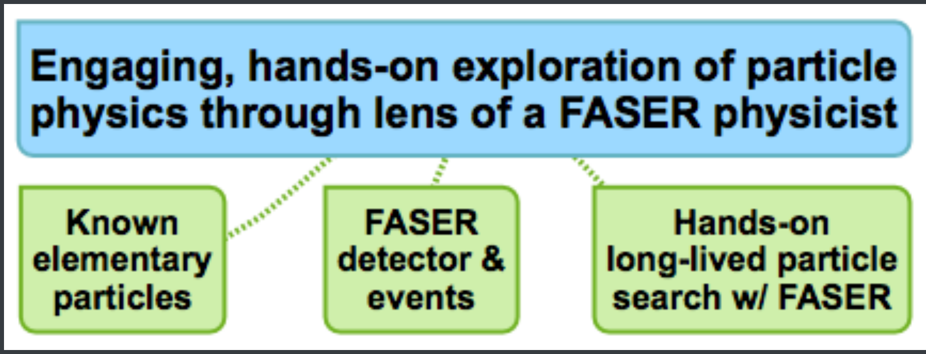
FASER Masterclass Development Notes

Class Goal & Objectives

- **Class goal:** to provide an engaging, hands-on learning opportunity for students to explore the world of elementary particle physics through the lens of a professional FASER physicist
- **Objectives** for students:
  - Develop a new perspective of the building blocks of our Universe, starting from prior knowledge (e.g. atoms $\rightarrow$ nucleons + electrons $\rightarrow$ quarks + electrons)
  - Develop an understanding of the FASER detector, how it detects particles, and what information is stored in events
  - Use FASER Collaboration simulations for a hands-on learning opportunity to conduct a simplified analysis searching for new long-lived particles



Current Class Components

Component	Purpose
Class Overview and Introduction	Welcome the students and present the class structure (background information in Parts 1-2, hands-on search for long-lived particles with FASER in Part 3)
1a. The Standard Model of Particle Physics and the LHC	Provide a broad overview of particle physics, the Standard Model, and the LHC
1b. Long-Lived Particles and FASER	Introduce long-lived particles, including the Standard Model neutrino + the compelling possibility long-lived dark sector particles
2a. The FASER Detector	Introduce the location + components of the FASER detector
2b. FASER Event and Object Reconstruction	Introduce event information obtained by FASER + objects that can be reconstructed from the event information
3. FASER Analysis	Provide a visual, hands-on analysis using FASER simulations, focusing on the signature of a long-lived dark sector particle in the FASER detector; conclude with combining results
Class Conclusion	Provide a brief summary / recap of the class and inform students that they should now have a good feel for the types of questions FASER physicists ask as well as the type of work they do

Planned Class Structure

- Feasible to have students prepare by reading background material (web materials) in advance?

- Background information (parts 1-2) to be presented using slides with **essential concepts only**
  - Companion slides to illustrate key points, *not* packed with loads of information
    (i.e. avoid presenting lots of details using lots of words in bullet points like these)
  - Slides to supplement webage content, *not* serve as a substitute for it
    (webpage content to serve as abbreviated "textbook")
  - **Activity-based learning** planned to be used in conjunction with lecture-style presentation

- Analysis (part 3) to **minimize computations**, though requiring them for important physics concepts (e.g. invariant mass)
  - Students should be able to spend most of the time thinking about the physics

To Do

- Finalize + professionalize webpage content (April-May 2020)
  - Right level of detail in each section?
  - Any other content that should be included?
    - See highlighted ideas below
  - Add links / citations for SM, LHC, FASER, etc. so that students can explore further if they would like
  - Add details / examples to dark photon analysis
    - Show how to calculate invariant mass, other kinematic quantities
    - Show examples of background-only vs. background+signal cases
- Develop a web-based event display (April-June 2020)
  - Currently developing a web-based event display similar to the one used in the CMS masterclass (see https://www.i2u2.org/elab/cms/ispy-webgl/)
- Develop a skimmed data format to be read into event display software (May-June 2020)
  - Will likely provide students with skimmed events in e.g. JSON format
- Add an example analysis for instructors / mentors + notes for each section (June 2020)
- Other suggestions?

↓↓↓ Webpage content ↓↓↓

FASER Masterclass

Class Overview and Introduction

The FASER masterclass is designed to give you an engaging opportunity to explore the world of elementary particle physics research through the lens of a professional high-energy physicist. Upon completing this class, you will have a new perspective of the building blocks of our Universe and will have the opportunity to use actual simulations from the FASER Collaboration to search for new subatomic particles of Nature.

The class is divided into the following three segments:

1. Introduction to particle physics (~15 minutes)
2. Introduction to the FASER detector and the events it records (~15 minutes)
3. Hands-on searches for long-lived particles with FASER using FASER Collaboration simulations (~30 minutes).

The first two segments provide all of the background information on the key concepts of particle physics and FASER so that you will then be ready to begin exploring the signatures of new long-lived particles in FASER using simulated events provided by the FASER Collaboration.

Background Information (Parts 1-2)

In this portion of the course, you will explore the following essential information:

- The Standard Model of particle physics and the LHC
- Physics beyond the Standard Model and long-lived particles
- The FASER detector
- FASER events and object reconstruction
- FASER searches for new long-lived particles

Hands-on Search for Long-lived Particles with FASER (Part 3)

In this portion of the course, you will have the opportunity to process some of the simulated FASER events generated by the FASER Collaboration. We will begin by having you view event displays using the web-based FASER event display available at [LINK] and then have you analyze simulated events from a file so that you can see the signatures of long-lived particles inside the FASER detector.

1a. The Standard Model of Particle Physics and the LHC

Particle physicists explore the highest-energy scales currently probable by modern particle accelerators and have discovered a number of "fundamental" particles that have no known substructure. These particles include the familiar electron, though do *not* include the proton or neutron -- the proton and neutron are each composed of three *quarks* bound toghether by force-carrying particles called *gluons*. And the electron is not alone -- it has heavier cousins (the *muon* and the *tau*), which have identical properties except larger mass. All of the fundamental particles discovered to date can be described by a single framework called the *Standard Model* (SM) of paricle physics. Figure 1 shows all of the SM particles, which include matter particles (the *leptons* and the *quarks*) along with force particles. The fundamental forces described by the SM include the electromagnetic force (carried by the familiar *photon*, which is also the constituent of light), the strong force (carried by *gluons*, which are responsible for holding protons, neutrons, and atomic nuclei together), and the weak force (carried by the *Z* and *W bosons*, which are responsible for some radioactive decays). Fortunately, you do not need to learn all of the SM particles to proceed with searching for new ones. For more information about the SM, you can explore LINK(S).

- To do: Add links to SM references

> Fun fact: The SM provides some of the most precise predictions in all of science. The measured value of a property of the electron (its *anomalous magnetic moment*) agrees with the value predicted by the SM so precisely that it would like measuring the distance from New York to Los Angeles to less than the width of a bacterium!

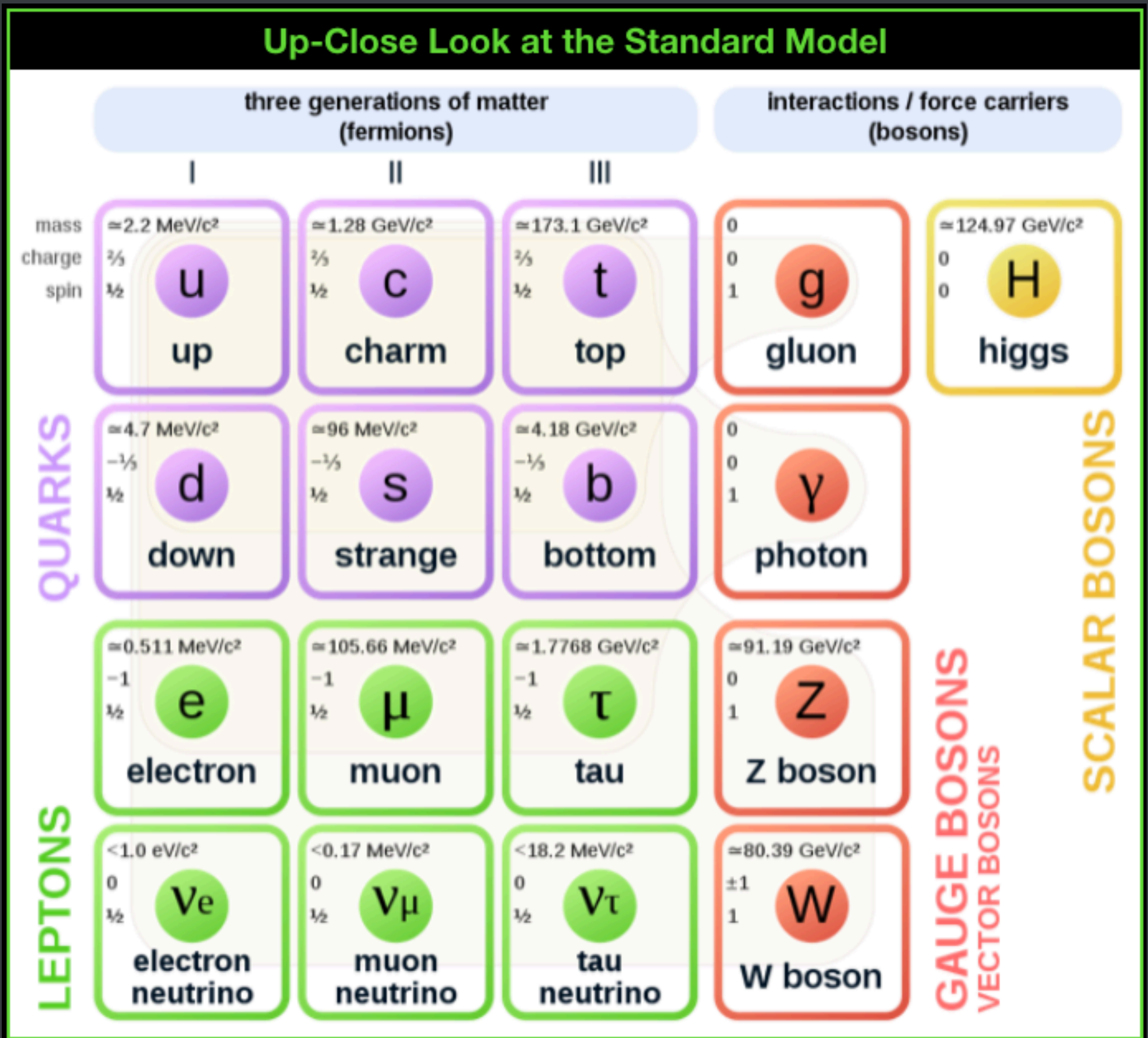


Figure 1. Standard Model (SM) of particle physics. The SM consists of matter particles (the *quarks* and the *leptons*) in addition to force-carrier particles responsible for interactions. The SM includes all fundamental particles discovered to date and describes all of the known fundamental forces except for gravity. Particle physicists have hypothesized a particle responsible for gravity (the *graviton*), though such a gravity particle has not yet been discovered.

The Large Hadron Collider (LHC) accelerates protons to faster than 99.999999% the speed of light. The protons are then collided at different points (the *interaction points*) around the 27-km-circumference ring. These high-energy collisions are capable of producing all of the known SM particles with the possibility of also producing non-SM particles that no one has yet observed. See Figure 2 for a peak inside. For more information about the LHC, have a look at CERN's **LHC webpage**.

- To do: Also include link(s) to particle physics intro guide(s)

Up-Close Look at the LHC

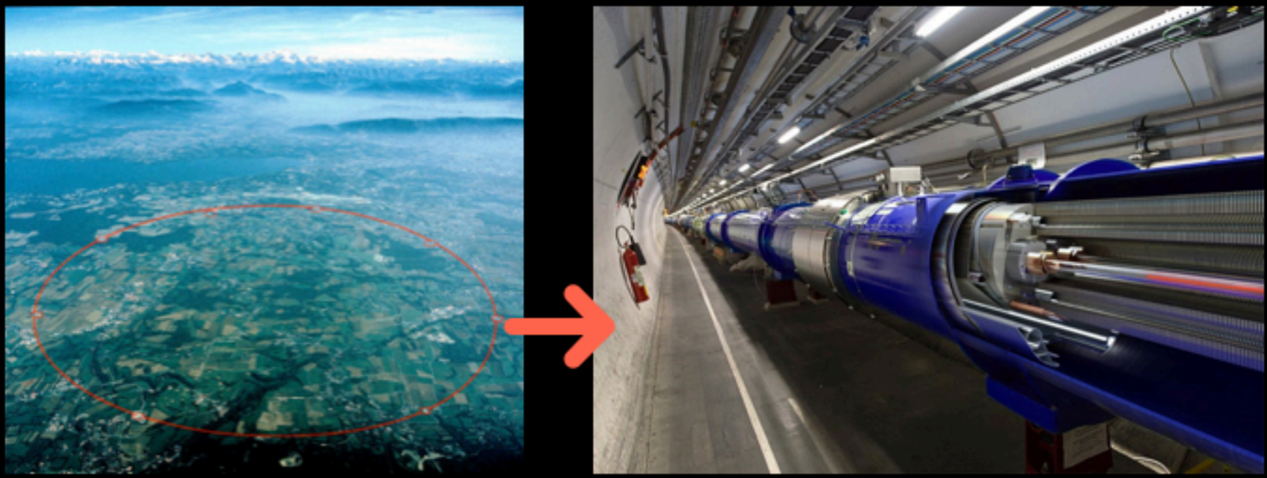


Figure 2. Large Hadron Collider (LHC). The LHC is a particle accelerator at the European Center for Nuclear Research (CERN) located near Geneva, Switzerland that accelerates protons to speeds exceeding 99.999999% the speed of light. In addition to protons, heavy ions are also collided at the LHC. There are a number of experiments at the LHC, each looking for answers to some of the unresolved problems in particle physics as well as for new discoveries that have never been proposed.

1b. Long-Lived Particles and FASER

While some of the Standard Model particles such as the electron are stable as far as we know, others quickly decay into other particles. How quickly a particle decays depends how strongly it interacts with other particles.

The ForwArd Search ExpeRiment (FASER) is a new experiment under construction at the LHC and has designed to detect long-lived particles that are able to travel through hundreds of meters of rock and concrete before reaching the FASER detector, which is almost half a kilometer away from the nearest proton-proton collisions (occurring in the ATLAS experiment around the main LHC ring). If that sounds like a long distance, note that SM neutrinos are able to pass through the entire Earth without interacting! Neutrinos are able to pass through such great distances of solid matter because they interact only through the weak and gravitational interactions -- they are electrically neutral (do not interact through electromagnetic interactions) and colorless (do not interact through strong interactions). The other SM particles are unable to pass through such great distances of rock and concrete because they get stopped by the atoms of the rock and concrete as a result of electromagnetic and strong interactions.

In addition to detecting neutrinos, FASER physicists hope to be able to detect other particles able to pass through the hundreds of meters of rock and concrete. Such particles may compose the dark matter responsible for causing outer stars in galaxies to orbit at much higher speeds than would be expected by the graviational effects of visible matter alone. To date, no dark matter particle has been discovered. For more information about dark matter, you can explore LINK(S).

- To do: Add dark matter links
- Also include references to other unresolved problems in particle physics?

2a. The FASER Detector

The FASER detector (see below) consists of multiple components, each responsible for measuring different properties of the different types of particles either entering the detector or being produced inside of the detector. See Figure 3 for a peak inside the detector.

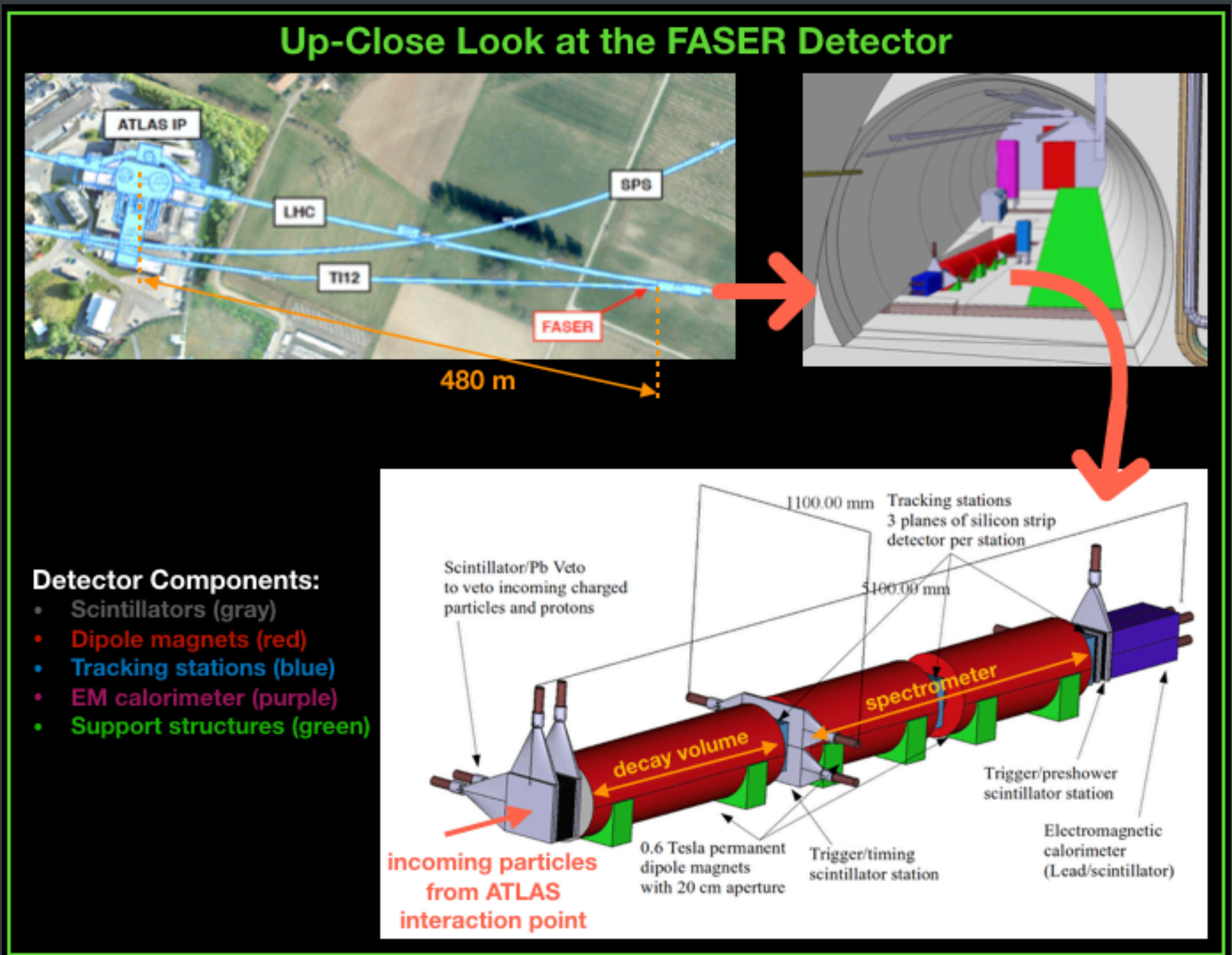


Figure 3. FASER detector location and description. Top: The FASER detector will be positioned directly on the beam collision axis line of sight inside tunnel TI12 (shown above), 480 m downstream from the interaction point where particles are collided in ATLAS and a few meters from LHC beam line. Bottom: The FASER detector will include 0.55-T permanent dipole magnets, a scintillator veto, a 1.5-m decay volume, a 2-m spectrometer, and an electromagnetic calorimeter. An emulsion detector (not shown) at the front for neutrino measurements has also been approved. See Table 1 below for the details about each detector component.

The main components of the detector and their respective purposes are the following:

Detector Component	Purpose

Scintillators	Veto >99.99% of charged particles produced outside of FASER (mostly high-energy muons), trigger events, provide timing information, provide pre-shower for calorimeter
Dipole magnets	Provide a magnetic field to cause moving charged particles to follow curved trajectories inside FASER's tracking stations
Tracking stations	Separate very closely spaced tracks; help determine the identity, speed, and charge of charged particles
Electromagnetic calorimeter	Stop electromagnetic particles to measure their energy; identify electrons and photons; trigger events
Support structures	Maintain the alignment of the tracking stations and magnets, adjust detector to changes in line of sight
Emulsion detector	Detect neutrinos of all flavors

For more detailed descriptions about the composition and purpose of each component of the FASER detector, you can browse the **FASER website**.

- Provide more details on detector description?

2b. FASER Event & Object Reconstruction

When particles enter the FASER detector, they are not able to "tell" the detector directly. Instead, particles can only be constructed after the fact using the primitive event information available such as the individual hits recorded by FASER's tracking system and individual energy deposits in the electromagnetic calorimeter. Because particles can interact with the detector material and emit other particles, the individual hits and deposits are often noisy. Starting with the noisy hits and deposits to infer which particles enter into or are produced inside of the FASER detector and at what times and locations is the process of *event reconstruction*. Fortunately, the reconstruction of particles has already been done for you in the simulation files you will be analyzing.

- Provide more details on event / object reco?

3. FASER Analysis

Now that you have developed some intuition about the known particles of the Standard Model and possibilities for new long-lived particles and their possible detection with FASER, it's time to put your understanding to use with actual simulations from the FASER Collaboration.

File Downloads

To proceed, please download the event simulation file assigned to your group:

- To do: Add the files once event display + skimmed data format is ready

Group	File
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Each simulation file contains 1000 events, and associated with each event are large amounts of information including timing information, all of the recorded tracker hits, all of the recorded energy deposits in the electromagnetic calorimeter, and lots of other information. Fortunately, the processing of the raw event information has already been done for you, and the files above contain information about the final objects (i.e. reconstructed particles) such as their energy, momentum, and charge.

Dark Photon Search

The dark photon is a hypothesized long-lived particle that has properties similar to those of the known photon of the SM, except that it has a nonzero mass. (The SM photon is exactly massless, which allows them to travel vast distances across the cosmos without decaying.)

- To do: Add description of full analysis here
- Also include other analysis options?

Class Conclusion

Congratulations! If you have worked through the previous sections, you have had the opportunity to get a taste of all of the core concepts for understanding why and how FASER will search for long-lived particles. You first learned about the elementary particles of the Standard Model (SM) of particle physics along some of the possibilities of long-lived particles detectable by FASER (including both SM neutrinos and so-far-undiscovered dark sector particles). You then had the chance to take a look under the hood of the FASER detector and perform a FASER analysis using actual FASER simulation datasets. You should now have a good feel for a day in the life of a professional particle physicist of the FASER Collaboration. If you have any remaining questions you would like to get answered, don't hesitate to ask your mentor!