BSM and LHC:

GRAND UNIFICATION

SUPERSYMMETRY

EXTRA DIMENSIONS

Fact without fancy

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STANDARD MODEL

$$G_{SM}: \quad \overset{g_c}{SU(3)_c} \times \overset{g}{SU(2)_L} \times \overset{g'}{U(1)_Y}$$

$$Q = T_{3L} + Y/2$$

- MATTER (quarks and leptons)

s

elds

(16?)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{matrix} u_R, & u_R, & u_R \\ d_R, & d_R, & d_R \end{matrix}$$

maximal L–R breaking

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R, (\nu_R\ !?)$$

. construction: charges $(q_d = -1/3,\ q_e = -1)$

$$\Rightarrow q_u = 2/3 \qquad q_\nu = 0$$

fixed by <u>arbitrary</u> Y

- needs symmetry breaking

(all particle massless)

STANDARD MODEL: POSITIVE

- M_W, $\sin\theta_W$ ($e \equiv g \sin\theta_W$; $\tan\theta_W = g'/g$):

  all weak interaction data

- Higgs remarkably simple (minimal)

$$V = \lambda/4 \left(\Phi^+\Phi \pm v^2 \right)^2$$

most general renormalizable potential

50% parameter space $\Rightarrow$ all masses

- B, L automatic in perturbation theory

  B-L anomaly free

  $\Downarrow$ gauged ?

  would need ν_R (per generation)

  $\Rightarrow \boxed{m_\nu \neq 0}$

  for $m_{\nu_R} \gg m_W$ (gauge singlet)

  $\Rightarrow$ see-saw mechanism:

  ν_L naturally light

LEP: $m_\varphi > 110$ GeV

WILL BE FOUND @ LHC!!!

- NO ν_R

$\Rightarrow m_\nu = 0$ in MSM

WRONG!

- SUN + ATMOSPHERE

(NEUTRINO OSCILLATIONS)

$$\Delta m^2_\odot \simeq 2 \times 10^{-3}\, eV^2, \quad \theta_\odot = 30^\circ \quad (\theta_C \simeq 13^\circ)$$

$$\updownarrow$$

$$\Delta m^2_A \simeq 10^{-5}\, eV^2, \quad \theta_A \simeq 45^\circ \quad \underbrace{(\theta_{23} \simeq 10^{-2})}_{\text{puzzle?}}$$

NO: NO connection between q and l in SM

Minkowski ;
Mohapatra, G.S. '79

• NEUTRINO MASS

ν_R : singlet of $SU(2)_L \times U_Y(1)$

$\Downarrow$

$M_R \, \nu_R^T C \nu_R$ (Majorana mass) ALLOWED

<u>ONLY SINGLETS</u> CAN HAVE MAJORANA MASS

$\Downarrow$

$$\begin{array}{c} \nu_L \\ \nu_R \end{array} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \qquad m_D = y_D M_W$$

$m_D \Longleftrightarrow m_f$

small Dirac mass

$M_R \gg M_W, m_D$

$\Downarrow$

$m_N \simeq M_R \qquad N = \nu_R + \varepsilon \nu_L$

$$\boxed{m_\nu \simeq m_D^2 / M_R} \qquad \nu = \nu_L - \varepsilon \nu_R$$

$\varepsilon \simeq m_D / M_R$

Issues

- Yukawa arbitrary : <u>no</u> connection between
  q and l masses and mixings
  $\Rightarrow$ impossible to predict m_ν, θ_ν
  GETS IMPROVED IN GRAND UNIFICATION
  • SO(10) •

- <u>no</u> connection between g_c, g, g'
  $\Rightarrow$ GRAND UNIFICATION

- Higgs mass not protected by symmetries
  (unlike m_f) from large scales
  gets worse in GUT (why $M_H \ll M_{GUT}$)
  $\Rightarrow$ supersymmetry

- origin of Parity breaking ?
  $\Rightarrow$ L − R symmetry, Pati − Salam
  • SO(10) •
  related to ν mass

$$SU(2)_L \times U(1) \times SU(3)_c$$
$$\cap$$
$$G$$

GRAND UNIFICATION

$(d=4)$

- UNIFICATION OF ELECTRO-WEAK and STRONG FORCE at $M_{GUT} \gg M_W$

$$G \xrightarrow[M_{GUT}]{} SM$$

$$\alpha_i = \alpha_{GUT} \quad (M_{GUT})$$
$$i = 1, 2, 3$$

- QUANTIZATION OF CHARGE

$$\mathrm{Tr}\, Q_{em} = 0$$

CONNECTS q AND ℓ CHARGES

example: $SU(2)$ Schwinger '57

$$Q = T_3$$

$1/2$, $-1/2$

1, 0, -1

$3/2$, $1/2$, 0, $-1/2$, $-3/2$

$\vdots$

$$\left.\begin{array}{c} SU(2) \\ \downarrow \\ U(1) \end{array}\right\} \text{PROTOTYPE}$$

UNIFY WHAT?

'LOW ENERGY' (~TeV) EFFECTIVE

THEORY?

- STANDARD MODEL

NO indication of new physics $\gtrsim$ TeV

($m_\nu \neq 0$: INDICATION FOR

NEW PHYSICS at $E \gg$ TeV

($\gg 10^{10}$ GeV)) Vissani

THEORETICAL PREJUDICE:

HIGGS MASS HIERARCHY

$\Rightarrow$ SUPERSYMMETRY at ~ TeV

NATURALNESS

$$m_H^2 = m_{H0}^2 + \frac{Y_t^2}{16\pi^2}\left(m_t^2 - m_{\tilde{t}}^2\right)$$

$Y_t \simeq O(1) \Rightarrow$ Higgs naturally 'tachyonic'

small $m_{\tilde{t}} \longleftrightarrow$ less fine-tuning (?)

PREDICTION (MAIN) :

$$m_H^2 \le M_Z^2 + Y_t^2 m_t^2 \ln \frac{m_{\tilde t}}{m_t}$$

does <u>not</u> predict m_H ($m_{\tilde t} = ?$)

still, it correlates m_H with $m_{\tilde t}$

$m_{\tilde t} \le$ TeV $\Rightarrow$ $m_H \le 130$ GeV

$m_{\tilde t} \le 10$ TeV $\Rightarrow$ $m_H \le 150$ GeV

LHC can rule out MSSM :

light stop ($m_{\tilde t} \le$ TeV) and

"heavy" Higgs ($m_H \gg 130$ GeV)

OTHERWISE, NO information

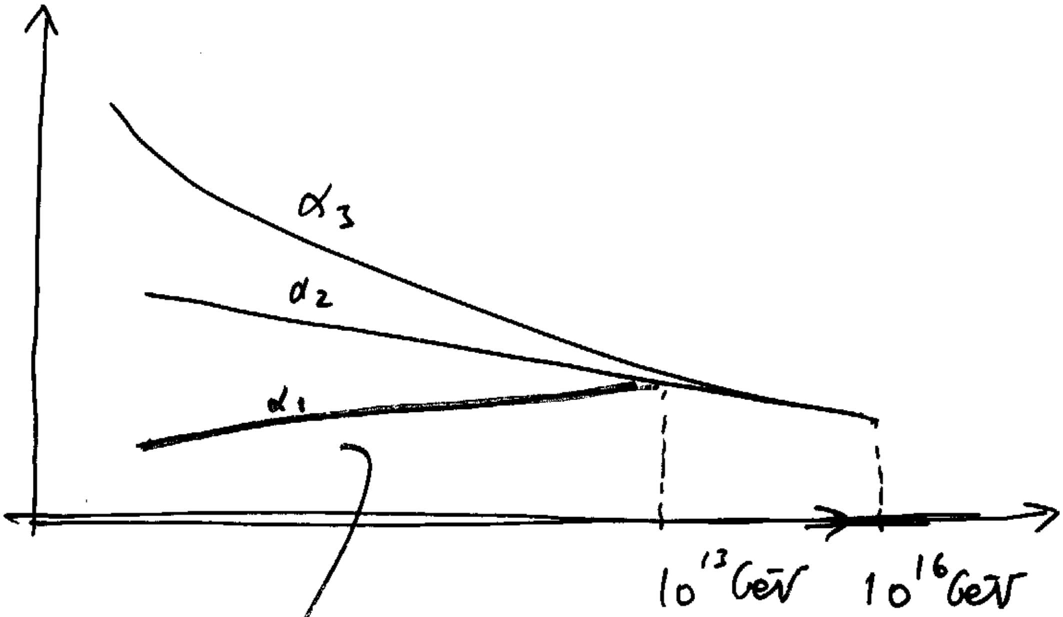
on $m_{\tilde f}$, gaugino, ...

- LUCKY scenario: all $\tilde p$ at LHC !?

DM?

GAUGE COUPLING UNIFICATION

SM



↑ nice
(proton stability)
($M_X \geq 10^{15.5}$ GeV)

problem if you assume
a desert

$\Updownarrow$

(minimal G) SU(5) : (not good for fermion (neutrino) masses)

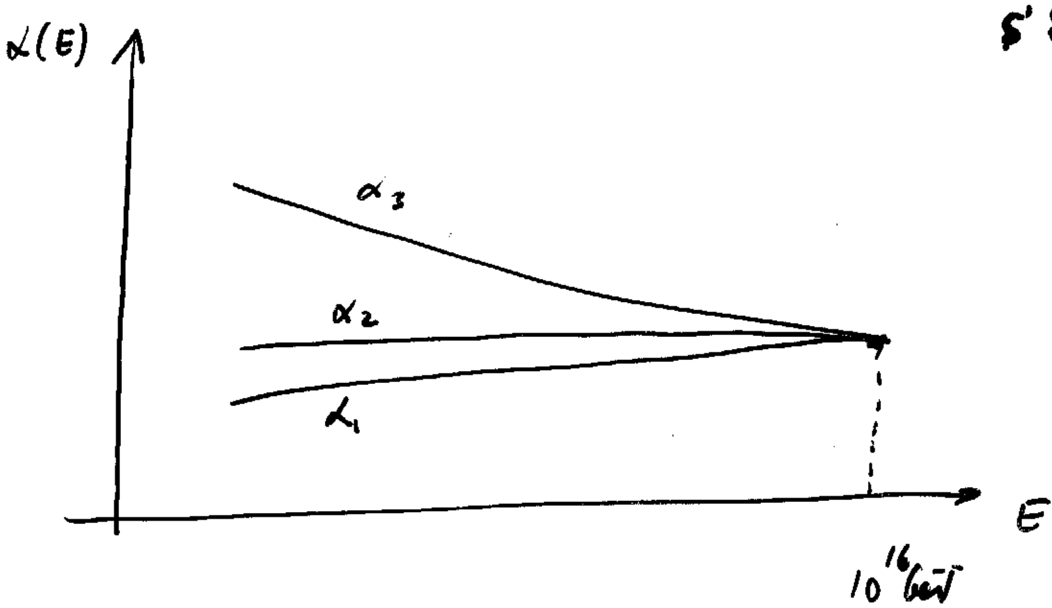
$\Downarrow$

$\boxed{\sin^2\theta_W = .2}$

exp. $\sin^2\theta_W = .23$

GAUGE COUPLING UNIFICATION

S'SM



$\Longleftrightarrow \quad \sin^2\theta_W = .23$

ANTICIPATED (predicted)

Einhorn, Jones

* Marciano, G.

• $\sin^2\theta_W = .2$ in '81

Dimopoulos

Ibáñez, Ro

* suggest: $\boxed{m_t \simeq 200 \text{ GeV}}$

$\Rightarrow \quad \rho > 1 \Rightarrow \sin^2\theta_W \uparrow$

$\not{B}$ and neutrino masses:

predicting m_ν, θ_ν

$q \longleftrightarrow l$ symmetry

$L \longleftrightarrow R$ — " —

FAMILY OF FERMIONS : [redacted]

$$SU(2)_{L,R} \downarrow \quad \begin{pmatrix} u & u & u & \vdots & \nu \\ d & d & d & \vdots & e \end{pmatrix}_{L,R}$$

$$\xleftrightarrow{\;SU(3)_c\;}$$

$$\underbrace{\qquad\qquad\qquad\qquad}_{SU(4)_c}$$

(Pati - Salam)

$$B-L = \begin{pmatrix} 1/3 & 1/3 & 1/3 & -1 \end{pmatrix}$$

BROKEN @ HIGH ENERGY SCALE

$$SU(2)_L \times \boxed{SU(2)_R} \times SU(4)_c$$

$$F = \underbrace{(2_L,\ 1_R,\ 4_c) + (1_L,\ 2_R,\ 4_c)}_{\text{16 elem. fermions in a family}}$$

$$16_F = \text{spinor of } \boxed{SO(10)}$$

analogy : Lorentz group

MINIMAL THEORY $SO(10)$

less parameters ↓ more predictive

- G fixed: $SO(10)$
- matter fixed: 16_F $(i = 1,2,3)$
- Higgs: minimal set *

⇓

EXTRACT ~~[illegible]~~ PREDICTIONS

(CONSISTENCY)

Aulakh, Bajic, Melfo, Vissani
G. S.

* depends on the realization of see-saw

(i.e. how you break B − L)

(spinor) 16_H $\overline{126}_H$ (5-index AS)

within each: only $SO(10)$

\+ minimal Yukawa

(a.) Minimal SO(10) prediction :

$$\tfrac{1}{25} \simeq |V_{cb}| \simeq \left(\frac{m_b}{m_s}\right)^{-1} |\cos 2\theta_A| \qquad \left(|\cos 2\theta_A| < \tfrac{1}{3}\right)$$

$$\leq 1/100 \qquad \theta_A \simeq 45^\circ$$

too small

opposite problem!

$\Downarrow$

theory of fermion masses

$\Rightarrow$ predict proton decay branching ratio

$\left(\tau_p \propto M_{GUT}^4 \Rightarrow \text{absolute rate hard} \right)$

work in progress

• HIERARCHY (HIGGS MASS)

$$m_H^2 = m_0^2 + Y_t^2/16\pi^2 \; \Lambda^2$$

cut-off

(ADD) $\Lambda \simeq$ TeV $\Rightarrow$ no problem

Q. what about $M_{pl} \simeq 10^{19}$ GeV???

A. Extra dimensions!

Hilbert: • $\mathcal{L}_{(4)} = M_{pl}^2 \int R \, d^4x$

d+4: $\mathcal{L}_{(d+4)} = M_F^{2+d} \int R \, d^{4+d}x$

$$M_{pl}^2 = M_F^{2+d} \, r_0^d$$ ← radius of extra dim.

• $M_F \simeq \Lambda \simeq$ TeV

$d=1 \Rightarrow r_0 \simeq 10^{13}$ cm wrong

$d=2 \Rightarrow r_0 \simeq 1$ mm borderline

⋮

$d=6 \Rightarrow r_0 \simeq 10^{-12}$ cm

- $r \le r_0 \Rightarrow$ gravity changes

$$V \propto \frac{1}{r^{1+d}}$$

- $E \simeq M_F \quad (\geq \text{TeV})$

  ↳ gravity strong

  $\Rightarrow$ e.g. black holes (LHC ??)

NO!!

$$\text{TeV} \le M_F \le 10^{19}\ \text{GeV}$$

more natural

explain why r_0 large?

OUTLOOK

NO theory of BSM
which makes predictions for LHC

SUSY: $m_{\tilde{p}} = ?$

TeV limit : only a desire

constraint : $m_H \longleftrightarrow m_{\tilde{t}}$

ONLY constraint (result) for LHC

EXTRA dim : $M_F = ?$

BSM physics: $\Lambda_{new} = ?$

SU(5) : minimal group

- Fermions not truly unified

$$10_F = (u^c \; u \; d \; e^c)_L \qquad 5_F = (d^c \; \nu \; e)_L$$

} NO ν^c : $m_\nu = 0$ (SM)

- add ν^c (singlet) (as in SM)
- add new Higgs ($\underline{15}_H$) (as in SM : triplet)

(as in SM)

$\Downarrow$

NO connection between neutrinos and charged fermions

$\Downarrow$

NO information for m_ν

NO connection between θ_q and θ_ℓ

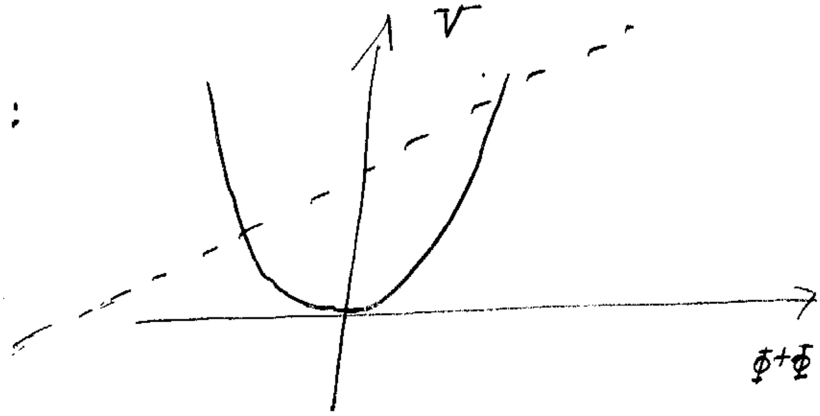
NEED: SO(10)

$$\boxed{\begin{array}{l} \nu^c \in R_f \text{ (charged fermions)} \\ q \leftrightarrow \ell \\ L \leftrightarrow R \;\; (\nu^c) \end{array}}$$

• $V(\Phi) = \frac{\lambda^2}{4}\left(\Phi^+\Phi \pm v^2\right)^2$ (+ const ?)

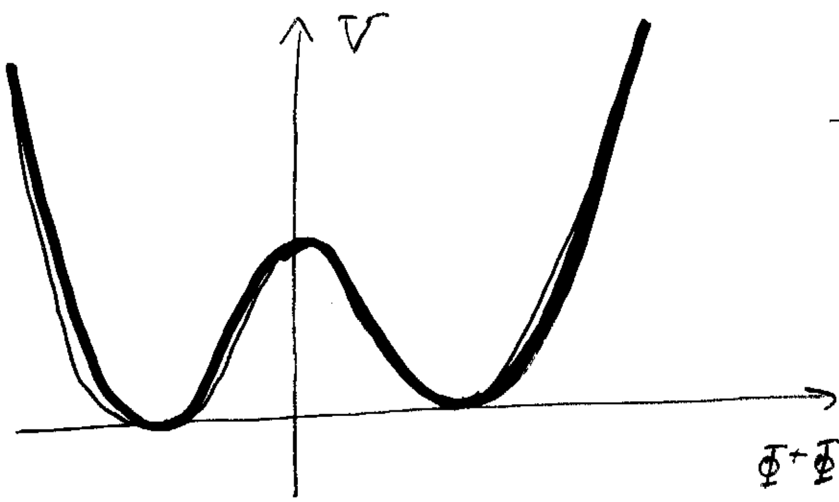
most general renormalizable potential

$+$:



bad : no symmetry breaking

$-$:



the chosen one

(half of the parameter space)

remarkably simple and efficient

$m_h = \lambda v$ ← not predicted

$m_h > 110$ GeV LEP

- LEPTOGENESIS

Fukugita, Yanagida '86

$$\nu_R \longrightarrow H + \ell \qquad \Delta L \neq 0$$

$$H^* + \bar{\ell} \qquad \text{(out-of-equilibrium; } \cancel{CP}\text{)}$$

SPHALERONS : $\Delta B \neq 0$

- $Y_\nu = ?$ $Y_D = ?$ $M_R = ?$ NO PREDICTIONS

- - - - - - - - - - -

$q - \ell$ symmetry: $SU(4)_c$ Pati - Salam

$$\underbrace{\underbrace{q \;\; q \;\; q}_{SU(3)_c} \;\; \ell}_{SU(4)}$$

connects ℓ and q Yukawas

$SU(4)$ $M_{PS} \gg M_W$