The Standard Model and Beyond

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I. Introduction

The Standard Model

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry and classical gravity
- Three families of SM fermions
- One Higgs doublet

The SM explains existing experimental data very well, including electroweak precision tests.

$$
\begin{aligned}
\mathcal{L}_{MSM} = &-\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
&-\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
&+|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
&+\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
&-\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) \ ,
\end{aligned}
$$

where $\tilde{H} = i\sigma_2 H^*$.

$\langle H^0 \rangle = \frac{v}{\sqrt{2}}$

Convincing evidence for physics beyond the SM

- Non-Baryonic Dark Matter
- Dark Energy
- Neutrino Masses and Mixinges
- Baryon Asymmetry
- Inflation

The SM is incomplete!

Major Problems in the SM

- Fine-tuning Problems

- Aesthetic Problems

Fine-tuning Problems:

- Cosmological constant problem: $\Lambda_{\mathrm{CC}} \sim 10^{-122} M_{\mathrm{Pl}}^4$?
- Gauge hierarchy problem
- Strong CP probelm
- SM fermion masses and mixings

Aesthetic Problems:

- Interaction unification
- Fermion unification
- Gauge coupling unification
- Charge quantization
- Too many parameters

II. Particle Physics Models

- Type I Models: New Physics
- Type II Models: Gauge Hierarchy Problem
- Type III Models: Aesthetic Problems

Type I Models:

- The New Minimal Standard Model [a]
- The Beautiful Standard Model [b]

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[a] H. Davoudiasl, R. Kitano, TL, and H. Murayama

[b] Talks by TL

Type II Models:

- The Supersymmetric Standard Models
- Technicolor
- Large Extra Dimensions: ADD Models
- Warped Extra Dimension: RS Models
- Universal Extra Dimensions
- Higgsless Models
- Little Higgs Models

Technicolor:

- No fundamental scalar Higgs and then no quadratic divergences
- SM Higgs is a condensate of new fermions due to nearby additional strong interaction
- Problem: electroweak precision test
- Walking TC, and Top color assisted TC

ADD

$$M_{\rm Pl}^2 \;=\; M_X^{n+2} V_n \;.$$

RS

$$M_{\rm Pl}^2 \;=\; M_{GUT}^2 e^{2kL}(1-e^{-2kL}), \quad \text{where} \;\; k = M_X \;.$$

If the universe is (or a slice of) AdS_5 space with 3-branes, the 5-dimensional GUT scale on each brane can be indetified as the 5-dimensional Planck scale, but, the 4-dimensional Planck scale is generated from the low 4-dimensional GUT scale exponentially in our world.

Higgsless Models: [a]

- No fundamental scalar Higgs
- The electroweak gauge symmetry is broken via boundary conditions in 5-dimension
- Problems: electroweak precision test, and the top and bottom quark masses

[a] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning; R. S. Chivukula, D. A. Dicus, H. J. He and S. Nandi

Little Higgs Models: [a]

- Higgs mass is not stable against the quantum corrections. New physics around 1 TeV scale is needed for stabilization of EW scale.
- Electroweak precision measurements put constraints on many operators which preserve baryon number, flavour and CP symmetries. No evidence for new physics up to 5-7 TeV.
- Higgs particle is a pseudo-Nambu-Goldstone boson of large symmetry, and take mass at two loop. No one-loop quadratic divergences to the little Higgs mass-squared.

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[a] N. Arkani-Hamed, A. G. Cohen and H. Georgi

Type III Models:

- The Grand Unified Theories.
- String Models

The Grand Unified Theories: $SU(5)$, and $SO(10)$, etc.

- Unification of the gauge interactions, and unifications of the SM fermions
- Charge quantization
- Gauge coupling unification in the MSSM, and Yukawa unification $y_t = y_b = y_\tau$
- Radiative electroweak symmetry breaking due to large top quark Yukawa coupling
- Weak mixing angle at weak scale M_Z
- Neutrino masses by see-saw mechanism

Problems:

- Gauge symmetry breaking
- Doublet-triplet splitting problem

  Higgs particles do not form complete GUT multiplet at low energy
- Proton decay problem
- Fermion mass problem

  GUT relation $m_e/m_\mu = m_d/m_s$

One possible solution: Orbifold GUTs.

The gauge symmetry is broken, and the doublet-triplet is splitted by the orbifold projections.

String Models:

- Calabi-Yau compactification of heterotic string theory
- Orbifold compactification of heterotic string theory

  Grand Unified Theory (GUT) can be realized naturally through the elegant E_8 breaking chain: $E_8 \supset E_6 \supset SO(10) \supset SU(5)$
- D-brane models on Type II orientifolds

  N stacks of D-branes gives us $U(N)$ gauge symmetry

III. The Beautiful Standard Model

String Landscape

- An enormous "landscape" for long-lived metastable string/M theory vacua [a].
- Weak Anthropic Principle [b].
- The first concrete explanation of the very tiny value of the cosmological constant, which can take only discrete values.
- Solution to Gauge Hierarchy Problem.

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[a] Giddings, Kachru and Polchinski; Kachru, Kallosh, Linde and Trivedi; Susskind; Denef and Douglas.
[b] Weinberg.

Although the tiny cosmological constant and light Higgs mass are not technically natural in QFT, they can indeed be natural in the string ladscape!

In the string landscape, the supersymmetry breaking scale can be high if there exist many supersymmetry breaking parameters or many hidden sectors [a].

Classification for the supersymmetry breaking scale [b]

- String scale;
- An intermediate scale;
- TeV scale.

For string-scale and intermediate-scale supersymmetry breakings, most of the problems associated with low energy supersymmetric models are solved automatically.

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[a] Giryavets, Kachru and Tripathy; Susskind; Douglas; Dine, Gorbatov and Thomas; Arkani-Hamed and Dimopoulos.

[b] Barger, Chiang, Jiang and TL.

SUSY breaking scale

- String landscape is based on the Type II orientifolds with flux compactifications.
- The SUSY breaking soft masses are universal and roughly M_S^2/M_{Pl}.
- M_S is about 10^{17} GeV, so, $M_{soft} \sim 10^{16}$ GeV.
- Universal GUT-scale supersymmetry breaking.

The SM from weak scale to GUT scale.

Strong CP Problem

- $\overline{\theta} = \theta + \theta_{\rm q}$ parameter is a dimensionless coupling constant which is infinitely renormalized by radiative corrections.
- No theoretical reason for $\overline{\theta}$ as small as 10^{-9} required by the experimental bound on the EDM of the neutron.

$$d_{\rm N} \sim \frac{e\overline{\theta}}{m_{\rm N}(m_u^{-1} + m_d^{-1} + m_s^{-1})} \sim 3 \times 10^{-16}\overline{\theta}\ {\rm e-cm} \quad \sim 6 \times 10^{-25}\ {\rm e-cm}\ .$$

- $\overline{\theta}$ may be a random variable with a roughly uniform distribution in the string landscape [a].

[a] Donoghue.

Peccei–Quinn Mechanism

- $\overline{\theta} = \theta + \theta_{\mathrm{q}} + a/f_a$

$$V_{\mathrm{Instanton}} \simeq \Lambda_{QCD}^4 \left(1 - \cos\overline{\theta}\right) .$$

- $10^{10}\ \mathrm{GeV} \ < \ f_a \ < \ 10^{12}\ \mathrm{GeV}$
- Axion can be a cold dark matter candidate.
- The axion solution can be stabilized by the gauged discrete PQ symmetry [a].

[a] Babu, Gogoladze, Wang; Barger, Chiang, Jiang, TL

Weak (Weinberg-Wilczek) Axion [a]

- Two Higgs doublets
- $f_a \sim 300$ **GeV**, $m_a \sim 30$ **keV**
- Weak coupling
- Ruled out by $K \to \pi a$ and $J/\Psi \to a\gamma$ experiments

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[a] Weinberg; Wilczek.

Invisible DFSZ Axion [a]

- Introduce two light Higgs doublets and a singlet
- f_a much larger than weak scale
- Coupling very weakly to quarks

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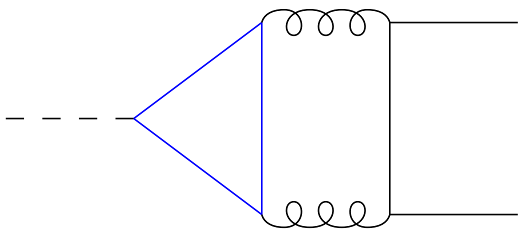
[a] Zhitnitskii; Dine, Fischler and Srednicki.

Invisible KSVZ Axion [a]

- Additional heavy quarks and Higgs
  $F^{\rm up}\bar{u}_L u_R \phi^* + F^{\rm down}\bar{d}_L d_R \phi + F^Q \overline{Q}_L Q_R S$
- Couplings to Q and G are $1/f_a$ suppressed
- Axion couples indirectly to quarks



In these models, m_a and $g_{\gamma a}$ simple functions of f_a

[a] Kim; Shifman, Vainshtein and Zakharov.

Axion Dark Matter

Coincidence: axion relic density

$$\Omega_a h^2 \sim \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{\frac{7}{6}} \left(\frac{200\mathrm{MeV}}{\Lambda_{\mathrm{QCD}}}\right)^{\frac{3}{4}} \; .$$

$$\Omega_D h^2 \sim 0.11 \; .$$

$$f_a \sim 10^{11}\mathrm{GeV} \; , \;\; m_a \sim 10^{-5}\mathrm{eV} \; .$$

Neutrino Masses and Mixings

- $(L\tilde{H})(L\tilde{H})/M_{\rm Pl}$ gives $m_\nu \lesssim 10^{-5}$ eV
- See-Saw Mechanism
- Type I, Type II, and Type III
- Two Right-Handed Neutrinos

Four New Degrees of Freedom

See-Saw Mechanism:

$$\mathcal{L}_{\mathrm{neutrino}} = -h_\nu L N \tilde{H} + m_N N N \ .$$

$$M_\nu \ = \ \begin{pmatrix} 0 & m \\ m & m_N \end{pmatrix} \ .$$

If $m_N >> m$, two eigenvalues: m^2/m_N, m_N

$$m_N \sim 10^{11-14} GeV \ .$$

Baryon Asymmetry via Leptogenesis:

- N_i decays generate net lepton numbers due to CP violation
- Sphaleron process preserve the $B - L$ while violate $B + L$
- Some of net lepton numbers transform into net baryon numbers
- Two right-handed neutrinos
- $T_R \gtrsim 10^{10}$ GeV

SM fermion masses and mixings

Solution: Froggatt-Nielsen Mechanism [a]

Introducing global $U(1)_{FN}$ symmetry, and ϕ with $U(1)$ charge -1.

$$
\begin{aligned}
-\mathcal{L} \;=\; & h_u^{ij}\left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{nQi+nUj} Q_i U_j \tilde{H} + h_d^{ij}\left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{nQi+nDj} Q_i D_j H \\
& + h_l^{ij}\left(\frac{\phi}{M_{\mathrm{Pl}}}\right)^{nLi+nEj} L_i E_j H \\
= \; & h_u^{ij}\epsilon^{nQi+nUj} Q_i U_j \tilde{H} + h_d^{ij}\epsilon^{nQi+nDj} Q_i D_j H + h_l^{ij}\epsilon^{nLi+nEj} L_i E_j H \;,
\end{aligned}
$$

where $\epsilon = \langle\phi\rangle / M_{\mathrm{Pl}} \sim 0.22$.

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[a] I. Gogoladze, C. A. Lee T. Li, and Q. Shafi , in preparation.

Inflation

- A real SM singlet field φ
- Quadratic Term drives Inflation–Chaotic Inflation
- $m \simeq 1.5 \times 10^{13}$ GeV, so, $\mu \lesssim 10^{6}$ GeV and $\kappa \lesssim 10^{-14}$.

One Degree of Freedom

Lagrangian

$$\mathcal{L}_\varphi = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!}\varphi^3 - \frac{\kappa}{4!}\varphi^4 \, .$$

The conventional slow-roll inflationary parameters are

$$\epsilon \equiv \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 \simeq \frac{2M_P^2}{\varphi^2}, \; \eta \equiv M_P^2 \left(\frac{V''}{V}\right) \simeq \frac{2M_P^2}{\varphi^2}, \; \xi \equiv M_P^4 \left(\frac{V V'''}{V^2}\right) \simeq 0 \,.$$

The overall scale of the inflationary potential is normalized by the WMAP data on density fluctuations:

$$\Delta_R^2 = \frac{V}{24\pi^2 M_{\rm Pl}^2 \epsilon} = 2.95 \times 10^{-9} A \quad : \quad A = 0.77 \pm 0.07,$$

$$V^{\frac{1}{4}} = M_{\rm Pl}^4 \sqrt{\epsilon \times 24\pi^2 \times 2.27 \times 10^{-9}} = 0.027 M_{\rm Pl} \times \epsilon^{\frac{1}{4}} \,,$$

$$m^{\frac{1}{2}} \varphi \;\simeq\; 0.038 \times M_{\rm Pl}^{\frac{3}{2}} \,.$$

Number of e-foldings

$$N \simeq \frac{1}{4}\frac{\varphi^2}{M_{\rm Pl}^2} \simeq 60 \ .$$

Inflaton Magnitude

$$\varphi \simeq \sqrt{240} \times M_{\rm Pl} \simeq 3.718 \times 10^{19} \ {\rm GeV} \ .$$

Inflaton Mass

$$m \simeq 1.444 \times 10^{13} \ {\rm GeV}.$$

Spectral Index

$$n_s = 1 - 6\epsilon + 2\eta = 1 - \frac{8M_P^2}{\varphi^2} \simeq 0.96667 \; ,$$

Tensor to Scalar Ratio

$$r \equiv \frac{A_T}{A_S} = 16\epsilon = \frac{32M_P^2}{\varphi^2} \simeq 0.13333 \; ,$$

Spectral-Index Running

$$\frac{dn_s}{d\ln k} = \frac{2}{3}\left[(n_s - 1)^2 - 4\eta^2\right] + 2\xi = \frac{32M_P^4}{\varphi^4} \simeq 5.5556 \times 10^{-4} \; .$$

Gauge Coupling Unification

It is well known that gauge coupling unification cannot be achieved in the SM with the canonical normalization of the $U(1)_Y$ hypercharge interaction, *i.e.*, the Georgi-Glashow $SU(5)$ normalization [a].

Gauge coupling unification can be achieved in the SM by introducing extra multiplets between the weak and GUT scales [b] or large threshold corrections [c].

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[a] Langacker and Luo; Ellis, Kelley and Nanopoulos; Amaldi, de Boer and Furstenau.
[b] Frampton and Glashow; Nandi; Murayama and Yanagida; Rizzo.
[c] Calmet.

Gauge coupling unification in the SM:

- The gauge couplings for $SU(3)_C$ and $SU(2)_L$ are unified at about 10^{16-17} GeV
- The gauge coupling for the $U(1)_Y$ depends on its normalization
- With a suitable normalization of the $U(1)_Y$, the three gauge couplings for $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ can in fact be unified at about 10^{16-17} GeV

Question: *is the canonical normalization for $U(1)_Y$ unique?*

For a four-dimensional GUT with a simple group, the canonical $U(1)_Y$ normalization is the only possibility, assuming that the SM fermions form complete multiplets under the GUT group.

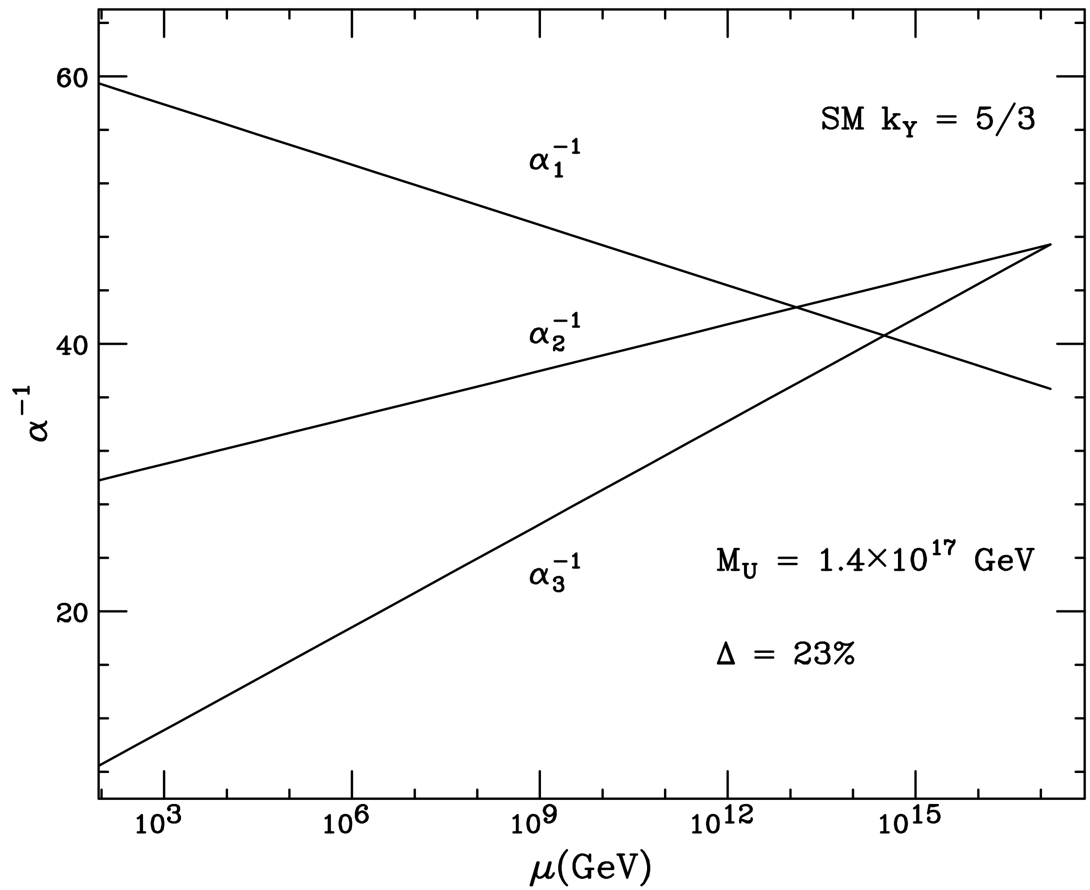

Figure 1: One-loop gauge coupling unifi cation for the SM with $k_Y = 5/3$.

Non-canonical $U(1)_Y$ normalization:

- In weakly coupled heterotic string theory, the gauge and gravitational couplings always automatically unify [a]

$$k_Y g_Y^2 = k_2 g_2^2 = k_3 g_3^2 = 8\pi \frac{G_N}{\alpha'} = g^2_{\text{string}} \ .$$

- In intersecting D-brane model building on Type II orientifolds, the normalization for the $U(1)_Y$ (and also other gauge factors) is not canonical in general [b].

- In orbifold GUTs [c] and their deconstruction [d], and the 4D GUTs with product gauge groups.

We assume $k_2 = k_3 = 1$.

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[a]Dienes.

[b]Blumenhagen, Cvetic, Langacker and Shiu.

[c]Kawamura; Altarelli and Feruglio; Hall and Nomura; Hebecker and March-Russell; TL; Asaka,ya Buchmuller and Covi; Gogoladze, Mimura and Nandi; Babu, Barr and Kyae; Kyae and Shafi .

[d]Arkani-Hamed, Cohen and Georgi; Hill, Pokorski and Wang; Csaki, Kribs and Terning; Cheng, Matchev and Wang; TL and Liu; Huang, Jiang and TL.

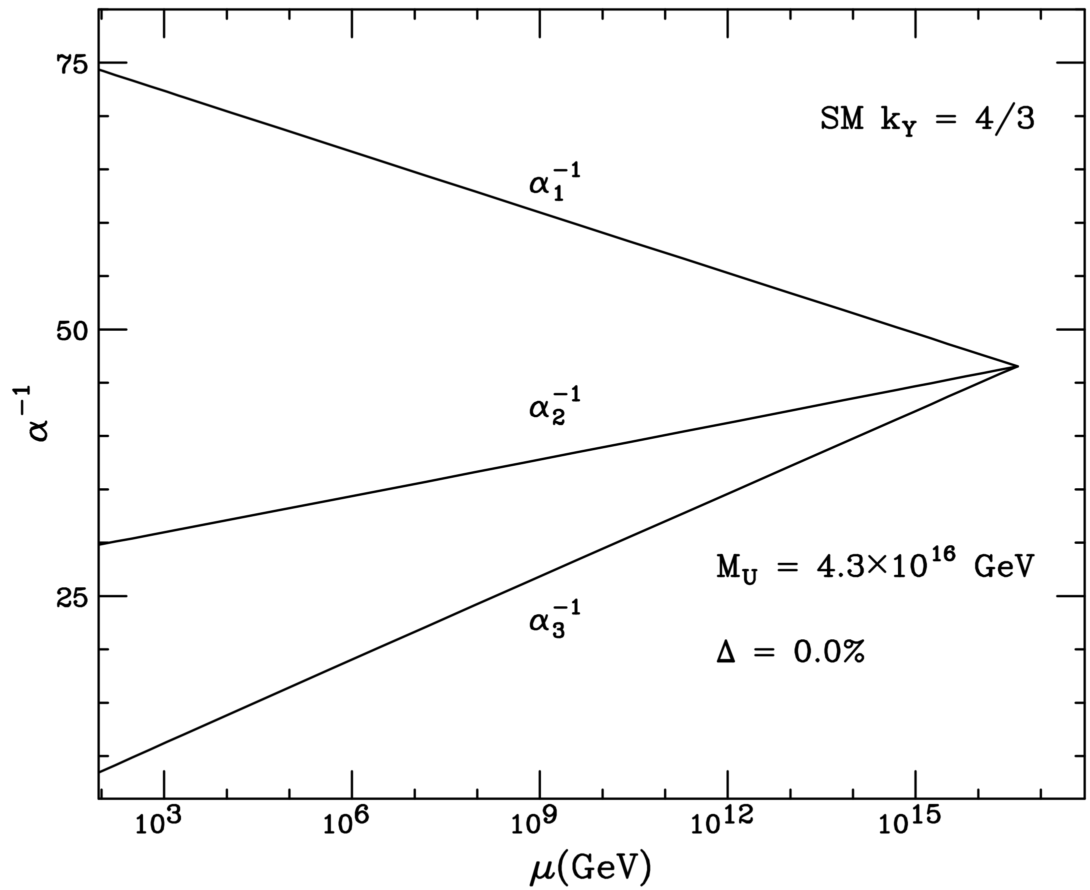

Figure 2: Two-loop gauge coupling unifi cation for the SM with $k_Y = 4/3$.

Orbifold GUTs with $k_Y = 4/3$:

- A right-handed top quark in the $SU(6)$ model and the SM fermions and Higgs fields in the $SU(8)$ models can be obtained from the zero modes of the bulk vector multiplet, and their hypercharges are determined from the construction. The other SM fermions and one pair of Higgs doublets can be put on the observable 3-brane.
- Charge quantization–Anomaly free conditions and the gauge invariance of the Yukawa couplings.
- The extra $U(1)$ gauge symmetries can be considered as flavour symmetries–the SM fermion masses and mixings.
- The supersymmetry can be broken at the GUT scale by the Scherk–Schwarz mechanism.

Higgs Boson Mass

If the Higgs particle is the only new physics discovered at the LHC and the SM is thus confirmed as the low energy effective theory, the most interesting parameter is the Higgs mass.

- SM Higgs doublet H: $H \equiv -\cos\beta i\sigma_2 H_d^* + \sin\beta H_u$
- Universal GUT scale supersymmetry breaking.
- The gauginos, squarks, sleptons, Higgsinos, and the other combination of the scalar Higgs doublets ($\sin\beta i\sigma_2 H_d^* + \cos\beta H_u$) have a universal supersymmetry breaking soft mass around the GUT scale.

Procedure:

- Calculate the Higgs boson quartic coupling λ at the GUT scale:

$$\lambda(M_U) = \frac{k_Y g_2^2(M_U) + g_1^2(M_U)}{4k_Y} \cos^2 2\beta \ .$$

- Evolve λ down to the weak scale via RGEs.
- Minimize the one-loop effective Higgs potential with top quark radiative corrections.
- Calculate the Higgs mass.

The one-loop effective Higgs potential

$$V_{eff} = m_h^2 H^\dagger H - \frac{\lambda}{2!}(H^\dagger H)^2 - \frac{3}{16\pi^2} h_t^4 (H^\dagger H)^2 \left[\log \frac{h_t^2 (H^\dagger H)}{Q^2} - \frac{3}{2}\right] .$$

For the $\overline{MS}$ top quark Yukawa coupling, we use the one-loop corrected value:

$$m_t = h_t v \left(1 + \frac{16}{3}\frac{g_3^2}{16\pi^2} - 2\frac{h_t^2}{16\pi^2}\right) .$$

Results:

- If we vary α_3 within its 1σ range, m_t within its 1σ range (171.4 ± 2.1 GeV), and $\tan\beta$ from 1.5 to 50, the predicted Higgs boson mass will range from 130.8 GeV to 148.5 GeV.
- The top quark mass can be measured to about 1 GeV accuracy at the LHC [a].
- Assuming this accuracy and a central value of 171.4 GeV, the Higgs boson mass is predicted to be between 132.7 GeV and 146.9 GeV.

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[a] M. Beneke *et al.*, arXiv:hep-ph/0003033.

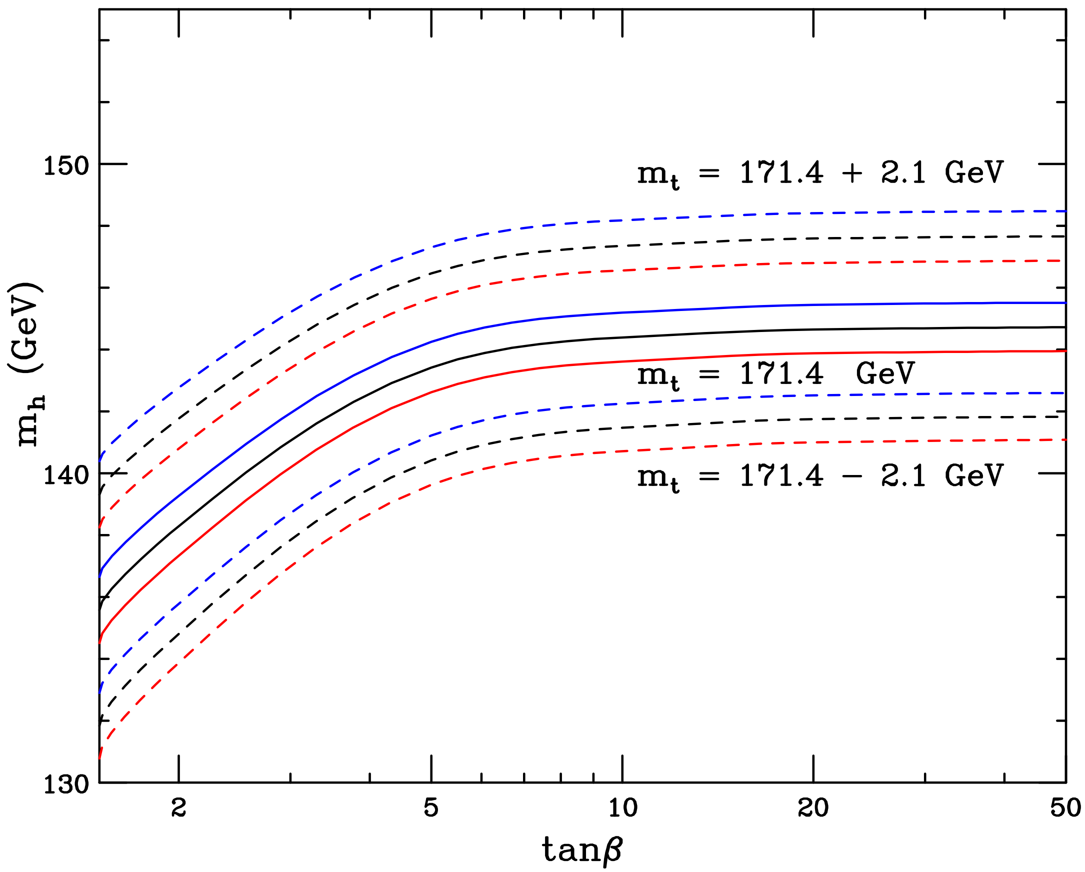

Figure 3: The predicted Higgs mass for the SM with $k_Y = 4/3$. The red (lower) curves are for $\alpha_3 + \delta\alpha_3$, the blue (upper) $\alpha_3 - \delta\alpha_3$, and the black α_3. The dash ones for $m_t \pm \delta m_t$, and the solid ones for m_t.

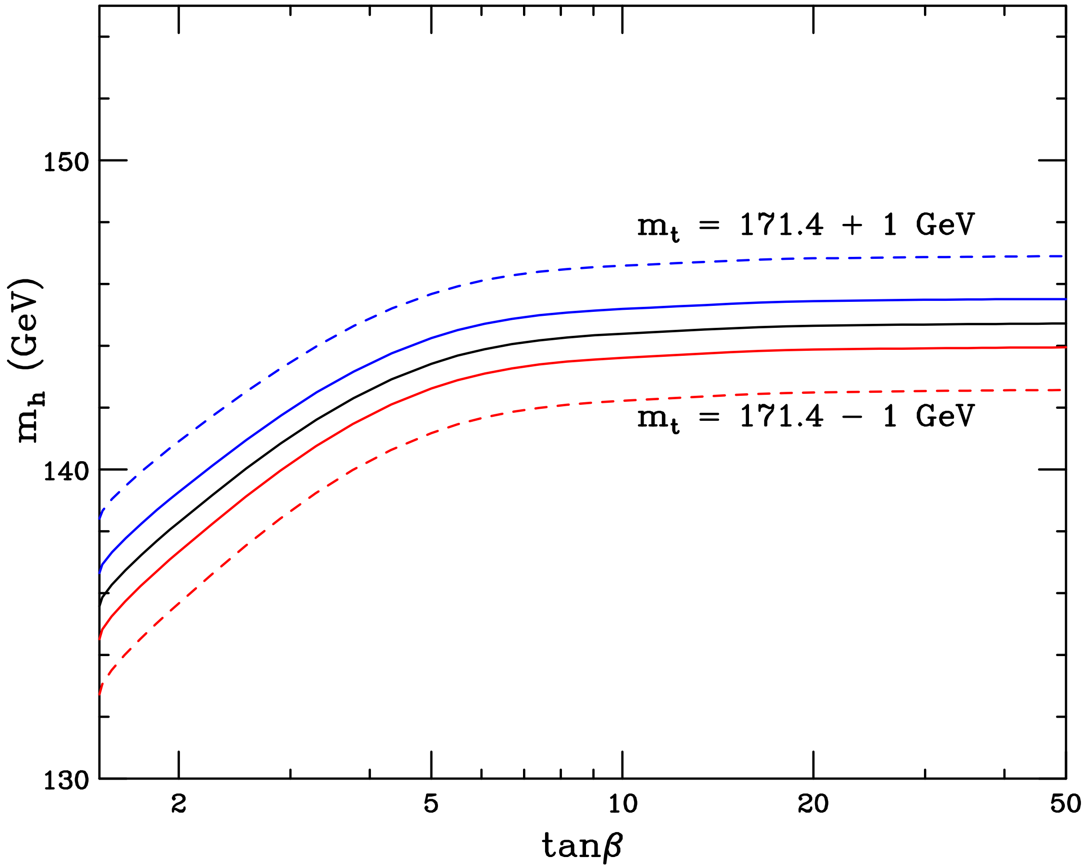

Figure 4: The predicted Higgs mass for the SM with $k_Y = 4/3$. The red (lower) curves are for $\alpha_3 + \delta\alpha_3$, the blue (upper) $\alpha_3 - \delta\alpha_3$, and the black α_3. The dash ones for $m_t \pm \delta m_t$, and the solid ones for m_t.

VI. SUPERSYMMETRIC STANDARD MODELS

- Solving the gauge hierarchy problem
- Gauge coupling unification
- Radiatively electroweak symmetry breaking

  Large top quark mass
- Natural dark matter candidates

  Neutralino, sneutrino, gravitino, ...
- Electroweak baryogenesis
- Electroweak precision: R parity

Problems in the MSSM:

- μ problem

  $\mu H_u H_d$

- Little hierarchy problem:

  Fine-tuning for lightest CP even Higgs mass

- CP violation and EDMs

- FCNC

- Dimension-5 proton decays

Mediation of supersymmetry breaking:

- Gravity mediation: CP and FCNC
- Anomaly mediation: No FCNC

  UV insensitive model: No CP
- Gauge mediation: CP and No FCNC
- Bulk mediation: Gaugino and radion mediation
- D-term breaking: Anomalous $U(1)$
- Scherk-Schwarz mechanism

Little hierarchy problem:

- Invisiable Higgs decays: $h \longrightarrow aa$

  Higgs is light and about 100 GeV

- Mirage mediation: Large A_{top} and small $B\mu$

- Flipped CP-even Higgs scenario: $h \leftrightarrow H$

- Additional F-term and/or D-term contribution to the Higgs quartic couplings

- Split supersymmetry

- High-scale supersymmetry

μ problem:

- NMSSM: Z_3 symmetry

$$W = hSH_uH_d + \frac{\kappa}{3}S^3 \ .$$

- nMSSM: Z_5^R and Z_7^R

$$W = hSH_uH_d + \kappa M_n^2 S \ .$$

- Singlet and Triplet SSM:

$$W = hSH_uH_d + \lambda_u H_u \bar{T} H_u + \lambda_d H_d T H_d + \lambda S T \bar{T} \ .$$

- $U(1)'$ Model: $U(1)'$

$$W = hSH_uH_d\ , \quad V_D = \frac{1}{2}g_{Z'}^2\left(Q_S|S|^2 + Q_{H_u}|H_u|^2 + Q_{H_d}|H_d|^2\right)^2 .$$

- Fat Higgs Model: $h \sim 2$ due to strong dynamics

  Due to Landau pole problem, $h < 0.7$, and $h < 0.82$ for the models with additional quarks, leptons or Higgs fields.

Proton Decay Problem:

- $QQQL/M_{\rm Pl}$ and $U^cD^cU^cE^c/M_{\rm Pl}$: $\tau_P \sim 10^{17}$ years
- Coefficients must be small, about 10^{-9}
- Froggatt-Nielsen Mechanism with anomoulos $U(1)$ symmetry

V. Summary

The beautiful Standard Model in string landscape

- Cosmological constant problem and gauge hierarchy problem could be solved.
- Axion–Strong CP problem/Dark matter;
- Two Right-handed neurtrinos–Neutrino masses and mixings/Baryon asymmetry;
- Froggatt-Nielsen mechanism–SM fermion masses and mixings;
- Inflation: A real scalar
- The gauge coupling unification can be achieved and the charge quantization can be realized.
- The Higgs mass can be predicted in a narrow range, and can be tested at the LHC and ILC.

I also review the main models on particle physics, in particular, the supersymmetric Standard Models.

Thank You Very Much for Your Attention!