

Initial Stage Decay Processes during Cosmic Decoupling

Thomas A. Kriz

Advanced Studies, Alpha Omega Research Foundation, Cedar Park, USA

Abstract Cosmic decoupling, as a matter formation process, occurs in three stages, beginning with an interaction between cosmic radiation and quark family #3, followed by quark family #2, and then finally by quark family #1. The first two of these interaction sets fail to successfully produce stable baryon matter particles largely because of excessively large quark particle size and lack of adequate cosmic radiation energy levels needed to satisfy baryon particle energy binding requirements. This paper discusses the particular details of the decay processes that cause quark family #3 to fail in its attempt to produce stable hadron particles. Included are: 1) Meson particle decay, 2) Weak Interaction particle decay, 3) Higgs mechanism-based decay, and 4) Quantum based decay of large quark particles.

Keywords Cosmic decoupling, Meson decay, Weak interaction, Higg's mechanism, Quantum decay

1. Introduction

As presented in a prior paper [1], the quark/hadron impact on cosmic decoupling requires it to occur as a three stage process involving the quark families as listed below in Table 1. [2]

Table 1. Quark Family Attributes

Family	Name	Mass (MeV/c ²)	J	B	Q	I ₃
1 st	up	2.3±0.7±0.5	½	+⅓	+⅔	+½
	down	4.8±0.5±0.3	½	+⅓	-⅓	-½
2 nd	charm	1275±2	½	+⅓	+⅔	0
	strange	95±5	½	+⅓	-⅓	0
3 rd	top 1	73210±1220	½	+⅓	+⅔	0
	bottom	4180±30	½	+⅓	-⅓	0

where **J** is total angular momentum, **B** is baryon number, **Q** is electric charge, and **I₃** is Isospin. Since quarks are always confined within hadrons, the chart data is indirectly derived from observations on particle based hadron collider experiments. The above table, which summarizes a list of relevant observed quark attributes, may be used then to analyze the role of quarks and hadrons at various stages of cosmic decoupling.

Recall first that a baryon particle such as a neutron can be viewed, from a quark viewpoint, as composed of two downs and one up, and a proton, as one down and two ups. Note also, however, that an isolated neutron particle set has only a mean lifespan of about 15 minutes [3] due to “weak interaction”

based Beta decay. But, by comparison, both the charm-strange family and especially the top-bottom family have significantly shorter life spans [4-7] and can be viewed as failed attempts to successfully hadronize during the beginning of a 3-stage cosmic decoupling process.

A second chart (Table 2) given below also defines the associated spin-½ lepton family particle attributes that are part of the atomic particle set that includes the above defined quark families. [8] The lepton life span data listed here also gives a close approximation of the life span attributes of Charm-Strange and Top-Bottom quark family groups during baryon based hadronization attempts.

Table 2. Associated Lepton Family Attributes

Family	Name	Mass (MeV/c ²)	Mean Life
1 st	electron	0.511	stable
2 nd	muon	106	2.2×10 ⁻⁶ s
3 rd	tau	1784	3.4×10 ⁻²³ s

The cosmic matter formation scenario in use here assumes that ultimately neutron particles develop first, and then decay into a proton/electron set due to Beta decay that leads to formation of Hydrogen particles. In order to see the need for a 3-stage decoupling process in this scenario, it is therefore necessary to consider the energy requirements of the quark family attributes listed above for neutron style particle generation. Assuming a first letter symbol for each quark type, the respective quark constituents for each family during the neutron-style hadronization attempts, are “udd”, “css”, and “tbb”. This then yields the following chart (Table 3) of approximate attributes for neutron-style hadronization activity during the three stage decoupling process, listed in reverse cosmic time order.

* Corresponding author:

t_kriz@yahoo.com (Thomas A. Kriz)

Published online at <http://journal.sapub.org/astronomy>

Copyright © 2018 Scientific & Academic Publishing. All Rights Reserved

Table 3. Neutron-style Hadronization Attempts

Family	Order	Mass (MeV/c ²)	Frequency
1 st	3	11.9	2.66×10 ²⁰
2 nd	2	1465	3.54×10 ²²
3 rd	1	181570	4.38×10 ²⁴

Table 3 assumes that radiation has a frequency equivalent mass energy property defined by [9]

$$m = \omega h / c^2 = 2\pi f h / c^2 \quad (1)$$

where ω is angular frequency, f is frequency defined in Hertz units, h is Planck's constant, and c is the speed of light. Note also that the chart does not include binding energy for a neutron particle. If the 1-Up/2-Down quark set in quark family #1 for a neutron included the binding energy, the total energy requirement [10] would be 939.57 MeV/c² at approximately a mass equivalent cosmic radiation frequency of 2.27×10^{23} Hz. It can be seen then that the neutron binding energy requirements play a significant role during the matter formation based cosmic decoupling era, and are the major cause of baryon hadronization failure by quark families #2 and #3. [1] Thus, quark-antiquark pair based mesons outside of an atomic nucleus can then be shown to be important contributors to decay found during early stages of a three stage cosmic decoupling process. Other important decay contributors during cosmic decoupling also include massive weak interaction force carrying bosons W^+ , W^- , and Z^0 , that decay to lepton and meson particle forms, baryon-meson interactions that support quark annihilation, and massive quark based particle decay due to inadequate radiation based energy support levels. All of these decoupling-based decay processes are reviewed in the following.

2. Yukawa Meson Theory

Three years after the development of the “Uncertainty Principal” by Heisenberg in 1932, Yukawa [11] found good use for it in the development of meson theory to characterize particle based nuclear forces. The usual starting point of the Uncertainty Principal in the development of meson theory [12] begins with an assertion that the location of a photon with momentum p and wavelength λ and frequency change $\Delta\nu$ cannot be predicted exactly, but has momentum of the order

$$\Delta p \geq h / 2\pi \lambda \geq \hbar \Delta \nu \quad (2)$$

where h is Planck's constant and \hbar is Planck's reduced constant. It can be seen from (2) that a larger wavelength λ infers less uncertainty than shorter one. Since frequency change $\Delta\nu = 1/\Delta t$, where Δt is time change, the corresponding impact of (2) on energy change ΔE is [13]

$$\Delta E \geq \hbar \Delta \nu / 2 \geq \hbar / 2 \Delta t \quad (3)$$

The form in (3) then can be used to define a relation between meson particle mass and the maximum nuclear force impact range r within an atomic particle by noting that

$$\Delta t = r / v \approx r / c \quad (4)$$

where $\Delta E \approx mc^2$, m is the mass of the meson, v is the velocity of the meson and c is the speed of light. In turn, (2,3) then imply that

$$\Delta E \Delta t \approx mc^2 (r/c) \approx \hbar \quad (5)$$

and that meson mass is

$$m \approx \hbar / rc. \quad (6)$$

For example, note that a π meson (also known as a pion) has total mass that is midway between that of an electron and the baryon (eg; a proton or neutron):

$$\begin{aligned} m_\pi &= (6.528 \times 10^{-19} \text{ MeV/c}^2 \text{ s}) / (1.55 \times 10^{-15} \text{ m}) (3 \times 10^8 \text{ m/s}) \\ &= 140 \text{ MeV/c}^2 \end{aligned} \quad (7)$$

It should also be noted that the measured mass of a pion particle is approximately 140 MeV/c². [14]

Later in the late 1960s, after the development of quark theory, it was also found that all mesons could be defined as an unstable hadron composite, that decayed at various rates, made of a quark-antiquark pair. [15] In this regard, it is worth noting that there are currently around 140 known meson flavors involving quark-antiquark pairs. [16, 17] In the nucleus of an atom, mesons are typically exchanged within the range r term in (4,5) between neutrons and protons to govern nuclear force flow. Theoretically, however, as will be discussed here, some meson flavors outside of an atomic nucleus can also be viewed as forms that contribute to decay processes. Such mesons can also be seen also as composed of quark-antiquark pairs that are governed by (5), but with a range term r that is confined internally. Such mesons are therefore inherently unstable and thus Yukawa theory is extendable to decay process phenomena that also occurs outside of an atomic nucleus. The well publicized Higgs boson [18] and associated weak force carrier bosons can then be viewed as working together with meson quark-antiquark pairs where the range term defined in (4,5) is confined internally.

During the matter formation based cosmic decoupling era, because of baryon hadronization failure by quark families #2 and #3, quark-antiquark pair based mesons outside of an atomic nucleus can then be shown to play a significant role in decay processes found during early stages of a three stage cosmic decoupling process. Other important decay contributors during cosmic decoupling also include massive weak interaction force carrying bosons W^+ , W^- , and Z^0 , that decay to lepton and meson particle forms, baryon-meson interactions that support quark annihilation, and massive quark based particle decay due to inadequate radiation based energy support levels.

3. Weak Interaction Model

As a first step, the well established weak interaction model of Glashow, Weinberg, and Salam [19] is invoked as a basis to demonstrate meson particle involvement during the early

stages of the cosmic decoupling process. This model that, includes massive force carrying bosons W^+ , W^- , and Z^0 that mediate the weak interaction, is also strongly related to “Higgs Mechanism” theory. Some interactions with quark-antiquark pairs can be seen in a chart, given below in Table 4, for the decay events triggered by the W^+ boson particle. The top quark based items listed in right-side column of the table, the existence of which have not been yet verified by particle collision experiments, are based on analytical results to be discussed latter in this paper.

Table 4. W Boson Interaction Based Decay Events

Leptons	up	charm	top
Electron	$u\bar{d}$	$c\bar{d}$	$t\bar{d}$
muon	$u\bar{s}$	$c\bar{s}$	$t\bar{s}$
tau	$u\bar{b}$	$c\bar{b}$	$t\bar{b}$

It can be seen that the quark-antiquark pairs listed in Table 4 are all meson particles. The decay width of the W^+ boson decay width to the mesons in the table is then proportional to the square of corresponding CKM matrix element [20-21] and the number of quark colors $N_c=3$. The flavors of the leptons listed in the table are e^+ , μ^+ , and τ^+ . As examples of Table 4 listed “up” based W^+ boson triggered decay processes, note that

$$d+W^+ \rightarrow u \quad (8)$$

and

$$u+W^- \rightarrow d. \quad (9)$$

It should be noted, however, in the case of lepton results, although these interactions are usually represented as a quark color change form as “d to u” defined by

$$d \rightarrow u + e^- + \nu_e, \quad (10)$$

where e^- is an electron and ν_e is an antineutrino, they can equally be represented more causally, as an equivalent quark-antiquark annihilation process between d and \bar{d} in a baryon-meson interaction

$$udd + u\bar{d} \rightarrow uud + W^+, \quad (11)$$

where W^+ then decays to become

$$W^+ \rightarrow e^+ + \bar{\nu}_e. \quad (12)$$

Similarly, during quark-antiquark annihilation interactions involving quark families # 2, and #3

$$css + c\bar{s} \rightarrow ccs + W^+, \quad (13)$$

and

$$tbb + t\bar{b} \rightarrow ttb + W^+, \quad (14)$$

where W^+ then decays instead to a quark families #2 muon and #3 tau based leptons. Thus, all W^+ and W^- boson based interactions with particle forms listed above in Table 4 can be viewed as involving an interaction with a meson particle that then also decays. Note, however, from Table 1, the process $udd + u\bar{d} \rightarrow uud + W^+$ defined by (10-11) leads to toward a stable lower energy state during cosmic decoupling,

whereas Equations (13-14) based interactions lead to unstable higher energy states $css + c\bar{s} \rightarrow ccs + W^+$, and $tbb + t\bar{b} \rightarrow ttb + W^+$.

On the other hand, note that the weak interaction boson Z^0 is commonly associated with lepton particle collisions with scattered neutrinos that alter momenta and energy. As implied by Equation (12), since the W^+ and W^- bosons are involved in the production of neutrino particles, there is then a fixed quantum-based mass interaction relationship between the Z^0 boson and the W bosons that is described by the Weinberg angle θ_W based relationship [22]

$$M_W/M_Z = \cos \theta_W \quad (15)$$

where M_W and M_Z respectively are the masses of the W and Z bosons, measured to be $M_W=80.385 \text{ GeV}/c^2$ and $M_Z=91.1876 \text{ GeV}/c^2$ with decay width $W: 2.085 \text{ GeV}/c^2$ and $Z: 2.495 \text{ GeV}/c^2$. [23] The decay half-life for both therefore is approximately $3 \times 10^{-25} \text{ s}$. This is then followed by the decay time of the meson in Table 4 that is triggered by the W and Z bosons during the earliest stage (eg; family #3) decoupling decay.

4. Other Quark Family #3 Decay Processes

During the initial stage of decoupling, interactions between cosmic radiation and quark family # 3 fail to successfully hadronize due to very large quark sizes and an insufficient energy supply from the cosmic radiation source. [1] The cosmic energy level at that stage, however, is marginally sufficient to support temporary elementary level formation of “ttb”, and “tb” quark collectives, but seriously insufficient to support the required particle “binding energy” requirements. The quark collectives named above therefore decay, following decay process form rules which are well defined by meson decay attributes, the “weak interaction” [16, 17], and the associated Higgs mechanism. [18] The question then is what is the relationship between those processes and quark family #3 defined quark collectives?

The analysis model used here to determine the relationship between quark family #3 particles and the Higgs mechanism is taken from the quantum field theory text by Peskin and Schroeder [24]. The model initially assumes a unitary invariant gauge scalar field of parameter ϕ defined by

$$\phi(x) = U(x)(\sqrt{2})^{-1}[0; \nu + h(x)] \quad (16)$$

where $[0; \nu + h(x)]$ is a two component column matrix, $\nu + h(x)$ is an arbitrary real valued two component spinor with the value of ν defined by the expectation $\langle \phi \rangle$, and $h(x)$ is a fluctuating real valued field with expected value $\langle h(x) \rangle = 0$. It is also assumed that spontaneous symmetry breaking of the SU(2) group acts to transform group $U(x)$ [25] and thereby produces a most general complex two-valued spinor in Equation (16). Making a gauge transformation to eliminate $U(x)$ from Equation (16), this forces ϕ to be a field with one degree of freedom. An explicit renormalizable Lagrangian \mathcal{L}

that leads to an expectation value on ϕ can then be define as

$$\mathcal{L} = |D_\mu \phi|^2 + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \quad (17)$$

In this case, the minimum potential energy of the vacuum occurs at

$$\nu = (\mu^2/\lambda)^{1/2}. \quad (18)$$

In unitary gauge, the potential energy terms in (17) then take the Lagrangian form

$$\mathcal{L}_\nu = -\mu^2 h^2 - \lambda \nu h^3 - \frac{1}{4} \lambda h^4 = -\frac{1}{2} m_h^2 h^2 - \sqrt{m_h} h^3 - \frac{1}{4} \lambda h^4 \quad (19)$$

where h is Planck's constant, m_h is the mass of the of the Higgs boson, and λ can be interpreted as a vacuum based coupling constant. It can be seen from (19) that

$$m_h = \sqrt{2}\mu = \sqrt{2}\nu\lambda^{1/2} \text{ GeV}/c^2 \quad (20)$$

where, so far, the numeric value of terms λ , μ , and ν still remain undefined numerically. Note, however, that the vacuum expectation term $\langle \phi \rangle = 2^{1/2}\nu$ in the ground state analytically, and has a known measured value of approximately $-250 \text{ GeV}/c^2$ [26] from collision experiment results. Thus, $\nu = -354 \text{ GeV}/c^2$. Moreover, weak interaction theory can also be associated with the Higgs field by noting that the four component scalar field (2x2) matrix for ϕ , that includes one zero boson. [27] mass photon related element and one element each for the W^+ , W^- , and Z^0 weak interaction]. It should then be noted that the sum of the W^+ , W^- , and Z^0 boson masses in this matrix is equal to $251 \text{ GeV}/c^2$, very closely equivalent to that of the measured value of the vacuum expectation of ϕ . This suggests that the vacuum coupling value of the λ term in Equation (20) is also closely similar to the g coupling value for the W^+ , W^- , and Z^0 bosons, with

$$g = 2m_W/\nu \approx 0.46, \quad (21)$$

and

$$(g^2 + g'^2)^{1/2} = 2m_Z/\nu \approx 0.52. \quad (22)$$

Thus, the coupling constant, at the heavy mass $2m_0 = 708 \text{ GeV}/c^2$, is $\lambda \approx 0.5/8 \approx 0.0625$ (or about 8 times smaller than that for m_Z) where $\lambda^{1/2} \approx 0.25$, and implies that

$$m_h = \sqrt{2}\mu \approx \sqrt{2} (354)/4 \approx \sqrt{2}(88.5) \approx 125.2 \text{ GeV}/c^2 \quad (23)$$

which closely agrees with the measured value and its predicted decay width of $\Gamma = 4.21 \times 10^{-3} \text{ GeV}/c^2$ and a mean lifetime of [28]

$$\tau(m_h) = h/\Gamma \approx 1.56 \times 10^{-22} \text{ s}. \quad (24)$$

Thereby, the results in (20) then can also be related to the hadron “ $t\bar{b}$ ”, and “ $t\bar{b}$ ” quark collectives from the Family #3 quark group, by noting that the mass of quark collective “ $t\bar{b}$ ”, equals $350 \text{ GeV}/c^2$, and is approximately equivalent to the mass of the above defined vacuum term ν , and m_h is approximately $\sqrt{2}$ smaller than the $177 \text{ GeV}/c^2$ mass of the meson $t\bar{b}$ quark collective. It should be noted here that both the “ $t\bar{b}$ ”, and “ $t\bar{b}$ ” quark collectives, due to their massive size, are also unstable and therefore decay to a W boson and a bottom quark with a predicted decay width [29].

$$\Gamma \approx (g^2 m_t^2) (64\pi m_W^2) \approx 286 \quad (25)$$

where m_t is the mass of the top quark, m_W mass of the W boson, and the mass of bottom quark is seen as small. The mean lifetime of the “ $t\bar{b}$ ”, and “ $t\bar{b}$ ” quark collectives is therefore predicted to be

$$\tau(m_t) = h/\Gamma \approx 6.49 \times 10^{-27} \text{ s}. \quad (26)$$

Subsequent to the top quark decay, $b\bar{b}$ mesons, with mass $9.46 \text{ GeV}/c^2$, form, and then decay with a mean lifetime of $\tau(b\bar{b}) \approx 1.22 \times 10^{-20} \text{ s}$. [30]

5. Conclusions

As shown above, the interaction between cosmic radiation and quark family #3 succeeds only in producing brief transient particles that decay and thereby fail to develop as stable particles. Some of these transient particles are unstable meson quark-antiquark pairs, that exist exterior to an atomic nucleus, with an impact range term that is confined internally. These are also frequently associated with other well-known decay processes, such as the weak interaction with its massive force carrying bosons W^+ , W^- , and Z^0 , and Higgs mechanism based processes that also produce only brief lifetime transient particles. The large size of quarks in family #3 also contribute decay hadronization attempts during the initial stage of decoupling to account for an additional decay mechanism that involves hadron based “ $t\bar{b}$ ”, and “ $t\bar{b}$ ” top and bottom-based quark collectives.

There are some novelties in the decay analysis themes presented here. One of these is the concept that quark color change process can be viewed as a quark annihilation process. Additional novelties concern the attributes of the weak interaction and associated Higgs mechanism features. It is shown analytically that the sum of the W^+ , W^- , and Z^0 masses is equal to the mass value of a unitary invariant gauge scalar field expectation $\langle \phi \rangle$ and that the Higgs boson coupling constant λ can be derived from the g couplings in the W^+ , W^- , and Z^0 boson set. These also can be related to the quark attributes of quark family #3 in that the attribute of the top quark and bottom based collective $t\bar{b}$ has an analytical relationship with the spontaneous symmetry broken vacuum attribute. Moreover, the mass of the Higgs boson is exactly $\sqrt{2}$ times smaller than the $177 \text{ GeV}/c^2$ mass of the meson $t\bar{b}$ quark collective.

Thus, it can be seen that there are no stable particles that are generated by the interaction between cosmic radiation and quark family #3; only transient particles with a brief mean lifetime. All of these transient particles decay with a mean lifetime that is shorter than approximately 10^{-20} s .

ACKNOWLEDGMENTS

The author wishes to express gratitude for the encouragement and critical review received during the early stages of the work present here received from E.J. Bacinich,

Director of the Alpha Omega Research Foundation, and several other members of our group, now deceased: Prof. Behram Kursunoglu and Dr. Walter Rosenthal. Prof. Kursunoglu was the Director of the Theoretical Institute at the University of Miami (FL), and pursued graduate studies at Cambridge University under P.A.M. Dirac. Dr. Walter Rosenthal was one of the last students to pursue graduate studies in physics at the University of Berlin under Max Planck.

REFERENCES

- [1] T.A. Kriz, 2017, An energy-based analysis of the quark-hadron impact on cosmic decoupling, *American J. of Modern Phys.*, 6(6) 148-152.
- [2] K.A. Olive et al., 2014, Review of particle physics, *China Physics C*, 38 (9), 090001.
- [3] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., p.482.
- [4] S.W. Herb et al., 1977, Observations on dimuon resonance at 9.5 GeV in 400 GeV proton nucleus collisions, *Phys. Rev. Letters*, 39 (5) 252.
- [5] S. Abachi et al., 1995, Search for high mass top quark production in pp collisions at 1.8 TEV, *Phys. Rev. Letters*, 74 (13) 2422-2436.
- [6] F. Abe et al., 1995, Observation of top quark production in pp collisions with the collider detector at Fermilab, *Phys. Rev. Letters*, 74 (14) 2626-2631.
- [7] K.W. Staley, 2004, *The evidence for the top quark*, Cambridge University Press, pp.31-33.
- [8] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., p.482.
- [9] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., p. 83.
- [10] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., *Phys. Const.* (inside front cover).
- [11] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., pp.409-411.
- [12] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., pp.111-112.
- [13] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., p.411.
- [14] A. Beiser, 1995, *Concepts of Modern Physics*, 5th ed., McGraw Hill, N.Y., p.482.
- [15] M. Gell-Mann, 1964, A schematic of baryons and mesons, *Phys. Letters*, 8(3) 214-215.
- [16] C. Amsler et al., 2008, (Particle Data Group), Review of particle physics (Search for 4th generation quarks), *Phys. Letters B* 667(1): pp. 1-1340.
- [17] W.E. Brehm and M. Jobes, 1995, *Nuclear and Particle Physics*, 2nd Ed., Longman, New York.
- [18] P. Higgs, 1964, Spontaneous symmetry breakdown without massless bosons, *Phys. Rev. Letters*, 145 (4)1156-1163.
- [19] D. Griffiths, 1987, *An Introduction to Elementary Particles*, John Wiley & Sons, New York, pp. 59-60.
- [20] N Cabibbo, 1963, Unitary symmetry and leptonic decays, *Phys. Rev. Letters*, 10(12) 531-533 *Phys. Rev. Letters*, 10(12) 531.
- [21] M. Kobayashi et al., 1973, CP-violation in renormalizable theory of the weak interaction, *Prog. of Theoretical Phys.*, 49(2) 652-657.
- [22] D. Peskin and M. Schroeder, 1995, *Introduction to Quantum Field Theory*, Addison-Wesley, New York, p. 703.
- [23] J. Beringer et al., 2012, 2012 review of particle physics-gauge and Higgs bosons, *Phys. Rev. D*, 806:1.
- [24] D. Peskin and M. Schroeder, 1995, *Introduction to Quantum Field Theory*, Addison-Wesley, New York, p. 715.
- [25] D. Peskin and M. Schroeder, 1995, *Introduction to Quantum Field Theory*, Addison-Wesley, New York, pp. 689, 700-701.
- [26] CERN Particle Data Group, Higgs Boson: theory and searches, 12 July 2012.
- [27] D. Peskin and M. Schroeder, 1995, *Introduction to Quantum Field Theory*, Addison-Wesley, New York, pp. 701-703.
- [28] Higgs Cross Section Working Group, 2012, *Handbook of LHC Cross Sections: 2. Differential Distributions*. CERN Report 2. (Tables A1-A20).
- [29] D. Peskin and M. Schroeder, 1995, *Introduction to Quantum Field Theory*, Addison-Wesley, New York, p. 749.
- [30] K.A. Olive et al., 2014, Meson Summary Table, <http://pdg.lbl.gov/2014/tables/rpp2024-qtab-mesons-pdf>.