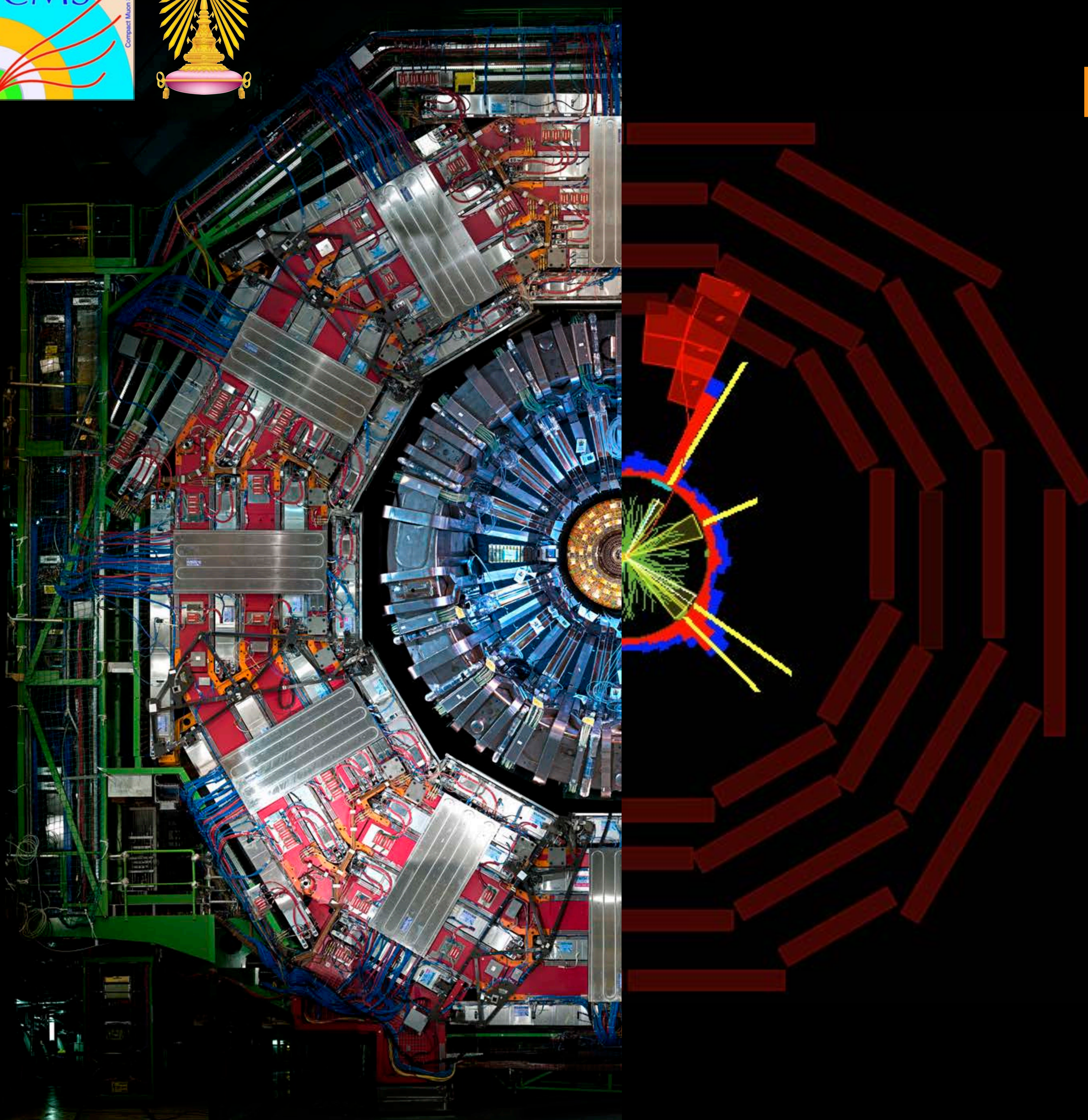
Introduction to Particle Physics

Experiment



Norraphat SRIMANOBHAS
CMS Collaboration
Chulalongkorn U., Thailand,

Singapore and Thailand Summer School 2017
CERN, May 29 - June 2, 2017

Fundamental questions

Painting by Paul Gauguin

Where Do We Come From? What Are We? Where Are We Going?
Note that this painting should be read from right to left.

Experimental particle physics

Basic research in the field of experimental and theoretical particle physics, finding out what the Universe is made of and how it works. At CERN, the world's largest and most complex scientific instruments are used to study the basic constituents of matter — the fundamental particles. By studying what happens when these particles collide, physicists learn about the laws of Nature.

http://acceleratingnews.web.cern.ch/content/accelerators-celebrating-international-year-light

How things work at CERN

LHC
- Accelerate protons/ions
- Collide bunches of particles

Theory
- Theoretical particle physics

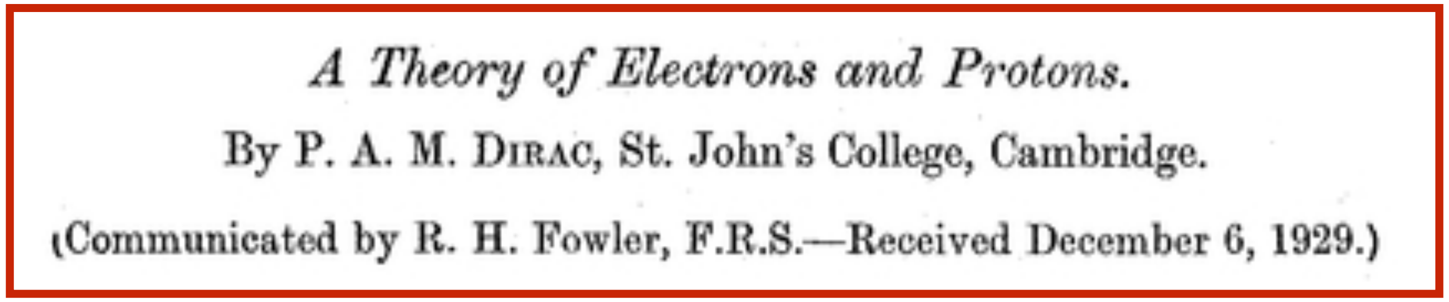
Applications
- Medical
- Space
- Materials
- Computing
- …

Experiments
- Detect particles coming from collisions
- Select events of interest
- Store RAW events, and transfer them around the world
- Do offline processing around the world
- Perform analyses

Statistics
- Statistical method

History from experimental side

Up to 1930 known particles: **Electron**, **photon** and **neutrino** (postulated to explain the missing energy in β-decay) , **proton** and **neutron** (inside Nucleus)
1932: The 1st Anti-particle - the **positron** - was discovered by **Carl Anderson** (1936 Noble prize in Physics for “his discovery of the positron”.

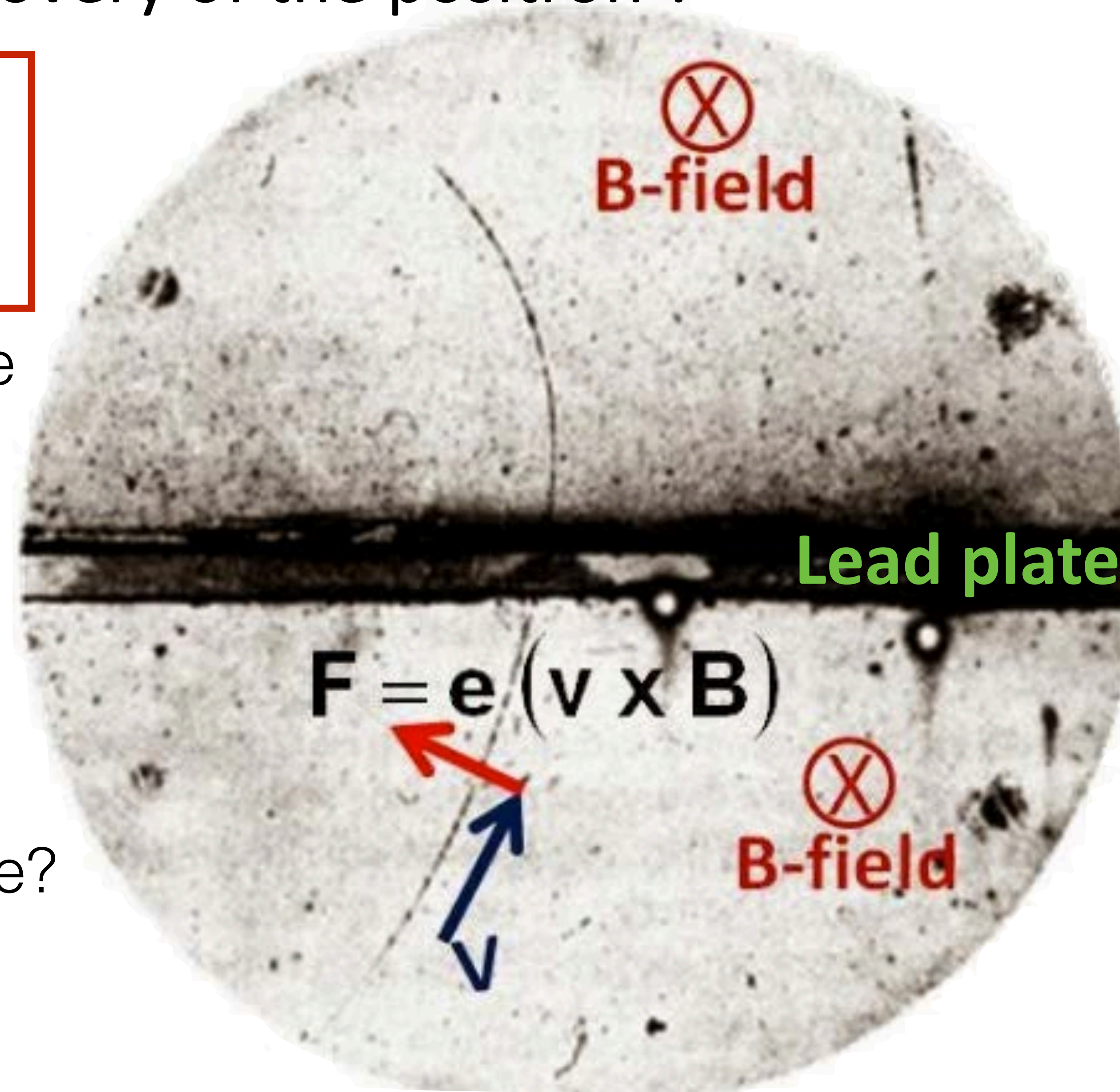


A Theory of Electrons and Protons.

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received December 6, 1929.)

Paper by **Dirac** to to explain the unavoidable negative-energy solution for the relativistic electron. Published 1 January 1930.
DOI: 10.1098/rspa.1930.0013



How did positron travel in the picture?
- ☐ From top to bottom
- ☑ From bottom to top

How do you know?

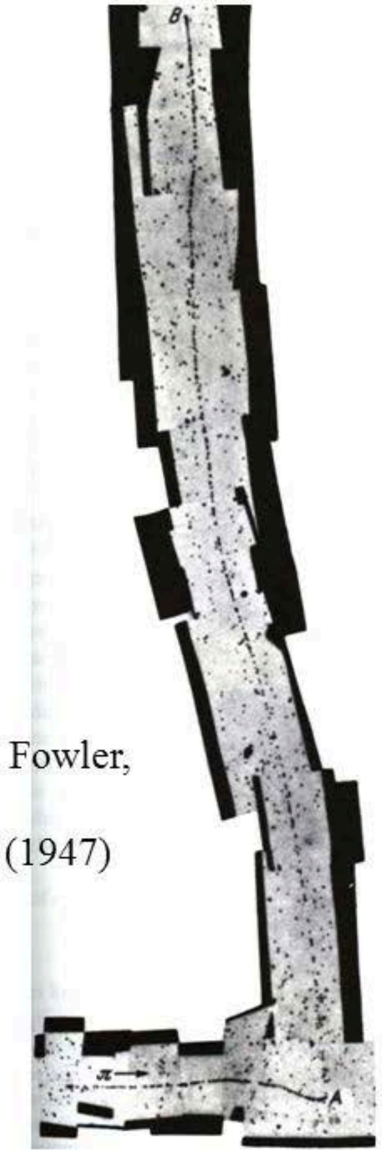
History from experimental side

1932: **James Chadwick** observed a free neutron.

1933: **Fermi** set out his theory of beta decay, $n \rightarrow p + e^- + \bar{\nu}_e$

1935: **Yukawa Hideki** proposed his Meson Hypothesis to describe the nuclear force due to exchange of particles with mass (Mesons).

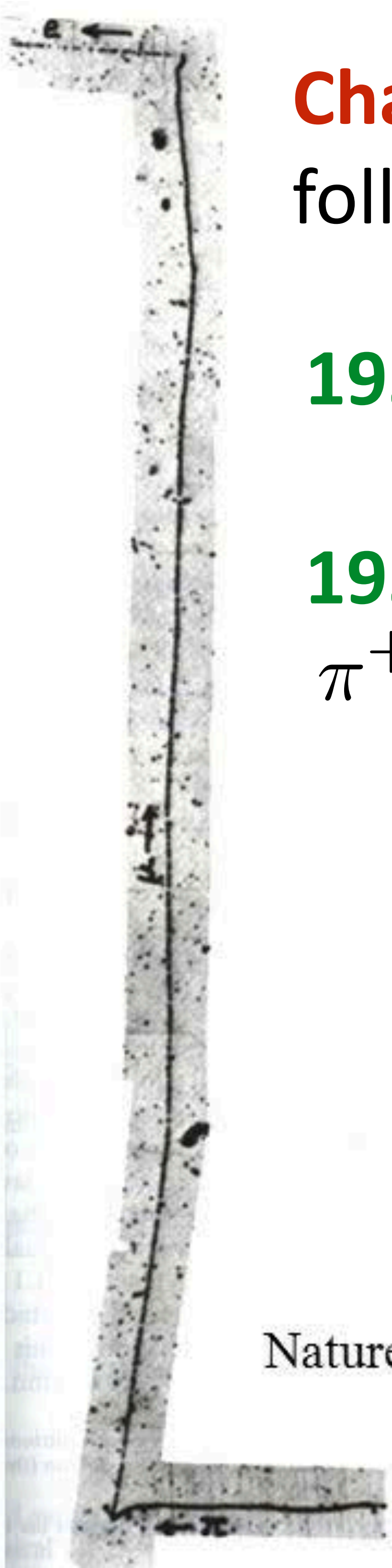
1936: **Anderson** and **Seth Nedermeyer** discovered the **muon** (assumed to be Yukawaís proposed Meson first) was far too penetrating in matter to be the required exchange particle between nucleons and it decayed to an $e^{\pm}$ at rest rather than being absorbed by the nucleus as a meson would be.



C.F.Powell, P.H. Fowler, D.H.Perkins Nature **159**, 694 (1947)

1946: **Powell**, **Lattes**, **Occhialini** discovered the **Charged Pion** observing the decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$

History from experimental side



Charged Pion decayed to muon and neutrino, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by muon decay, $\mu^+ \rightarrow e^+ + \nu_e$.

Nature **163**, 82 (1949)

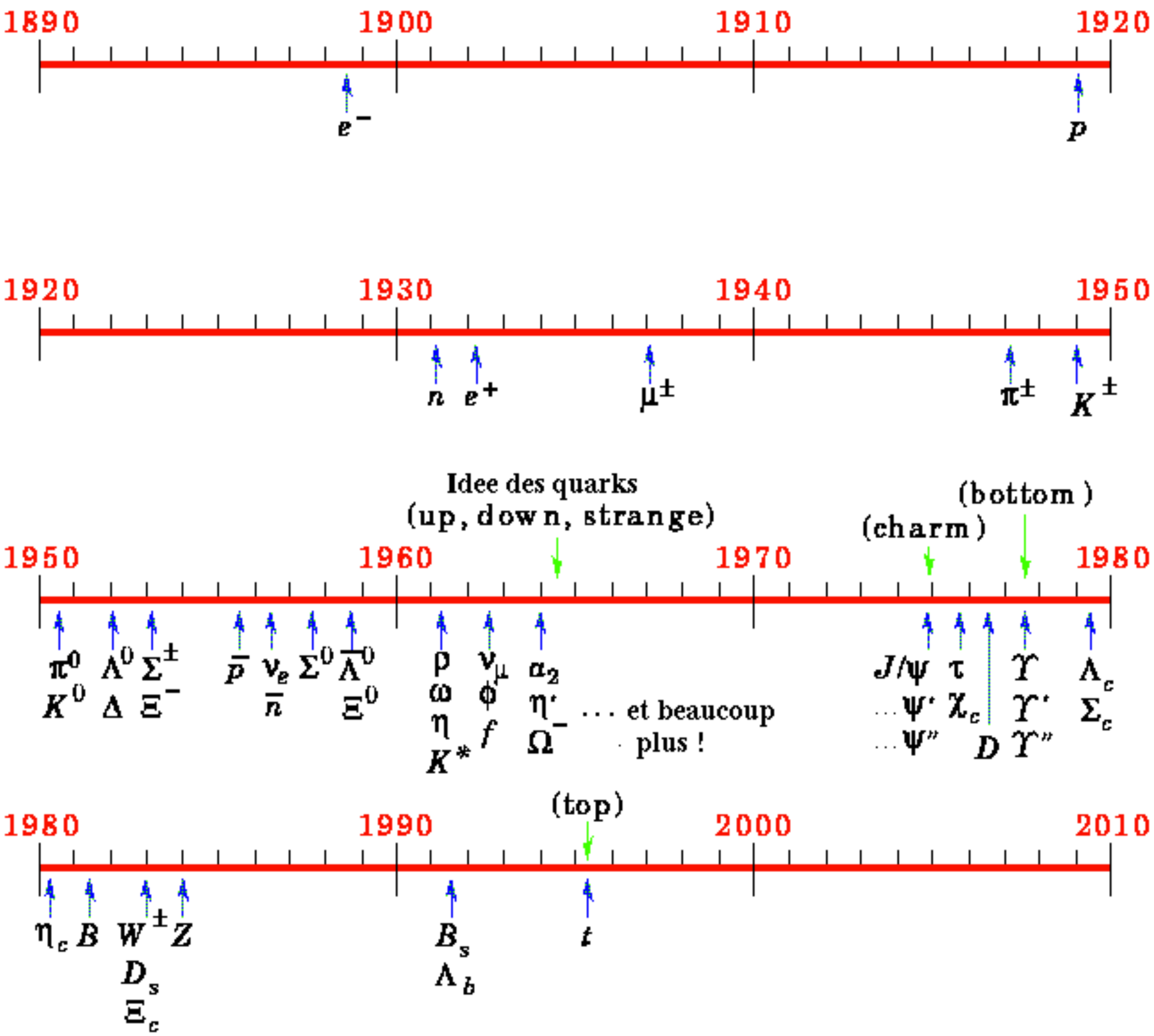
1950: Neutral Pion seen decaying to 2 Photons

1958: Discovery of electron mode of charged pion decay $\pi^+ \rightarrow e^+ + \nu_e$ at CERN Synchrocyclotron.

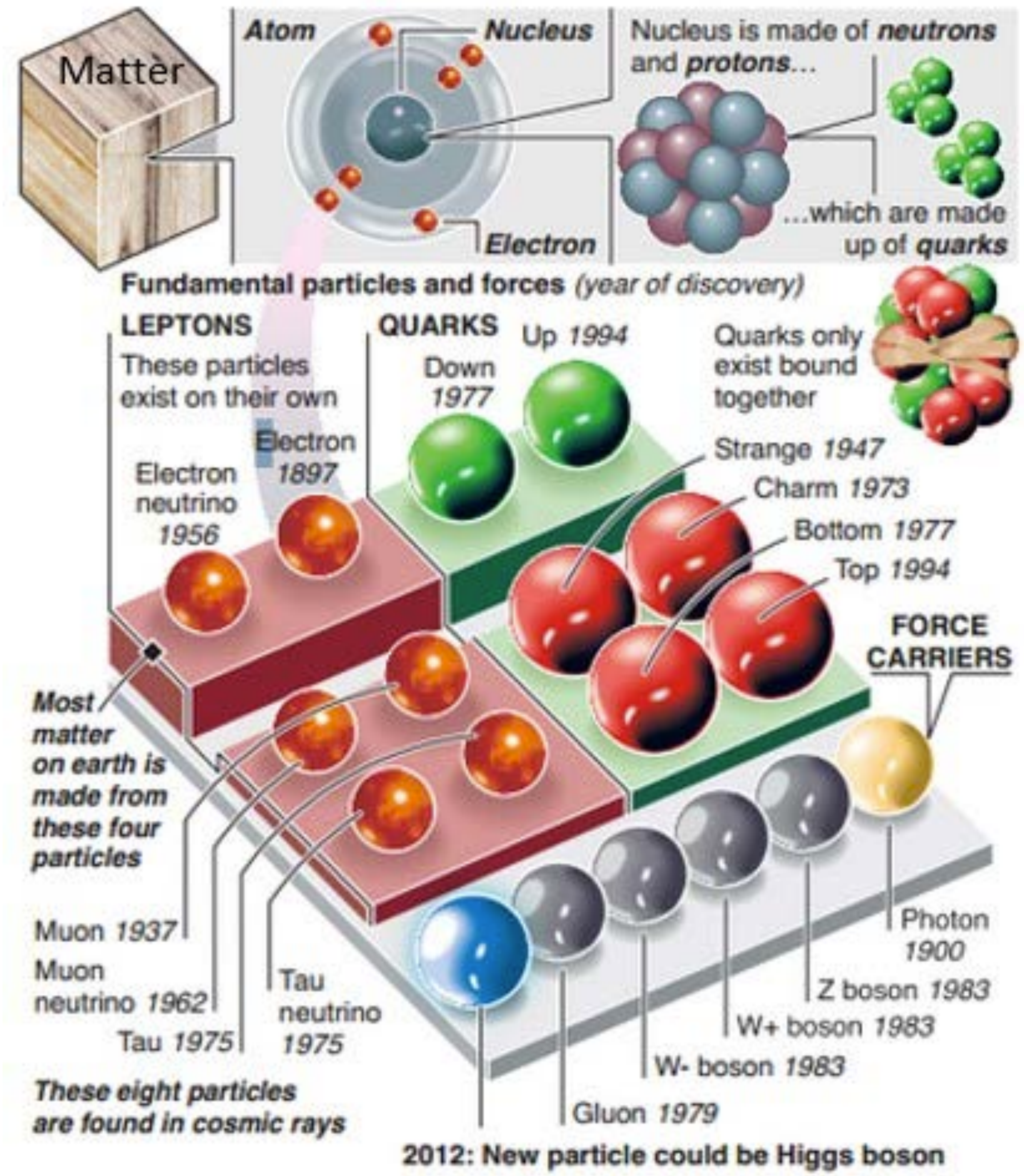
https://home.cern/fr/cern-people/updates/2014/02/maria-and-giuseppe-lives-intertwined-cerns-history

Giuseppe and Maria Fidecaro. Giuseppe set up a group and prepared the basic equipment for experiments that was used in 1958 for a successful search for pions decaying into an electron and a neutrino.

History from experimental side



http://lappweb.in2p3.fr/archives/vulgarisation/initour/refa.html



http://www.eoht.info/page/Particle

LHC experiments

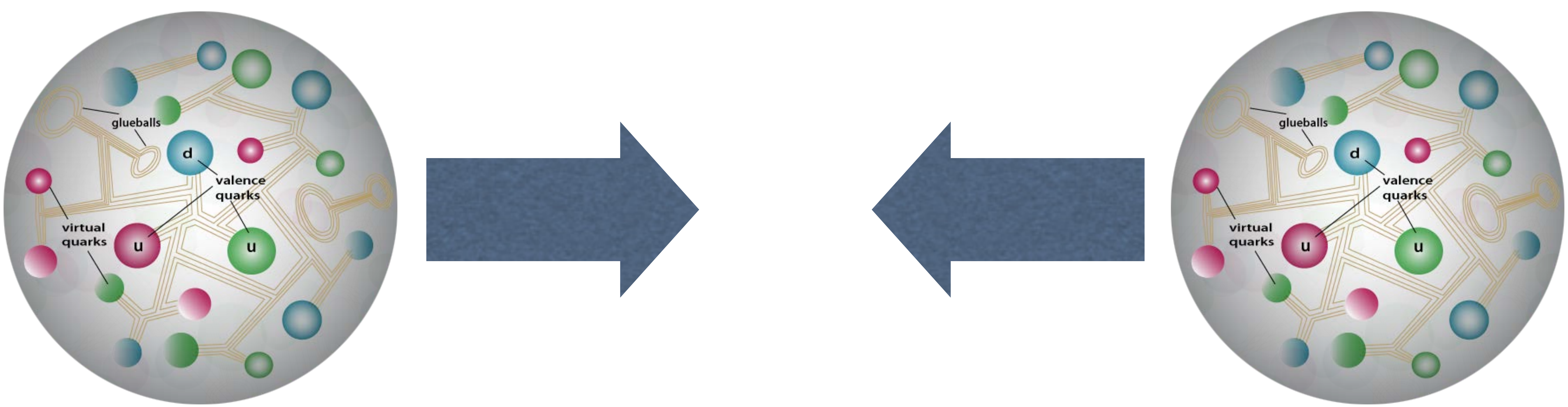
Proton collisions

Parton

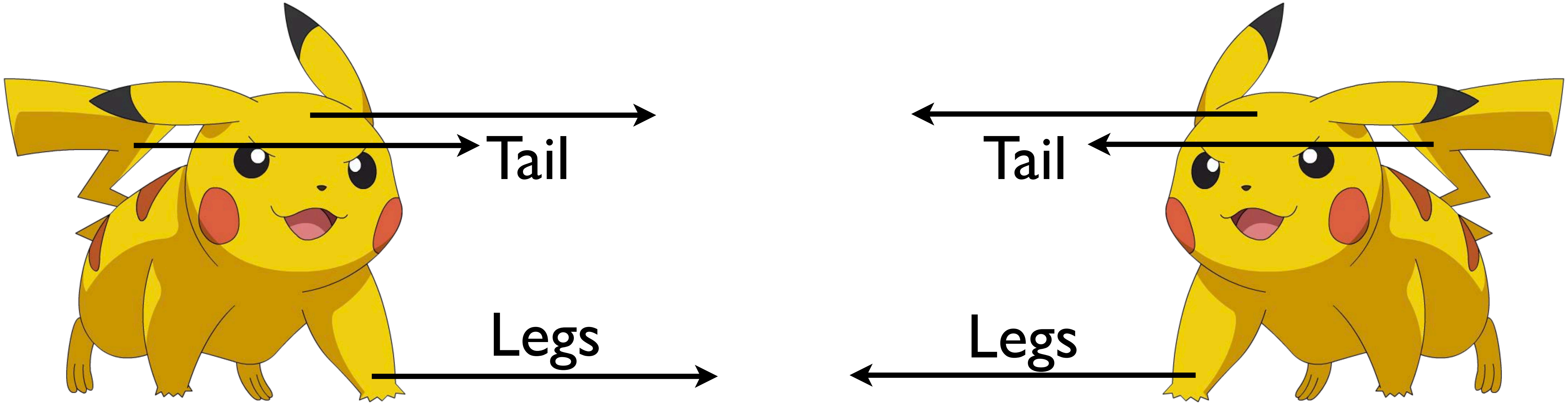
- The name was proposed by **Richard Feynman** in **1969**.
- Generic description for any particle constituent within hadrons (i.e. proton)
- Referred today as quarks and gluons.

Proton

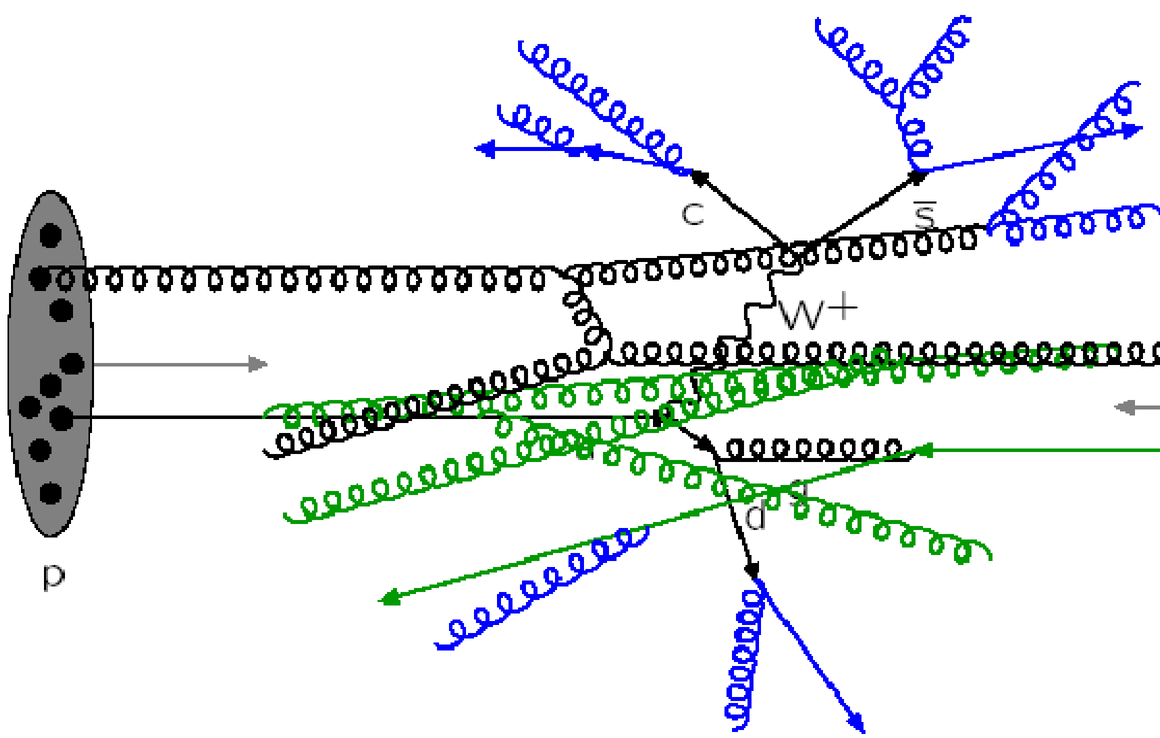
- Three free non-interacting quarks (valence quarks) is not enough.
- Valence quarks are imbedded in a sea of virtual quark-antiquark pairs generated by the gluons which hold the quarks together in the proton.
- Partons = valence quarks, sea quarks and gluons.



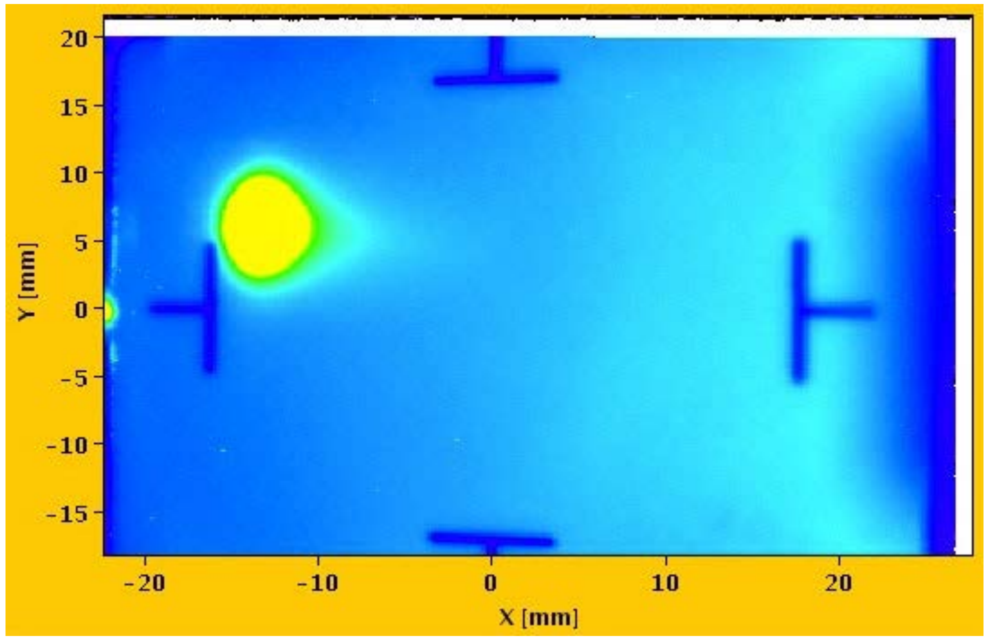
Proton collisions



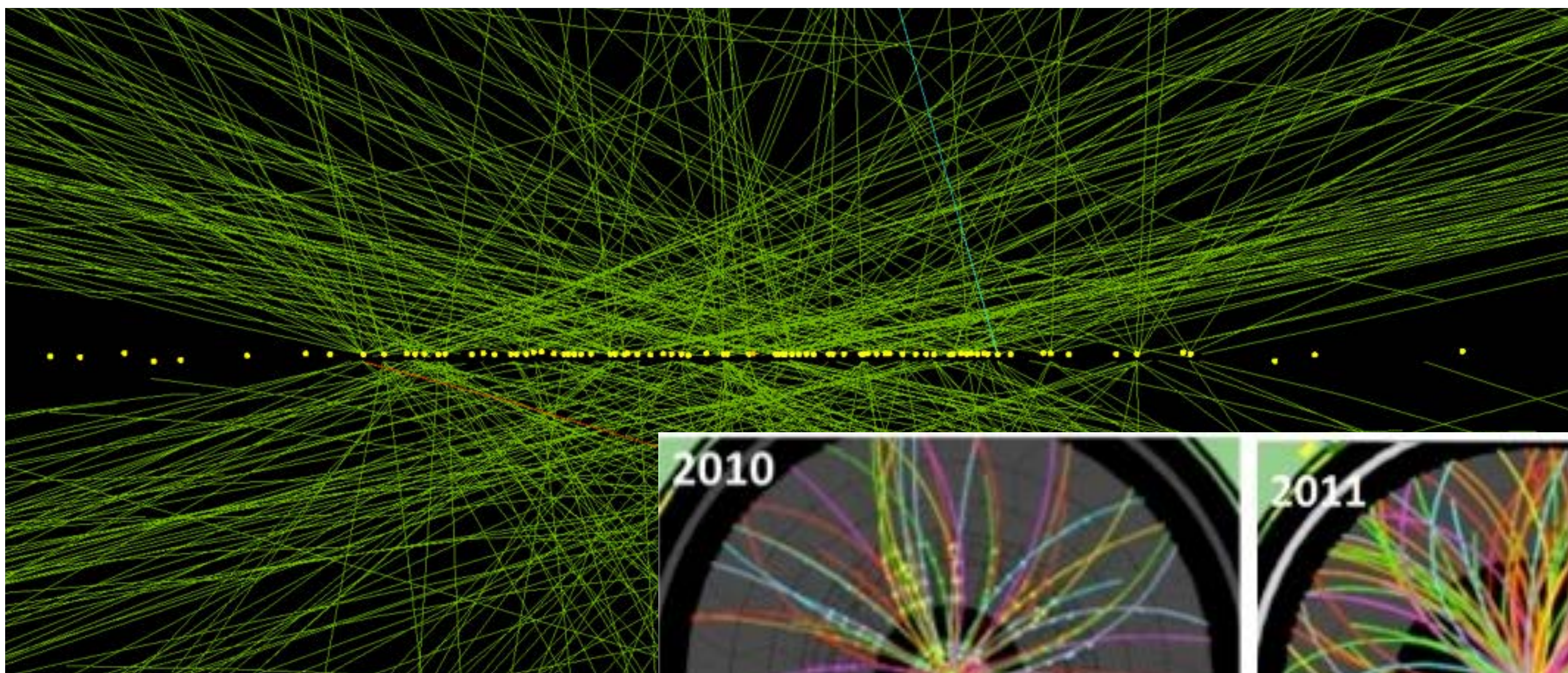
When “You” watch Pikachu fighting, you watch one-by-one interaction, i.e. Head-vs-Head, Tail-vs-Head, Head-vs-Leg, and then you are looking for the final result. This is the same case as proton interaction.



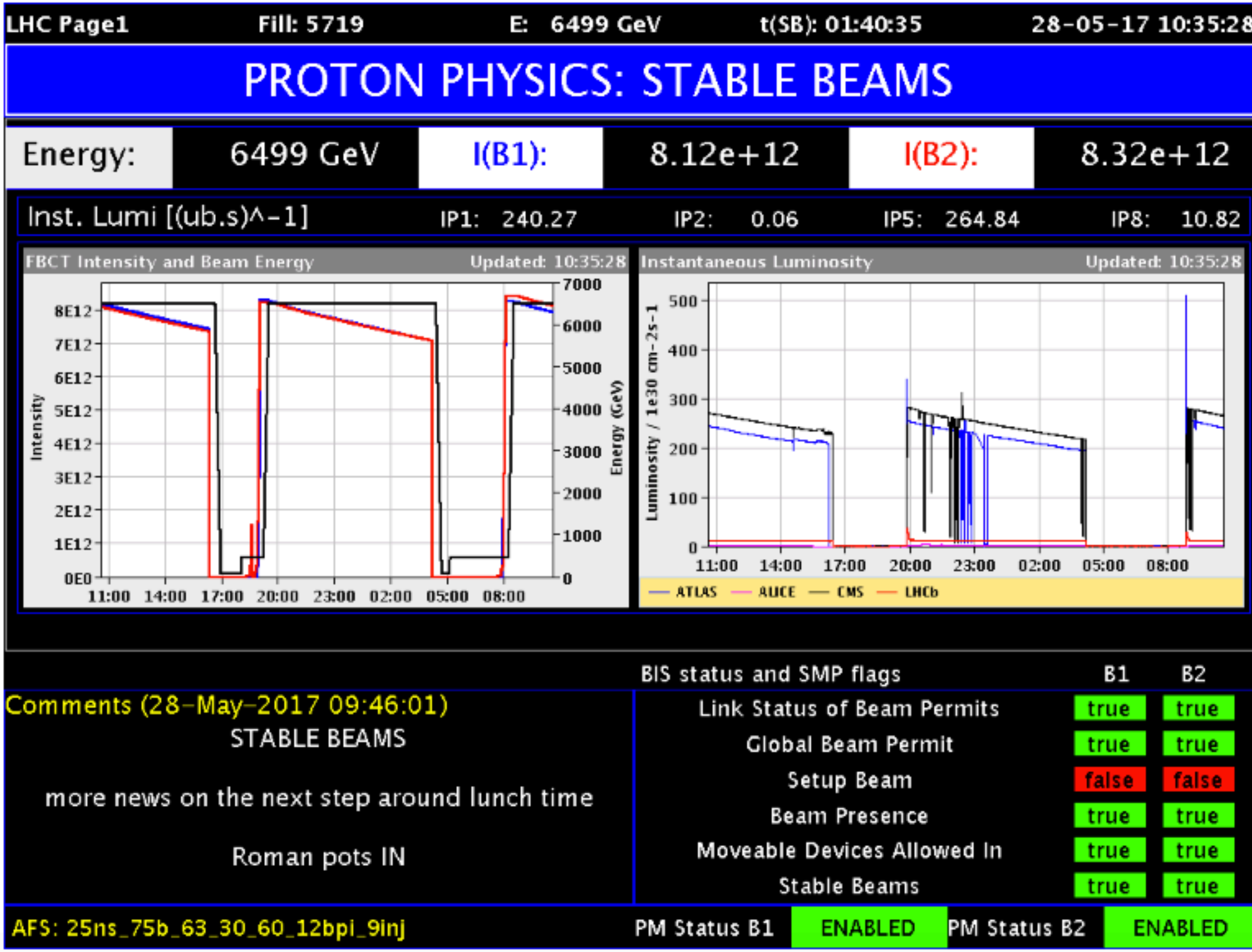
Proton collisions



- First bunch of proton at LHC [Aug 2008]
- A bunch of protons at the LHC contains roughly 10^{11} protons.
- Multiple pictures of proton-proton collision in the same time (Pile up).



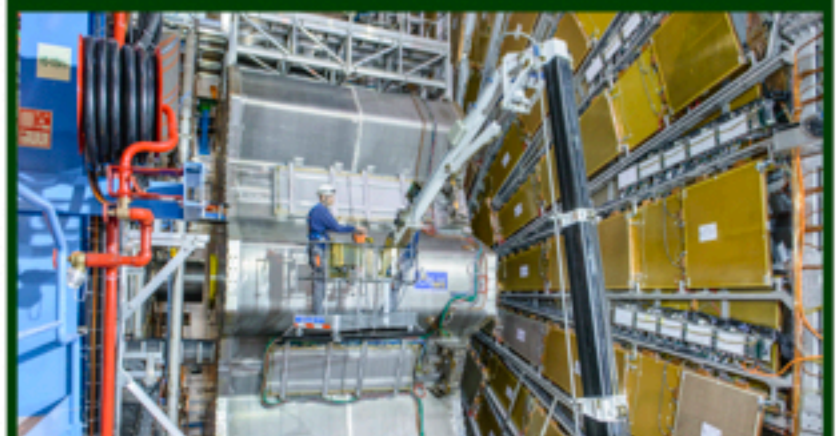
LHC monitoring



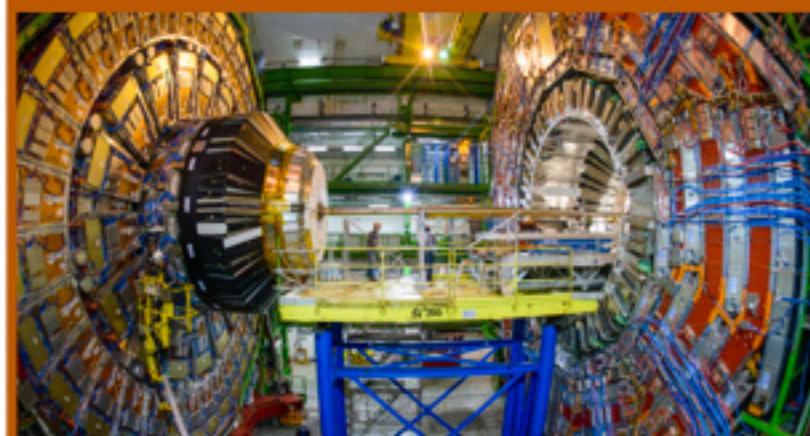
LHC experiments

ALICE

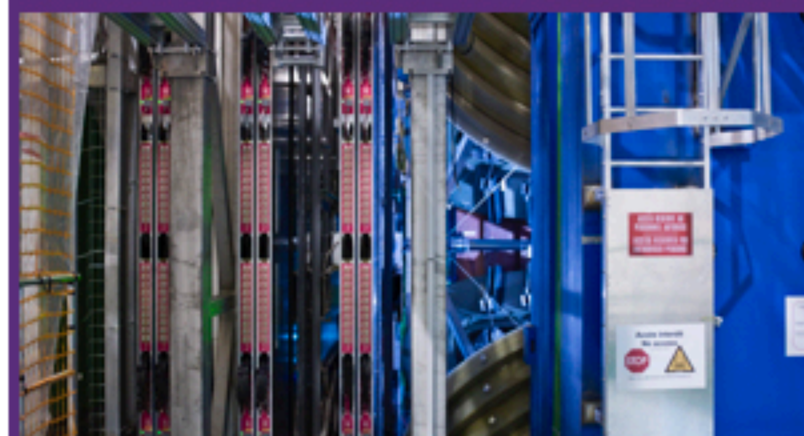
ATLAS



CMS



LHCb



LHCf

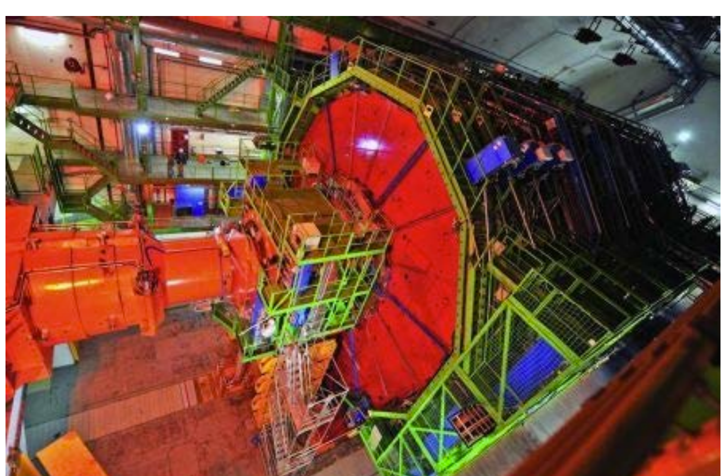
MoEDAL

TOTEM

From collision to physics results

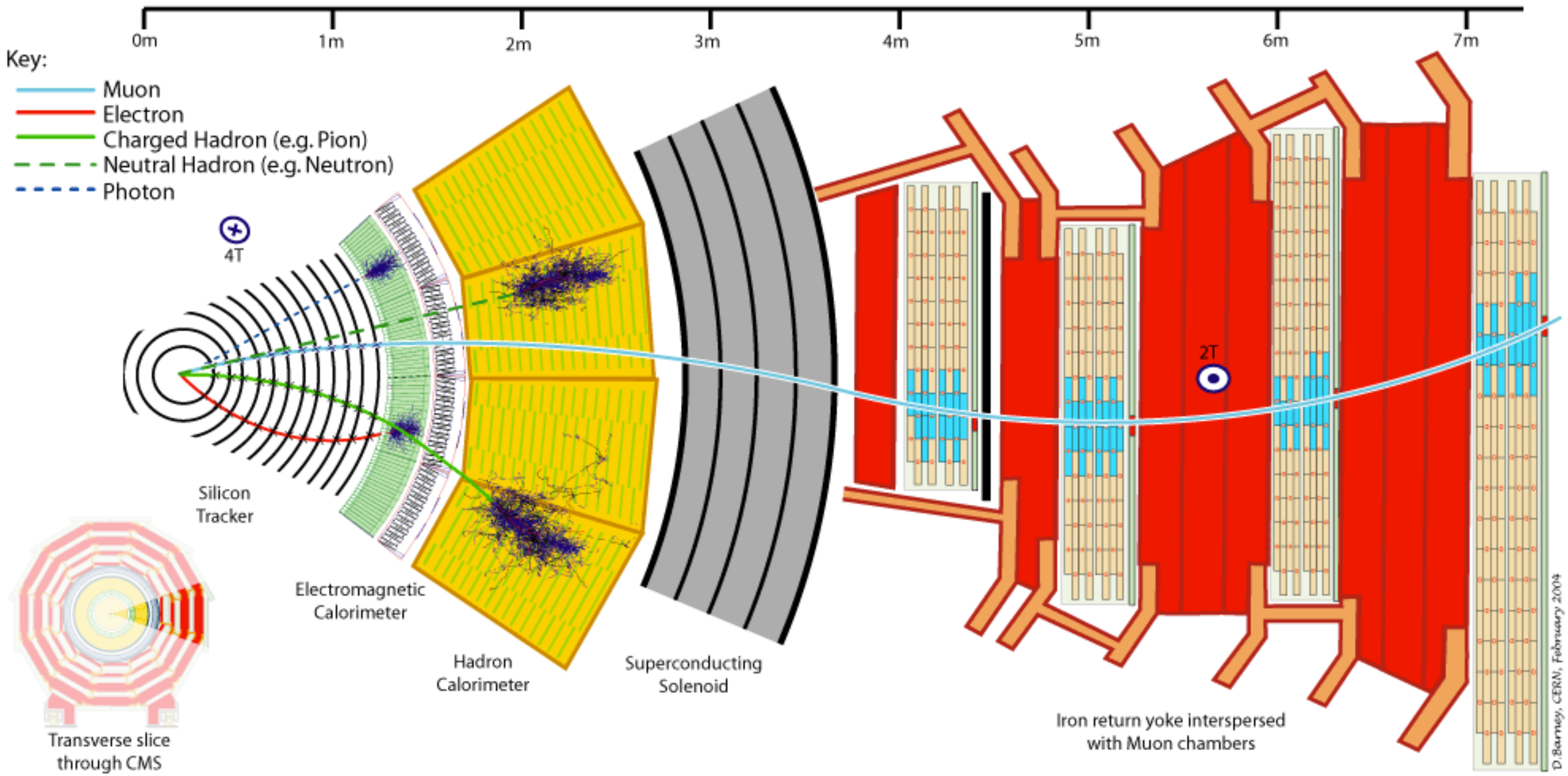
- **Analysis**: Physics of interest
- **WLCG**: Distribute the data worldwide

- **Trigger**: Event selection



- **Particle detector**: Interactions between particle and materials

Particle detector



Aim: to detect as many of the stable and long-lived particles produced in a particle collision

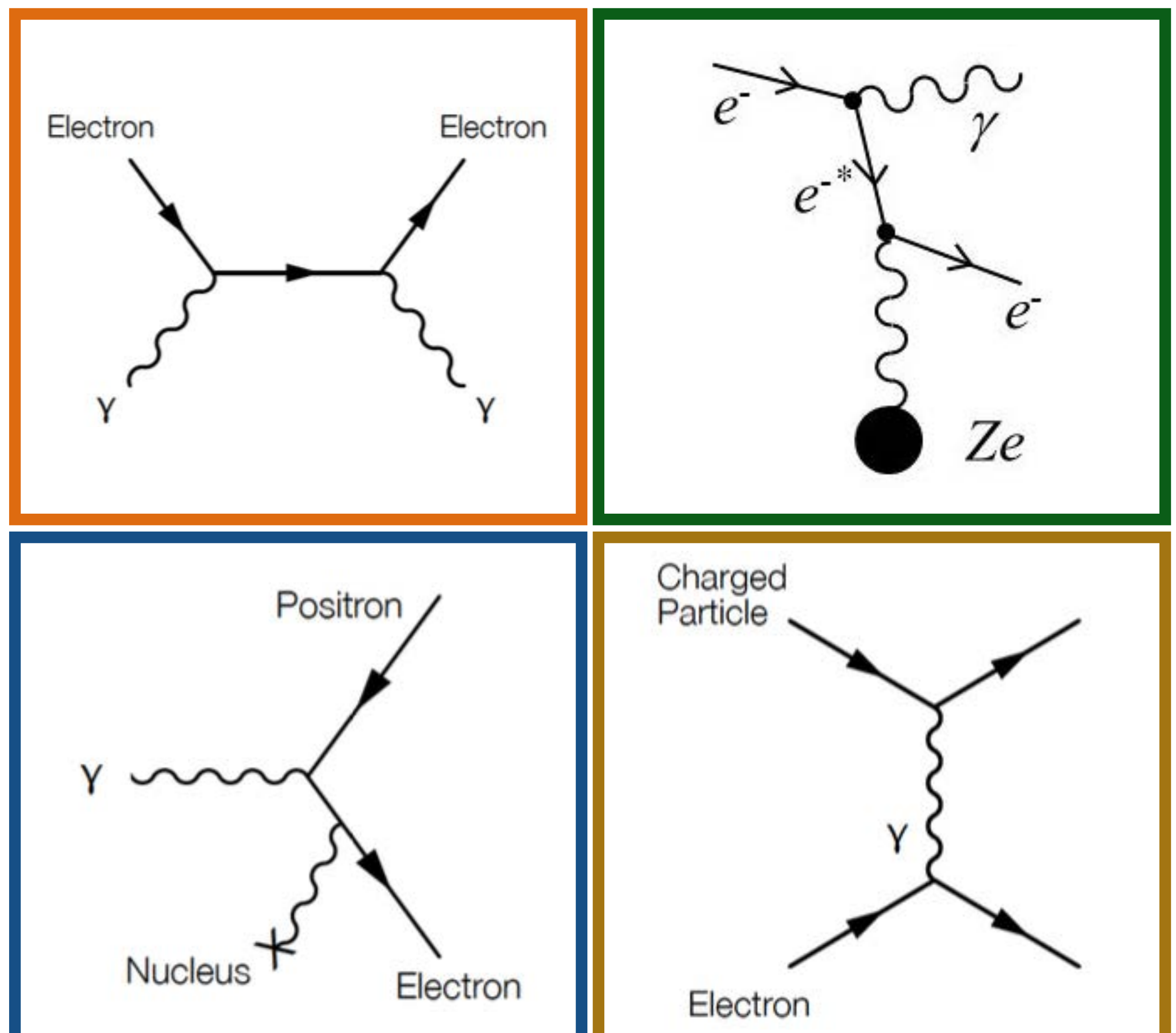
Need to measure: Charge, Mass, Energy, Direction

Keyword: Particle Interactions

A charged particle interacts with the electrons and nuclei in matter. Electromagnetic interaction causes **ionisation** along the path of the particle. Ionisation loss used in almost all types of charged particle detectors: Emulsions, Bubble, Spark, Scintillation, Wire and Drift Chambers. **[visit microcosm]**

Not only the ionization

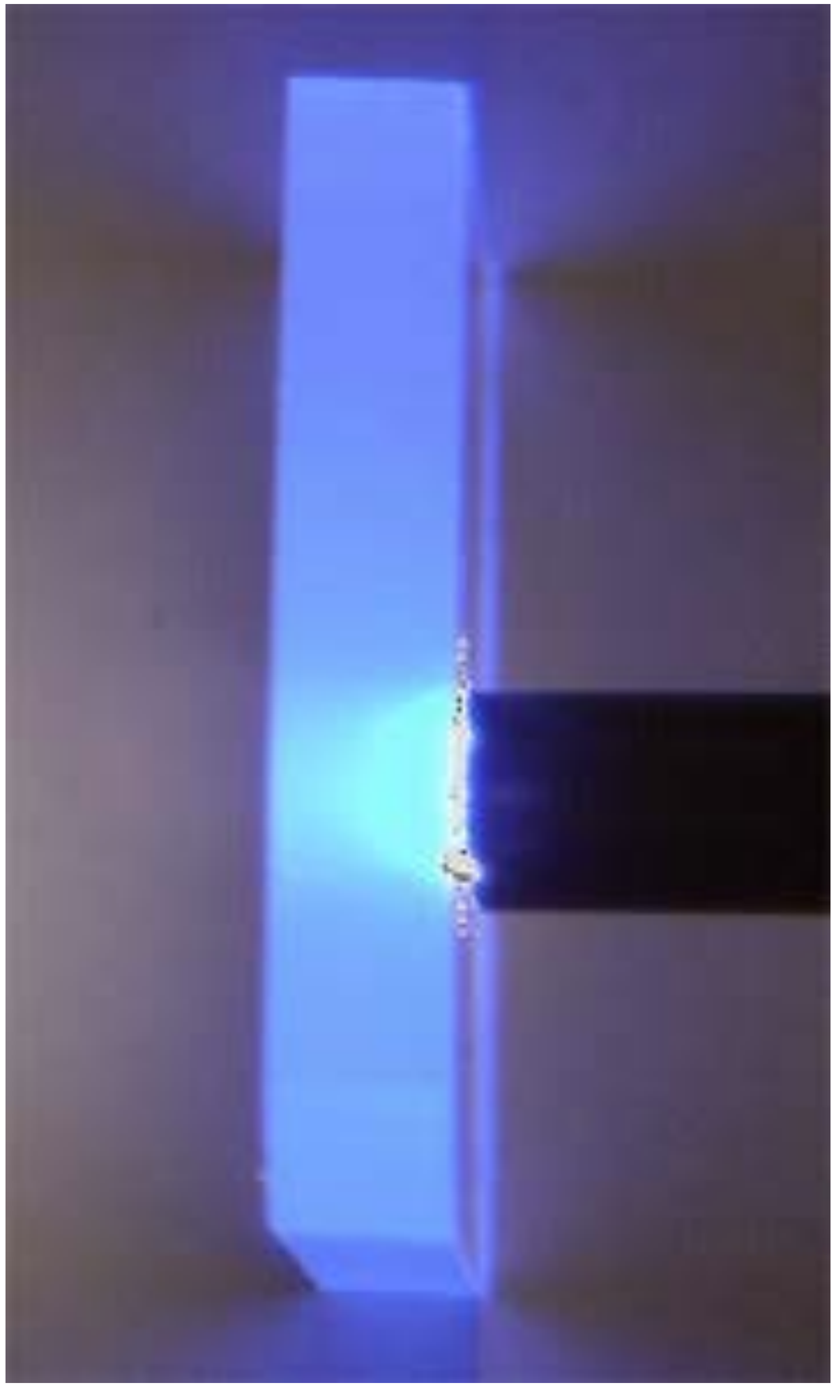
- Pair production
- Compton scattering
- Bremsstrahlung
- ...



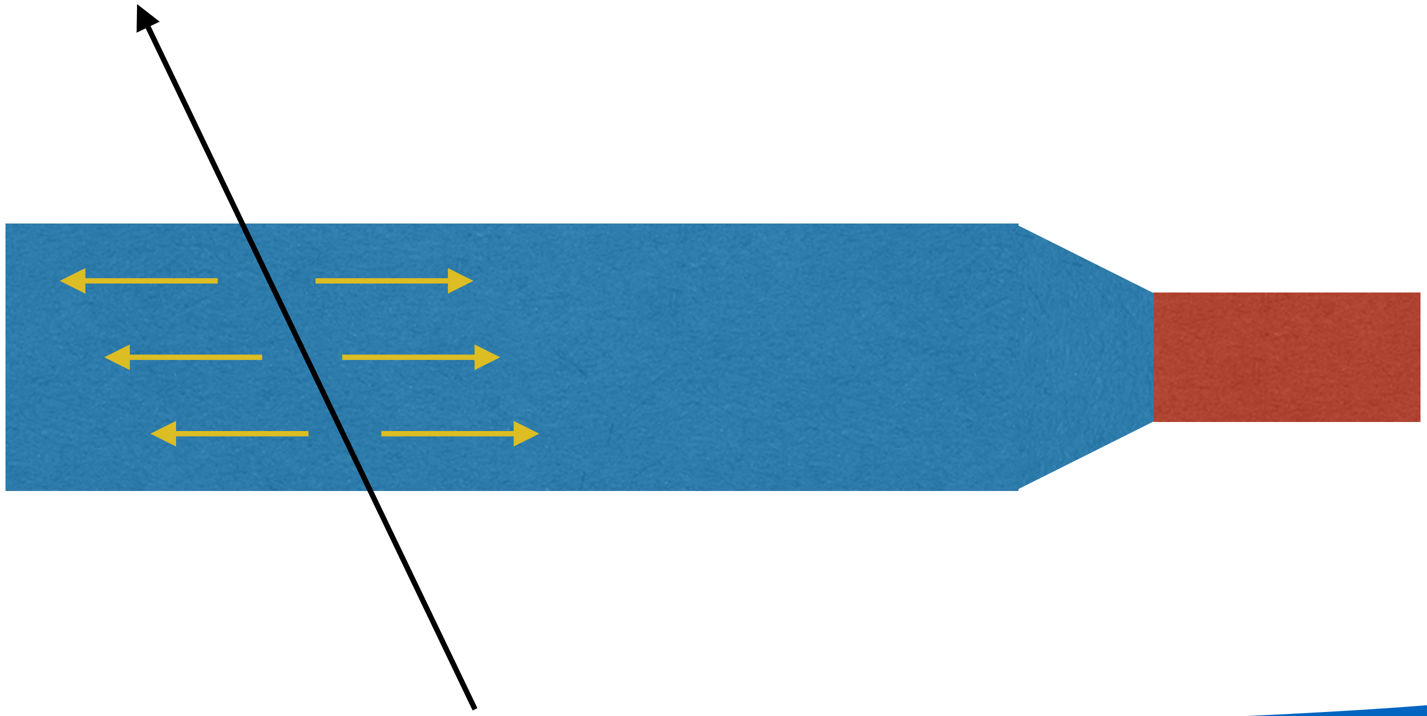
What are these processes?

Signal creation

Charged particle traversing matter leave excited atoms, electron-ion pairs (gases) and electrons-hole pairs (solids)

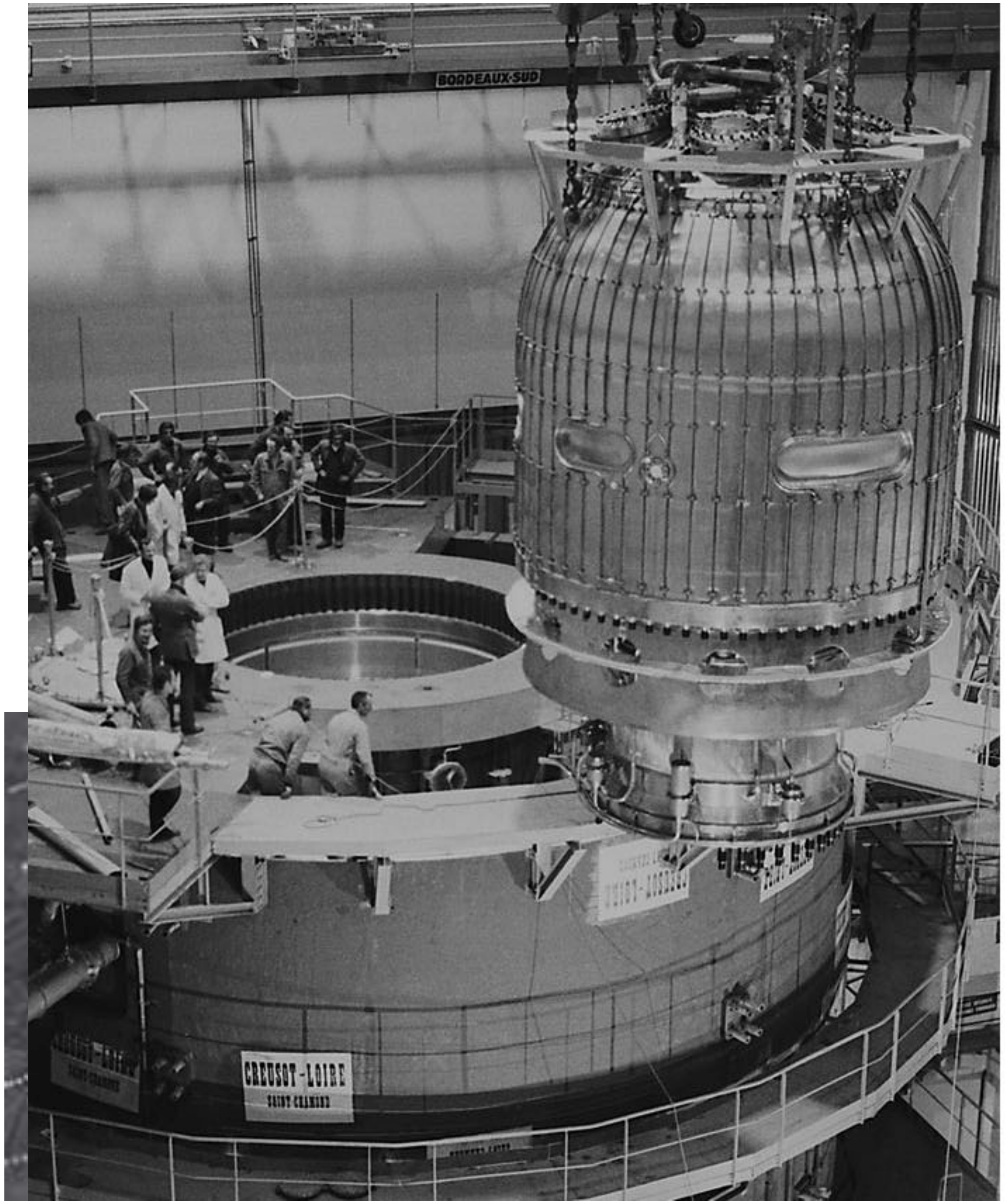


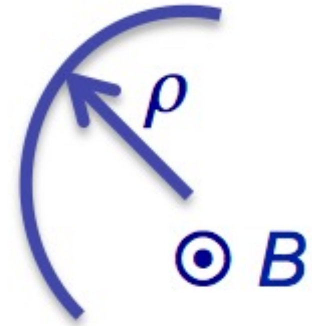
- Excitation: Photons emitted by the excited atoms in transparent materials can be detected with photon detectors.
- Ionization: By applying an electric field in the detector volume, the ionization electrons and ions can be collected on electrodes and readout.



Particle detector: Momentum & Charge

Charged particles are deflected by magnetic field

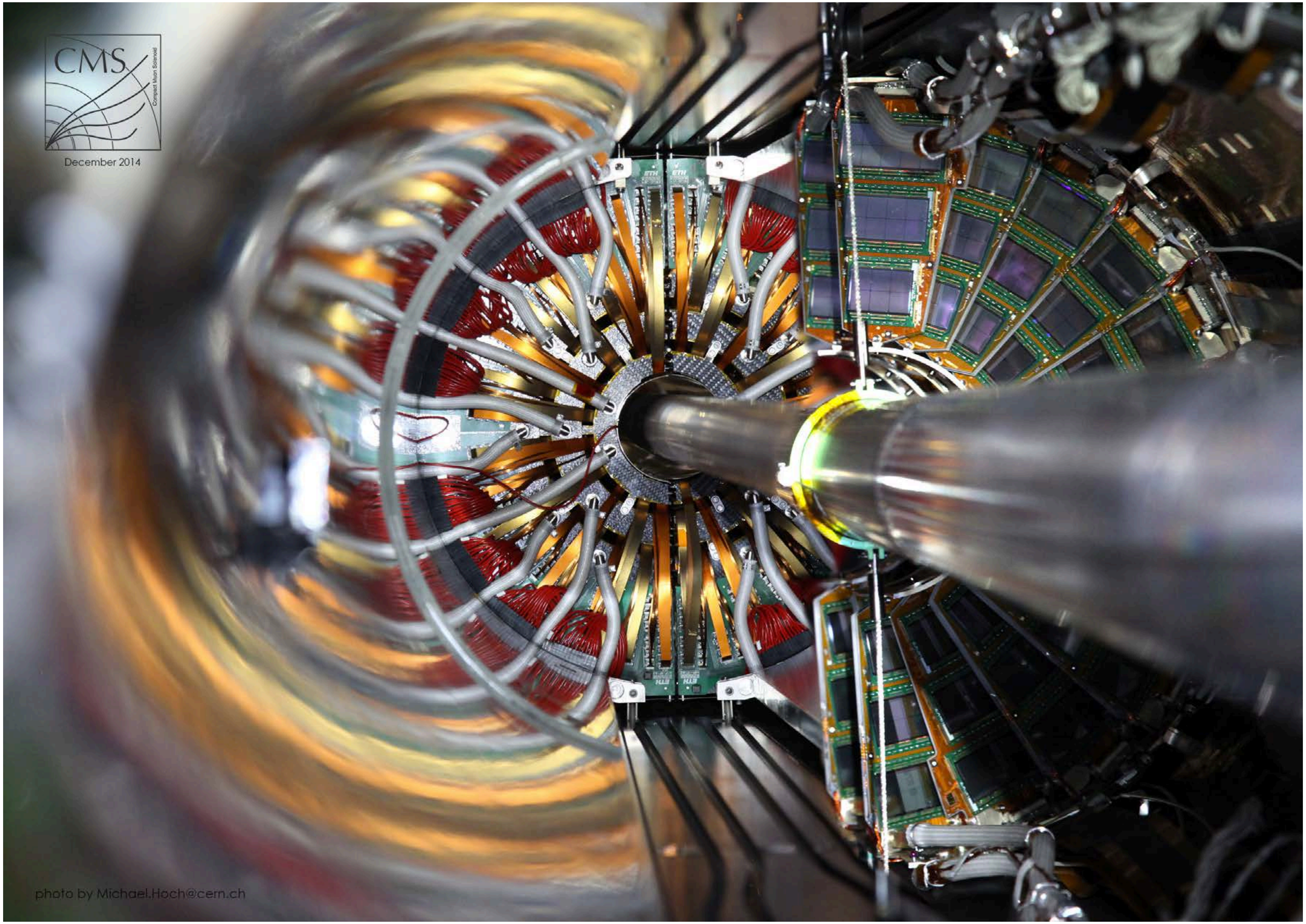




$$\rho = \frac{p_T}{q|B|} = \frac{\gamma m_0 \beta c}{q|B|}$$

- By measuring the radius of curvature we can determine the momentum of a particle.
- If we can measure also β independently we can determine the particle mass.

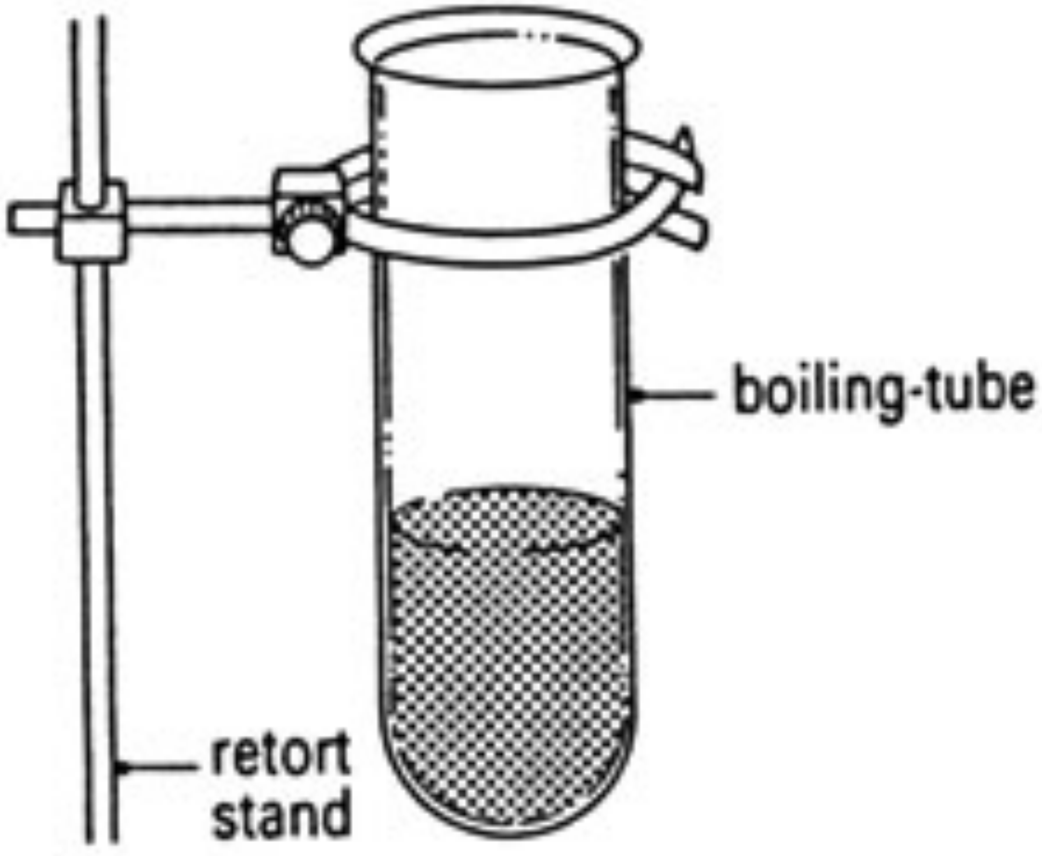
Particle detector: Tracker



Particle detector: Energy

How do we measure the energy in food?

Google said "Burn food samples under a boiling tube containing a measured amount of water. Measure the temperature increase in the water. Calculate the amount of energy needed to cause that temperature increase. This gives an estimate of the amount of energy stored in the food."



Food, burn it!

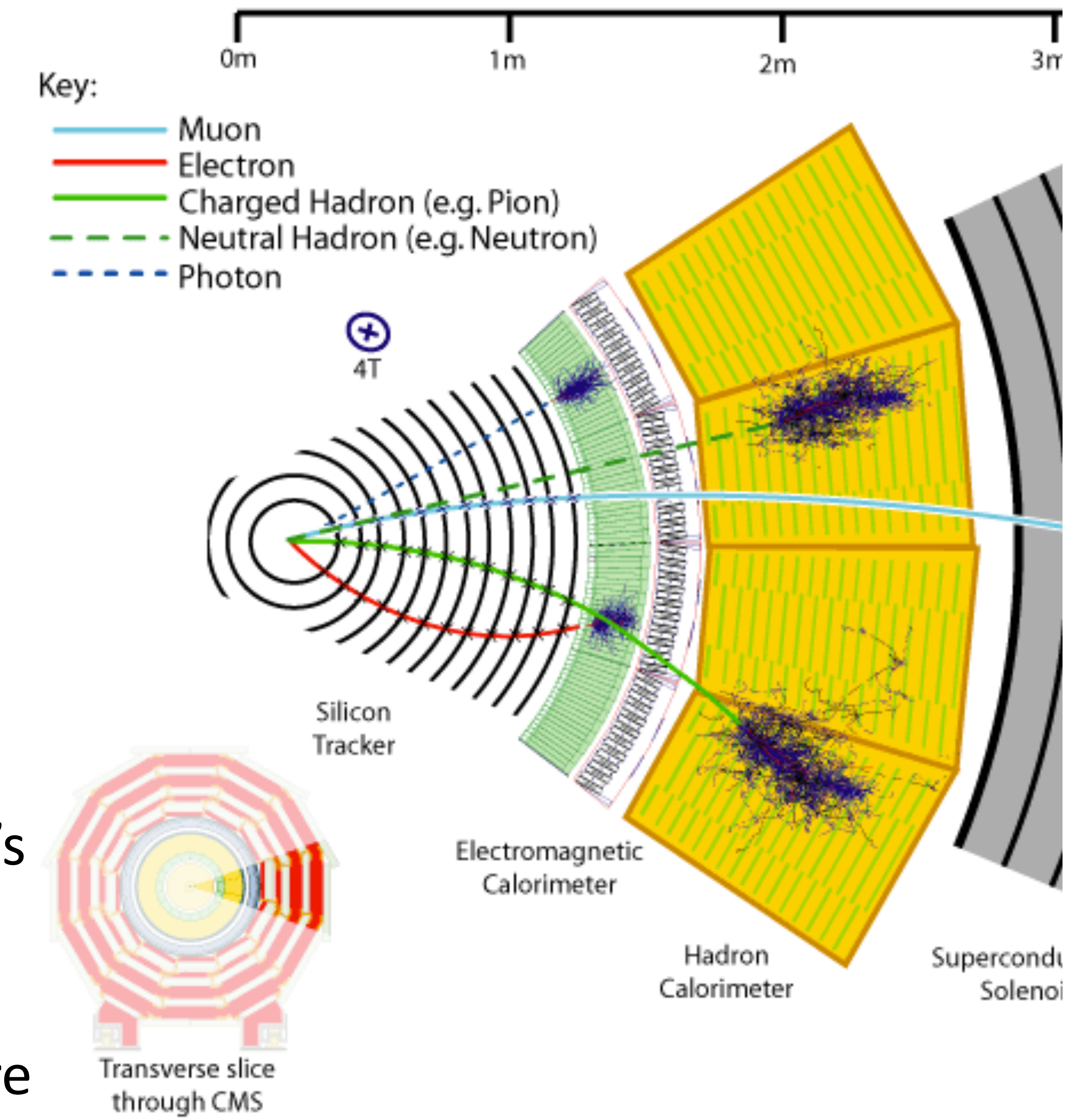
What is the concept behind this experiment?

Release the food energy to boil water until the food is gone.

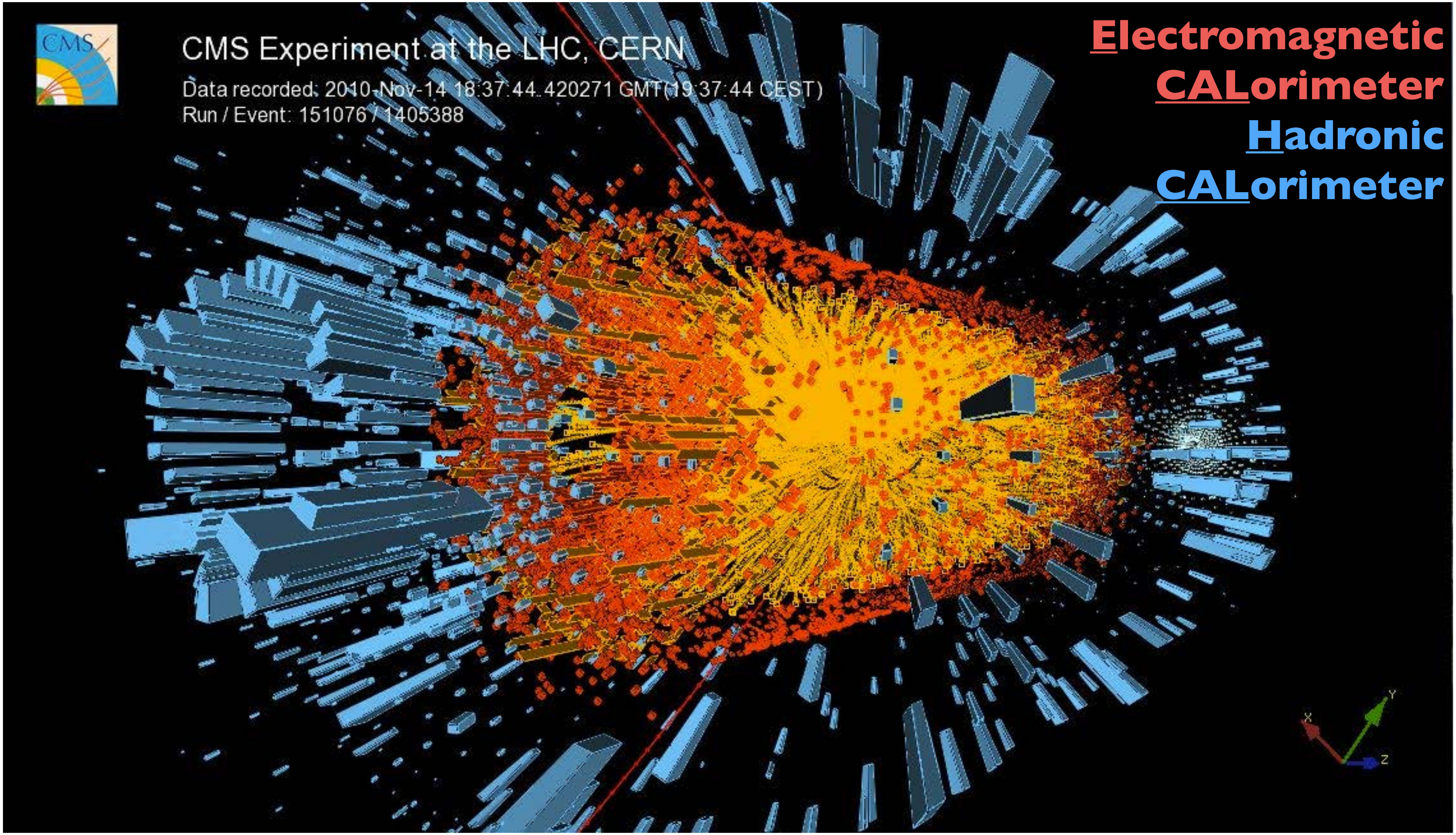
Particle detector: Calorimeter

In nuclear and particle physics calorimetry refers to the detection of particles through total absorption in a block of matter.

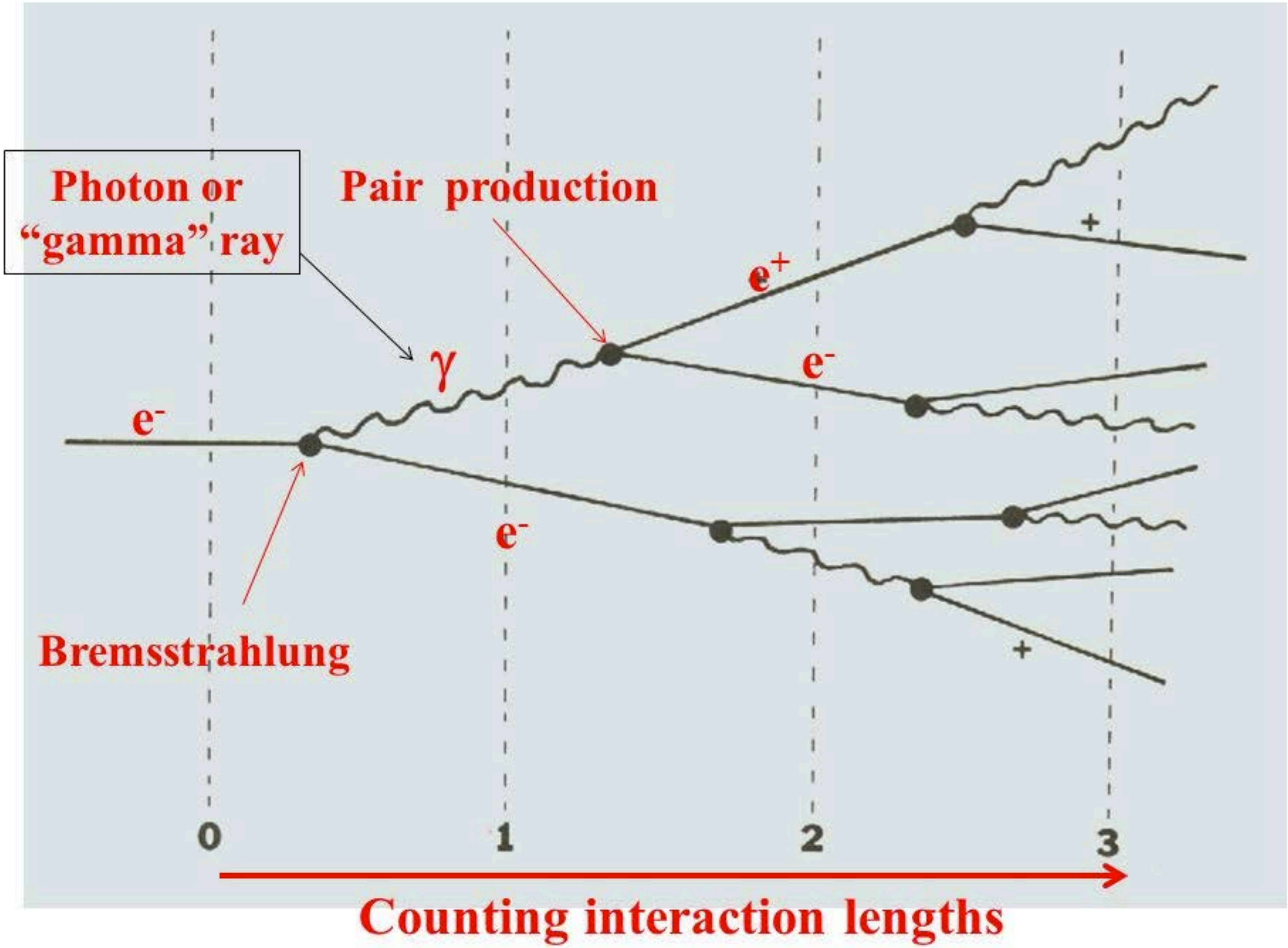
- The measurement process is destructive for almost all particle.
- The exception are muons (and neutrinos)
  - Identify muons easily since they penetrate a substantial amount of matter
  - In the absorption, almost all particle’s energy is eventually converted to heat → calorimeter
  - Calorimeters are essential to measure neutral particles



Particle detector: Energy

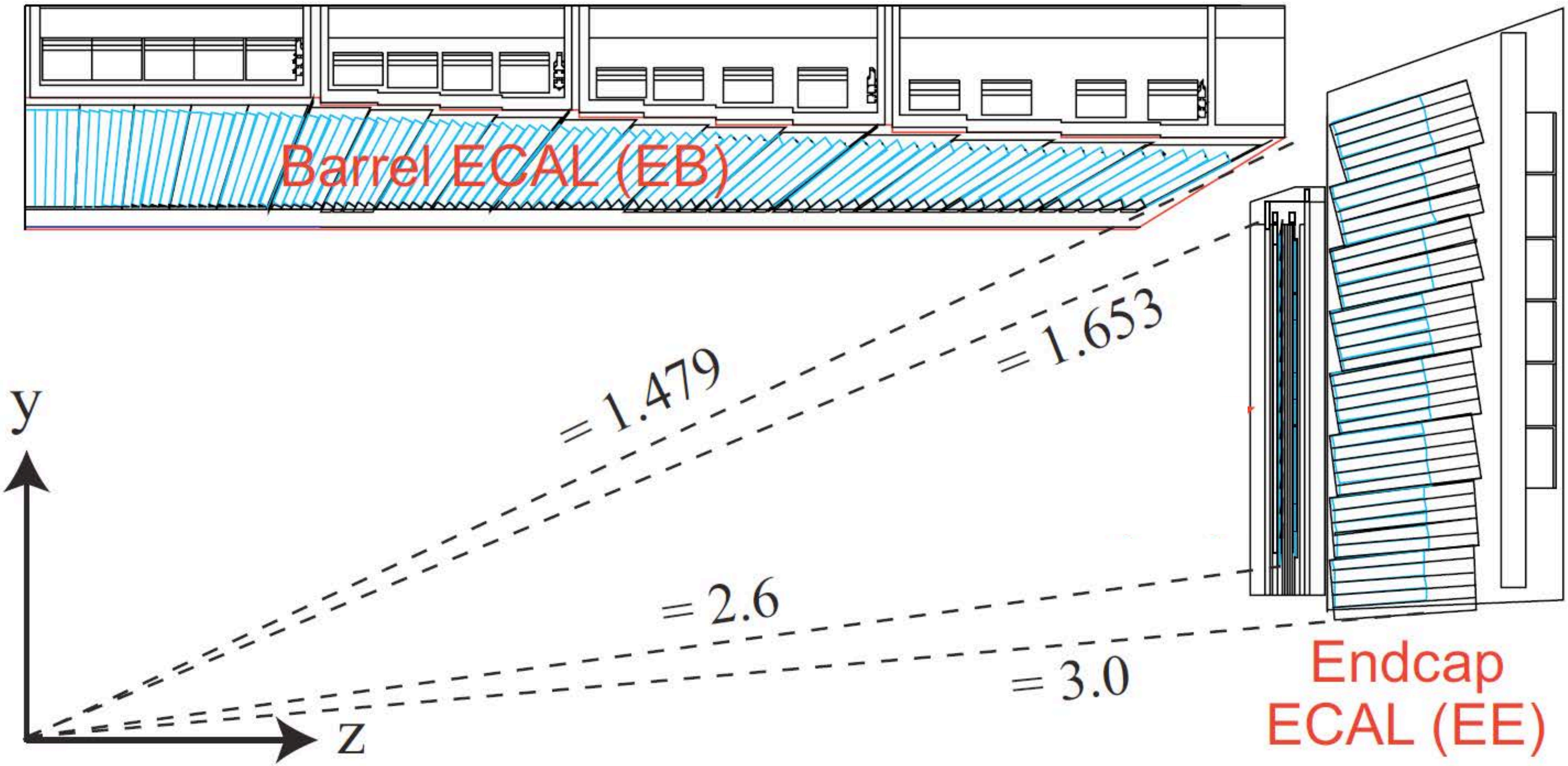


Electromagnetic calorimeter



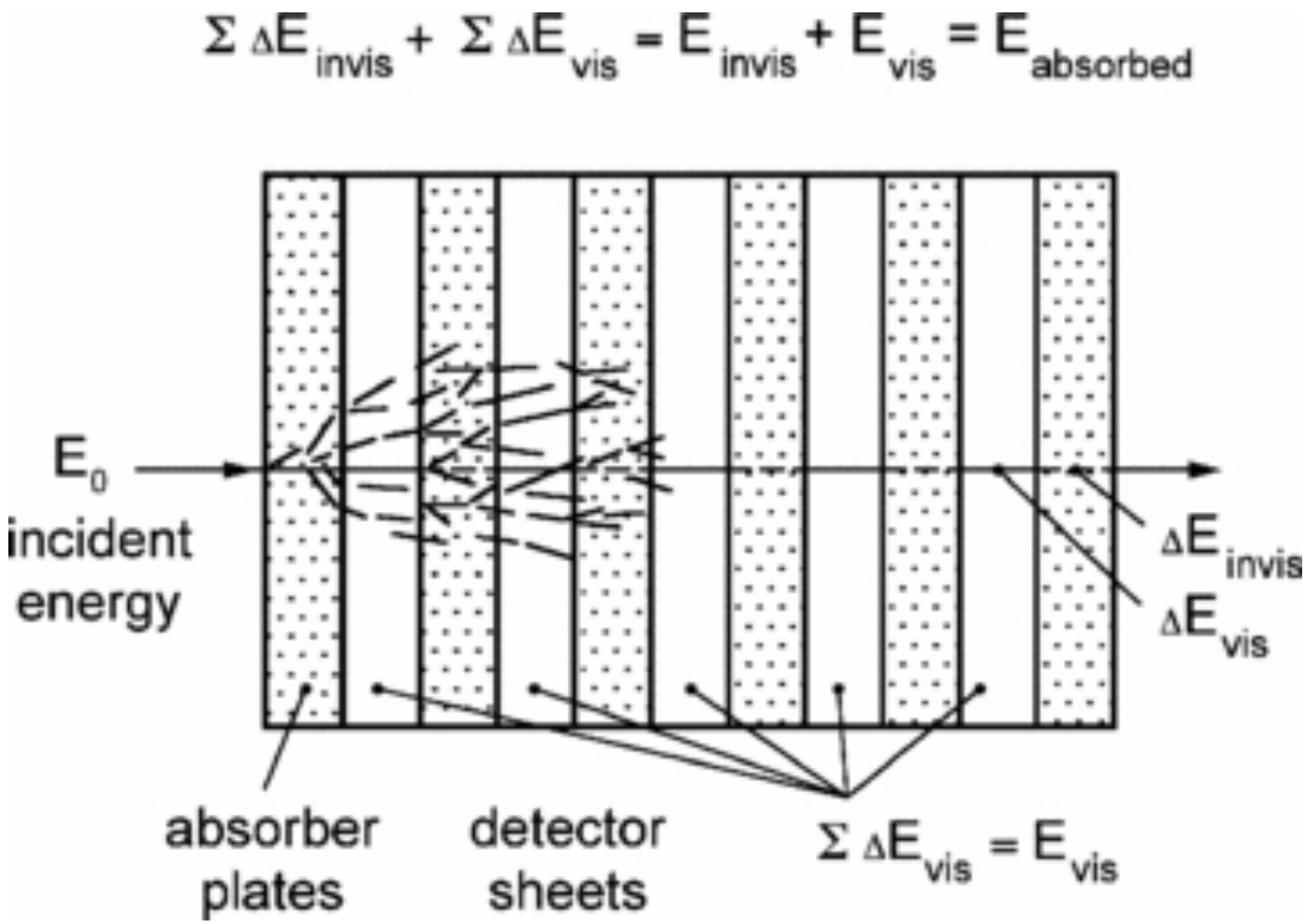
Electromagnetic calorimeter

- CMS ECAL is homogeneous (Entire volume is sensitive and contributes a signal)



Hadronic calorimeter

- Hadrons interact with detector material also through the strong interaction
- Most of HCAL is a sampling calorimeter (Material that produces the particle shower is distinct from the material that measures the deposited energy)



Discussion: Pros & Cons between total absorption and sampling calorimeter

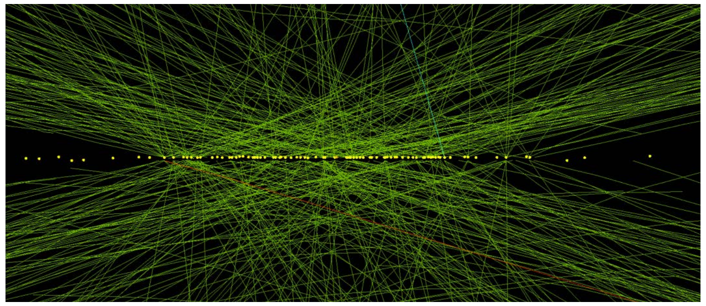
Experimental particle physics

http://www.symmetrymagazine.org/article/august-2012/particle-physics-tames-big-data

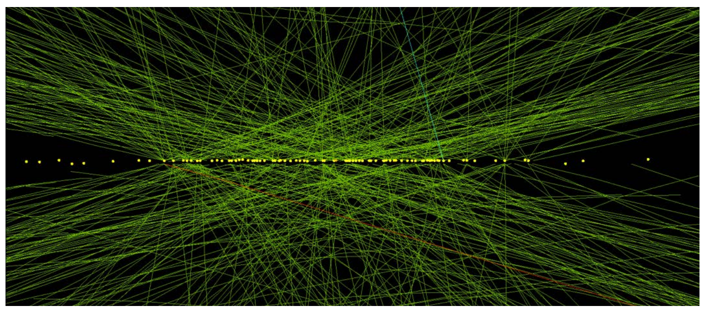
High Energy Physics is a statistical science:
Processes have a probability to happen.

The smaller it is, the more data (collisions) are needed for an observation, discovery or finally precision measurement.

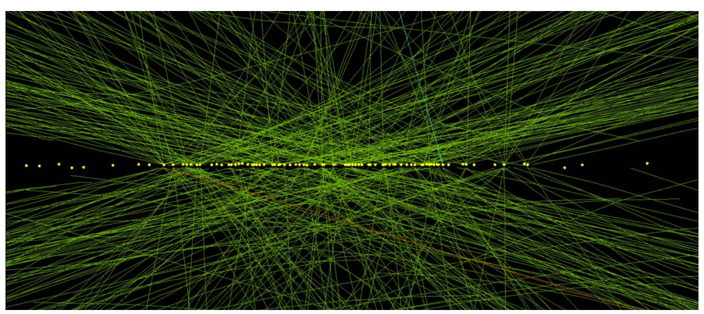
Triggering events



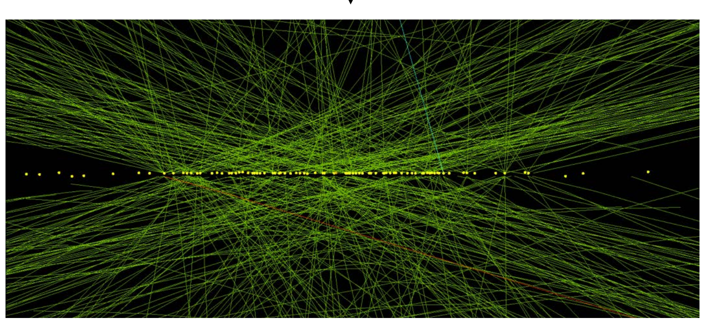
↓ 25 ns



↓ 25 ns



↓ 25 ns



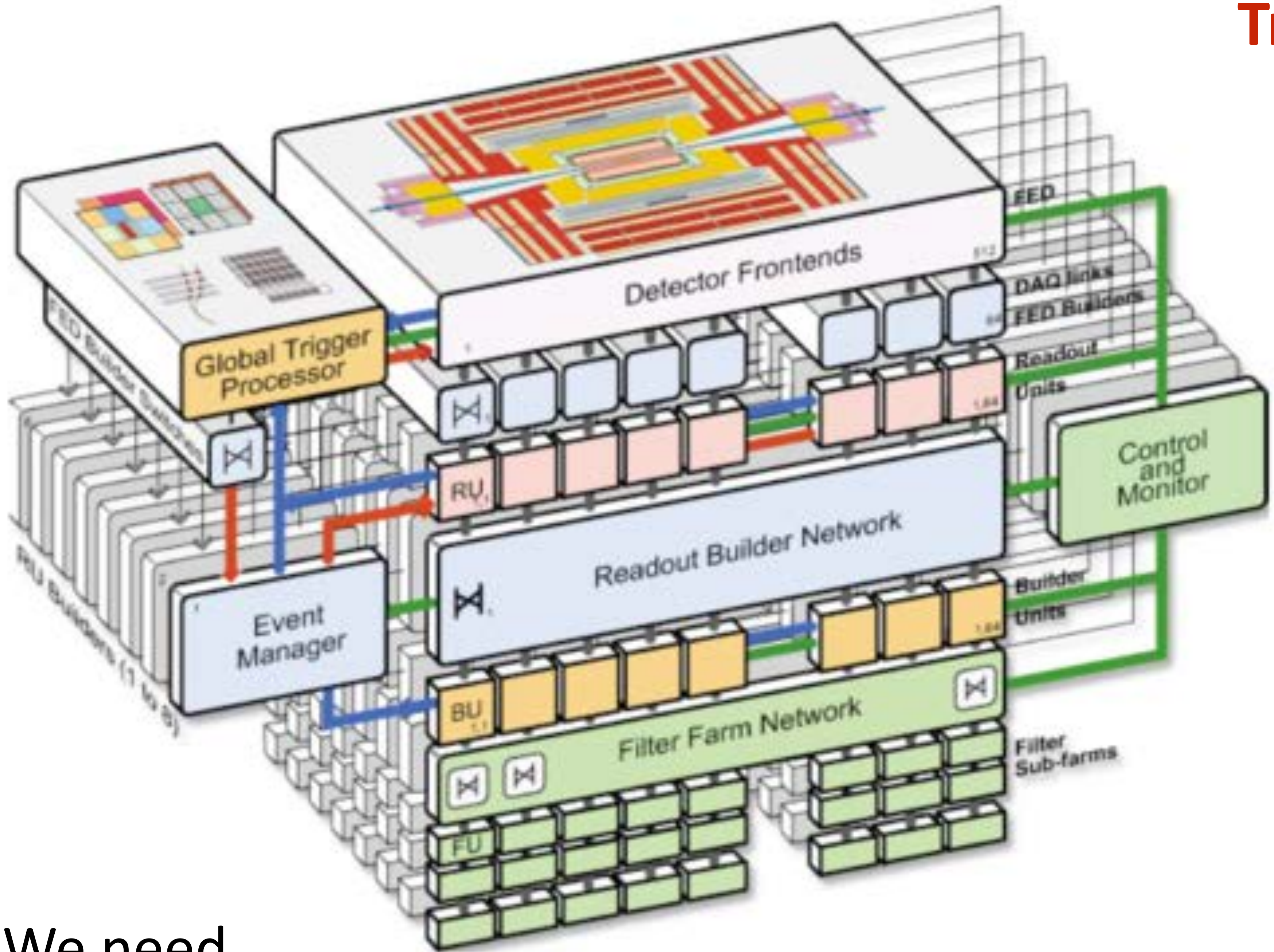
↓ 25 ns

- Collision every 25 ns (40M events per sec)
- ~2 MB per events
- 80 TB per sec

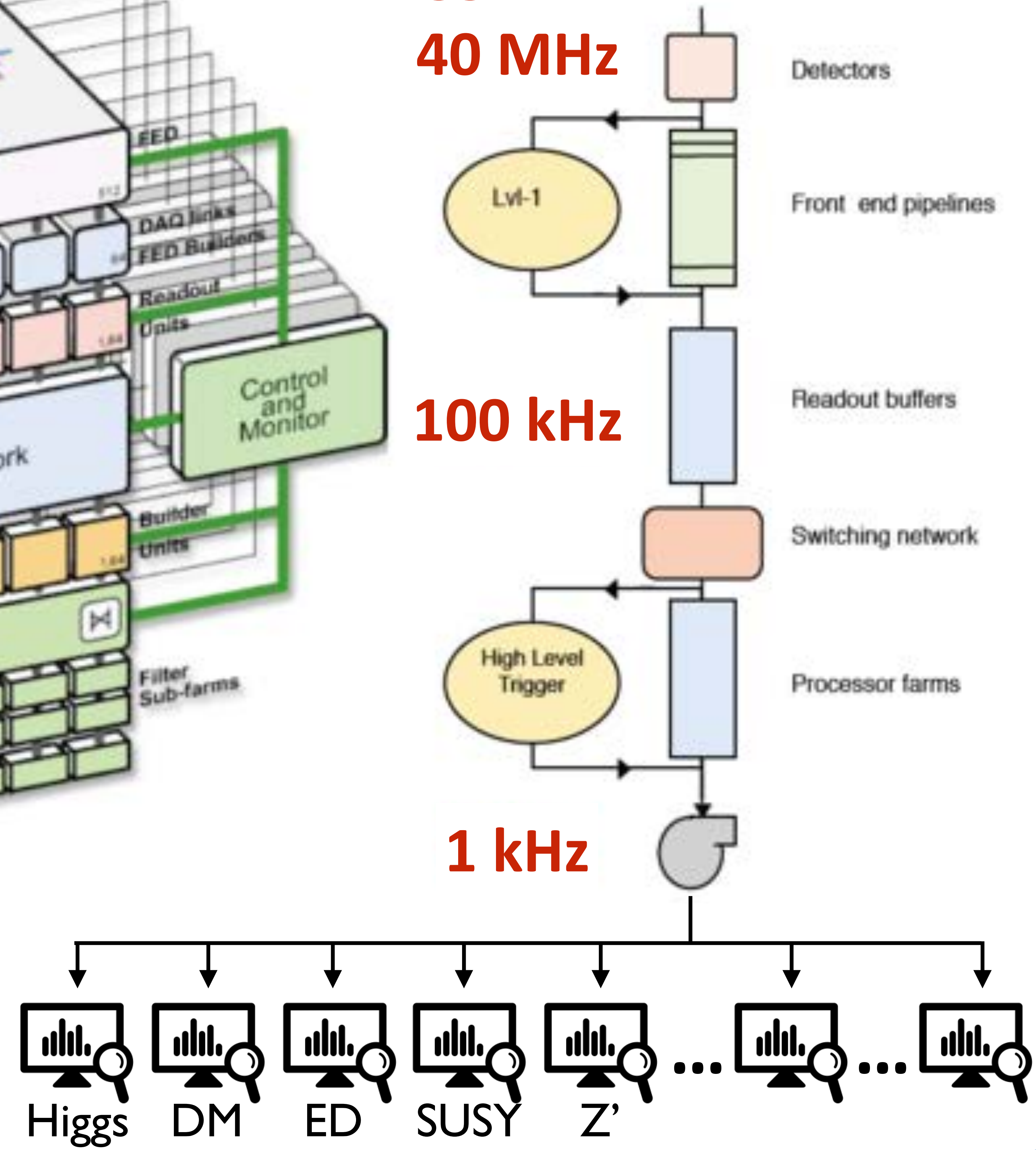
Impossible for storage and CPU to process all events

- We need pre-selection based on physics of interest
  - ➡ i.e. Higgs decay modes (e.g. H to ZZ to 4mu)
  - ➡ We look for “stable” products, i.e. lifetime is larger enough and those particles interact with detector
- Trigger system
  - ➡ Electronics
  - ➡ Computing (full pictures of collision)

Triggering events



Trigger Rate

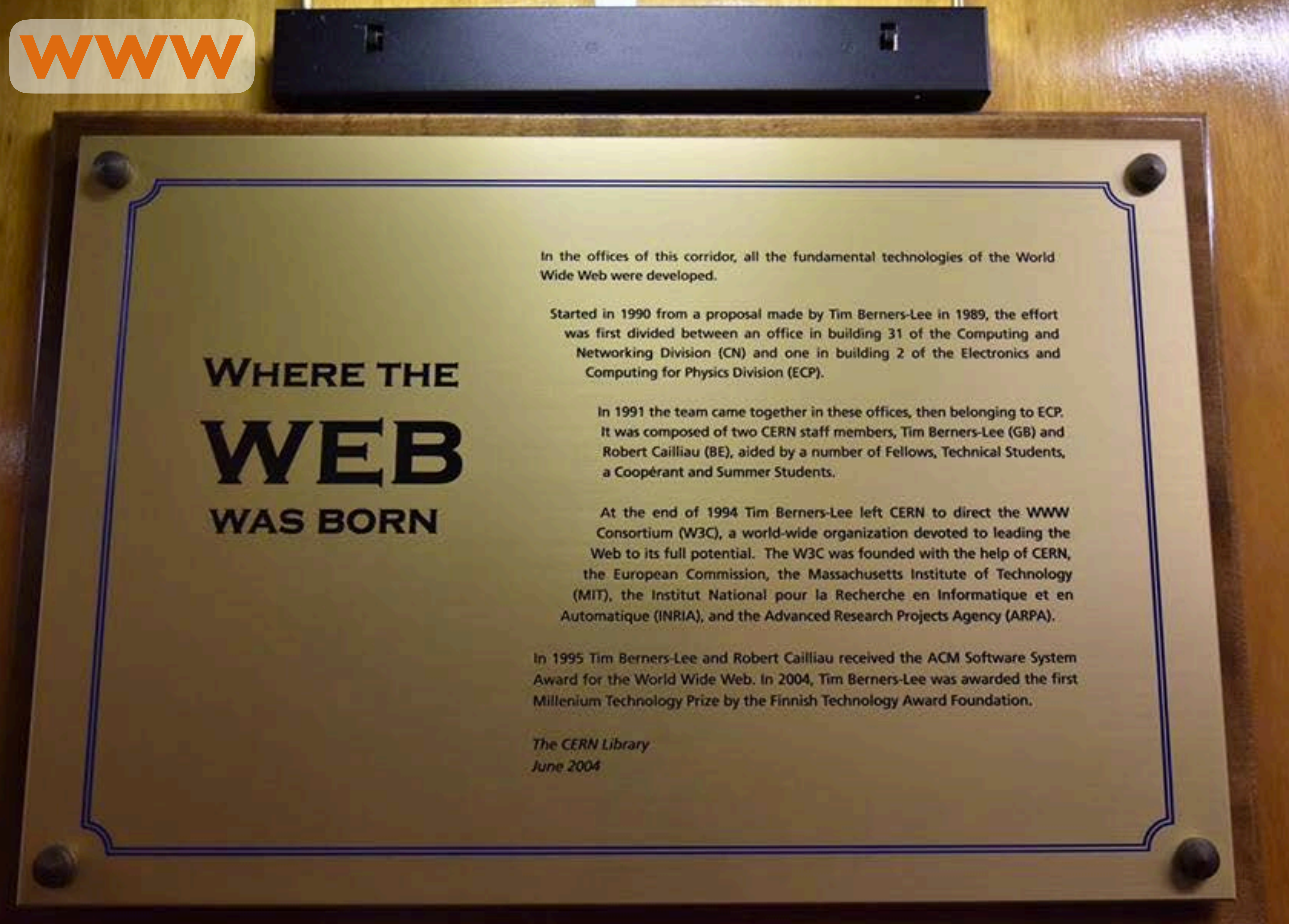


We need

- ➡Fast electronic devices
- ➡Fast computing algorithms

to make a trigger system

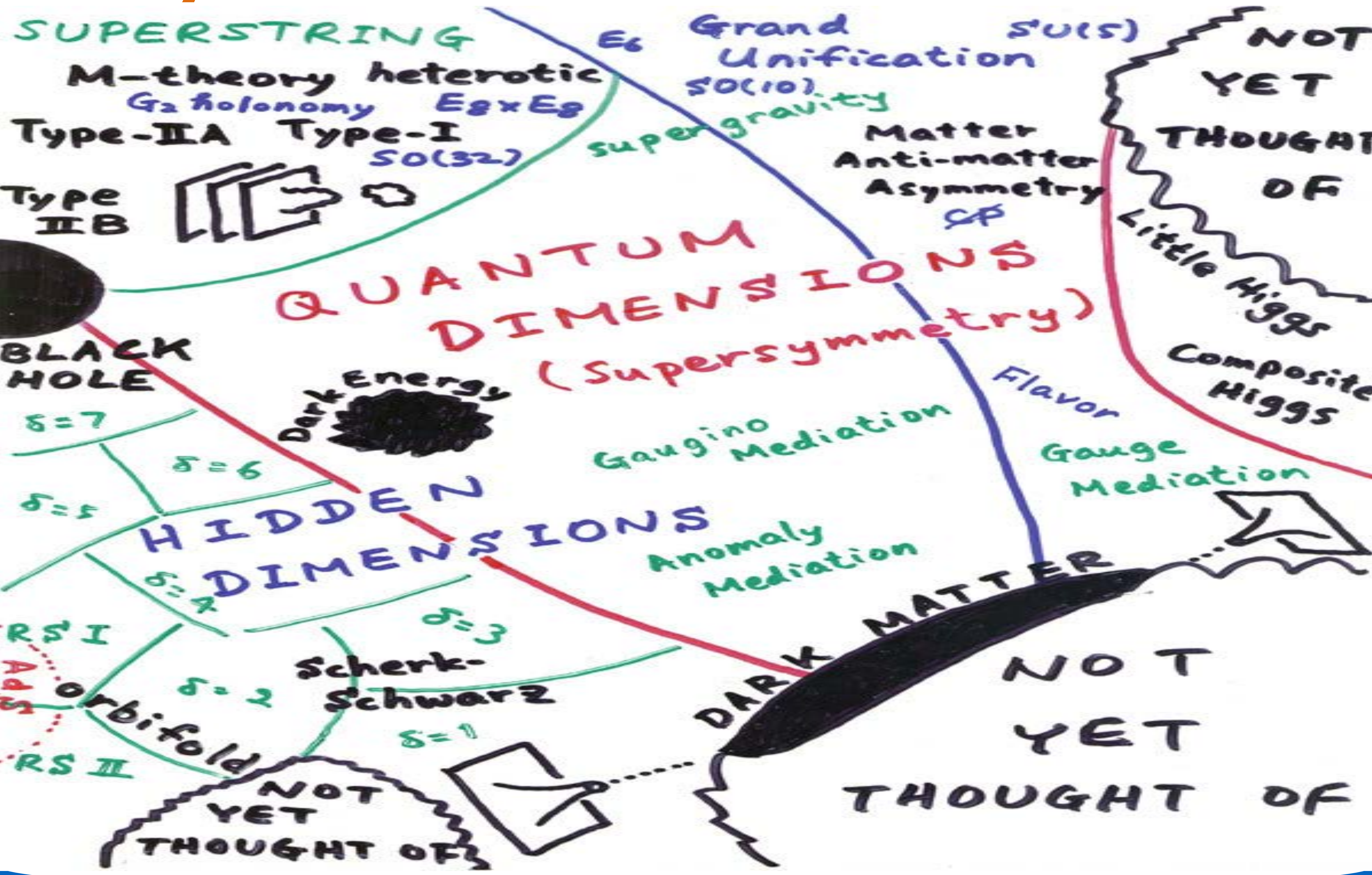
WWW



WHERE THE
WEB
WAS BORN
In the offices of this corridor, all the fundamental technologies of the World Wide Web were developed.
Started in 1990 from a proposal made by Tim Berners-Lee in 1989, the effort was first divided between an office in building 31 of the Computing and Networking Division (CN) and one in building 2 of the Electronics and Computing for Physics Division (ECP).
In 1991 the team came together in these offices, then belonging to ECP. It was composed of two CERN staff members, Tim Berners-Lee (GB) and Robert Cailliau (BE), aided by a number of Fellows, Technical Students, a Coopérant and Summer Students.
At the end of 1994 Tim Berners-Lee left CERN to direct the WWW Consortium (W3C), a world-wide organization devoted to leading the Web to its full potential. The W3C was founded with the help of CERN, the European Commission, the Massachusetts Institute of Technology (MIT), the Institut National pour la Recherche en Informatique et en Automatique (INRIA), and the Advanced Research Projects Agency (ARPA).
In 1995 Tim Berners-Lee and Robert Cailliau received the ACM Software System Award for the World Wide Web. In 2004, Tim Berners-Lee was awarded the first Millenium Technology Prize by the Finnish Technology Award Foundation.
The CERN Library
June 2004

Worldwide LHC Computing Grid

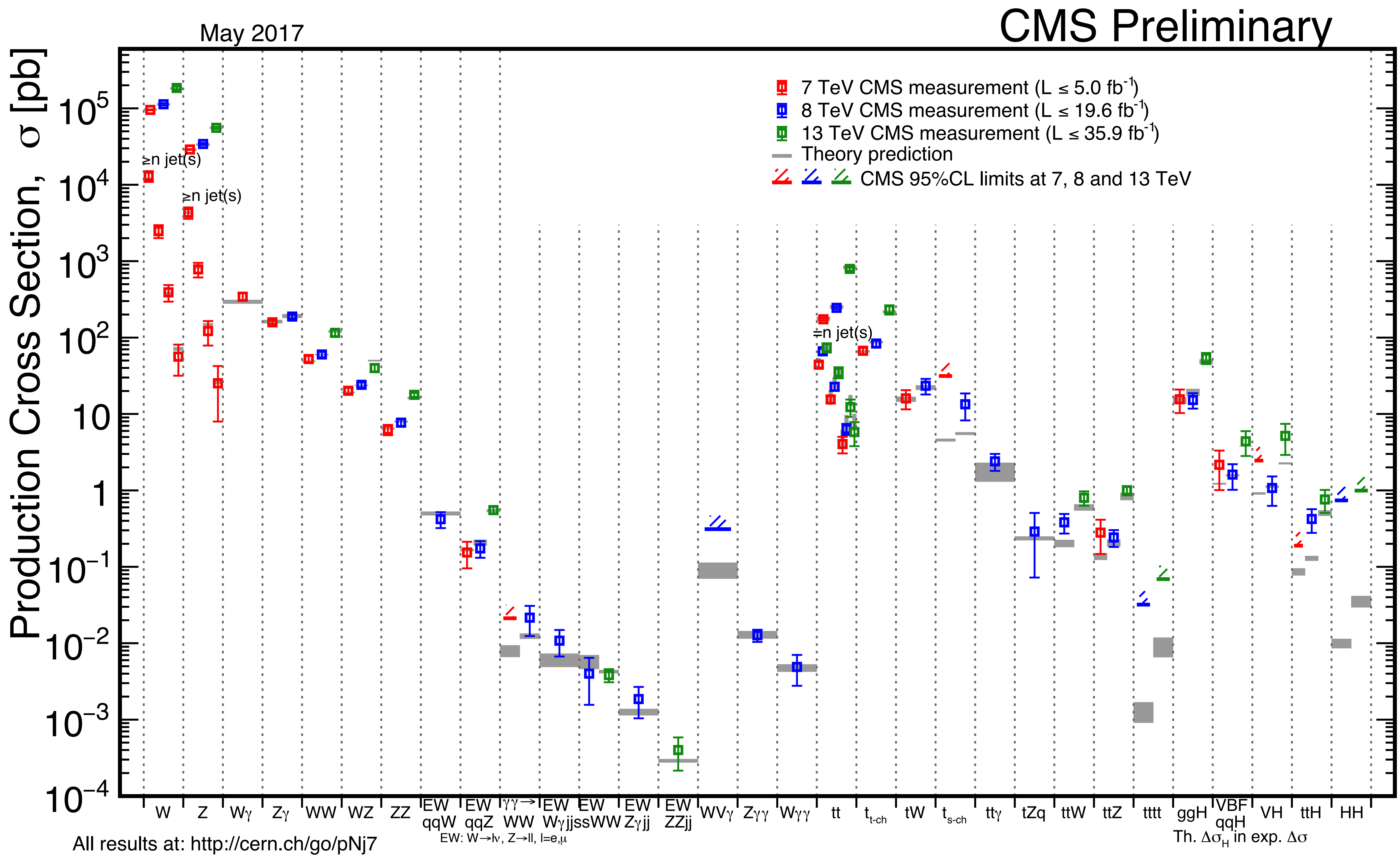
Analysis



SUPERSTRING
M-theory
heterotic
G2 holonomy
E8xE8
Type-IIA
Type-I
SO(32)
Type IIB
BLACK HOLE
E6
Grand Unification
SU(5)
SO(10)
supergravity
Matter Anti-matter Asymmetry
CP
NOT YET THOUGHT OF
Little Higgs
Composite Higgs
QUANTUM DIMENSIONS
(Supersymmetry)
Dark Energy
Flavor
Gaugino Mediation
Gauge Mediation
δ=7
δ=6
δ=5
δ=4
δ=3
δ=2
δ=1
HIDDEN DIMENSIONS
Anomaly Mediation
RS I
AdS
orbifold
RS II
Scherk-Schwarz
DARK MATTER
NOT YET THOUGHT OF
NOT YET THOUGHT OF

Standard model

- Measuring any quantities related to SM processes, i.e. mass, cross-section



BSM: Extra-Dimensions

Hierarchy problem

- M_{Pl} ~10^{19} GeV
- M_{EW} ~100 GeV
- M_{QCD} ~100 MeV
- Why gravity is so weak?
- Few different ways to solve this problems (from theory point of view)
  - ➡ Extra dimensions
  - ➡ Supersymmetry

February 1, 2008

SLAC-PUB-7769
SU-ITP-98/13

The Hierarchy Problem and New Dimensions at a Millimeter

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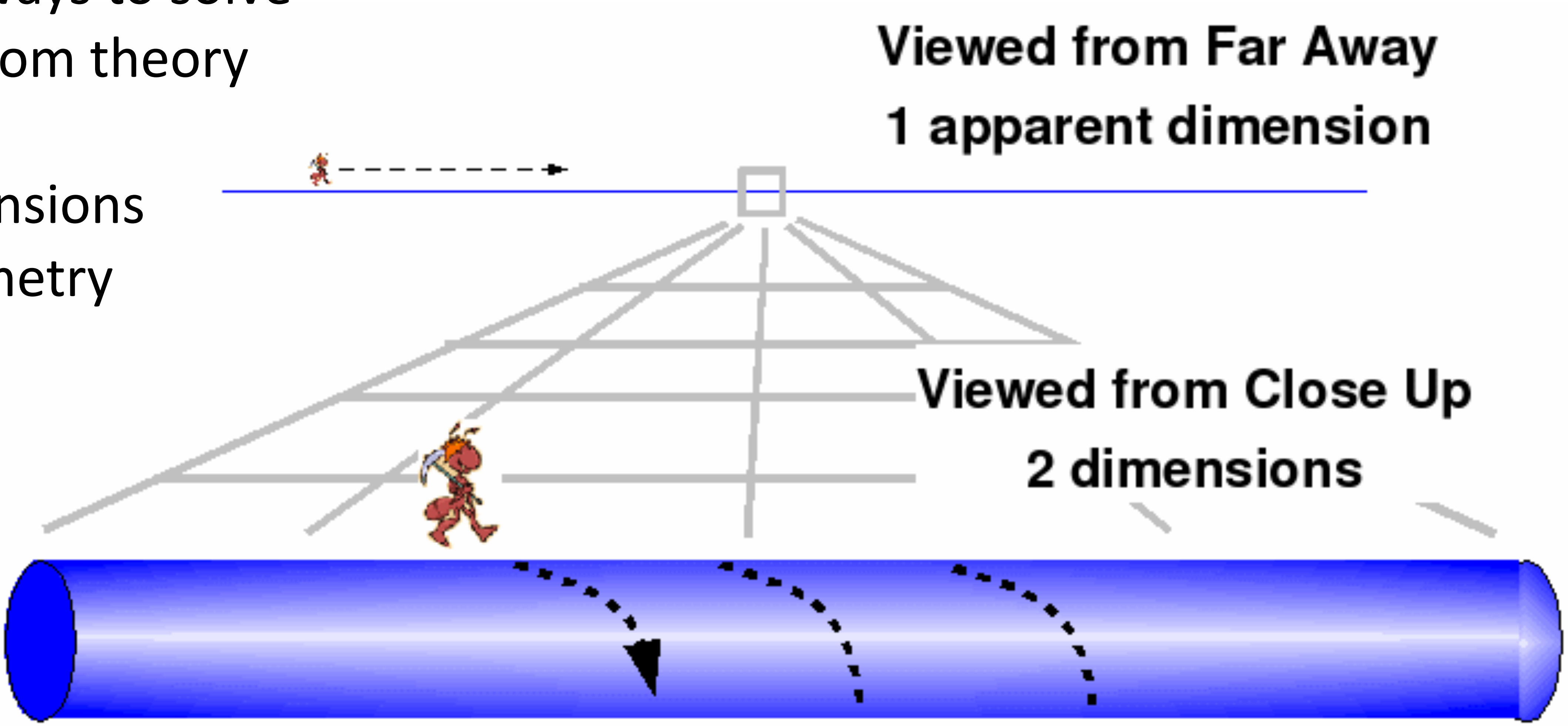
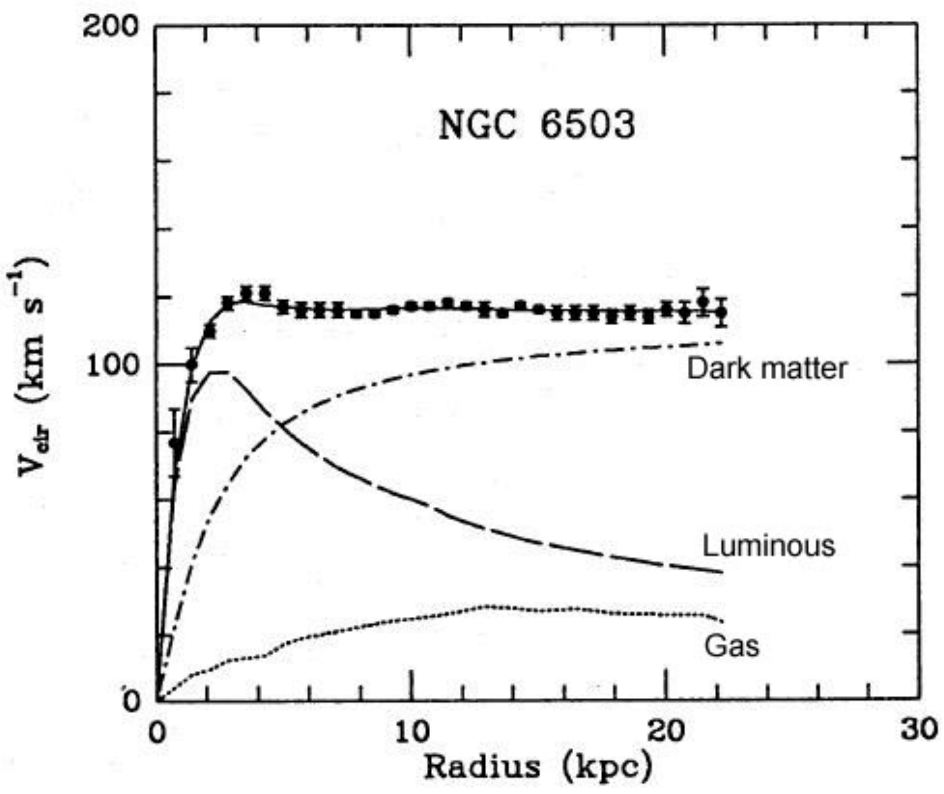
** Physics Department, Stanford University, Stanford, CA 94305, USA
† ICTP, Trieste, 34100, Italy

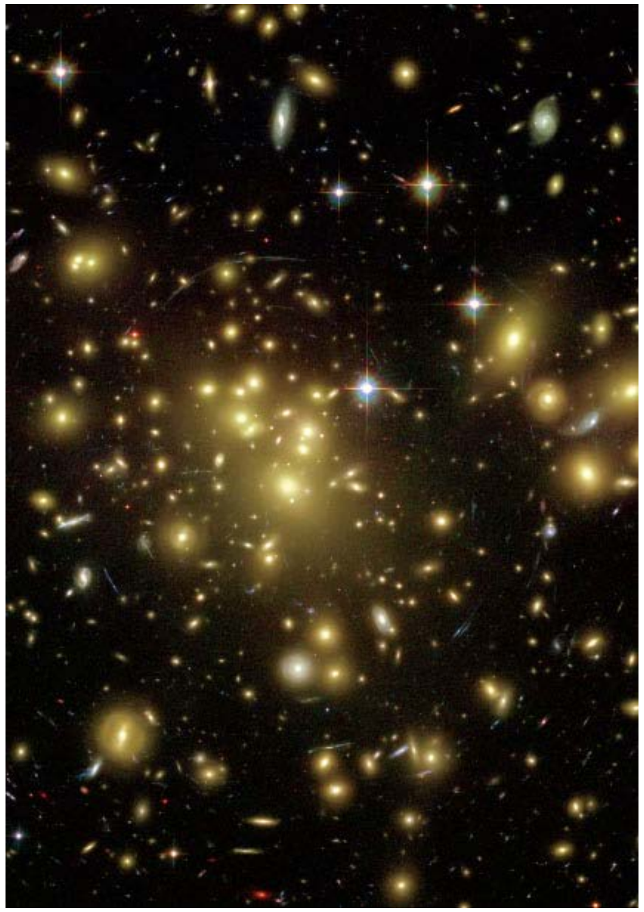


BSM: Dark matter

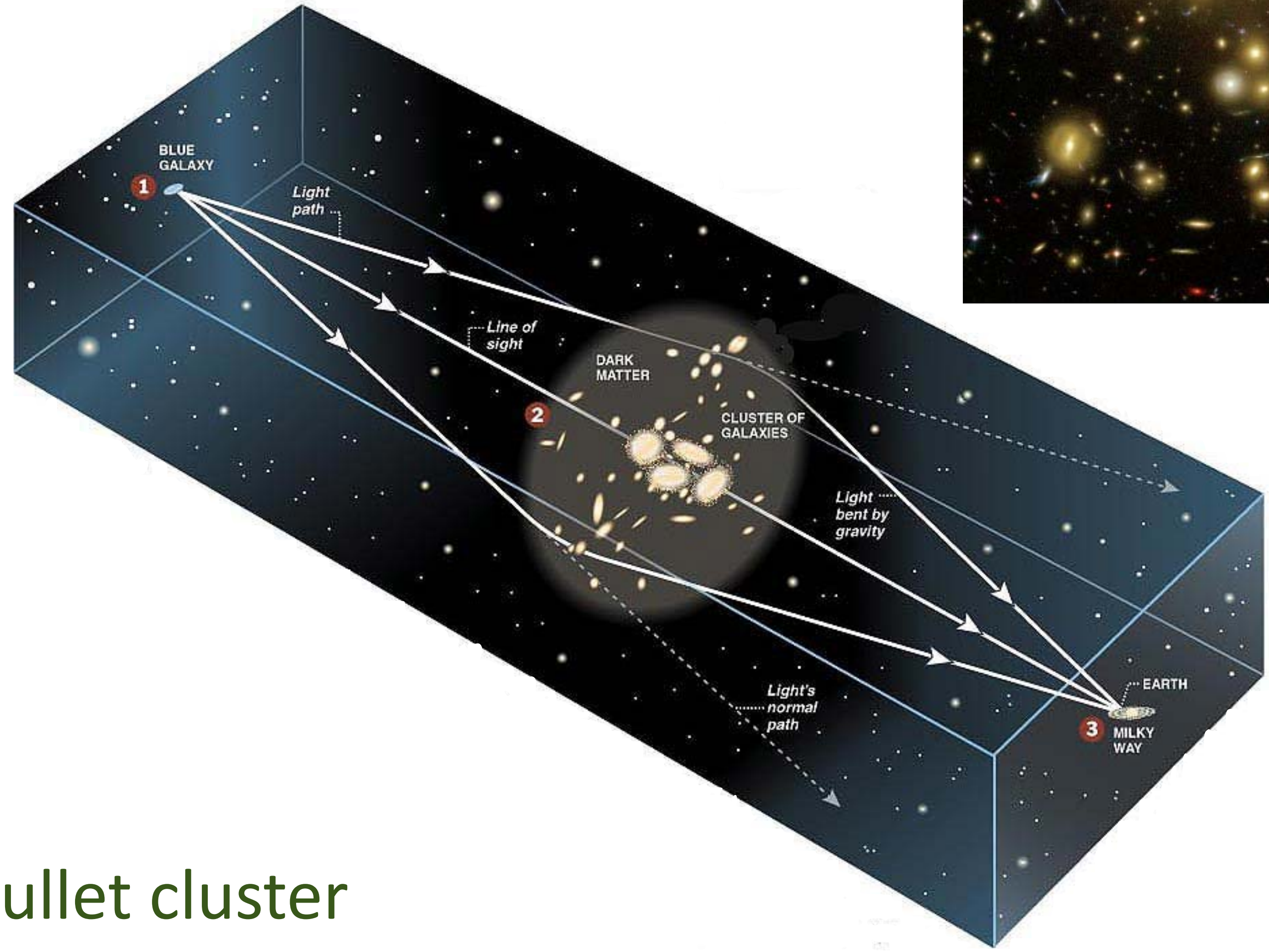
Strong evidences for the existence of dark matter, i.e. :

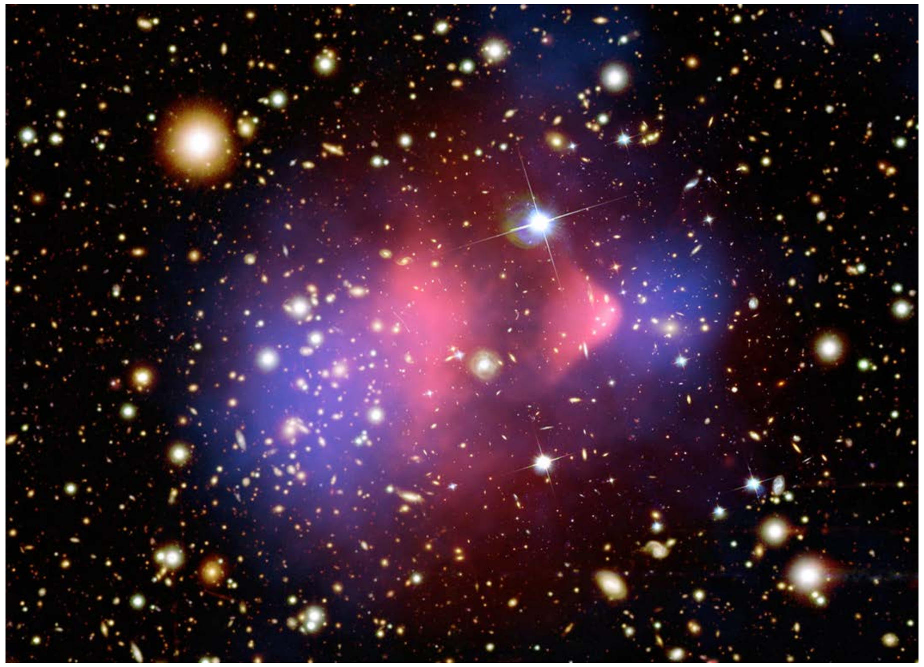


Galactic rotation curves



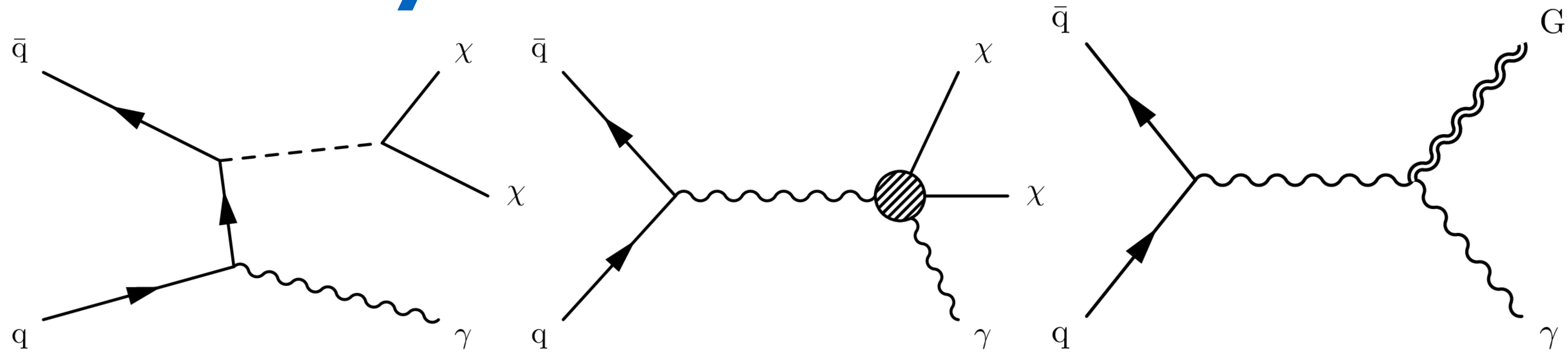
Strong Gravitational Lensing



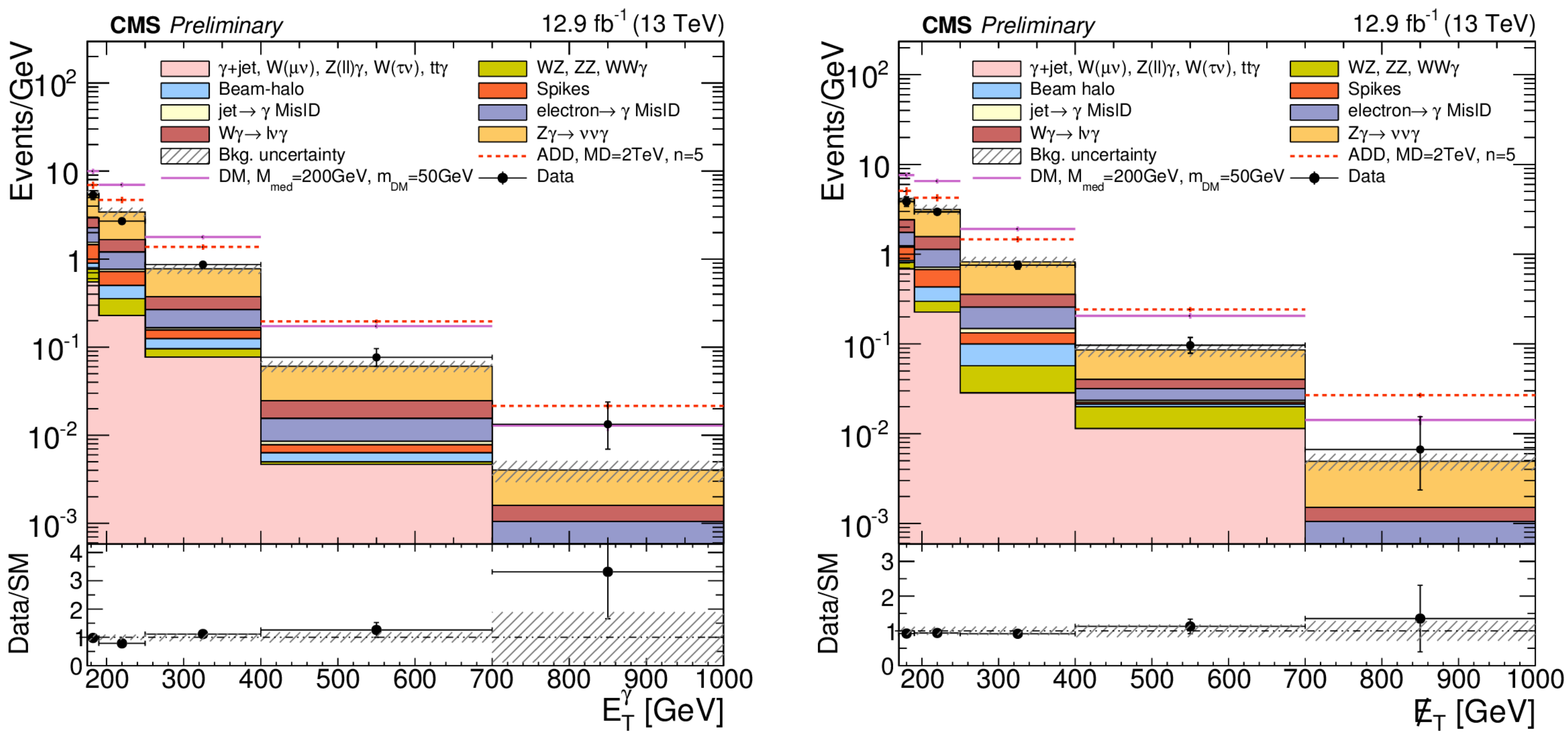


Bullet cluster

BSM: Analysis of ED & DM

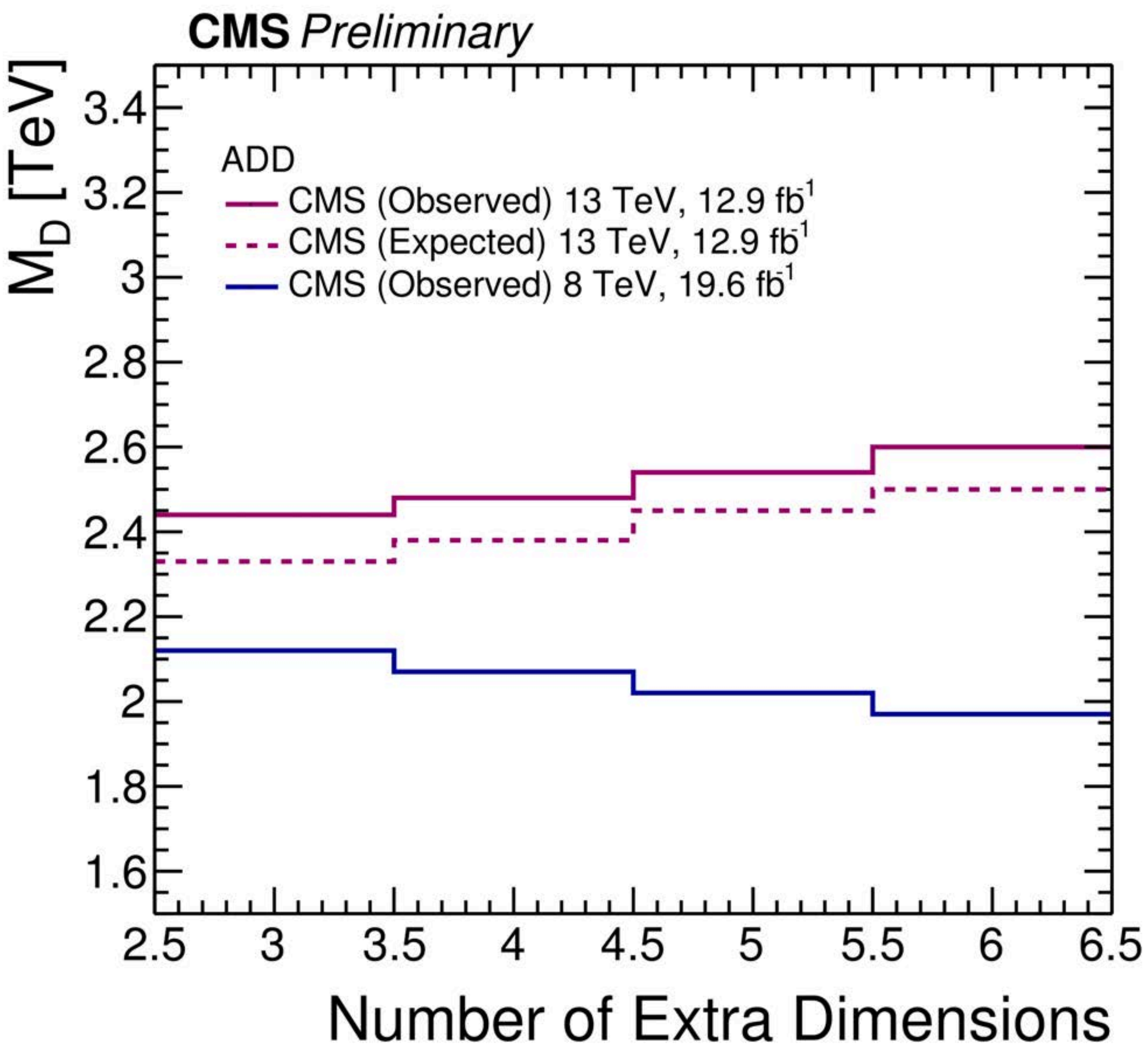


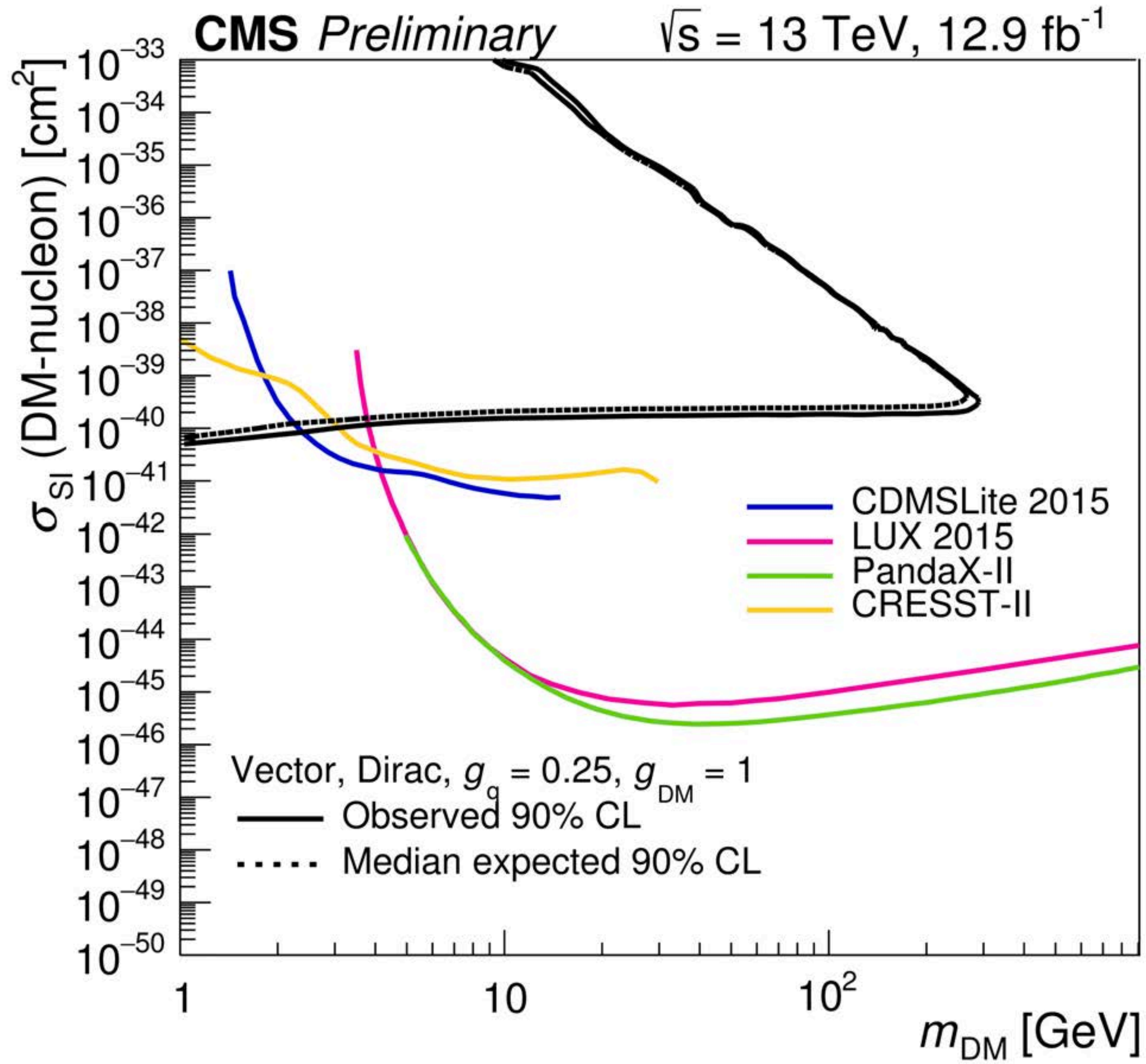
(a) DM simplified model. (b) Electroweak-DM effective interaction. (c) ADD graviton production.



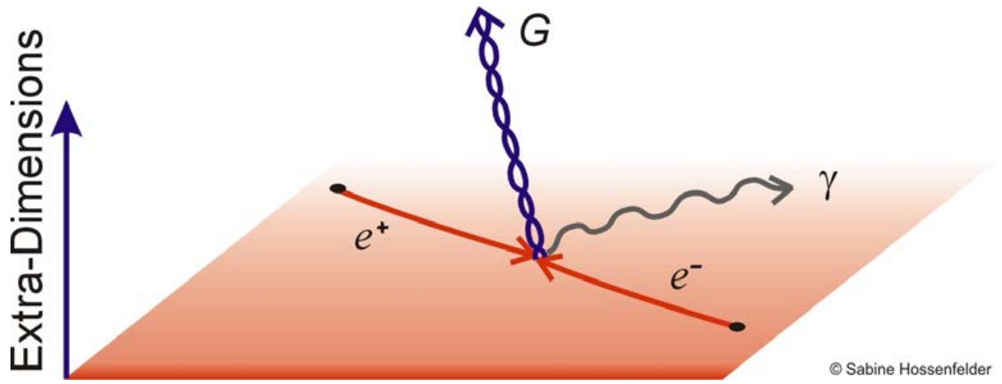
(a) Photon p_T (b) Particle Flow $\not{E}_T$

BSM: Analysis of ED & DM



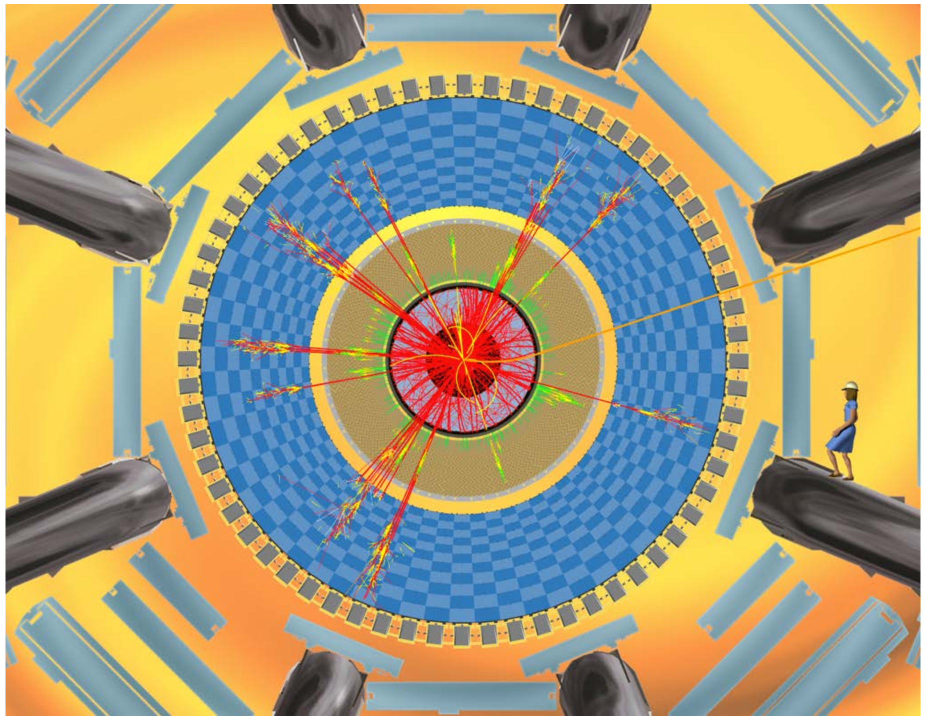


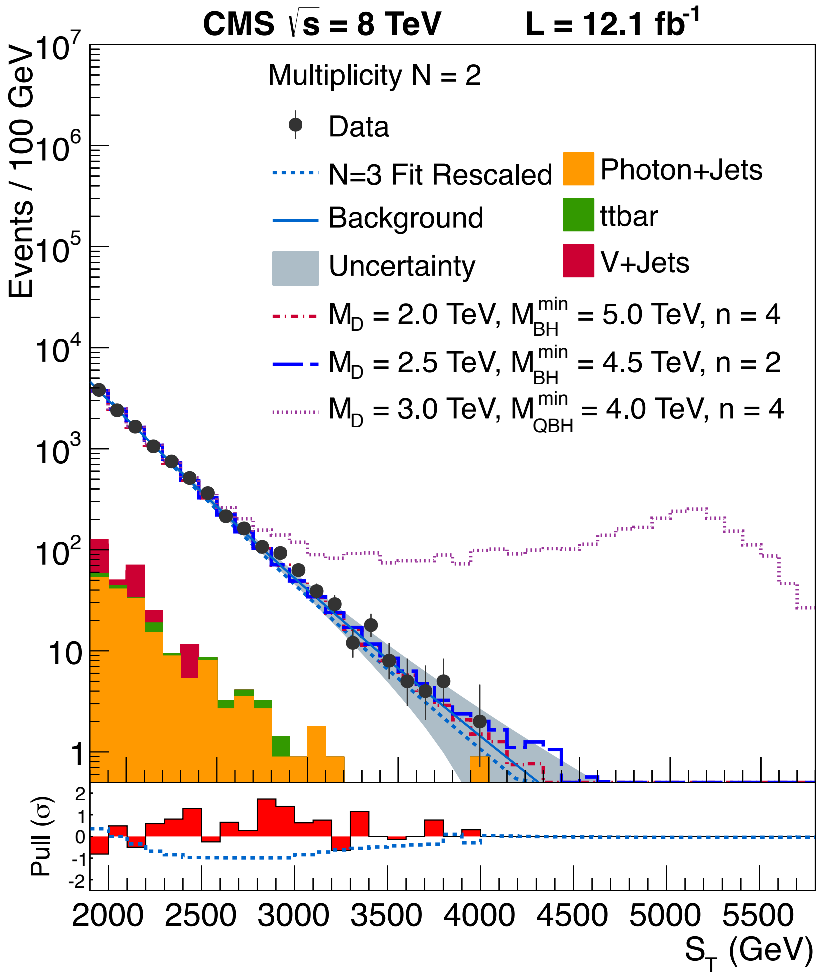
BSM: Black Hole



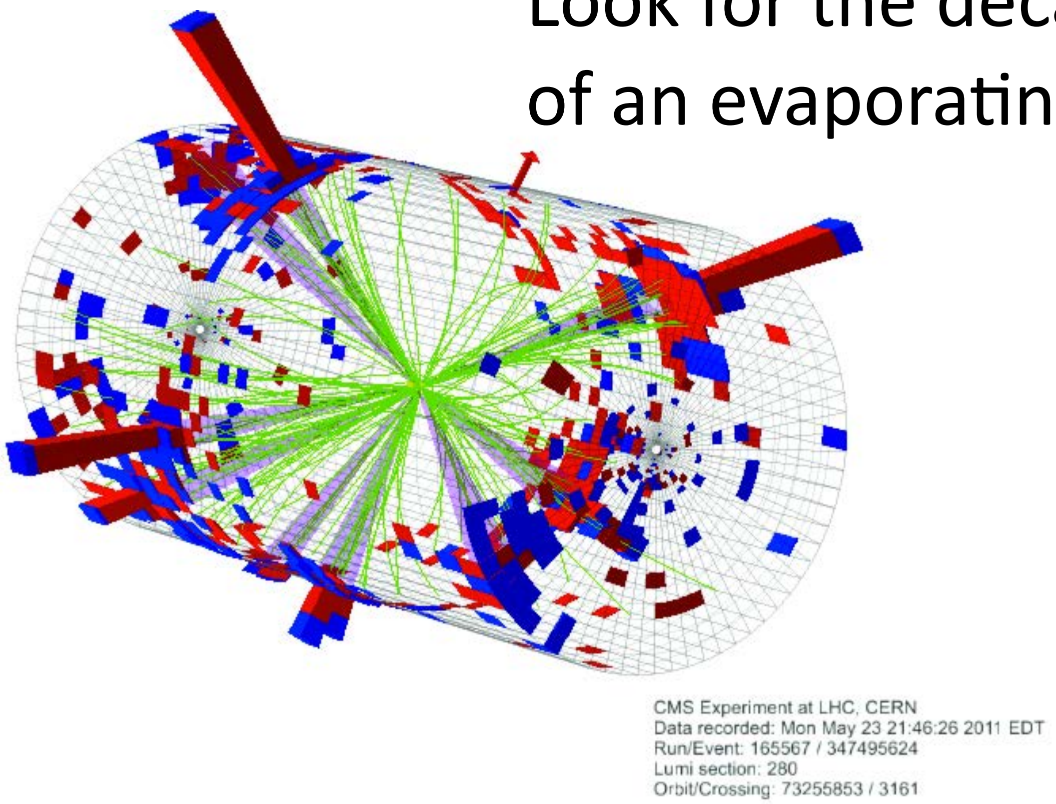
Extra Dimensions

Planck scale
a few TeV?

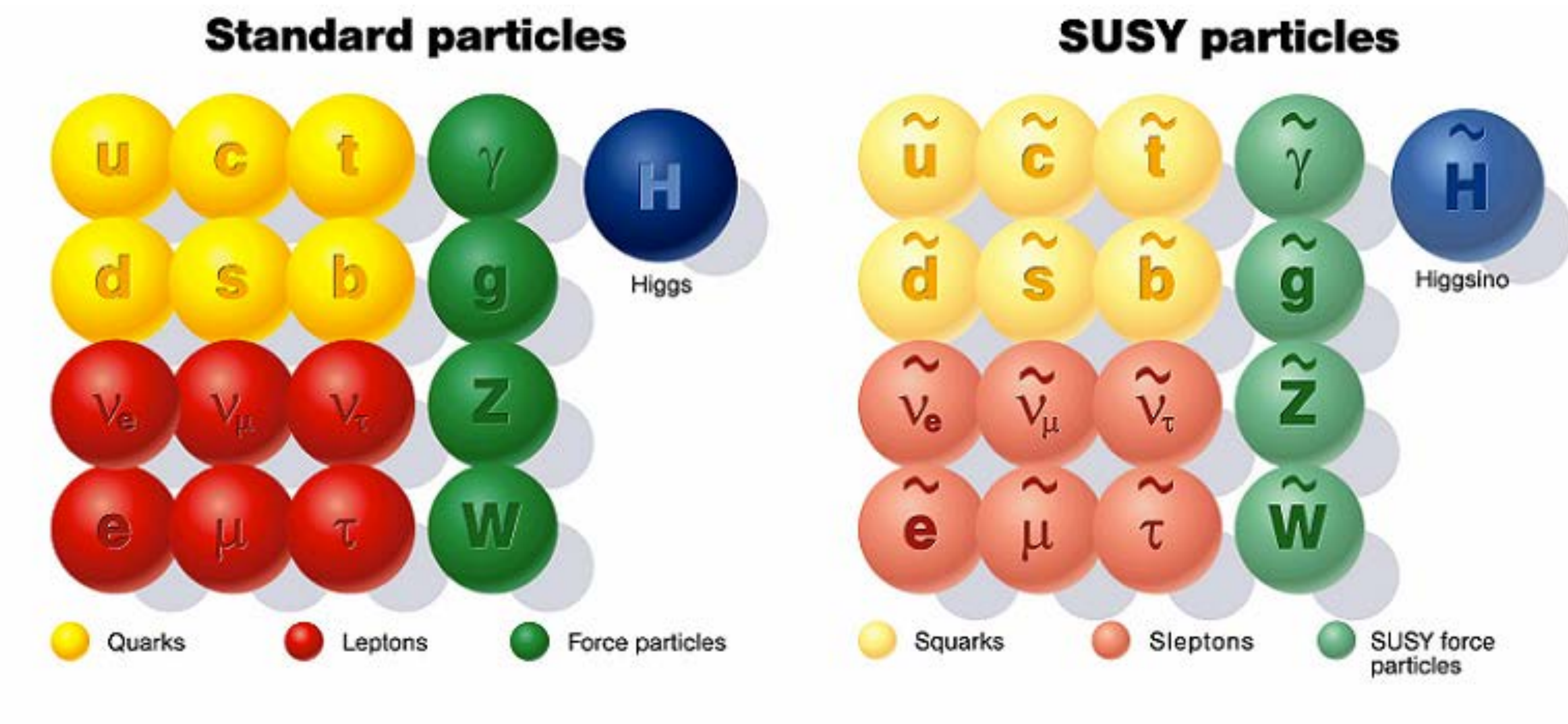




Look for the decay products of an evaporating **black hole**

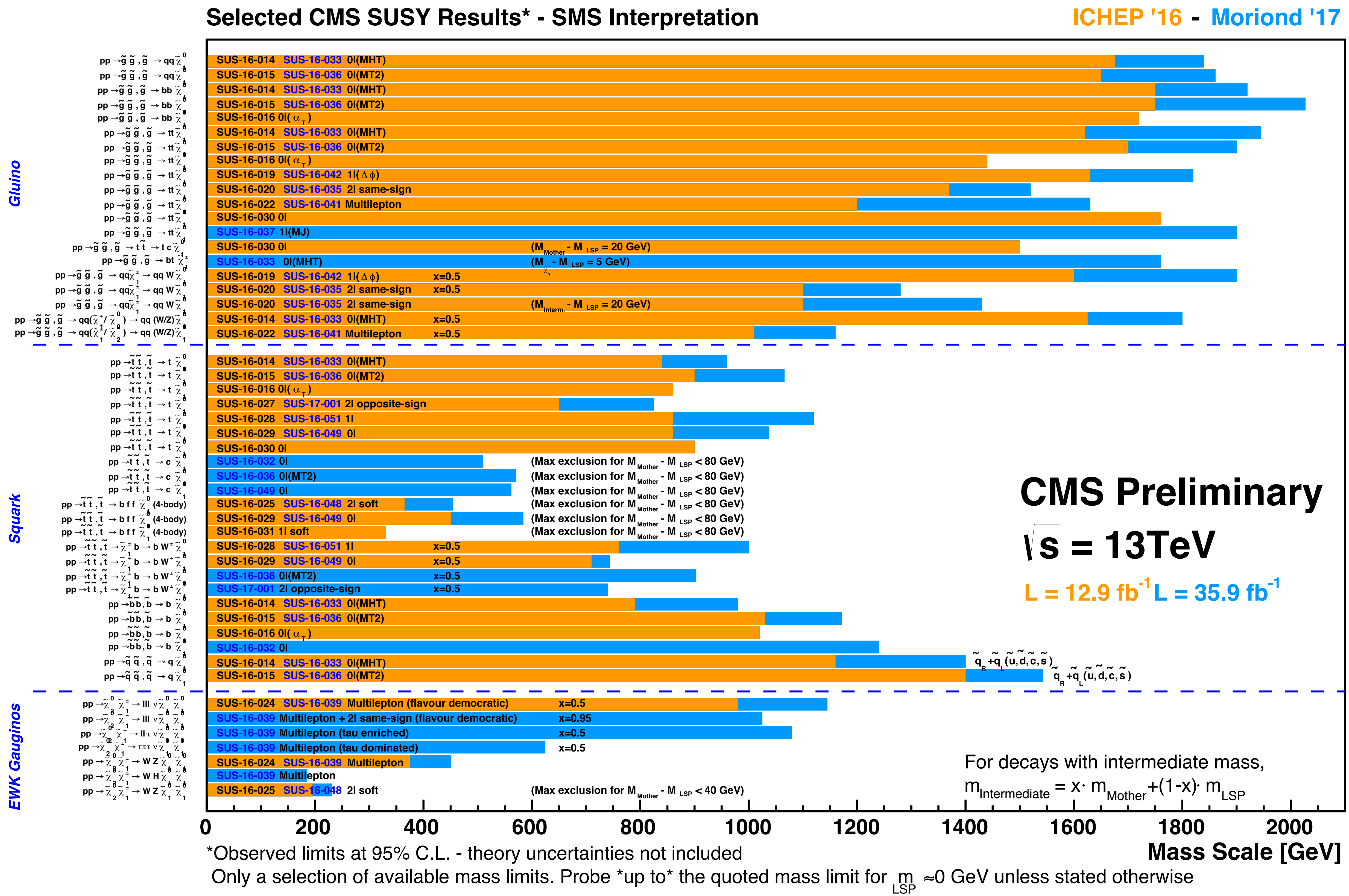


BSM: Supersymmetry

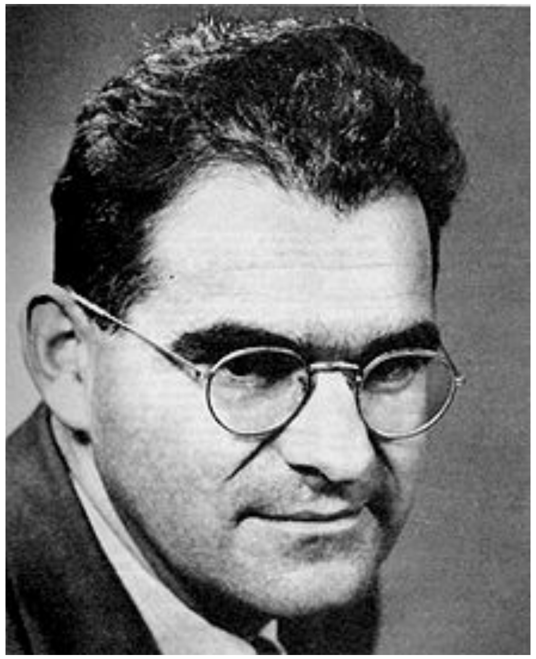


- Bridges between particle and space; New type symmetry
- Provides the good candidate of Dark Matter (WIMP)
- Higgs mass becomes light & E scale naturally is provided.
- Unifies 3 Forces (EM, Weak and strong)

BSM: Supersymmetry



Summary



Victor Weisskopf (CERN director-general, 1961-1966)

Question:
Why do so many of the brightest students want to do theory?

1) Almost all courses are theoretical
2) Almost all textbooks are theoretical

"*We choose to go to the Moon, we choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills*"

John F. Kennedy, Rice University, Sept. 12, 1962

Questions

History from experimental side

Up to 1930 known particles: **Electron**, **photon** and **neutrino** (postulated to explain the missing energy in β-decay) , **proton** and **neutron** (inside Nucleus)

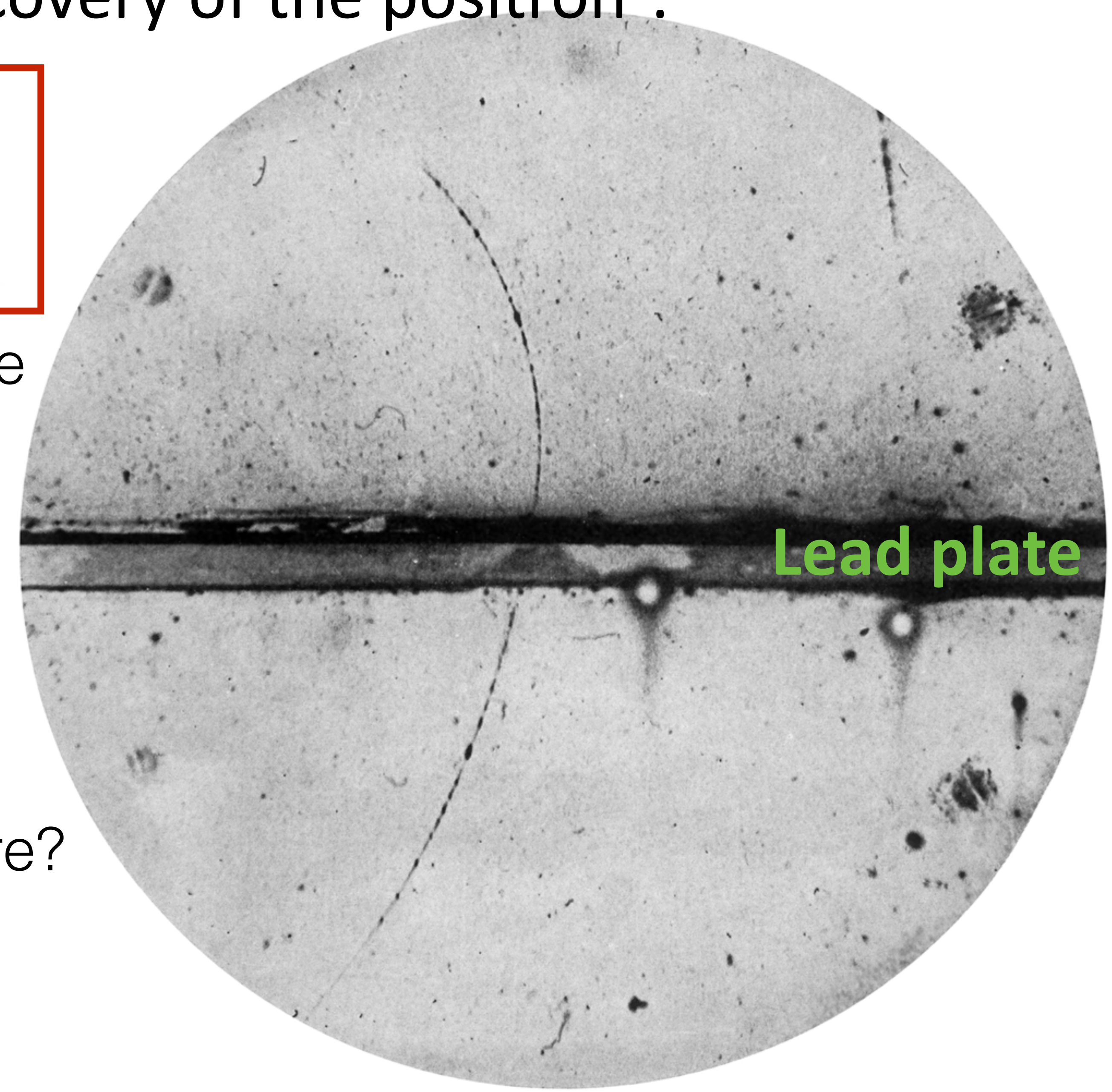
1932: The 1st Anti-particle - the **positron** - was discovered by **Carl Anderson** (1936 Noble prize in Physics for "his discovery of the positron".

A Theory of Electrons and Protons.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received December 6, 1929.)

Paper by **Dirac** to to explain the unavoidable negative-energy solution for the relativistic electron. Published 1 January 1930.
DOI: 10.1098/rspa.1930.0013



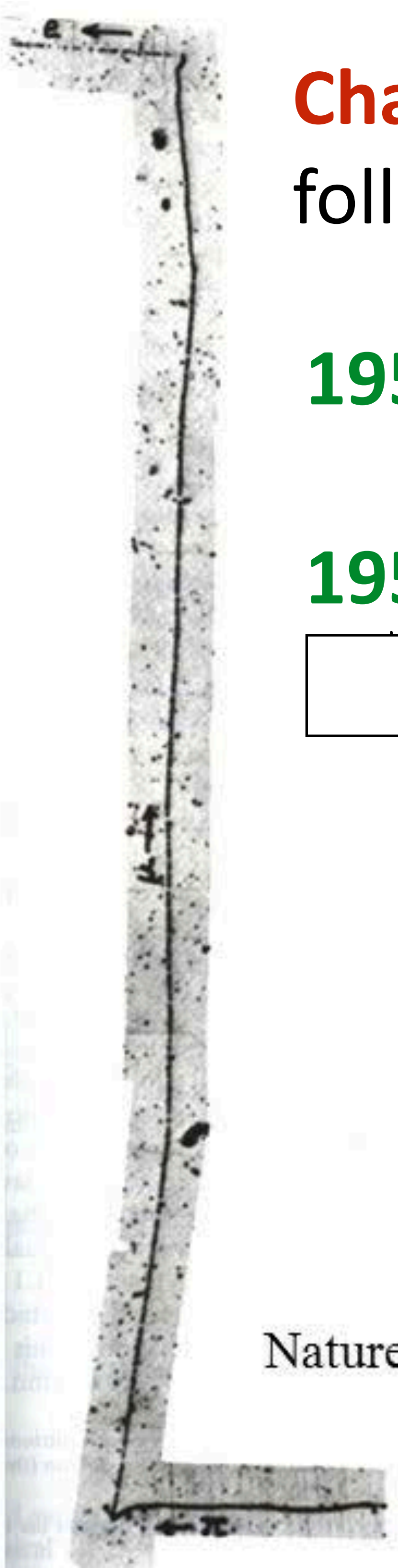
Question I [1 point]

How did positron travel in the picture?

- ☐ From top to bottom
- ☐ From bottom to top

How do you know?

History from experimental side



Charged Pion decayed to muon and neutrino, $\pi^+ \rightarrow \mu^+ + \nu_\mu$, followed by muon decay, $\mu^+ \rightarrow e^+ + \nu_e$.

1950: Neutral Pion seen decaying to 2 Photons

Question 2
[1 point]

1958: Discovery of ____________ ____________ at CERN Synchrocyclotron.

Nature **163**, 82 (1949)

https://home.cern/fr/cern-people/updates/2014/02/maria-and-giuseppe-lives-intertwined-cerns-history

Giuseppe and Maria Fidecaro. Giuseppe set up a group and prepared the basic equipment for experiments that was used in 1958 for a successful search for pions decaying into an electron and a neutrino.

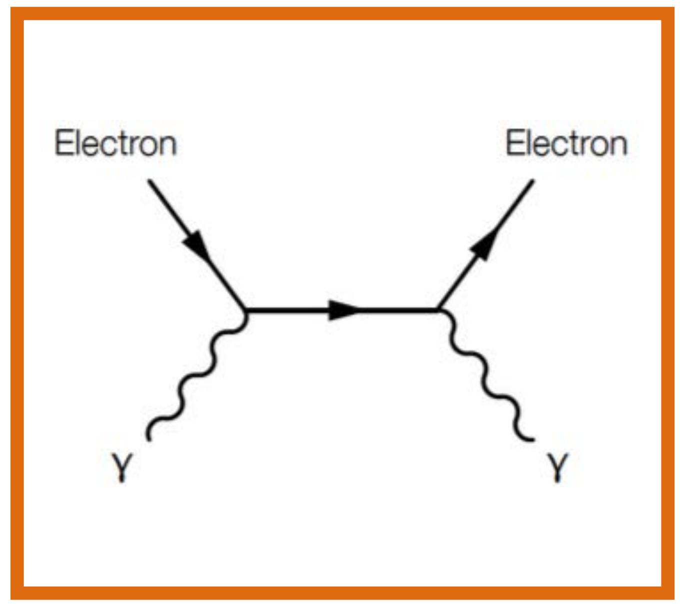
Keyword: Particle Interactions

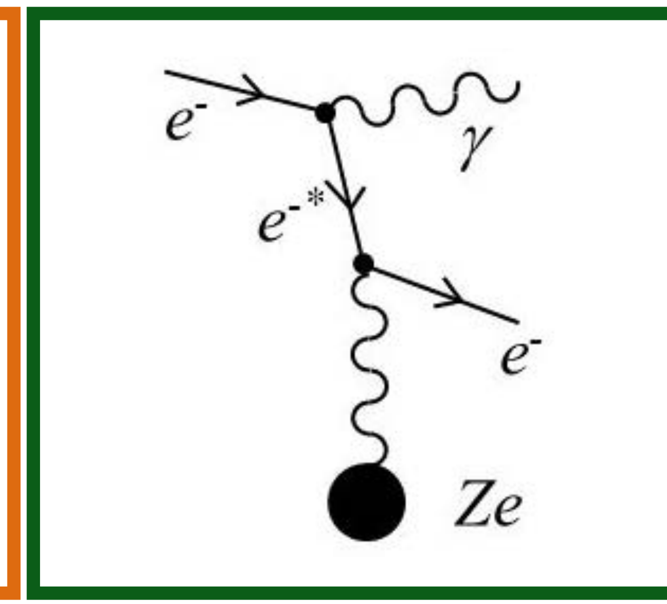
A charged particle interacts with the electrons and nuclei in matter. Electromagnetic interaction causes **ionisation** along the path of the particle. Ionisation loss used in almost all types of charged particle detectors: Emulsions, Bubble, Spark, Scintillation, Wire and Drift Chambers. [visit microcosm]

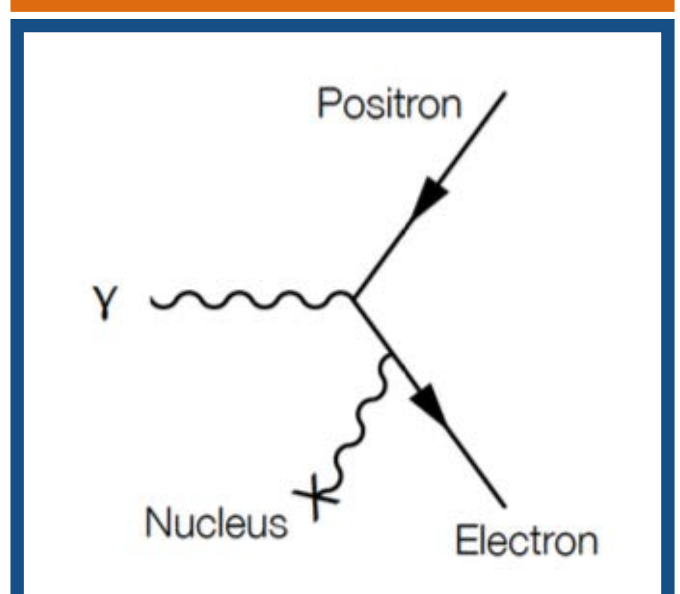
Not only the ionization
- Pair production
- Compton scattering
- Bremsstrahlung
- ...

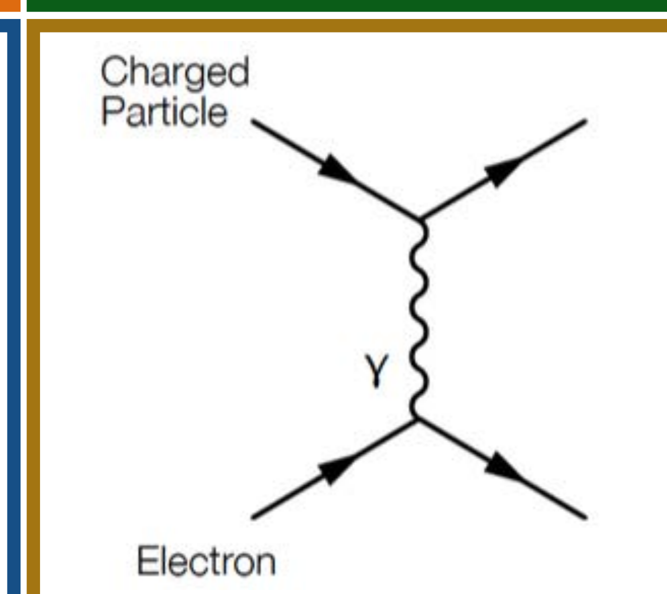
Question 3 [2 point]

What are these processes?









Exercises

Question 4 [1 point]
Tim Berners-Lee, a British scientist at CERN, proposed the World Wide Web (WWW) in ………… (Year).

Question 5 [1 point]
What is an order of number of protons per bunch at LHC? 10^x, x = ………

Question 6 [1 point]
The beam space between bunches of protons at LHC in 2016 is ……… ns (nano-sec).

Question 7 [3 point]
How many experiments we have at the LHC? [1 point] …………….
List them all [2 point]: ………………………………………………………. …