Physics Beyond the Standard Model of Particle Physics

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Cosmo '04
Thought of

NOT YET

Majoron

axion

familon

string

weak

weak

3HD

unbroken

supersymmetry

3rd

supersymmetry

discovery

LHC

SM

discovery
Physics Beyond the Standard Model of Particle Physics

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My Models of Physics Beyond the Standard Model of Particle Physics

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Physics Beyond the SM

- Defined by what it is not:
  - anything that doesn’t belong the SM is “beyond the SM”
  - “unknown unknowns”

- 1984-1998, no real data challenged the SM
- strong focus on “theoretical issues”, mostly naturalness
Examples

- Why $G_F \gg G_N$?
- Why is universe superconducting?
- Why $|Q_e + 2Q_u + Q_d| \ll 10^{-20}$?
- Why is the universe so big, smooth, and flat?
- Why $|\theta_{QCD}| < 10^{-10}$?
- Why $m_e \ll m_t$?
- How do we quantize gravity?

supersymmetry, technicolor, extra dimensions, grand unification, inflation, axion, flavor symmetry, string theory
Time has changed

Now there are “known unknowns”

- Neutrino oscillation
- Dark Matter
- Dark Energy
- Scale-invariant density fluctuation

We have to at least address these!
Outline

- **Ultra-conservative**
  - No lavish new spending (i.e., particles);
  - absolute minimum expense
  - ⇒ “New Minimal Standard Model”

- **Liberal/Moderate**
  - At least make hierarchy stable
  - ⇒ supersymmetry

- **Super-liberal**
  - Every physics within experimental reach
  - ⇒ Low-scale quantum gravity

- **Election**
Ultra-Conservative
Absolute minimum

- Dark Matter
- Dark Energy
- Neutrino Mass
- Inflation
- Baryon asymmetry

⇒ Repeat what the Standard Model did: write a most general renormalizable theory with the minimum particle content that accommodates all physics we know
⇒ “New Minimal Standard Model”
(Davoudiasl, Kitano, Li, HM)
Non-baryonic Dark Matter

- Clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field $S$: \textbf{dof=1}
- assign odd $Z_2$ parity to $S$, everything else even
- Most general renormalizable coupling

$$L_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2} |H|^2 S^2 - \frac{h}{4!} S^4.$$
Dark Energy & Inflation

- Dark Energy is just a cosmological constant: $\text{dof}=0$
  \[ L_\Lambda = (2.3 \times 10^{-3} \text{ eV})^4 \]

- Nearly scale-invariant Gaussian fluctuation strongly suggests inflation

- Pick your favorite one-field model, e.g., chaotic inflation: $\text{dof}=1$
  \[ L_\varphi = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!} \varphi^3 - \frac{\kappa}{4!} \varphi^4. \]
Neutrino Mass

Need at least two right-handed neutrinos:
\[ \text{dof}=4 \]
Either Majorana or Dirac possible
However, once adopted inflation (even with \( N>10 \) required by structure formation), any initial baryon asymmetry gets wiped out
Baryogenesis mandatory
Leptogenesis by the decay of a heavy Majorana right-handed neutrino a natural choice w/o extra dof

\[ L_N = \tilde{N}_\alpha i \not{\partial} N_\alpha - \left( \frac{M_\alpha}{2} N_\alpha N_\alpha + h^\alpha_i N_\alpha L_i \tilde{H} + c.c. \right). \]
Consistency check (I)

- **Successful chaotic inflation:**
  \[ L_\varphi = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!} \varphi^3 - \frac{\kappa}{4!} \varphi^4. \]
  \[ \Rightarrow \text{m} \sim 10^{13} \text{ GeV, } \mu \leq 10^6 \text{ GeV, } \kappa \leq 10^{-14} \]

- **Reheating**
  \[ L_{RH} = -\mu_1 |H|^2 - \mu_2 \varphi S^2 - \kappa_H \varphi^2 |H|^2 - \kappa_S \varphi^2 S^2 - (y_N^{\alpha \beta} \varphi N_\alpha N_\beta + c.c.). \]
  \[ \Rightarrow \text{Can reheat the universe to } T_{RH} > 10^{10} \text{ GeV } \]
  enough for leptogenesis if \( y > 10^{-4} \)
  \[ \Rightarrow \text{couplings small enough to maintain flatness of the potential } \kappa \sim y^4/(4\pi)^2 \leq 10^{-14} \]
Consistency check (II)

- correct Dark Matter abundance
- evades direct detection limits
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data
The Minimal Model of particles & universe

\[ L_\Lambda = (2.3 \times 10^{-3} \text{ eV})^4 \quad \text{dof=0} \]

\[ L_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2} |H|^2 S^2 - \frac{h}{4!} S^4. \quad \text{dof=1} \]

\[ L_\varphi = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!} \varphi^3 - \frac{\kappa}{4!} \varphi^4. \quad \text{dof=1} \]

\[ L_N = \bar{N}_\alpha i \not\partial N_\alpha - \left( \frac{M_\alpha}{2} N_\alpha N_\alpha + h^{\alpha i}_\nu N_\alpha L_i \tilde{H} + c.c. \right). \quad \text{dof=4} \]

\[ L_{RH} = -\mu_1 \varphi |H|^2 - \mu_2 \varphi S^2 - \kappa_H \varphi^2 |H|^2 - \kappa_S \varphi^2 S^2 - (y^\alpha_\beta N_\alpha N_\beta + c.c.). \]

\[ L_{NMSM} = L_{MSM} + L_S + L_\Lambda + L_N + L_\varphi + L_{RH} \]

Explain all known established data
Naturalness Issues

- The hierarchy $G_F \gg G_N$ not stable against radiative corrections: need fine-tuning order by order in perturbation theory.
- The flatness and small couplings in the inflaton potential put in by hand.
- No explanation why $S$ is around TeV.
- Terrible fine-tuning in the cosmological constant.

$\Rightarrow$ Could be solved by string landscape? anthropic principle?
Baseline

- Nonetheless, NMSM provides the baseline
- Summarizes the current state of knowledge about particles and universe
- Anything beyond the NMSM should be considered yet another discovery
Liberal/Moderate
Once upon a time, there was a hierarchy problem...

At the end of 19th century: a “crisis” about electron

Like charges repel: hard to keep electric charge in a small pack

Electron is point-like

At least smaller than \(10^{-17}\) cm

Need a lot of energy to keep it small!

\[
\Delta m_e c^2 \sim \frac{\alpha}{r_e} \sim \text{GeV} \frac{10^{-17} \text{cm}}{r_e}
\]

Correction \(\Delta m_e c^2 > m_e c^2\) for \(r_e < 10^{-13}\) cm

Breakdown of theory of electromagnetism

\(\Rightarrow\) Can’t discuss physics below \(10^{-13}\) cm
Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble
  ⇒ only 10% of mass
  even for Planck-size

\[
\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(m_e r_e)
\]
History repeats itself?

- Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force

Double #particles again ⇒ superpartners

“Vacuum bubbles” of superpartners cancel
the energy required to contain Higgs boson in itself

\[
\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)
\]
Good

- Even with Planck-scale cutoff, supersymmetry protects the hierarchy
- Dark Matter is quite natural in supersymmetry, once “R-parity” is imposed to avoid too rapid proton decay
  - Typically neutralino=photino+zino+higgsino
  - but could be gravitino etc
- makes gauge coupling constants unify \(\Rightarrow\) GUT
- string theorists like it
Bad

- Tends to give excessive flavor-changing and/or CP-violating effects
- gravitino decays late and screw up Big-Bang Nucleosynthesis

\[ \sigma \sim \frac{1}{M_{\text{Pl}}^2}, \]
\[ Y_{3/2} \sim \sigma T^3 / (T^2 / M_{\text{Pl}}) \sim T / M_{\text{Pl}} \]
Two solutions

- Make gravitino heavy possible in anomaly-mediated SUSY breaking because
  \[ m_{\text{SUSY}} \sim m_{3/2} \times g^2/(4\pi)^2 \]
  (Randall, Sundrum; Giudice, Luty, HM, Rattazzi)

- solves the flavor-changing problem with consistent EWSB (Kitano, Kribs, HM; Ibe, Kitano, HM)

Kawasaki, Kohri, Moroi
Two solutions

- Condensate of right-handed Sneutrino
- enough asymmetry for $T_{RH} > 10^6 \text{GeV}$ (HM, Yanagida + Hamaguchi)
- acts as a curvaton (Moroi, HM)
- May even be a chaotic inflaton (HM, Suzuki, Yanagida, Yokoyama)
Super-liberal
Ultimate energy scale quantum gravity @ TeV

Dream case for particle physics
The “end of physics” within experimental reach
Possible with “large” extra dimensions
Production of blackhole and string excitations at the LHC
Measure #dim at ILC
Great return with high risk

- The ultimate cutoff scale $\Lambda \sim 1-100$ TeV
- proton decay with $\Gamma \sim m_p^5/\Lambda^3 \leq 10^{-10}$ sec
- neutrino mass $m_\nu \geq \nu^2/\Lambda > \text{GeV}$
- Need to somehow protect baryon and lepton numbers
- But global symmetries broken by quantum gravity
- Need new gauge symmetries (continuous or discrete)
Gauged Discrete Symmetry

- Unique choice within the minimal particle content (Davoudial, Kitano, Kribs, HM)
- $Z_3$ lepton $\otimes Z_9$ baryon
- Neutrino mass requires $Z_3$ lepton broken
- Network of low-scale domain wall (keV-MeV)
- If network frustrated, domain wall can make dark energy with $w=-2/3$ (Friedland, HM, Perelstein)
- Not excluded yet (Conversi, Melchiorri, Mersini, Silk)
Election
We need data!

Of course, we don’t decide by a popular vote (nor by electorates), but rather by experimental data.

The experimental program is quite clear.
EWSB and Hierarchy Problem

Large Hadron Collider (LHC)

International Linear Collider (ILC)
Particle Dark Matter

- WIMP (Weakly Interacting Massive Particle) strongly favored
- Stable heavy particle produced in early Universe, left-over from near-complete annihilation

\[ \Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{\text{ann}}M_{\text{Pl}}^3} \frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2}{(\text{TeV})^2} \frac{\sigma_{\text{ann}}}{\sigma_{\text{ann}}} \]

- TeV the correct energy scale
- We hope to produce DM directly at colliders
Concordance model of Dark Matter?

- cosmological measurement of dark matter
  - ⇒ abundance \( \propto (\text{annihilation cross section})^{-1} \)
- detection experiments
  - ⇒ scattering cross section
- production at colliders
  - ⇒ mass, couplings
  - ⇒ can calculate cross sections
- Will know what Dark Matter is
- Will understand universe back to \( t \sim 10^{-10} \text{sec} \)
  just like BBN!
Plausibility Test of Leptogenesis

- CP-violation may be observed in neutrino oscillation

- Plans to shoot neutrino beams over thousands of kilometers to see this
Dark Energy

- Precision measurements of $w$, $w'$
- more thoughts
Conclusion

Many possibilities of physics beyond the SM
Don’t know who will win
One thing is clear:
It’ll be fun!