- SiLab Lecture Series -
Physics is Tops

Caleb Fangmeier

University of Nebraska - Lincoln

December 3, 2016

The Standard Model Today

Physics is Tops

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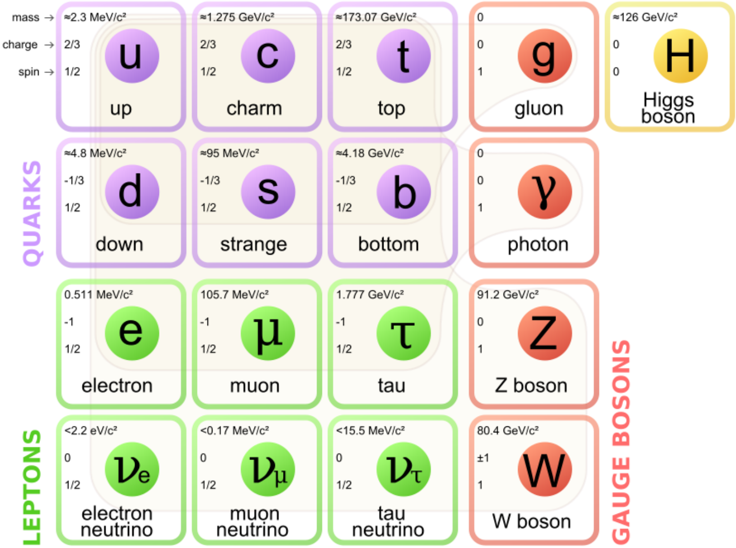

The Standard Model Circa 1973

- Only discovered quarks were up, down, and strange
- Parity and charge have been discovered to be independently violated in

$$\pi^+ \to \mu^+ + \nu_\mu$$

- So CP was proposed as the "real" mirror symmetry
- CP violation led to the proposal of a third generation of quarks

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The Neutral Kaon

- K^0 are produced via strong interactions with definite quark flavour content.
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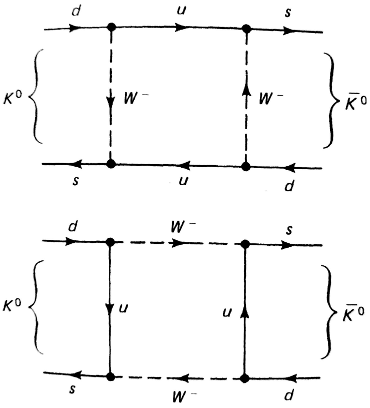

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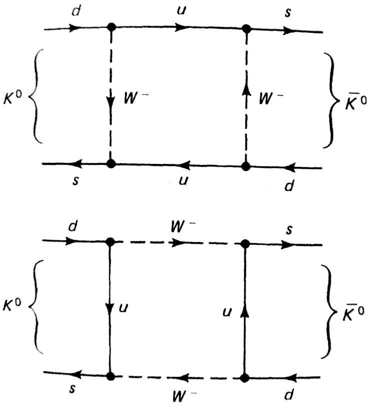

The Neutral Kaon - CP Eigenstates

- The action of C,P, and CP on the $|K^0\rangle$, $|\overline{K^0}\rangle$ system:

$$C\,|K^0\rangle = |\overline{K^0}\rangle \qquad C\,|\overline{K^0}\rangle = |K^0\rangle$$
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$$CP\,|K^0\rangle = -\,|\overline{K^0}\rangle \qquad CP\,|\overline{K^0}\rangle = -\,|K^0\rangle$$

- Two eigenstates of CP can be formed.

$$|K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right), \quad |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right)$$

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The Neutral Kaon - Allowed Decays

- If the weak interaction conserves CP, then $|K_1\rangle$ can only decay into states with $CP = 1$ and $|K_2\rangle$ only to states with $CP = -1$.
- For example,

$$K_1 \rightarrow 2\pi \qquad K_2 \rightarrow 3\pi$$

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The Neutral Kaon - CP Violation

- Furthermore, since the $K_1 \to 2\pi$ process happens much more quickly, the K_1 component of the superposition

$$|\Psi\rangle = \alpha\,|K_1\rangle + \beta\,|K_2\rangle$$

quickly disappears, leaving only

$$|\Psi\rangle = |K_2\rangle$$

- So a beam of neutral kaons consists of only a tiny fraction of K_1 after a few meters.
- If the "forbidden" process $K_2 \to 2\pi$ is observed down the beamline, it means that CP is not a true symmetry.

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CP Violation

- CP Violation posed a theoretical problem with only two quark generations.
- The weak eigenstates of the down type quarkes are related to the flavor eigenstates via the Cabibbo angle θ_C.

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

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- However, with three quark generations there is instead this relation

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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CP Violation - Mechanism

The reason why such a complex phase causes CP violation is not immediately obvious, but can be seen as follows. Consider any given particles (or sets of particles) a and b, and their antiparticles $\bar{a}$ and $\bar{b}$. Now consider the processes $a \to b$ and the corresponding antiparticle process $\bar{a} \to \bar{b}$, and denote their amplitudes M and $\bar{M}$ respectively. Before CP violation, these terms must be the *same* complex number. We can separate the magnitude and phase by writing $M = |M|e^{i\theta}$. If a phase term is introduced from (e.g.) the CKM matrix, denote it $e^{i\phi}$. Note that $\bar{M}$ contains the conjugate matrix to M, so it picks up a phase term $e^{-i\phi}$. Now we have:

$$M = |M|e^{i\theta}e^{i\phi}$$
$$\bar{M} = |M|e^{i\theta}e^{-i\phi}$$

Physically measurable reaction rates are proportional to $|M|^2$, thus so far nothing is different. However, consider that there are *two different routes* (e.g. intermediate states) for $a \to b$. Now we have:

$$M = |M_1|e^{i\theta_1}e^{i\phi_1} + |M_2|e^{i\theta_2}e^{i\phi_2}$$
$$\bar{M} = |M_1|e^{i\theta_1}e^{-i\phi_1} + |M_2|e^{i\theta_2}e^{-i\phi_2}$$

Some further calculation gives:

$$|M|^2 - |\bar{M}|^2 = 4|M_1||M_2|\sin(\theta_1 - \theta_2)\sin(\phi_1 - \phi_2)$$

Thus, we see that a complex phase gives rise to processes that proceed at different rates for particles and antiparticles, and CP is violated.

Bottom Quark Discovery - 1977

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

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J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

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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.

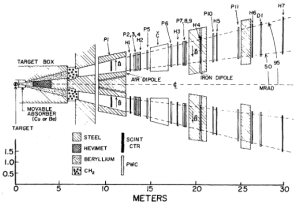

FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

Top Quark Discovery - 1995

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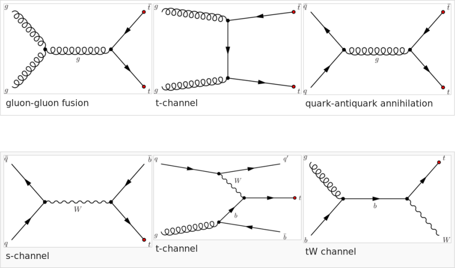
Search for High Mass Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

TABLE II. Efficiency × branching fraction ($\varepsilon \times \mathcal{B}$) and the expected number of events ($\langle N \rangle$) in the seven channels, based on the central theoretical $t\bar{t}$ production cross section of Ref. [12], for four top masses. Also given are the expected backgrounds, integrated luminosity, and the number of observed events in each channel.

m_t(GeV/c^2)	$e\mu$ + jets	ee + jets	$\mu\mu$ + jets	e + jets	μ + jets	e + jets/μ	μ + jets/μ	All
$\varepsilon \times \mathcal{B}$ (%)	0.31 ± 0.04	0.18 ± 0.02	0.15 ± 0.02	1.1 ± 0.3	0.8 ± 0.2	0.6 ± 0.2	0.4 ± 0.1	
140 $\langle N \rangle$	0.71 ± 0.12	0.41 ± 0.07	0.25 ± 0.04	2.5 ± 0.7	1.3 ± 0.4	1.4 ± 0.5	0.7 ± 0.2	7.2 ± 1.3
$\varepsilon \times \mathcal{B}$ (%)	0.36 ± 0.05	0.20 ± 0.03	0.15 ± 0.02	1.5 ± 0.4	1.1 ± 0.3	0.9 ± 0.2	0.5 ± 0.1	
160 $\langle N \rangle$	0.40 ± 0.07	0.22 ± 0.04	0.12 ± 0.02	1.7 ± 0.5	0.9 ± 0.3	1.0 ± 0.3	0.4 ± 0.1	4.7 ± 0.8
$\varepsilon \times \mathcal{B}$ (%)	0.39 ± 0.05	0.21 ± 0.03	0.14 ± 0.02	1.6 ± 0.4	1.1 ± 0.3	1.1 ± 0.2	0.7 ± 0.1	
180 $\langle N \rangle$	0.22 ± 0.04	0.12 ± 0.02	0.06 ± 0.01	0.9 ± 0.3	0.5 ± 0.1	0.6 ± 0.1	0.3 ± 0.1	2.7 ± 0.4
$\varepsilon \times \mathcal{B}$ (%)	0.40 ± 0.05	0.30 ± 0.04	0.14 ± 0.02	1.8 ± 0.4	1.3 ± 0.3	1.4 ± 0.1	0.8 ± 0.2	
200 $\langle N \rangle$	0.12 ± 0.02	0.09 ± 0.02	0.03 ± 0.01	0.5 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.2 ± 0.1	1.7 ± 0.3
Background	0.27 ± 0.06	0.16 ± 0.07	0.33 ± 0.06	1.3 ± 0.7	0.7 ± 0.5	0.6 ± 0.2	0.4 ± 0.1	3.8 ± 0.9
$\int \mathcal{L} dt$ (pb^{-1})	13.5 ± 1.6	13.5 ± 1.6	9.8 ± 1.2	13.5 ± 1.6	9.8 ± 1.2	13.5 ± 1.6	9.8 ± 1.2	
Data	1	0	0	2	2	2	2	9

Top Quark Production at LHC

Some common top quark production modes



"Parton Distribution Function" for a proton at $Q = 2\text{GeV}$

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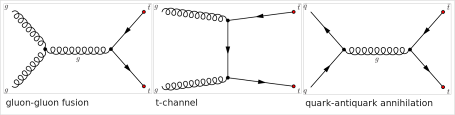

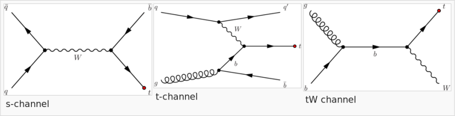

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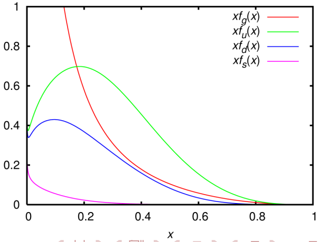
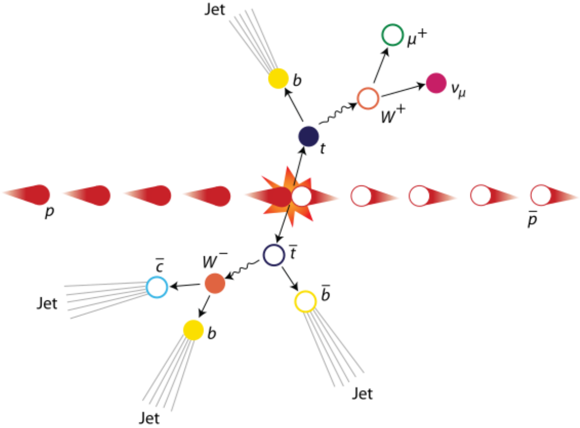


Top Quark Decay



Possible Final States

- 2 B-Jets + 4 “light” Jets
- 2 B-Jets + 2 “light” Jets + 1 lepton + 1 neutrino
- 2 B-Jets + 2 leptons + 2 neutrinos

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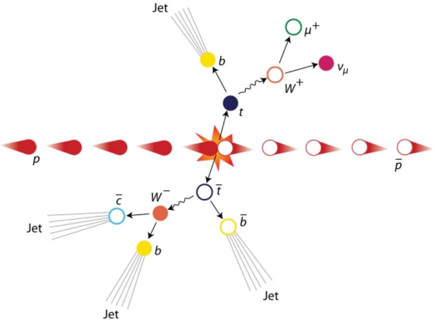

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