Experiment

"Particles, particles, particles."

confronts theory

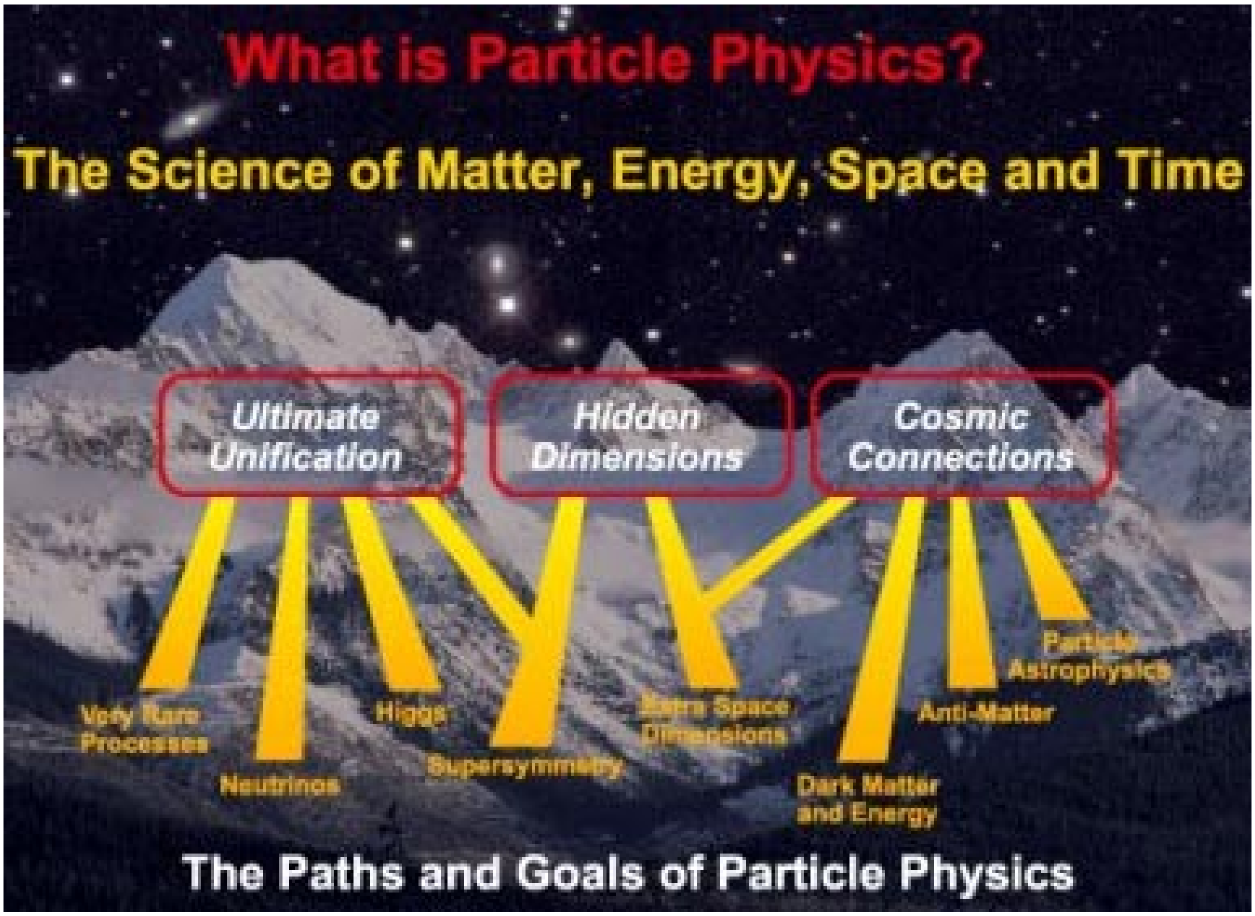
A Plumbers' Guide to Electroweak Unification

Kevin McFarland
University of Rochester

Department of Physics and Astronomy Colloquium

10 April 2002

Modest Goals. . .



Ultimate Unification of fundamental forces and particles into a coherent picture

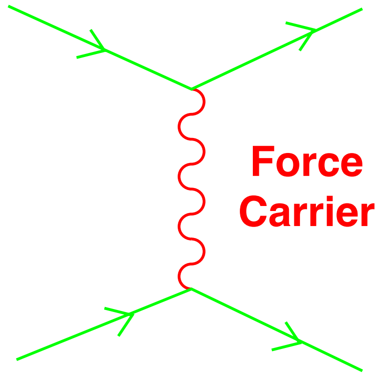
Hidden Dimensions , either quantum or physical, that add structure to our Universe

Cosmic Connections between the microphysical and totality of the Universe in space and time

. . . and paths to these goals.

Fundamental Forces

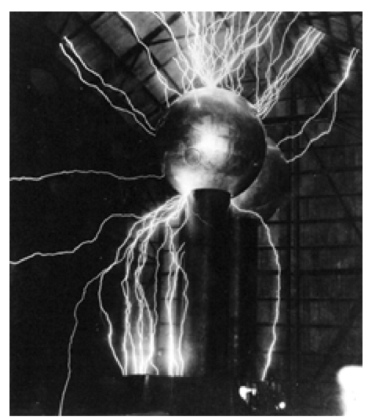
Quantum Mechanical Picture of a Force



Gravity at Work

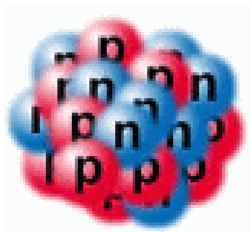
- Gravity
  - ↪ Attractive force between particles with mass or energy
  - ↪ Long range, macroscopic
  - ↪ Holds planets, solar systems, galaxies together

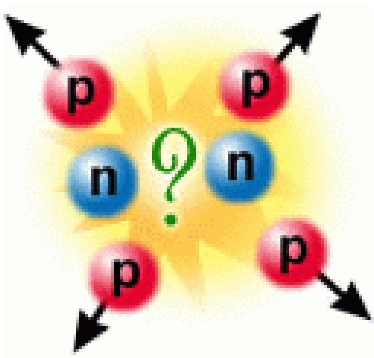
- Electromagnetism
  - ↪ Attractive or repulsive force between particles with electric charge
  - ↪ Long range, macroscopic
  - ↪ Holds atoms together, keeps matter from collapsing under gravity



Shockingly Electromagnetic

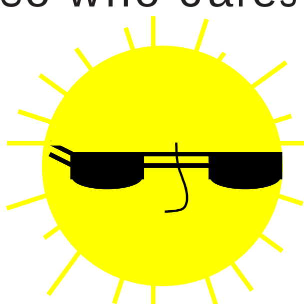
Fundamental Forces (cont'd)

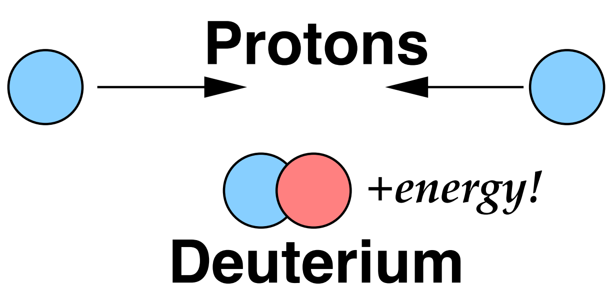




- Strong Nuclear Force
  - ↪ The nucleus of an atom contains lots of protons that repel each other electromagnetically
  - ↪ Strong force binds them
  - ↪ Microscopic *because* it is strong!

- Weak Nuclear Force
  - ↪ Textbook answer: "it's responsible for β decay"
  - ↪ So who cares?

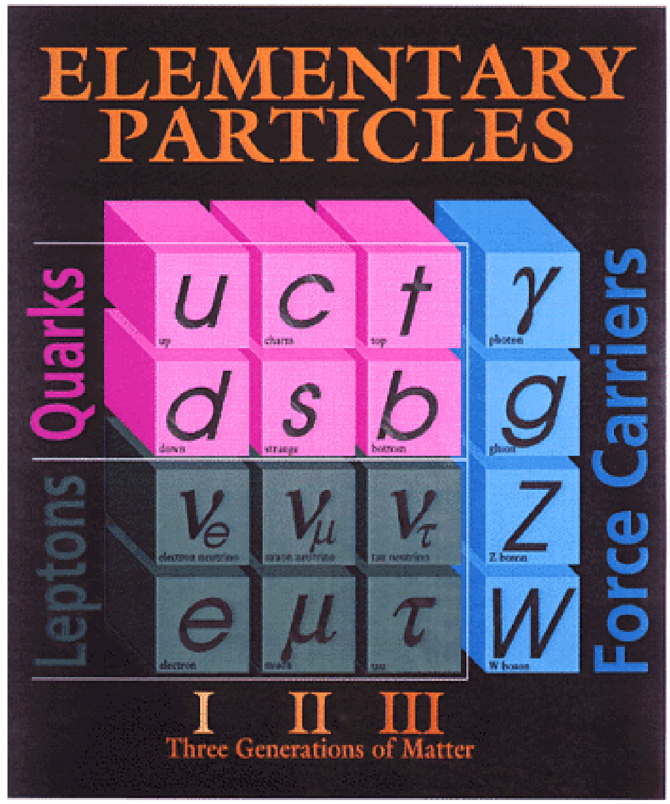


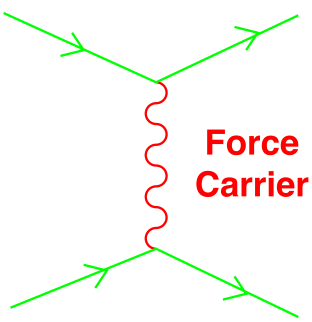


  - ↪ Fusion requires that protons change into neutrons
  - ↪ This is the inverse process of β decay!

Particle Periodic Table

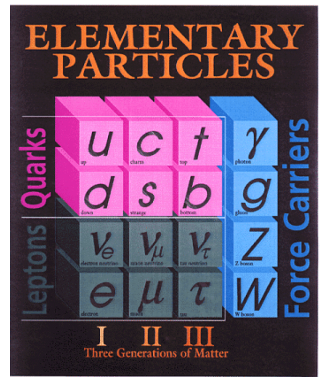
What is the matter?





- "Force Carriers" are the particles responsible for creating the four forces
- "Quarks" are the things that make up protons and neutrons and are bound together inside a nucleus
- "Leptons" include the electron and neutrinos

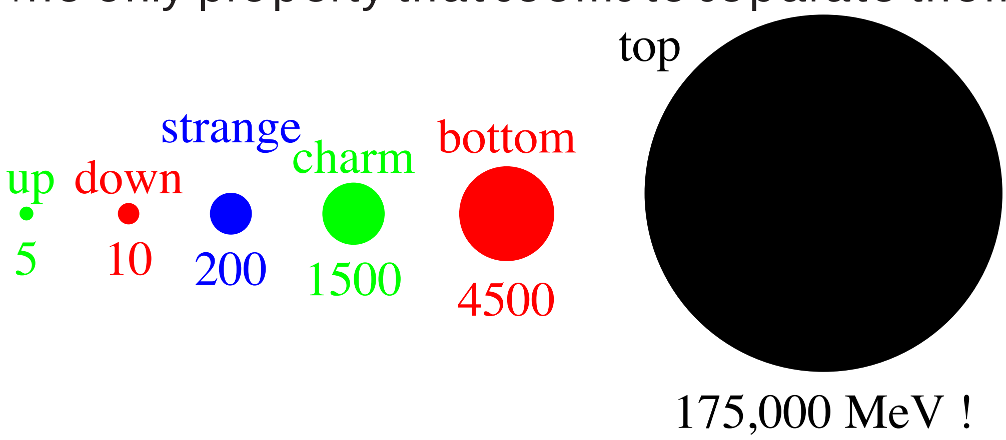
Weak Interactions and the Particle Periodic Table



If ordinary matter around us is made of up and down quarks and electrons...

...what are all those other particles doing there?

- Good question!
- There appear to be three copies of each of the "light" particles that make up ordinary matter
- Particle physicists call these "generations"
- The only property that seems to separate them is mass



- And the only way for particles of one generation to change into another is...

the weak interaction ("β-decay")

Unification?

Maxwell (1873) Unification of Electricity and Magnetism

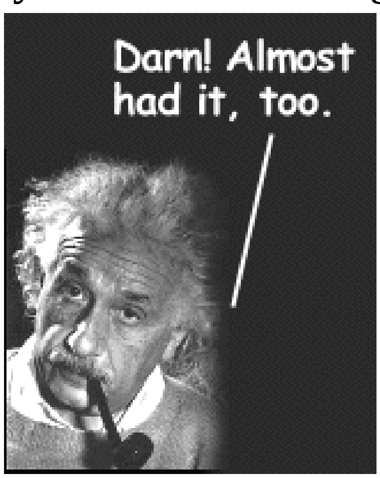
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

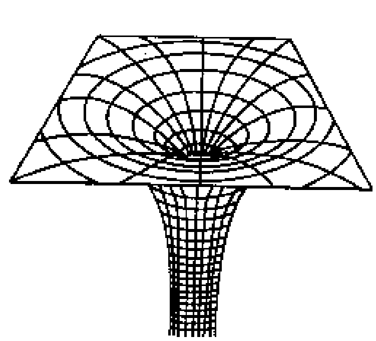
$$\nabla \bullet \vec{D} = \rho$$

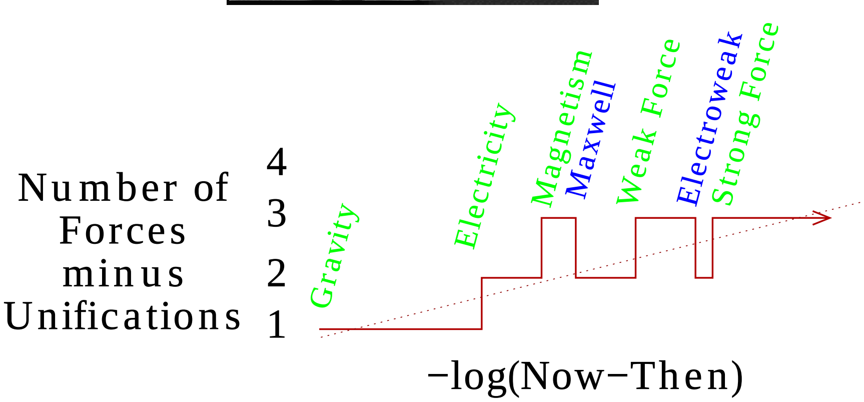
$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \bullet \vec{B} = 0$$

Einstein speculates about unified description
of gravity and electromagnetism. No realization...



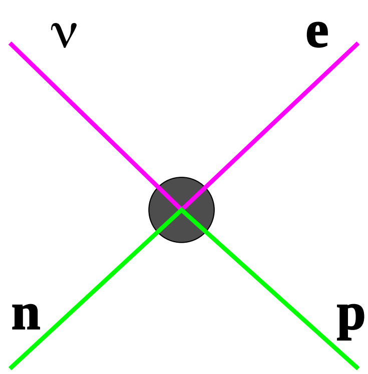




Not an encouraging trend!

Electromagnetic-Weak Force?

At first glance, these forces might not appear to be the poster children for unification!



In 1934, Maxwell theory was a "text-book" fact, but Fermi's Theory of the charged weak interaction can't get published!

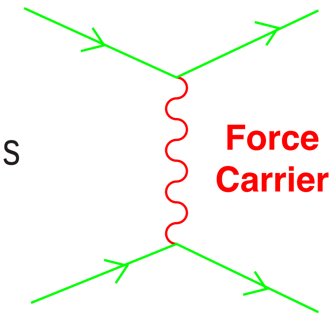
$$H_W = \frac{G_F}{\sqrt{2}} J^\mu J_\mu$$

Nature:"It contains speculations too remote from reality to be of interest to the reader"

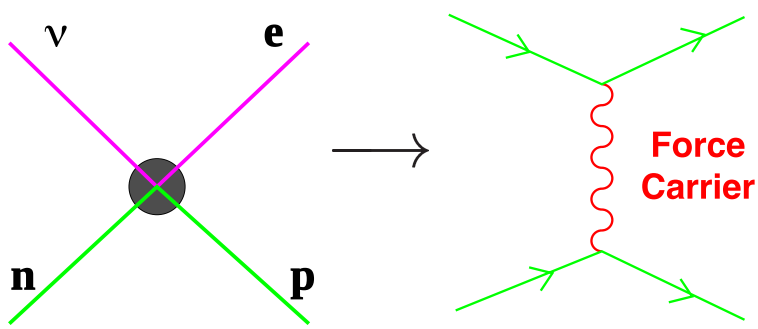
Circa 1960, the situation is...

Electromagnetism	Weak Force
Long-range ($\frac{1}{r^2}$)	Unobserved in atom outside nucleus
"Strong"($\tau_{\pi^0} \sim 10^{-16}$sec)	"Weak" ($\tau_{\pi^+} \sim 10^{-8}$sec)
Conserves parity and particle-antiparticle symmetry	Violates both $\approx$ maximally
Vector interaction	V-A interaction (Marshak)
Electrons and Muons	Electrons, Muons and Neutrinos!
Conserves particles	Changes particles

Sometimes if you think hard enough. . .



- Yang-Mills theory (1954): interactions of massless vector bosons
  - ↪ Electromagnetism!
- Higgs (and Hagen *et al.*) mechanism (1964): a way to build a theory of interactions carried by *massive* vector bosons
  - ↪ This gives a consistent, calculable (renormalizable) theory for Fermi's weak interactions!



$$\frac{G_F}{\sqrt{2}} \longrightarrow \frac{g^2}{8} \times \frac{1}{Q^2 - M_W^2}$$

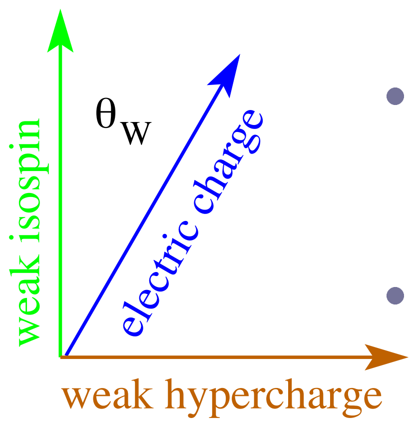
  - ↪ Fermi constant is replaced by a "fundamental" boson-fermion coupling and a kinematic suppression of the heavy weak boson
    - ⋆ g is similar to e in electromagnetism!
    - ⋆ One more important prediction. . . (to revisit)

Electroweak Unified Theory

"The standard model" of electroweak interactions
(Glashow, Weinberg, Salam)

Unification of Weak and Electromagnetic Forces

- SU(2) group: "weak isospin" ⇒ isotriplet of gauge bosons
- U(1) group: "weak hypercharge" ⇒ single gauge boson



- Weak isospin is quantum charge associated with Fermi's charge-carrying weak interaction
- Combination of weak isospin and weak hypercharge gives electro-magnetic interaction

Unified Electroweak Lagrangian:

$$\mathcal{L} = g\vec{J}_\mu \cdot \vec{W}_\mu + g' J^Y_\mu B_\mu,$$
$$J^Y_\mu = J^{em}_\mu - J^{(3)}_\mu.$$

Known Force Carriers are: $W^\pm$, photon

$$W^\pm_\mu = \frac{1}{\sqrt{2}}(W^{(1)}_\mu \pm \imath W^{(2)}_\mu).$$

$$photon_\mu = \frac{1}{\sqrt{g^2 + g'^2}}(g' W^{(3)}_\mu + g B_\mu),$$

so photon couples only to the electromagnetic current.

Electroweak Theory (cont'd)

Elements of the unified theory:

- Fermi charge-carrying weak interaction
  (exchange of $W^{\pm}$ bosons)
- Electromagnetism
  (exchange of photons)
- In the theory, the Higgs mechanism gives mass to
  a *triplet* of W bosons

Full Lagrangian is:

$$\begin{aligned}\mathcal{L} &= \frac{g}{\sqrt{2}}(J^{-}_{\mu}W^{+}_{\mu} + J^{+}_{\mu}W^{-}_{\mu}) \\ &+\sqrt{g^2+g'^2}\left(J^{(3)}_{\mu} - \frac{g'^2}{g^2+g'^2}J^{em}_{\mu}\right) Z_{\mu} \\ &+\frac{gg'}{\sqrt{g^2+g'^2}}J^{em}_{\mu}(photon)_{\mu}.\end{aligned}$$

Remaining term

$$Z^{0}_{\mu} = \frac{1}{\sqrt{g^2+g'^2}}(gW^{(3)}_{\mu} - g'B_{\mu}).$$

predicts

- Another massive (Higgs mechanism) boson
  (and therefore another *weak* force)
- That does *not* carry charge

. . . a bold prediction with no experimental basis!

Electroweak Theory (cont'd)

Parameters of unified theory (g, M_W, g') can be related to low energy parameters (e, G_F)

Let $g' \equiv g \tan\theta_W$; then:

$$
\begin{aligned}
e &= g \sin\theta_W, \\
G_F &= \frac{g^2\sqrt{2}}{8{M_W}^2}, \\
\frac{M_W}{M_Z} &= \cos\theta_W
\end{aligned}
$$

- Theory not only predicts a new weak interaction...
- But all of its properties follow from a single parameter, one of M_W, M_Z or θ_W

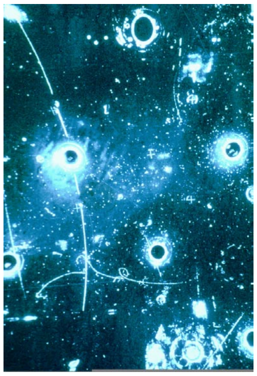
Finally, by invoking the Higgs mechanism, the theory predicts an additional particle: the Higgs boson

- A *scalar* boson
- In order for it to do its job (to generate boson mass), $m_H \lesssim 1$ TeV ($\Gamma_H \sim G_F M_H^3$)

Astoundingly, these theoretical predictions have charted a course for experimental particle physics for a third of a century!

Weak Neutral Current Experiments

Discovery of Weak Neutral Current



- Summer 1973
- ν_μ interaction w/ no final state μ
- Gargamelle, HWPF (E1A)
- Successful pred. of EW theory

First Generation of Experiments

- Experiments in late 1970's
- Typically of 10% precision
- Basic structure of SM correct
- Key input to SM Mw,Mz

SLAC e-D
APV

Second Generation of Experiments

- Experiments in late 1980's
- Discovery of W, Z bosons
- Typically of 1-5% precision
- Radiative corrs important
- First useful limits on Mtop

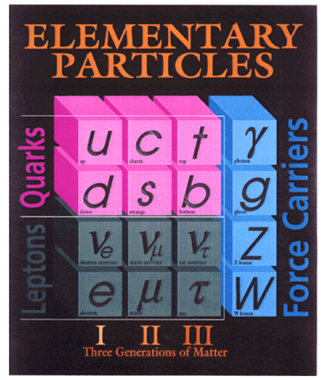
CCFR, CDHS
CHARM, CHARM II
UA1,UA2
PETRA,TRISTAN,APV

Third Generation of Experiments

- Typically $\leq$1% precision
- Test internal consistency of SM
- Search for new physics
- Constrain Higgs boson mass
- Foundation for light Higgs

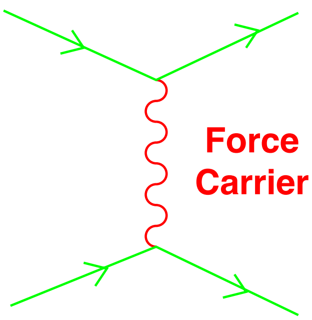
NuTeV, DØ, CDF
LEP I, SLD
LEP II,APV

Discovery I



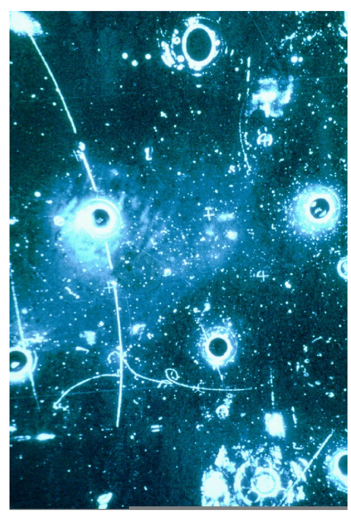
Neutrino interactions fill an important experimental niche

- Their only interactions are weak!
- Both $W^\pm$ and Z^0 exchange are common



- Incoming neutrino (ν_μ) exchanges a W or Z boson with target
- W boson ("charged-current"): outgoing μ
- Z boson ("neutral-current"): no outgoing μ

$\nu_\mu e^- \to \nu_\mu e^-$
in Gargamelle bubble chamber



This process can only be exchange of a neutral force carrier

Discovery I (cont'd)

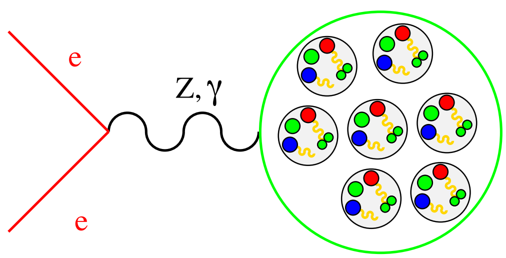
$$R^{\nu} = \frac{\sigma_Z^{\nu}}{\sigma_W^{\nu}} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{27}\sin^4\theta_W$$
$$R^{\overline{\nu}} = \frac{\sigma_Z^{\overline{\nu}}}{\sigma_W^{\overline{\nu}}} = \frac{1}{2} - \sin^2\theta_W + \frac{20}{9}\sin^4\theta_W$$

Gargamelle at CERN, HPW and CalTech-FNAL experiments at Fermilab find

$$R^{\nu} \sim 0.3 \qquad R^{\overline{\nu}} \sim 0.4$$

This matches electroweak theory with $\sin^2\theta_W \sim 0.2$

$\gamma - Z$ Interference

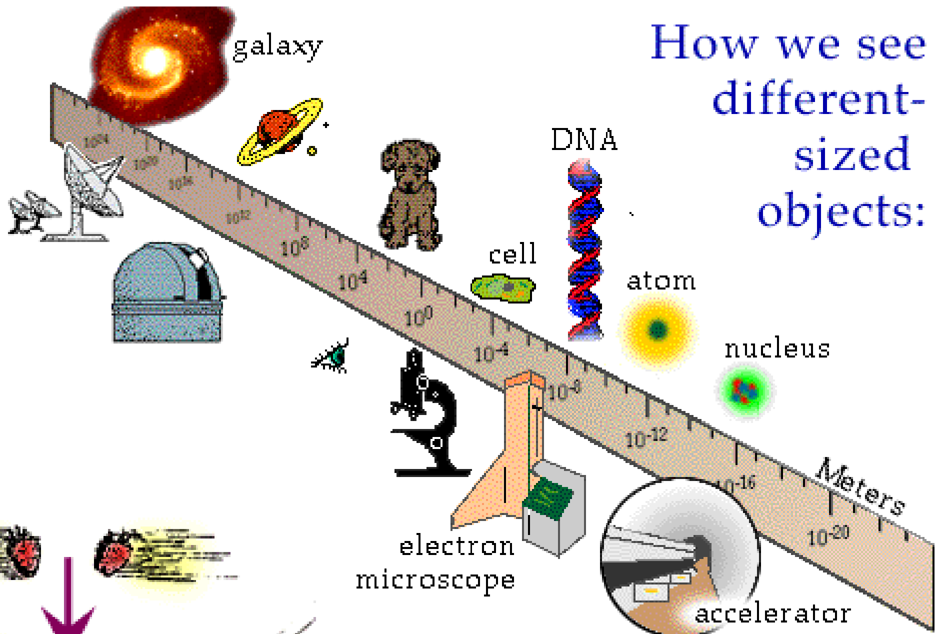


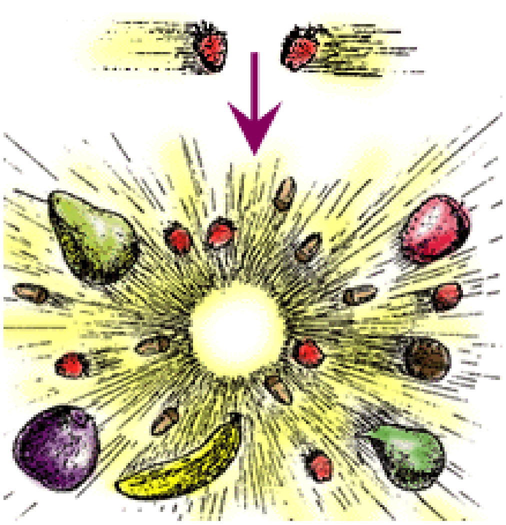
- Magnitude of γ-Z interference (parity-violating) relative to γ-exchange gives
  $\langle Q_{Weak}\rangle / \langle Q_{EM}\rangle$ of target
- Suppressed by low momentum transfer, q^2/M_Z^2
  Need short-distance or high momentum transfer!
- Prescott *et al.* at SLAC

Discovery II

A complementary technique to study weak interactions is to produce the force carriers!

- Direct study of $W^{\pm}$ and Z^0 interactions
- Can attempt in scattering processes...





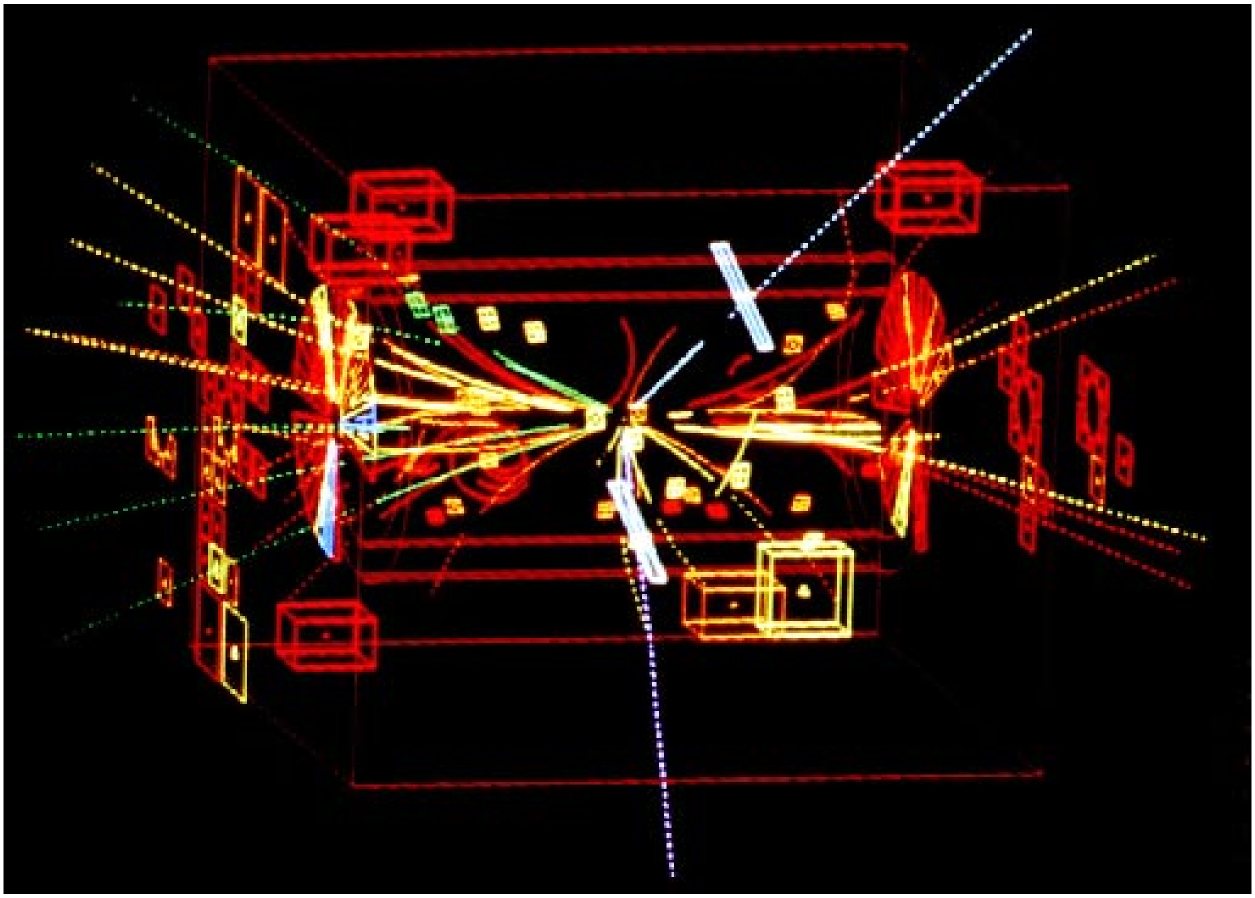
Can also use the energy contained in the beams to produce matter that was not originally there!

$p\overline{p} \rightarrow$ FRUIT

...but this is much simpler at colliders!

Discovery II (cont'd)

UA1 experiment at CERN S$p\overline{p}$S collider ($\sqrt{s} = 540$ GeV)



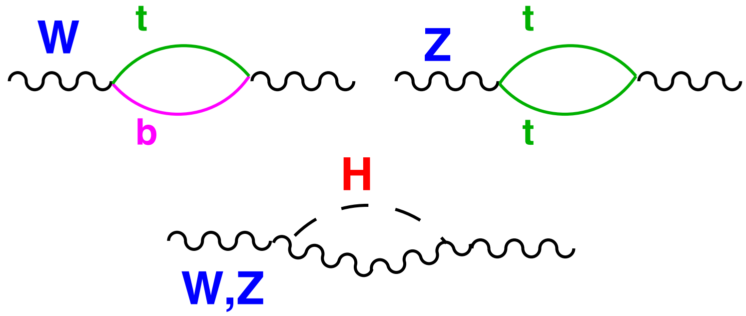
$M_W \approx 81$ GeV, $M_Z \approx 91$ GeV

- Provides direct confirmation of theory
- Separates couplings from boson mass

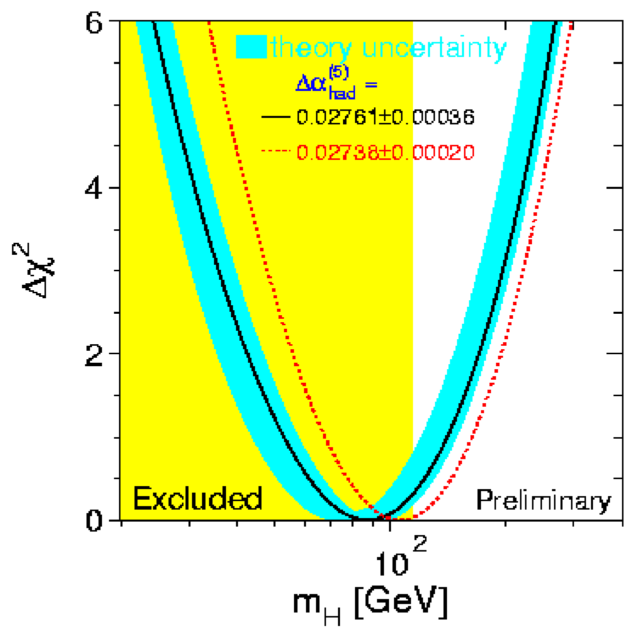
$$G_F = \frac{g^2\sqrt{2}}{8{M_W}^2}$$

Era of Quantum Corrections

- α_{em}, known to 45 ppb
  (but only to 200 ppm at $Q^2 \sim M_Z^2$)
- G_F, known to 10 ppm
- M_Z, known to 23 ppm

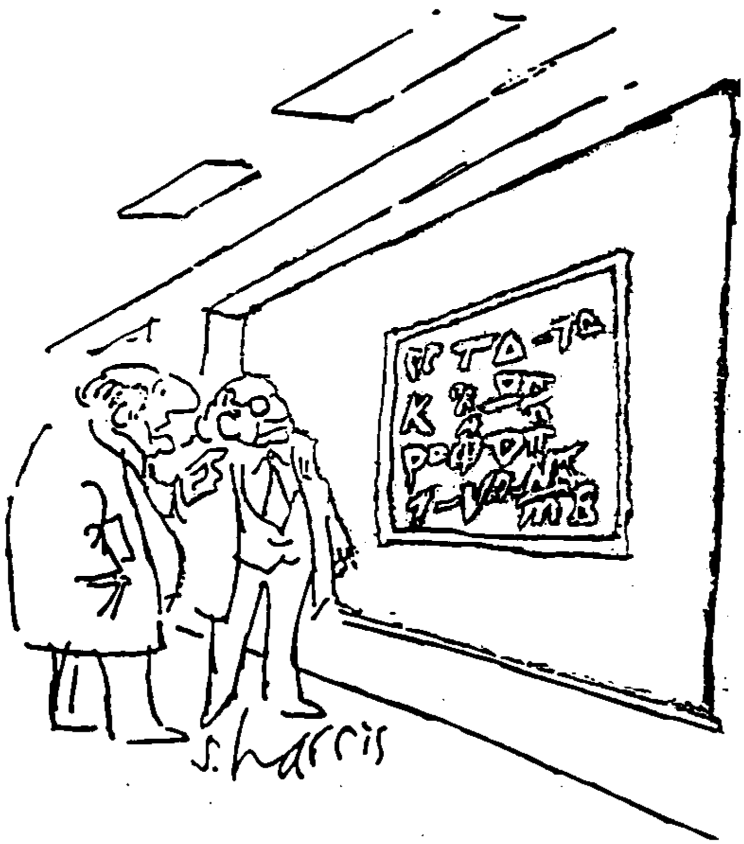


- Radiative corrections large, well-understood
- Gives a large m_t, m_H dependence of boson masses



Why continue to test at high precision?

1. Testing in a wide range of processes and momentum scales ensures universality of the electroweak theory
2. Hope to observe new physics in discrepancies among measurements
   - Loop (quantum) corrections
   - Tree level (new process) contributions



"Putting a box around it, I'm afraid, does not make it a unified theory."

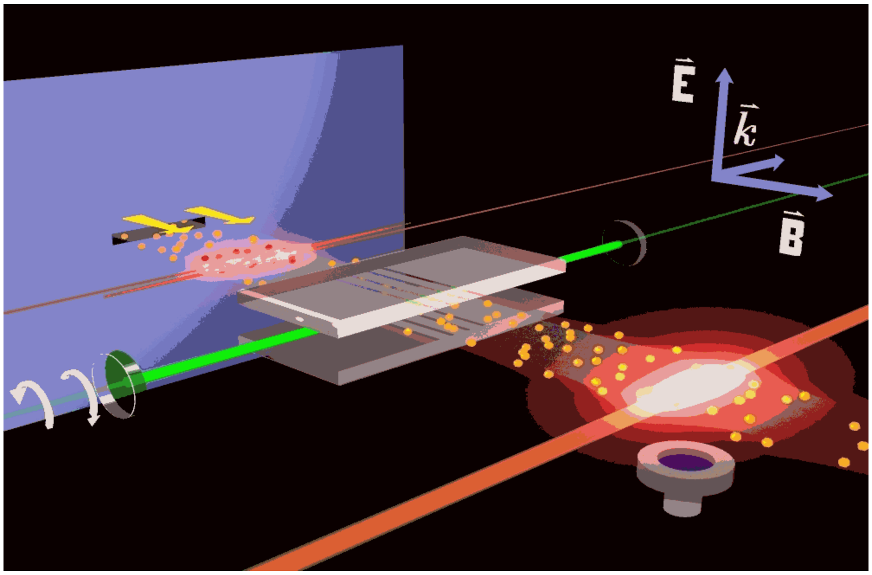
Atomic Parity Violation

Technique measures $\gamma - Z^0$ interference through forbidden (parity violating) atomic transitions

Recent measurement (JILA/Boulder;Ce):

Bennett,S.C. and Wieman,C.E. PRL 82, 2482-2487 (1999)

$Q_{Weak} = -72.06(28)_{exp}(34)_{theory}$ $\Rightarrow 2.5\sigma$ deviation from theory



Many-body atomic theory that is the input is complex.

Later authors have re-evaluated theory

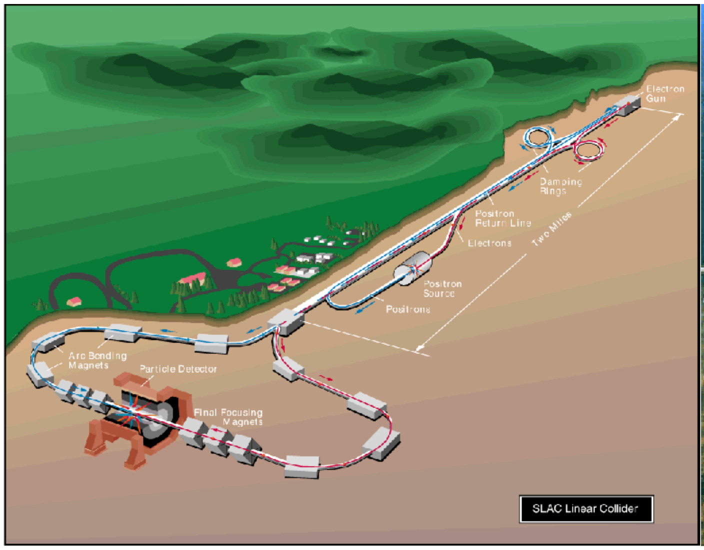
"average" $Q_W = -72.5 \pm 0.8$

(Kozlov *et al.*, PRL **85**, 1618. Dzuba *et al.*, PR **A63**, 044103. Average: Rosner, hep-ph/0109239)

$$\frac{Q_W^{\rm exp} - Q_W^{\rm SM}}{Q_W^{\rm SM}} = 0.014 \pm 0.006 \quad (or\ 0.008 \pm 0.011)$$

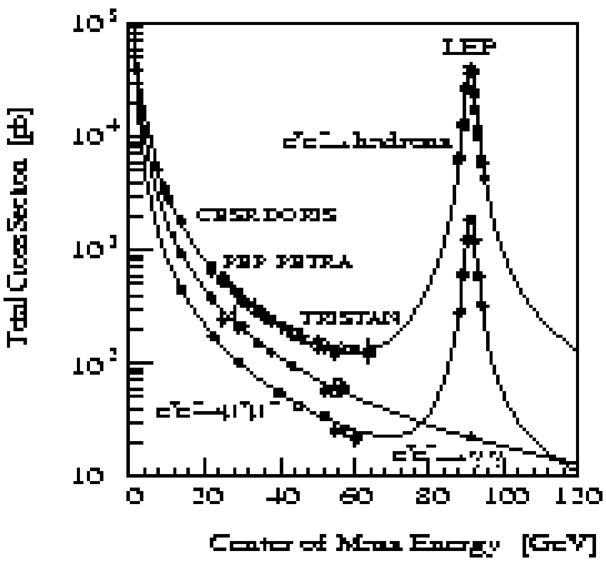
$$= 5.1436(\delta u_L + \delta u_R) + 5.7729(\delta d_L + \delta d_R) - 2\,\delta g_A^e$$

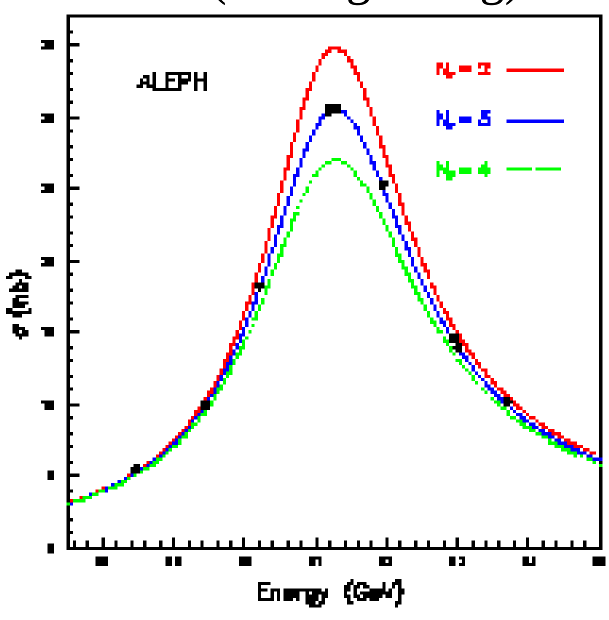
Z Factories: LEP and SLD



SLC at SLAC
(proto−linear collider)

LEP at CERN
(storage ring)



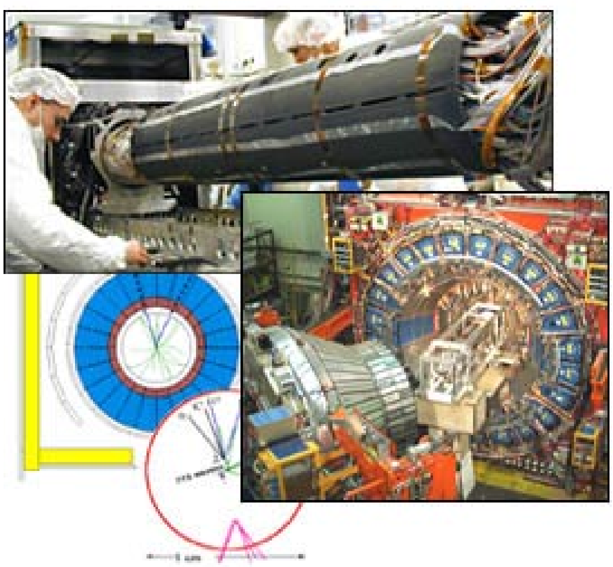


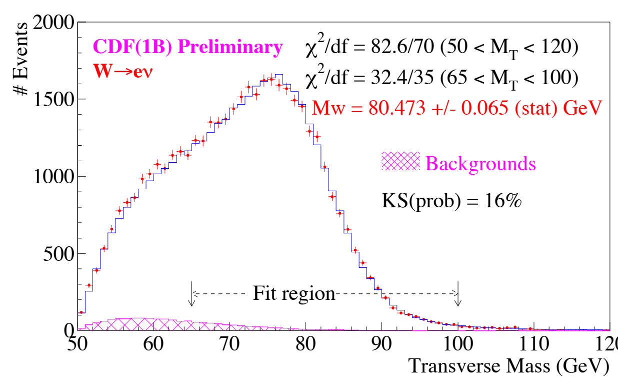
Since $Z \to \nu\overline{\nu}$, Γ_Z is sensitive to the number of neutrinos with $M_\nu < M_Z/2 \approx 45$ GeV

$\Longrightarrow$ Experimental Basis for Three Generations

TeVatron: Energy Frontier

- "Run II" of the TeVatron has begun
  - ↪ $\sqrt{s} = 1960$ GeV
  - ↪ $\mathcal{L} \sim 10^{31}$, c.f. design $\mathcal{L}$ of $\times 10^{32}$

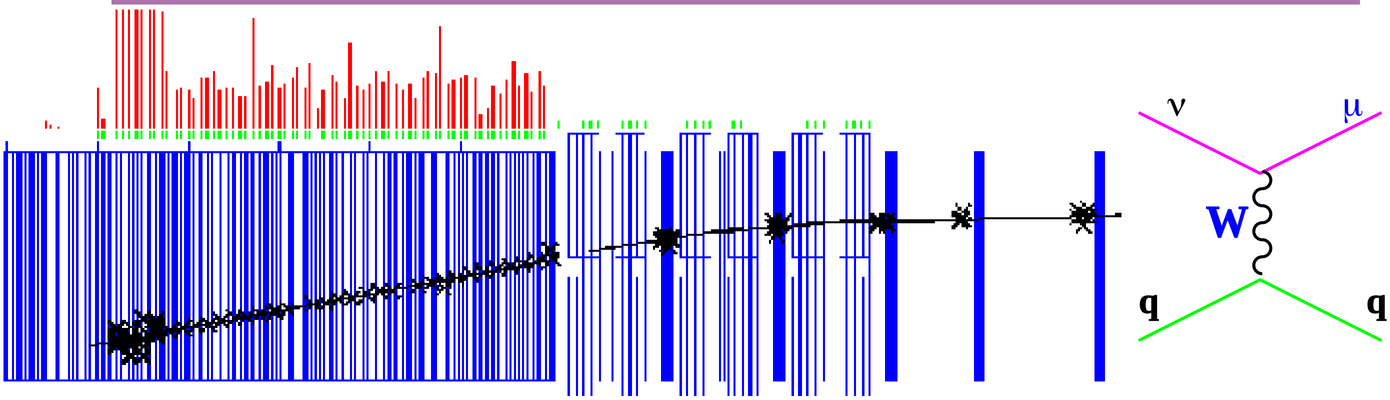


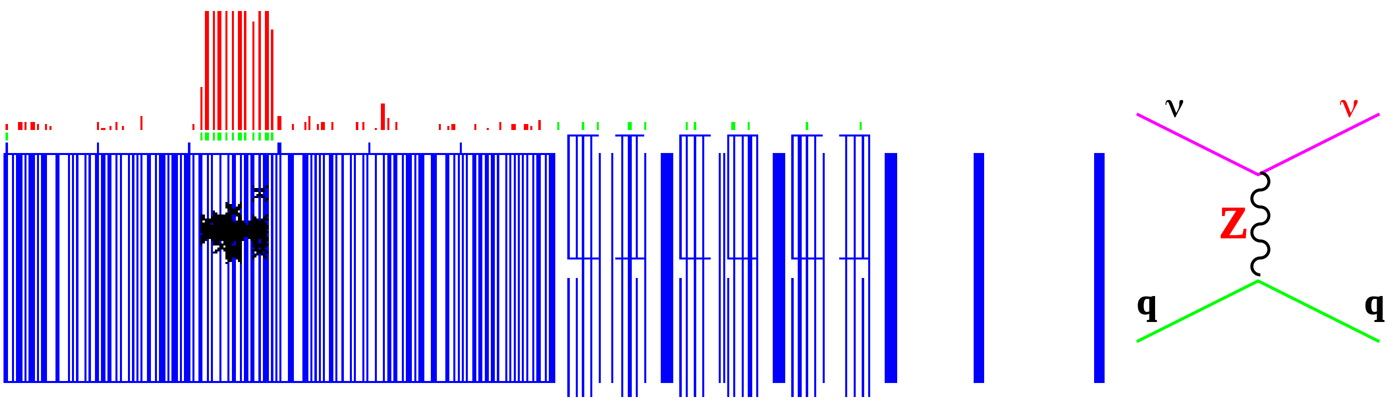


Run II will

- Observe $\mathcal{O}(1$ Million$)$ $W^{\pm}$ boson decays useful for W property measurements
- Make first precise measurements of top quark electroweak properties
- Extend searches for new weak bosons to higher mass

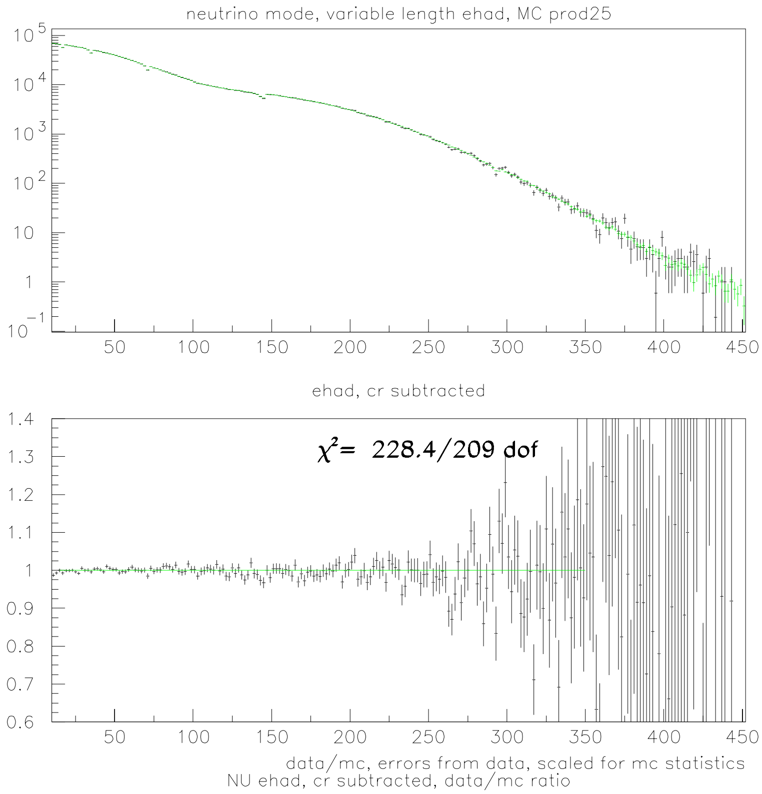
NuTeV: Heir to the Neutrino



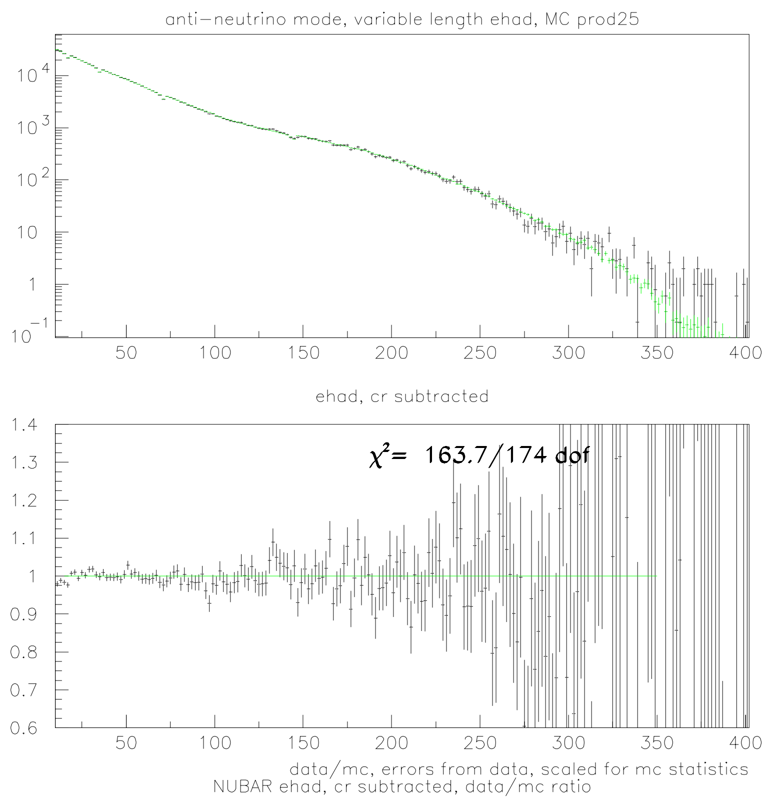


- Why can NuTeV make a precision test?
  - ↪ Need few part per mil tests!
  - ↪ Millions of neutrino interactions!
    - ⋆ Beam is fed by 0.5 Coulombs of 800 GeV protons
    - ⋆ Massive (690 ton) detector
- Why should NuTeV make a precision test?
  - ↪ Weak scattering approach is complementary to direct Z^0 measurements
    - ⋆ Other interactions could contribute!
  - ↪ Neutrino-Z^0 coupling is not well measured

The Raw Data



1.62×10^6 events in the ν beam

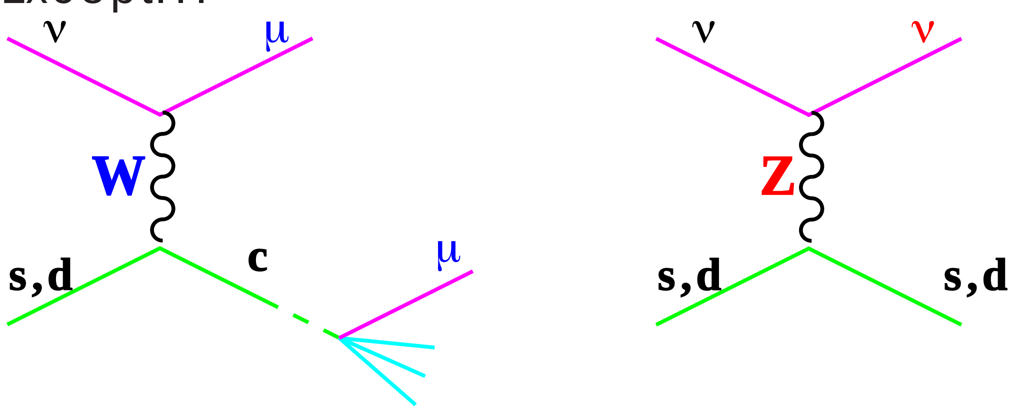


0.35×10^6 events in the $\overline{\nu}$ beam

Counting Experiment?

$$R^{\nu(\overline{\nu})} = \frac{\sigma_Z^{\nu(\overline{\nu})}}{\sigma_W^{\nu(\overline{\nu})}} = \rho^2 \left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W \left(1 + \frac{\sigma_W^{\overline{\nu}(\nu)}}{\sigma_W^{\nu(\overline{\nu})}} \right) \right)$$

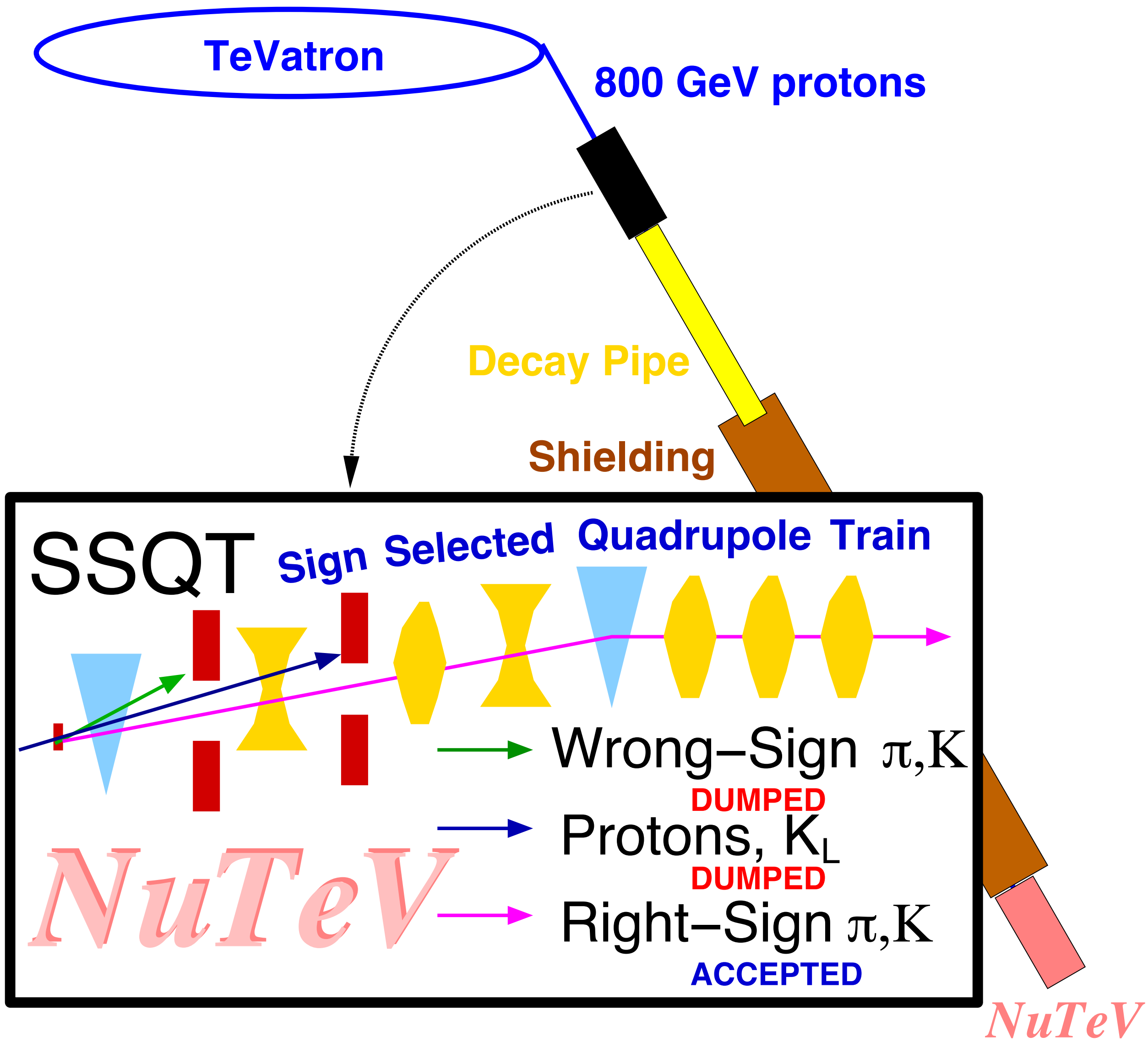
- Separate interactions, take ratio, done?
- Except...



Suppression of only $W^\pm$ exchange cross section for interactions with massive charm quark in final state

- NuTeV's trick is to accumulate massive, separated ν and $\overline{\nu}$ samples
  - ↪ Charm suppression is larger for $\overline{\nu}$
  - ↪ Dependence on $\sin^2\theta_W$ is larger only for ν
  - ↪ $\overline{\nu}$ becomes a *control sample* for precision studies

NuTeV Beamline

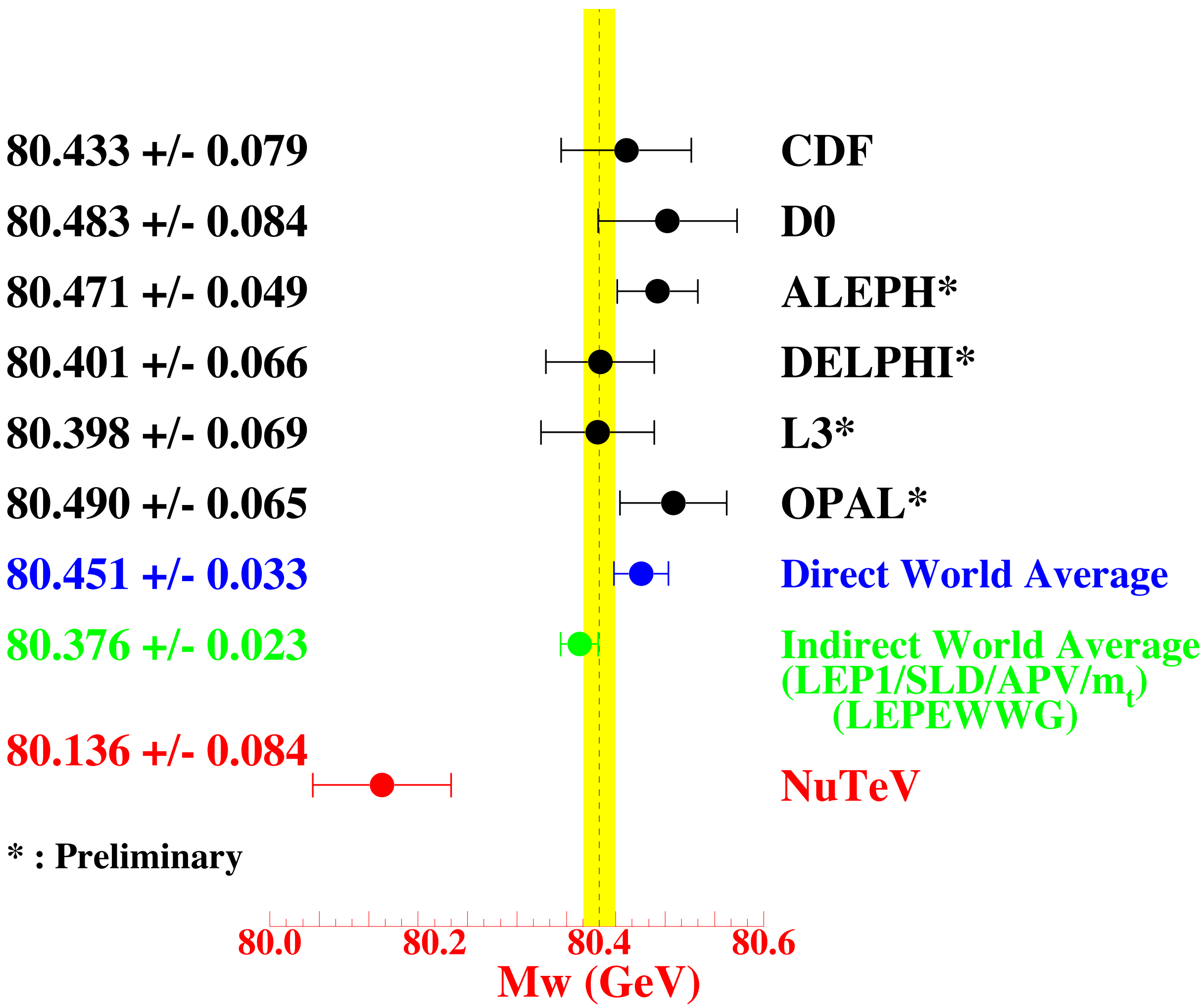


- 10^{10} ν per 60 sec cycle
- Beam is almost purely ν or $\overline{\nu}$:
  ($\overline{\nu}$ in ν mode 3×10^{-4}, ν in $\overline{\nu}$ mode 4×10^{-3})
- Beam is ~1.6% electron neutrinos

The Result

$$\sin^2\theta_W^{(on-shell)} = 0.2277 \pm 0.0013\,(stat) \pm 0.0009\,(syst) - 0.00022 \cdot \left(\frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2}\right) + 0.00032 \cdot \ln\left(\frac{M_{Higgs}}{150\,GeV}\right)$$

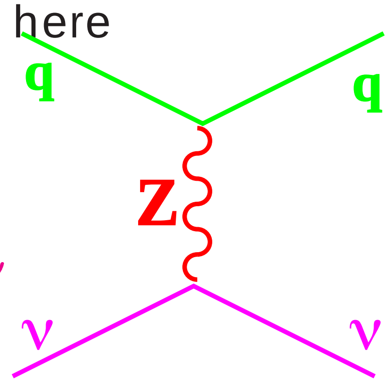
- In good agreement with previous νN: $\sin^2\theta_W$ = 0.2277 $\pm$ 0.0036
- Standard Model fit (LEPEWWG): 0.2227 ± 0.00037

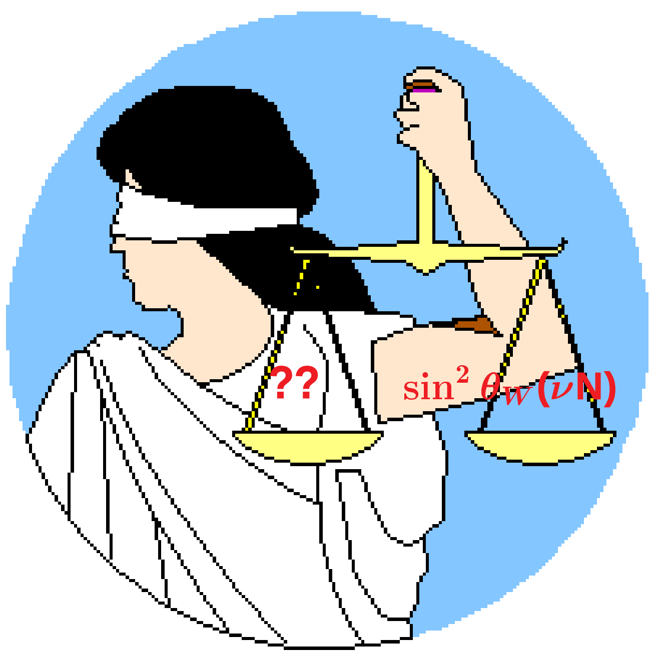


- More inconsistent with direct M_W than other data

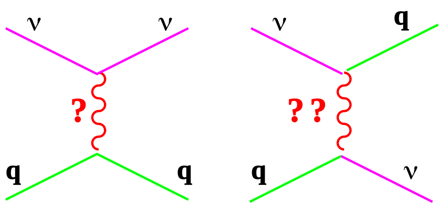
Interpretations

- Misunderstanding of our target (symmetry violations)
  - ↪ Much interest and investigation here
  - ↪ But no explanation currently
- New Interactions?
- Neutral current coupling of ν





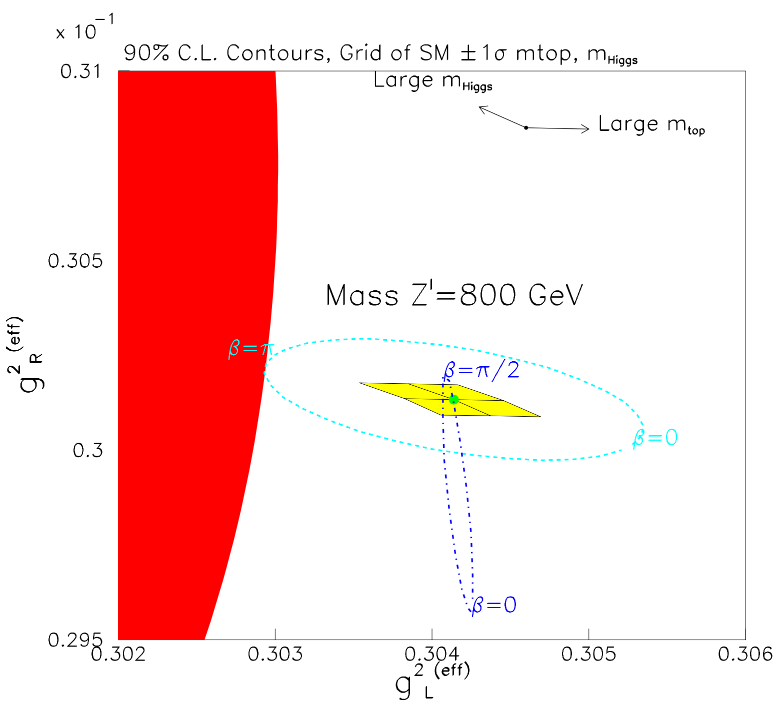
New Interactions?



- "Natural" interpretation of result
- Z' (a new "weaker" neutral force carrier)
- Leptoquarks?

- $E(6)$ Z' accounts for NuTeV?
  - ↪ New $E(6)$ interactions are embedded in a theory unifying strong and electroweak interactions
  - ↪ Unfortunately...
    - ⋆ Allowed contact terms shift wrong coupling
    - ⋆ Mixing terms, disfavored by Z^0 data, could account for NuTeV however

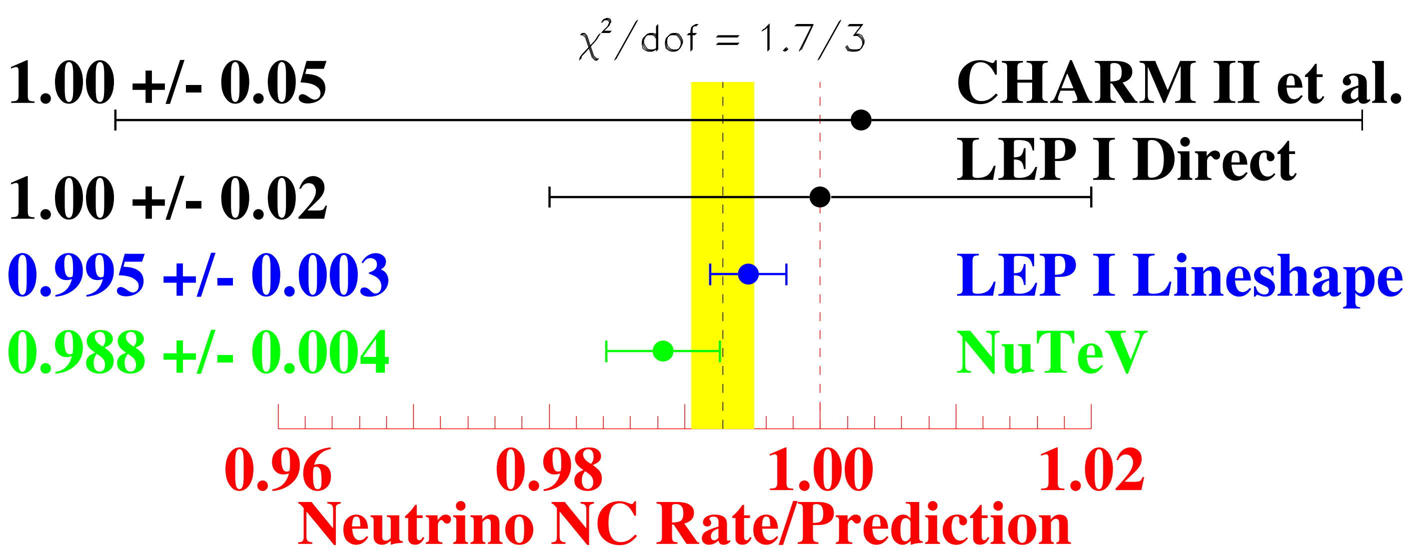
(Cho *et al.*, Nucl. Phys. **B531**, 65.
Zeppenfeld and Cheung, hep-ph/9810277.
Langacker *et al.*, Rev. Mod. Phys. **64** 87.)



- In general, Z' interactions certainly can explain data
- Parity-violating Z', similar to SM Z^0, works well
  $M_{Z'} \sim 1$ TeV is viable
- Observable at FNAL TeVatron or at CERN LHC

Neutral Current ν Interactions

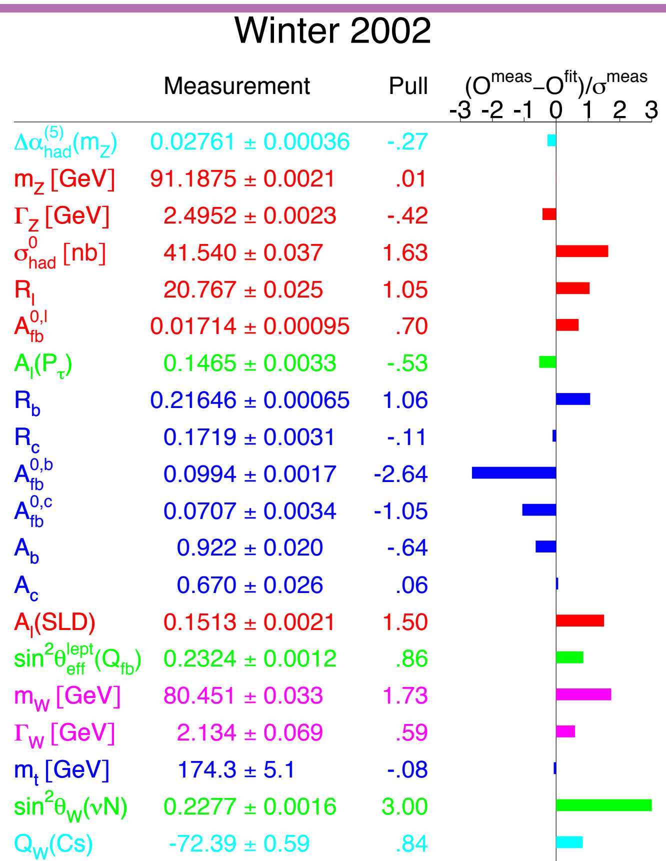
- LEP I measures Z lineshape and decay partial widths to infer the "number of neutrinos"
  - ↪ Their result is $N_\nu = 3\frac{\Gamma_{exp}(Z\to\nu\overline{\nu})}{\Gamma_{SM}(Z\to\nu\overline{\nu})} = 3 \times (0.9947 \pm 0.0028)$
  - ↪ LEP I "direct" partial width ($\nu\nu\gamma$) $\Rightarrow N_\nu = 3 \times (1.00 \pm 0.02)$
- $\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ scattering (CHARM II *et al.*)
  - ↪ PDG fit: $g_V^2 + g_A^2 = 0.259 \pm 0.014$, cf. 0.258 predicted
- NuTeV can fit for a deviation in ν&$\overline{\nu}$ NC rate
  - ↪ $\rho_0^2 = 0.9884 \pm 0.0026(stat) \pm 0.0032(syst)$

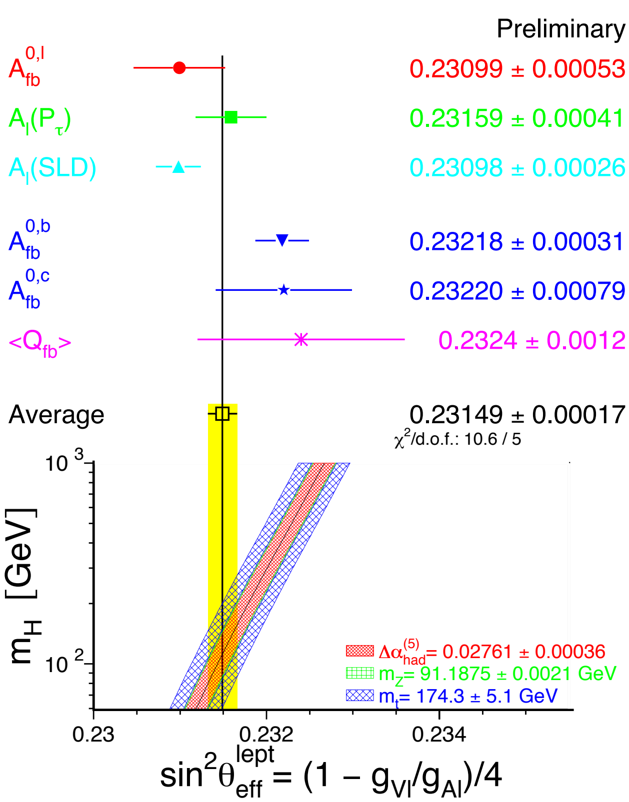


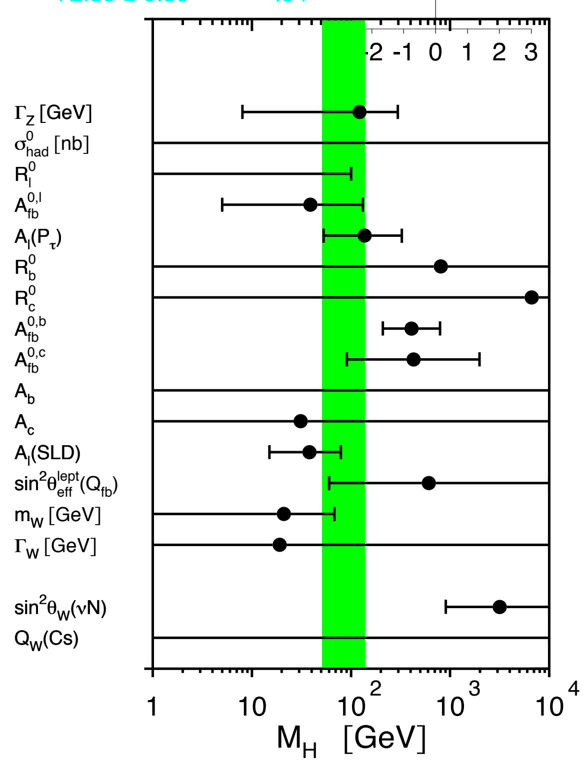
- In this interpretation, NuTeV confirms and strengthens LEP I indications of "weaker" neutrino neutral current
  - ↪ NB: This is not a unique or model-independent interpretation!

Electroweak Data in Its Totality

- Global fit has a χ^2 of $\chi^2/\mathrm{dof} = 19.6/14$ (probability of 14%)
- Two most precise measurements of $\sin^2\theta_W$ at Z pole differ by 3σ
- Data suggest light Higgs except $A^{0,b}_{FB}$
- σ_{had} also off by $\sim 2\sigma$
- Adding NuTeV: $\chi^2/\mathrm{dof} = 28.8/15$ (probability of 1.7%)

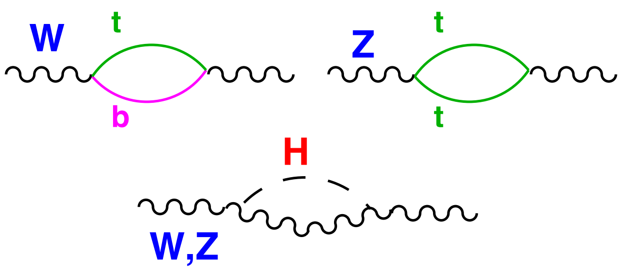


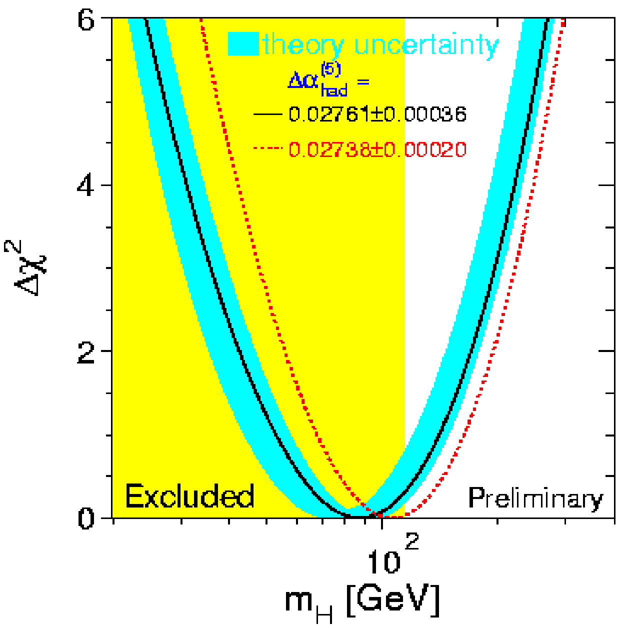




Where is the Higgs?

- Measurements of the quantum corrections suggest a very light Higgs

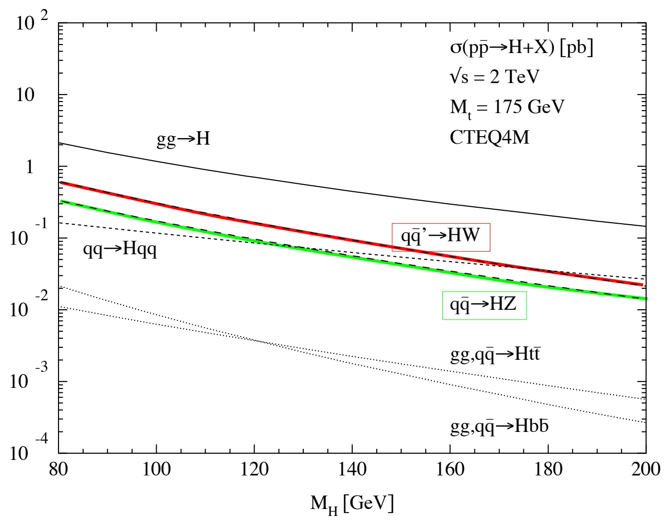


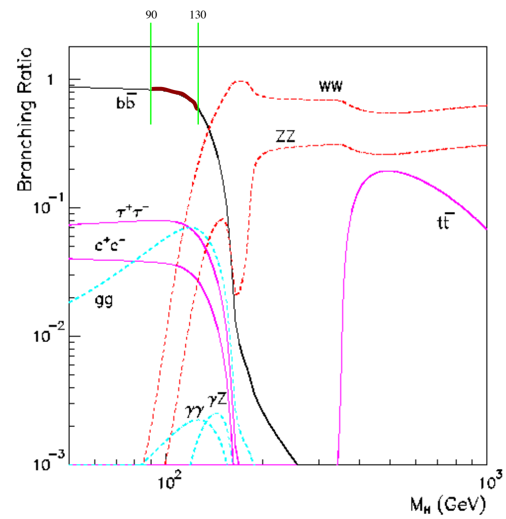


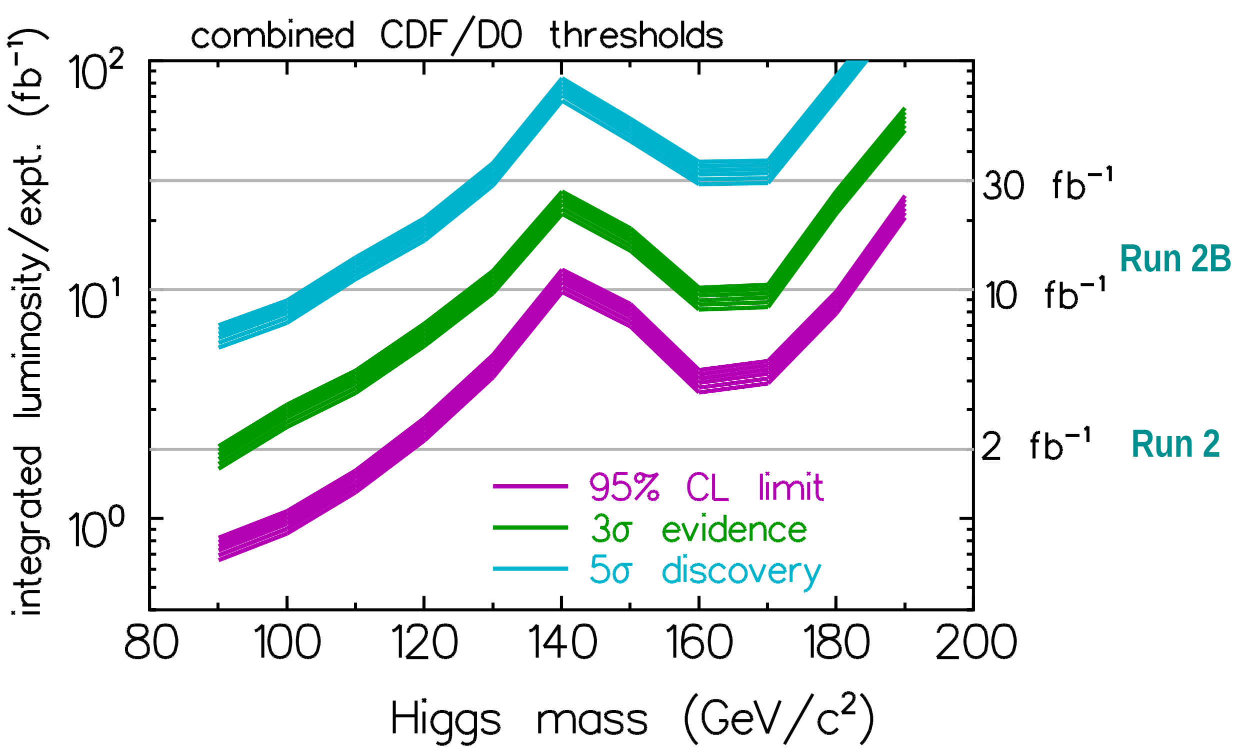
- Good news and bad news
  - ↪ The good news is that the data suggests the Higgs is within reach!
    $m_H < 196$ GeV at 95% confidence
  - ↪ The bad news is the poor consistency of the data
    Self-consistency is excluded at 98% confidence

Discovering the Higgs

If the Higgs boson is light, the Fermilab TeVatron is the next opportunity for a glimpse





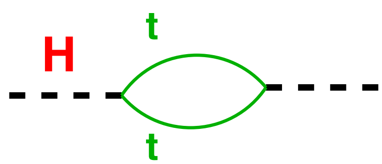


(Run II Higgs Working Group, All VH Channels and $gg \to H, H \to WW^*$)

Hidden Dimensions and the Higgs

The picture of the single Higgs scalar boson has a significant weakness

- Quantum corrections to the Higgs self-energy at short distances are large



$$\Delta\mu^2_{top} \sim \frac{1}{r^2_{Higgs}}$$

- This suggests a breakdown in the theory at a "Higgs size" comparable to the Higgs potential ($\sim 1/(100$ GeV$)$

but we have seen analogous situations in the past...

(an analogy I learned from Hitoshi Murayama)

Consider the Coulomb field of an electron

- It contributes a self-energy to the electron of

$$\Delta E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

where r_e is an electron size, a "cut-off" to keep the contribution finite

- The problem is that we know experimentally that $r_e \lesssim 1/(1\,TeV)$
- So $\Delta E \sim 10$ GeV! Ludicrous compared to 0.511 MeV

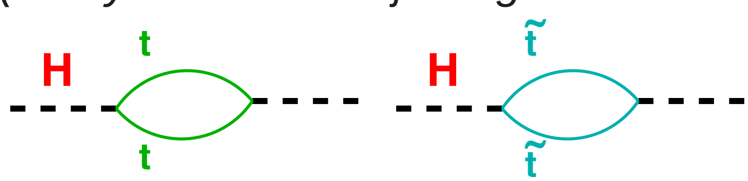
Hidden Dimensions and the Higgs (cont'd)

The "out" of course is the discovery of anti-matter

- The small-scale vacuum can fluctuate to e^+e^- pairs because of matter-antimatter symmetry
- This generates quantum corrections that modifies the self-energy at a distance scale of $\frac{1}{2m_e}$
  - ↪ Short-distance effect largely cancels (becomes logarithmic in r_e)

An analogous "out" exists for the Higgs in a theory called "Supersymmetry"

- Supersymmetry predicts massive "superpartners" for normal matter
- "Top quark" $\rightarrow$ "Stop squark"
  (I only wish I were joking about the name!)

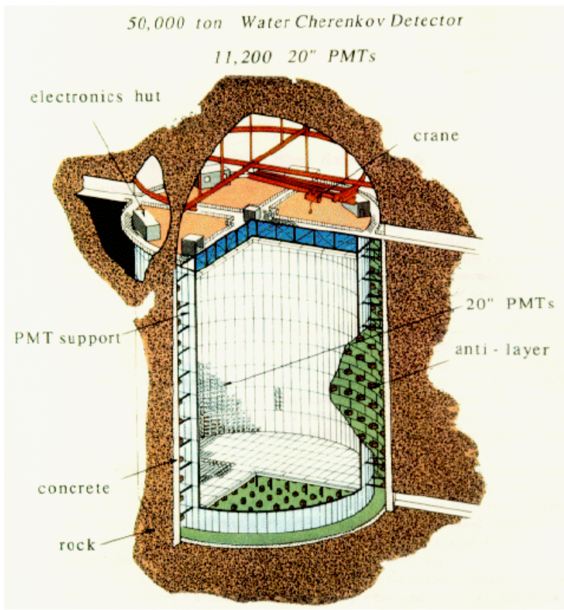


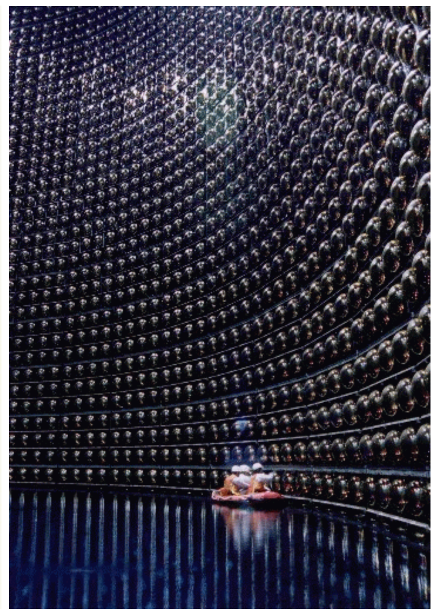
- For SUSY to do its job, some "sparticles" must be light, $m_S \ll 1$ TeV

...Supersymmetry is a "hidden" quantum dimension!

What about the strong force?

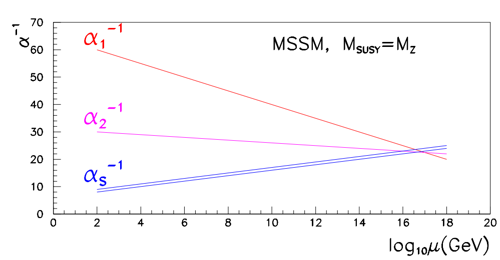
- A key prediction of theories of strong-electroweak unification is that the proton should decay into lighter particles, e.g., $p \to \pi^0 e^+$
- Unfortunately this hasn't been observed





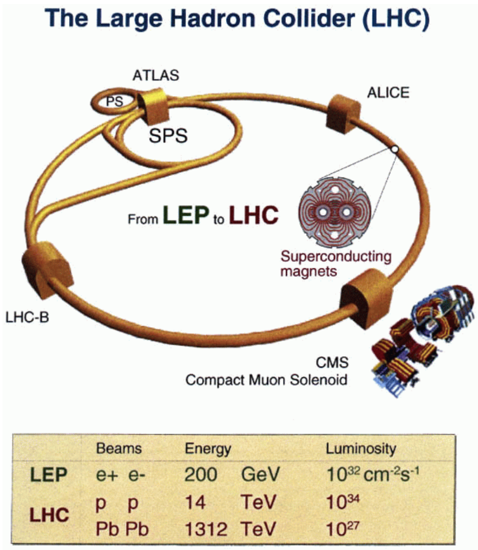
- In the Superkamoikande Detector, 50 kilotons of water has been watched for a long time
- No events observed, $\tau \gtrsim 10^{34}$ years
- This is a serious challenge to viability of strong-electroweak unified theories
- Are SUSY GUTs the answer?

  ↪ Unified couplings at *very high* mass scales

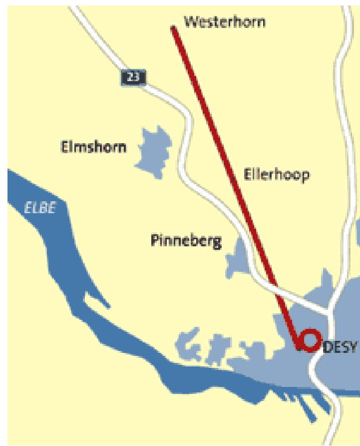


LHC and LC

These beautiful thoughts are associated with concrete next steps at accelerators



CERN LHC
~2007
14 TeV pp, 28km



Linear Collider Proposals
e.g., TESLA at DESY
500−800 GeV e^+e^-
33km length, 500x5nm beams

- Large Hadron Collider at CERN
  - ↪ A discovery machine with energy reach to a few TeV
  - ↪ But details of what is found may be difficult to unravel
  - ↪ *technical challenge:* extremely high rates
- e^+e^- Linear Colliders
  - ↪ Capable of precision studies of Higgs, SUSY
    - ⋆ Or whatever else is in nature
  - ↪ *technical challenges:* acceleration, stability

Heresy

- It is, of course, *possible*...
  - ↪ That there is no SUSY
  - ↪ That there is no Higgs
- There are, however, *very* general arguments that indicate that massive weak bosons *must* be associated with new and accessible physics
  - ↪ "TeV scale"

While theory has led the way in my lifetime, this is not an axiom of nature!

Conclusions

- Electroweak Unification
  - ↪ is a great triumph of theoretical physics
  - ↪ has driven the experimental program
- But both theoretical and experimental motivations suggest the theory is incomplete
- Tremendous opportunities on the horizon
  - ↪ TeVatron, LHC, e^+e^- linear colliders
- ***Will experimental results or theory lead in this next energy regime?***
  - ↪ ***Time will tell***