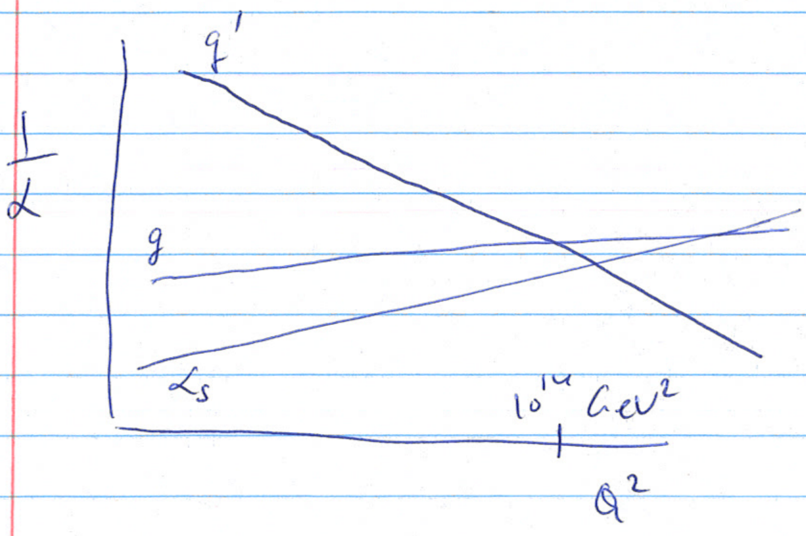


If gauge couplings unify, then perhaps forces unify?

Below ~10^{14} GeV : observe 3 forces

Above ~ 10^{14} GeV : only 1 force?

"grand unification"

In SM, forces arise from imposing local gauge invariance under some symmetry group.

We like to keep that for grand unification : group G

$$G \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

The rank of G must be at least 4.

The simplest group that can do this is $SU(5)$

(Glashow / Georgi 1975)

All fermions should be part of representations of $SU(5)$

Gauge bosons: $SU(N)$ has N^2-1 generators

$SU(5)$ has 24 generators
↙
gauge bosons

After some trial and error:

Fermions contained in a quintuplet and a decuplet

$5: \left(d^c_{red\,L} \quad d^c_{blue\,L} \quad d^c_{green\,L} \quad e_L \quad \nu_L \right)$

$10: \left(u^c_{red\,L} \quad u^c_{blue\,L} \quad u^c_{green\,L} \, , \, e_L^c \right.$

$\left. u_{red\,L} \quad u_{blue\,L} \quad u_{green\,L} \quad d_{red\,L} \quad d_{blue\,L} \quad d_{green\,L} \right)$

SU(5) operations: transform 1 member inside a multiplet to another one

QCD: red → green

weak: $e_L \to \nu_L$

SU(5): $d^c_{green\,L} \to e_L$!

$u_{green\,L} \to d_{green\,L}$!

<u>new interactions</u>

Gauge bosons:

$24 = (8,1) + (1,3) + (1,1) + (3,2) + (\bar{3},2)$

(8 → color, 1 → SU(2))

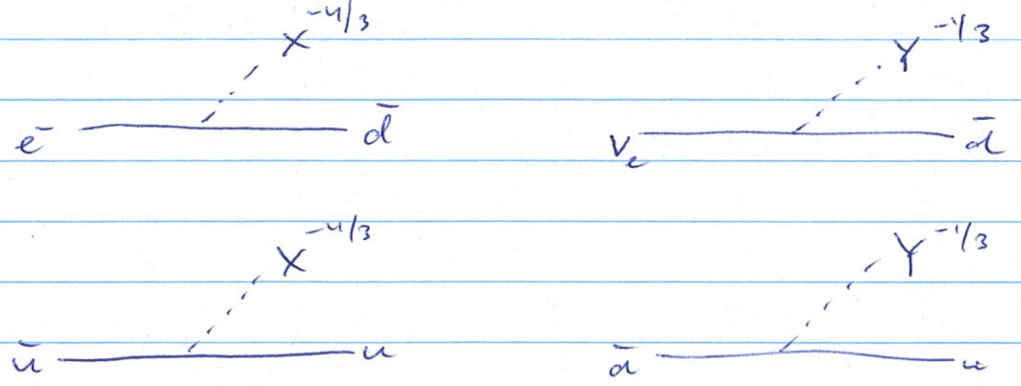
color → gluons

(1,3) → W_1, W_2, W_3 → $W^+ W^- Z, \gamma$

(1,1) → B

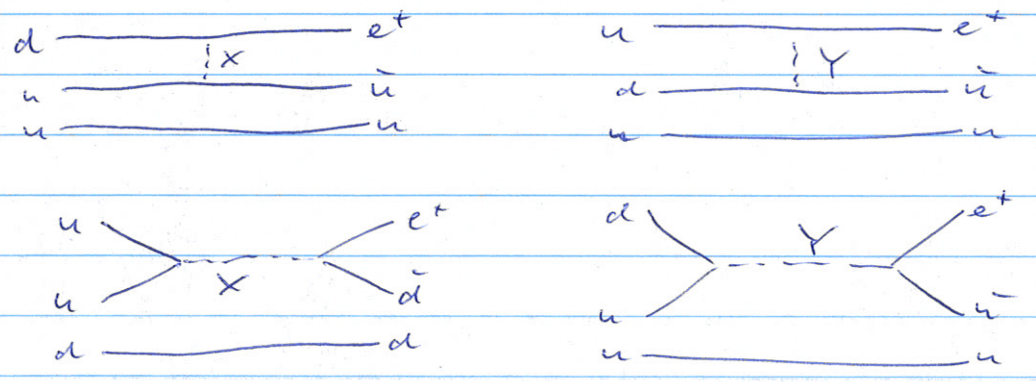
$(3,2) + (\bar{3},2)$ → new X, Y bosons, charge $\pm\frac{4}{3}$ and $\pm\frac{1}{3}$

Interactions mediated by new gauge bosons:



etc.

In particular:



$p \to \pi^0 e^+$ proton decay.

Compare this to weak decay, for example $\mu \to e\nu\nu$

lifetime $\tau_\mu = \frac{a}{g^4} \frac{M_W^4}{m_\mu^5}$

a is some constant, g = weak coupling strength

In analogy: $\tau_p = \frac{a'}{g'^4} \frac{M_X^4}{m_p^5}$

can be made very large by making M_X very heavy (e.g. 10^{14} GeV)

Taking into account other decay modes:

$p \to e^+ \pi^0$ 40–60 %

$\bar{\nu}_e \pi^+$ ~20 %

$e^+ \omega$ or $e^+ \rho$ ~ 20–30 %

Observations: $$\frac{\tau_p}{BR(p \to e\pi^0)} > 8 \cdot 10^{33} \text{ year}$$

$$\frac{\tau_n}{Br(n \to e^+\pi^-)} > 2 \cdot 10^{32} \text{ year}$$

puts limits on M_X of order 10^{16} GeV

This "rules out" simplistic SU(5) models

In supersymmetry:

β functions are modified by new particles

In fact, gauge couplings can be made to all unify at $M \sim 10^{16}$ GeV

(assuming new SUSY particles kicking in from 1–10 TeV)

Also in SUSY GUTs: $p \to K^+ \bar{\nu}_e$ dominates

Current data do not (yet) rule out SUSY SU(5) but comes very close

A different but also interesting gauge group is $SO(10)$

It has a fundamental representation of 16
i.e. all SM fermions, plus ν^c !

$SO(10)$ then also has new interactions mediating between the $SU(5)$ multiplets.

Inspired by string theory: E_6
But representation > 16 : where are the particles?

If energy drops below masses of GUT gauge bosons, GUT breaks down to individual subgroups

$$SO(10) \rightarrow SU(5) \times U(1)$$

$$\text{or} \rightarrow SU(4) \times SU(2)_L \times SU(2)_R$$

$U(1)$: new gauge group, <u>not</u> $U(1)_Y$
$\Rightarrow$ new gauge boson Z'

Typically, the couplings of Z' are determined by the structure of the gauge group, which can <u>differ</u> from SM

For convenience, Z'_{SSM} (sequential Standard Model) is sometimes used: Z' with same couplings as Z.
Not very well motivated by theory.

The Z' originating from $SO(10) \rightarrow SU(5) \times U(1)$ is sometimes called Z'_χ (and $E_6 \rightarrow SO(10) \times U(1)_\psi$)

Beware: Z' can mix with SM Z boson.

$SU(4) \times SU(2)_L \times SU(2)_R$

Pati-Salam : lepton number as the 4th color

left-right symmetric models

$SU(2)_R \rightarrow$ triplet of W_R^1, W_R^2, W_R^3

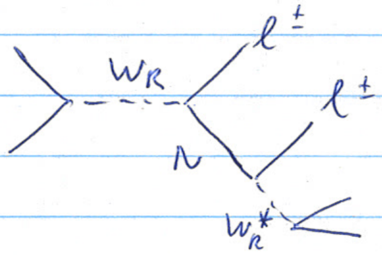
W_R would couple to $\ell^\pm N$ with N right-handed neutrino

Nice idea, would make the SM more symmetric

But: not observed (yet). $\Rightarrow W_R$ very massive ?

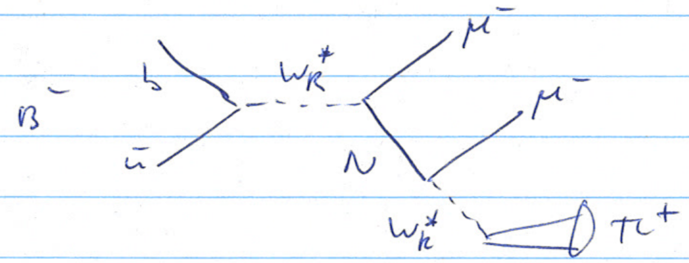
Searches :

ATLAS/CMS:



same-sign leptons + 2 jets

LHCb:



$B^- \rightarrow \pi^+ \mu^- \mu^-$

same sign leptons