Particle Builder – The Particle Physics Board Game

Contents

Particle Builder is a board game developed by the physics teachers who took part in the High School Teacher Program at CERN in 2016. Lachlan McGinness and Harri Leinonen originally created the game (now also known as "The Particle Physics Board Game"), designed it and tested it with the other teachers taking on board their feedback.

In 2018, Rowan McGinness created the artwork for the game, allowing it to be transformed from its black and white original to a colourful and more engaging game. It has now been downloaded over 2000 times and used by teachers in many countries including Australia, Germany, the United States and New Zealand. In 2024 Lachlan McGinness worked with a group of ANU School of Computing students (Mohammad Attar, Andrew Carse, Yeming Chen, Jeong-Yeon Ha, Amy McWilliams, Theirry Panggabean, Jing Ru, Jiacheng She, and Zilun Wei) to transform the game to an online format.

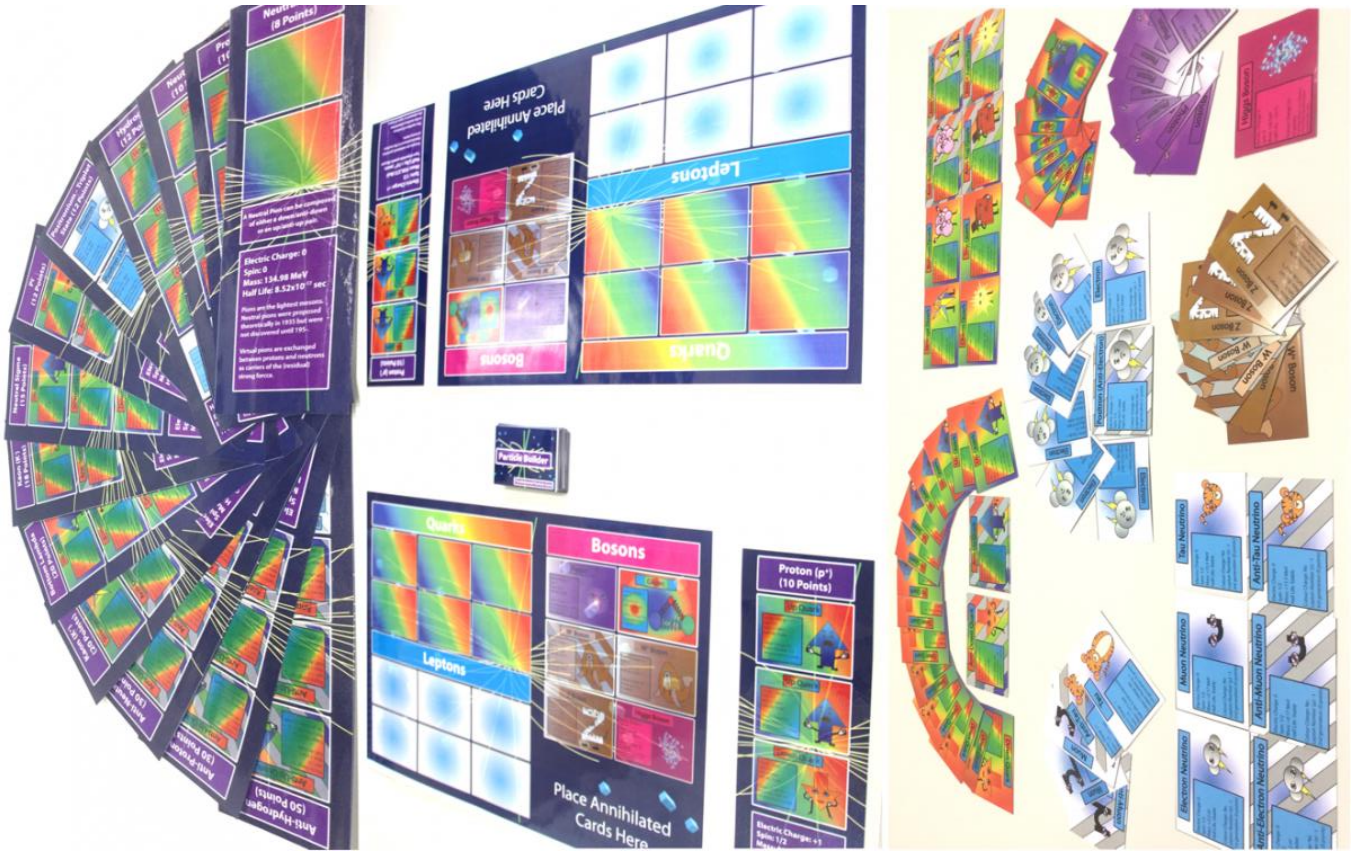
In 2024, the team did a formal study to evaluate the use of Particle Builder as a teaching tool. The results showed that it was an effective first lesson in particle physics requiring no pre-requisite knowledge, was more fun and engaging and resulted in greater learning than a typical lesson. The study also found that the game was accessible to students as young as 13 years old.

If you know a science teacher that would like to use the game in their classroom, or a board game enthusiast that would like a professionally printed version of the game please feel free to put them in touch with Lachlan McGinness at Lachlan.mcginness@anu.edu.au

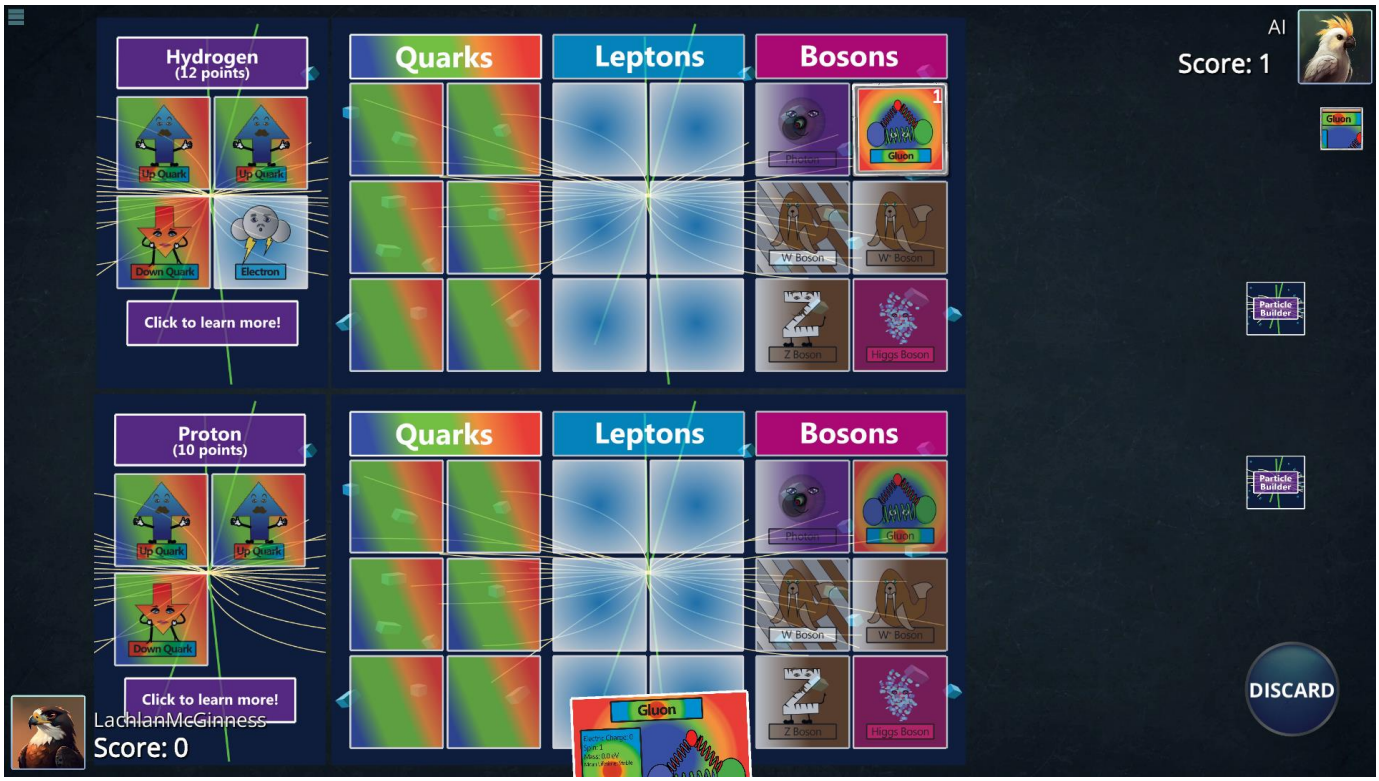
Introduction to Particle Builder

Particle Builder is a 10-minute board game which is designed to teach high school students about particle physics. The game can be played online or as a physical board game. The game aligns with the physics curriculum in many programs and countries including the IB and the Australian Curriculum.

The physical board game can be downloaded from Zenodo for free here: https://doi.org/10.5281/zenodo.1341746



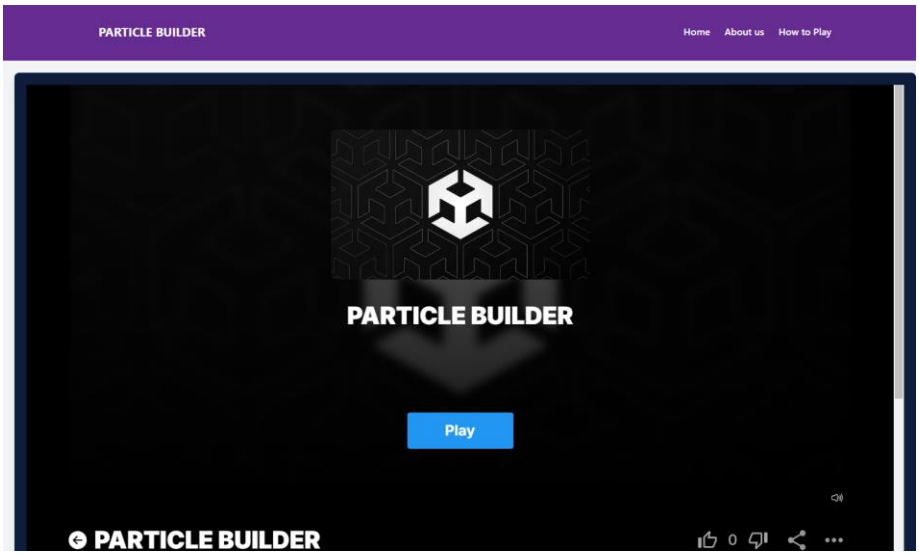
The online game can also be played freely at this link: https://particle-builder.anu.edu.au/



Online Tutorial

To access the online tutorial follow this link or scan the QR code:
https://particle-builder.anu.edu.au/

This will take you to the Particle Builder Website, which should look like this:



Click “Play” and the screen below should appear. Click the full screen button (see yellow arrow), then type in any username and click login.

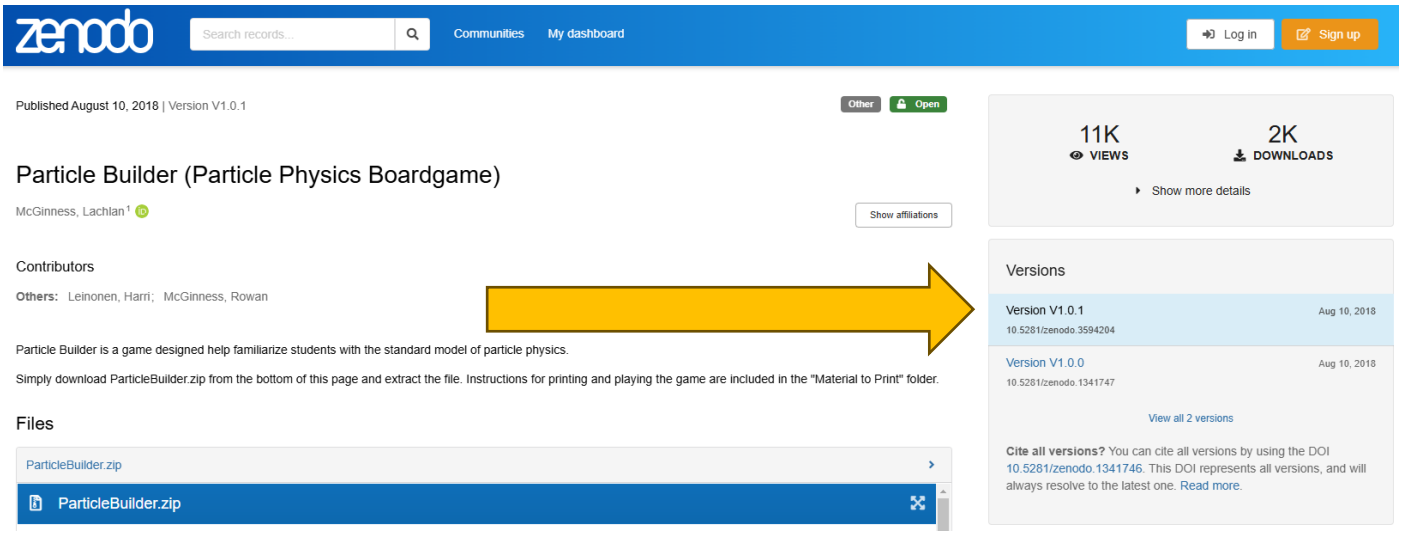
Select Level 1 and then click Tutorial. This will take you to the online tutorial that will show you how to play the game. Note that full screen mode is required for the tutorial.

If you do not have access to the internet or would prefer to read the rules, please proceed to the following pages. These contain the rules for each of the levels 1 to 7.

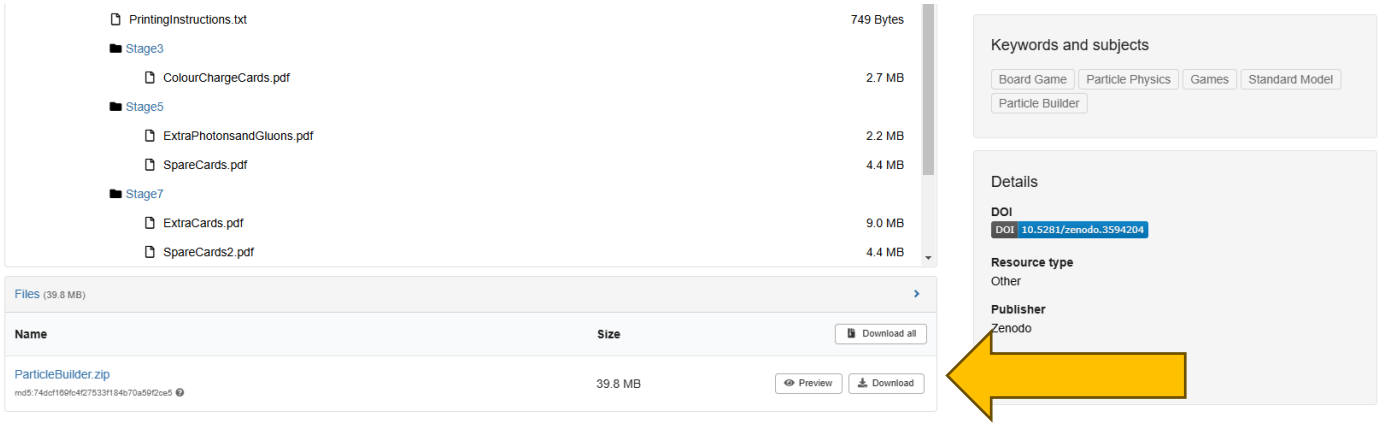
Printing the Board Game

In order to print the board game go to the Zenodo Website: https://doi.org/10.5281/zenodo.1341746

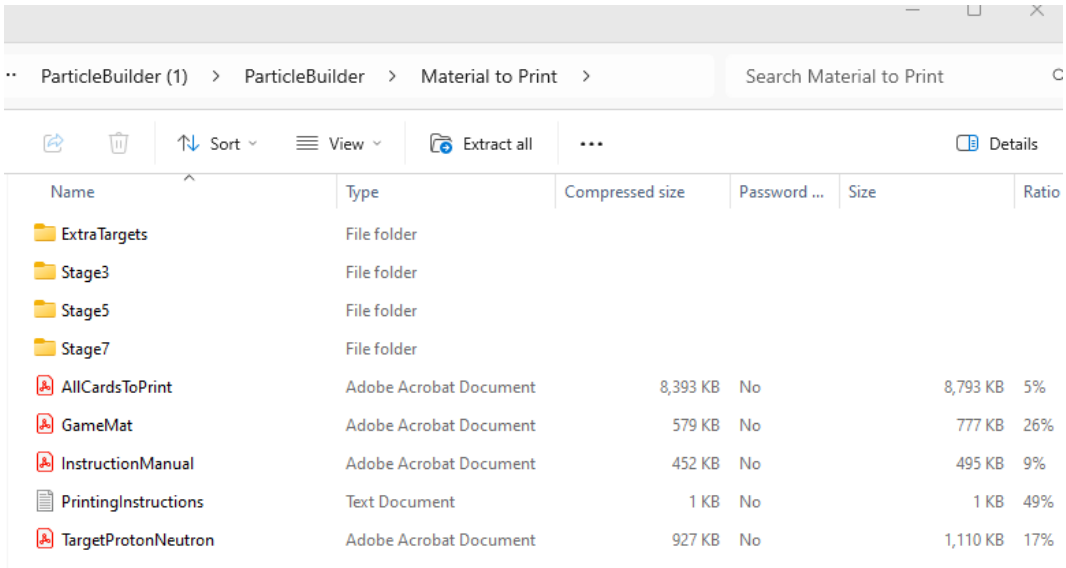
Find and select the most recent version:



Then scroll down and select download:



Extract the contents and then navigate to the *material to print* folder. There are four pdf files that you need to play the base game: AllCardsToPrint.pdf, GameMat.pdf, InstructionManual.pdf and TargetProtonNetron.pdf. The files in Level 3, Level 5 and Level 7 are needed for playing higher levels of the game. The ExtraTargets folder allows you to print additional particle systems to play the game with.

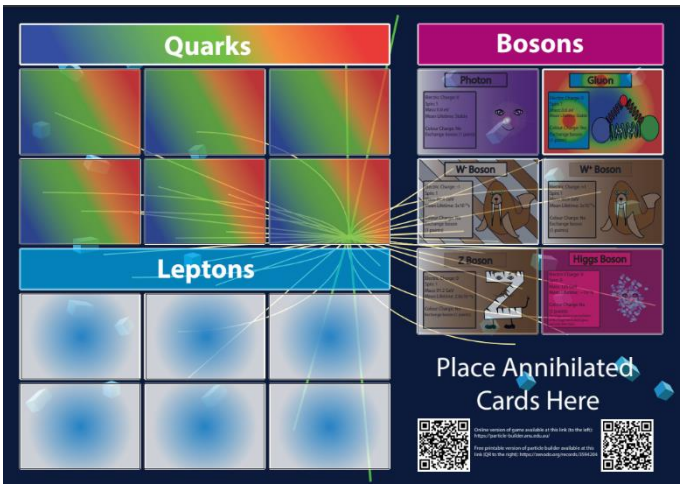


Instruction Manual

InstructionManual.pdf contains this instruction manual. It contains the rules to play the game. We recommend printing it double sided on A4 paper with a staple on the top left corner.

Game Mat

The game mat should look like the file shown to the right.



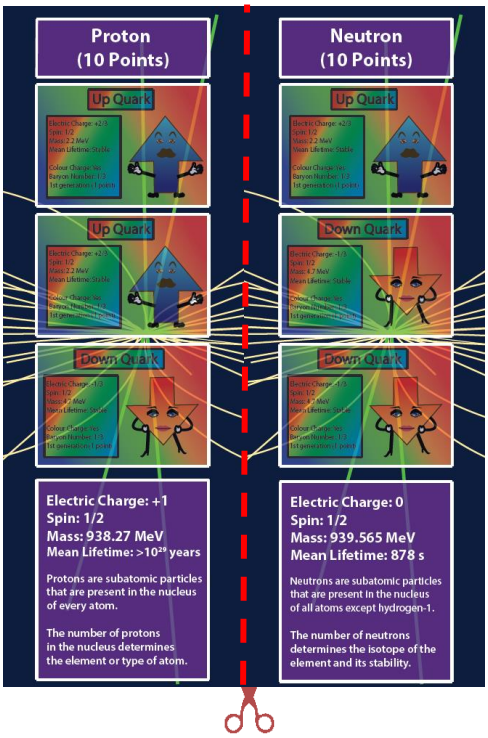
You need one copy for each player. It should be printed single sided on A3 paper.

For teachers, we recommend laminating the game so it is durable and will last multiple years.

The Game mat has 18 places for placing particle cards (6 for quarks, 6 for leptons and 6 for bosons).

Particle System Target Card

The particle system target should look like the image shown below on the left. There are many different interesting targets in the game, however for your first game we recommend choosing either a proton or a neutron.



Each player needs one target card but note that each pdf contains two particle system targets.

Target cards should be printed on A4 paper and then cut down the middle after printing.

It can be printed as a single sided page, or it can be printed double sided and have a back.

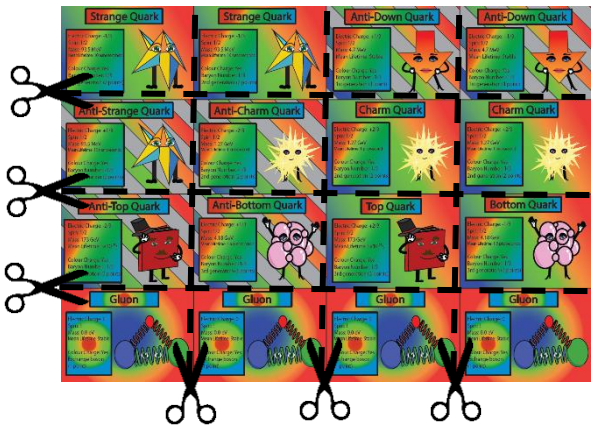
Target cards contain either two, three or four areas to place particle cards.

Targets are the objective of the game, the game finishes when one of the players collects all of the required cards for their target.

Targets which are hard to build are worth more points.

Particle Cards

Particle Cards should look like the image shown below on the right.



There should be a total of four sheets per deck of cards. These should be printed on A4 paper, double sided and require a significant amount of cutting.

One deck is needed for each group of two or three players.

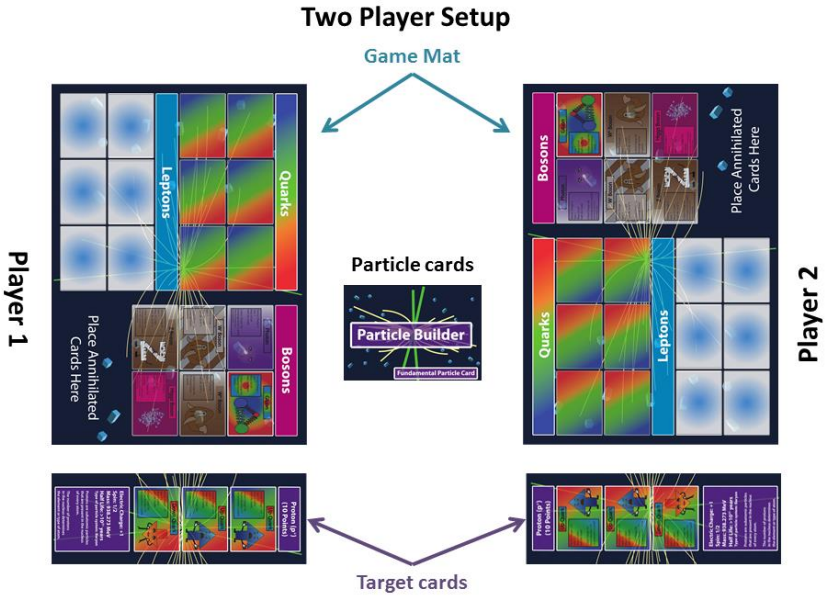
Each card represents a fundamental particle. Players will collect these throughout the game.

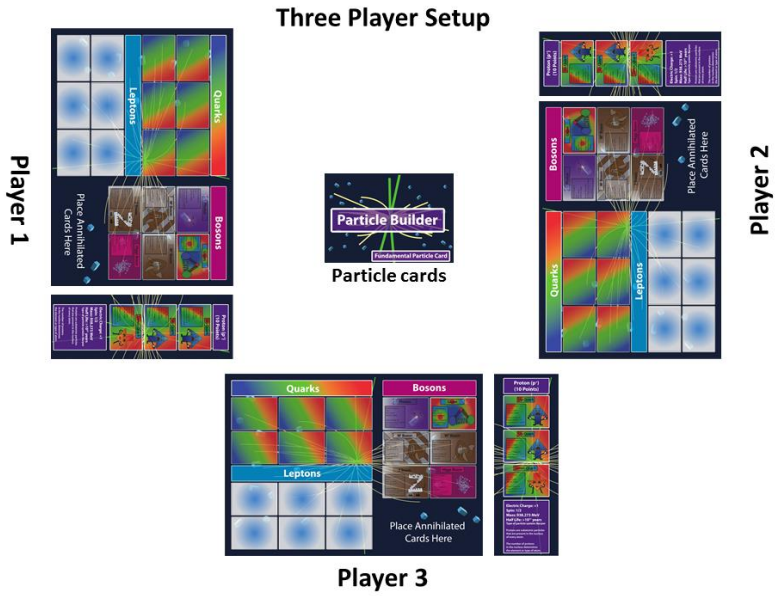
Particle Builder Rules

This game is best played in pairs (or groups of 3 if there are odd numbers), where each player is competing against the others to get the most points. If you have four players, you can just split into two pairs. The game is quick (approximately 10 minutes), so you can regularly swap opponents if you wish. There are seven different levels that can be played. It is recommended that players play Level 1 for at least their first two games. Once players are familiar with the rules, they can add higher levels which incorporate more laws of physics into the game mechanics.

Level 1 (Getting to know the particles) – For beginners

1.) Each player gets a game mat and a target card. The mats, target cards and game cards are set up as shown below:

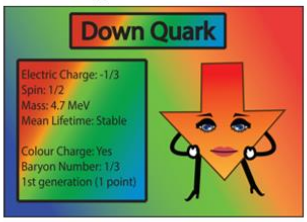




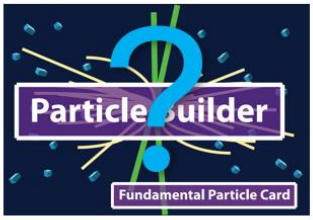
2.) As mentioned previously, each player gets a particle system target card. It is recommended in the first round that each player has the proton or neutron target card. The aim of the game is for a player to build their target by gathering all the required particles. Once a single player has obtained all the required cards the game is over. For example, for the proton target, when a player obtains two up quarks and one down quark, then the game is over. This player usually wins because the particle system targets are worth a large number of points.

Step 1: Player draws card

Player's Card



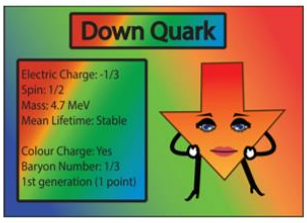
Opponent's Card



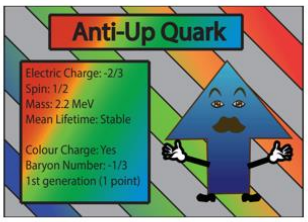
Step 1: The player and the opponent draw a card. The player then choses a statistic (either 'electric charge', 'spin', 'mass', or 'mean lifetime') to compare with the opponent's unknown card.

Step 2: Reveal and Swap

Player's Card

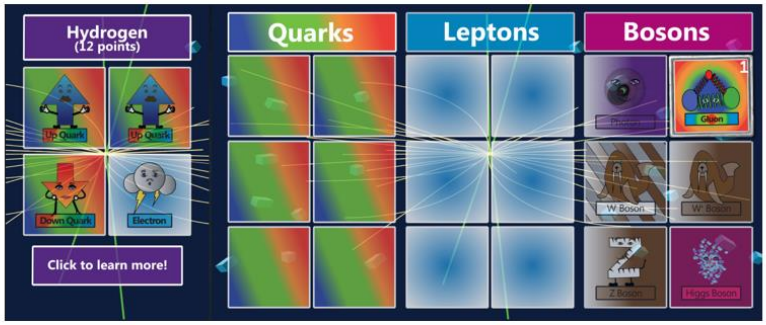


Opponent's Card



Step 2: The opponent reveals their card. If the player has chosen a statistic which is higher than the opponent's corresponding statistic, they can choose to swap cards.

Step 3: Place Card

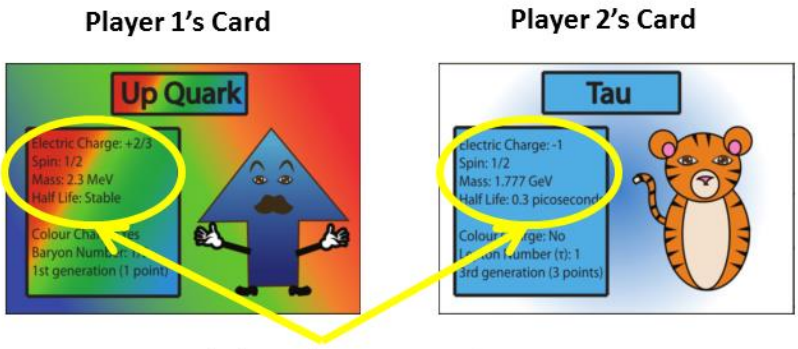


Step 3: The player must identify which section of their mat that their card belongs to and place their card in the relevant area.

Step 4: Players swap roles and repeat.

3.) The deck of particle cards is placed in a face down pile in the middle of the table. Both players draw from this deck of cards.

4.) Most of the game follows the four-step process shown on the previous page. The game starts with the first player's turn. Each player picks up a card but does not show it to the other players. The first player then chooses a statistic from the card, either charge, spin, mass or mean lifetime. See diagram below:



Statistics to be compared.

If it is player 1's turn, player 1 must choose one of the statistics highlighted in yellow (before seeing player 2's card). After the statistic is chosen the players must compare the statistic. If player 1 chose a statistic that is higher then he/she wins and may swap cards with player 2. If not both players keep their card.

If the first player's chosen statistic is higher than all the other players' then they may choose to swap cards with another player of their choice. If not, they keep their card. Starting with the player whose turn it is and then going clockwise, the players put the (new) card in their hand onto the relevant area of the game mat (see instruction 5).

Note the following rules when comparing statistics:

- If there are 3 or more players, then in order to win the player must beat every other player. Then they may choose to swap cards with any individual player.
- A tie always results in all players keeping their own card (same as losing).
- If the mean lifetime is stable this count as infinity and beats all finite mean lifetimes.
- It is the highest charge that wins not the highest magnitude of charge. Therefore positive charges always beat negative charges.

5.) Placing the Cards on the Game Mat

When a player goes to put the card down on their game mat, they must identify what type of particle they have.

Placing Quarks and Leptons

If the card is a quark or lepton there are three places where they can place their card:

1.) The corresponding area on their game mat. A quark or lepton must be placed in an empty slot; they cannot be stacked, not even with others of the same kind (Pauli Exclusion Principle).
2.) On an empty slot on their target card. This option is only available if the target card requires the specific quark or lepton. Players may move cards between their target card and their game mat at any time.
3.) Players may use a special ability if possible, such as annihilation (see section 7).

If none of these options are available, then the players must discard their card.

Placing Bosons

If the particle is a boson there are two options to place the card:

1.) The boson can be placed in the corresponding position in the boson section on the right hand side of the mat. Players may stack multiple bosons in the same position (Pauli Exclusion Principle does not apply to particles with integer spin). For example there is no limit to the number of photons a player may have, they simply stack them in the allocated position.
2.) Players may alternatively use a special ability if possible.

Physics of Particle Builder (Pauli Exclusion Principle) - Particles with half-integer spin (leptons and quarks) are called leptons. Leptons obey a rule called the Pauli Exclusion Principle, which means they are forbidden to be in the same state. Particles with integer spin do not obey this rule and are allowed to be in the same state.

6.) Next Player's Turn

It then becomes player 2's turn. All players draw a card and player 2 chooses a statistic. If player 2's statistic is highest, player 2 may choose to swap cards with another player.

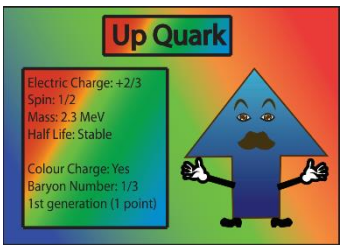
It then becomes the next player's turn. This turn taking process continues and players build up a collection of particles until one player has enough particles to build their target card or the deck of cards runs out. In these cases the game is over and the players add up their points. The player with the highest total wins.

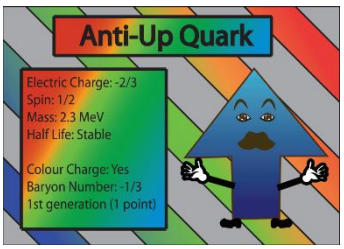
7.) Special Rule: Annihilation

In Level 1 the only special rule is annihilation of anti-particles. Anti-matter particles are represented with grey stripes in this game.

If the card in a player's hand is the anti-particle of a card on any game mat (theirs or another player's), then rather placing it on their game mat, they may choose to annihilate it and the corresponding anti-particle. In this case the player takes both cards puts them in the annihilation area on their game mat and adds the total points to their score at the end of the game.

An anti-particle pair is formed of one particle and one anti-matter particle. For example one up quark and one anti-up quark, in other words, the up quark is the anti-particle of the anti-up quark.





8.) Ending the Game

When a player has all the required particles for their particle system target they receive the given number of points and the game is over. If any players still have cards in their hands they may put them down on their own mat, but they may not use special abilities (for example annihilation). If the deck runs out of cards then the game is over and neither player gets points for their target card. Players then calculate their final score by adding the points for each particle on their game mat. The player with the most points wins.

The purpose of Level 1 is for students to see which particles belong to each category and learn some basic facts about them. Students will also be exposed to particle physics terminology.

You are now ready to stop reading a play Level 1. If you are looking for something more advanced after you have finished playing, you can read on and play Level 2.

Level 2 is more fun as it allows you to attract (steal) your opponents' particles.

Level 2 – Introduction to Interactions

The rules for Level 2 are the same as Level 1, however some of the bosons gain a new special ability, "interaction". Interaction is a new special ability that you can use instead of playing the card: some bosons can be used as force carrying particles to attract your opponents' particles. If you use the interaction ability, then the boson is discarded. These following bosons gain the interaction ability in Level 2:

- **Gluon** – If a player has a particle with colour charge, instead of placing a gluon on the mat, the player may instead use the gluon to 'attract' (steal) a quark or gluon from an opponent's game mat or target. In this case the stolen quark or gluon is moved into the corresponding position on the player's mat or target. The used gluon is 'absorbed' and discarded.
- **Photon** – If a player has an electrically charged particle, instead of placing a photon on the mat, the player may use a photon to 'attract' (steal) an electrically charged particle from an opponent. In this case the stolen electrically charged particle is moved into the corresponding position on the player's mat or target card. The used photon is 'absorbed' and discarded.
- **Z Boson** – As long as you have a particle, you may use a Z boson to 'attract' (steal) any quark or lepton from an opponent. In this case the stolen particle is moved into the corresponding position on the player's mat or target card. In this case the Z-boson is absorbed and discarded.

The purpose of Level 2 is to teach students about the strong force, weak force and the electromagnetic force as well as which particles these act on.

Level 3 – Introduction to Colour

In order to play Level 3, players require colour tokens. These can simply be pieces of paper which have the colours blue, green, red, anti-blue, anti-green and anti-red written on them. Alternatively you can print the colour charge tokens from Zenodo (see Level 3 subfolder in the Material to Print folder).

The rules for Level 3 are the same as Level 2, with the following exceptions:

- There are colour tokens. Whenever a player puts down a quark card they must choose a colour for that quark card. The colour token is then placed on that quark. An anti-quark must be allocated an anti-colour (anti-blue, anti-green and anti-red).
- Gluons gain a new ability, 'change colour charge'. Similar to the interaction ability, the Gluon is discarded: it may be used to change the colour of any quark or anti-quark (either a player's own quarks or their opponent's). In this case the gluon is 'absorbed' and discarded.
- In order to complete their target, a player must obtain a colour neutral set. This means they need a red, green and blue quark for a baryon target or a colour and its anti-colour for a meson target.

More physically accurate variant: Technically colour charge is conserved. If the players want, they may decide that the 'change colour charge' ability is replaced by 'swap colour charge'. In this case a gluon can be used to swap two colour charge tokens between any two quarks or any two anti-quarks.

The purpose of Level 3 is to teach students about the colour charge and realise that all hadrons are colour neutral.

Level 4 – Cross Sections

In order to play Level 4, dice are required.

The rules are the same as Level 3, with the following exceptions:

- Whenever a player attempts an annihilation, they role a die. If they role an odd number, the annihilation does not occur and instead they place the particle card on the relevant area on their own mat.
- Whenever a player attempts to use a boson card to change the colour charge or attract a particle, they roll they role a die. If they role an odd number, the interaction does not occur and they place the particle on their own mat.

The purpose of Level 4 is to introduce the idea that particles do not obey deterministic laws but are probabilistic by nature.

Warning: for Level 5 and beyond the Rules become complicated! (And an extra set of cards is required)

Level 5 – Transformations

In order to play Level 5, a set of spare cards is required. Adding extra W^+ and W^- bosons to the deck makes the game more fun!

The rules are the same as Level 4, with the following exceptions. Instead of playing a W^+ or a W^- Boson on their mat, they can use it to transform a particle according to the rules below:

- Conservation of electric charge. If a W^+ is used to transform a particle then the product must have an electric charge 1 greater than the original. If a W^- is used to transform a particle then the product must have electric charge 1 less than the original.
- Conservation of baryon number. Quarks may only be transformed into other quarks. Anti-quarks may only be transformed into anti-quarks. Leptons may not be transformed into quarks.
- Conservation of lepton family number – Leptons may only be transformed into other leptons of the same generation. For example, a tau may only be transformed into a tau neutrino.

A player may transform a particle that is on their own mat, or the mat of another player.

When a W^+ or a W^- is used to transform a particle, it is absorbed and discarded.

Special Rule Annihilation: When a player annihilates a charged lepton/anti-lepton pair they may put two photon cards onto the photon section of their mat. When a player annihilates a quark/anti-quark pair they may put two photon cards or two gluon cards onto their mat. When a player annihilates a neutrino/anti-neutrino pair they place a single Z boson on their mat.

Rather than rolling an even number, in order to annihilate a neutrino-anti-neutrino pair a player must role a 6.

The purpose of Level 5 is to introduce students to the types of transformations that are allowed by the standard model and conservation laws.

Level 6 – Neutrino Oscillations

Warning: Although this level incorporates more modern physics, it makes the game more time consuming with almost no extra fun added.

At the start of a player's turn they roll a die for each neutrino and anti-neutrino on their mat. The neutrino then transforms according to the following rules:

- Roll a 1 or 2: Neutrino becomes (or remains) an electron neutrino
- Roll a 3 or 4: Neutrino becomes (or remains) a muon neutrino
- Roll a 5 or 6: Neutrino becomes (or remains) a tau neutrino

The purpose of Level 6 is to introduce students to phenomenon of neutrino oscillations (2015 Nobel Prize was awarded for this). This occurs because the mass eigenstates of neutrinos are different to the flavour eigenstates of neutrinos.

Level 7 – Spontaneous Transformations (Decays)

This Level is too complicated, don't play it, run away while you still can and enjoy life!

For Level 7, players will need a large number of face up W^+ and W^- cards in addition to a spare set of cards, dice and a lot of patience.

When each player starts a new turn, they must role a die for each second or third generation particle, W^+, W^-, Z^0 and Higgs Boson on their mat. Depending on the number rolled, the particle transforms as specified below. The same decays occur for anti-particles, just exchange the listed matter particles (and W bosons) with their anti-particles.

Quark Spontaneous Transformations

Quarks decay according to following rules which are summarised in the diagram below. Electric charge is always conserved in decays so the player also receives a W^- or a W^+ boson.

Top:

- if 3-6 is rolled it becomes a bottom quark
- if 2 is rolled it becomes a strange quark
- if a 1 is rolled it becomes a down quark

Bottom:

- if 3-6 is rolled it becomes a charm quark
- if 2 is rolled it becomes an up quark
- if a 1 is rolled it remains a bottom quark

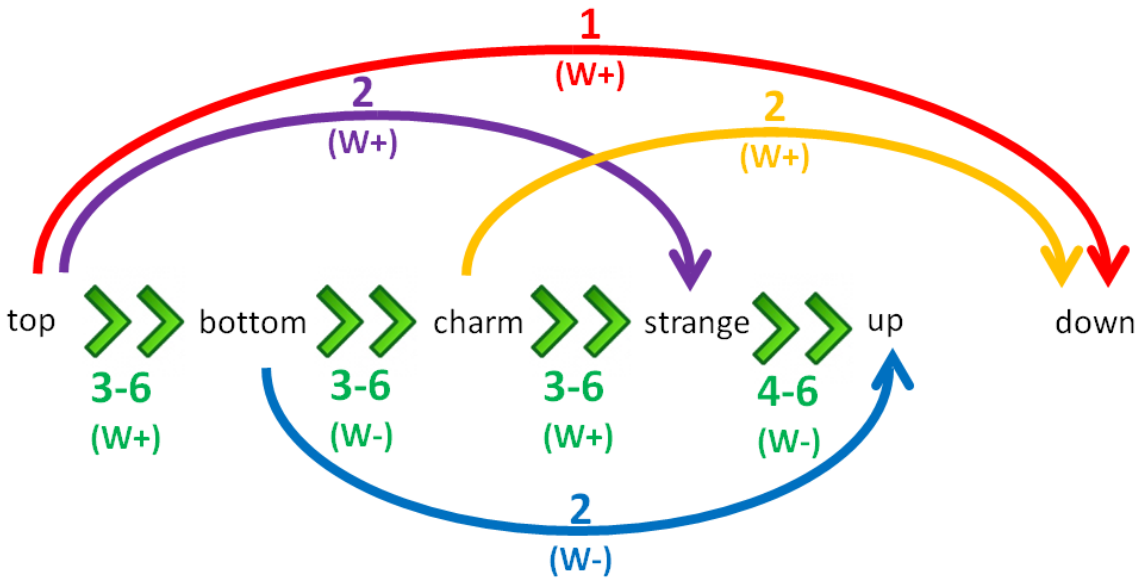
Charm:

- if 3-6 is rolled it becomes a strange quark
- if 2 is rolled it becomes a down quark
- if a 1 is rolled it remains a charm quark

Strange:

- if 4-6 is rolled it becomes an up quark
- otherwise it remains a strange quark

The diagram below summarises the transformation of quarks. Note that these probabilities are indicative of the most likely decays but are not at all numerically accurate.



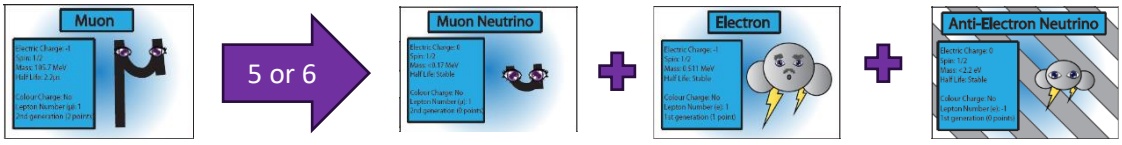
Anti-quarks decay according to the same rules, but the player should receive the corresponding anti-quark and a W boson with opposite charge.

Lepton Spontaneous Transformations

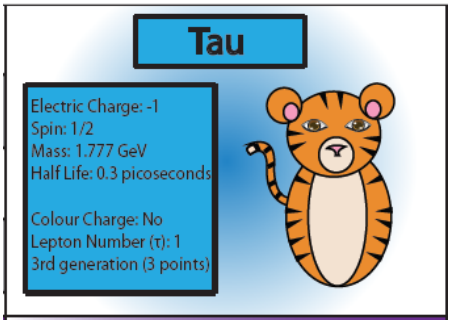
Leptons decay according to following rules which are summarised in the diagram below. Charge is always conserved in decays so the player also receives a W^- or a W^+ boson.

Muon

- If 5 or 6 is rolled it becomes an muon neutrino, electron, and anti-electron neutrino. All of these particles must be placed in the lepton area if there is space, or discarded if not.
- If a 1, 2, 3 or 4 is rolled, it remains a muon.



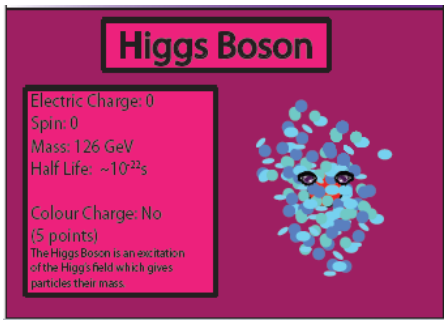
Tau



- if a 6 is rolled the tau transforms into a tau-neutrino, a muon and an anti-muon neutrino.
- if a 5 is rolled the tau transforms into a tau-neutrino, an electron and an anti-electron neutrino.
- If a 4 is rolled the tau transforms into a tau-neutrino, a down quark and an anti-up quark
- If a 3 is rolled the tau transforms into a tau-neutrino, a down quark, an anti-up quark and a neutral pion (player's choice of an up/anti-up pair, or a down/anti-down pair)
- If a 2 is rolled the tau transforms into a tau-neutrino, a down quark, an anti-up quark and two neutral pions (player's choice of an up/anti-up pair, or a down/anti-down pair)
- Otherwise it remains a tau.

Anti-muons and anti-taus decay the same way except the corresponding anti-particles are created instead of the listed particles.

Higgs Boson Spontaneous Transformation



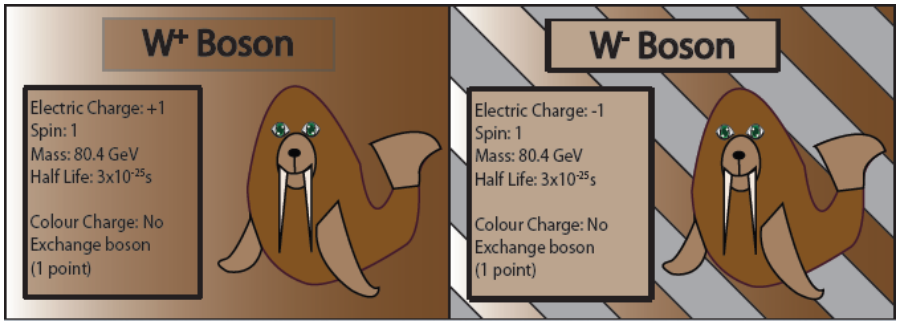
- if 4-6 is rolled it becomes a bottom/anti-bottom pair
- if a 3 is rolled it becomes a W^+/ W^- boson pair
- if a 2 is rolled, roll another die:
  - if a 4-6 is rolled it becomes two gluons
  - if a 2-3 is rolled it becomes a tau/anti-tau pair
  - if a 1 is rolled it becomes a charm/anti-charm pair
- if a 1 is rolled, it remains a Higgs Boson:

The decays here are the most probable decays to occur according to the standard model. However there are other possible decays. The probabilities when rolling a dice are somewhat indicative of actual Higgs decay.

W^+ and W^- Spontaneous Transformation

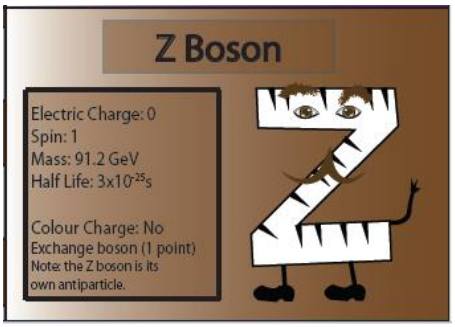
W^+ bosons decay according to the following rules. W^- Bosons decay to the corresponding antiparticles with the same probabilities.

- if a 5-6 is rolled a charm/anti-strange pair is produced
- if a 3-4 is rolled a down/anti-up pair is produced
- if a 1-2 is rolled, roll another die:
    - If a 5-6 is rolled a tau neutrino/anti-tau pair is produced
    - If a 3-4 is rolled a muon neutrino/anti-muon pair is produced
    - If a 1-2 is rolled an electron neutrino/positron pair is produced



Z Boson Spontaneous Transformation

Z Bosons (Z^0) decay according to the following rules:



- if a 3-6 is rolled a roll another die:
    - if a 6 is rolled a bottom/anti-bottom pair is produced
    - if a 5 is rolled a charm/anti-charm pair is produced
    - if a 4 is rolled a strange/anti-strange pair is produced
    - if a 3 is rolled a down/anti-down pair is produced
    - if a 2 is rolled an up/anti-up pair is produced
    - if a 1 is rolled, roll again until you get a 2-6.
- if a 1-2 is rolled, roll another die:
    - If a 3-6 is rolled, role another die:
        - If a 5-6 is rolled a tau neutrino/ anti-tau neutrino pair is produced
        - If a 3-4 is rolled a muon neutrino/ anti-muon neutrino pair is produced
        - If a 1-2 is rolled an electron neutrino/anti-electron neutrino pair is produced
    - If a 1-2 is rolled, role another die:
        - If a 5-6 is rolled a tau neutrino/ anti-tau neutrino pair is produced
        - If a 3-4 is rolled a muon neutrino/ anti-muon neutrino pair is produced
        - If a 1-2 is rolled an electron neutrino/anti-electron neutrino pair is produced

Level 7 introduces students to particle decays and branching ratios. The reasons behind the branching ratios are complicated. However, if students wish to learn more, they can research some of the following terms: "Quantum Numbers", "Branching Ratios", "Decay Modes", "Energy conservation in particle decays" "CKM matrix", "Coupling constant", "Chirality" (of leptons) and "Off mass shell". Please note that because there are 3 different colour charges, decay through quark channels become 3 times as more likely for Z, W and Higgs Boson decays.