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 . . .

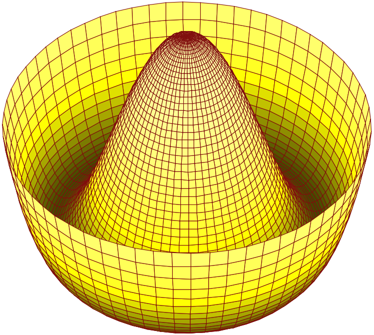
- The hierarchy problem: if light *H*, new physics implicated on the TeV scale
- WIMPs as dark matter: reproduce relic density for masses 0.1–1 TeV

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

What Hides the Electroweak Symmetry?



A force of a new character, based on an elementary scalar

New gauge force, perhaps acting on new constituents

Strong dynamics among electroweak bosons

An echo of extra spacetime dimensions?

Parameters of the Standard Model

3 coupling parameters: α_s, α_{EM}, $\sin^2\theta_{\mathrm{W}}$

2 parameters of the Higgs potential

1 vacuum phase of QCD

6 quark masses

3 quark mixing angles

1 CP-violating phase

3 charged-lepton masses

3 neutrino masses

3 leptonic mixing angles

1 leptonic CP-violating phase (+ Majorana)

$\geq$ 26 arbitrary parameters

Flavor physics . . .

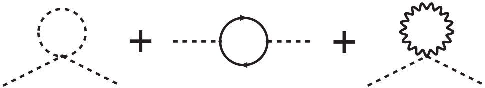
may be where we see, or diagnose, the break in the SM

Some opportunities (see Buras, Flavour Theory: 2009)

- CKM matrix from tree-level decays (LHC*b*)
- $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$
- $D^0 - \bar{D}^0$ mixing; CP violation
- FCNC in top decay: $t \to (c, u)\ell^+\ell^-$, etc.
- Correlate virtual effects with direct detection of new particles to test identification
- Tevatron experiments demonstrate capacity for very precise measurements: e.g., B_s mixing.

The Hierarchy Problem

Evolution of the Higgs-boson mass

$M_H^2(p^2) = M_H^2(\Lambda^2) +$ 

quantum corrections from particles with $J = 0, \frac{1}{2}, 1$

Potential divergences:

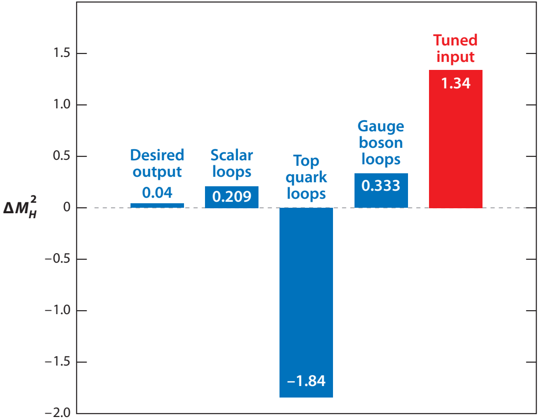
$$M_H^2(p^2) = M_H^2(\Lambda^2) + \mathcal{C}g^2 \int_{p^2}^{\Lambda^2} dk^2 + \cdots \ ,$$

Λ: naturally large, $\sim M_{\text{Planck}}$ or $\sim U \approx 10^{15-16}$ GeV

How to control quantum corrections?

A Delicate Balance . . . even for $\Lambda = 5$ TeV

$$\delta M_H^2 = \frac{G_F \Lambda^2}{4\pi^2\sqrt{2}}(6M_W^2 + 3M_Z^2 + M_H^2 - 12m_t^2)$$



Light Higgs + no new physics: LEP Paradox

The Hierarchy Problem
Possible paths

- Fine tuning
- A new symmetry (supersymmetry)
  fermion, boson loops contribute with opposite sign
- Composite "Higgs boson" (technicolor . . .)
  form factor damps integrand
- Little Higgs models, etc.
- Low-scale gravity (shortens range of integration)

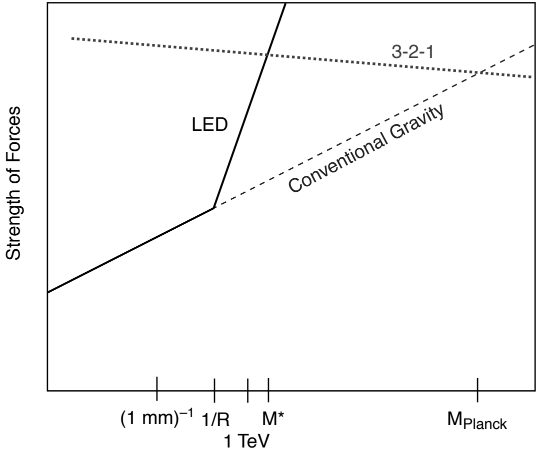
All but first require new physics near the TeV scale

Gravity at a Low Scale

At scale R ... gravity propagates in $4 + n$ dimensions

$$1/r^2 \rightsquigarrow 1/r^{2+n}$$

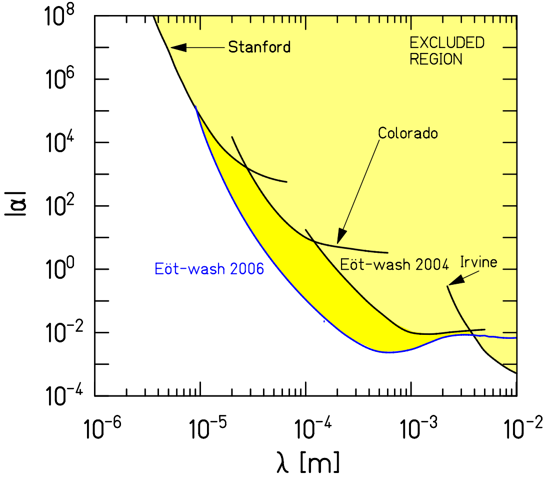
Gauss law: $G_{\mathrm{N}} \sim M^{*-n-2} R^n$ $\qquad$ M^*: gravity's true scale



M_{Planck} would be a mirage!

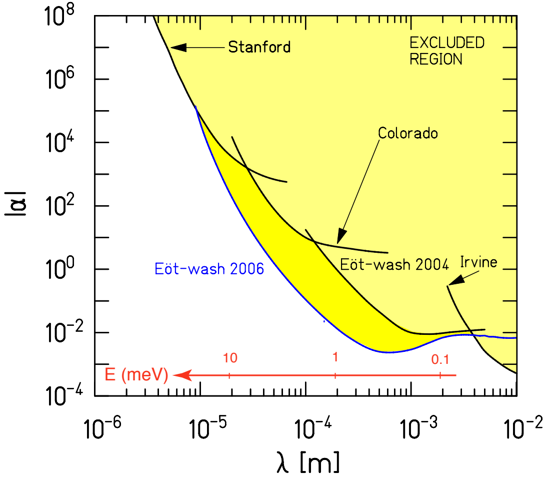
Gravity follows $1/r^2$ law to $\lesssim 1$ mm

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



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

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



Some Recent Inventions

- In Little Higgs models, Higgs mass instability is canceled by particles of the same spin: e.g. spin-1/2 “heavy top”
  temporary solution, up to perhaps 10 TeV
- If a gauge (vector) field lives in this 5D space, it appears to a 4D observer as 2 fields: spin-1 and spin-0
- “Higgsless” models: 5D incarnations of 4D supersymmetry

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

Yukawa terms consistent with SUSY induce dangerous lepton- and baryon-number violations:

$$\lambda_{ijk} L^i L^j E^k + \lambda'_{ijk} L^i Q^j \bar{D}^k + \lambda'' \bar{U}^i \bar{D}^j \bar{D}^k$$

45 free parameters . . . Transitions like

$$\mathcal{L}_{LLE} = \lambda_{ijk}\, \tilde{\nu}_L^i e_L^i \bar{e}_R^k + \dots$$

To banish these, impose symmetry under R-parity:

$$R = (-1)^{3B+L+S}$$

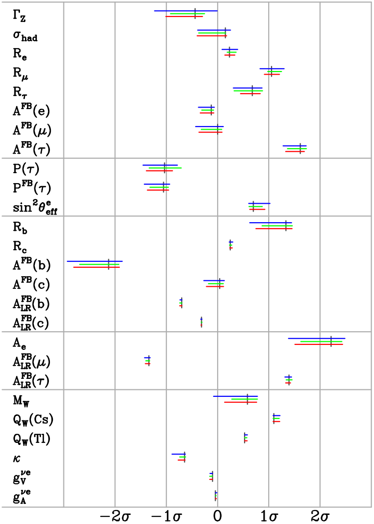
. . . even for particles, odd for superpartners.

Superpartners produced in pairs

Lightest superpartner is stable

Five physical Higgs bosons:
CP even h^0, H^0; CP odd A^0; $H^\pm$

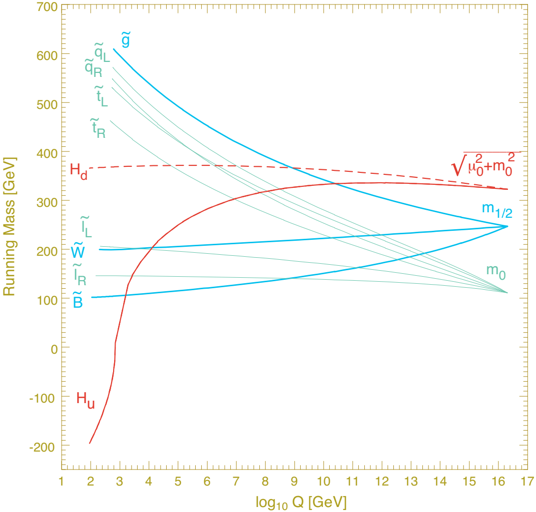
MSSM closely resembles standard EW theory



Erler & Pierce: SUSY *vs.* SM, hep-ph/9801238 — Cho & Hagiwara, hep-ph/9912260

| SM — SUGRA — $5 \oplus 5^\star$ GMSB — $10 \oplus 10^\star$ GMSB

For heavy top, SSB may follow naturally in SUSY



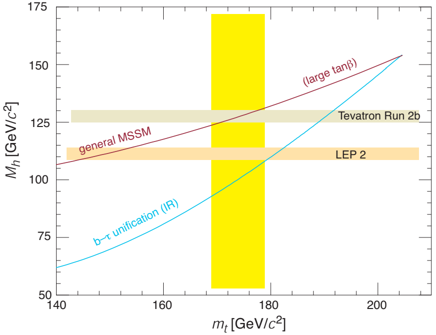
...(sign of M^2 indicated)

Kane, *et al.* (hep-ph/9312272, *Phys. Rev. D***49**, 6173 (1994))

Upper bounds on M_h in the MSSM

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \cdots\right] \lesssim (130\ \mathrm{GeV}/c^2)^2$$

Upper bound on $M_h \Leftrightarrow$ large M_A limit, ($M_s = 1$ TeV)



Carena, *et al.*, *Phys. Lett.* **B355**, 209 (1995)

If nonminimal SUSY Higgs couplings are perturbative up to M_U,

$$M_h \lesssim 150\ \mathrm{GeV}$$

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.

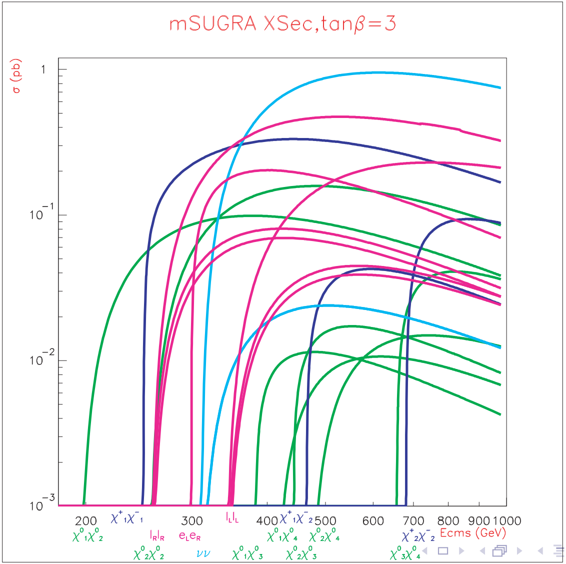
But SUSY is not automatically right, either!

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.

If weak-scale SUSY is present, we should see it soon in the Higgs sector and beyond, . . . and we will live in "interesting times"

Example SUSY thresholds in e^+e^-



Grahame Blair

My view

Supersymmetry is (almost) certain to be true . . . . . . as a path to the incorporation of gravity

Whether SUSY resolves the problems of the 1-TeV scale is a logically separate question . . . answer less obvious

Experiment will decide

A look at technicolor: "QCD path" to EWSB

massless u, d quarks	$\longrightarrow$	new fermions "technifermions"
QCD color	$\longrightarrow$	new interaction "technicolor"

Choose scale of interaction so that

$$f_\pi \longrightarrow F_\pi = v = (G_F\sqrt{2})^{-\frac{1}{2}}$$

Generates correct M_W, M_Z, *but* produces no Yukawa couplings, so no fermion masses

Shows possibility that gauge-boson masses & fermion masses . . . have *different* origins

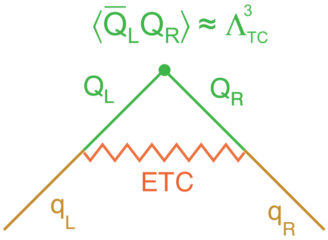
To generate fermion mass, embed technicolor in a larger extended technicolor gauge group

$$G_{\text{ETC}} \supset G_{\text{TC}}$$

that couples quarks and leptons to technifermions

$$\text{If} \quad G_{\text{ETC}} \to G_{\text{TC}} \quad \text{at scale } \Lambda_{\text{ETC}},$$

then quarks and leptons may acquire masses $m \sim \Lambda_{\text{TC}}^3/\Lambda_{\text{ETC}}^2$



"radiative" mechanism

Standard ETC is challenged by problems of reproducing wide range of quark masses while avoiding FCNC traps

Consider $|\Delta S| = 2$ interactions

$$\mathcal{L}_{|\Delta S|=2} = \frac{g_{\mathrm{ETC}}^2 \theta_{sd}^2}{M_{\mathrm{ETC}}^2} (\bar{s}\Gamma^\mu d)(\bar{s}\Gamma'_\mu d) + \cdots$$

$$\Delta M_K < 3.5 \times 10^{-12}\ \mathrm{MeV} \quad \Longrightarrow \quad \boxed{\frac{M_{\mathrm{ETC}}^2}{g_{\mathrm{ETC}}^2 \left|\theta_{sd}\right|^2}\ \text{very large}}$$

$\Longrightarrow$ hard to generate heavy enough c, s, t, b

Multiscale TC (Eichten & Lane)

Many fermions (in different TC reps)
$\Longrightarrow$ many technipions
light ρ_{T}, ω_{T}, π_{T}

Generation of fermion mass is where all the *experimental threats* to Technicolor arise:

- Flavor-changing neutral currents
- Matter content (S parameter)

Lesson: QCD is not a good model for TC

Keep in mind: *In addressing problems of fermion mass, ETC is much more ambitious than global supersymmetry*

Overview: K. Lane, hep-ph/0202255

Review: Hill & Simmons, hep-ph/0203079

Recent developments: Sannino, arXiv:0911.0931

Lattice developments: Lucini, arXiv:09110020

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!