Introduction to Accelerators
Physics and Particle Colliders

Emmanuel Tsesmelis
CERN & University of Oxford

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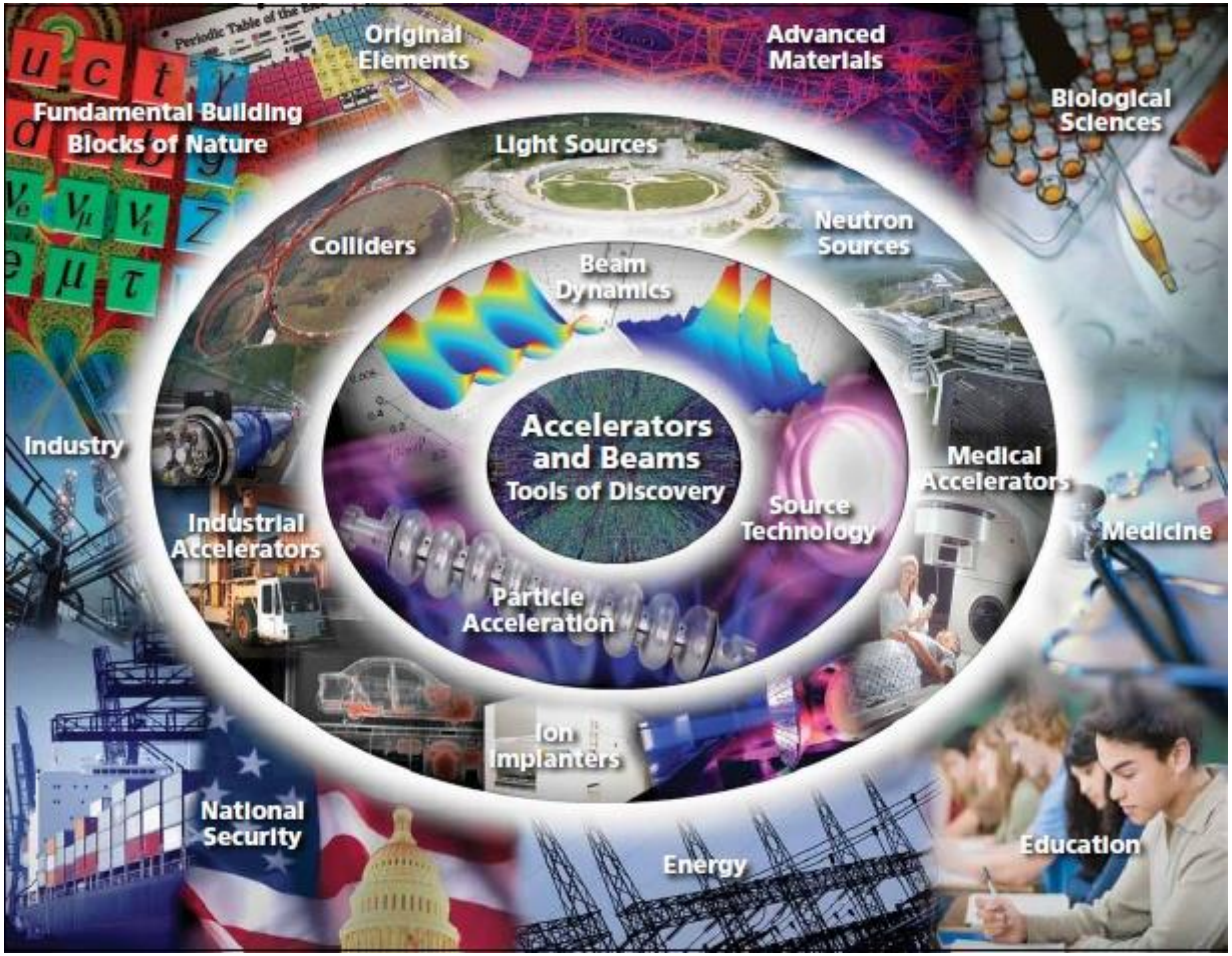
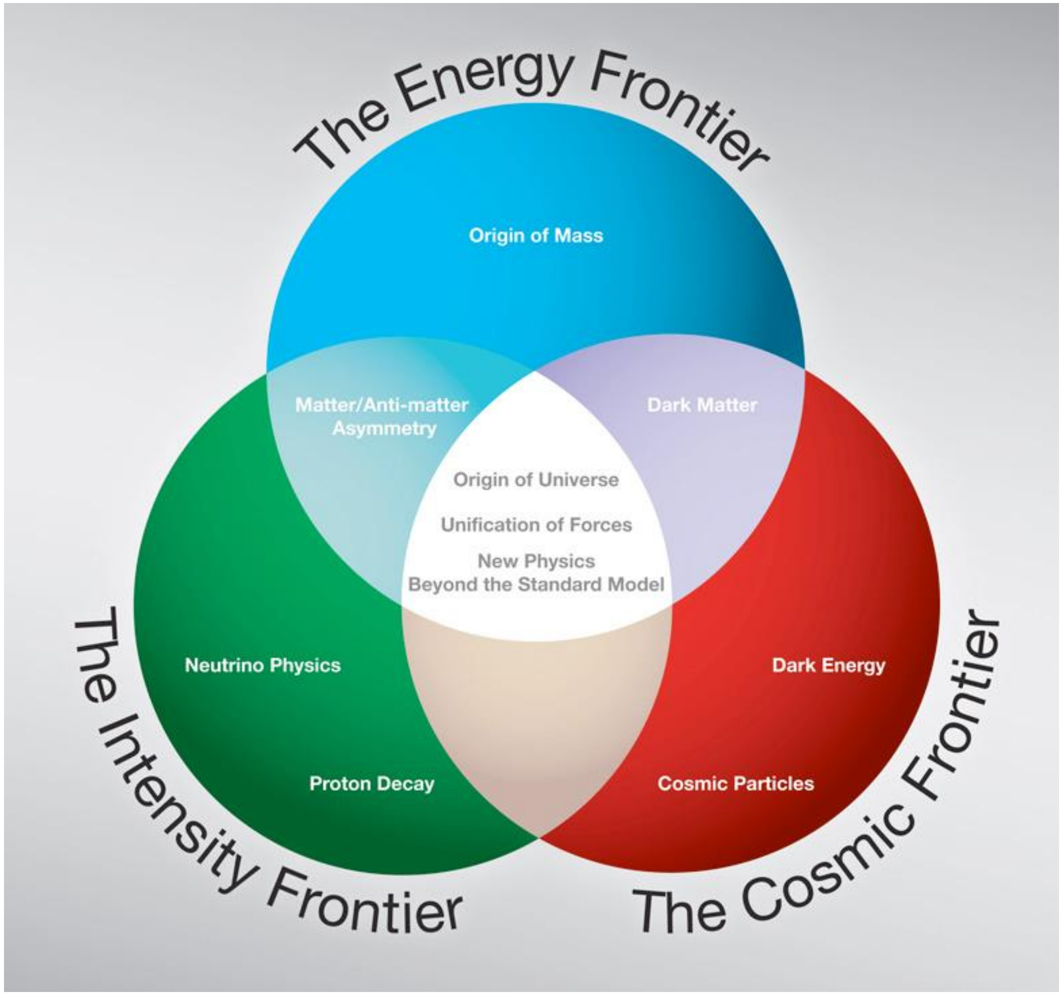
Introduction

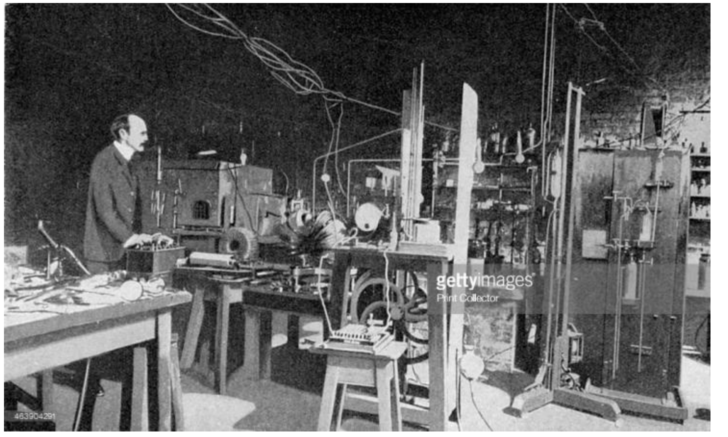


The Three Frontiers

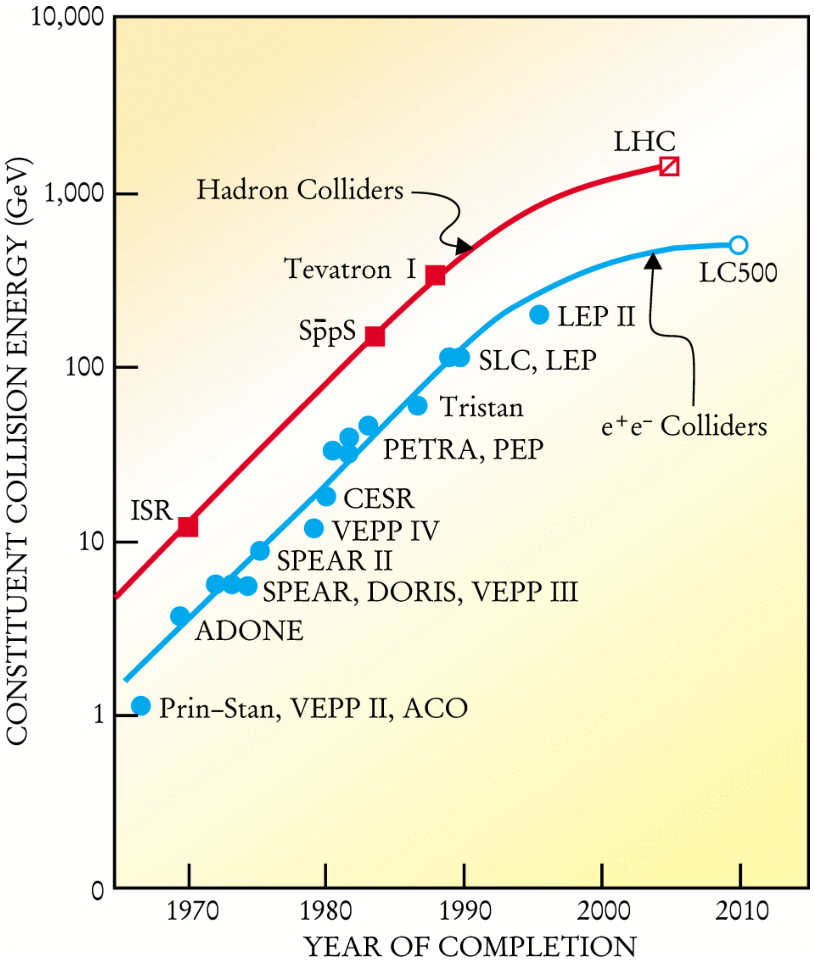


Accelerator Development

- Characterised by rapid progress for over a century.
  - From cathode-ray tubes to the LHC.
  - From the discovery of the electron to the discovery of the Higgs boson.
- Advances in accelerators require corresponding advances in accelerator technologies
  - Magnets, vacuum systems, RF systems, diagnostics,...
- But timelines becoming long, requiring:
  - Long-term planning.
  - Long-term resources.
  - Global collaboration.

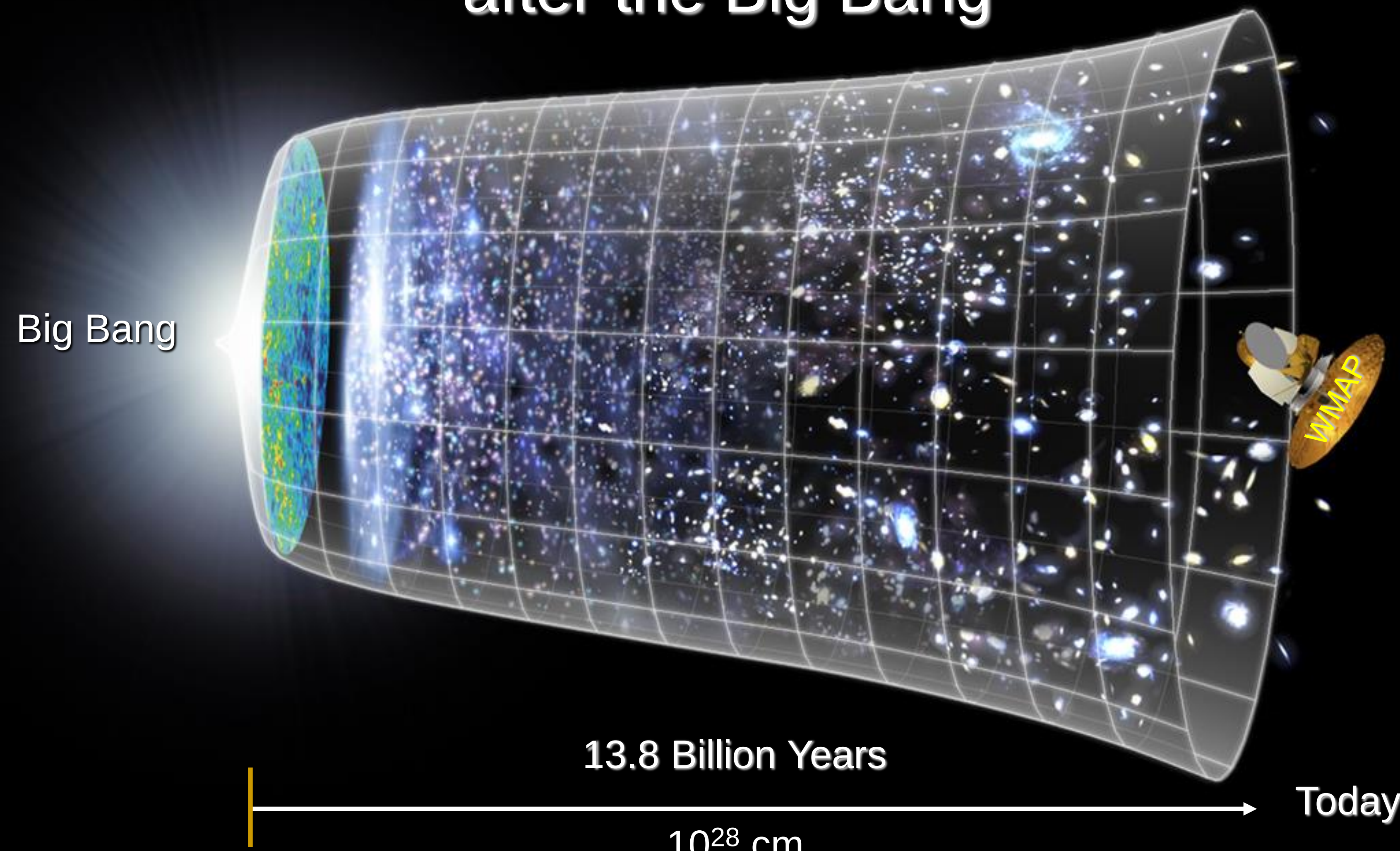


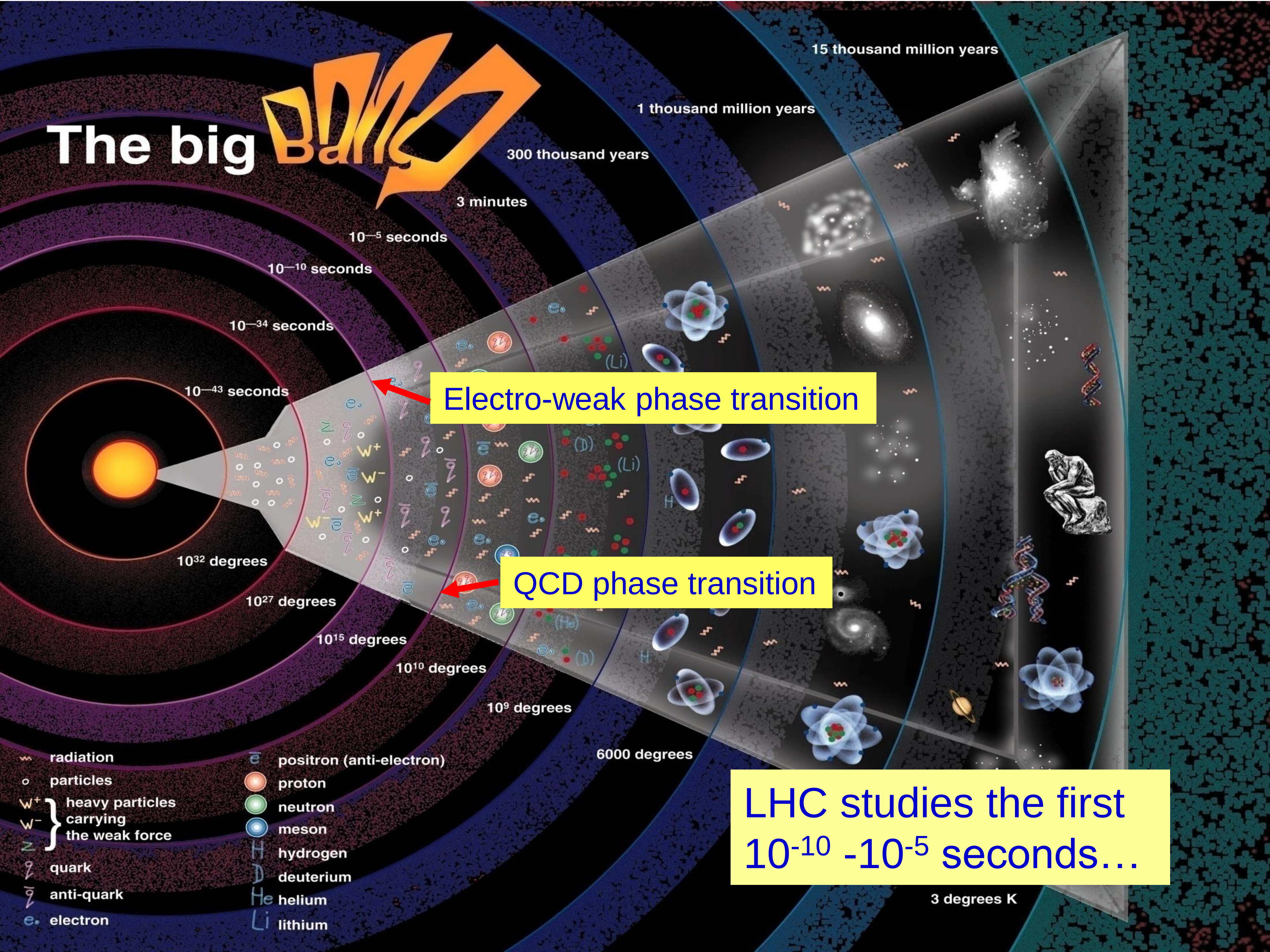
Livingston Plot

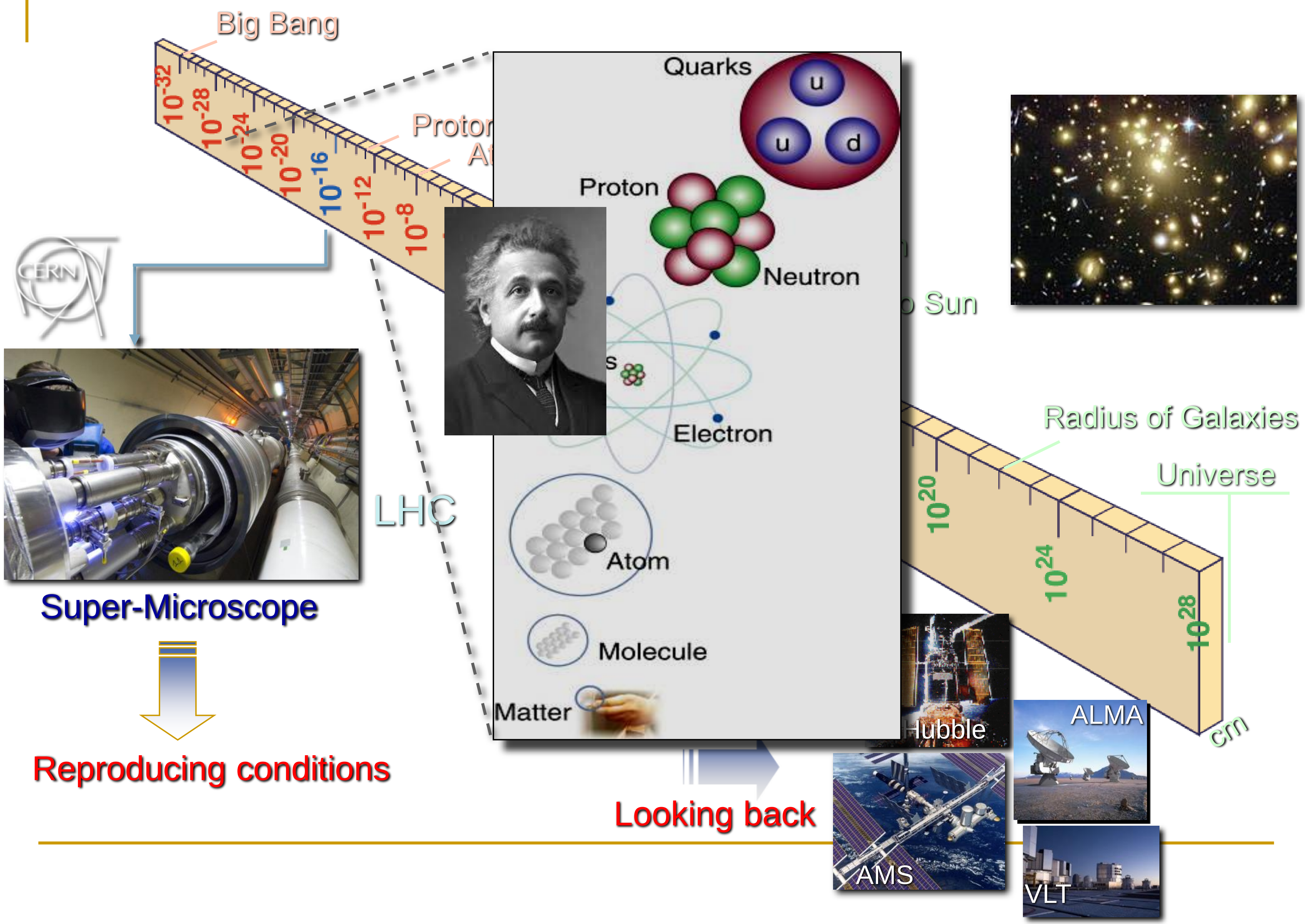


- Around 1950, Livingston made following observation:
  - Plotting energy of accelerator as a function of year of commissioning, on semi-log scale, the energy gain has linear dependence.
- Observations today:
  - Exhibition of saturation effect:
    - New technologies needed.
  - Overall project cost increased
    - Project cost increased by factor of 200 over last 40 years.
  - Cost per proton-proton E_{CM} energy decreased by factor of 10 over last 40 years.

Scientific Challenge:
to understand the very first moments of our Universe after the Big Bang

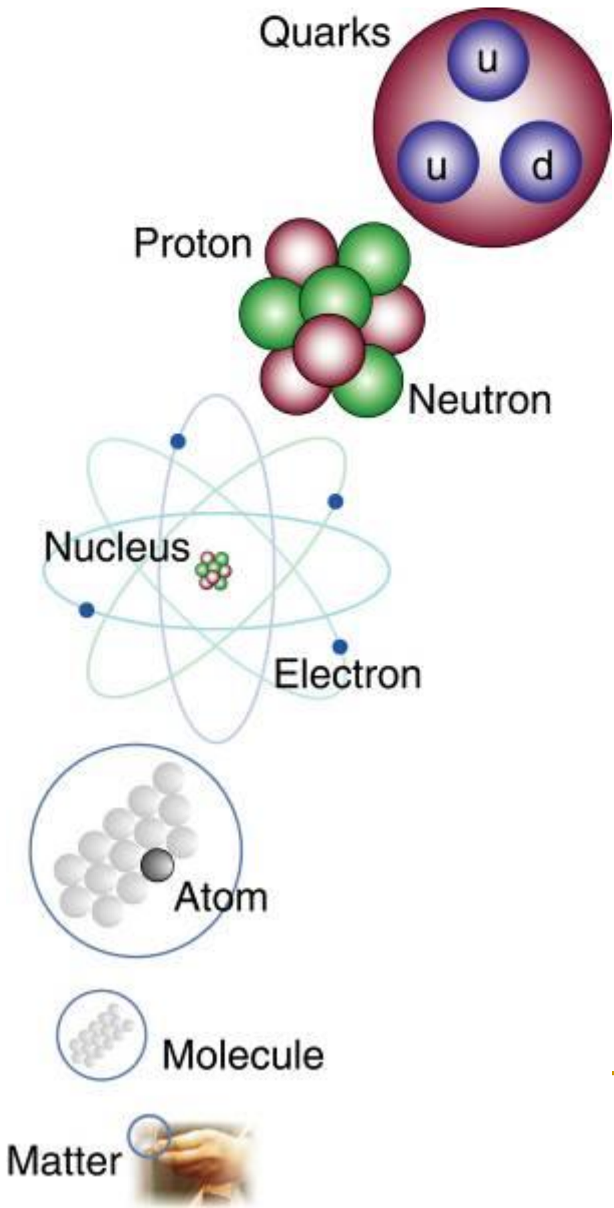


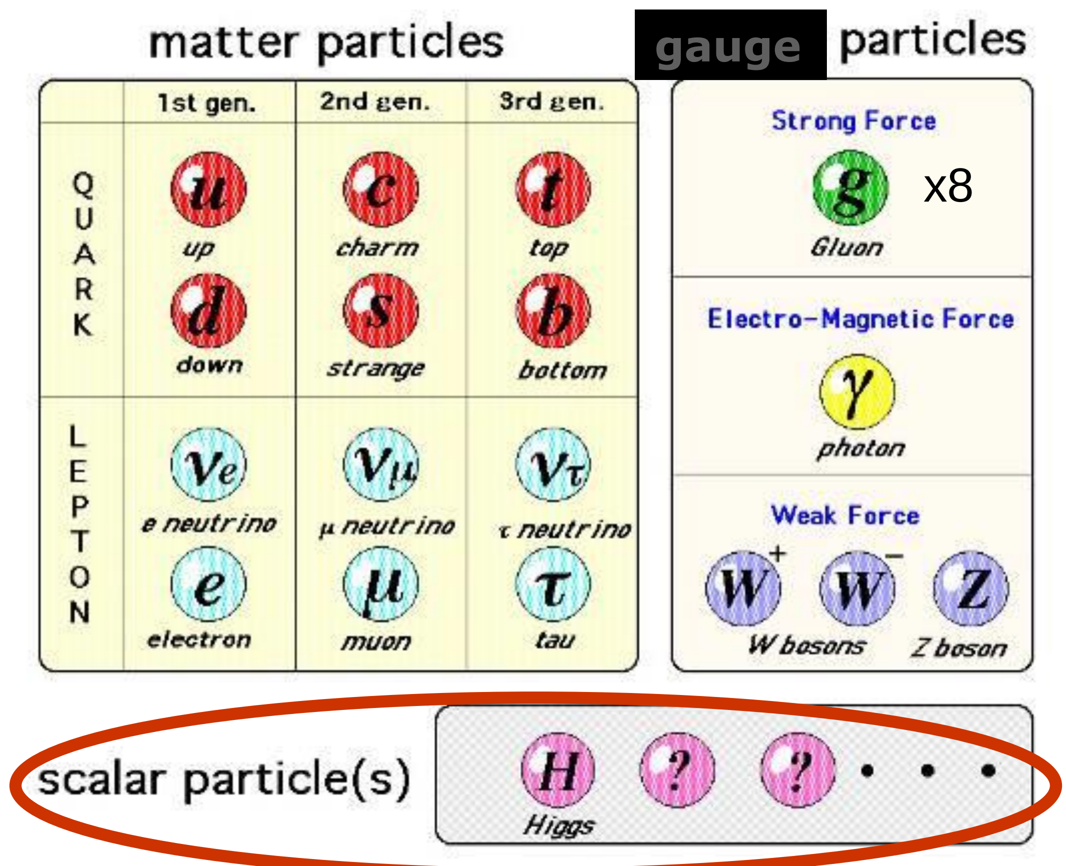

The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
3 degrees K
Electro-weak phase transition
QCD phase transition
LHC studies the first 10^{-10} - 10^{-5} seconds…
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium



Big Bang
Proton
Quarks
u
u
d
Proton
Neutron
Electron
Atom
Molecule
Matter
Sun
Radius of Galaxies
Universe
cm
CERN
LHC
Super-Microscope
Reproducing conditions
Looking back
Hubble
ALMA
AMS
VLT

The Study of Elementary Particles & Fields & Their Interactions





Elements of the Standard Model

Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Open Issues in Particle Physics

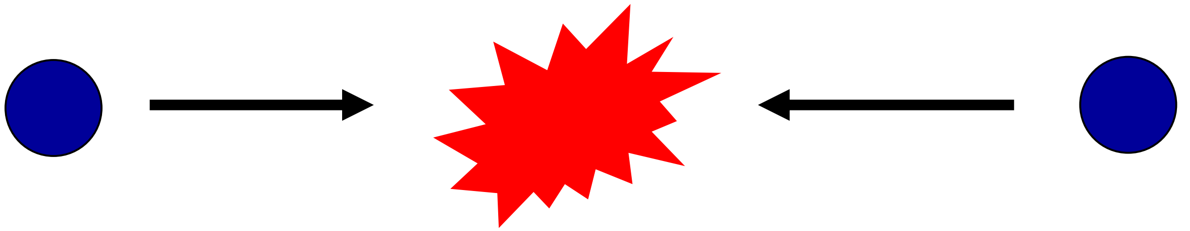
- Complete understanding of Higgs boson properties.
- Why are there so many types of matter particles?
- What is the cause of matter-antimatter asymmetry?
- What are the properties of the primordial plasma?
- What is the nature of the invisible dark matter?
- Can all fundamental particles be unified?
- Is there a quantum theory of gravity?

The present and future accelerator-based experimental programmes at colliders will address these questions and may well provide definite answers.

Accelerator Parameters (I)

Particle colliders designed to deliver two basic parameters to HEP user.

I. Centre-of-Mass Energy E_{CM}



$E = mc^2 = \gamma m_0 c^2$

Higher energy produces more massive particles.

When particles approach speed of light, they become more massive but not faster.

Why Colliders?

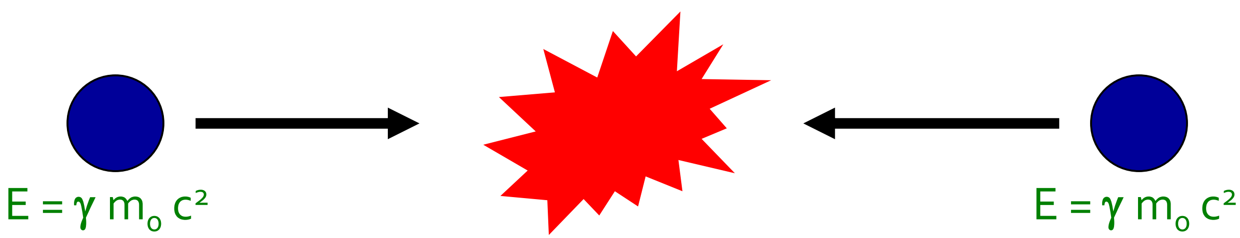
Fixed-target

$E = \gamma m_o c^2$

$P = \gamma m_o v$

Only a tiny fraction of energy converted into mass of new particles
(due to energy and <u>momentum</u> conservation)

Colliders



Entire energy converted into the mass of new particles

De Broglie Wavelength

Momentum

$$\lambda = h / p \; (1.2\,\mathrm{fm} / \mathrm{p}\,[\mathrm{GeV/c}]\,)$$

De Broglie wavelength

Planck Constant

De Broglie Wavelength

Wave-particle duality for higher E, probe shorter distances inside matter.

Accelerator Parameters (II)

Particle colliders designed to deliver two basic parameters to HEP user.

II. Luminosity

- Measure of collision rate per unit area.
- Event rate for given event probability (“cross-section”):

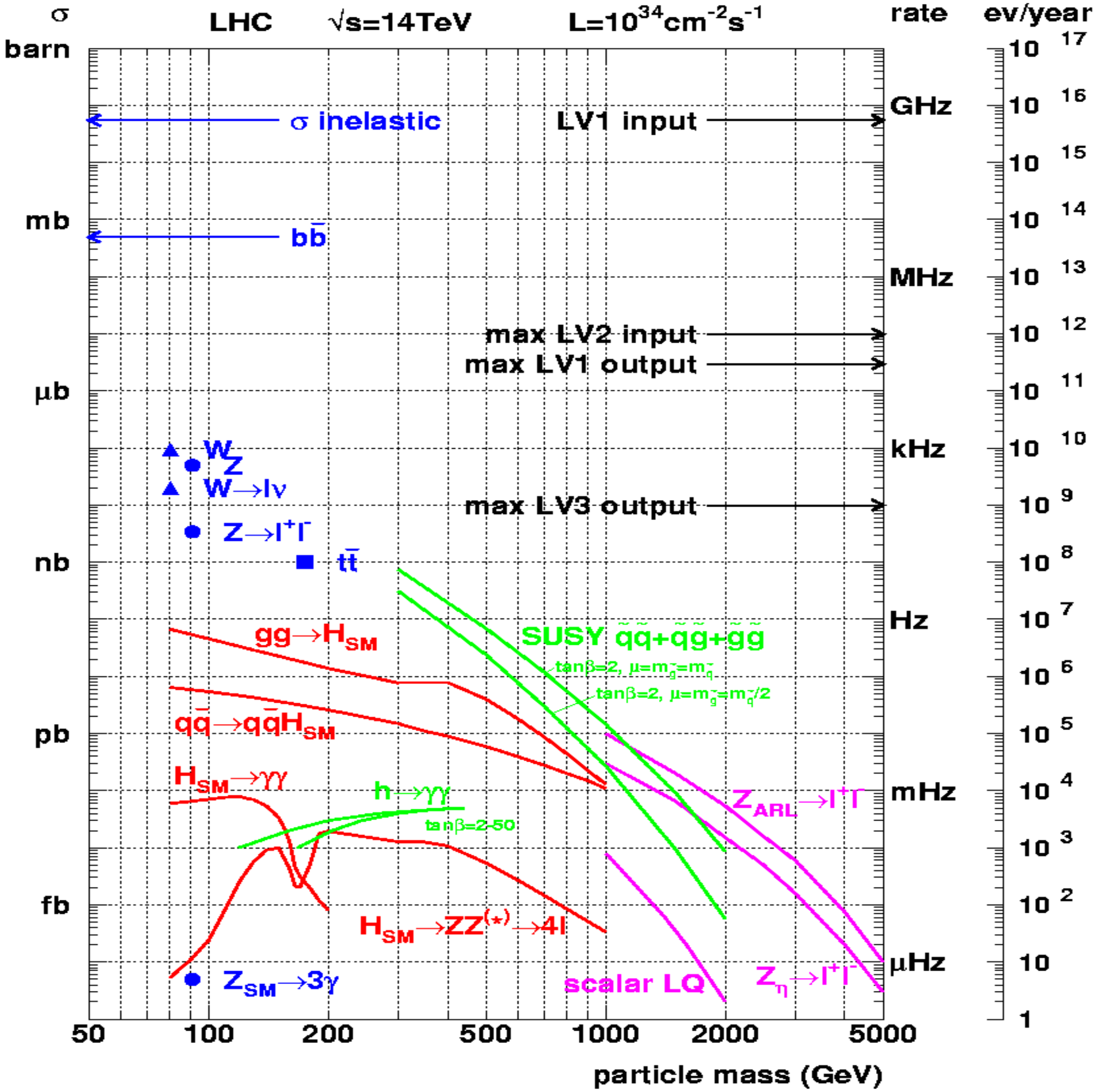
$$R = \mathcal{L}\sigma$$

For a Collider, instantaneous luminosity $\mathcal{L}$ is given by

$$\frac{N_+ N_- f_c}{4\pi \sigma_x^* \sigma_y^*}$$

- → Require intense beams, high bunch frequency and small beam sizes at IP.

Cross-sections at the LHC



"Well known" processes. Don't need to keep all of them …

New Physics!!
We want to keep!!

High-field Accelerator Magnets

- Magnetic rigidity $B\rho$ used to describe motion of relativistic particle of charge e and momentum p in magnetic field of strength B and bending radius ρ

$$B\rho = p / e \text{ (in SI units)}$$

$$B\rho \text{ [T.m]} \sim 3.3356\, p \text{ [GeV/c]}$$

  - Two approaches for raising collision energy:
    - Increase magnetic field of bending magnets.
    - Increase ring circumference and hence radius ρ.
- Final focus Quadrupoles

$$B L_q \approx 1 / \sigma^*$$

    - Design quadrupoles for largest integrated field $B L_q$ to obtain smallest beam size σ^* at IP.

Varying the SCRF Frequency

Collider Types

- Hadron Colliders
  - Desire high energy
    - Only ~10% of beam energy available for hard collisions producing new particles
      - Need *O*(10 TeV) Collider to probe 1 TeV mass scale.
      - High-energy beam requires strong magnets to store and focus beam in reasonable-sized ring.
  - Desire high luminosity
    - Use proton-proton collisions.
      - High bunch population and high bunch frequency.
    - Anti-protons difficult to produce if beam is lost
      - *c.f.* SPS Collider and Tevatron

Collider Types

- Lepton Colliders (e+e-)
  - Synchrotron radiation - most serious challenge for circular colliders
    - Energy loss of a particle per turn

$$U_0 = \frac{4\pi}{3}\frac{r_e\gamma^4}{R}\text{mc}^2$$

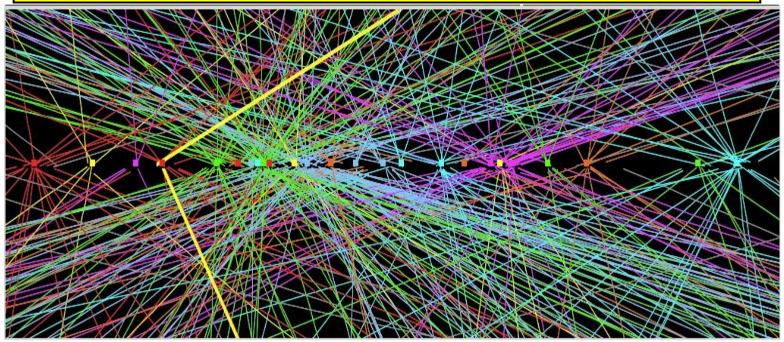
    - Emitted power in circular machine is

$$P_{SR}[\text{kW}] = \frac{88.5\,E^4[\text{GeV}]I[\text{A}]}{\rho[\text{m}]}$$

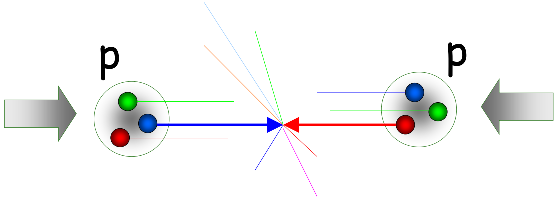
      - For collider with E_{CM} = 1 TeV in the LHC tunnel with a 1 mA beam, radiated power would be 2 GW
        - Would need to replenish radiated power with RF
        - Remove it from vacuum chamber
  - Approach for high energies is Linear Collider.

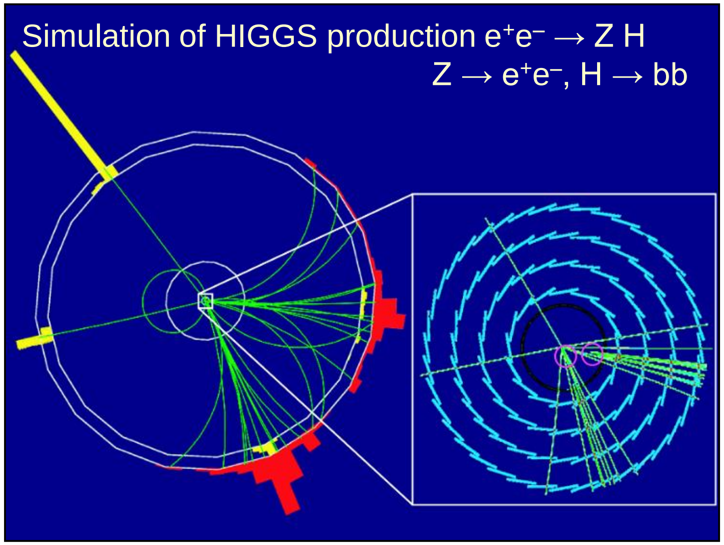
Collider Characteristics

ATLAS Z → μμ event from 2012 data with 25 reconstructed vertices

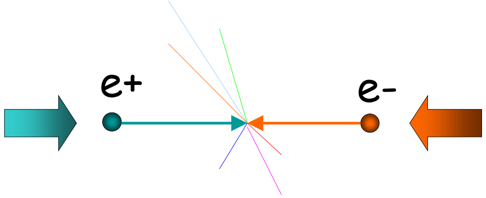


- Hadron collider at the frontier of physics
  - Huge QCD background
  - Not all nucleon energy available in collision

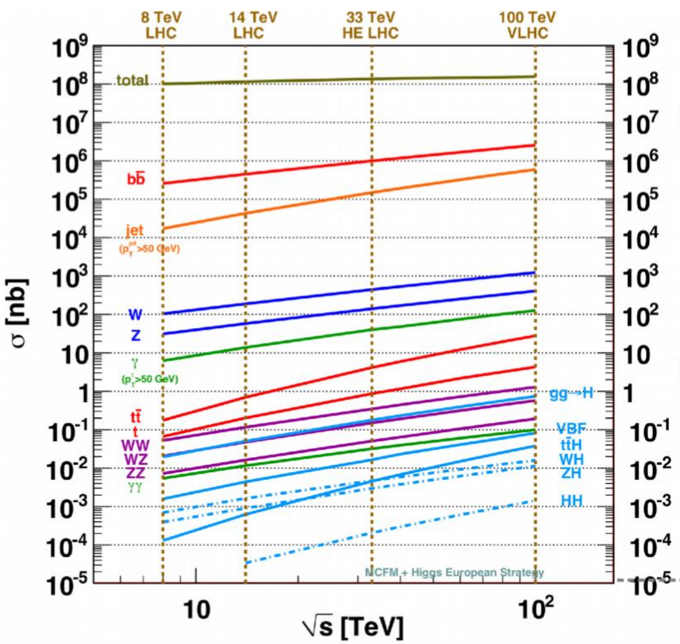




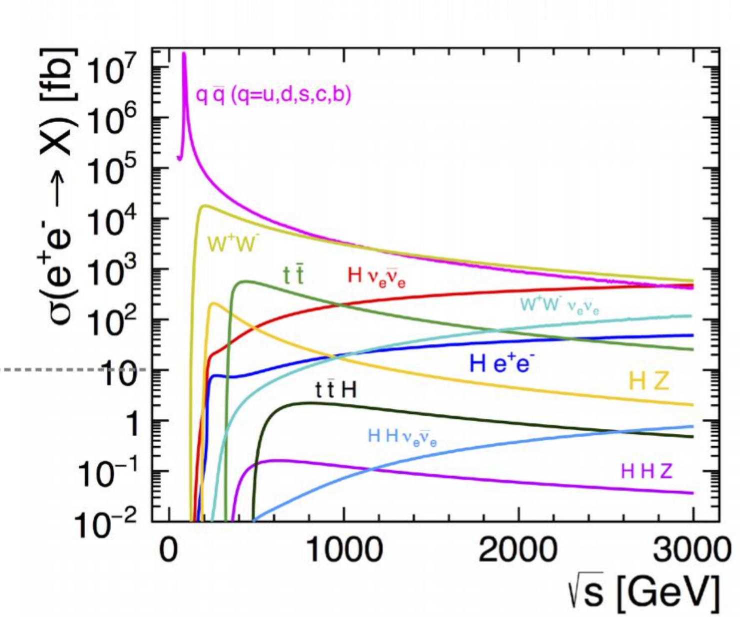
- Lepton collider for precision physics
  - Well defined initial energy for reaction
  - Colliding point like particles



Collider Characteristics



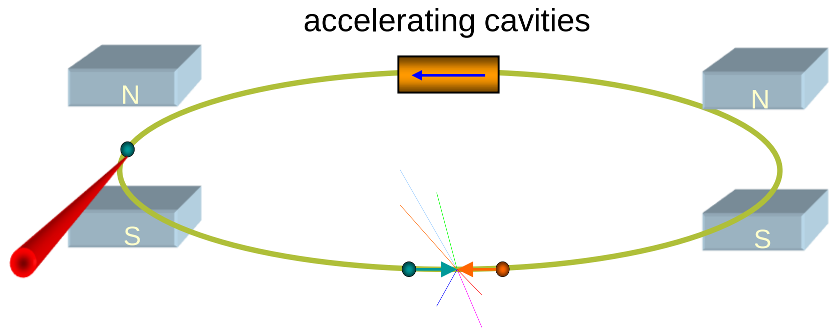
8 orders of Magnitude!



pp collisions:
Interesting events need to be found in a huge number of collisions

e^+e^- collisions:
More "clean", all events usable

Circular versus Linear Collider

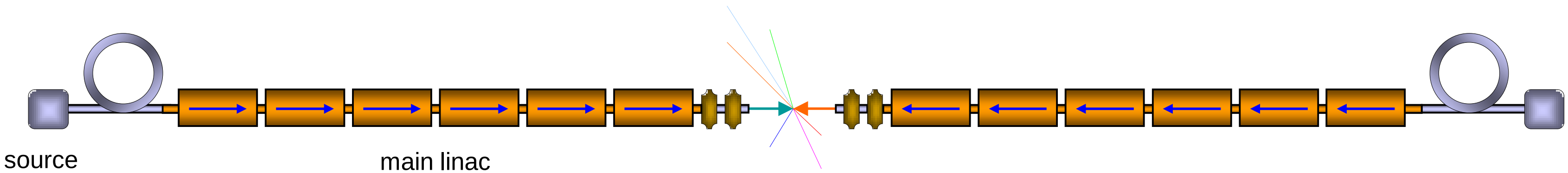


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

→ higher synchrotron radiation losses (E^4/m^4R)



Linear Collider

few magnets, many cavities, single pass beam

higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

A Global Strategy

- Encourage strategic studies and planning of international facilities for particle physics in different regions of the world
  - ILC in Japan
  - CEPC/SPPC in China
  - CLIC/FCC in Europe
  - LBNF in US (neutrinos & the intensity frontier)

- Encourage global coordination in planning future energy frontier colliders
  - ILC and CLIC groups working together
    - Linear Collider Board (and Linear Collider Collaboration) under ICFA
  - FCC and CEPC/SPPC


Thank You!
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
CMS
ALICE
LHC 27 km