Higgs and Beyond

ESHEP 2023
Grenaa, Denmark

Lecture 4/4

Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

( christophe.grojean@desy.de )
Outline

- **Lecture #1**
  - Symmetries, Fields, Lagrangians
  - From Fermi theory to the Standard Model
  - Chirality and mass problem

- **Lecture #2**
  - Spontaneous symmetry breaking, aka Higgs mechanism
  - Particles masses, unitarity and the Higgs boson
  - Higgs phenomenology (decay and production at colliders)
  - Higgs quantum potential (vacuum (meta)stability, naturalness)
  - Hierarchy problem

- **Lecture #3**
  - Supersymmetry
  - Composite Higgs
  - Extra dimensions

- **Lecture #4**
  - Connections particle physics-cosmology
  - Quantum gravity: landscape vs swampland
  - BSM searches beyond colliders
HEP with a Higgs boson

The Higgs discovery has been an important milestone for HEP but it hasn’t taught us much about BSM yet.

\[
\frac{\delta g_h}{g_h} \sim \frac{v^2}{f^2} = \frac{g_\star^2 v^2}{\Lambda_{BSM}^2}
\]

typical Higgs coupling deformation:

**current (and future) LHC sensitivity**

\[O(10-20)\% \Leftrightarrow \Lambda_{BSM} > 500(g_\star/g_{SM}) \text{ GeV}\]

not doing better than direct searches unless in the case of strongly coupled new physics (notable exceptions: New Physics breaks some structural features of the SM e.g. flavour number violation as in \(h \rightarrow \mu \tau\))

**Higgs precision program is very much wanted to probe BSM physics**
What is the scale of New Physics?

### High Scale Wishes

- small EDMs, FCNC: \[
  \frac{g F_{\mu\nu} \bar{\psi} H \sigma^{\mu\nu} \psi}{M_{NP}^2}
\]
- tiny neutrino masses: \[
  \frac{(LH)^2}{M_{NP}}
\]
- slow proton decay: \[
  \frac{UUDE}{M_{NP}^2}
\]

### Low Scale Wishes

- small EDMs: \[
  \propto \text{axion?}
\]
- tiny vacuum energy: \[
  \propto ?
\]
- light Higgs boson: \[
  m_H^2 \approx M_{NP}^2 \gg (125\text{GeV})^2
\]
- \[\text{argdet} Y \leq 10^{-10}\]

Where is everyone?

even new physics at few hundreds of GeV might be difficult to see and could escape our detection

- compressed spectra
- displaced vertices
- no MET, soft decay products, long decay chains
- uncoloured new physics

R-susy

Neutral naturalness (twin Higgs, folded susy)

Relaxion
The Standard Model: Matter
—The particles seen in a detector—

<table>
<thead>
<tr>
<th>Absolutely stable particles</th>
<th>Collider stable particles</th>
<th>Sort of stable particles</th>
<th>Displaced vertex particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ ($m=0$)</td>
<td>n ($m=940\text{MeV, ct}=10^{14}\text{mm}$)</td>
<td>$\Xi, \Lambda, \Sigma, \Omega$ ($m=1-2\text{GeV, ct}=10-100\text{mm}$)</td>
<td>B, D</td>
</tr>
<tr>
<td>($G$ ($m=0$))</td>
<td>$\mu$ ($m=940\text{MeV, ct}=10^6\text{mm}$)</td>
<td>$K_S$ ($m=500\text{MeV, ct}=30\text{mm}$)</td>
<td>$\Xi_{c,b}, \Lambda_{c,b}$ ($m=2-5\text{GeV, ct}=0.1-0.5\text{mm}$)</td>
</tr>
<tr>
<td>$\nu$ ($m\sim0$)</td>
<td>$K_L$ ($m=500\text{MeV, ct}=10^4\text{mm}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>e$^-$ ($m=511\text{keV}$)</td>
<td>$\pi^\pm$ ($m=140\text{MeV, ct}=10^4\text{mm}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>p ($m=938\text{MeV}$)</td>
<td>$K^\pm$ ($m=500\text{MeV, ct}=10^3\text{mm}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

You don’t “see” most of the SM particles!
You have to infer their existence.
Physics probed at Colliders

Colliders are best places to search for

<table>
<thead>
<tr>
<th>Heavy objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>With short lifetime</td>
</tr>
<tr>
<td>That are rarely produced</td>
</tr>
<tr>
<td>That have a direct coupling to quarks/gluons or electrons</td>
</tr>
</tbody>
</table>

Are we sure that BSM falls in this category?
No, and actually, we only have evidence that BSM has gravitational interactions.
There are compelling arguments that BSM can be seen at colliders.
But we can also find mind-bogging BSM signatures beyond colliders.
Cosmological relaxation
Is the Higgs doing anything for the Universe?

- **Astrophysics**: it gives mass to the W and allows the stars to burn

- **Nucleosynthesis**: it gives masses to the up and down quarks and in a subtle (fine-tuned?) way prevents the proton to decay into neutron

- **Baryogenesis**: source of CP-violation and out-of-equilibrium phase?

- **Inflation**: slow-rolling scalar energy density to drive the (early) inflationary expansion of the Universe?

The first 2 points only rely on the Higgs vev (static)

The last 2 points need the Higgs field (dynamic)
(and also additional new physics beyond the Standard Model)

Is Cosmology doing anything for the Higgs?
The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac: hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language? In which sense is it addressing the stability of small numbers at the quantum level?

- $m_H(t)$: $m_H^2(t = -\infty) = \Lambda^2_{\text{cutoff}} \rightarrow m_H^2(\text{now}) = -(125 \text{ GeV})^2$
- Higgs mass-squared promoted to a field, the “relaxion"
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But “Why/How/When does it stop evolving?”
- The Higgs mass-squared reaches a small negative value
- The electroweak symmetry breaking back-reacts on the relaxion field and stops the time-evolution of the dynamical system

— Self-organized criticality —

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from dynamics not from symmetries anymore!

important consequences on the spectrum of new physics
Higgs-axion Cosmological Relaxation

Graham, Kaplan, Rajendran '15

\[ \phi \] slowly rolling field (inflation provides friction) that scans the Higgs mass

\[ \Lambda^2 \left( -1 + f \left( \frac{g\phi}{\Lambda} \right) \right) |H|^2 + \Lambda^4 V \left( \frac{g\phi}{\Lambda} \right) + \frac{1}{32\pi^2} \frac{\phi}{f} \tilde{G}^{\mu\nu} G_{\mu\nu} \]

- Higgs mass depends on \( \phi \)
- Potential needed to force \( \phi \) to roll-down in time (during inflation)
- Axion-like coupling that will create the potential barrier stopping the rolling of \( \phi \) when the Higgs develops its vev

\[ \Lambda_{QCD}^3 h \cos \frac{\phi}{f} \]

If \( \phi \) continues rolling, the Higgs vev increases, the potential barrier gets larger and ultimately prevents \( \phi \) from rolling down further.
Higgs-axion Cosmological Relaxation

Graham, Kaplan, Rajendran ’15

Hierarchy problem solved by light weakly coupled new physics and not by TeV scale physics
Consistency Conditions

- **Higgs vev stops cosmological rolling**
  \[ \Lambda_{\text{QCD}}^3 \frac{v}{f} \sim \frac{\partial}{\partial \phi} \left( \Lambda^4 V(g\phi/\Lambda) \right) \sim g\Lambda^3 \]

- **Slow rolling:**
  \[ H_I > \frac{\Lambda^2}{M_P} \]
  ensures that the energy density stored in \( \phi \) does not affect inflation

- **Classical rolling:**
  \[ H_I^3 < g\Lambda^3 \]

\[ \frac{1}{H_I} \frac{d\phi}{dt} = \frac{1}{H_I^2} \frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2} \]

\[ \frac{\Lambda^6}{M_P^3} < g\Lambda^3 = \Lambda_{\text{QCD}}^3 \frac{v}{f} \]
i.e. \[ \Lambda < 10^7 \text{ GeV} \left( \frac{10^9 \text{ GeV}}{f} \right)^{1/6} \]

*note:* \( v \ll \Lambda \) provided that \( g \ll 1 \). It doesn’t explain why the coupling is small (that question can be postponed to higher energies, requires more model-building engineering, relaxion=PGB?) but it ensures that the solution is stable under quantum correction.
Two classes of relaxion models

- **H-dependent potential barrier**
  Graham, Kaplan, Rajendran ’15
  Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant ’15

  Potential barriers in the relaxion potential appear soon after EWSB occurs and the relaxion gets trapped in one minimum.

- **H-dependent friction**
  Hook, Marques-Tavares ’16
  You ’17
  Fonseca, Morgante, Servant ’18

  The potential barriers in the relaxion potential always exist but there is no friction to stop the relaxion until the Higgs vev approaches a critical value where particle production takes place and stops the evolution. But beware of relaxion fragmentation due to fluctuation growth.

drawings borrowed from A. Matsedonskyi, DESY workshop seminar ’17
Phenomenological Signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below $\Lambda \sim 10^9$GeV is in the form of (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim \left( \frac{g \Lambda^5}{f v^2} \right)^{1/2} \sim (10^{-20} - 10^2) \text{ GeV}$$
Phenomenological Signatures

A QFT rationale for light and weakly coupled degrees of freedom

—interesting cosmology signatures—

○ BBN constraints
○ decaying DM signs in $\gamma$-rays background
○ ALPs
○ superradiance

—interesting signatures @ SHiP—

○ production of light scalars by B and K decays

—interesting atomic physics—

○ change of atom sizes
○ relaxion halo around earth/sun which induce $\Delta m_e/m_e$ and $\Delta \alpha/\alpha$

Espinosa et al ’15
Flacke et al ’16
Choi and Im ’16
Banerjee et al ’19
or another way to dynamically select our vacuum none

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N

N
Naturalness

N copies of the SM

High Higgs cutoff $\Lambda_H$, high gravity cutoff $\Lambda_G$

Two effects:

1. Random UV contributions $\rightarrow$ flat distribution of $m_H^2$ between $\pm \Lambda_H^2$

2. Large number of species renormalizes Planck scale (e.g. graviton wavefunction renorm.)

Gravitational strong coupling scale $\Lambda_G$

At least 1 copy w/ $|m_H| \sim \Lambda_H/\sqrt{N}$
Now…why does the copy with the smallest $m_H$ dominate?

**Cosmology.**

Reheaton $\phi$ starts universe via $\phi |H_i|^2$ couplings

Decays (provided $m_\phi < |m_{H_i}|$)

\[ m_{H,i}^2 < 0 \]

\[ m_{H,i}^2 \geq 0 \]

\[ \Gamma \propto \frac{1}{m_{H,i}^2} \]

\[ \Gamma \propto \frac{1}{m_{H,i}^2} \]

Preferentially reheats copy w/ smallest $|m_H|$ & $m_{H}^2 < 0$

The Universe reheats/populates the patch with EWSB and light Higgs, the other patches are left empty.
Landscape of Higgs Masses populated by inflation

\[-M_*^2 \leq m_H^2 \leq M_*^2\]
Sliding Naturalness

After reheating and a time

$$t_c \sim \frac{1}{H(\Lambda_{\text{QCD}})} \sim 10^{-5} \text{ s}$$

All patches where the Higgs vev

$$\langle H^0 \rangle \equiv h$$

Is outside of a certain range

$$h_{\text{min}} \lesssim h \leq h_{\text{crit}}$$

crunch
Only universes with the observed value of the weak scale can live cosmologically long times. **Today the multiverse looks like:**

\[
\langle h \rangle \simeq v
\]
This scenario can be realised by two new scalars apparently decoupled from each other with suitable interactions with the Higgs field.
Swampland: UV/IR mixing
Can the SM be embedded in a theory of quantum gravity at the Planck scale? Can QG be really decoupled at low energy?

Would certainly be true if any QFT can be consistently coupled to QG

Instead Vafa conjectured in 2005 that there exists a **swampland**

This conjecture has potentially far-reaching implications for phenomenology
Landscape/Swampland Conjectures

0) No exact global symmetry

For a review, see Banks, Seiberg ‘10

1) Gravity is the weakest force

In any UV complete U(1) gauge theory there must exist at least one charged particle with mass $M$ such that: $M/M_P < g \cdot q$

Why? otherwise extremal charged BH cannot decay!

$Q=M$

BH can decay iff $M_1+M_2<M$, i.e. $M_1<M-M_2=Q-q_2=q_1$

Arkani-Hamed, Motl, Nicolis, Vafa ‘06
Landscape/Swampland Conjectures

2) non-susy AdS vacua ($V_{\text{min}}<0$) are unstable

Consider the SM (with cc) compactified on a circle of radius $R$

\[ V(R) \simeq \frac{2\pi r^3 \Lambda_4}{R^2} - 4 \left( \frac{r^3}{720\pi R^6} \right) + \sum_i (2\pi R)(-1)^{s_i} n_i \rho_i(R) \]

From 4D c.c.

\[ \gamma, g_{\mu\nu} \]

\[ \rho(R) = \pm \sum_{n=1}^{\infty} \frac{2m^4 K_2(2\pi Rmn)}{(2\pi)^2 (2\pi Rmn)^2} \]

Heavier particles have exponentially small contribution

Majorana neutrinos leads to an AdS vacuum $\Rightarrow$ in swampland

Dirac neutrinos avoid AdS vacuum if $m_\nu^4 < \Lambda_4$

\[ \langle H \rangle < 1.6 \frac{\Lambda_4^{1/4}}{Y_\nu} \Rightarrow \text{Large quantum corrections end up in swampland (for fixed } \Lambda_4 \text{ and } Y_\nu) \]

SM with 3 families but without Higgs also develops AdS vacuum $\Rightarrow$ in swampland
Swampland Conjectures

3) \( M_P \parallel \nabla_i \phi_i V(\phi_i) > c V(\phi_i) \) with \( c \) is \( O(1) \) for any field configuration

Obied, Ooguri, Spodyneiko, Vafa '18

- Pure positive cosmological constant, i.e. vacuum energy, (dS vacuum) is forbidden

- Quintessence: Agrawal, Obied, Steinhart, Rafa ‘18

\[
V(\phi) = \Lambda^4 e^{-\kappa \phi / M_P}
\]

\[
\frac{M_P \parallel \nabla_i \phi_i V(\phi_i)}{V(\phi_i)} = \frac{\kappa \Lambda^4}{\Lambda^4 + \lambda v^4 + V_0} \quad \text{at} \quad (H = 0, \phi = 0)
\]

\[
\frac{M_P \parallel \nabla_i \phi_i V(\phi_i)}{V(\phi_i)} = \frac{\kappa \Lambda^4}{\Lambda^4 + V_0} \quad \text{at} \quad (H = v, \phi = 0)
\]

- Quintessence + Higgs: Denef, Hebecker, Wrase ‘18

\[
V(H, \phi) = \Lambda^4 e^{-\kappa \phi / M_P} + \lambda (|H|^2 - v^2)^2 + V_0:
\]

- Quintessence + axion: Murayama, Yamazaki, Yanagida ‘18

\[
V(\theta, \phi) = \Lambda^4 e^{-\kappa \phi / M_P} + \Lambda^4_{QCD} (1 - \cos(\theta/f)) + V_0:
\]

\[
\frac{M_P \parallel \nabla_i \phi_i V(\phi_i)}{V(\phi_i)} = \frac{\kappa \Lambda^4}{\Lambda^4 + V_0} \quad \text{at} \quad (\theta = 0, \phi = 0)
\]

\[
\frac{\kappa \Lambda^4}{\Lambda^4 + \Lambda^4_{QCD} + V_0} \quad \text{at} \quad (\theta = \pi f, \phi = 0)
\]

Planck data \( \Rightarrow \) swampland conjecture

0.6 > \kappa > c

at least one of them is as small as

\[
\mathcal{O} \left( \frac{cc}{EW^4} \right) \sim \left( \frac{10^{-3} \text{ eV}}{100 \text{ GeV}} \right)^4 \sim 10^{-56}
\]

\[
\mathcal{O} \left( \frac{cc}{QCD^4} \right) \sim \left( \frac{10^{-3} \text{ eV}}{200 \text{ MeV}} \right)^4 \sim 10^{-44}
\]
It is not that String Theory rules out the SM as we know it. But non-trivial interactions among seemingly decoupled sectors must exist: UV enforces interactions among IR degrees of freedom, like anomaly conditions enforce constraints on IR physics.
Gravitational waves
The pictures that shook the Earth

GW150914

1.3 billion years later on earth

what did it teach us?

- never give up against strong background when you know you are right
- $m_g < 10^{-22}$ eV ($c_g - c_\gamma < 10^{-17}$ GRB observed together with GW with the same origin?)
- no spectral distortions: scale of quantum gravity $> 100$ keV
The Cosmos: GW Wave spectrum
July 12, 2017
EPS HEP 2017, Venice

GW and astrophysics/cosmology

Relic radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae

Space detectors
Rein radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae

10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz

Inflation Probe
Pulsar timing
Ground interferometers

Supermassive BH Binaries
BH and NS Binaries
Binaries coalescences

Supermassive BH Binaries
BH and NS Binaries
Binaries coalescences

Supernovae
Spinning NS

Ground interferometers
Laser Interferometer Gravitational Wave Observatory

EPS-HEP2017

Supernovae

Extreme Mass Ratio Inspirals
BH and NS Binaries
Binaries coalescences
Spinning NS

Inflation Probe
Pulsar timing
Ground interferometers

Relic radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae

Supermassive BH Binaries
BH and NS Binaries
Binaries coalescences

Supernovae
Spinning NS

Ground interferometers
Dynamics of EW phase transition

The asymmetry between matter-antimatter can be created dynamically it requires an out-of-equilibrium phase in the cosmological history of the Universe.

An appealing idea is EW baryogenesis associated to a first order EW phase transition.

The dynamics of the phase transition is determined by Higgs effective potential at finite $T$ which we have no direct access at in colliders (LHC≠Big Bang machine).

finite $T$
Higgs potential

Higgs couplings
at $T=0$

SM: first order phase transition iff $m_H < 47$ GeV
BSM: first order phase transition needs some sizeable deviations in Higgs couplings.
GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

direct probe of physical process of the very early universe

possible cosmological sources:
inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

ElectroWeak Phase Transition (if 1\textsuperscript{st} order)

typical freq. \(\sim (\text{size of the bubble})^{-1} \sim (\text{fraction of the horizon size})^{-1}\)

@ \(T = 100\ \text{GeV}\),

\[
H = \sqrt{\frac{8\pi^3}{45}} \frac{T^2}{M_{Pl}} \sim 10^{-15} \ \text{GeV}
\]

redshifted freq.

\[
f \sim \# \frac{2 \cdot 10^{-4} \ \text{eV}}{100 \ \text{GeV}} 10^{-15} \ \text{GeV} \sim \# 10^{-5} \ \text{Hz}
\]

The GW spectrum from a 1\textsuperscript{st} order electroweak PT is peaked around the milliHertz frequency
GW and the ElectroWeak Phase Transition

GW interact very weakly and are not absorbed

$M_{\text{QCD}}$  $M_{\text{TeV}}$  $M_{\text{PeV}}$

The GW spectrum from a 1st order electroweak PT is peaked around the milliHertz frequency
"Large" deviations of the Higgs (self-)couplings expected to obtain a 1st order phase transition
BSM and Atomic Physics
Atomic Clocks as a BSM probe

Physics beyond QED contributes to the frequency of the radiation

\[
\frac{1}{\lambda} = R Z^2 \left( \frac{1}{n^2} - \frac{1}{n'^2} \right)
\]

\(|\psi(0)|^2/n^3\) is the wave-function-density at the origin.

\[
V_{\text{weak}}(r) = -\frac{8G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi} e^{-rm Z_0} \frac{e^{-rm Z_0}}{r}
\]

\[
\delta E_{nlm}^{\text{weak}} = -\frac{8G_F m_Z^2}{\sqrt{2}} \frac{g_e g_A}{4\pi m_Z^2} |\psi(0)|^2 \frac{\delta_{l,0}}{n^3}
\]

fifth force

Exp sensitivity in atomic clock measurements \(O(10^{-18})\)

(ms over one billion years)

Not all transitions can be used (yet) for BSM frequency shifts \(O(1\text{-}100 \text{ Hz})\) over frequencies \(O(1\text{THz})\): still a sensitivity \(O(10^{-6}\text{-}9)\)

can be used to detect new (long range) forces
Atomic Clocks as a BSM probe

$$\frac{\delta(E_2 - E_1)}{E_2 - E_1}$$
Isolating the signal: isotope shifts

\[ \nu_{i}^{AA'} = \nu_{i}^{A} - \nu_{i}^{A'} \]

\[ \delta\nu_{AA'}^{i} = K_{i} \mu_{AA'} + F_{i} \delta \langle r^2 \rangle_{AA'} + H_{i}(A - A') \]

\( K_{i} \) and \( F_{i} \) are difficult to compute to the accuracy needed but they are the same for different isotopes.

The King Plot

W. H. King,


- First, define modified IS as \( m\delta\nu_{AA'}^{i} \equiv \delta\nu_{AA'}^{i}/\mu_{AA'} \)
- Measure IS in two transitions. Use transition 1 to set \( \delta \langle r^2 \rangle_{AA'}/\mu_{AA'} \) and substitute back into transition 2:

\[ m\delta\nu_{AA'}^{2} = K_{21} + F_{21} m\delta\nu_{AA'}^{1} - AA'H_{21} \]

- Plot \( m\delta\nu_{AA'}^{1} \) vs. \( m\delta\nu_{AA'}^{2} \) along the isotopic chain
Isolating the signal: isotope shifts

\[ \nu_i^{AA'} = \nu_i^A - \nu_i^{A'} \]

\[ \delta \nu_{AA'}^i = K_i \mu_{AA'} + F_i \delta \langle r^2 \rangle_{AA'} + H_i (A - A') \]

\( K_i \) and \( F_i \) are difficult to compute to the accuracy needed by 

The

- First, measure masses \( m \)
- Measure isotope shifts \( m \delta \nu \)
- Use Eq. (10) to set \( \delta \nu_{AA'} \)

\[ m \delta \nu_{AA'}^2 = K_{21} + F_{21} m \delta \nu_{AA'}^1 - AA' \]

\[ H_{21} \]

- Plot \( m \delta \nu_{AA'}^1 \) vs. \( m \delta \nu_{AA'}^2 \) along the isotopic chain
Constraining light NP

As long as King linearity deviation is not observed, one can bound new physics sources. More tricky to interpret if a signal is observed.
Quantum sensing (metrology) for HEP

Allow measuring events with tiny depositions of energy (even with practically no-momentum transfer)

Coherent/fragile effects may allow to enhance detection possibilities

Low thresholds ideally for “substantial” fluxes with tiny cross-sections.

May represent a fundamental frontier to be understood in any measurement

There is a revolution in the frontier of cutting-edge quantum metrology
Quantum sensing (metrology) for HEP

D. Blas, EPS’23

i) DM and cosmic neutrinos w/ atomic clocks and co-magnetometers

ii) Large atomic interferometers

iii) GWs in (superconducting radio-frequency) cavities
EDM
Electric Dipole Moment

\[ L_{\text{dipole}} = -\frac{\mu}{2} \bar{\Psi} \sigma^{\mu\nu} F_{\mu\nu} \Psi - \frac{d}{2} \bar{\Psi} \sigma^{\mu\nu} i \gamma^5 F_{\mu\nu} \Psi \]

Non-relativistic limit

\[ H = -\mu \vec{B} \cdot \vec{S} - d \vec{E} \cdot \vec{S} \]

Nonvanishing EDM breaks CP

SM predictions

3-loop since one needs to involve 3 families of quarks to break CP

EDMs violate chirality, so putting in the electron mass a spurion, we expect an effect of order:

\[ d_e \sim \delta_{\text{CPV}} \left( \frac{\lambda}{16\pi^2} \right)^k \frac{m_e}{M^2} \]

Then dimensional analysis tells us that the experiment probes masses

<table>
<thead>
<tr>
<th>0-loop</th>
<th>1-loop</th>
<th>2-loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>800 TeV</td>
<td>40 TeV</td>
<td>2 TeV</td>
</tr>
</tbody>
</table>

Preliminary: experimental result not yet known

(M. Riembau, PhD defense ‘18)

(M. Reece, SUSY ’18)
EDM - experimental status

\[ |d_e| < 9.4 \cdot 10^{-29} \, e \text{ cm} \quad \text{at 90\% CL} \]

\[ |d_e| \lesssim 0.5 \cdot 10^{-29} \, e \text{ cm} \quad \text{(ACME II)} \]

\[ |d_e| \lesssim 0.3 \cdot 10^{-30} \, e \text{ cm} \quad \text{(ACME III)} \]

\[ |d_e| \lesssim 10^{-30} \, e \text{ cm} \quad \text{arXiv:1704.07928} \]

\[ |d_e| \lesssim 5 \cdot 10^{-30} \, e \text{ cm} \quad \text{arXiv:1804.10012} \]

\[ |d_e| \lesssim 10^{-35} \, e \text{ cm} \quad \text{arXiv:1710.08785} \]
EDM as a BSM probe

Panico, Riembau, Vantalon ‘17

e.g., EDM can help testing the presence of top partners in composite Higgs models
Conclusion(s)
Higgs boson at the LHC

producing a Higgs boson is a rare phenomenon since its interactions with particles are proportional to masses and ordinary matter is made of light elementary particles.

NB: the proton is not an elementary particle, its mass doesn’t measure its interaction with the Higgs substance.

From electrons:

\[
\begin{array}{c}
e \\
\downarrow \\
h \downarrow e
\end{array}
\]

probability \( \sim 10^{-11} \)

From top quarks:

\[
\begin{array}{c}
\uparrow \downarrow \\
h \downarrow \uparrow
\end{array}
\]

probability \( \sim 1 \)

but no top quark at our disposal.
Higgs boson at the LHC

Difficult task
Homer Simpson’s principle of life:

If something’s hard to do, is it worth doing?
The Higgs Boson is Special

The knowledge of the values of the **Higgs couplings** is essential to understand the deep structure of matter/Universe

- $m_W, m_Z \leftrightarrow$ Higgs couplings
  - lifetime of stars
  - (why $t_{\text{Sun}} \sim t_{\text{life evolution}}$?)

- $m_e, m_u, m_d \leftrightarrow$ Higgs couplings
  - size of atoms
  - nuclei stability

- EWSB @ $t \sim 10^{-10}s \leftrightarrow$ Higgs self-coupling

- matter/anti-matter $\leftrightarrow$ CPV in Higgs sector

---

*LHC will make remarkable progress but it won’t be enough. A new collider will be needed!***
Executive summary on status of BSM

BAD NEWS

Experimentalists haven’t found (yet) what theorists told them they will find

GOOD NEWS

There are rich opportunities for mind-boggling signatures @ colliders and beyond
Sailing to India with the right tool...

Once upon a time...

Columbus had a great proposal: “reaching India by sailing towards the West”

He had a theoretical model
  ‣ the Earth is round,
  ‣ Eratosthenes of Cyrene first estimated its circumference to be 250’000 stadia
  ‣ other measurements later found smaller values (Toscanelli’s map)
  ‣ lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70’000 stadia, so he believed he could reach India in 4 weeks

He had the right technology
  ‣ Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost
Sailing to India with the right tool...

Once upon a time...

Columbus had a great proposal: “reaching India by sailing towards the West”

He had a theoretical model

- the Earth is round,
- Eratosthenes of Cyrene first estimated its circumference to be 250’000 stadia
- other measurements later found smaller values ➔ Toscanelli’s map
- lost in unit-conversion or misled by post-truth statements, Columbus thought it was only 70’000 stadia, so he believed he could reach India in 4 weeks

He had the right technology

- Caravels were the only ships at that time to sail against the wind, necessary tool to fight the prevailing winds, aka Alizée. Actually, the Vikings had the right technology too but the knowledge was lost

His proposal was scientifically rejected twice (by Portuguese’s & Salamanca U.) by the decision was overruled by Isabel ... and America became great (already)

Moral(s)

“if your proposal is rejected, submit it again”

“you need the right technology to beat your competitors”

“theorists don’t need to be right! but progress needs theoretical models to motivate exploration”
Knowledge is power

B. Clinton, Davos 2011

Homework (2nd part of the outreach competition):
imagine what the former US president could say about science and HEP.
Thank you for your attention. Good luck for your studies!

if you have question/want to know more
do not hesitate to send me an email

christophe.grojean@desy.de
Bonus Slides

on topics requested by some students
Evolution of coupling constants

Classical physics:
the forces depend on distances

Quantum physics:
the charges depend on distances

QED
virtual particles screen
the electric charge: $\alpha \downarrow$ when $d \uparrow$

QCD
virtual particles (quarks and *gluons*) screen
the strong charge: $\alpha_s \uparrow$ when $d \uparrow$

‘asymptotic freedom’

$$\frac{\partial \alpha_s}{\partial \log E} = \beta(\alpha_s) = \frac{\alpha_s^2}{\pi} \left( -\frac{11N_c}{6} + \frac{N_f}{3} \right)$$
Grand Unified Theories

A single form of matter
A single fundamental interaction
SU(5) GUT: Gauge Group Structure

SU(3)\(_c\)xSU(2)\(_L\)xU(1)\(_Y\): SM Matter Content

\[ Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2)_{1/6}, \quad u_R^c = (\bar{3}, 1)_{-2/3}, \quad d_R^c = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad e_R^c = (1, 1)_1 \]

How can you ever remember all these numbers?

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5) \]

Additional U(1) factor that commutes with SU(3)xSU(2)

SU(5) Adjoint rep.

\[ \text{Tr}(T^a T^b) = \frac{1}{2} \delta^{ab} \]

\[ \begin{array}{c}
\bar{5} = (1, 2)_{-\frac{1}{2}} \sqrt{\frac{3}{5}} + (3, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \\
5 = L + d_R^c
\end{array} \]

\[ 10 = (5 \times 5)_A = (\bar{3}, 1)_{-\frac{2}{3}} \sqrt{\frac{3}{5}} + (3, 2)_{\frac{1}{5}} \sqrt{\frac{3}{5}} + (1, 1)_{\frac{5}{3}} \]

\[ 10 = u_R^c + Q_L + e_R^c \]

\[ g_5 T^{12} = g' Y \]

\[ g_5 \sqrt{\frac{3}{5}} = g' \quad g_5 = g = g_s \]

\[ \sin^2 \theta_W = \frac{3}{8} @ M_{\text{GUT}} \]
SU(5) GUT: Gauge Group Structure

SU(3)_c \times SU(2)_L \times U(1)_Y: SM Matter Content

\[ Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2)_{1/6}, \quad u_R^c = (\bar{3}, 1)_{-2/3}, \quad d_R^c = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad e_R^c = (1, 1)_{1} \]

How can you ever remember all these?

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)

Adjoint rep.

\[ \begin{pmatrix} -1/3 \\ -1/3 \\ -1/3 \end{pmatrix} \]

\[ \begin{pmatrix} \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \\ \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} + (1, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \end{pmatrix} \]

\[ Q_L = (3, 2)_{1/6}, \quad u_R^c = (\bar{3}, 1)_{-2/3}, \quad d_R^c = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad e_R^c = (1, 1)_{1} \]

How can you ever remember all these?

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)

Adjoint rep.

\[ \begin{pmatrix} -1/3 \\ -1/3 \\ -1/3 \end{pmatrix} \]

\[ \begin{pmatrix} \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \\ \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} + (1, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \end{pmatrix} \]

\[ Q_L = (3, 2)_{1/6}, \quad u_R^c = (\bar{3}, 1)_{-2/3}, \quad d_R^c = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad e_R^c = (1, 1)_{1} \]

How can you ever remember all these?

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)

Adjoint rep.

\[ \begin{pmatrix} -1/3 \\ -1/3 \\ -1/3 \end{pmatrix} \]

\[ \begin{pmatrix} \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \\ \frac{1}{2} \sqrt{\frac{3}{5}} + (\bar{3}, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} + (1, 1)_{\frac{1}{3}} \sqrt{\frac{3}{5}} \end{pmatrix} \]

\[ Q_L = (3, 2)_{1/6}, \quad u_R^c = (\bar{3}, 1)_{-2/3}, \quad d_R^c = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad e_R^c = (1, 1)_{1} \]

How can you ever remember all these?

the SM matter fits nicely into representations of SU(5), even more nicely into SO(10) unification baryon-lepton

SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)

Adjoint rep.
SU(5) GUT: low energy consistency condition

\[ \frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \quad i = SU(3), SU(2), U(1) \]

\[ \alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z) \quad \text{experimental inputs} \]

\[ b_3, b_2, b_1 \quad \text{predicted by the matter content} \]

3 equations & 2 unknowns \((\alpha_{GUT}, M_{GUT})\)

one consistency relation on low energy parameters

\[ \epsilon_{ijk} \frac{b_j - b_k}{\alpha_i(M_Z)} = 0 \]

\[ \sin^2 \theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \]

\[ \alpha_{em}(M_Z) \approx \frac{1}{128} \quad \alpha_s(M_Z) \approx 0.1184 \pm 0.0007 \]

\[ \sin^2 \theta_W \approx 0.207 \quad \text{not bad… (observed value: 0.23)} \]

Even better in MSSM
SU(5) GUT: low energy consistency condition

$$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_{GUT}} - \frac{b_i}{4\pi} \ln \frac{M_{GUT}^2}{M_Z^2} \quad i = SU(3), SU(2), U(1)$$

$$\alpha_3(M_Z), \alpha_2(M_Z), \alpha_1(M_Z)$$ ← experimental inputs

$$b_3, b_2, b_1$$ ← predicted by the matter content

3 equations & 2 unknowns \((\alpha_{GUT}, M_{GUT})\)

one consistency relation on low energy parameters

$$M_{GUT} = M_Z \exp \left(2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)}\right) \approx 7 \times 10^{14} \text{ GeV}$$

$$\alpha_{GUT}^{-1} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 41.5$$

self-consistent computation:
- \(M_{GUT} < M_{Pl}\) safe to neglect quantum gravity effects
- \(\alpha_{GUT} \ll 1\) perturbative computation
SU(5) GUT: SM $\beta$ fcts

g, g' and $g_s$ are different but it is a low energy artifact!

$$\beta = \frac{dg}{d \log \mu} = -\frac{1}{16\pi^2}bg^3 + \ldots$$

$$\frac{1}{g^2(Q)} = \frac{1}{g^2(Q_0)} + \frac{b}{16\pi^2} \ln \frac{Q^2}{Q_0^2}$$

$$b = \frac{11}{3} T_2(\text{spin-1}) - \frac{2}{3} T_2(\text{chiral spin-1/2}) - \frac{1}{3} T_2(\text{complex spin-0})$$

$$\text{Tr} (T^a(R)T^b(R)) = T_2(R)\delta^{ab} \quad T_2(\text{fund}) = \frac{1}{2} \quad T_2(\text{adj}) = N$$

$$b_{SU(3)} = \frac{11}{3} \times 3 - \frac{2}{3} \left( \frac{1}{2} \times 2 \times 3 + \frac{1}{2} \times 1 \times 3 + \frac{1}{2} \times 1 \times 3 \right) = 7$$

$$b_{SU(2)} = \frac{11}{3} \times 2 - \frac{2}{3} \left( \frac{1}{2} \times 3 \times 3 + \frac{1}{2} \times 1 \times 3 \right) - \frac{1}{3} \times \frac{1}{2} = \frac{19}{6}$$

$$b_Y = -\frac{2}{3} \left( \frac{1}{6} \right)^2 3 \times 2 \times 3 + \left( -\frac{2}{3} \right)^2 3 \times 3 + \left( \frac{1}{3} \right)^2 3 \times 3 + \left( -\frac{1}{2} \right)^2 2 \times 3 + (1^2) \times 3 - \frac{1}{3} \left( \frac{1}{2} \right)^2 \times 2 = -\frac{41}{6}$$

$\Rightarrow b_{T12} = -\frac{41}{10}$
SU(5) GUT: SM vs MSSM $\beta$ fcts

**chiral superfield**
- complex spin-0
- Weyl spin-1/2
  - in same representation of gauge group

**vector superfield**
- Weyl spin-1/2
- real spin-1
  - in same representation of gauge group

\[
b = \frac{11}{3}T_2(\text{vector}) - \frac{2}{3}T_2(\text{vector}) - \frac{2}{3}T_2(\text{chiral}) - \frac{1}{3}T_2(\text{chiral}) = 3T_2(\text{vector}) - T_2(\text{chiral})
\]

### MSSM Chiral Content

\[
Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (3, 2)_{1/6}, \quad U = (\bar{3}, 1)_{-2/3}, \quad D = (\bar{3}, 1)_{1/3}, \quad L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = (1, 2)_{-1/2}, \quad E = (1, 1)_1, \quad H_u = (1, 2)_{1/2}, \quad H_d = (1, 2)_{-1/2}
\]

\[
g ^{Q_L} = (3, 2)_{1/2}\quad U = (3, 1)_{-2/3}\quad D = (3, 1)_{1/3}\quad L = (1, 2)_{-1/2}\quad E = (1, 1)_1, \quad H_u = (1, 2)_{1/2}, \quad H_d = (1, 2)_{-1/2}
\]

\[
b_{SU(3)} = 3 \times 3 - \left(\frac{1}{2} \times 2 \times 3 + \frac{1}{2} \times 1 \times 3 + \frac{1}{2} \times 1 \times 3\right) = 3
\]

\[
b_{SU(2)} = 3 \times 2 - \left(\frac{1}{2} \times 3 \times 3 + \frac{1}{2} \times 1 \times 3\right) - \frac{1}{2} - \frac{1}{2} = -1
\]

\[
\begin{align*}
\nu_Y &= - \left(\frac{1}{6}\right)^2 3 \times 2 \times 3 + \left(\frac{2}{3}\right)^2 3 \times 3 + \left(\frac{1}{3}\right)^2 3 \times 3 + \left(-\frac{1}{2}\right)^2 2 \times 3 + (1)^2 \times 3\right) - \left(\frac{1}{2}\right)^2 \times 2 - \left(\frac{1}{2}\right)^2 \times 2 = -11
\end{align*}
\]

\[
b_{T_{12}} = -\frac{33}{5}
\]
SU(5) GUT: MSSM GUT

\[ b_3 = 3, \quad b_2 = -1, \quad b_1 = -\frac{33}{5} \]

low-energy consistency relation for unification

\[ \sin^2 \theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{em}(M_Z)}{\alpha_s(M_Z)} \approx 0.23 \]

squarks and sleptons form complete SU(5) reps \( \rightarrow \) they don’t improve unification!

gauginos and higgsinos are improving the unification of gauge couplings

GUT scale predictions

\[ M_{GUT} = M_Z \exp \left( 2\pi \frac{3\alpha_s(M_Z) - 8\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \right) \approx 2 \times 10^{16} \text{ GeV} \]

\[ \alpha^{-1}_{GUT} = \frac{3b_3\alpha_s(M_Z) - (5b_1 + 3b_2)\alpha_{em}(M_Z)}{(8b_3 - 3b_2 - 5b_1)\alpha_s(M_Z)\alpha_{em}(M_Z)} \approx 24.3 \]
why is the proton stable?
electric charge conservation?
baryon number conservation?

in GUT, “matter” is unstable
decay of proton mediated by new
SU(5)/SO(10) gauge bosons

938.2720813(58) MeV

GUT: \( \tau_p (p \rightarrow e^+ \pi^0) = \left( \frac{M_X}{10^{15}\text{ GeV}} \right)^4 \times 10^{31-32}\text{ yr} \)

Exp: \( \tau_p (p \rightarrow e^+ \pi^0) > 8.2 \times 10^{33}\text{ yr} \)

other decay mode:
\( p^+ \rightarrow K^+ \bar{\nu} \)

(G. Giudice SSLP’15)
1.3.2 Proposed Proton Decay Search Experiments

Some of these proposals are inactive or discontinued, while others are being actively discussed in various communities. There are a variety of proposals to continue the search for nucleon decay with a new generation of experiments.

1.3 Nucleon Decay Experiments: Past, Present and Future
Proton Decay

in GUT, matter is unstable
decay of proton mediated by new SU(5)/SO(10) gauge bosons

\[
\begin{align*}
\text{GUT: } \tau_p(p \rightarrow e^+\pi^0) &= \left(\frac{M_X}{10^{35} \text{ GeV}}\right)^4 10^{31-32} \text{ yr} \\
\text{Exp: } \tau_p(p \rightarrow e^+\pi^0) > 8.2 \times 10^{33} \text{ yr}
\end{align*}
\]

(Age of the Universe: 10^{10} years)
Proton Decay

<table>
<thead>
<tr>
<th>Mode</th>
<th>Partial mean life (10^{30} years)</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antilepton + meson</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_1 ) ( N \rightarrow e^+ \pi )</td>
<td>( &gt; 2000 ) (n), ( &gt; 8200 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_2 ) ( N \rightarrow \mu^+ \pi )</td>
<td>( &gt; 1000 ) (n), ( &gt; 6600 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_3 ) ( N \rightarrow \nu \pi )</td>
<td>( &gt; 1100 ) (n), ( &gt; 390 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_4 ) ( p \rightarrow e^+ \eta )</td>
<td>( &gt; 4200 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_5 ) ( p \rightarrow \mu^+ \eta )</td>
<td>( &gt; 1300 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_6 ) ( n \rightarrow \nu \eta )</td>
<td>( &gt; 158 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_7 ) ( N \rightarrow e^+ \rho )</td>
<td>( &gt; 217 ) (n), ( &gt; 710 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_8 ) ( N \rightarrow \mu^+ \rho )</td>
<td>( &gt; 228 ) (n), ( &gt; 160 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_9 ) ( N \rightarrow \nu \rho )</td>
<td>( &gt; 19 ) (n), ( &gt; 162 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{10} ) ( p \rightarrow e^+ \omega )</td>
<td>( &gt; 320 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{11} ) ( p \rightarrow \mu^+ \omega )</td>
<td>( &gt; 780 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{12} ) ( n \rightarrow \nu \omega )</td>
<td>( &gt; 108 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{13} ) ( N \rightarrow e^+ K )</td>
<td>( &gt; 17 ) (n), ( &gt; 1000 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{14} ) ( p \rightarrow e^+ K^0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_{15} ) ( p \rightarrow e^+ K^+ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_{16} ) ( N \rightarrow \mu^+ K )</td>
<td>( &gt; 26 ) (n), ( &gt; 1600 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{17} ) ( p \rightarrow \mu^+ K^0 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_{18} ) ( p \rightarrow \mu^+ K^+ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_{19} ) ( N \rightarrow \nu K )</td>
<td>( &gt; 86 ) (n), ( &gt; 5900 ) (( \rho ))</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{20} ) ( n \rightarrow \nu K^0 )</td>
<td>( &gt; 260 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{21} ) ( p \rightarrow e^+ K^+(892)^0 )</td>
<td>( &gt; 84 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{22} ) ( N \rightarrow \nu K^+(892) )</td>
<td>( &gt; 78 ) (n), ( &gt; 51 ) (( \rho ))</td>
<td>90%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>Partial mean life (10^{30} years)</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antilepton + mesons</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \tau_{23} ) ( p \rightarrow e^+ \pi^+ \pi^- )</td>
<td>( &gt; 82 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{24} ) ( p \rightarrow e^+ \pi^0 \pi^0 )</td>
<td>( &gt; 147 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{25} ) ( n \rightarrow e^+ \pi^- \pi^0 )</td>
<td>( &gt; 52 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{26} ) ( p \rightarrow \mu^+ \pi^+ \pi^- )</td>
<td>( &gt; 133 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{27} ) ( p \rightarrow \mu^+ \pi^0 \pi^0 )</td>
<td>( &gt; 101 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{28} ) ( n \rightarrow \mu^+ \pi^- \pi^0 )</td>
<td>( &gt; 74 )</td>
<td>90%</td>
</tr>
<tr>
<td>( \tau_{29} ) ( n \rightarrow e^+ K^0 \pi^- )</td>
<td>( &gt; 18 )</td>
<td>90%</td>
</tr>
</tbody>
</table>

**\( \Delta B = \Delta L = 1 \) decay bounds**

\[ \Delta B = \Delta L = 1 \]

\[ p \rightarrow e^+ \pi^+ \pi^- \]
\[ > 82 \] (90% confidence)
\[ n \rightarrow e^+ \pi^- \pi^0 \]
\[ > 52 \] (90% confidence)
\[ p \rightarrow \mu^+ \pi^+ \pi^- \]
\[ > 133 \] (90% confidence)
\[ n \rightarrow \mu^+ \pi^- \pi^0 \]
\[ > 74 \] (90% confidence)
\[ n \rightarrow e^+ K^0 \pi^- \]
\[ > 18 \] (90% confidence)
**SU(5) GUT: Composite Higgs β fcts**

**Strong sector**
- SU(5) invariant

**Interactions between strong & elementary sectors**
- SU(5) breaking

\[
\frac{d\alpha_i}{d \ln Q} \in - \frac{b_{\text{comp}}}{2\pi} \alpha_i^2 + \frac{B_{ij}}{2\pi} \frac{\alpha_j^3}{4\pi} + \frac{C_{if}}{2\pi} \frac{\lambda_f^2}{16\pi^2}
\]

- Doesn’t contribute to the *differential* running
- Cannot be computed (non-perturbative)
- But negative and bounded from below

- Affects the unification of the gauge couplings

**Higgs**
- Light composite state \( \leftrightarrow \) may contribute to the differential running only below composite scale

**\( t_R \)**
- Light composite fermion \( \leftrightarrow \) doesn’t contribute to the running either

\{ subtract H, \( t_R \) and \( t_R^c \) from the \( \beta \) fcts \}
SU(5) GUT: Composite Higgs $\beta$ fcts

Agashe, Contino, Sundrum '05

\( b_{\text{SU}(3)} = b_{\text{SU}(3)}^{\text{SM}} + \frac{2}{3} \left( \frac{1}{2} + \frac{1}{2} \right) = \frac{23}{3} \)

\( b_{\text{SU}(2)} = b_{\text{SU}(2)}^{\text{SM}} + \frac{1}{3} \times \frac{1}{2} = \frac{10}{3} \)

\( b_Y = b_Y^{\text{SM}} + \frac{2}{3} \left( \left( -\frac{2}{3} \right)^2 \times 3 + \left( -\frac{2}{3} \right)^2 \times 3 \right) + \frac{1}{3} \left( \frac{1}{2} \right)^2 \times 2 = -\frac{44}{9} \quad \Rightarrow \quad b_{T_{12}} = -\frac{44}{15} \)

low-energy consistency relation for unification

\[ \sin^2 \theta_W = \frac{3(b_3 - b_2)}{8b_3 - 3b_2 - 5b_1} + \frac{5(b_2 - b_1)}{8b_3 - 3b_2 - 5b_1} \frac{\alpha_{\text{em}}(M_Z)}{\alpha_s(M_Z)} \approx 0.228 \]

improving the unification of gauge couplings by removing chiral matter!
SU(5) GUT: SM vs MSSM vs MCHM

\[ \alpha_{GUT}^{-1} \]

\[ \log \frac{M_{GUT}}{1 \text{ GeV}} \]

\[ b_{\text{comp}} = 0 \]

\[ b_{\text{comp}} = -5 \]

MCHM

SM

MSSM