Teaching with open research data:
Experiences from five years of exploration-driven lab exercises in subatomic physics for undergraduate students

Fysikdagarna, Lund, June 15-17, 2022

Christian Ohm

Outline

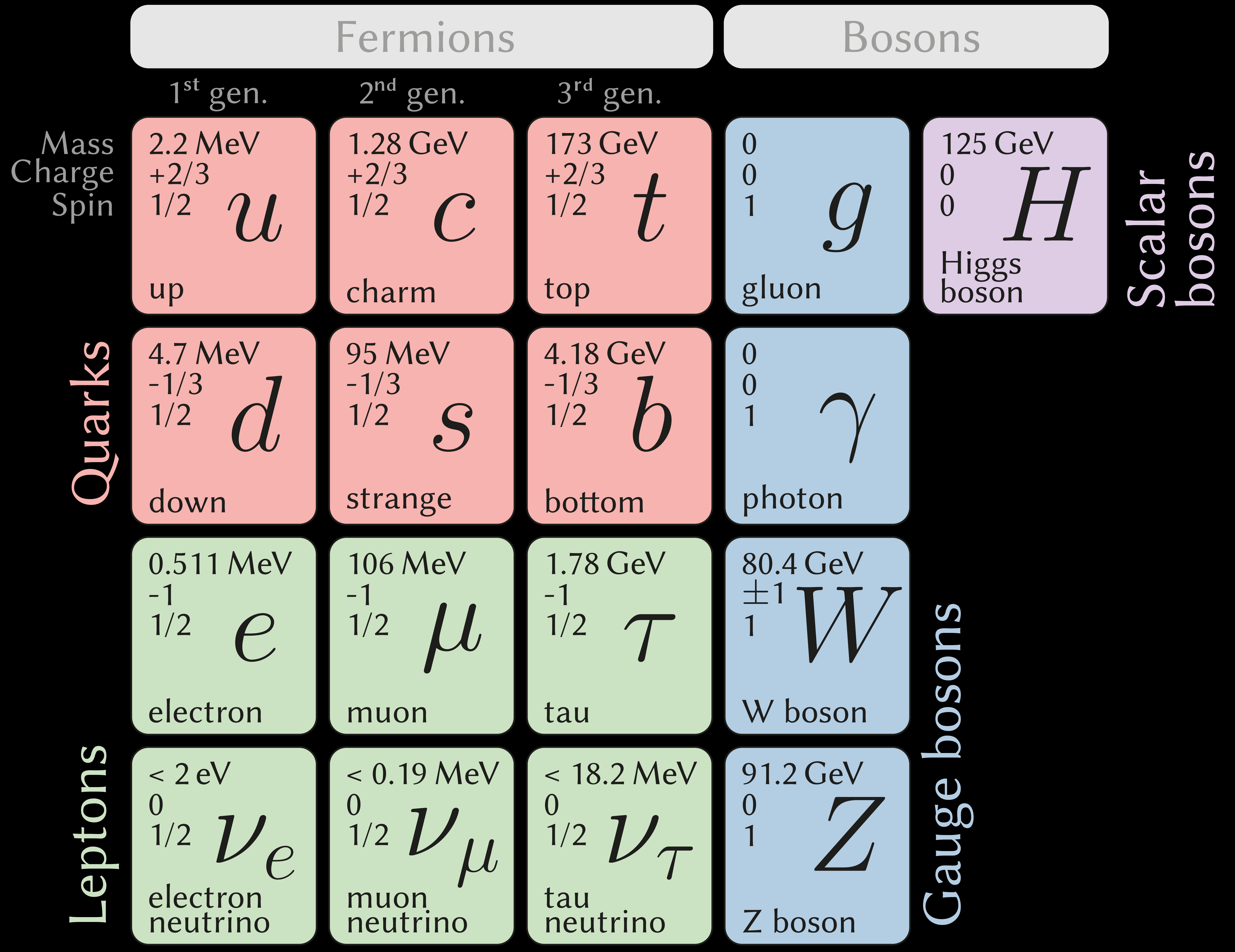
- Experimental research in particle physics - ATLAS experiment at CERN
- Labs with open research data
    - Applied Modern Physics (3rd year BSc)
    - Subatomic Physics (1st year MSc)
- Take-away messages and discussion points

Standard Model of particle physics

Matter particles (fermions)

Force particles (gauge bosons)

Higgs (scalar boson)



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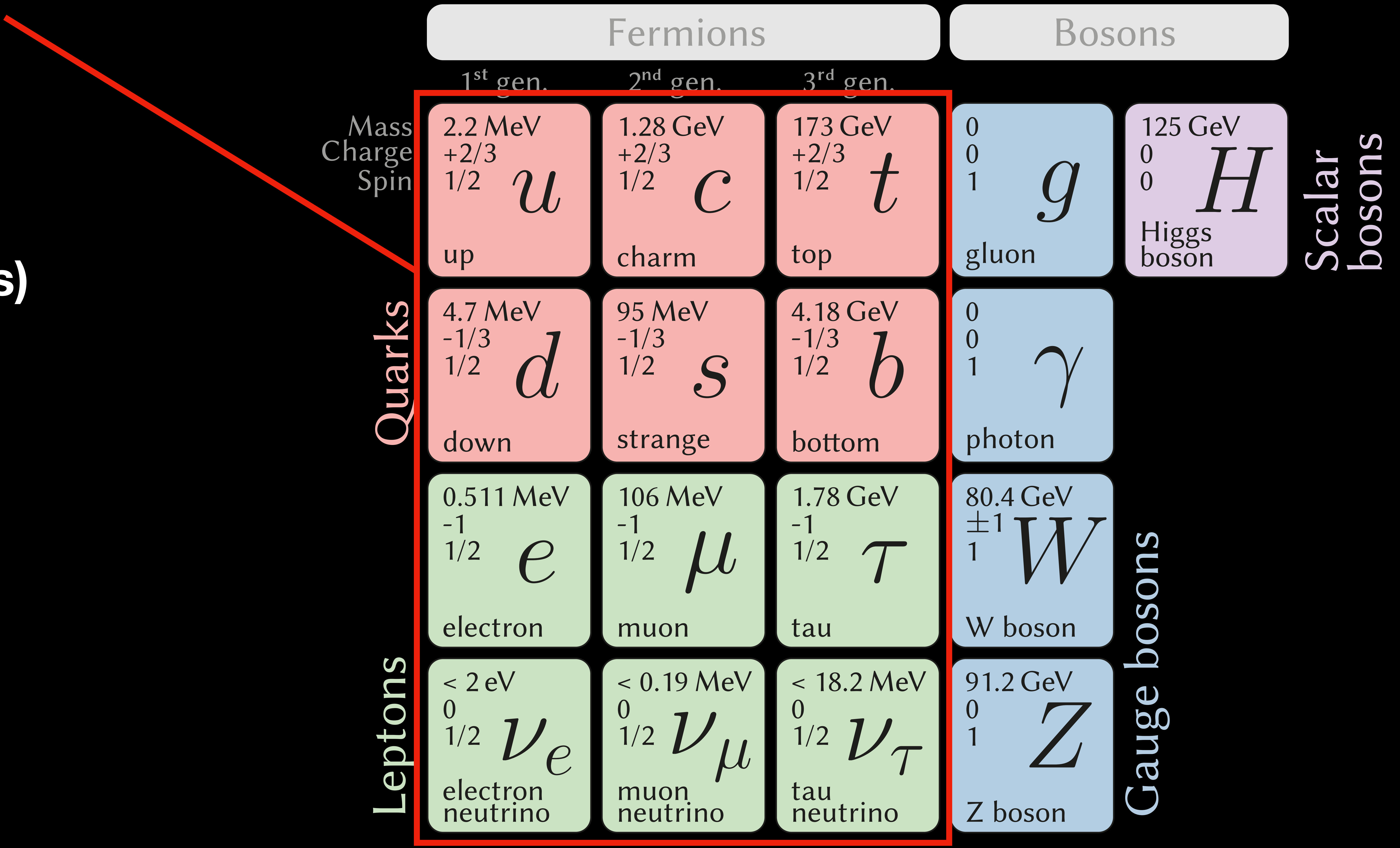

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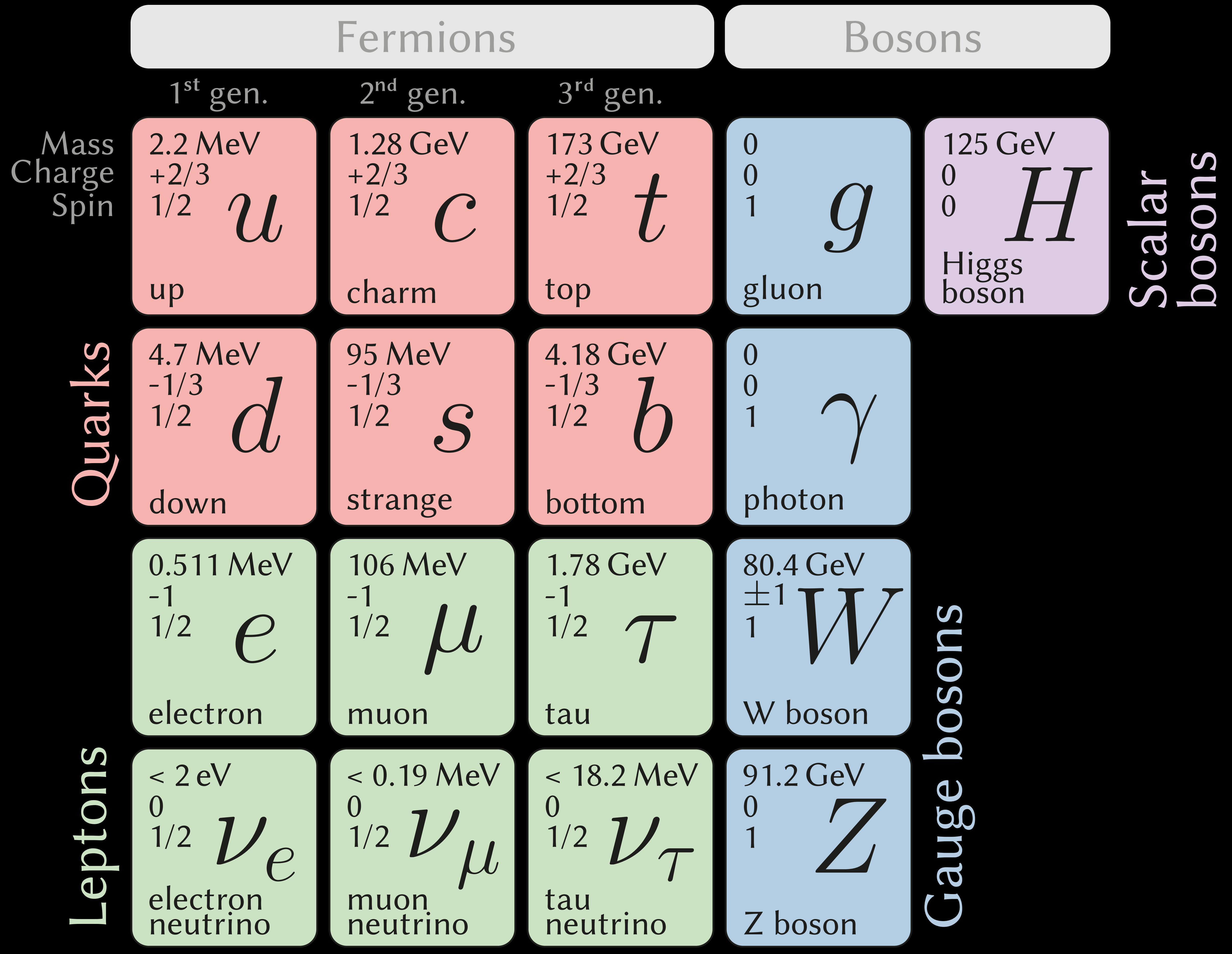

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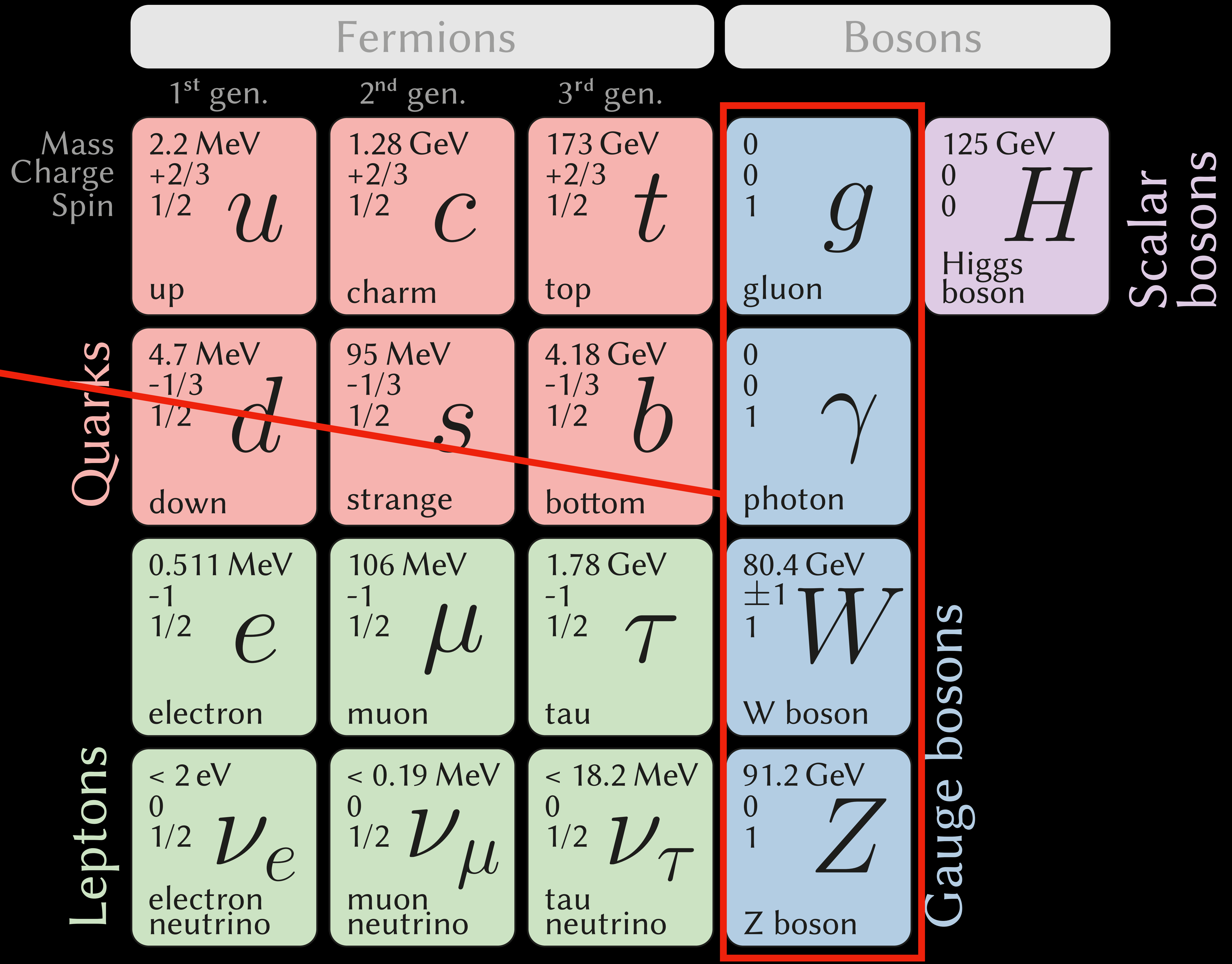

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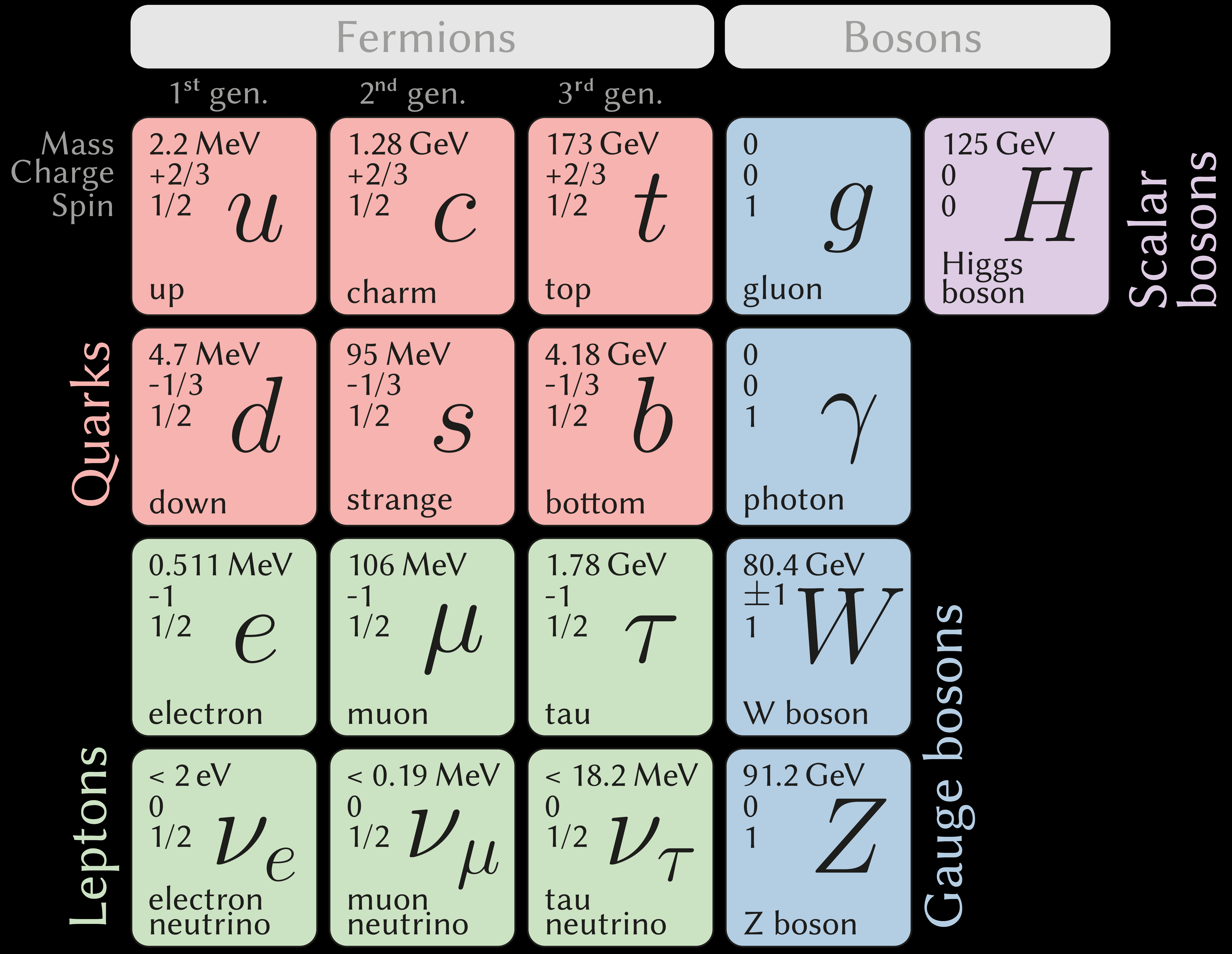

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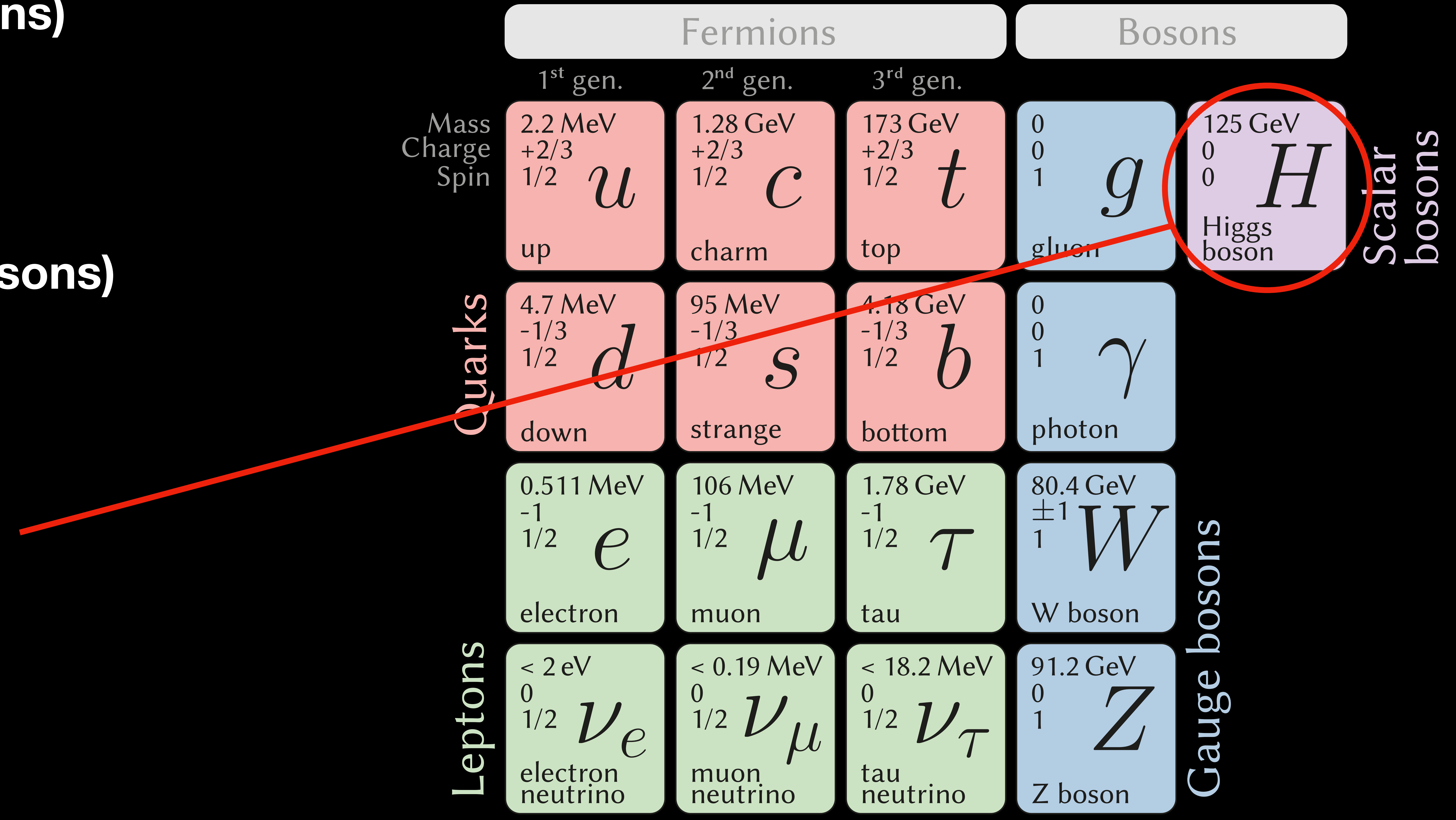

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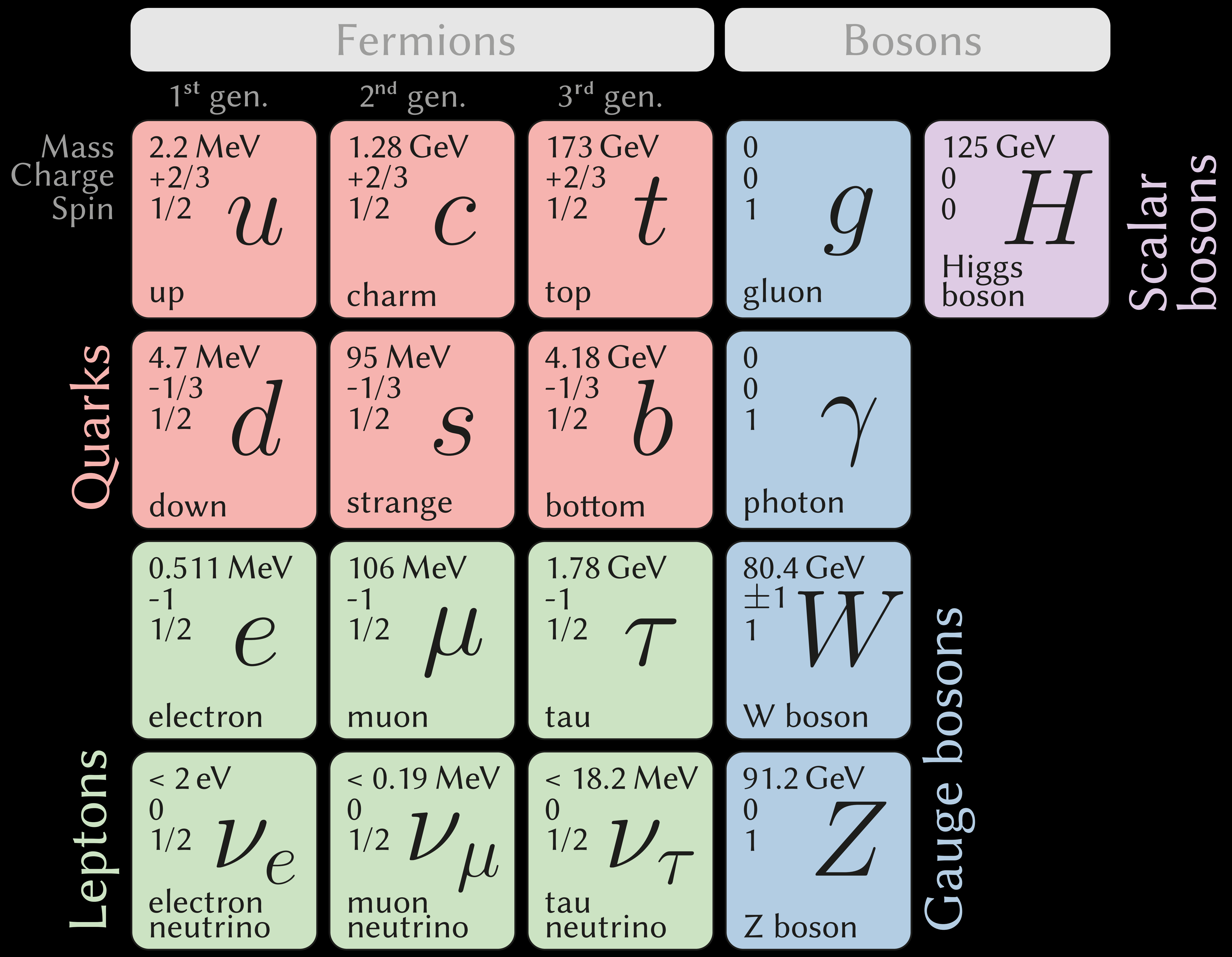

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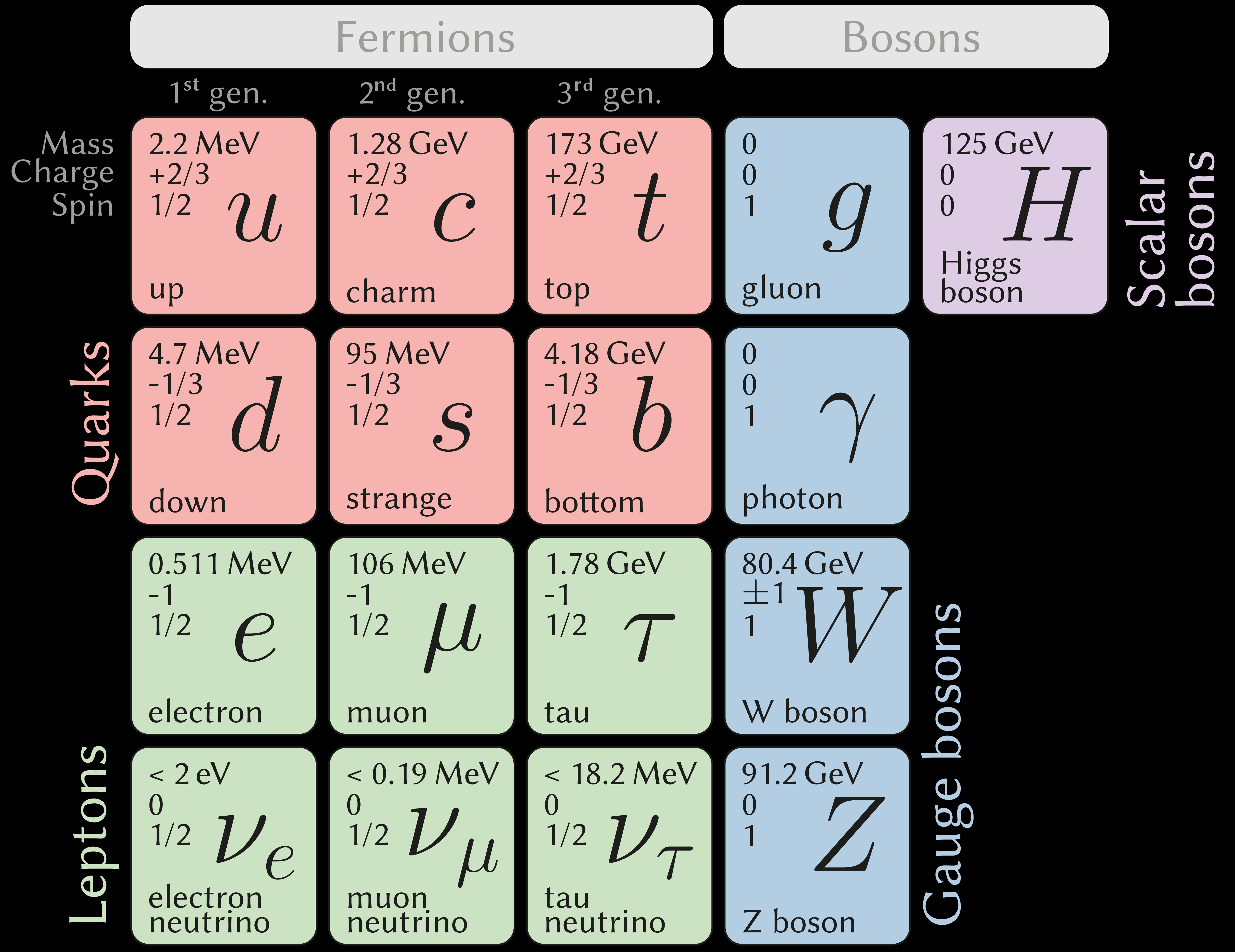

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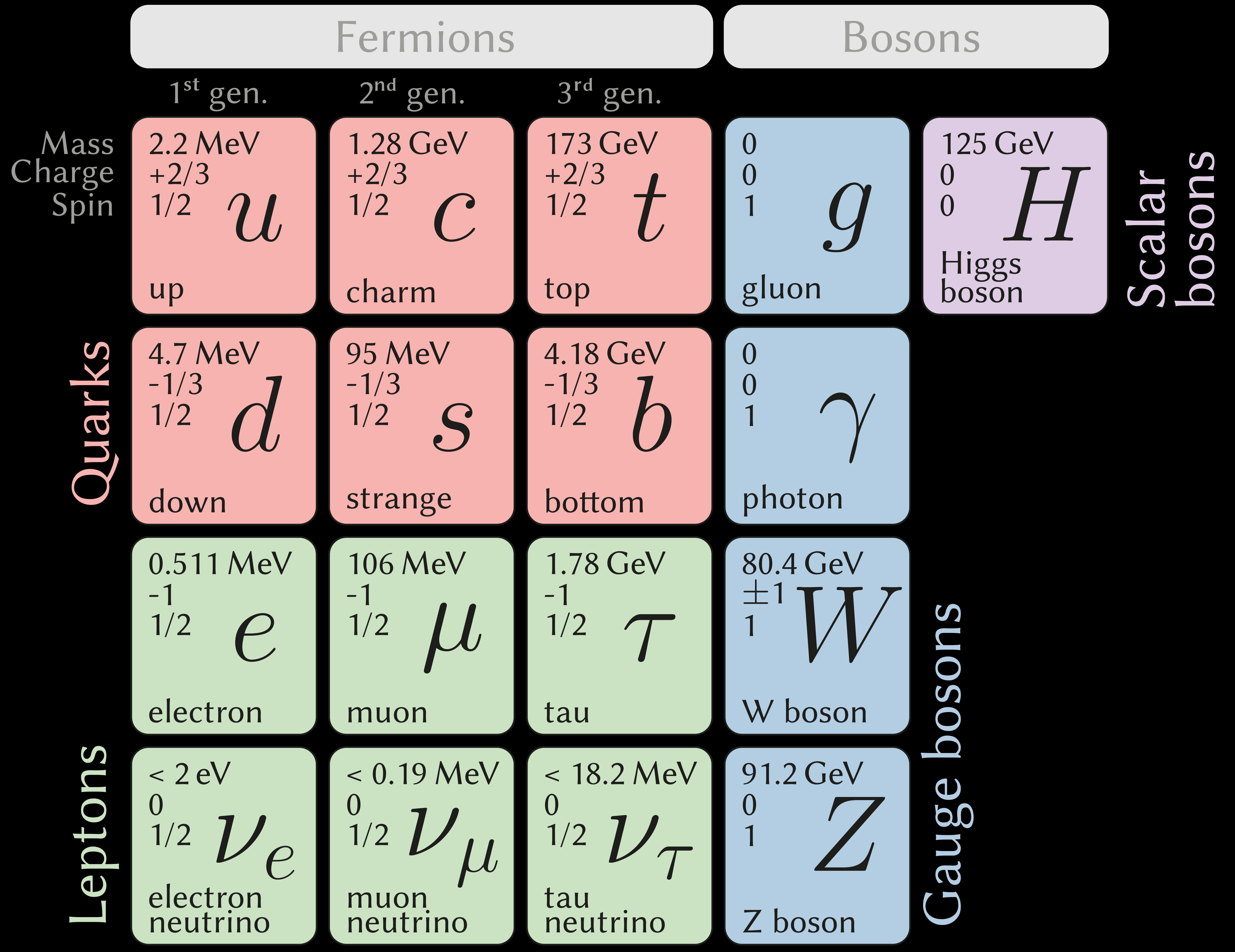
NB! Gravity is not included!



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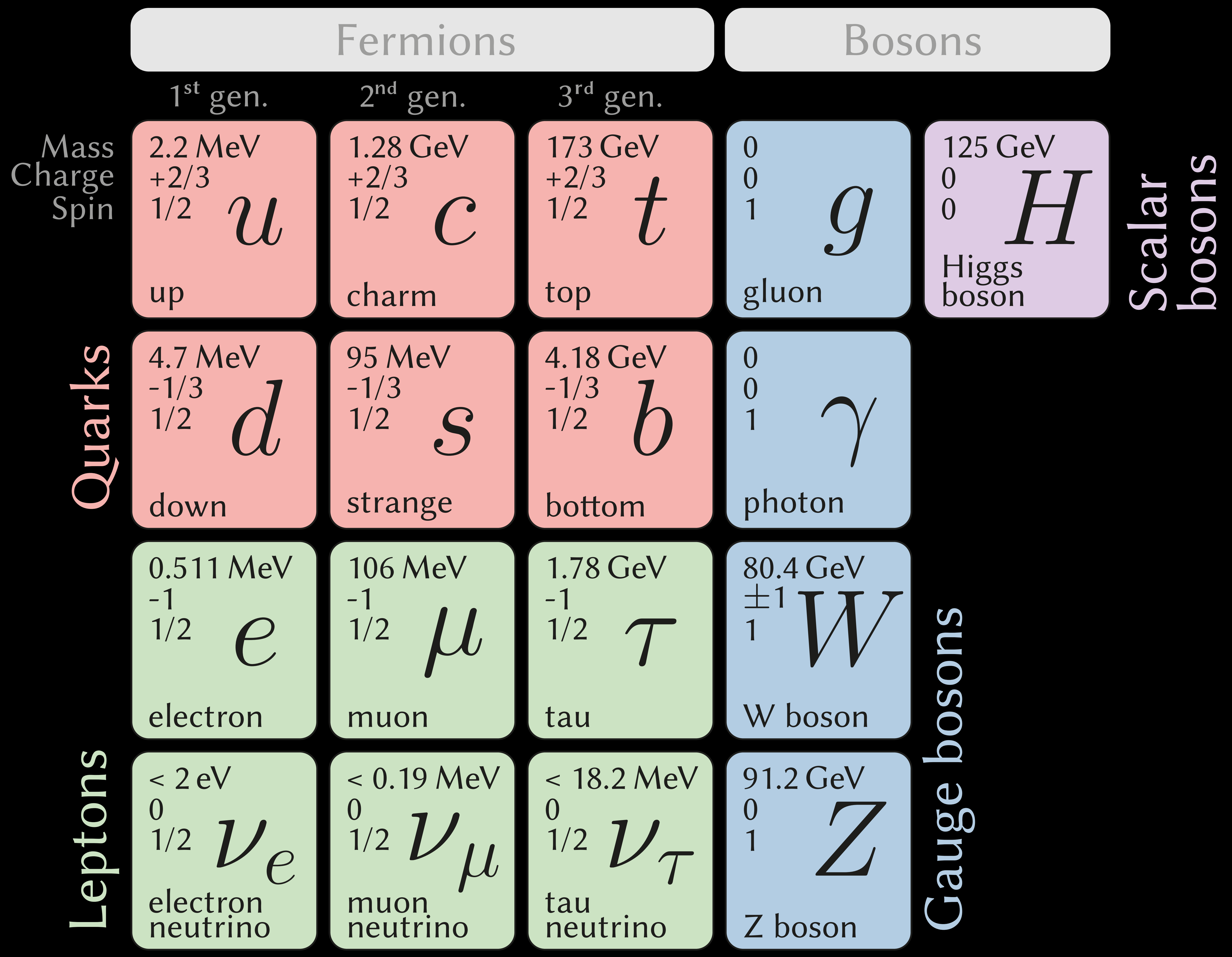

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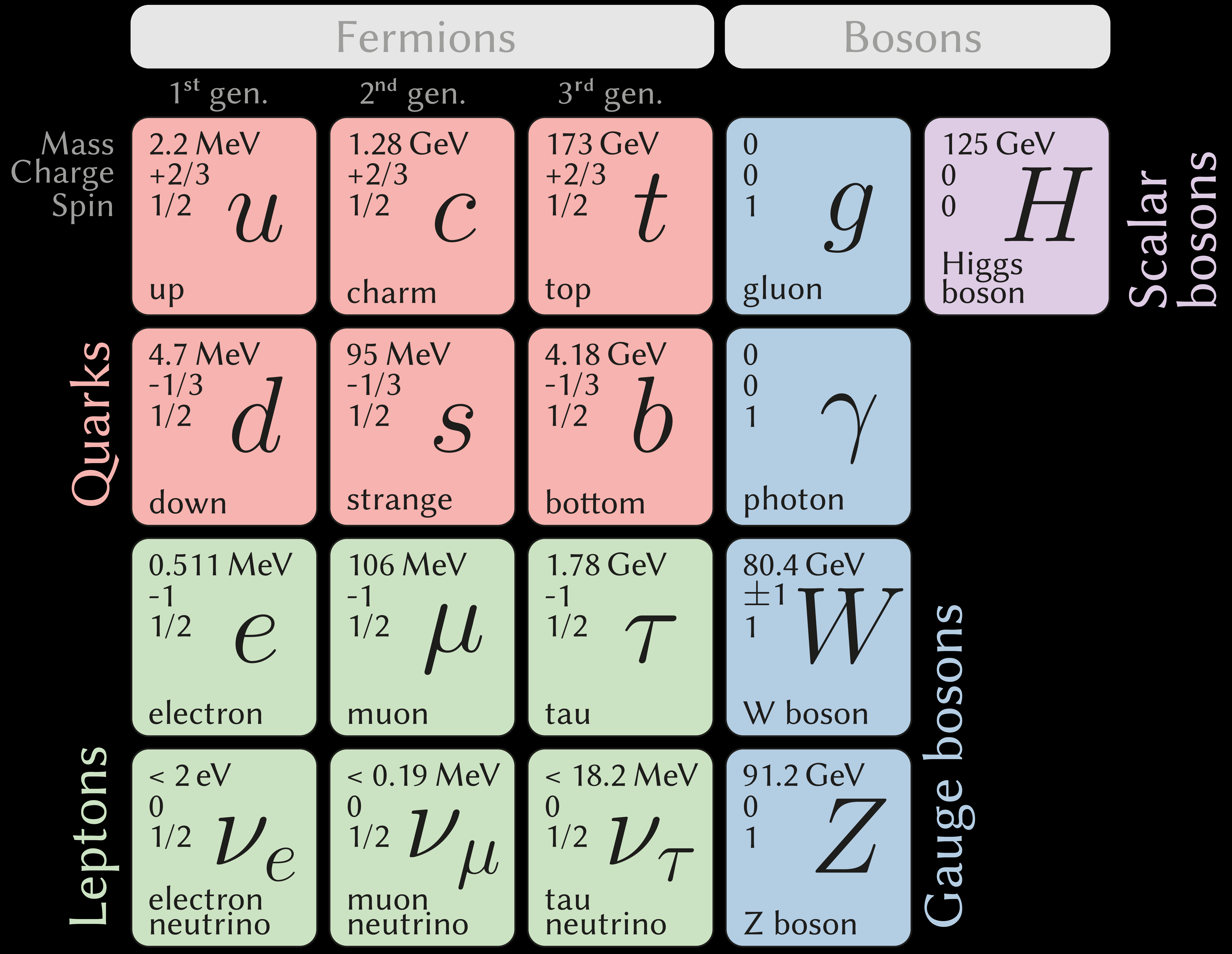

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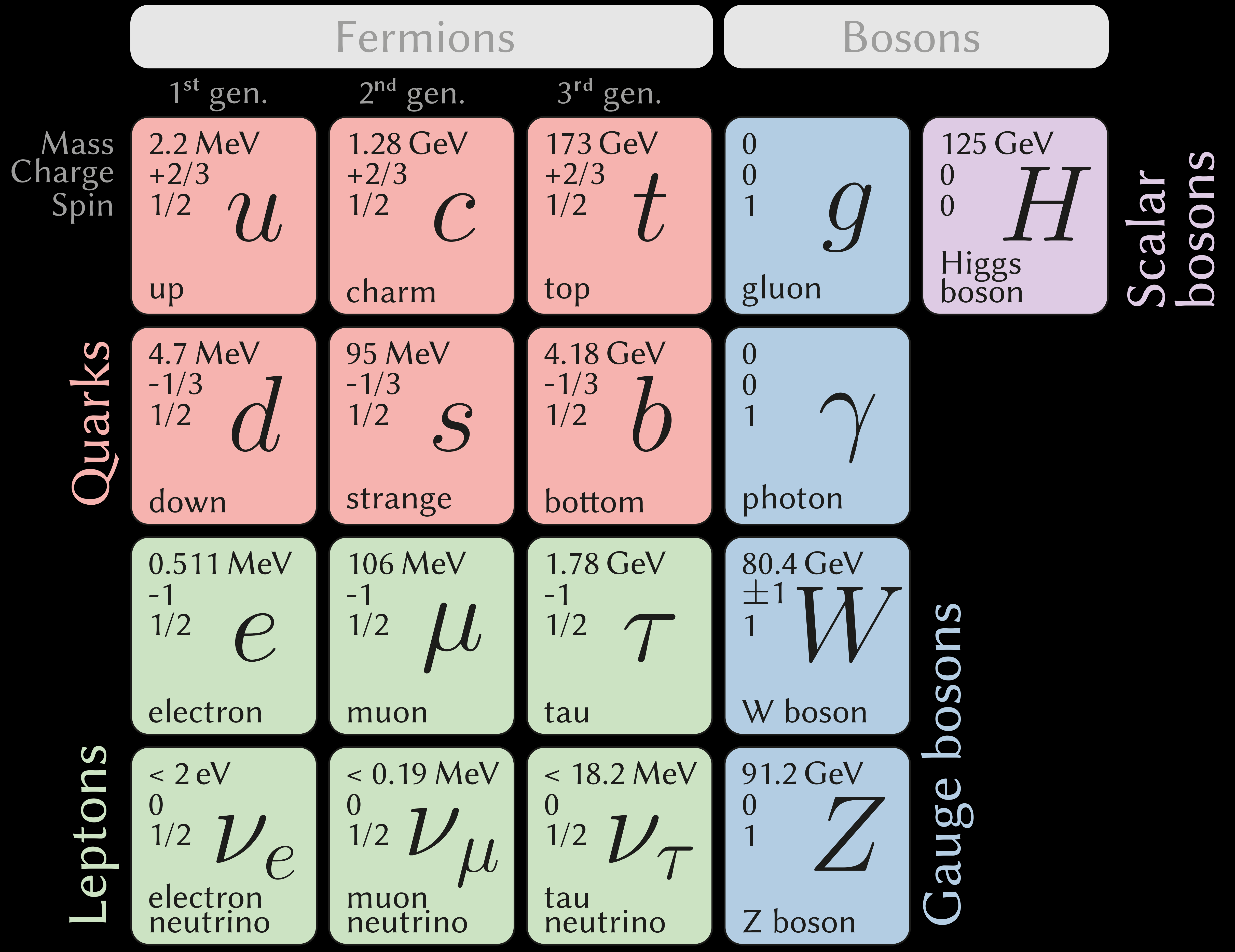

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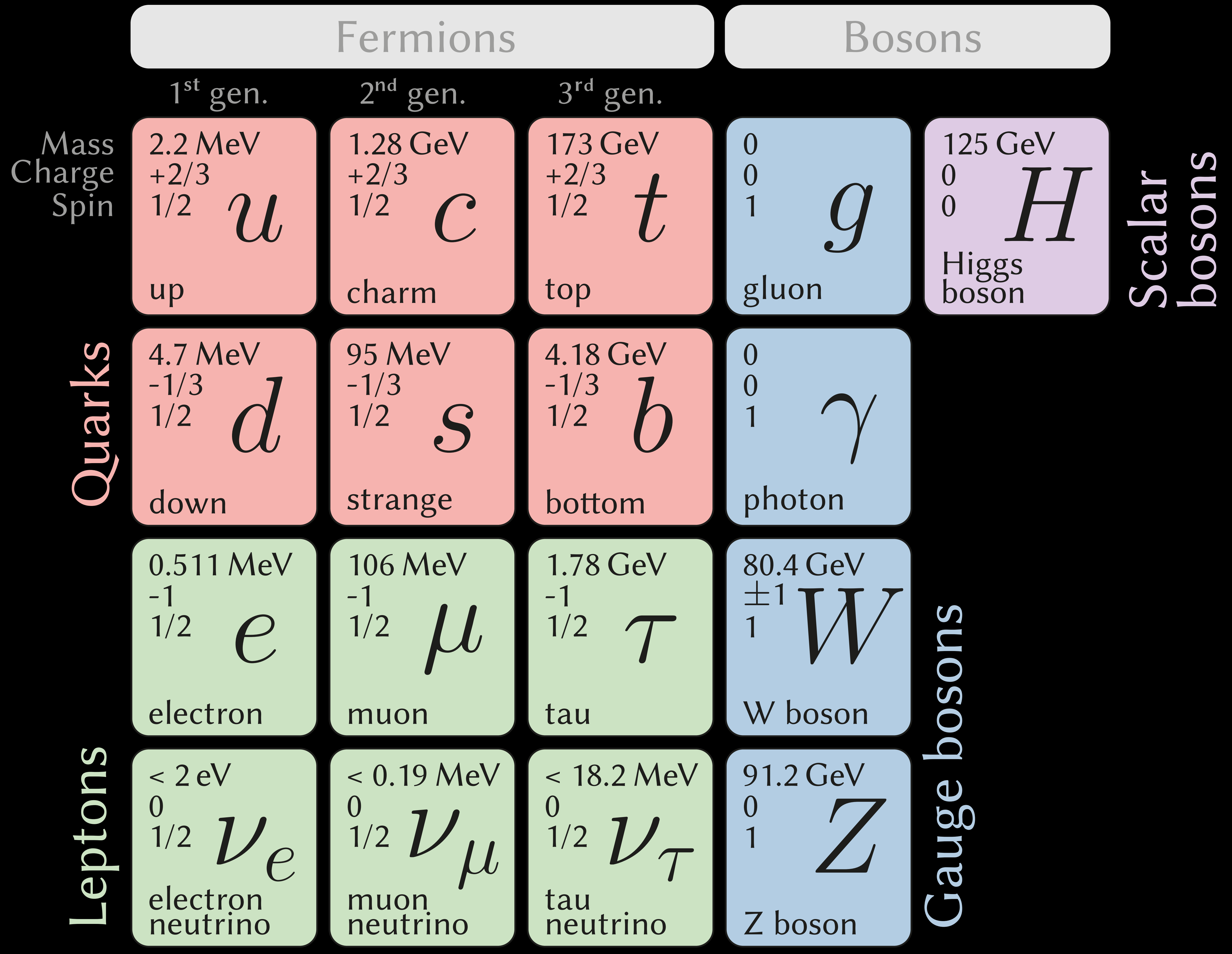

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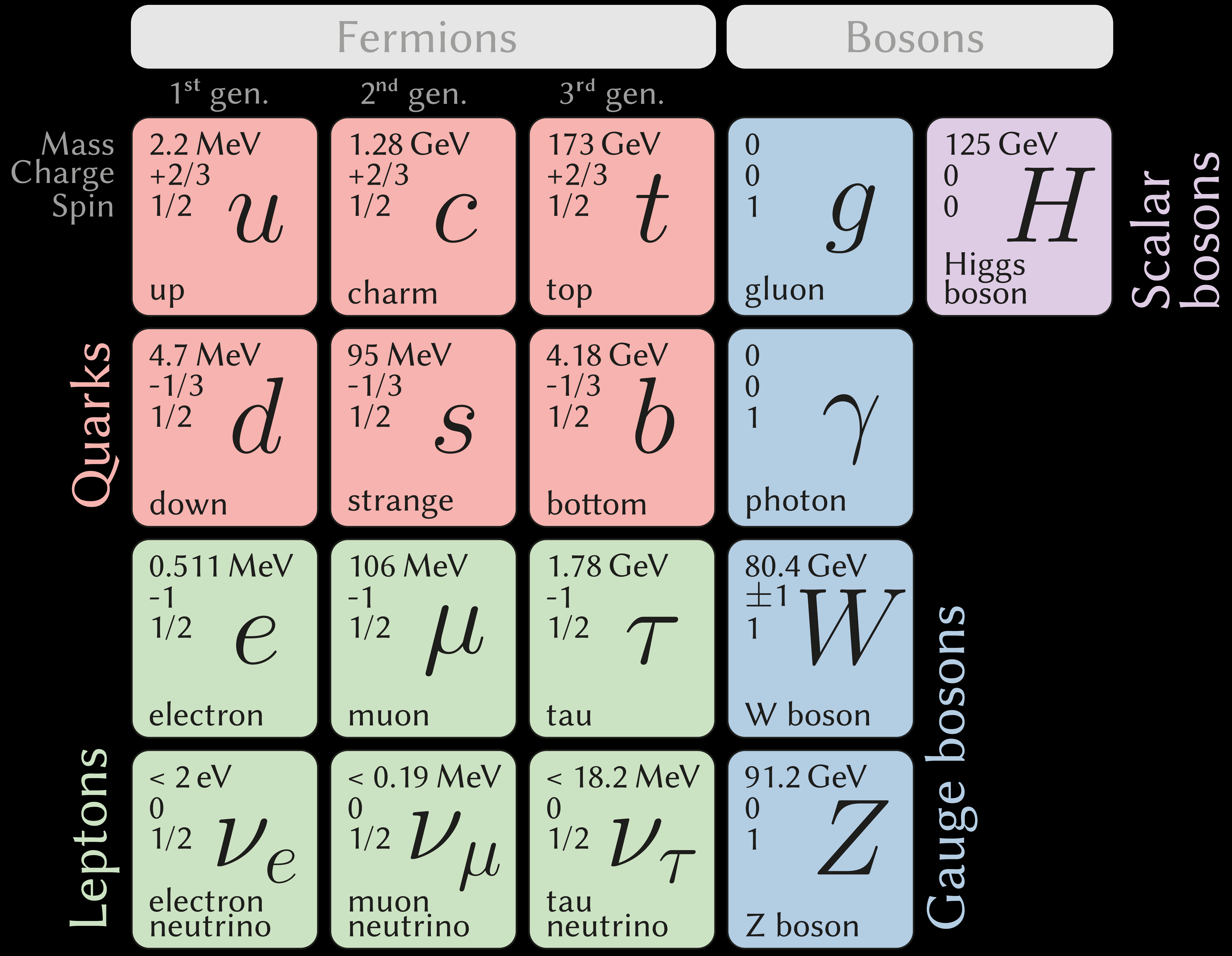

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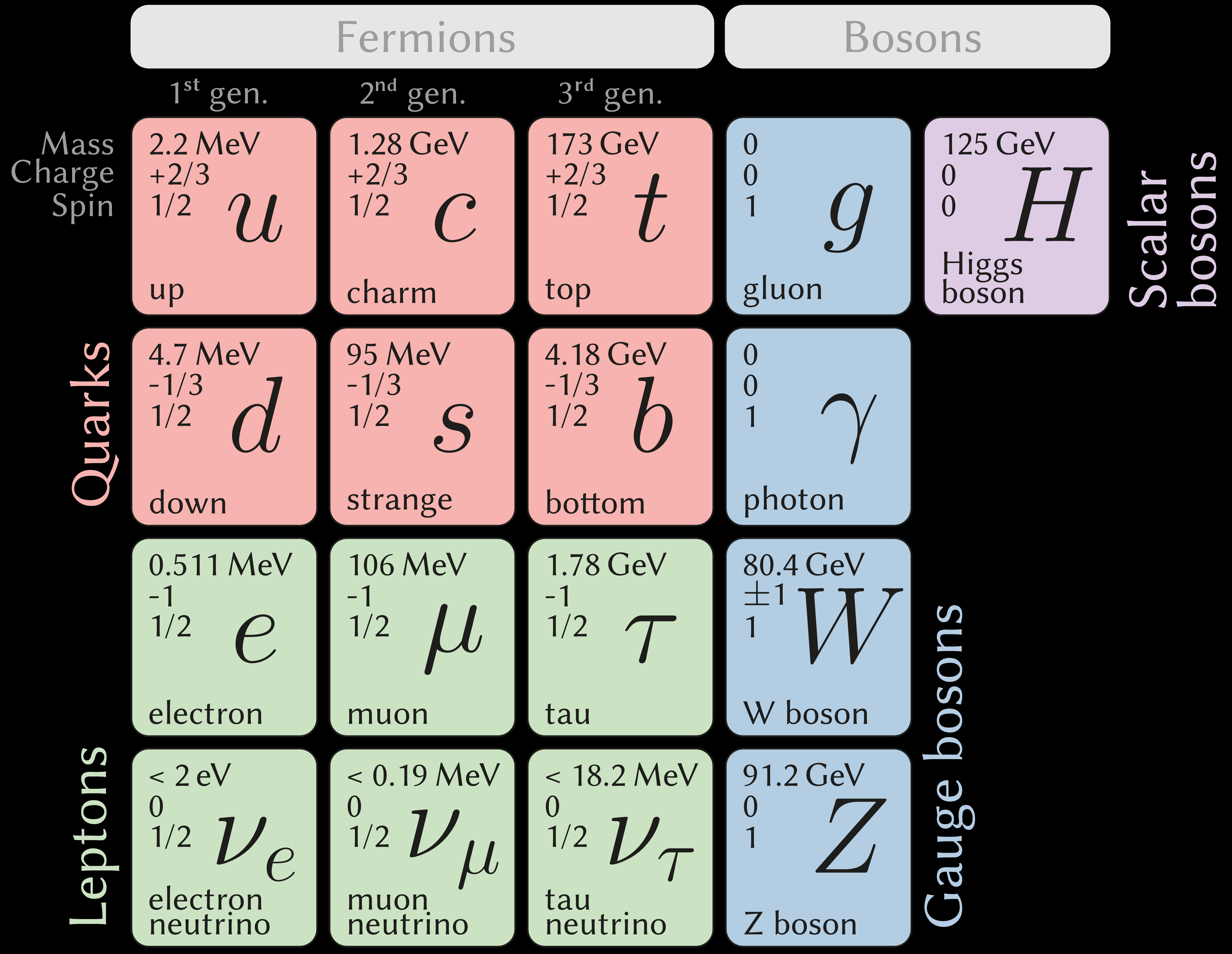

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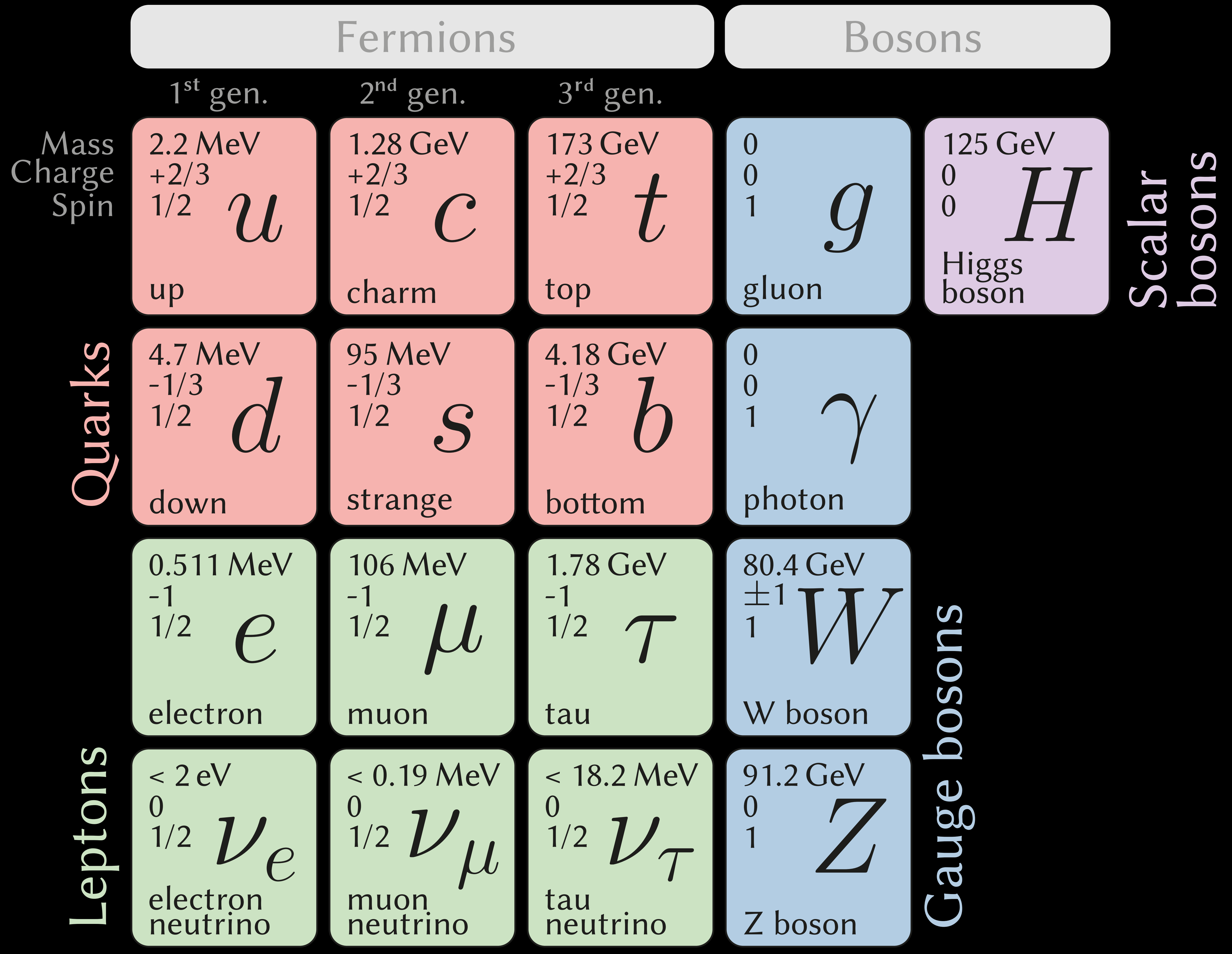
  - Theory: $a_e = 0.001159652181643$



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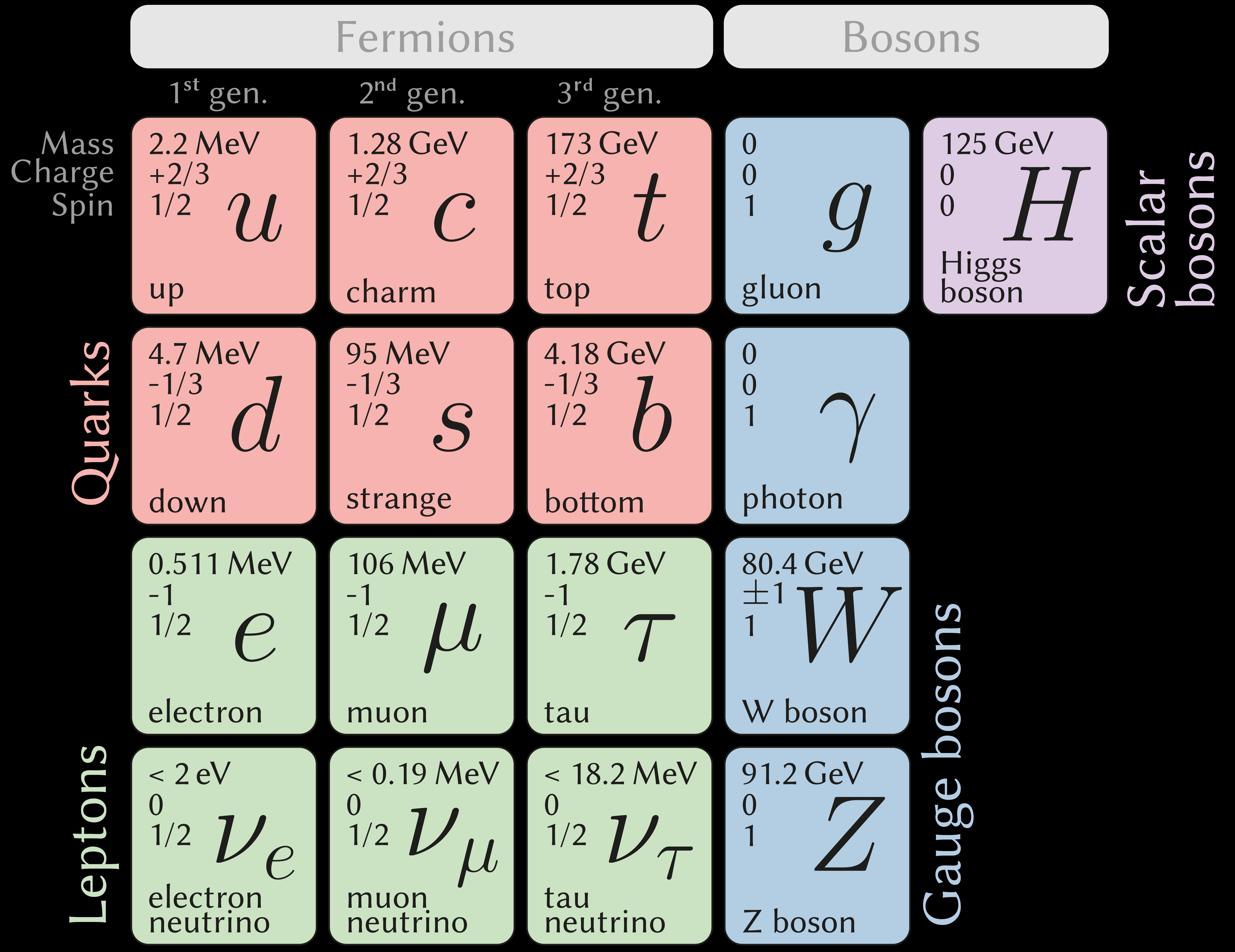

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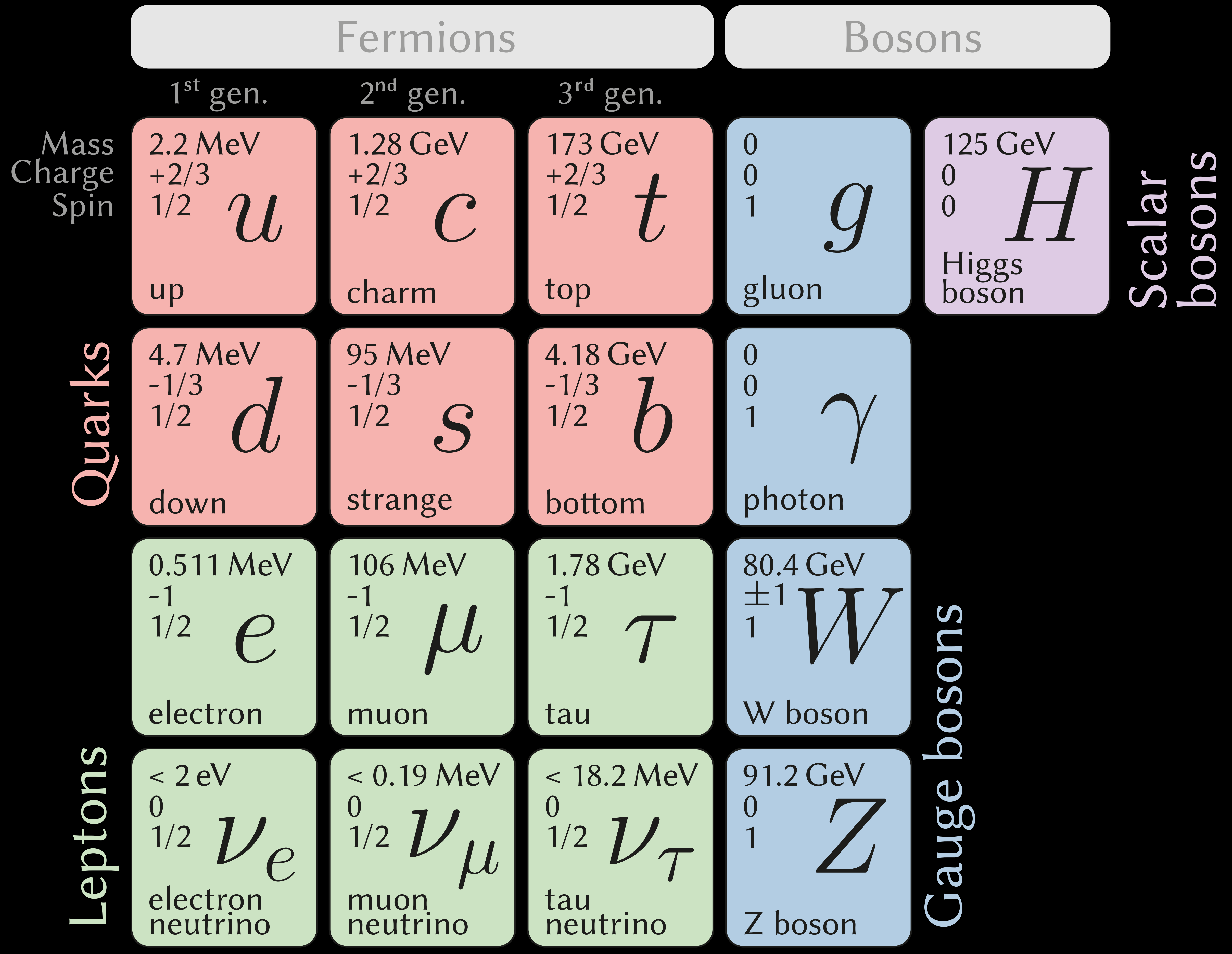
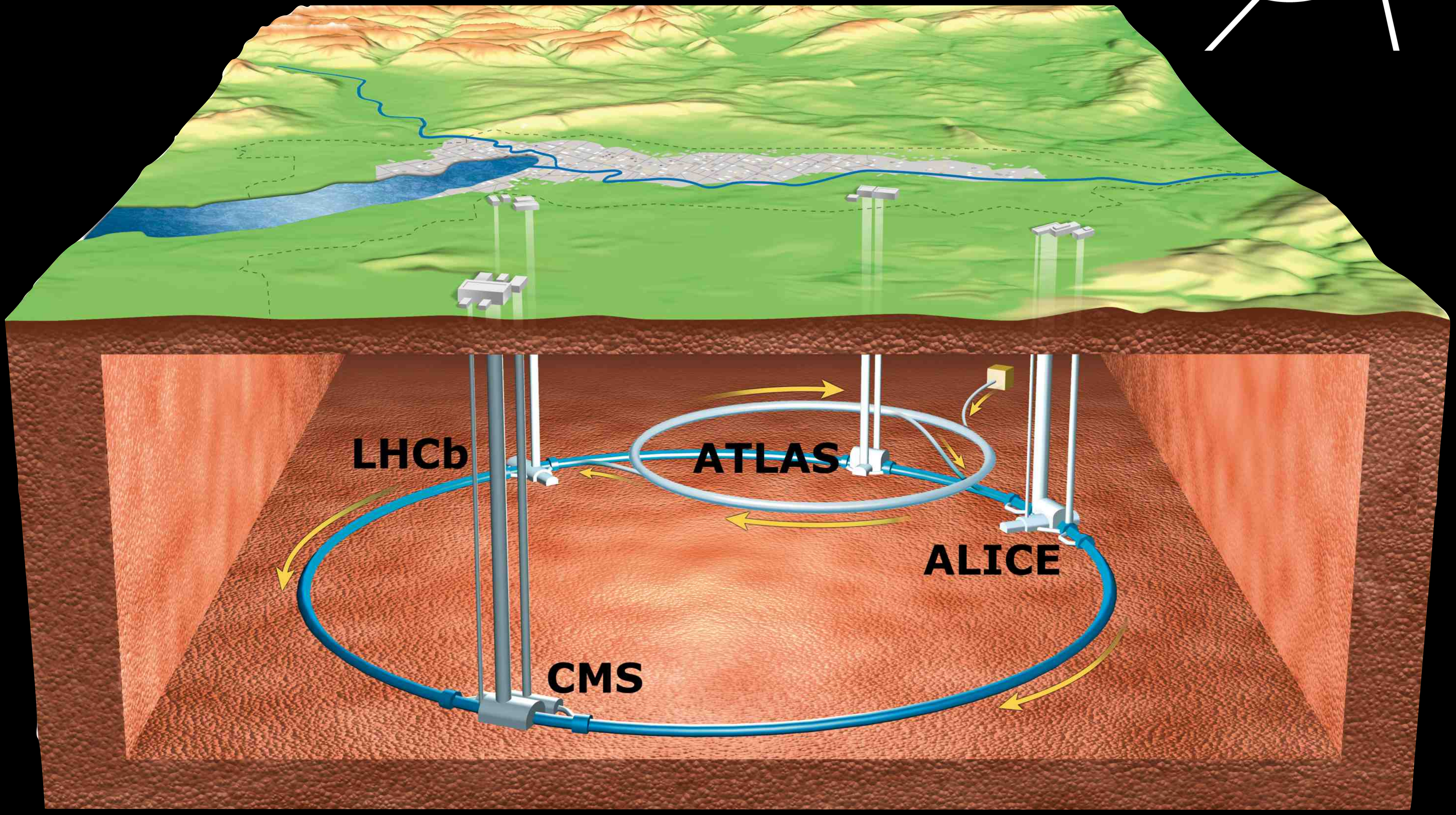
- Incredibly successful theory, predicting and explaining decades of experimental measurements, e.g.
  - Theory: $a_e = 0.001159652181643$
  - Measurement: $a_e = 0.00115965218073$
- Beautiful mathematical formulation - complex but fits on a t-shirt

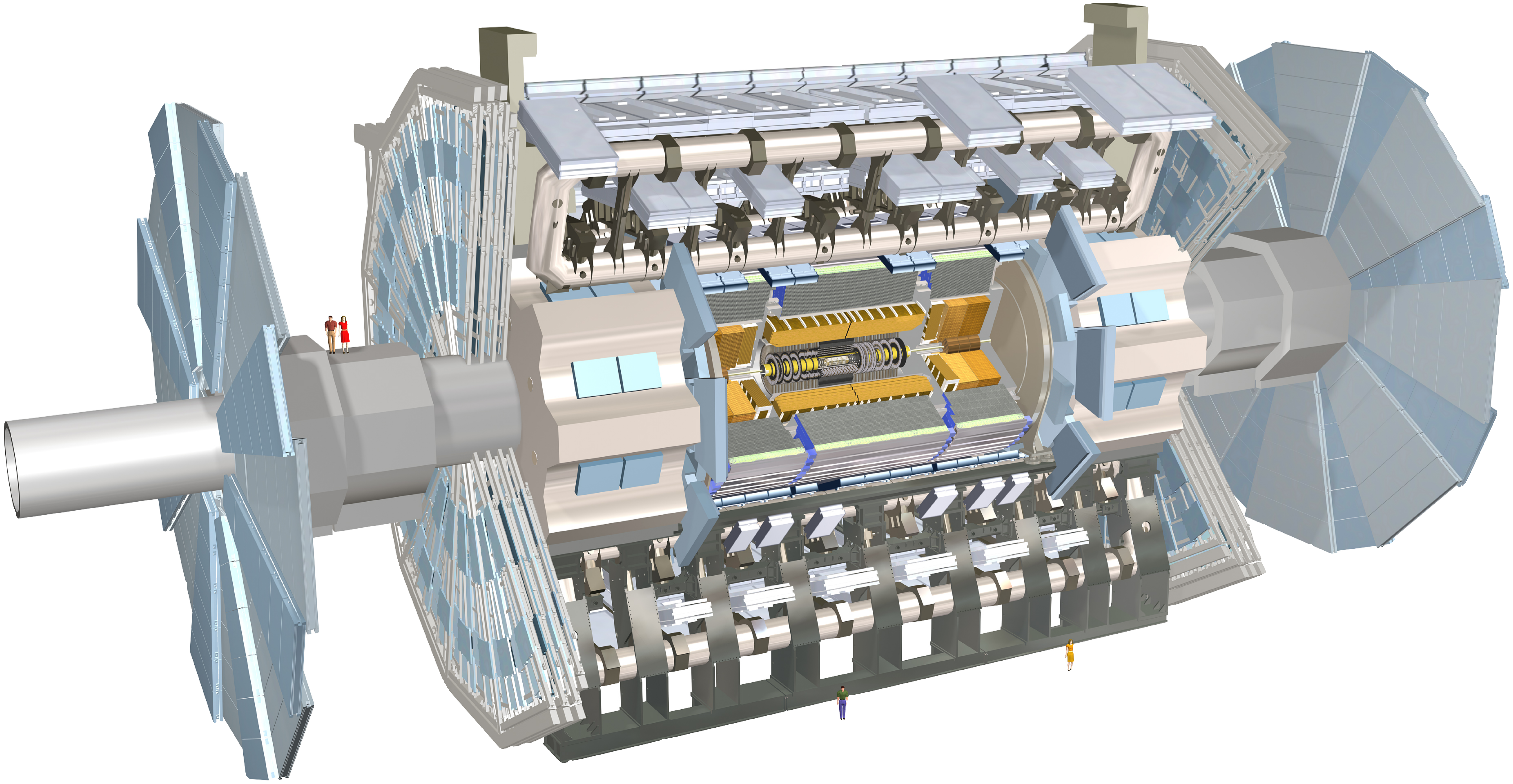


Large Hadron Collider (LHC)

- Circular underground tunnel, 27 km in circumference
- Beams of protons accelerated by electric fields in both directions to collision energy of 6.5+6.5 TeV (99.999999% of *c*)
- Superconducting magnets bend the beams to keep them in orbit
- Beams make 11 000 turns per second
- Planned since 1980s, first collisions in 2009



The ATLAS detector



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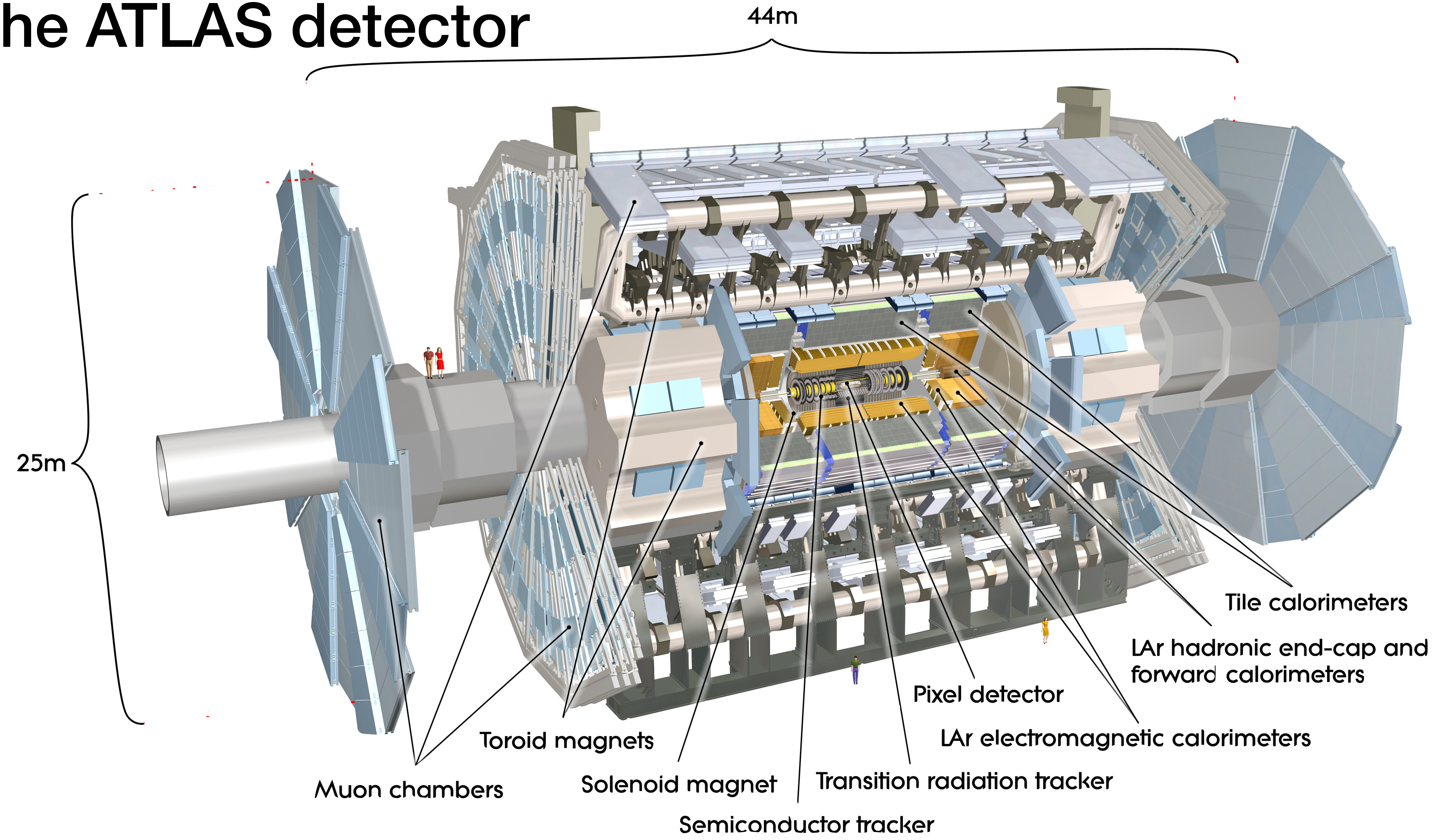

ATLAS Collaboration

- Formed in 1992, now includes ~5000 members (~3000 authors) from 181 institutions in 38 countries
- Around 1200 PhD students are being trained as researchers
- Most collaborators are at based at their home institutes, but during normal times we come to CERN to help operate the detector, discuss, plan for the future upgrades, etc

Many students find this fascinating, but a bit hard to grasp, and it sounds pretty far away from their experiences

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Can we overcome that?

History of our open-data labs

- In 2018 we decided to make a new lab for Applied Modern Physics (SH1015), a third-year course taken by ~120 students in the Engineering Physics BSc program

Content and learning outcomes

Course contents *

Lab. exercises where the student investigates several phenomena in modern physics

A project focusing on a research area within modern physics.

Intended learning outcomes *

After completing this course a student should be able to:

- report on practical experience concerning experimental methods within modern physics
- apply knowledge and problem solving skills in modern physics during lab experiments and project work.
- complete a simple research project with a modern physics focus as part of a small group

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  - **Challenge:** setting up the ***software environment*** needed is fragile and cumbersome - but there are new powerful tools!

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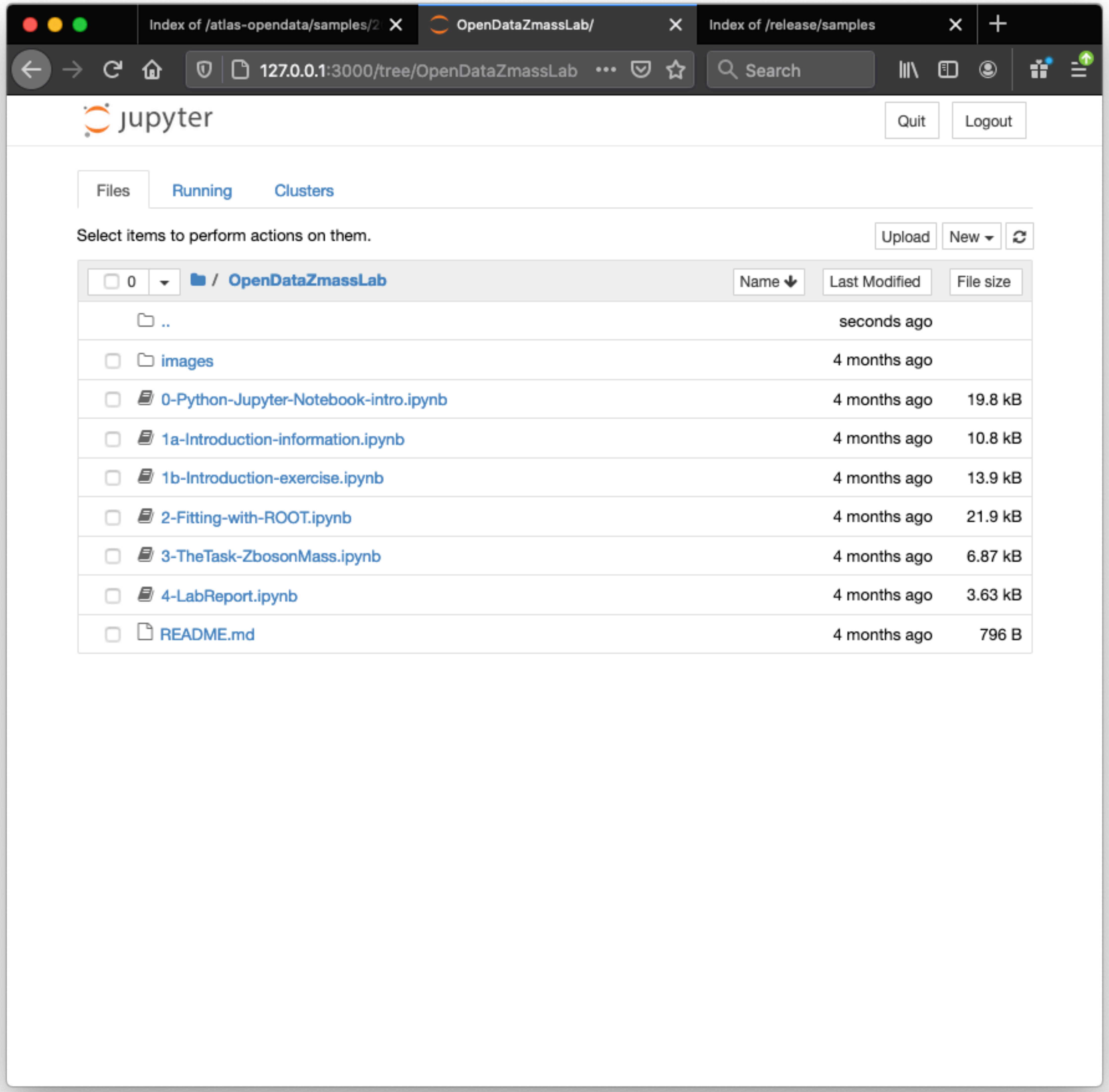
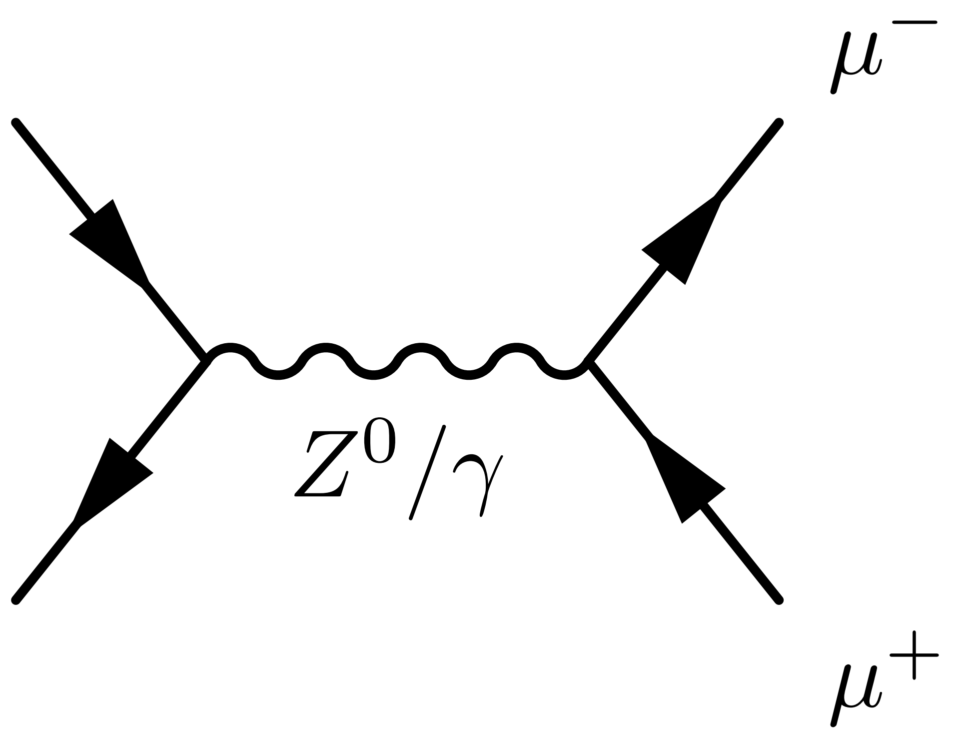
Jupiter notebooks





Feynman diagram shows what particles are produced in the decay and can be measured in the detector

- A series of notebooks contain brief tutorials:
  - python and ROOT: histograms, functions, looping over events
  - ATLAS: detector, coordinate systems, p_T, η, ϕ and ***invariant mass***
  - *Z* boson: role in SM, decay modes
  - How to fit a distribution, extract model parameters, determine fit quality (χ^2/n_DoF)

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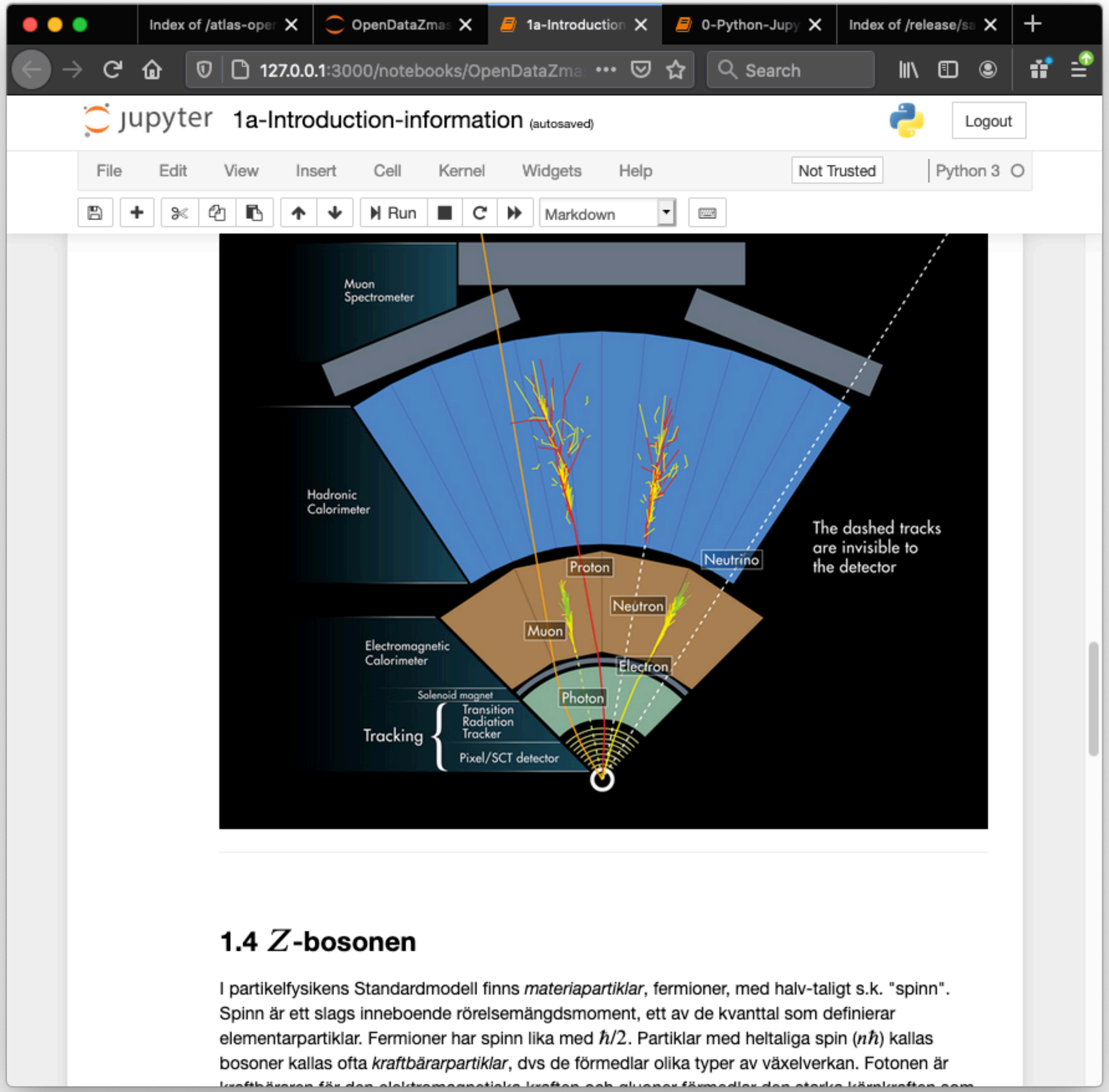

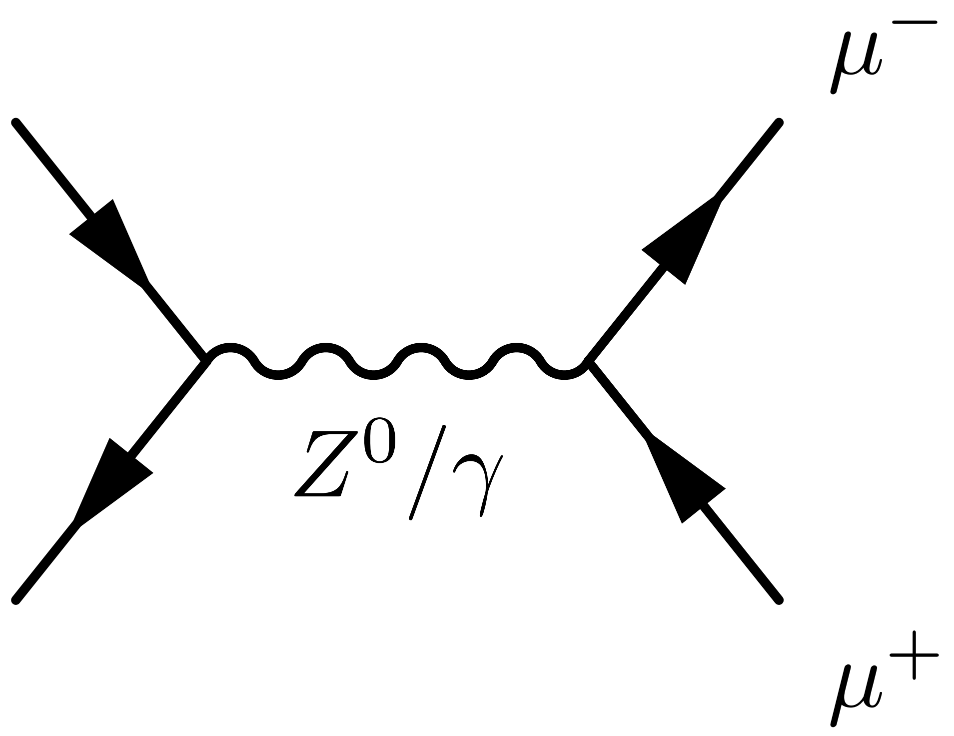

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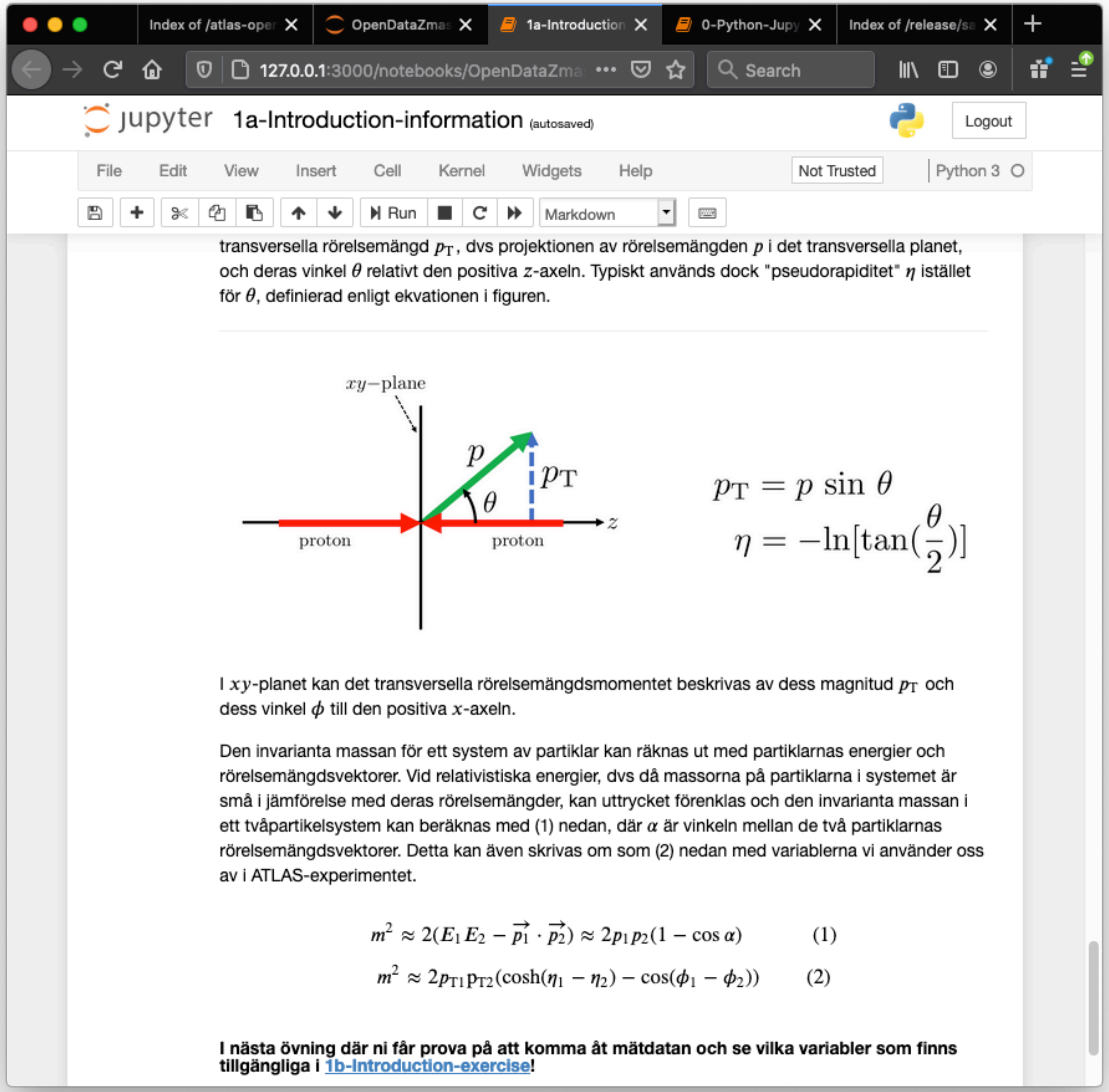

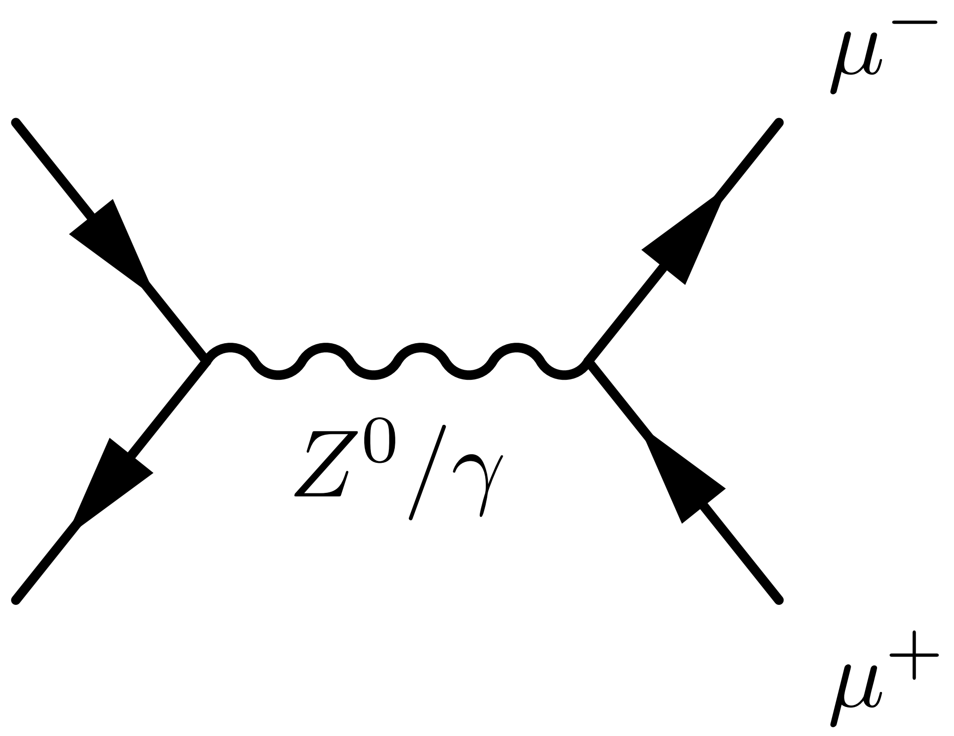

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Results from 1st year

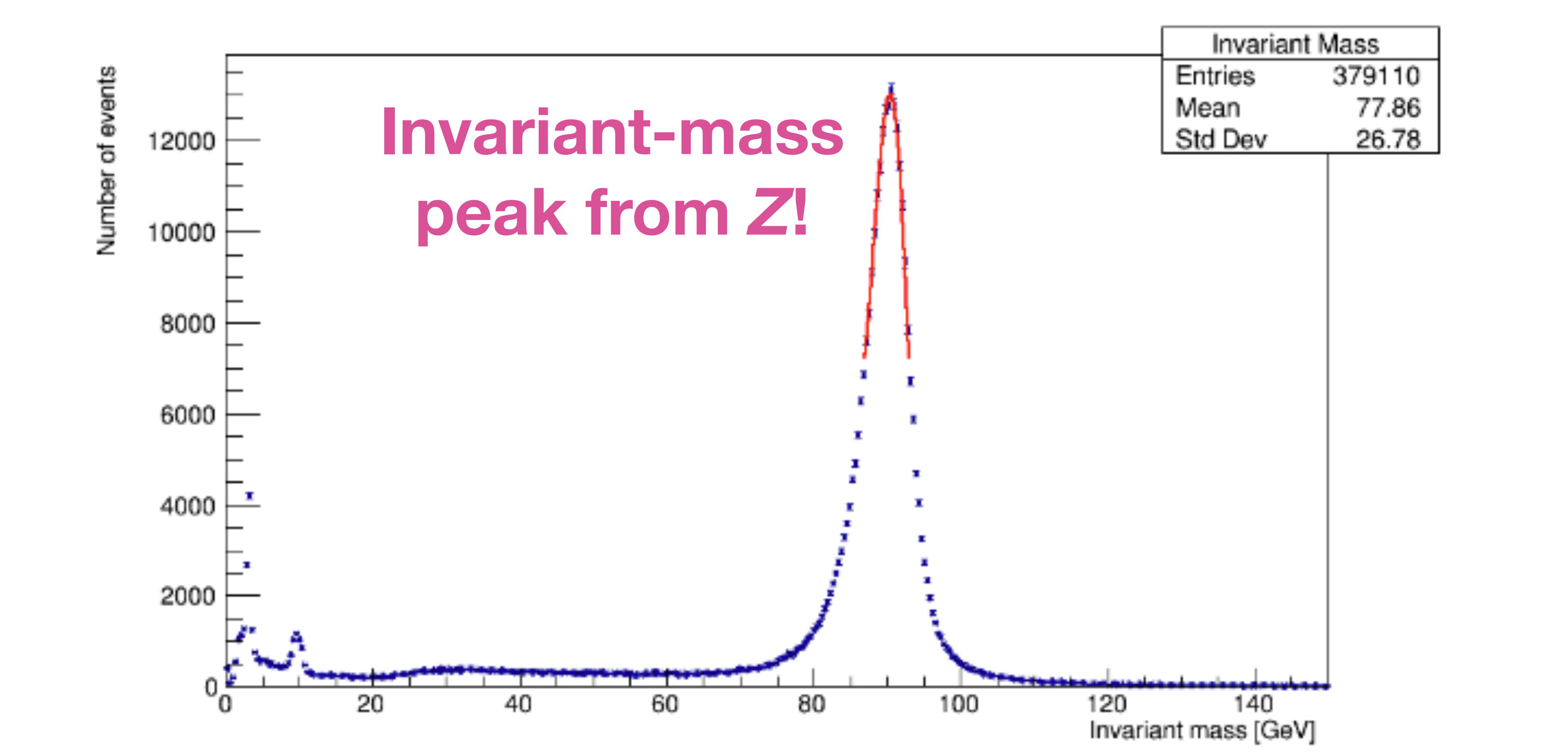
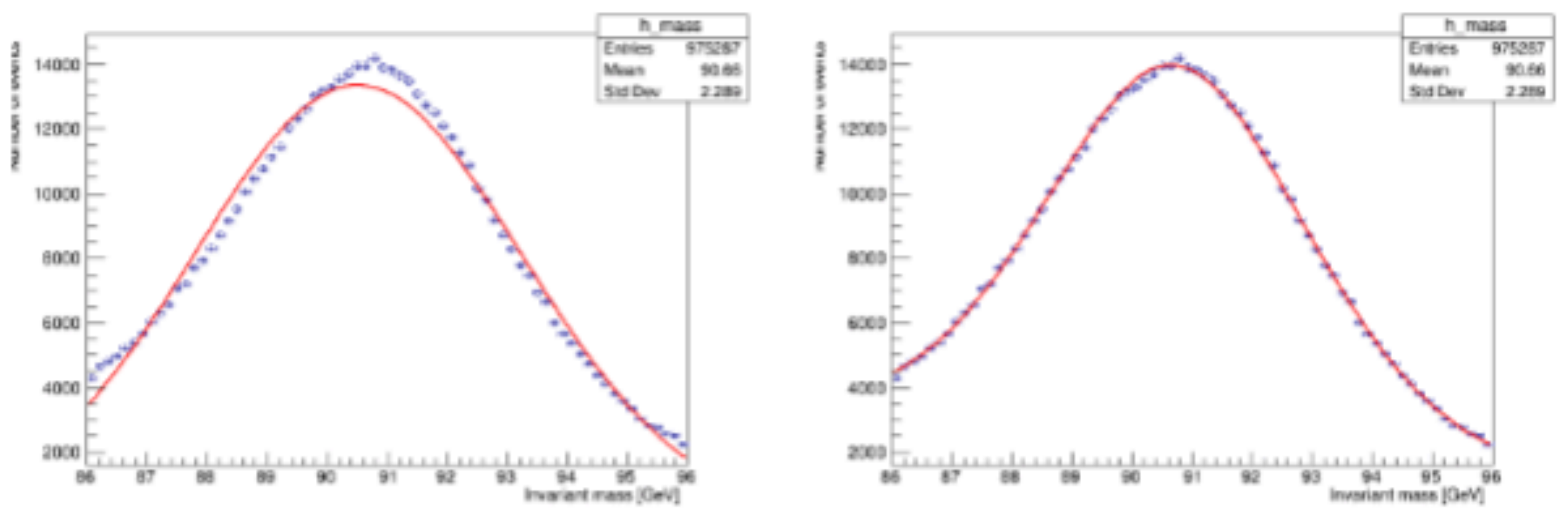


Figure 3: Invariant mass of the Z^0 boson, approximated as the function (4), on the range [87, 93] [GeV].

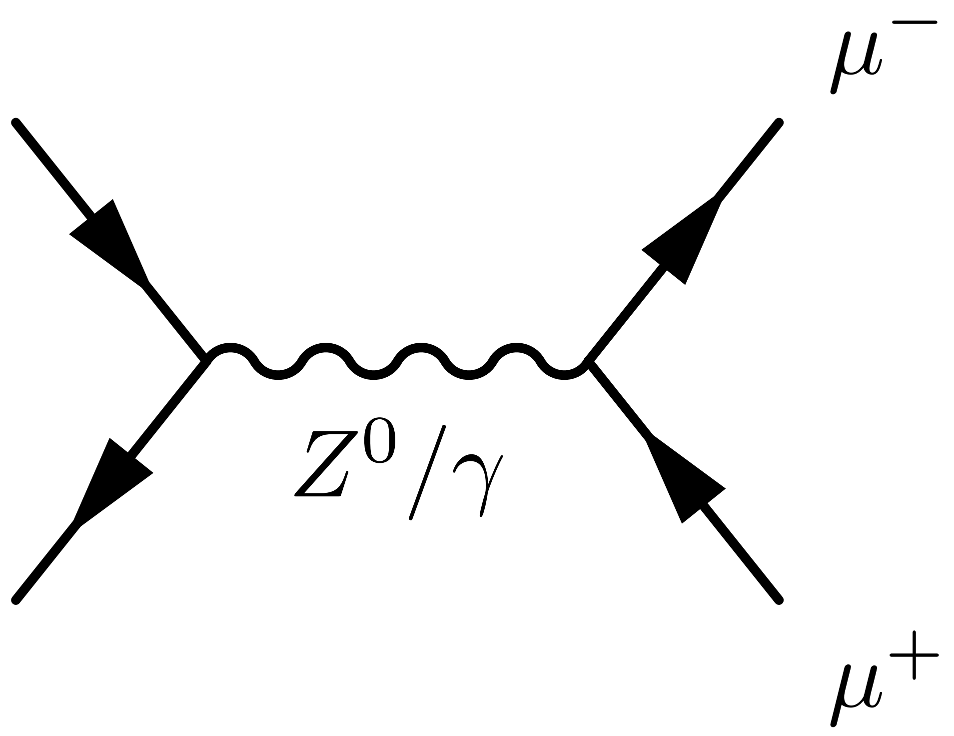
Z^0 boson mass SH1015 HT 2018



(a) Gaussian, χ^2/DF = 24.4

(b) Breit-Wigner + background, χ^2/DF = 1.2

Figure 5: Fitting different distributions to the results. DF signifies the number of degrees of freedom



Feynman diagram shows what particles are produced in the decay and can be measured in the detector

- Lots to learn:
  - Different Z shapes for e^+e^- and $\mu^+\mu^-$ - bremsstrahlung, resolution, etc
  - Width-lifetime connection
  - Background processes, small but still important to model

Another lab created in 2019

- ***Subatomic Physics*** (SH2103) is an ***intro to nuclear and particle physics***, compulsory for 4th-year students taking the *Subatomic and Astrophysics* MSc track - typically ~20 students (I took over as course responsible in 2019)
  - Mainly based around lectures, with two labs - one about nuclear physics and one about particle physics
  - Previous particle lab quite dated: shallow "analysis" of (old) event displays to learn a bit about signatures of different events at collider experiments
  - Coincided exactly with release of 10 fb^{-1} of data —> decided to let the students try to find the Higgs!

Subatomic Physics (SH2103), 7.5 hp

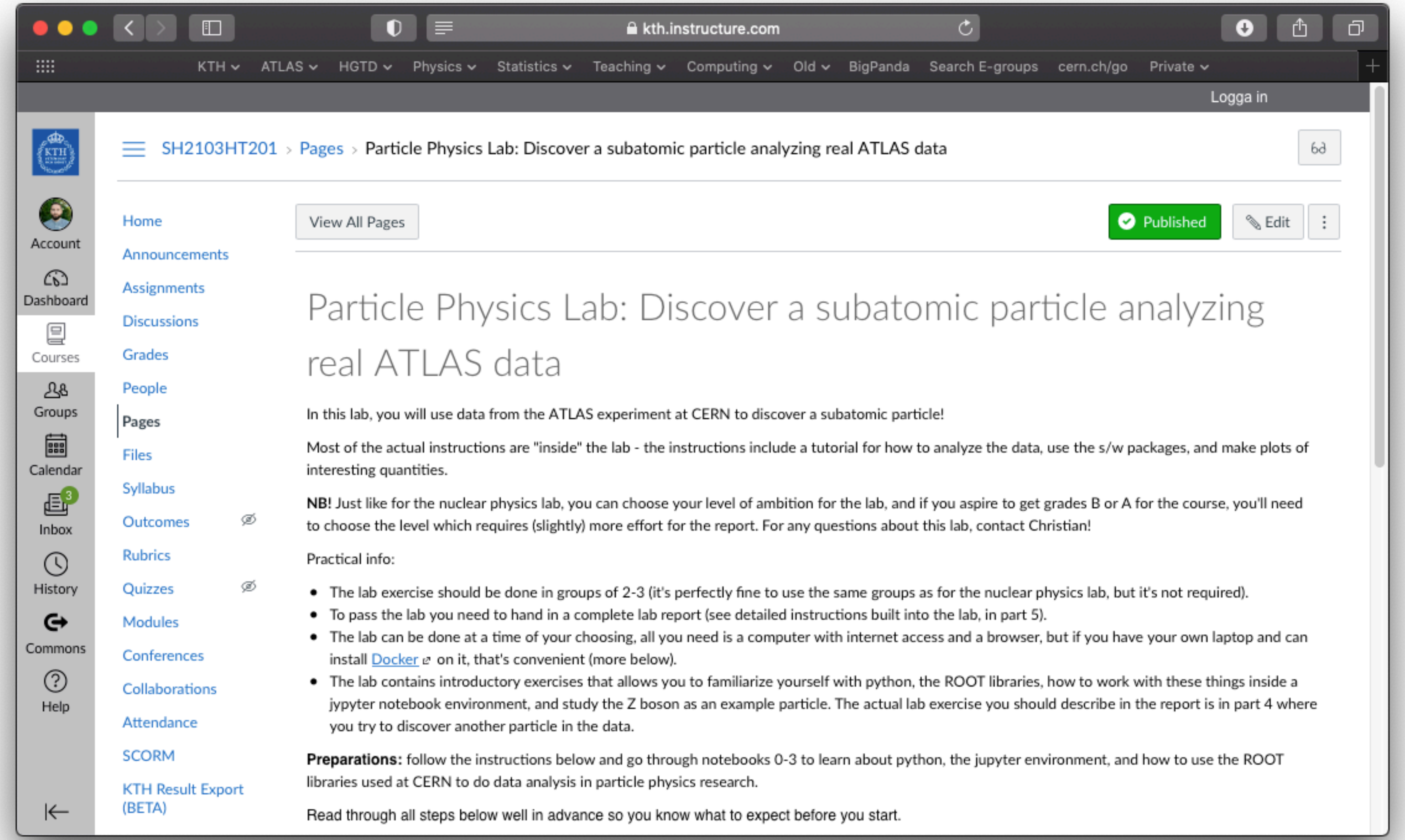
Course Coordinator: Christian Ohm, Particle Physics, KTH
Lecturers: Ayse Atac Nyberg (aanyber@kth.se) and Christian Ohm (chohm@kth.se)
Course Code: SH2103
Credits: 7.5 hp
Grades: A,B,C,D,E,F,Fx
Language: English

Compulsory Course for the Subatomic specialisation of the Master Programme in Engineering Physics.

The course is scheduled in Period 2 (October-December) and starts on October 28, 2019, 13-15, in FD41 at Albanova. The schedule is available in KTH Social, and will be updated with any changes automatically for registered students who have subscribed to it.

Lectures: 36 hours
Lab. Exercises 2x5 hours

Instructions



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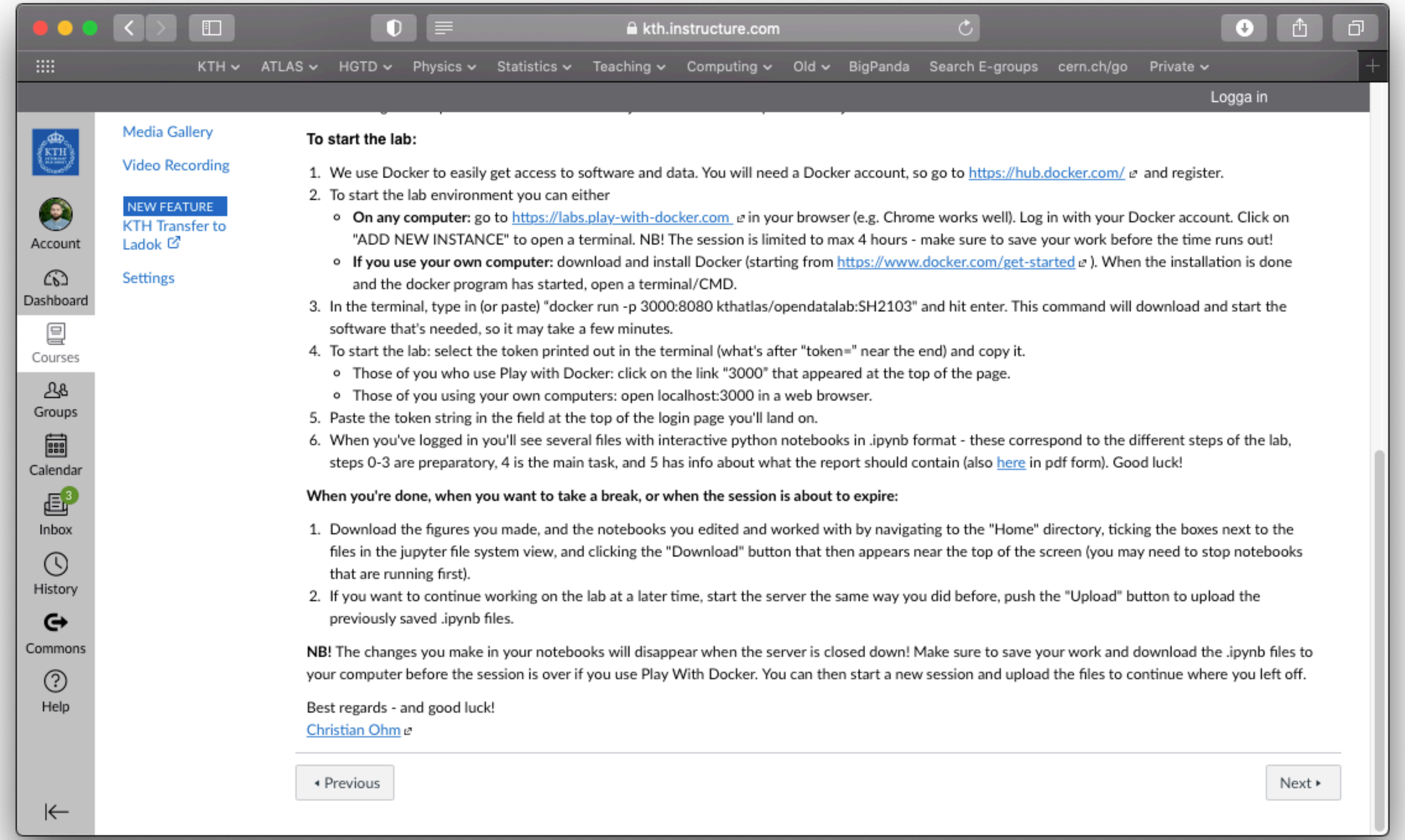
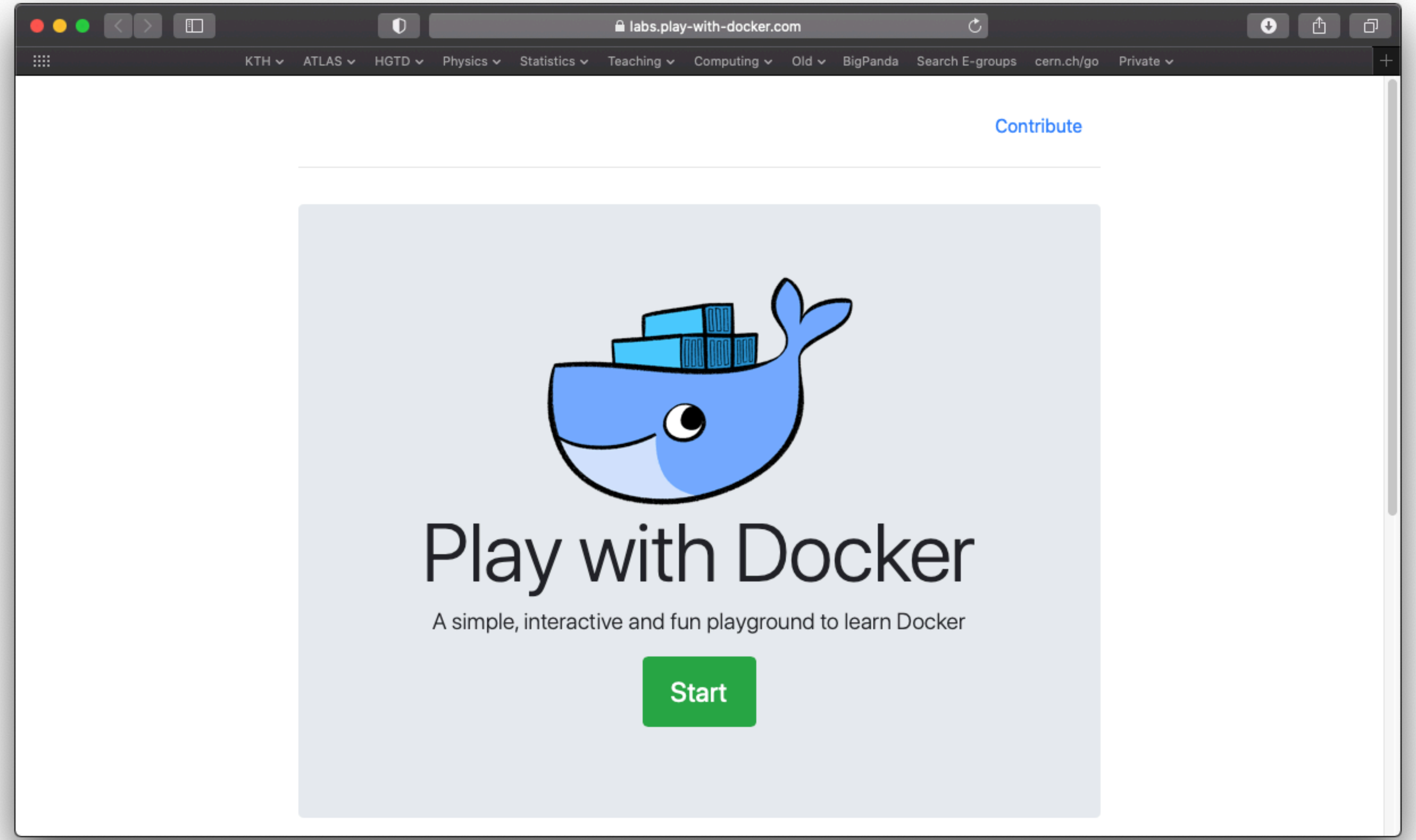


- Clear instructions are imperative!
- Especially important for ***technical instructions!***
- Tried to be as clear as possible first year, refined technical setup and covered corner cases based on student experiences

Play with Docker



- Benefit of Docker - they provide sandbox with web interface → all that's needed is a browser!

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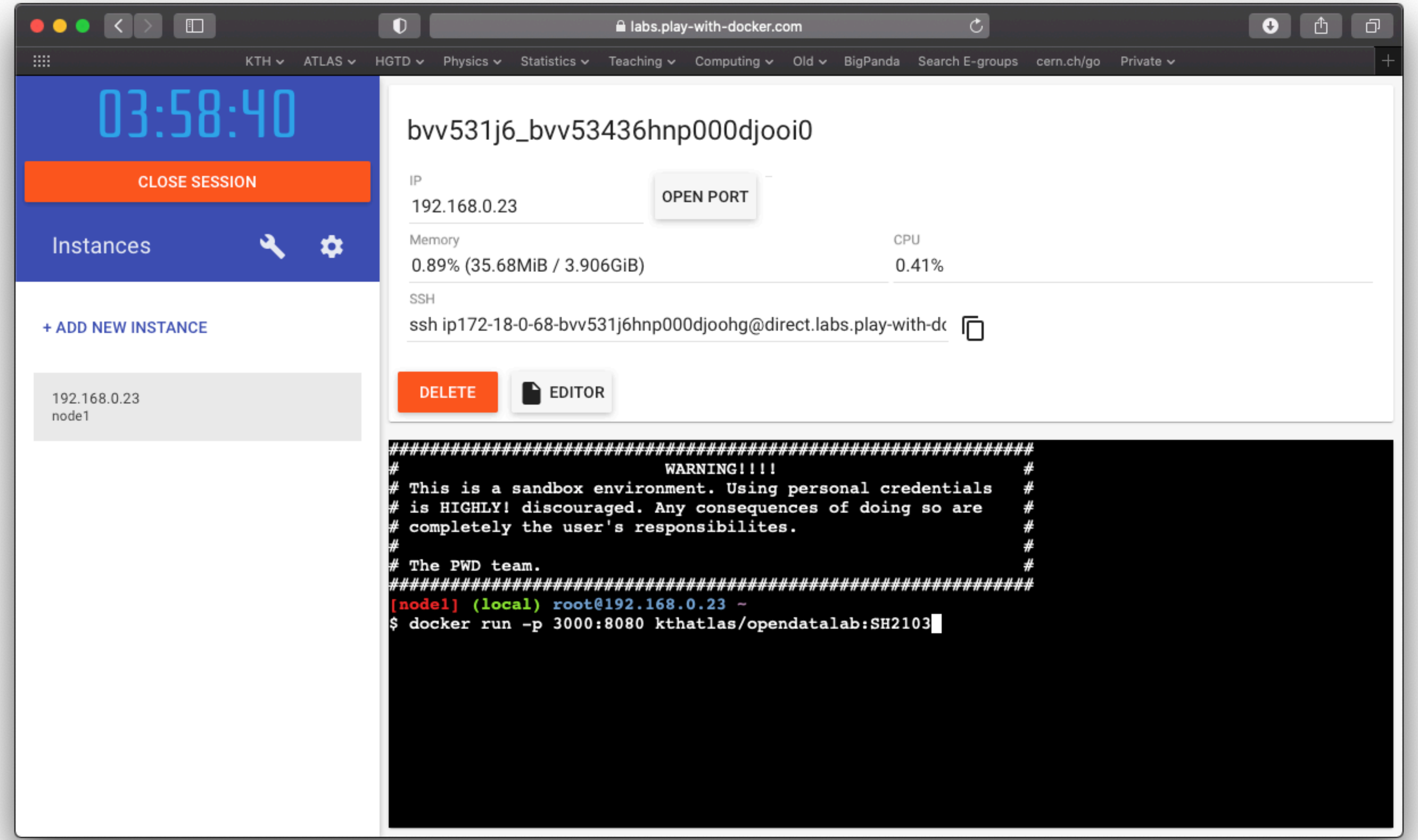

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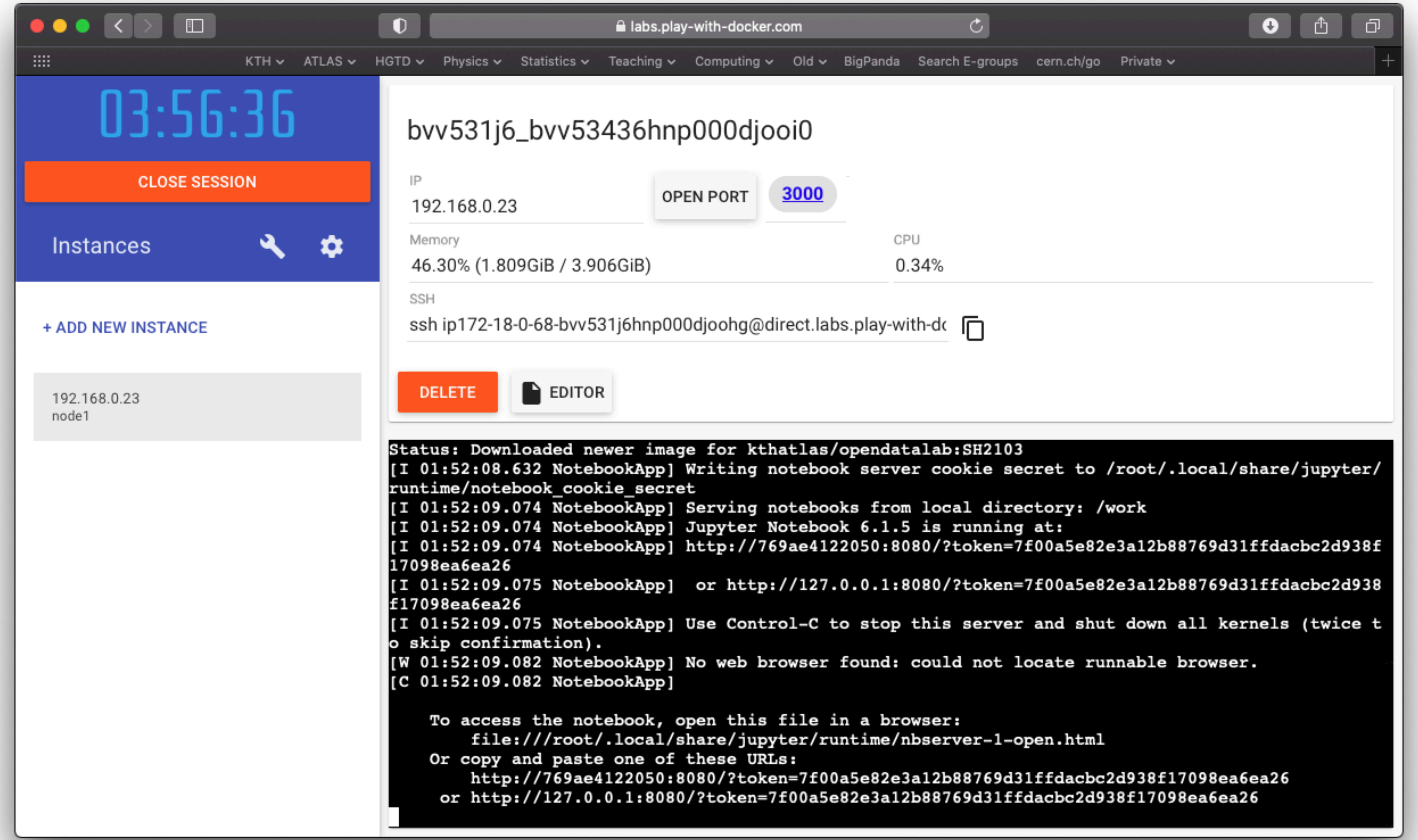

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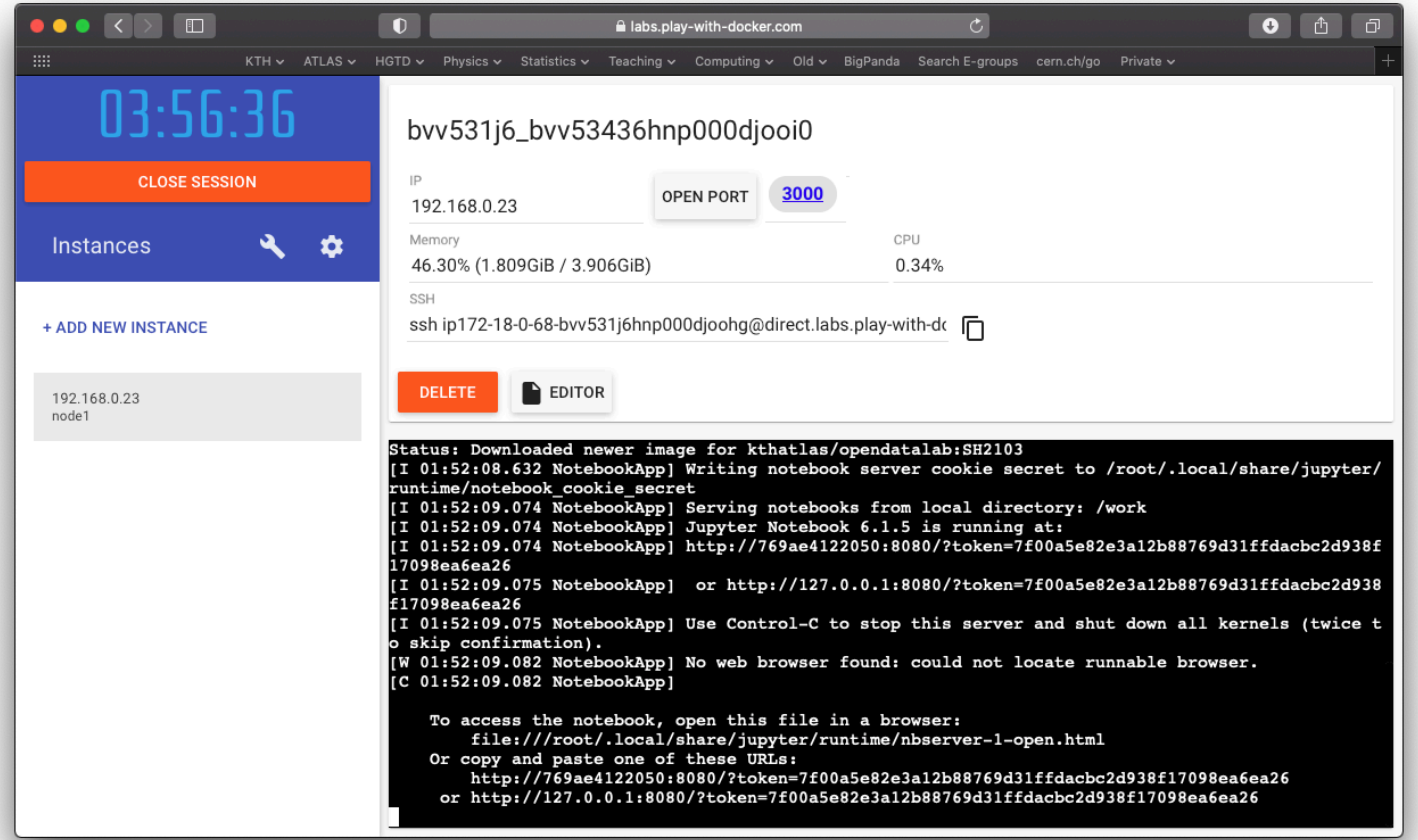

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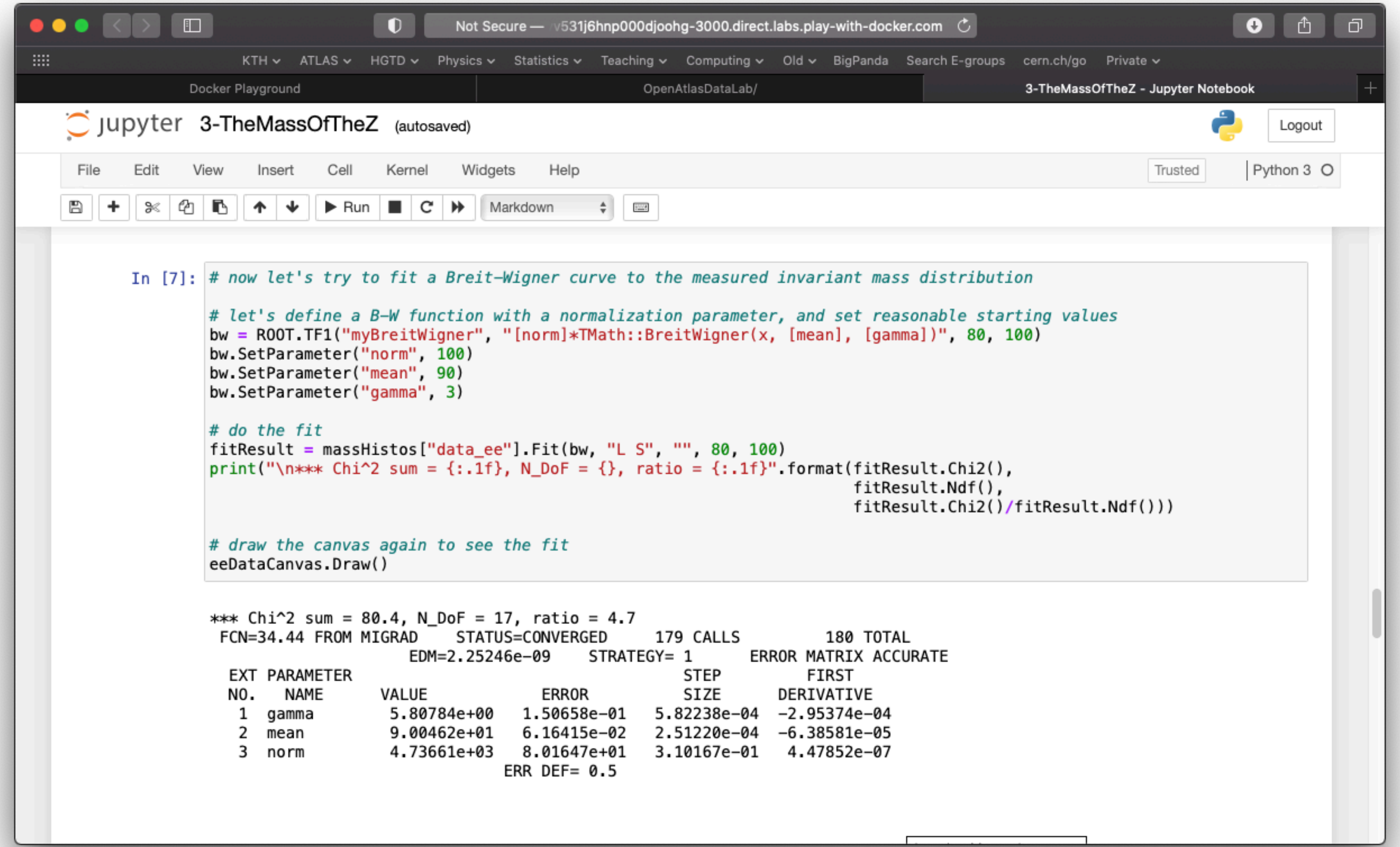
- NB! Always think about ***backup solutions*** when using third party services - probably can't rely on this service to always be available

Use Z as example




```
# now let's try to fit a Breit-Wigner curve to the measured invariant mass distribution

# let's define a B-W function with a normalization parameter, and set reasonable starting values
bw = ROOT.TF1("myBreitWigner", "[norm]*TMath::BreitWigner(x, [mean], [gamma])", 80, 100)
bw.SetParameter("norm", 100)
bw.SetParameter("mean", 90)
bw.SetParameter("gamma", 3)

# do the fit
fitResult = massHistos["data_ee"].Fit(bw, "L S", "", 80, 100)
print("\n*** Chi^2 sum = {:.1f}, N_DoF = {}, ratio = {:.1f}".format(fitResult.Chi2(),
                                                                    fitResult.Ndf(),
                                                                    fitResult.Chi2()/fitResult.Ndf()))


# draw the canvas again to see the fit
eeDataCanvas.Draw()
```

```
*** Chi^2 sum = 80.4, N_DoF = 17, ratio = 4.7
 FCN=34.44 FROM MIGRAD    STATUS=CONVERGED     179 CALLS         180 TOTAL
                     EDM=2.25246e-09    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                   STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  gamma        5.80784e+00   1.50658e-01   5.82238e-04  -2.95374e-04
   2  mean         9.00462e+01   6.16415e-02   2.51220e-04  -6.38581e-05
   3  norm         4.73661e+03   8.01647e+01   3.10167e-01   4.47852e-07
                               ERR DEF= 0.5
```

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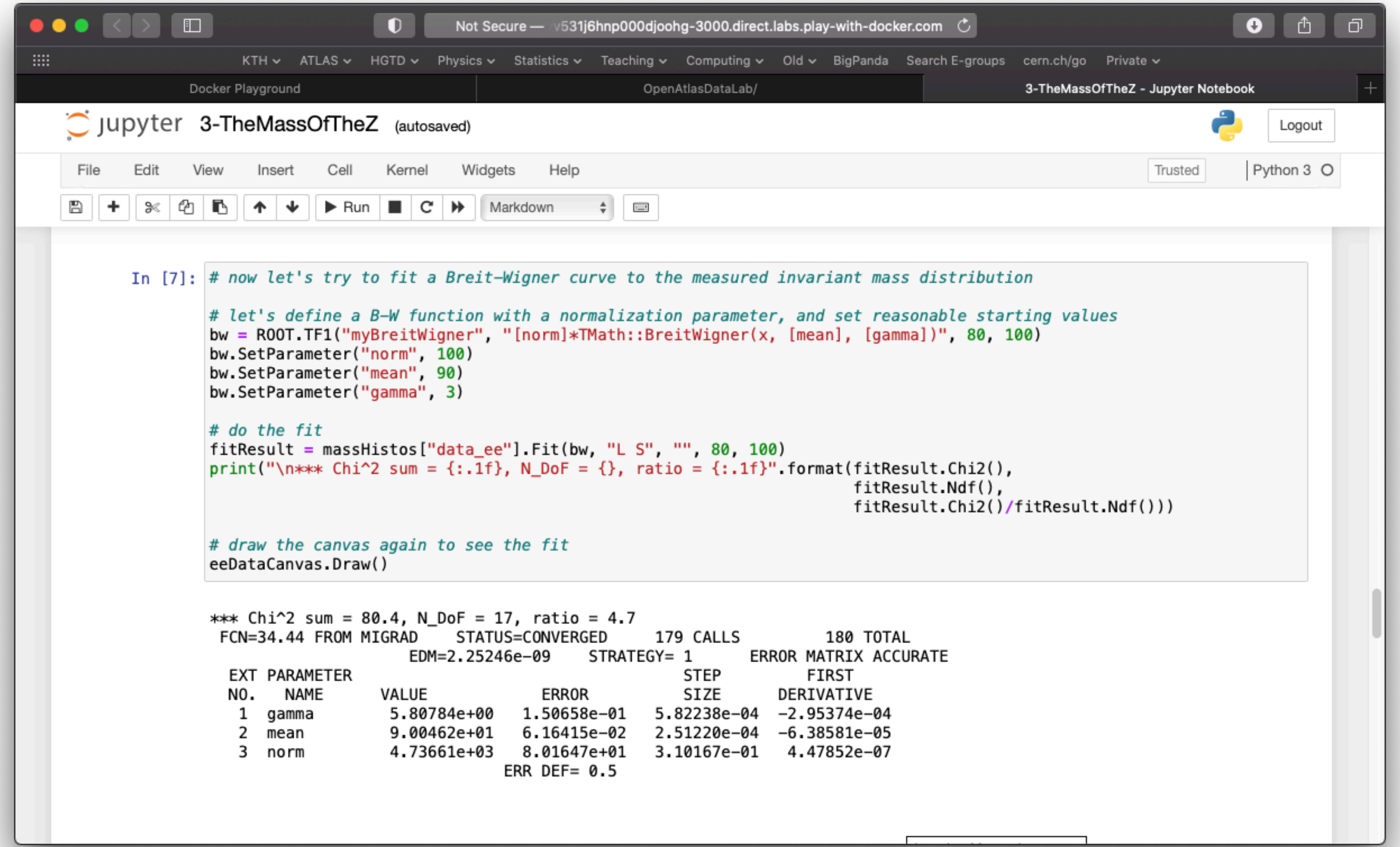

- Focus of this lab is more on the physics

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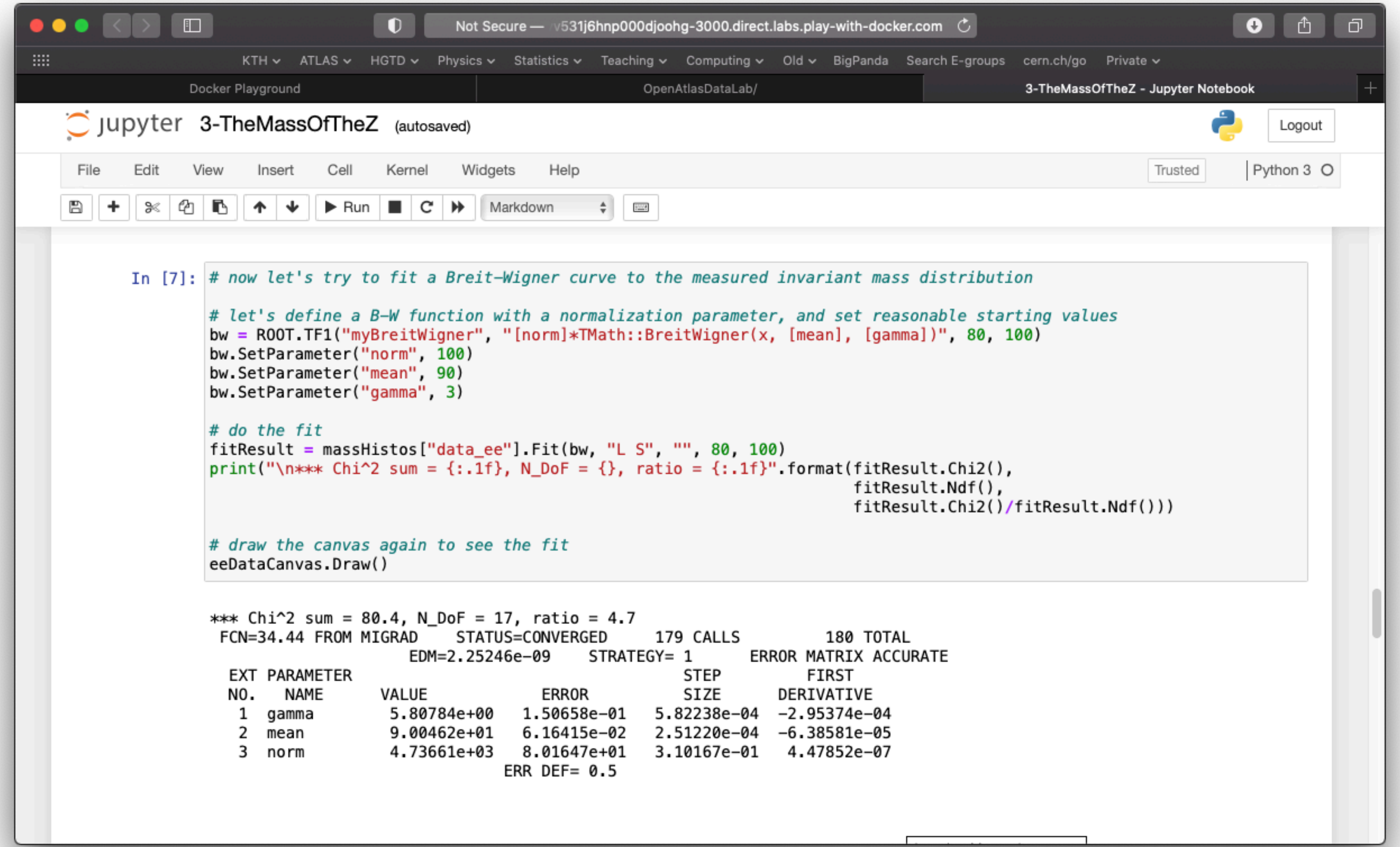

- Focus of this lab is more on the physics
- Give example of $Z \to \ell^+\ell^-$

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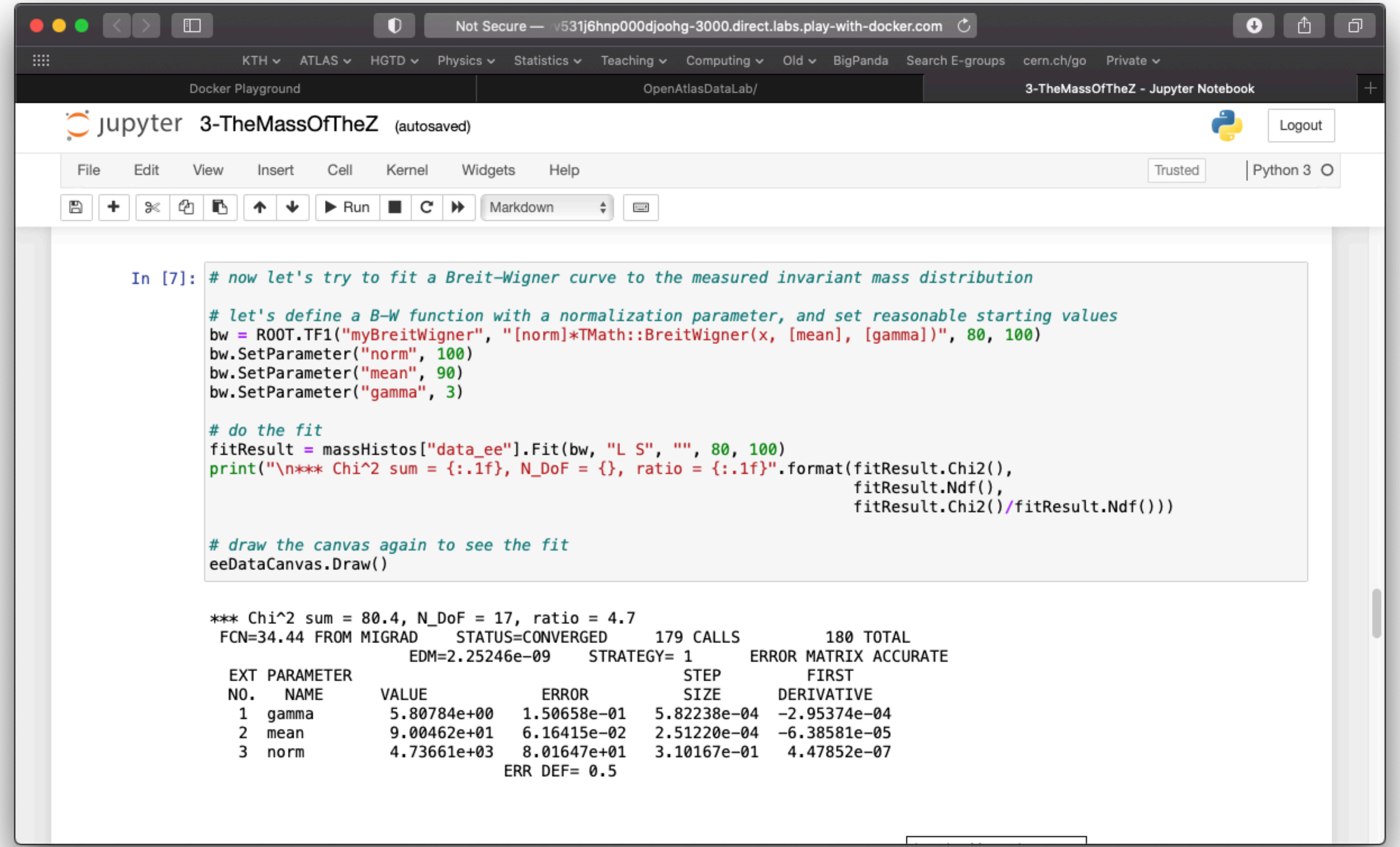
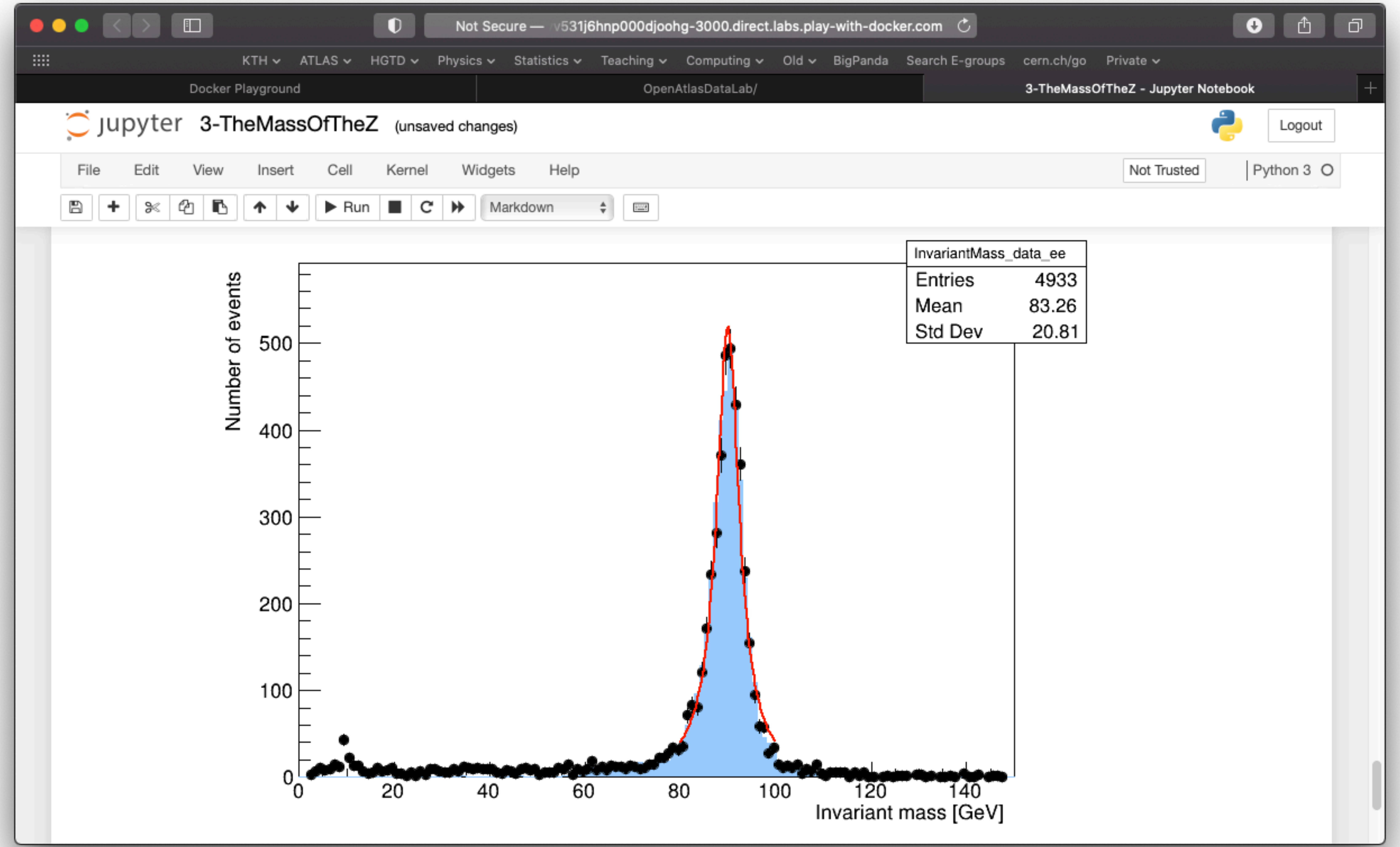


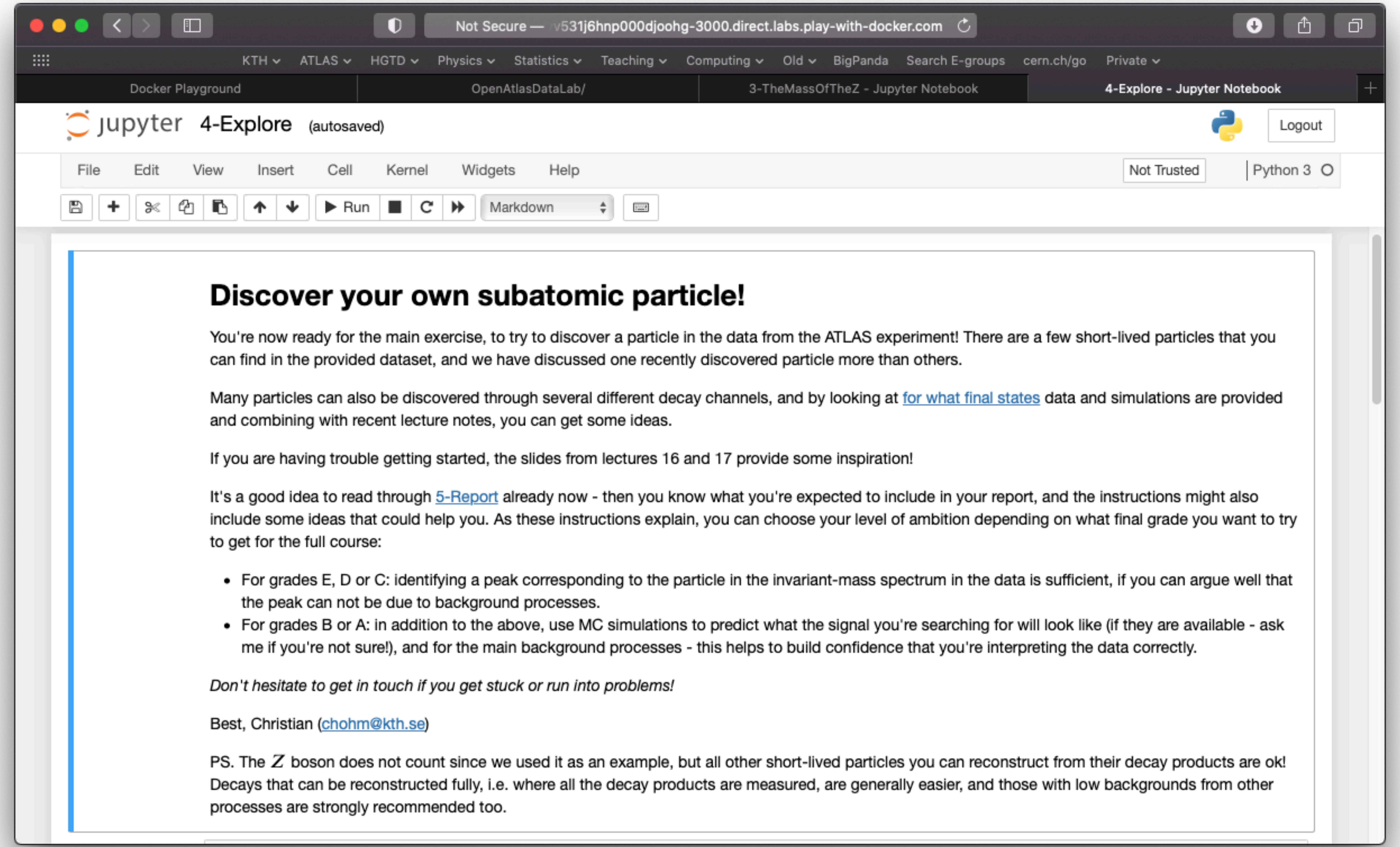
- Focus of this lab is more on the physics
- Give example of $Z \to \ell^+\ell^-$

Use Z as example



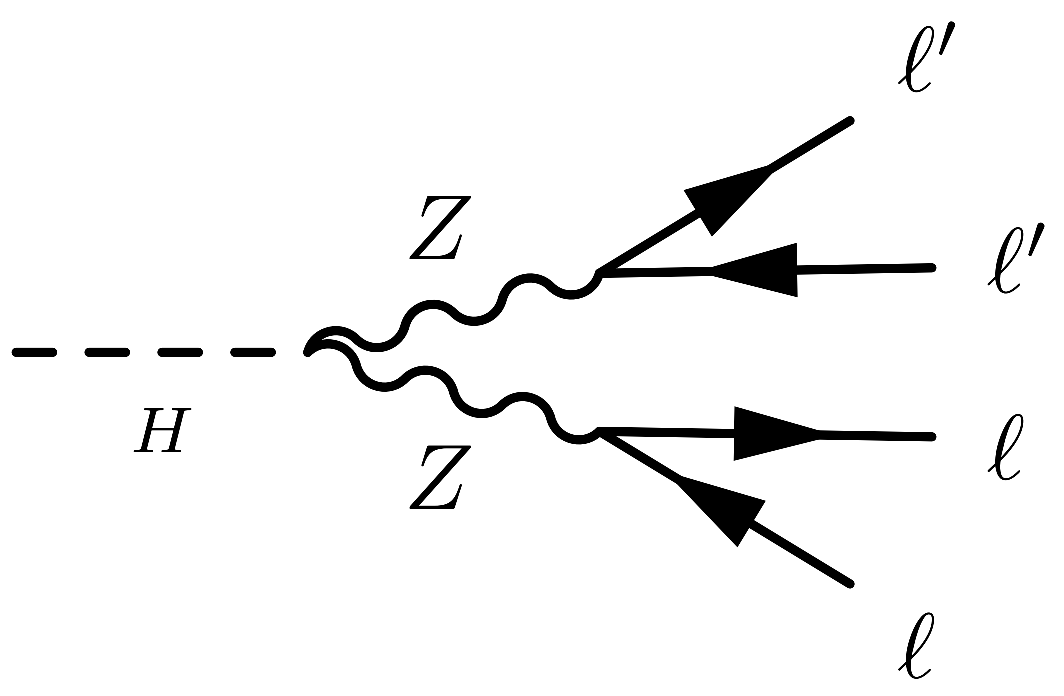
- Focus of this lab is more on the physics
- Give example of $Z \rightarrow \ell^+\ell^-$

The task (bare bones)



- Focus of this lab is more on the physics
- Give example of $Z \to \ell^+\ell^-$
- More open task: ***explore the data and try to find a subatomic particle!***

Results



- The lectures given when the lab is made available is focused on the discovery of the Higgs — most students take the hint and try to find it in the data!

- Quite nice results! This is without much more than requiring two OSSF lepton pairs!

- Also had one group that tried both 4l and diphoton - the latter requires quite a bit more work, but the students went digging in the Higgs discovery papers for details and managed to dig out a small bump

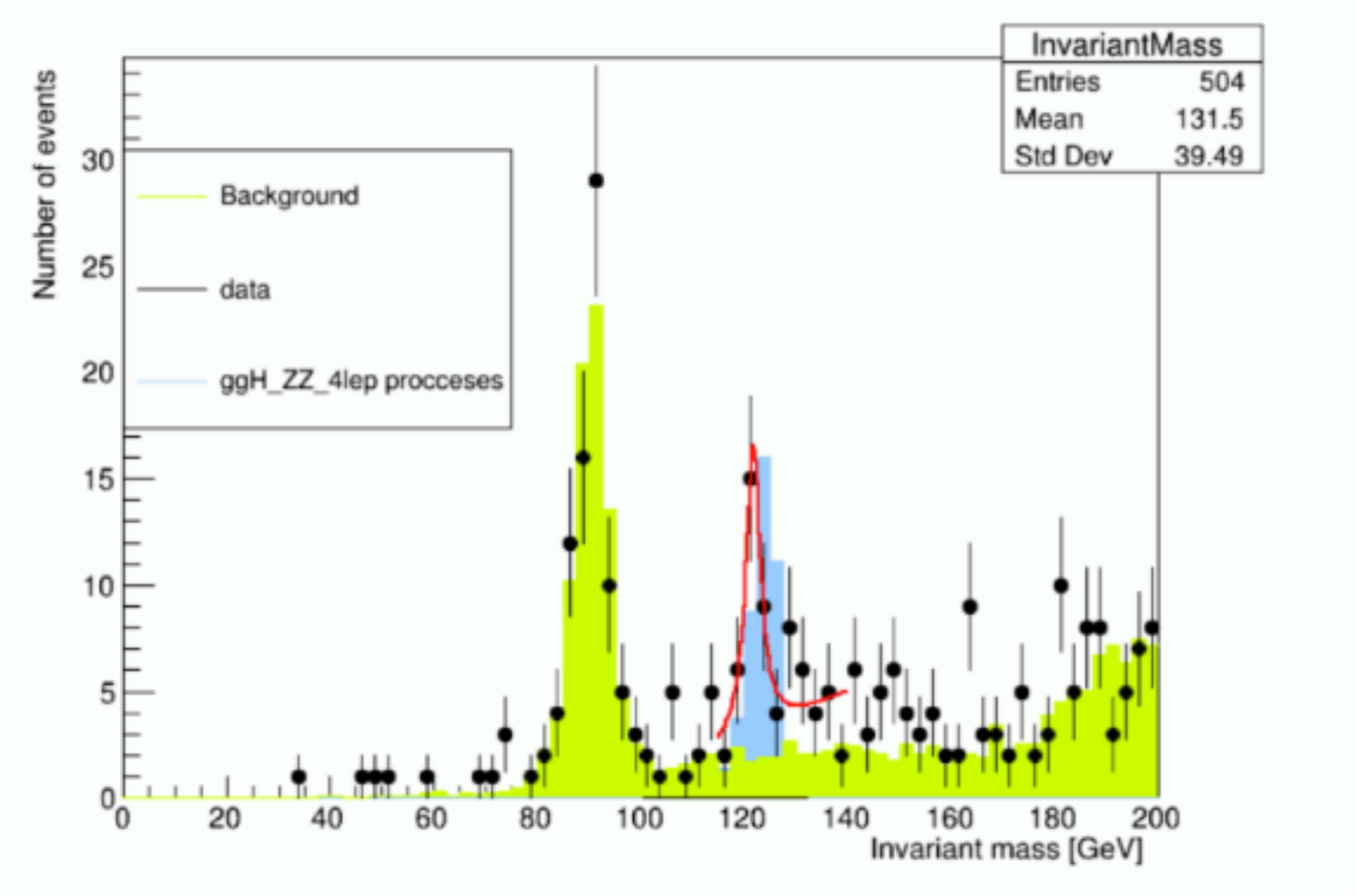


Figure 2.2.7: The simulated invariant mass histogram for the production of the Higgs boson and the simulated invariant mass histogram for background processes resulting in 4 lepton on top of the experimentally attained invariant mass histogram for the production of 4 leptons.

The students like it!

What was the best aspect of the course?

What was the best aspect of the course? (I worked: 6-8 timmar/vecka)
The labs were fun and the teachers nice.
The course was interesting. The material was well contained within the literature and lectures (although I did not attend the lectures, the lecture slides were helpful).
The teachers. I they were both very inspiring
Hands down the Particle Physics lab. Very interesting to be able to work with real ATLAS data. In general I think the labs were very useful in understanding the material and its relevance.
To learn about interesting things in the science of subatomic physics

What was the best aspect of the course? (I worked: 9-11 timmar/vecka)
The teachers

What was the best aspect of the course? (I worked: 12-14 timmar/vecka)
The course curriculum was well defined and scheduling was well structured to divide the course and not burden the students at the end of the semester.

What was the best aspect of the course? (I worked: 15-17 timmar/vecka)
The particle physics part was interesting.

The students like it!

What was the best aspect of the course?

What was the best aspect of the course? (I worked: 6-8 timmar/vecka)
The lab exercises.

What was the best aspect of the course? (I worked: 9-11 timmar/vecka)
Jag tyckte att de två bästa var att det var en bra sammanfattande och inledande kurs i programmet, samt labbarna.
I really enjoyed the Particle Physics Lab ! Truly a great way to apply what we learn to real data.
The constant reminders and ways to try and teach us difficult concepts which made them stick e.g Feynman diagram.

What was the best aspect of the course? (I worked: 12-14 timmar/vecka)
The organization and order of topics was logical and easy to follow. Also high engagement from the teachers which made the subjects more interesting to study.
Learning more about particle and nuclear physics. The fact that the course was open and inclusive, and that it was really important to the teacher. I felt welcome in this course. The teachers, they were open, were there to help us achieve and learn new things.
The quiz in the end of lectures
In general it was an interesting topic and good lecturers.

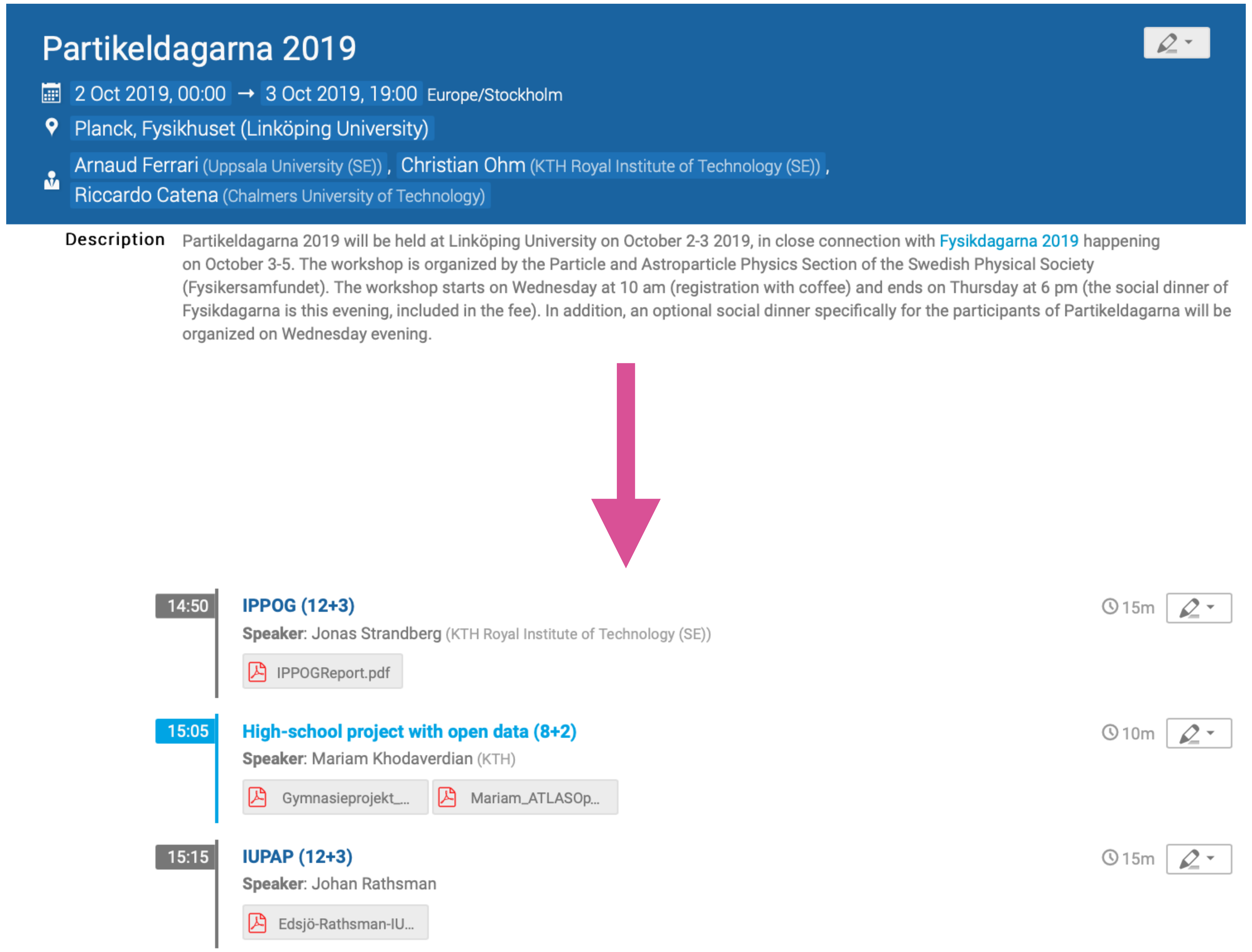
What was the best aspect of the course? (I worked: 15-17 timmar/vecka)
The labs and the teachers passion from the subject
The nuclear lab was very fun. I also liked all the lectures

What was the best aspect of the course? (I worked: 18-20 timmar/vecka)
The labs were very interesting. I love the subject.

Works also for high school

(Link to agenda)

- Every now and then get contacted by high school students who are interested in particle physics
- Tried to use this setup for such a project — worked very well!
- Student had very rudimentary experience with programming but learned python quite quickly and could analyse the research data — got a lot more done than I had hoped!



Works also for high school

[(Link to agenda)]

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Partikeldagarna 2019

2 Oct 2019, 00:00 → 3 Oct 2019, 19:00 Europe/Stockholm

Planck, Fysikhuset (Linköping University)

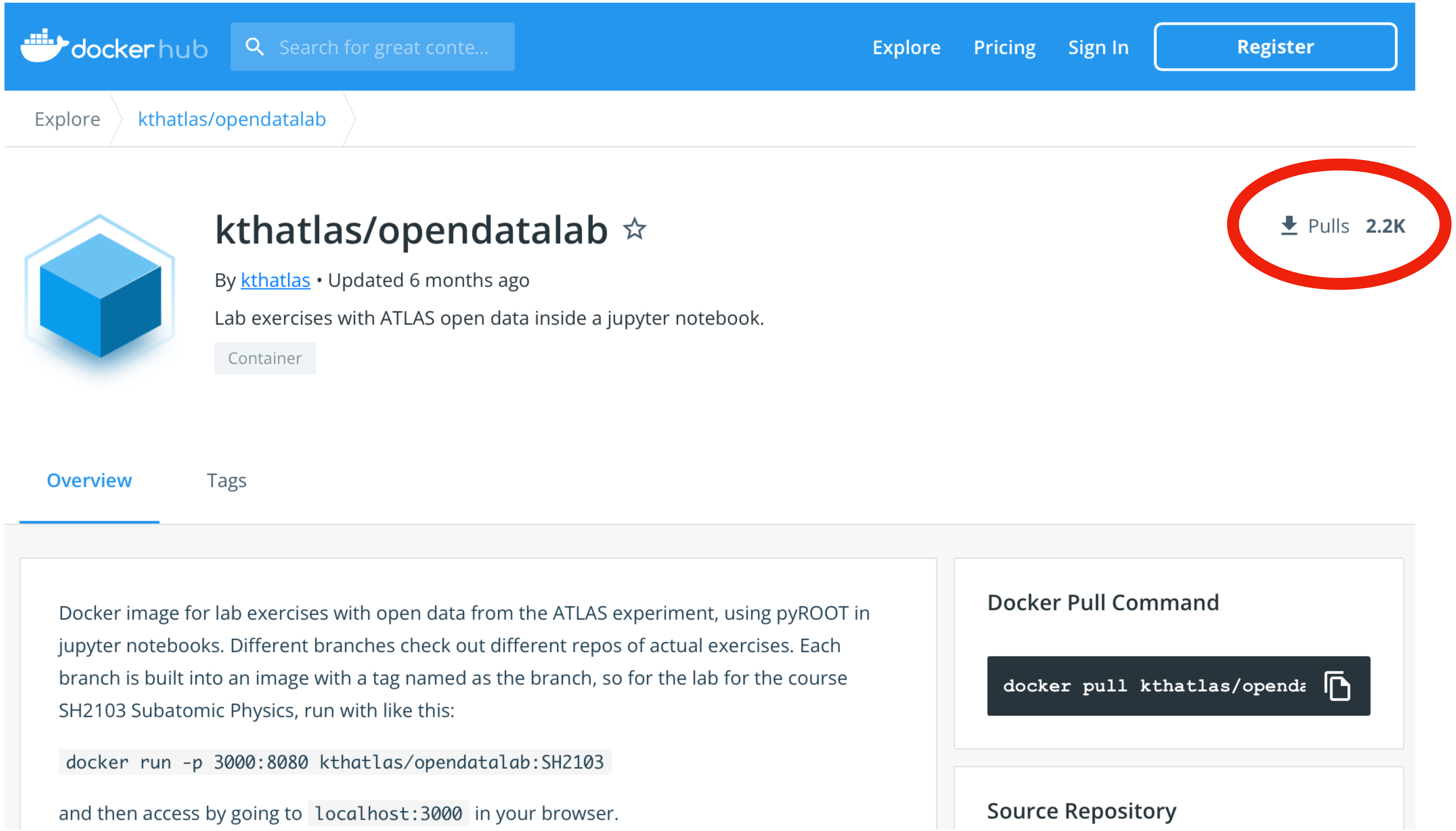
Arnaud Ferrari (Uppsala University (SE)), Christian Ohm (KTH Royal Institute of Technology (SE)), Riccardo Catena (Chalmers University of Technology)

Description: Partikeldagarna 2019 will be held at Linköping University on October 2-3 2019, in close connection with Fysikdagarna 2019 happening on October 3-5. The workshop is organized by the Particle and Astroparticle Physics Section of the Swedish Physical Society (Fysikersamfundet). The workshop starts on Wednesday at 10 am (registration with coffee) and ends on Thursday at 6 pm (the social dinner of Fysikdagarna is this evening, included in the fee). In addition, an optional social dinner specifically for the participants of Partikeldagarna will be organized on Wednesday evening.

My experience

- Fun and interesting
- New concepts
- Challenging
- Most difficult: ROOT and programming
- Most interesting: The theory

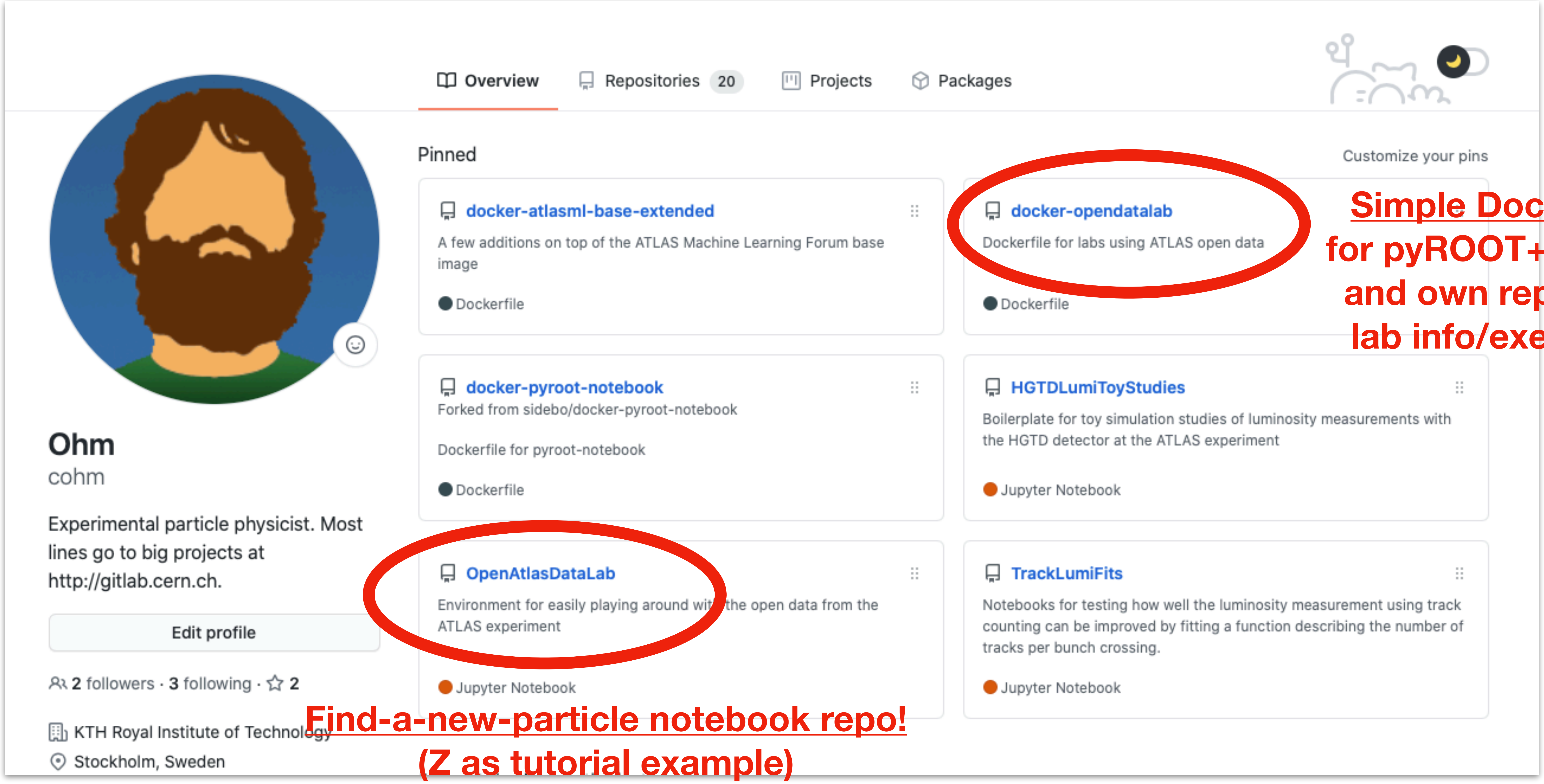
Try out the docker image!



[Link to docker image]()

All repositories are public

Feel free to fork and adapt (credit/link appreciated), also very happy to discuss and exchange ideas!



Simple Dockerfile for pyROOT+Jupyter and own repo with lab info/exercises

Find-a-new-particle notebook repo! (Z as tutorial example)

It’s worth pointing out that these labs worked very well and required little adjustment for the very different year of 2020 and 2021

(But supervising labs remotely via Zoom does require more preparation than when walking around between groups in person)

Summary

- Designed two labs for engineering students using open research data from the ATLAS experiment
- I find it incredibly powerful to ***pique the students' interest and curiosity*** when asking them to explore themselves
- The students get access to the subatomic world, and gain real hands-on experience with analysing experimental data
- Main lessons for me:
    - Make technical part as simple as possible, ***exact instructions are key*** - docker is powerful!
    - ***The students really like to explore*** - we use this a lot!
- Very happy to discuss and share experiences - we've pushed ~500 students through measuring the *Z* mass by now, and ~60 trying to find the Higgs!