How are things slowed down? — probing our understanding of mass —
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The Dilemma of Gauge Symmetry

The structure of the weak interactions follows a certain symmetry pattern: (non-Abelian) gauge symmetry.

Gauge symmetry forbids elementary particles to have mass (at first sight).

Without mass all particles race around with light speed!

Why are (most) elementary particles not travelling at light speed?

The Origin of the Electroweak Interaction

- Beta decay 1911: Hahn, Meitner: observation: \( n \rightarrow p e^- + \) missing energy
- Puzzle: continuous energy spectrum of electrons observed
- discrete spectrum expected (discrete energy difference between \( n \) and \( p \) state)
- Bohr: energy is really missing Pauli (1930): \( n \rightarrow p e^- + \) neutrino (very weakly interacting)
- Fermi (1934): "Fermi Model"
  - short-range interaction
  - good description for energies well below \( G_\text{e}/2 \approx 300 \text{ GeV} \)
  - (length scales well above \( \approx 0.01\text{fm} \) size of atomic nuclei).
- but: bad high energy behaviour

- Beta decay: current understanding:
  - quark parton model [Bjorken, Paschos; Feynman 1969]
  - unification of electromagnetic and weak force
  - massive vector bosons \( Z, W^+, W^- \)
  - short range interaction
  - SU(2) \( \times \) U(1) gauge symmetry
  - forbids explicit mass terms for \( Z, W^+, W^- \)
  - spontaneous symmetry breaking via Higgs mechanism
  - dynamics respects symmetry, ground state not
  - \( Z, W^+, W^- \) masses generated dynamically
  - high energy behaviour
  - theory applicable above 300 GeV (\(< 10^{-16} \) m)

- Project 2: Higgs + Jet Production
  - Motivation:
    - Finding a 100–140 GeV Higgs is challenging.
    - The main channel is \( H \rightarrow \gamma \gamma \) via gluon fusion.
    - Suggestion (confirmed by simulations): events with additional high-p_T jet are easier to detect.
  - Results for SM and supersymmetric model (MSSM)
    - MSSM with \( \tan\beta \leq 20 \)
    - small sizeable contribution from superpartners
    - ultra-weak coupling
    - data taken by LHC

- Project 3: HiggsBounds
  - The Program
    - Tool to test models with arbitrary Higgs sectors against exclusion bounds from LEP and the Tevatron.
    - easy access to all relevant Higgs exclusion limits
    - model independent
    - combination of results from LEP and Tevatron possible
    - experimental sensitivities of Higgs search channels compared
    - 3 ways to use it: command line, Fortran subroutines, web interface: www.ippp.dur.ox.uk/HiggsBounds
  - Sample application:
    - MSSM benchmark scenarios, exclusion update
      - a) Published LEP result
        - [EUCL 4G(0.047)]
      - b) HiggsBounds
        - with new top mass, improved NLO QCD predictions, Tevatron data included

How to produce Higgs Bosons?

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  - Higgs couplings \( \propto m \)
    - most important couplings:
      - \( W/Z + \) heavy or antihiggs coupling at hadron collider
      - \( W/Z \) + light or antihiggs coupling at hadron collider
      - problem: ordinary matter (e, u, d-quarks) is very light!
      - At colliders: Higgs couples to heavy intermediate particles with non-suppressed couplings to ordinary matter.

- Project 1: SM Higgs Strahlenberg @ NNLO QCD
  - Process @ next-to-next-to-leading order in QCD
  - Results: NNLO correction factors (K-factors) and scale variation:
    - most precisely known Higgs production process at hadron colliders
    - results regularly used by Tevatron collaborations
    - currently, we provide updated predictions of cross sections and uncertainties for the ATLAS collaboration
    - Collaboration with Alliance nodes Wuppertal and Aachen

- Predictions: SM Higgs production @ LHC:
  - Gluon fusion
  - Vector boson fusion
  - Higgs decays
  - SM Higgs decay probability (branching ratio)
  - signal significance for Higgs detection @ LHC
  - How to detect Higgs Bosons?
    - Essential for Higgs discovery is:
      - [production rate] \( \times [\text{decay probability}] \times [\text{detection efficiency}]
    - Higgs events need to be silhouetted against huge amount of non-Higgs events
    - e.g. hopeless to see \( H \rightarrow bb \) via gluon fusion

How to find Higgs Bosons?

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- How to produce Higgs Bosons?
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- The Higgs Boson: What is it good for?
  - The Higgs mechanism (in the electroweak Standard Model):
    - The Higgs field has 4 components and doesn’t vanish in the ground state
    - The ground state configuration acts as a medium (background field)
    - with which all particles interact (coupling strength \( \propto m \))
    - 3 components promote \( Z, W^+, W^- \) to massive (3 component) vector particles from massless (2 component) ones
    - 1 component is an additional physical degree of freedom \( H \) — the Higgs boson
    - (coupling strength to other particles \( \propto m \))
  - The Higgs gives mass to all elementary particles: (e.g., electrons, quarks, \( Z, W^+ \))
    - the Higgs mechanism is a general concept (choice of Higgs field not unique)
  - It explains how masses arise but not what mass values
  - The Higgs cures bad high energy behaviour: (example \( W, W \) scattering)
  - ranges of theory validity (here):
    - QED only: \( \approx 300 \text{ GeV} \)
    - SM, no Higgs: \( \approx 1000 \text{ GeV} \)
    - SM with Higgs: very high
  - general remarks:
    - SM may be applicable up to very high energy.
    - If no Higgs exists, new phenomena around 1000 GeV are expected.