α_s for New Physics

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Why α_s?

— Every parameter better known as precisely as possible

(Impacts on collider physics, …)

— Developments of technologies / understandings

(Issues with SCET determination, …)

— …

Scenarios in which the α_s value plays a crucial role?

- Grand unification
  - — Grand unification in higher dimensions
- “Multiverse”
  - — Precision Higgs mass prediction

(Note: different scenarios … mutually *in*compatible)

Grand Unification in Higher Dimensions

For a review, Hall, Y.N., hep-ph/0212134

Grand unification

Beautiful understanding of quark / lepton quantum numbers

$$
\begin{array}{lcc}
SU(3)_C \times SU(2)_L \times U(1)_Y & SU(5) & SO(10) \\
\left.\begin{array}{l} q(\mathbf{3},\mathbf{2})_{1/6} \\ u^c(\mathbf{3}^*,\mathbf{1})_{-2/3} \\ e^c(\mathbf{1},\mathbf{1})_1 \end{array}\right\} & T(\mathbf{10}) & \\
\left.\begin{array}{l} d^c(\mathbf{3}^*,\mathbf{1})_{1/3} \\ l(\mathbf{1},\mathbf{2})_{-1/2} \end{array}\right\} & F(\mathbf{5}^*) & \psi(\mathbf{16}) \\
n^c(\mathbf{1},\mathbf{1})_0 \quad \rightarrow & N(\mathbf{1}) &
\end{array}
$$

Predictions:

⇛ • 3 forces of the Standard Model unified at a high energy scale M_{GUT}

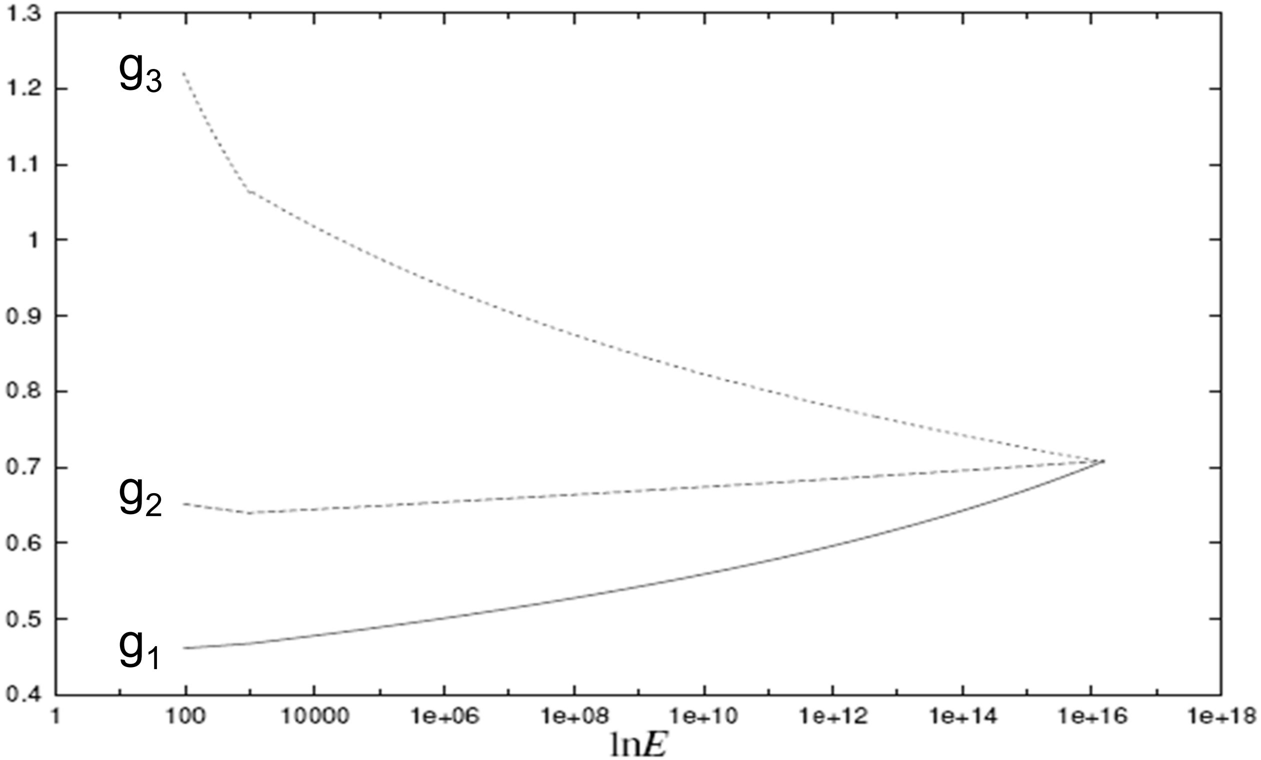
→ can be tested through α_s measurements

• Proton decay caused by exchange of unified gauge bosons

Gauge coupling unification

… works particularly well with weak scale supersymmetry

(introduced to solve the gauge hierarchy problem: why $v_{EW} \ll M_{GUT/Pl}$)



What is the *precise* prediction of α_s?

Hard to even quantify the errors

… threshold corrections from the weak **and** unified scales

e.g. Minimal SUSY SU(5)

$$\alpha_3^{-1}(m_Z) = \frac{12}{7}\alpha_2^{-1}(m_Z) - \frac{5}{7}\alpha_1^{-1}(m_Z) - \frac{1}{4\pi}\left\{\frac{18}{7}\ln\frac{M_{H_C}}{(M_V^2 M_\Sigma)^{1/3}} - \frac{19}{7}\ln\frac{m_{\rm SUSY}}{m_Z}\right\}$$

Unknown masses of GUT-scale particles

cf. Hisano, Murayama, Yanagida ('92)

GUT-scale threshold corrections become even larger in extended models …

For "exact unification"

$$\alpha_s(m_Z) = 0.130 + 0.009\left(\frac{m_{t,\rm pole}^2 - (173.1\ {\rm GeV})^2}{(173.1\ {\rm GeV})^2}\right) - \frac{19\alpha_s^2}{28\pi}\ln\frac{m_{\rm SUSY}}{m_Z}$$

Somewhat large

cf. Langacker, Polonsky ('95)

$m_{\rm SUSY}$: "effective" superpartner scale

SUSY GUT has problems

- Gauge breaking & Doublet-triplet splitting

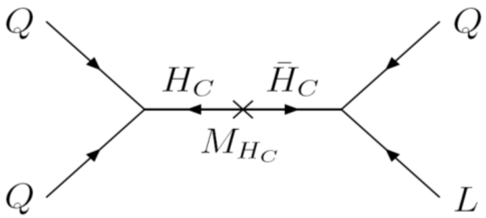
Why $M_{H_C} \gg M_{H_{u,d}}$?

$$W = H\,(M_H + \lambda\Sigma)\,\bar{H}$$

$$\langle\Sigma\rangle = \begin{pmatrix} 2 & & & & \\ & 2 & & & \\ & & 2 & & \\ & & & -3 & \\ & & & & -3 \end{pmatrix} V_\Sigma \quad \Longrightarrow \quad \begin{cases} M_{H_C} = M_H + 2\lambda V_\Sigma \sim M_{\rm GUT} \\ M_{H_{u,d}} = M_H - 3\lambda V_\Sigma \ll M_{\rm GUT} \end{cases}$$

… extreme fine-tuning

- Dimension five proton decay



$$\Longrightarrow \quad W \approx \frac{1}{M_{H_C}} QQQL$$

… excluded by Super-Kamiokande

- Fermion mass relations

$$W = y\,TF\bar{H} \begin{cases} \nearrow\ y\,QDH_d \\ \searrow\ y\,LEH_d \end{cases} \quad \Longrightarrow$$

m_b/m_τ : good

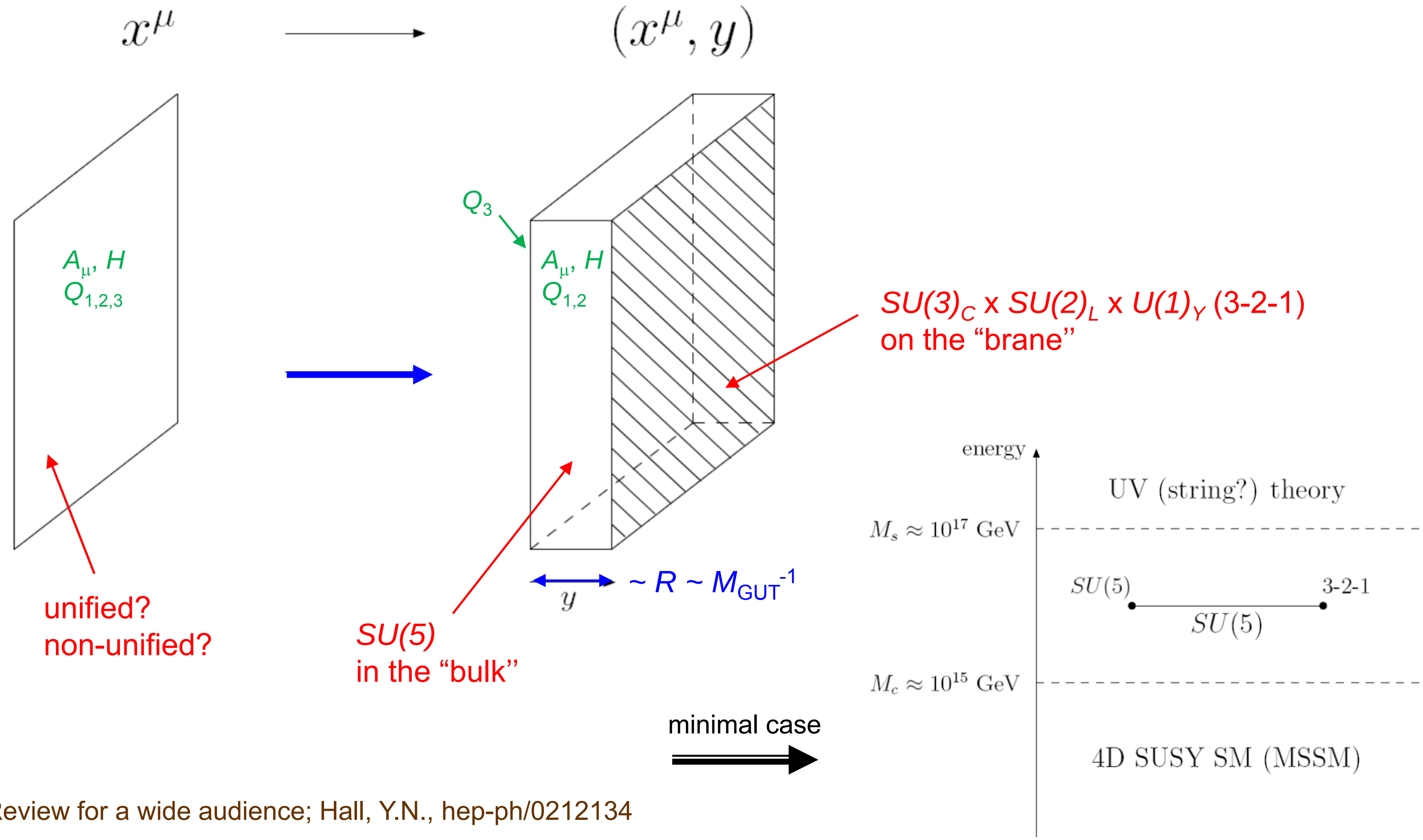
m_s/m_μ : bad

… something seems wrong

Grand unification in higher dimensions

Hall, Y.N.; Kawamura ('00 - '02)

The basic framework



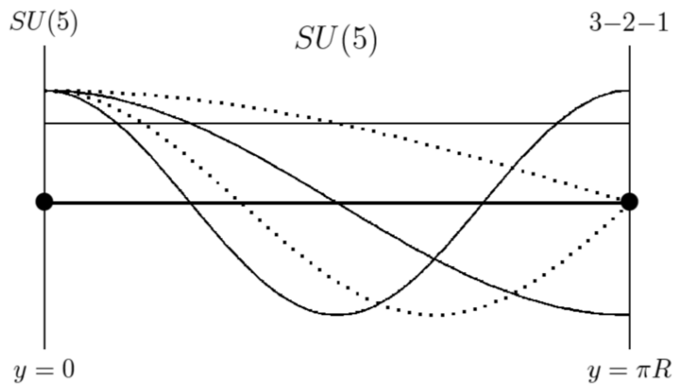
Review for a wide audience; Hall, Y.N., hep-ph/0212134

Consistent quantum theory

"boundary condition"

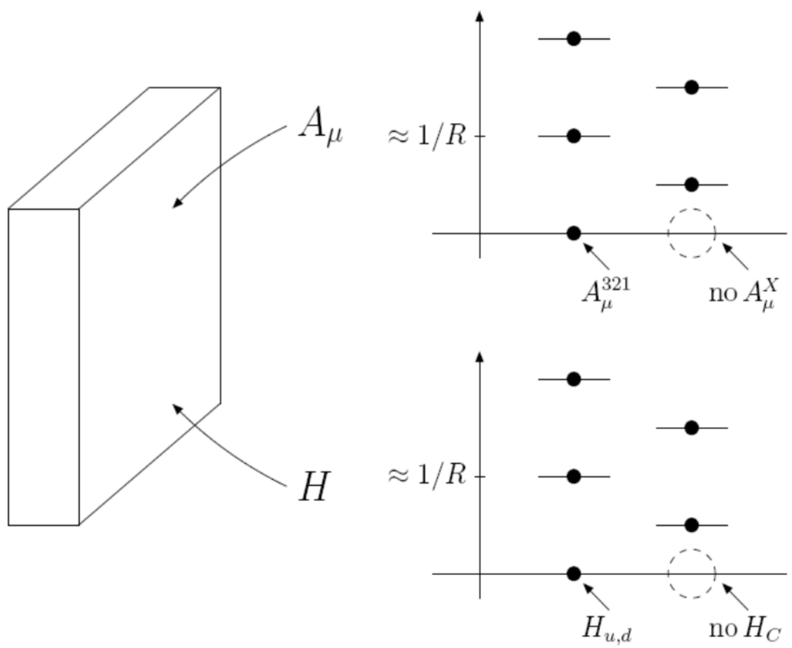
A_μ^{321} (+,+): ———

A_μ^{X} (+,-): ⋯⋯⋯



(compactified on an S^1/Z_2 orbifold)

From 4 dimensional point of view,



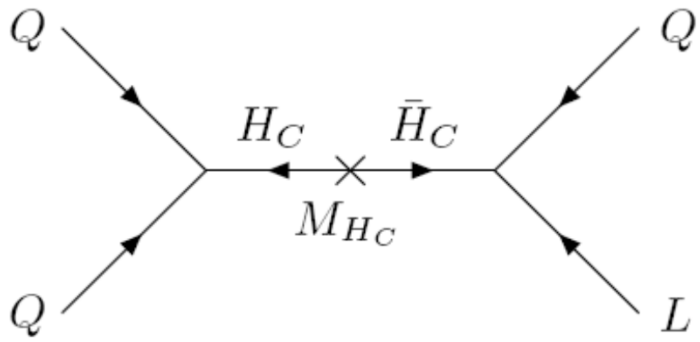
Gauge breaking
& doublet-triplet splitting

… *automatic !*

Suppressed *d*=5 proton decay

- 4D

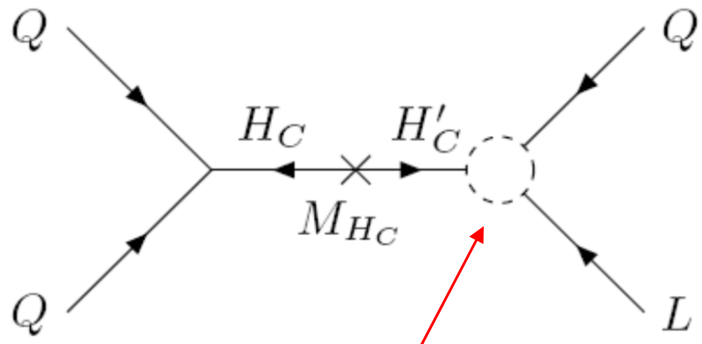
$$W = M_{H_C} H_C \bar{H}_C$$



- 5D

5D partners

$$W = M_{H_C}(H_C H'_C + \bar{H}_C \bar{H}'_C)$$



simply absent

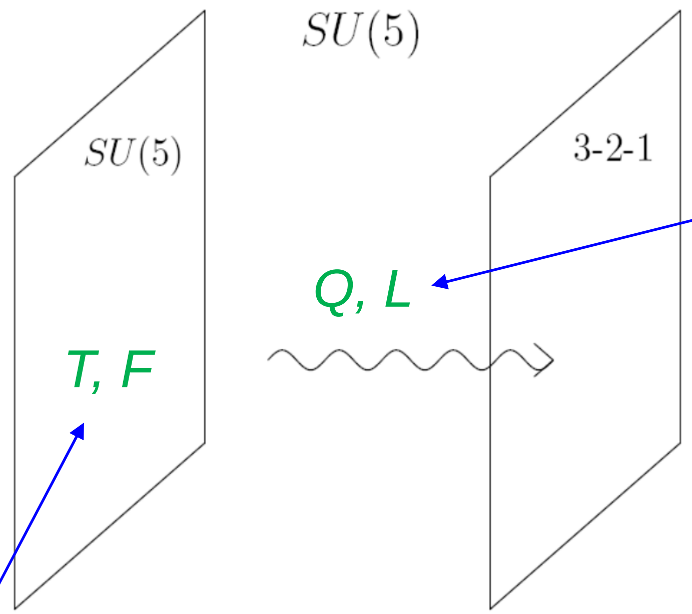
- $U(1)_R$ symmetry

$T(1)$, $F(1)$, $H(0)$, $\bar{H}(0)$, $H'(2)$, $\bar{H}'(2)$, …

… *d*=5 proton decay does not arise

Matter fields

- Matter fields can be either on a brane or in the bulk



bulk matter: touch to the defect

- *SU(5)* prediction for m_q/m_l does not arise
- No d=6 proton decay

⇓

Light (volume dilution)

brane matter: locally *SU(5)* symmetric

- *SU(5)* prediction for m_q/m_l holds

⇓

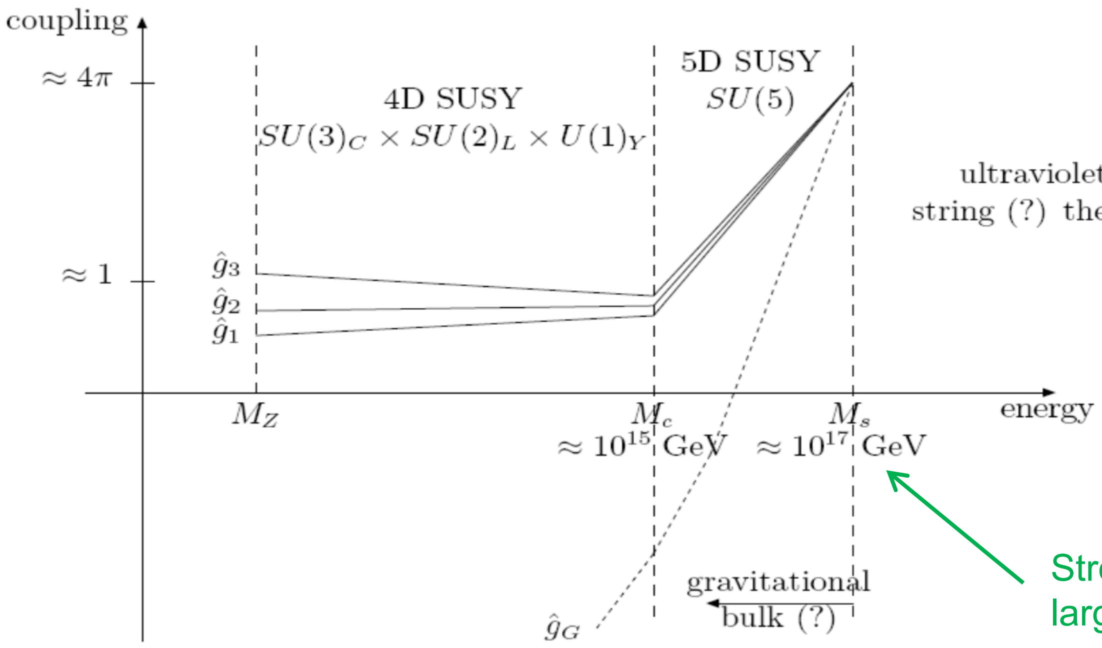
Heavy (no volume dilution)

… Successful correlation!

Gauge coupling unification preserved

… but with (slightly) modified prediction for α_s

e.g. Minimal model



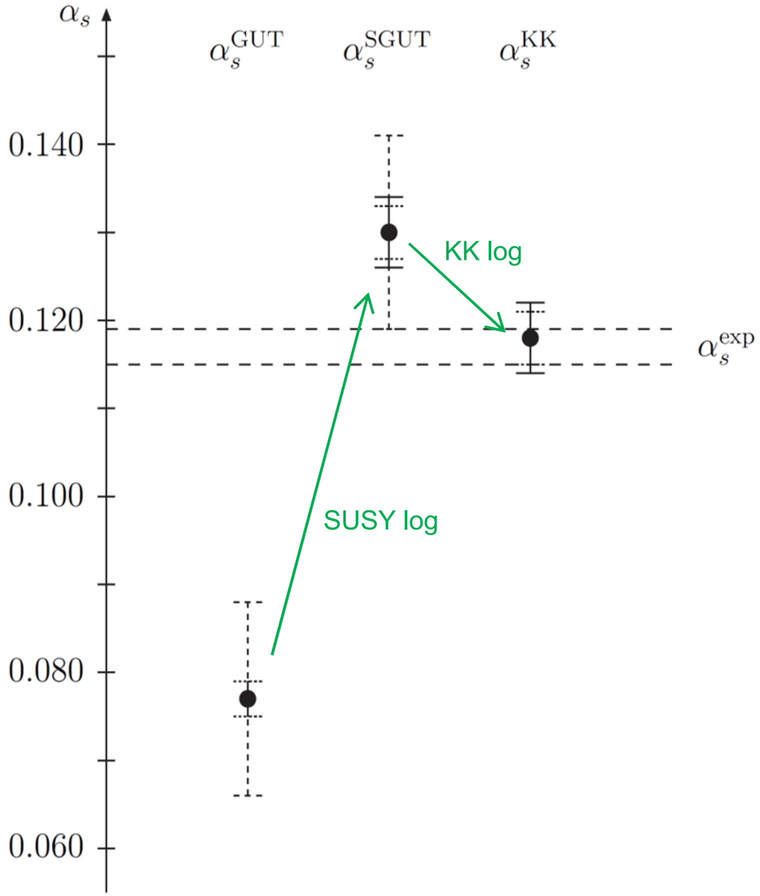
Strong coupling:
largest volume for extra dim.

No arbitrary parameters (masses)

$\rightarrow$ threshold corrections are calculable!

Precision unification prediction

Precise predictions for $\alpha_s(m_Z)$



$\alpha_s(m_Z) = 0.118 \pm 0.005$

$M_c \equiv 1/R \approx 10^{15}$ GeV

$M_s \approx 10^{17}$ GeV (in the minimal model)

… improved prediction!

The α_s value depends on gauge group, # of extra dim, …

→ Important window into high energy physics

Precision Higgs Mass Prediction

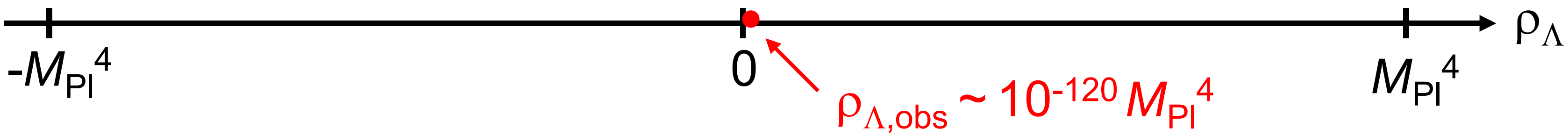
Hall, Y.N., arXiv:0910.2235

String compactification

Structure of low energy theory / vacua may be "complex"

Multiverse

Cosmological constant problem



Unnatural (Note: $\rho_\Lambda = 0$ is NOT special from theoretical point of view)

- String landscape

Compact (six) dimensions
→ huge number of vacua

ex. $O(100)$ fields with $O(10)$ minima each
→ $O(10^{100})$ vacua

- Eternal inflation

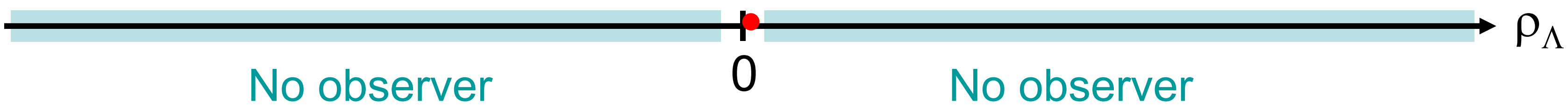
Inflation is (generically) future eternal → populate all the vacua

String compactification

Structure of low energy theory / vacua may be "complex"

Multiverse

Cosmological constant problem



Natural to see $\rho_{\Lambda,\mathrm{obs}}$, if different values of ρ_Λ are "sampled"

- String landscape

  Compact (six) dimensions
  $\rightarrow$ huge number of vacua

  ex. $O(100)$ fields with $O(10)$ minima each
  $\rightarrow$ $O(10^{100})$ vacua

- Eternal inflation

  Inflation is (generically) future eternal $\rightarrow$ populate all the vacua

Significant implications

What is natural? … anthropic considerations mandatory

What is generic? … minimality not (automatically) justified

Weak scale supersymmetry really "needed"?

The origin of the weak scale may be environmental

$\Longrightarrow$ the scale of ~~SUSY~~ masses determined by statistics

$$\boxed{d\mathcal{N} \sim f(\tilde{m})\frac{v^2}{\tilde{m}^2}\,d\tilde{m}} \qquad f(\tilde{m}) \sim \tilde{m}^{p-1}$$

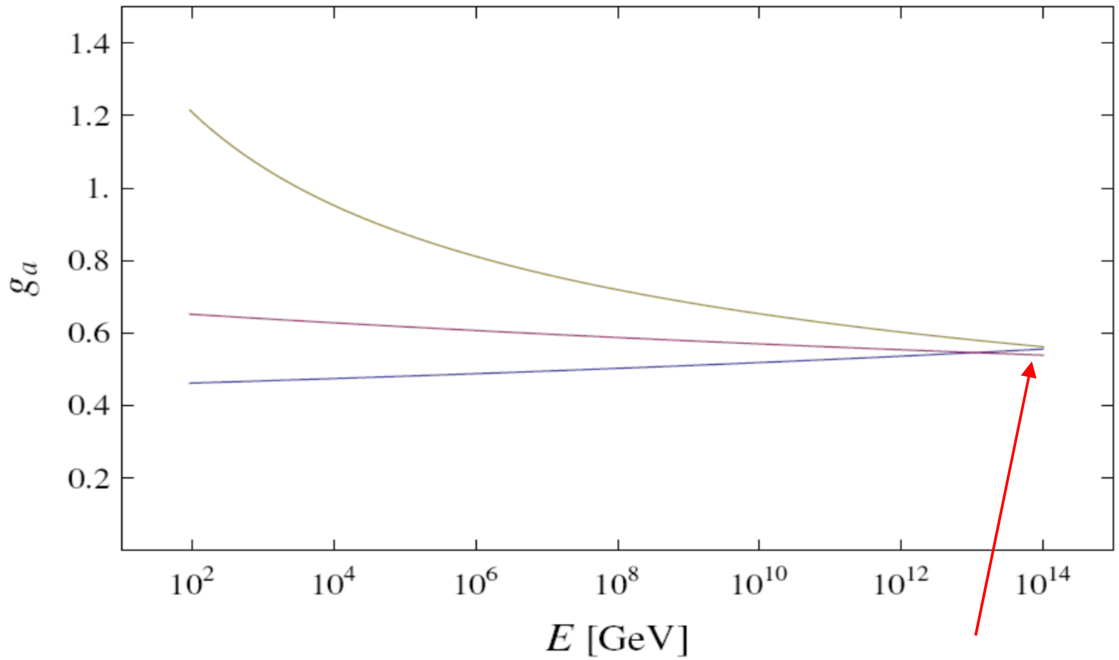
For $p < 2$, weak scale SUSY results,

but for $p > 2$, $\tilde{m}$ prefers to be large…

What if $\tilde{m}$ shoots up?

"Minimal" scenario (for large $\tilde{m}$)

Standard Model:



Unification at the level of $\delta g_a^2 \sim 6\%$ at $E \sim 10^{14}$ GeV

unification ~~SUSY~~ $\sim 10^{14}$ GeV

Dark matter can be axions — $\theta_{QCD} \ll 1$ … need mechanism

Doesn't seem that bad…

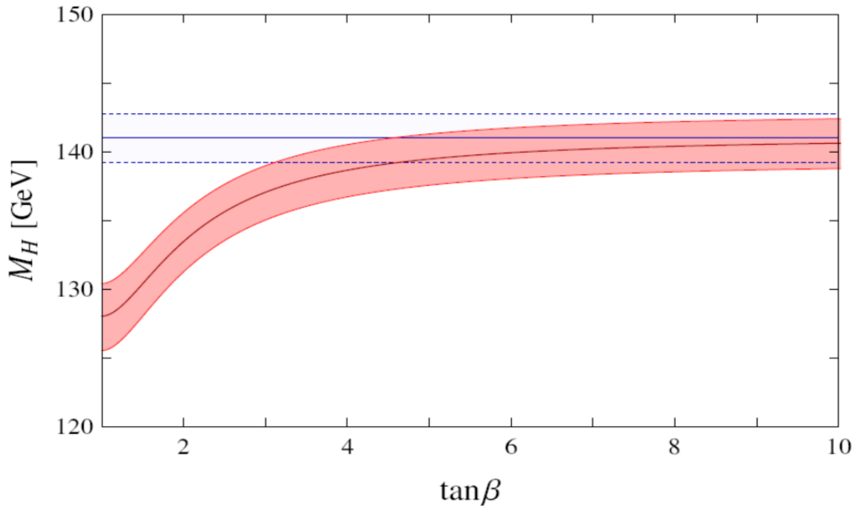
(Note: no SUSY flavor problem, SUSY CP problem, μ problem, gravitino problem, axino problem, or …)

High scale ~~SUSY~~ — nothing left?

SUSY boundary condition on the Higgs quartic λ

$$\boxed{\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8} \cos^2 2\beta}$$

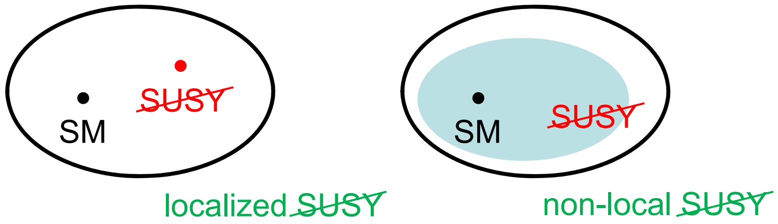
$\lambda(m) \;\rightarrow\; \lambda(v) \;\rightarrow\; M_H$ prediction



$M_H \approx (128 – 141)$ GeV

Many theories lead to this “edge value”

Corrections from the cutoff can be small



… volume / loop suppressed $\rightarrow$ $\delta\lambda \ll 1$

2-loop RGE + 1-loop threshold
QCD threshold up to 3 loops

m_t = 173.1 ± 1.3 GeV
$\alpha_s(M_Z)$ = 0.1176 ± 0.002

"M_H Prediction" — crazy?

Do we know $\tilde{m}$?

What about threshold corrections?

$$\boxed{\lambda(\tilde{m}) = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{8}\{1 + \delta(\tilde{m})\}}$$

$\tilde{m}$: matching scale

includes all threshold corrections

(No possibility to measure these directly)

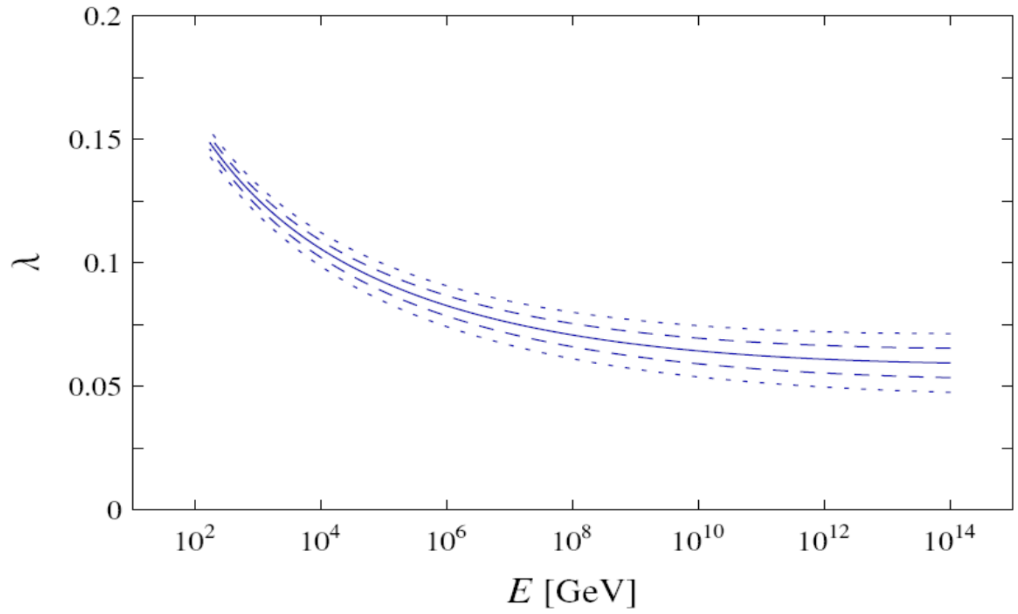
Miracles!

Uncertainties dominated by $\delta m_t|_{\mathrm{exp}}$, $\delta\alpha_s(M_Z)|_{\mathrm{exp}}$,
and small

… sensitivities to the high energy physics extremely mild

Infrared convergence property

RGE for λ



δ = 0, ±0.1, ±0.2
for $\tilde{m} = 10^{14}$ GeV

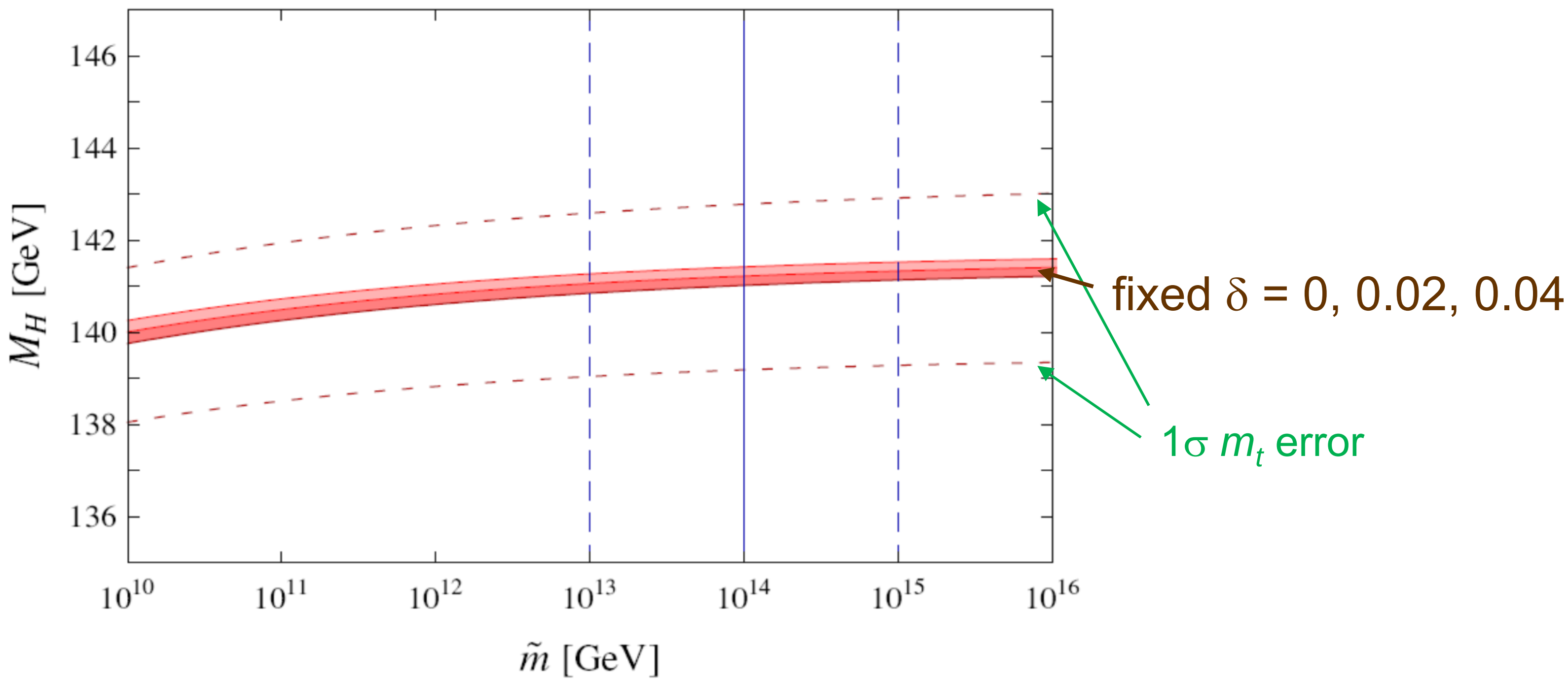
The fractional uncertainty reduced by ~ a factor of 6

$$\delta M_H = 0.10 \text{ GeV} \left(\frac{\delta}{0.01}\right)$$

The attraction not so strong as erasing the sensitivity to SUSY b.c.

Extreme insensitivity to $\tilde{m}$

We do not know the precise value of $\tilde{m}$



Explicit dependence on $\tilde{m}$ extremely mild !

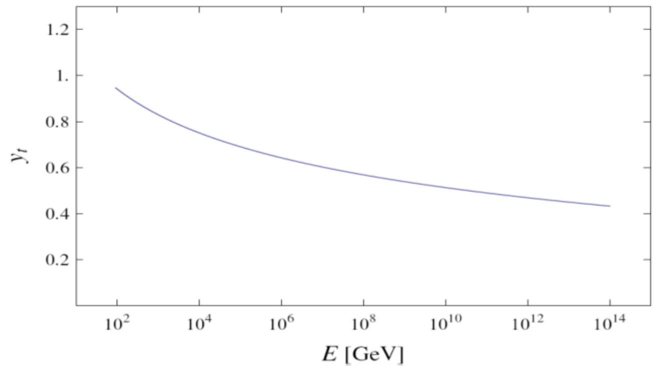
$$\delta M_H = 0.14 \text{ GeV} \left(\log_{10} \frac{\tilde{m}}{10^{14} \text{ GeV}} \right)$$

Suppressed threshold corrections

SUSY corrections

$$\delta_s = \frac{3y_t^4}{32\pi^2\lambda}\left(\frac{2A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{6m_{\tilde{t}}^4}\right) \simeq 0.007\left(\frac{2A_t^2}{m_{\tilde{t}}^2} - \frac{A_t^4}{6m_{\tilde{t}}^4}\right)$$

Very small ! For $A_t = m_{\tilde{t}}$ $(3m_{\tilde{t}})$, $\delta_s \approx 0.013$ (0.031) $\longrightarrow$ $\delta M_H \approx 0.1$ (0.3) GeV



$y_t(\tilde{m}) \approx 0.5\, y_t(v)$

(δ_s proportional to y_t^4)

$\Longrightarrow$ Largest uncertainties

$\delta m_t|_{exp} = \pm 1.3$ GeV $\longrightarrow$ $\delta M_H = \pm 1.8$ GeV

$\delta\alpha_s(M_Z)|_{exp} = \pm 0.002$ $\longrightarrow$ $\delta M_H = \mp 1.0$ GeV

[Residual uncertainties small: $\delta M_H = \pm 0.5$ GeV (estimate)]

Precision Higgs mass prediction

$$M_H = 141.0 \text{ GeV} + 1.8 \text{ GeV} \left(\frac{m_t - 173.1 \text{ GeV}}{1.3 \text{ GeV}} \right) - 1.0 \text{ GeV} \left(\frac{\alpha_s(M_Z) - 0.1176}{0.002} \right)$$
$$+ 0.14 \text{ GeV} \left(\log_{10} \frac{\tilde{m}}{10^{14} \text{ GeV}} \right) + 0.10 \text{ GeV} \left(\frac{\delta}{0.01} \right) \pm 0.5 \text{ GeV}$$

$\delta = \delta_\beta + \delta_s + \delta_\nu + \ldots$ $\left[\delta_\beta = -\frac{4}{\tan^2\beta} + O\left(\frac{1}{\tan^4\beta}\right) \right]$

$M_H = (141 \pm 2)$ GeV

Uncertainties from high energy theories extremely small, ~ ±0.4 GeV !

If found,

- "Discovery" of SUSY, but near M_{unif}
- Apparent success of SUSY unification accident
- Fine-tuning of > $O(10^{20})$ in m_h^2 $\rightarrow$ environmental origin of v

Strong evidence for the multiverse

(Improving precision on m_t and α_s crucial)

Summary

We will soon probe the TeV scale physics

— what will we see?

- Weak scale supersymmetry
  - — "TeV cloud" could be gone
    - … Weak scale physics (threshold) may be determined

- More generally
  - — Determination of the last SM parameter, M_H

In any case, it is possible that α_s plays an important role in exploring higher energy / more fundamental physics

… Convergence on $\alpha_s(m_Z)$ very much wanted!