How are things slowed down ?

— probing our understanding of mass —

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PHYSICS AT THE TERA SCALE — Helmholtz Alliance

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 ?

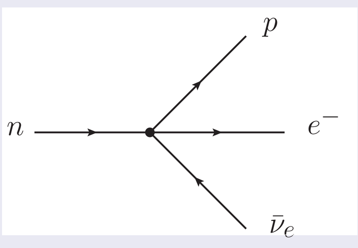
The Origin of the Electroweak Interaction

■ Beta decay 1911: Hahn, Meitner: observation : $n \to p\, e^- +$ 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): $n \to p\, e^-$ + neutrino (very weakly interacting)

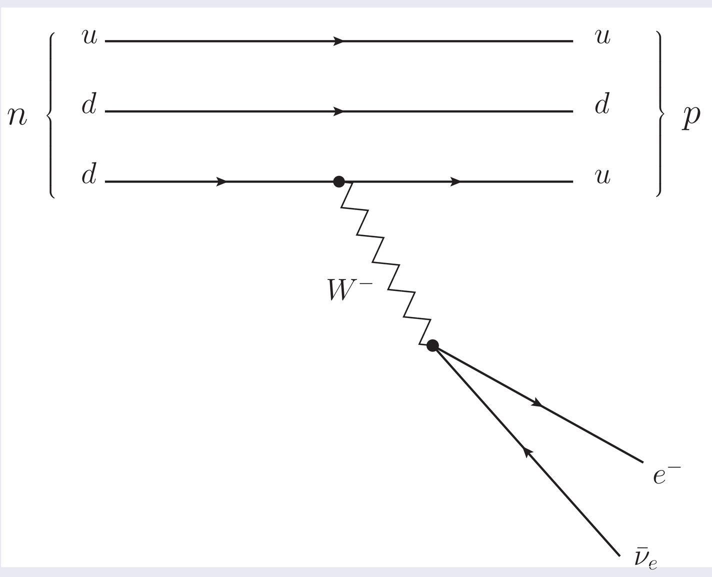
Fermi (1934): "Fermi Model"



- short-range interaction
- good description for energies well below $G_F^{-1/2} \approx 300$ GeV (length scales well above $\approx 10^{-18} m$ [= 0.001 × size of atomic nuclei]).
- but: bad high energy behaviour

■ Beta decay: current understanding:

quark parton model [Bjorken, Paschos; Feynman 1969]:
with electroweak interaction [Glashow 1961, Salam 1968, Weinberg 1967]



- unification of electromagnetic and weak force
- massive vector bosons Z, W^+, W^-
  → short range interaction
- SU(2)×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
  → good high energy behaviour
  → theory applicable above 300 GeV ($< 10^{-18} m$)

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 ∝ mass)
- 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 ∝ mass)

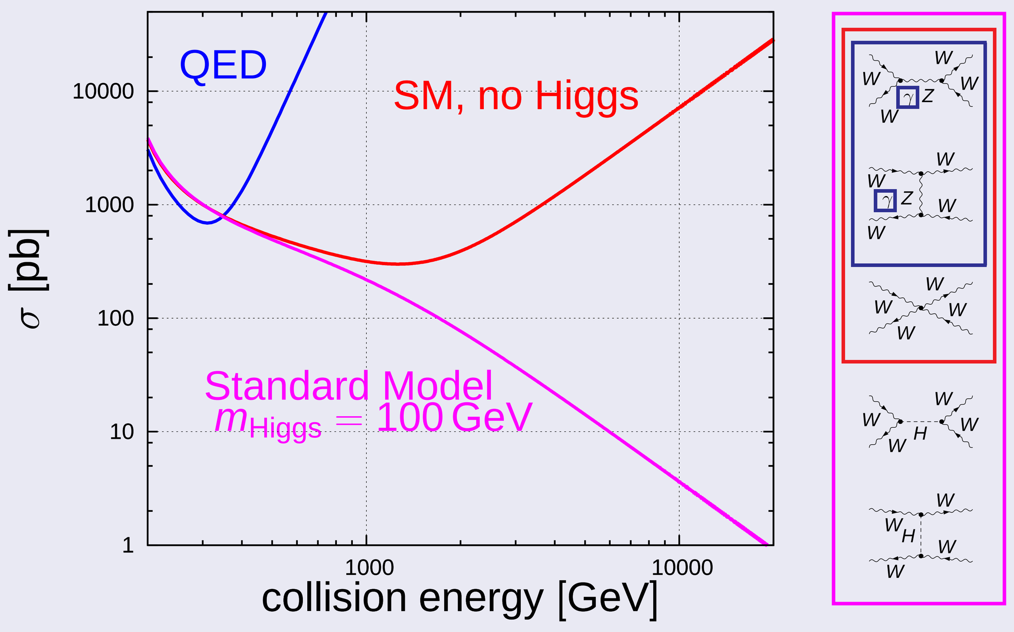
■ The Higgs gives mass to all elementary particles: (e.g. electrons, quarks, Z, $W^\pm$)

- 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 $W_L W_L$ scattering)

ranges of theory validity (here):
- QED only: ≈ 300 GeV
- SM, no Higgs: ≈ 1000 GeV
- SM with Higgs: very high

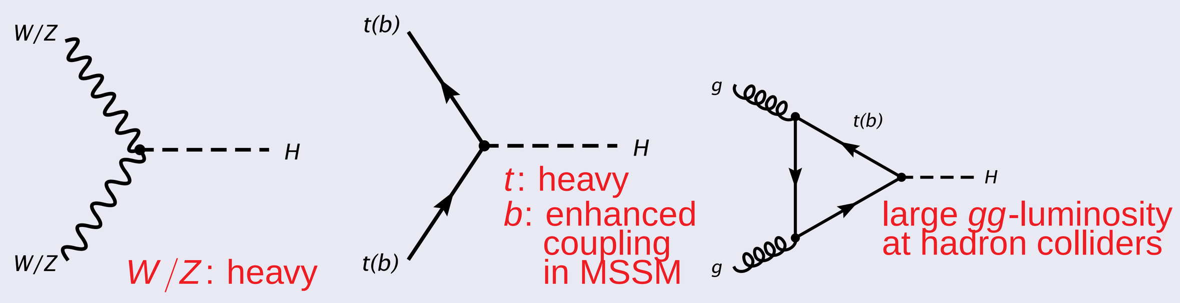
general remarks:
- SM may be applicable up to very high energy.
- If no Higgs exists, new phenomena around 1000 GeV are expected.



How to find Higgs Bosons ?

■ How to produce Higgs Bosons ?

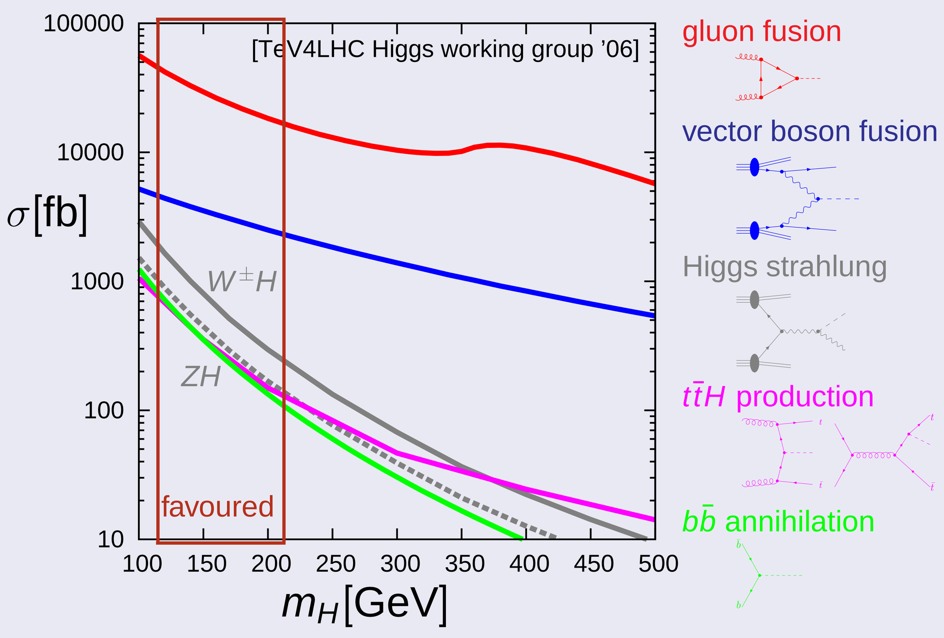
- Higgs couplings ∝ mass
  → most important couplings:



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.

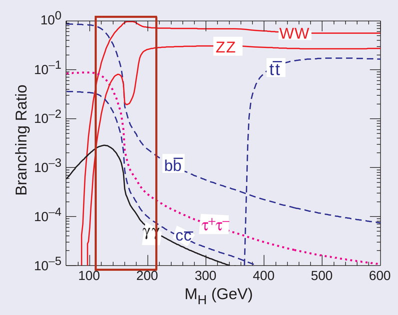
■ Predictions: SM Higgs production @ LHC :



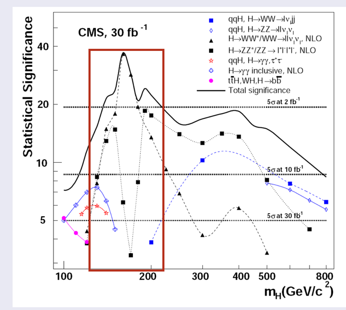
■ How to detect Higgs Bosons ?

- Essential for Higgs discovery is:
  [production rate]×[decay probability]×[detection efficiency]
- Higgs events need to be silhouetted against *huge* amount of non-Higgs events
  → e.g. hopeless to see $H \to b\bar{b}$ via gluon fusion

⋆ SM Higgs decay probability (branching ratio):

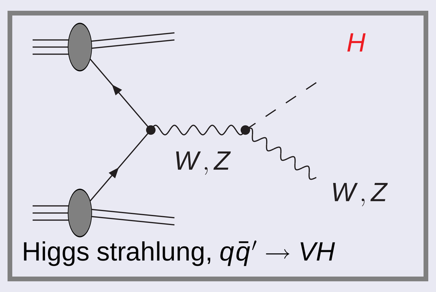


⋆ signal significance for Higgs detection @ LHC:

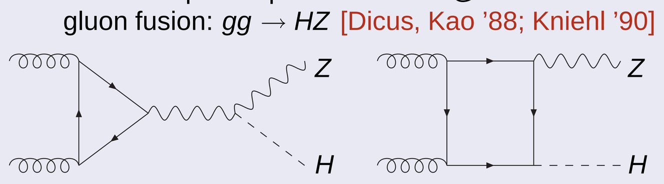


Project 1: SM Higgs Strahlung @ NNLO QCD

■ Process @ next-to-next-to-leading order in QCD

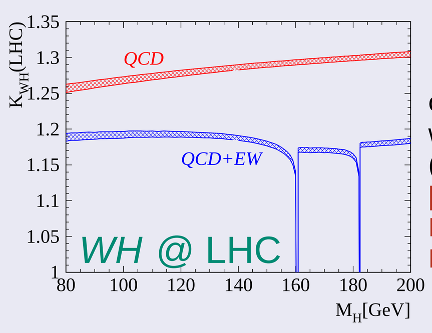


note! additional parton process for ZH @ NNLO: gluon fusion: $gg \to HZ$ [Dicus, Kao '88; Kniehl '90]

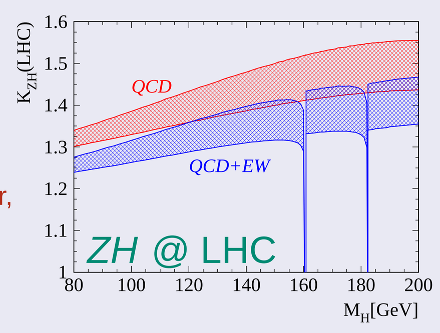


[OBr, Djouadi, Harlander '03]

■ Results:
NNLO correction factors (K-factors) and scale variation:



our results combined with NLO electroweak (EW) corrections: [OBr, Ciccolini, Dittmaier, Djouadi, Harlander, Krämer '04

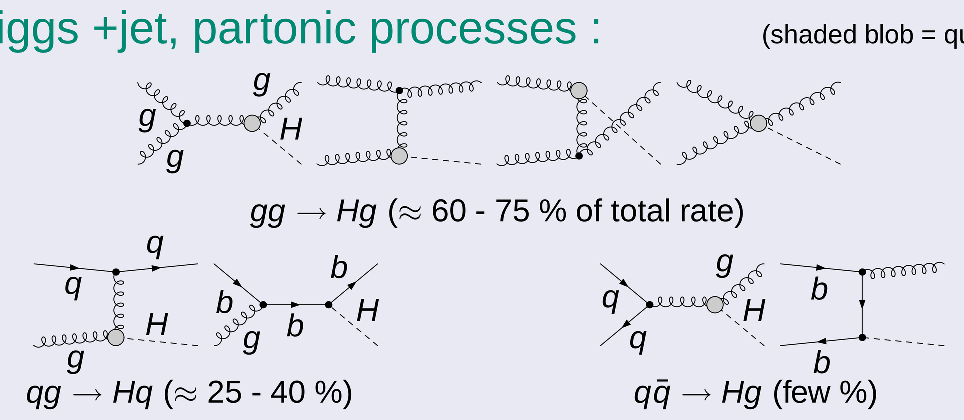


- most precisely known Higgs production process at hadron colliders
- results regularly used by Tevatron collaborations
- currently, we provide updated predictions of cross sections and uncertainties for the ATLAS collaboration

[Collaboration with Alliance nodes Wuppertal and Aachen]

Project 2: Higgs + Jet Production

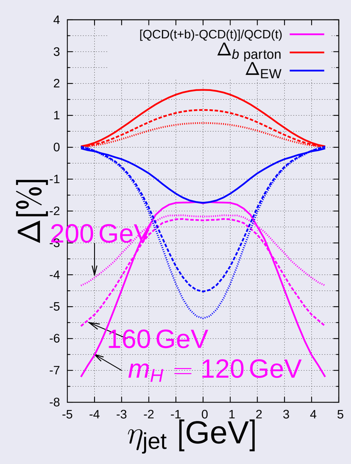
■ Higgs +jet, partonic processes : (shaded blob = quark loop)



■ Motivation

- Finding a 100–140 GeV Higgs is challenging. The main channel is $H \to \gamma\gamma$ 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)

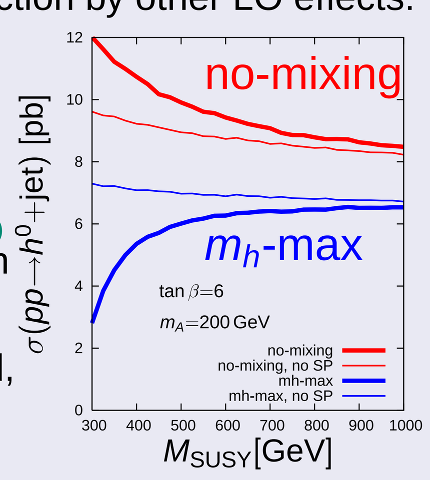


← Standard Model (H + jet @ Tevatron)
- NLO QCD (heavy top limit) known (acc. 10%)
- change Δ in cross section by other LO effects:
  – electroweak
  – bottom mass
  – bottom parton

[Keung, Petriello '09; OBr '09]

→ MSSM (h^0 + jet @ LHC)
- sizeable contribution from superpartners (mass scale: M_{SUSY})
- code HJET 1.3 provided, used by ATLAS people

[OBr, Hollik '03; '07; OBr '09]



Project 3: HiggsBounds

■ The Program [Bechtle, OBr, Heinemeyer, Weiglein, Williams '08]

Tool to test models with arbitrary Higgs sectors against exclusion bounds from LEP and the Tevatron.

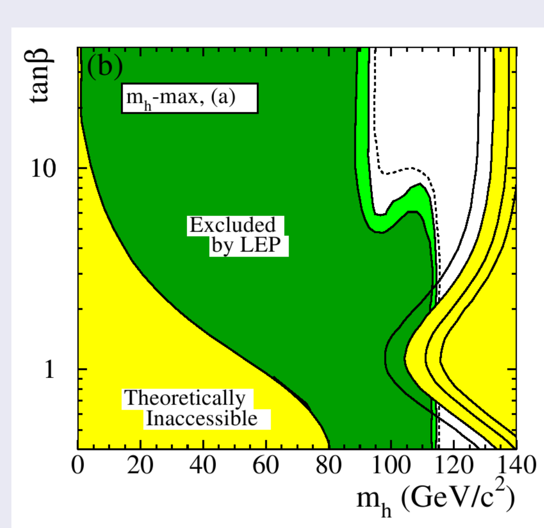
- easy access to all relevant Higgs exclusion limits
- model independent
- combination of results from LEP and Tevatron possible experimental sensitivities of Higgs search channels compared
- 3 ways to use it: command line, Fortran subroutines, web interface: www.ippp.dur.ac.uk/HiggsBounds

[Collaboration with Alliance nodes Bonn(th.)/DESY(th. & exp.)]

■ Sample application :

MSSM benchmark scenarios, exclusion update

a) Published LEP result
[EPJC 46(2006)547]



b) HiggsBounds
with: new top mass, improved m_h prediction, Tevatron data included