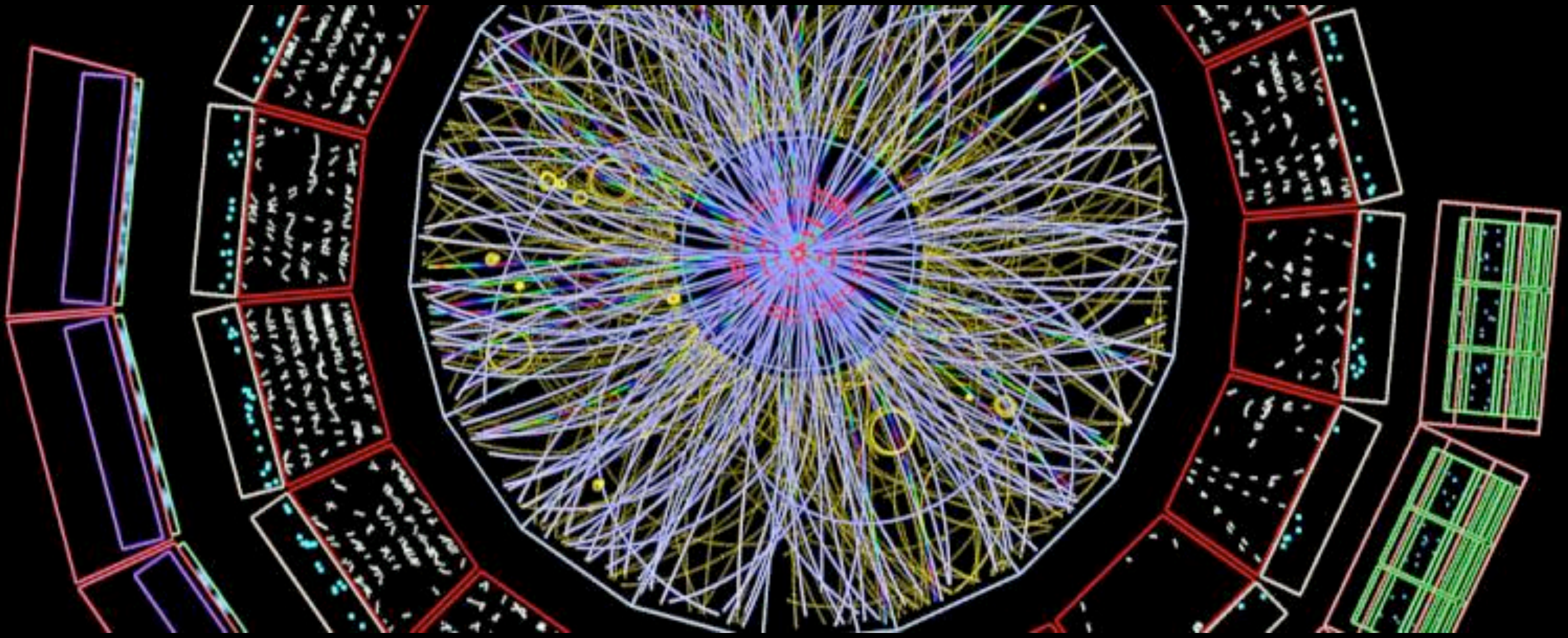
Subatomic Physics

Introduction

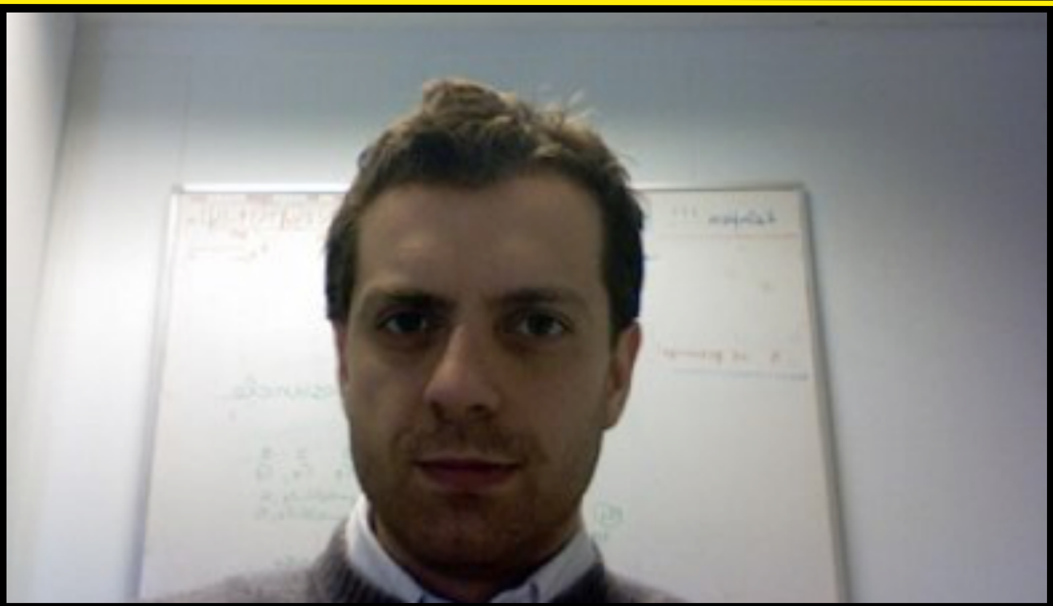


Panos Christakoglou

Nikhef and Utrecht University

Briefly about me…

- Working at CERN from 2003 until 2010
- Senior scientist at Nikhef, Amsterdam,
- Assistant professor at UU, Institute of gravitational and subatomic physics (GRASP)



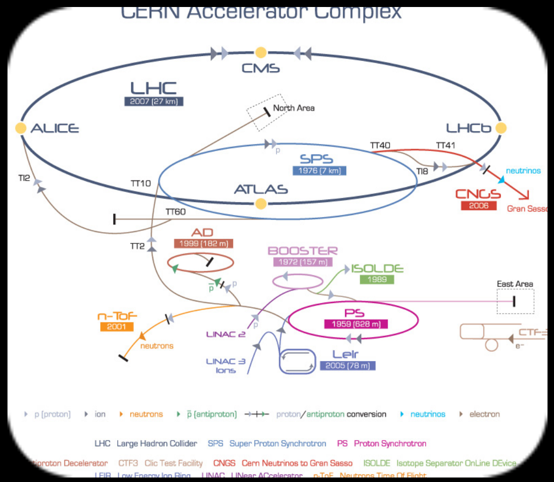
- E-mail addresses
  - Panos.Christakoglou@nikhef.nl
  - Panos.Christakoglou@cern.ch
  - p.christakoglou@uu.nl

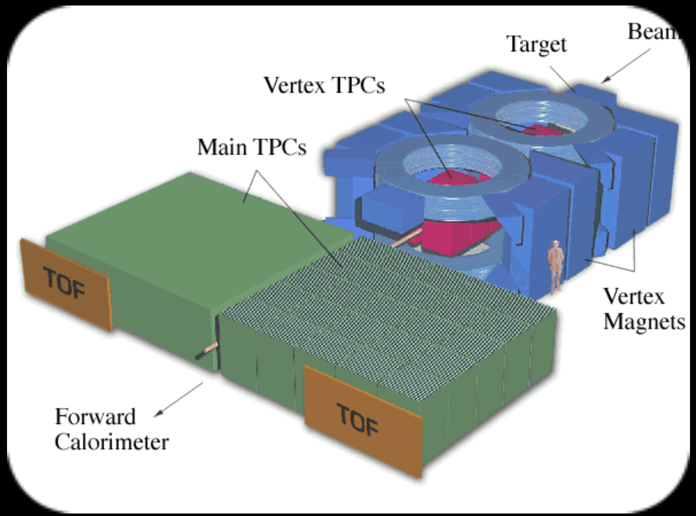
- Where can you find me?
  - Nikhef, Office N327, Science Park 105 Amsterdam
  - S. Ornsteinlaboratorium Princetonplein 1, Office 259, 3584 CC Utrecht

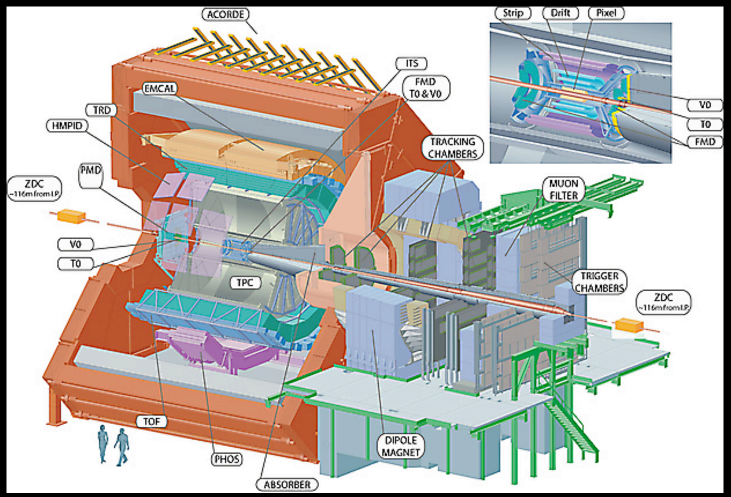
Briefly about me…

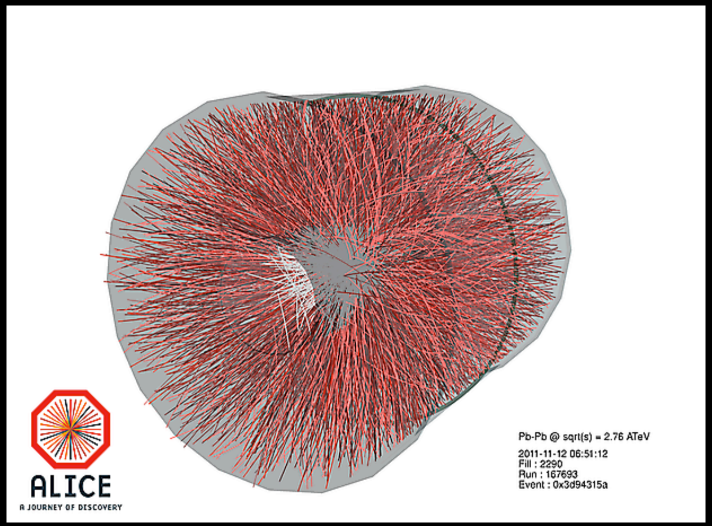
✔ Research interests

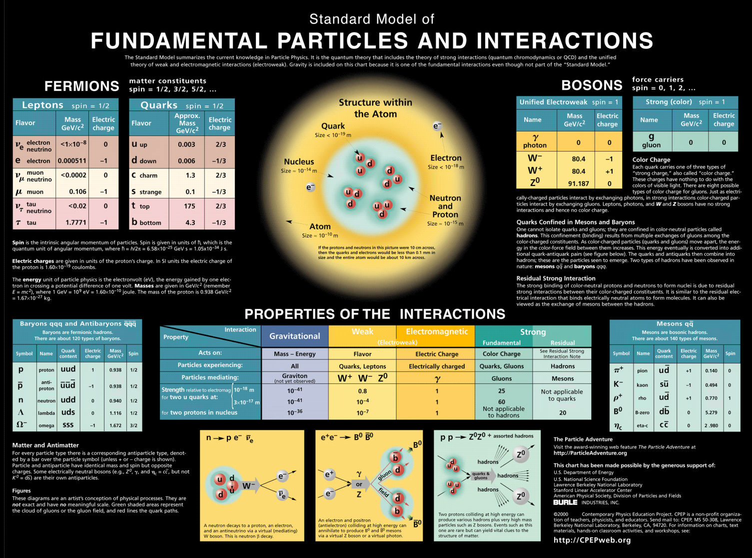
- Quantum chromodynamics
- Heavy-ion physics
- Alice @ LHC





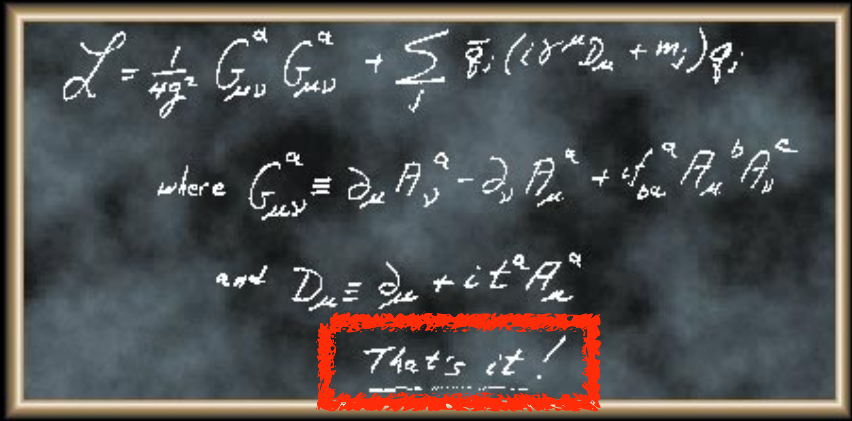






✔ Teaching

- Subatomic physics (3rd year bachelor)
- Particle physics 2: QCD (MSc)



Feel free to visit my web site

but before going to the lecture…

let's fix the (not so) important things first…

Grading scheme

- You pass the course if you score 5.5 (rounded to 6) and above in your final grade
- If your final grade is 5.49 and below that means you have failed

- The final grade is calculated considering the grade of the
  - Homework (HW_Grade in the next slides)
  - Exams (Exam_Grade in the next slides)
    - Mid-term exam
    - Final or retake exam

Final grade

if(**Exam_Grade** >= 5.5)

grade = max[**Exam_Grade** ,
(**Exam_Grade***0.8 + **HW_Grade***0.2)]

Panos.Christakoglou@nikhef.nl

Homework

- This is a homework motivating scheme!
- No matter how many sets you handed in, the part of the grade related to homework is an average over all sets
  - You get **rewarded if you hand in all your homework sets**
- Homework can be handed in no later than one week from the relevant lecture i.e. today's homework set can be handed in no later than next Wednesday
  - Homework and questions about exercises can be sent to the SAP TAs
    - The TAs this semester are **Iris Keizer** (i.j.keizer@uu.nl), Edoardo Bellincioni (e.bellincioni@uu.nl) and Christos Pliatskas (c.pliatskasstylianidis@uu.nl)



- Homework can account for 20% of the final grade
  - You can get up to 2 bonus points
- This homework grade can work only in your favour!!!

Mid-term exam: Friday 8th of March

- ✓ The course has a mid-term exam scheduled on the 10th week
- ✓ Friday 12.03.2021 between 14:00 and 17:00 **on campus**
- ✓ That Friday there is **neither Hoorcollege nor Werkcollege**
- ✓ The **mid-term is compulsory** and accounts for 40% of the grade of the exam

vr 12 mrt.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT →	CANCELLED!!!	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT	MIN - 2.07 MIN - 2.08	

On campus!!!

Final exam

On campus!!!

week 15			
wo 14 apr.			
	15:15 - 18:15	NS - Tentamen	Subatomaire fysica - Eindresultaat CONCEPT

On campus!!!

About all exams

- All exams contain closed and open questions
  - You **can not** bring with you
    - Your lecture notes
    - The main (see next slide) or any textbook
    - The solved exercise sheets from the Werkcollege
  - You can bring with you a calculator

- The Exam_Grade is calculated as the weighted average between the mid-term grade (40%) and the final exam (60%)
- If you fail the course you can participate in the retake
  - The grade of the retake takes the place of the grade of the final exam in the calculation and nothing else changes
    - You carry over both the homework and the mid-term grades

Exam_Grade

Exam_Grade = mid-term_Grade*0.4 + final-exam_Grade*0.6

Grading scheme

- The final grade is calculated considering the grade of the
  - Homework (HW_Grade) ==> 0 up to 20% of the total grade
  - Exams (Exam_Grade) ==> 100 down to 80% of the total grade
    - Mid-term exam ==> 40% of the exam grade
    - Final or retake exam ==> 60% of the exam grade

- Practical examples on how the grade is calculated can be found here

- I consider myself reasonable…a couple of hours per day
  - (Please) do not send mails about the final grade

Final grade

if(**Exam_Grade** >= 5.5)

grade = max[**Exam_Grade** ,
(**Exam_Grade***0.8 + **HW_Grade***0.2)]

Grading scheme: examples

- **Example A:** A student hands in all or part of the exercise sheets and gets an average of 9.0 for this part. The same student scores 6.3 and 7.3 in the mid-term and final exams, respectively. The final grade is then the maximum between $0.8 \cdot (0.4 \cdot 6.3 + 0.6 \cdot 7.3) + 0.2 \cdot 9.0 = 7.32 \to 7.5$ (including homework) and $0.4 \cdot 6.3 + 0.6 \cdot 7.3 = 6.9 \to 7.0$. That means that in this case the final grade will be 7.5.

- **Example B:** A student hands in all or part of the exercise sheets and gets an average of 6.0 for this part. The same student scores 8.5 and 8.1 in the mid-term and final exams, respectively. The final grade is then the maximum between $0.8 \cdot (0.4 \cdot 8.5 + 0.6 \cdot 8.1) + 0.2 \cdot 6.0 = 7.8 \to 8.0$ (including homework) and $0.4 \cdot 8.5 + 0.6 \cdot 8.1 = 8.26 \to 8.5$. That means that in this case the final grade will be 8.5.

- **Example C:** A student hands in all or part of the exercise sheets and gets an average of 8.0 for this part. The same student scores 4.5 and 6.0 in the mid-term and final exams, respectively. The weighted average of the two exams is $0.4 \cdot 4.5 + 0.6 \cdot 6.0 = 5.4 \to 5.0$, which is the final grade i.e. the student did not pass the course. In this case the student won't have the possibility to use the homework bonus which would have raised the grade to $0.8 \cdot (0.4 \cdot 4.5 + 0.6 \cdot 6.0) + 0.2 \cdot 8.0 = 5.92 \to 6.0$

Rooster

week 6					
wo 10 feb.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 12 feb.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	BBG - 083	
week 7					
wo 17 feb.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 19 feb.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	

Nikhef

Rooster

week 8					
wo 24 feb.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 26 feb.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	BBG - 083	

Rooster

week 9					
wo 3 mrt.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 5 mrt.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT	MIN - 2.07 MIN - 2.08	

Rooster

week 10					
wo 10 mrt.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 12 mrt.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT	MIN - 2.07 MIN - 2.08	

Rooster

week 11					
wo 17 mrt.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 19 mrt.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT	MIN - 2.07 MIN - 2.08	

Rooster

week 12					
wo 24 mrt.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
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	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
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		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	BBG - 083	
week 13					
wo 31 mrt.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 2 apr.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	

Rooster

week 14					
wo 7 apr.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	ONLINEONDERWIJS - ONLINE	
vr 9 apr.	09:00 - 11:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	14:00 - 17:00	NS - Werkcollege	Subatomaire fysica - Werkcollege 01 CONCEPT *NS-369B*	BBG - 219	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 02 CONCEPT *NS-369B*	BBG - 023	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 03 CONCEPT *NS-369B*	BBG - 017 BBG - 020	
		NS - Werkcollege	Subatomaire fysica - Werkcollege 04 CONCEPT *NS-369B*	BBG - 083	

week 15					
wo 14 apr.	13:15 - 15:00	AGWF	Subatomaire fysica - Hoorcollege 01 CONCEPT	ONLINEONDERWIJS - ONLINE	
	15:15 - 18:15	NS - Tentamen	Subatomaire fysica - Eindresultaat CONCEPT		

Office hours

- You have questions or comments about the lectures?
  - I reserved two hours every Thursday, between 11:00 and 13:00 for those of you who have questions.
  - Address: Leonard S. Ornsteinlaboratorium, Princetonplein 1, Room 259
  - This way might be readjusted if we see that it’s not practical e.g. everybody shows up in my office at the same time

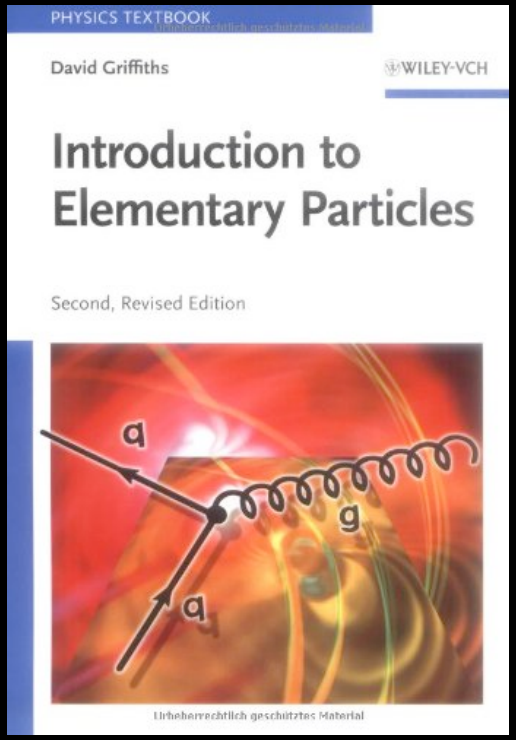
- You could also send a mail
  - I promise to try to answer as fast as possible
    - Note my heavy teaching duties of this semester (i.e. teaching also the QCD course for the MSc program but in Amsterdam every Monday and Wednesday)
    - Also other responsibilities e.g. research (ALICE @ LHC), committees, PhD supervision,…, and maybe a life

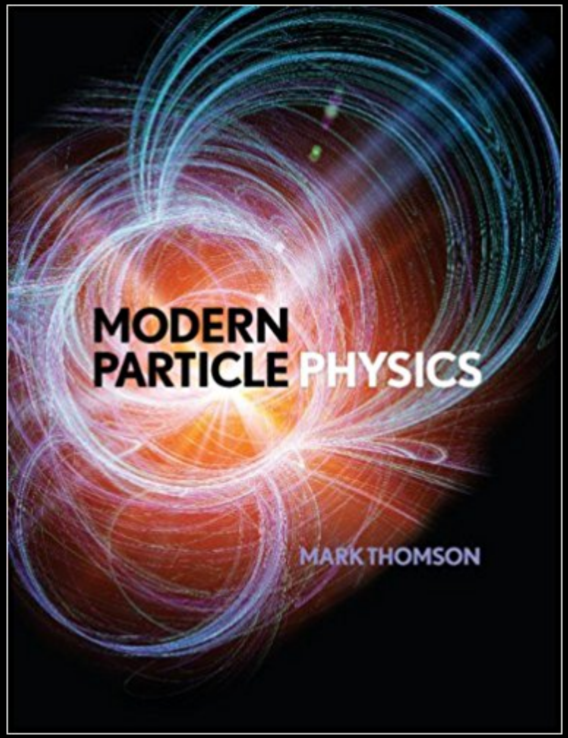
- I will be more than glad to receive your comments, suggestions, criticism and ideas on how to improve the course!

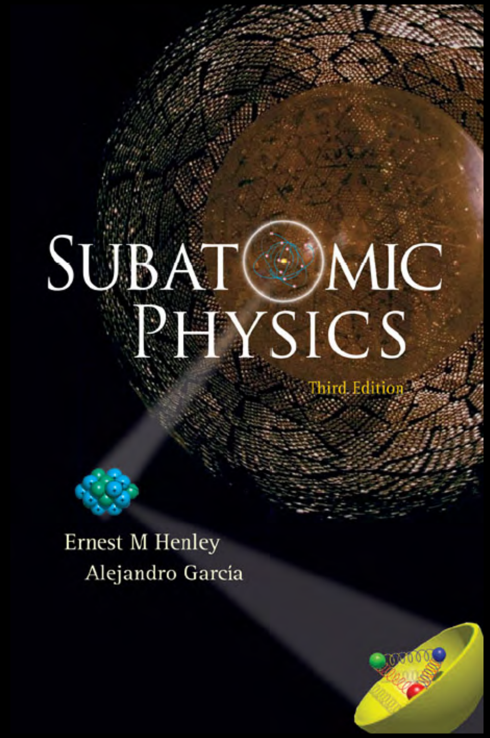
Literature

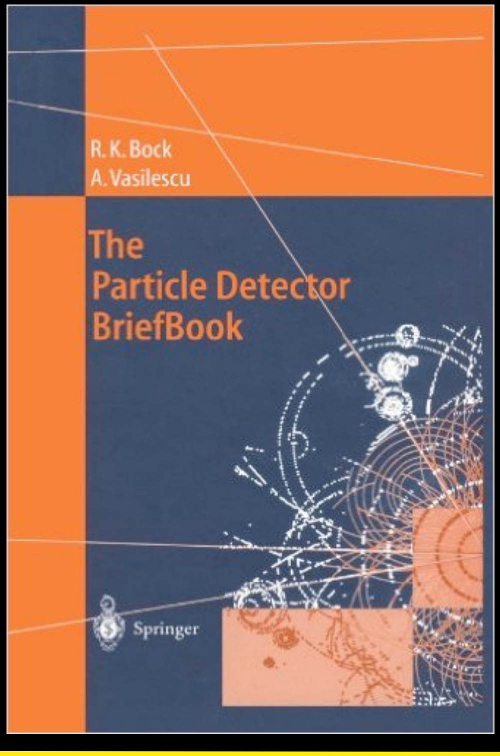
In my lectures I also use some, limited material from these sources

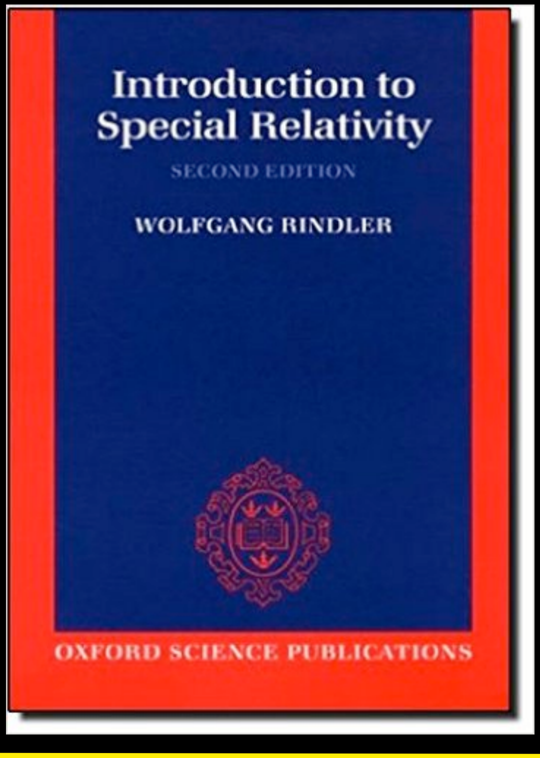
The lectures use material mainly from this book











Mode of operation

- Reading material
  - Distributed via blackboard (e.g. a couple of days) before each lecture
  - Meant to give you time to skim through if you want and get familiar with the topic
- Lectures
  - As self contained as possible
    - Even if you should have been familiar with a given topic, you won't feel it
  - Quite some time on the board (working out things…), but also lectures with slides
  - I try to trigger your interest…so please don't hesitate to ask/participate/answer
  - Expect some overlap with other courses…this is not to be considered negative
- Tutorials
  - The follow the topic discussed during the lecture
  - Homework should be handed in not later than one week from the assignment
- Communication: I send a summary of what is discussed after each lecture and give an indication of what the next lecture will be about + reading material

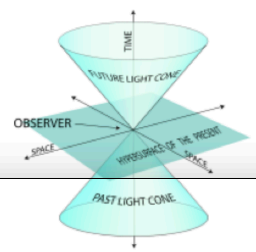
Material also posted on my web page

WELCOME RESEARCH PUBLICATIONS PRESENTATIONS TEACHING ▾ ALUMNI ▾ CONTACT

PANOS CHRISTAKOGLOU

Physics can be pretty simple...physicists can not

Bachelor level courses



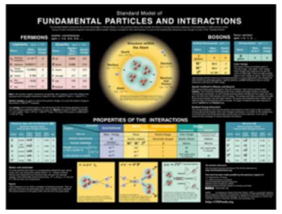
Introduction to special relativity

- The lectures were given at Utrecht University
- During this series of lectures, students are introduced to the following:
  - Concepts of special relativity
  - Time dilation
  - Space contraction
  - Causality
  - Velocity transformations
  - Four-vector notation
  - Covariant and contravariant notations
  - Invariant quantities
  - Proper time
  - Energy-momentum four-vectors
  - Relativistic collisions
- Lectures on special relativity

Office hours

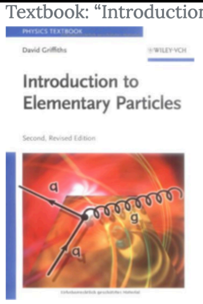
- Every **Tuesday** between **11:00 and 13:00 @ Nikhef** (Office N327)

- Every **Thursday** between **11:00 and 13:00 @UU** (Leonard S. Orsteinlaboratorium - Office 259)



Subatomic Physics

- Basic information
  - The course is part of the curriculum of the physics department of UU
  - It is given in the second semester to 3rd year bachelor students at UU
  - The lectures are given in Utrecht every Wednesday from 13:00 to 19:00 and Friday from 11:00 to 17:00, including the exercise sessions.
  - Prerequisites: Course on quantum mechanics
- Textbook: "Introduction to Elementary Particles", D. Griffiths



- Grading scheme
  - There is a mid-term exam usually scheduled on the 5th week.
  - In addition, the course has significant homework that allows you to get max 2 bonus points
  - The grade from the exams is calculated as the weighted average of the mid-term and the final exam with 40%-60% weight, respectively.
  - The final grade is estimated as the maximum between the grade from the exams and the weighted average of the grade from the exams and the homework with 80%-20% weight, respectively.
  - The grading scheme together with some basic examples on how this works practically can be found here.
- Reading material
  - Introduction
  - Special relativity and 4-vectors
  - Symmetries and conservation laws - slides
  - The particle zoo: types of particles and their properties - slides
  - Interaction of particles with matter - slides
  - Fermi's golden rule - slides
  - Introduction to gauge theories
  - QED and the E/M interactions - slides
  - Elastic scattering, form factors, charge distributions
  - QCD and the strong interactions - slides
  - GWS and the weak interactions
  - The Higgs mechanism
  - Nuclear and particle astrophysics - slides

Evaluation

- Very important for all courses so please take some time and participate
- Criticism is always welcome but it's effective if it is constructive
  - Textbook is good enough?
  - Improvements in the way lectures are given?
  - Ideas for modifications in the tutorial sessions?
  - Exam questions can be adjusted?
- I can assure you that all comments are considered quite seriously

• The exam should have been somewhat different than last year. All old exams can be found on A-Eskwdraat, so it will be more challenging if different questions are asked.

Action from my side

Exam questions and in general its nature was changed significantly (you can blame the students of previous years)

• Panos' lectures are very relaxed and they're just very nice to attend. I think Panos would make a great uncle.

Action from my side

…

Be aware of my sense of humour (or whatever that is)

Be present at the lectures!!!

The course in a nutshell

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

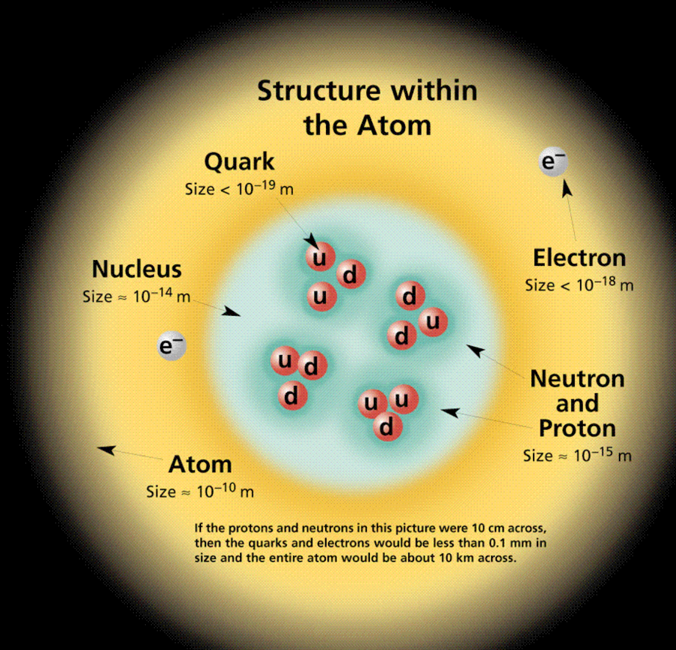
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and **W** and **Z** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons. There are about 120 types of baryons.

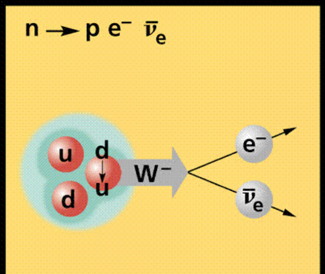
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons. There are about 140 types of mesons.

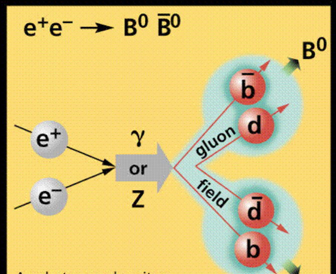
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

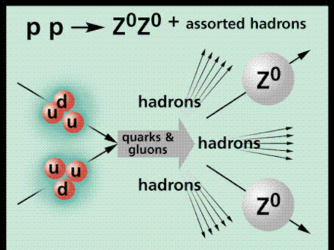
Figures
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

Distance scales…

~10fm = 10^{-14}m

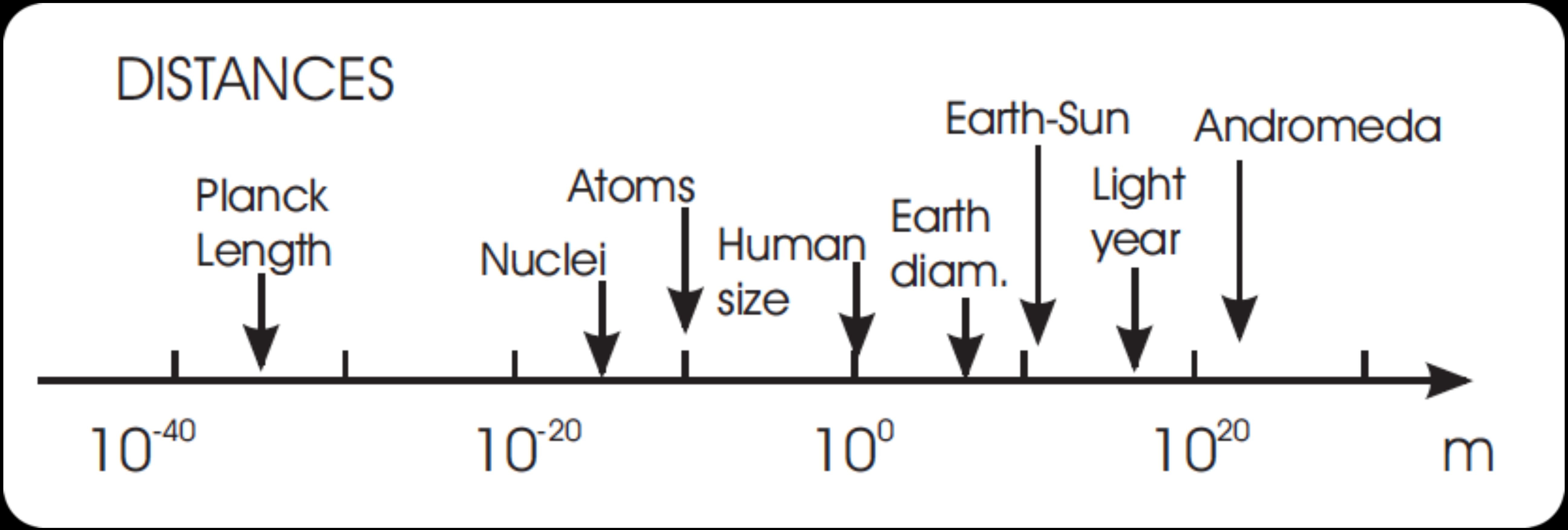
~12742 Km

~2.5x10^{6} light years

10^{-35}m

1.7m

~149.6x10^{6} Km



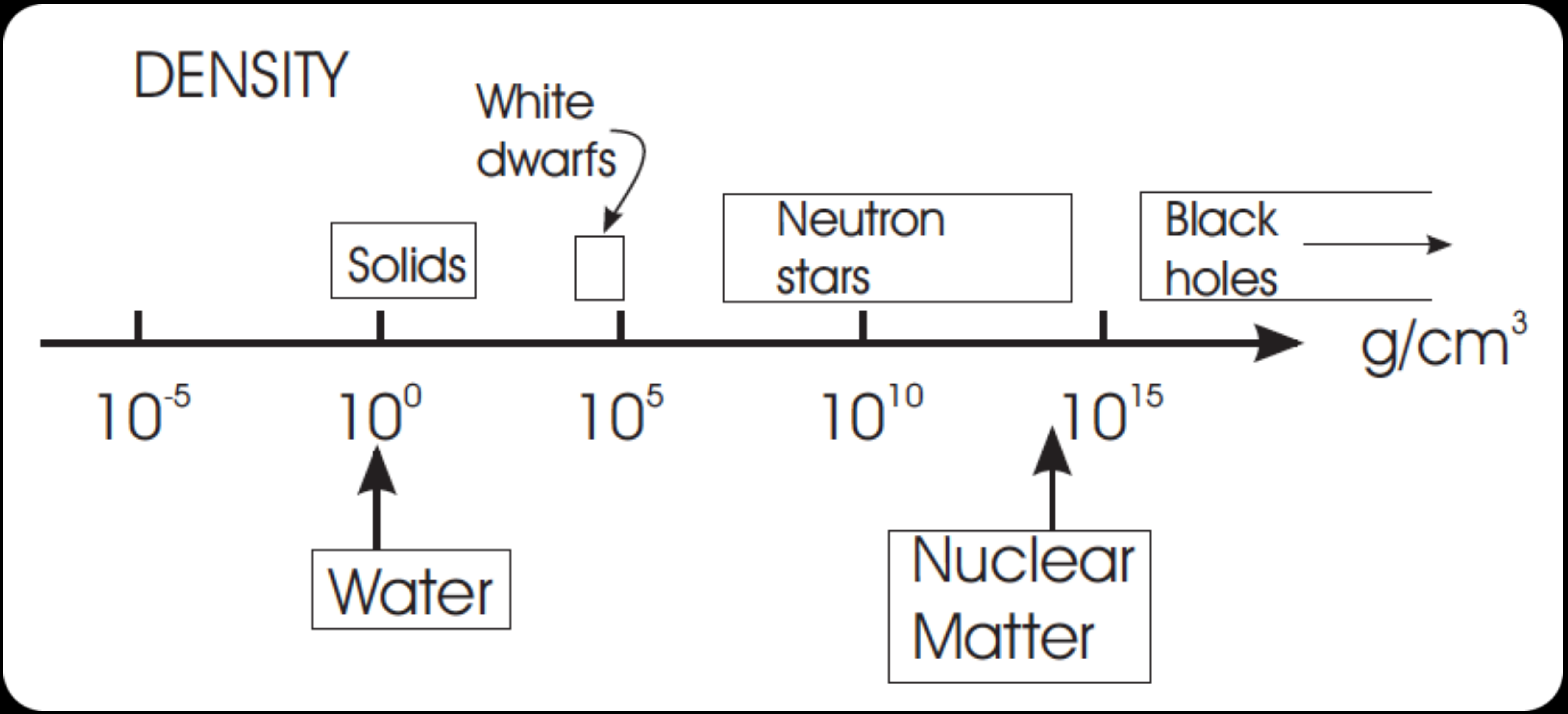
~20-250pm = 20-250x10^{-12}m

~9.46x10^{12} Km

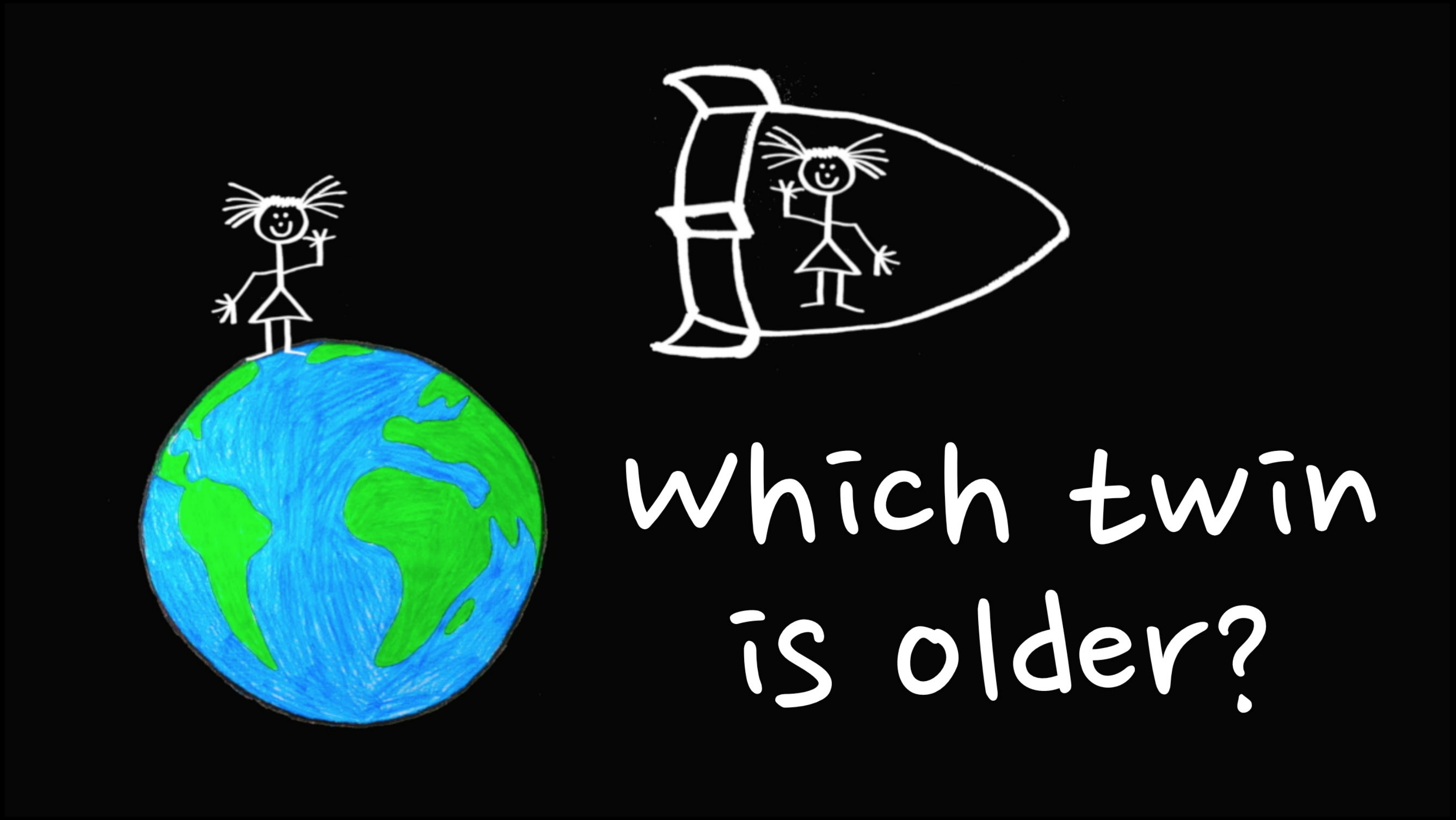
~12742 Km

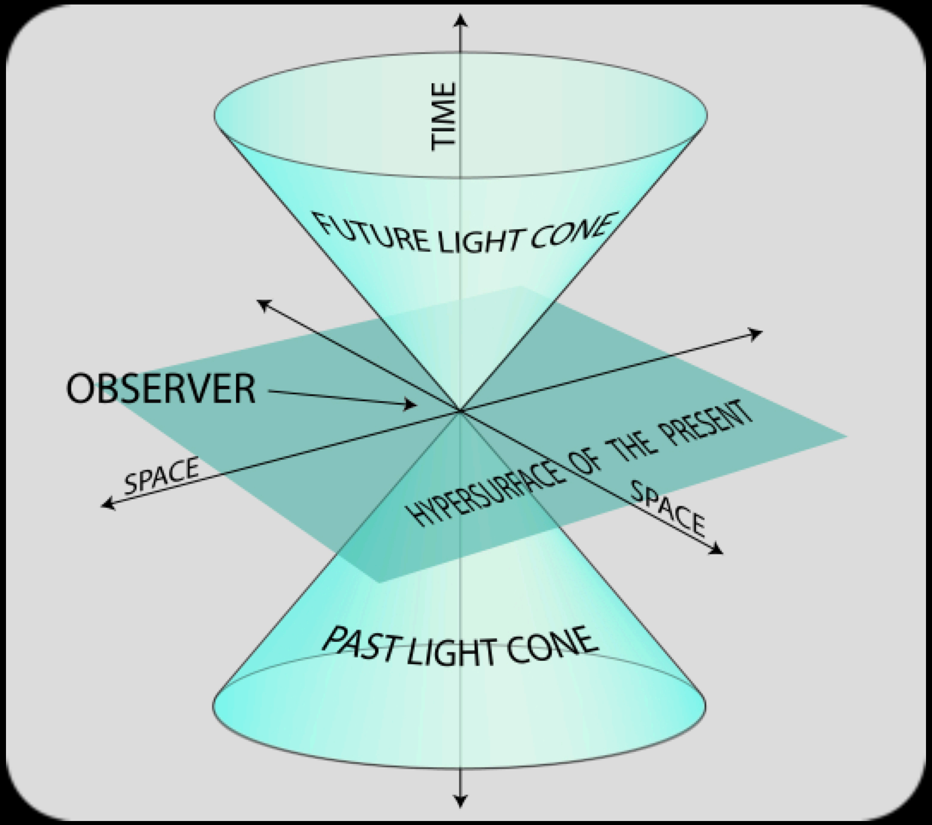
Density scales…

~10^9 Kg/m^3 ~10^{17} Kg/m^3



~10^{19} Kg/m^3


Which twin
is older?


TIME
FUTURE LIGHT CONE
OBSERVER
SPACE
HYPERSURFACE OF THE PRESENT
SPACE
PAST LIGHT CONE

Special relativity and 4-vectors

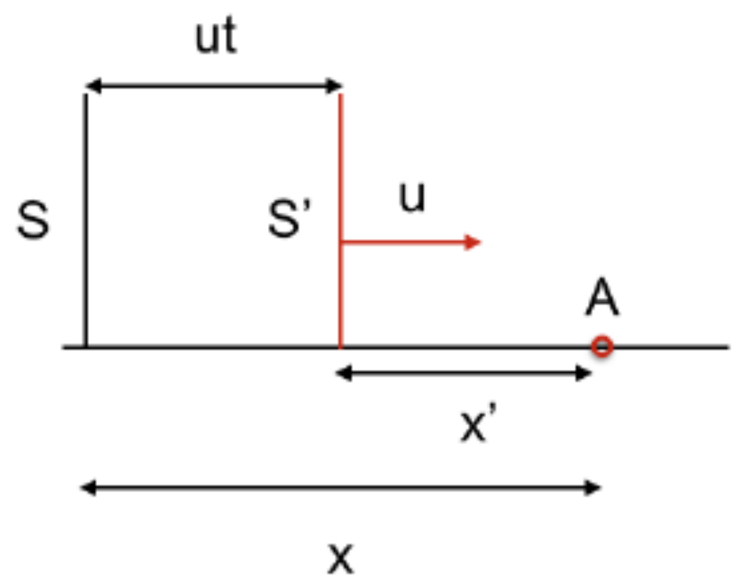


Fig. 1.1: A Galilean transformation between the two reference systems S and S'.

- ✓ To Lorentz transformations…

$$\Delta x' = \frac{\Delta x - u\Delta t}{\sqrt{1 - \frac{u^2}{c^2}}}$$

$$\Delta t' = \frac{\Delta t - \frac{u}{c^2}\Delta x}{\sqrt{1 - \frac{u^2}{c^2}}}$$

- ✓ And causality…

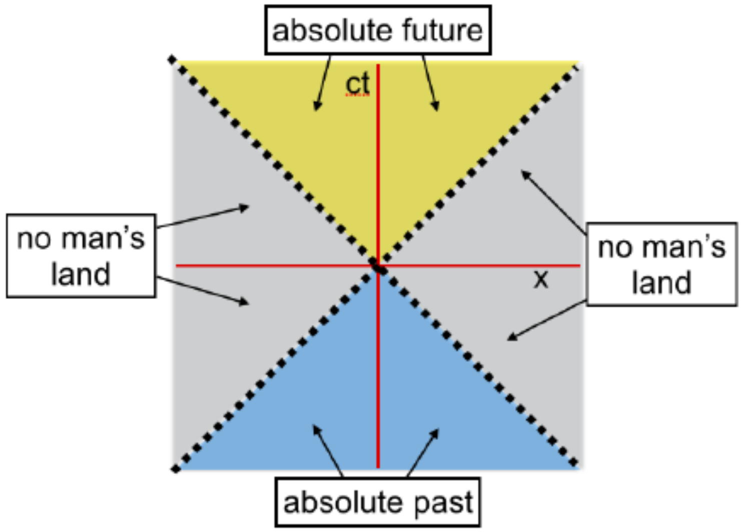


Fig. 1.3: The light cone in special relativity.

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4-vectors

- Lorentz transformations…with 4-vectors

$$x^{\mu'} = \Lambda^{\mu}_{\nu} x^{\nu}$$

- Higher order tensors

$$S^{\mu\nu'} = \Lambda^{\mu}_{\kappa}\Lambda^{\nu}_{\sigma}S^{\kappa\sigma}$$

$$t^{\mu\nu\lambda'} = \Lambda^{\mu}_{\kappa}\Lambda^{\nu}_{\sigma}\Lambda^{\lambda}_{\tau}S^{\kappa\sigma\tau}$$

- 4-momentum

$$p^{\mu} = \begin{pmatrix} E/c \\ \mathbf{0} \end{pmatrix} = \begin{pmatrix} mc \\ \mathbf{0} \end{pmatrix}$$

$$p^{\mu} = \begin{pmatrix} E/c \\ \mathbf{P} \end{pmatrix}$$

- Calculations for relativistic collisions…

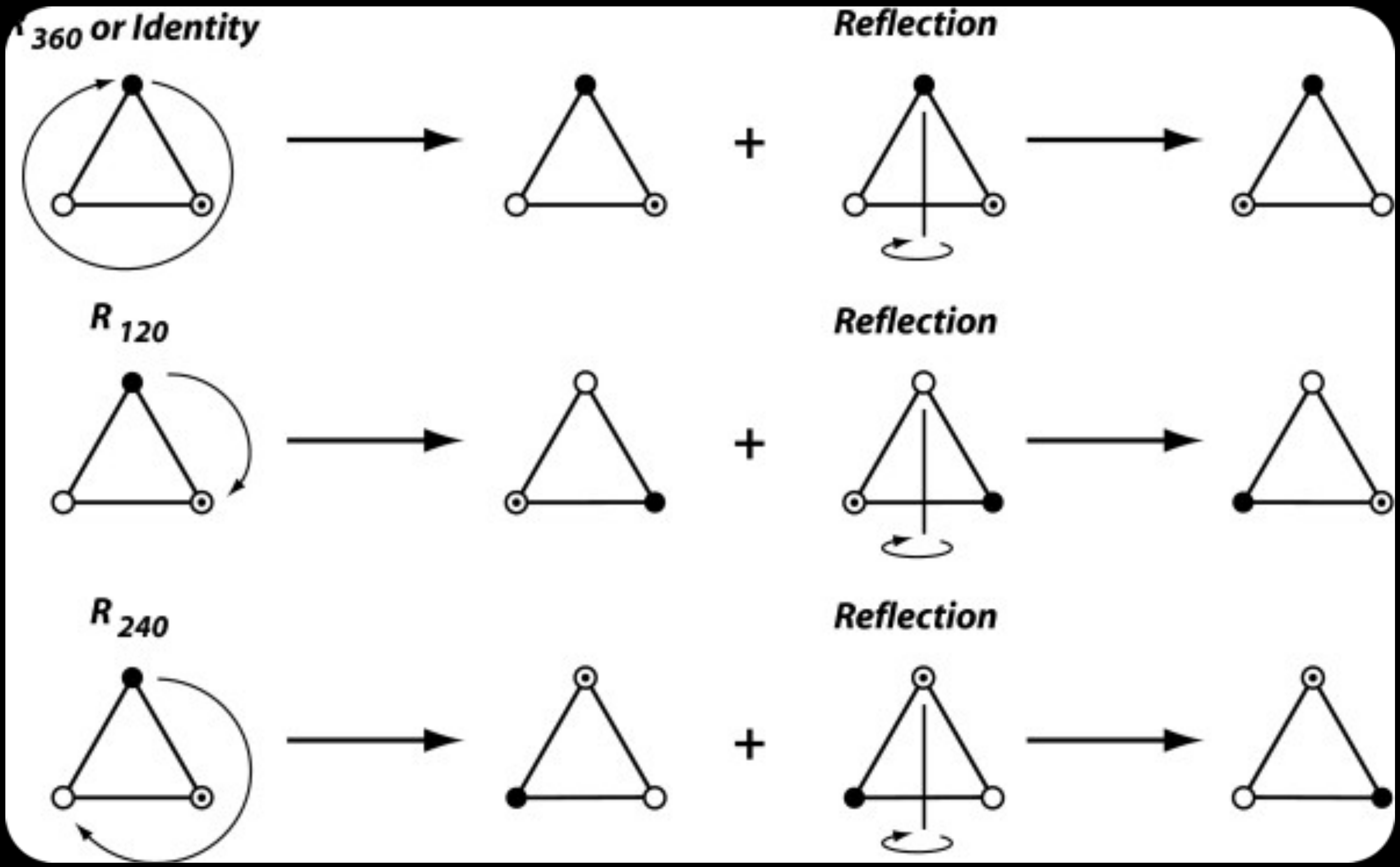
$$(k+P_0)^{\mu} = P_1^{\mu} \Leftrightarrow (k+P_0)_{\mu}(k+P_0)^{\mu} = P_{1\mu}P_1^{\mu}$$

$$\Leftrightarrow P_{0\mu}P_0^{\mu} + k_{\mu}k^{\mu} + 2k_{\mu}P_0^{\mu} = m'^2c^2$$

$$\Leftrightarrow m^2c^2 + 0 + 2\frac{\omega}{c}m = m'^2c^2$$

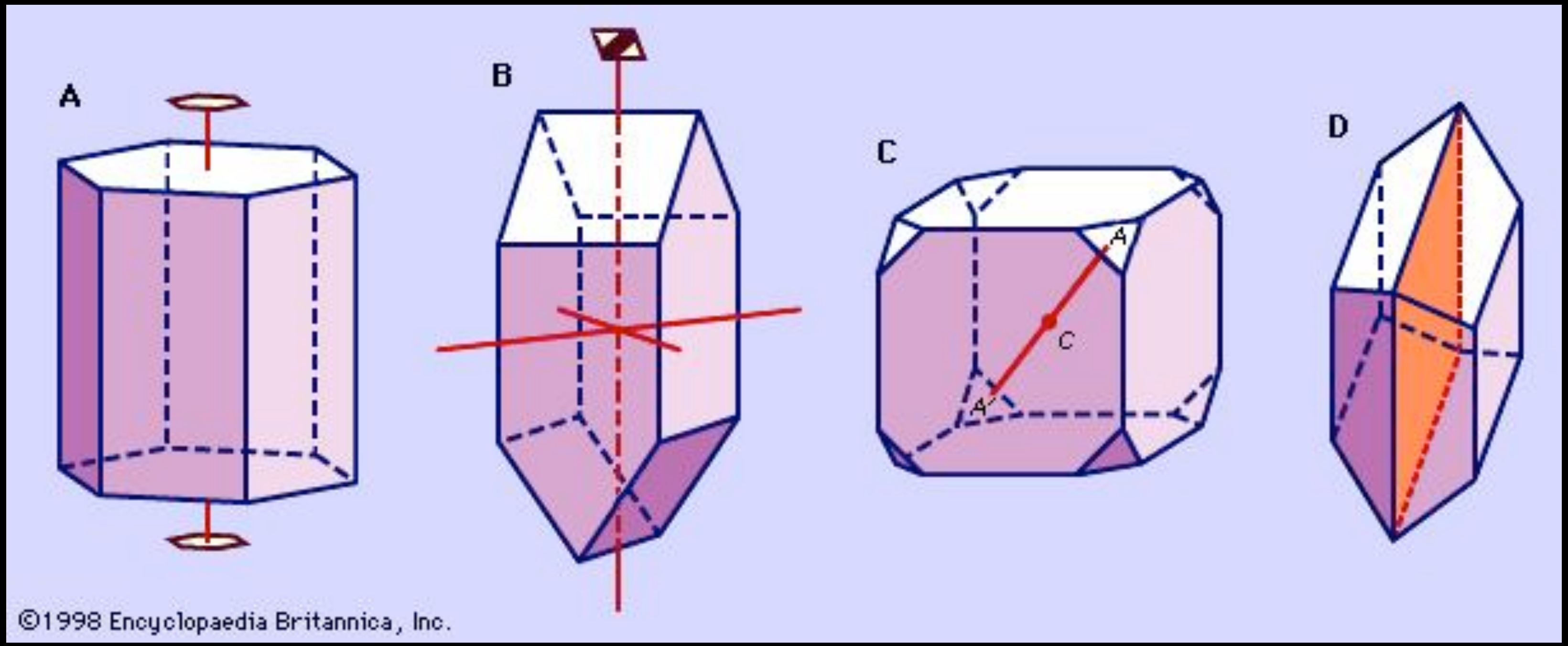
$$\Leftrightarrow m'^2 = m^2 + 2\frac{kc}{c^2}m = m^2\left(1 + 2\frac{k}{mc}\right)$$

$$\Leftrightarrow m' = m\sqrt{1 + \frac{2k}{mc}}$$


R 360 or Identity
Reflection
+
R 120
Reflection
+
R 240
Reflection
+

Symmetries

- Symmetries and invariances are important notions in physics
  - They describe how a system remains unaltered under a given transformation
- We will focus on dynamical symmetries of motion and not on static symmetries e.g. as in crystals
- Noether's theorem connects symmetries with conservation laws
  - "Every symmetry in nature yields a conservation law and inversely every conservation law reveals an underlying symmetry
  - Momentum conservation: invariance under a translation in space
  - Angular momentum conservation: invariance under rotation in space



Emmy Noether (1882 - 1935)

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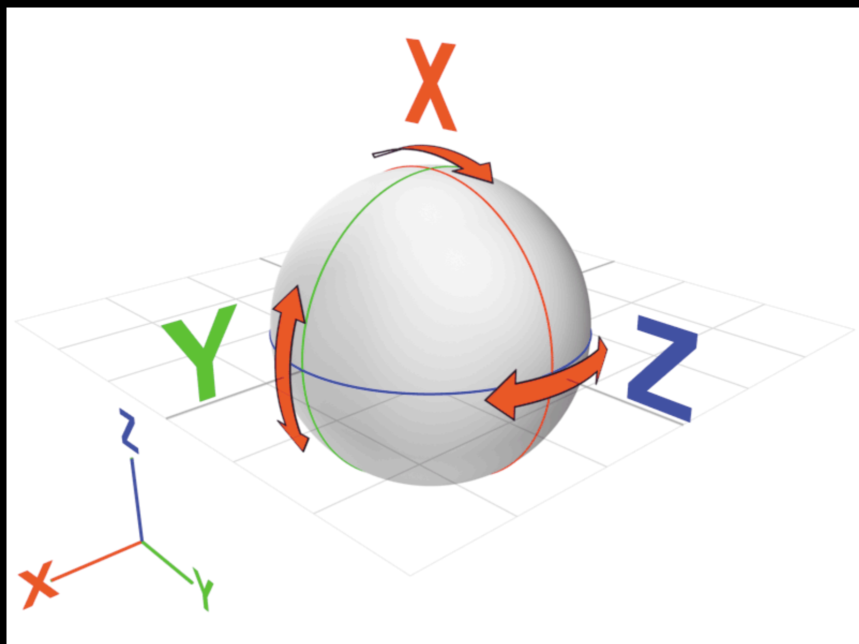
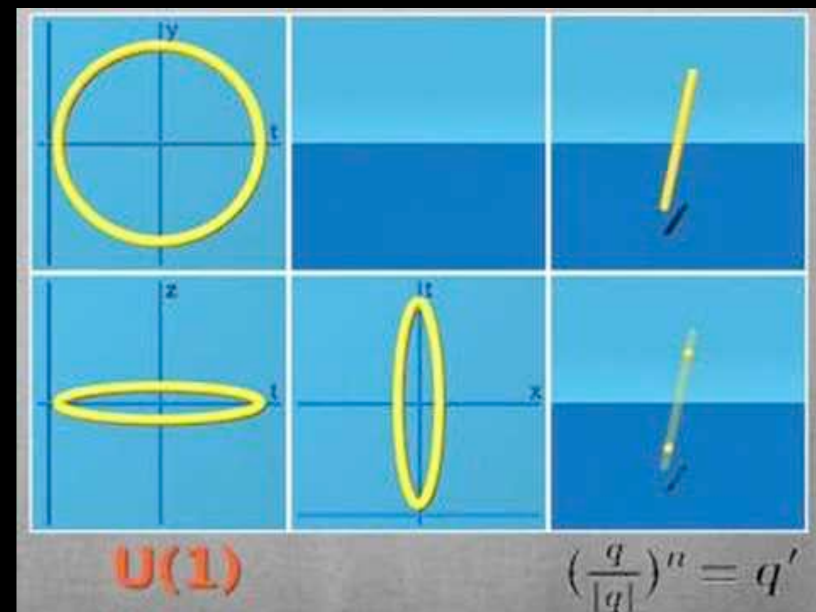
Groups

SO(3): rotations in 3D space



U(1): transformations in hypercharge space → QED



SU(2): rotations in weak isospin space → weak

$$\sigma_1 = \sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$
$$\sigma_2 = \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$
$$\sigma_3 = \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

SU(3): rotations in colour space → QCD

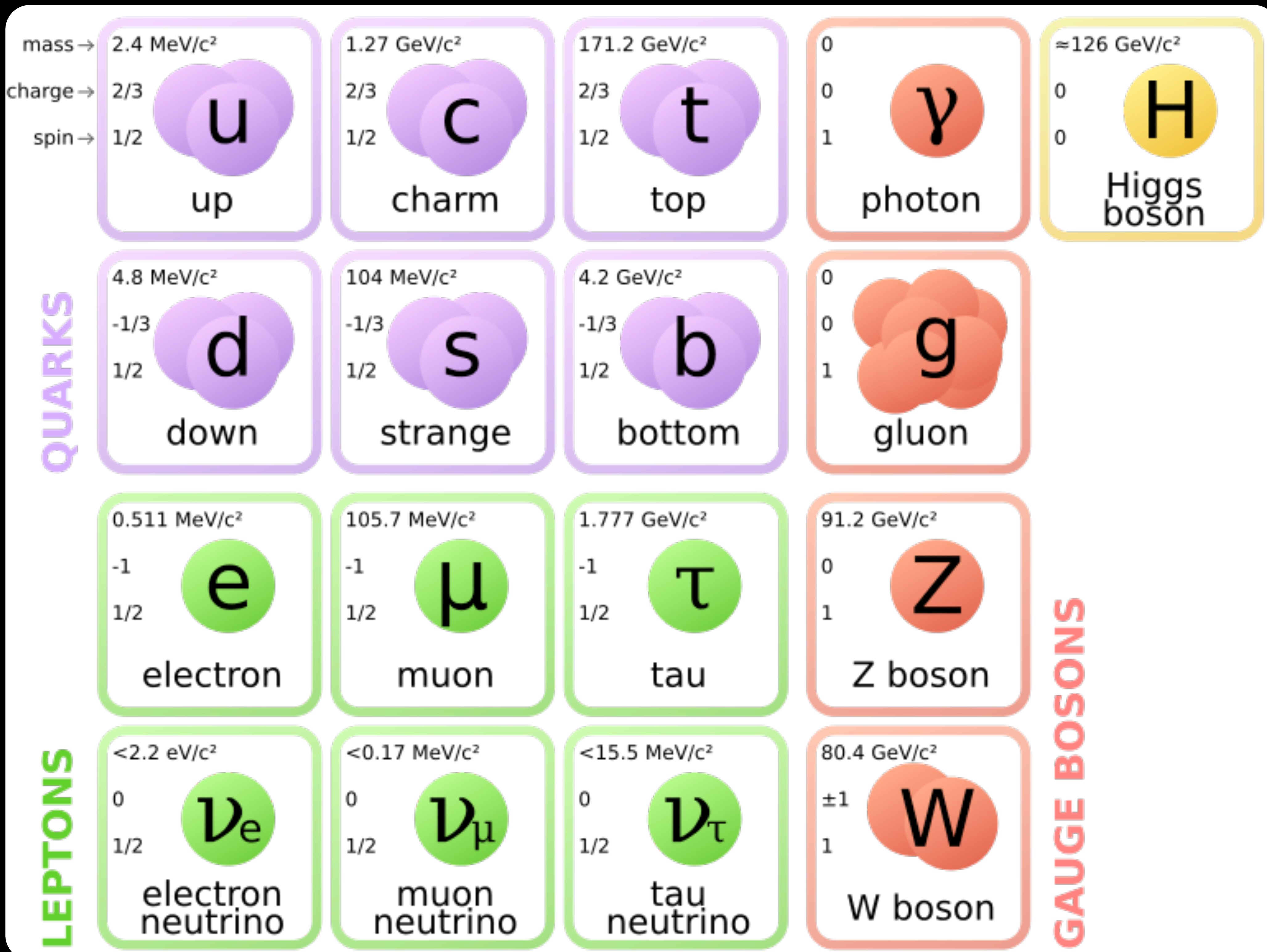
$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

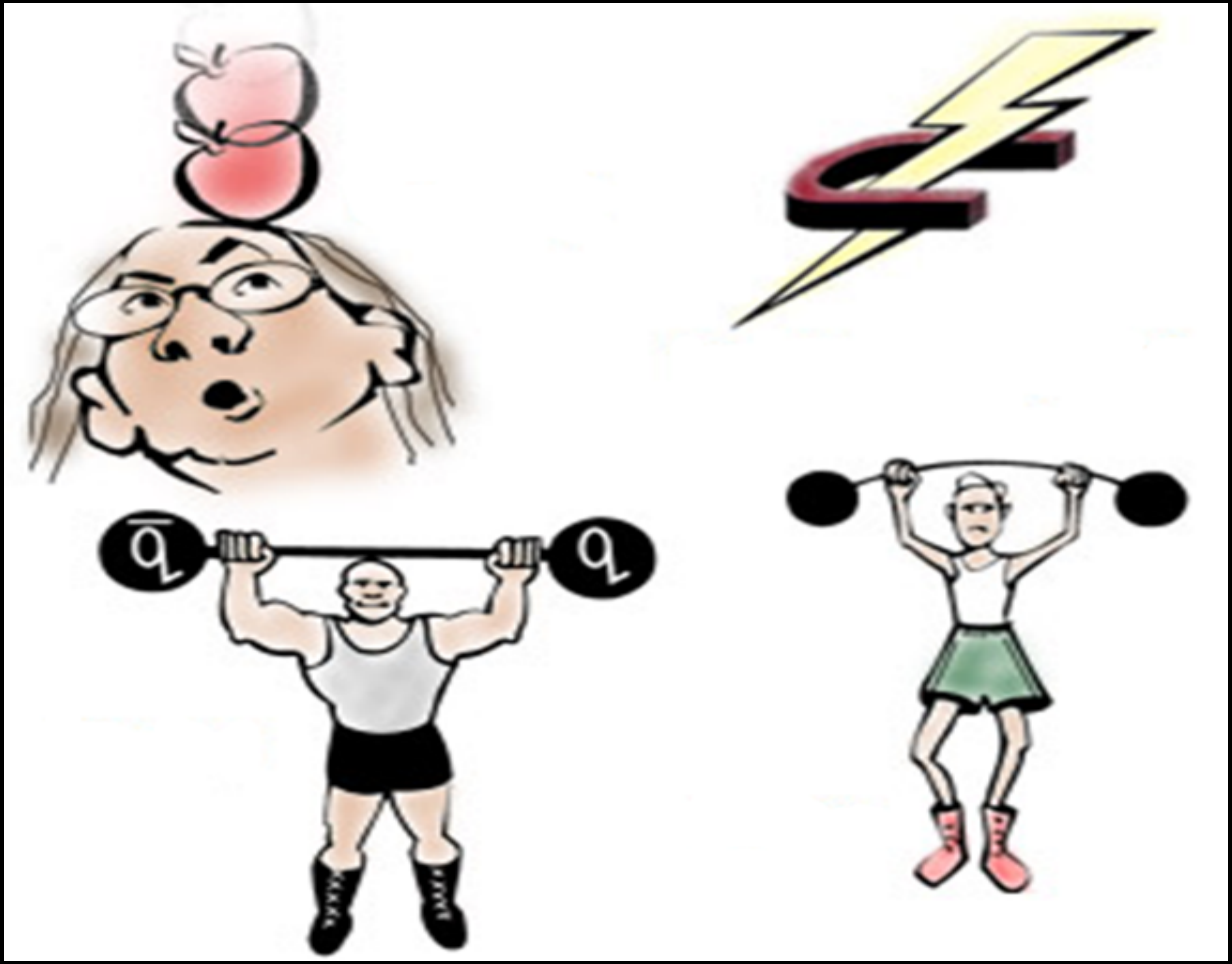
$$\lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \quad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}.$$

Chapter 4: Particle zoo

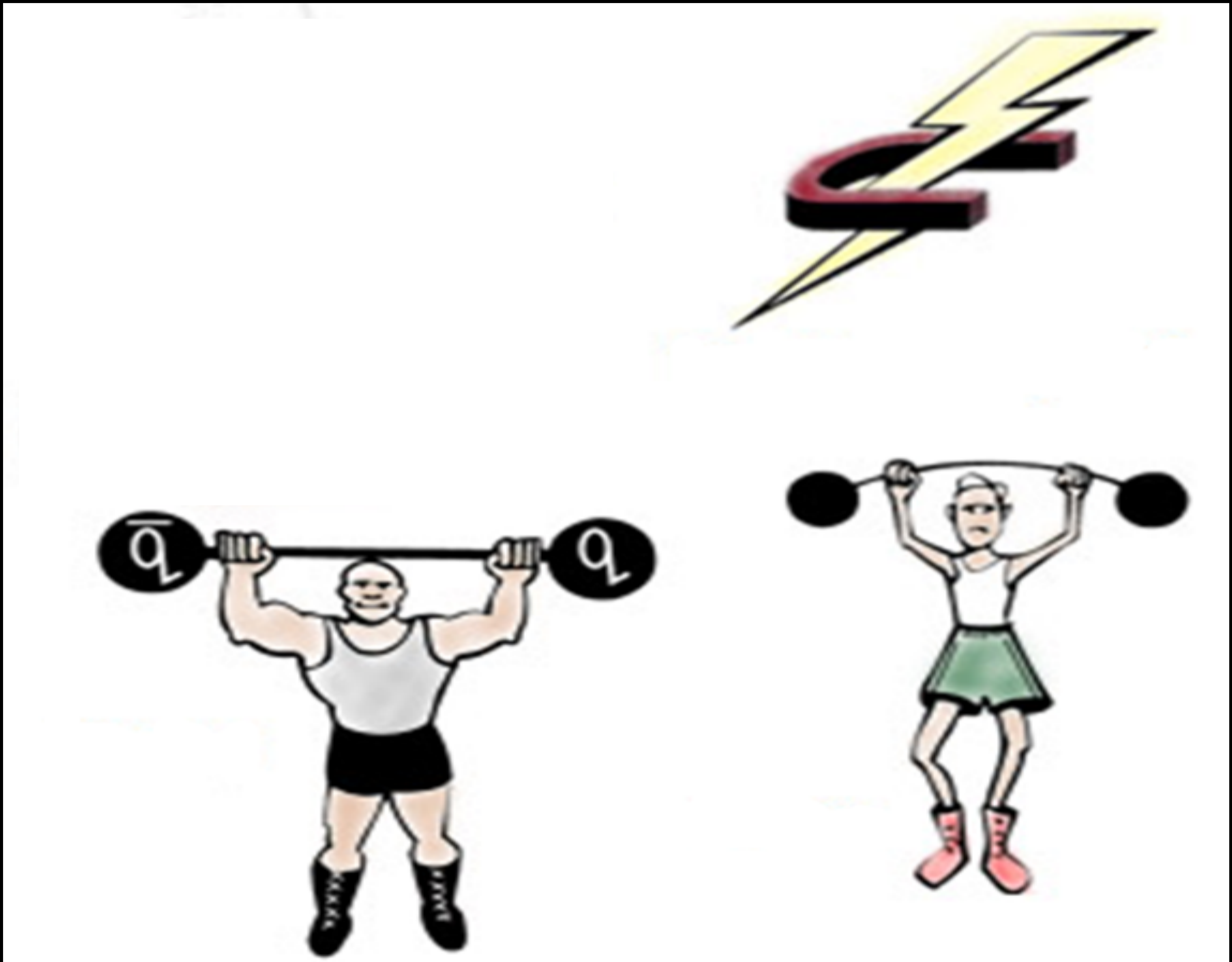
Periodic table of particle physics

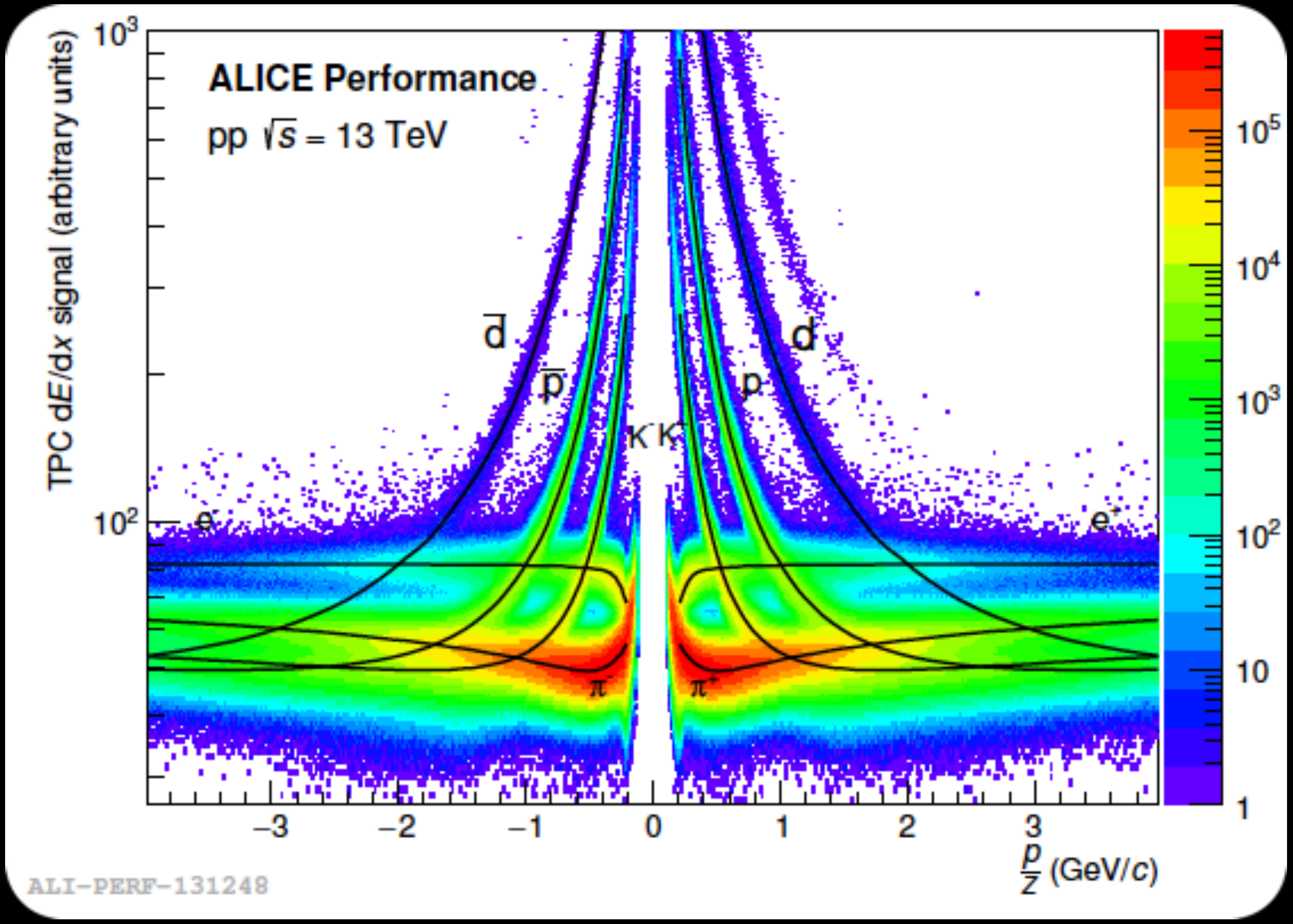


Forces and mediators



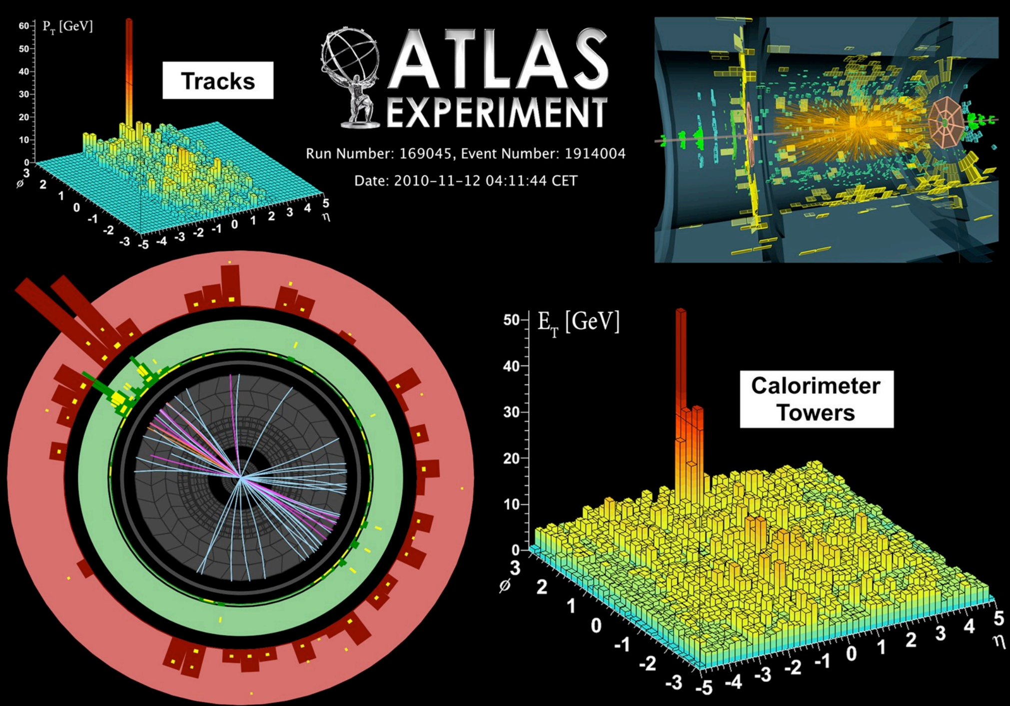
Forces and mediators

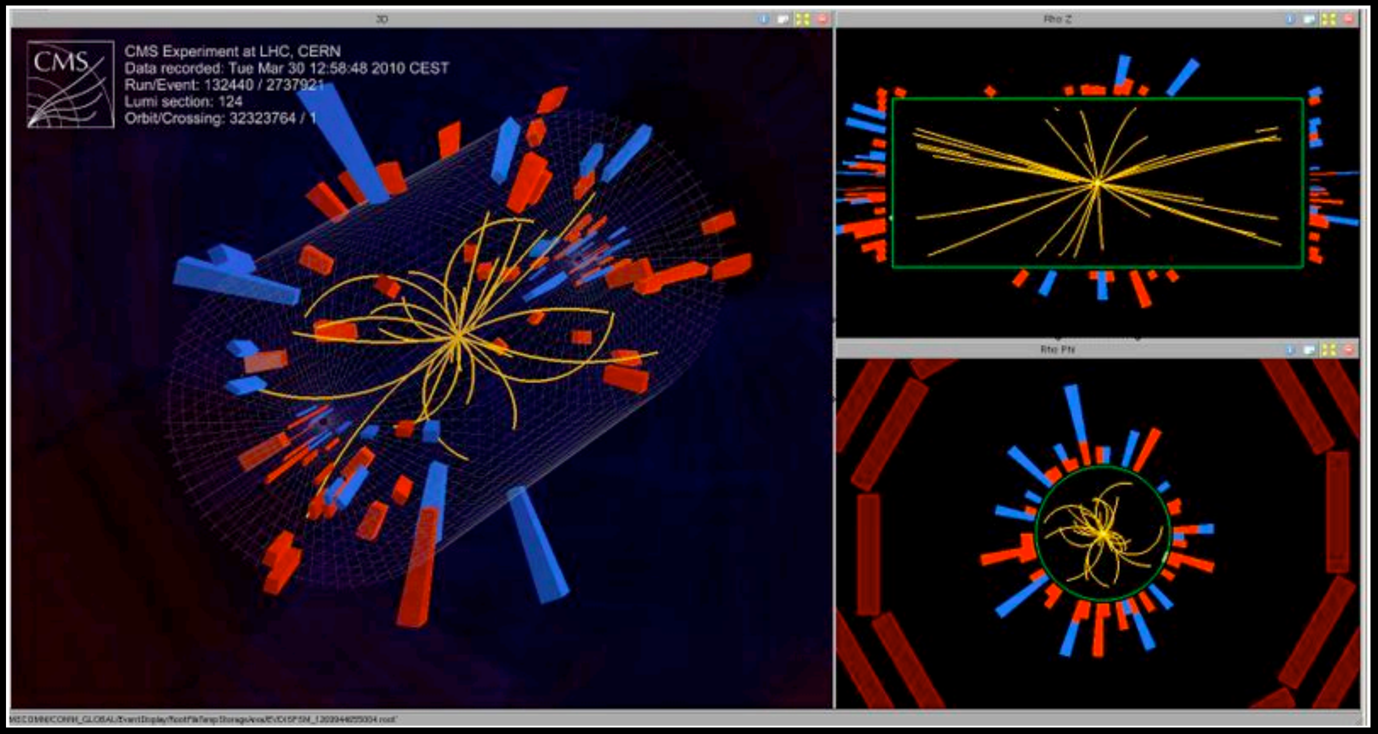


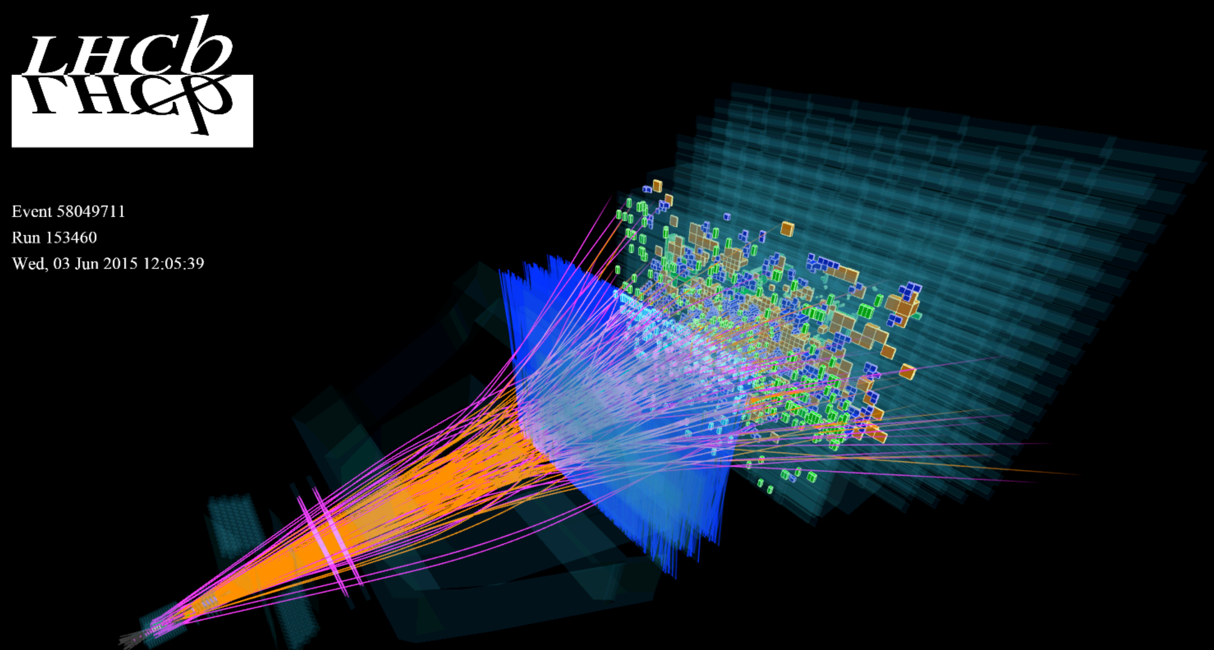

ALICE Performance
pp √s = 13 TeV
TPC dE/dx signal (arbitrary units)
p/z (GeV/c)
ALI-PERF-131248

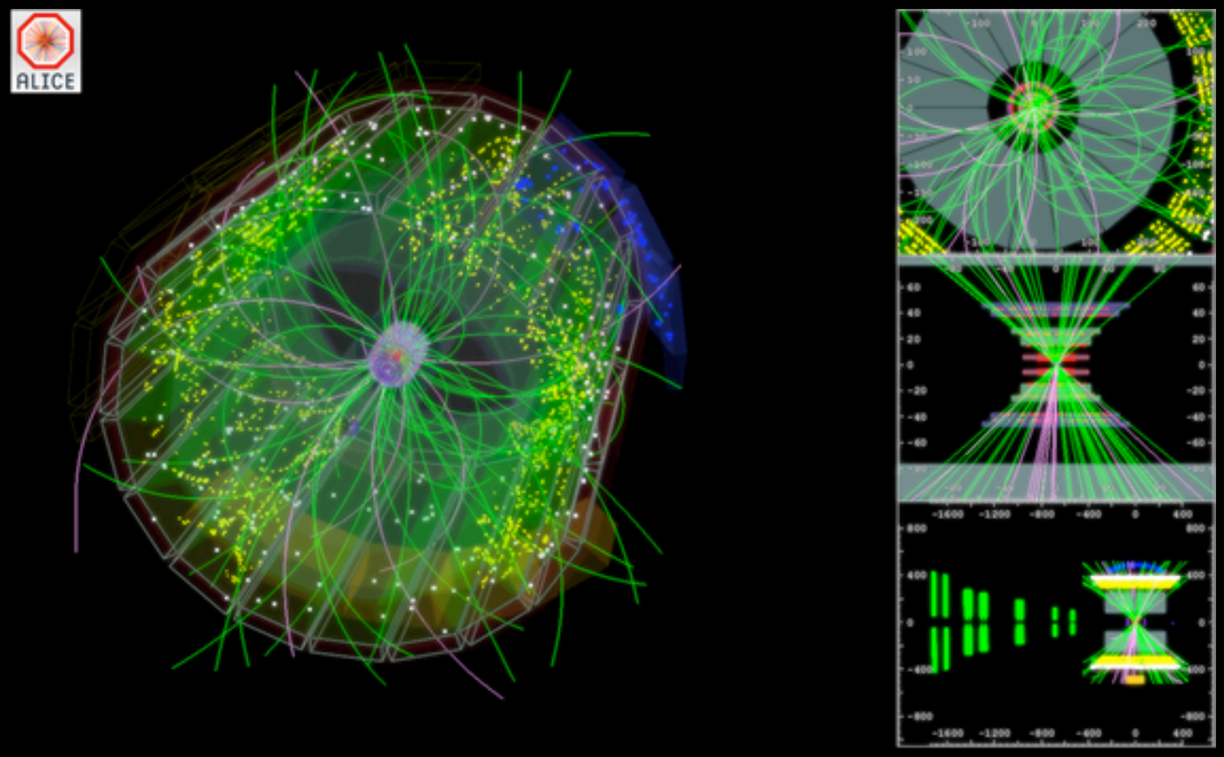
Particle accelerators

Particle detectors (pp collisions ➡ small number of particles)



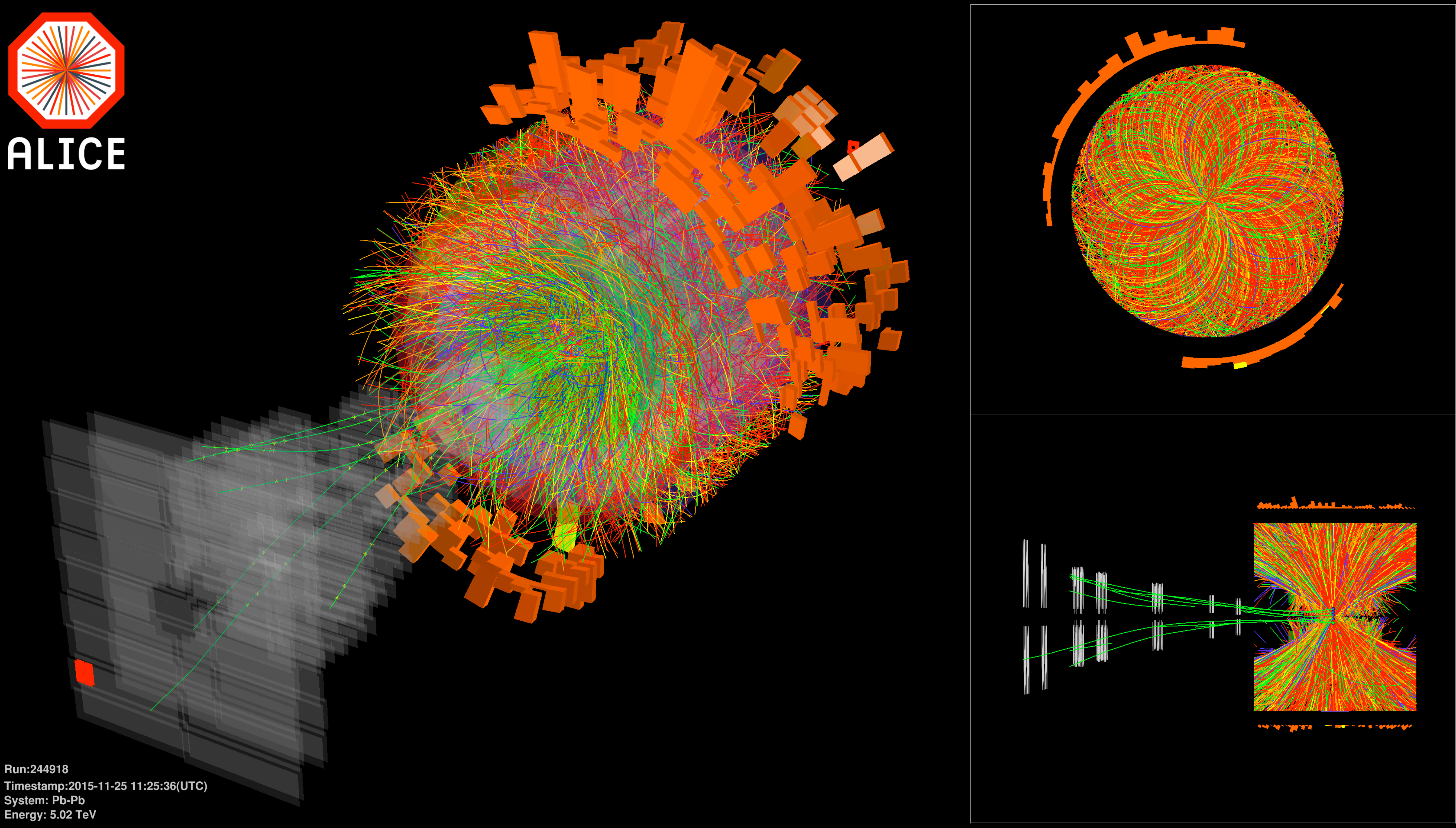




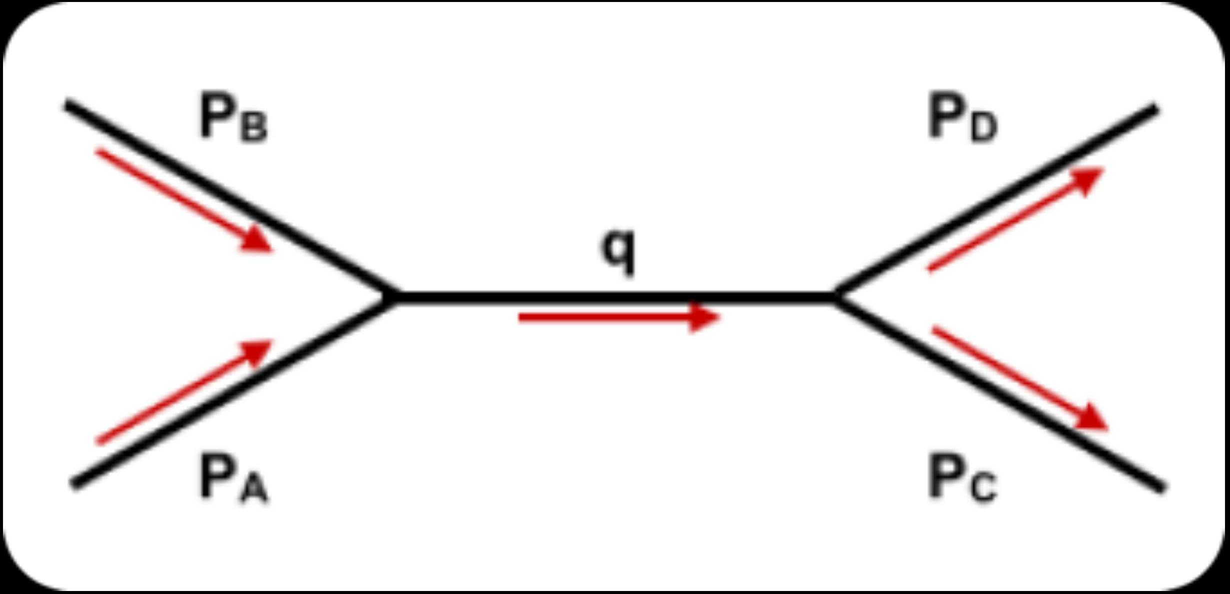


Particle detectors (Pb-Pb collisions ➡ large number of particles)

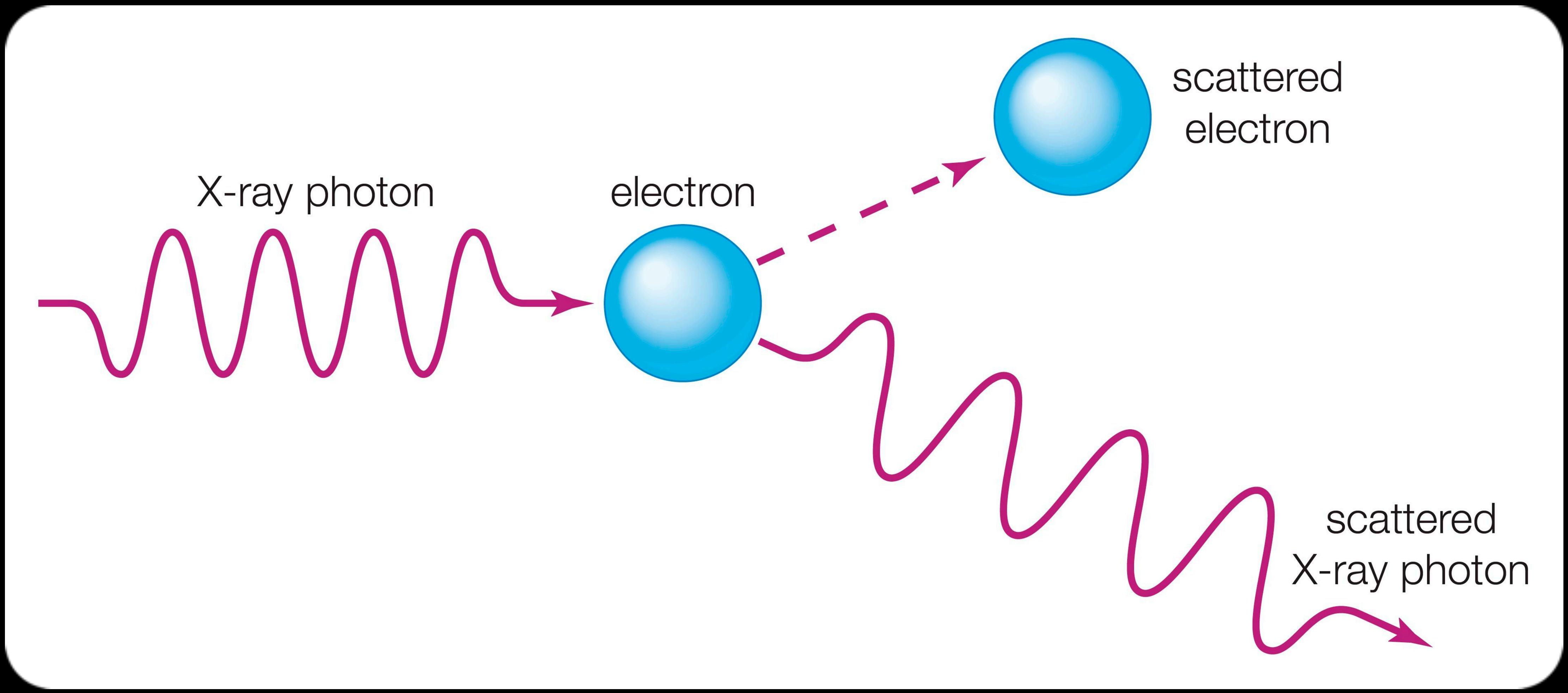
ALICE



$$(\text{transition rate}) = \frac{2\pi}{\hbar}|M_{if}|^2 \times (\text{phase space factor})$$



	Lagrangian density	Euler-Lagrange equation	Equation of motion
	$\mathcal{L}_{KG}=\frac{1}{2}(\partial_\mu\Phi)(\partial^\mu\Phi)-\frac{1}{2}m^2\Phi^2$		$(\Box+m^2)\Phi=0$
Spin-1/2 field	$\mathcal{L}_{Dirac}=i\overline{\Psi}\gamma_\mu\partial^\mu\Psi-m\overline{\Psi}\Psi$	$\partial_\mu\left(\frac{\partial\mathcal{L}}{\partial(\partial_\mu\Phi)}\right)-\frac{\partial\mathcal{L}}{\partial\Phi}=0$	$(i\gamma_\mu\partial^\mu-m)\Psi=0$ $(i\gamma_\mu\partial^\mu+m)\overline{\Psi}=0$
Spin-1 field	$\mathcal{L}_{Proca}=-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}+\frac{1}{2}M^2A_\mu A^\mu$		$(\Box+M^2)A^\mu-\partial^\mu(\partial_\nu A^\nu)=0$


X-ray photon
electron
scattered
electron
scattered
X-ray photon

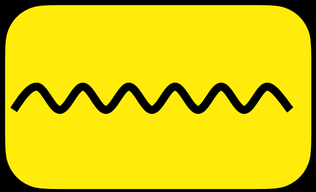
Symmetries and gauge tranformations (QED)

Conserved quantities → Charge: ψ

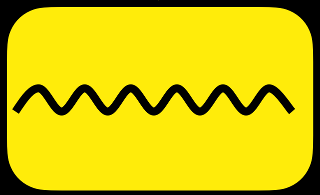
Gauge transformation → $\Psi \to \Psi' = e^{i\alpha}\Psi$

Symmetry group → U(1) (QED)

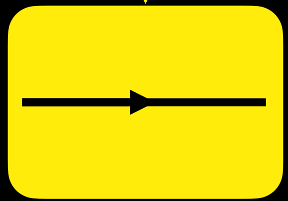
Field → A_μ (photon)



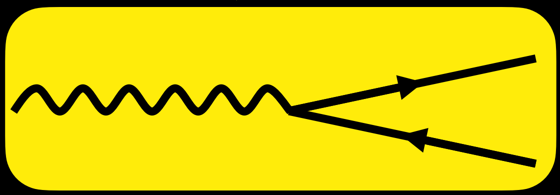
$$\mathcal{L}_{QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\,(i\gamma_\mu\partial^\mu - m)\,\psi - qA_\mu\,\bar{\psi}\,\gamma^\mu\psi$$



Free photon field A^μ

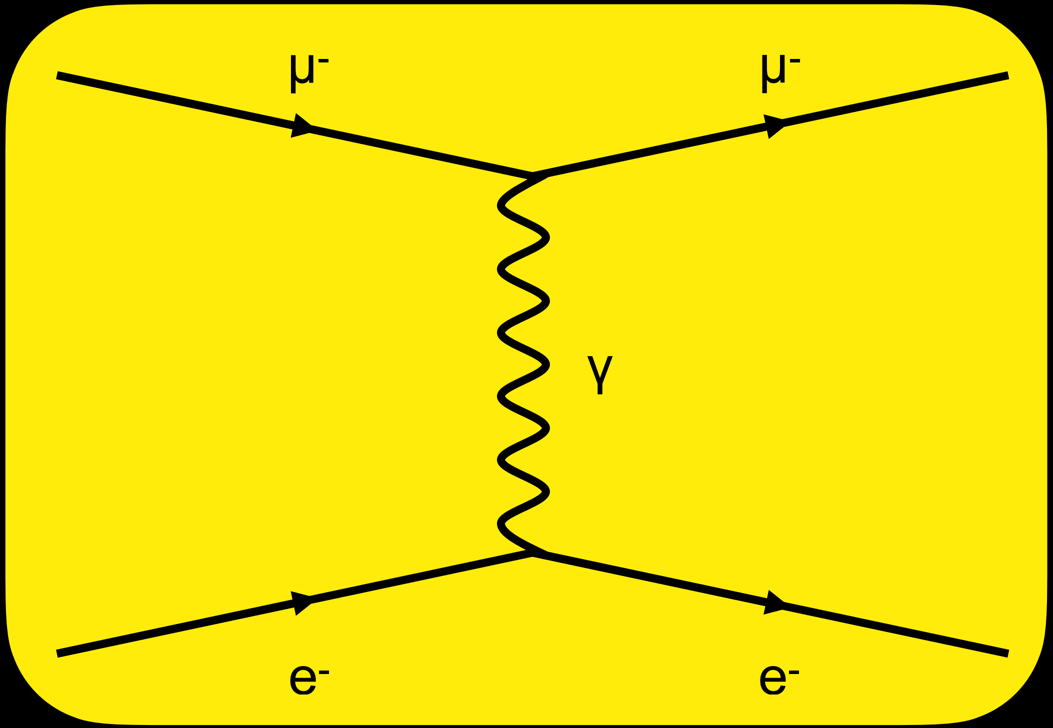


Fermion ψ with mass m

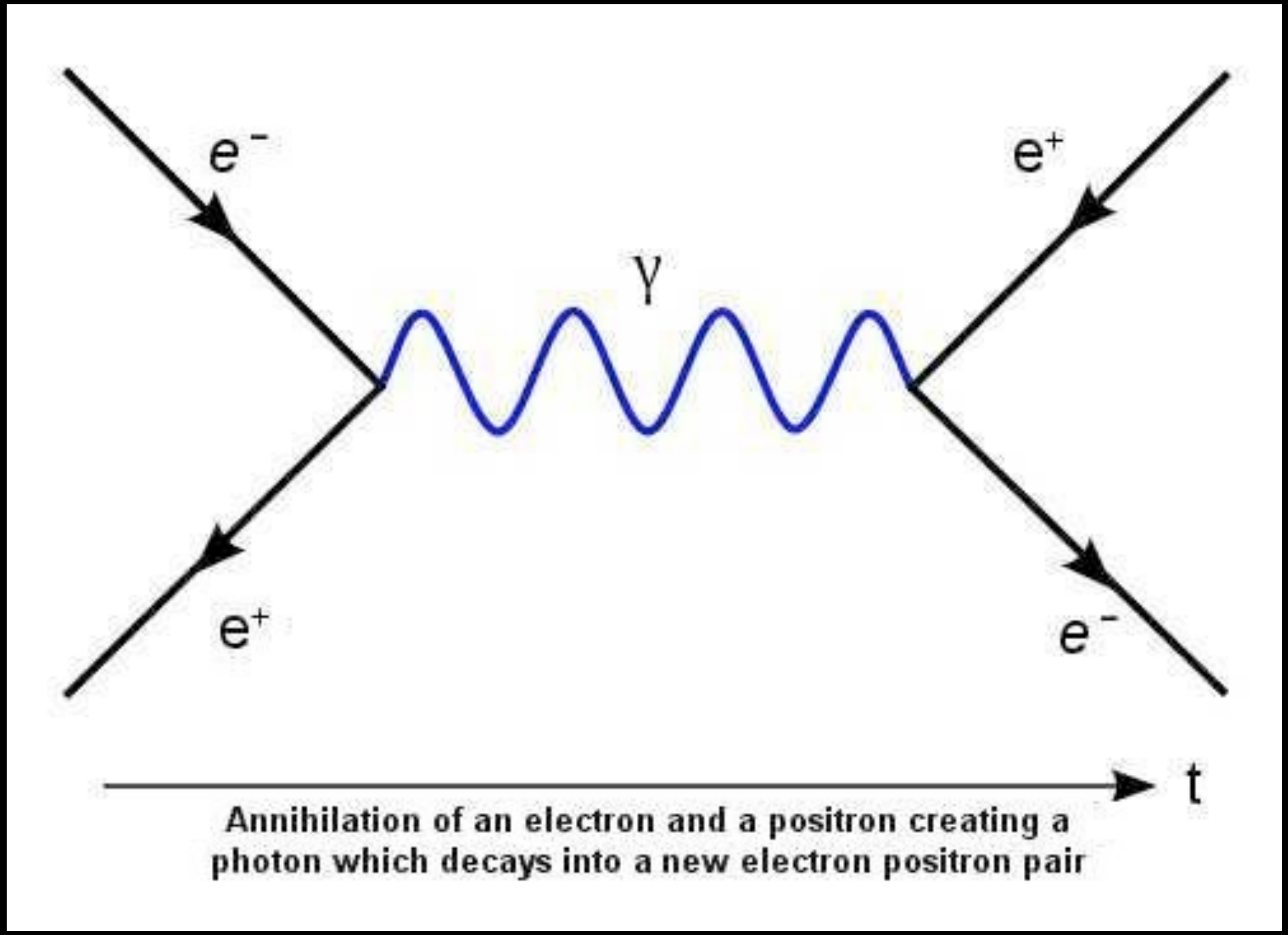


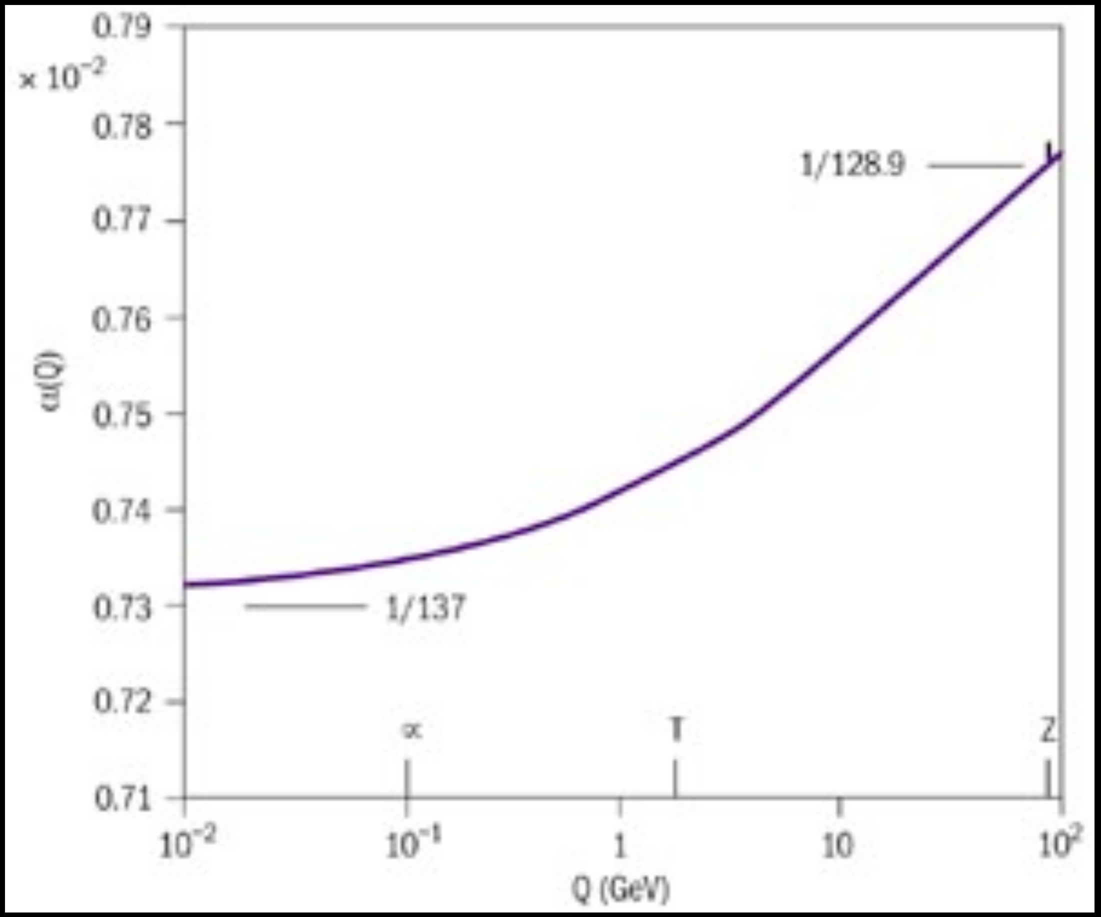
Interaction with coupling α

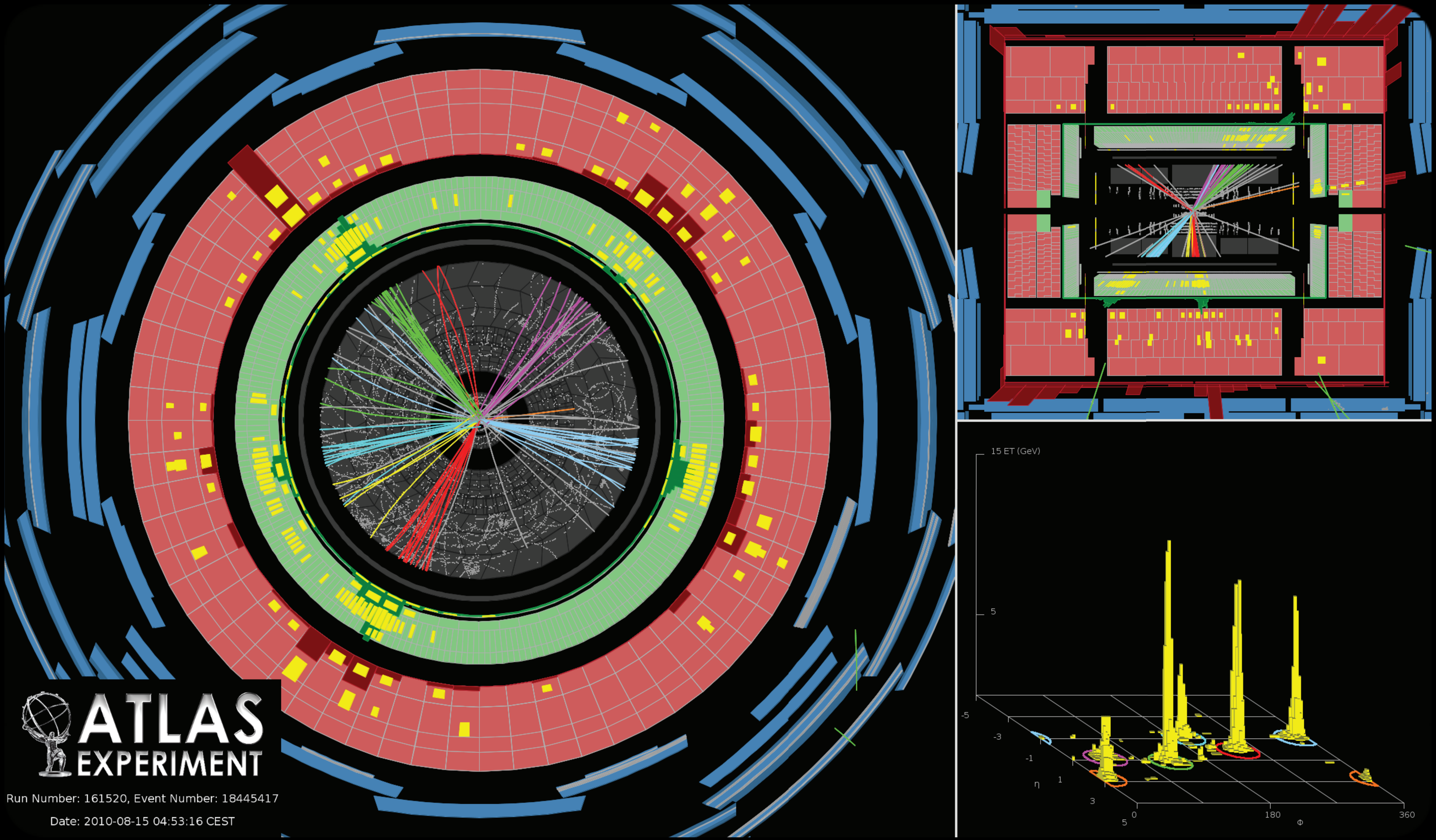
e-μ scattering



Quantum ElectroDynamics (QED)



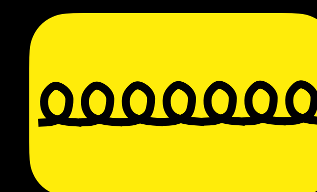


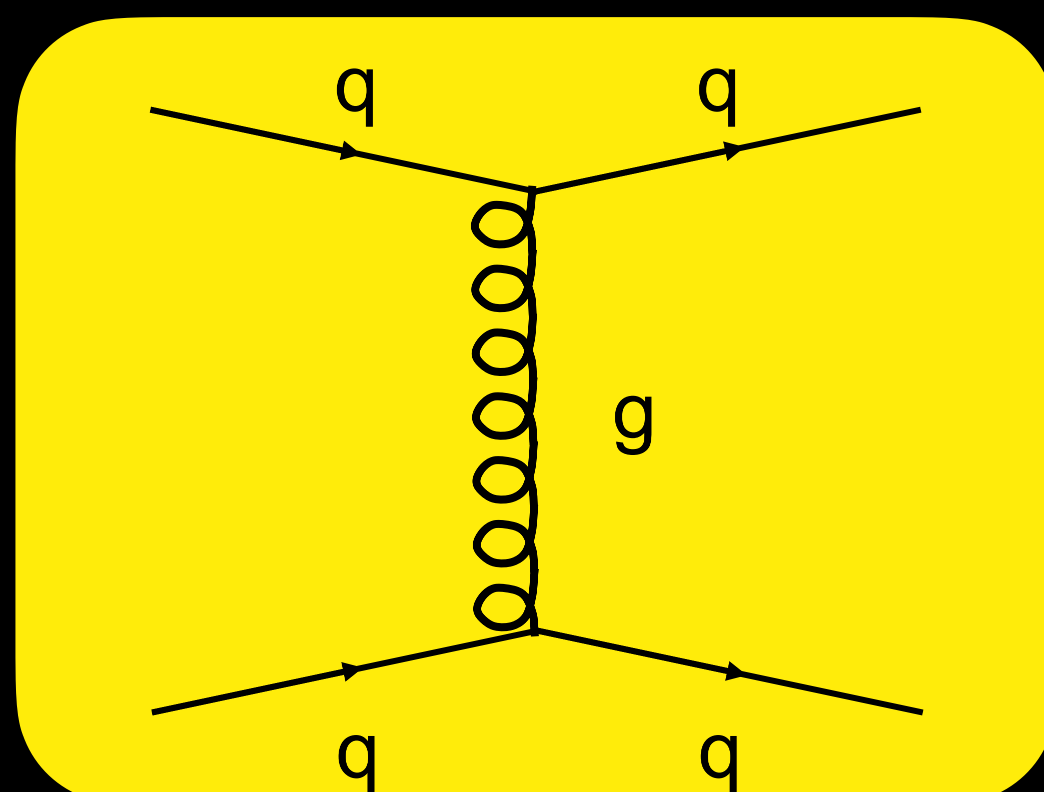

ATLAS
EXPERIMENT
Run Number: 161520, Event Number: 18445417
Date: 2010-08-15 04:53:16 CEST
15 ET (GeV)
5
η
Φ
0
180
360

Symmetries and gauge transformations (strong)

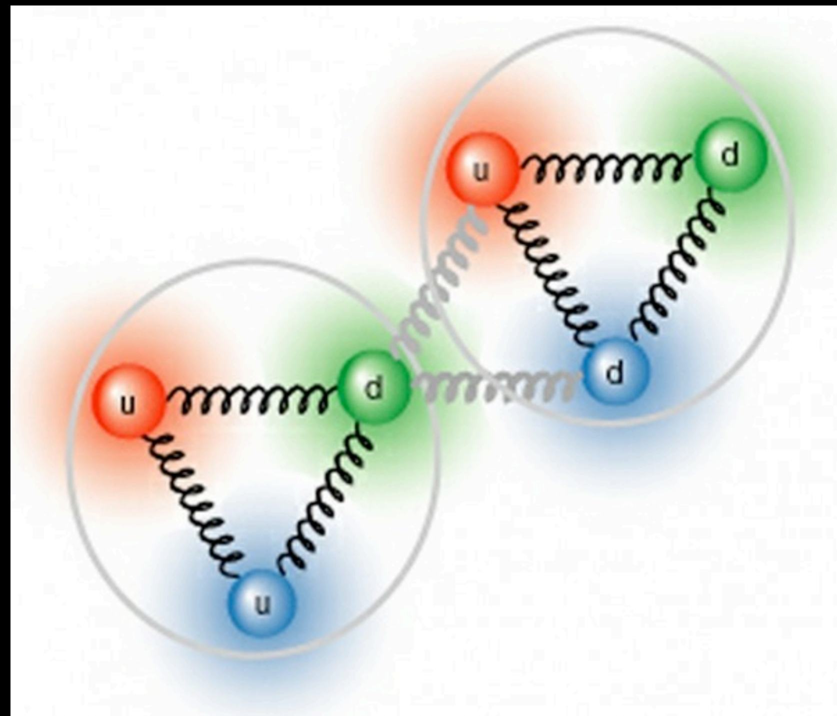
Conserved quantities	Gauge transformation	Symmetry group	Field
Colour	$\Psi \rightarrow \Psi' = e^{\frac{i}{2}\sum_{i=1}^{8}\theta_a \lambda_a}\Psi$	SU(3) (QCD)	A_μ (8 gluons g)

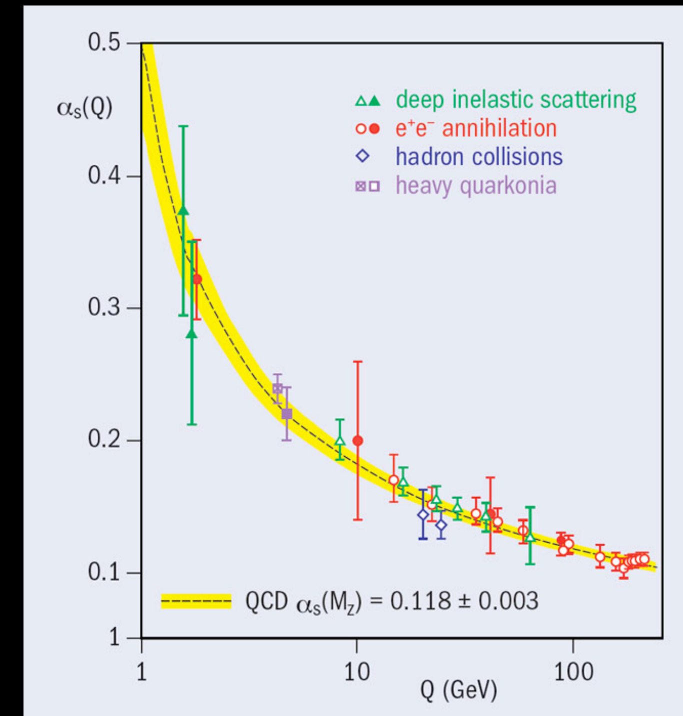
$$\psi = \begin{pmatrix} r \\ g \\ b \end{pmatrix}$$

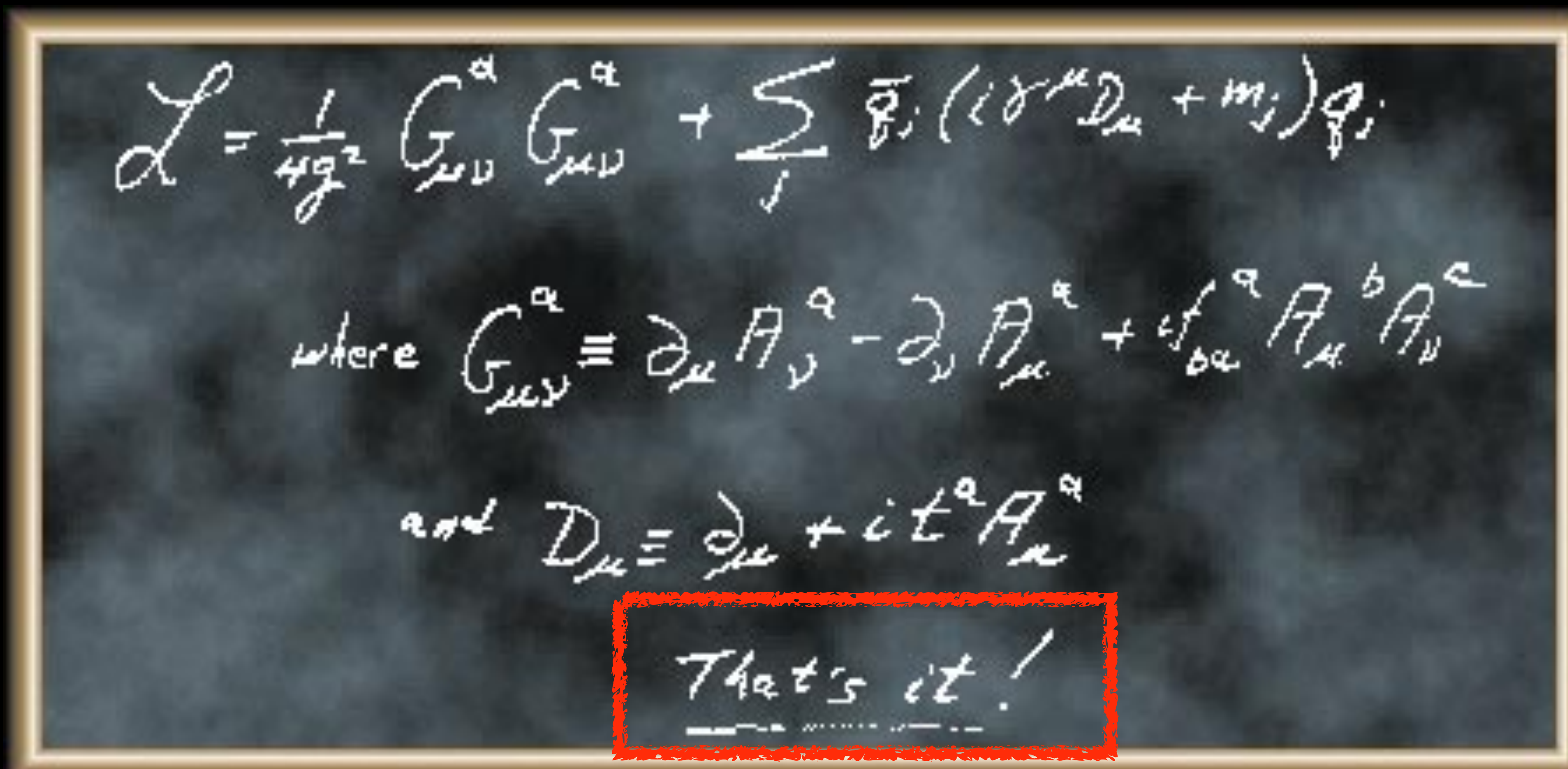


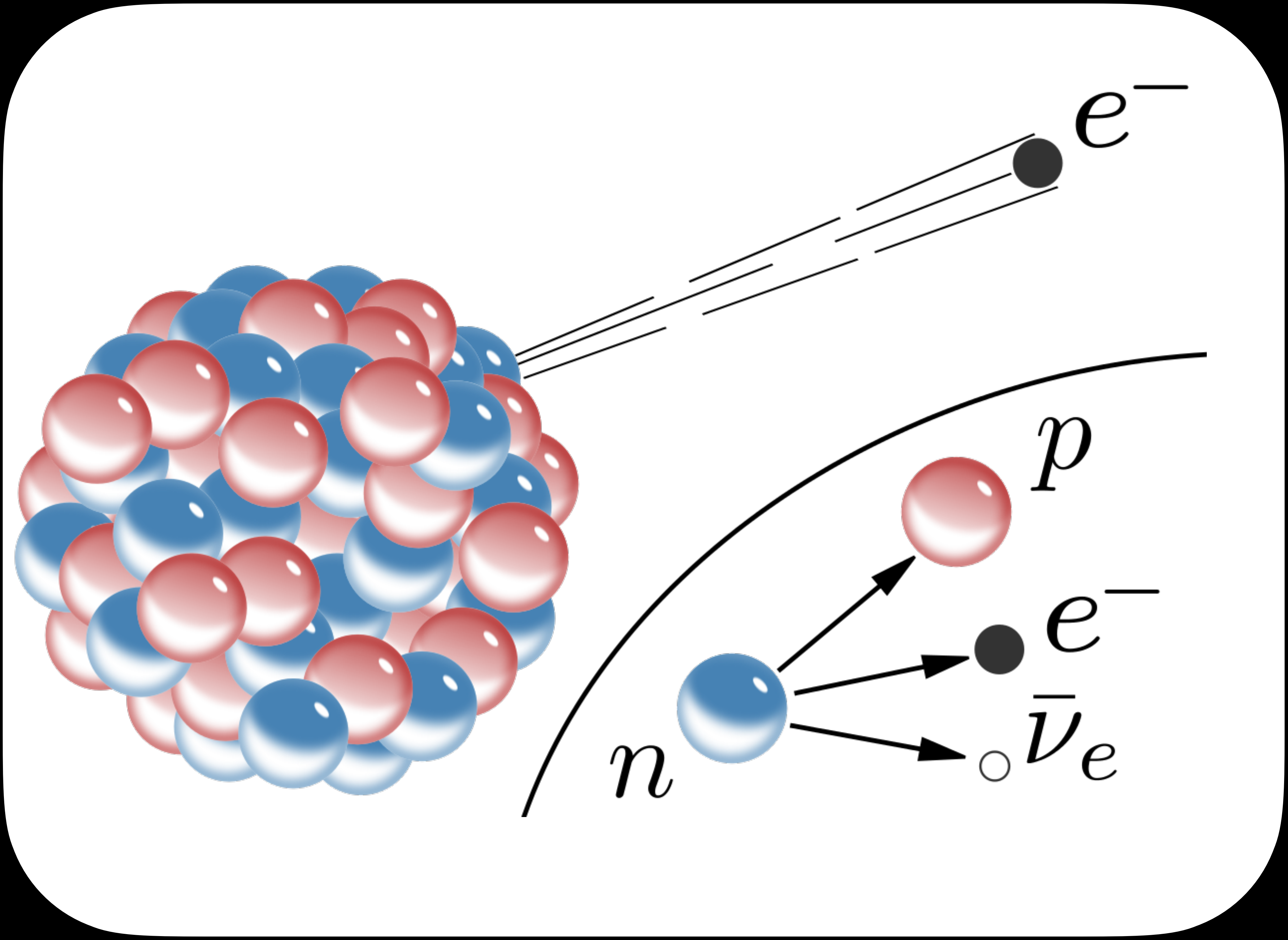


Quantum ChromoDynamics (QCD)





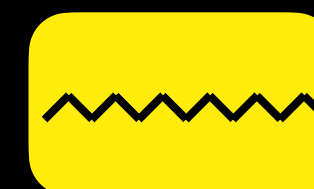



e^-
p
e^-
$\bar{\nu}_e$
n

Symmetries and gauge tranformations (Weak)

Conserved quantities	Gauge transformation	Symmetry group	Field
Weak isospin	$\Psi \rightarrow \Psi' = e^{\frac{i\vec{\tau}\,\vec{\alpha}}{2}}\Psi$	SU(2) (weak)	A_μ (3 bosons, $W^\pm$, Z^0)

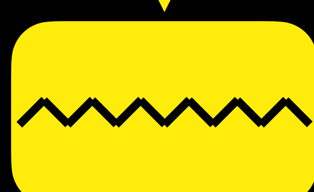
$\psi = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad \psi = \begin{pmatrix} u \\ d \end{pmatrix}$



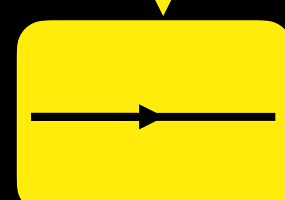
Weak

$$\mathcal{L}_{weak} = -\frac{1}{4}\vec{F}_{\mu\nu}\vec{F}^{\mu\nu} + \overline{\psi}\,(i\gamma_\mu D^\mu - m)\psi$$

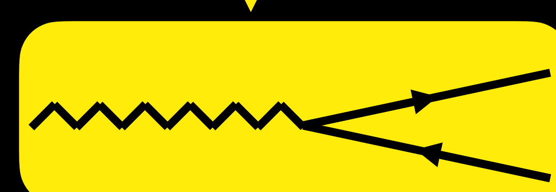
$$= -\frac{1}{4}\vec{F}_{\mu\nu}\vec{F}^{\mu\nu} + I\,\overline{\psi}\,(i\gamma_\mu\partial^\mu - m)\psi - \frac{g}{2}\,\overline{\psi}\,\gamma_\mu\,\vec{\tau}\,\vec{\alpha}^\mu\,\psi$$



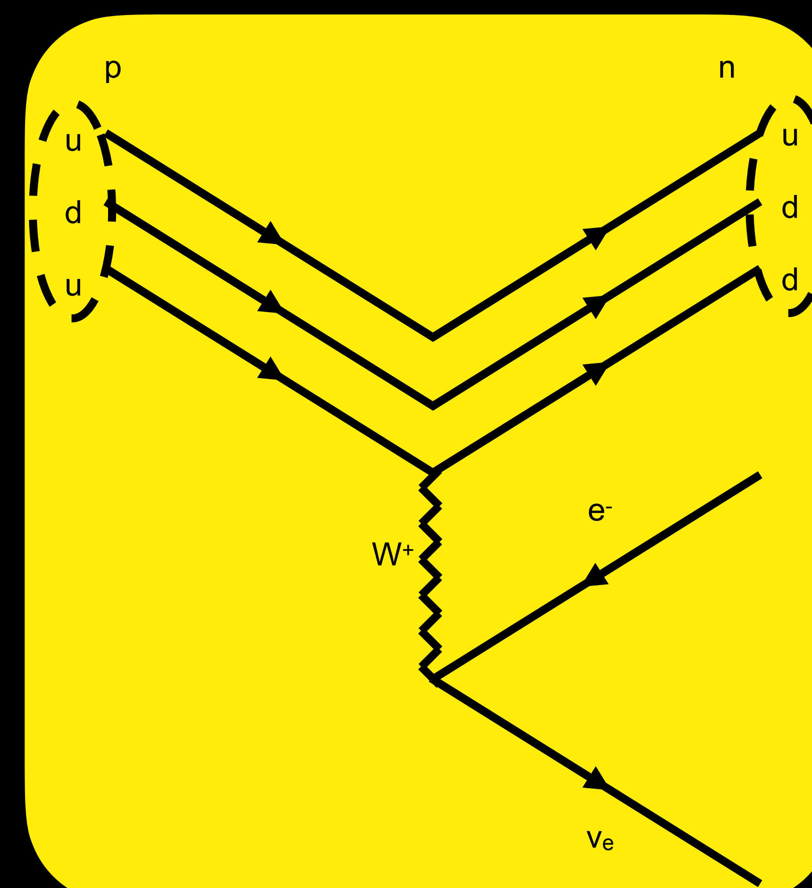
Three gauge boson fields A^μ ($W^\pm$ Z^0)



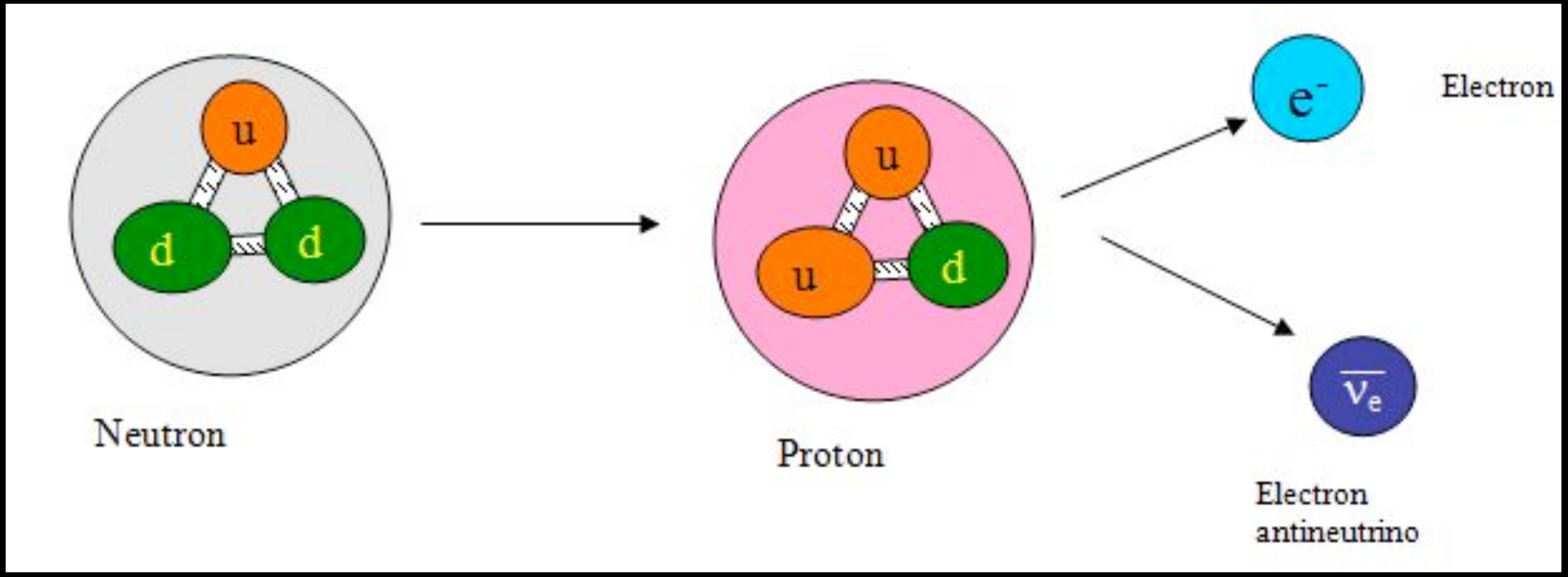
Fermion ψ with mass m

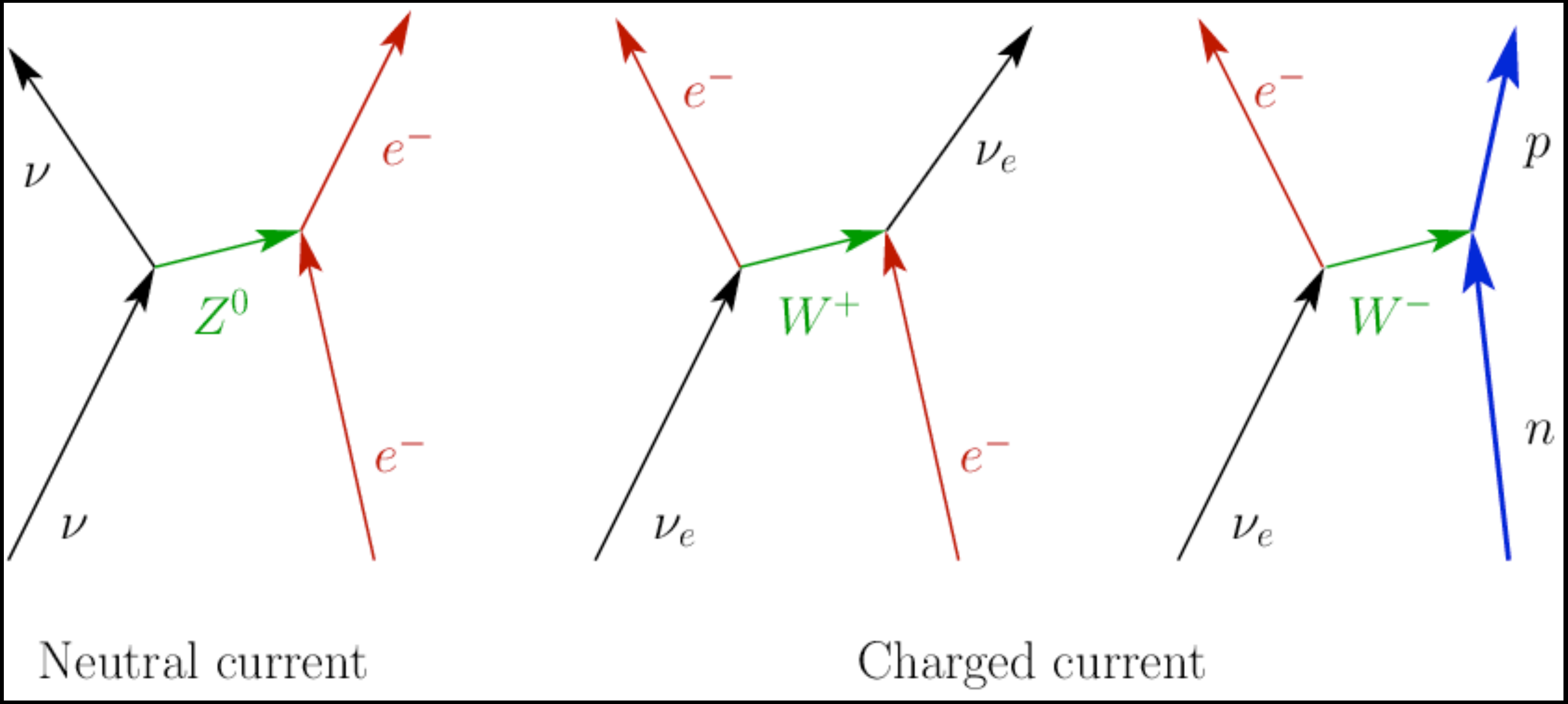


Interaction with coupling g



Weak interactions (Glashow-Weinberg-Salam theory)





The Standard Model (theoretical framework)

Quantum ElectroDynamics (QED)

The Nobel Prize in Physics 1965
Sin-Itiro Tomonaga, Julian Schwinger, Richard P. Feynman

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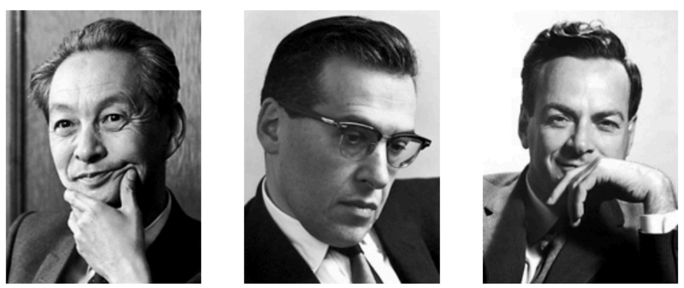
The Nobel Prize in Physics 1965



Sin-Itiro Tomonaga Prize share: 1/3 | **Julian Schwinger** Prize share: 1/3 | **Richard P. Feynman** Prize share: 1/3

The Nobel Prize in Physics 1965 was awarded jointly to Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman *"for their fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles".*

Electroweak Unification (GSW)

The Nobel Prize in Physics 1979
Sheldon Glashow, Abdus Salam, Steven Weinberg

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The Nobel Prize in Physics 1979

Sheldon Lee Glashow Prize share: 1/3 | **Abdus Salam** Prize share: 1/3 | **Steven Weinberg** Prize share: 1/3

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg *"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".*

Quantum ChromoDynamics (QCD)

The Nobel Prize in Physics 2004
David J. Gross, H. David Politzer, Frank Wilczek

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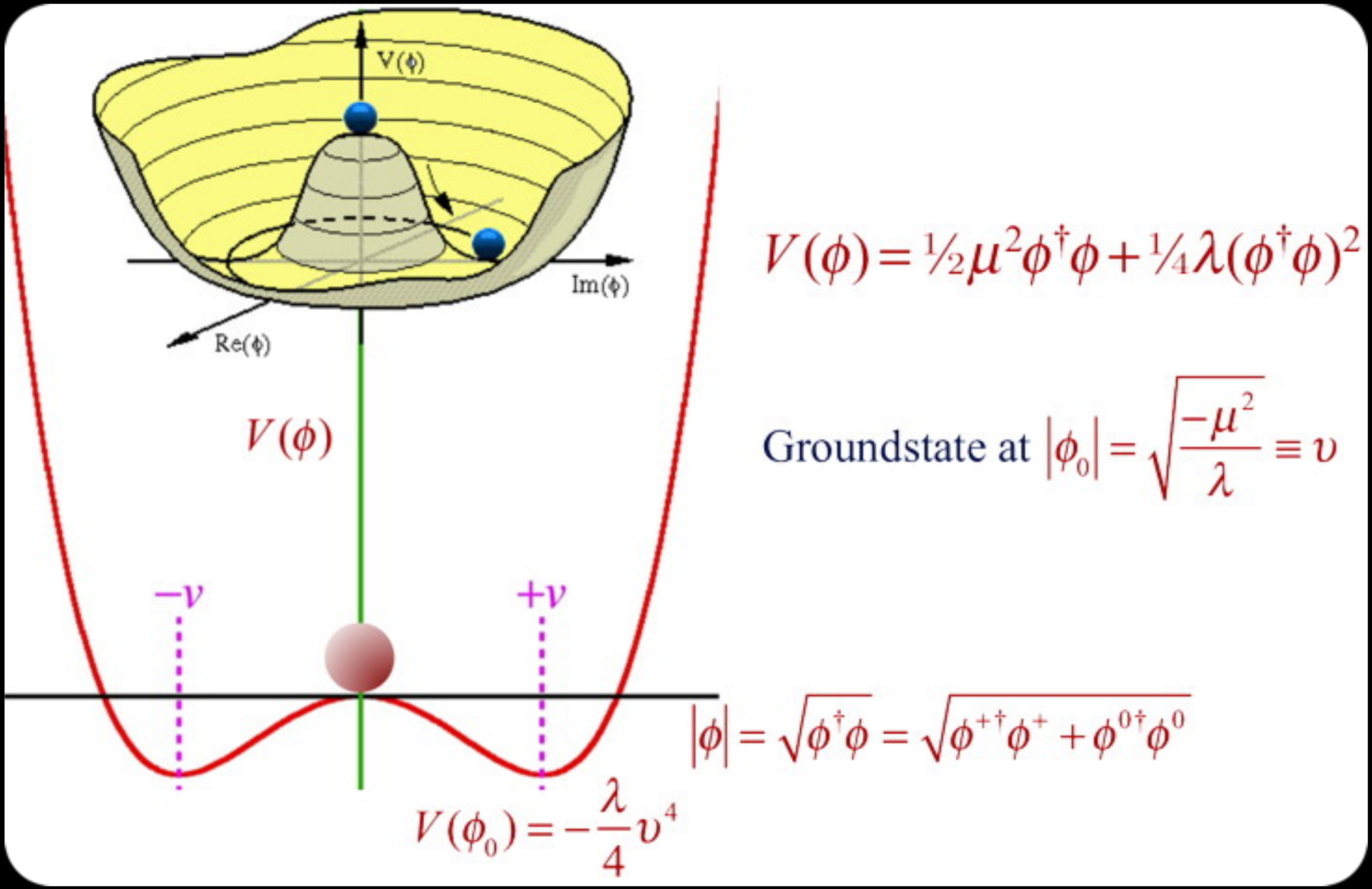
The Nobel Prize in Physics 2004

David J. Gross Prize share: 1/3 | **H. David Politzer** Prize share: 1/3 | **Frank Wilczek** Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction".*


V(ϕ)
Im(ϕ)
Re(ϕ)
$V(\phi)$
$-v$
$+v$
$V(\phi) = \frac{1}{2}\mu^2\phi^\dagger\phi + \frac{1}{4}\lambda(\phi^\dagger\phi)^2$
Groundstate at $|\phi_0| = \sqrt{\frac{-\mu^2}{\lambda}} \equiv \upsilon$
$|\phi| = \sqrt{\phi^\dagger\phi} = \sqrt{\phi^{+\dagger}\phi^+ + \phi^{0\dagger}\phi^0}$
$V(\phi_0) = -\frac{\lambda}{4}\upsilon^4$

The Standard Model (theoretical framework)

The Higgs mechanism

•

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

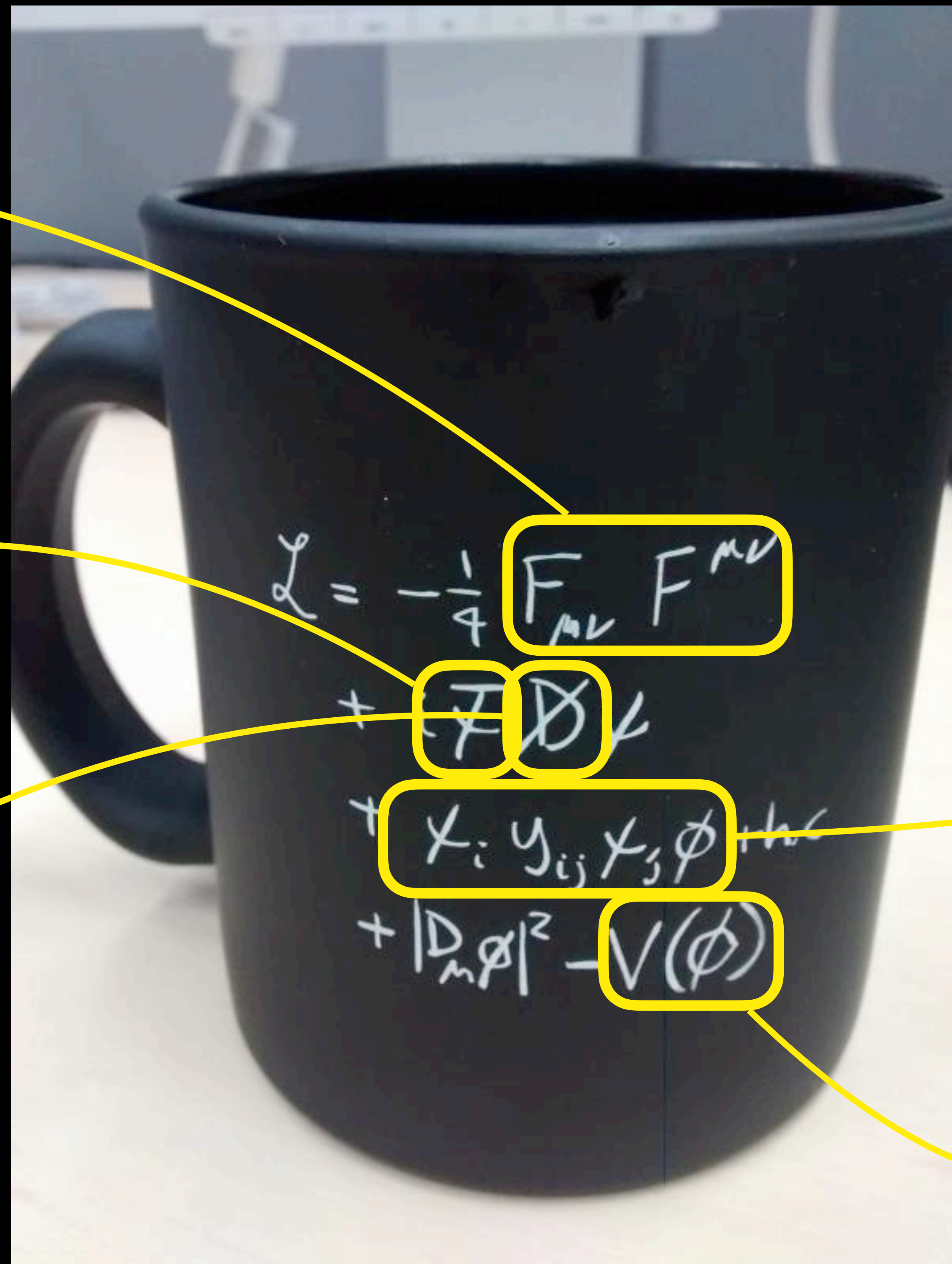
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The Standard Model Lagrangian (simplified…)

Field description $F_{\mu\nu}$
Photons, gluons
Maxwell equations, E- and B-fields, self interactions

Particles ψ
normal matter, particles and antiparticles, quarks, leptons

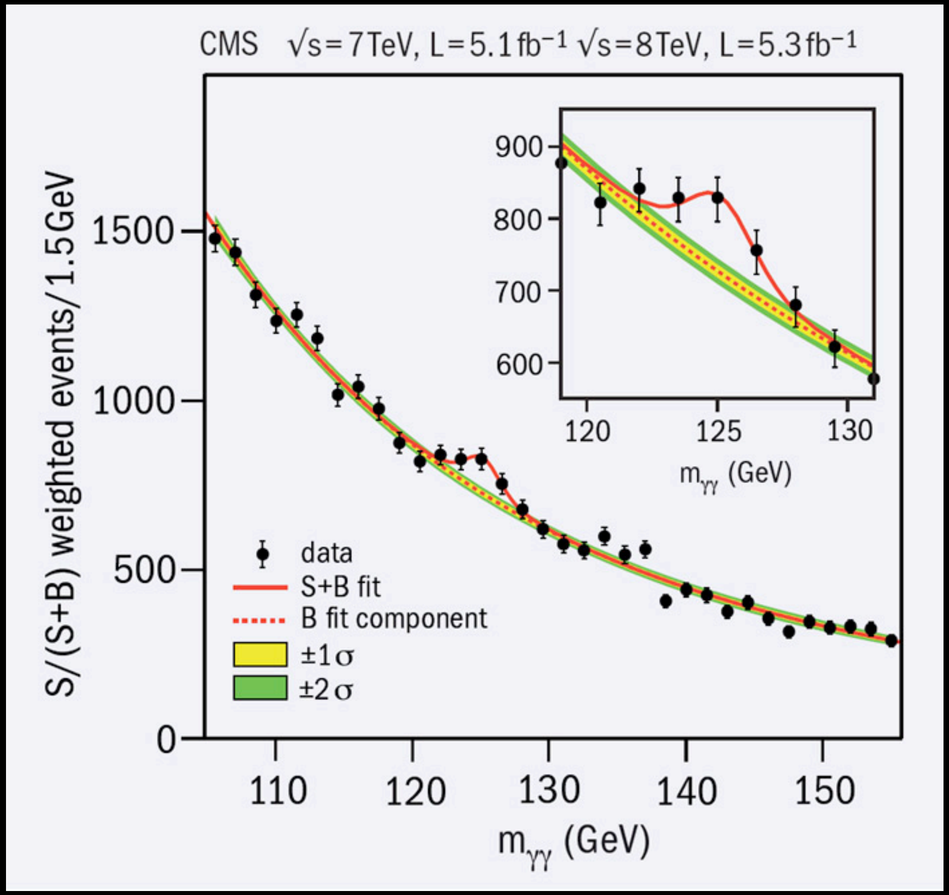
Interactions D
interactions between particles and fields

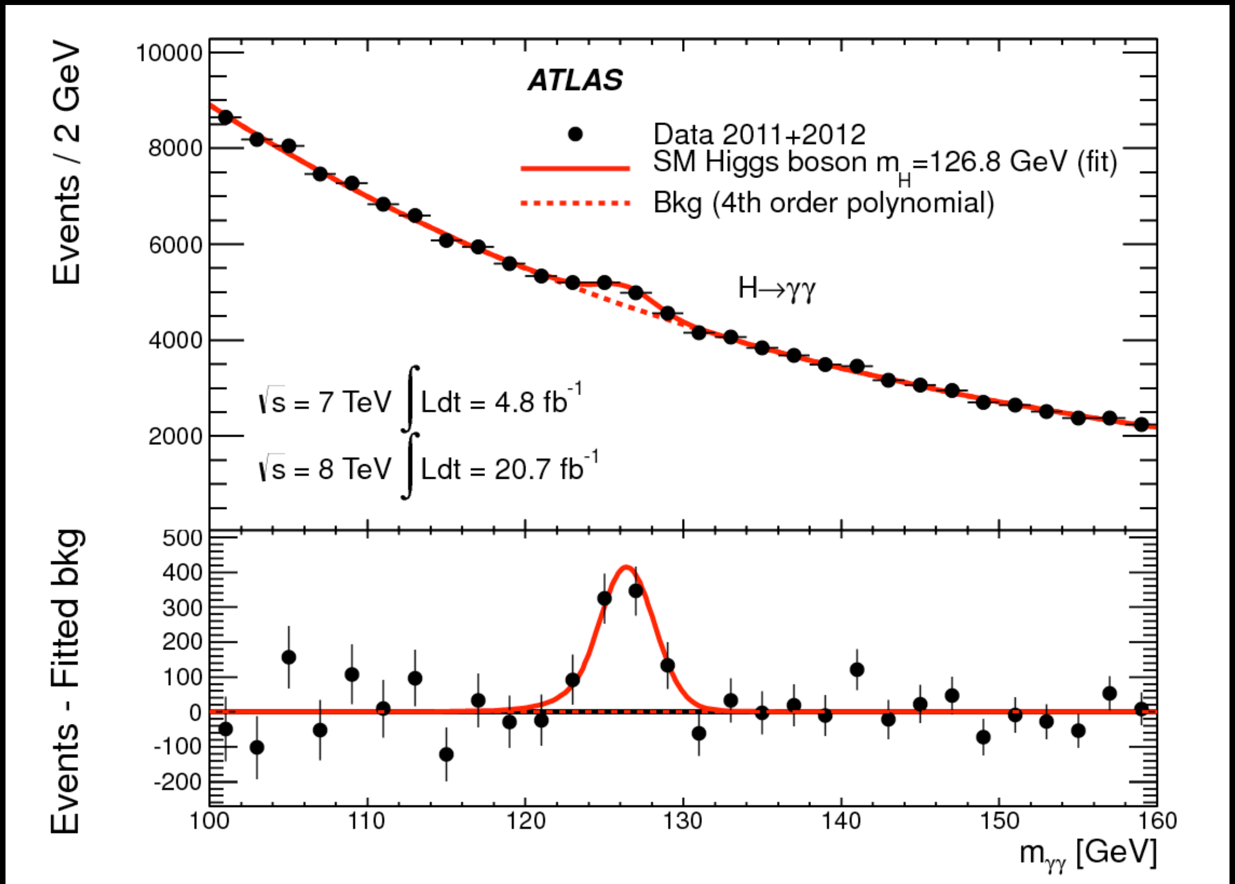


Mass ψψφ
how particles acquire mass by interacting with the Higgs field

Higgs field

The Higgs discovery





Schedule of the course

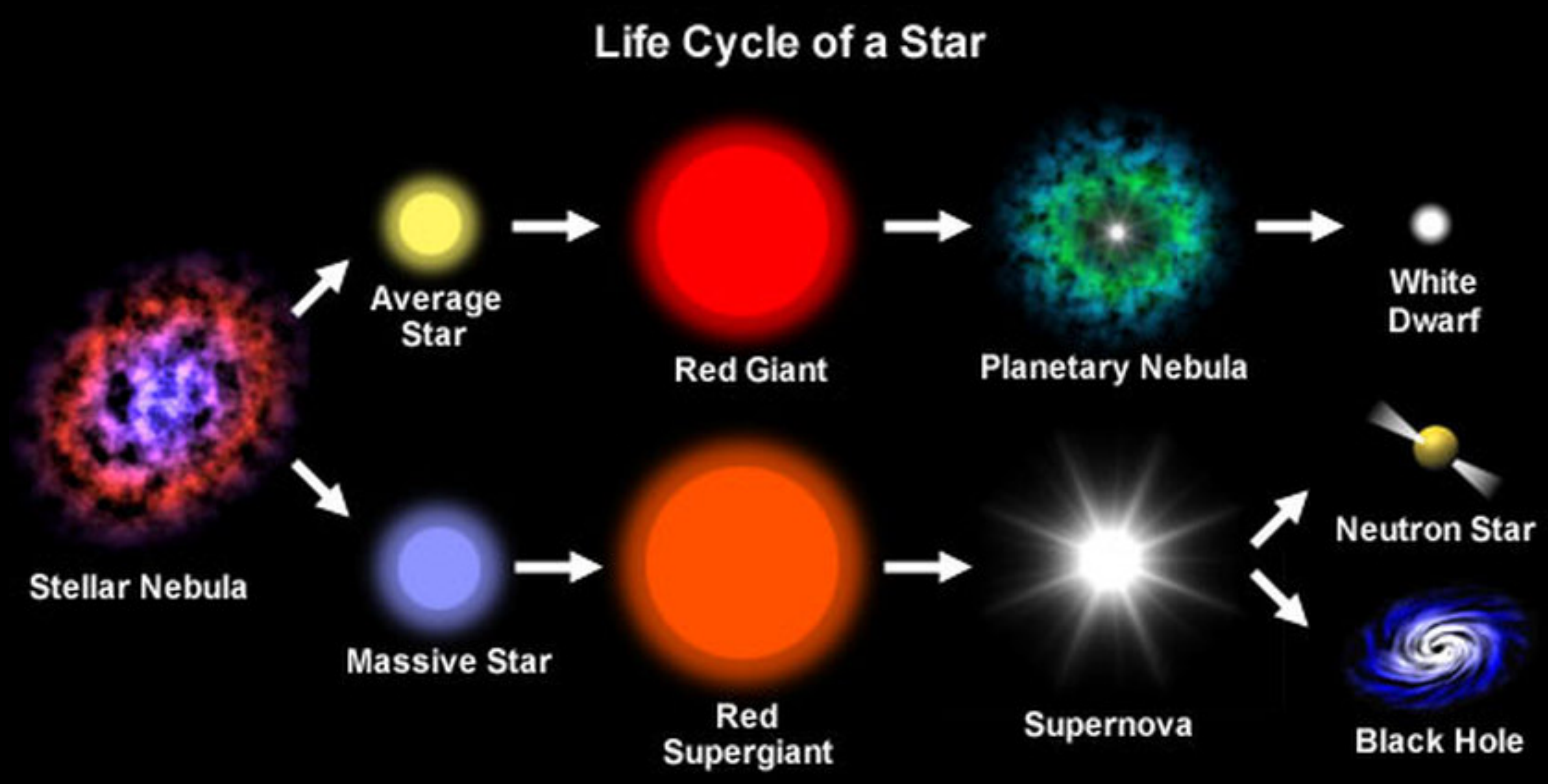
Dates	Wednesday	Friday
Week 6	Special relativity & 4-vectors	Special relativity & 4-vectors
Week 7	Lagrangian formalism, transformations, conserved quantities	Lagrangian formalism, transformations, conserved quantities
Week 8	Continuous/discrete transformations, global/local gauge, C, P transformations	Elementary particles, mass. charge, magnetic dipole moment, angular momentum, CG
Week 9	Quark model, colour, conservation laws	accelerators, particles interaction with matter, detectors
Week 10 (mid-term)	Golden rule	Mid-term
Week 11	Gauge theories	QED
Week 12	QED, elastic scattering, form factors, charge distributions	QCD
Week 13	QCD, inelastic scattering, DIS, quark	Weak
Week 14	Weak & Higgs	BONUS
Week 15 (Final exam)	Final exam	

Bonus lecture

Be there!!!

- ✓ Last lecture will be about career prospects beyond the bachelor level
  - Master programs offered in UU
  - Focus on the "Experimental Physics" curriculum
- ✓ Research opportunities e.g. @ Nikhef
- ✓ Q&A about the life of a PhD student
- ✓ Q&A about the life in academia
- ✓ Statistics from alumni

Backup


Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole

What are we after?