Dissertation

Automated optimization of sensitivity in a search for boosted VBF Higgs pair production in the $b\bar{b}b\bar{b}$ quark final state with the ATLAS detector

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Abstract

I am an abstract.

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Chapter 1

Theory

The Standard Model (SM) of Particle Physics is the current theory that describes three of the four fundamental forces, namely the electromagnetic, strong, and weak forces, with the exception of gravity. Over the last decades it has been probed with remarkable precision but although there are observational phenomena that lie beyond its scope.

The SM is based on symmetry principles and is described by a lorentz-invariant Quantum Field Theory (QFT) that is renormalizable and invariant under local gauge transformations. This means that within the non-abelian gauge group

$$G = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y, \tag{1.0.1}$$

the equations of motions are invariant. $SU(3)_C$ is the special unitary group of rank 3 representing the color symmetry within Quantum Chromodynamics (QCD), the QFT describing the strong interactions. $SU(2)_L \otimes U(1)_Y$ exhibits the unification of the weak and electromagnetic interaction into the electro-weak force of $SU(2)_L$ left-chiral fermions of the weak force and right-handed $U(1)_Y$ fermions with hypercharge Y of the electromagnetic force described by Quantum Electrodynamics Quantum Electrodynamics (QED).

The following describes the particles of the SM and gives a brief overview of the QFT's used to describe aforementioned forces. The content of this chapter draws inspiration primarily from [1–4]. Natural units are assumed everywhere $\hbar = c = 1$.

1.1 Particles of the Standard Model

All currently known elementary particles are included in the SM and can be organized as depicted in figure 1.1. This includes 12 fermions, that are particles of half-integer spin, 12 vector bosons with spin 1, and the Higgs boson, a scalar particle with spin 0.

The fermions can be categorized into three generations each consisting of a charged lepton, a neutral neutrino and two quarks. Except for their masses, particles of the different generations have the same quantum numbers. Ordinary matter consists only of particles from the first generation. Moreover each particle has an associated anti-particle with all the quantum numbers inversed.

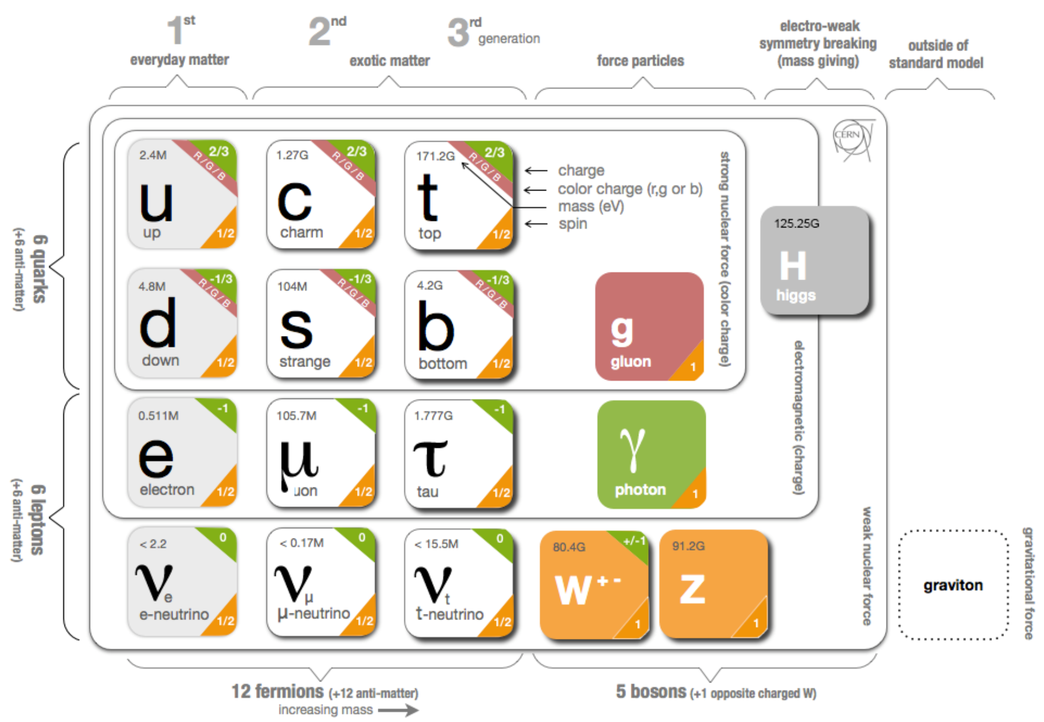

Figure 1.1: Particles in the SM. Adopted from [5]. Higgs Boson mass corrected to the current value [6].

Quarks possess both electric charges and color charges, causing them to interact with each other via weak, electromagnetic, and strong forces. Each generation consists of an up quark (up, charm and top quark) with an electric charge of Q = 2/3 and a down quark (down, strange and bottom quark) with a charge of Q = -1/3. Quarks can only be observed as composite particles - hadrons due to color confinement. This states that if one tries to separate a hadron, it is always energetically favorable to produce a quark-antiquark pair instead. Hadrons constitutes either bound states of 2 quarks - Mesons, e.g. a pion or 3 quarks - Baryons e.g. the proton. To not break Pauli's exclusion principle quarks in a bound state must have different color states.

Leptons in turn do not carry a color charge and encompasses the electron e, muon μ and tau τ and their associated neutrinos ν_e, ν_μ and ν_τ. In the SM neutrinos are considered to be massless. Neutrinos also do not carry a charge and interact solely via the weak force whereas the ones (e, μ, τ) with a charge $Q = -1$ participate also interact electromagnetically.

In the interaction picture of QFT, forces are mediated by particles specific to the particular force. These particles are bosons and are mediating as 8 massless gluons g the strong force, as 1 massless photon γ the electromagnetic force and as 3 massive bosons W^+, W^-, Z the weak force.

The scalar Higgs particle has a unique role in the Standard model. As will be explained in more detail in section 1.3 a locally gauge free QFT requires a massless mediator which the $W^\pm, Z$ are not. When unifying the weak force and the electromagnetic force into the electroweak force a new field - the Higgs field - can incorporate mass to these mediators by leaving the qft gaguge invariant. This will be discussed in detail in section **??**. The Higgs field can explain the masses of all fermions as the coupling to each fermion is proportional to its mass. This essentially means that the heavier the particle, the stronger its interaction is with the Higgs field.

If not further specified the following always includes the anti-particles when referred to a species or a particular particle.

particle	field type	Lagrange
spin-0 (scalar)	scalar ϕ	$\mathcal{L}_{\text{Klein-Gordon}} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{m^2}{2}\phi^2$
spin-1/2 (fermion)	spinor ψ	$\mathcal{L}_{\text{Dirac}} = \overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi$
spin-1 (boson)	vector A_μ	$\mathcal{L}_{\text{Proca}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{m^2}{2}A_\mu A^\mu$

Table 1.1: Quantum fields appearing in the SM. With $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ the electromagnetic field strength tensor.

1.2 Quantum Field Theory

Elementary Particles can be created, transformed and vanish in all sorts of particle interactions.Quantum mechanics states that energy can vary greatly on short time scales via the uncertainty principle. Special relativity relates energy with mass allowing energy to manifest as massive particles. Though special relativity lacks a quantum mechanical description and in non-relativistic quantum mechanics the particle number is conserved. Neither of these descriptions is sufficient to fully describe the observations therefore a new theory - QFT - was developed.

For a field description some quantity $\phi(x, y, z, t) = \phi(x)$ is assigned to some region in spacetime x. Similar to the Lagrangian formalism in classical mechanics here a Lagrangian density in spacetime governs the dynamics of the system $\mathcal{L}(\phi_1, \dots, \phi_n)$. The generalized Euler-Lagrange equations of qft then give the according equations of motion for each field component ϕ_i

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)} \right) = \frac{\partial \mathcal{L}}{\partial \phi_i}. \tag{1.2.1}$$

This relation gives the equations of motion for the Lagrangians associated to fields which appear in the SM and are summarized in 1.1 table.

The conventional strategy to describe particle dynamics is to start with a free field and treat the interactions of particles as a small perturbation to a chosen order. In the path integral formulation it fundamentally reduces to integrals of the form $\int D\phi e^{i\int d^4x L(\phi(\boldsymbol{x},t))}$. Where $\int D\phi$ is the integral over all possible paths a particle could take. Through back and forth expansions of the e function the integral can be solved to a desired order of perturbation and the result is a probability - theamplitude - usually denoted with $\mathcal{M}$. Via this one can derive the Feynman rules and calculate cross sections.

The principle of local gauge invariance generates all the symmetries for the different forces and is inspired by gauge invariance from classical electrodynamics. In the following, this is explained for each of the forces.

1.3 Quantum Electrodynamics

The QFT-description of the electromagnetic interaction QED can be derived from the free fermion field given by the Dirac equation

$$\mathcal{L}_{\text{Dirac}} = \overline{\psi}(i\gamma^\mu \partial_\mu - m)\psi. \tag{1.3.1}$$

This Lagrangian is invariant under a change of phase α

$$\psi(x) \to e^{-i\alpha}\psi(x). \tag{1.3.2}$$

The requirement that this transformation also holds locally means that α now additionally depends on the point x in spacetime $\alpha \to \alpha(x)$. Since this gives another term because of the derivative, the Lagrangian can be made invariant again by introducing a vector field A_μ and replacing the derivative ∂_μ by the covariant derivative D_μ

$$\partial_\mu \to D_\mu = \partial_\mu + ieA_\mu(x), \tag{1.3.3}$$

with e the electron charge. Thus, the new Lagrangian

$$\mathcal{L} = \overline{\psi}(i\gamma^\mu D_\mu - m)\psi = \underbrace{\overline{\psi}(i\gamma^\mu \partial_\mu - m)\psi}_{\mathcal{L}_{\text{Dirac}}} + \underbrace{e\overline{\psi}\gamma^\mu \psi A_\mu}_{\mathcal{L}_{\text{int}}} \tag{1.3.4}$$

becomes invariant under the local gauge transformations

$$\psi(x) \to e^{-i\alpha(x)}\psi(x) \tag{1.3.5}$$

$$A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu \alpha(x) \tag{1.3.6}$$

forming the electromagnetic $U(1)$ gauge group. This is also called the minimal substitution rule. This Lagrangian describes a fermion interacting with a vector field A_μ - the photon. A kinetic term for the vector field can be from the Proca Lagrangian in table 1.1. $F_{\mu\nu}$ is local gauge invariant whereas the $A_\mu A^\mu$ is not, which is why the gauge field is required to be massless. The full QED lagrangian with coupling strength then

$$\mathcal{L}_{\text{QED}} = \underbrace{\overline{\psi}(i\gamma^\mu\partial_\mu - m)\psi}_{\mathcal{L}_{\text{Dirac}}} + \underbrace{e\overline{\psi}\gamma^\mu\psi A_\mu}_{\mathcal{L}_{\text{int}}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\mathcal{L}_{\text{Maxwell}}}. \tag{1.3.7}$$

Saying that this symmetry for $\alpha(x)$ holds locally for all unitary 1×1 matrices $U(1)$ is a bit extravagant, but the formalism is extendable to higher orders as for the electroweak theory and QCD case. It is called an abelian gauge group as any 1×1 matrix also commutes with itself.

1.4 Quantum Chromodynamics

Along the same lines as QED is derived in section 1.3, the theory of the strong interactions QCD is now a non-abelian gauge theory of the symmetry group $SU(3)$. The latter is generated by the 3×3 Gellmann matrices λ_a with $a \in \{1,\dots,8\}$. The fundamental charge is now color and each quark is a triplet of the three color fermion fields $\Psi_k = (\psi_r, \psi_g, \psi_b)^T$ for all quark flavors k. Local gauge invariance of the Lagrangian

$$\mathcal{L} = \sum_k \begin{pmatrix}\overline{\psi}_r & \overline{\psi}_g & \overline{\psi}_b\end{pmatrix}(i\gamma^\mu\partial_\mu - m)\begin{pmatrix}\psi_r\\ \psi_g\\ \psi_b\end{pmatrix} = \sum_k \overline{\Psi}_k(i\gamma^\mu\partial_\mu - m)\Psi_k \tag{1.4.1}$$

can be achieved via the gauge transformations of the spinors

$$\Psi_k(x) \to e^{i\alpha_a(x)\lambda_a/2}\Psi_k(x), \qquad \alpha \in \mathbb{R}, \quad a \in \{1,\dots,8\}, \tag{1.4.2}$$

with $\alpha_a(x)$ a local phase and the index a for the 8 gluons. Here and in the following summation over equal indices $\alpha_a(x)\lambda_a = \sum_i \alpha_a(x)\lambda_a$ is assumed. As in QED a covariant derivative is introduced

$$D_\mu = \partial_\mu - i g_s \frac{\lambda_a}{2} G^a_\mu, \tag{1.4.3}$$

involving the eight gluon vector fields G^a_μ and the coupling strength g_s, which is related to the strong coupling constant as

$$\alpha_s = \frac{g_s^2}{4\pi}. \tag{1.4.4}$$

Again self coupling terms are added

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^a_{\beta\gamma} G^\beta_\mu G^\gamma_\nu, \qquad \text{with } [\lambda_a, \lambda_b] = i f^c_{ab} \lambda_c, \tag{1.4.5}$$

to get the gauge invariant QCD Lagrangian

$$\begin{aligned} \mathcal{L}_{\text{QCD}} &= \sum_k \overline{\Psi}_k \left(i\gamma^\mu D_\mu - m_k \right) \Psi_k - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} && (1.4.6) \\ &= \sum_k \overline{\Psi}_k \left(i\gamma^\mu \partial_\mu - m_k \right) \Psi_k + g_s \overline{\Psi}_k \gamma^\mu \frac{\lambda_a}{2} \Psi_k G^a_\mu - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}. && (1.4.7) \end{aligned}$$

This Lagrange consists of a kinetic term for each quark, an interaction term of the quarks with the gluons and gluon-gluon interactions giving vertices shown in 1.2. This becomes clear when $G^a_{\mu\nu}$ is squared and also leads to cubic and quartic terms for the fields.

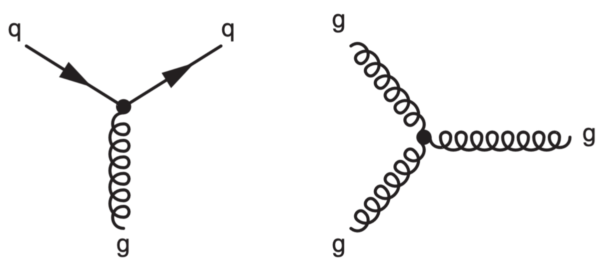

Figure 1.2: left: A quark interacting with a gluon. middle and right: triplet and quartic self coupling of gluons. Adopted from [3].

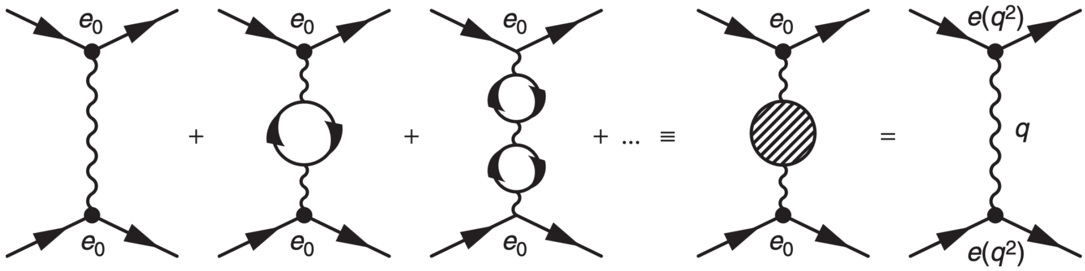

Figure 1.3: Higher order loop corrections in QED schematically treated as one effective diagram. Adopted from [3].

1.5 Renormalization

When trying to calculate amplitudes $\mathcal{M}$ of higher order diagrams in QED like the second or third one in figure 1.5 it results in diverging integrals. These diagrams are also referred to as vacuum polarization as virtual particle-antiparticle pairs screen the actual charge of the electron e_0 like a dielectric medium in classical electrodynamics. The situation can be fixed by absorbing the appearing infinities into an effective charge/coupling $e(q^2)$ which is now a function of the squared four momentum q^2 at the virtual photon vertex shown schematically in figure 1.5. For the diagram involving only one loop correction (the second one in figure 1.5) it can be shown that for some measured coupling $e(q^2 = \mu^2)$ the actual coupling $e(q^2)$ follows a scaling behavior that holds if q^2 and μ^2 are larger than the electron mass [3]. This so-called running coupling constant $e(q^2)$ reads in terms of the fine structure constant $\alpha(q^2) = e^2(q^2)/4\pi$,

$$\alpha(q^2) = \frac{\alpha(\mu^2)}{1 - \alpha(\mu)\frac{1}{3\pi}\ln\left(\frac{q^2}{\mu^2}\right)}. \tag{1.5.1}$$

With increasing momentum transfer or viewed in a collision as particles getting closer to each other the coupling at the virtual photon vertex increases qualitatively as in figure.

Renormalization in QCD can be derived similarly but also the quartic and triplet couplings exemplified in figure 1.5 need to be considered resulting in a

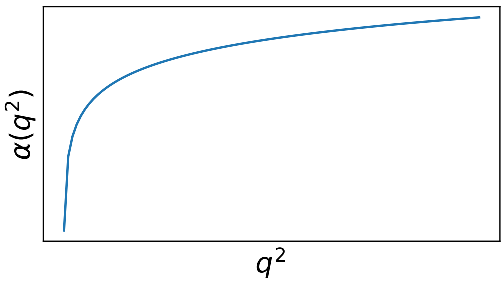

Figure 1.4: Behavior of equation 1.5.1, the running coupling constant of QED.

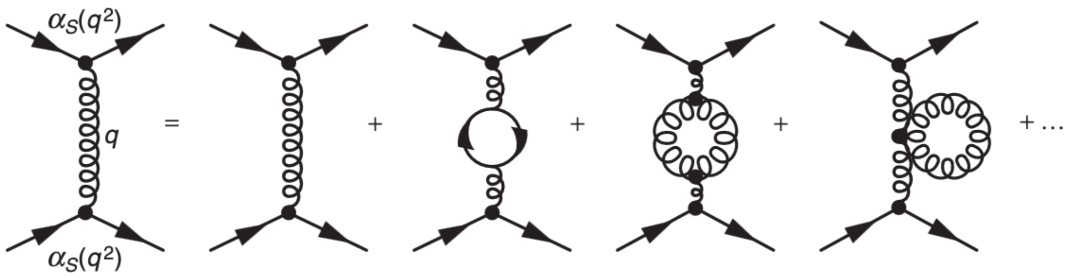

Figure 1.5: Some higher order loop corrections in QCD. Adopted from [3].

scaling for the strong coupling constant

$$\alpha_s(\mu_R^2) = \frac{12\pi}{(33 - 2n_f)\ln(\frac{\mu_R^2}{\Lambda_{\mathrm{QCD}}^2})}. \tag{1.5.2}$$

no particles with color charge

Appendix A

Acronyms

CERN Organisation européenne pour la recherche nucléaire

ATLAS A Toroidal LHC Apparatus

SM Standard Model

QFT Quantum Field Theory

QCD Quantum Chromodynamics

QED Quantum Electrodynamics

EWSB electroweak symmetry breaking

VEV vacuum expectation value

LHC Large Hadron Collider

HL-LHC High Luminosity LHC

ID Inner Detector

SCT semiconductor tracker

TRT transition radiation tracker

ITk Inner Tracker

IBL insertable *b*-layer

EM electromagnetic

LAr liquid argon

MS muon spectrometer

RPCs resistive plate chambers

TGCs thin gap chambers

MDTs monitored drift tubes

CSCs cathod strip chambers

HLT high level trigger

RoI region of interest

L1 Level-1

PDF Parton Distribution Function

DGLAP Dokshitzer–Gribov–Lipatov–Altarelli–Parisi

MC Monte Carlo

MPI multi-parton interaction

PS parton shower

ME matrix element

ISR initial state radiation

FSR final state radiation

4FS four-flavour scheme

5FS five-flavour scheme

NLO next-to-leading order

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