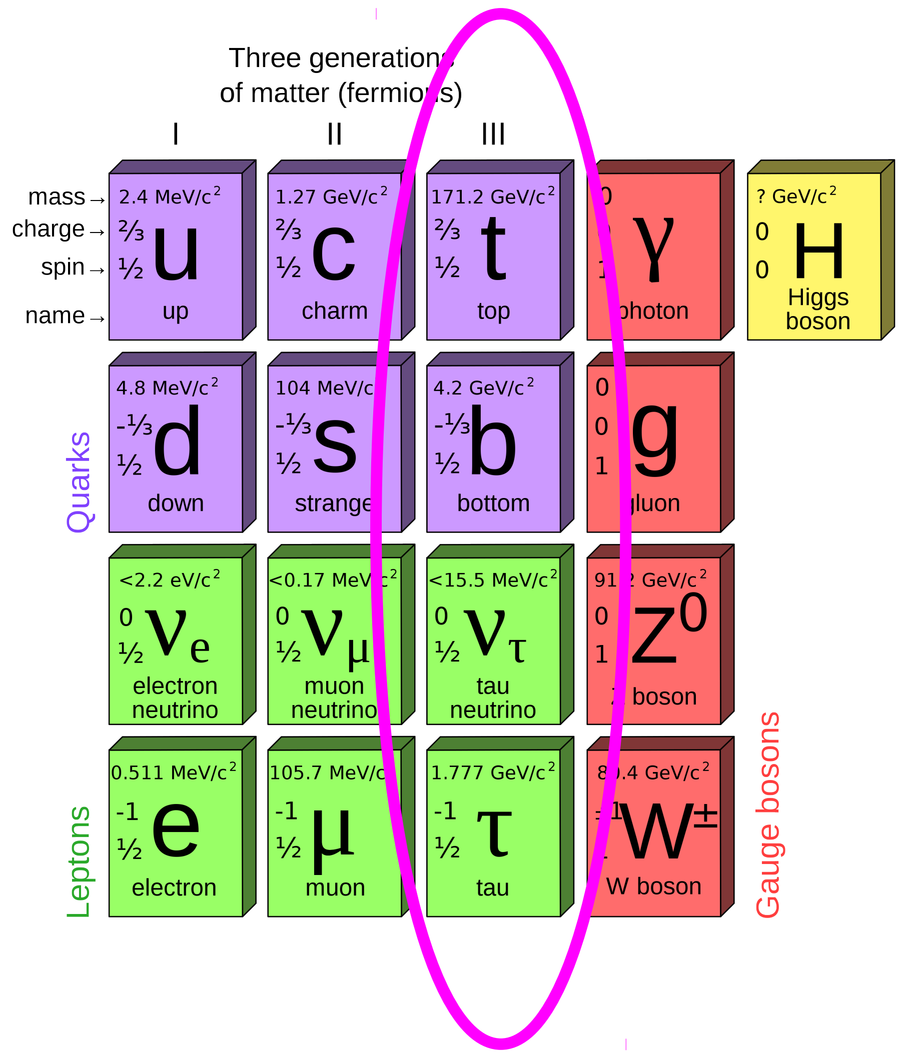
# The third generation



$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}. \quad \Longrightarrow \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \tag{8.40}$$

$$g_{\alpha\beta} = g_W V_{\alpha\beta} \quad (\alpha = u, c, t; \beta = d, s, b).$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{8.43}$$

# How to evaluate the b couplings

$$\begin{pmatrix} u \\ d' \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix}, \quad \begin{pmatrix} t \\ b' \end{pmatrix} \tag{8.41}$$

- Because the t is much heavier than the b, the only decays are:
  - Non favored: b → s
  - Non favored: b → u

# Compare to tau decays (heaviest lepton: 1.77 GeV)

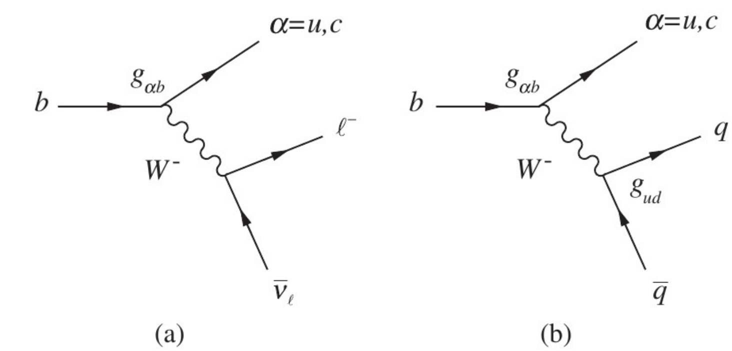



Figure 8.19 The dominant decays of the $b$ quark to lighter quarks and leptons. Here $\ell = e, \mu$ or $\tau$ and $q\bar{q} = d\bar{u}, d\bar{c}, s\bar{u}$ or $s\bar{c}$.

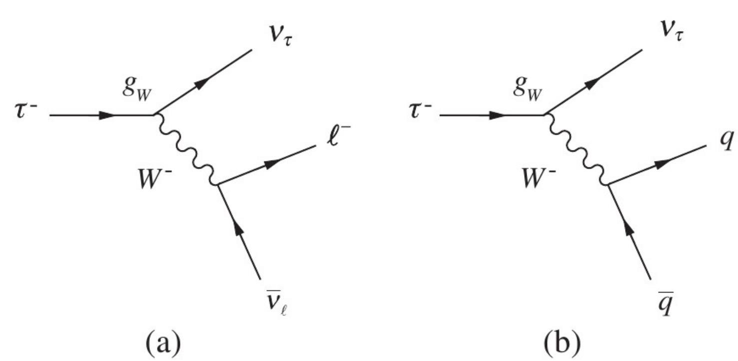



Figure 8.20 The dominant decays of the $\tau$ lepton to quarks and leptons. Here $\ell = e$ or $\mu$ and $q\bar{q} = d\bar{u}$ or $s\bar{u}$.

Experimentally we find:

$$\tau_b \approx 10^{-12}\,\mathrm{s} \qquad (8.46)$$

Naive theoretical estimate:

$$\tau_b \approx \frac{1}{N}\left(\frac{m_\tau}{m_b}\right)^5 \tau_\tau \approx 10^{-15}\,\mathrm{s}$$

The theoretical estimate dues not work because:

$$|V_{ub}|^2 \approx 2 \times 10^{-5} \quad \text{and} \quad |V_{cb}|^2 \approx 2 \times 10^{-3}. \qquad (8.48)$$

# Important conclusion

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad (8.43)$$

- This is a very good approximation of nature!
- The mixing between b and d and s is very small
  - But this is as mentioned very important for c decays

# Best values for the Cabibbo–Kobayashi–Maskawa matrix

$$V_{\rm CKM} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}, \qquad (11.27)$$

and the Jarlskog invariant is $J = (3.05^{+0.19}_{-0.20}) \times 10^{-5}$.

http://pdg.lbl.gov/2009/reviews/rpp2009-rev-ckm-matrix.pdf

# The Nobel Prize in Physics 2008
## Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa



Photo: University of Chicago

### Yoichiro Nambu

© The Nobel Foundation Photo: U. Montan

### Makoto Kobayashi

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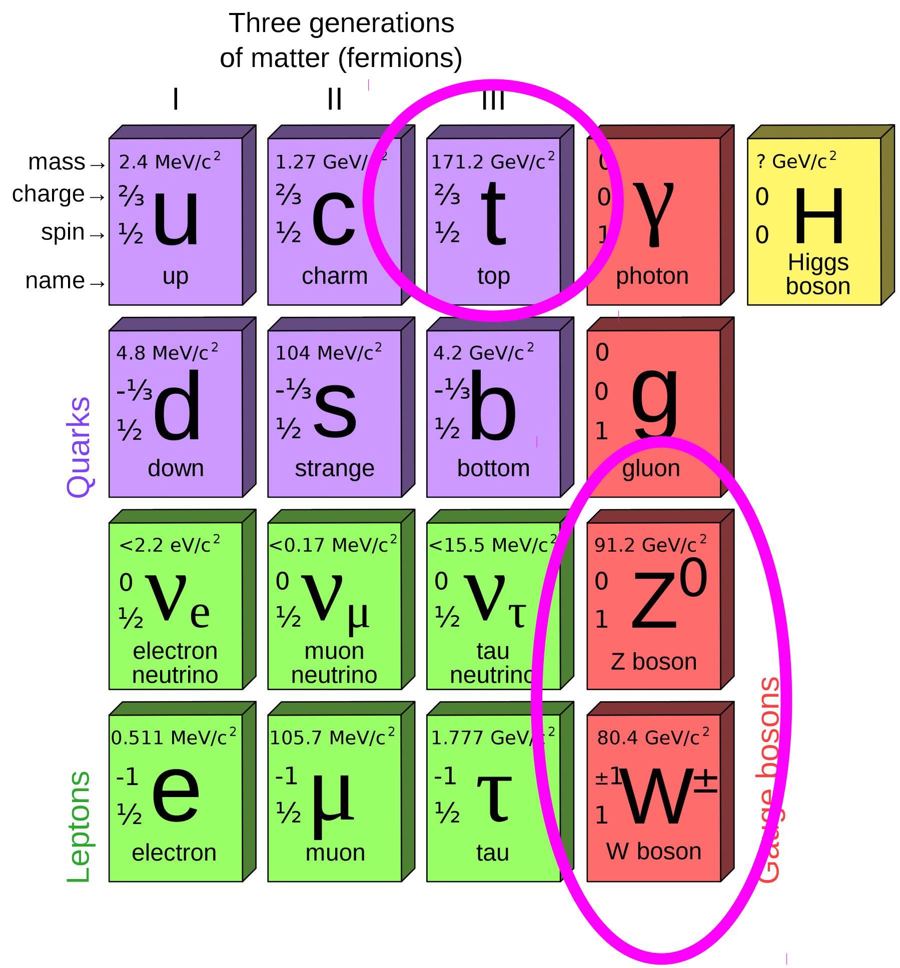
### Toshihide Maskawa

The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

# Why the top quark is special




The mass of the t quark is bigger than Z and W →
The fermi coupling $G_F$ is no longer good approximation

# How the t decays

- CKM matrix: $g_{td}$~0, $g_{ts}$~0, $g_{tb}$~1
- So : t → b + W+     (t-bar → b-bar + W-)
- The decay time is so fast: $\tau \sim 4 * 10^{-25}$s
- The length traveled is ~ 0.1 fm!
- No time to form hadrons (no t hadrons measured). Directly decays to b quark!

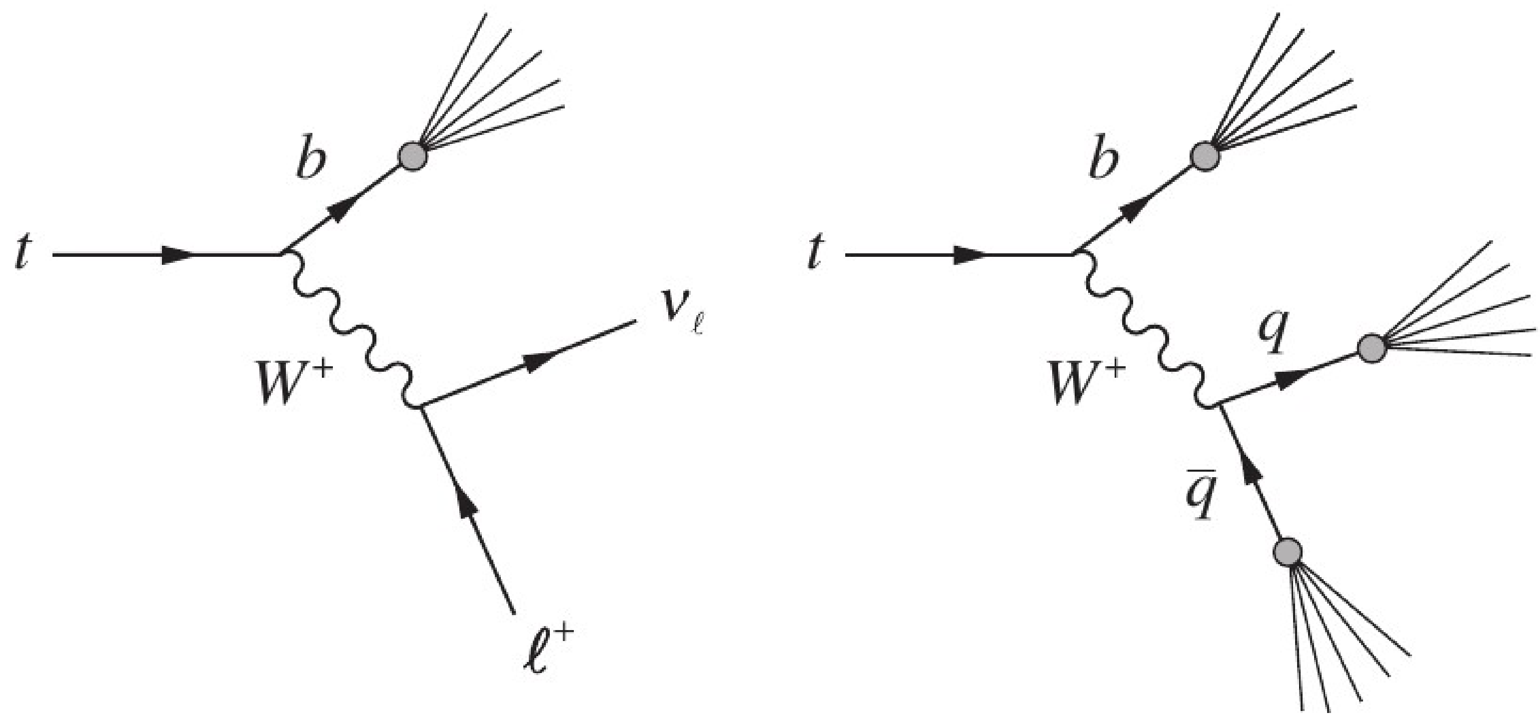
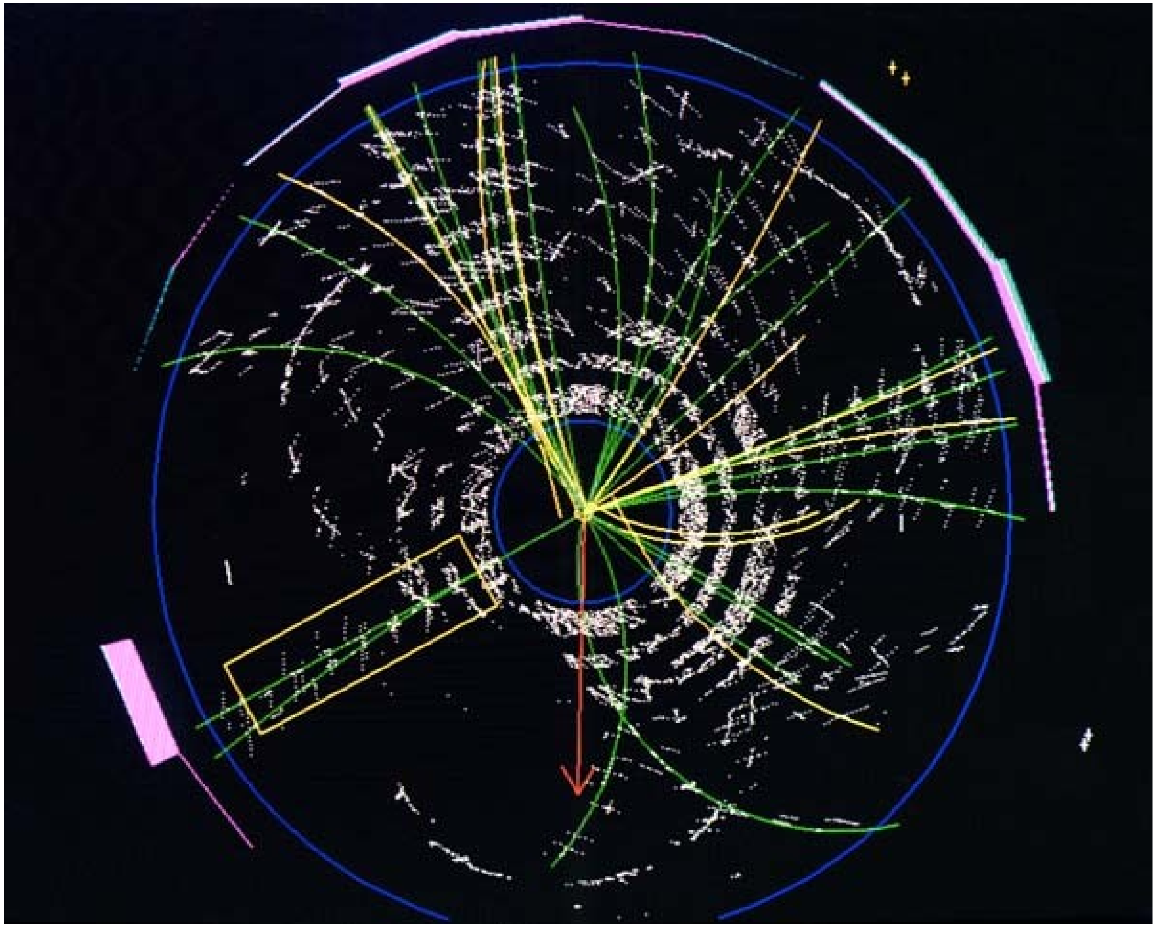



Figure 8.22 Production of hadrons jets from the decay $t \to b + W^+$, where the $W$ boson decays to give either leptons or hadrons.

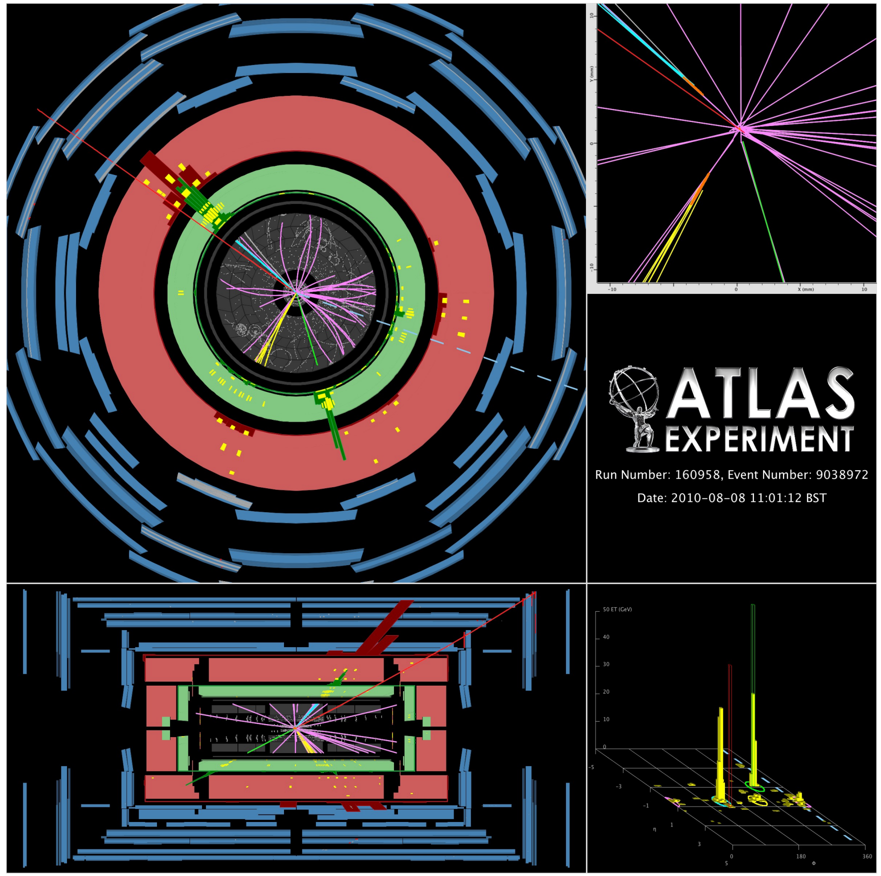
# CDF event display
# (real data)



Clearly a challenging analysis!

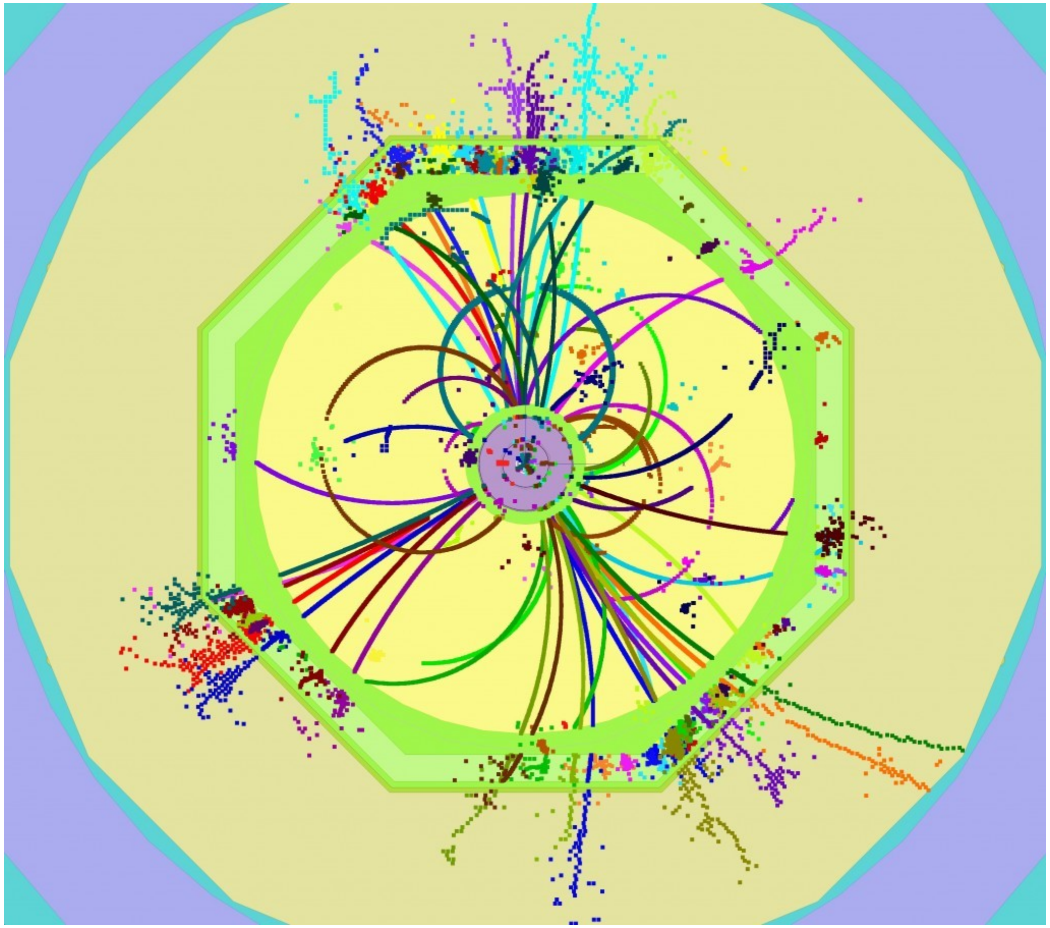
http://www-cdf.fnal.gov/events/detpic/top_cot.jpg

# ATLAS event display




Event display of a top pair e-mu dilepton candidate with two b-tagged jets. The electron is shown by the green track pointing to a calorimeter cluster, the muon by the long red track intersecting the muon chambers, and the missing ET direction by the dotted line on the XY view. The secondary vertices of the two b-tagged jets are indicated by the orange ellipses on the zoomed vertex region view.

# Even in a future linear collider!
# (simulated event display)



# How the t+t-bar is produced

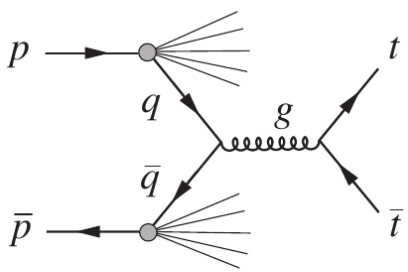
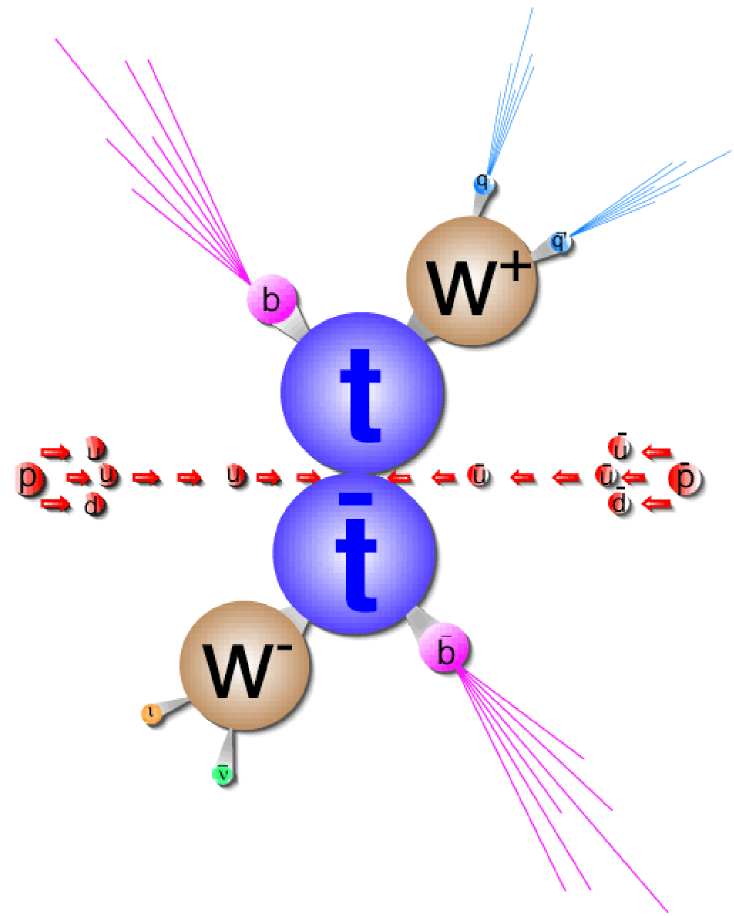



Figure 8.23 The dominant mechanism for top quark production in proton–antiproton collisions at 1.8 TeV, the energy of the $p\bar{p}$ collider at Fermilab.



# Because the signature is not clean: we will have a background

★ *8.2.3(b) Background events*

So far we have identified a distinctive class of events that can arise from the production and decay of top quarks. As in all experiments, it is necessary to consider whether such events could arise from other 'background' processes. In the present case, the most important backgrounds arise when the subprocess (8.53)

$$q + \bar{q} \to t + \bar{t}$$

is replaced by a subprocess of the type

$$q + \bar{q} \to W^{\pm} + (N \geq 3) \text{ jets.} \tag{8.57}$$

Examples of such processes, corresponding to

$$q + \bar{q} \to W + q + \bar{q} + g + g \tag{8.58a}$$

and

$$q + \bar{q} \to W + g + g + g, \tag{8.58b}$$

# Feynman diagrams of background

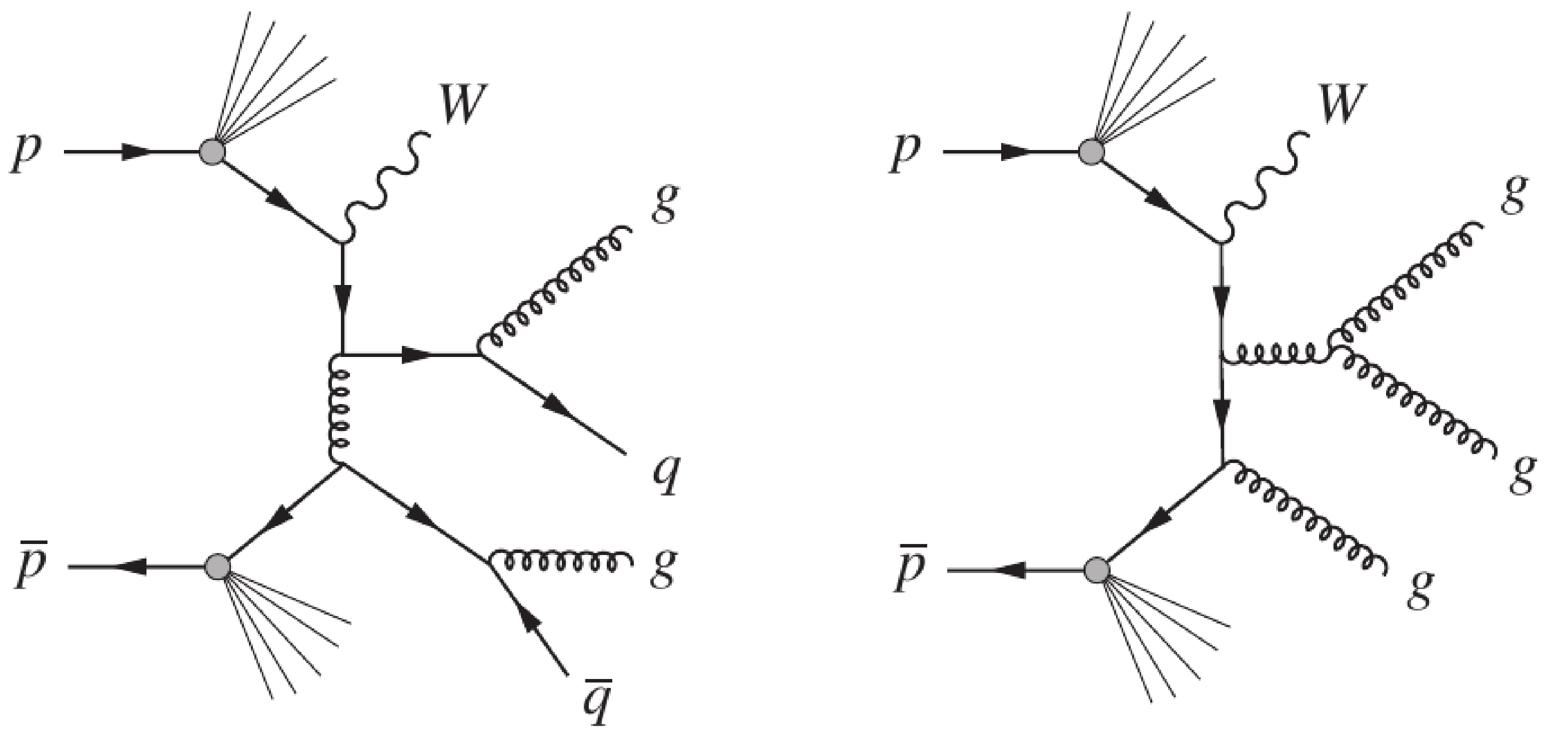



Figure 8.24 Reactions involving the subprocesses of Equations (8.57) that contribute to the background for top quark production. The quarks and gluons are observed as jets.

# First measurement! (1995)

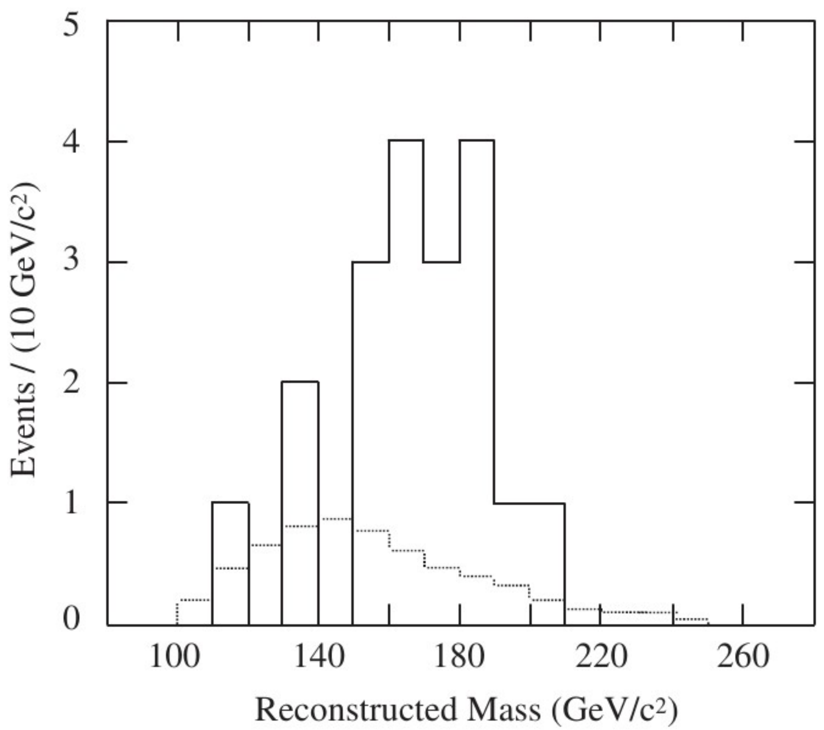
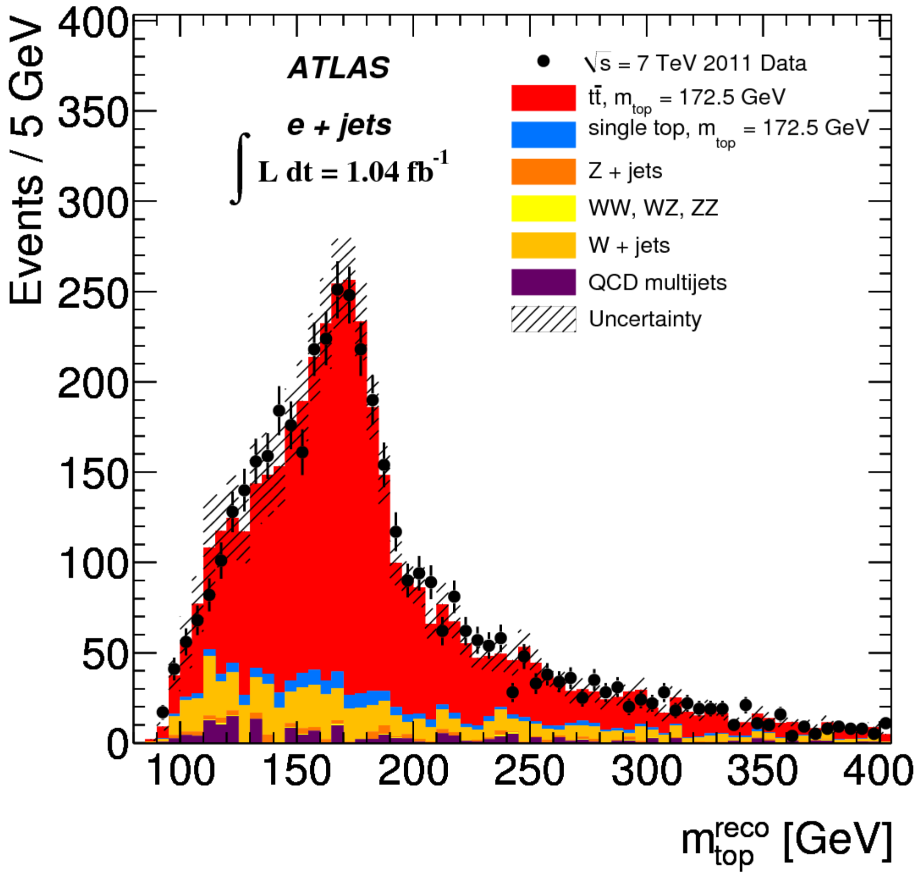



Figure 8.25 The reconstructed *t* quark mass distribution for the *b*-tagged 'four-jet plus lepton' events of type (8.56). The shape expected for background events (dotted line) is also shown. (Reprinted Figure 3 with permission from K. Abe *et al.*, *Phys. Rev. Lett.*, **74**, 2626. Copyright 1995 American Physical Society.)

# More recent result from ATLAS



# ATLAS top mass