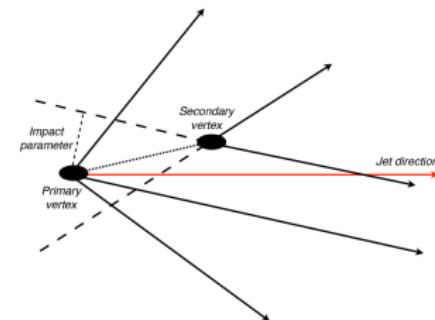
## Introduction

- 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

B Tagging at CMS at  $\sqrt{s}$  of 7 TeV

## Identification by Track Impact Parameters (IP)

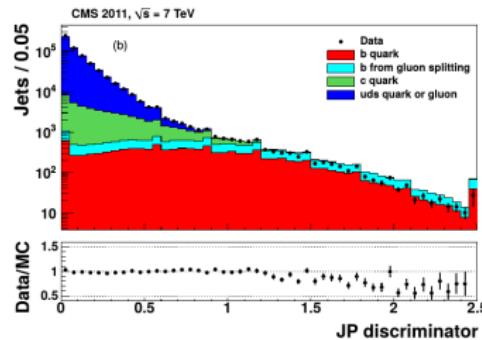
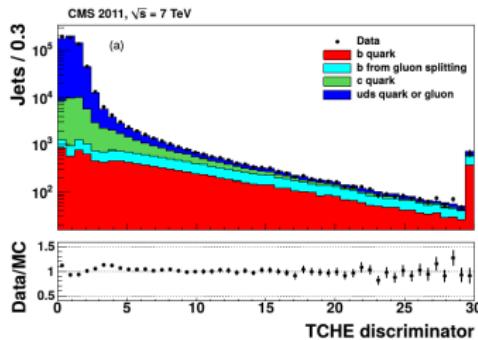
- IP: transverse and longitudinal distance of track from primary vertex
- IP calculated in 3D using good resolution from the pixel detector along  $z$
- tracks from decay along jet-axis  $\rightarrow$  tend to  $IP > 0$
- strong dependence on  $p_T$  and  $\eta$



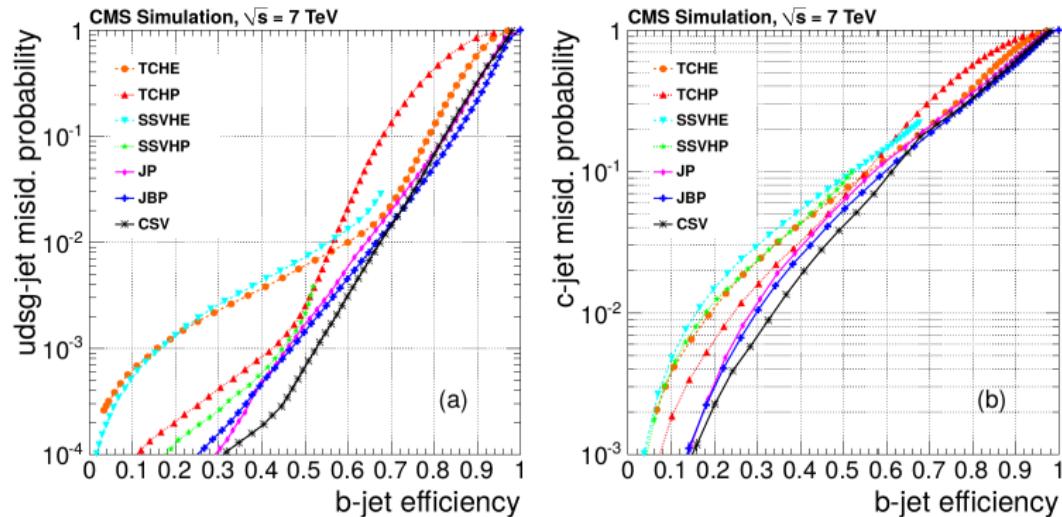
B Tagging at CMS at  $\sqrt{s}$  of 7 TeV

## 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)  $\rightarrow$  *Track Counting High Efficiency (TCHE)*
- likelihood that all tracks from one jet cone come from primary vertex  $\rightarrow$  *Jet Probability (JP)*



## Performance



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

# Discovery Paper

## Observation of the Top Quark

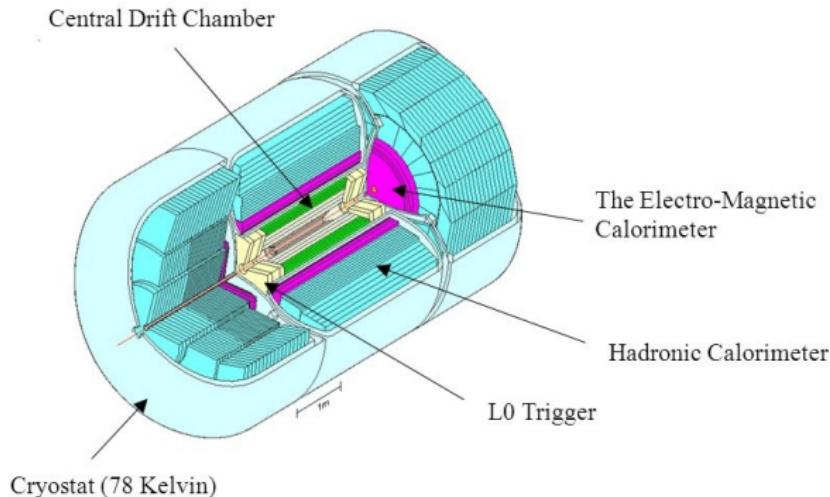
S. Abachi,<sup>12</sup> B. Abbott,<sup>33</sup> M. Abolins,<sup>23</sup> B.S. Acharya,<sup>40</sup> I. Adam,<sup>10</sup> D.L. Adams,<sup>34</sup> M. Adams,<sup>15</sup> S. Ahn,<sup>12</sup> H. Aihara,<sup>20</sup> J. Alitti,<sup>36</sup> G. Álvarez,<sup>16</sup> G.A. Alves,<sup>8</sup> E. Amidi,<sup>27</sup> N. Amos,<sup>22</sup> E.W. Anderson,<sup>17</sup> S.H. Aronson,<sup>3</sup> R. Astur,<sup>38</sup> R.E. Avery,<sup>29</sup> A. Baden,<sup>21</sup> V. Balamurali,<sup>30</sup> J. Balderston,<sup>14</sup> B. Baldin,<sup>12</sup> J. Bantly,<sup>4</sup> J.F. Bartlett,<sup>12</sup> K. Bazizi,<sup>7</sup> J. Bendich,<sup>20</sup> S.B. Beri,<sup>31</sup> I. Bertram,<sup>34</sup> V.A. Bezzubov,<sup>32</sup> P.C. Bhat,<sup>12</sup> V. Bhatnagar,<sup>31</sup>  
.  
:

### 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  $50 \text{ pb}^{-1}$ . 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  $3.8 \pm 0.6$  events. The probability for an upward fluctuation of the background to produce the observed signal is  $2 \times 10^{-6}$  (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  $199^{+19}_{-21} (\text{stat.}) \pm 22 (\text{syst.}) \text{ GeV}/c^2$  and its production cross section to be  $6.4 \pm 2.2 \text{ pb}$ .

## D0 Detector

### The Run-I Era D0 Detector



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

## Discovery at D0

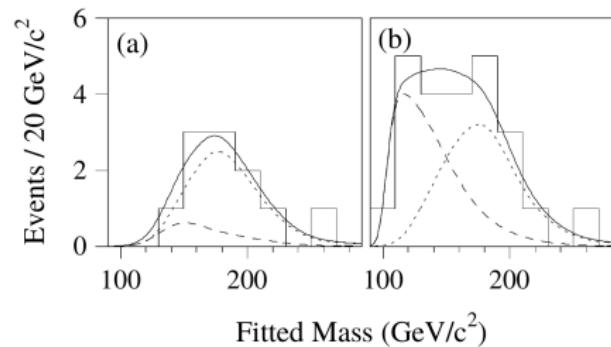
## Results

- 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

$$P_c = 2.0 \times 10^{-6} \text{ (4.6 } \sigma)$$

$$m_{\text{top}} = 199 \pm 20 \pm 22 \text{ GeV}/c^2$$

$$\sigma_{t\bar{t}} = (6.4 \pm 2.2) \text{ pb}$$



## Section 4

### Conclusion

# The Truth Quark

- empty
- moreempty
- moremoreempty