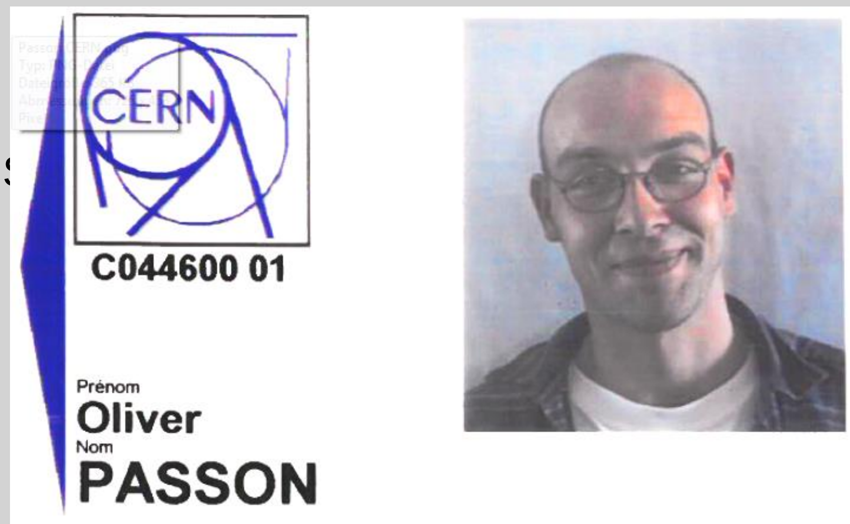
How to teach Elementary Particle Physics

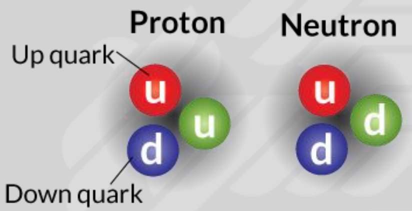


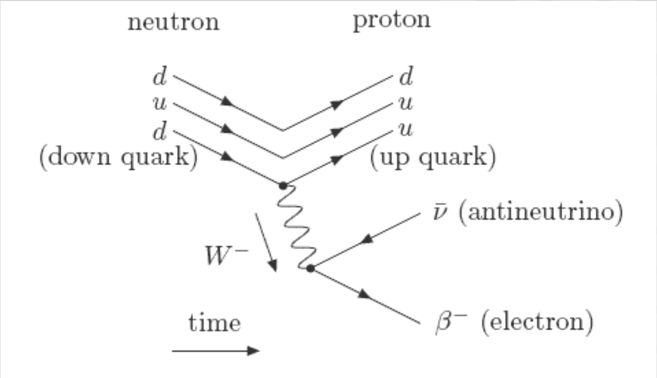
Stage setting

- Some countries have included particle physics into the **physics curricula** on high school level.

- Particle physics = **Standard model**
  - **Particle content** of the SM
  - The model of **exchange** particles

- **Challenge** to teacher trainers, teachers and students





International publications on the teaching of particle physics:

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General overview

Farmelo G 1992 Teaching particle physics in The Open University's science foundation course *Phys. Ed.* **27** 96–101

Ryder L H 1992 The Standard Model *Phys. Ed.* **27** 66–70

Jones G T 2002 The uncertainty principle virtual particles and real forces *Phys. Ed.* **37**(3) 223–233

Hoekzema D, Schooten G, van den Berg E and Lijnse P 2005 Conservation Laws, Symmetries, and Elementary Particles *The Physics Teacher* **43** 266–271

Daniel M 2006 Particles, Feynman diagrams and all that *Phys. Ed.* **41**(2) 119–129

van den Berg E and Hoekzema D 2006 Teaching conservation laws, symmetries and elementary particles with fast feedback *Phys. Ed.* **41** 47–56

Organtini G Matter and interactions: a particle physics perspective *Phys. Ed.* **46** 544–550

Hobson, A 2012 Teaching elementary particle physic, Part I *The Physics Teacher* **49** 12–15

Hobson, A 2012 Teaching elementary particle physic, Part II *The Physics Teacher* **49** 136–138

Johansson K E 2013 Exploring quarks, gluons and the Higgs boson *Phys. Ed.* **48**(1) 96–104

Johansson K E and Watkins P M 2013 Exploring the standard model of particles *Phys. Ed.* **48**(1) 105–114

Woithe J, Wiener G J and Van der Veken F F 2017 Let's have a coffee with the Standard Model of particle physics! *Phys. Ed.* **52**(3) 034001

Main focus on Feynman diagrams

Lambourne R 1992 Predicting the physics of particles *Phys. Ed.* **27** 71–75

Allday J 1997 The nature of force in particle physics *Phys. Ed.* **32**(5) 327–332

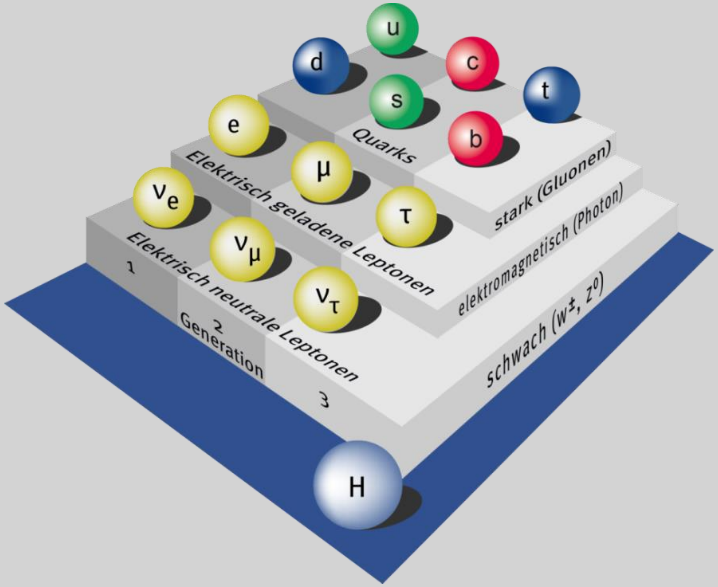
Dunne P 2001 Looking for consistency in the construction and use of Feynman diagrams *Phys. Ed.* **36** 366–374

Pascolini A and Pietroni M 2002 Feynman diagrams as metaphors: borrowing the particle physicist's imagery for science communication purposes *Phys. Ed.* **37**(4) 324–328

Kontokostas G and Kalkanis G 2013 Teaching Electron-Positron-Photon interaction with Hands-on Feynman Diagrams *Phys. Teach.* **51** 232–233

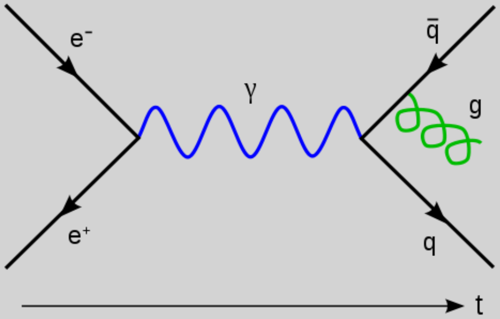
Particle physics in 90 seconds

The common narrative of particle physics



Particle contend of the Standard Model

DELPHI detector at LEP (1989-2000)



Feynman diagram for quark production in e^+e^- annihilation

Hadronic event at DELPHI

Apparently an ok story, however, unambiguous only to the working physicist who has…

- … additional **background knowledge** (e.g. asymptotically free states can be viewed as particles approximately), and…

- … to whom this talk is embedded into a **scientific practice**!

To the layperson misconception could arise:

  - What are elementary particles?
  - Feynman diagrams and interactions

What are elementary particles?

From our viewpoint, it is not only permissible, but even advisable to speak directly of elementary particles instead of field excitations when discussing basic principles of particle physics *qualitatively* in high school.

Woithe et al. 2017

This is a very exciting time in our investigation of the smallest particles and the fundamental forces that act between them.

Johansson and Watkins 2013

The waves concerned are, however, mysterious ones: they determine the relative probabilities of where an electron (that has gone through a two-slit experiment in our case) will be found.

Jones 2002

There are no particles, there are only fields

Hobson 2013

“**Particles**” may be confused with small chunks of ordinary matter (frequently reported in chemistry education)

“**Field excitations**” are problematic, since the “quantum field” is operator valued…

“**quantum waves**” are problematic, since e.g. the photon has no wave function with probability interpretation in position-space…

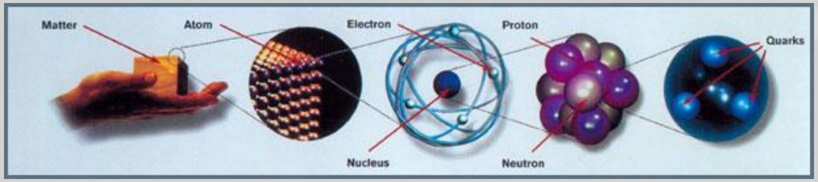
How the story should be told:
The “particle” concept gets impoverished…

Particle properties	Classical Mechanics e.g. kinetic theory of gases	QM e.g. electrons	QFT e.g. photons
Number	√	√	(√)
Position	√	(√)	
Trajectory	√		
distinguishable	√		

Thesis 1
If particle physics transcends the limits of our (ordinary) imagination, the use of every day and intuitive notions does a disservice to the students.

Big Proton with Mini Quarks and Gluon
$41.99

Thesis 1b
To explain how the particle concept has changed can help to develop the ability to differentiate and the capacity for abstraction.



Feynman diagrams as the "royal road" to particle physics?

Figure 2. The set of pieces to construct Feynman diagrams: notice that both ends of the photon line have the same circular shape, whereas the electron line has a hexagonal head and a square tail.

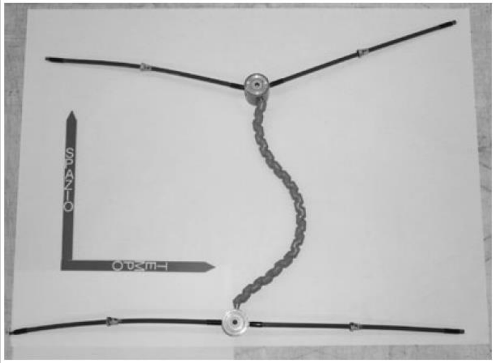


Figure 4. The process $e^-e^- \to e^-e^-$ constructed with the toy elements.

Pascolini and Pietroni (2002)

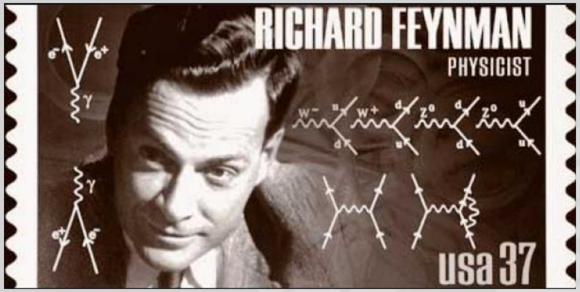
"literal reading" of Feynman diagrams

> Each diagram—constructed according to well-defined rules—represents a possible physical process and, making it so valuable to physicists, it can be unambiguously translated into a mathematical expression, giving the probability for that process.

Pascolini and Pietroni (2002)

Feynman diagrams and their interpretation

- Introduced by Feynman on the Pocono meeting in 1948
- Formalized and derived from field theory by Freeman Dyson in 1949



Dyson 1963

"Nobody but Dick could use his theory, because he was always invoking his intuition to make up the rules of the game as he went along. Until the rules were codified and made mathematically precise, I could not call it a theory." (cited from Kaiser (2005, p. 188))

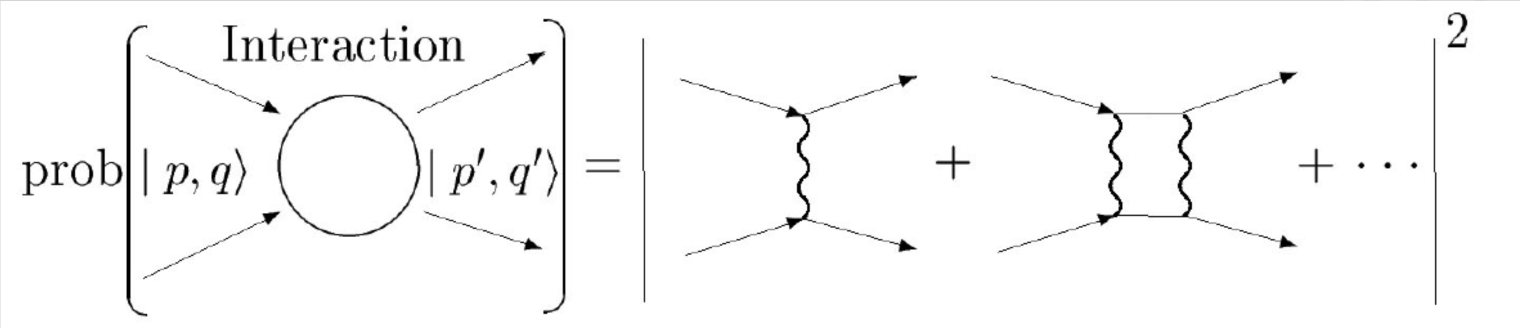
We have introduced the Feynman graphs simply as a convenient pictorial way of visualizing the analysis of an operator into its normal constituents. The graphs are just diagrams drawn on the paper.

F. Dyson in "Advanced Quantum Mechanics"
Cornell lecture 1951

Feynman diagrams represent formulae – not physical processes.

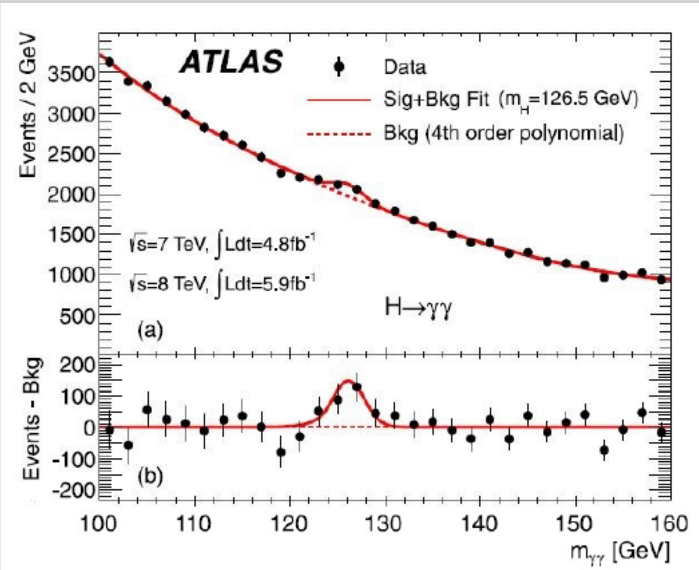
Single Feynman diagrams do not happen: The argument from superposition

The single Feynman diagram is only part of an perturbative expansion of the scattering matrix S. Only $|S|^2$ relates to an observable quantity:

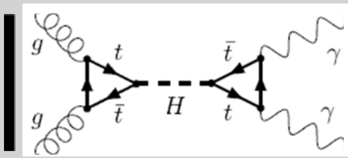


- The probability is given by the square of sums – and not by the sum of squares. The additional “interference term” can not be assigned to a single Feynman diagram
- Recall the double slit in QM: observable pattern =$|$slit 1 + slit 2$|^2$. A single Feynman diagram is like the probability amplitude for the electron passing to one slit…
- Allday (1997): “no single diagram is happening – they are all involved”.

The argument from superposition in the Higgs discovery



$\sigma \sim \Big|$



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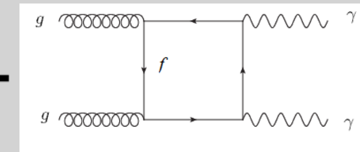
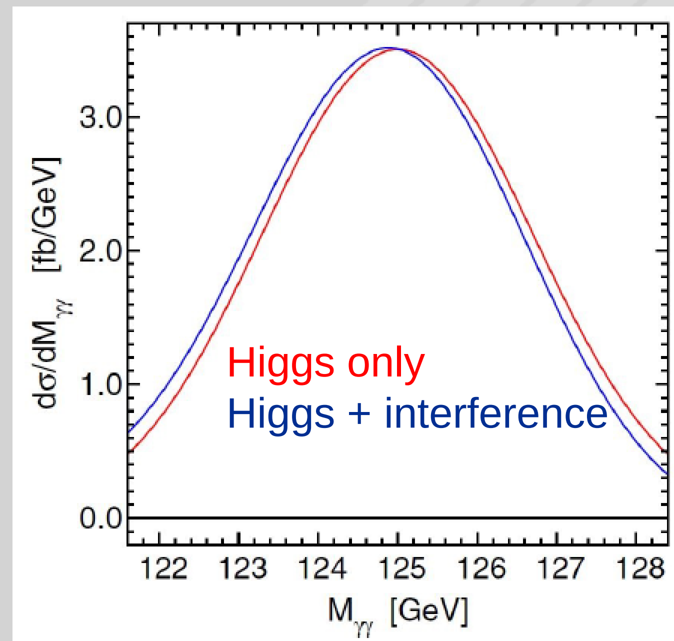


$+\cdots\Big|^2$

The “Higgs-mass-peak” gets shifted by this interference!

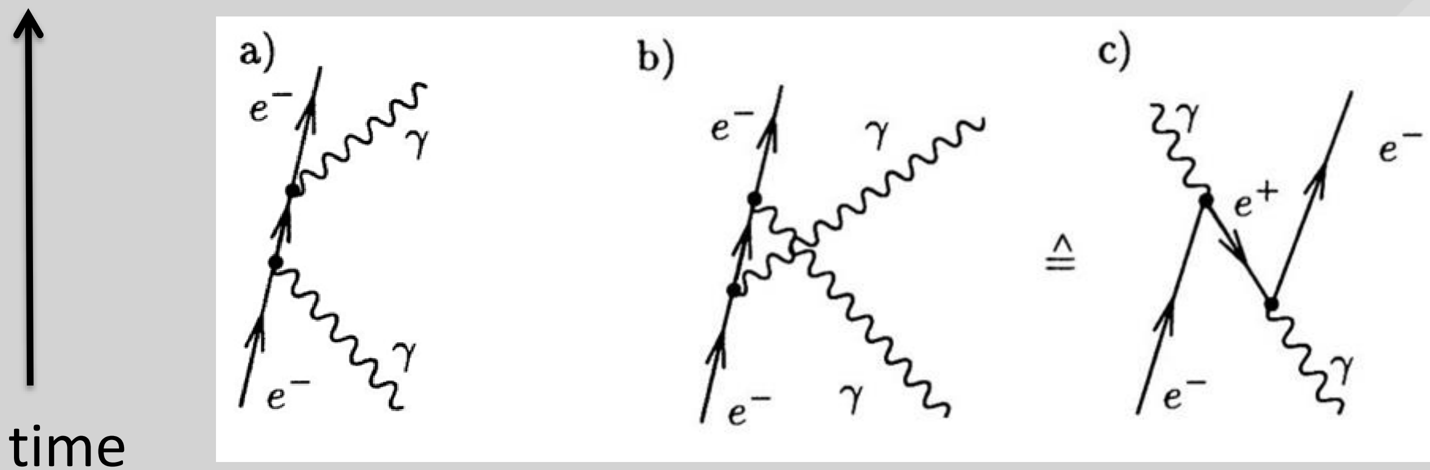
To say “$H \rightarrow \gamma\gamma$ has been observed” is misleading… it singles out one amplitude which can not be “observed” in isolation…



Martin (2012) Phys. Rev. D 86 073016.

Feynman diagrams do not tell a story about the physical process: The argument from „topological equivalence“

Compton scattering in leading order:



- b) and c) are topological equivalent, i.e. they can be continuously deformed into each other. They describe the same amplitude! Only one needs to be considered to avoid double-counting.
- Their “stories” are completely different: b) emission **before** absorption c) **pair production** of electron and positron
- If each diagram is just the representative of this equivalence class (each member “telling a different story”) it can not tell any story at all….

Thesis 1

If particle physics transcends the limits of our (ordinary) imagination, the use of every day and intuitive notions does a disservice to the students.

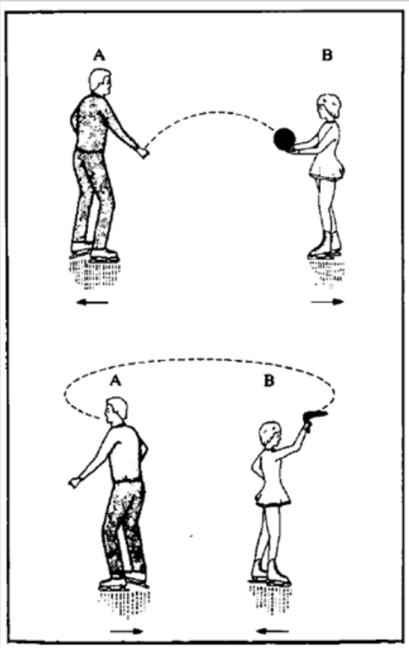
Thesis 1b

To explain how the particle concept has changed can help to develop the ability to differentiate and the capacity for abstraction.

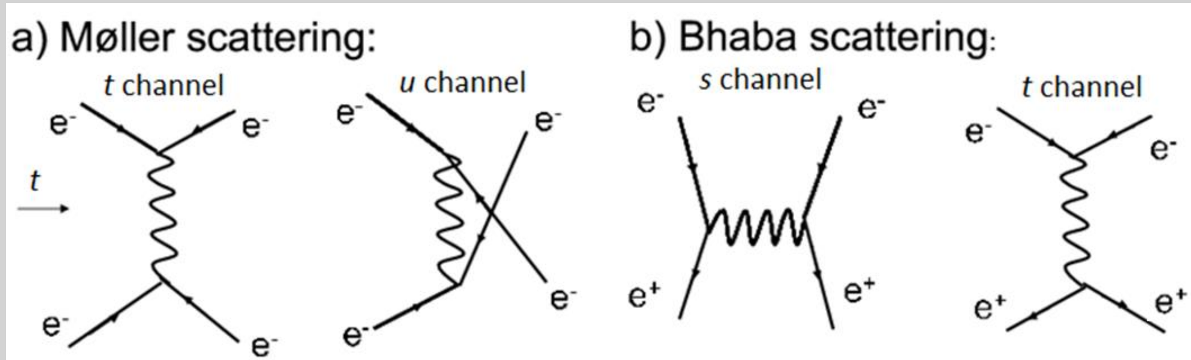
Thesis 2

A “realist” interpretation of Feynman diagrams is scientifically untenable and their visual appeal is highly misleading. They represent not physical processes but formulae.

Virtual exchange-particles as carriers of the fundamental interactions: A notion supported by Feynman diagrams



Aus: G. Farmelo (1992) Phys. Ed. **27**: 96-101



The most absurd way of explaining this that I have seen is to accuse the exchange particle of being like a boomerang that curves away from the emitter in the opposite direction to what one would expect. It then whips round behind the target and knocks it towards the emitter.

Allday (1997)

Some other problems with the "throwing-ball/boomerang-analogy":

- How "particle-like" are the gauge bosons?
- What about their being "virtual"?
- The analogy suggests a space-time picture of the process.

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If particle physics transcends the limits of our (ordinary) imagination, the use of every day and intuitive notions does a disservice to the students.

Thesis 1b
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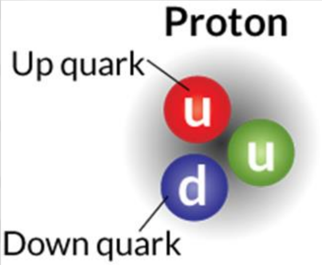
Thesis 2
A "realist" interpretation of Feynman diagrams is scientifically untenable and their visual appeal is highly misleading. They represent not physical processes but formulae.

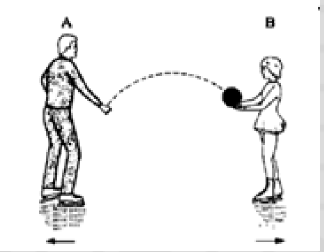
Thesis 2b
One could reach a very important educational goal (namely autonomy) by correcting the common misrepresentations of Feynman diagrams in the classroom. The notion of "exchange particles" should be viewed as a metaphor only.

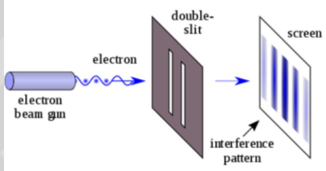
Summary and conclusion:

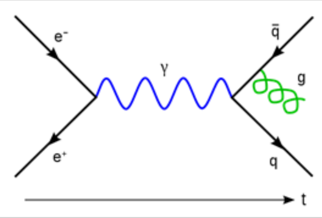
If in the teaching of particle physics its concepts are adapted to established ideas already acquired one may wonder why it should be taught anyway!

- …If protons were build out of up and down quarks like atoms out of the nucleus and electrons that would be rather boring.
- …If a mechanical model would capture the notion of force in particle physics that would be really odd, given that EM exceeds the scope of mechanics already.
- …If quantum mechanics does not permit to tell a story about events between preparation and measurement, particle physics (i.e. quantum field theory) should not permit it either!









Postscript:

Educational processes result from “irritation” (i.e. the encounter with the foreign, unexpected, unusual that evades any simple explanation).

While we need to simplify particle physics – we should resist the temptation to explain it away and to trivialize it. Quantum physics is a great way to irritate.

Thank you!

Photons and probability: From R. Peierls, Surprise in Theoretical Physics", Princeton University press, 1979, p. 12

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The other side of the problem relates to the possibility of treating photons as classical particles. This would require treating the position of a photon as an observable. If this were possible, quantum mechanics would have to be able to predict the outcome of such observations. There should therefore exist an expression for the probability of finding the photon in a given volume element. Such an expression would have to behave like a density, i.e., it should be the time component of a four-vector. Being a probability, it should also be positive definite, i.e., it should equal a square or a

The conclusion that the position of a photon cannot be observable is somewhat surprising. One must remember, of course, that we can certainly localize photons to the accuracy of geometrical optics, within which particle and wave description are equivalent. We are talking about the determination of a position within the wave packet or beam of geometrical optics, analogous to an observation which might locate an electron within the hydrogen atom.

Further problems of the literal reading of Feynman diagrams:

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- The length of the lines carries no
- The angle between the lines carries no information
- The exact position of the vertex carries no information
- Feynman diagrams give no spatio-temporal picture of any process (no world-lines, no Minkowski diagram)

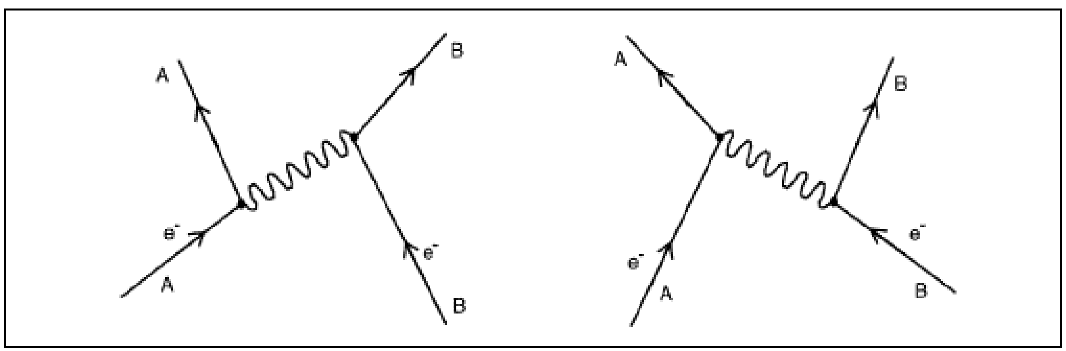


Figure 2. *If Feynman diagrams had a vertical time axis, then these two diagrams would represent different time orderings of the events. The Feynman diagram of figure 1 is relativistically invariant and so covers both these diagrams.*

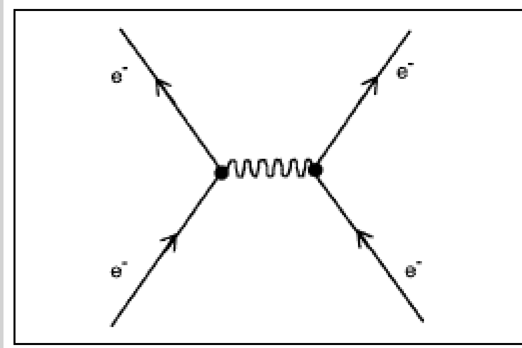
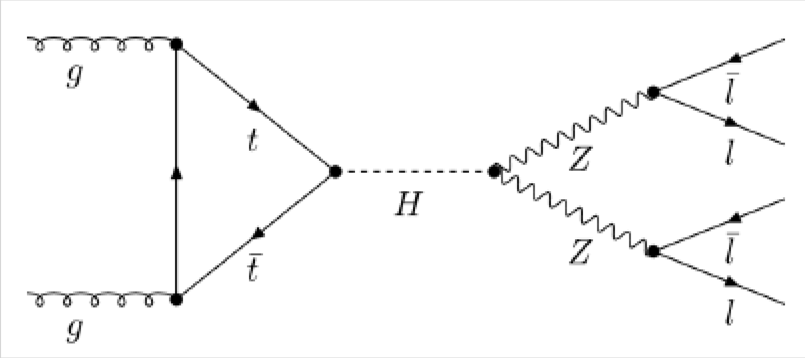


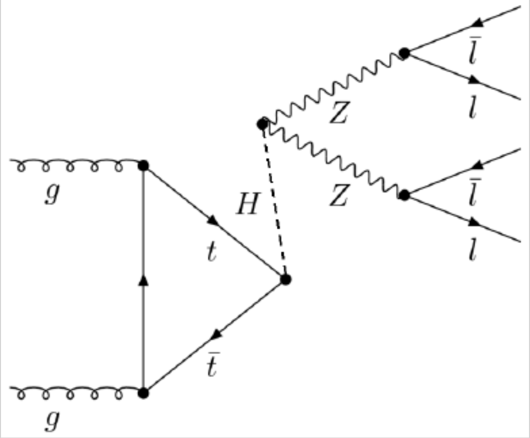
Figure 1. *A Feynman diagram showing how a photon can be exchanged between two electrons.*

From J. Allday (1997)

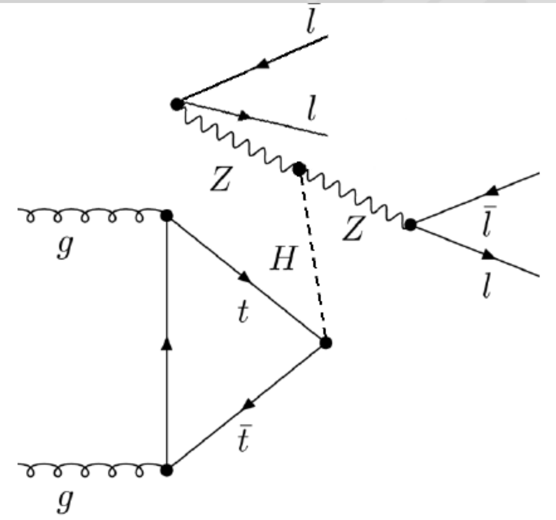
Topological equivalence and the Higgs discovery



Top loop induced Higgs production in gg Fusion with subsequent decay into ZZ and 4 charged leptons



HZZ production. The Higgs subsequently annihilates with a top pair



A Higgs radiated off a Z which was produced from the vacuum together with 2 charged leptons…