Institute of High Energy Physics

Machine learning meets physics

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04 September 2021

Background reference: https://www.symmetrymagazine.org/article/six-fabulous-facts-about-the-standard-model

What is Machine Learning?

- It all starts with a "HOW" (data inference)
  - The strategy is to look at the data and try to establish a mathematical formulation that describes the behavior and should be able to make further predictions
  - Most of the times it's tedious to find such a mathematical formulation. For example selling products on different e-websites (amazon, ebay, wallmart ....)
- Machine learning holds the key to this problem!
  - Giving computers the ability to **learn from data** without explicitly programming them
  - Mathematical models learnt from data that characterise the patterns, regularities, and relationships amongst variables in the system ⇔ same way we (humans) learn and improve our understanding
  - Machine learning is everywhere. For example, it’s how Spotify gives you suggestions of what to listen to next or how Siri answers your questions.

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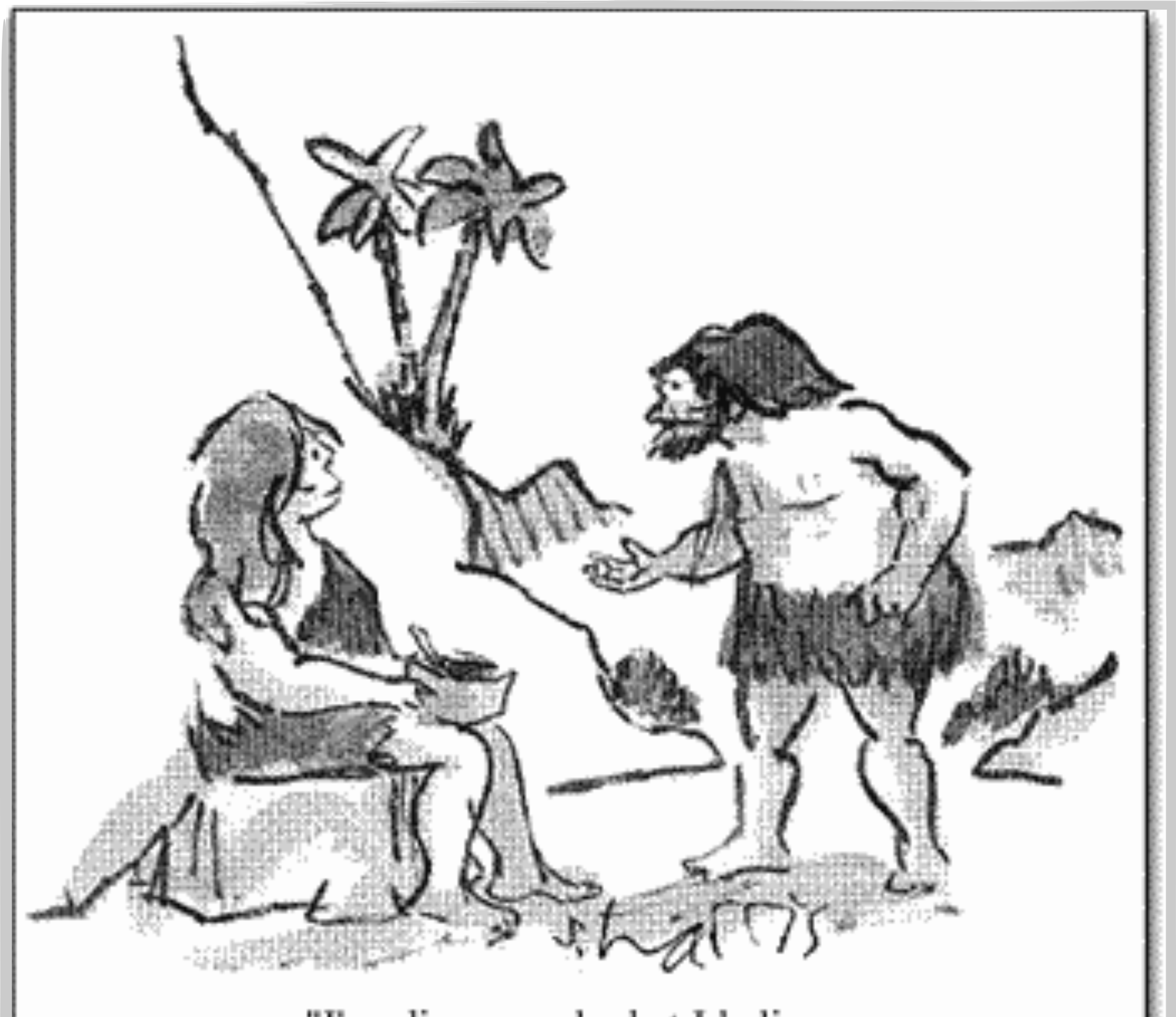
What we (experimental particle physicist) all have is data!!!

Data? In Physics? How? Why?

- Physics? ⇒ Study of Nature by analyzing the experimental data & to check if our current understanding about the Nature (theoretical models) is able to describe it
- For example:
  - Is the formula given by Newton correct, which describes how an apple falls from tree?
  - Solution: Do an experiment, collect data and analyze it
  - Drop the apple from top of a building and measure the time it takes to hit the ground, and repeat. If the measured time and the predicted time (using the gravitational formula) are in agreement, we say EUREKA ☺️😎
- Experiment ⇔ Theory

Most sort-after question of all Humankind!!!

Ref: http://www.sciencecartoonsplus.com/gallery/astronomy/galastro2c.php#



"I've discovered what I believe to be the elementary basic particle: a small stone."

http://www.sciencecartoonsplus.com/forsale/scimags2.php#

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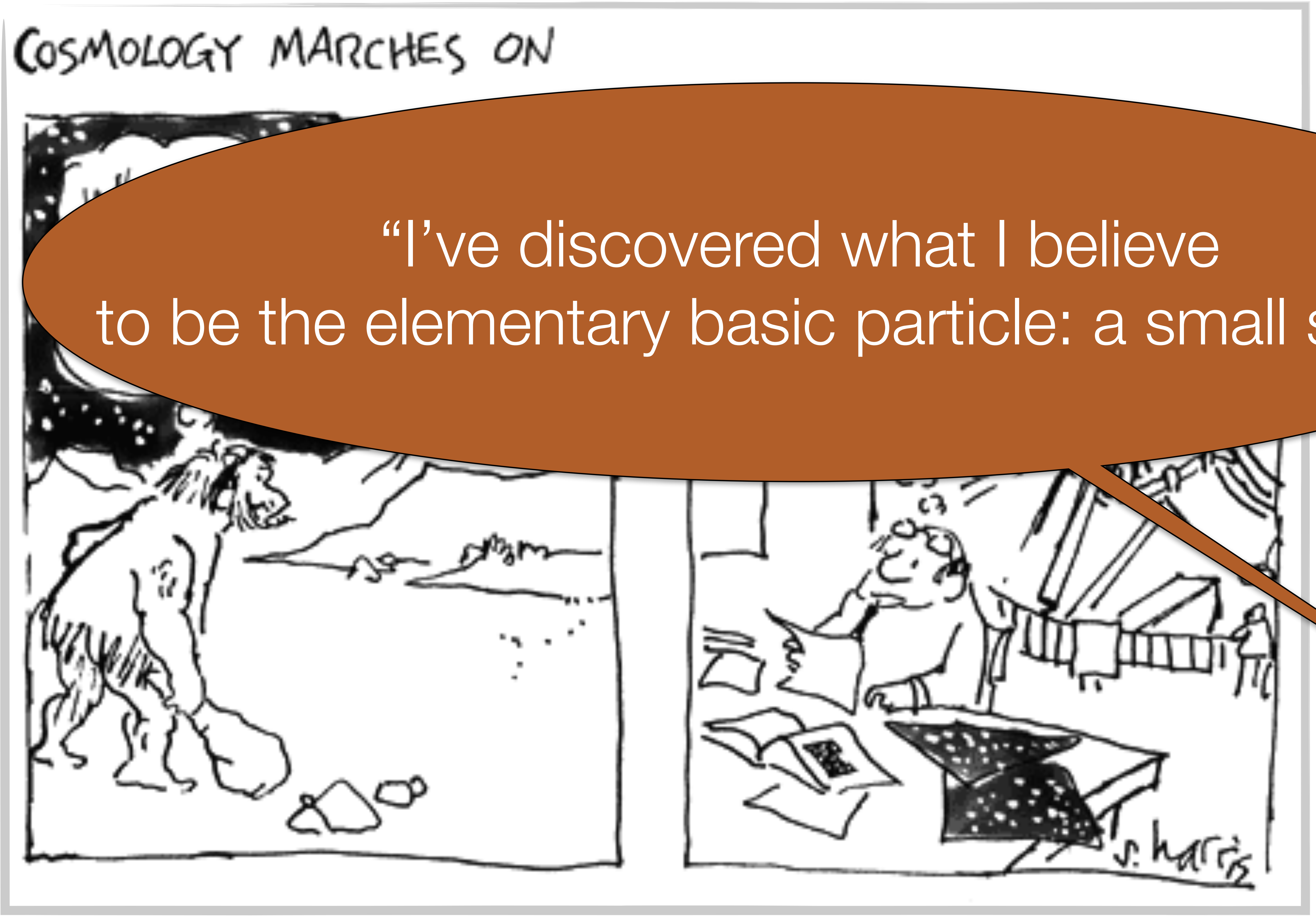

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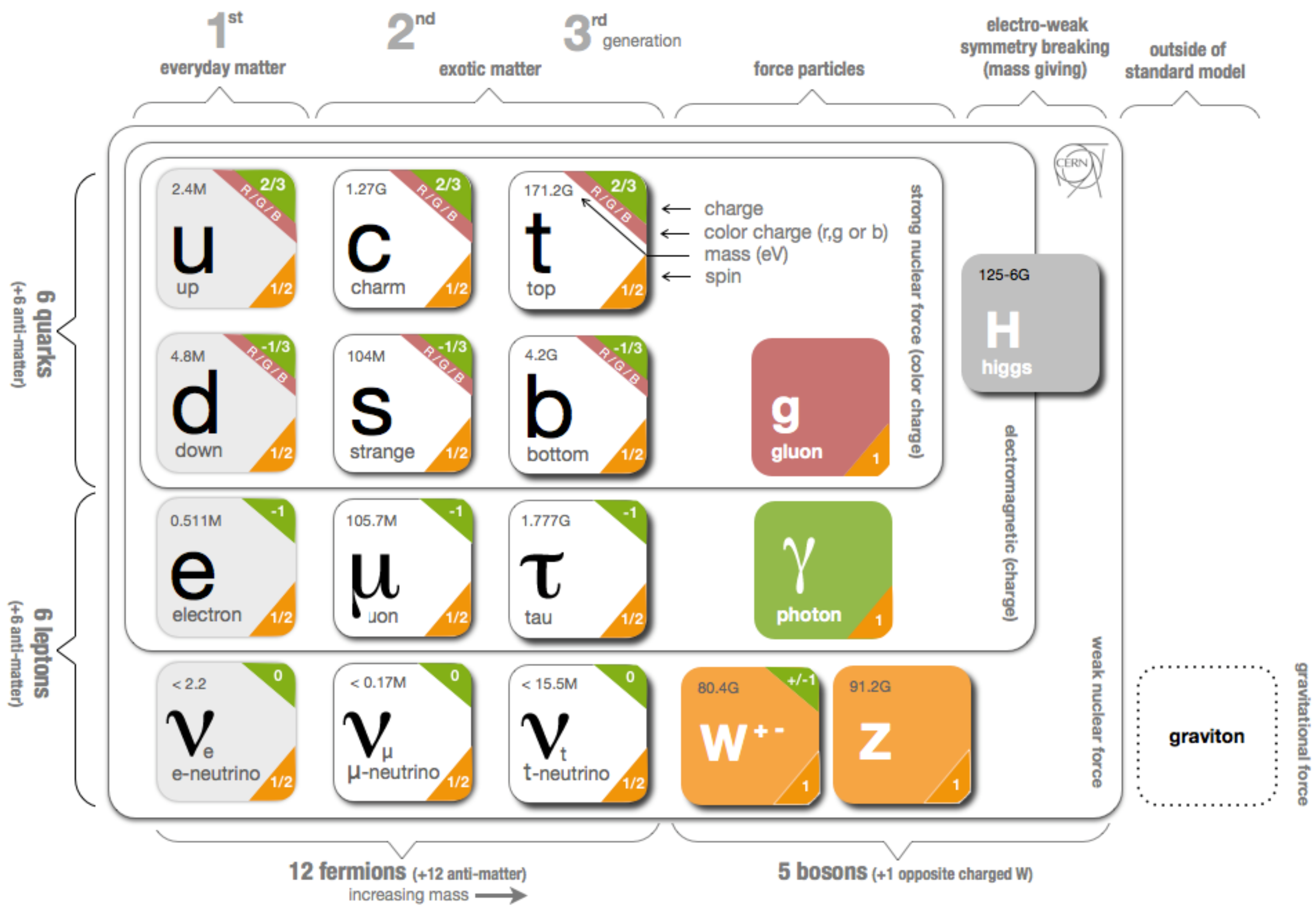
http://www.sciencecartoonsplus.com/forsale/scimags2.php#

High Energy Physics *(a very brief introduction)*

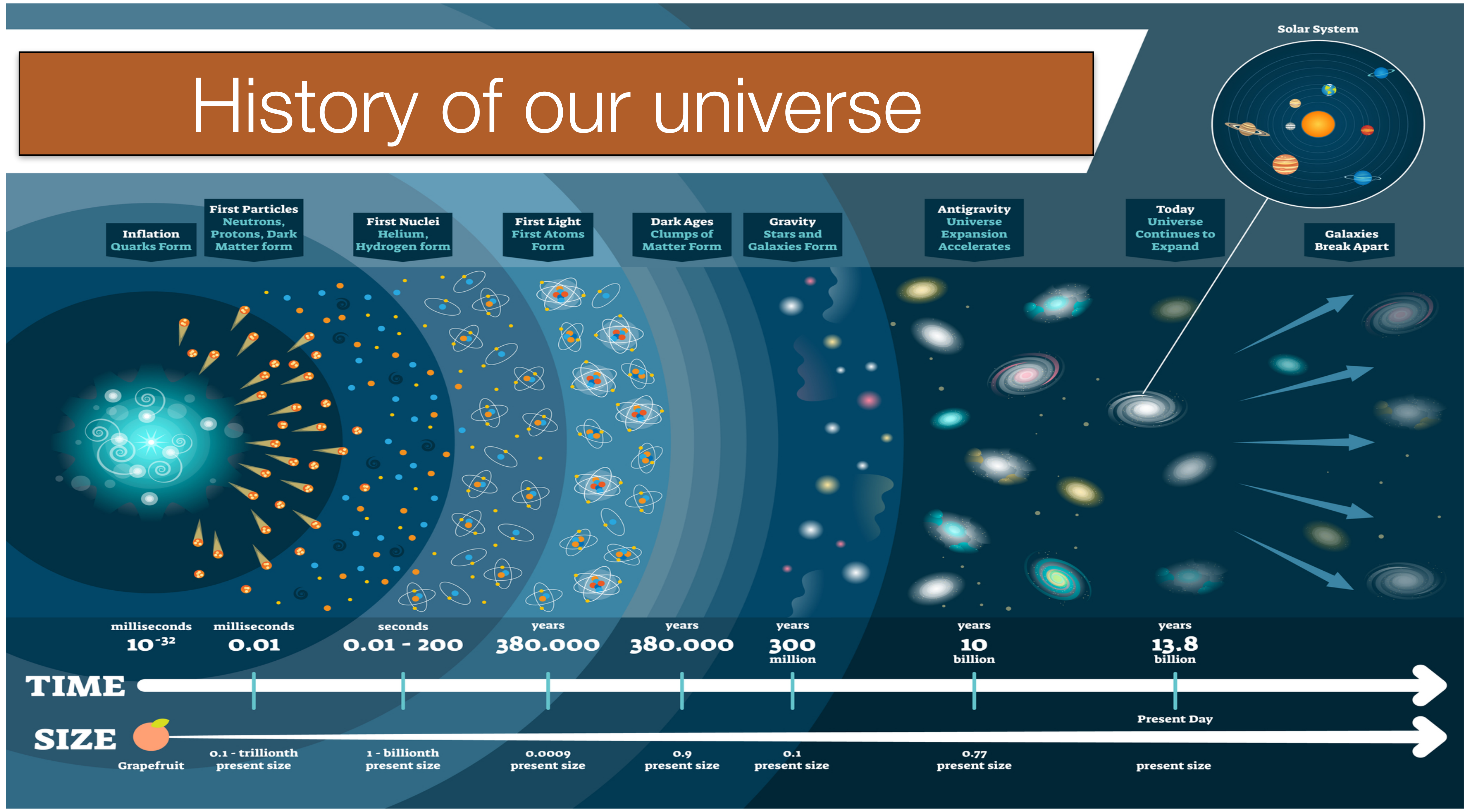
- Branch of physics dealing with the study of basic building blocks of matter
- Standard Model of particle physics: Experimentally very-well established & the most dominating theory (so far!) explaining the nature of fundamental particles and their interactions
- Fundamental particles: Quarks & leptons
- Interaction between particles are mediated by particles called Bosons (W/Z/g)
- Particles acquire mass via Higgs mechanism



Ref: http://www.thomasgmccarthy.com/an-introduction-to-collider-physics-i

Questions …

Started with big-bang



NOW

Same amount of matter & antimatter was created

\> \> \>

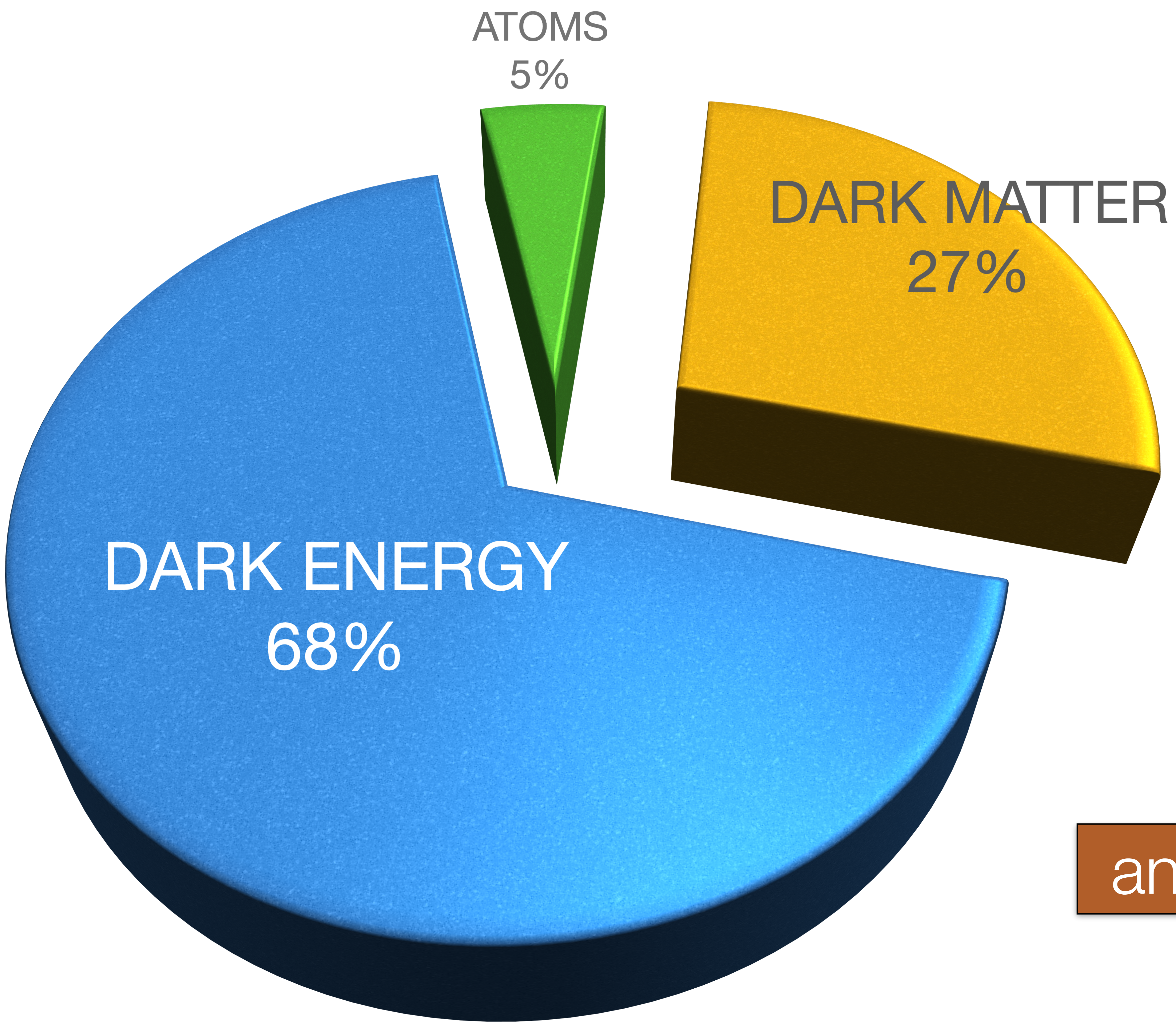
Why?

Only matter (us) survived

$$\frac{N_{baryons}}{N_{photons}} \approx 10^{-9}$$

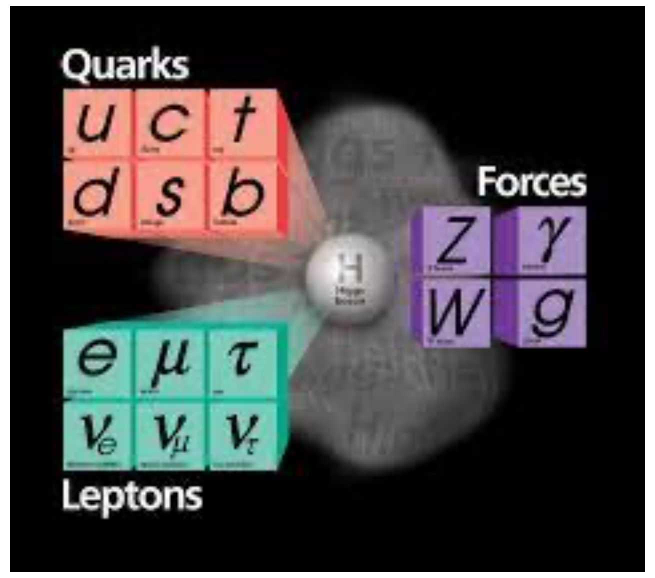
Questions …

Our universe

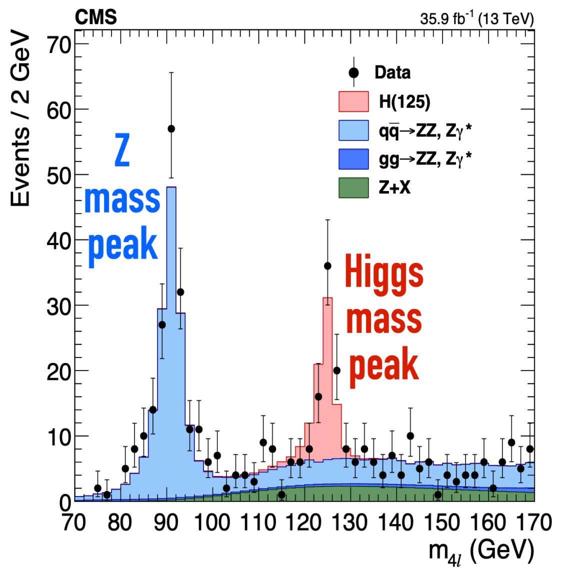


and the other 95%?

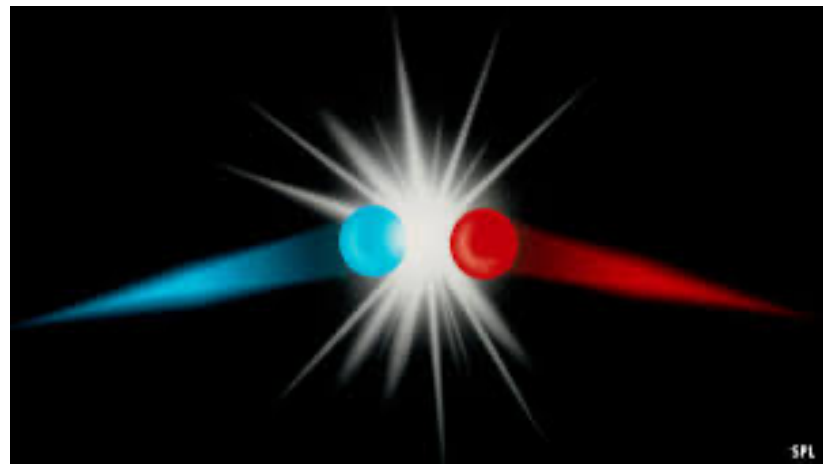
Experiments at CERN, in particular the LHC, are designed to answer the key questions in physics!

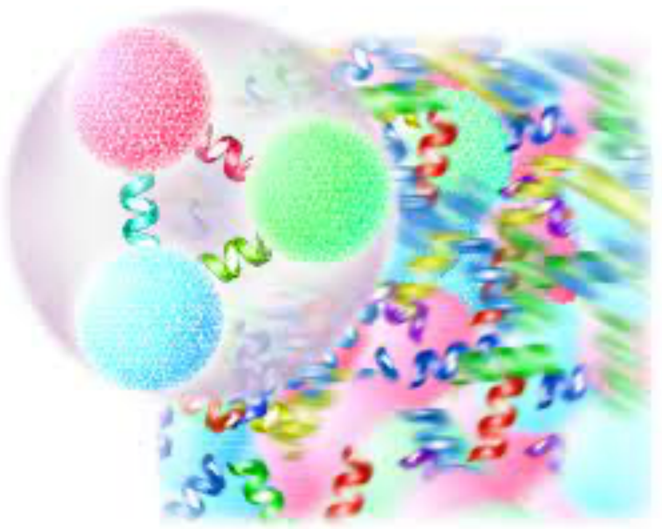


Did we find “THE STANDARD MODEL” Higgs?



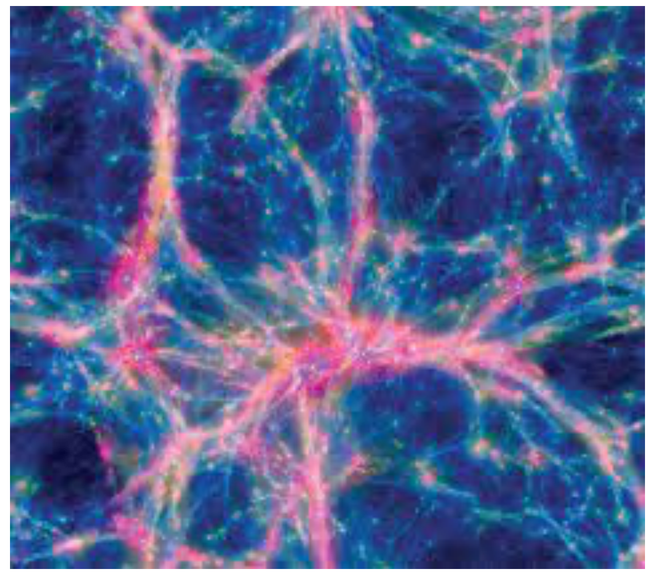
Why matter dominates over antimatter?





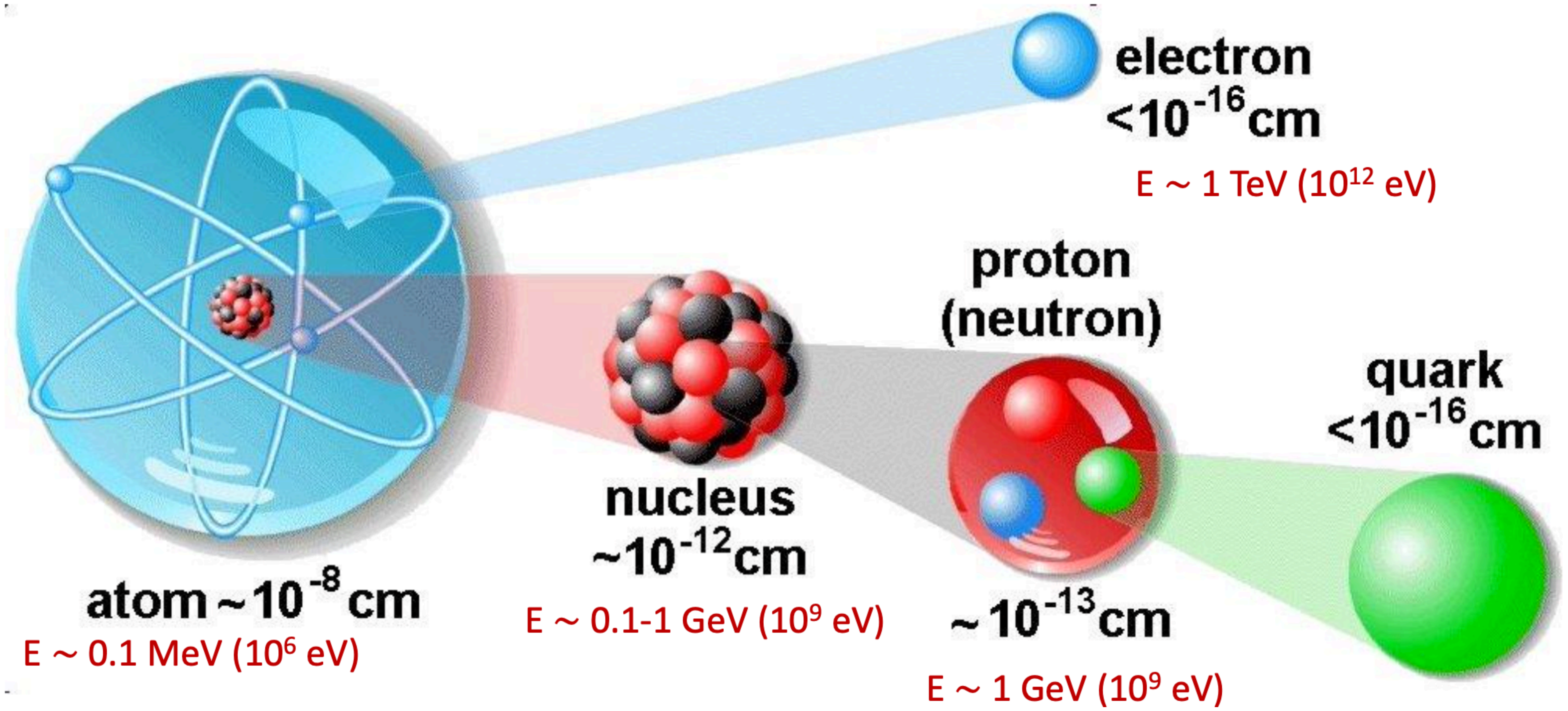
Do we understand the “primordial state of matter” after the Big-bang before protons and neutrons formed?

Nature and composition of “dark matter”?



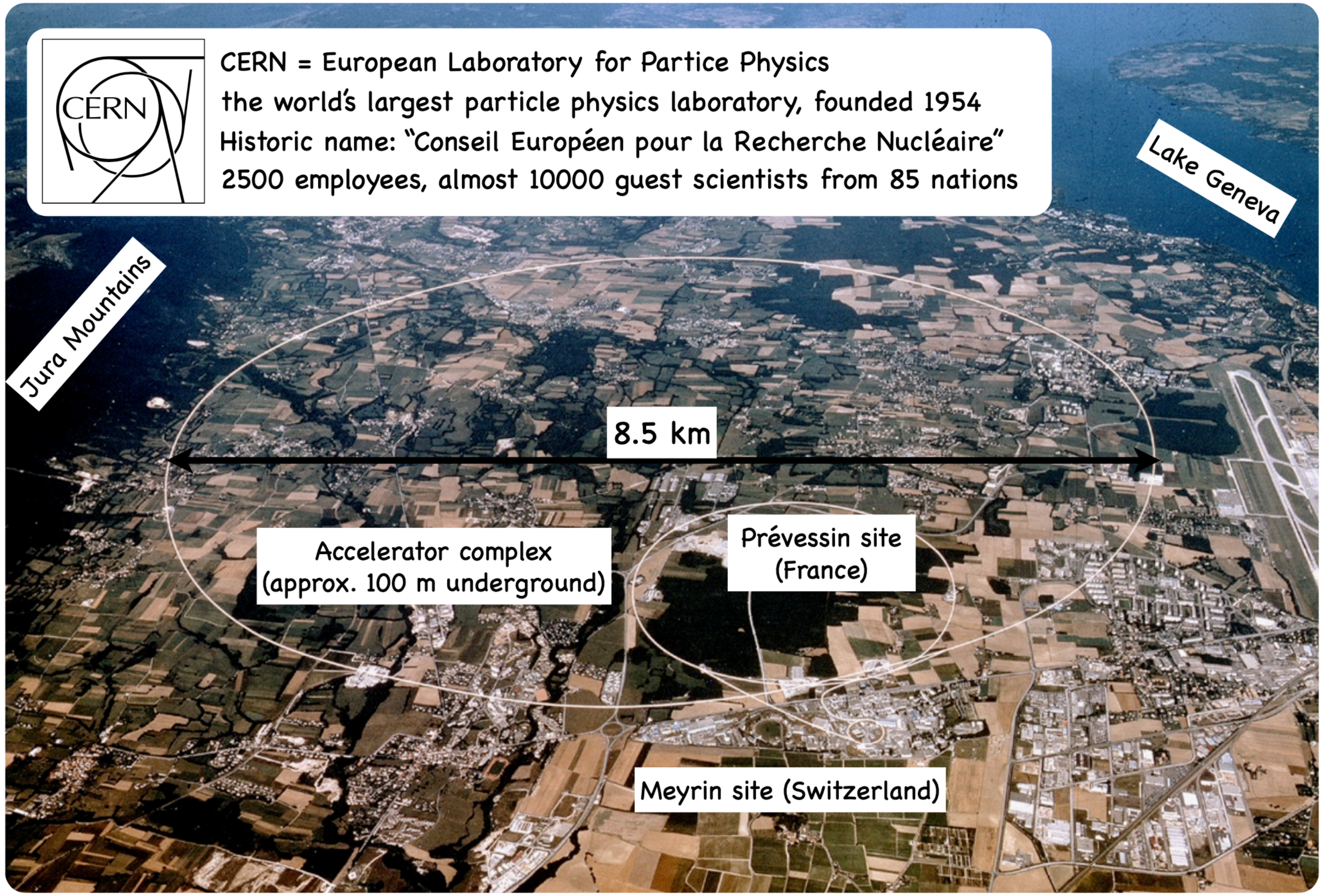
How do we explore small scales or create & discover new particles?

- **Resolving structures**: Use particle beams as a microscope. Need very short wavelength, i.e. particles at very high energies **E = hc/λ**
- **Creating new particles**: collide particles with “available” collision energy corresponding to at least the rest mass of the new particle $E = mc^2$



Large Hadron Collider - 1/2

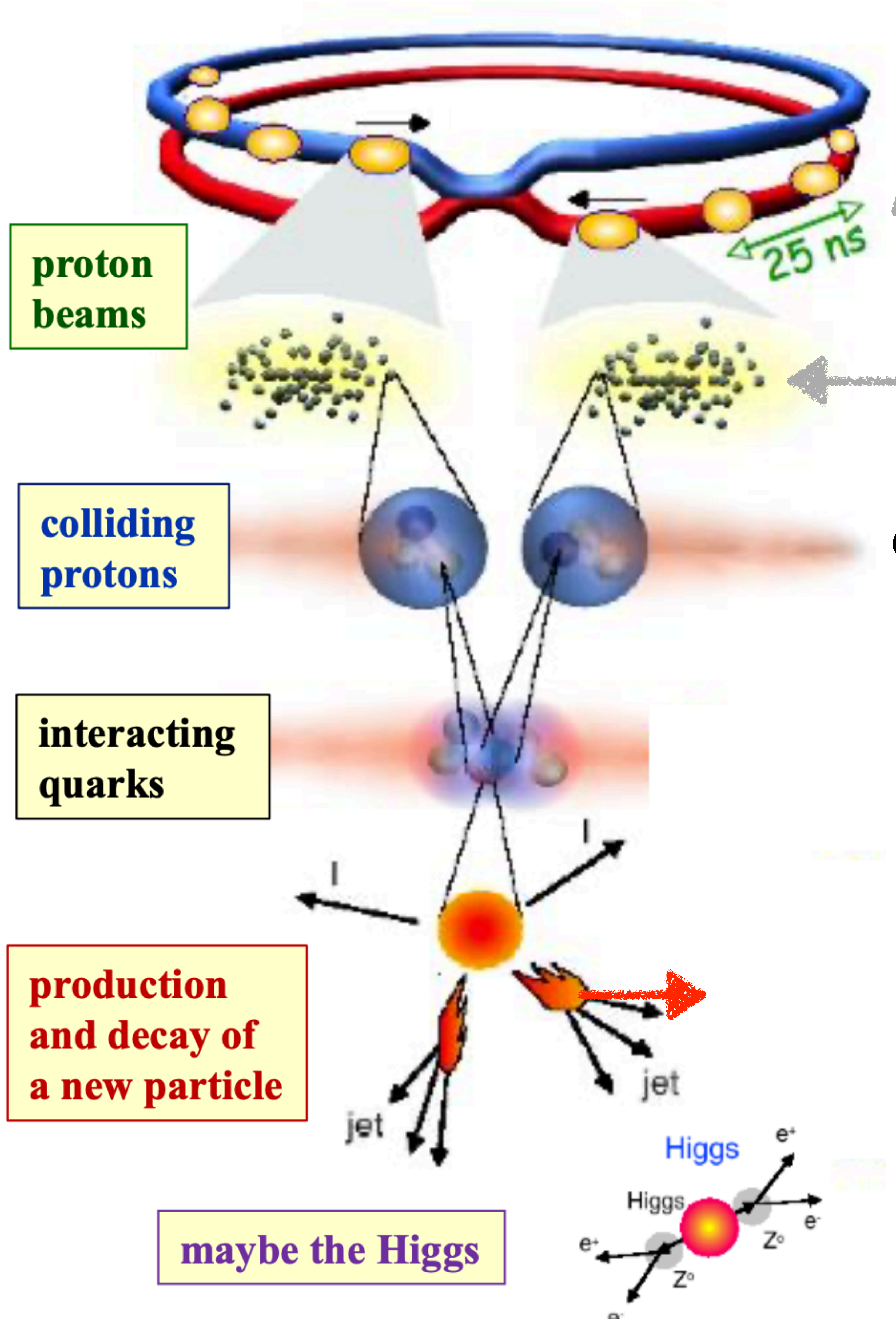
- Use the brutal way to find the answers
  - **Collide two proton beams moving close to the speed of light (299,792 km/sec)**
  - Keep all the information (**collect data**) coming from the collision of protons and **analyse it**



"Well it's one way of popularising our work at CERN!"

https://www.cartoonstock.com/cartoon?searchID=CS317716

Large Hadron collider - 2/2



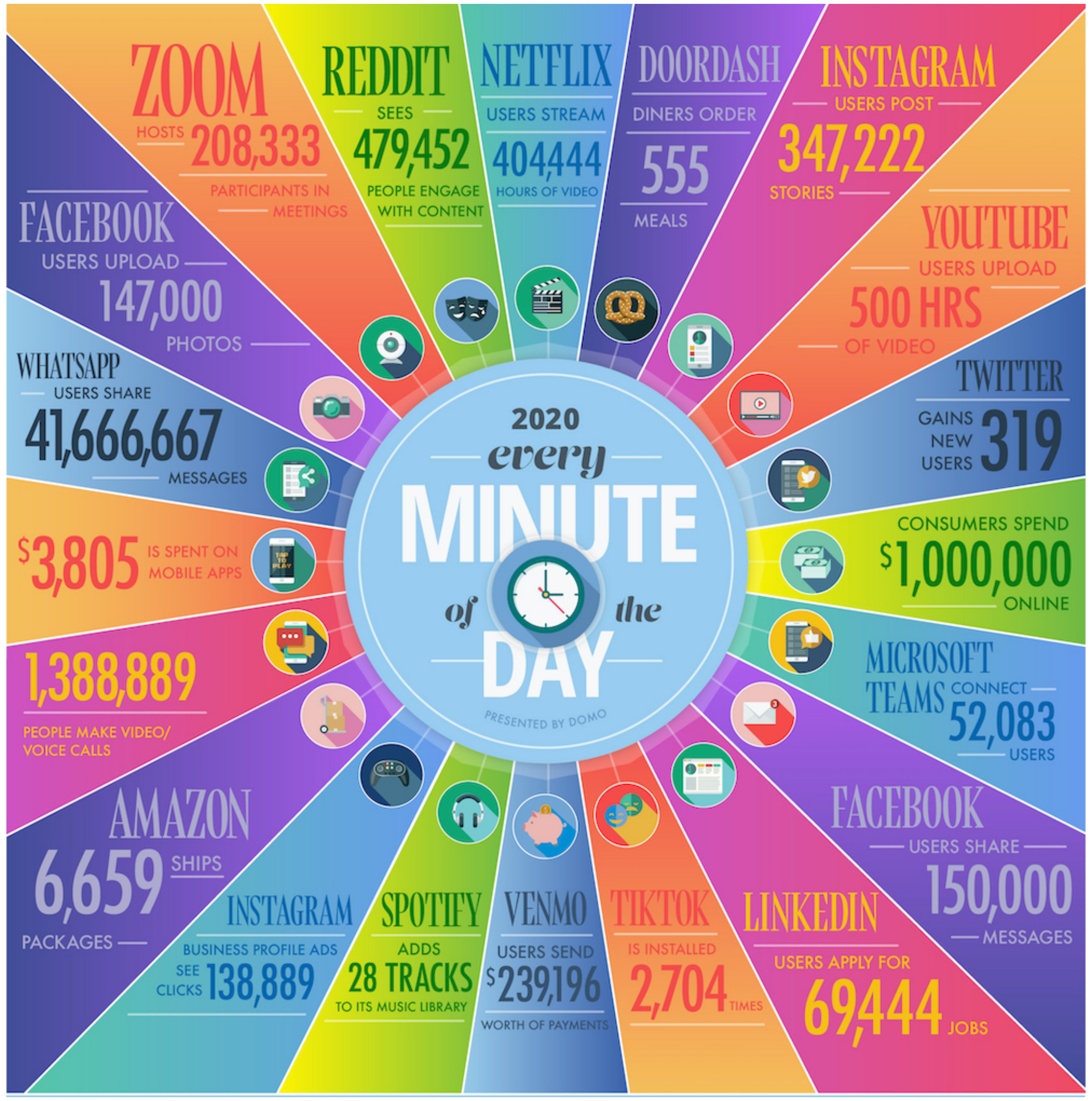
2028 Bunches of protons per beam

Beam energy: 7 TeV

10^{11} protons/bunch

Crossing rate: 40M collision/sec

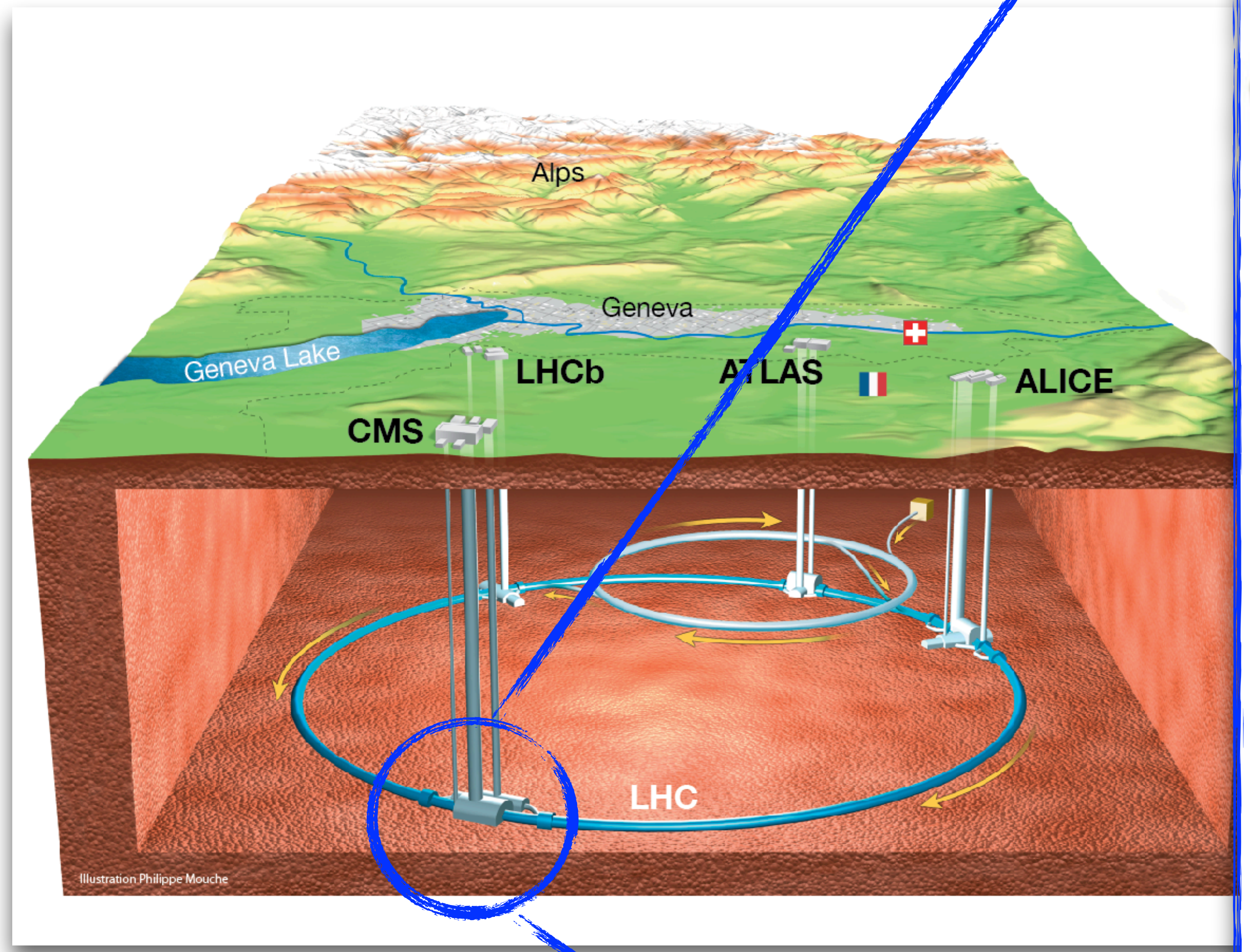
40 TB/sec

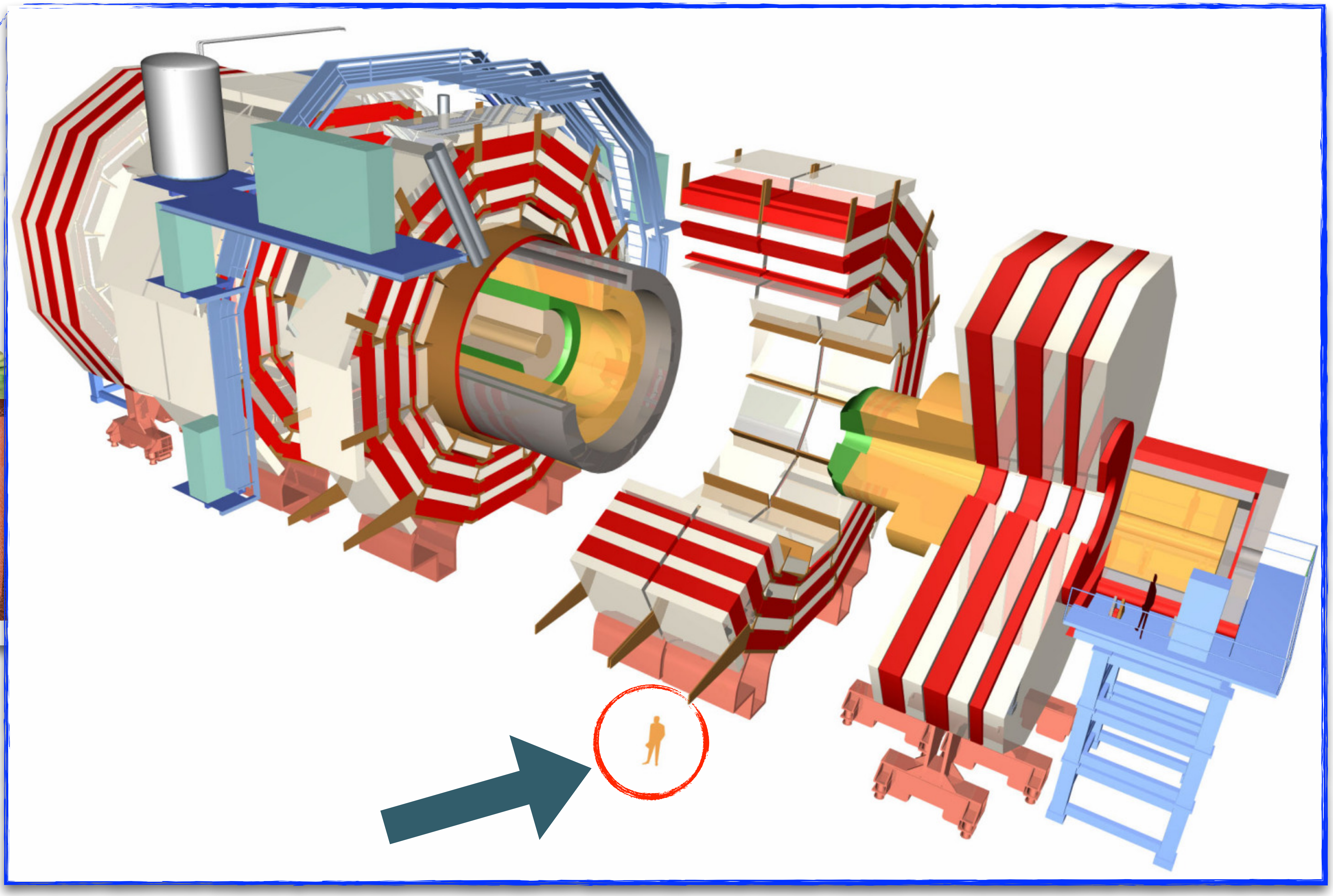


Source: DOMO

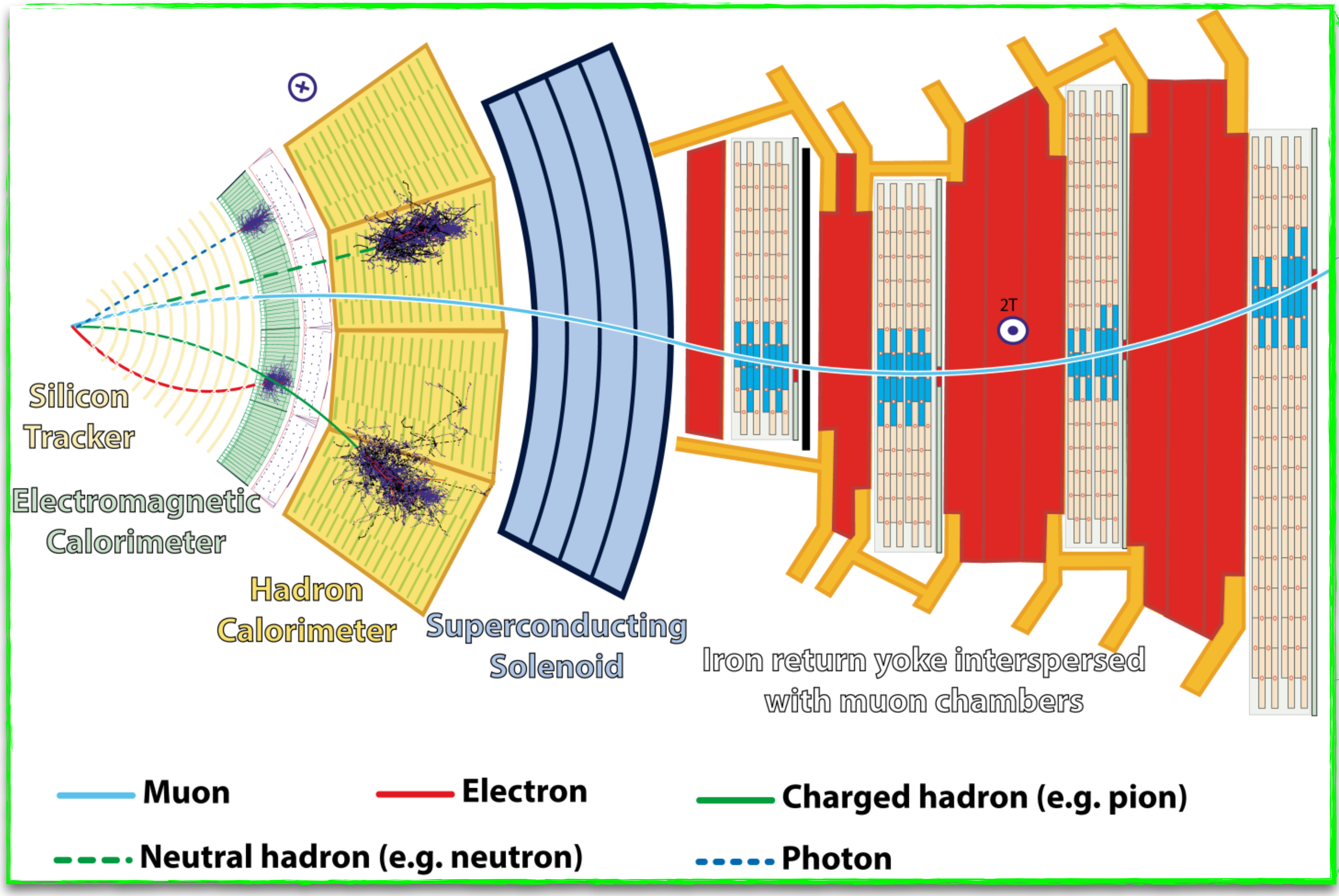
+ + + … ~29 TB/sec

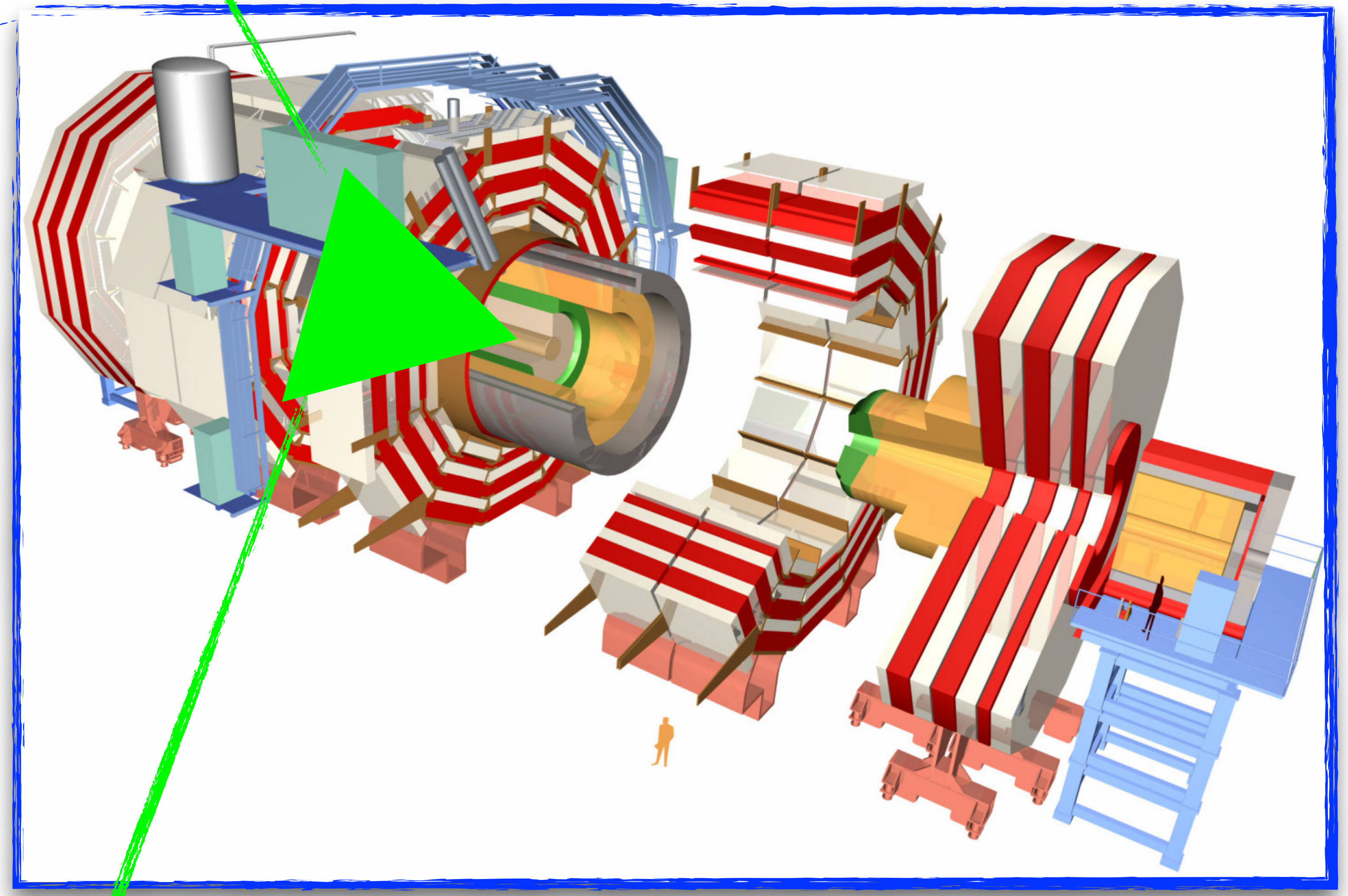
Compact **M**uon **S**olenoid Detector (One of two general purpose detector installed at the LHC)





CMS Detector Slice

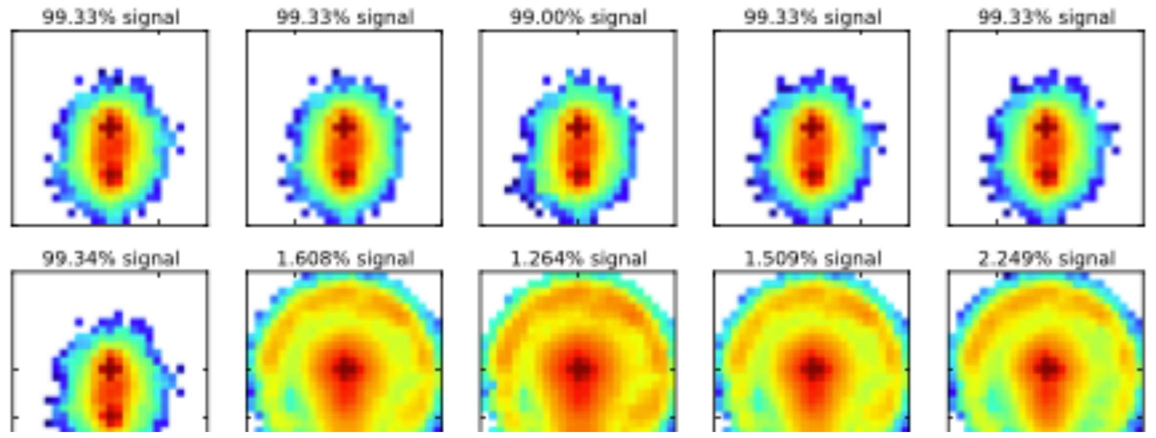
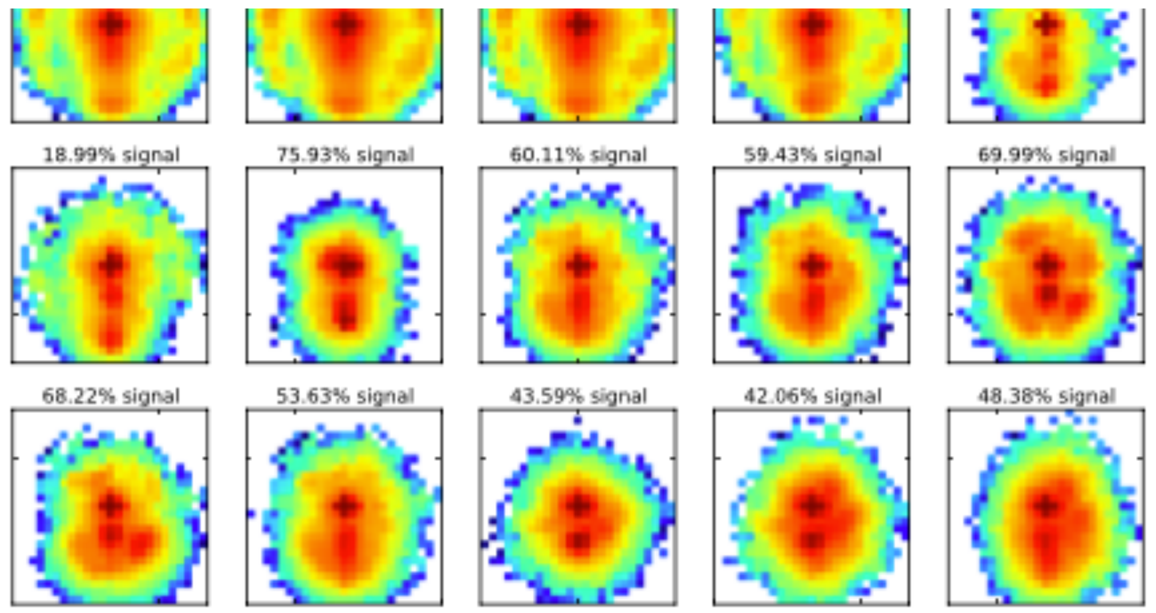




APPLICATIONS IN HEP

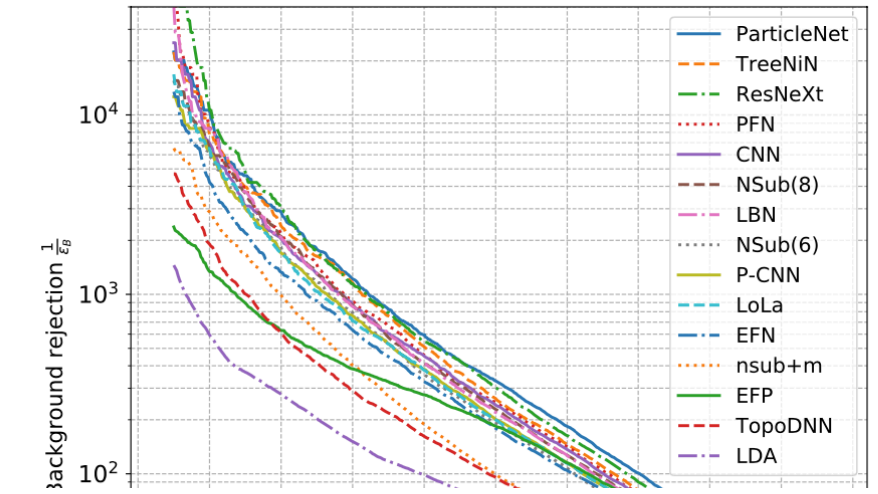
(a few!) ML applications in HEP

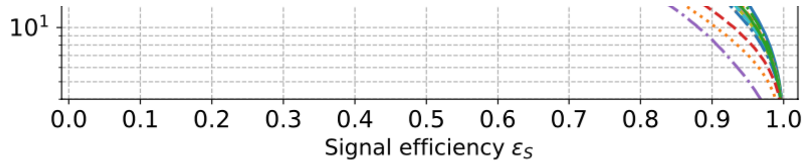
First workshop on ML titled Artificial Intelligence in High-Energy and Nuclear Physics (AIHENP), was held in 1990 (link)

Jet-Images -- Deep Learning Edition

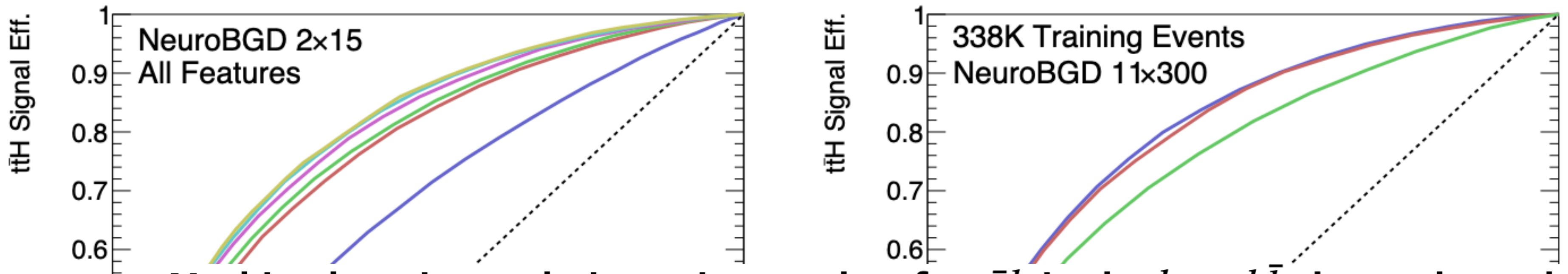
Luke de Oliveira, Michael Kagan, Lester Mackey, Benjamin Nachman, Ariel Schwartzman





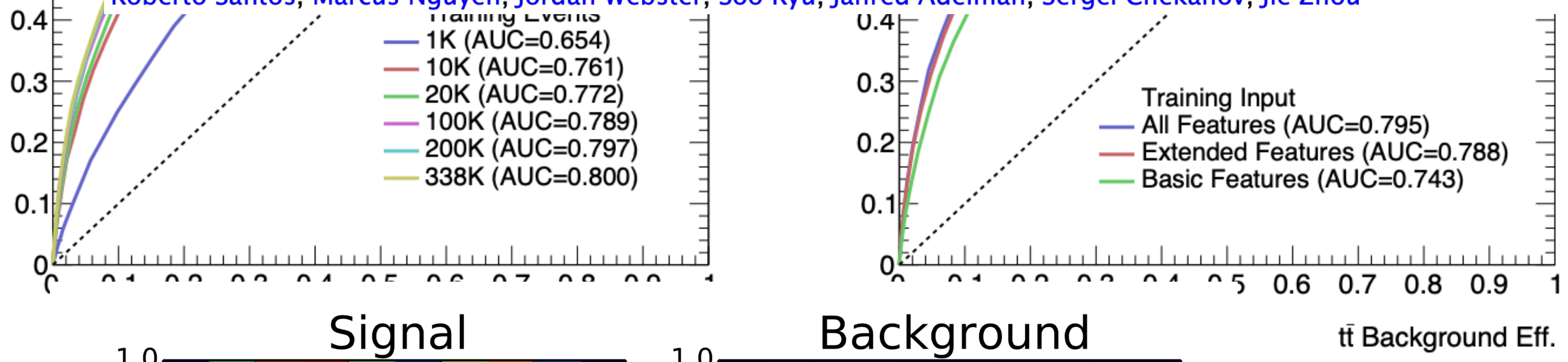
The Machine Learning Landscape of Top Taggers

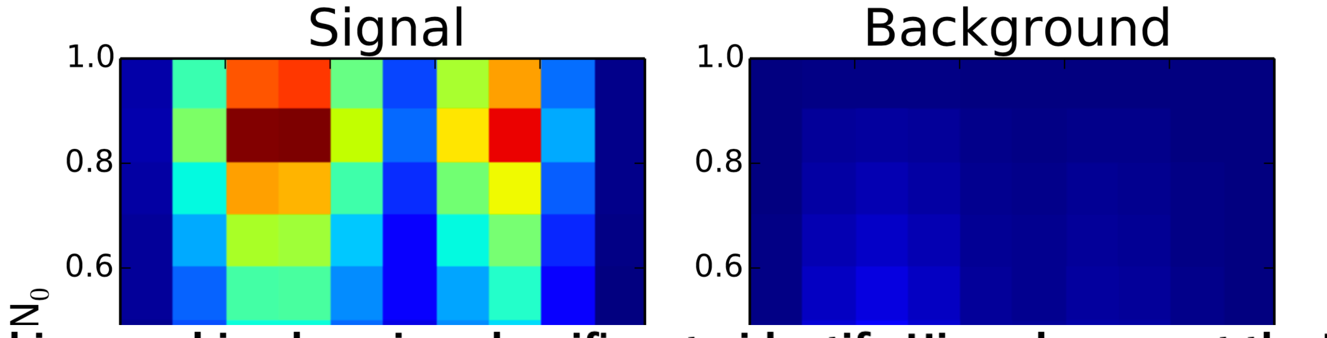
G. Kasieczka (ed), T. Plehn (ed), A. Butter, K. Cranmer, D. Debnath, B. M. Dillon, M. Fairbairn, D. A. Faroughy, W. Fedorko, C. Gay, L. Gouskos, J. F. Kamenik, P. T. Komiske, S. Leiss, A. Lister, S. Macaluso, E. M. Metodiev, L. Moore, B. Nachman, K. Nordström, J. Pearkes, H. Qu, Y. Rath, M. Rieger, D. Shih, J. M. Thompson, S. Varma



Machine learning techniques in searches for $t\bar{t}h$ in the $h \to b\bar{b}$ decay channel

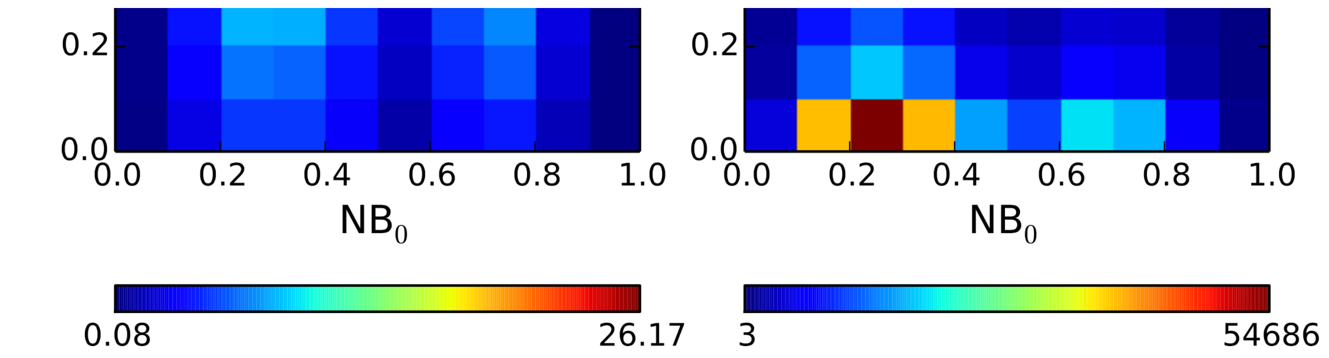
Roberto Santos, Marcus Nguyen, Jordan Webster, Soo Ryu, Jahred Adelman, Sergei Chekanov, Jie Zhou

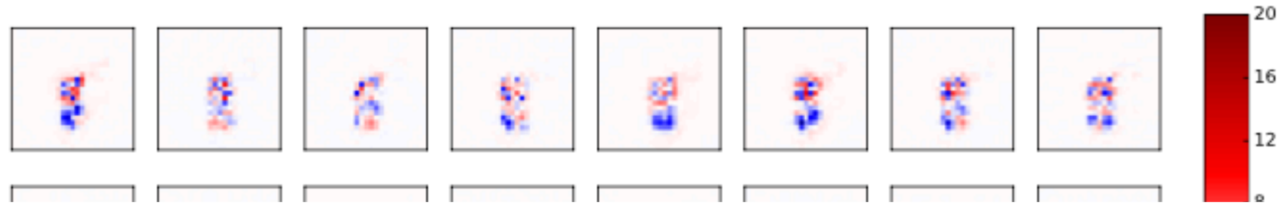




Stacking machine learning classifiers to identify Higgs bosons at the LHC

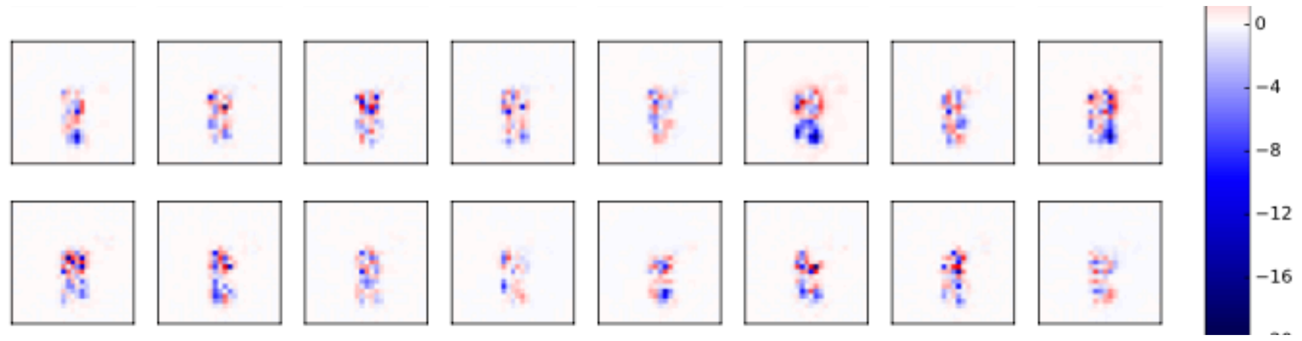
Alexandre Alves

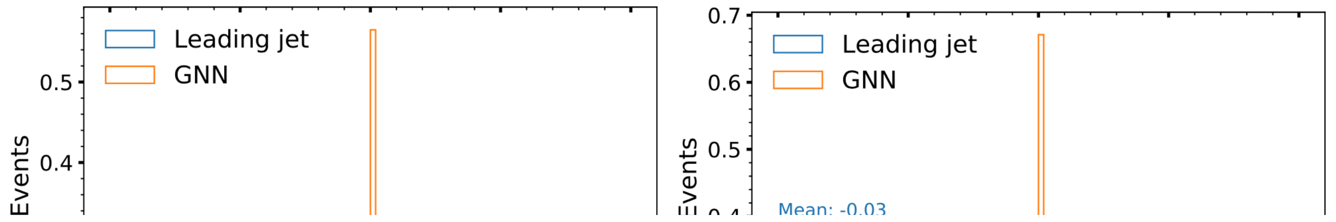




Learning Particle Physics by Example: Location-Aware Generative Adversarial Networks for Physics Synthesis

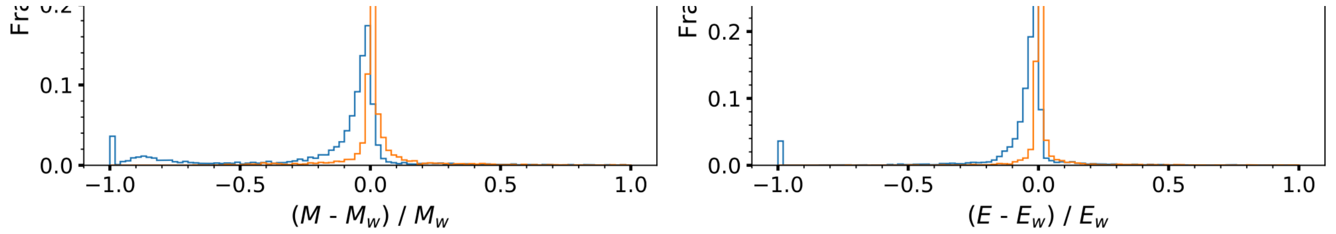
Luke de Oliveira, Michela Paganini, Benjamin Nachman

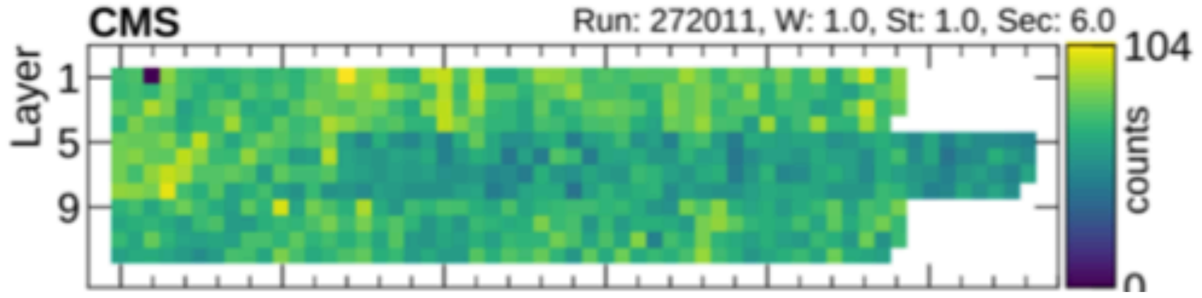




Supervised Jet Clustering with Graph Neural Networks for Lorentz Boosted Bosons

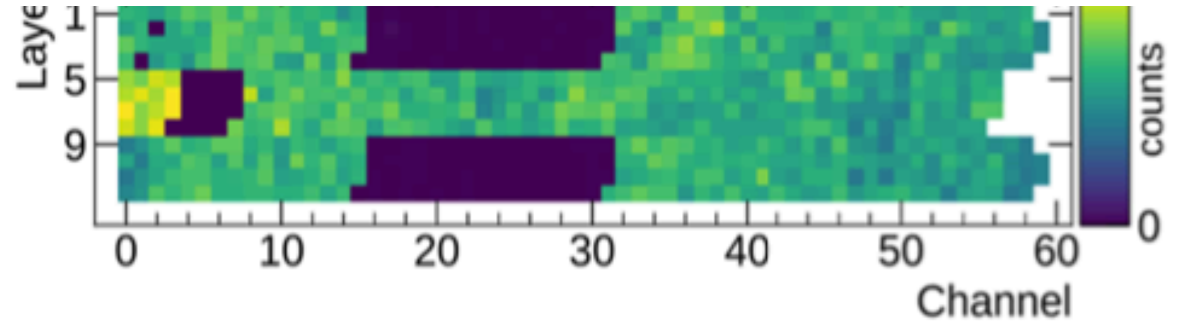
Xiangyang Ju, Benjamin Nachman

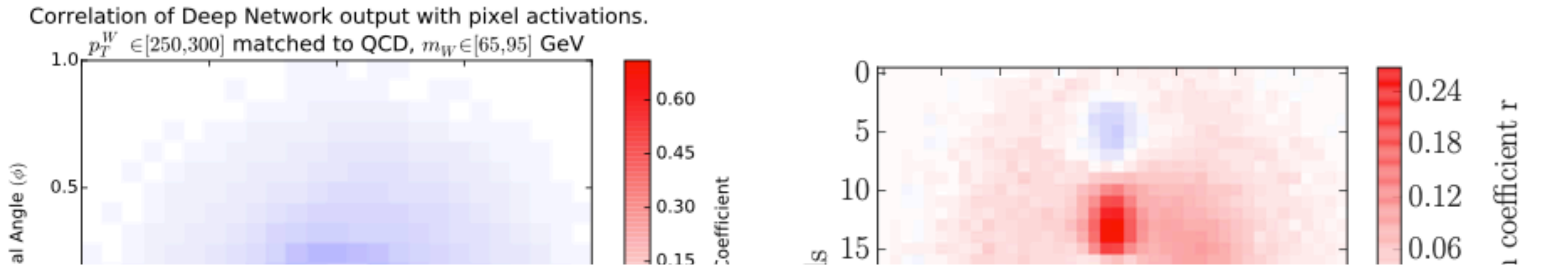




Using Machine Learning techniques for Data Quality Monitoring in CMS and ALICE experiments

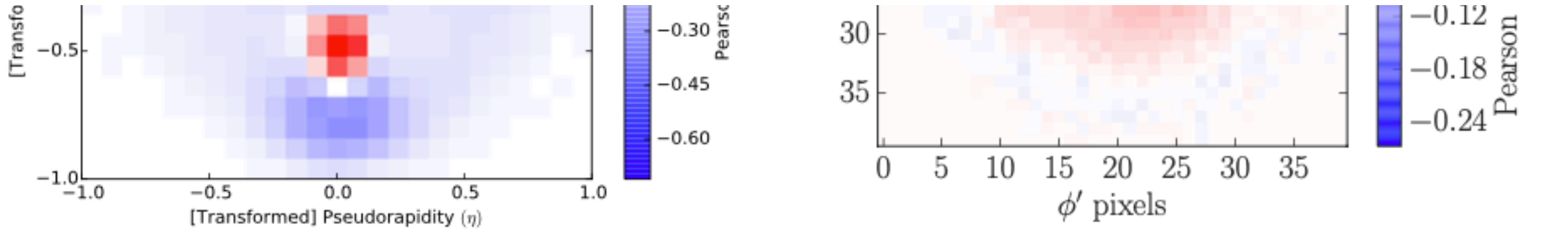
K.R. Deja* *on behalf of the CMS and Alice Collaborations*

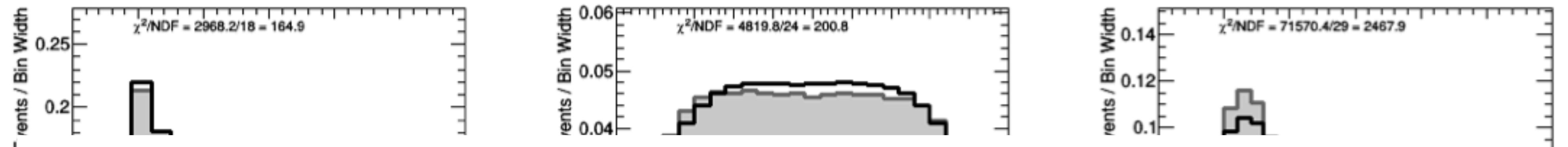




Jet Substructure at the Large Hadron Collider: A Review of Recent Advances in Theory and Machine Learning

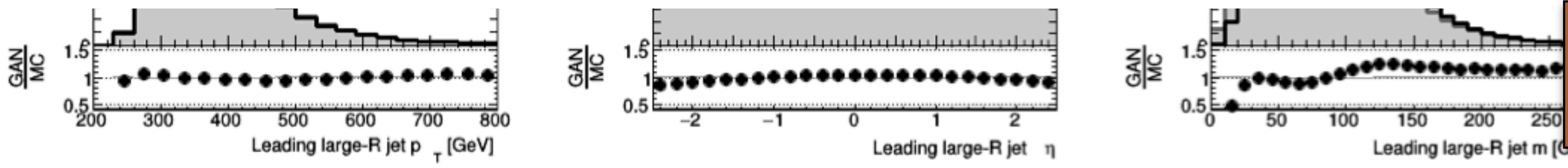
Andrew J. Larkoski, Ian Moult, Benjamin Nachman





A Generative-Adversarial Network Approach for the Simulation of QCD Dijet Events at the LHC

R. Di Sipio*, *M. Faucci Giannelli, S. Ketabchi Haghighat and S. Palazzo*



Why Machine Learning?

- Looking for a subtle signal in a very messy environment at hadron colliders
- Like to draw decision boundaries between the signal and the background processes in the physics phase space as precisely as we can do
- Huge amount of data processing requires not only state-of-the-art theory calculations but also exploiting recent developments in Data Science & Machine Learning techniques
- ML algorithms are “universal approximations” & should do this job well
- Help in many areas of HEP (e.g. particle identification, event simulation, background rejection etc.) while offering considerable savings in computing and time resources
- *LHC is an amazing & the biggest machine in the history of particle physics (so far!): Realize it's full potential and extract the best possible physics output from it!!!*

ML in industry & HEP: Analogy

- Credit card fraud detection
- Discrimination b/w fraud vs real transections ⇔ Discrimination b/w signal & background
    - Signal: interesting process (or physics) that we are looking (fraud transection done by a person)
    - Background: All other processes apart from the signal

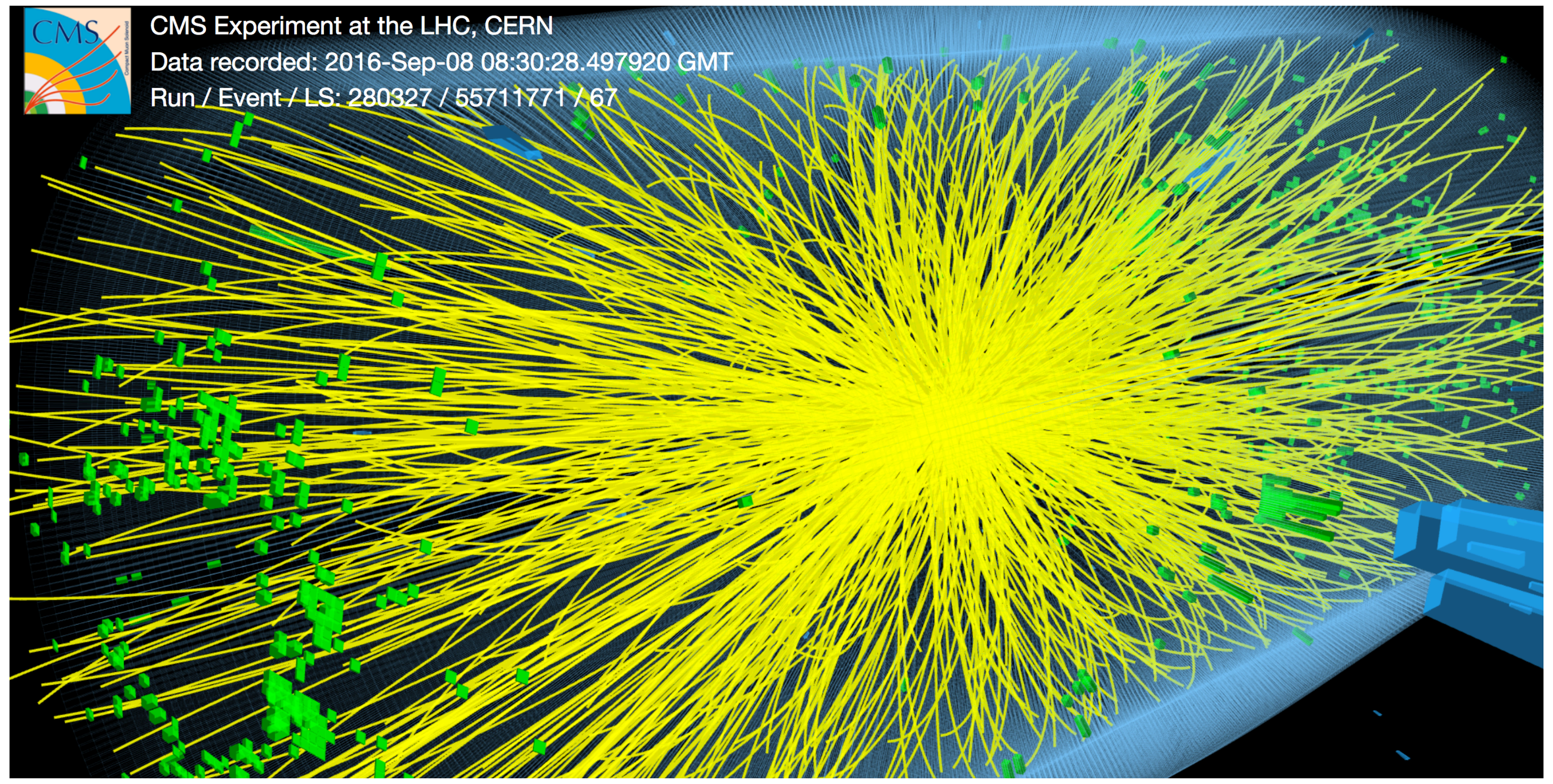
Looking for this
Particular particle (signal)

- World population ~7.6×10^{10}
- Very rare decay $B(B_s \to \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

ML use in industry & HEP: Analogy

A scanning worker analysing a bubble-chamber photograph in 1980

- Bubble chamber days:
  - 1960s-1980s: People manually analyze countless photographs from the bubble chamber
- Moved away from photograph to collision data collected with the electronic detectors
  - Leads to marriage between the high-energy physics & computing
  - Next paradigm change is based on artificial intelligence
  - Earlier people analyzed the photograph with naked eyes to extract the useful information but now we can do the image processing using ML techniques and extract the results
- Task vary from identifying images of human faces to Isolating particles into which the Higgs boson decays from a background of identical particles coming from different processes



Machine Learning in CMS

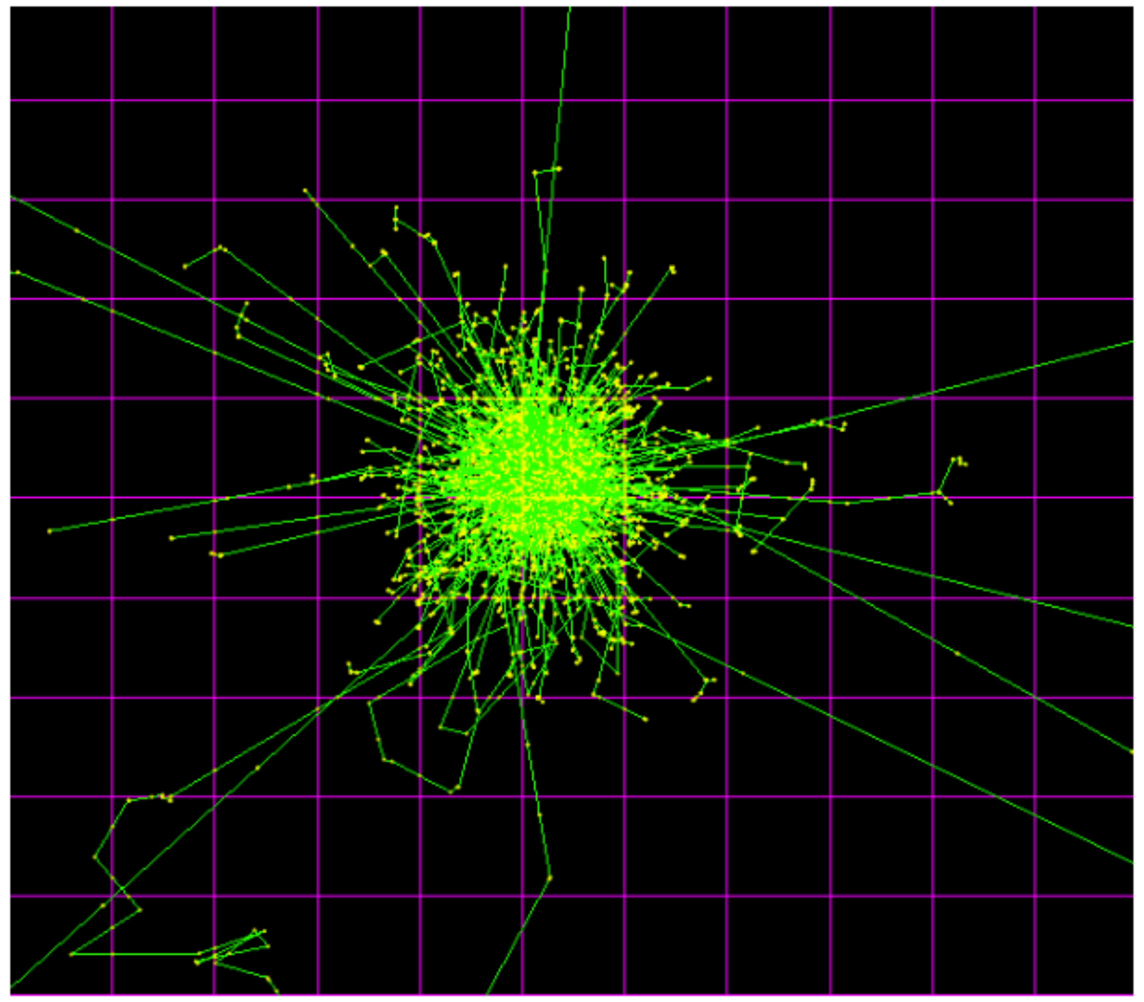
- ML technique employed in many HEP analysis, including the Higgs discovery.
- CMS has a broad program of machine learning applications for multiple tasks, including:
  - **Event reconstruction/selection:** Helps to extract small signal from the towering LHC backgrounds. **Classification algorithms** helps
  - **Particle identification & tagging**: Once a collision occurs we need to identify various particles based on the detector information
  - **Monte-carlo event simulation**: These process are very time consuming and CPU intensive. **Generative networks** should help here
  - **Imaging calorimetry**: In calorimetry, energy is deposited by a particles and this can be viewed as an image. **Image processing** helps a lot
  - **Tracking for particles**: Duplicate removal, quality selection
  - **Data quality monitoring**: Outlier rejection
  - **Triggers**: Improve the capturing the interesting events in limited time (~μs) using ML methods on Field-Programable Gate Arrays (FPGA).

Few examples where ML methods are used

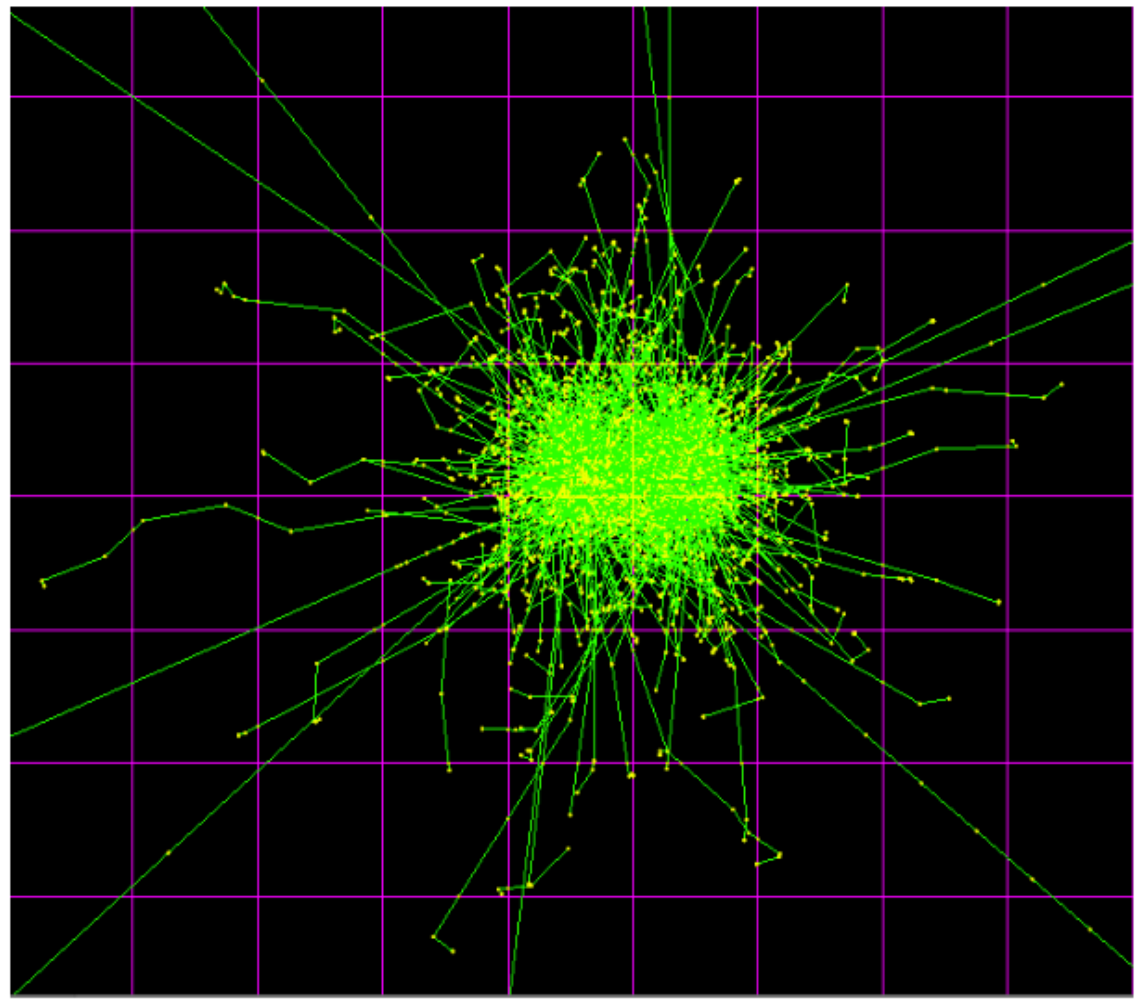
Example – 1: Distinguish prompt photon from π^0 and beam halo

Distinguish prompt photon from π^0 and beam halo

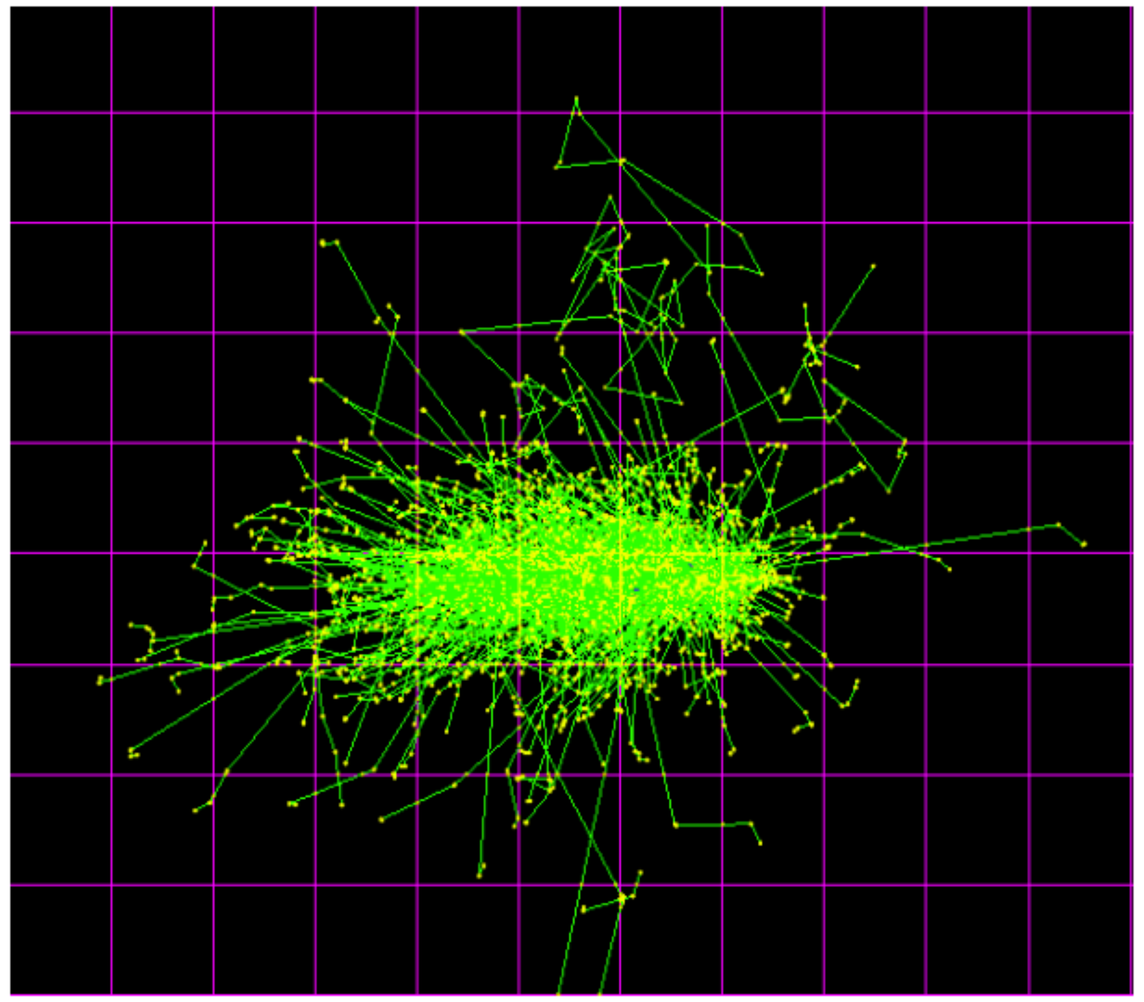
S. Ghosh et al 2019 JINST 14 P01011



Prompt photon



π^0

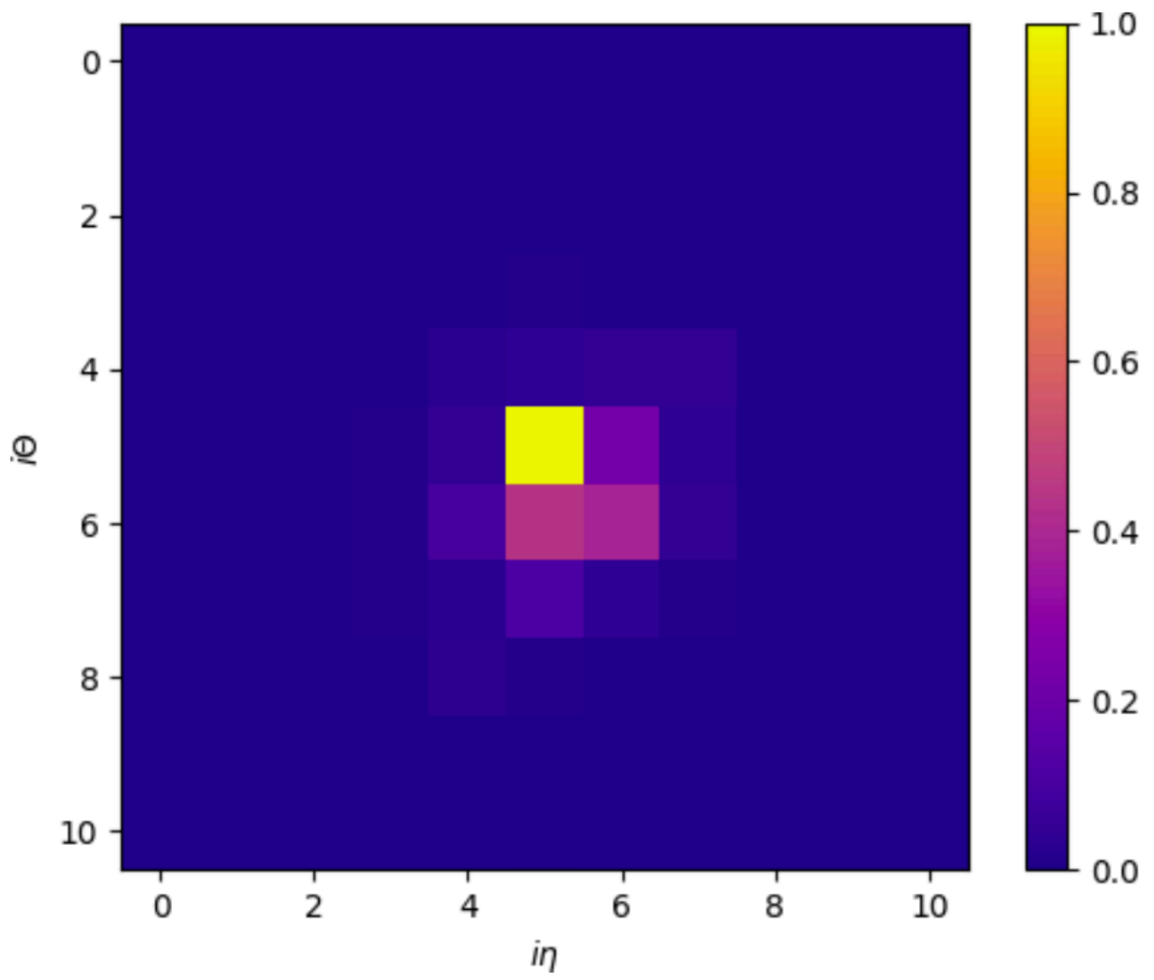


Beam halo photon

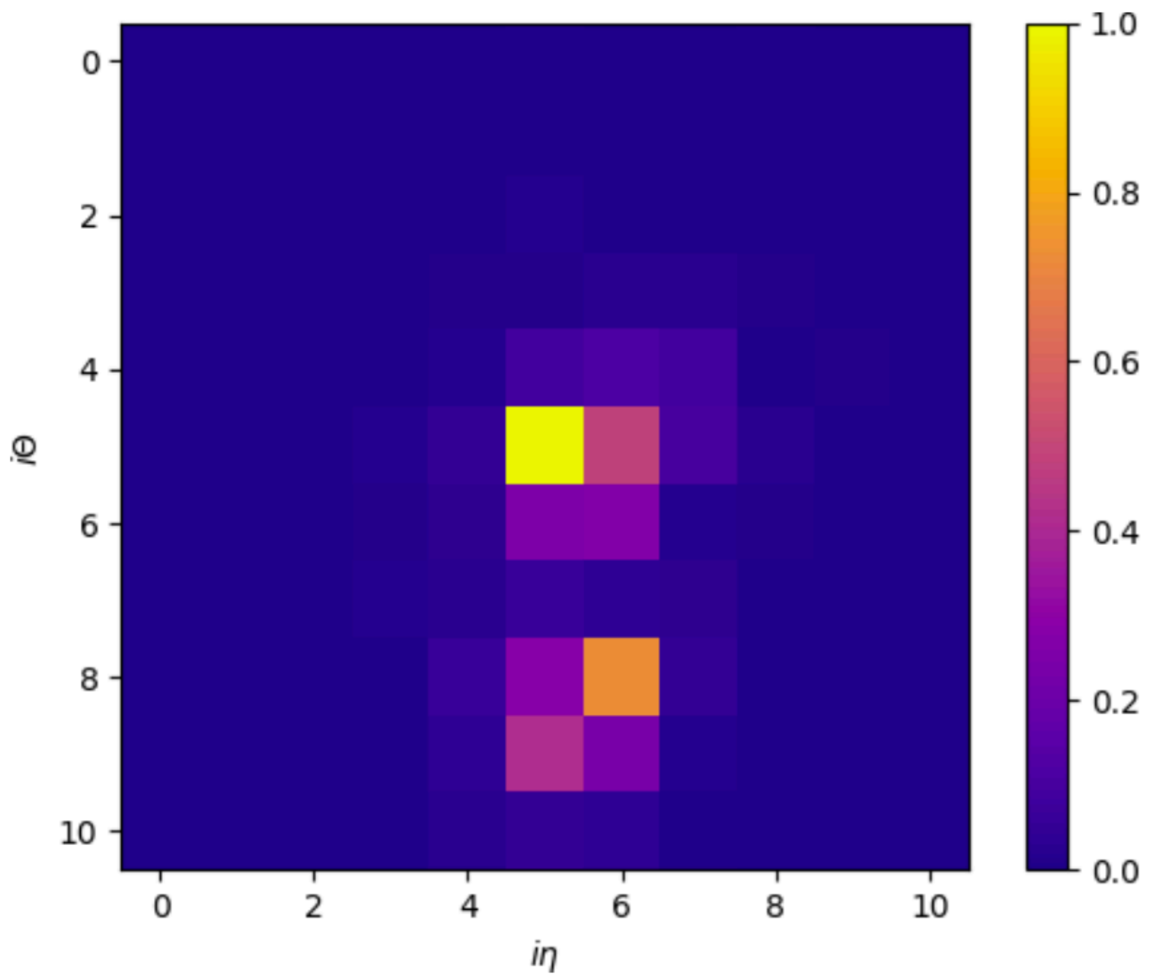
- Energy deposition image in the ECAL has distinct shapes.

Image representation of the energy deposition pattern

Prompt photon



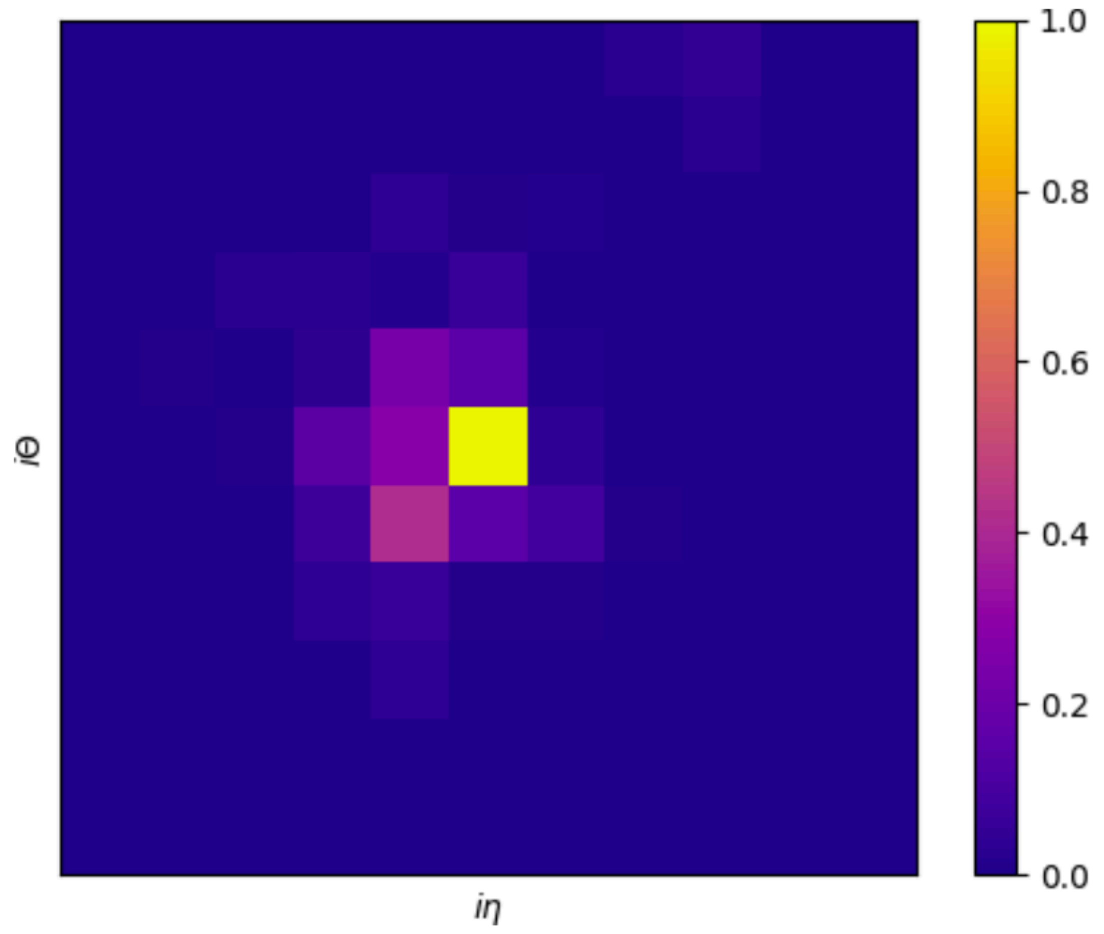
(a)

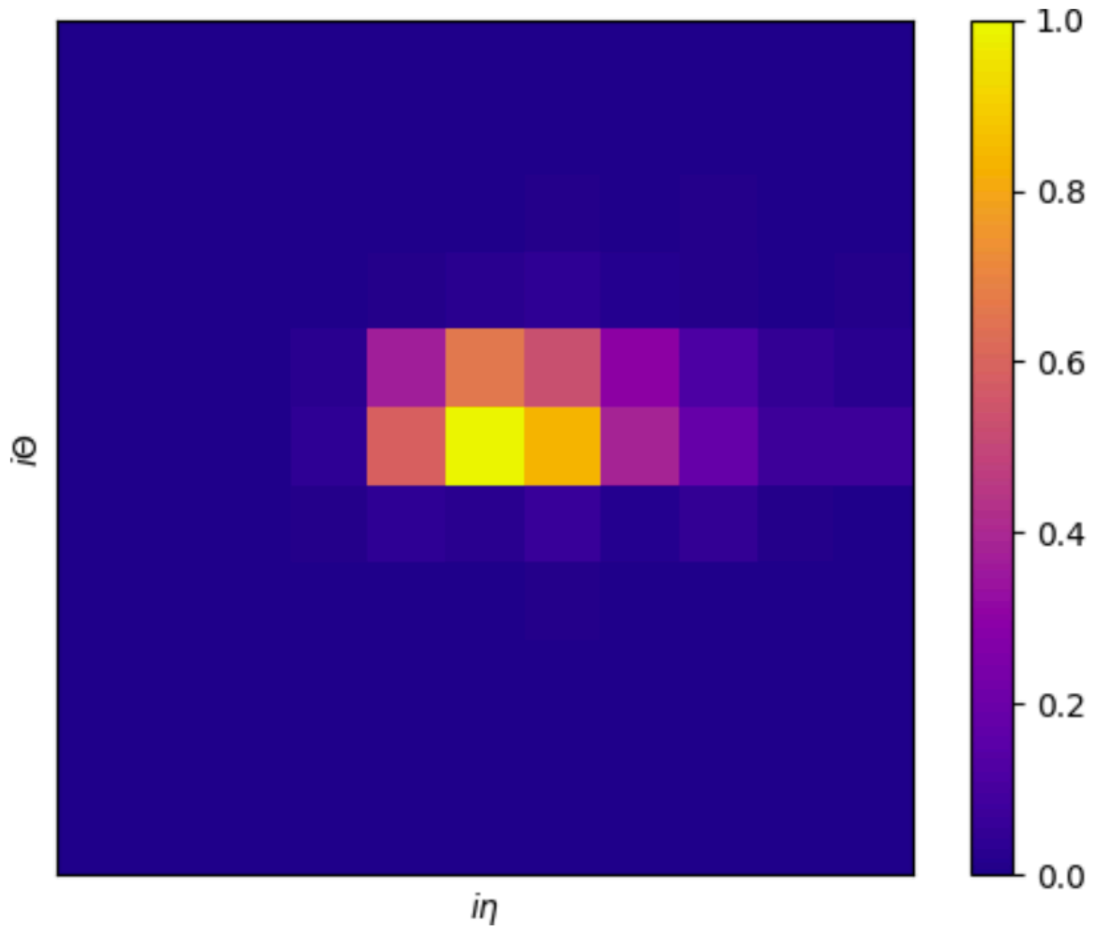


(b)

Converted photons

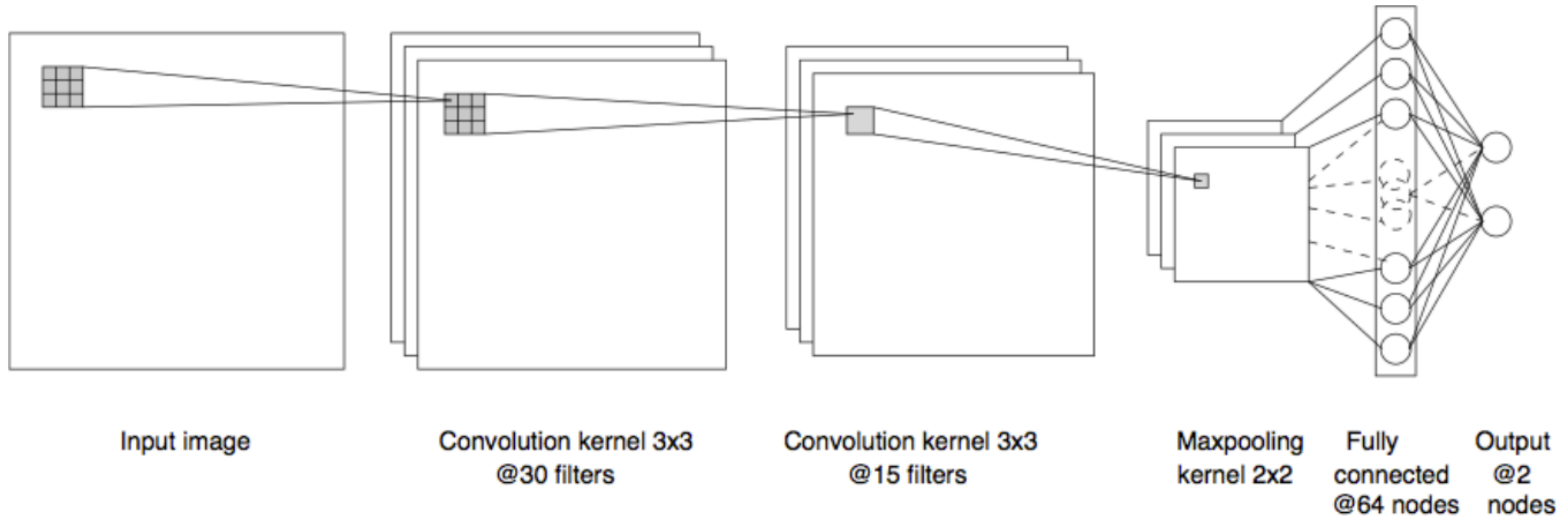
π^0



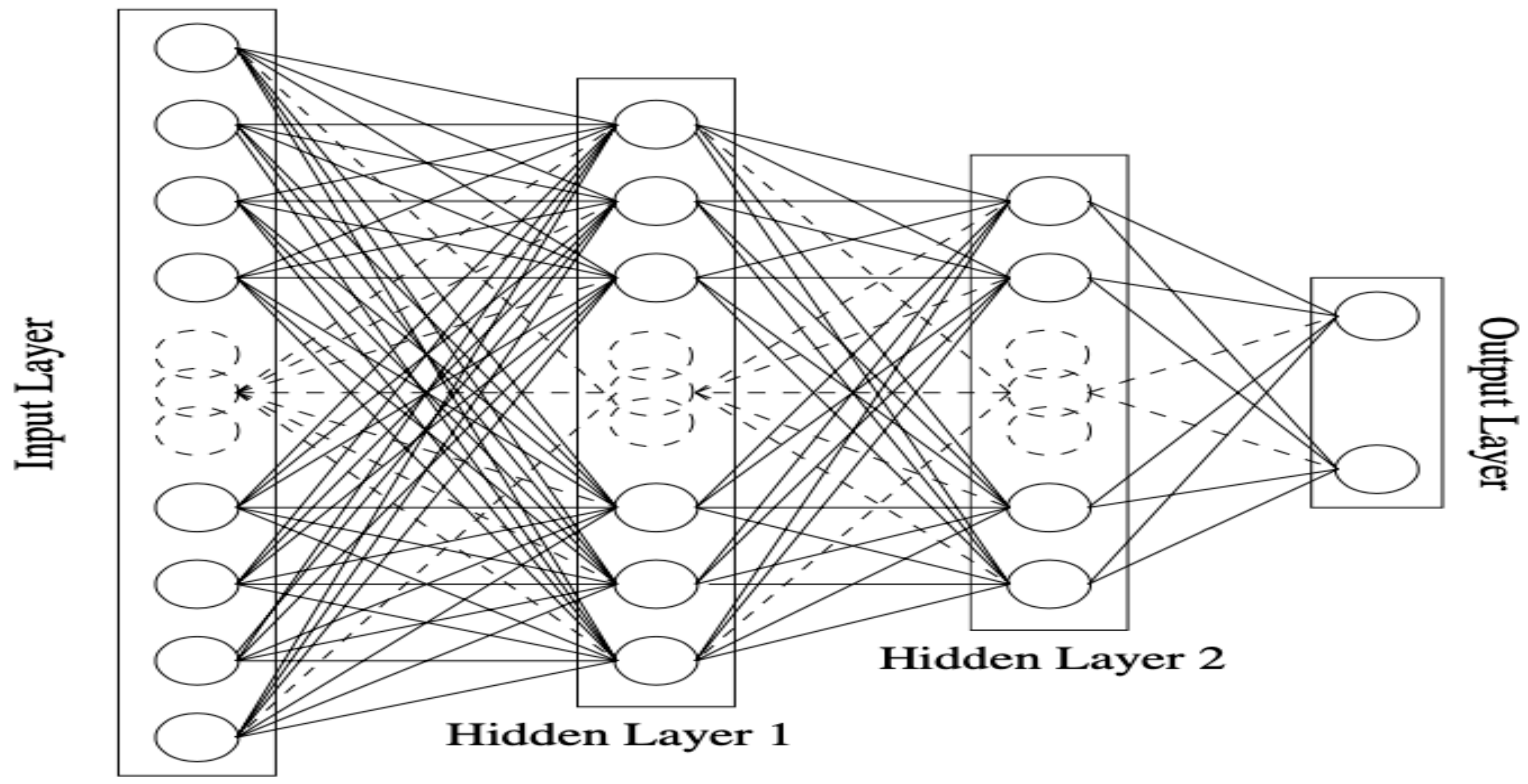


A beam halo photon

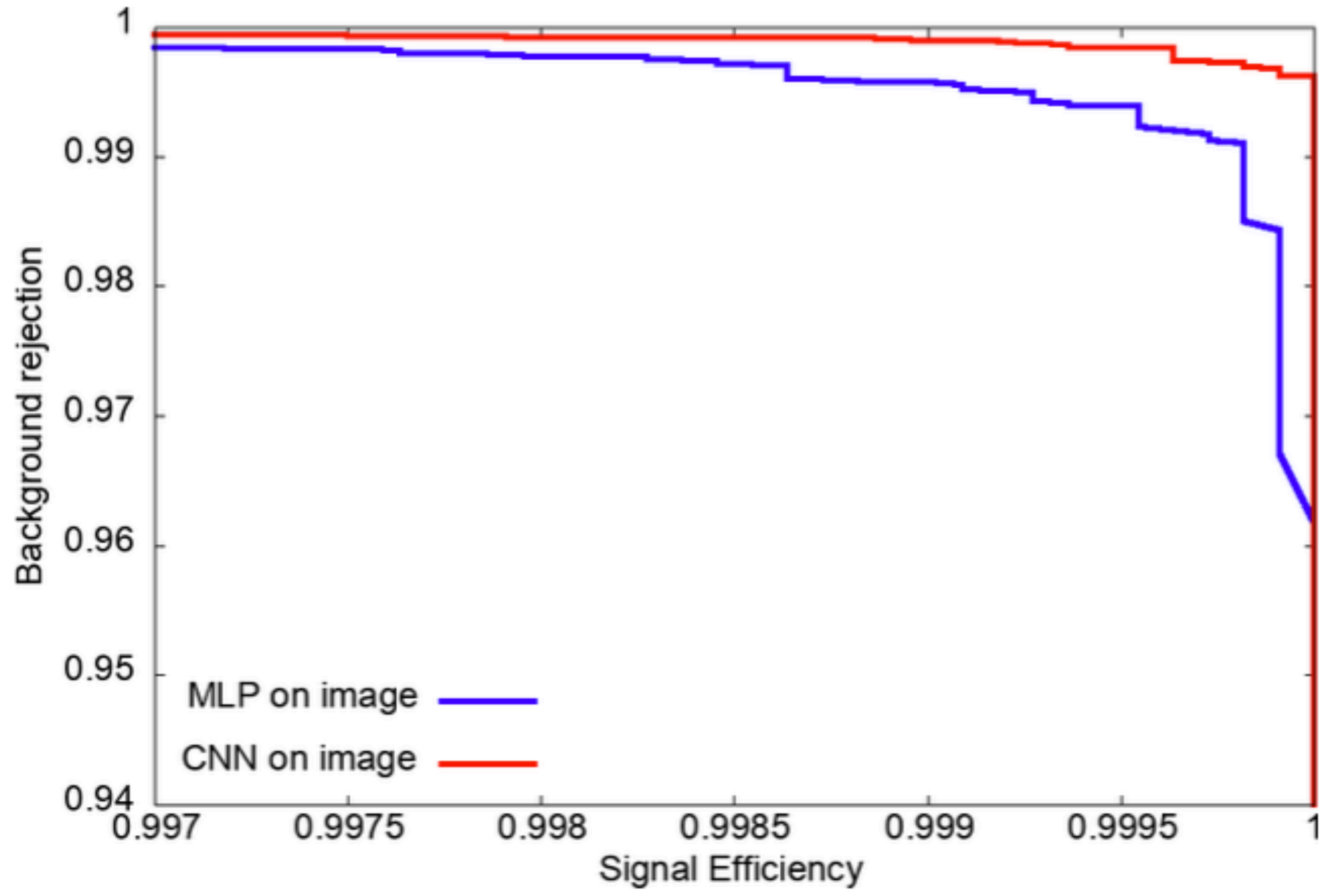
Performance



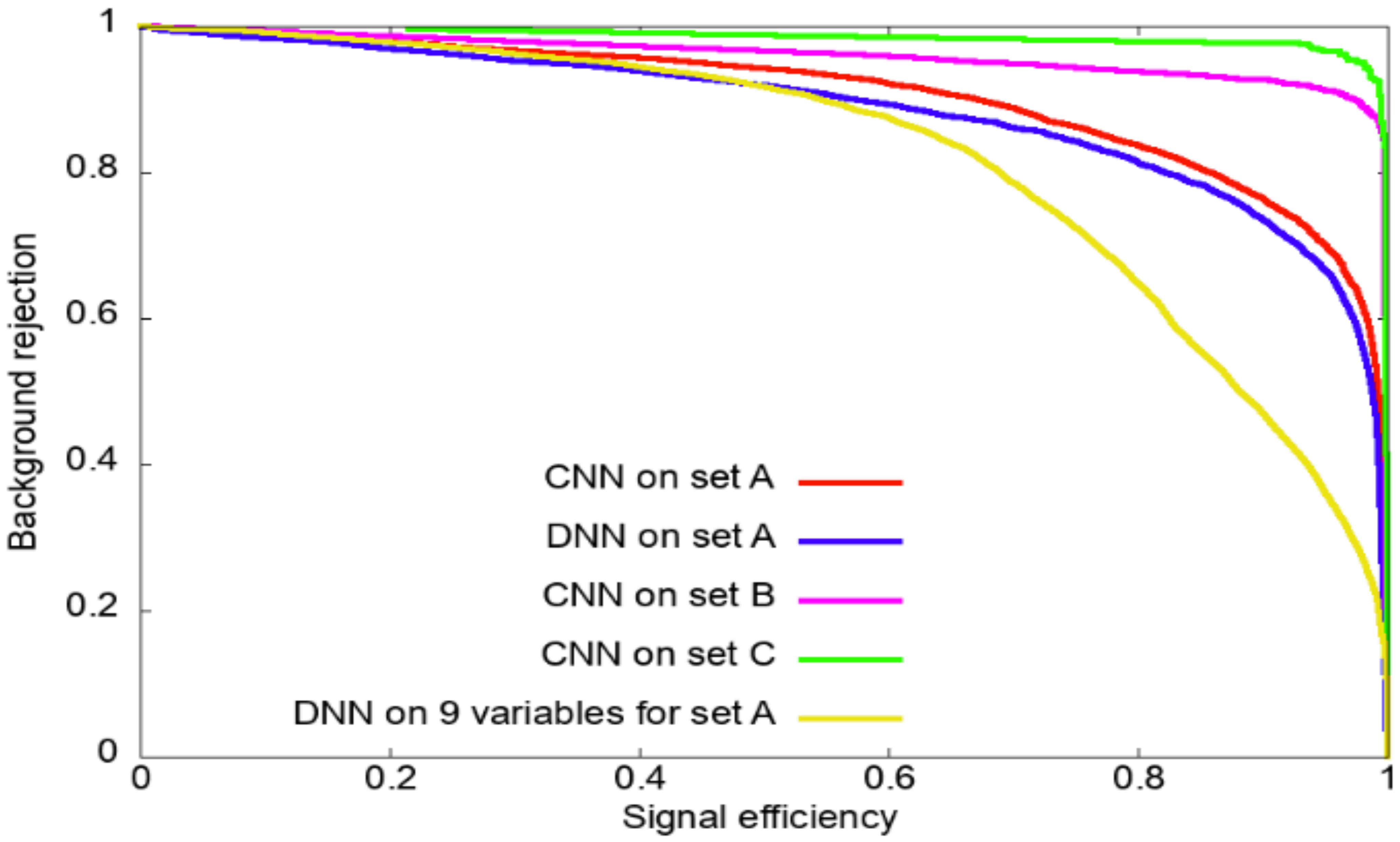
CNN: The input image is of size 11×11 for beam halo rejection and 25×25 for π^0 rejection.



DNN: The network for π^0 separation has two hidden layers with 64 and 32 nodes respectively



ROCs for the separation of prompt photons and beam halo photons



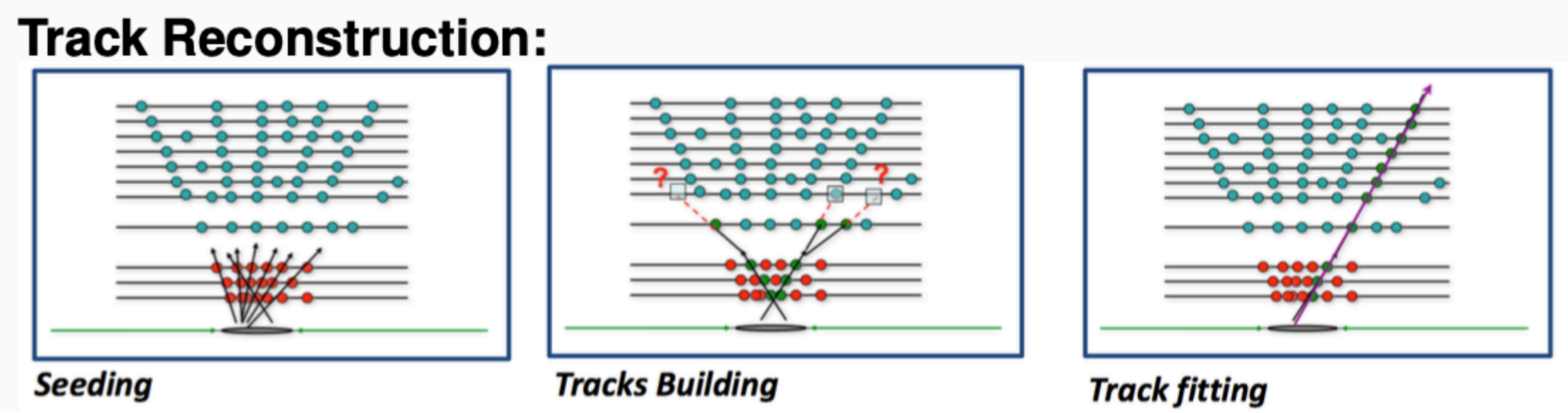
ROCs for all the methods used for separation of π^0 s and prompt photons.

Example - 2: CNN for track seed filtering

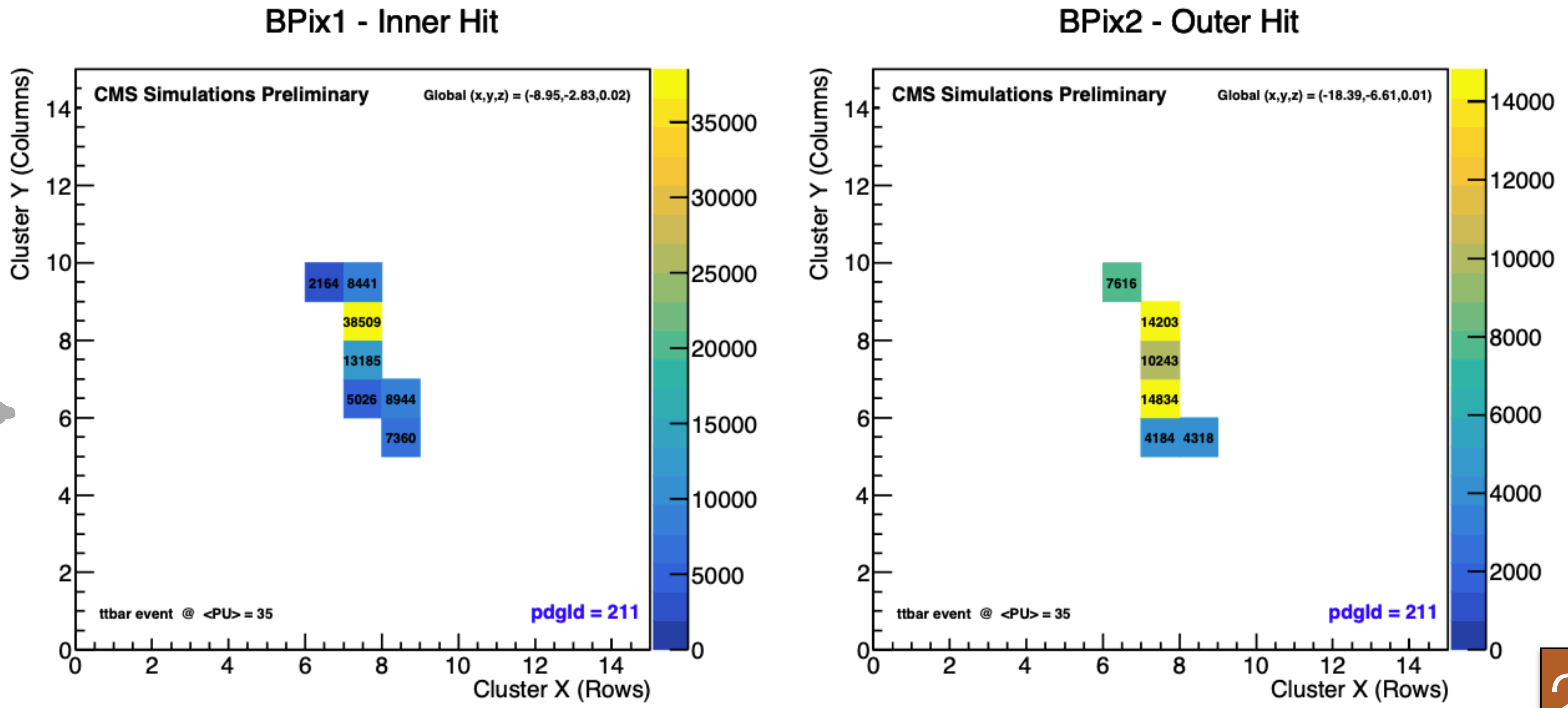
CNN @CMS **H**igh **L**evel **T**rigger

Adriano Di Florio et al 2018 J. Phys.: Conf. Ser. 1085 042040

- CMS Trigger (Capturing of interesting events)
  - Designed two level system to capture interesting events:
    - Level 1 (L1) - 40MHz in/ 100 kHz out
    - HLT 100 kHz in / 1 kHz out
  - Simplified global reco (Including tracking)

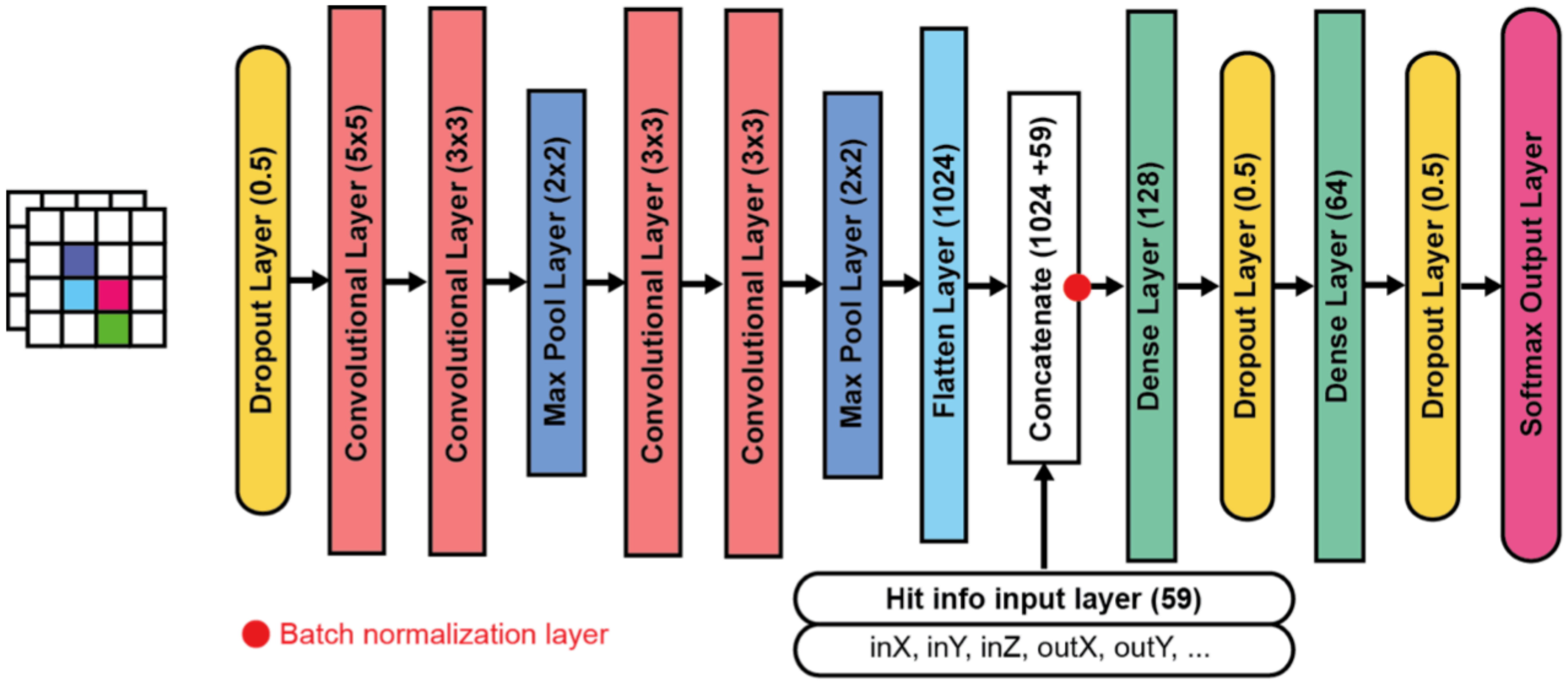


- Doublets seeds from a couple of hits
- Hits are collections of pixels
- They look like 2D images
- Case for CNNs

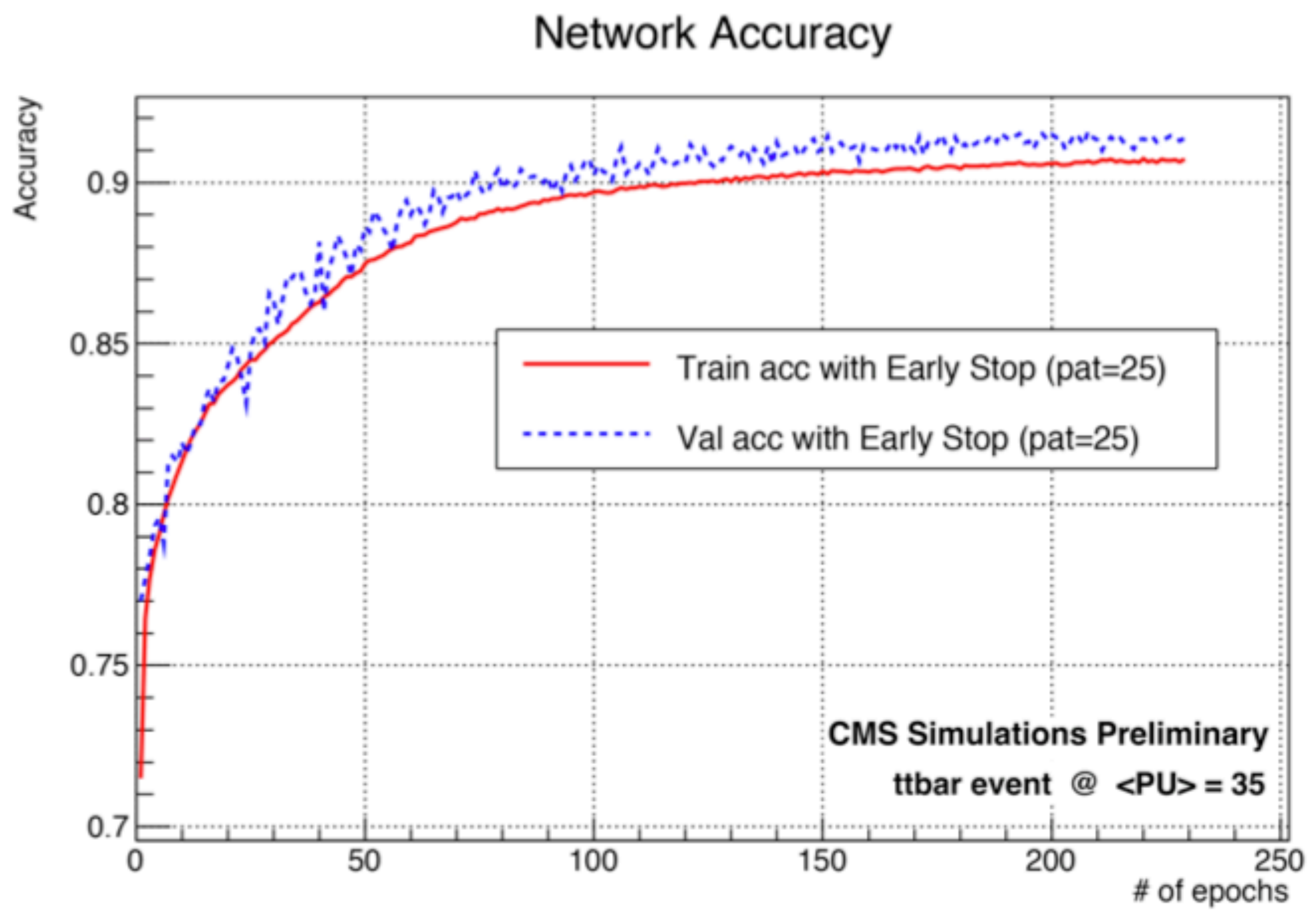


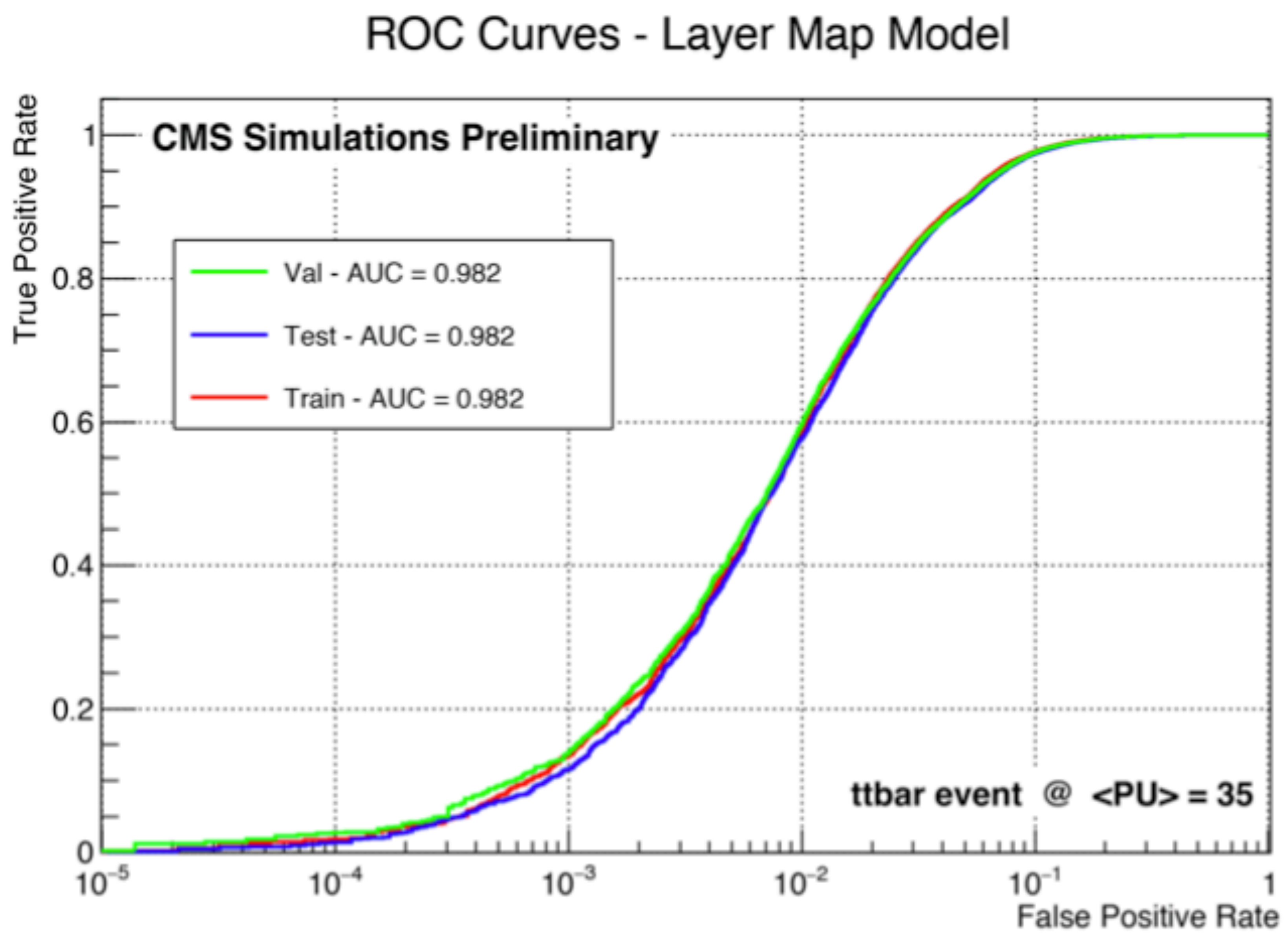
Network architecture

- Doublets:
  - Each doublet has two 15 × 15 images
  - Plus a set of local info (position, charge, . . .)
- NN architecture:
  - 20 inputs channels, 10 tracker layers-2 hits
  - 4 convolutional layers + Max pooling
  - 2 dense layers + doublets info



Result





			TN/N at fixed TP/P		**TP/P at fixed TN/N**	
	AUC	**Acc**	**TP/P = 0.99**	**TP/P= 0.999**	**TN/N=0.99**	**TN/N=0.5**
Train	0.982	0.940	0.85426	0.6706	0.5896	0.9997
Test	0.982	0.941	0.8542	0.6709	0.5899	0.9996
Val	0.982	0.939	0.8525	0.6707	0.5948	0.9996


neutrino
network
cosmic
net
machine
AI
interaction
reconstruction
HEP
vision
layer
neural
training
dark
quantum
recursion
CNN
classifier
Science
Fermilab
NOvA
algorithm
framework
sigmoid
TMVA
regression
bdt
BDT
LHC
REL-U
IML
neutrinos
evaluation
MicroBooNE
darkTMVA
background
amet
algorithm
sigmoid

Summary

Summary: Machine learning & High Energy Physics

- Machine learning algorithms are already transforming our world, from the way we move, shop and heal ourselves, to our understanding of what makes us unique as humans
- In the context of LHC data analysis and interpretation, ML tools are ubiquitous, from event selection deep in the detector chain (triggering) to particle tagging and the event simulation using Generative Adversial Network (GAN).
- Can't use ML tool as a black box: A detailed understanding of both the physical and the algorithmic aspects of the problem is essential!

Why spending on a billion dollar project? Instead of serving people?

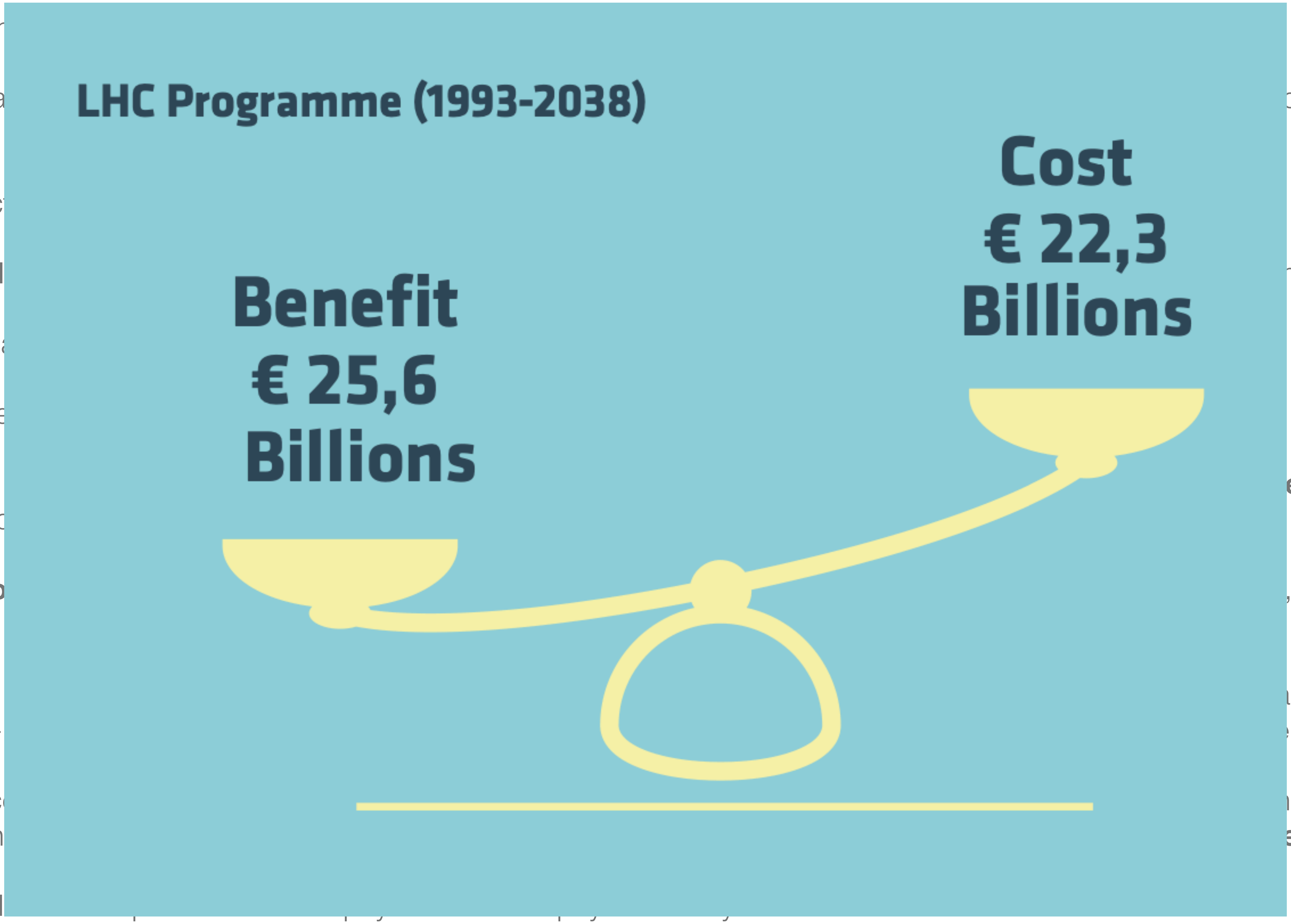
- Scientist work because they are fascinated by the universe
    - Wants to unpin the basic question “How God created this universe & how it works”
- While working on our interests, we develop the knowledge that serves the humanity. For example:
    - Develop devices such at GPS trackers and smartphones, etc.
    - This story repeated in countless domains for a century or more

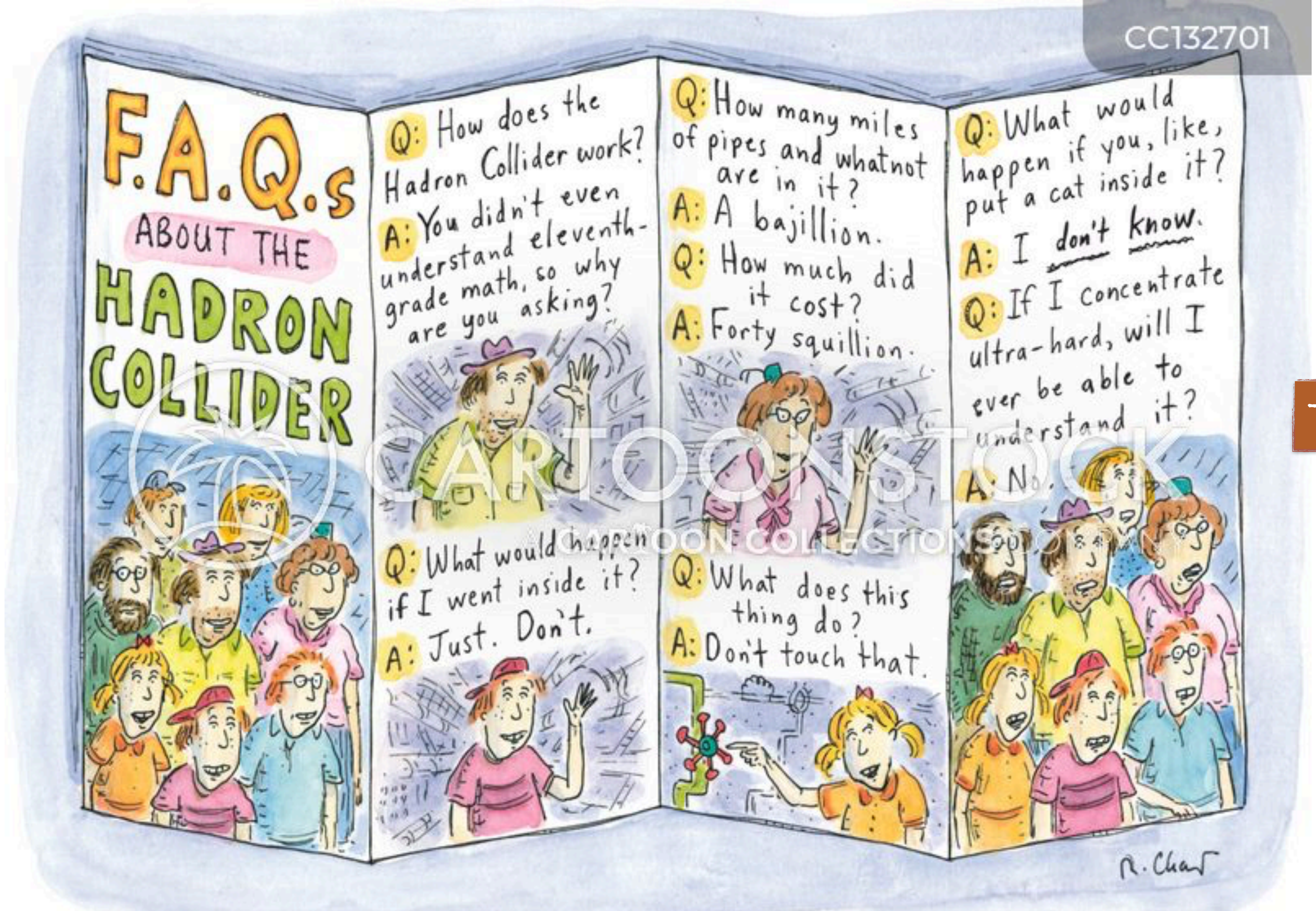
High energy research impact

- CERN subjected to the economic impact assessment since 1970s with one of recent cost-benefit analysis of the LHC, conducted by economists.
  - Conclusion: 92% probability that benefit exceed costs even when attaching the very conservative figure of zero the the value of the organisation's scientific discoveries. [link]
- Few important CERN impact:
  - Invention of **World Wide Web (WWW)** at CERN was driven by the need for better communication among scientists around the world.
  - **Hadron therapy** aims at treating tumours with beams of protons and light ions
  - **Medical imaging** benefits from new types of fast, bright, and dense scintillating crystals for PET scanners
  - Software for simulating particle interactions in detectors is used e.g. to **calculate the precise radiation dose for cancer treatment** planning systems and for space applications
  - **Pixel detector technologies** developed at CERN ("Medipix") are used e.g. in **medical diagnostics**, **industrial processes**, x-ray based material analysis and space missions on the International Space Station
  - **Global IT companies** (e.g. Huawei, Intel, Oracle, Siemens) collaborate within CERN's "openlab" and profit from the performance demands from particle physics in terms of big- data storage and analysis. **Firms use CERN as a test-bed for optimising and stress-testing their latest products**
  - The World-Wide LHC computing grid (WLCG) is a distributed computing infrastructure providing more than 500,000 CPUs and 500 PB of data storage in over 200 computer centres in 35 countries [1]. **CERN is one of the biggest producers and consumers of big data in the world.**
- At the end of the day, the billion dollar price is worth to pay from the tax payers money.

High energy research impact

- CERN subjected to the econ … by economists.
    - Conclusion: 92% proba … of the organisation's scientific discoveries. [link]
- Few important CERN impac
    - Invention of **World Wid** … ne world.
    - **Hadron therapy** aims
    - **Medical imaging** bene
    - Software for simulating … **eatment** planning systems and for space applicatio
    - **Pixel detector techno** … , x-ray based material analysis and space missions on
    - **Global IT companies** … nce demands from particle physics in terms of big- … **ir latest products**
    - The World-Wide LHC c … d 500 PB of data storage in over 200 computer cen … **e world.**
- At the end of the day, the bil





Thank you...

https://www.cartoonstock.com/cartoon?searchID=CC132701

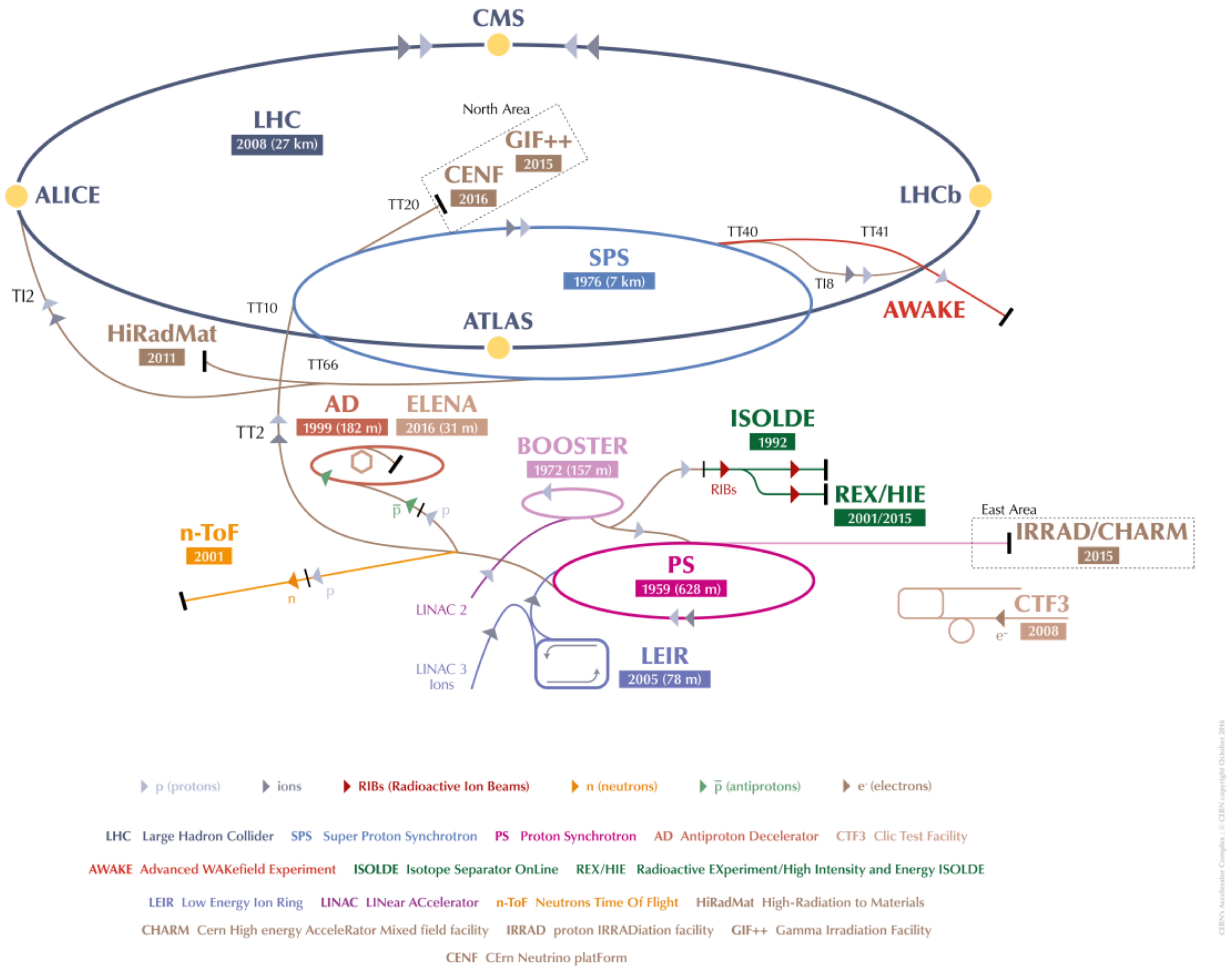
Backup

The Big Bang

What happened
at times less
than 10-9s
is uncertain

CERN Accelerator complex

Ref: https://cds.cern.ch/record/2225847?ln=en



Particle Physics

-

the story so far

Next 6 slide, summary sheets about particle physics: https://www.pp.rhul.ac.uk/hep/hep_handouts.html

Royal Holloway University of London

funded by PPARC

Particle Physics

the story so far

The smallest particles

Particle physics is the study of the smallest particles of matter in the universe (called quarks and leptons) and of the forces between them. It is carried out using huge machines that accelerate particles to close to the speed of light before smashing them together. By studying the debris from large numbers of such collisions physicists can learn about the particles and forces.

These same forces govern the behaviour of everything in the universe from the earliest times in the Big Bang. Thus there are strong links between particle physics and cosmology, currently two of the most fundamental and exciting areas of research in physics.

Particle cosmology

Cosmology is the study of the origin of the universe. Particle cosmologists understand the development of the very early universe using knowledge gained from the collisions observed at particle accelerators.

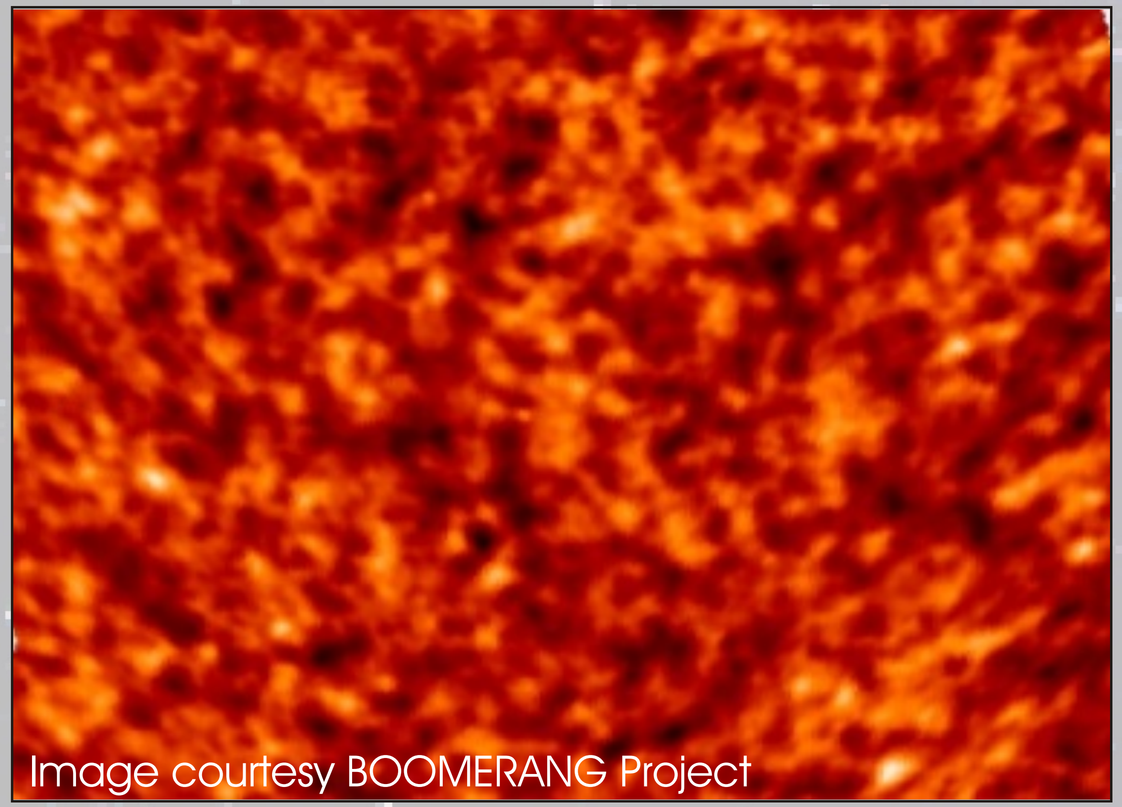
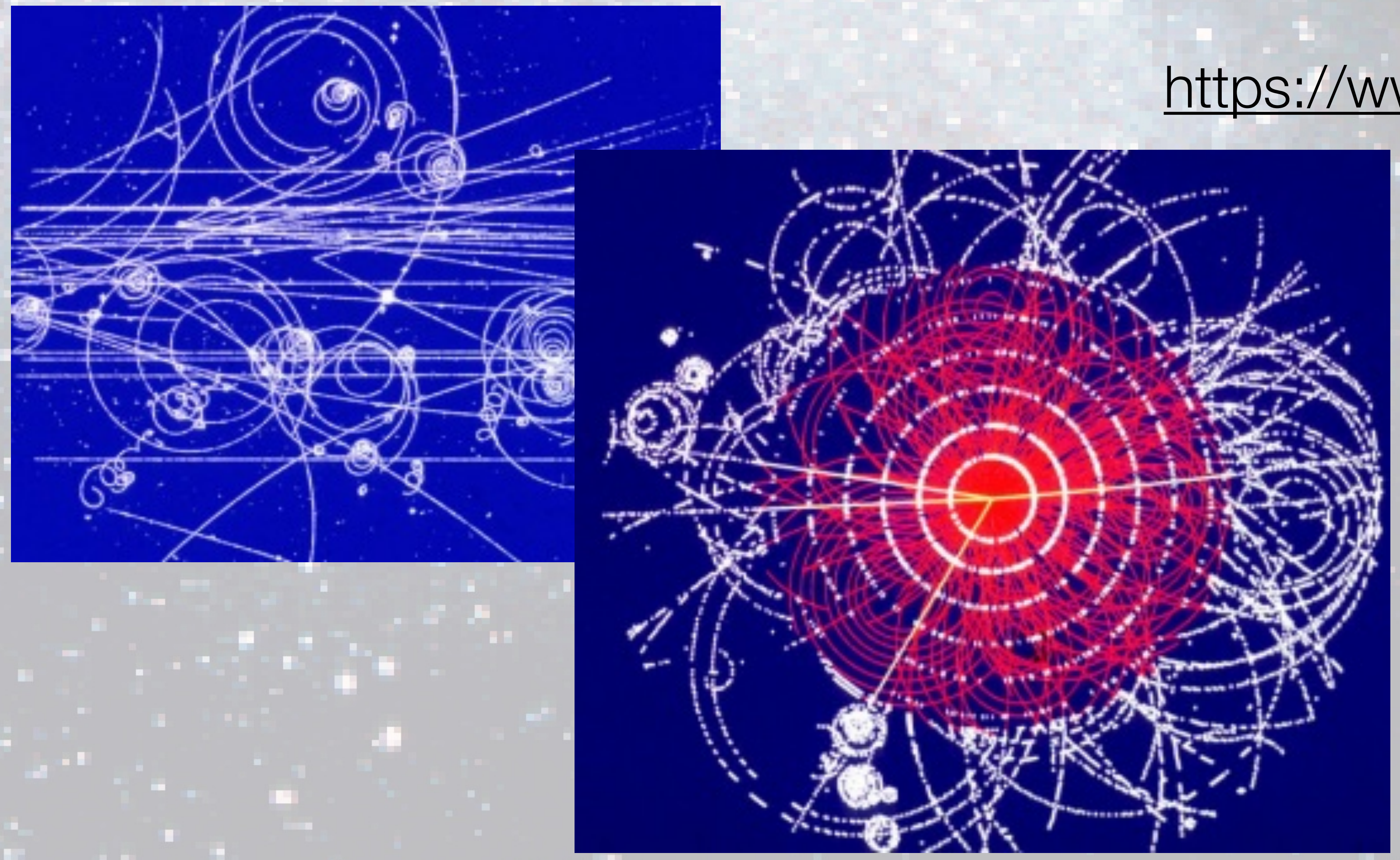


Image courtesy BOOMERANG Project

The distant Universe as it makes its transition from a glowing 2700 deg C plasma to a perfectly transparent gas, approximately 14 billion years ago, a mere 300,000 years after the Big Bang.

Collisions at particle accelerators

From an event recorded by a bubble chamber in 1970 to a simulated decay of a Higgs boson in the ATLAS detector.



https://www.pp.rhul.ac.uk/hep/hep_handouts.html

Background: M31 The Andromeda Galaxy, only 2.6 million light years away

This second series of summary sheets has been produced by the Centre for Particle Physics at Royal Holloway, University of London with financial support from the Particle Physics and Astronomy Research Council (PPARC). They may be freely copied or additional copies can be obtained from the Physics Secretary, Royal Holloway, University of London, Egham, Surrey TW20 0EX. Tel. 01784 443448.
Copies and other material for schools is also available from our website at www.pp.rhul.ac.uk

PPARC (www.pparc.ac.uk)

CERN (www.cern.ch)

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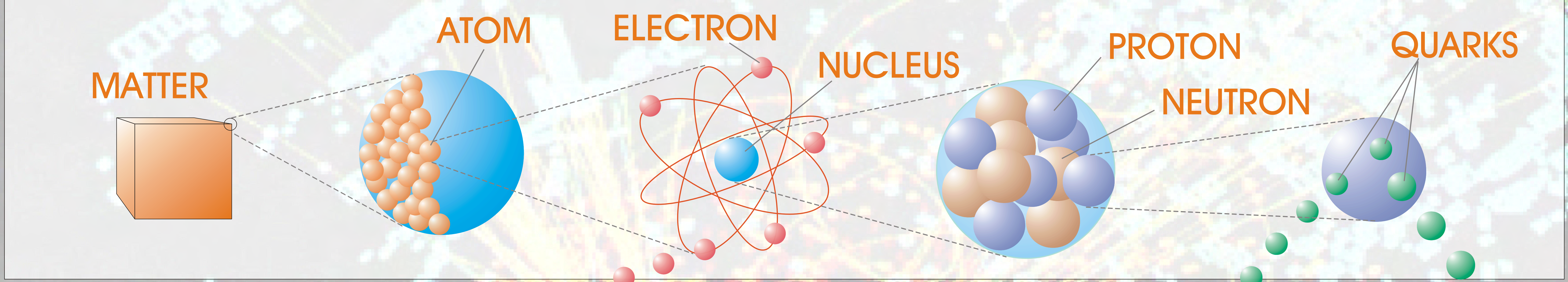
The Structure of Matter

Particle Physics 2



LEPTONS

These particles exist on their own

QUARKS

These particles only exist bound together

		Charge = -1	Charge = 0	Charge = +2/3	Charge =-1/3
Constituents of ordinary matter.	1st Family	ELECTRON (e^-) Responsible for electricity and chemical reactions. Mass = 0.51 MeV/c^2	ELECTRON NEUTRINO (ν_e) Rarely interacts with other matter. Observed 1956.	UP (u) Mass ~ 3 MeV/c^2	DOWN (d) Mass ~ 6 MeV/c^2
				Protons are made up of two up quarks and one down quark. Neutrons are made up of one up quark and two down quarks.	
These particles existed in the early moments after the Big Bang. Now they are found only in cosmic rays and at particle accelerators.	2nd Family	MUON (μ^-) A heavier relative of the electron. Discovered 1937. Mass = 0.106 GeV/c^2	MUON NEUTRINO (ν_μ) A relative of ν_e Discovered 1962.	CHARM (c) A heavier relative of the up quark. Discovered 1973. Mass ~ 1.2 GeV/c^2	STRANGE (s) A heavier relative of the down quark. Evidence 1947. Mass ~ 0.1 GeV/c^2
	3rd Family	TAU (τ^-) A heavier relative of the electron and muon. Discovered 1975. Mass = 1.78 GeV/c^2	TAU NEUTRINO (ν_τ) Indirect evidence 1975. Directly observed 2000.	TOP (t) The heaviest quark. Discovered 1994. Mass ~ 175 GeV/c^2	BOTTOM (b) A heavier relative of the down and strange quarks. Discovered 1977. Mass ~ 4.2 GeV/c^2

https://www.pp.rhul.ac.uk/hep/hep_handouts.html

Until recently it was generally thought that the neutrinos have zero mass.
Several recent experiments suggest that the mass of the neutrinos is not zero.

ALL OF THE ABOVE PARTICLES HAVE AN ANTIPARTICLE COUNTERPART.

A particle and its antiparticle can annihilate to produce the bosons that carry forces, e.g. $e^+e^- \longrightarrow \gamma\gamma$.

A particle - antiparticle pair can be produced from a force-carrying boson, e.g. $Z \longrightarrow b\bar{b}$, $\gamma \longrightarrow e^+e^-$.

Background: Simulation of a Higgs decay to two hadronic jets

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The Forces

Four . . . .

. . . . or one ?

The forces of nature between matter particles (quarks and leptons) arise from the exchange of other 'force carrying' particles called bosons. If a boson is emitted by one quark or lepton and is absorbed by another, then there is a force between the two.

Force	Boson	Source	Relative strength*	Range
gravity	graviton	mass	10^{-39}	infinite
weak	W^+, W^-, Z	weak charge	10^{-5}	10^{-18}m
electromagnetism	photon	charge	10^{-2}	infinite
strong	gluons	colour	1	10^{-15}m

* in the nucleus

https://www.pp.rhul.ac.uk/hep/hep_handouts.html

Gravity

The weakest force, but responsible for the attraction between astronomical objects. The graviton has not been observed. Felt by all particles.

Strong

Felt by quarks only, this force also holds nuclei together. There are eight different types of gluons carrying different combinations of colour.

The weak force and electromagnetism are different manifestations of the electroweak force. The mathematical theory of this force predicts the existence of the Higgs boson, responsible for the mass of all objects.

Weak

Z

Responsible for radioactive β decay. The force carriers ($W^\pm$, Z bosons) have mass and were discovered at CERN in 1983-4. Felt by all matter particles.

W^-

W^+

Electromagnetism

Holds atoms together and plays a major role in everyday life. The force carrier is the familiar photon. Electricity and magnetism are simply different manifestations of this force. Felt by all particles except neutrinos, which are uncharged.

Can all four forces be described as different aspects of a more general theory ?

Background: Simulation of a Higgs event

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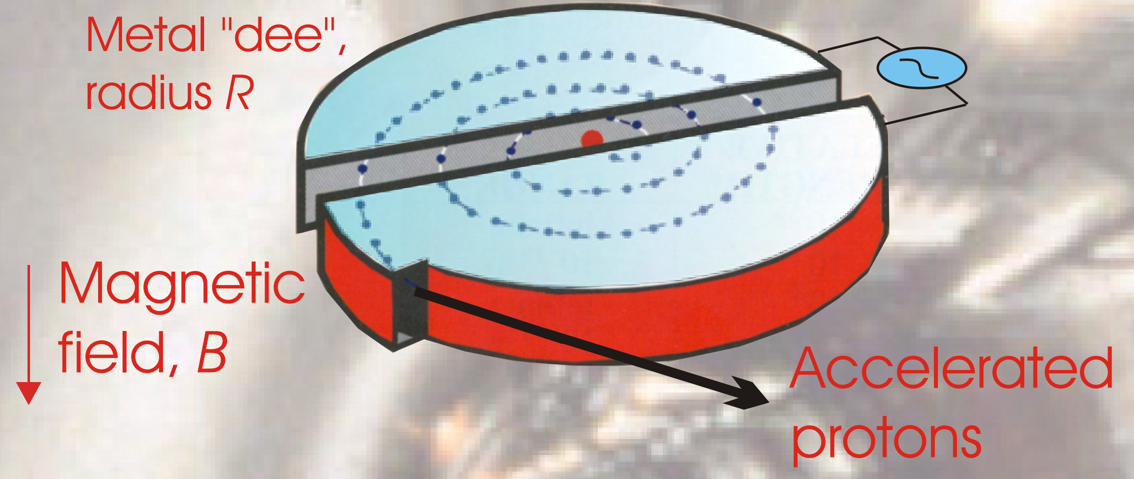
Particle Accelerators

Cyclotron

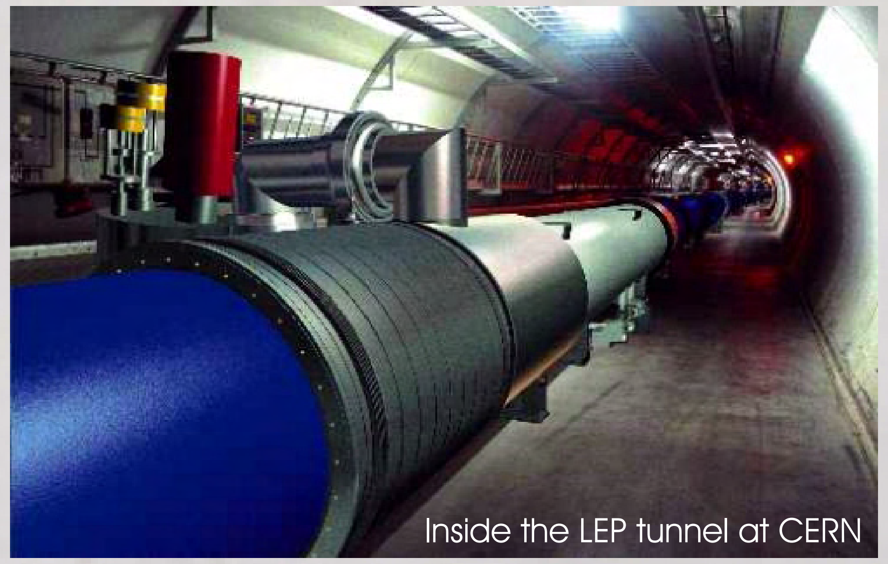
The first circular accelerator was the cyclotron.



Equating forces $mv^2/r = Bev$ and the time for half a turn, $t = \pi r/v$; hence $t = \pi m/eB$. This is independent of radius, so with the correct choice of frequency for the ac voltage protons will be accelerated every time they cross the gap. The final kinetic energy = $(BeR)^2/2m$ and is about 10 MeV for $R = 0.3$ m.

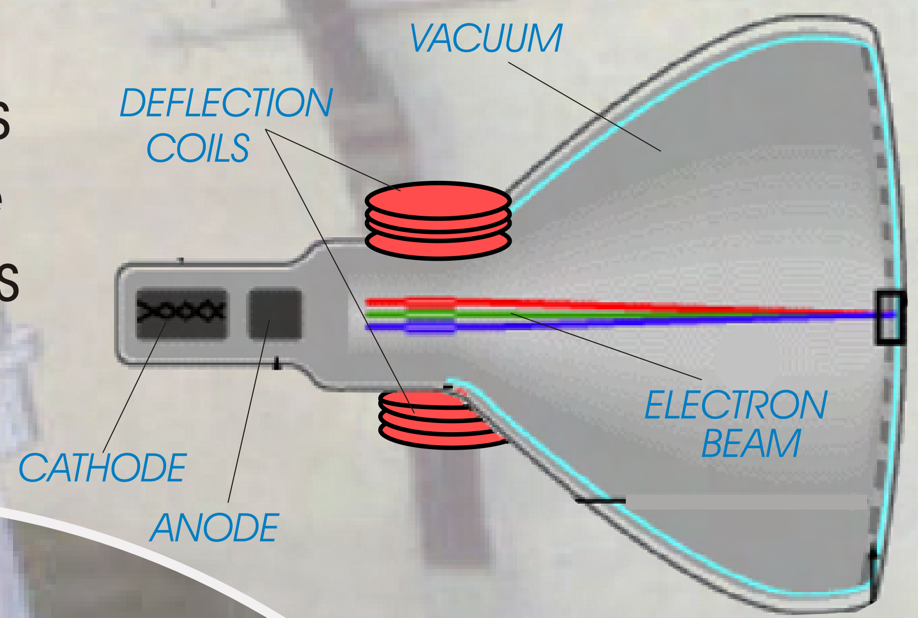
The largest machines

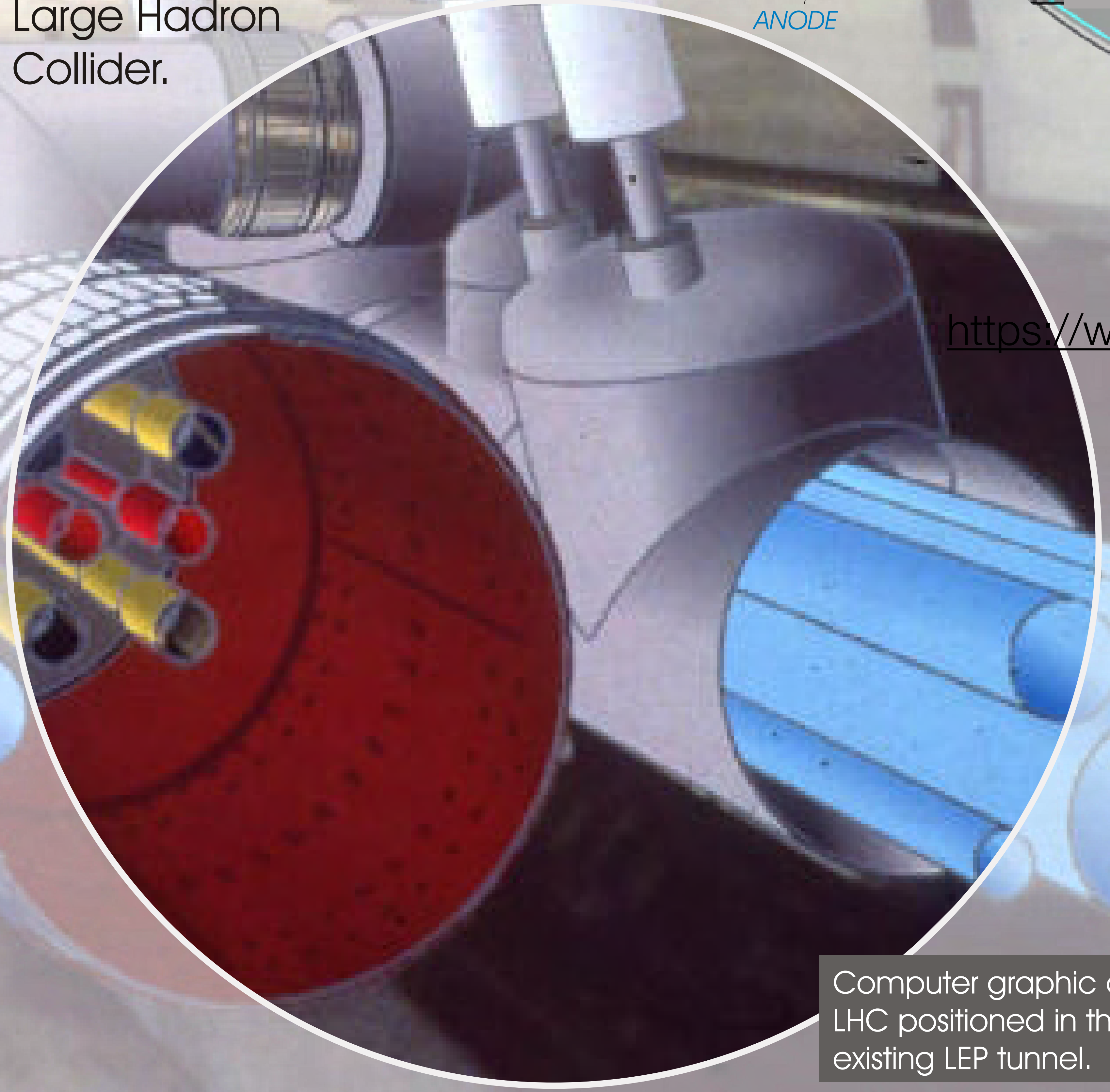
Some of the largest machines ever built accelerate the smallest particles to a speed very close to the speed of light. The equation $E \approx hc/\lambda$ shows that high energy particles have a short wavelength and can therefore probe smaller distances when they collide. In the largest accelerators particles circulate at a fixed radius and the magnetic field is increased as they gain energy.


Inside the LEP tunnel at CERN

Television set

A television set is a particle accelerator in which electrons reach an energy of about 20 keV. The same features were found in the LEP accelerator at CERN. LEP accelerated electrons and positrons to 100 GeV before colliding them. LEP completed its research programme in 2000 and is being replaced by the Large Hadron Collider.




Computer graphic of LHC positioned in the existing LEP tunnel.

Background: Computer graphic of the LHC

https://www.pp.rhul.ac.uk/hep/hep_handouts.html

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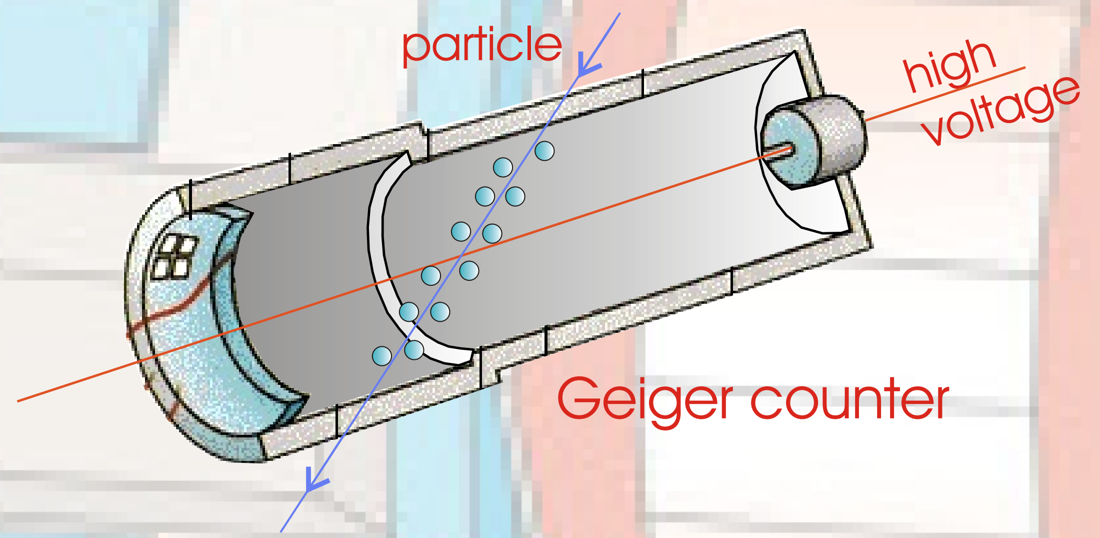
Particle Detectors

Particle detection

Particle detection can be based on several effects such as ionisation, Cerenkov radiation and electron-hole pair production in semiconductors.

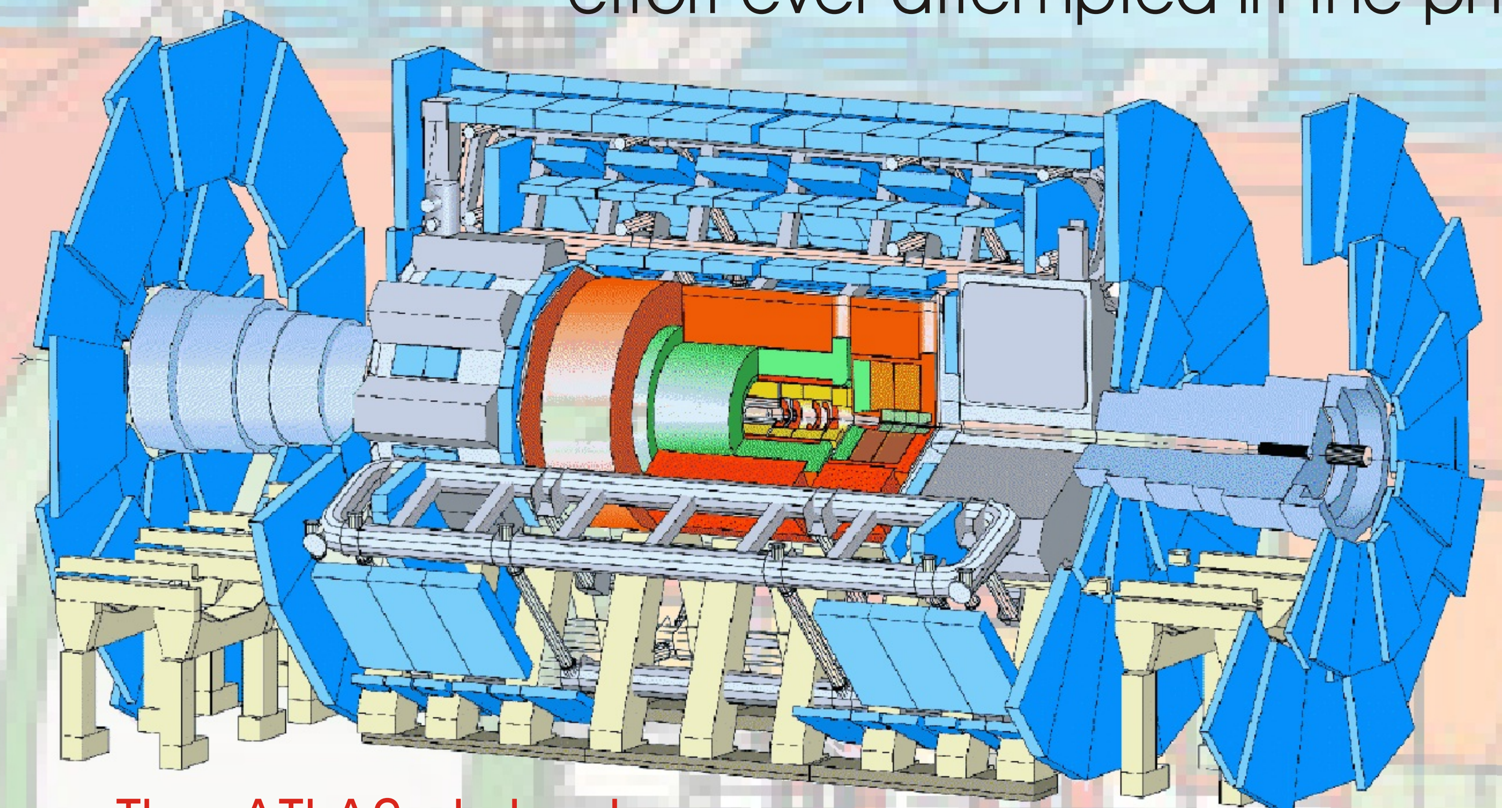
A charged particle passing through a Geiger counter causes ionisation. The ionisation electrons drift towards the wire creating further ionisation, producing a large signal.



Geiger counter

The ATLAS detector

The ATLAS experiment is under construction by 1700 collaborators in 150 institutes around the world. It is the largest collaborative effort ever attempted in the physical sciences. It will study proton-proton interactions at the Large Hadron Collider (LHC) at CERN. The primary purpose of the detector is to search for the Higgs boson and hence increase our understanding of mass. It is also able to study the properties of the top quark.



The ATLAS detector

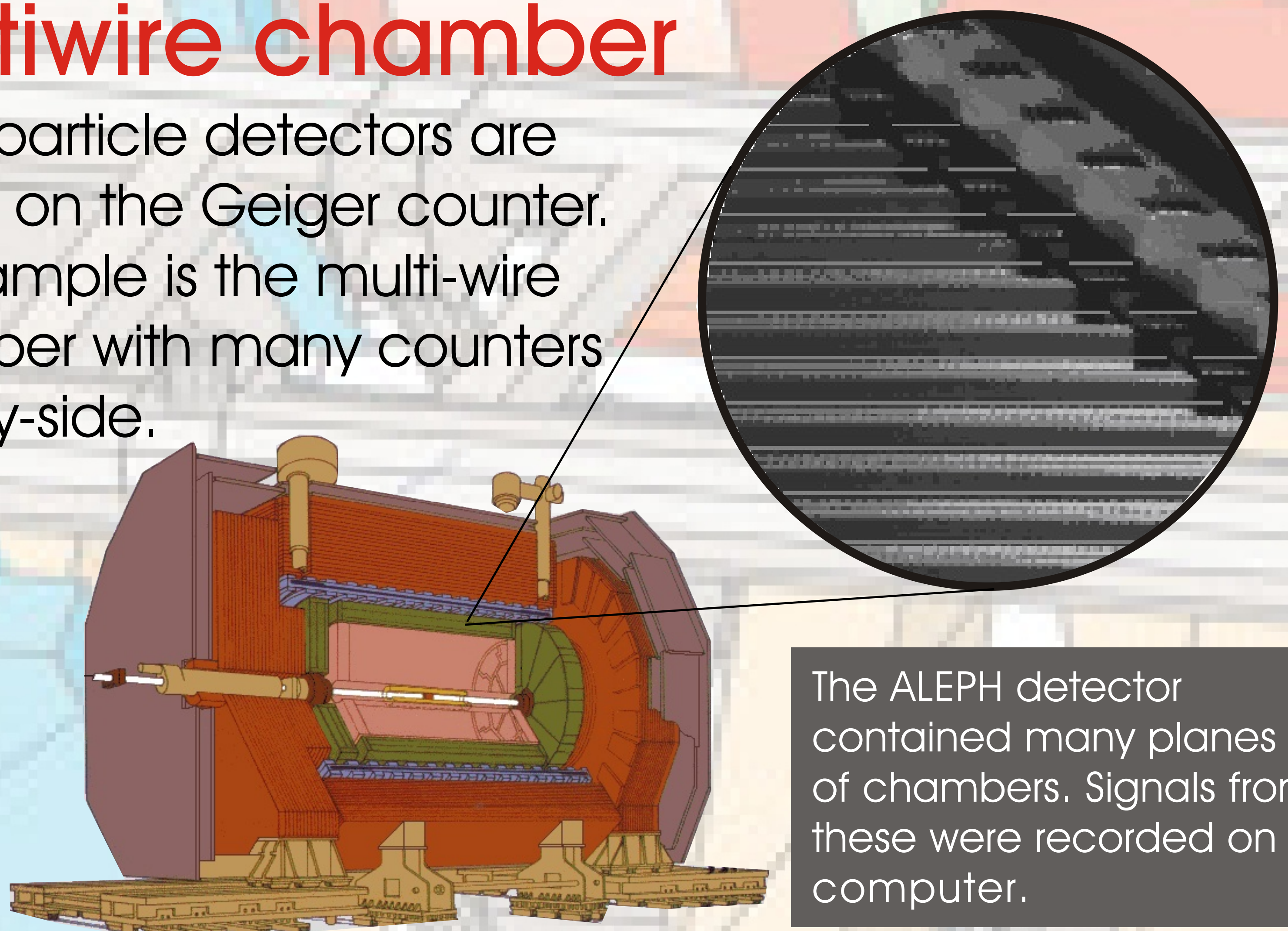
The ATLAS detector is 22 m high and 44 m long.

Further information:
atlasinfo.cern.ch/Atlas/public

https://www.pp.rhul.ac.uk/hep/hep_handouts.html

Multiwire chamber

Many particle detectors are based on the Geiger counter. An example is the multi-wire chamber with many counters side-by-side.



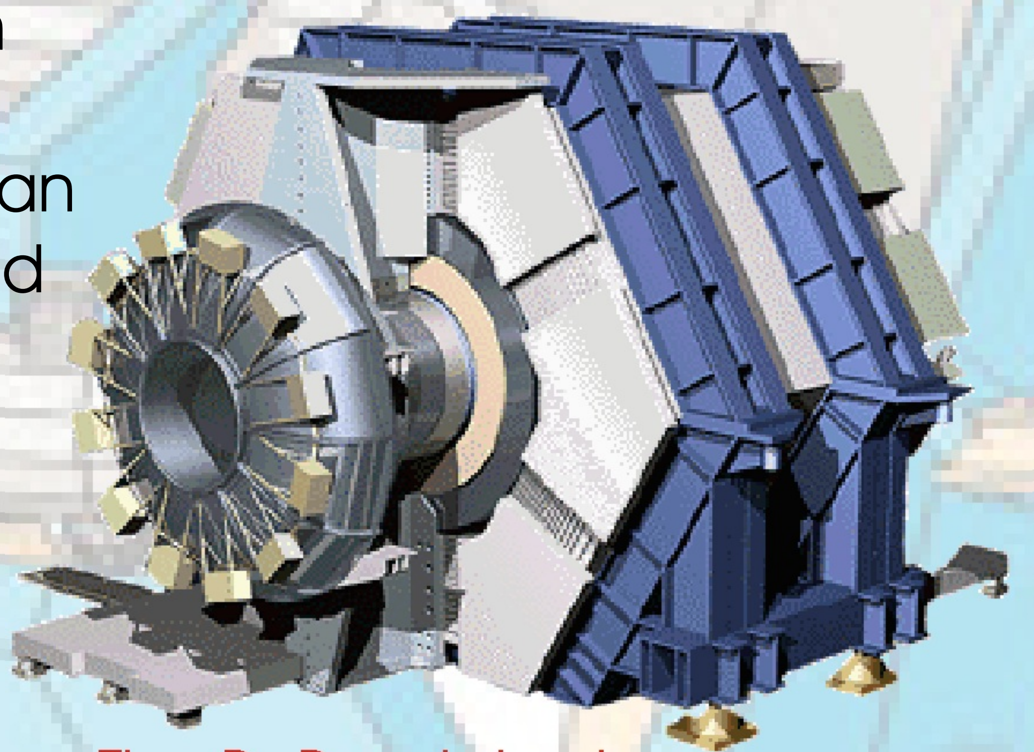
The ALEPH detector contained many planes of chambers. Signals from these were recorded on a computer.

The BaBar detector

The BaBar detector is exploring the small difference in the behaviour of matter and antimatter that may be responsible for our existence. It can record subtle distinctions in the way B mesons and anti-B mesons decay. Both are more than five times the mass of protons and survive just over a trillionth of a second. It is operating at the Stanford Linear Accelerator Center in California.

Further information:
www2.slac.stanford.edu/VVC

SLAC



The BaBar detector

Background: Image of the ATLAS detector

The Higgs Boson

What is mass?

We still do not understand what mass is and why the quarks and leptons have different masses. Our current best idea is that a "Higgs field" fills the universe and mass is a measure of the resistance to movement through this field.

To understand the Higgs mechanism, imagine that a room full of physicists quietly chattering is like space filled only with the Higgs field …

… a well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step …

… this increases his resistance to movement, in other words, he acquires mass, just like a particle moving through the Higgs field …

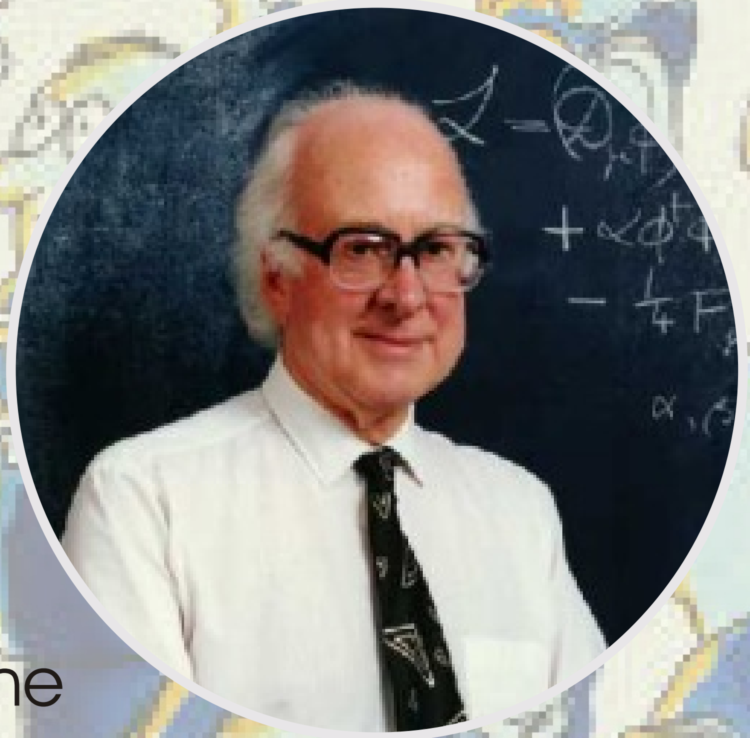
… if a rumour crosses the room…

… it creates the same kind of clustering, but this time among the scientists themselves. In this analogy, this cluster is a Higgs particle.

From an idea by David Miller, University College, London.

Explanation for mass

This explanation for mass was developed in the 1960's by a number of physicists, including Peter Higgs, now Emeritus Professor at the University of Edinburgh, whose name has been associated with the idea.



Peter Higgs

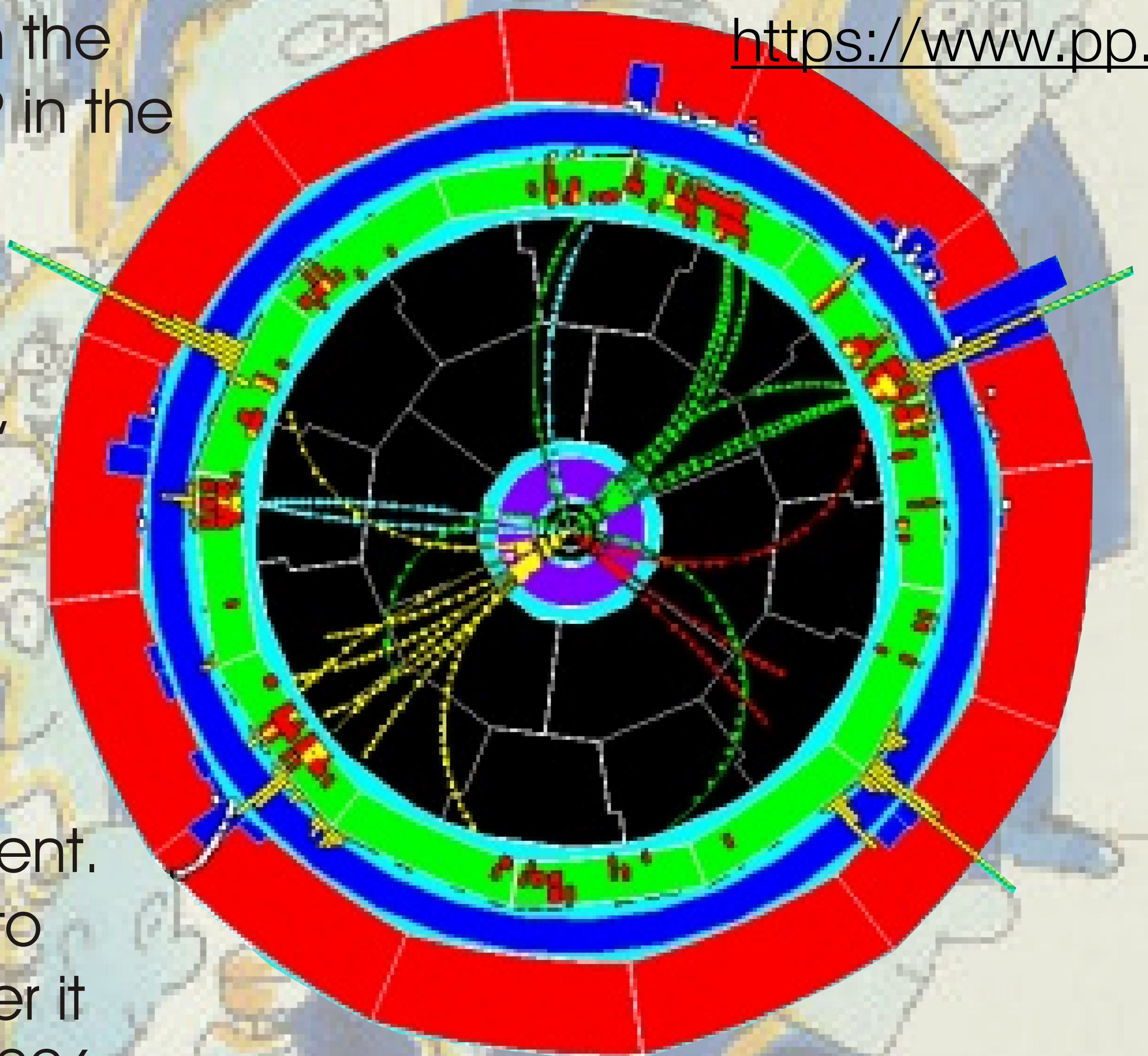
Many searches have been made for the Higgs boson; the most detailed were using the LEP accelerator at CERN during the 1990's. Indirect evidence suggests it has a mass lower than 200 GeV/c^2 and direct searches show that its mass is above 110 GeV/c^2.

In 2000, physicists at LEP may have glimpsed the first hints of a Higgs boson signal: a few events consistent with a mass of 115 GeV/c^2 were observed.

Background: image courtesy of CERN

Possible evidence

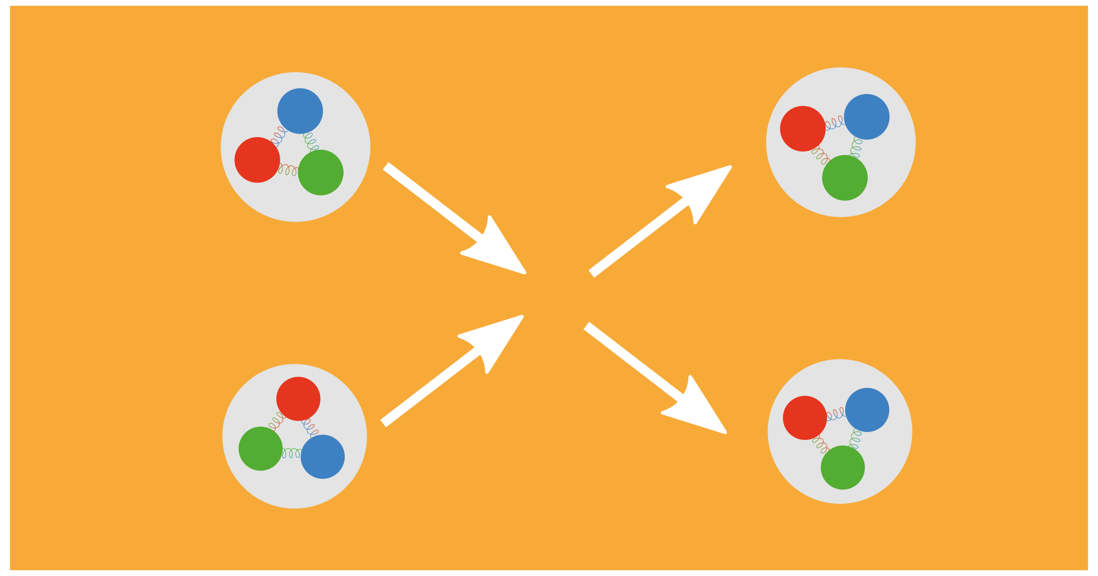
for the Higgs boson in the ALEPH detector at LEP in the reaction $e^+e^- \longrightarrow HZ$. The Higgs boson has decayed into the green and yellow jets, the Z boson to the red and blue jets. It is also possible, however, that other processes could be responsible for this event. The LHC is expected to resolve the puzzle after it begins operation in 2006.



https://www.pp.rhul.ac.uk/hep/hep_handouts.html

proton - proton collisions

collisions proton - proton

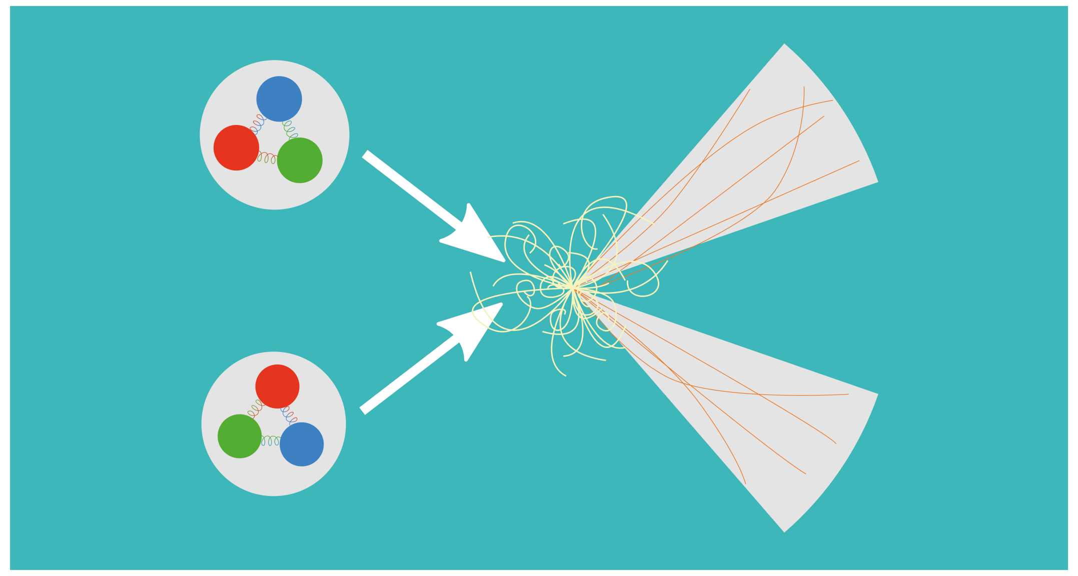


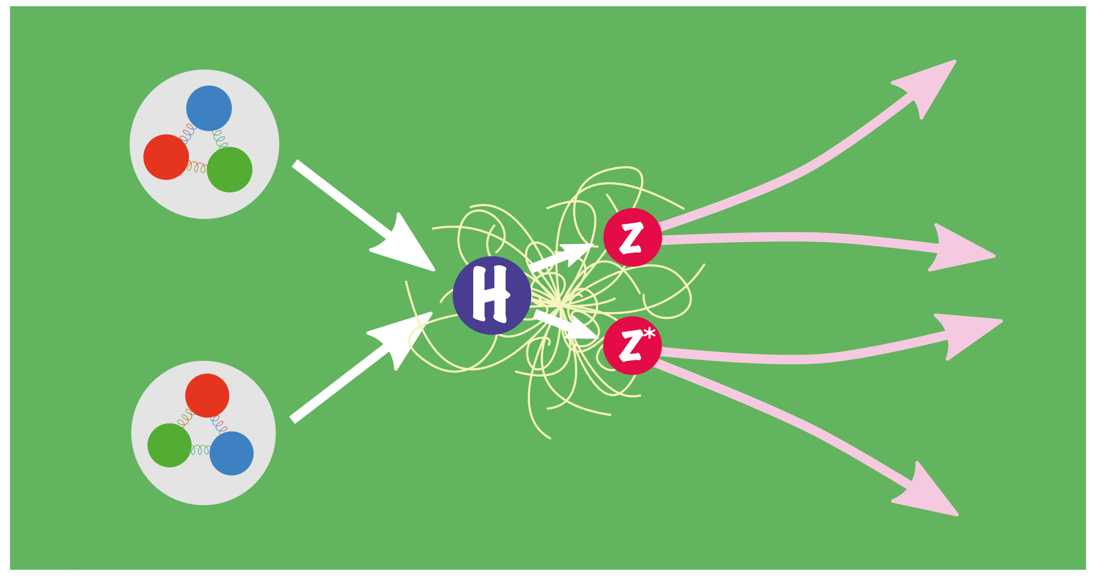
at **low** energies, protons will bounce off each other

*à **basses** énergies, les protons rebondissent l'un sur l'autre*

as the collision energy increases, the constituent quarks and gluons will start to interact **inelastically**

*lorsque l'énergie augmente, les quarks et gluons qui composent le proton interagissent de façon **inélastique***



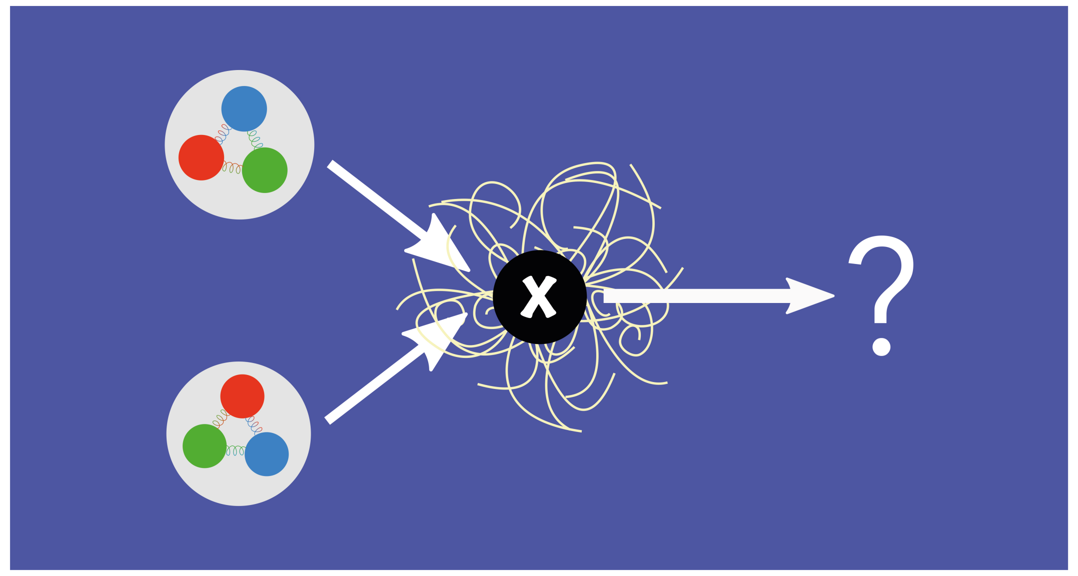


inelastic collisions will also sometimes create a **Higgs Boson**

*les collisions inélastiques créent parfois un **Boson de Higgs***

at the high energies in LHC collisions, it's possible that **heavy new particles** are created

*à haute énergie, il est possible de créer de **nouvelles particules***



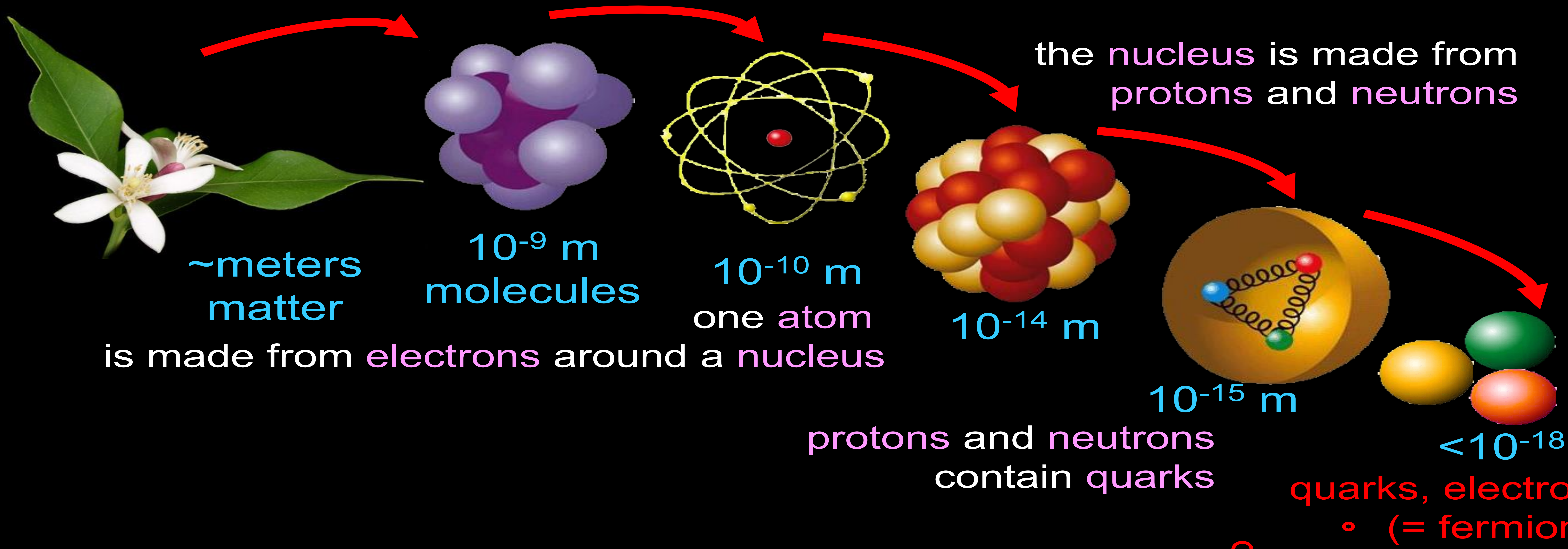
increasing energy • *énergie qui augmente*

ATLAS EXPERIMENT

https://cds.cern.ch/record/2691983

https://wonderopolis.org/wonder/what-caused-the-big-bang

What is ‘normal’ matter made from?

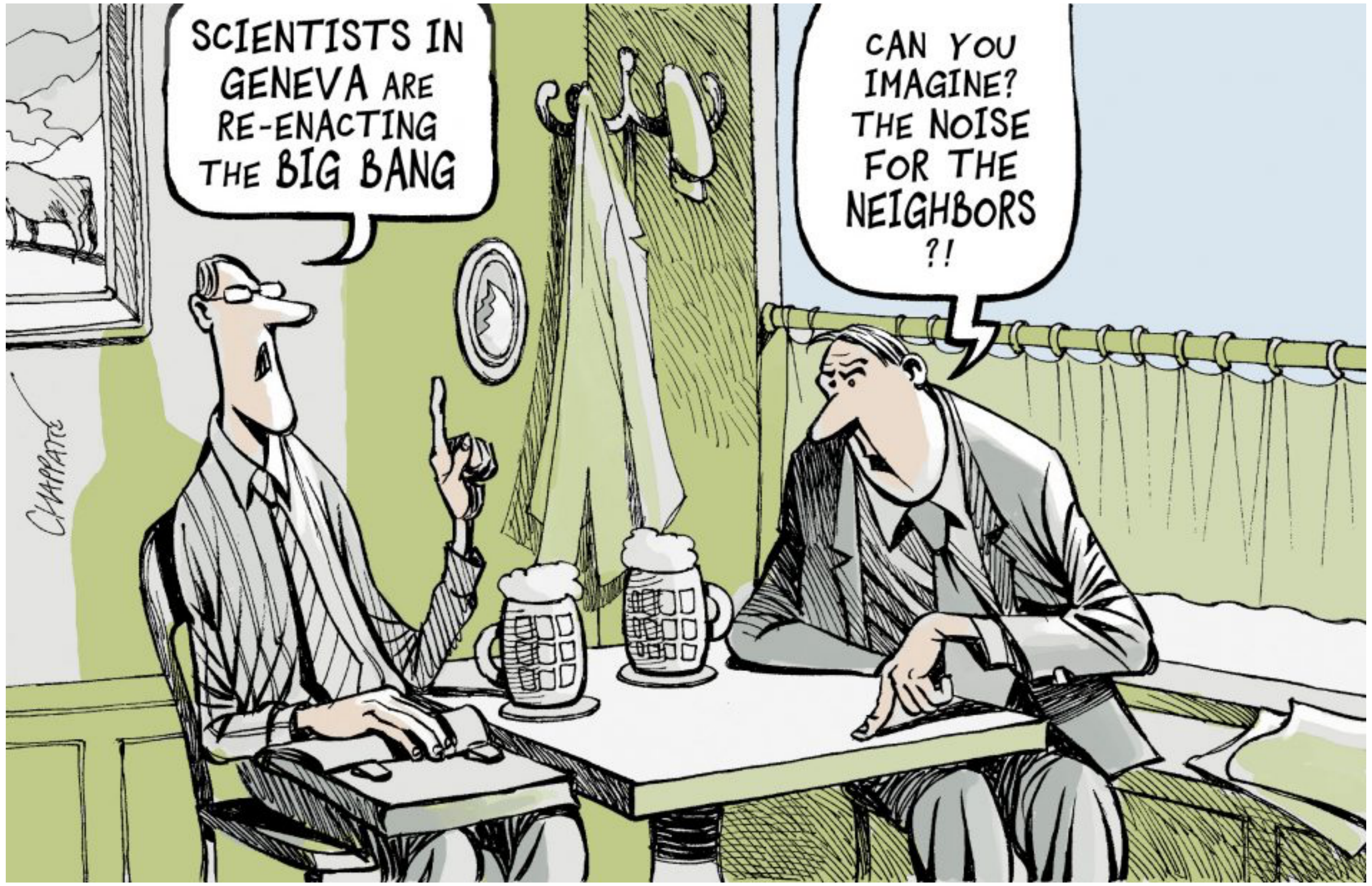


electron, quark < 10^{-18} m = 0.000,000,000,000,000,001 m
→ fundamental constituents

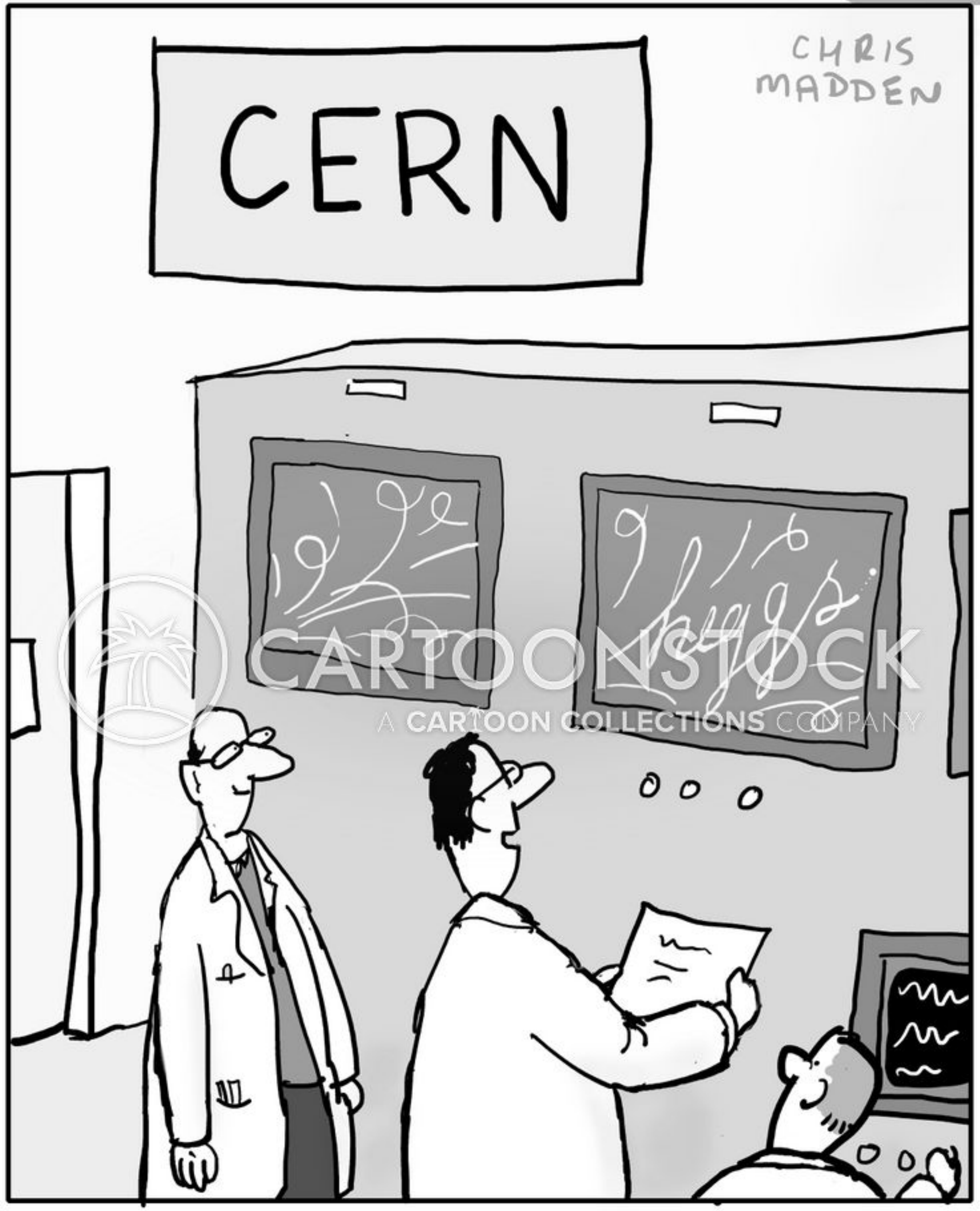
https://indico.cern.ch/event/777129/contributions/3249458/attachments/1842776/3022233/An_introduction_to_High_Energy_Physics_at_CERN.pdf

What is particle physics?

- Particle physics is a branch of physics which re-creates the universe just after the Big-Bang and hopes to answer our questions, like:
    - Where do we come from?
    - What are we made up of?



https://www.chappatte.com/en/images/cern-launches-particle-collider/



"Take a look at this everyone - it just could be the signature we've been looking for!"

"You should not trust an atom. They make up EVERYTHING!"