What is particle physics?

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LHC days in Split/Hvar, 2024

So what is it?

Easy to answer: find building blocks of nature which appear elementary at a given time and describe their interactions

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The question is how to come up with a theory, and what is a theory supposed to do?

↓

Consult Feynman

True theory in a sense of Feynman

Make a guess
say, equivalence principle

Einstein 1915

↓

Minimal formulation
based on guess

↓

Leave it
so we can compute predictions

unambiguous predictions = self-contained theory

↓

Experiment

Example: Standard Model

The crux of it all

What is at the essence of the SM?

- Gauge principle and Higgs mechanism (SSB)
- Maximal parity violation in weak interaction

} Deeply connected

Gauge principle ⇒ SM

QED = U(1) gauge theory

Electroweak SU(2) gauge theory (W^+, W^-, A)

instructive failure

Schwinger, Glashow 1957-60

$$Q_{em} = T_3 \qquad \Rightarrow \qquad q_{em} = \pm\frac{1}{2}n$$

Charge quantised. Pity it's wrong

Great tragedy of science = beautiful theories killed by ugly facts of nature

Huxley 1870

Electroweak SU(2) x U(1) gauge theory

Glashow 1961

$Q_{em} = T_3 + \frac{Y}{2}$ Y = arbitrary $\Rightarrow$ no prediction of charge

Predictions from gauge principle

Glashow 1961

- universal Z current $J^\mu_Z = \bar{f}(T_3 - \sin^2\theta_W\, Q_{em})\gamma^\mu f$

- W mass determined $$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2\sin^2\theta_W}$$

$$\Rightarrow \quad M_W \simeq \frac{40\,GeV}{\sin\theta_W} \simeq 80\,GeV$$ ⬅ exp $\Rightarrow \sin\theta_W \simeq 1/2$

Eventually Z mass too

Nobody cared - Feynman says nothing about it :(

⬇

Glashow forgets his model?

Glashow - YM model, Inference 2020

Maximal P violation ⇒ SM

Lee, Yang '56

Wu et al '56

V-A ↓ Marshak, Sudarshan 1957

EW gauge theory

Glashow 1961

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad e_R \quad u_R \quad d_R$$

↓

fermions (and gauge bosons) massless

↓

Higgs mechanism (no mass term for W)

Brout, Englert 1964

Higgs 1964

Higgs mechanism completes SM

Weinberg '67

need a Higgs doublet - and it suffices → gives mass to all: W, Z, Higgs, charged fermions

↓

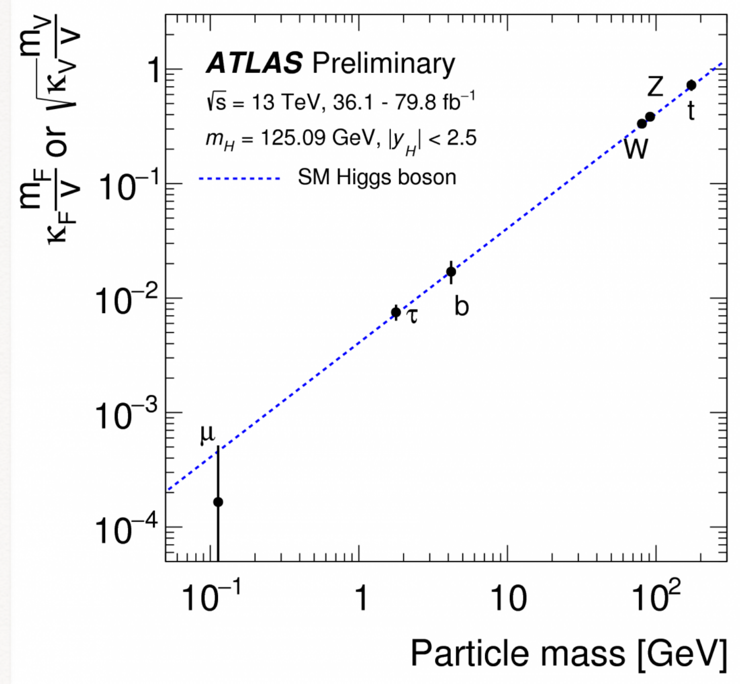
Higgs boson

Goldstone '61

Higgs '64

$$\Gamma(h \to \bar{f} f) \propto y_f^2\, m_h \propto \left(\frac{m_f}{M_W}\right)^2 m_h$$

$$M_W = M_Z \cos\theta_W$$



$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$ but, neutrino massless e_R

Higgs mass determined

$$A(h+h \to h+h) \propto \lambda^2 \propto \left(\frac{m_h}{M_W}\right)^2$$

talk by Cadamuro

poster by Sculac

SM theory of weak interaction $\Rightarrow$ theory of the origin of mass

SM: problems?

Only problem = no problem at all

Problems of numbers?

Why is electron mass what it is?

Why is Cabibbo angle what it is?

Why is vacuum energy small?

Why is Higgs mass small? Hierarchy problem

....

Problems of theory of gravity?

Why is Sun mass what it is?

Why is earth where it is?

Why is cosmological constant small?

....

SM = incomplete

Predicts massless neutrino

wrong - neutrino oscillations

↓

actually not wrong -
just incomplete: $m_\nu \simeq 0.1\, eV$

↓

Not true problem - still, (the?) door to new physics

Logical route

If no true problem, follow a fundamental theory
with clear predictions of new physics

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- LR symmetric theory
- grand unified theory

True theory in a sense of Feynman

Make a guess

↓

Minimal formulation

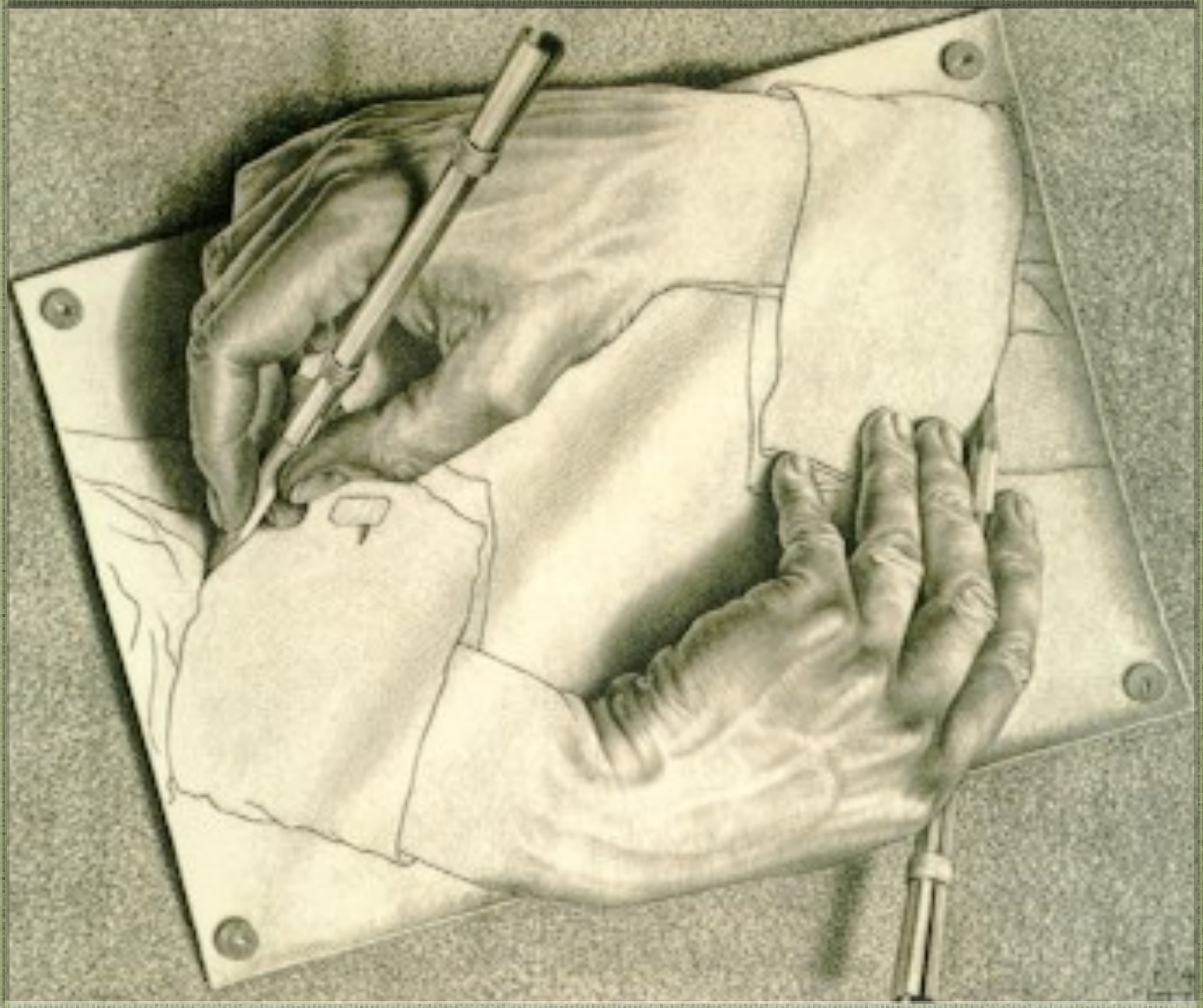
↓

Leave it

↓

Experiment

Parity and SM
- and beyond



P violation: blessing or curse?

LR symmetry → massive neutrino

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

Instructive exercise:

try to build the SSB SM with P ⇒ you will fail miserably

↓

Maximal P violation at root of it all

↓

Neutrino massless

Break P spontaneously?

Left-Right Symmetric Model

Mohapatra, Pati, Salam '74

Mohapatra, GS '75

GS '79

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \Big| \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

W_L | W_R

$$M_{W_R} \gg M_{W_L}$$

↓

Neutrino mass long before experiment

talk by Tello

Seesaw mechanism = Majorana neutrino

Minkowski '77

Mohapatra, GS '79

N = ν_R LR breaking: $M_N \propto M_{W_R}$

Yanagida 1979

Gell-Mann et al, 1979

Glashow 1979

$$m_\nu \propto \frac{1}{M_{W_R}}$$

talk by Tello

small neutrino mass ⇔ near maximal parity violation

Neutrino = anti-neutrino

$\nu^c = \nu \qquad N^c = N$

Majorana 1937

⇓

Lepton Number Violation (LNV)

⇓

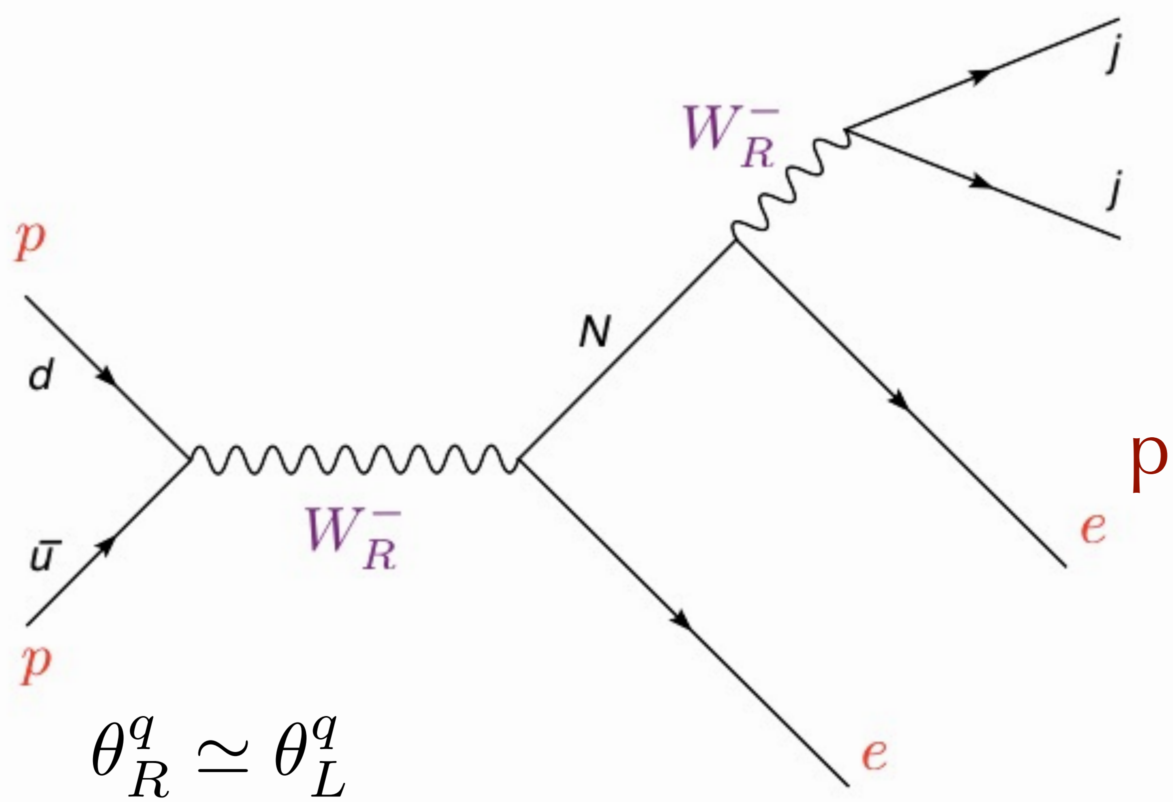
- Neutrinoless double beta decay — *Furry '38*
- LNV at hadron colliders (LHC?) — *Keung, GS '83*

From Majorana to LHC

Keung, GS   1983

Lepton Number Violation: same sign charged leptons

Talks of Leonidopoulos and Tello



probe of Majorana nature of N:

50% lepton
50 % anti-leptons

$$\theta_R^q \simeq \theta_L^q$$

Tello, GS 2015

Tello et al   2011

Tello, PhD thesis 2012

LR = theory of neutrino mass

$$\Gamma(h \to f\bar{f}) \propto m_h (m_f/M_W)^2 \quad \Leftrightarrow \quad \Gamma(N \to W\ell) \propto M_N (m_\nu M_N/M_W^2)$$

SM - charged fermions

Weinberg '67

GIM '69

LR - neutrino

Nemevsek, GS, Tello '12

GS, Tello '16- '20

Plethora of other processes - all calculable

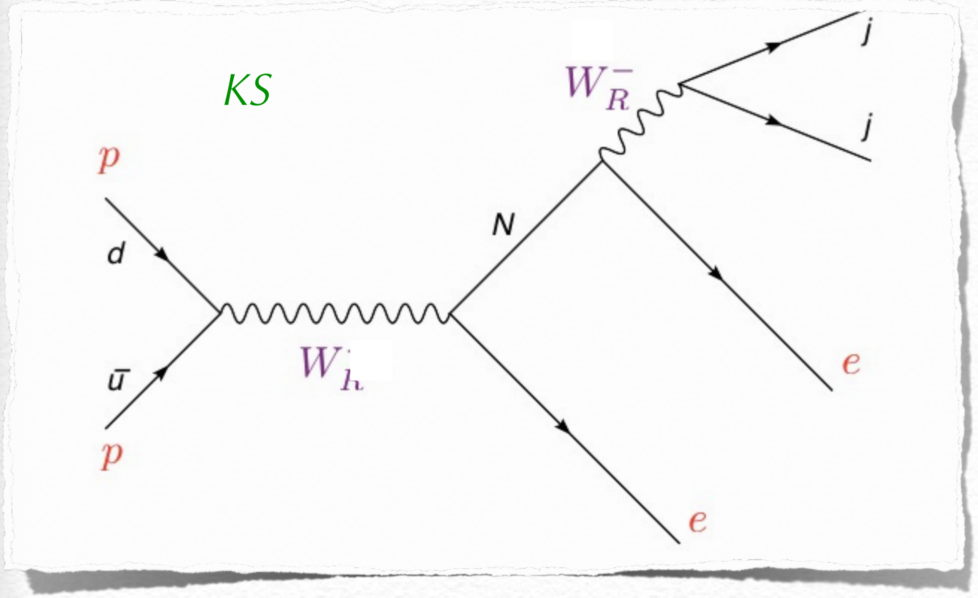
Self-contained theory in a sense of Feynman

Nemevsek, Nesti, Popara, Vasquez…

LR@LHC

ATLAS. CMS

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than



$$M_{W_R} \gtrsim 5\, TeV$$
$$\text{for } 100GeV \lesssim M_N \lesssim 3TeV$$

Also $M_{W_R} \gtrsim 4\, TeV$ from $W_R^- \to \bar{t} + b$

Talks of Leonidopoulos and Tello

KS = some 10 years before follow-ups $\Rightarrow$ I had forgotten about it

Scale of LR?

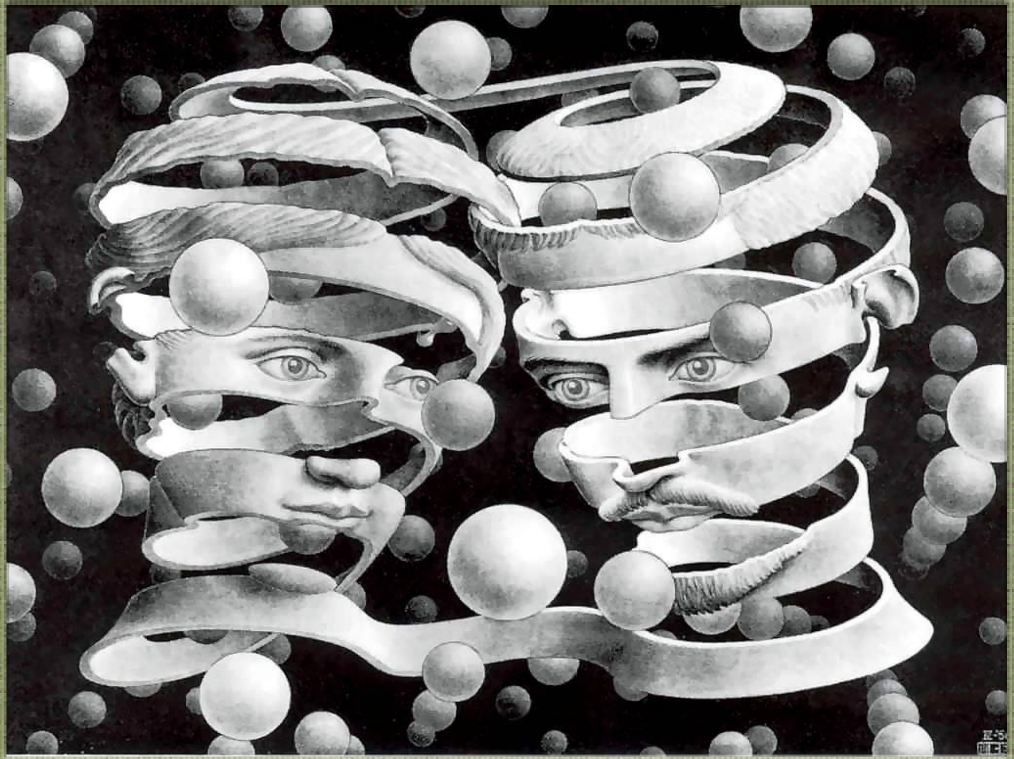
Neutrinoless double beta: e = RH

$$\Downarrow$$

$$M_R \lesssim 20\, TeV$$

tailor made for future hadron collider

Grand unification



Unification of forces

⬇

- Magnetic monopoles

Monopole ⇒ charge quantised — Dirac '31

Charge quantised ⇒ monopoles — 't Hooft '74, Polyakov '74

- Proton decay

Quarks and leptons together

Minimal SU(5)

Georgi, Glashow '74

Talk by Zantedeschi

SU(5) = minimal group that unifies SU(3)×SU(2) ⇒ U(1) for free
⇒ death of SU(2) EW theory not a tragedy of science?

Works with d > 4 operators -
in spite of more than 2 decades of necrologies

- New light states, possibly at LHC ⇒ modifies W mass

GS, Zantedeschi '22

- $\tau_p \lesssim 10^{35}\,yr$ - around the corner?

GS, Zantedeschi '24

Original SU(5): instructive failure

wrong relation $m_e = m_d$ ↓ Georgi, Glashow '74

proton decay

$$\mathcal{L}_{X,Y} = X^\mu(\overline{u^c}\gamma_\mu u + \bar{e}\gamma_\mu d^c + \bar{d}\gamma_\mu e^c) + Y^\mu(\overline{u^c} V_{CKM}\gamma_\mu d + \bar{\nu} V_{PMNS}\gamma_\mu d^c + \bar{u}\gamma_\mu e^c)$$

Mohapatra '79

theory of proton decay - all branching ratios predicted

Beautiful theory killed by ugly facts of nature?

Huxley 1870

Minimal SO(10)

Georgi '74

Fritzsch, Minkowski '74

Talk by Zantedeschi

$$\Psi_{16} = \begin{pmatrix} u \\ u \\ u \\ \nu \\ d \\ d \\ d \\ e \\ e^c \\ d^c \\ d^c \\ d^c \\ \nu^c \\ u^c \\ u^c \\ u^c \end{pmatrix}$$

Generation unified → (heavy) RH neutrino

works with d > 4 operators

↓

New light states, possibly at LHC ⇒ modifies W mass

Preda GS, Zantedeschi '22

Preda GS, Zantedeschi to appear

Grand unification

no theory of proton decay such as original SU(5)

↓

not a theory in a sense of Feynman

↓

Makes you think of Huxley :(

Message

Keep testing SM

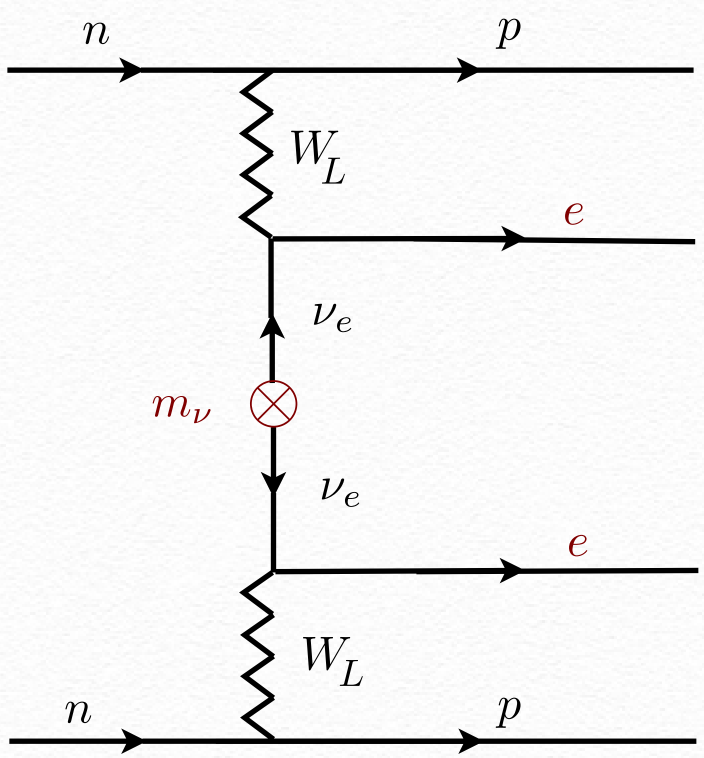
Study & probe physically motivated theories

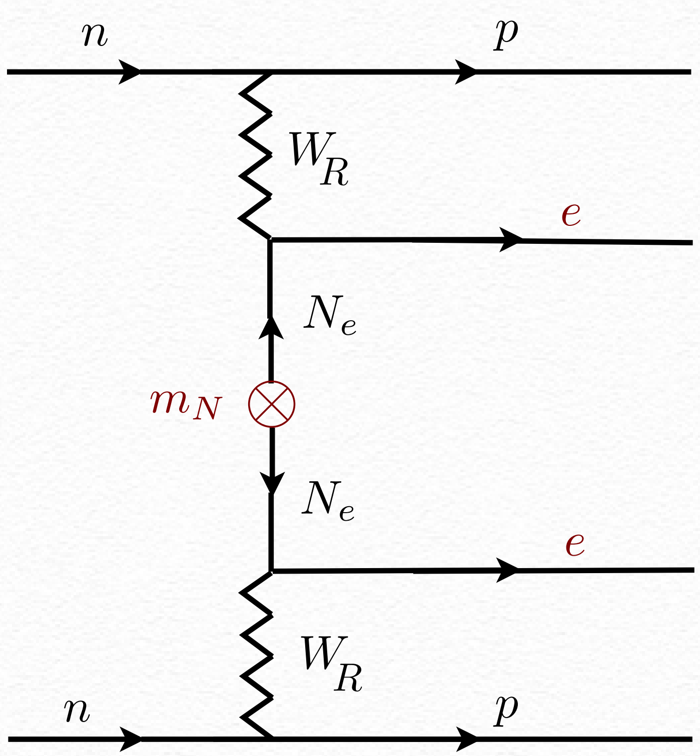
Hard to find a black cat in a dark room -
especially if one is blind

Thank you

Neutrinoless double beta & LR

Mohapatra, GS '79, '81





e = RH → deep connection with LHC

Tello et al '11

Talk of Tello

Producing N without W_R

Seesaw ⇒ $\theta_{\nu N} \simeq \sqrt{\frac{m_\nu}{M_N}}$

⬇

$$\theta_{\nu N} \bar{N}_L \gamma^\mu e_L W^+_\mu$$

⬇

$$\sigma(N) \propto \frac{m_\nu}{M_N} \simeq 0$$

SM: problems?

Often argued: fermion mass protected - Higgs mass not -
against large scales (cut-off)

After all, fermion mass ~ chiral symmetry

Wrong

Renormalisation: $$y_f = y_f^0 \left[1 + \left(\frac{\alpha}{4\pi} + \frac{(y_f^0)^2}{16\pi^2} \right) \ln \frac{\Lambda}{v} \right]$$

$$\lambda = \lambda^0 + \frac{g^4}{16\pi^2} \ln \frac{\Lambda}{v} + \ldots$$

Yukawa protected more - but nothing to do with large scales

small Yukawa = stable against loops
small λ not - but λ is not small ($m_h \simeq M_W$)

You could worry about instability at astronomical scales
- but these are LHC days: don't worry, be happy :)

Hierarchy problem = problem of scale?

$$v^2 = (v^0)^2 + \Lambda^2$$

- Why is weak scale much smaller than Planck scale?

$$G_N = \frac{1}{M_{Pl}^2} = \frac{g^2}{M_F^2} \qquad g \ll 1 \Longrightarrow M_F \ll M_{Pl}$$

Glashow ‘85

ADD ‘98

- How to keep v small in perturbation theory?

Low E supersymmetry -> makes first question far more dramatic: now another scale too much smaller than Planck scale?

Questions - **not problems -** just renormalise v

Argument → new physics around the corner

Problem: corner not well defined

Strong CP violation in SM

QCD - extra interaction $\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} \propto \theta \vec{E}\vec{B}$

violates both P and T(CP)

CP violating physical term $\bar{\theta} = \theta + \arg\det M_q$

neutron electric dipole moment $(\bar{\theta})_{exp} \lesssim 10^{-10}$

Again, perfectly consistent in SM:
experiments decides

In perfect analogy with CKM determined by experiment

Question of naturalness?

Ellis, Gaillard '79

perturbation theory
of the strong CP parameter

$$(\bar{\theta})_{loop} \simeq 10^{-19}$$

$$(\bar{\theta})_{inf} \simeq (\frac{\alpha}{2\pi}\frac{m_q}{M_W})^6 \ln\frac{\Lambda_{cutoff}}{\Lambda_{QCD}}$$

$$\Lambda_{cutoff} = M_{Pl} \Rightarrow (\bar{\theta})_{inf} \simeq 10^{-19}$$

No strong CP problem whatsoever in SM

Simple: measure as many dipole moments. If agree with the value of $\bar{\theta}$ - SM is complete

SM: incomplete?

- Lacks DM candidate

Not the task of SM -
and too many candidates

- Genesis not explained?

Not the task of SM -
and no predictive theory

- No inflation

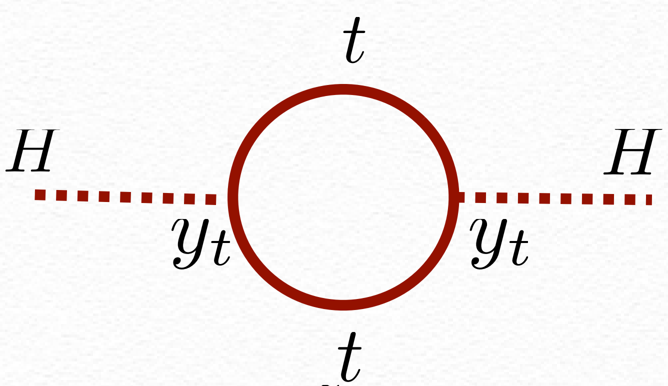
Not the task of SM -
and no theory

Attempt: Higgs of SU(5) 24_H

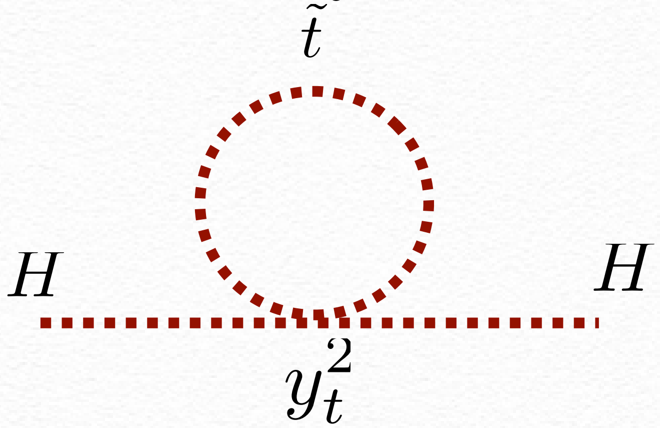
Guth '80

Neutrino mass = the task of SM. Unique theory = LRSM

Low energy supersymmetry



$$\delta m_H^2 = \frac{y_t^2}{16\pi^2}\left(\Lambda^2 + m_t^2\right)$$



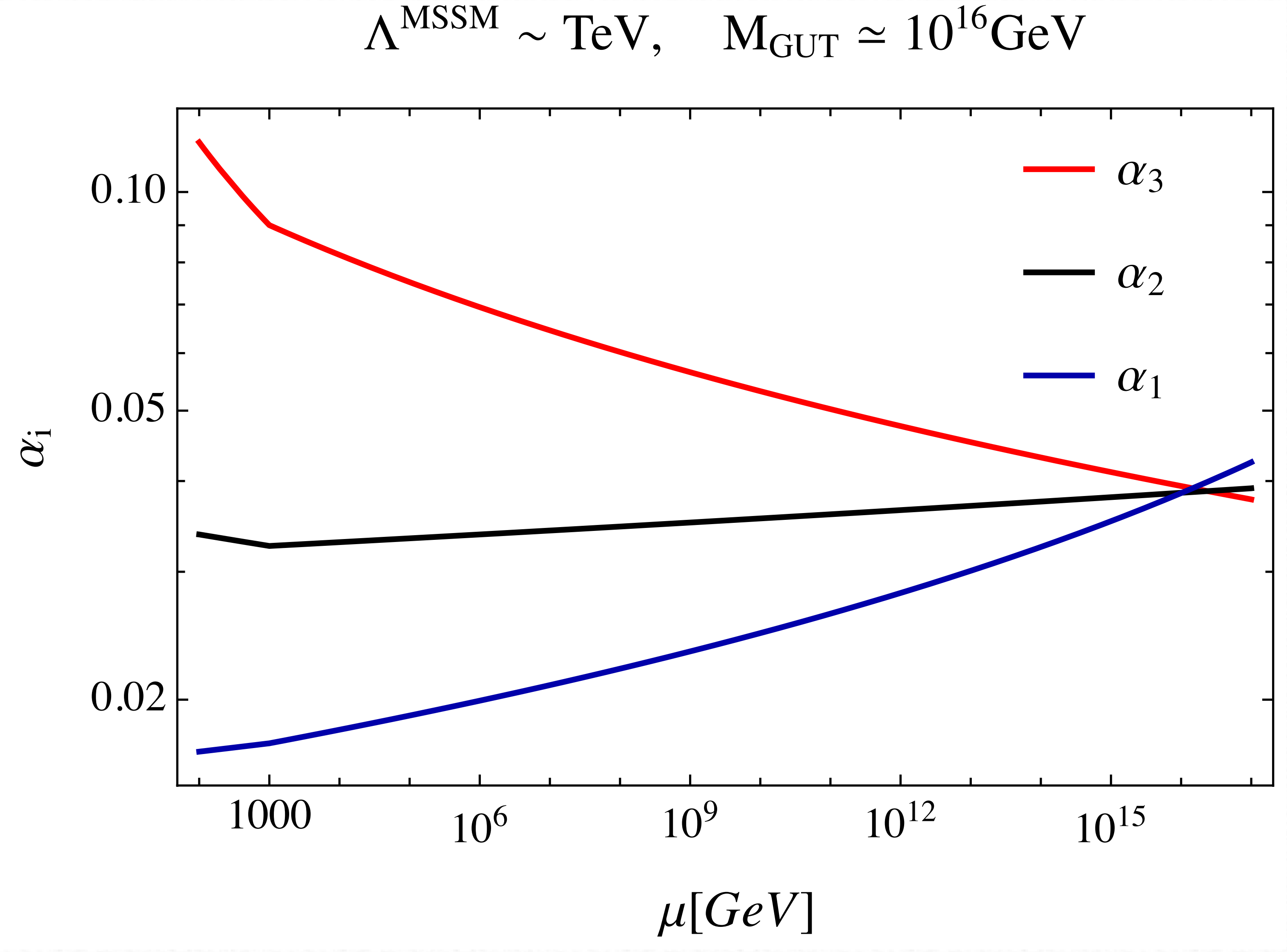
$$\delta m_H^2 = -\frac{y_t^2}{16\pi^2}\left(\Lambda^2 + m_{\tilde{t}}^2\right)$$

➡ $$\delta m_H^2 = -\frac{y_t^2}{16\pi^2}\left(m_{\tilde{t}}^2 - m_t^2\right)$$

$$m_{\tilde{t}} \leq TeV$$

vague - how can you quantify fine-tuning?

old claim: @LEP



$m_{\tilde{p}} \simeq TeV$

Low E supersymmetry $\Rightarrow$ predicts $\sin^2\theta_W = 0.23$

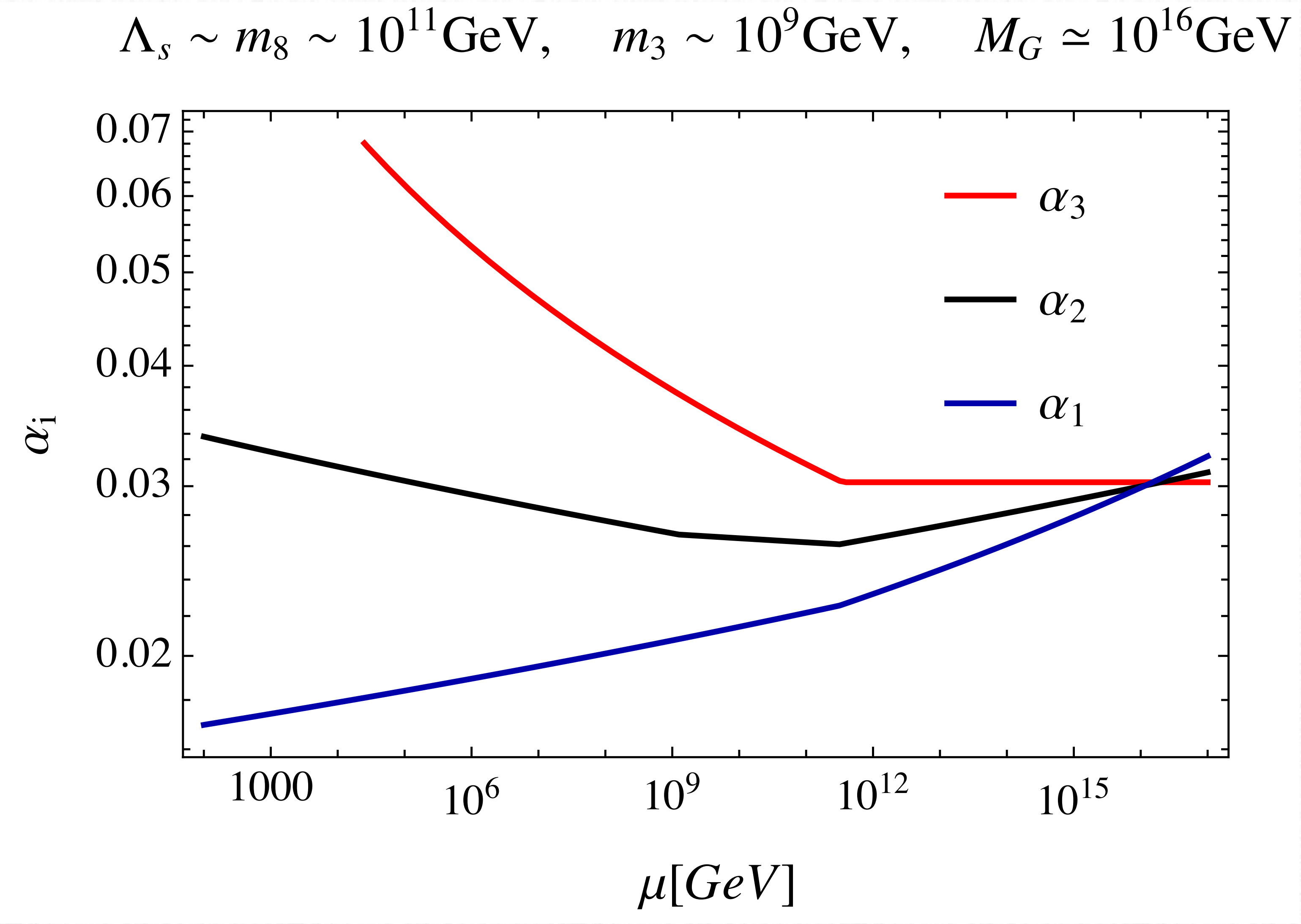
$m_t \simeq 200\,GeV$

Marciano, GS '81

Talk by Zantedeschi

Needs naturalness, otherwise: $$\Lambda = \Lambda^{\mathrm{MSSM}} \left(\frac{M_{\mathrm{GUT}}^2}{m_3 m_8} \right)^{3/4} .$$

GS, Zantedeschi '22



Low scale = double hierarchy problem

Higgs mass in MSSM

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

$$M_S^2 \equiv \tfrac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2),\ x_t \equiv X_t/M_S$$

$$X_t \equiv A_t - \mu\cot\beta,\ X_b \equiv A_b - \mu\tan\beta$$

- No real prediction - dependence on parameters
- If Λ_{susy} large $\Rightarrow$ decoupling $\Rightarrow$ empty statement
- For $\Lambda_{susy} = M_P \Rightarrow m_h \lesssim 5M_Z$ for $x_t = 2$
  and $m_h \lesssim TeV$ for $x_t = \sqrt{6}$
- SM consistency: 90 GeV $\lesssim m_h \lesssim$ 150 GeV

Ellis, Ridolfi, Zwirner '90s

Assuming low scales = no prediction. Low LR scale is more 'natural'