Czech Technical University in Prague
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High pT jets in RunII of the ATLAS Experiment

MASTER'S DEGREE PROJECT

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Zadani prace

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V Praze dne ....

Jan Lochman

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Introduction

Chapter 1

QCD

Is the purpose of theoretical physics to be no more than a cataloging of all the things that can happen when particles interact with each other and separate? Or is it to be an understanding at a deeper level in which there are things that are not directly observable (as the underlying quantized fields are) but in terms of which we shall have a more fundamental understanding?

Julian Schwinger

The theoretical framework of particle physics is called Standard Model (SM). The SM describes the way how the fundamental components of matter interact with each other through strong, weak and electromagnetic interactions. Mathematically the SM is gauge quantum field theory with local internal symmetries of the direct product group $SU(3) \times SU(2) \times U(1)$. Gauge bosons are assigned to generators of this symmetry - there are 8 massless gluons from $SU(3)$ intermediating strong interaction between quarks and 3 massive $W^{\pm}, Z$ bosons with 1 massless boson γ for electroweak $SU(2) \times U(1)$ sector. Higgs mechanism has to be introduced in electroweak sector to assign $W^{\pm}, Z$ bosons mass and as consequence the new particle - Higgs boson - emerges in the SM theory. All bosons have integer spin.

In addition to the bosons the SM introduces spin-1/2 fermions which are divided into three quark and three lepton families. Fermions are assumed to be point-like because there is no evidence for their internal structure to date. All fermions interact weakly, if they have electrical charge, they interact electromagnetically as well. Quarks are the only fundamental fermions which do interact strongly. System of fundamental particles of the SM is shown in figure 1.1.

Quarks bind together to form hadrons and there are hundreds (?source?) of known hadrons up to date. Theory describing the interaction between quarks is called Quantum Chromodynamics (QCD) which key features will be discussed in this chapter. The reasoning for quark existence and for the description their strong interaction as $SU(3)$

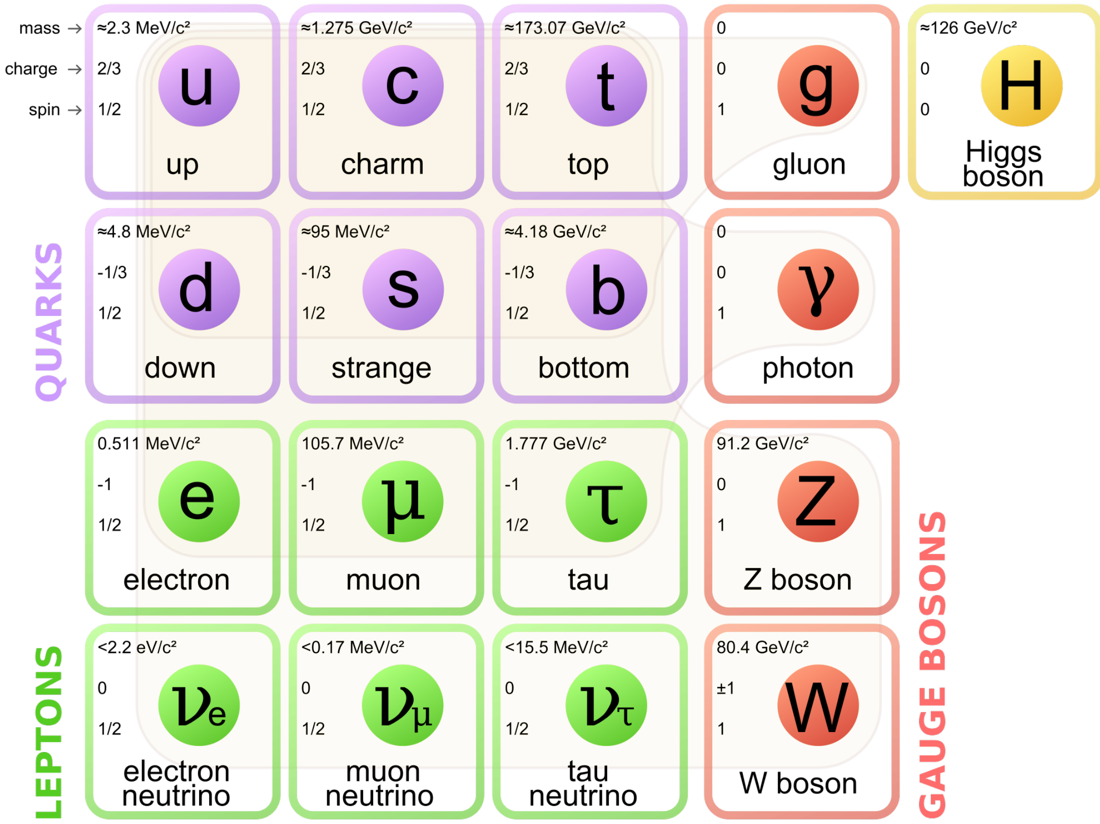

Figure 1.1: The system of fundamental particles of the SM. Figure from [1]

gauge theory will be presented. Running coupling constant will be discussed to split QCD into perturbative and non-perturbative regions - two regions, where QCD has to use different mathematical approach for description of strong interaction. Most of ideas presented here is overtaken from the following textbook [2].

1.1 Theoretical Ansatz

In 1950s there have already been discovered tens of new hadrons thanks to new particle accelerators and a lot of effort was exerted to categorize them. To each particle there was assigned a series of quantum numbers including isospin T with its third component T_3, hypercharge Y, electrical charge Q, strangeness S, baryon number B and others. Soon it was recognized, that there are some symmetries between these quantum numbers, like Gell-Mann–Nishijima relation [3, 4]

$$Q = T_3 + 1/2Y \quad , \quad Y = B + S + \dots , \tag{1.1}$$

	S	Y	T	T_3	Q
p	0	1	1/2	1/2	1
n				-1/2	0
Σ^+	-1	0	1	1	1
Σ^0				0	0
Σ^-				-1	-1
Λ			0	0	0
Ξ^0	-2	-1	1/2	1/2	0
Ξ^-				-1/2	-1

Table 1.1: Quantum numbers of selected baryons known in 1950s. S strangeness, Y hypercharge, T isospin, T_3 third component of isospin, Q electrical charge.

where dots denotes charm, bottomness and topness. Some of the hadrons known by then are shown in table 1.1. In 1960s the known particles were successfully categorized with the so called Eightfold Way, which was published independently by Murray Gell-Mann (?citace?) and George Zweig (?citace?) in 1964. The Eightfold Way successfully predicted the existence of new particle Ω^{--} including its mass. Basic ideas of Eightfold way will be discussed in this section.

The key feature of Eightfold Way is to understand hadrons as the part of different representations of infinitesimal generators of $SU(3)$ flavor symmetry group. Lie algebra of $SU(3)$ is real eight-dimensional Lie algebra $\mathfrak{su}(3)$ which fundamental representation is usually derived from Gell-Mann matrices

$$\begin{aligned}
&\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
&\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \\
&\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} .
\end{aligned} \tag{1.2}$$

The generators are usually chosen $g_a = \frac{1}{2}\lambda_a$ and obey the commutation relation $[g_a, g_b] = i f_{abc} g_c$ with f_{abc} being structure constants. Cartan subalgebra of fundamental representation of $\mathfrak{su}(3)$ is generated by $H_1 = g_3$ and $H_2 = g_8$. The eigenstates of three-dimensional representation of $\mathfrak{su}(3)$ can be chosen

$$u = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \leftrightarrow \left(\frac{1}{2}, \frac{\sqrt{3}}{6} \right), \quad d = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} \leftrightarrow \left(-\frac{1}{2}, \frac{\sqrt{3}}{6} \right), \quad s = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \leftrightarrow \left(0, -\frac{\sqrt{3}}{3} \right), \tag{1.3}$$

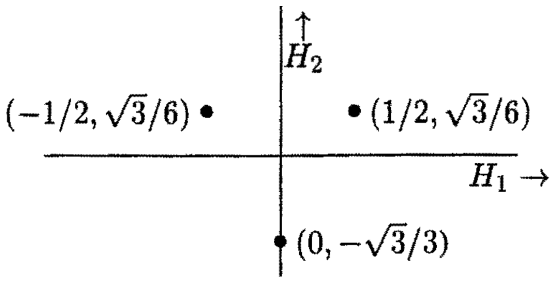

Figure 1.2: Eigenvalues of 3-dimensional representation of $\mathfrak{su}(3)$ Lie algebra. Figure from [5].

where the eigenvalues to generators of the Cartan subalgebra was assigned $H_1 u = \frac{1}{2}u$, $H_2 u = \frac{\sqrt{3}}{6}u$ and similarly for d and s eigenstates. These eigenvalues are shown in figure 1.2. Other important representation of $\mathfrak{su}(3)$ is eight-dimensional adjoint representation. This representation has the following eigenstates and corresponding eigenvalues

$$\begin{aligned}
&\frac{1}{\sqrt{2}}(g_1 \pm i g_2) \leftrightarrow (\pm 1, 0)\,,\\
&\frac{1}{\sqrt{2}}(g_4 \pm i g_5) \leftrightarrow \left(\pm\frac{1}{2}, \pm\frac{\sqrt{3}}{2}\right),\\
&\frac{1}{\sqrt{2}}(g_6 \pm i g_7) \leftrightarrow \left(\mp\frac{1}{2}, \pm\frac{\sqrt{3}}{2}\right),
\end{aligned} \tag{1.4}$$

where again when denoting $A = \frac{1}{\sqrt{2}}(g_1 + i g_2)$ then the upper sign of the first expression reads $[H_1, A] = A$ and $[H_2, A] = 0$ and similarly for remaining 5 eigenstates. Defining

$$H_1 = T_3 \quad \text{and} \quad H_2 = \frac{\sqrt{3}}{2} Y \tag{1.5}$$

one can easily assign hadrons from table 1.1 to corresponding eigenvalues of adjoint representation in 1.4 according to its third component of isospin T_3 and its hypercharge Y. This is depicted in figure 1.3.

When the same redefinition is done to the eigenstates of three-dimensional representation in 1.3, one can assign to eigenstates the hypercharge Y and strangeness S as well. The concrete values for states u, d, s are shown in table 1.2.

It is possible to find another representations of Lie algebra, to which the observed hadrons can be assigned. The simplest way seems to be through highest weight defining representation. From eigenvalues of adjoint representation 1.4 one can find simple roots $\alpha^1 = \left(\frac{1}{2}, \frac{\sqrt{3}}{2}\right)$, $\alpha^2 = \left(\frac{1}{2}, -\frac{\sqrt{3}}{2}\right)$, which are defining the highest weights $\mu^1 = \left(\frac{1}{2}, \frac{\sqrt{3}}{6}\right)$, $\mu^2 = \left(\frac{1}{2}, -\frac{\sqrt{3}}{6}\right)$. New representation of Lie algebra can be constructed from highest weight. This procedure is described in [5] in detail.

	S	Y	T	T_3	Q
u	0	1/3	1/2	1/2	2/3
d	0	1/3	1/2	-1/2	-1/3
s	-1	-2/3	0	0	-1/3

Table 1.2: Quantum numbers of three quarks which existence was predicted by Gell-Mann and Zweig in 1964.

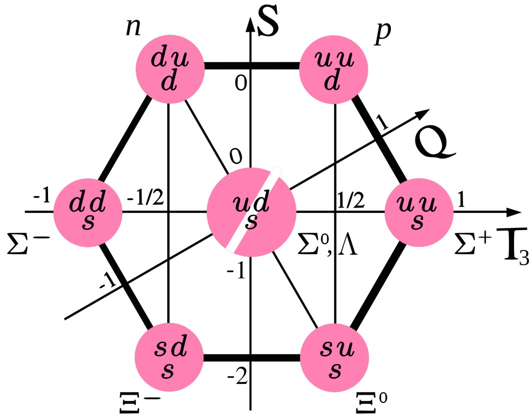

Figure 1.3: Baryonic octuplet encapsulating baryons from table 1.1. For baryons in this diagram, the relation $Y = S + 1$ holds. Figure from [6].

Representations defined by highest weight μ^1 or μ^2 respectively are called fundamental. Fundamental representation defined by μ^1 is usually denoted **3** and its weight diagram is shown at figure 1.2, corresponding to three different quark states. The second fundamental representation corresponds to three anti-quark states and is usually denoted $\bar{\mathbf{3}}$. Representation depicted in figure 1.3 is defined by the highest weight $\mu^1 + \mu^2$.

Special interest is in representations with dimensions 10, 8 and 1. These multiplets are present in decompositions $\mathbf{3}\otimes\mathbf{3}\otimes\mathbf{3} = \mathbf{10}\oplus\mathbf{8}\oplus\mathbf{8}\oplus\mathbf{1}$, which correspond to the baryons composed of three quarks, and $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{8} \oplus \mathbf{1}$ corresponding to mesons from quark and anti-quark.

Important feature of quark model just presented is its capability to predict hadron masses. This is done using Gell-Mann–Okubo mass formula (?citace?)

$$M = a_0 + a_1 S + a_2 \left(T(T+1) - \frac{1}{4} S^2 \right), \tag{1.6}$$

where a_0, a_1 and a_2 are free parameters which are common for all hadrons in one multiplet.

In less than a year after publication of Gell-Mann–Zweig quark model, Sheldon Lee Glashow and James Bjorken proposed (?citace?) an extension which predicted existence of fourth flavor of quark - charm quark.

In 1973 the Makoto Kobayashi and Toshihide Moskawa proposed (?citace?) that the existence of 6 different quark flavors could explain the experimental observation of CP violation.

1.2 Experimental Ground

1.3 QCD as Gauge Theory

1.4 Perturbative QCD

1.5 Non-Perturbative QCD

Chapter 2

QCD on ATLAS

Chapter 3

ATLAS Detector

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Bibliography

[1] "Standard model — Wikipedia, the free encyclopedia." `http://en.wikipedia.org/wiki/Standard_Model`, 2015.

[2] W. Greiner, D. Bromley, S. Schramm, and E. Stein, *Quantum Chromodynamics*. Springer, 2007.

[3] T. Nakano and K. Nishijima, "Charge independence for v-particles," *Progress of Theoretical Physics*, vol. 10, no. 5, pp. 581–582, 1953.

[4] M. Gell-Mann, "The interpretation of the new particles as displaced charge multiplets," *Il Nuovo Cimento*, vol. 4, no. 2, pp. 848–866, 1956.

[5] H. Georgi, *Lie Algebras in Particle Physics: From Isospin to Unified Theories*. Frontiers in Physics Series, Westview Press, 1999.

[6] "Eightfold way — Wikipedia, the free encyclopedia." `http://de.wikipedia.org/wiki/Eightfold_Way`, 2015.