ETH
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ETH Institute for Particle Physics

The Discovery of the Heavy Quarks

Experimental Foundations of Particle Physics

Michael Reichmann

20th November 2017

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Introduction

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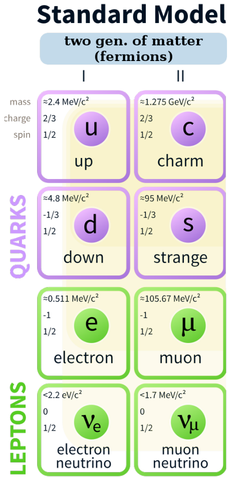

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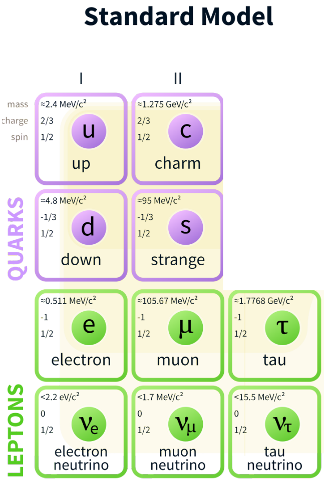
- in 1975 Perl et al. discovered τ-lepton and its neutrino
- indiction of another pair of quarks



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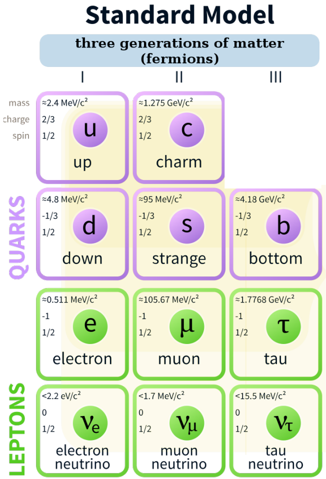

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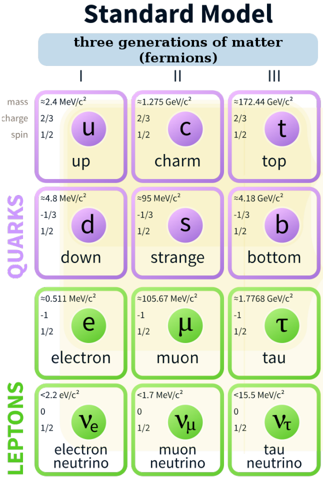
- in 1995 discovery of the top (truth) quark
- complete set of fermions until now



Section 2

The Truth Quark

Introduction

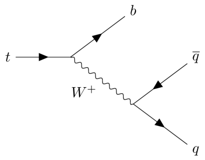
- in early 90s all SM particles except H and t-quark discovered
- beauty discovery $\rightarrow$ weak isospin partner was undoubted
- quark masses are fundamental parameters in the SM
- early estimates: $\mathrm{m_t} \approx 3\mathrm{m_b} \approx 15\,\mathrm{GeV}$
- many new accelerator could only push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

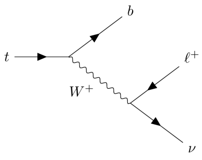
- estimate on m_t in 1994: $\sim$180 GeV
- prior to discovery: behaviour completely predicted by SM
- $m_t > m_W \rightarrow$ main decay channel ($\sim$96 %): $\mathbf{t \longrightarrow W^+ b}$

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

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



(a) $\sim$67 %

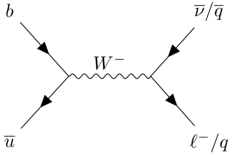


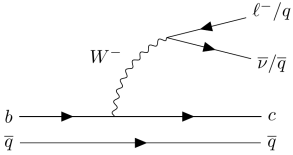
(b) $\sim$33 %

- 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: $t\bar{t} \longrightarrow W^+bW^-\overline{b}$
- b decay:

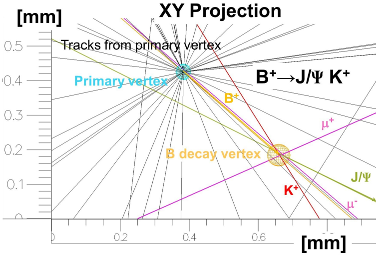




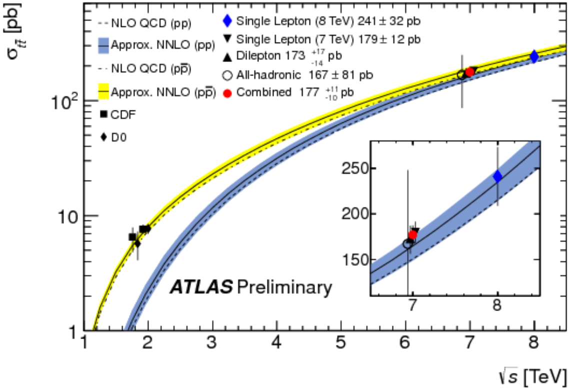
- typical signals:
  - 2 b-jets + dilepton (e^+e^-, $\mu^+\mu^-$, $e^+\mu^-$, μ^+e^-)
  - 2 b-jets + single lepton + two jets
  - 2 b-jets + 4 jets
- huge background on pure QCD process due to other more common QCD processes
- how to discriminate b-jets from other jets?

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
- 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 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 $\overline{p}p$ 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]
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N. Turini,[24] T. Uchida,[32] N. Uemura,[32] F. Ukegawa,[22] G. Unal,[22] S.C. van den Brink,[23] S. Vejcik III,[17] G. Velev,[24]
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H.H. Williams,[22] P. Wilson,[5] B.L. Winer,[26] D. Wolinski,[17] J. Wolinski,[30] X. Wu,[24] J. Wyss,[21] A. Yagil,[7] W. Yao,[15]

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

Discovery Paper (2)

K. Yasuoka,[32] Y. Ye,[12] G. P. Yeh,[7] P. Yeh,[29] M. Yin,[6] J. Yoh,[7] C. Yosef,[18] T. Yoshida,[20] D. Yovanovitch,[7] I. Yu,[35] J. C. Yun,[7] A. Zanetti,[24] F. Zetti,[24] L. Zhang,[34] W. Zhang,[22] and S. Zucchelli[2]

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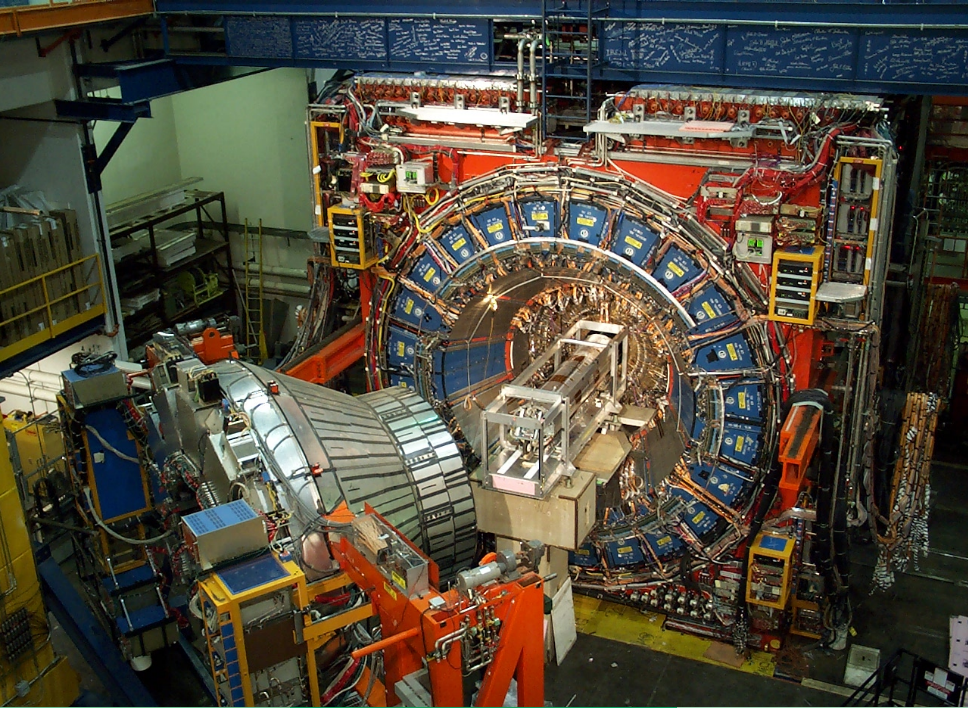
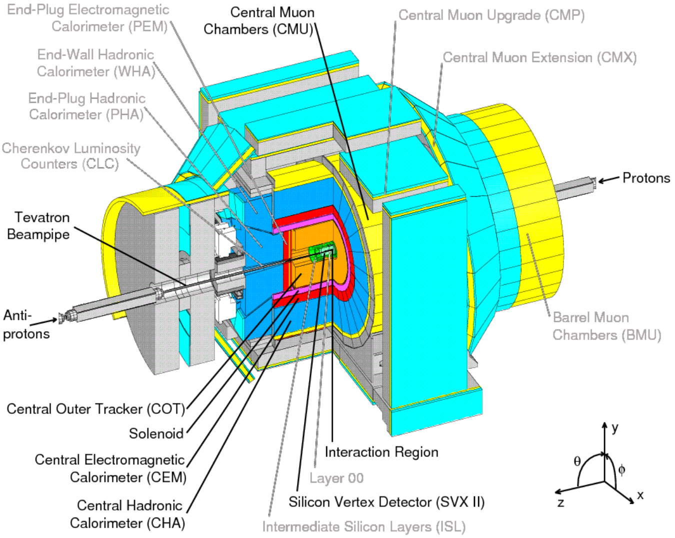
(Received 24 February 1995)

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



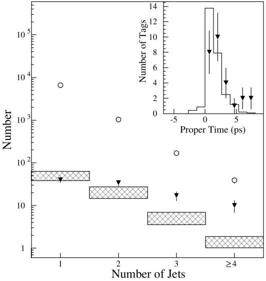
Introduction

- 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

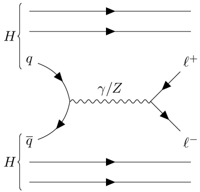
SVX tagging:

- 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, $b\bar{b}$



- 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

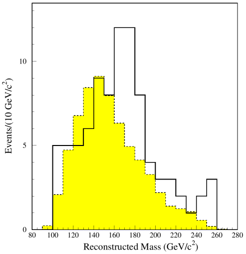
Results

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}

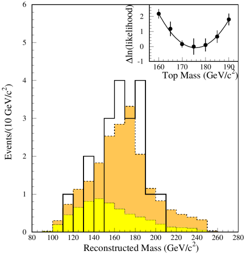
- combined likelihood of the background fluctuating up: 1×10^{-6} ($4.8\,\sigma$)

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:

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

- reconstructed mass:

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

- cross section:

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

Section 3

Conclusion

The Truth Quark

- empty
- moreempty
- moremoreempty