A Decade of Discovery Past

- Electroweak theory validated [Z, e^+e^-, $\bar{p}p$, νN, ...]
- Higgs-boson influence observed [EW experiments]
- Neutrino oscillations: $\nu_\mu \to \nu_\tau$, $\nu_e \to \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- Discovery of top quark [$\bar{p}p$]
- Direct CP violation in $K \to \pi\pi$ decay [fixed-target]
- B-meson decays violate CP [$e^+e^- \to B\bar{B}$]
- Flat U, mostly dark matter & energy [SN Ia, CMB, LSS]
- Detection of ν_τ interactions [fixed-target]
- Constituents structureless at TeV scale [mainly colliders]

Electroweak theory consequences

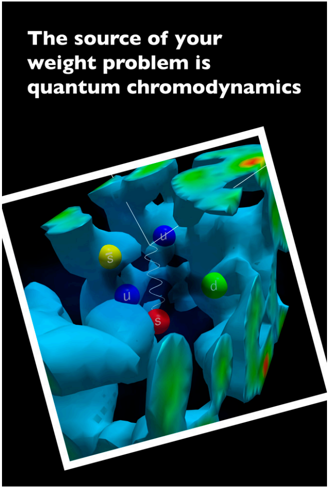
- Weak neutral currents
- Need for charmed quark
- Existence and properties of $W^{\pm}$, Z^{0}
- No flavor-changing neutral currents at tree level
- No right-handed charged currents
- CKM Universality
- KM phase dominant source of CP violation
- Existence and properties of Higgs boson
- Higgs interactions determine fermion masses, *but* . . .
- (Massless neutrinos: no neutrino mixing)

SM shortcomings

- No explanation of Higgs potential
- No prediction for M_H
- Doesn't predict fermion masses & mixings
- M_H unstable to quantum corrections
- No explanation of charge quantization
- Doesn't account for three generations
- Vacuum energy problem
- Beyond scope: dark matter, matter asymmetry, etc.

$\rightsquigarrow$ imagine more complete, predictive extensions

QCD accounts for (most) visible mass in Universe



(*not* the Higgs boson)

What about atoms?

Suppose some light elements produced in BBN survive

Massless $e \Longrightarrow \infty$ Bohr radius

No meaningful atoms

No valence bonding

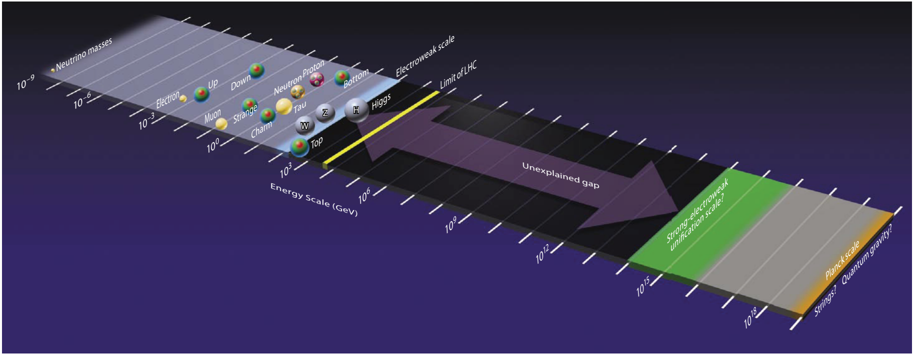
No integrity of matter, no stable structures

Electroweak Questions for the LHC. I

- What hides electroweak symmetry: a Higgs boson, or new strong dynamics?
- If a Higgs boson: one or several?
- Elementary or composite?
- Is the Higgs boson indeed light, as anticipated by the global fits to EW precision measurements?
- Does H only give masses to $W^{\pm}$ and Z^0, or also to fermions? (Infer $t\bar{t}H$ from production)
- Are the branching fractions for $f\bar{f}$ decays in accord with the standard model?

If all this: what sets the fermion masses and mixings?

The Hierarchy Problem



How to keep the distant scales from mixing in the face of quantum corrections? *OR*

How to stabilize the mass of the Higgs boson on the electroweak scale? *OR*

Why is the electroweak scale small?

Lecture 4: Beyond the Standard Model
More physics on the TeV scale?

Partial-wave unitarity analysis of WW scattering argues for new physics on the TeV scale.
In SM: a Higgs boson or strongly interacting gauge sector
In general, something new on the TeV scale

At the level of suggestion, rather than theorem ...

- The hierarchy problem: if light H, new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses 0.1–1 TeV

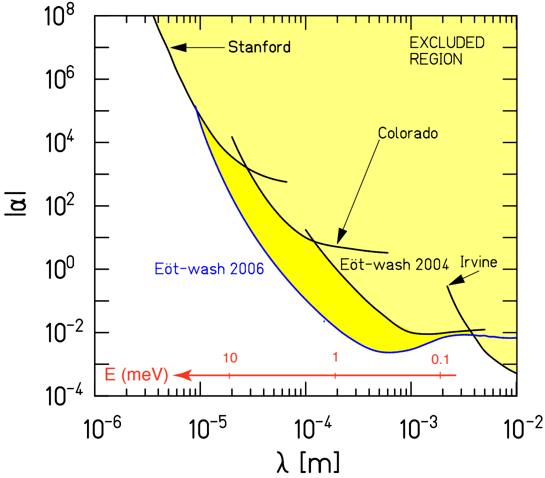
Beyond the Standard Model
More physics on the TeV scale?

At the level of *Why not?* ...

- alternatives to the Higgs mechanism
- quark and lepton compositeness (contact interactions)
- new quarks and leptons
- new forms of matter
- new phenomena in flavor physics

Gravity follows $1/r^2$ law to $\lesssim 1$ mm (few meV)

$$V(r) = -\int dr_1 \int dr_2 \frac{G_N \rho(r_1)\rho(r_2)}{r_{12}} \left[1 + \varepsilon_G \exp(-r_{12}/\lambda_G)\right]$$



Supersymmetry

- A fermion-boson symmetry that arises from new *fermionic* dimensions
- Most general symmetry of S-matrix: SUSY + Poincaré invariance + internal symmetries
- Relates fermion to boson degrees of freedom: roughly, each particle has a superpartner with spin offset by $\frac{1}{2}$
- SUSY relates interactions of particles, superpartners
- Known particle spectrum contains no superpartners $\Rightarrow$ SUSY doubles the spectrum
- SUSY invariance or anomaly cancellation requires two Higgs doublets to give masses to $I_3 = \pm\frac{1}{2}$ particles

Why Supersymmetry?

- Closely approximates the standard model
- Maximal (unique) extension of Poincaré invariance
- Path to gravity: local supersymmetry $\longrightarrow$ supergravity
- Solution to naturalness problem: allows fundamental scalar at low E
- (+ unification) $\sin^2\theta_W$, coupling constant unification
- (+ universality) Can generate SSB potential
- (+R-parity) LSP as dark matter candidate

SUSY Challenges . . .

- Extra dynamics needed to break SUSY
  "Soft" SUSY breaking $\Longrightarrow$
  MSSM with $\boxed{124}$ parameters

  Contending schemes for SUSY breaking:
  - *Gravity mediation.* SUSY breaking at a very high scale, communicated to standard model by supergravity interactions
  - *Gauge mediation.* SUSY breaking nearby ($\lesssim$ 100 TeV), communicated to standard model by (nonperturbative ?) gauge forces.
  - . . .

  None meets all challenges

...SUSY Challenges

- Weak-scale SUSY protects M_H, but does not explain the weak scale ("μ problem")
- Global SUSY must deal with the threat of FCNC
- (Like SM) Clear predictions for gauge-boson masses, not so clear for squarks and sleptons
- So far, SUSY is well hidden Contortions for $M_H \gtrsim 115$ GeV
- (SUSY didn't relate particles & forces, but doubled spectrum)
- Baryon- and lepton-number violating interactions arise naturally, are abolished by decree

. . . SUSY Challenges

- SUSY introduces new sources of CP violation that are potentially too large.
- We haven't found a convincing and viable picture of the TeV superworld.

This long list of challenges doesn't mean that Supersymmetry is wrong, or even irrelevant to the 1-TeV scale.

But SUSY is not automatically right, either!

If SUSY does operate on the 1-TeV scale, then Nature must have found solutions to all these challenges . . .
. . . and we will need to find them, too.

Electroweak Questions for the LHC. II

- New physics in pattern of Higgs-boson decays?
- Will (unexpected or rare) decays of H reveal new kinds of matter?
- What would discovery of > 1 Higgs boson imply?
- What stabilizes M_H below 1 TeV
- How can a light H coexist with absence of new phenomena?
- Is EWSB emergent, connected with strong dynamics?
- Is EWSB related to gravity through extra spacetime dimensions?
- If new strong dynamics, how can we diagnose? What takes place of H?

In a decade or two, we can hope to …

Understand electroweak symmetry breaking
Observe the Higgs boson
Measure neutrino masses and mixings
Establish neutrinos = antineutrinos
Thoroughly explore CP violation in B decays
Exploit rare decays (K, D, …)
Observe neutron's EDM, pursue electron's
Use top quark as a tool
Observe new phases of matter
Understand hadron structure quantitatively
Uncover the full implications of QCD
Observe proton decay
Understand the baryon excess
Catalogue matter and energy of the universe
Measure dark energy equation of state
Search for new macroscopic forces
Determine the unifying symmetry

Detect neutrinos from the universe
Learn how to quantize gravity
Learn why empty space is nearly massless
Test the inflation hypothesis
Understand discrete symmetry violation
Resolve the hierarchy problem
Discover new gauge forces
Directly detect dark-matter particles
Explore extra spatial dimensions
Understand the origin of large-scale structure
Observe gravitational radiation
Solve the strong CP problem
Learn whether supersymmetry is TeV-scale
Seek TeV-scale dynamical symmetry breaking
Search for new strong dynamics
Explain the highest-energy cosmic rays
Formulate the problem of identity

… learn the right questions to ask ...

… and rewrite the textbooks!