The Importance of Mass and How We Describe it

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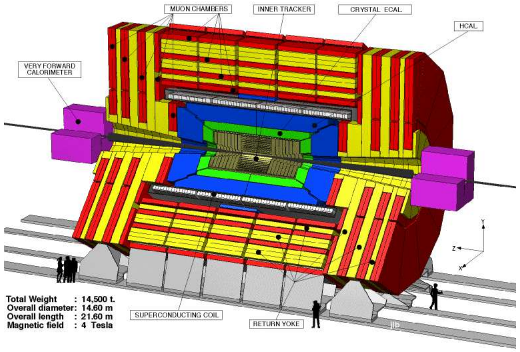
06/25/2005

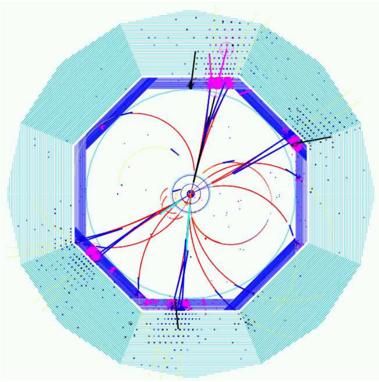
Outline

- What does this concept of mass mean at all?
- Why the heck are masses so important?
- What would happen, if the fundamental masses would only slightly change?
- So, if we need to describe mass, how do we do it?
- What do we know about it and what can we learn in the future?
- Most importantly: Why particle physics really explains the everyday world!

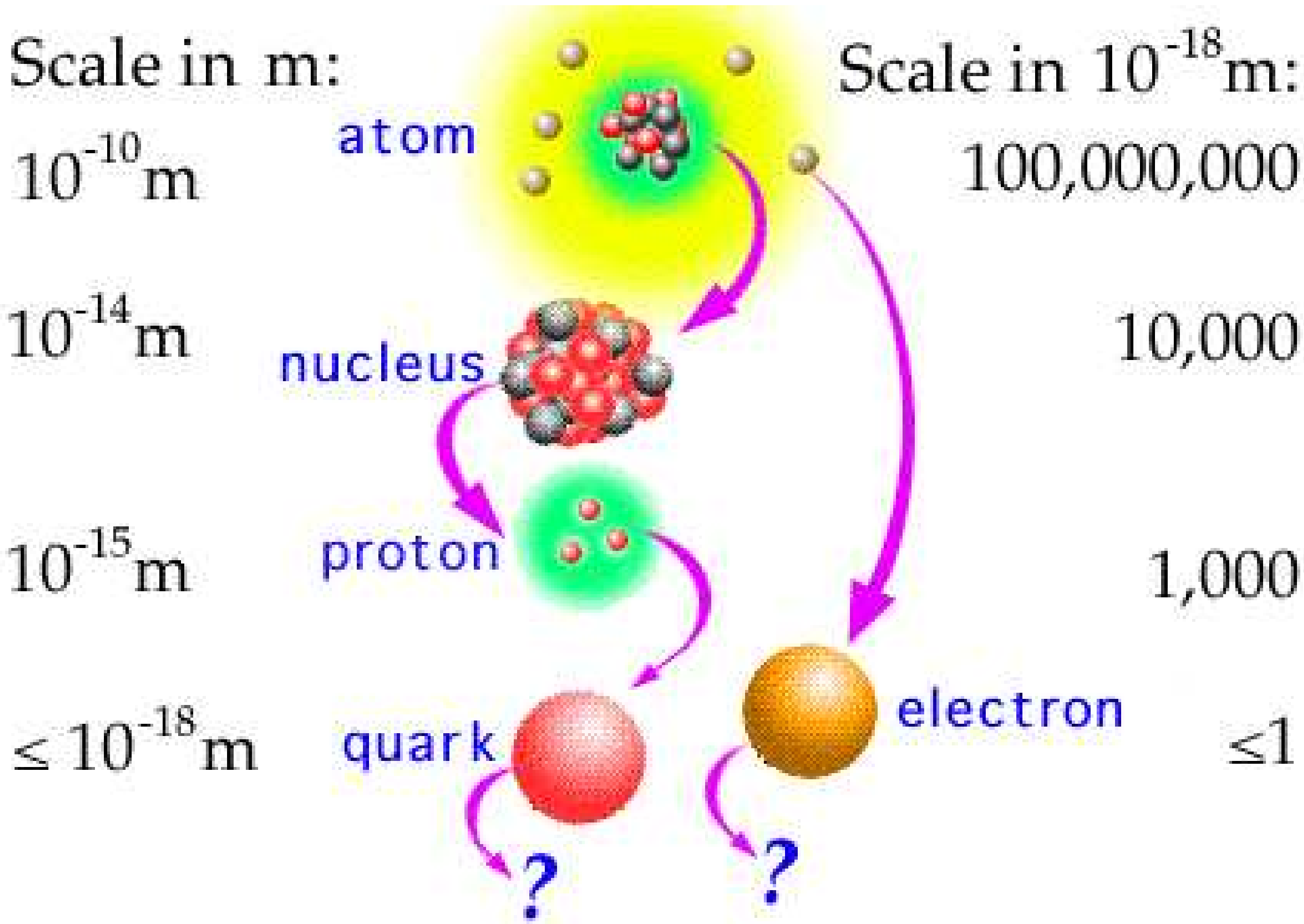
About this talk

- What it is:
  - A discussion of why investigating fundamental properties of nature is interesting for our everyday life
  - An introduction into the concepts behind our understanding of mass
- What it is not:
  - A talk about the experimental techniques of searching and investigating the mass of elementary particles
  - For that, please refer to previous (or future?) presentations about the LHC and the ILC



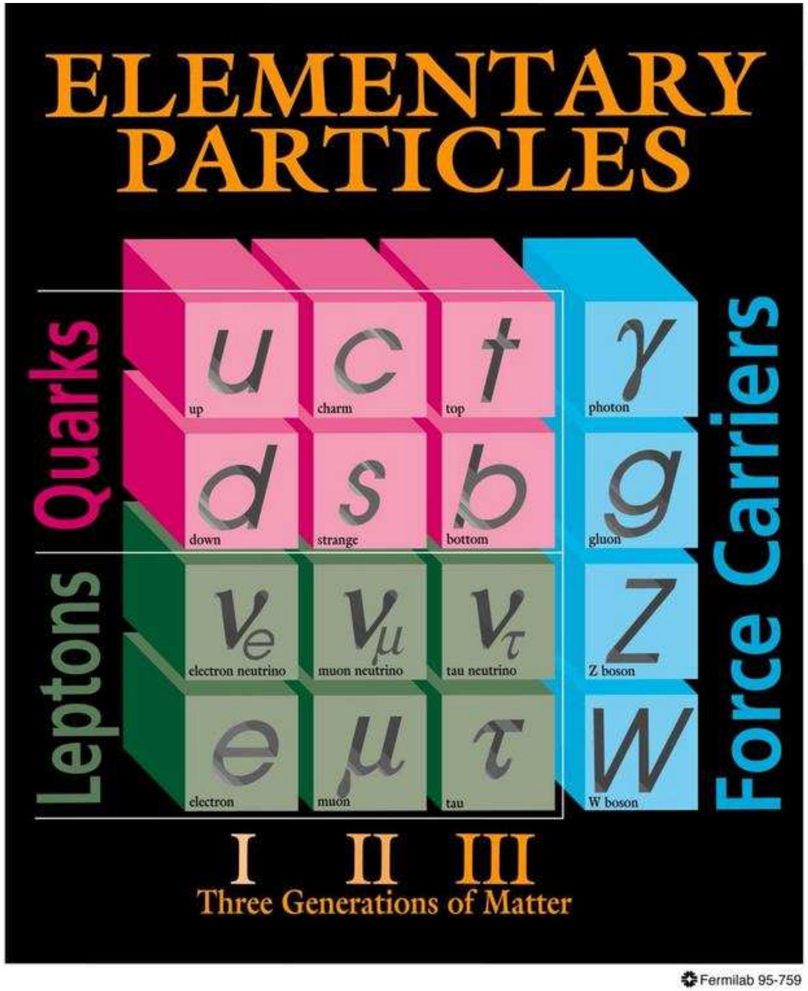


What are we investigating?



- How are we influenced by the most tiny objects we know of?

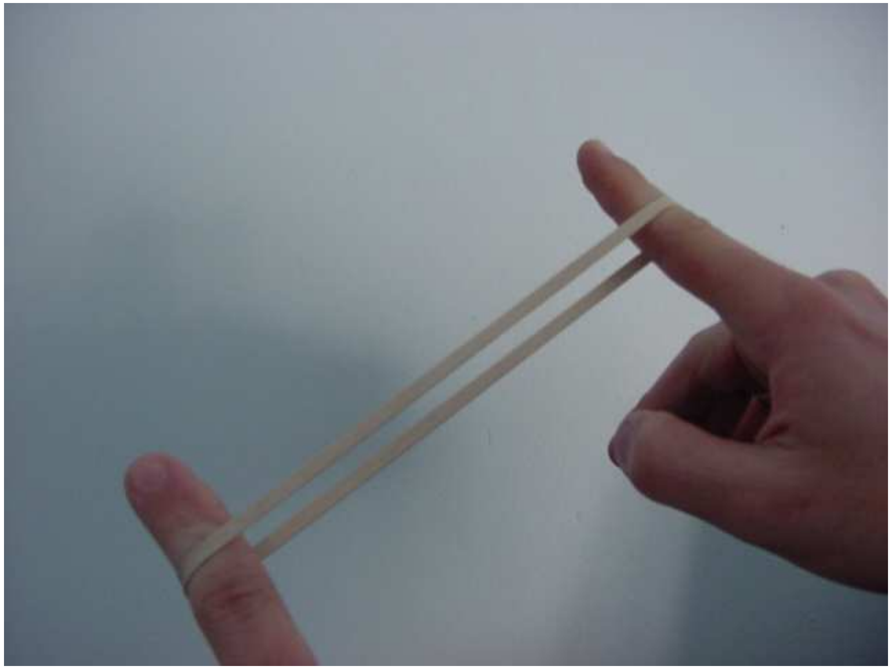
What are we investigating?



- The building blocks of all visible matter

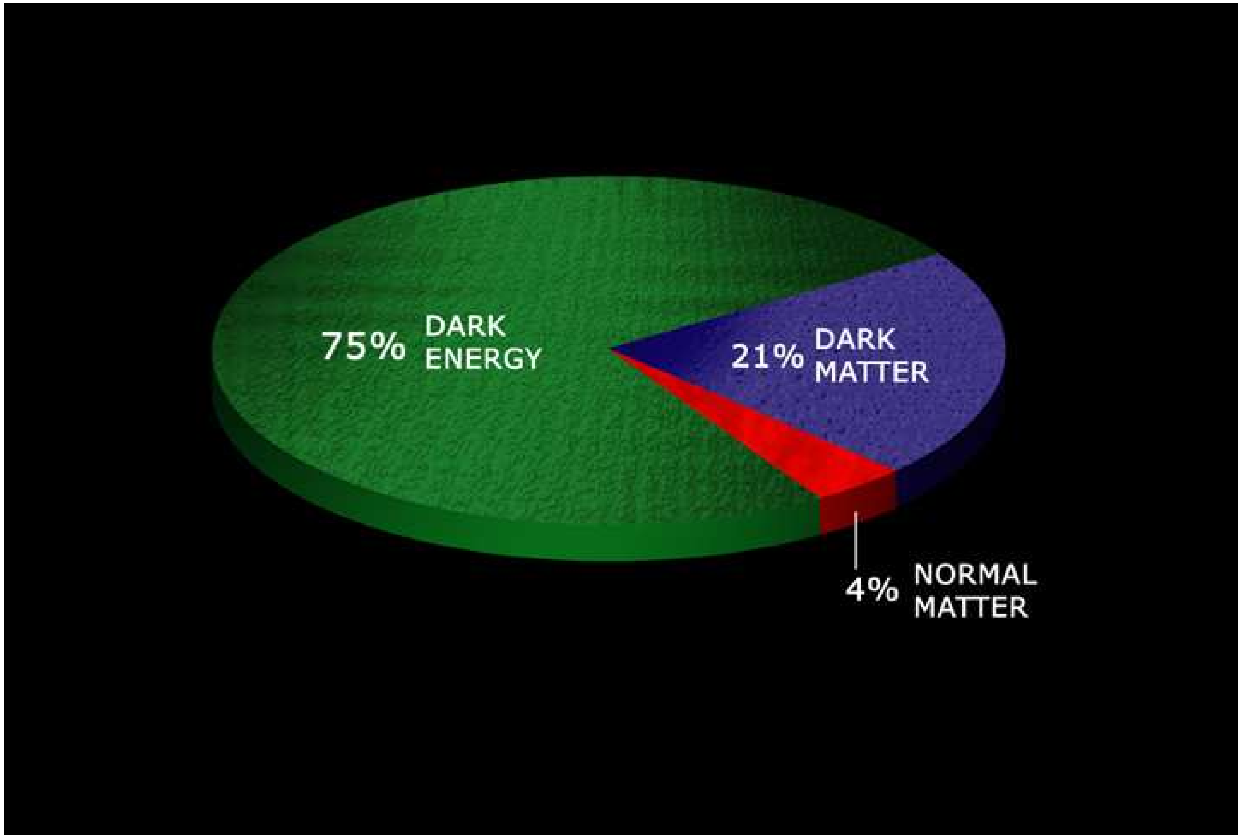
What is mass, after all??

- Mass ist stored energy



- in an interaction
- in a motion not observed from outside (like temperature)

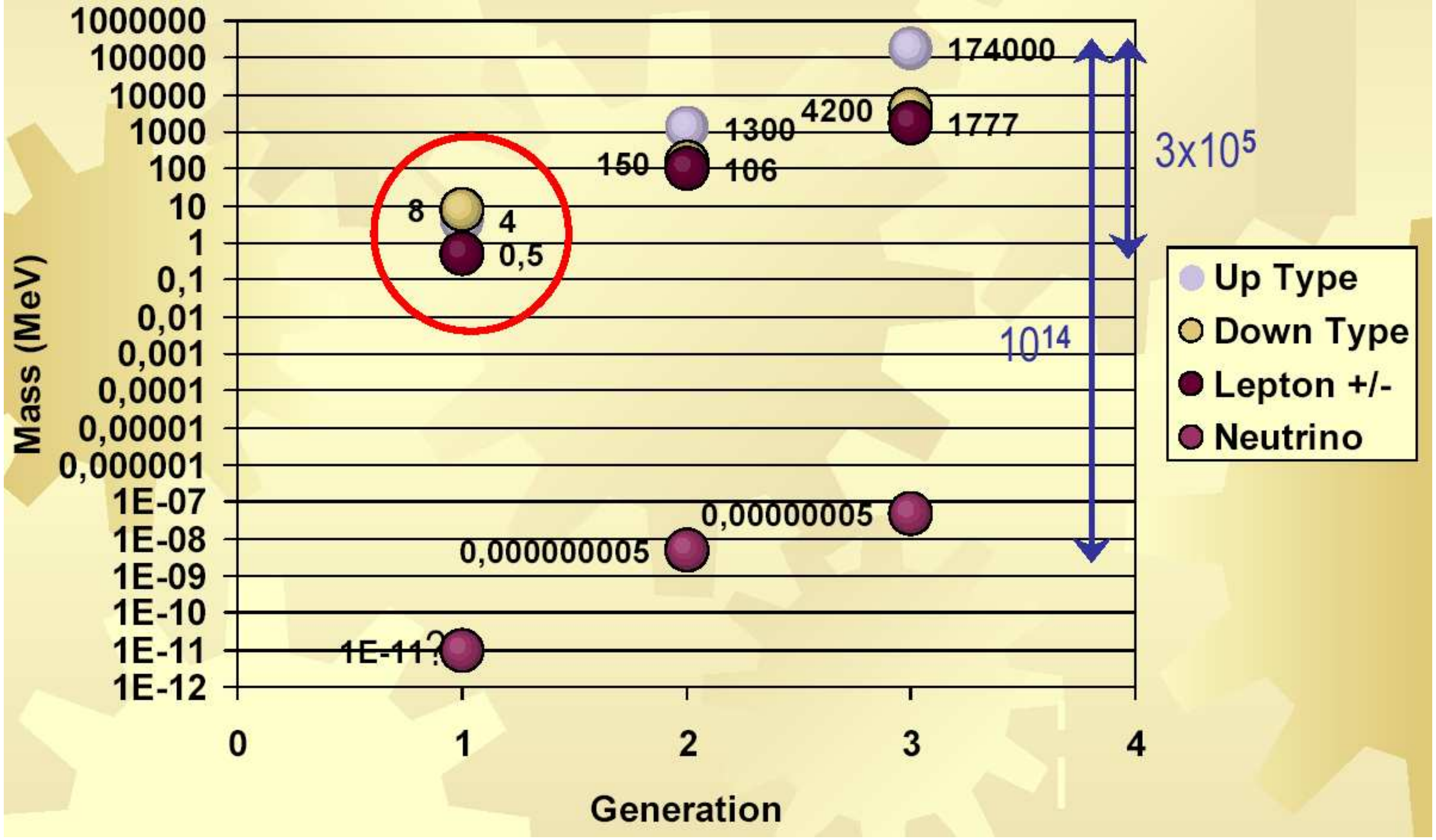
What is the Universe made of?



- This discussion is only about the 4 % ’ordinary matter’
- We hopefully are on the verge of finding out what the 21 % dark matter are made of

Which Mass are we Talking About?

- The masses of the building blocks of matter:



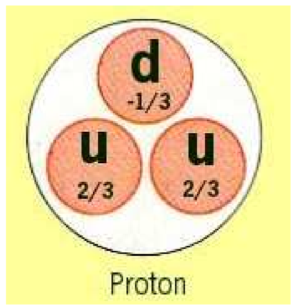
- No idea yet why they look like that . . .
- But it is extremely important that they look like that!

Influence of the Fundamental Mass

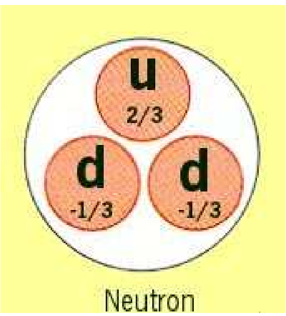
- For hydrogen (or any other atom):
  - $m_p + m_e = 938.8$ MeV
  - $2m_u + m_d + m_e = 16.5$ MeV
  - $\Rightarrow 98\%$ of all macroscopic mass is from
    - interaction energy in the strong interaction
    - kinetic energy of the quarks and gluons in the nucleus
- If the contribution of the fundamental mass is so small, why is it so important?
- Changing m_u, m_d or m_e would have
  - Small effects on macroscopic masses
  - Small effects on Ω_{matter}
  - Huge effects on the behaviour of matter
- Let's see why ...

Protons and Neutrons

- The proton does not decay

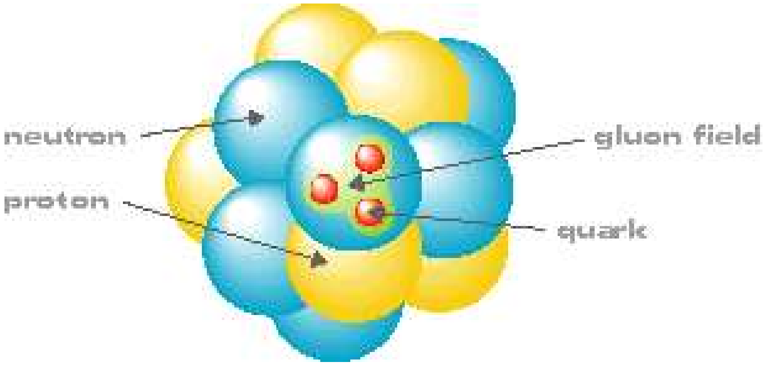


$\not\rightarrow$



$+e^+ + \nu_e$

- Stable neutrons exist only in heavy nuclei



- Heavy nuclei would be disrupted by the electromagnetic force if they had no neutrons

What makes nuclei stable?

- The proton does not decay (thus there can be much hydrogen).
  - $p \not\to n + e^+ + \nu_e$, because
  - $m_n - m_p = 939.6 - 938.8$ MeV $= 1.3$ MeV ($> m_e$: neutron decays)
    - $\Delta m_{\text{mass}} = m_d - m_u \approx 3 - 4$ MeV
    - $\Delta m_{\text{elec}} = \alpha_{em}(q_d^2 - q_u^2)/\langle r_{qq} \rangle = -0.5\,\text{MeV}/\langle r_{qq}\,(\text{fm})\rangle \approx -(2-3)$ MeV
- If the neutron decays, why does it exist in stable nuclei?
  - In nucleus: $n \not\to p + e^- + \bar{\nu}_e$, because
  - Neutron is stronger bound in nucleus than proton
  - Binding energy difference
    $E_b(n) - E_b(p) \approx \text{ some MeV } > m_d - (m_u + m_e) + \Delta m_{\text{elec}} = 0.8$ MeV
    is larger than energy gain from neutron decay
- Stability of nuclei is a delicate interplay between
  Strong force, electromagnetic force and masses

What if m_d changes?

- m_d influences nuclei
- Consider small changes of m_d (with respect to the total range of $1/10^{14}$!)
- Increase m_d by a factor of 2: $m_d = 16$ MeV
  - Allows $n \to p + e^- \bar{\nu}_e$ in nuclei, since
  - $E_b(n) - E_b(p) \approx \text{ some MeV } < m_d - (m_u + m_e) + \Delta m_{\text{elec}} = 8.8$ MeV
  - Nuclei with $Z = A$, broken by electromagnetic force above ${}^6_6C$
  - No oxygen, no water, no life as we know it
- Decrease m_d by a factor of 2: $m_d = 4$ MeV
  - allows $p \to n + e^+ + \nu_e$, also in D, since
  - $m_p - m_n = 934.3 - 931.6\,\text{MeV} = 2.7\,\text{MeV}$
  - forbids $n + n \to D + e^- + \bar{\nu}_e$, since $2m_n < m_D + m_e$
  - No protons, no stars, just neutrals n, γ, ν

What if m_e changes?

- m_e and α_{em} govern chemical processes
- Rydberg energy $R = \frac{1}{2}\alpha_{em}^2 m_e$
- Bohr radius $a = 1/\alpha_{em} m_e$
- Decrease m_e by factor 25: $m_e = 0.02$ MeV
  - Huge atoms, small binding energies
  - Humans are giants, 130 feet tall
  - covalent bindings in carbohydrates ($CH_4 \rightarrow C + 2H_2$) break at $140\,^oF$
- Increase m_e by factor 3: $m_e = 1.5$ MeV
  - K-capture in hydrogen: $p + e^- \rightarrow n + \nu_e$
  - Star formation from stable n, D replaces hydrogen
  - Humans are dwarfs, 2 feet tall

Part 2:

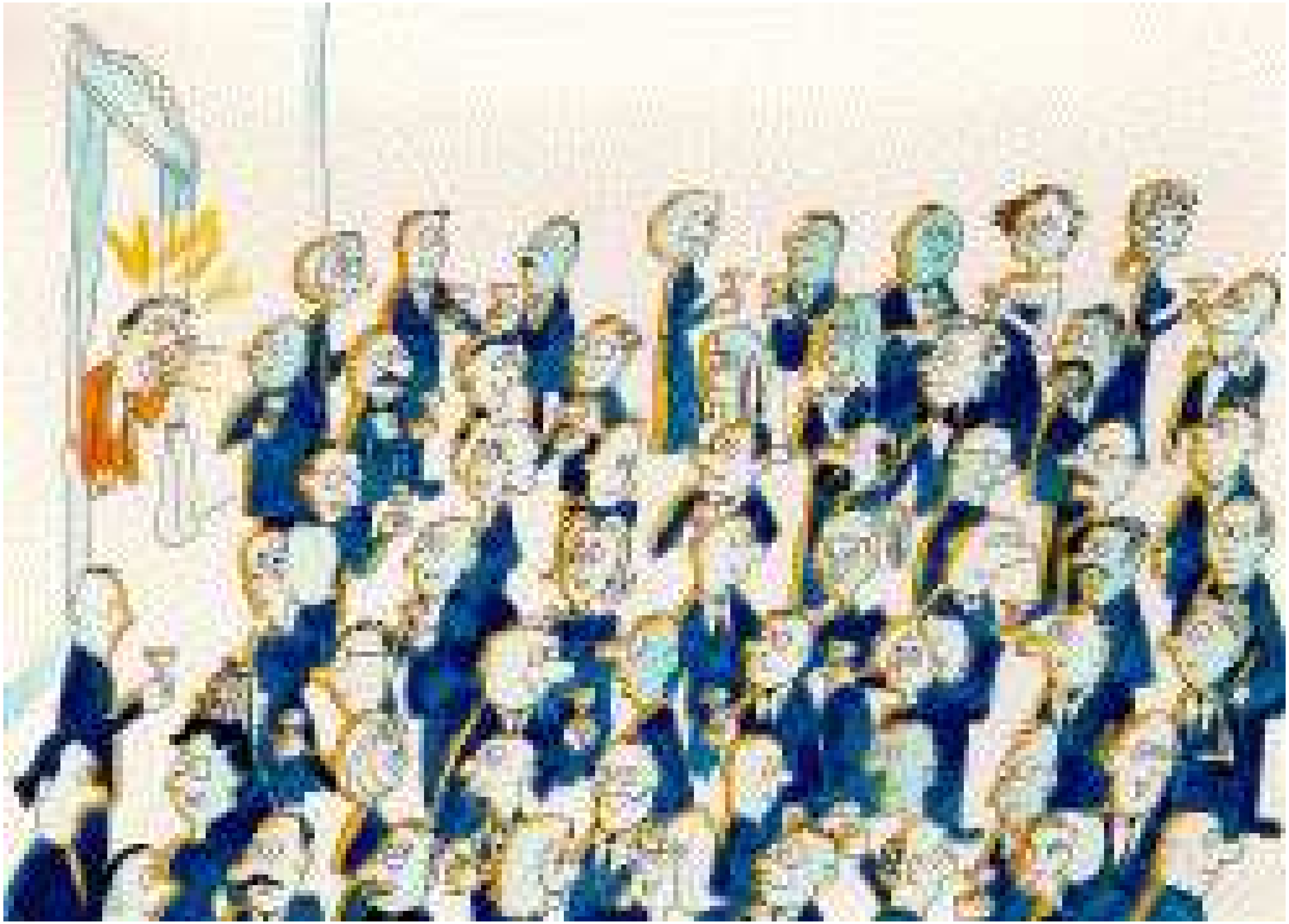
How does our concept of what fundamental mass is look like?

The Higgs Mechanism

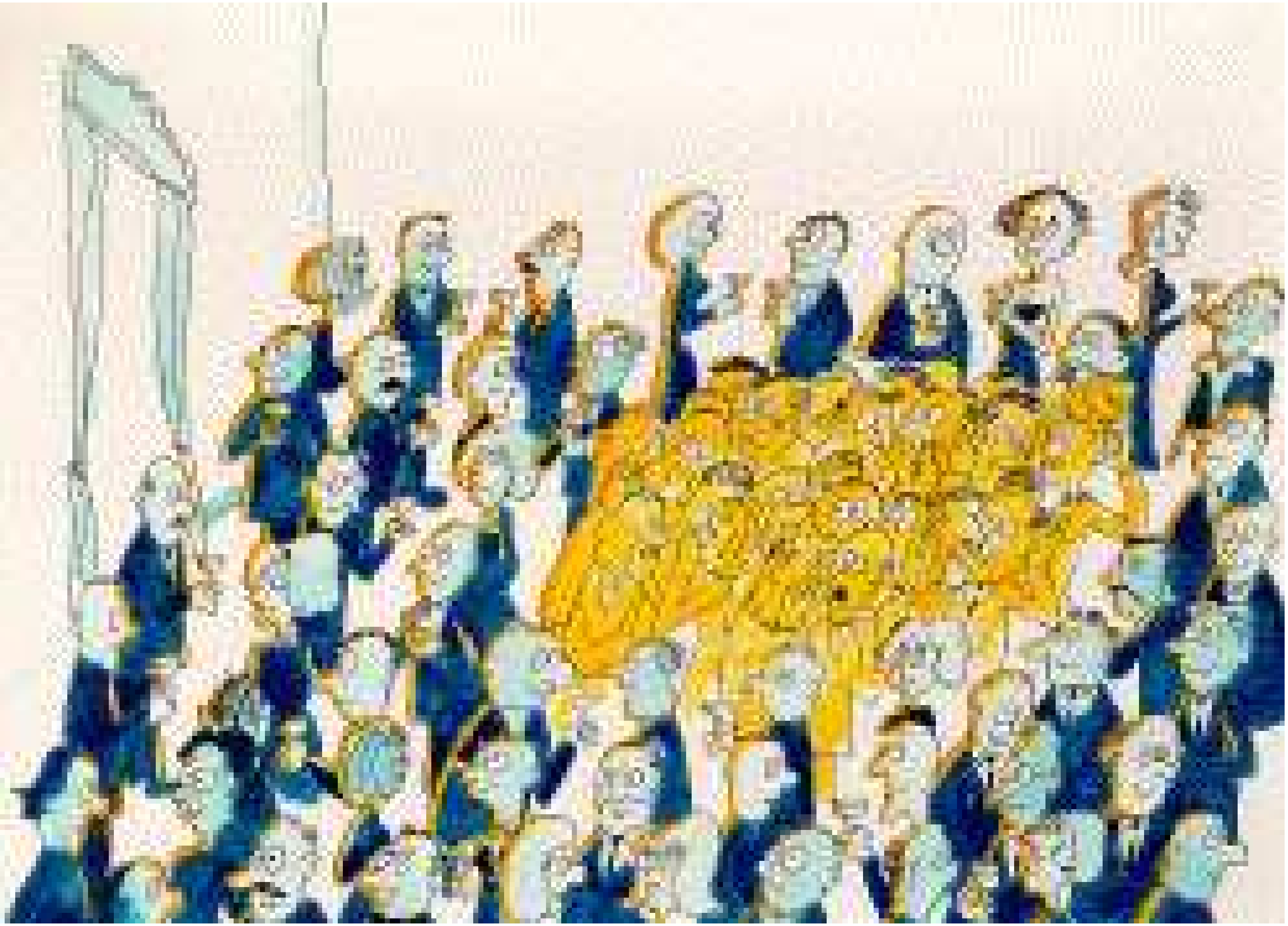
The Higgs Mechanism

The Higgs Mechanism

The Higgs Boson Itself



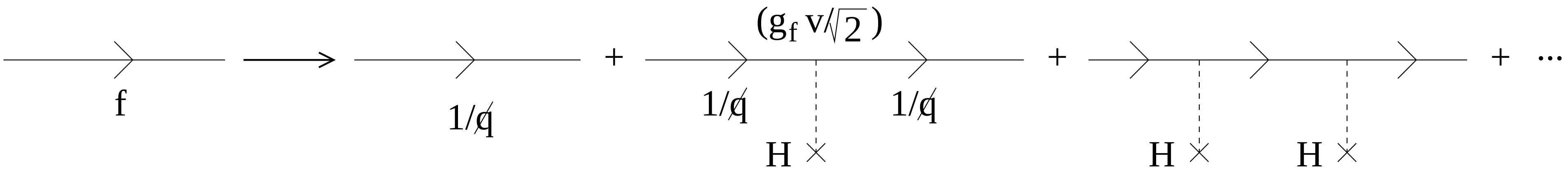
The Higgs Boson Itself



The Higgs and its Interaction

Dynamic generation of mass



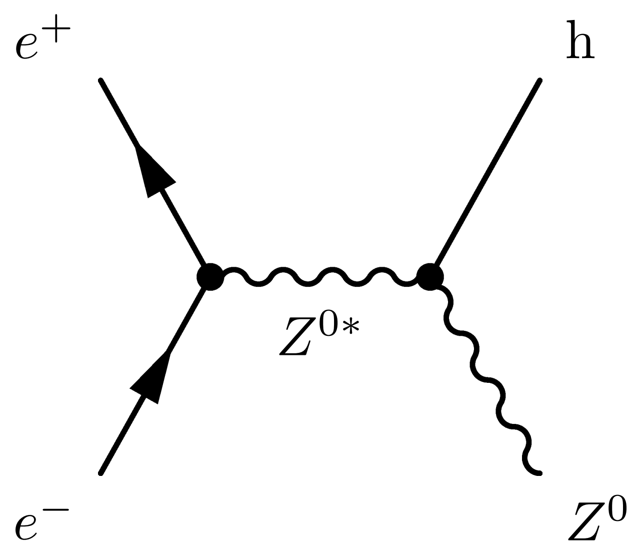


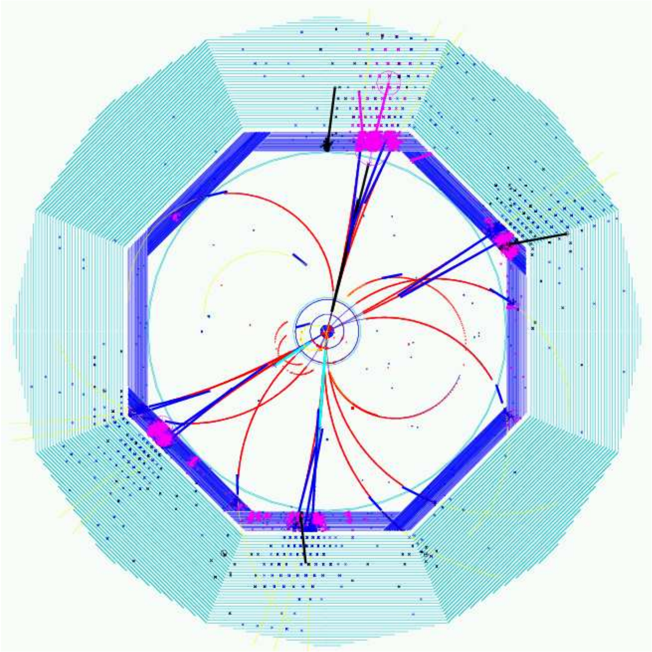
$$\frac{1}{\not{q}} + \frac{1}{\not{q}}\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not{q}} + \cdots = \frac{1}{\not{q}}\sum_{n=0}^{\infty}\left[\left(\frac{g_f v}{\sqrt{2}}\right)\frac{1}{\not{q}}\right]^n = \frac{1}{\not{q} - \left(\frac{g_f v}{\sqrt{2}}\right)}$$

Why is there always a field?

How to find the Higgs Boson?

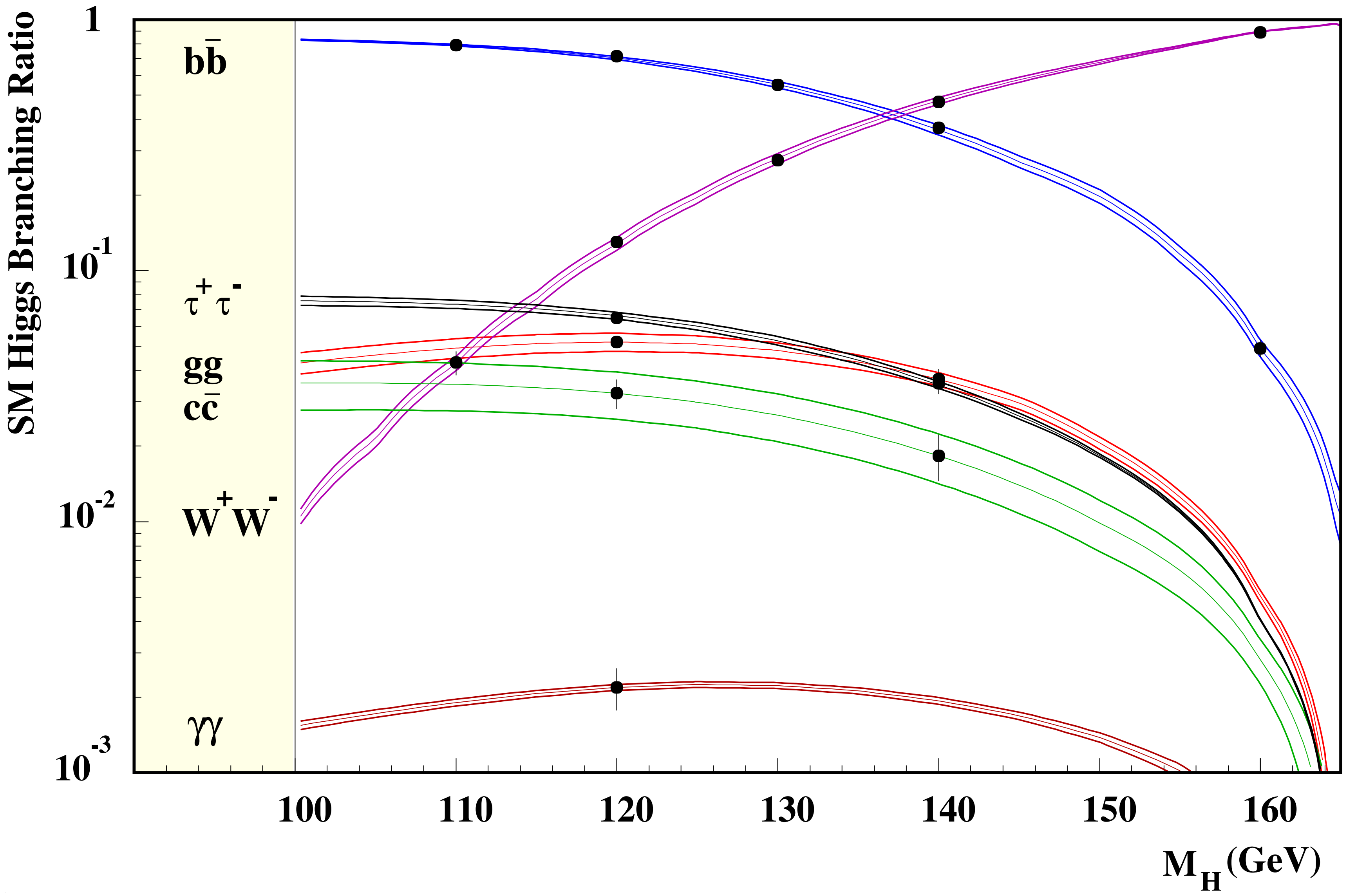
- The heavier a particle, the stronger its coupling to the Higgs field
- $\Rightarrow$ in order to find the Higgs, produce heavy particles and see whether they emit a Higgs boson





- If such a particle is found: measure its properties
- If no such process is found at LHC and ILC: Higgs theory is wrong

How to Measure its Properties?

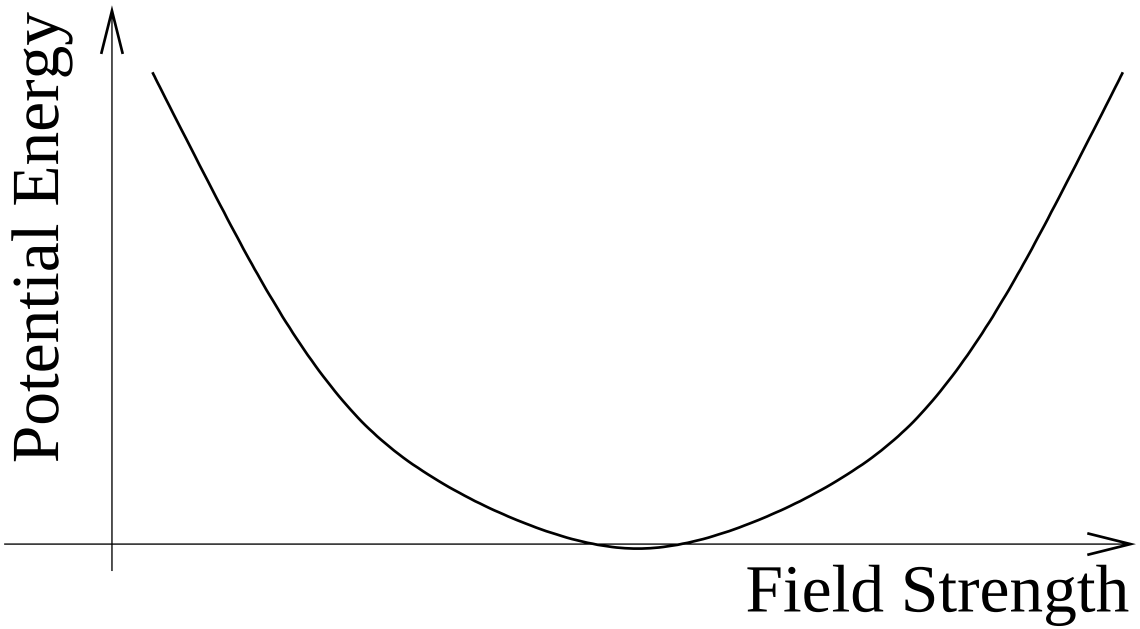


Outlook

- The fundamental pattern of masses is extremely important for the way the universe behaves
- We are just at the beginning of exploring the origins of mass
- Open question: How does the mechanism of the origin of fundamental particle masses work?
- Completely open question: What causes the mass hierarchies?
- An extremely interesting time lies ahead . . .
  to be studied at LHC and ILC

Necessary Ingredients

- Need a non-vanishing background field with no preferred direction
- That means: The energy of the field must be at its lowest value, if there is a field, not if there is no field



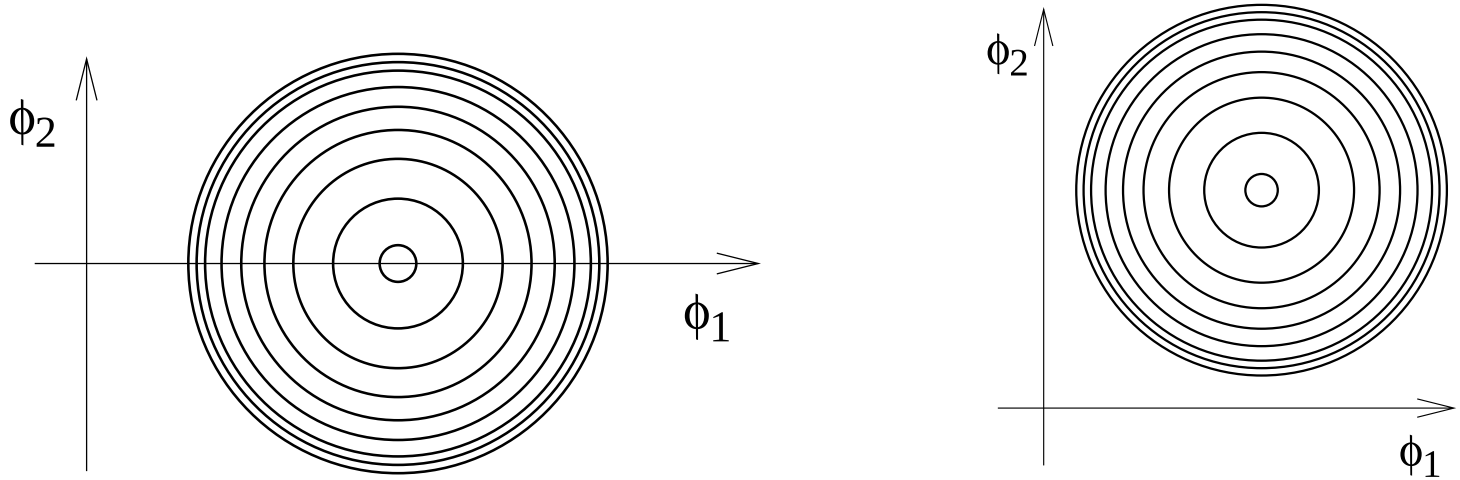
- But: Theory must obey symmetries
- Simplified example of a $U(1)$ symmetry: $\vec{E} = \vec{\nabla}\phi$
  Invariant under symmetry operation $\phi' = \phi + \text{constant}$

Rotational Symmetries

- Another symmetry defining the fundamental interactions: SU(2)
- Can be simplified as a rotation in 2 dimensions:

$$\Phi' = \begin{pmatrix} \phi'_1 \\ \phi'_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

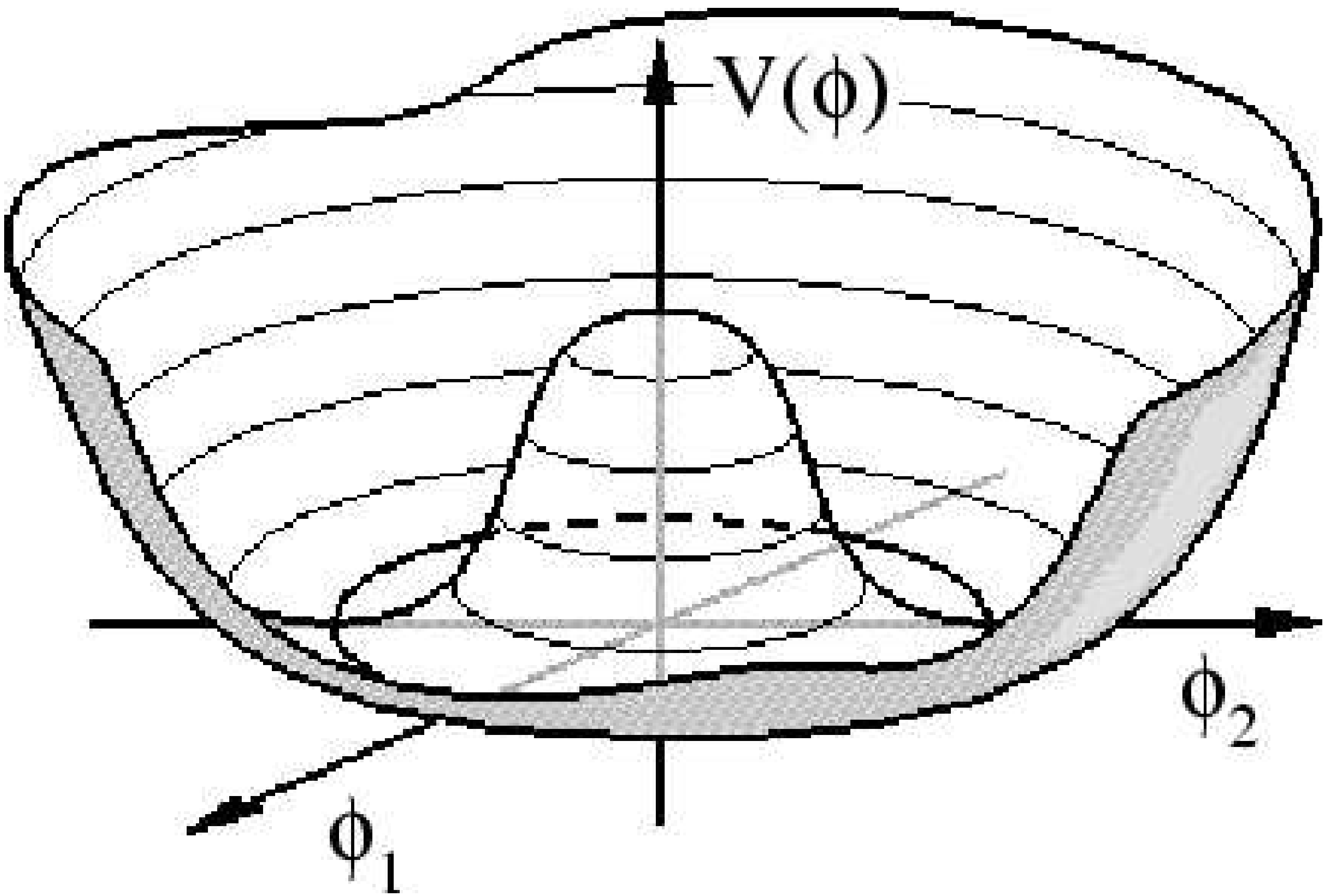
- We can extend our simple potential from before to two dimensions



- But the field in it moves over the 2D plane under symmetry operations!

Spontaneous Symmetry Breaking

- Clever Idea: Construct rotational symmetric potential:



- Result: Theory is symmetric under rotations, ground state is at $\phi \neq 0$