# Exotic Physics: Standard Model and Feynman diagrams for Mid School and High School teaching with games as tools 

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## Curriculum \& classroom connections

All of this article's authors agree in the necessity, or at least desirability, of including the Standard Model (SM) and Feynman Diagrams (FD) in their respective countries' curricula. Unfortunately from among the authors' countries only the IB programme in Denmark and Montenegro do so with SM and FD.

Of course, that doesn't mean that particle physics is not covered in the other countries, but in those it's up to the teacher to expand the basics in order to give it an appropriate context to make sense of the topic. It's our understanding, thus, that the treatment of modern physics is left without two of the best tools, i.e. SM and FD, to teach and learn it properly.

## Key ideas

In order to make a more clear explanation of the key ideas of SM and FD we divide the students in two groups, mid school and high school, i.e. students between 12 and 15 and between 16 and 18 years old.

We have considered a global approach when trying to figure out the best ways to introduce our students to both SM and FD, and which ideas would be strategically better suited to let them understand the topic of modern physics. Our conclusion has been to include only SM in mid school, and to focus on the basic list of fundamental particles, including its division in fermions (quarks and leptons) and bosons. About their properties, in this point we consider enough to learn their energies (masses) in a qualitative way.

Another important factor that the mid school students should clearly understand after studying this topic is that, as far as our understanding reaches, everything we know is made of the finite set of fundamental particles of the SM. These particles, furthermore, are smaller than anything they know from daily life and can only be detected with expert scientific instruments as done, for example, at CERN.

Once in high school, we recommend to widen the knowledge of the SM to include the antiparticles, the order of magnitude of the energies (masses) of the particles, their generation and their quantum numbers. Only then should we begin the introduction of the FD. The most important ideas the students should acquire knowledge about would that be that quarks and leptons interact with one another through bosons, and that the FD are the the graphical representations of these interactions. They, of course, should also be able to use the basic symbols and elements that represent all the fundamental particles (straight lines, wavy lines...). Finally, they should learn the basic conservation laws that take place at the vertices and how they limit the sort of interactions possibles in nature.

## Potential student conceptions \& challenges

## SM:

- Difficult to accept that there are particles with 0 mass.
- Students may be confusing mass and size.
- Students think that antimatter does not exist.
- Students are not aware that there are other type of charges than electric charges, i.e colour charge
- Difficult to accept fractional charges.

FD:

- Space and time in Feynman diagrams may be confused with the space and time coordinates students know from kinematics.
- Lines representing particles may be confused with particle trajectories.
- It may be difficult for the students to realise that interactions take a finite time rather than happening instantaneously.
- Vertex may be confused with a physical entity rather than a mathematical tool.
- Possible confusion can arise if the direction of time line is not clearly indicated.


## Helpful material and resources

We strongly recommend the lectures included in the CERN programs:
STP2017 (Spanish): https://indico.cern.ch/event/572737/timetable/
HST2018 (English): https://indico.cern.ch/event/651996/timetable/
We also recommend to watch the documentary: "Particle Fever" (2014)

## Best practice examples

Playing one way or another is usually one of the activities most looked forward to by our students. We propose, then, to use this fact in order to get them exposed to the SM and FD topics through the following games, which we have designed.
1.- First game: Quarksdices

Objective: Familiarize the names of the quarks and how they will be composed making new particles according to the standard model

## Designed for 13-15 age students

With this game of dice we intend to introduce our students to the world of fundamental particles. Although some of our school textbooks mention in passing the existence of quarks, none of them refers to how they integrate matter in itself.

The game is designed for middle school students (13-15 years) and only seeks to familiarize the names of the quarks and how they will be composed to build new particles according to the standard model.

A) In a first version of the game, it will be enough to find, in multiple random throws of dice, as many protons and neutrons as possible taking into account the neutrality of the final color charge.

B) In a second stage of the game we can go further: we will try to find combinations of three quarks to recognize some heavy hadrons

C) In a third stage of the game we can familiarize ourselves with the concept of antimatter. In this way we can build antiprotons, antineutrons and a certain number of mesons.


The great number of possibilities open new lines of research. Is it possible to build a tetraquark? (It should be made by two pairs of quark-antiquark) And even further, is it possible to build a pentaquark by putting together three quarks and with a quark-antiquark pair?

Although the reality is much more complicated than can be seen in this simple game, we are sure that it will generate curiosity in the students and they will ask themselves questions. That is the most important aspect of the game and its main objective.

## 2. Second game: The Hadron Cacheta

This game is based on a very common game in Brazil called "cacheta" in which each player gets nine cards and has to make three sets of three (or four) cards of same number but different suits or same suit and numbers in a row. In every turn, each player picks one card and discards one from his hand. The next player can either pick one card from the deck or the last discarded one. The winner of the round is the first one to use all his cards to make three sets. If he/she uses 9 nine cards to do it, he/she wins one point. If he/she uses 10 cards, he/she wins two points.

In this alternative game, instead of normal deck, it uses quarks deck. The whole deck consists of 36 cards representing each quark and antiquark and its colour charge, as shown below:


Instead of making sets of cards, the player must build hadrons with his/her cards, which can be:

- Baryon: consisting of three quark cards or three antiquark cards of different colours;
- Meson: consisting of one quark card and one antiquark card of complementary colours.

To win one point, a player must use his/her nine cards and build three bayons or one baryon and two mesons. Here are two examples in which the player wins one point:


It's also possible to use 10 cards instead of nine. In this case, the player doesn't discard the last card and wins two points for the round. The possibilities featuring 10 cards are two bayons and two mesons or five mesons, as shown on the examples below:


The first player to win 10 points is the winner of the game.

## 3. Third game: Guess what

The game we developed relates to the subject of elementary particles. We suggest to use this game in the middle of particle physics teaching process. The game is for middle and high school students.

Goals of the game:

- Students will be familiar with the standard model
- Students will be familiar with the different properties of the various particles
- Students will be able to associate each particle with its properties
- Students will be able to order particles in accordance to their masses

Each player starts the game with a board that includes information of 24 different particles including their name, type, mass and electric charge on cards standing up. Each player selects a card of their choice from a separate pile of cards containing the same 24 cards. The object of the game is to be the first to determine which card one's opponent has selected. Players alternate asking various yes or no questions to eliminate candidates, such as "Does your particle have electric charge?" The player will then eliminate candidates by flipping those cards down until all but one is left. Well-crafted questions allow players to eliminate one or more possible cards. Questions might include:

- "Does your particle have a mass?"
- "Is a particle mass big?"
- "Is boson the type of your particle?"

In our 'Table of particles for the game' (see Appendix 1) we made some adaptations about masses of particles, since middle school students might have some difficulty in complex numbers and units of mass.

| name |  | symbol | Mass | Electric charge | Type |
| :---: | :---: | :---: | :---: | :---: | :---: |
| electron | 1 | e | Tiny | - | Lepton |
| electron neutrino | 2 | $\nu_{e}$ | undetermined | 0 | Lepton |
| muon | 3 | $\mu^{-}$ | Small | - | Lepton |
| muon neutrino | 4 | $\nu_{\mu}$ | undetermined | 0 | Lepton |
| tau | 5 | $\tau^{-}$ | Big | - | Lepton |
| tau neutrino | 6 | $\nu_{\tau}$ | undetermined | 0 | Lepton |
| positron | 7 | $\mathbf{e}^{+}$ | Tiny | + | Lepton |
| photon | 8 | $\gamma$ | No mass | 0 | Boson |
| gluon | 9 | g | No mass | 0 | Boson |
| W+ boson | 10 | W+ | Huge | + | Boson |
| W-boson | 11 | W- | Huge | - | Boson |
| Z boson | 12 | Z0 | Huge | 0 | Boson |
| Higgs boson | 13 | H | Huge | 0 | Boson |
| Proton | 14 | $\mathrm{p}^{+}$ | Big | + | Baryon |
| Neutron | 15 | $\mathrm{n}^{0}$ | Big | 0 | Baryon |
| Delta positive | 16 | $\Delta^{+}$ | Big | + | Baryon |
| Delta negative | 17 | $\Delta^{-}$ | Big | - | Baryon |
| Delta neutral | 18 | $\Delta^{0}$ | Big | 0 | Baryon |
| Pion positive | 19 | $\pi^{+}$ | Small | + | Meson |
| Pion negative | 20 | $\pi^{-}$ | Small | - | Meson |
| Pion neutral | 21 | $\pi^{0}$ | Small | 0 | Meson |

4. Fourth game: Feynman diagrams
A) Contents

Cards representing each one of the fundamental particles of the Standard Model.

- Quarks
- $6 \times U p$
- $6 \times$ Down
- $4 \times$ Charm
- $\quad 4 \times$ Strange
- $2 \times$ Top
- $\quad 2 \times$ Bottom
- $\quad 3 x$ anti - Up
- $3 x$ anti - Down
- $2 x$ anti - Charm
- $2 x$ anti - Strange
- $1 \times$ anti - Top
- $1 \times$ anti - Bottom
- Leptons
- $6 \times$ Electron
- $\quad 4 \times$ Muon
- $\quad 2 \times$ Tau
- $6 \times$ Electron Neutrino
- $\quad 4 \times$ Muon Neutrino
- $2 \times$ Tau Neutrino
- $3 x$ anti - Electron (Positron)
- $2 \times$ anti - Muon
- $1 \times$ anti - Tau
- $3 x$ anti - Electron Neutrino
- $2 \times$ anti - Muon Neutrino
- 1 x anti - Tau Neutrino
- Bosons
- $9 \times$ Photon
- $4 \times$ Gluon
- $\quad 3 x Z^{0}$
- $\quad 3 \times \mathrm{W}^{+}$
$-\quad 3 \times W-$
- $2 x$ Higgs
- Plastic tokens or cards representing the vertices at the Feynman diagrams (as many as needed).
B) Rules

The cards will be separated in 3 decks, one for quarks, one for leptons and one for bosons, all facing down and shuffled. Each player in sequence will draw three cards in any combination he decides from all three decks. After drawing cards the player can take as many tokens as needed to use as vertices in a Feynman diagram or pass so the next player can play his/her turn.

Every diagram has to respect the conservation rules, so the following quantities has to be conserved after and before each vertex:

1. Electric charge.
2. Baryon number.
3. Lepton number for every generation.

The score for every diagram will be the result of adding the amount printed on each card, plus 2 points for each vertex used, plus a 1 point bonus for every card above 3 used in the diagram.

The game will be played until there are no more cards in any deck and all players are unable to form more diagrams with their cards.

The winner will be the player with he higher amount of points. In case of a draw, the winner will be the player that used the highest number of cards in a single diagram. In case of two players having used the same amount of cards in his/her bigger diagram both players will be considered winners.
C) Cards

| Name | Up |
| :--- | :---: |
| Type | Quark |
| Generation | 1 st |
| Electric charge | $+2 / 3$ |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 1 |


| Name | anti - Up |
| :--- | :---: |
| Type | Quark |
| Generation | 1st |
| Electric charge | $-2 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 2 |


| Name | Down |
| :--- | :---: |
| Type | Quark |
| Generation | 1 st |
| Electric charge | $-1 / 3$ |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 1 |


| Name | anti - Down |
| :--- | :---: |
| Type | Quark |
| Generation | 1st |
| Electric charge | $+1 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 2 |


| Name | Charm |
| :--- | :---: |
| Type | Quark |
| Generation | 2nd |


| Electric charge | $+2 / 3$ |
| :--- | :---: |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 2 |


| Name | anti - Charm |
| :--- | :---: |
| Type | Quark |
| Generation | 2nd |
| Electric charge | $-2 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 4 |


| Name | Strange |
| :--- | :---: |
| Type | Quark |
| Generation | 2nd |
| Electric charge | $-1 / 3$ |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 2 |


| Name | anti - Strange |
| :--- | :---: |
| Type | Quark |
| Generation | 2nd |
| Electric charge | $+1 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 4 |


| Name | Top |
| :--- | :---: |
| Type | Quark |
| Generation | 3rd |
| Electric charge | $+2 / 3$ |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 3 |


| Name | anti - Top |
| :--- | :---: |
| Type | Quark |


| Generation | 3 3rd |
| :--- | :---: |
| Electric charge | $-2 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 6 |


| Name | Bottom |
| :--- | :---: |
| Type | Quark |
| Generation | 3rd |
| Electric charge | $-1 / 3$ |
| Baryon number | $+1 / 3$ |
| Lepton number | 0 |
| Score | 3 |


| Name | anti - Bottom |
| :--- | :---: |
| Type | Quark |
| Generation | 3rd |
| Electric charge | $+1 / 3$ |
| Baryon number | $-1 / 3$ |
| Lepton number | 0 |
| Score | 6 |


| Name | Electron |
| :--- | :---: |
| Type | Lepton |
| Generation | 1st |
| Electric charge | -1 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 1 |


| Name | anti - Electron (Positron) |
| :--- | :---: |
| Type | Lepton |
| Generation | 1 st |
| Electric charge | +1 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 2 |

Name

| Type | Lepton |
| :--- | :---: |
| Generation | 2nd |
| Electric charge | -1 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 2 |


| Name | anti - Muon |
| :--- | :---: |
| Type | Lepton |
| Generation | 2nd |
| Electric charge | +1 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 4 |


| Name | Tau |
| :--- | :---: |
| Type | Lepton |
| Generation | 3rd |
| Electric charge | -1 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 3 |


| Name | anti - Tau |
| :--- | :---: |
| Type | Lepton |
| Generation | 3rd |
| Electric charge | +1 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 6 |


| Name | Electron neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 1 st |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 1 |


| Name | anti - Electron neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 1st |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 2 |


| Name | Muon neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 2nd |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 2 |


| Name | anti - Muon neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 2nd |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 4 |


| Name | Tau neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 3rd |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 1 |
| Score | 3 |


| Name | anti - Tau neutrino |
| :--- | :---: |
| Type | Lepton |
| Generation | 3rd |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | -1 |
| Score | 6 |


| Name | Photon |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 0 |
| Score | 1 |


| Name | Gluon |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 0 |
| Score | 1 |


| Name | Z $^{0}$ |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 0 |
| Score | 2 |


| Name | $\mathrm{W}^{+}$ |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | 1 |
| Baryon number | 0 |
| Lepton number | 0 |
| Score | 2 |


| Name | W- |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | -1 |
| Baryon number | 0 |
| Lepton number | 0 |


| Score | 2 |
| :--- | :--- |


| Name | Higgs |
| :--- | :---: |
| Type | Boson |
| Generation | - |
| Electric charge | 0 |
| Baryon number | 0 |
| Lepton number | 0 |
| Score | 4 |

The following samples can be used as examples of presentation of the cards.


