Evolving the Standard Model

Chris Quigg

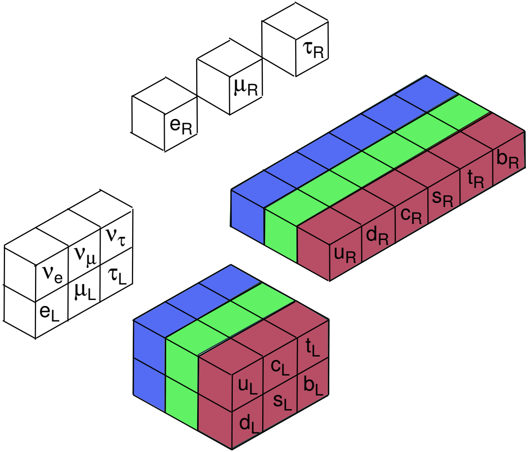
Fermilab

quigg@fnal.gov

Particle Data Group · 50 Years · Berkeley Lab · 23 September 2006

Elements of the Standard Model

Pointlike constituents ($r < 10^{-18}$ m)



Few fundamental forces: gauge symmetries $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

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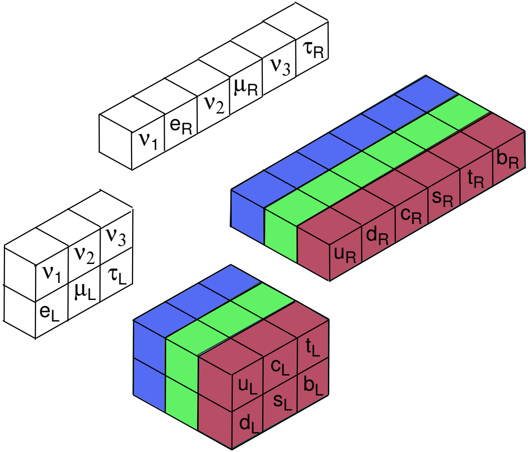
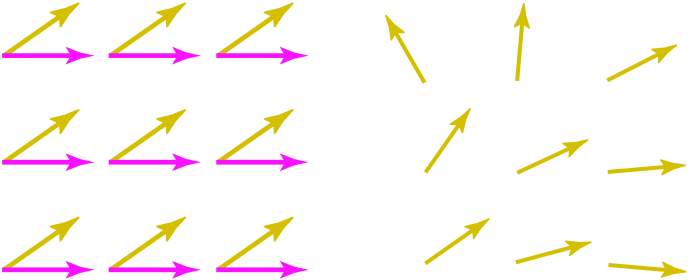


Few fundamental forces: gauge symmetries $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$.

Local gauge symmetries

Global rotation — same everywhere: $\psi \to e^{i\theta}\psi$



A different convention at each point: $\psi \to e^{i\theta(x)}\psi$

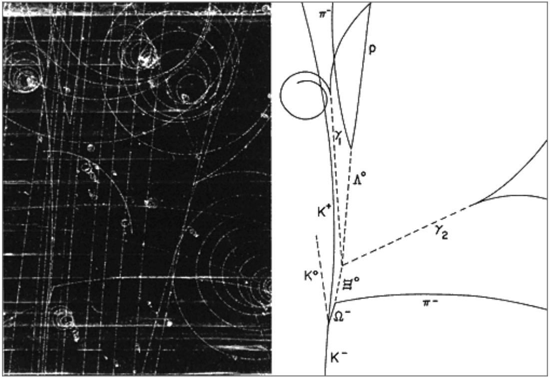
Requires interactions: U(1) $\rightsquigarrow$ QED

Yang, Mills, Shaw: isospin $\rightsquigarrow$ non-Abelian gauge theory

Hadron spectroscopy $\rightsquigarrow$ SU(3)$_{\text{flavor}}$

Gell-Mann, Ne'eman: SU(3) classification symmetry

- Mesons: **1** and **8**
- Baryons: **1** and **8** and **10**



Babar, 2006: $S_{\Omega^-} = \frac{3}{2}$

Hadron spectroscopy $\rightsquigarrow$ SU(3)$_{\text{flavor}}$ $\rightsquigarrow$ quark model

Zweig, Gell-Mann: fundamental **3** of quarks: u, d, s

- Mesons as $q\bar{q}$
- Baryons as qqq

Relations among amplitudes; selection rules (Dalitz)

Two problems and a question:

- Exquisite rareness of free quarks
- Symmetry of the spin-$\frac{3}{2}$ wavefunctions
- Origin of the $q\bar{q}$, qqq rules

Greenberg, Han, Nambu: 3 colors of each flavor

Bjorken Scaling: SLAC–MIT Experiment

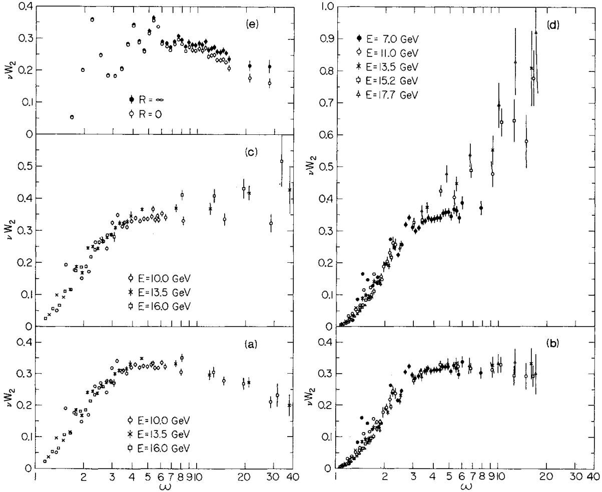


FIG. 2. νW_2 vs $\omega = 2M\nu/q^2$ is shown for various assumptions about $R = \sigma_S/\sigma_T$. (a) 6° data except for 7-GeV spectrum for $R=0$. (b) 10° data for $R=0$. (c) 6° data except for 7-GeV spectrum for $R=\infty$. (d) 10° data for $R=\infty$. (e) 6°, 7-GeV spectrum for $R=0$ and $R=\infty$.

Interpreting the Clues ...

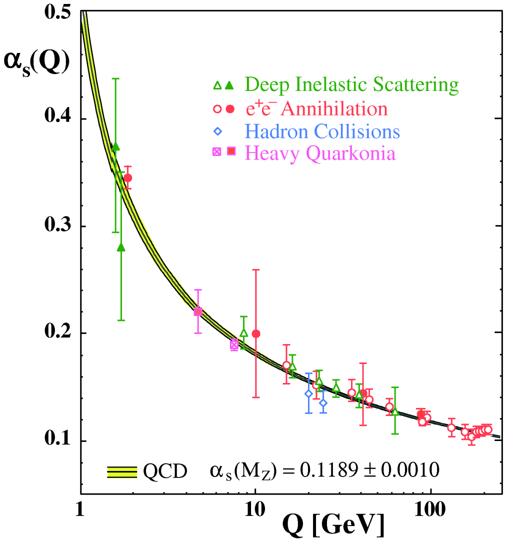
- Feynman's parton model
- Bjorken & Paschos: are partons quarks?
- Neutrino scattering: Yes!
- But ... neutral partons carry half the proton's momentum
- Quasifree but confined partons incompatible with many field theories — Gell-Mann: the "put-on model"

Growing interest in color gauge theory of strong interactions

$\boxed{\text{Asymptotic freedom} \rightsquigarrow \text{Quantum Chromodynamics}}$

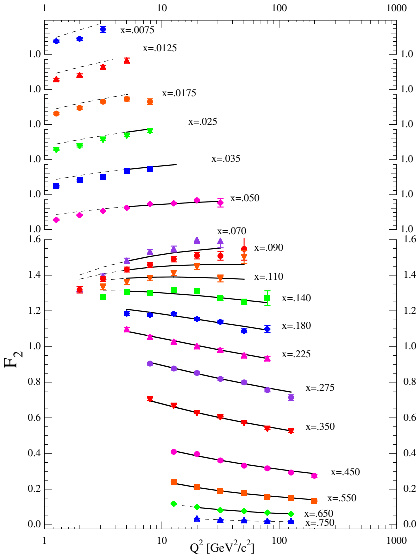
Politzer, Gross & Wilczek, 1973

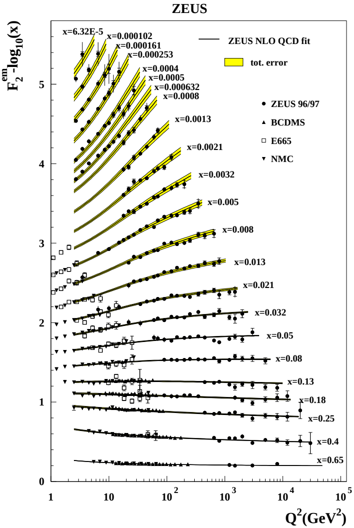
Evolution of the Strong Coupling Constant



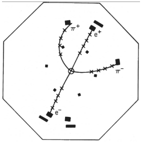
S. Bethke, hep-ex/0606035

Quantitative description of evolving structure functions . . .

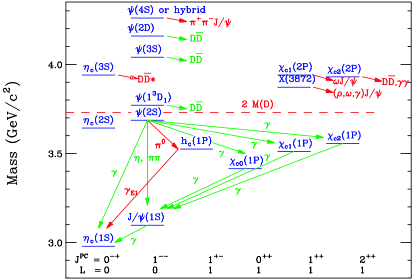


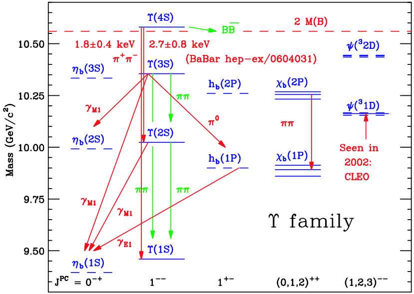


$Q\bar{Q}$ bound states as limiting case



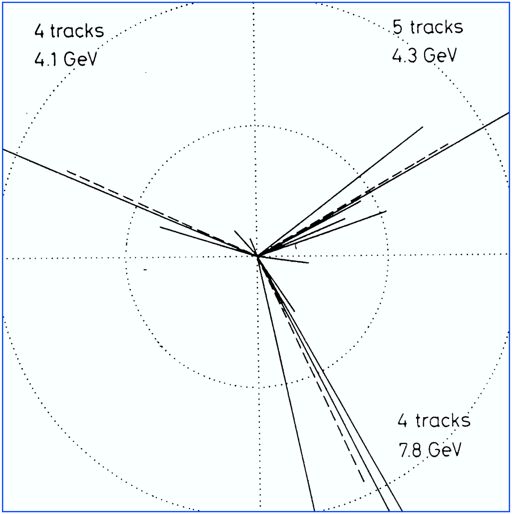
Appelquist & Politzer: nonrelativistic motion





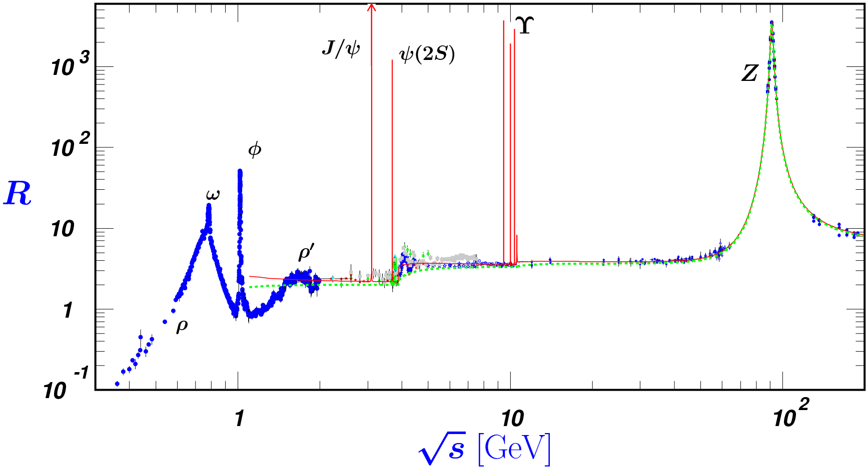
Pure one-gluon exchange as $M_Q \to \infty$, but top lifetime too short

Early three-jet event from TASSO @ PETRA



Color **8** vector gluons; carry proton's missing momentum

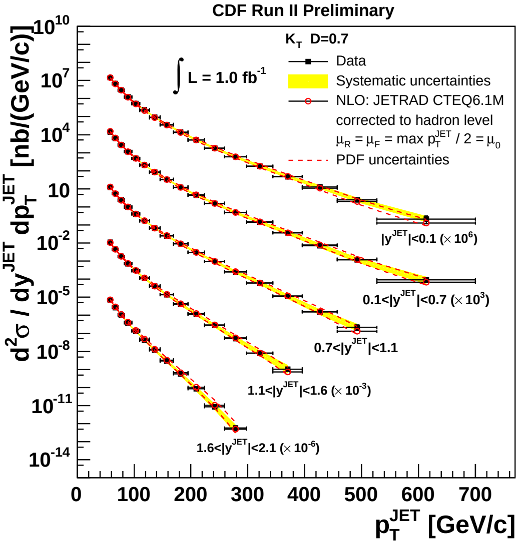
Perturbative QCD: $e^+e^- \to$ hadrons



$R \approx 3 \sum_{\text{flavors}} e_{q_i}^2$

Color **3** quarks ...

Perturbative QCD: Inclusive jet production



Gluons as partons and force particles

Nonperturbative QCD: hadron spectrum, static properties

- Current algebra: up and down quarks are light!
  $m_u = 1.7 \pm 0.3$ MeV; $m_d = 3.9 \pm 0.5$ MeV
- Proton mass is not the sum of its parts, but confinement energy: a new kind of matter!

  "Mass without mass": $M = E/c^2$

  We understand the origin of nearly all the visible mass of the Universe: QCD

- Lattice QCD becomes a quantitative tool ... and a source of insights:

  $Q\bar{Q}$ spectra, $f_{Q\bar{q}}$, light hadrons, ...

QCD Frontiers

- QCD validated to ~ 1 TeV
- Unified theories suggest that we can understand where the strong interactions become strong
- Exploring the richness of QCD in heavy-ion collisions
- Techniques for (higher-order) multiparton amplitudes
- Effective field theories, approximations, models
- Dynamical fermions on the lattice
- Strong-weak interplay (nonleptonic enhancement)
- An analytic proof of confinement?
- Derive nuclear forces?
- One dark cloud: the strong-CP problem ($G\widetilde{G}$) axions?
- . . . the irony of isospin

Currents in the electroweak synthesis

- β decay, the neutrino(s)
- The paradigm of Quantum Electrodynamics
- Fermi's theory of weak (charged-current) interactions
- Universality of the weak interactions $\rightsquigarrow$ Cabibbo
- Parity violation and the $V - A$ theory
- W-boson: analogy with photon and unitarity (high-energy behavior) of $\nu_\mu e \to \mu \nu_e$
- Positing an intermediate vector boson brings its own unitarity problems: $\mathcal{M}(\nu\bar{\nu} \to W_L^+ W_L^-) \propto s$

Symmetry of laws $\not\Rightarrow$ symmetry of outcomes

Nambu, Goldstone, . . .

Weak interactions from a symmetry?

Left-handed weak-isospin doublets,

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d_\theta \end{pmatrix}_L$$

- Schwinger (before $V - A$), Bludman, . . . , (Klein)
- $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$: Glashow
  But, gauge symmetry $\rightsquigarrow$ massless gauge bosons

Guidance from superconductivity: the Meissner effect

Ginzburg–Landau vacuum hides U(1) gauge symmetry

- *Gauge boson* γ acquires mass within superconductor

Higgs, Brout & Englert, . . .

The Electroweak Synthesis

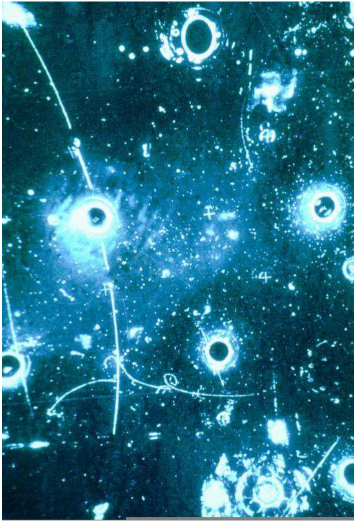
Spontaneously broken $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$: Weinberg, Salam

- Charged-current mediated by massive $W^{\pm}$-boson,
  $$M_W = \left(\pi\alpha / G_F\sqrt{2}\sin^2\theta_W\right)^{1/2}$$
  $$\propto \langle\phi\rangle_0 = (G_F\sqrt{8})^{-1/2} \approx 174\ \mathrm{GeV}$$
- Massless γ mediates electromagnetism
- Weak neutral current mediated by Z^0,
  $$M_Z^2 = M_W^2/\cos^2\theta_W$$
- Fermions can acquire mass $\langle\phi\rangle_0 \times$ Yukawa coupling
  but all fermion masses lie beyond the standard model!
- A massive neutral scalar: "Higgs boson"

Quarks + Leptons to cancel anomalies: Bouchiat, et al.

$\boxed{\text{Renormalizability: 't Hooft, \ldots}}$

Gargamelle $\bar{\nu}_\mu e \to \bar{\nu}_\mu e$ event (1973): Neutral Currents



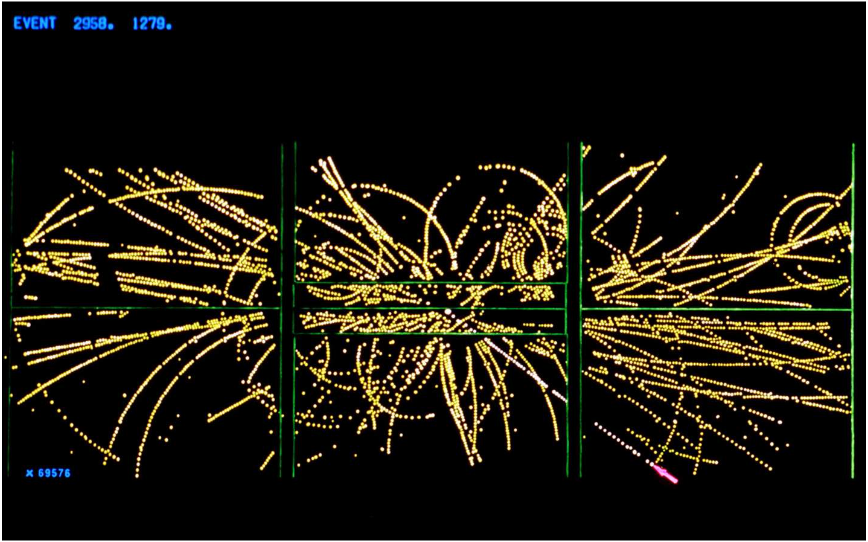
$\Rightarrow$ charm (eliminate flavor-changing neutral currents) · GIM

The Period of Splendid Confusion

Incomplete or misleading experiments
Exploratory model building

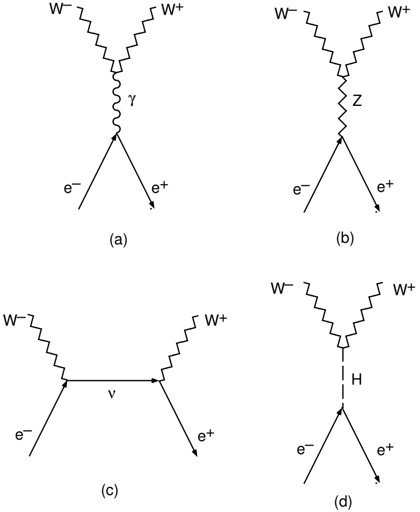
- The long wait ($1\frac{1}{2}$ years!) for charm
- Coincident τ, charm thresholds
- High-y anomaly in $\bar{\nu}N \rightarrow \mu^+ + \text{anything}$
- Atomic parity violation (conflict w/ $\mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$)
- Parity violation in inelastic $\vec{e}$d scattering
- Υ family and B mesons
- ...

Discovery of $W^{\pm}$ and Z^0



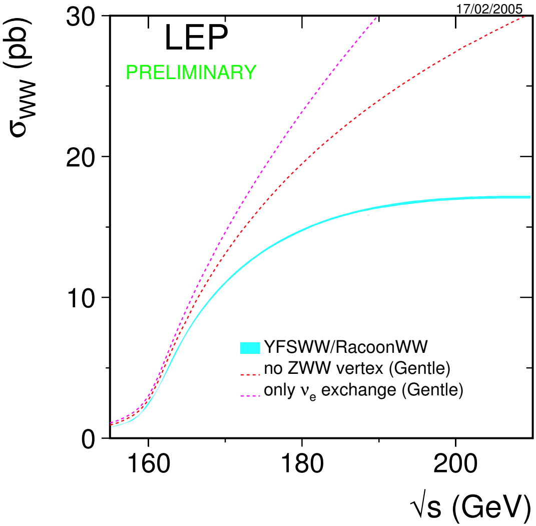
UA-1 (1983)

Gauge cancellation in $e^+e^- \to W^+W^-$



$\mathcal{M}^{(a,b,c)} \propto s$ for longitudinal gauge bosons

Gauge cancellation in $e^+e^- \to W^+W^-$



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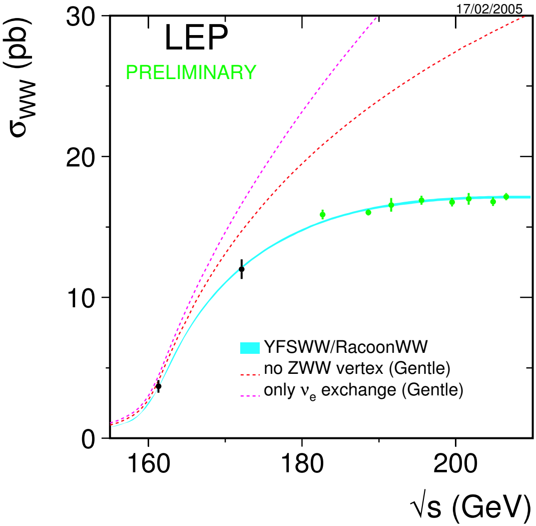
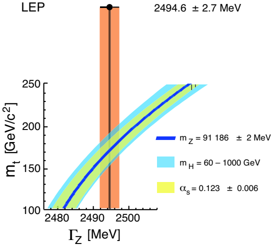


Global fits to precision EW measurements

- precision improves with time / calculations improve with time



11.94, LEPEWWG: $m_t = 178 \pm 11^{+18}_{-19}$ GeV/c^2

Direct measurements: $m_t = 171.4 \pm 2.2$ GeV/$c^2 \approx \langle\phi\rangle_0$

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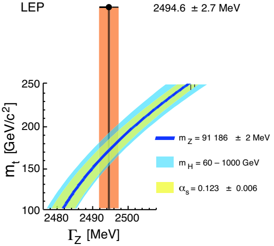

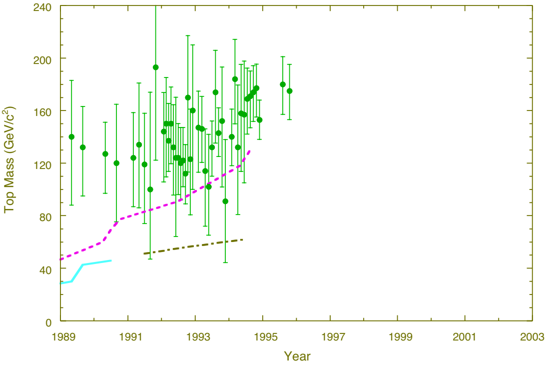

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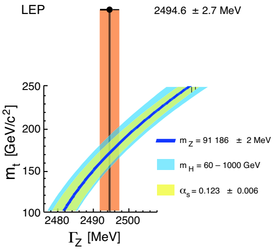

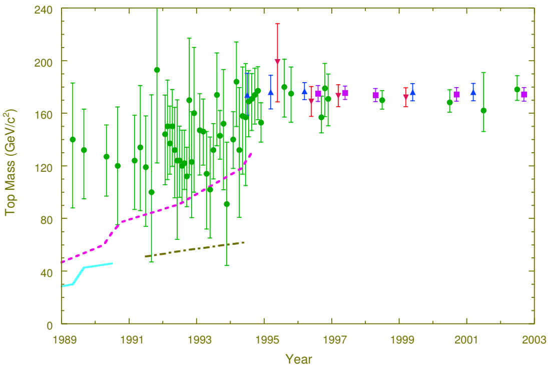

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Successful predictions of $SU(2)_L \otimes U(1)_Y$ theory:

- neutral-current interactions
- necessity of charm
- existence and properties of $W^\pm$ and Z^0

$+$ a decade of precision EW tests (one-per-mille)

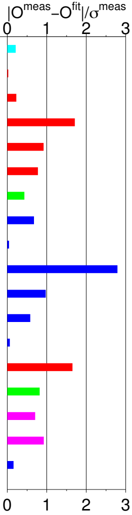
M_Z	$91\,187.6 \pm 2.1$ MeV/c^2
Γ_Z	2495.2 ± 2.3 MeV
$\sigma^0_{\text{hadronic}}$	41.541 ± 0.037 nb
Γ_{hadronic}	1744.4 ± 2.0 MeV
Γ_{leptonic}	83.984 ± 0.086 MeV
$\Gamma_{\text{invisible}}$	499.0 ± 1.5 MeV

$$\Gamma_{\text{invisible}} \equiv \Gamma_Z - \Gamma_{\text{hadronic}} - 3\Gamma_{\text{leptonic}}$$

light ν : $N_\nu = \Gamma_{\text{invisible}}/\Gamma^{\text{SM}}(Z \to \nu_i\bar{\nu}_i) = 2.994 \pm 0.012 \quad (\nu_e, \nu_\mu, \nu_\tau)$

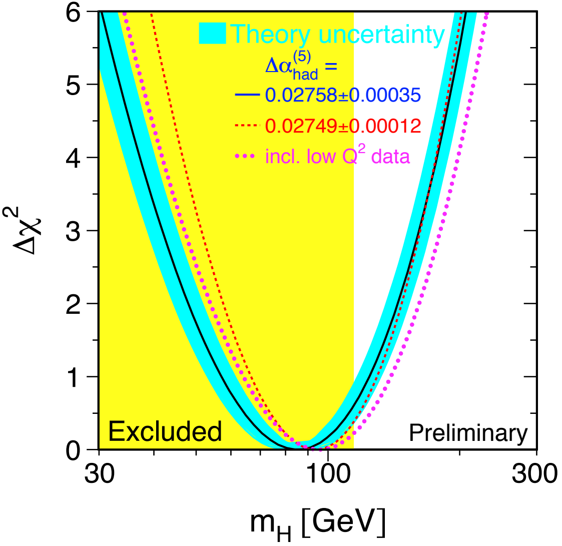
Pulls in a global fit

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1037
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



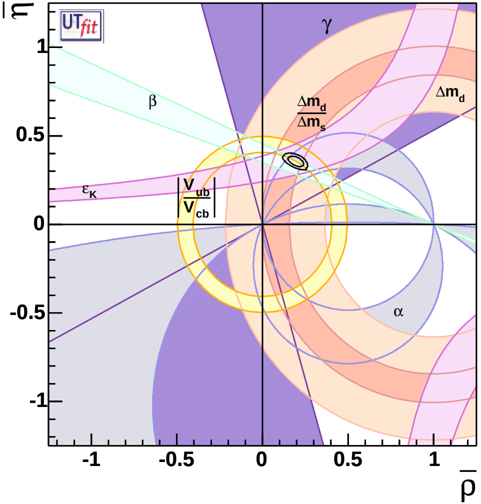
LEP Electroweak Working Group, Summer 2006

Fit to a universe of data



Standard-model $M_H \lesssim 200$ GeV at 95% CL

Constraints on quark mixing parameters



Kobayashi–Maskawa: 3 families $\rightsquigarrow$ CP violation UT Fit, hep-ex/0606167

10 years precise measurements: no significant deviations

Quantum corrections tested at $\pm 10^{-3}$

No "new physics" ... yet!

Theory tested from 10^{-17} cm to interplanetary distances

origin	Coulomb's law (tabletop experiments)
smaller	$\begin{cases} \text{Atomic physics} \rightarrow \text{QED} \\ \text{high-energy expts.} \rightarrow \text{EW theory} \end{cases}$
larger	$M_\gamma < 6 \times 10^{-17}$ eV

What is the nature of the mysterious new force that hides electroweak symmetry?

- A fundamental force of a new character, based on interactions of an elementary scalar field (Ginzburg–Landau)
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among the weak gauge bosons
- An echo of extra spacetime dimensions

We have explored examples of all four, theoretically.

$\boxed{\text{Which path has Nature taken?}}$

The importance of the 1-TeV scale

EW theory does not predict Higgs-boson mass

Thought experiment $\rightsquigarrow$ *conditional upper bound*

$W_L^+W_L^-, Z_L^0Z_L^0, HH, HZ_L^0$ satisfy s-wave unitarity, for

$$M_H \leq \left(8\pi\sqrt{2}/3G_F\right)^{1/2} = 1\ \mathrm{TeV}$$

- If the bound is respected, perturbation theory is everywhere reliable
- If the bound is violated, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

New phenomena are to be found ~ 1 TeV

With no Higgs mechanism . . .

- Quarks and leptons would remain massless
- QCD would confine the quarks in color-singlet hadrons
- *N mass little changed,* but p outweighs n
- QCD breaks EW to EM, gives $(1/2500\times\text{observed})$ masses to W, Z, so weak-isospin force doesn't confine
- Rapid! β-decay $\Rightarrow$ lightest nucleus is n; no H atom
- Some light elements in BBN (?), but ∞ Bohr radius
- No atoms (as we know them) means no chemistry, no stable composite structures like solids and liquids

. . . the character of the physical world would be profoundly changed

Electroweak frontiers

- EW theory validated at 0.1%
- Find the Higgs boson, explore its properties
- Does H generate mass for gauge bosons, fermions?
- How does H interact with itself?
- A dark cloud: the vacuum energy problem
  $\varrho_H \equiv M_H^2 v^2/8 \gtrsim 10^8\ \mathrm{GeV}^4 \quad \approx 10^{24}\ \mathrm{g\ cm}^{-3}$
  Observed vacuum energy density $\varrho_{\mathrm{vac}} \lesssim 10^{-46}\ \mathrm{GeV}^4$
  (A chronic dull headache for thirty years . . .)
- *Depending on* M_H, new physics required for EW consistency
- Hierarchy problem—stabilizing $M_H \lesssim 1$ TeV—invites new physics on 1-TeV scale

Opportunities beyond the standard model

- What makes a top quark a top quark, an electron an electron, a neutrino a neutrino?
- What is the origin of CP violation?
- Is Nature left-handed? If so, why?
- What is dark matter? How many species?
- What accounts for the accelerated expansion of the Universe?
- How does the matter-antimatter asymmetry arise?
- Why is matter so exquisitely neutral?
- Can we unify quarks & leptons, the $\mathrm{SU(3)_c} \otimes \mathrm{SU(2)_L} \otimes \mathrm{U(1)}_Y$ interactions?
- What about gravity?
- ...

Happy Birthday, Art & Matts!