Andrew
Apurva
SG 9 :
Future
Accelerators
Suranan
Sarah
John

Our Structure

1. Curriculum and classroom connections- Andrew
2. Key Ideas- Apurva
3. Potential students conceptions and challenges - John
4. Helpful material and resources - Suranan
5. Best Practice Example - Sara

Curriculum & Classroom Connections

We all teach a variety of different syllabi and schemes with some degree of overlap but massive discrepancies.

We are however united in one thing: No matter how far away we are from CERN, or the relative esteem in which particle physics is held in in our home countries, one thing held true across the entirety of our studies.

None of our countries had future colliders as a topic in their specification.

The ideas required to understand future colliders barely arise.

When discussing the words required to understand the mechanics /function /aspirations of future colliders, we settled on these words as the most relevant.

Collider	Boson	Antimatter
Super-Collider	Luminosity	Muon
Accelerator	Super-Conductor	Pion
Proton-Proton	Hadron	Positron
PET	Fermion	Lepton
Quark	Dark Energy	Dark Matter

Colleagues in the course sent in their specification and the presence of these key terms was as follows:

					Mechanics			Collisions
Country		Sent	Collider	Super-Collider	Luminosity	Super-Conducting	Accelerator	Proton-Proton
United Kingdom		Sent	No	No	Yes	Yes	No	No
United States- Indiana		Sent	No	No	No	No	Yes	No
New Zealand		Sent	No	No	No	No	No	No
Netherlands		Sent	No	No	No	No	Yes	No
Philippines		Sent	No	No	No	No	No	No
Australia		Sent	No	No	Yes	No	Yes	Yes
Bosnia and Hercegovina		Sent	Yes	No	Yes	Yes	Yes	No
Canada		Sent	No	No	No	No	No	No

							Particles						Outcomes	
Country		Sent	Quark	Lepton	Boson	Muon	Pion	Positron	Hadrons	Fermions	PET Scans	Dark Energy	Dark Matter	AntiMatter
United Kingdom		Sent	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No
United States- Indiana		Sent	No	No	No	No	No	No	No	No	No	No	No	No
New Zealand		Sent	Yes	Yes	No	No	No	No	No	No	No	No	No	No
Netherlands		Sent	No	No	No	No	No	Yes	No	No	Yes	No	No	No
Philippines		Sent	No	No	No	Yes	No	No	No	No	No	No	No	No
Australia		Sent	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	No	No
Bosnia and Hercegovina		Sent	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Partial	Yes	Yes	No
Canada		Sent	No	No	No	No	No	No	No	No	No	No	No	No

Country		Sent	Collider	Super-Collider	Luminosity	Super-Conducting	Accelerator	Proton-Proton	Quark	Lepton	Boson	Muon	Pion	Positron	Hadrons	Fermions	PET Scans	Dark Energy	Dark Matter	AntiMatter
United Kingdom		Sent	No	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	No
United States- Indiana		Sent	No	No	No	No	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No
New Zealand		Sent	No	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	No	No	No	No
Netherlands		Sent	No	No	No	No	Yes	No	No	No	No	No	No	Yes	No	No	Yes	No	No	No
Philippines		Sent	No	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
Australia		Sent	No	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	No	No	No
Bosnia and Hercegovina		Sent	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Partial	Yes	Yes	No
Canada		Sent	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No

The following terms were commonly missing

Proton-Proton	One of the more significant collisions- its absence challenges our ability to express what is being accelerated.
PET Scans	One of the defining characteristics of medicine derived from nuclear physics- prevents us from grounding our teaching in reality.
Boson	Inhibits our discussions of sub atomic forces.
Fermion	Inhibits our discussion of what is collided/released during collisions.
Dark Matter/Energy	Prevents discussion of what future colliders are seeking to find/worth investing in.
Muon/Pion/Positron	Denies a level of specificity in describing particle collision consequences

Every outside spec topic introduced in the classroom takes a set time, which we have a limited amount of.

How therefore can we justify finding that time/spending it on future colliders?

Moral justification for discussing future colliders

- Debate taking place within the Scientific Community as to how much an economy should be allocated to scientific research at the expense of the poor.
    - Chen Ning Yang vs Yifang Wang

- Democratizes Physics.
    - We are the front line in ensuring our students, the majority of whom are among the most disadvantaged are prominent in the next generation of advancements in Science. Without our active participation, hegemonies will simply reproduce themselves.

- Establishes Physics as an open field.
    - Our subject is alive and developing daily- real, material discoveries are being made, particles are being named, and collaboration places us as a field with hundreds of thousands of engineer, theoretical and experimental positions available which provide worthwhile and dignified work exploring the universe.

How to do it:

- In class debates with a focus on oracy on Scientific advancement and its cost.

- Extracurricular “Journal” clubs on future colliders.

- Further reading over the summer holidays on Theoretical Physics
  - Quantum Mechanics (George Hrabovsky and Leonard Susskind), Existential Physics (Sabine Hassenfelder)

- Introducing the luminosity formula to demonstrate the weakness in “triangle” methods of equation solving, the relevance of the surface area of a sphere.

$$L = \frac{N^2 k_b f}{4\pi \sigma_x \sigma_y}$$

How to do it:

- Demonstrating simple Feynman equations and the principles for solving.

- Organizing school tours to visit CERN (so more people can meet & love Jeff).

- Use of prefixes- Femto/Pico/Exo/Peta
- Thought experiments-
  - What are the parameters colliders currently work on?
  - How could they be adjusted for improvement?
  - What would a new design/experiment look like?

Interleaving within the Curriculum

Evolution of Accelerators : Electrostatic to Oscillating	Lorentz Force
Linear accelerators,	Relativistic Transformation
Electric and Magnetic Fields	Focusing force
Constant and Oscillating Fields	Dipoles and Quadrupoles
Cyclotrons	Superconductors
Synchrotrons	Collisions
Hooke’s law	Harmonic Oscillators

The Key Ideas – why should our students care about future accelerators?

A look at the beginning: Electrostatic to Oscillating accelerator

- Most high schoolers will relate if we tell them about **Rutherford** and his "demand" for higher energy to split the atoms!

- **1932**, Cockcroft & Walton- used a 400 kV transformer to accelerate protons and shoot them onto a lithium target --- **first entirely man controlled splitting of the atom!(Nobel prize, 1951!)**
- **1928**, Wideroe demonstrates Ising's principle of resonant acceleration with 1 MHz, 25 kV oscillator to make 50 keV potassium ions.

Proton accelerator used by Walton & Cockroft to split the atom. Walton sits in the small observation cabin and watches the produced alpha particles on a fluorescent screen.
Credit: cambridgephysics.org

Key concepts

Linear accelerators!

Synchrotrons!

Cyclotrons!

Constant fields

Loretnz Force

Focusing force
←-→
- Hooke's Law
- Quadrupole Fields
- Harmonic Oscillation

Dipoles and Quadrupoles

Cyclotron frequency!

Electric Field

Relativistic transformation

Collisions!

Magnetic Field

Oscillating Fields

electon-volt(eV)

Superconductors

LHC! Higgs Boson! Big Bang??? (Discuss and Debate)

- World's largest and most powerful accelerator!
- The LHC can reproduce the conditions that existed within a billionth of a second of the Big Bang

- 2012: discovery of Higgs Boson!
- More that 50 other hadrons detected since then!
- One "pentaquark" and two "tetraquarks" found on 5th July, 2022!

- Finally the question: **WHY** do we need **MORE** accelerators, if we already have the LHC running, now at an unprecedented energy of 13.6 TeV ???

Because still there is a lot more to know!!

Because still there is a lot more to know!!

Physics beyond the Standard Model!

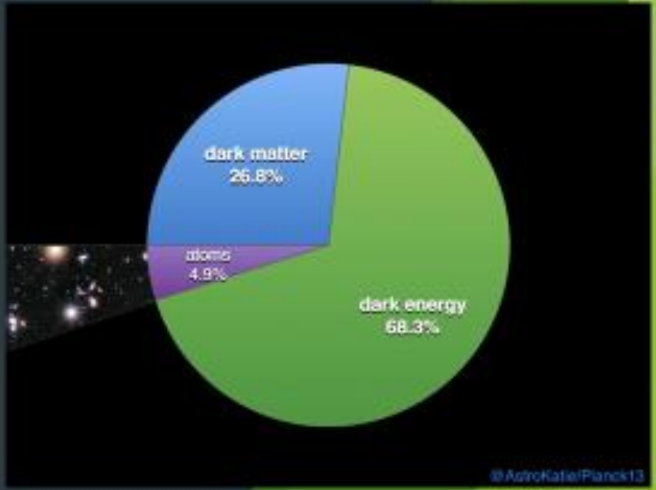
Supersymmetry

Matter > Antimatter?

Dark matter?

Future accelerators are needed to explain..

- what dark matter is,
- what dark energy is and why it exists at all,
- why there's more matter than antimatter in the Universe,
- and how particles got to have the fundamental properties that they actually possess.

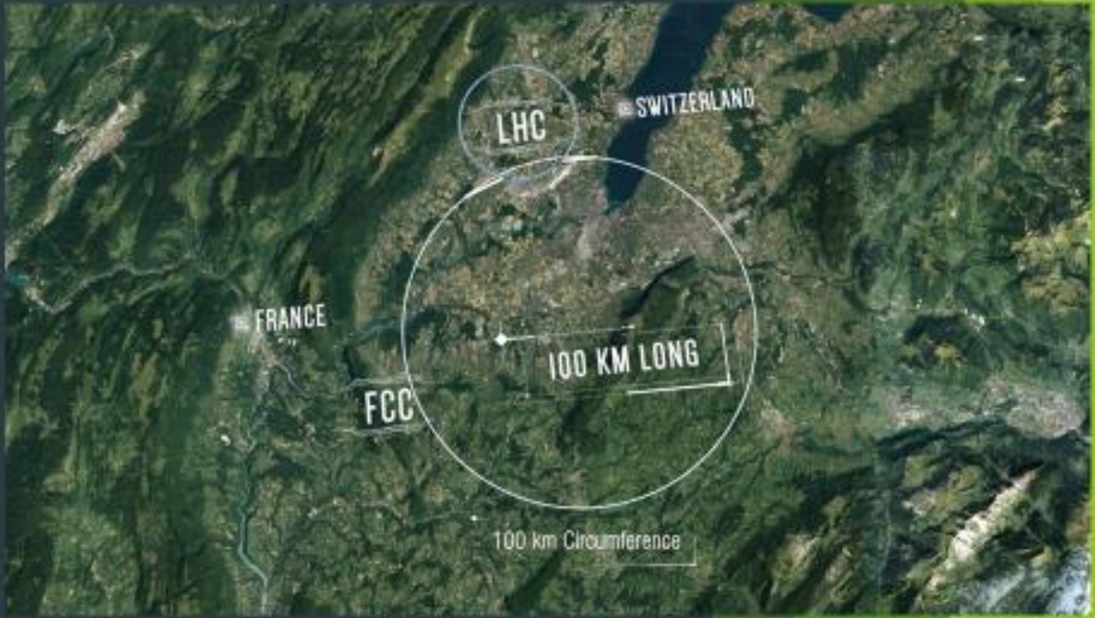


Can we “improve” the LHC?

- That’s HL - LHC for you!
- HL= High Luminosity
- Luminosity= Number of “hits” or colliding particles at interaction
- **The higher the luminosity, the more data the experiments can gather to allow them to observe rare processes**
- Expected to start functioning from beginning of 2029!

Beyond LHC: Future circular collider (FCC)

- electron–positron collisions (FCC-ee): 90- 350 GeV
- hadron (proton–proton and heavy ion) collisions (FCC-hh): 100 TeV

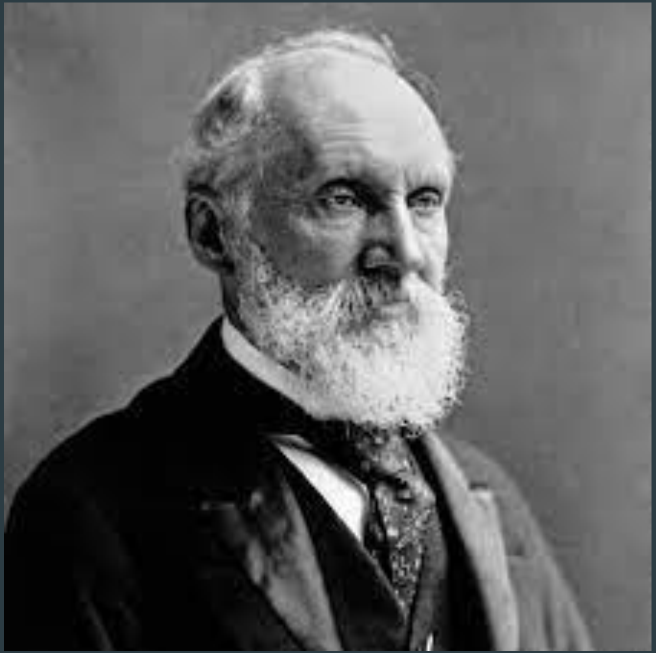


Some more future colliders….

- Higgs/ Electroweak collider
- Positron/Electron Collider
- Super Proton- Proton Collider
- Muon Colliders

John- Potential Students Conceptions and Challenges

- Idea that Physics is inherently too boring or maths based
- Idea that Physics has intrinsic difficulty which makes it inaccessible
- Only 1/3 of US high school students enroll in physics today



"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

John- Potential Students Conceptions and Challenges

How do we challenge those idas?

Structuring Physics in an accessible manner that renders all information in a straightforward, constructive way.

Having a procedure for maths which goes through the sequences of an equation step by step to avoid cognitive overload.

John- Potential Students Conceptions and Challenges

Most of all by filling our lessons with colour and life, and the rich tapestry of Physics which has been made, and the unlimited potential of what is to come.

Along with the discussion my students will put on a “physics circus” demonstrating and explaining multiple aspects of physics concepts they will encounter in a physics course and whenever possible tie the concept to present and future accelerators.

The purpose is to build excitement about physics while demystifying the subject and to remove the fear factor associated with the study of physics making more exciting and accessible and helping students to understand the importance of building the next generation of colliders and the role they may play in that endeavor.

Helpful Material and Resources

frontiers | Frontiers in Physics

REVIEW
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Challenges of Future Accelerators for Particle Physics Research

Stephen Gourlay[1]*, Tor Raubenheimer[2] and Vladimir Shiltsev[3]

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For over half a century, high-energy particle accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity Frontier research in particle and nuclear physics continuously push the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more power efficient. The accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals. The technical maturity of the proposed facilities ranges from shovel-ready to those that are still largely conceptual. At this time, over 100 contributed papers have been submitted to the *Accelerator Frontier* of the US particle physics decadal community planning exercise known as *Snowmass'2021*. These papers cover a broad spectrum of topics: beam physics and accelerator education, accelerators for neutrinos, colliders for Electroweak/Higgs studies and multi-TeV energies, accelerators for *Physics Beyond Colliders* and rare processes, advanced accelerator concepts, and accelerator technology for Radio Frequency cavities (RF), magnets, targets and sources. This paper provides an overview of the present state of accelerators for particle physics and gives a brief description of some of the major facilities that have been proposed, their perceived advantages and some of the remaining challenges.

Keywords: accelerators, colliders, beam physics, magnets, particle sources, RF acceleration, plasma acceleration

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1 INTRODUCTION

There are more than 30,000 particle accelerators in operation around the world. Most of them use low energy beams ($\ll$ 1 MeV) and are used in industry [1]. Less numerous are high energy accelerators for research where there are just over a hundred, many of which have been recently constructed for photon science. Particle physics requires pushing the accelerated beams to the highest possible energies [2] and to the highest possible intensities [3]. Below, we briefly consider the most actively developing accelerator projects, such as the high energy lepton and hadron colliders and accelerators for neutrino studies and rare processes searches, and outline the status and progress in accelerator beam physics as well as in the core accelerator technologies - magnets, Radio Frequency cavities (RF), plasma, targets and sources. There are about two dozen energy Frontier colliders that complement or exceed the LHC in their discovery potential. Among them is the three TeV center-of-mass (CoM) CLIC option (100 MV/m accelerating gradient, 50 km long), two 100 km circumference *pp* colliders: the SPPC in China (75 TeV CoM, based on 12 T Superconducting (SC) magnets) and the FCC-hh at CERN (100 TeV CoM, 16 T SC

Proceedings of the 2019 CERN–Accelerator–School course on *High Gradient Wakefield Accelerators, Sesimbra, (Portugal)*

Introduction to Particle Accelerators and their Limitations

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Abstract
The paper gives a short overview of the principles of particle accelerators, their historical development and the typical performance limitations. After an introduction to the basic concepts, the main emphasis is to sketch the layout of modern storage rings and their limitations in energy and machine performance. Examples of existing machines - among them clearly the LHC at CERN - demonstrate the basic principles and the technical and physical limits that we face today in the design and operation of these particle colliders. Pushing for ever higher beam energies motivates the design of the future collider studies and beyond that, the development of more efficient acceleration techniques.

Keywords
Accelerator physics; synchrotrons and storage rings; particle colliders; acceleration gradients; performance limits.

https://arxiv.org/pdf/2007.04075.pdf

https://www.frontiersin.org/articles/10.3389/fphy.2022.920520/full

Helpful Material and Resources

Eur. Phys. J. Special Topics **224**, 2615–2620 (2015)

DOI: 10.1140/epjst/e2015-02572-x

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

CERN needs for future accelerators in high energy physics

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Received 3 July 2014 / Received in final form 31 August 2015
Published online 26 October 2015

Abstract. Several new accelerator projects are being studied at CERN in a broad energy range from atomic to Tera scale level. The beam energy as well as the beam quality requirements raise the need for new future acceleration concepts to achieve more efficient accelerating structures and / or more compact devices. The article gives a number of examples of the studies, the beam parameters that are foreseen in the different projects and their proposed technical layout.

https://link.springer.com/content/pdf/10.1140/epjst/e2015-02572-x.pdf

nature reviews physics

Comment | Published: 07 March 2019

The physics and technology of the Future Circular Collider

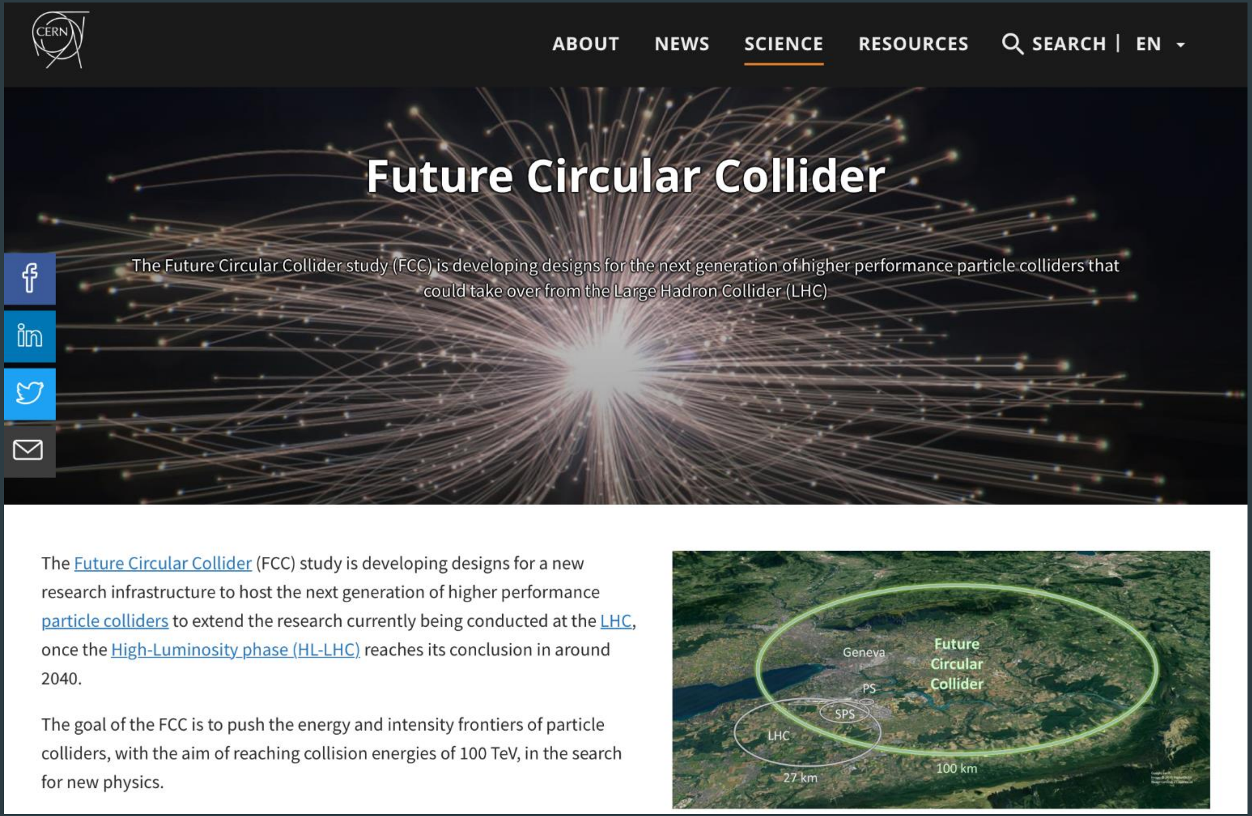
Michael Benedikt & Frank Zimmermann

Nature Reviews Physics **1**, 238–240 (2019) | Cite this article

Michael Benedikt and Frank Zimmermann describe the Future Circular Collider, a proposed collider-based research infrastructure that can be realized in successive steps.

https://www.nature.com/articles/s42254-019-0048-0

Helpful Material and Resources



This is a CERN homepage which provides the future circular collider study. It gives an overview of a new scientific tool for the post-LHC landscape, a scientific mission for the 21st century, preparing the next-generation of particle colliders to boost the energy and intensity frontiers, designing a sustainable research infrastructure through collaborative R&D, and the FCC conceptual design reports.

https://home.cern/science/accelerators/future-circular-collider

Helpful Material and Resources

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ation of particle colliders to boost the energy and intensity frontiers, designing a sustainable research infrastructure through collaborative R&D, and the FCC conceptual design reports

Best Practice Examples

The Higgs boson was found 10 years ago…so where do we go now?

The discovery of the Higgs boson has dramatically changed the particle physics landscape, opening the door to the study of many qualitatively new fundamental interactions.

GOAL: to search for new particles or forces of nature and to **extend** or **replace** the current standard model of particle physics.

BUT the needed technology has yet to be developed!

Reaching ambitious scientific objectives, like those envisioned by the FC studie, requires the development of **advanced instruments**, **new technologies** as well as the training of the next generation of researchers in different fields. Investing in large-scale research project like the FC can bring **tremendous benefit to society and the economy.**

There are still many aspects of the universe that SM can’t explain. Among these is dark matter: the enigmatic substance which makes up much of the universe’s overall mass, but whose composition remains completely unknown to researchers.

We hope to have an answer to the question of why the universe contains so much more matter than antimatter

A remind: historically BASE physics has lead to great NEWS: think about lasers or PET

Keep in mind: there are positive and negative lessons which future projects can learn from previous generations of accelerators.

And keep an eye on the cost! ;)

Future High Energy Frontier Colliders

One possibility for the future is the FCC programme that has been developed to directly observe and study these interactions of the Higgs, with the W and Z bosons, quarks and leptons, and of the Higgs with itself, the keystone of the Standard Model of particle physics.

The FCC will also offer a broad physics programme beyond the Higgs sector, including searches for answers to many of the other major open questions of particle physics, such as the **nature of dark matter,** the **origin of the matter–antimatter asymmetry in the Universe, and the source of neutrino masses**.

The future accelerator would reach collision energies of 100 teraelectronvolts (TeV), compared with the 14 TeV of the LHC, which also collides protons and is currently the most powerful accelerator in the world. New coliders could lead to future direction of the field of particle physics and, ideally, lead to solutions to unanswered questions and problems with the Standard Model."

Higher B-field technology: sc magnet technology is required and it is going to be more and more expensive

High Energy Lepton Colliders: Limited by Synchrotron Radiation and RF Power

Circular e+ / e- colliders are severely limited by synchrotron radiation losses

and have to be replaced for higher energies by linear accelerators

There is a discussion going on between Circular vs. Linear Colliders

An idea is to realize CLIC: Normal conducting RF system

This would avoid all the problems related to the superconductivity staff!

There are several groups already working on Plasma Wake Acceleration particle beam driven / LASER driven (100 GeV/m) as Plasma waves are a possible (compact and cheaper) alternative - providing a route to university scale accelerators and radiation sources

What‘s next ??? Dark Matter & Dark Energy Physics beyond the Standard Model

Open questions in particle physics

Dark matter & Energy

… on which energy scale to look for it ?

Physics beyond the standard model

... Lepton or Proton colliders ?

Beam dynamics aspects

... Circular or linear ?

Technical aspects

... Traditional, sc / nc or PWA ?