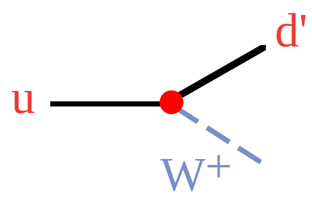
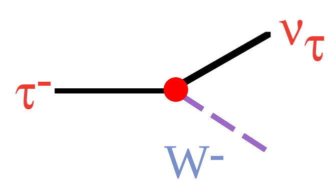
Weak SU(2) Gauge Theory

The group describing the spin states of a fermion is SU(2). So an SU(2) gauge theory is the "obvious" theory for the weak interaction. A gauge theory needs bosons to transfrom between all types of "charge" in the theory, i.e.

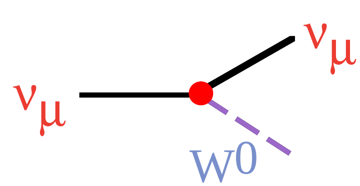
W^+: $T_3=+1$ $\{(T_3={}^1/_2) \rightarrow (T_3=-{}^1/_2)\}$, e.g.



W^-: $T_3=-1$ $\{(T_3=-{}^1/_2) \rightarrow (T_3={}^1/_2)\}$, e.g.



W^0: $T_3=0$: $\frac{1}{\sqrt{2}}\langle[(+{}^1/_2,\overline{+{}^1/_2})-(-{}^1/_2,\overline{-{}^1/_2})]\rangle$ $\{(T_3=\pm{}^1/_2) \rightarrow (T_3=\pm{}^1/_2)\}$, e.g.



Unified SU(2)×U(1) Electroweak Theory

The W^0 has the same quantum numbers as the photon, so mixing occurs leading to a unified electroweak theory.

Pure $SU(2)_L$ Bosons (Weak Isospin=1)

$$W^+, W^0, W^-$$

Pure $U(1)_Y$ Boson (Weak Isospin=0)

$$B^0$$

("Y" refers to the fact that B^0 boson couples to a mixture of weak isospin and electric charge known as "hypercharge".)

The actual observed bosons are the γ and the Z^0.

$$\gamma = \cos\theta_W \, B^0 - \sin\theta_W \, W^0$$

$$Z^0 = \sin\theta_W \, B^0 + \cos\theta_W \, W^0$$

Both the Z^0 and the γ are part SU(2) and part U(1) gauge bosons, so the coupling of the Z^0 depends on both the electric charge and the T_3 of the fermions. *i.e*. The coupling of the Z^0 to "up" type quarks is different from the coupling to "down" type quarks, which is different from charged leptons, which is different from neutrinos.

The amount of mixing is determined by an experimentally measured parameter, θ_W, known as the weak mixing angle or Weinberg angle.

No Electroweak Flavour Changing Neutral Currents

Both the Z^0 and the γ couple only fermions to themselves.

e.g. Only

Never

Predictions of electroweak theory

- **Neutral currents exist**

$$\sigma\left(\nu_\mu e^- \rightarrow \nu_\mu e^-\right) = \frac{G_F^2 m_e E_\nu^{lab}}{2\pi}\left[\left(1-2\sin^2\theta_W\right)^2 + \frac{4}{3}\sin^4\theta_W\right]$$

$$\sigma\left(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-\right) = \frac{G_F^2 m_e E_\nu^{lab}}{2\pi}\left[\frac{1}{3}\left(1-2\sin^2\theta_W\right)^2 + 4\sin^4\theta_W\right]$$

Neutral currents discovered 1973 at CERN.

(These cross sections give us θ_W.)

- **$W^\pm$ and Z^0 bosons exist**, with predicted masses

$$m_W = \sqrt{\frac{\sqrt{2}\alpha}{8 G_F \sin^2\theta_W}} \quad \text{and} \quad m_Z = \frac{m_W}{\cos\theta_W}$$

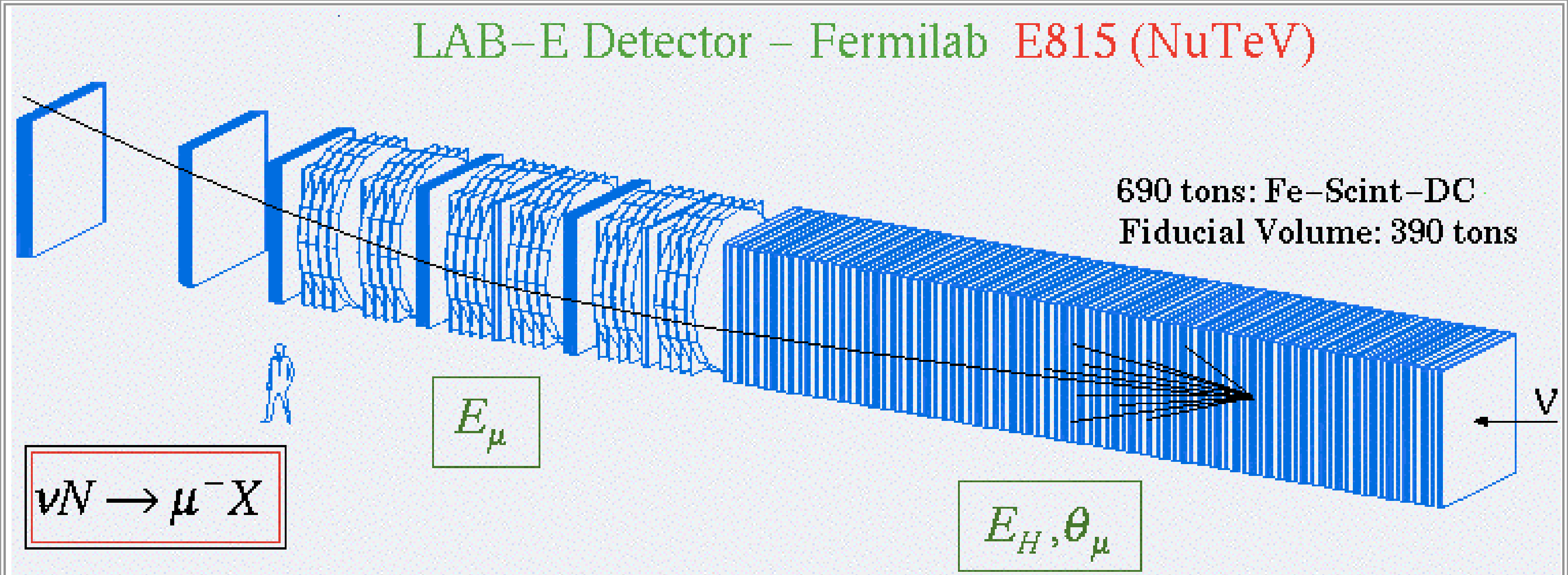
The $W^\pm$ & Z^0 were discovered with the expected masses in 1982 at CERN.

- **the top quark must exist**

  or else the b quark would not have full weak coupling

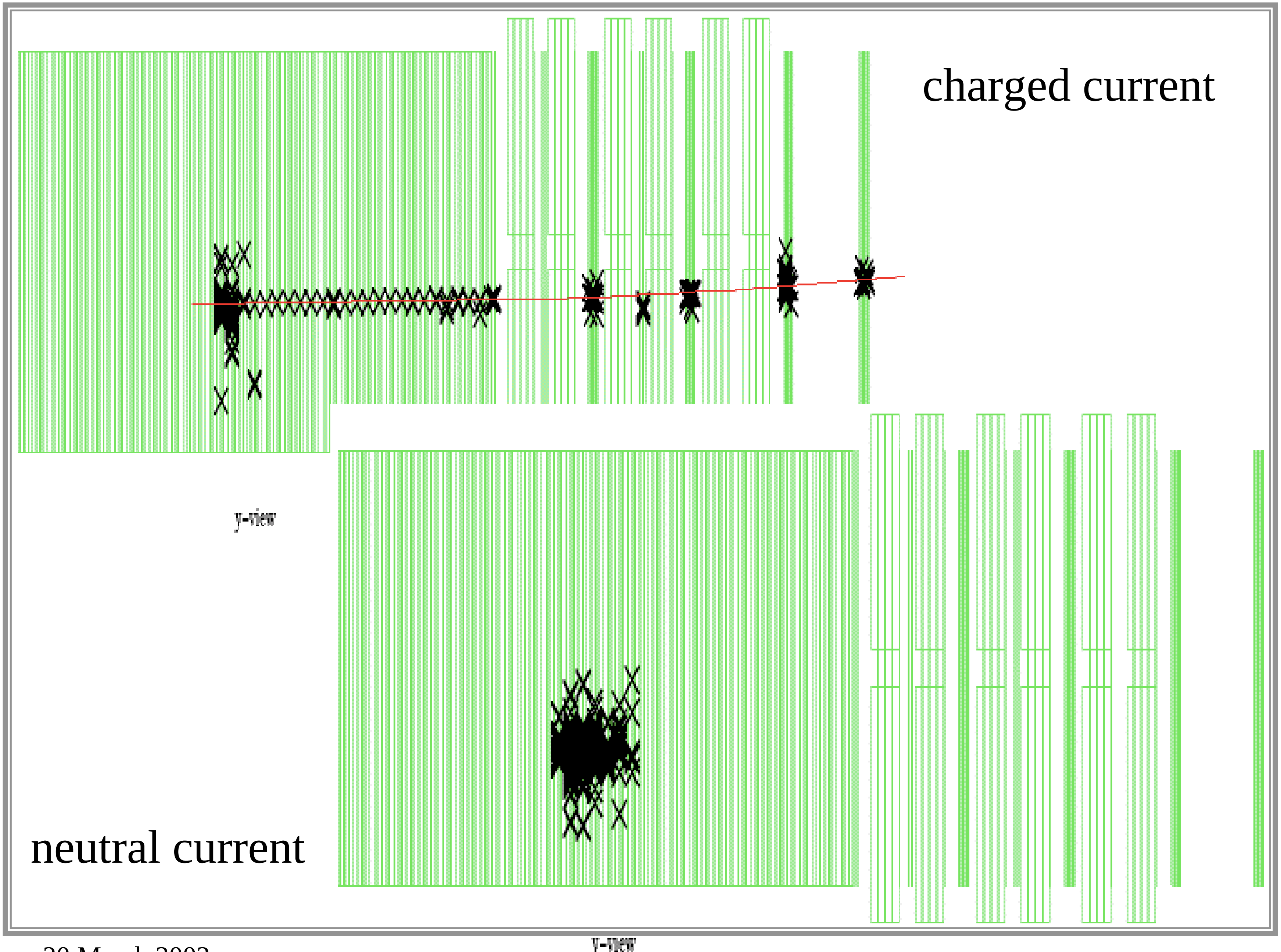
The top quark was discovered in 1994 by the CDF experiment at Fermilab.

NuTeV Detector

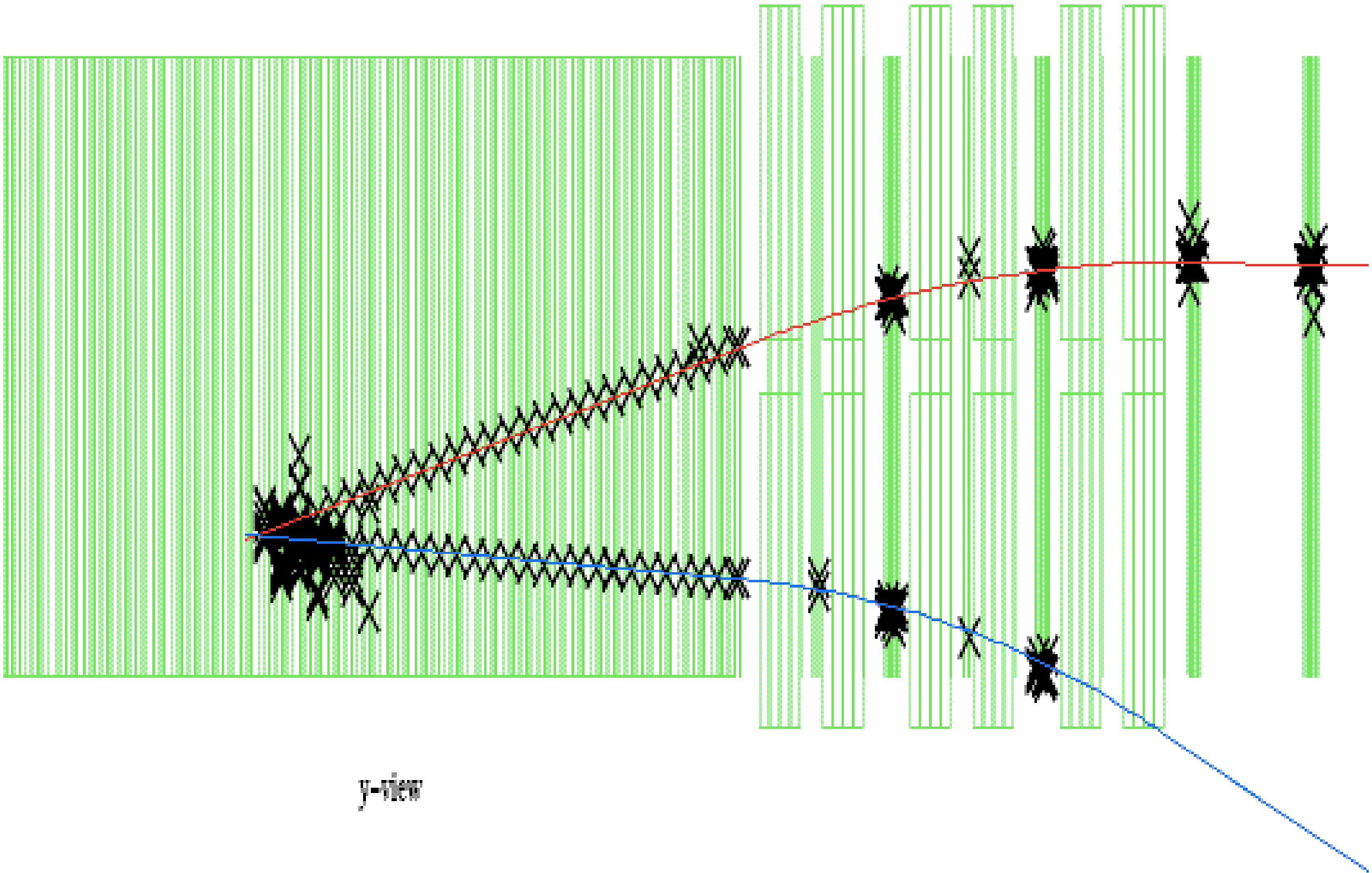


http://www-e815.fnal.gov

NuTeV Events

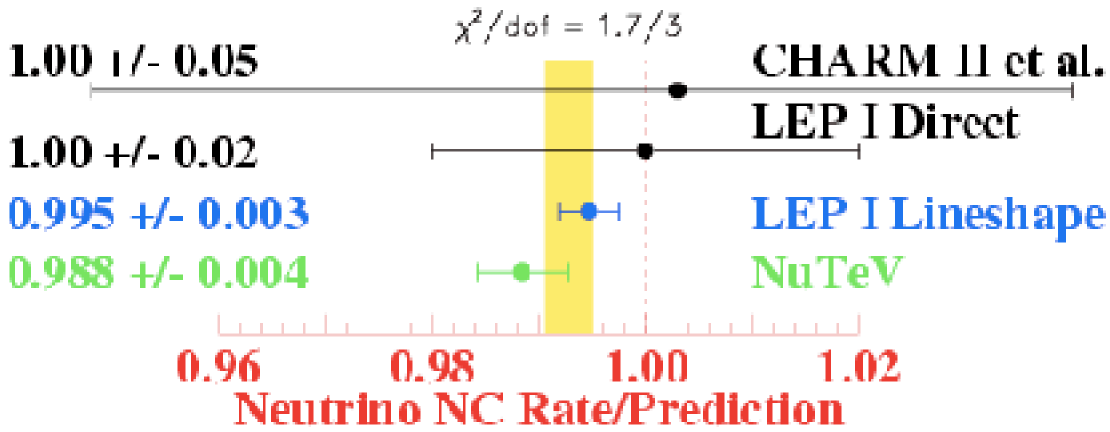


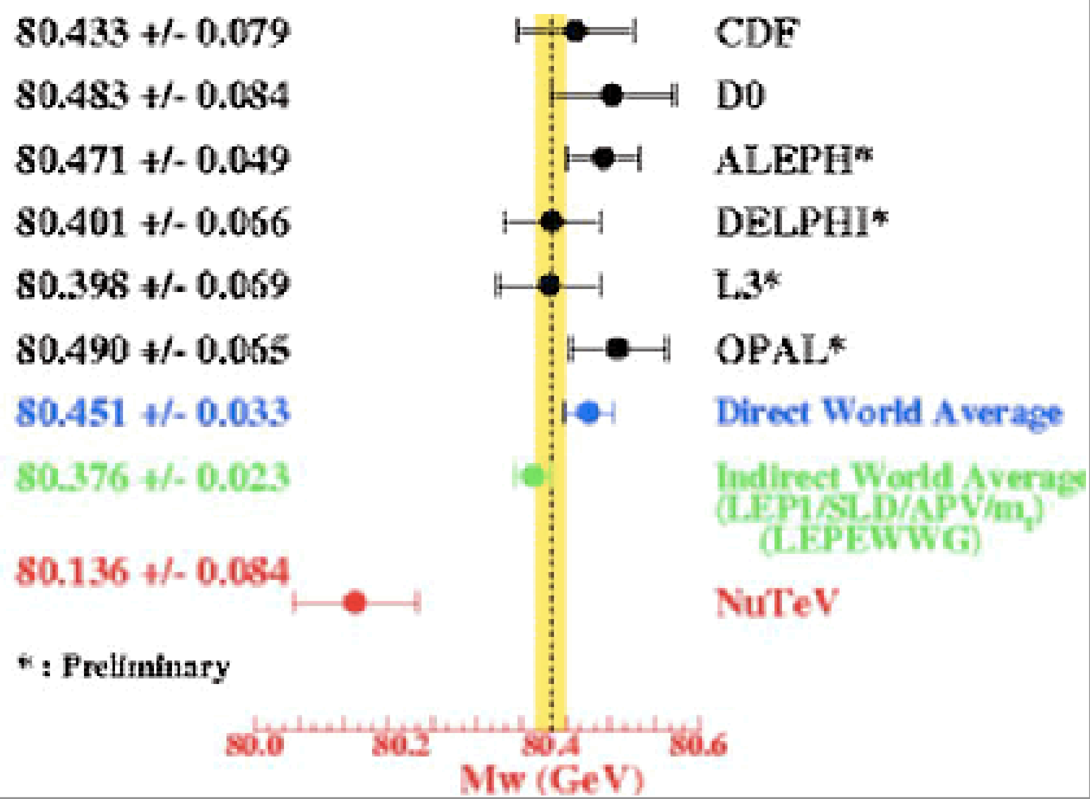
Dimuon Event



Opposite sign dimuons come from charm production;
this is weird, but rate consistent with background.

Failure of Universal Weak Interaction?

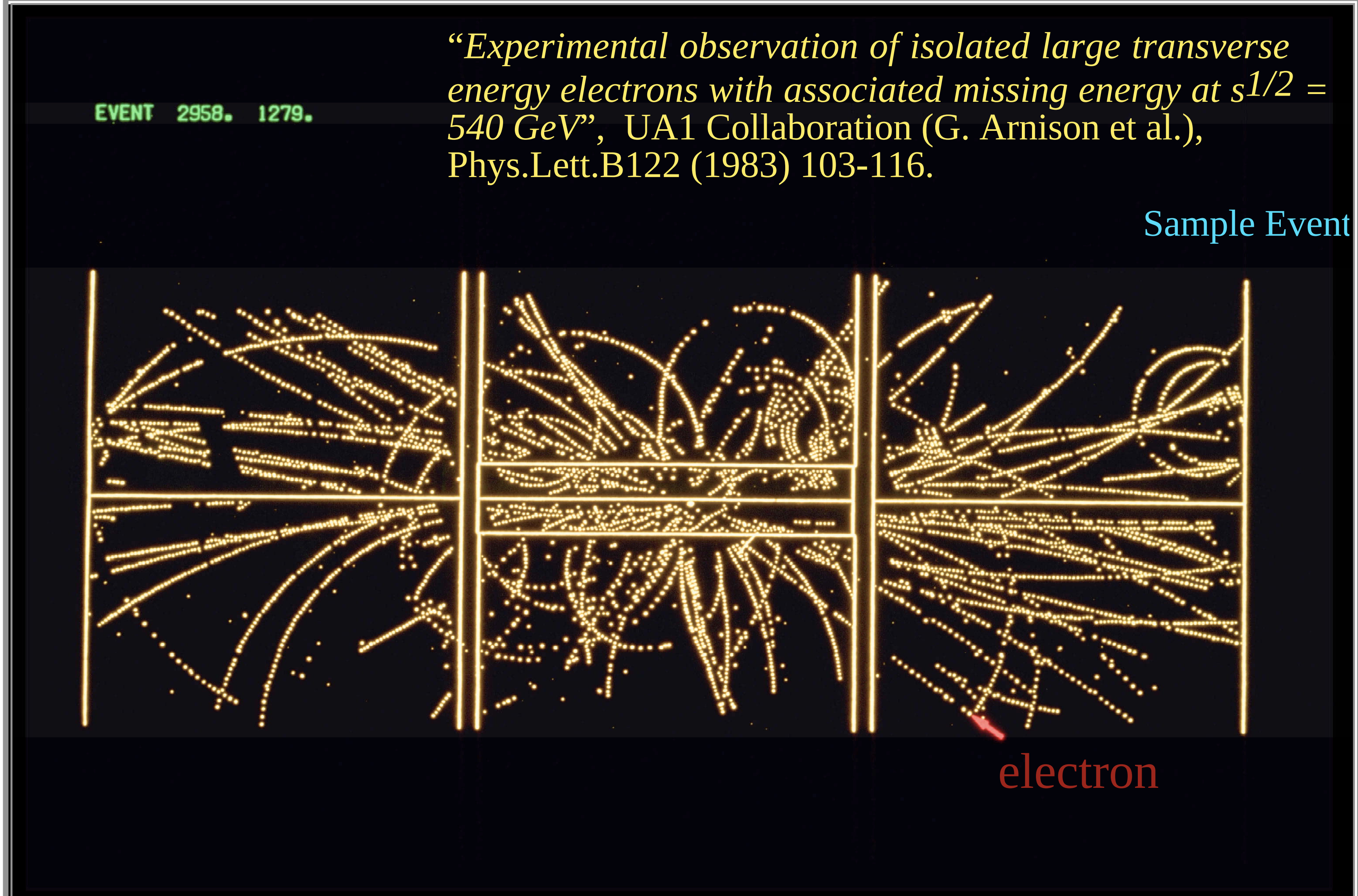




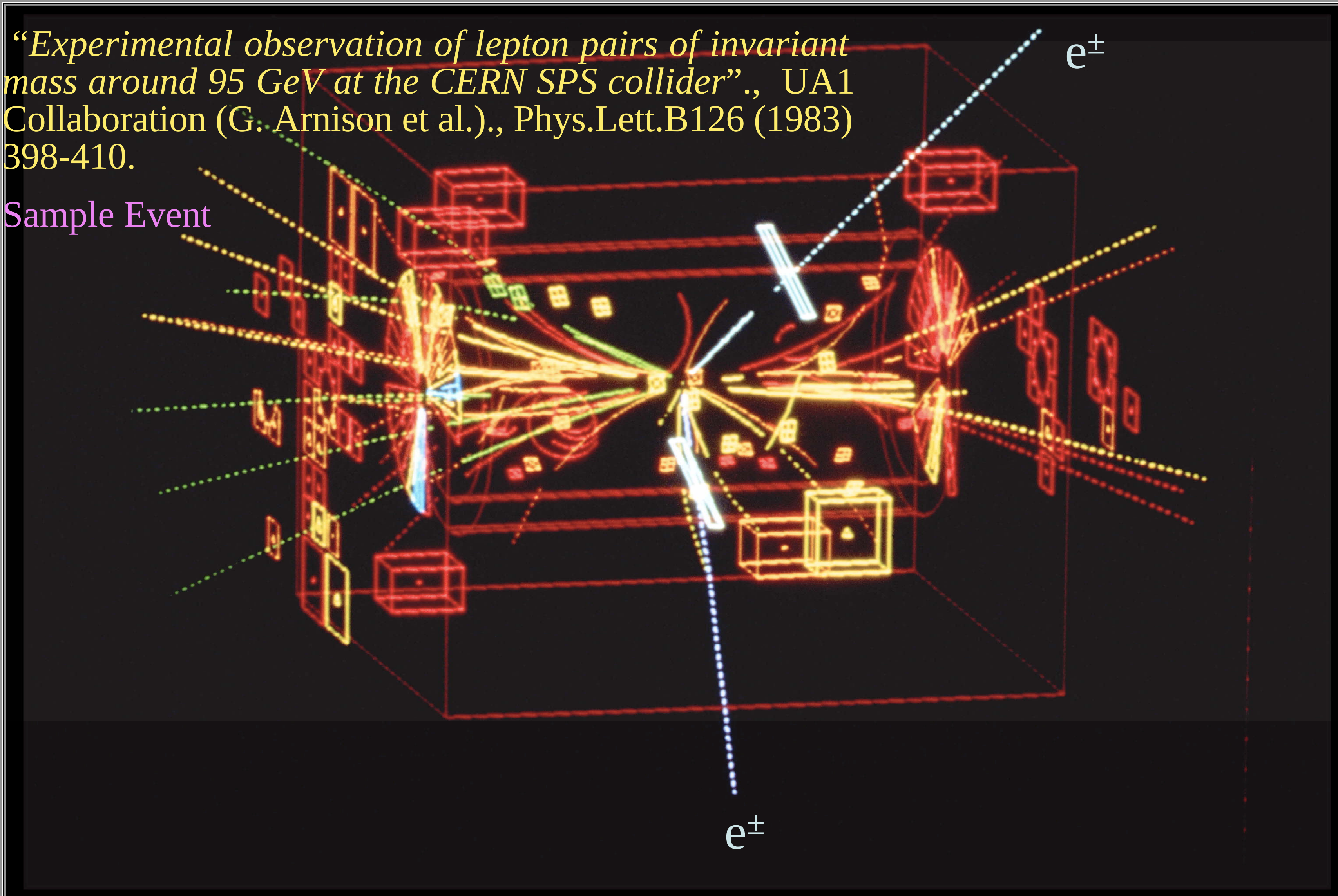
The neutral current to charged current rates are 3σ off. This is not predicted by any popular theory.

Discovery of the W

"Experimental observation of isolated large transverse energy electrons with associated missing energy at $s^{1/2}$ = 540 GeV", UA1 Collaboration (G. Arnison et al.), Phys.Lett.B122 (1983) 103-116.

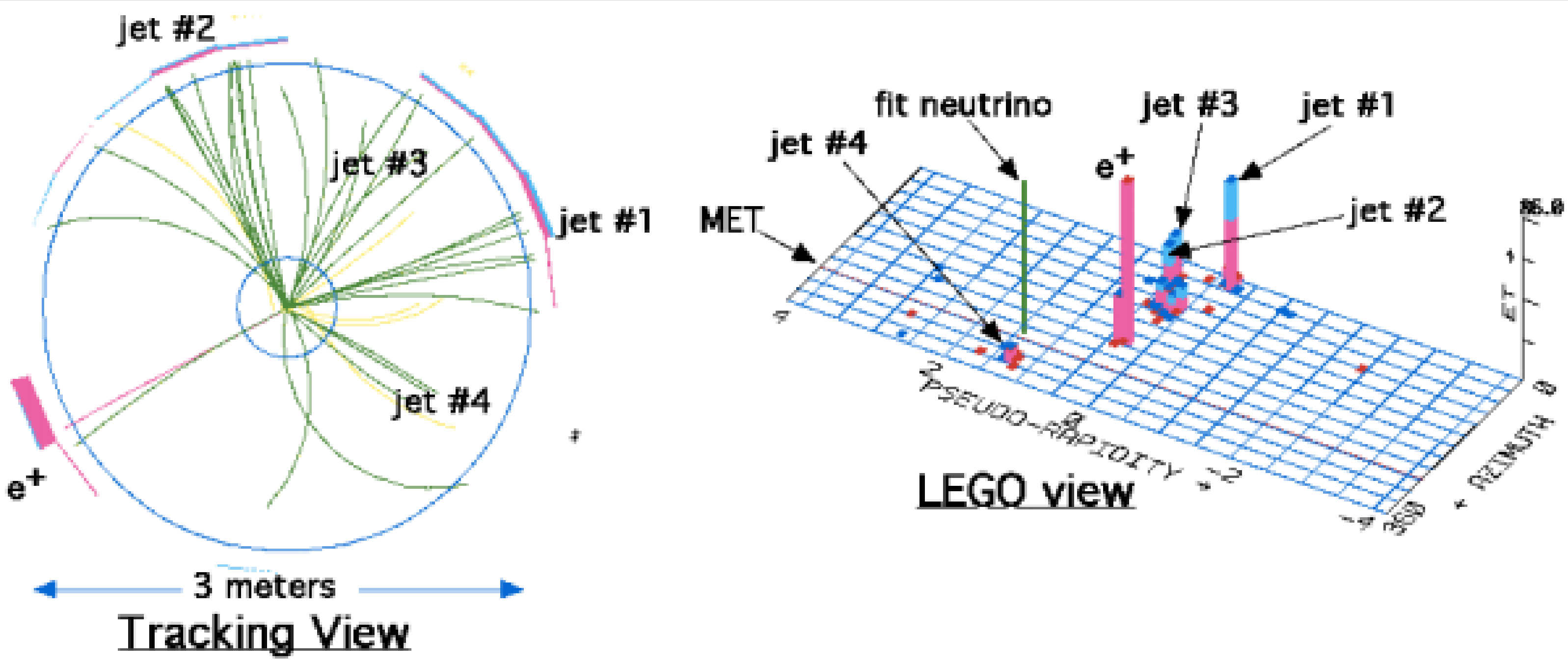


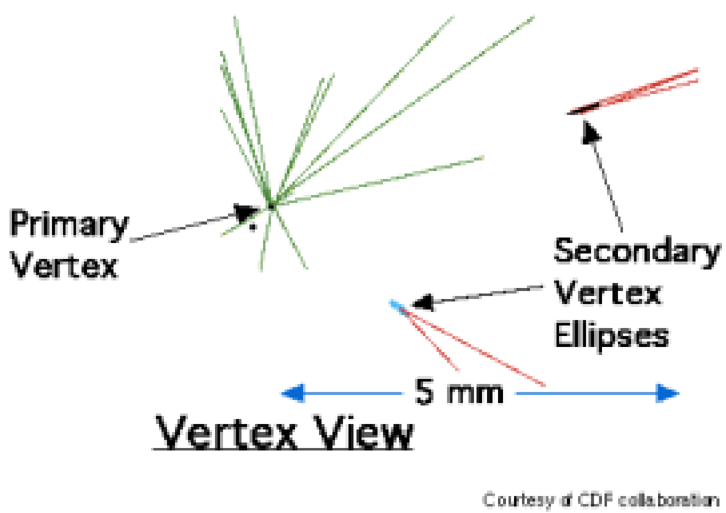
Discovery of the Z^0



CERN photo

Top





"GOLDEN" Top Event - This event has a 109 GeV e^+, and 4 Jets of (1) 90, (2) 77, (3) 64, and (4) 38 GeV. Jets (1) & (4)are tagged as b-jets by the CDF Silicon Vertex Detector. Jets (1,2,3) are from top; (2) & (3) are from a W. The event fit gives a Top Quark Mass of 170 ± 10 GeV.

(http://www-cdf.fnal.gov/experiment/events/events.html)

Unanswered Questions

Some questions about electroweak gauge theory:

- Why is it left handed? $SU(2)_L$!

W_R? $(M_R >> M_L)$

- How is unitarity violation resolved? $\sigma(WW \to WW) \sim s$!

Higgs?

- Why is gauge symmetry broken? $M_W, M_Z \neq 0$! Masses?

Higgs?

Need the Large Hadron collider

Why do particles have mass?

1) they are made from constituents with mass

- *e.g.* atoms made from neutrons, protons, and electrons, less binding energy

but why do constituents have mass?

2) deus ex machina

- they just are what they are
- spontaneous symmetry breaking

generated by couplings to higgs,
but what determines the couplings?

3) generated by interactions

The masses of light hadrons are mostly generated by the glue binding the light quarks together, with small contributions from the bare quark up and down quark masses, and electromagnetic interactions.

- energy in fields

e.g. energy in electromagnetic fields of a charged particle
e.g. energy in fields binding together composite systems

- interactions with media

e.g. photon mass in a medium (i.e. $n \neq 1$, $v \neq c$)
e.g. Higgs field? (see deus ex machina above)

- dynamical symmetry breaking

e.g. technicolour

4) Theories of Everything

- superstrings in 11 dimensions?