Theory constraints on new physics

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outline

- unification
- naturalness
- constraints

theory = model

$$SU(3) \times SU(2) \times U(1) \times SO(1,3)$$

theory

$SU(3) \times SU(2) \times U(1) \times SO(1,3)$

constraints?

theory

SU(3) x SU(2) x U(1) x SO(1,3)

internal symmetries

matter

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_{-1} \qquad \begin{pmatrix}u\\ d\end{pmatrix}_{1/3} \qquad \bar{u}_{-4/3} \qquad \bar{d}_{-2/3} \qquad \bar{e}_{2}$$

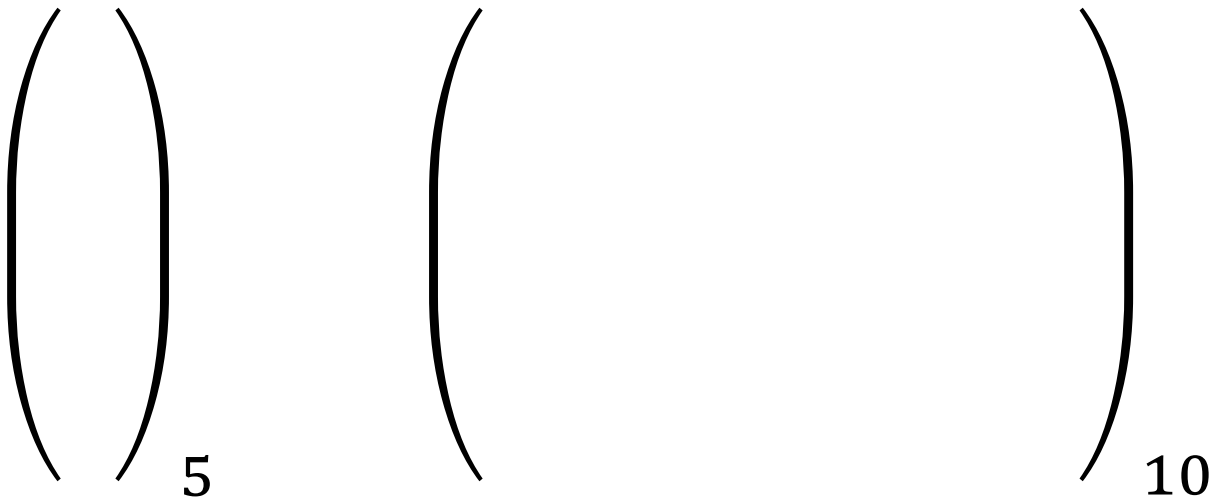
multiplets of fundamental representations

matter

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_{-1} \qquad \begin{pmatrix}u\\ d\end{pmatrix}_{1/3} \qquad \bar{u}_{-4/3} \qquad \bar{d}_{-2/3} \qquad \bar{e}_{2}$$

quantum numbers make no sense

matter



unified matter

$$\begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e \end{pmatrix}_{\bar{5}} \qquad \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \bar{e} \\ & & & & 0 \end{pmatrix}_{10}$$

a generation = two SU(5) multiplets

unified matter

$$\begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e \end{pmatrix}_{\bar{5}} \qquad \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \bar{e} \\ & & & & 0 \end{pmatrix}_{10}$$

SU(5) explains fermionic quantum numbers …

unified matter

$$\begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e \end{pmatrix}_{\bar{5}} \qquad \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \bar{e} \\ & & & & 0 \end{pmatrix}_{10}$$

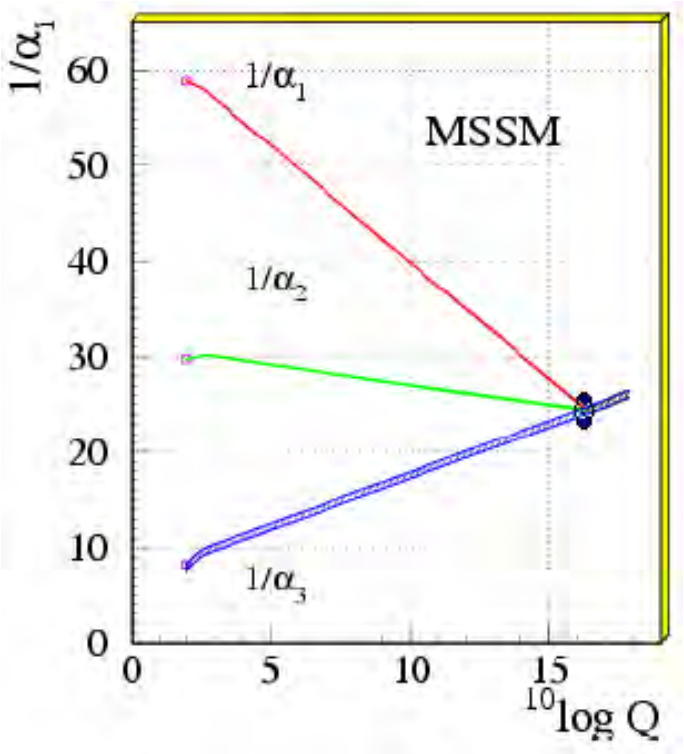
… leptons as fourth color …

unified forces

$$\begin{pmatrix} \bar{d} \\ \bar{d} \\ \bar{d} \\ \nu \\ e \end{pmatrix}_{\bar{5}} \qquad \begin{pmatrix} 0 & \bar{u} & \bar{u} & u & d \\ & 0 & \bar{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \bar{e} \\ & & & & 0 \end{pmatrix}_{10}$$

… the value of the weak mixing angle …

unified forces



… and gauge unification

unified matter

SU(5) explains various standard puzzles …

unified matter

SU(5) explains various standard puzzles …

… and constrains new physics

unified model

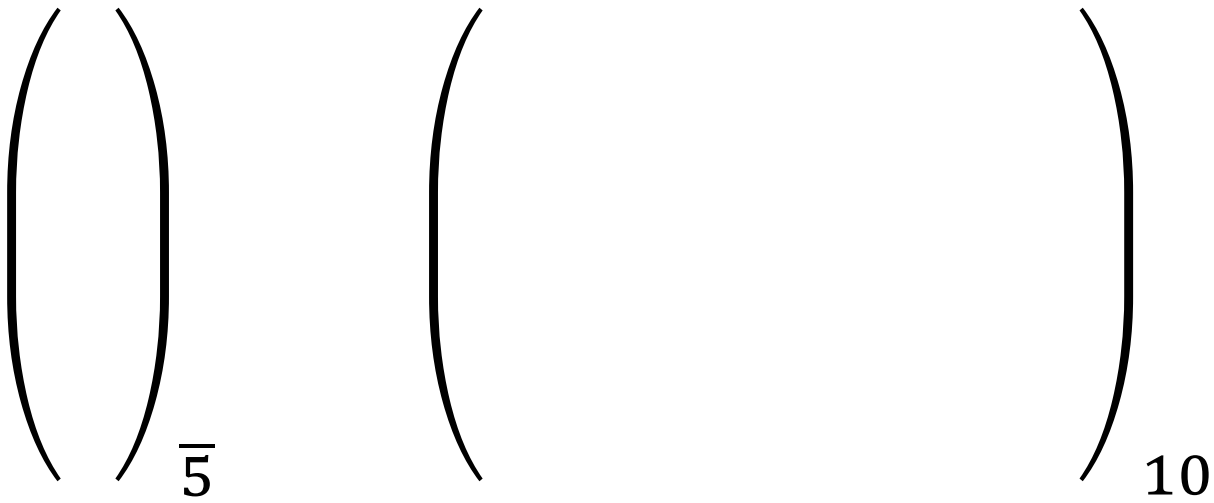
$SU(5) \times SO(1,3)$

unified model

SU(5) x SO(1,3)

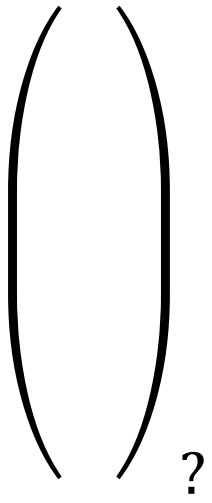
unified model?

unified model



can we do better?

unified model



unified matter

1 generation = fundamental 16-plet of SO(10)

unified matter

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SO(10) predicts the right-handed neutrino …

unified matter

1 generation = fundamental 16-plet of SO(10)

… and hints at the see-saw mechanism

unified model

SO(10) x SO(1,3)

unified model

SO(10) x SO(1,3)

unified model?

combined internal & gauge symmetry?

$$SO(10) \times SO(1,3) \overset{?}{\subset} G$$

no-go: Coleman & Mandula

$$SO(10) \times SO(1,3) \not\subset G$$

go-around: supersymmetry

SO(10) x SO(3,1)

only way to extend

supersymmetry

$$SO(1,3) \oplus S \approx Sp(4) \otimes O(1) \equiv Osp(4|1)$$

S spanned by anti-commuting (fermionic) generators

supersymmetry

$SO(10) \times Osp(4|1)$

supersymmetry

SO(10) x Osp(4|1)

supersymmetry connects matter and forces

unified model

$SO(10) \times Osp(4|1)$

unified model

SO(10) x Osp(4|1)

is that it?

Ed Witten, July 2002

(19)

THERE ISN'T ANY FOUR-DIMENSIONAL MODEL THAT DOES BETTER - BUT THERE IS ONE MOREMODEL WORTHY OF NOTE - THE E_6 MODEL (GURSEY, RAMOND, etc.

WHAT IS E_6?

FOR GAUGE THEORY, WE NEED TO PICK A GAUGE GROUP.

THERE ARE INFINITE FAMILIES

$SO(N)$
$SU(N)$
$Sp(N)$
} ANY N

OF POSSIBLE GROUPS, TWO OF WHICH - $SU(5)$ AND $SO(10)$ - ARE USED IN MODELS I MENTIONED SO FAR

(20)

AND THERE ARE FIVE EXCEPTIONS

G_2, F_4, E_6, E_7, E_8

NATURE IS EXCEPTIONAL, SO WHY NOT DESCRIBE IT USING AN EXCEPTIONAL LIE GROUP?

THERE IS ONE THAT BEAUTIFULLY WORKS - THE E_6 MODEL

IT CAPTURES THE SUCCESSES OF THE $SO(10)$ MODEL "EXCEPTIONALLY

Ed Witten, Hamburg, July 2002

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unified matter

$SO(10) \subset E(6)$

unification of matter and Higgses

unified everything

$$E(6) \subset E(8)$$

3 generations + forces + Higgses in a SUSY multiplet…

unified everything

$E(6) \subset E(8)$

3 generations + forces + Higgses in a SUSY multiplet…

… in 10 dimensions

unified everything

$E(8) \times E(8) \times OSp(10|N)$

naturalness

naturalness

"Everything is natural: if it weren't, it wouldn't be."

Mary Catherine Bateson

gauge

$$\begin{pmatrix} \text{gluons} & X, Y \\ X, Y & W, Z \end{pmatrix}$$

SU(5) force carriers

gauge hierarchy

$$\begin{pmatrix} \text{gluons} & X, Y \\ X, Y & W, Z \end{pmatrix}$$

X,Y mediate p^+ decay

so: $m_{W,Z} << m_{X,Y}$

gauge hierarchy problem

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X,Y mediate p^+ decay

so: $m_{W,Z} << m_{X,Y}$

why?

gauge hierarchy problem

$$\begin{pmatrix} \text{gluons} & X, Y \\ X, Y & W, Z \end{pmatrix}$$

X,Y mediate p^+ decay

so: $m_{W,Z} << m_{X,Y}$

unbroken SU(2) protects $m_{W,Z}$ until weak scale

gauge hierarchy problem

$$\begin{pmatrix} \text{gluons} & X,Y \\ X,Y & W,Z \end{pmatrix}$$

$$m_W = g\ v/2 = g\ m_H/(2\ \lambda) \approx m_H$$

$$m_H \approx m_W << m_{X,Y}$$

why?

gauge hierarchy problem

$$\begin{pmatrix} \text{gluons} & X,Y \\ X,Y & W,Z \end{pmatrix}$$

$$m_W = g\ v/2 = g\ m_H/(2\ \lambda) \approx m_H$$

$$m_H \approx m_W << m_{X,Y}$$

nothing protects m_H

gauge hierarchy solution

supersymmetry protects m_H

little hierarchy problem

supersymmetry protects m_H

if spartners are heavy $\Rightarrow$ protection is weak

little hierarchy problem

the natural value of m_h in a minimal 4D SUSY GUT is

$$m_h \approx m_Z$$

electroweak fine-tuning

so people measure fine-tuning in terms of

$$m_h/m_Z$$

electroweak fine-tuning

so people measure fine-tuning in terms of

$$m_h/m_Z - 1 = (m_h - m_Z)/m_Z \approx (m_h - m_Z)/m_h = \Delta m_h/m_h$$

electroweak fine-tuning

if $m_h = m_Z + \alpha\,\mu$

then $m_h/m_Z - 1 = \alpha\,\mu/m_Z \approx \alpha$

fine-tuning

other people measure fine-tuning in terms of

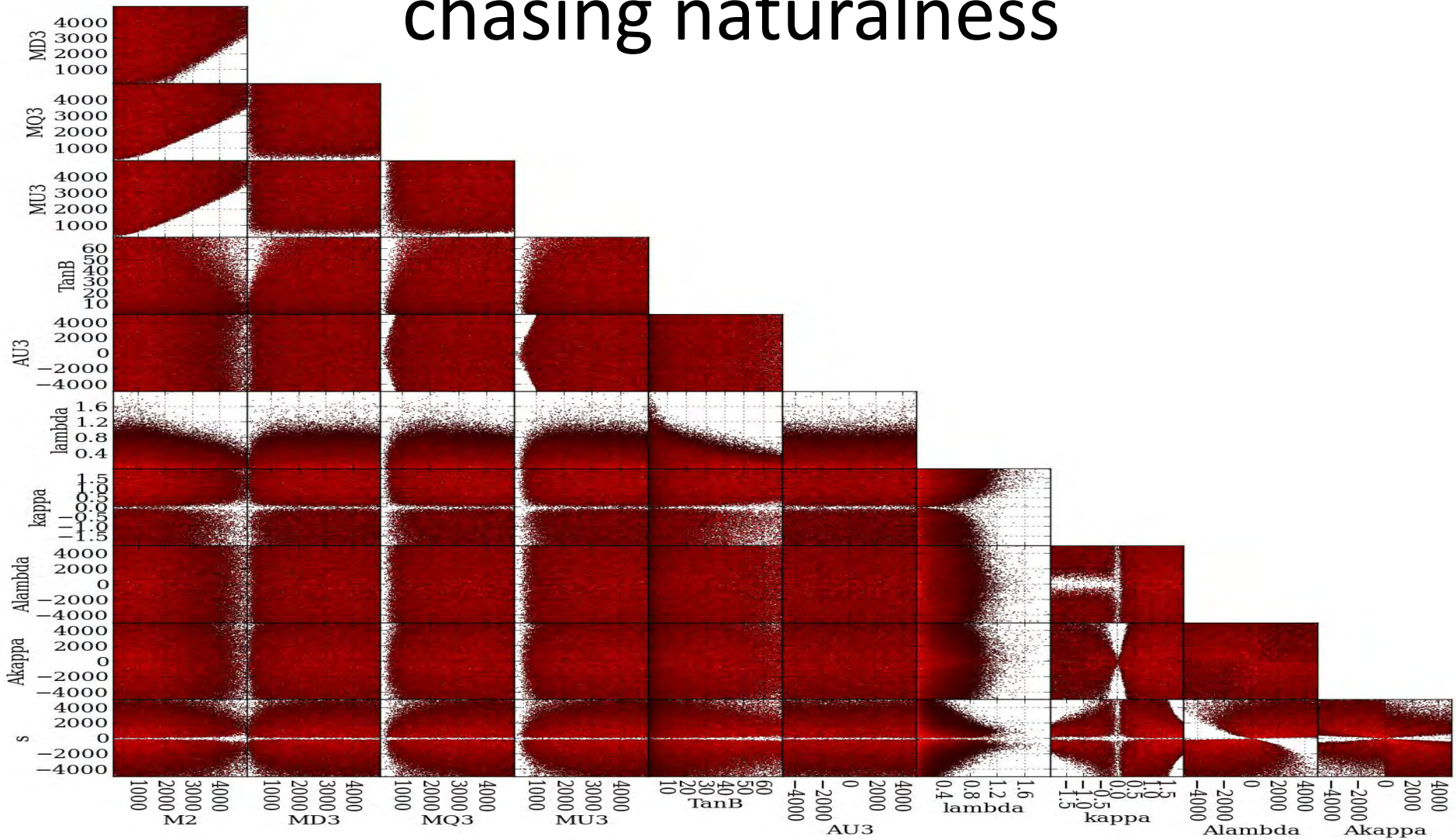
$$\partial m_Z / \partial \mu$$

fine-tuning

if $m_h = m_Z + \alpha\,\mu$

then $|\partial m_Z/\partial\mu| = |\partial m_h/\partial\mu| = \alpha$

chasing naturalness



fine-tuning maps in the NMSSM based on $\partial m_h/\partial p$

Peter Athron, Cs.B., Doyoun Kim, Ben Farmer, Elliot Hutchison in preparation

chasing naturalness

is gauge hierarchy the right guiding principle…

chasing naturalness

is gauge hierarchy the right guiding principle…

… if new physics is not a 4D SUSY GUT?

chasing naturalness

Should we still believe in constrained supersymmetry?

Cs.B., Andy Buckley, Daniel Carter, Ben Farmer, Martin White to appear

new symmetry	new physics predicted
SU(5)	$\sin^2\theta_w$, p^+ decay
SO(10)	ν mass, Z’
E(6)	leptoquarks, SM singlets, Z’
E(8)	3 generations, extra dimensions
E(8) x E(8)	mirror matter, axions
SUSY	spartners, dark matter
SUSY GUTs	gauge unification, desert

new symmetry	new physics predicted
SU(5)	✓ $\sin^2\theta_W$, ✗ p^+ decay
SO(10)	✓ ν mass, ✗ Z'
E(6)	✗ leptoquarks, ✗ SM singlets, ✗ Z'
E(8)	✓ 3 generations, ✗ extra dimensions
E(8) x E(8)	? mirror matter, ✗ axions
SUSY	✗ spartners, ? dark matter
SUSY GUTs	? gauge unification, ? desert

what's dark matter?

what's dark matter?

- lightest supersymmetric particle
- lightest Kaluza-Klein particle
- standard model singlet
    - inert Higgs
    - Z', Z'', …
    - dark photon
    - mirror matter
    - …
- axion (axino, saxion)
- primodial black holes
- …
- all the above? none of the above?

what to expect at the collider?

Ed Witten, Hamburg, July 2002

(38)

IF THIS APPROACH IS RIGHT, WHAT MAY WE FIND AT ACCELERATORS?

THE HIGGS BOSON REALLY SHOULD BE IN REACH - PERHAPS AT 115 GeV AS HINTED AT LEP - SINCE GUT-THEORIES DON'T WORK WITHOUT IT.

IT SHOULD APPEAR AT FERMILAB IF THE LUMINOSITY IS REACHED....

(40½)

WE HAVE A HUNCH THAT SUPERSYMMETRY WILL BE FOUND.

BUT IF IT IS FOUND, THE DETAILS WILL BE SURPRISING, AT LEAST TO ME, SINCE NO MODEL OF THE TeV SCALE SUPERWORLD IS REALLY CONVINCING ... THAT IS PART OF WHAT MAKES THE SEARCH SO EXCITING

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