

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)

		Fermions			Bosons	
		1 st gen.	2 nd gen.	3 rd gen.		
Mass Charge Spin	Quarks	2.2 MeV +2/3 1/2 <i>u</i> up	1.28 GeV +2/3 1/2 <i>c</i> charm	173 GeV +2/3 1/2 <i>t</i> top	0 0 1 <i>g</i> gluon	125 GeV 0 0 <i>H</i> Higgs boson
		4.7 MeV -1/3 1/2 <i>d</i> down	95 MeV -1/3 1/2 <i>s</i> strange	4.18 GeV -1/3 1/2 <i>b</i> bottom	0 0 1 γ photon	
	Leptons	0.511 MeV -1 1/2 <i>e</i> electron	106 MeV -1 1/2 μ muon	1.78 GeV -1 1/2 τ tau	80.4 GeV ± 1 1 <i>W</i> W boson	
		< 2 eV 0 1/2 ν_e electron neutrino	< 0.19 MeV 0 1/2 ν_μ muon neutrino	< 18.2 MeV 0 1/2 ν_τ tau neutrino	91.2 GeV 0 1 <i>Z</i> Z boson	

Scalar bosons

Gauge bosons

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Gauge bosons

Almost all of these have antiparticles!

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NB! Gravity is not included!

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- Mathematically formulated as a **quantum field theory**

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- Incredibly successful theory, predicting and explaining decades of experimental measurements, e.g.

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 - Theory: $a_e = 0.001159652181643$

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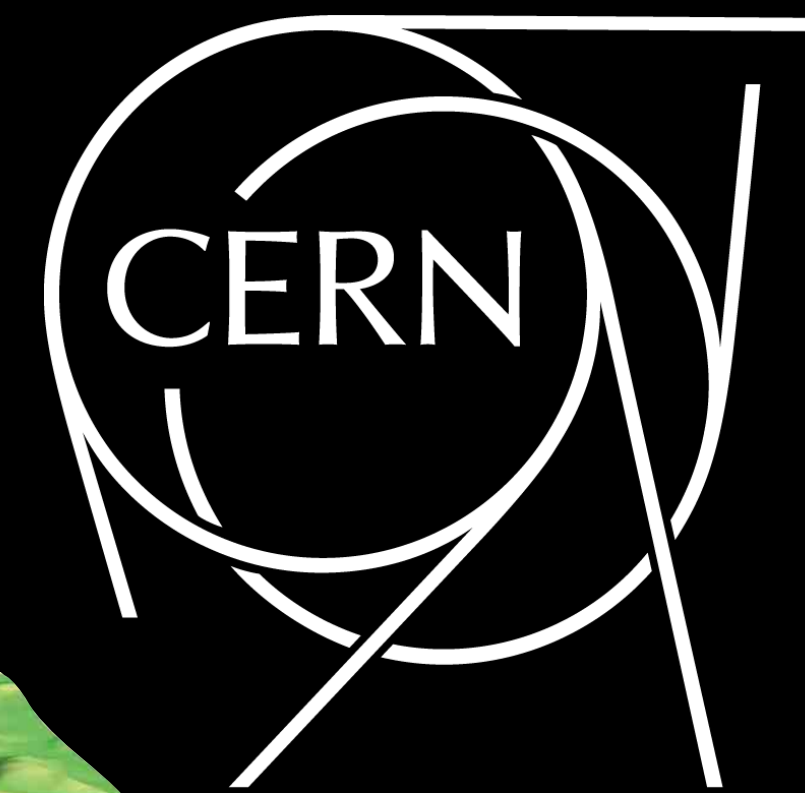
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- Incredibly successful theory, predicting and explaining decades of experimental measurements, e.g.
 - Theory: $a_e = 0.001159652181643$
 - Measurement: $a_e = 0.00115965218073$
- Beautiful mathematical formulation - complex but fits on a t-shirt

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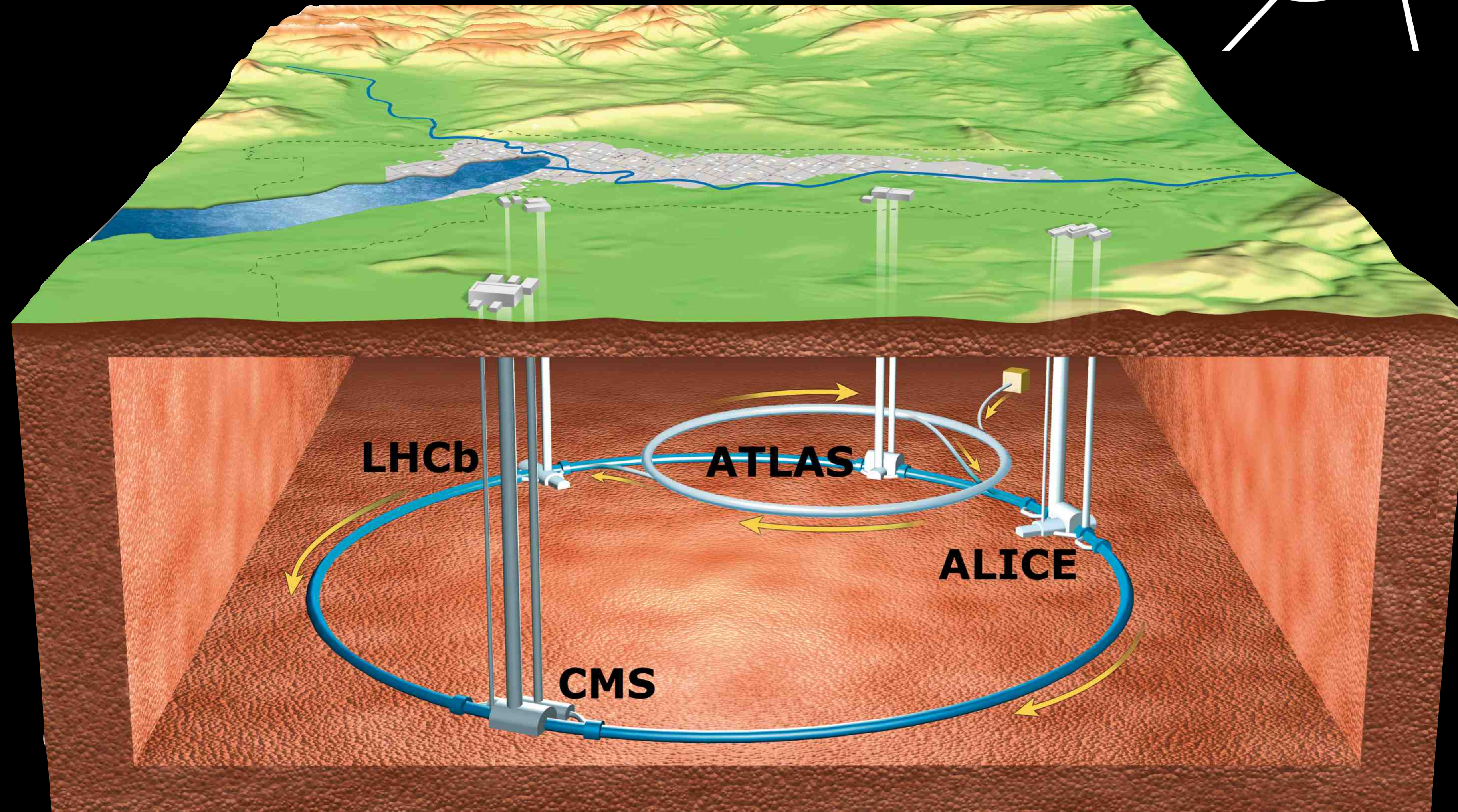
Scalar bosons

Gauge bosons

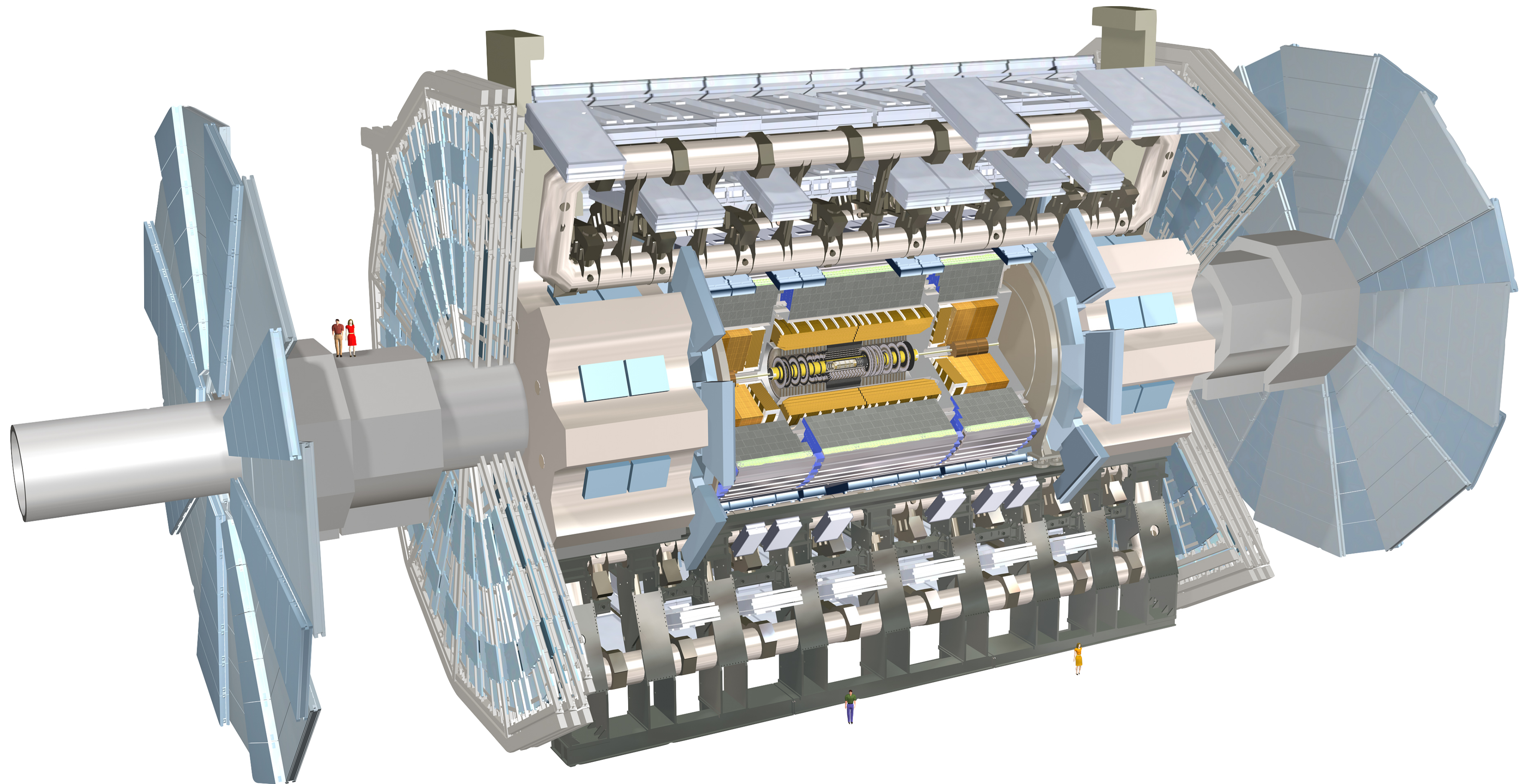
Large Hadron Collider (LHC)



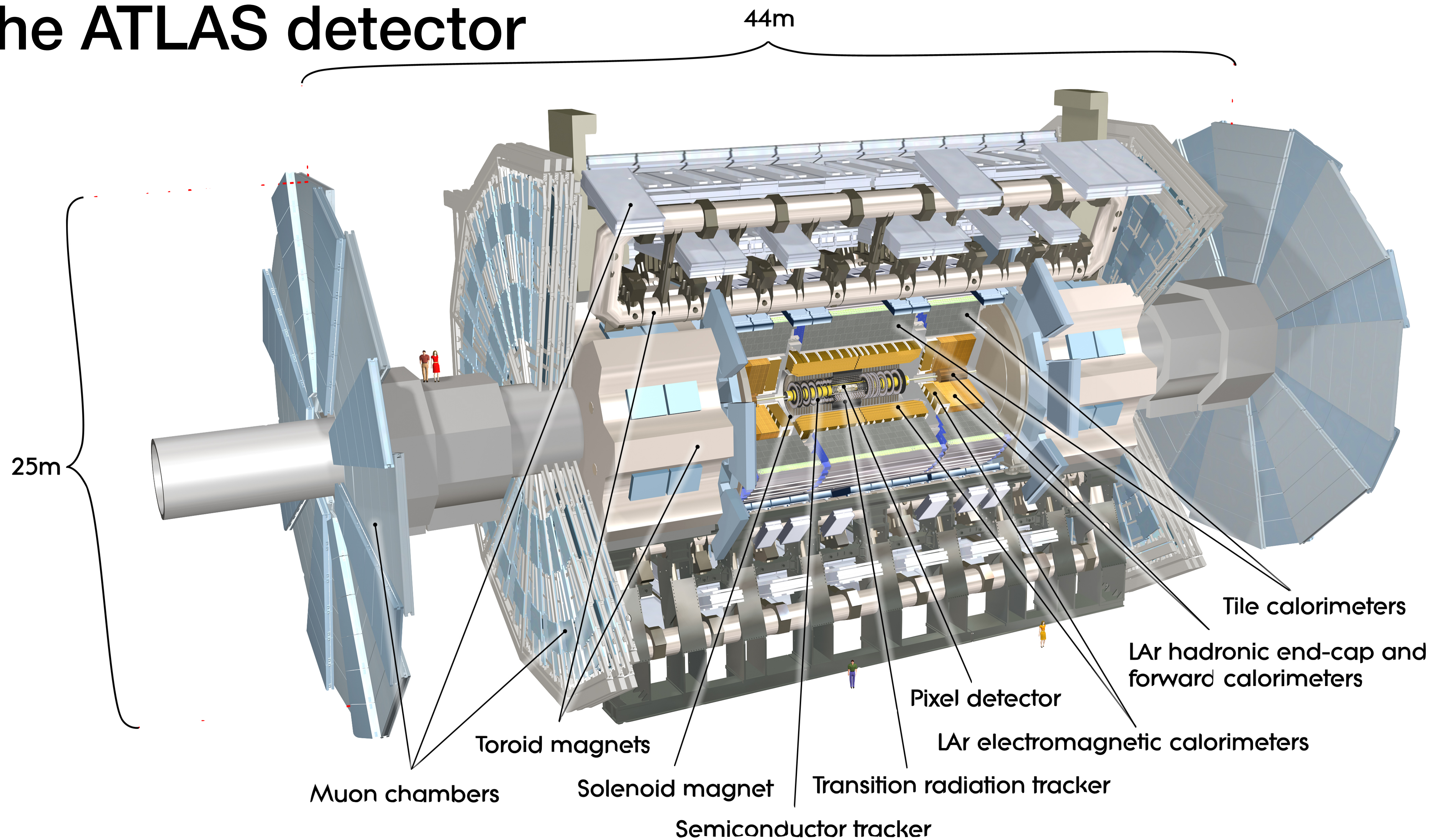
- Circular underground tunnel, 27 km in circumference
- Beams of protons accelerated by electric fields in both directions to collision energy of 6.5+6.5 TeV (99.999999% of c)
- Superconducting magnets bend the beams to keep them in orbit
- Beams make 11 000 turns per second
- Planned since 1980s, first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



The ATLAS detector



The ATLAS detector



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



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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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 - *Students are interested in the research at CERN* - can we design a lab where they get to explore the subatomic world? Coincided with release of public dataset from ATLAS.

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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
 - Four labs and a longer project connected to research at the department
 - **Main learning goals:** *get hands-on experience with modern physics*, get experience of statistical analysis, learning to *apply statistical methods to extract measurements* (fit and evaluate models with data)
 - *Students are interested in the research at CERN* - can we design a lab where they get to explore the subatomic world? Coincided with release of public dataset from ATLAS.
 - **Challenge:** setting up the *software environment* needed is fragile and cumbersome - but there are new powerful tools!

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.

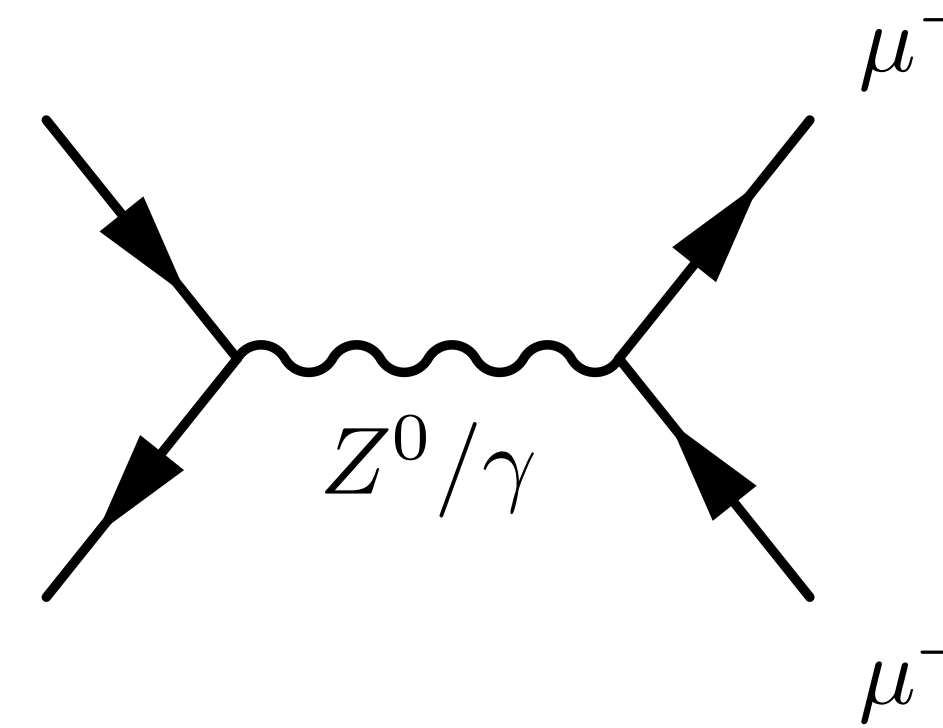
Intended learning outcomes *

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

Jupyter notebooks

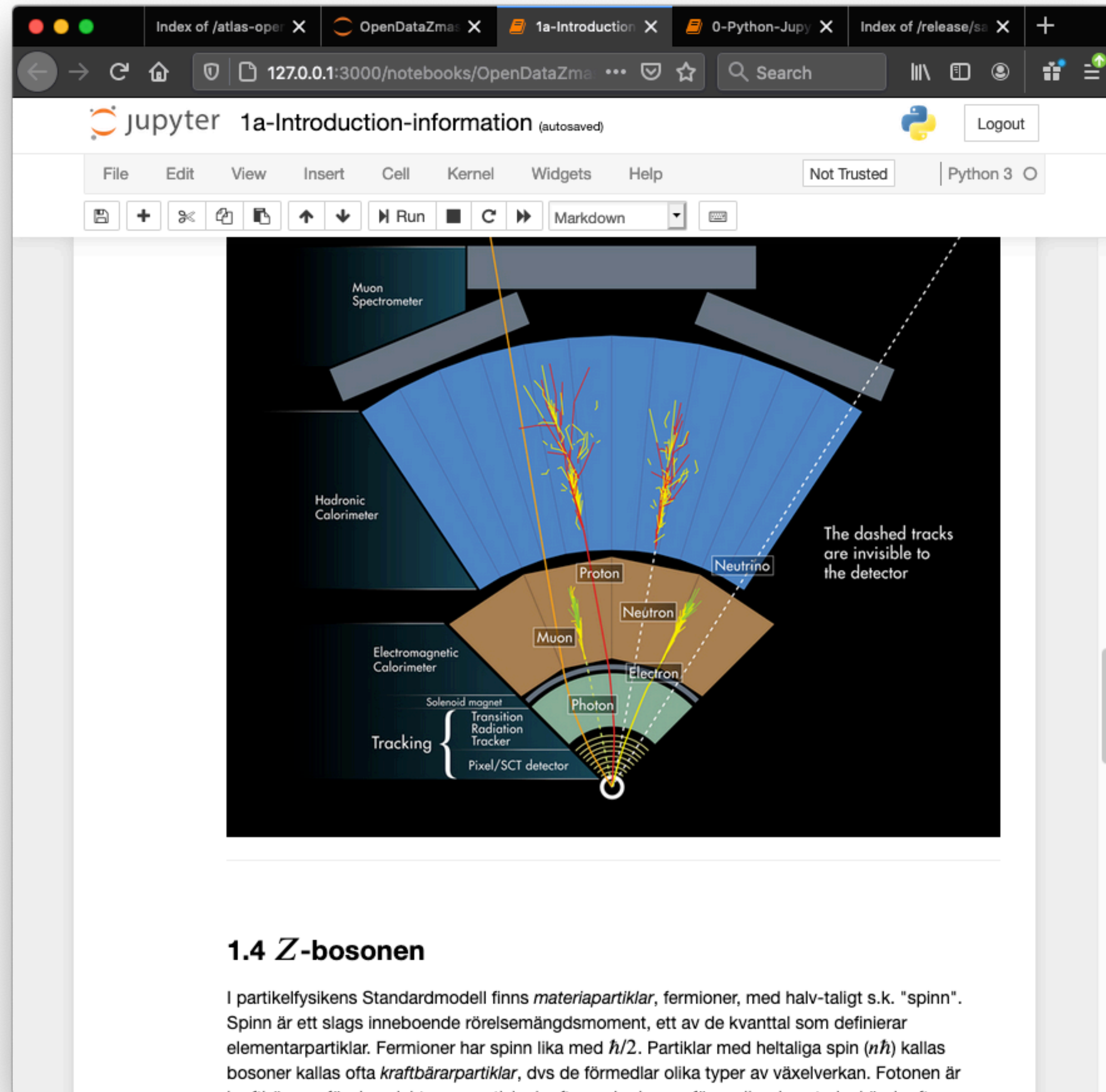
Name	Last Modified	File size
..	seconds ago	
images	4 months ago	
0-Python-Jupyter-Notebook-intro.ipynb	4 months ago	19.8 kB
1a-Introduction-information.ipynb	4 months ago	10.8 kB
1b-Introduction-exercise.ipynb	4 months ago	13.9 kB
2-Fitting-with-ROOT.ipynb	4 months ago	21.9 kB
3-TheTask-ZbosonMass.ipynb	4 months ago	6.87 kB
4-LabReport.ipynb	4 months ago	3.63 kB
README.md	4 months ago	796 B



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})

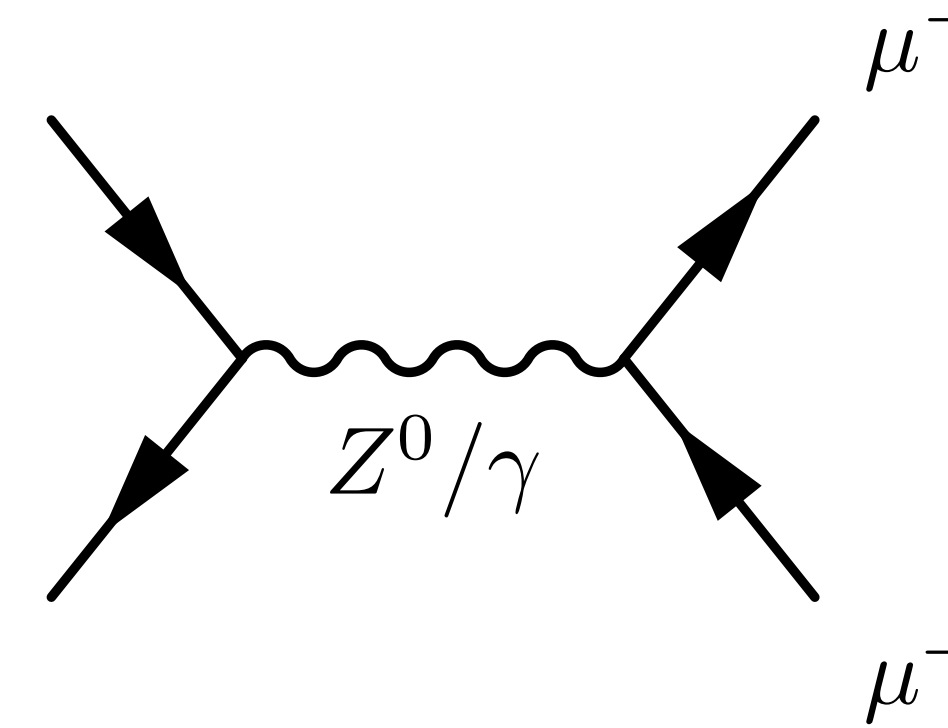
Jupyter notebooks



The screenshot shows a Jupyter notebook titled "1a-Introduction-information" with a menu bar (File, Edit, View, Insert, Cell, Kernel, Widgets, Help) and a toolbar (Run, Stop, Refresh, etc.). The main content is a diagram of a particle detector cross-section. The diagram is divided into several regions: Muon Spectrometer (top), Hadronic Calorimeter (middle), Electromagnetic Calorimeter (bottom), Solenoid magnet (inner), Tracking (outer), Transition Radiation Tracker (inner), and Pixel/SCT detector (inner). Various particles are shown as tracks: Muon, Neutron, Electron, Photon, Proton, and Neutrino. A note states "The dashed tracks are invisible to the detector".

1.4 Z-bosonen

I partikelfysikens Standardmodell finns *materiapartiklar*, fermioner, med halv-taligt s.k. "spinn". Spinn är ett slags inneboende rörelsemängdsmoment, ett av de kvanttal som definierar elementarpartiklar. Fermioner har spinn lika med $\hbar/2$. Partiklar med heltaliga spin ($n\hbar$) kallas bosoner kallas ofta *kraftbärande partiklar*, dvs de förmedlar olika typer av växelverkan. Fotonen är kraftbäraren för den elektromagnetiska kraften och gluonen förmedlar den starka kärnkraften som



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

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 - Z boson: role in SM, decay modes
 - How to fit a distribution, extract model parameters, determine fit quality (χ^2/n_{DoF})

Jupyter notebooks

transversella rörelsemängd p_T , dvs projektionen av rörelsemängden p i det transversella planet, och deras vinkel θ relativt den positiva z -axeln. Typiskt används dock "pseudorapiditet" η istället för θ , definierad enligt ekvationen i figuren.

$$p_T = p \sin \theta$$

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

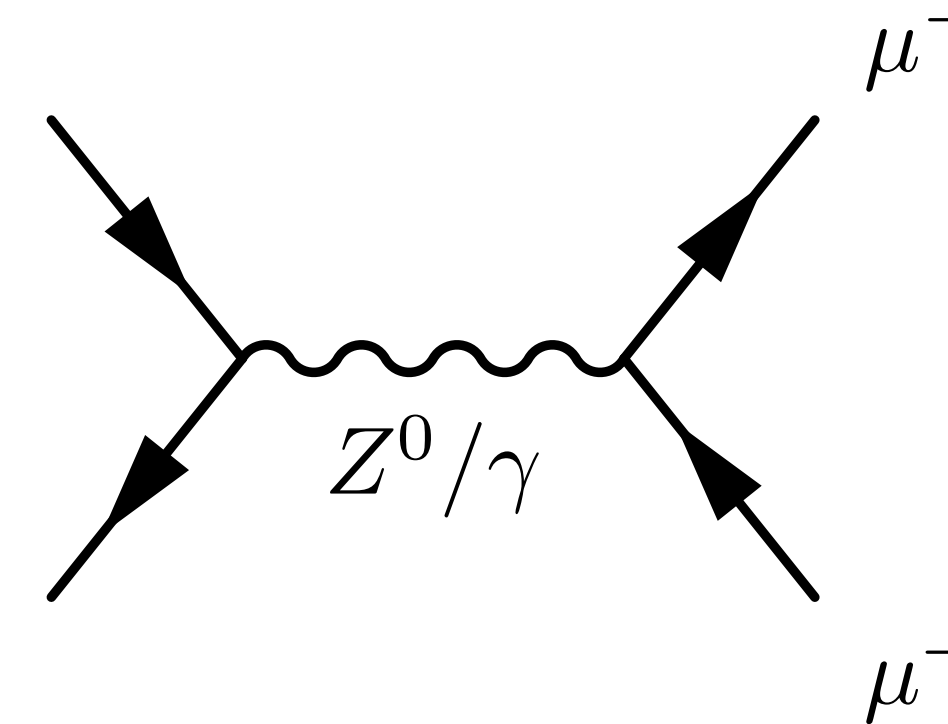
I xy -planet kan det transversella rörelsemängdsmomentet beskrivas av dess magnitud p_T och dess vinkel ϕ till den positiva x -axeln.

Den invarianta massan för ett system av partiklar kan räknas ut med partiklarnas energier och rörelsemängdsvektorer. Vid relativistiska energier, dvs då massorna på partiklarna i systemet är små i jämförelse med deras rörelsemängder, kan uttrycket förenklas och den invarianta massan i ett tvåpartikelsystem kan beräknas med (1) nedan, där α är vinkeln mellan de två partiklarnas rörelsemängdsvektorer. Detta kan även skrivas om som (2) nedan med variablerna vi använder oss av i ATLAS-experimentet.

$$m^2 \approx 2(E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2) \approx 2p_1 p_2 (1 - \cos \alpha) \quad (1)$$

$$m^2 \approx 2p_{T1} p_{T2} (\cosh(\eta_1 - \eta_2) - \cos(\phi_1 - \phi_2)) \quad (2)$$

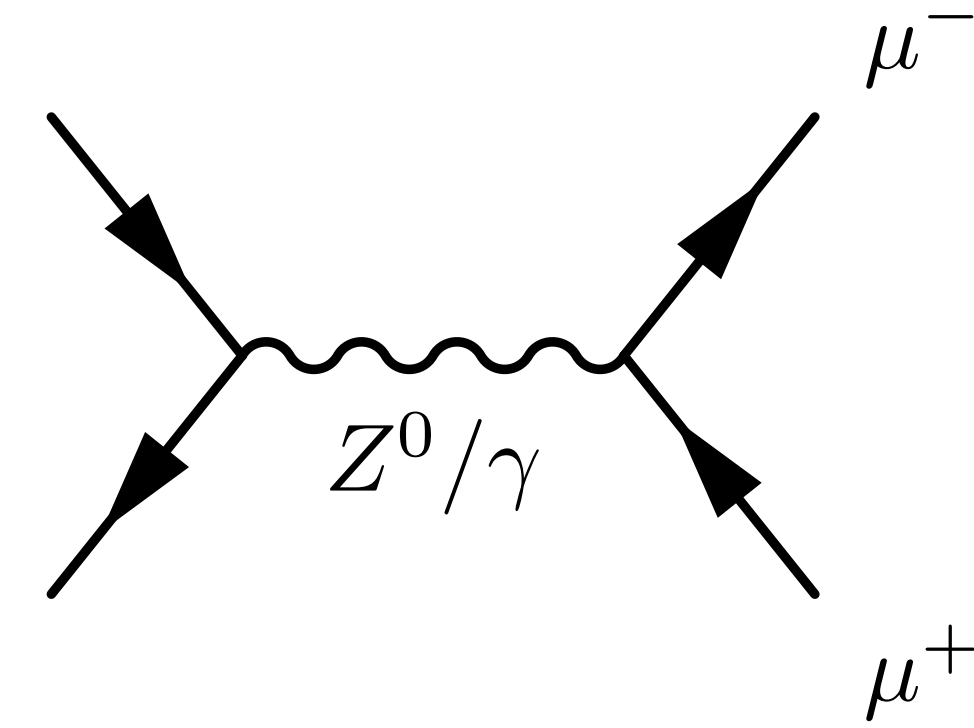
I nästa övning där ni får prova på att komma åt mätdatan och se vilka variabler som finns tillgängliga i [1b-Introduction-exercise!](#)



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})

Results from 1st year



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

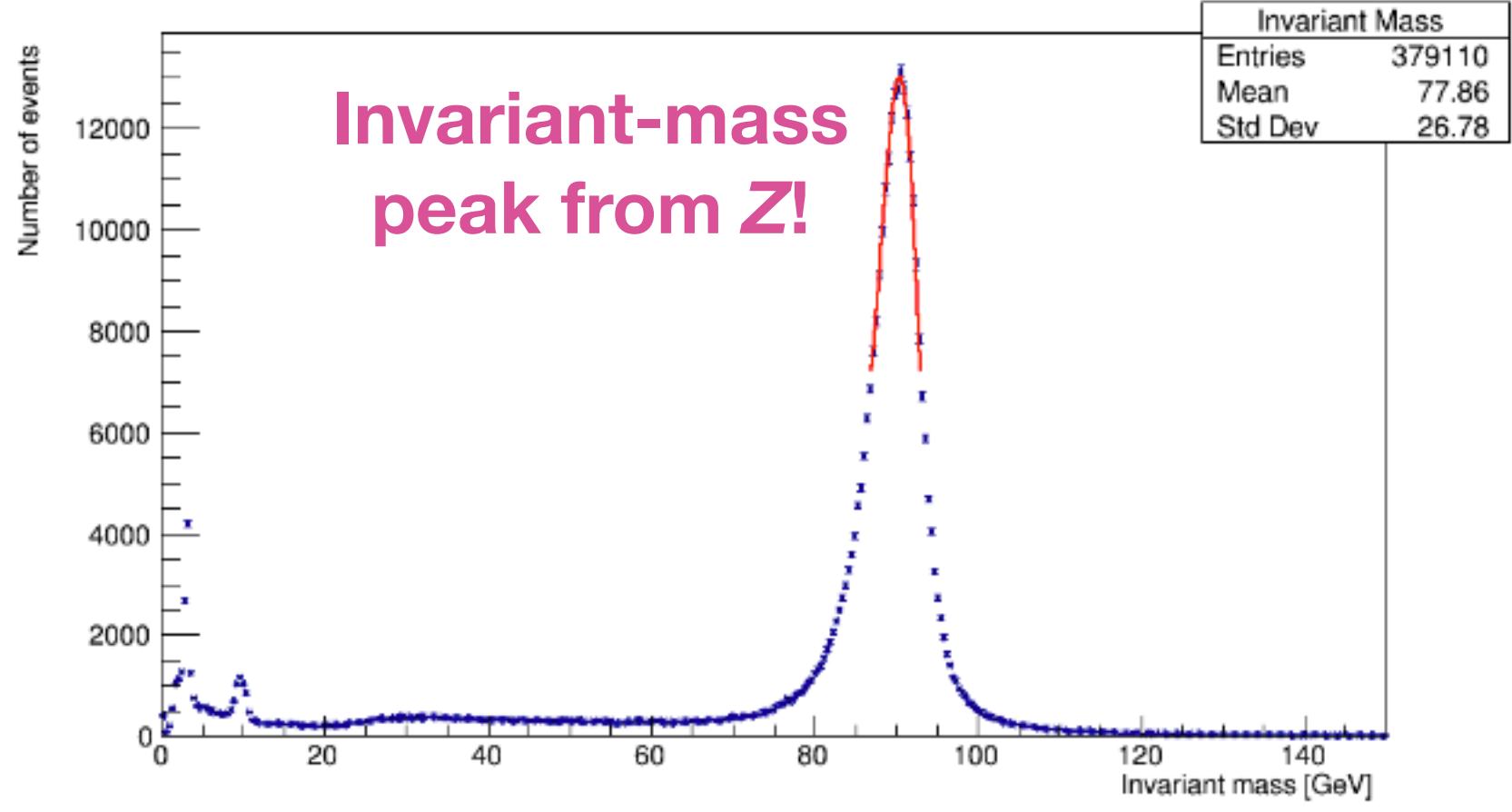


Figure 3: Invariant mass of the Z^0 boson, approximated as the function (4), on the range [87, 93] [GeV].

- 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

Z^0 boson mass SH1015 HT 2018

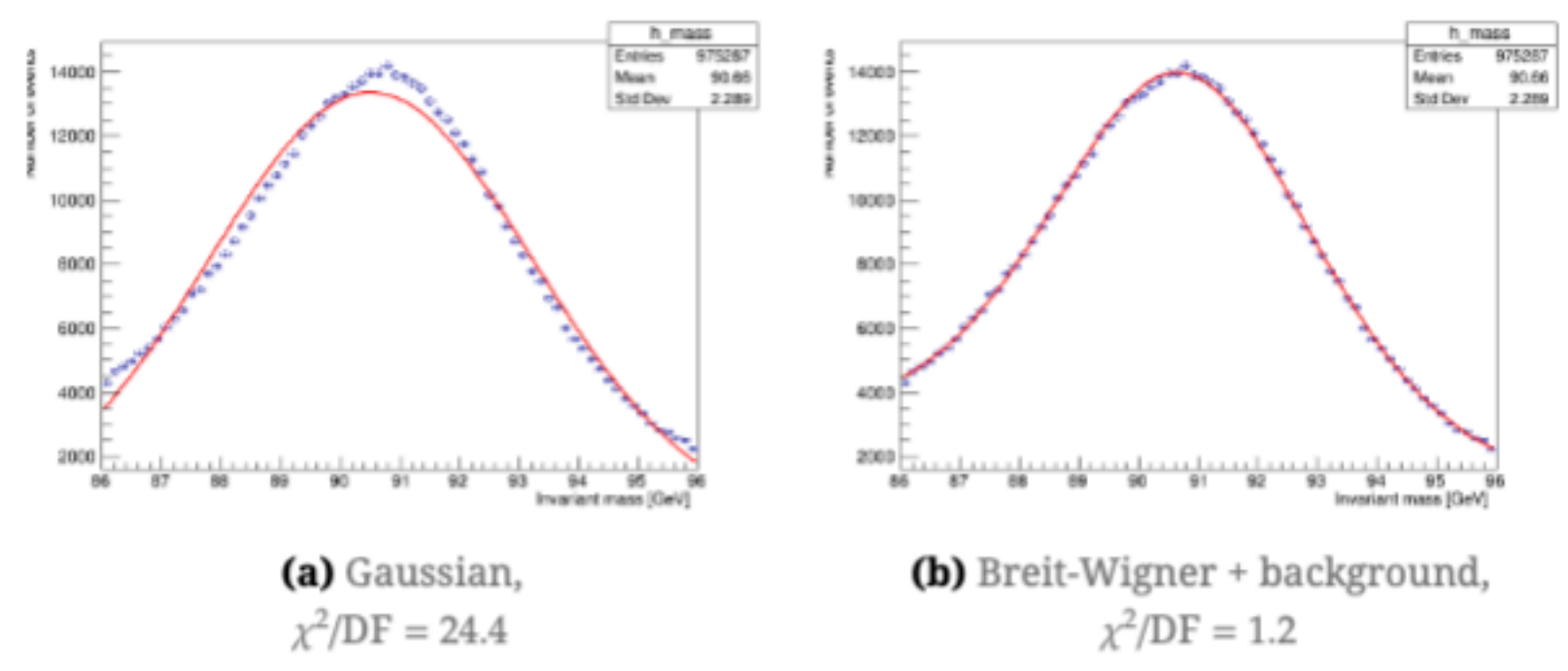


Figure 5: Fitting different distributions to the results. DF signifies the number of degrees of freedom

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

- Clear instructions are imperative!

The screenshot shows a web browser window displaying a course page on kth.instructure.com. The page is titled "SH2103HT201 > Pages > Particle Physics Lab: Discover a subatomic particle analyzing real ATLAS data". The page content includes:

- A "View All Pages" button.
- A "Published" status indicator and an "Edit" button.
- The main heading: "Particle Physics Lab: Discover a subatomic particle analyzing real ATLAS data".
- Introductory text: "In this lab, you will use data from the ATLAS experiment at CERN to discover a subatomic particle!"
- Text: "Most of the actual instructions are 'inside' the lab - the instructions include a tutorial for how to analyze the data, use the s/w packages, and make plots of interesting quantities."
- A note: "**NB!** Just like for the nuclear physics lab, you can choose your level of ambition for the lab, and if you aspire to get grades B or A for the course, you'll need to choose the level which requires (slightly) more effort for the report. For any questions about this lab, contact Christian!"
- A section titled "Practical info:" followed by a bulleted list:
 - The lab exercise should be done in groups of 2-3 (it's perfectly fine to use the same groups as for the nuclear physics lab, but it's not required).
 - To pass the lab you need to hand in a complete lab report (see detailed instructions built into the lab, in part 5).
 - The lab can be done at a time of your choosing, all you need is a computer with internet access and a browser, but if you have your own laptop and can install [Docker](#) on it, that's convenient (more below).
 - The lab contains introductory exercises that allows you to familiarize yourself with python, the ROOT libraries, how to work with these things inside a jupyter notebook environment, and study the Z boson as an example particle. The actual lab exercise you should describe in the report is in part 4 where you try to discover another particle in the data.
- A "Preparations" section: "follow the instructions below and go through notebooks 0-3 to learn about python, the jupyter environment, and how to use the ROOT libraries used at CERN to do data analysis in particle physics research."
- A concluding sentence: "Read through all steps below well in advance so you know what to expect before you start."

Instructions

The screenshot shows a web browser window with the URL `kth.instructure.com`. The page content is as follows:

To start the lab:

1. We use Docker to easily get access to software and data. You will need a Docker account, so go to <https://hub.docker.com/> and register.
2. To start the lab environment you can either
 - **On any computer:** go to <https://labs.play-with-docker.com/> in your browser (e.g. Chrome works well). Log in with your Docker account. Click on "ADD NEW INSTANCE" to open a terminal. NB! The session is limited to max 4 hours - make sure to save your work before the time runs out!
 - **If you use your own computer:** download and install Docker (starting from <https://www.docker.com/get-started>). When the installation is done and the docker program has started, open a terminal/CMD.
3. In the terminal, type in (or paste) `docker run -p 3000:8080 kthatlas/opendatalab:SH2103` and hit enter. This command will download and start the software that's needed, so it may take a few minutes.
4. To start the lab: select the token printed out in the terminal (what's after "token=" near the end) and copy it.
 - Those of you who use Play with Docker: click on the link "3000" that appeared at the top of the page.
 - Those of you using your own computers: open `localhost:3000` in a web browser.
5. Paste the token string in the field at the top of the login page you'll land on.
6. When you've logged in you'll see several files with interactive python notebooks in .ipynb format - these correspond to the different steps of the lab, steps 0-3 are preparatory, 4 is the main task, and 5 has info about what the report should contain (also [here](#) in pdf form). Good luck!

When you're done, when you want to take a break, or when the session is about to expire:

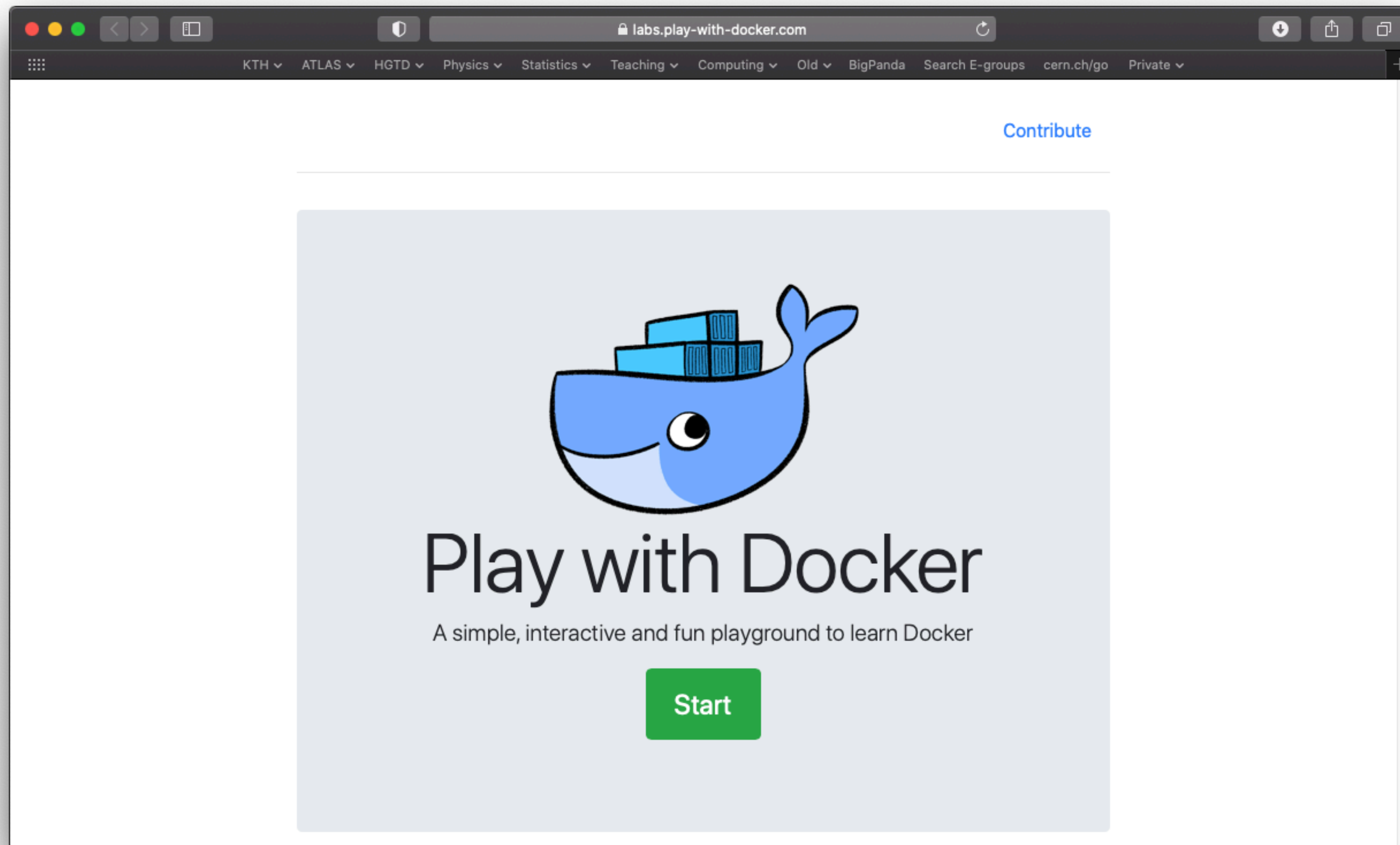
1. Download the figures you made, and the notebooks you edited and worked with by navigating to the "Home" directory, ticking the boxes next to the files in the jupyter file system view, and clicking the "Download" button that then appears near the top of the screen (you may need to stop notebooks that are running first).
2. If you want to continue working on the lab at a later time, start the server the same way you did before, push the "Upload" button to upload the previously saved .ipynb files.

NB! The changes you make in your notebooks will disappear when the server is closed down! Make sure to save your work and download the .ipynb files to your computer before the session is over if you use Play With Docker. You can then start a new session and upload the files to continue where you left off.

Best regards - and good luck!
[Christian Ohm](#)

- 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!

Play with Docker

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

The screenshot shows a web browser window at `labs.play-with-docker.com`. The interface includes a top navigation bar with various categories like KTH, ATLAS, HGTD, Physics, Statistics, Teaching, Computing, Old, BigPanda, Search E-groups, cern.ch/go, and Private. A large digital clock displays `03:58:40` and a red `CLOSE SESSION` button is visible. Below the clock, there's a section for 'Instances' with a '+ ADD NEW INSTANCE' button and a list of instances, including one with IP `192.168.0.23` and name `node1`. The main content area displays details for a specific container: `bvv531j6_bvv53436hnp000djooi0`. It shows the IP `192.168.0.23` with an `OPEN PORT` button, memory usage at `0.89% (35.68MiB / 3.906GiB)`, and CPU usage at `0.41%`. An SSH command is provided: `ssh ip172-18-0-68-bvv531j6hnp000djoohg@direct.labs.play-with-dc`. Below this are `DELETE` and `EDITOR` buttons. At the bottom, a terminal window shows a warning message and a successful `docker run` command: `$ docker run -p 3000:8080 kthatlas/opendatalab:SH2103`.

Play with Docker

The screenshot shows the 'labs.play-with-docker.com' web interface. The top navigation bar includes links for KTH, ATLAS, HGTD, Physics, Statistics, Teaching, Computing, Old, BigPanda, Search E-groups, cern.ch/go, and Private. A digital clock displays '03:56:36' and a 'CLOSE SESSION' button is visible. The main content area shows an instance named 'bv531j6_bv53436hnp000djooi0' with IP '192.168.0.23', memory usage of 46.30% (1.809GiB / 3.906GiB), and CPU usage of 0.34%. There are buttons for 'OPEN PORT' (set to 3000), 'DELETE', and 'EDITOR'. The terminal output at the bottom shows the following logs:

```
Status: Downloaded newer image for kthatlas/opendatalab:SH2103
[I 01:52:08.632 NotebookApp] Writing notebook server cookie secret to /root/.local/share/jupyter/runtime/notebook_cookie_secret
[I 01:52:09.074 NotebookApp] Serving notebooks from local directory: /work
[I 01:52:09.074 NotebookApp] Jupyter Notebook 6.1.5 is running at:
[I 01:52:09.074 NotebookApp] http://769ae4122050:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f17098ea6ea26
[I 01:52:09.075 NotebookApp] or http://127.0.0.1:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f17098ea6ea26
[I 01:52:09.075 NotebookApp] Use Control-C to stop this server and shut down all kernels (twice to skip confirmation).
[W 01:52:09.082 NotebookApp] No web browser found: could not locate runnable browser.
[C 01:52:09.082 NotebookApp]

To access the notebook, open this file in a browser:
    file:///root/.local/share/jupyter/runtime/nbserver-1-open.html
Or copy and paste one of these URLs:
    http://769ae4122050:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f17098ea6ea26
    or http://127.0.0.1:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f17098ea6ea26
```

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

Play with Docker

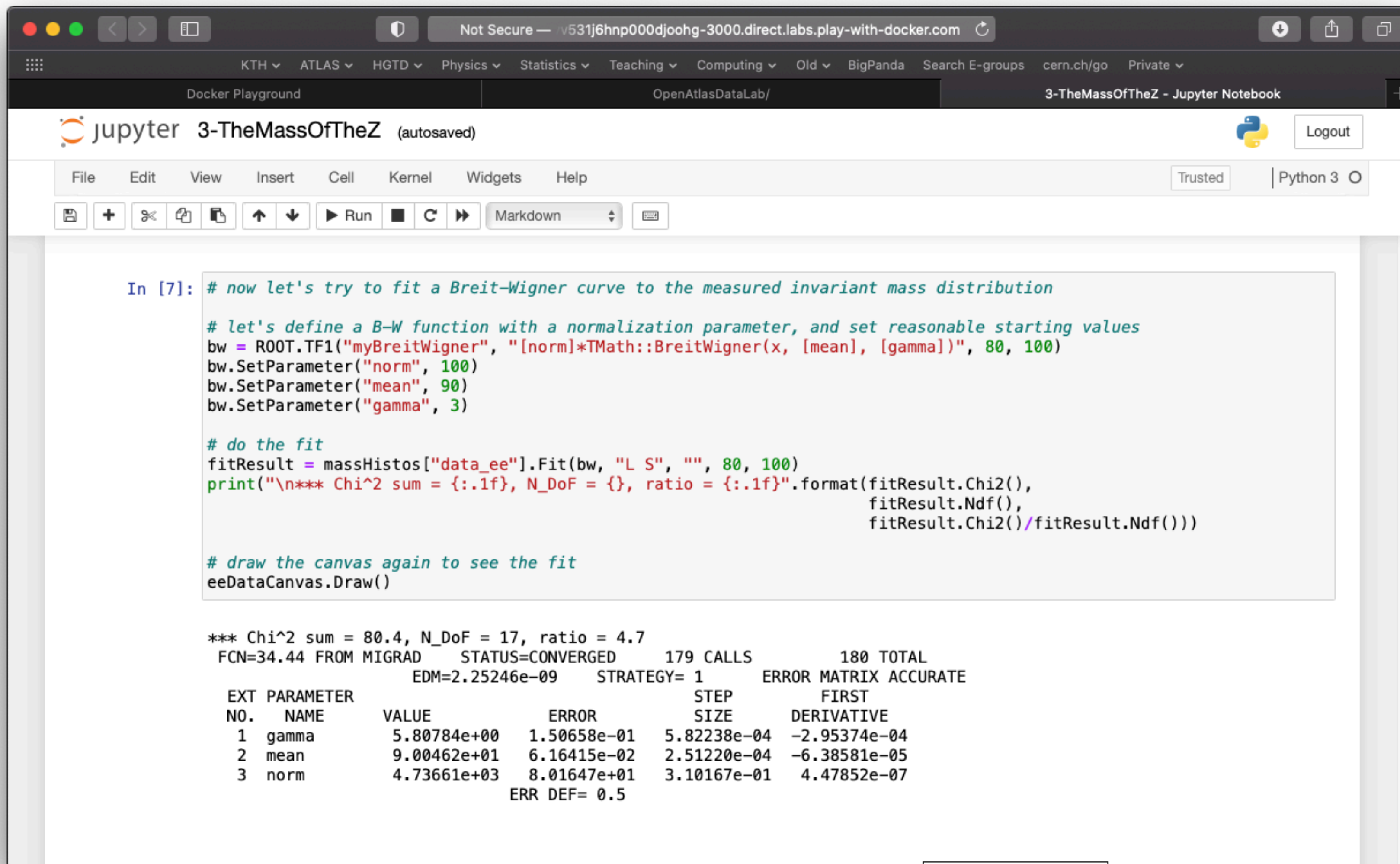
The screenshot shows the 'labs.play-with-docker.com' web interface. The top navigation bar includes links for KTH, ATLAS, HGTD, Physics, Statistics, Teaching, Computing, Old, BigPanda, Search E-groups, cern.ch/go, and Private. A digital clock displays '03:56:36' and a 'CLOSE SESSION' button is visible. The main content area shows an instance named 'bv531j6_bv53436hnp000djooi0' with IP '192.168.0.23', memory usage of 46.30% (1.809GiB / 3.906GiB), and CPU usage of 0.34%. There are buttons for 'OPEN PORT' (set to 3000), 'DELETE', and 'EDITOR'. Below this is a terminal window with the following output:

```
Status: Downloaded newer image for kthatlas/opendatalab:SH2103
[I 01:52:08.632 NotebookApp] Writing notebook server cookie secret to /root/.local/share/jupyter/
runtime/notebook_cookie_secret
[I 01:52:09.074 NotebookApp] Serving notebooks from local directory: /work
[I 01:52:09.074 NotebookApp] Jupyter Notebook 6.1.5 is running at:
[I 01:52:09.074 NotebookApp] http://769ae4122050:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f
17098ea6ea26
[I 01:52:09.075 NotebookApp] or http://127.0.0.1:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938
f17098ea6ea26
[I 01:52:09.075 NotebookApp] Use Control-C to stop this server and shut down all kernels (twice t
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[C 01:52:09.082 NotebookApp]

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Or copy and paste one of these URLs:
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or http://127.0.0.1:8080/?token=7f00a5e82e3a12b88769d31ffdacbc2d938f17098ea6ea26
```

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



```
In [7]: # 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()))

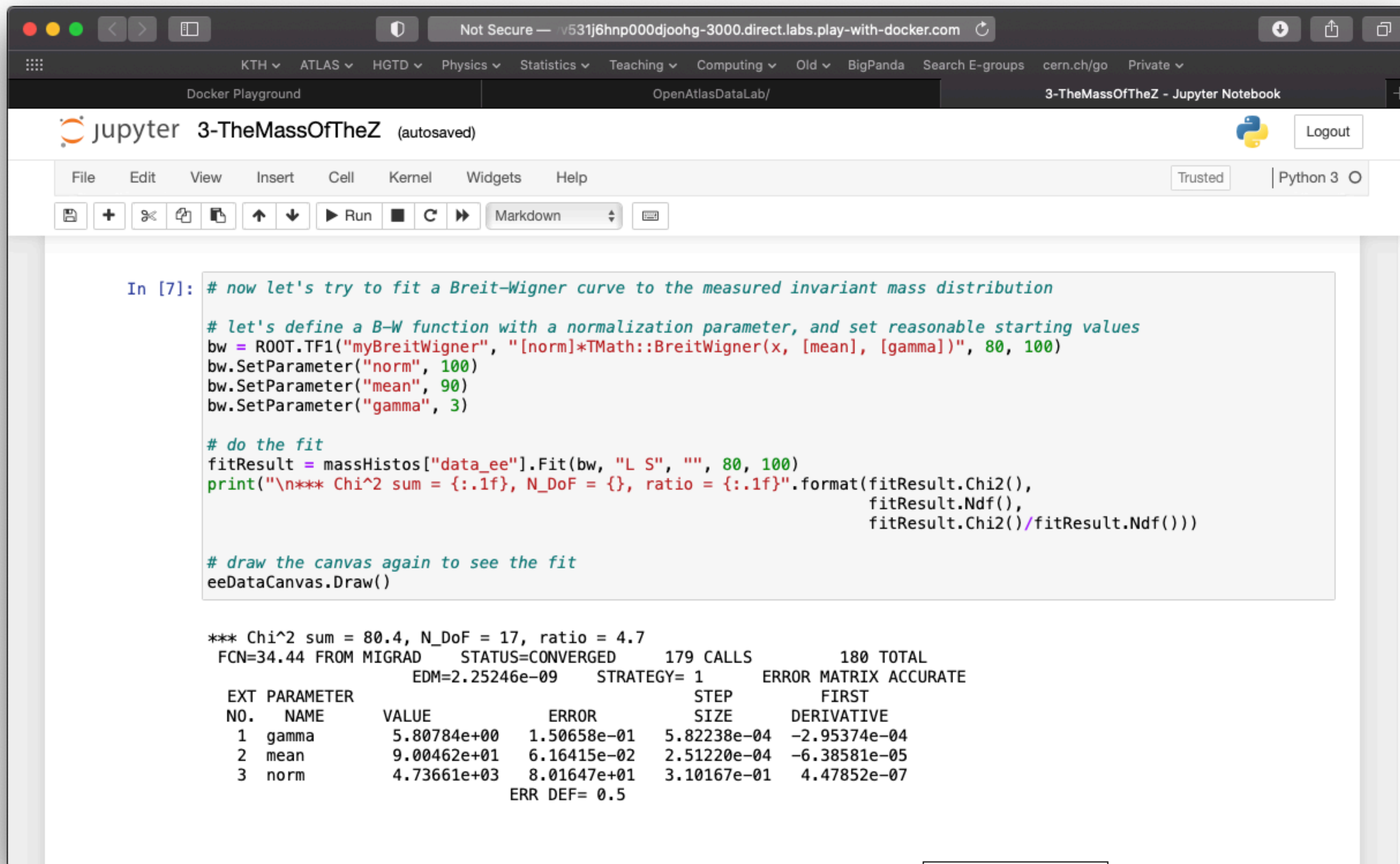
# draw the canvas again to see the fit
eeDataCanvas.Draw()
```

*** 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	VALUE	ERROR	STEP	FIRST
NO.	NAME			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

Use Z as example



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In [7]: # now let's try to fit a Breit-Wigner curve to the measured invariant mass distribution

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bw = ROOT.TF1("myBreitWigner", "[norm]*TMath::BreitWigner(x, [mean], [gamma])", 80, 100)
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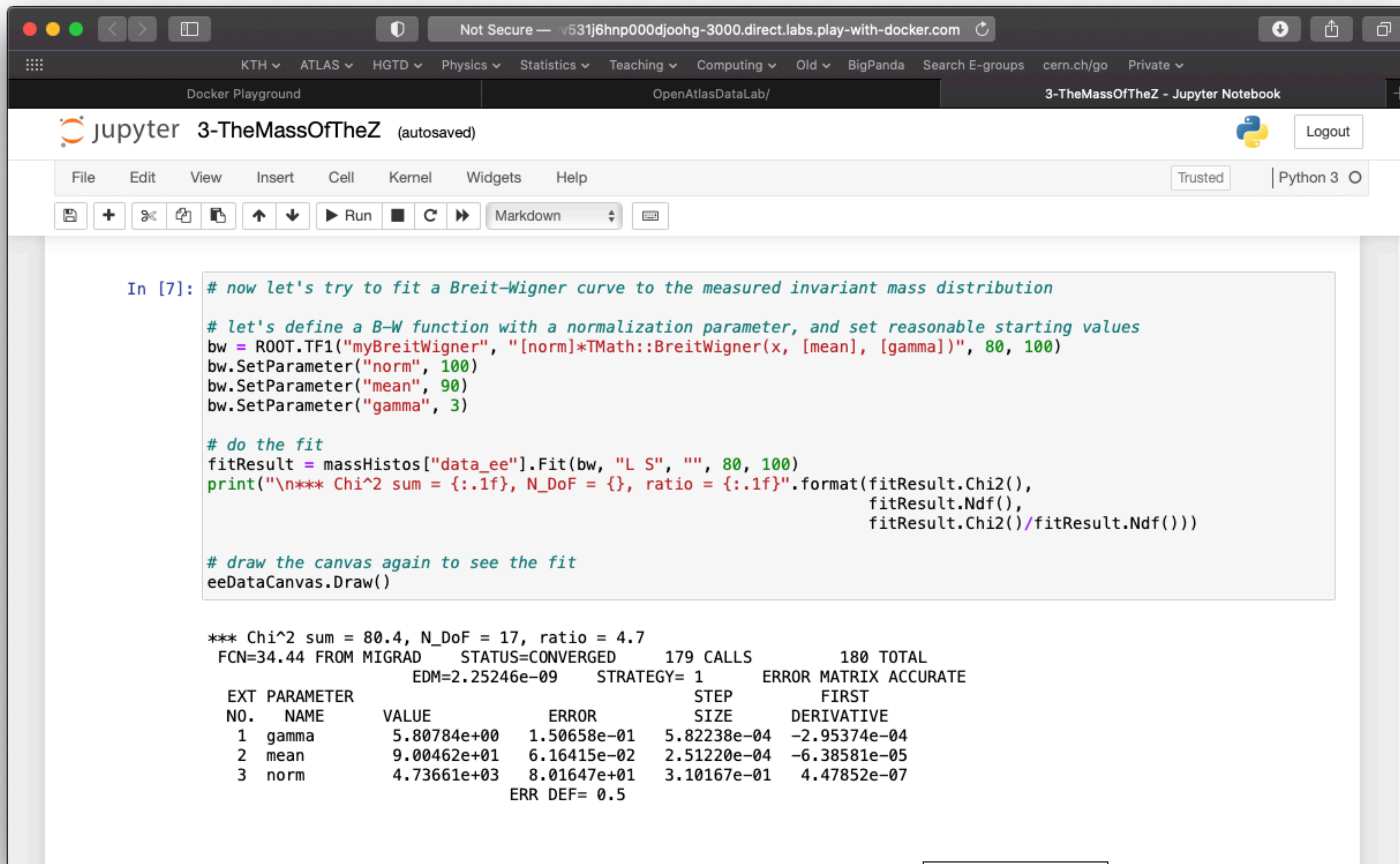
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3	norm	4.73661e+03	8.01647e+01	3.10167e-01	4.47852e-07

ERR DEF= 0.5

- Focus of this lab is more on the physics

Use Z as example



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In [7]: # 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
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                                                                fitResult.Ndf(),
                                                                fitResult.Chi2()/fitResult.Ndf()))

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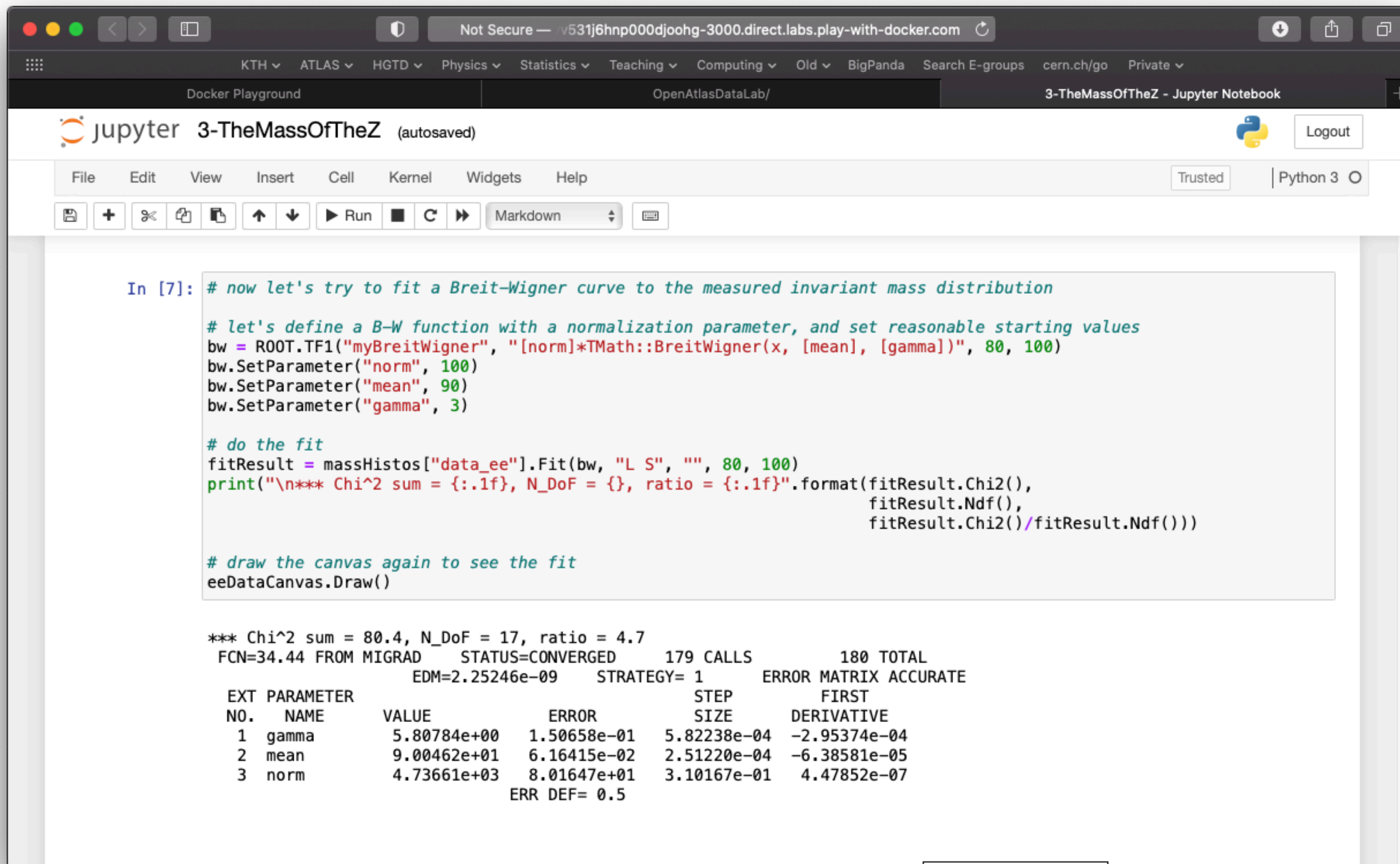
EXT	PARAMETER	VALUE	ERROR	STEP	FIRST
NO.	NAME			SIZE	DERIVATIVE
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2	mean	9.00462e+01	6.16415e-02	2.51220e-04	-6.38581e-05
3	norm	4.73661e+03	8.01647e+01	3.10167e-01	4.47852e-07

ERR DEF= 0.5

- Focus of this lab is more on the physics

- Give example of $Z \rightarrow \ell^+ \ell^-$

Use Z as example



The screenshot shows a Jupyter Notebook titled "3-TheMassOfTheZ" in a browser. The code cell contains the following Python code:

```
In [7]: # 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)
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                                                                fitResult.Ndf(),
                                                                fitResult.Chi2()/fitResult.Ndf()))

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

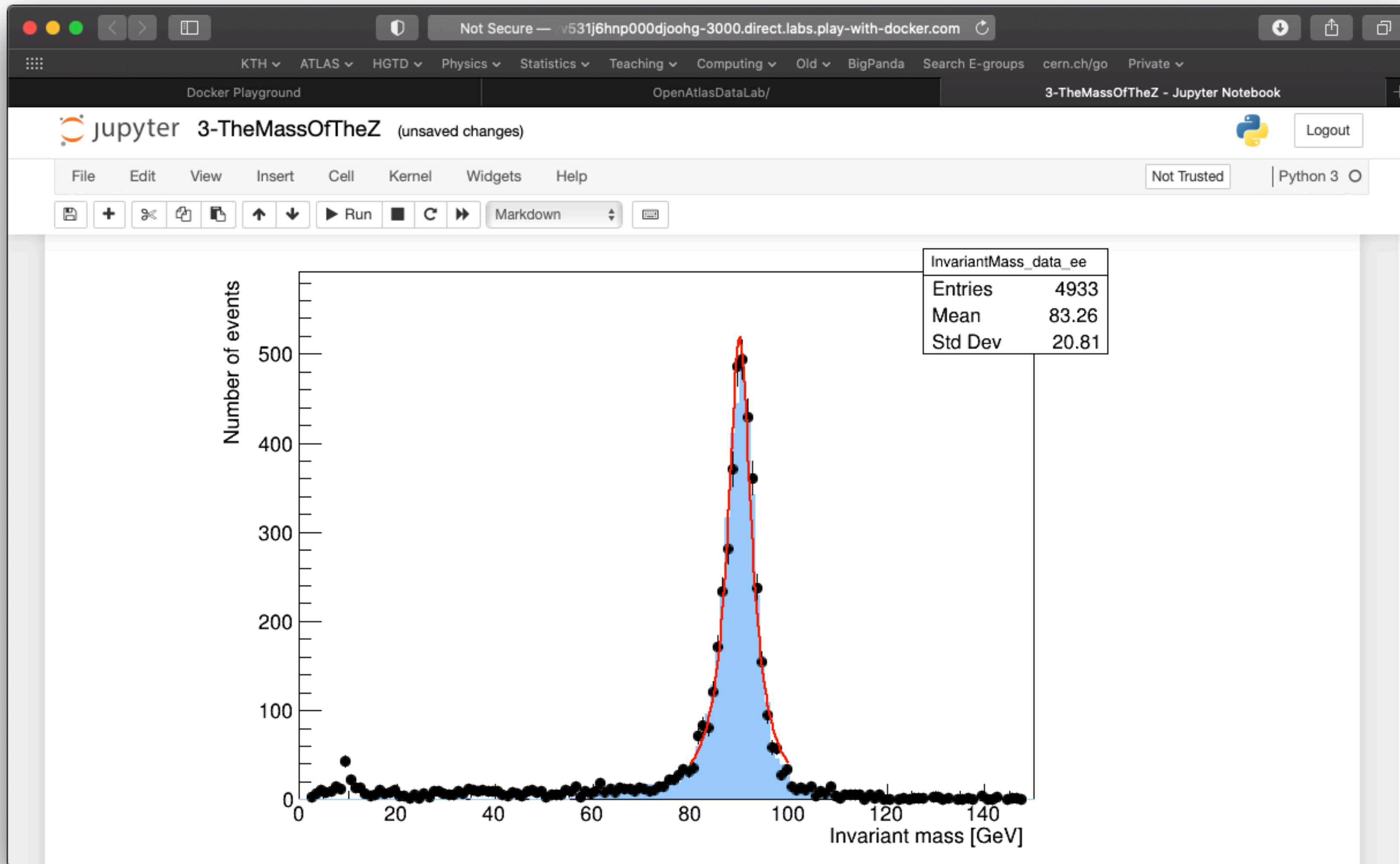
The output of the code cell is:

```
*** 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
NO. NAME VALUE ERROR STEP FIRST
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
```

- Focus of this lab is more on the physics

- Give example of $Z \rightarrow \ell^+ \ell^-$

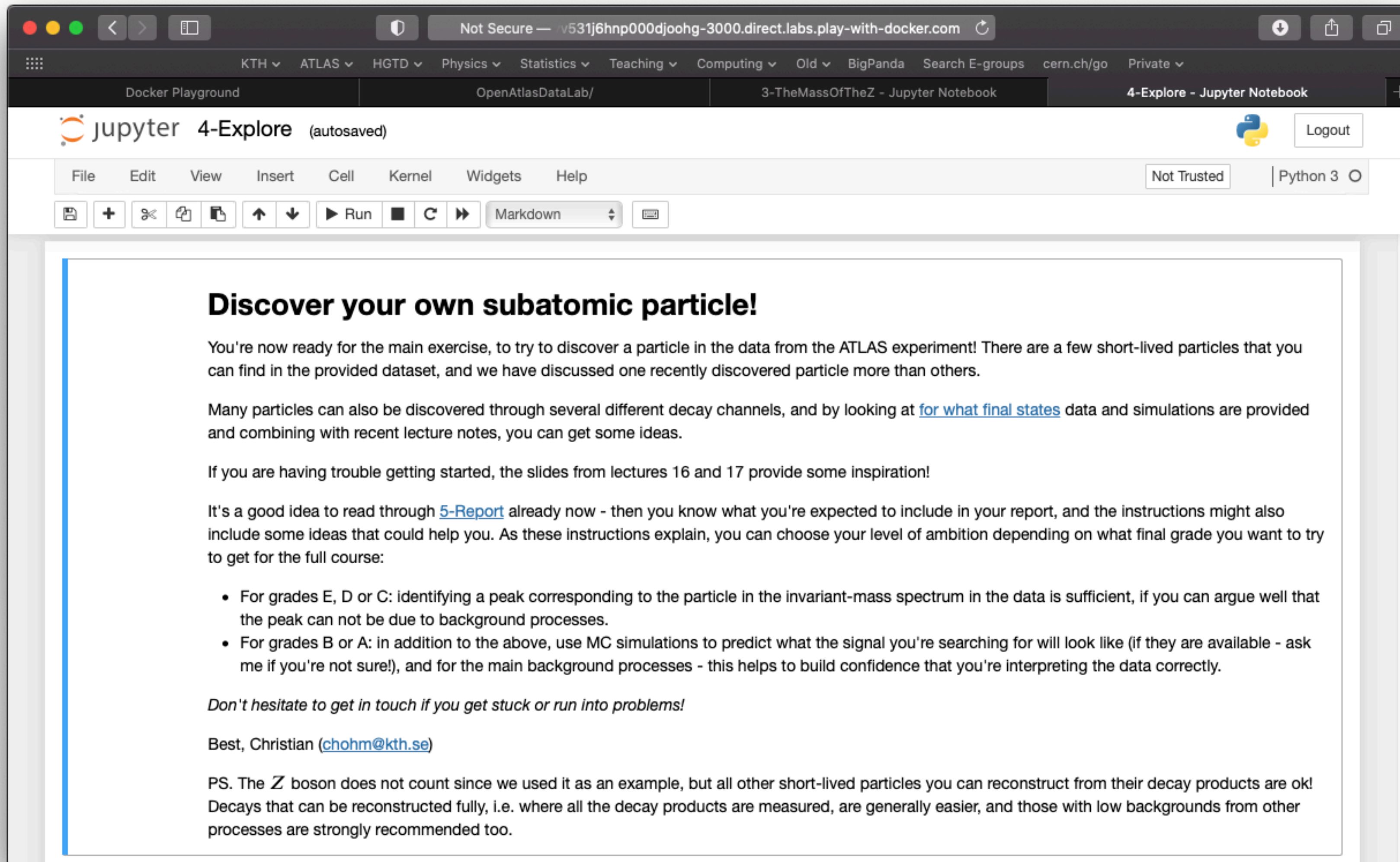
Use Z as example



- Focus of this lab is more on the physics

- Give example of $Z \rightarrow \ell^+ \ell^-$

The task (bare bones)



The screenshot shows a Jupyter Notebook interface in a browser. The browser address bar shows a URL from 'direct.labs.play-with-docker.com'. The notebook title is '4-Explore (autosaved)'. The interface includes a menu bar (File, Edit, View, Insert, Cell, Kernel, Widgets, Help) and a toolbar with icons for file operations, running, and markdown. The main content area contains the following text:

Discover your own subatomic particle!

You're now ready for the main exercise, to try to discover a particle in the data from the ATLAS experiment! There are a few short-lived particles that you can find in the provided dataset, and we have discussed one recently discovered particle more than others.

Many particles can also be discovered through several different decay channels, and by looking at [for what final states](#) data and simulations are provided and combining with recent lecture notes, you can get some ideas.

If you are having trouble getting started, the slides from lectures 16 and 17 provide some inspiration!

It's a good idea to read through [5-Report](#) already now - then you know what you're expected to include in your report, and the instructions might also include some ideas that could help you. As these instructions explain, you can choose your level of ambition depending on what final grade you want to try to get for the full course:

- For grades E, D or C: identifying a peak corresponding to the particle in the invariant-mass spectrum in the data is sufficient, if you can argue well that the peak can not be due to background processes.
- For grades B or A: in addition to the above, use MC simulations to predict what the signal you're searching for will look like (if they are available - ask me if you're not sure!), and for the main background processes - this helps to build confidence that you're interpreting the data correctly.

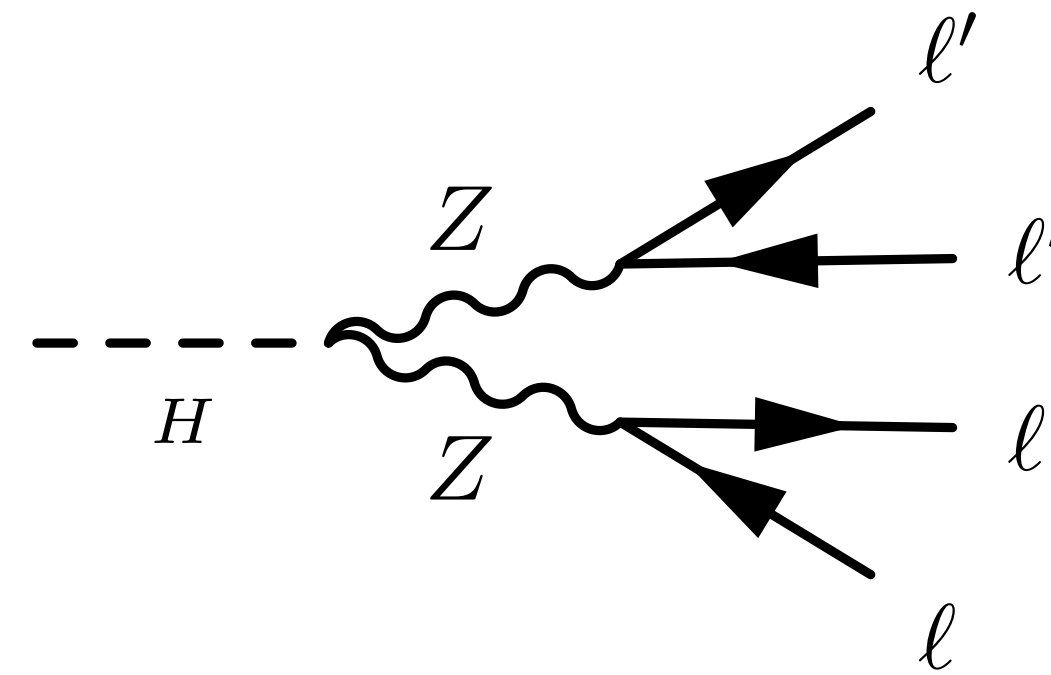
Don't hesitate to get in touch if you get stuck or run into problems!

Best, Christian (chohm@kth.se)

PS. The Z boson does not count since we used it as an example, but all other short-lived particles you can reconstruct from their decay products are ok! Decays that can be reconstructed fully, i.e. where all the decay products are measured, are generally easier, and those with low backgrounds from other processes are strongly recommended too.

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

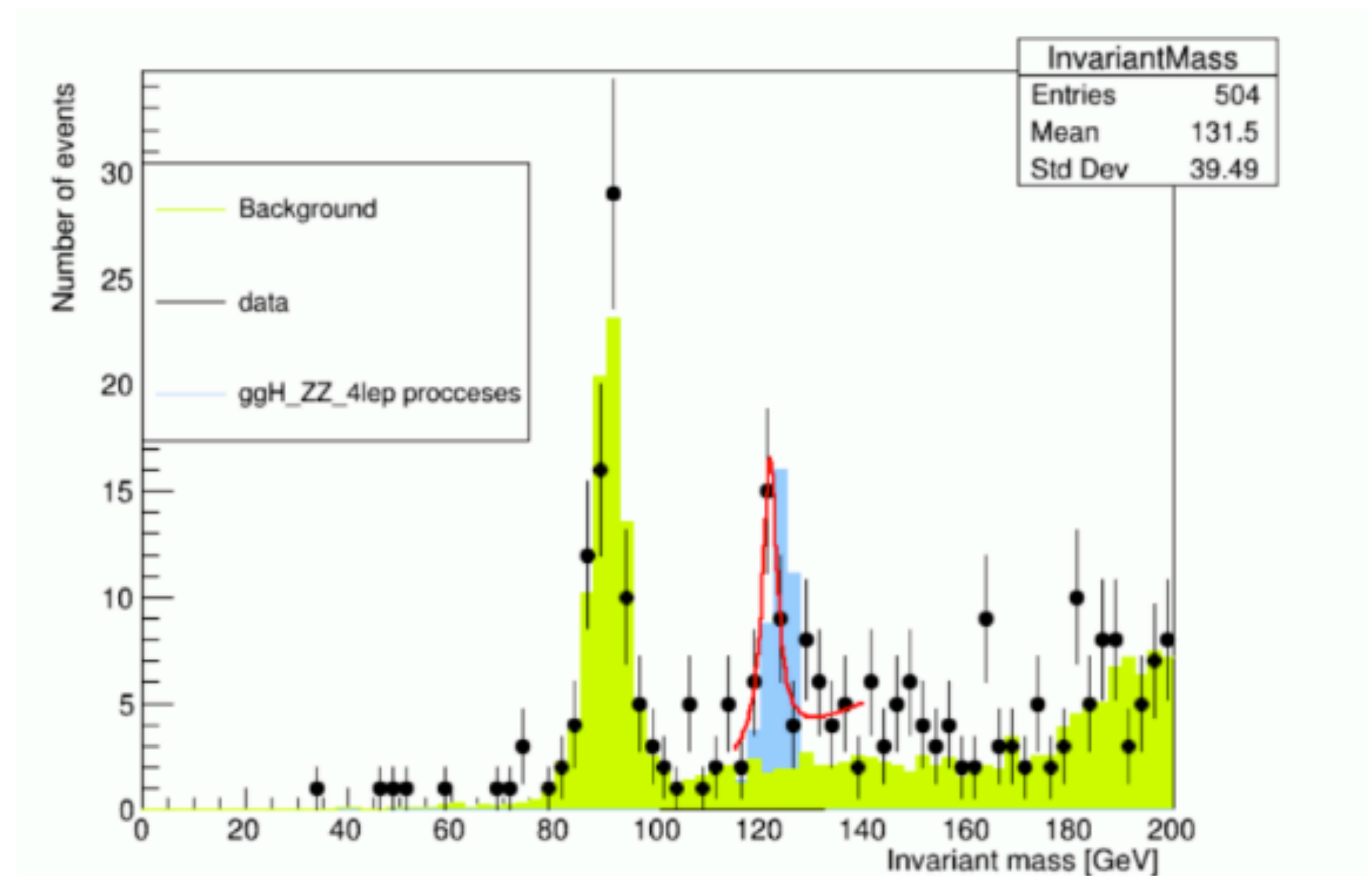


Figure 2.2.7: The simulated invariant mass histogram for the production of the Higgs boson and the simulated invariant mass histogram for background processes resulting in 4 lepton on top of the experimentally attained invariant mass histogram for the production of 4 leptons.

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!

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.

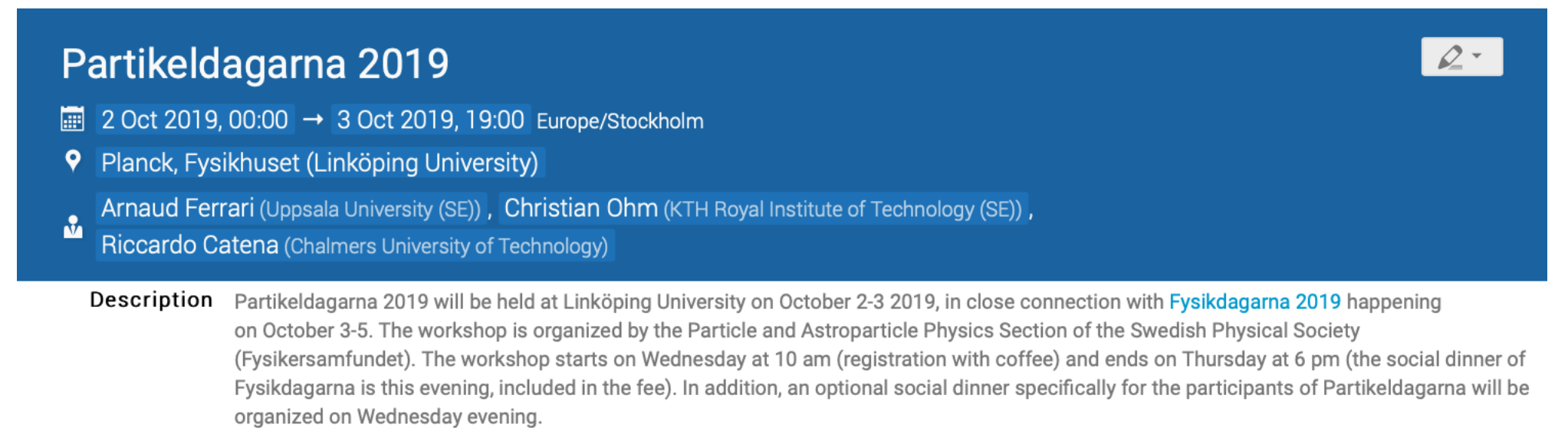


14:50	IPPOG (12+3) Speaker: Jonas Strandberg (KTH Royal Institute of Technology (SE)) IPPOGReport.pdf	15m
15:05	High-school project with open data (8+2) Speaker: Mariam Khodaverdian (KTH) Gymnasieprojekt... Mariam_ATLASop...	10m
15:15	IUPAP (12+3) Speaker: Johan Rathsman Edsjö-Rathsman-IU...	15m

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!



Partikeldagarna 2019 📅

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

📍 Planck, Fysikhuset (Linköping University)

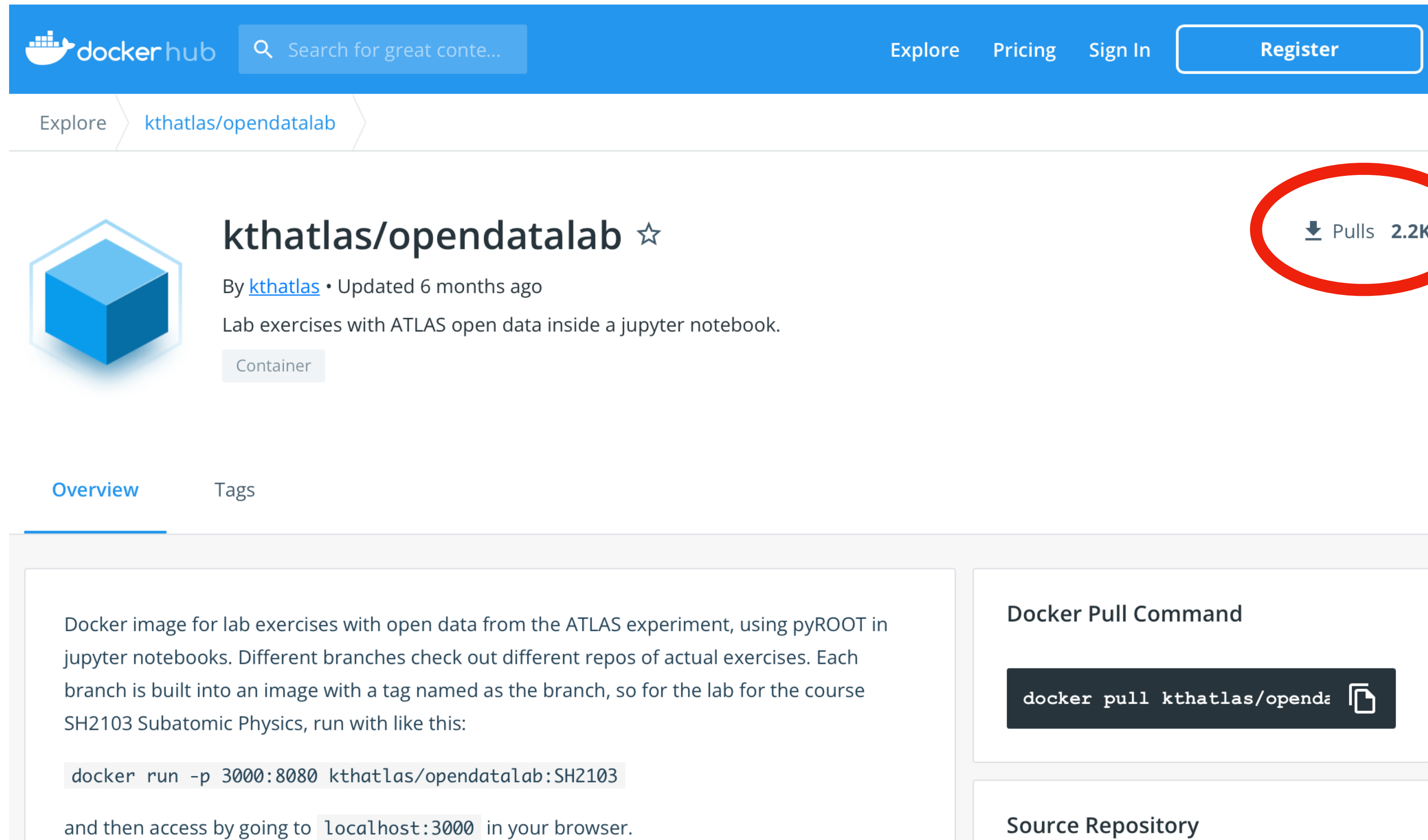
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My experience

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

Try out the docker image!



The screenshot shows the Docker Hub interface for the repository `kthatlas/opensdatallab`. The top navigation bar includes the Docker Hub logo, a search bar, and links for Explore, Pricing, Sign In, and Register. The breadcrumb trail shows the path: Explore > kthatlas/opensdatallab. The repository details include a blue cube icon, the name `kthatlas/opensdatallab` with a star, the author `kthatlas`, and the update date "Updated 6 months ago". A description states: "Lab exercises with ATLAS open data inside a jupyter notebook." A "Container" tag is present. The pull count "Pulls 2.2K" is circled in red. Below the repository name are tabs for "Overview" and "Tags". The "Overview" tab is active, showing a description: "Docker image for lab exercises with open data from the ATLAS experiment, using pyROOT in jupyter notebooks. Different branches check out different repos of actual exercises. Each branch is built into an image with a tag named as the branch, so for the lab for the course SH2103 Subatomic Physics, run with like this:" followed by the command `docker run -p 3000:8080 kthatlas/opensdatallab:SH2103`. Below the command, it says "and then access by going to localhost:3000 in your browser." To the right, the "Docker Pull Command" section shows the command `docker pull kthatlas/opensdatallab` with a copy icon. Below that is the "Source Repository" section.

[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!*

The screenshot shows the GitHub profile of 'Ohm' (cohm), an experimental particle physicist. The profile includes a bio, a link to their GitLab page, and a list of pinned repositories. Two repositories are circled in red: 'docker-openseriallab' and 'OpenAtlasDataLab'. Red text annotations provide context for these repositories.

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!