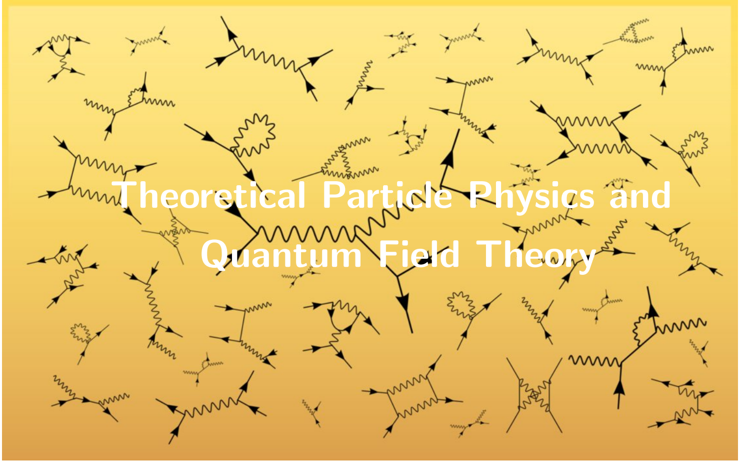
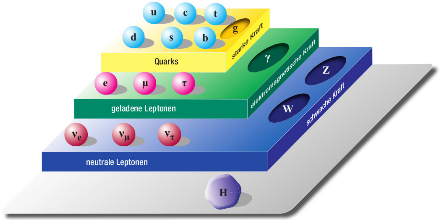


Theoretical Particle Physics and Quantum Field Theory

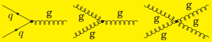
AG Dittmaier

Albert-Ludwigs-Universität Freiburg

Elementary particles and their interactions



Strong Force

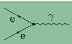


Force mediator: gluon

Theory: Quantum Chromo Dynamics (QCD)

Phenomena: "zoo of hadrons" (e.g. proton, neutron)

Electromagnetic Force

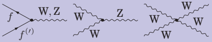


Force mediator: photon

Theory: Quantum Electro Dynamics (QED)

Phenomena: electricity, magnetism, structure of atoms, chemistry ...

Weak Force



Force mediator: W, Z bosons

Theory: (electro)weak interaction

Phenomena: radioactive beta decay

Gravity ? no consistent quantum theory yet ?

Force mediator: graviton

Theory: Einstein's general relativity

Phenomena: gravitational force, stars, planets, ...

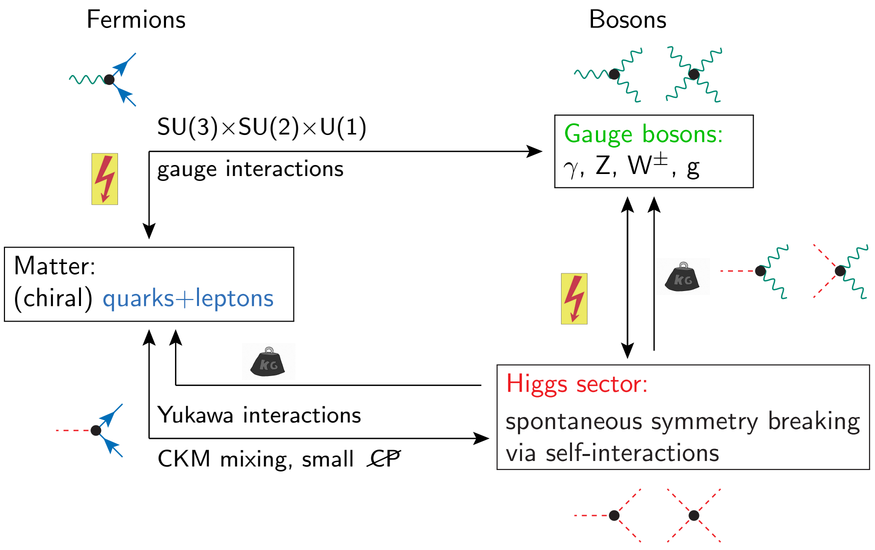
Mission of particle physics:

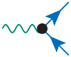
- push the limits of the Standard Model (SM)
- find fundamental (unifying?) structures

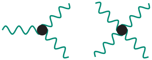
Our contribution:

- precise predictions for particle reactions
- concepts and techniques in (perturbative) QFT

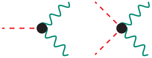
Structure and elementary interactions of the SM

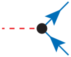




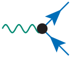


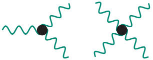
Test of the model
⇔ Exp. reconstruction of the $\underbrace{\text{elementary couplings}}_{\text{Feynman rules}}$





Structure and elementary interactions of the SM



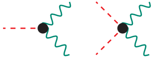


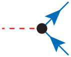
Test of the model

$\Leftrightarrow$ Exp. reconstruction of the $\underbrace{\text{elementary couplings}}$

Feynman rules

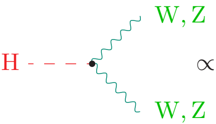
Building blocks for particle reactions



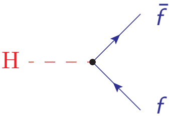


Higgs production and decay at the LHC

Higgs bosons couple proportional to particle masses:



$\propto M_{\mathrm{W}}$

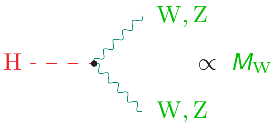


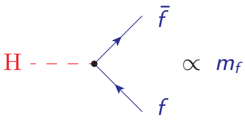
$\propto m_f$

$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Higgs production and decay at the LHC

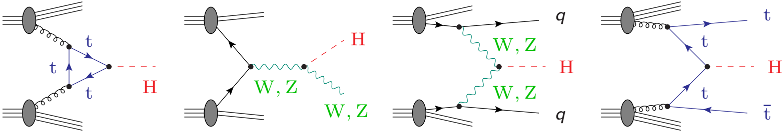
Higgs bosons couple proportional to particle masses:





$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($\mathrm{p\bar{p}/pp}$):



Higgs production and decay at the LHC

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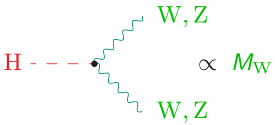
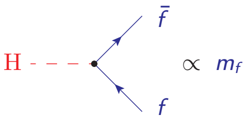
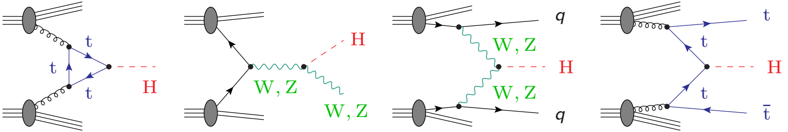


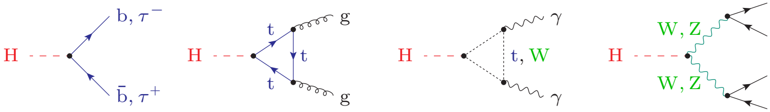


⇒ Higgs production via couplings to W/Z bosons or top-quarks

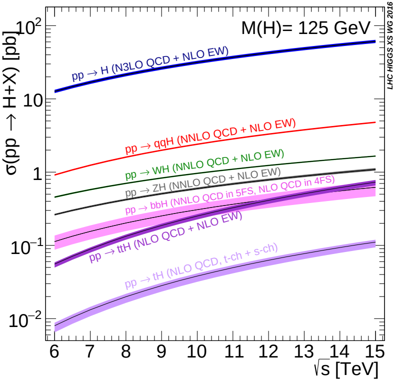
Processes at hadron colliders ($p\bar{p}/pp$):



Decay channels for Higgs bosons of moderate mass:



Higgs cross-section predictions with contributions from our AG



Recall:

"total cross section"

$\hookrightarrow$ reaction probability

"differential cross section"

$\hookrightarrow$ information on distributions in production angles, energies, etc.

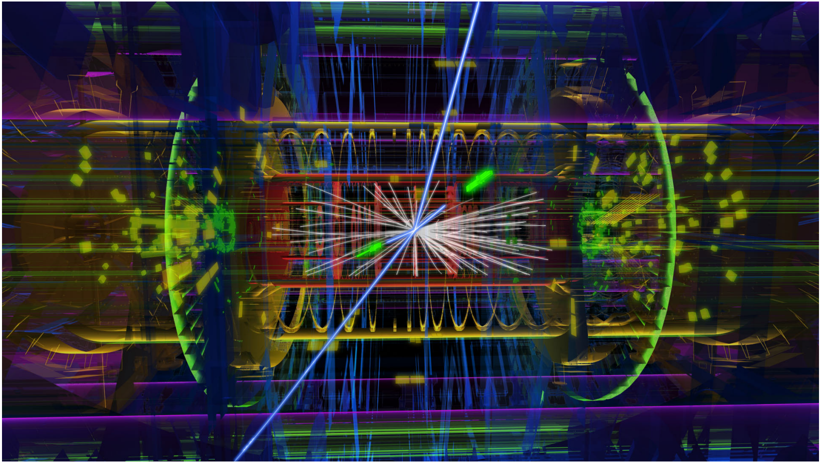
Important features:

- strong (QCD) corrections $\sim$ 10–100%
- electroweak (EW) corrections $\sim$ 1–5%
- band widths = theoretical/parametric uncertainty

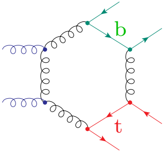
Current frontiers:

- refinements of SM predictions
- precision calculation in SM extensions (e.g. more Higgs bosons, new particles)

An event of $\mathrm{pp} \to \mathrm{H}(\to \mu^+\mu^-\mathrm{e}^+\mathrm{e}^-) + X$ observed at ATLAS/LHC



What we typically calculate ...



$$= \frac{g_{\mathrm{s}}^6}{2^4}\, f^{afc}\, f^{bfd}\, \mu^{2(4-D)} \int \frac{\mathrm{d}^D q}{(2\pi)^D}\, \varepsilon^{\alpha,a}(p_1)\, \varepsilon^{\beta,b}(p_2)$$

$$\times\, \bar{u}_{\mathrm{b},k}(k_3)\, (\lambda^e \lambda^c)_{kl}\, \gamma^\mu\, \frac{m_{\mathrm{b}} - \not{q}}{q^2 - m_{\mathrm{b}}^2}\, \gamma^\nu\, v_{\bar{\mathrm{b}},l}(k_4)$$

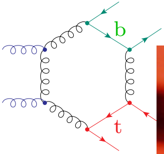
$$\times\, \bar{u}_{\mathrm{t},i}(k_1)\, (\lambda^d \lambda^e)_{ij}\, \gamma^\rho\, \frac{m_{\mathrm{t}} - \not{k}_2 - \not{k}_3 - \not{q}}{(q+k_2+k_3)^2 - m_{\mathrm{t}}^2}\, \gamma_\mu\, v_{\bar{\mathrm{t}},j}(k_2)$$

$$\times\, \frac{\left[(q+2p_1-k_4)_\nu g_{\alpha\sigma} + (q-p_1-k_4)_\sigma g_{\nu\alpha} - (2q+p_1-2k_4)_\alpha g_{\nu\sigma}\right]}{(q+k_3)^2\,(q+p_1+p_2-k_4)^2\,(q+p_1-k_4)^2\,(q-k_4)^2}$$

$$\times\, \left[(2q+2p_1+p_2-2k_4)_\beta g_{\rho\sigma} - (q+p_1-p_2-k_4)_\rho g_{\beta\sigma} - (q+p_1+2p_2-k_4)_\sigma g_{\beta\rho}\right]$$

- loop integration over D-dim. Minkowski space (D = complex)
  - UV singularities $\rightarrow$ renormalization
  - huge algebraic complexity $\rightarrow$ computer algebra
- multi-dim. phase-space intergation
  - Monte Carlo techniques, HPC @ NEMO cluster
  - IR singularities $\rightarrow$ subtraction / slicing techniques

What we typically calculate ...



$\times\ \overline{u}_{\mathrm{b}}$

$\times\ \overline{u}_{\mathrm{t}},$

$\times\ \frac{[(}{}$

$\times\ [(2 \quad \ldots \quad p_2 - k_4)_\sigma g_{\beta\rho}]$

- loop int ... ex)
  - UV
  - huge algebraic complexity $\rightarrow$ computer algebra
- multi-dim. phase-space intergation
  - Monte Carlo techniques, HPC @ NEMO cluster
  - IR singularities $\rightarrow$ subtraction / slicing techniques

How can students grow into this?

Field very demanding → solid basis in theory + mathematics needed!

Field well structured → "learning by doing" with close guidance

MSc theses: "1st step towards research projects"

- typical goals:
  - precision ingredients for a specific particle reaction
  - issues in QFT
  - predictions in SM extensions
- MSc thesis = often stepping stone towards PhD

BSc theses: more like "learning projects"

- typical goal: specific basic topic in particle phenomenology or QFT
- ideal: BSc thesis in parallel to introductory QFT lecture
- BSc theses off main stream:
  selected topics of theoretical physics (class. mechanics, QM, ...)