Εισαγωγή στους Επιταχυντές Σωματιδίων

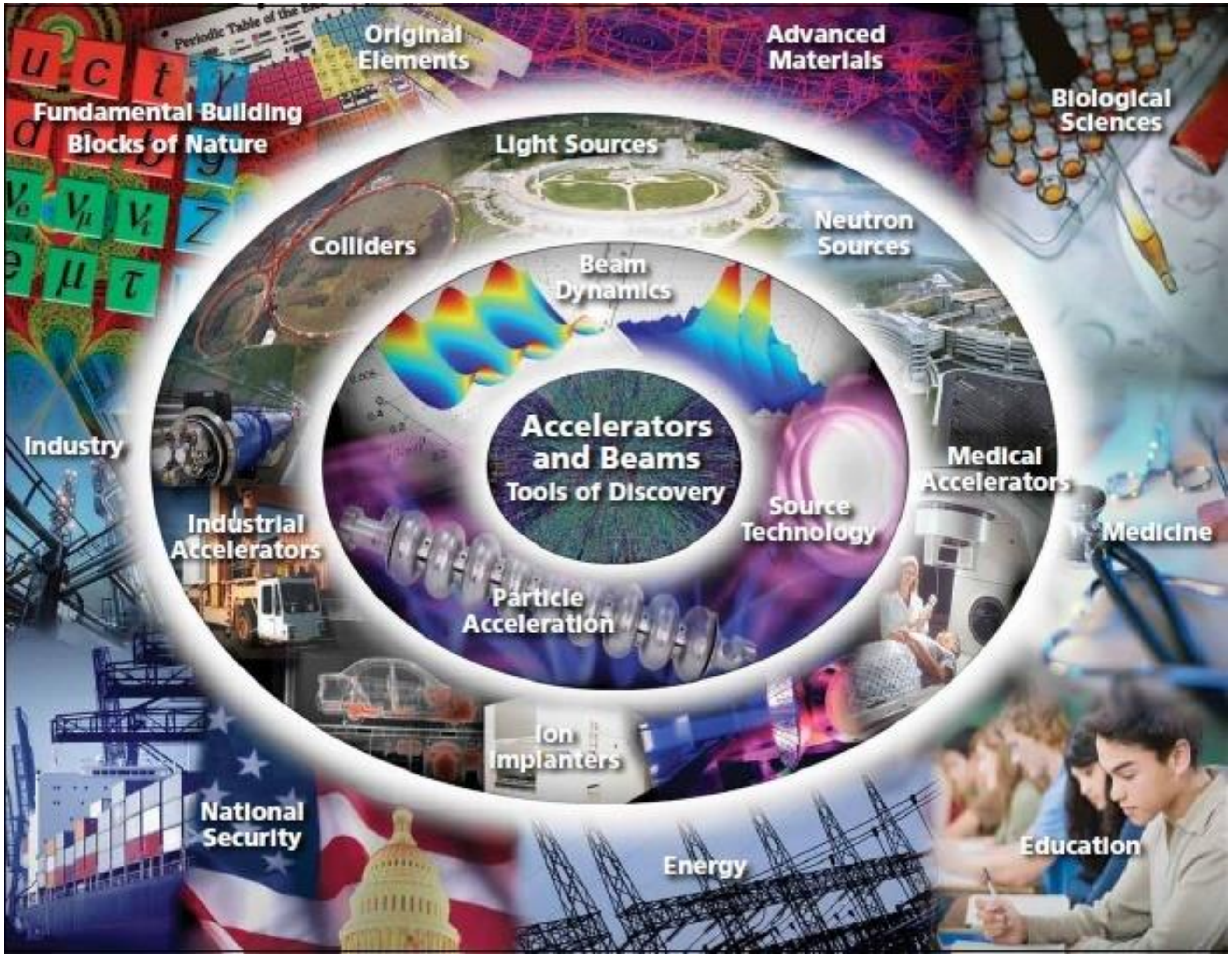
Καθ. Εμμανουήλ Τσεσμελής

CERN & University of Oxford

Greek High School Teachers Programme

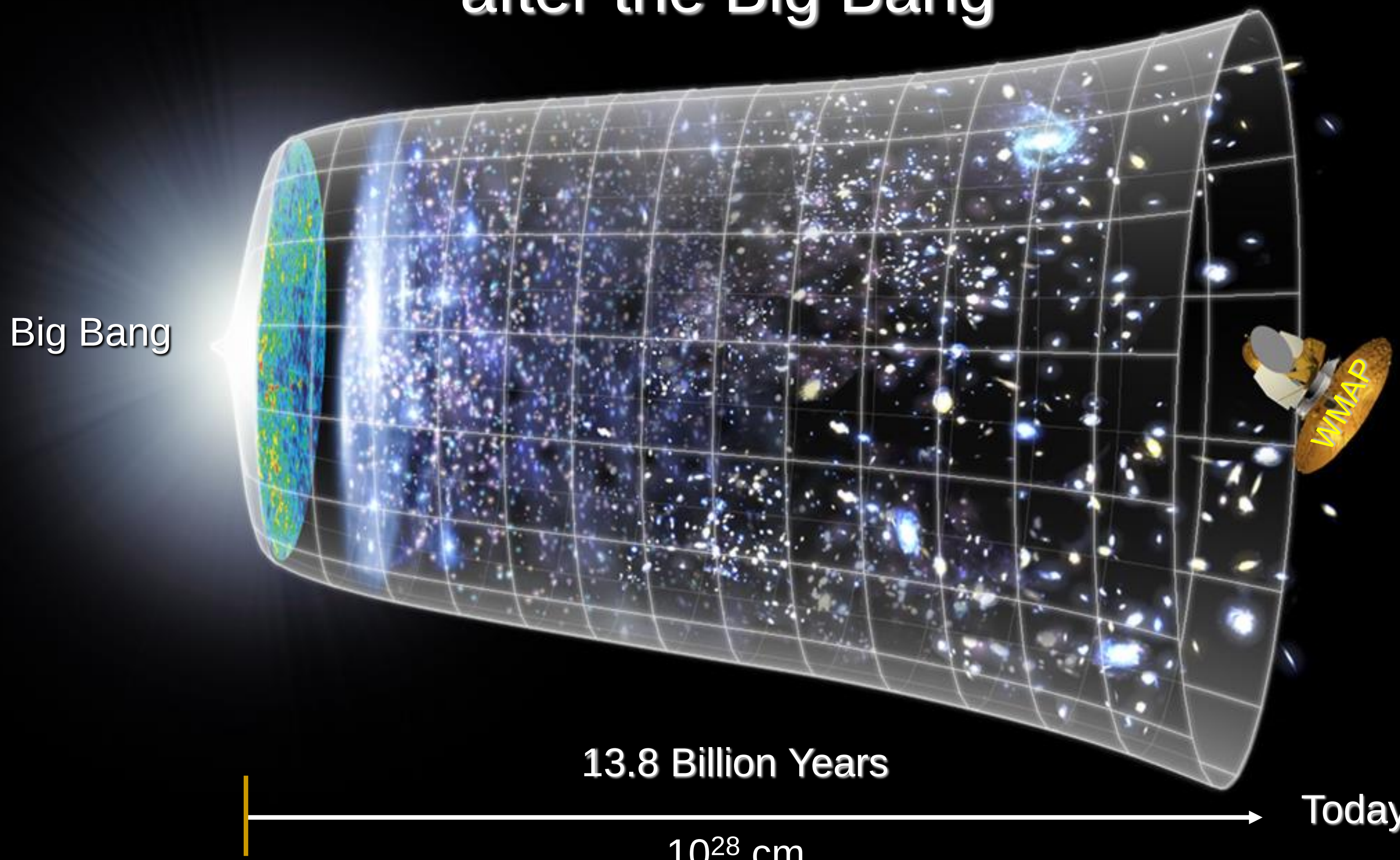
Αύγουστος 2019

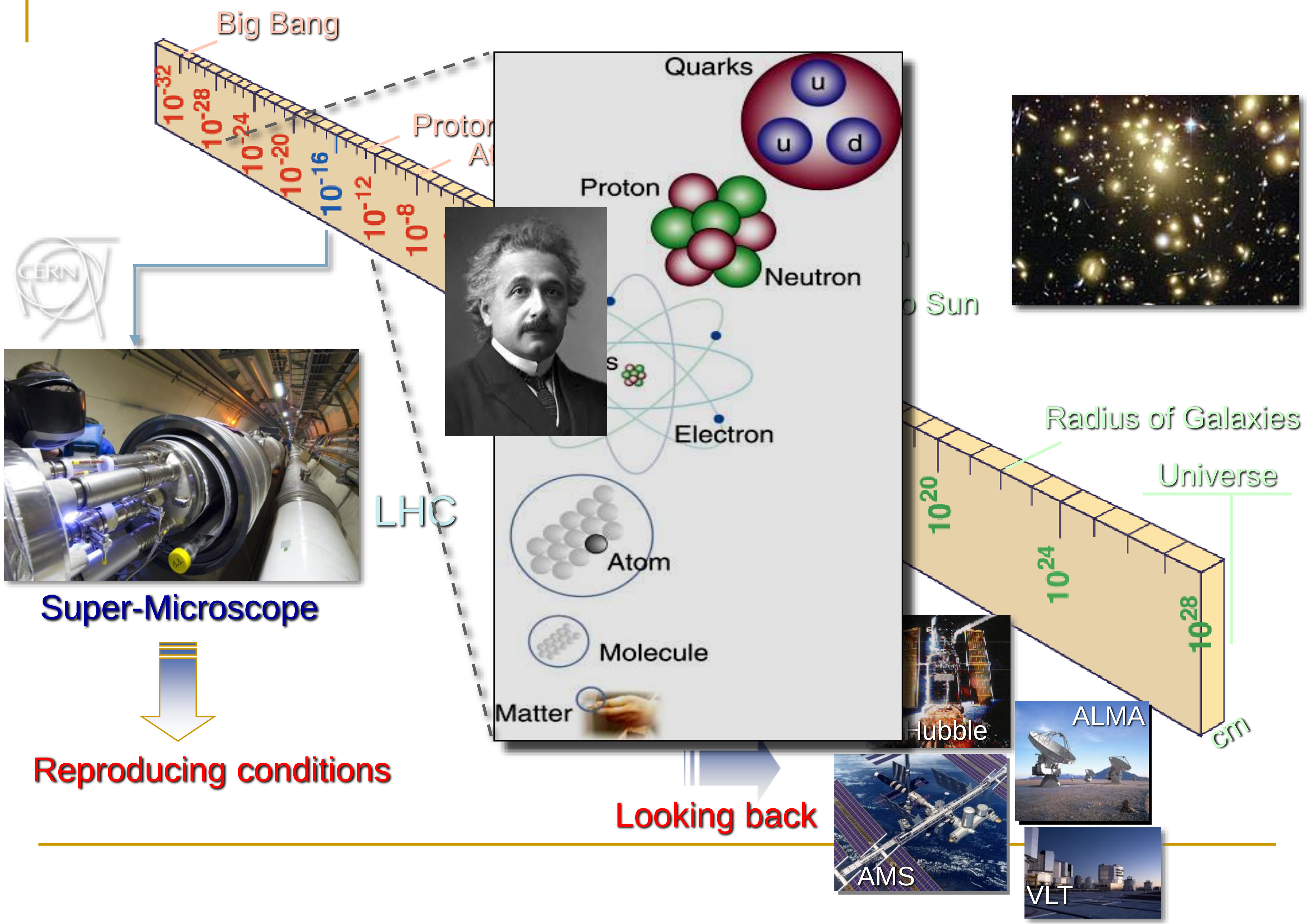
Introduction



Scientific Challenge:

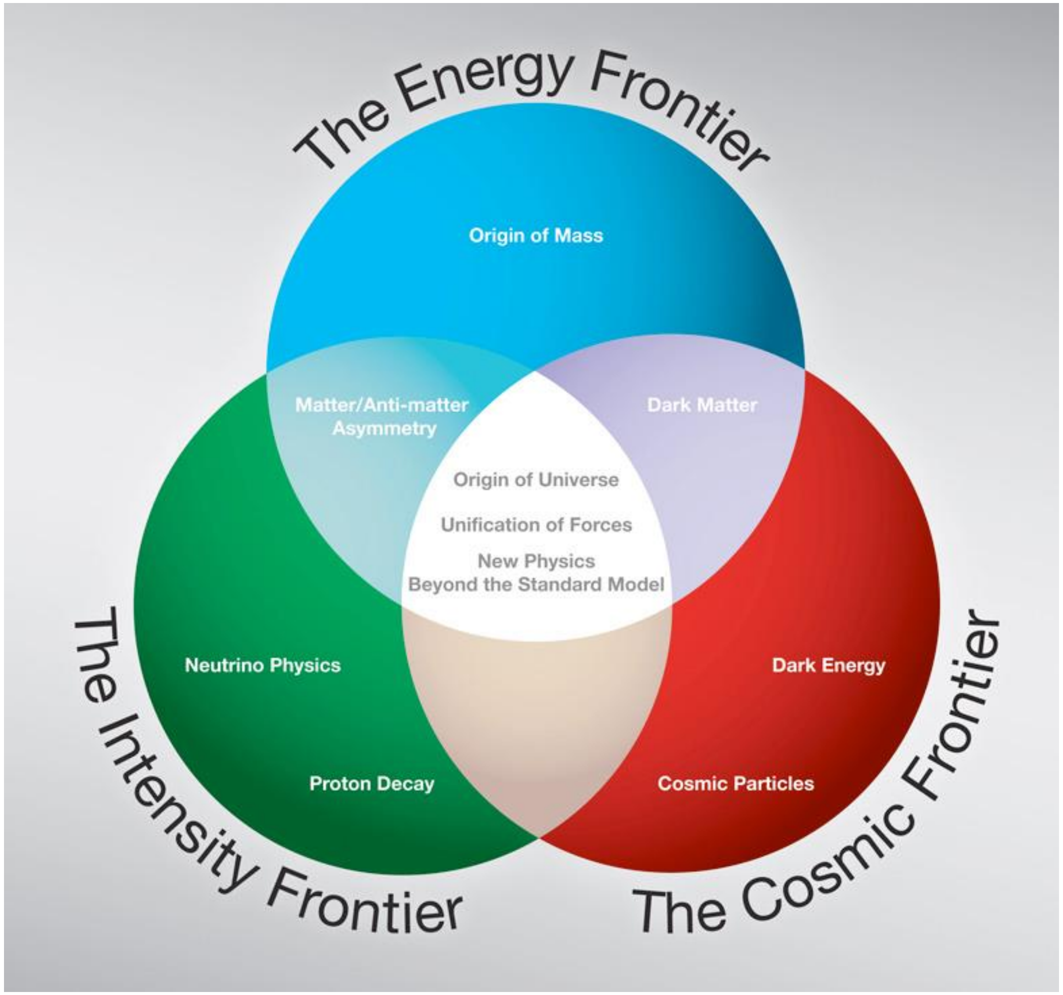
to understand the very first moments of our Universe after the Big Bang





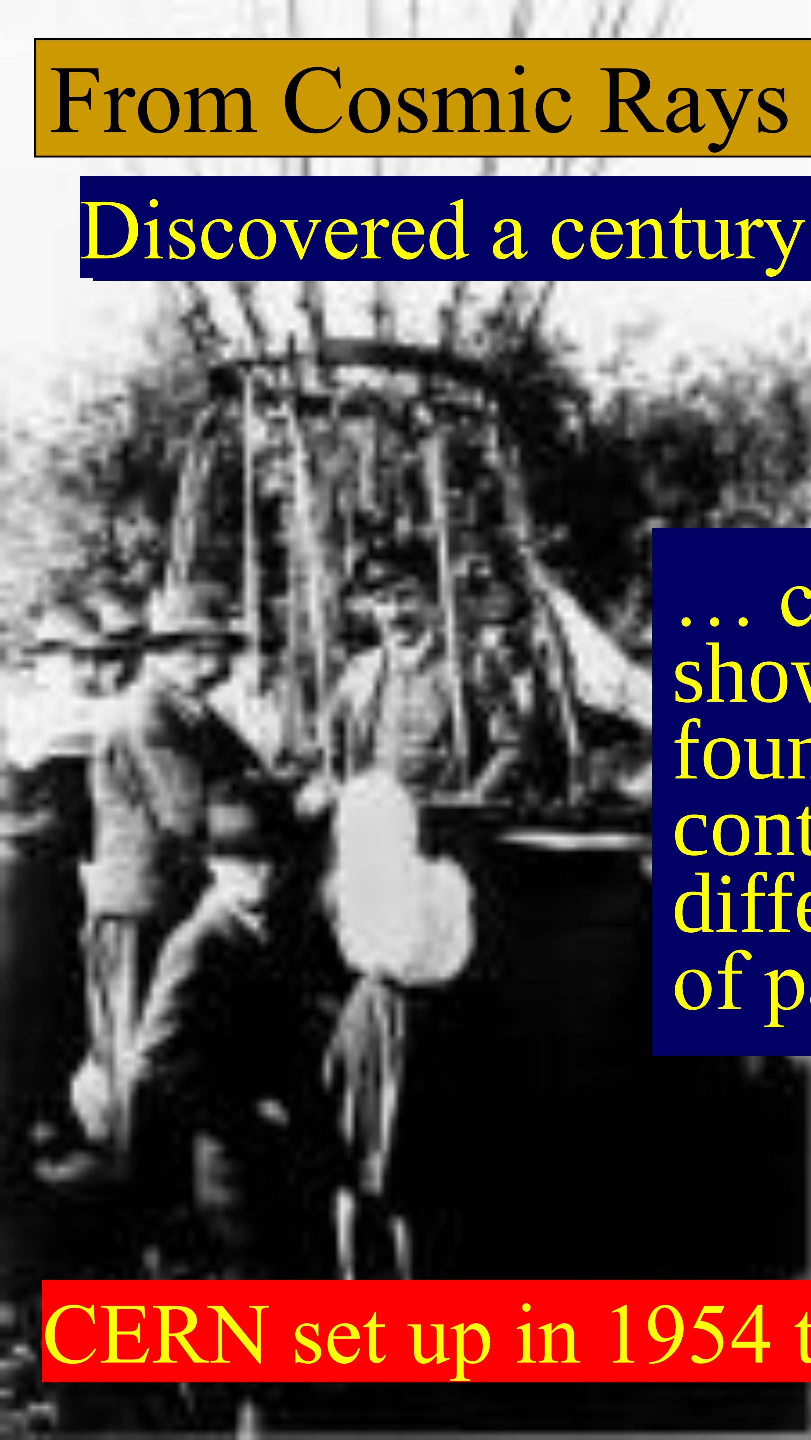
Big Bang
10^{-32}
10^{-28}
10^{-24}
10^{-20}
10^{-16}
10^{-12}
10^{-8}
Quarks
u
u
d
Proton
Neutron
Electron
Atom
Molecule
Matter
LHC
Super-Microscope
Reproducing conditions
Looking back
Radius of Galaxies
Universe
10^{20}
10^{24}
10^{28}
cm
ALMA
AMS
VLT

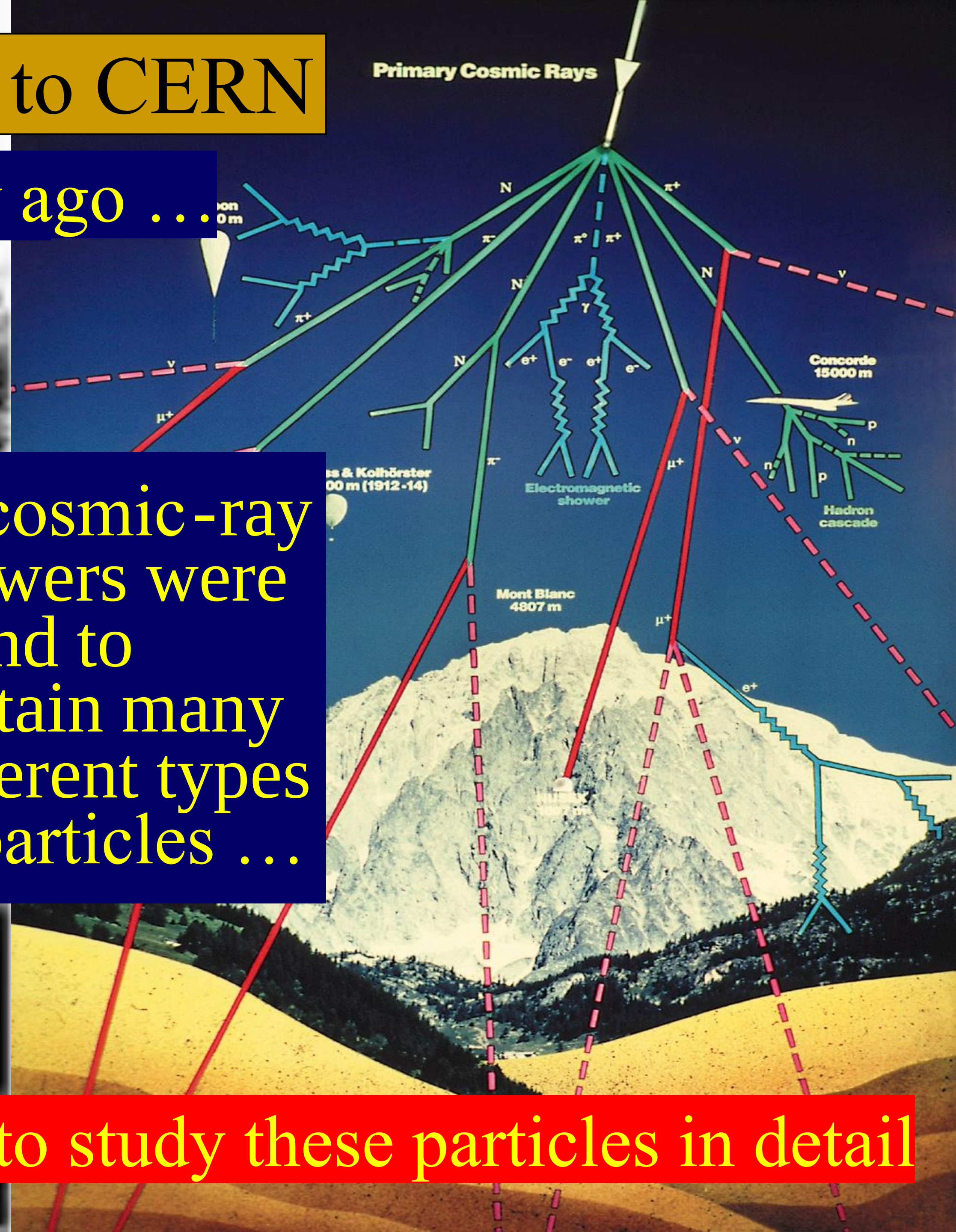
The Three Frontiers



From Cosmic Rays to CERN

Discovered a century ago …



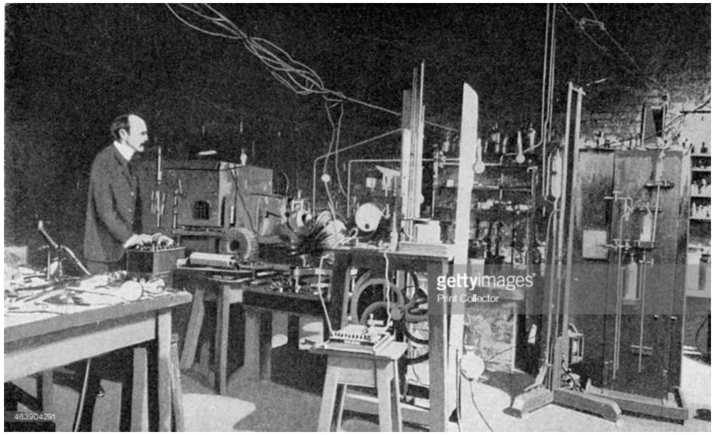


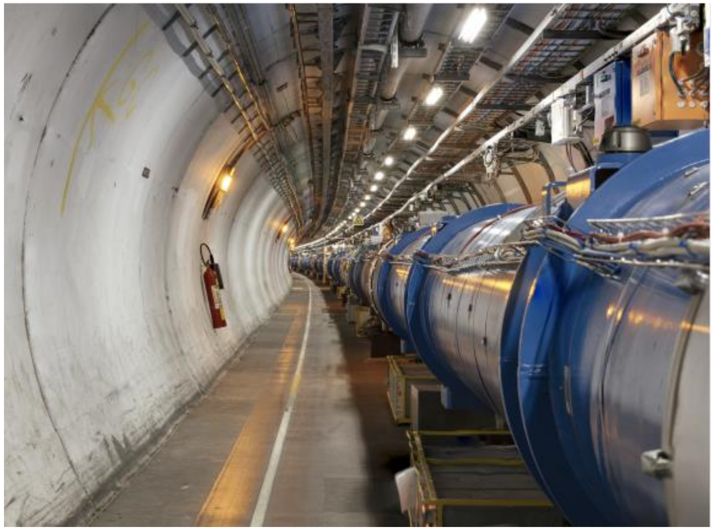
… cosmic-ray showers were found to contain many different types of particles …

CERN set up in 1954 to study these particles in detail

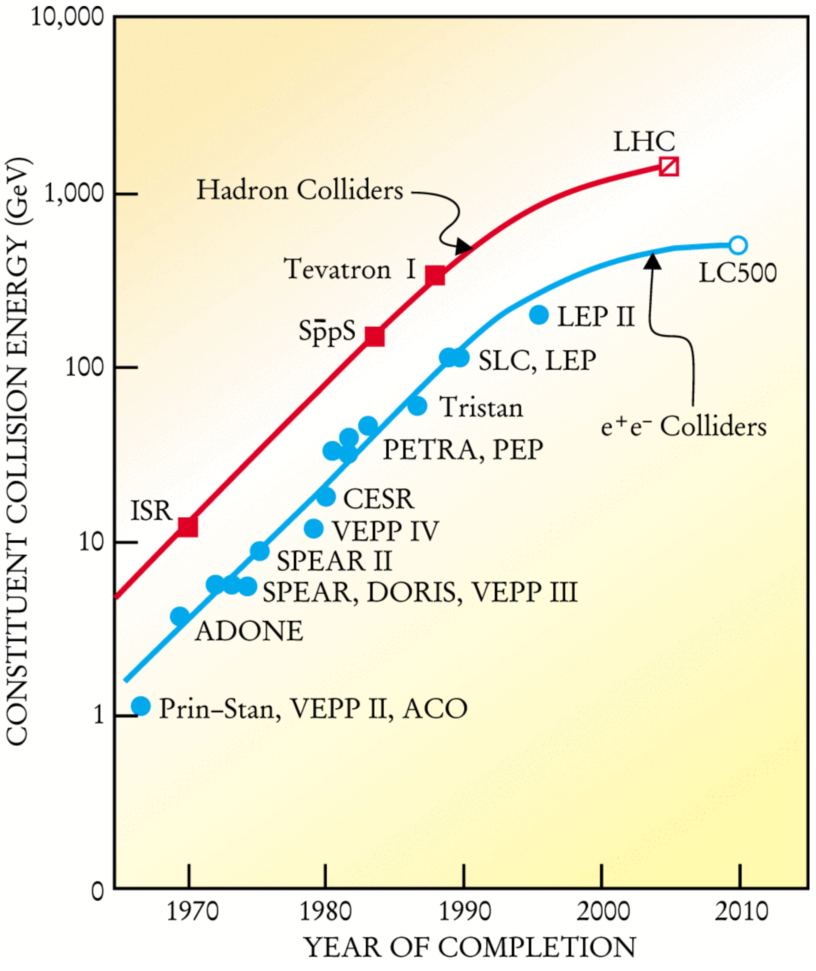
Accelerator Development

- 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.

24 (+1) Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Lawrence invented the cyclotron at the University of Californian at Berkeley in 1929 [12].
1951	John D. Cockcroft and Ernest T.S. Walton	Cockcroft and Walton invented their eponymous linear positive-ion accelerator at the Cavendish Laboratory in Cambridge, England, in 1932 [13].
1952	Felix Bloch	Bloch used a cyclotron at the Crocker Radiation Laboratory at the University of California at Berkeley in his discovery of the magnetic moment of the neutron in 1940 [14].
1957	Tsung-Dao Lee and Chen Ning Yang	Lee and Yang analyzed data on K mesons (θ and τ) from Bevatron experiments at the Lawrence Radiation Laboratory in 1955 [15], which supported their idea in 1956 that parity is not conserved in weak interactions [16].
1959	Emilio G. Segrè and Owen Chamberlain	Segrè and Chamberlain discovered the antiproton in 1955 using the Bevatron at the Lawrence Radiation Laboratory [17].
1960	Donald A. Glaser	Glaser tested his first experimental six-inch bubble chamber in 1955 with high-energy protons produced by the Brookhaven Cosmotron [18].
1961	Robert Hofstadter	Hofstadter carried out electron-scattering experiments on carbon-12 and oxygen-16 in 1959 using the SLAC linac and thereby made discoveries on the structure of nucleons [19].
1963	Maria Goeppert Mayer	Goeppert Mayer analyzed experiments using neutron beams produced by the University of Chicago cyclotron in 1947 to measure the nuclear binding energies of krypton and xenon [20], which led to her discoveries on high magic numbers in 1948 [21].
1967	Hans A. Bethe	Bethe analyzed nuclear reactions involving accelerated protons and other nuclei whereby he discovered in 1939 how energy is produced in stars [22].
1968	Luis W. Alvarez	Alvarez discovered a large number of resonance states using his fifteen-inch hydrogen bubble chamber and high-energy proton beams from the Bevatron at the Lawrence Radiation Laboratory [23].
1976	Burton Richter and Samuel C.C. Ting	Richter discovered the J/Ψ particle in 1974 using the SPEAR collider at Stanford [24], and Ting discovered the J/Ψ particle independently in 1974 using the Brookhaven Alternating Gradient Synchrotron [25].
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Glashow, Salam, and Weinberg cited experiments on the bombardment of nuclei with neutrinos at CERN in 1973 [26] as confirmation of their prediction of weak neutral currents [27].
1980	James W. Cronin and Val L. Fitch	Cronin and Fitch concluded in 1964 that CP (charge-parity) symmetry is violated in the decay of neutral K mesons based upon their experiments using the Brookhaven Alternating Gradient Synchrotron [28].
1981	Kai M. Siegbahn	Siegbahn invented a weak-focusing principle for betatrons in 1944 with which he made significant improvements in high-resolution electron spectroscopy [29].
1983	William A. Fowler	Fowler collaborated on and analyzed accelerator-based experiments in 1958 [30], which he used to support his hypothesis on stellar-fusion processes in 1957 [31].
1984	Carlo Rubbia and Simon van der Meer	Rubbia led a team of physicists who observed the intermediate vector bosons W and Z in 1983 using CERN's proton-antiproton collider [32], and van der Meer developed much of the instrumentation needed for these experiments [33].
1986	Ernst Ruska	Ruska built the first electron microscope in 1933 based upon a magnetic optical system that provided large magnification [34].
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Lederman, Schwartz, and Steinberger discovered the muon neutrino in 1962 using Brookhaven's Alternating Gradient Synchrotron [35].
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics [36].
1990	Jerome I. Friedman, Henry W. Kendall, and Richard E. Taylor	Friedman, Kendall, and Taylor's experiments in 1974 on deep inelastic scattering of electrons on protons and bound neutrons used the SLAC linac [37].
1992	Georges Charpak	Charpak's development of multiwire proportional chambers in 1970 were made possible by accelerator-based testing at CERN [38].
1995	Martin L. Perl	Perl discovered the tau lepton in 1975 using Stanford's SPEAR collider [39].
2004	David J. Gross, Frank Wilczek, and H. David Politzer	Gross, Wilczek, and Politzer discovered asymptotic freedom in the theory of strong interactions in 1973 based upon results from the SLAC linac on electron-proton scattering [40].
2008	Makoto Kobayashi and Toshihide Maskawa	Kobayashi and Maskawa's theory of quark mixing in 1973 was confirmed by results from the KEKB accelerator at KEK (High Energy Accelerator Research Organization) in Tsukuba, Ibaraki Prefecture, Japan, and the PEP II (Positron Electron Project II) at SLAC [41], which showed that quark mixing in the six-quark model is the dominant source of broken symmetry [42].

A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

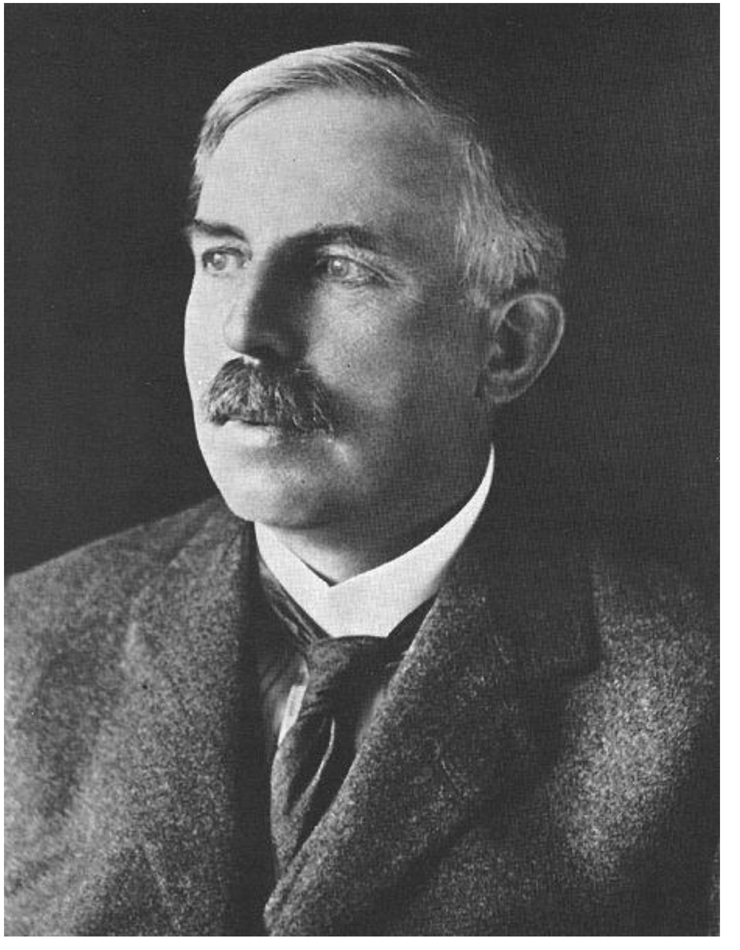
Nobel Prize in Physics 2013

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".*

Rutherford fired the starting pistol

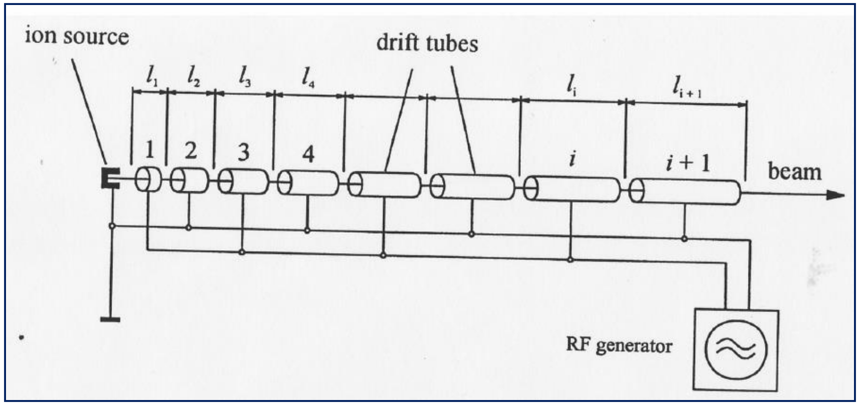
At the Royal Society in 1928 he said:

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances".

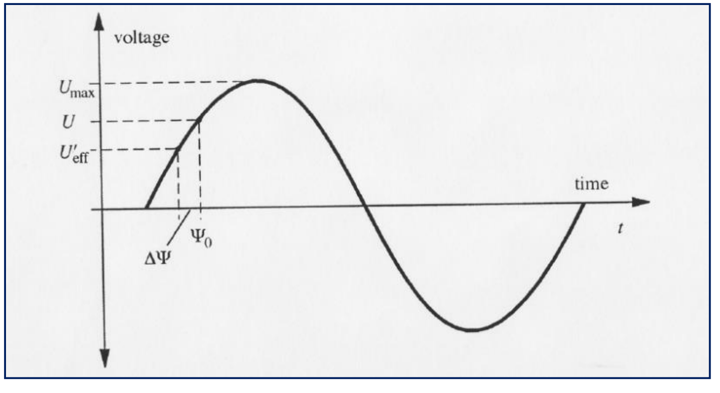


Linear Accelerators

Wideröe linear accelerator

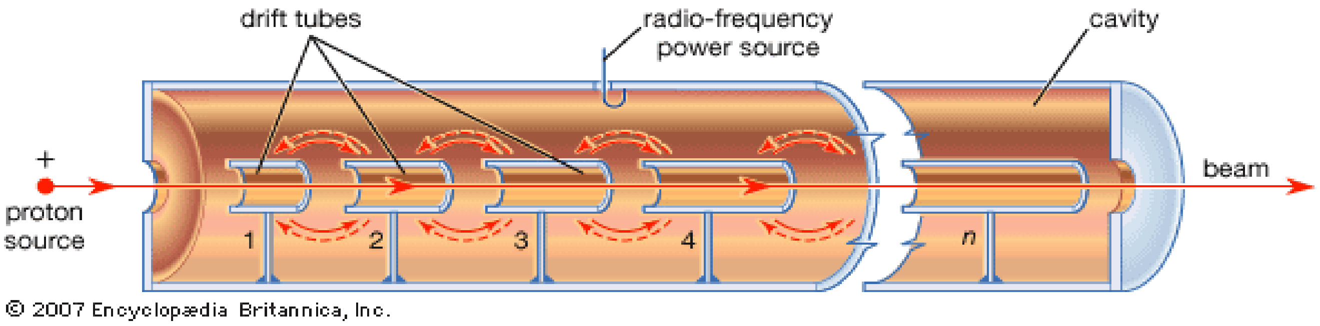


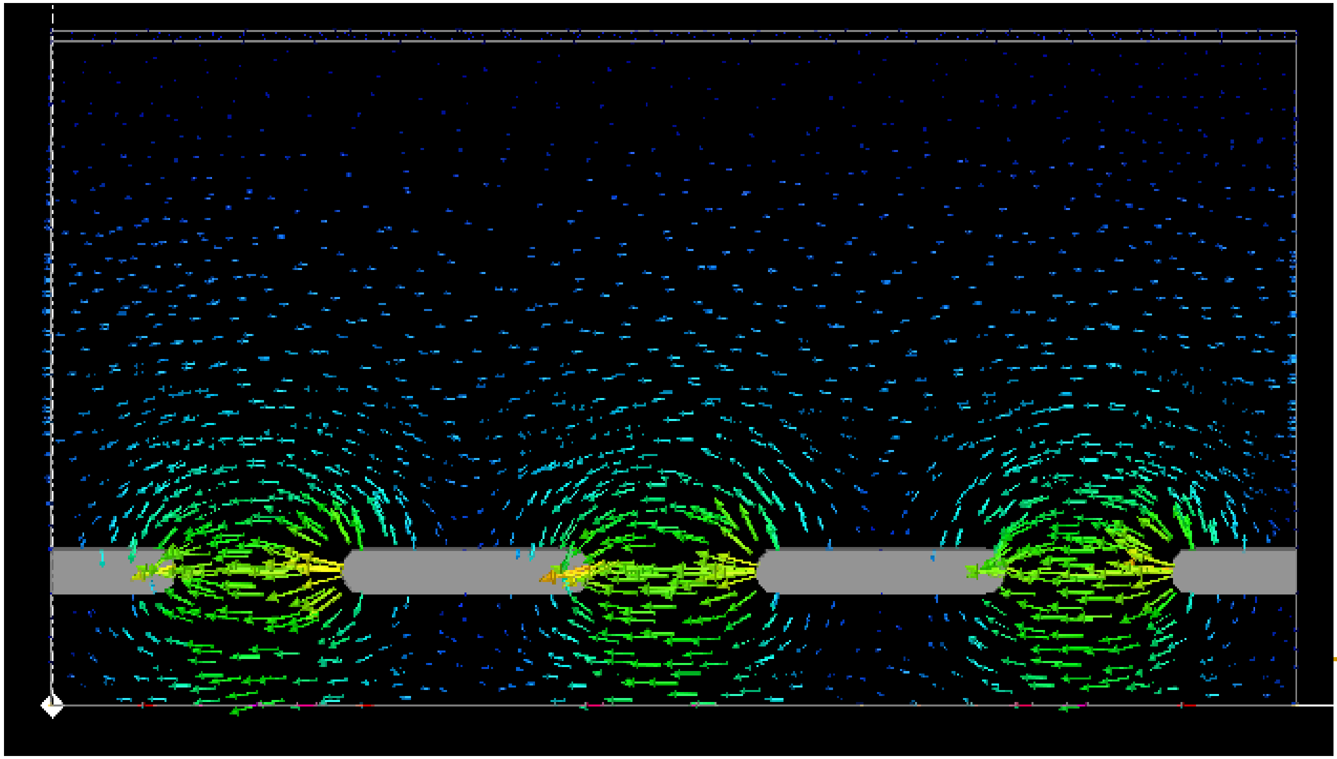
Phase focusing in linacs



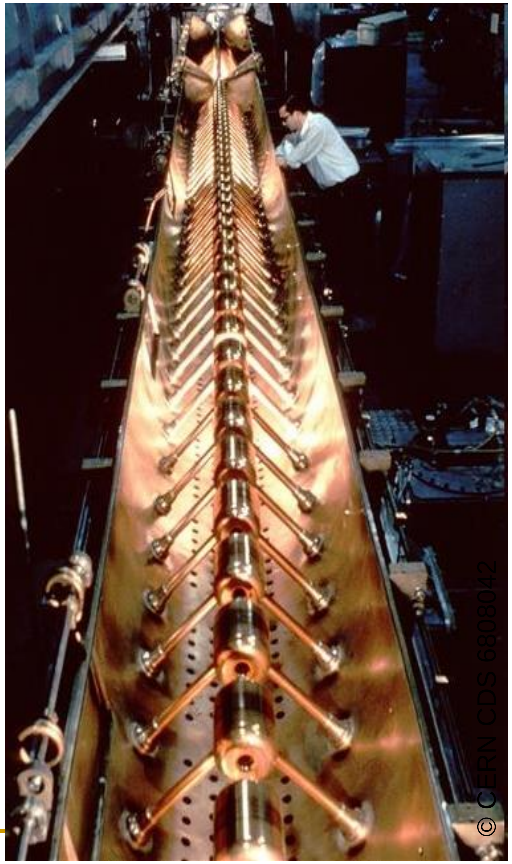
- Principle
  - Use rapidly-changing high frequency voltages instead of direct voltages (Ising)
  - Energy is proportional to number of stages *i* traversed by particle.
  - The largest voltage in entire system is never greater than V_{max}
    - Arbitrary high energies without voltage discharge.

Drift Tube Linac: Higher Integrated Field



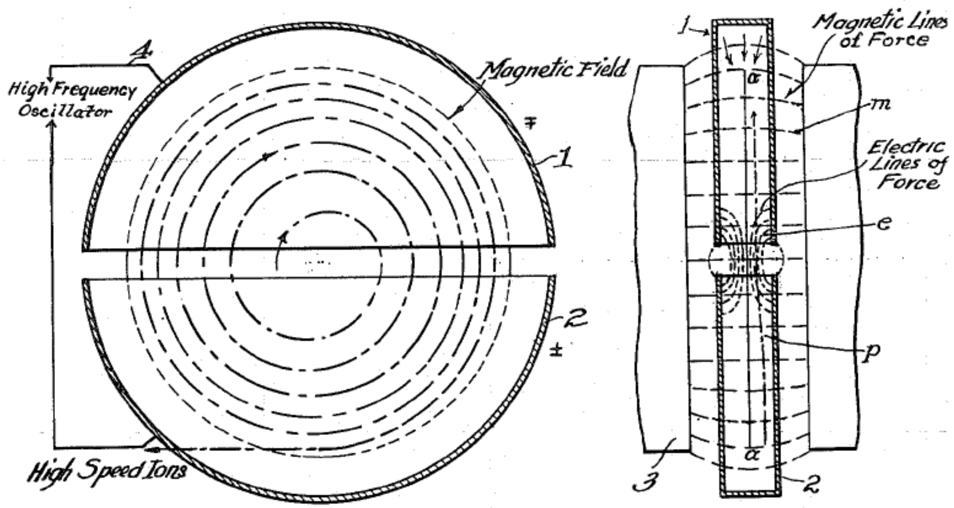


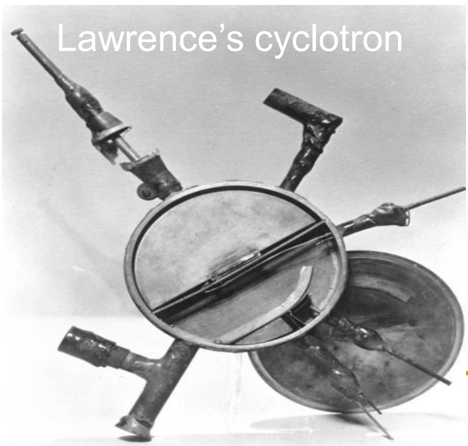
CERN LINAC1

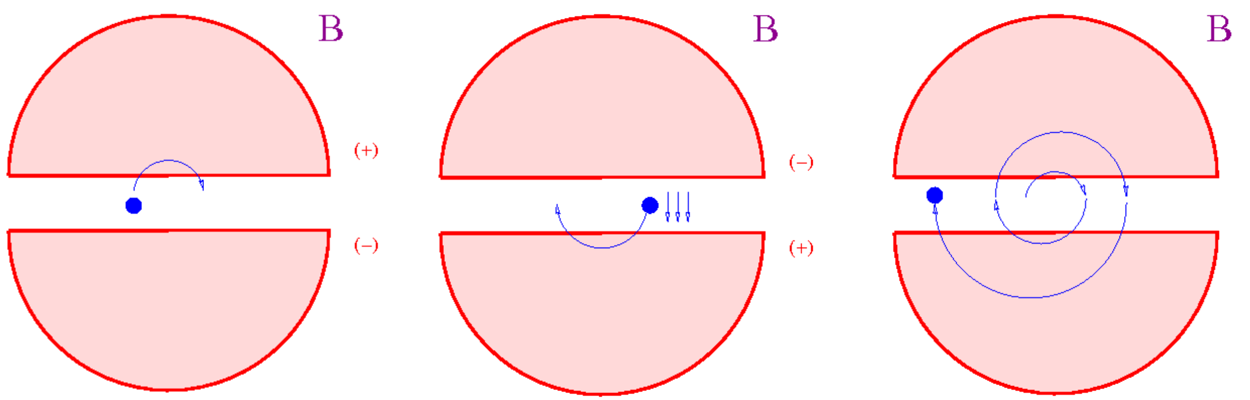


Cyclic Accelerators

- In 1931 Lawrence designed a “cyclotron”, a circular device made of two electrodes placed in a magnetic field.
- Cyclotrons can accelerate (e.g.) protons up to hundreds of MeV.





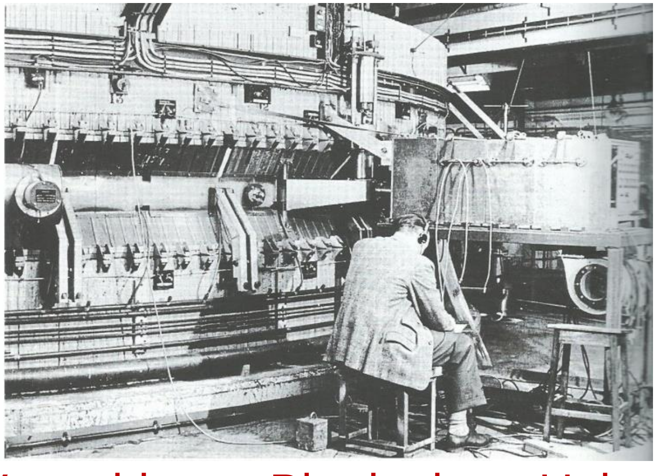


Mark Oliphant & the Synchrotron

"Particles should be constrained to move in a circle of constant radius thus enabling the use of an annular ring of magnetic field...which would be varied in such a way that the radius of curvature remains constant as the particle gains energy through successive accelerations by an alternating electric field applied between coaxial hollow electrodes."

Mark Oliphant, Oak Ridge, 1943

With Ernest Rutherford in 1932



1 GeV machine at Birmingham University

Synchrotrons

- From

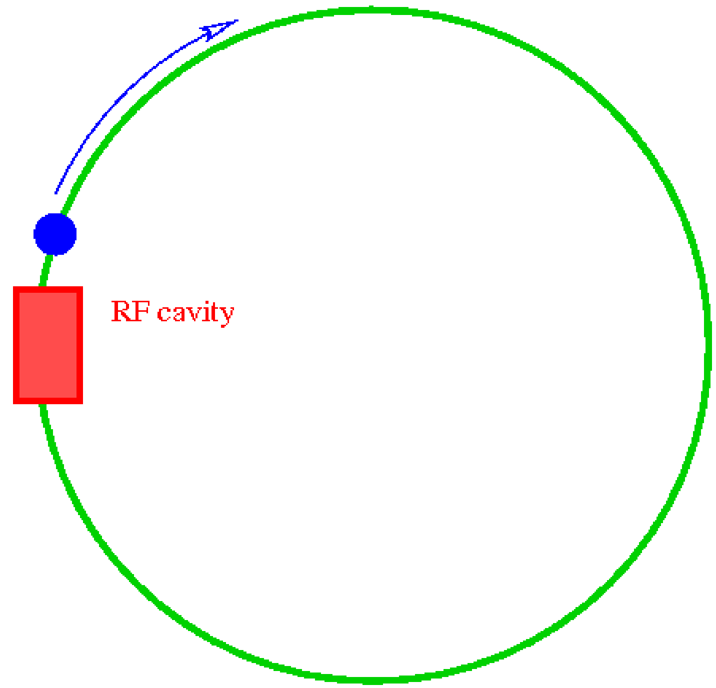
  $R = E / (ecB)$

  E/B kept constant since R is fixed.

  B increases synchronously with rising *E*

- Synchrotrons can accelerate to much higher energies.
  - e.g., LHC is synchrotron

- Limitation of synchrotrons (especially for electrons) is due to “synchrotron radiation”.



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.

Steering the Particle Beams

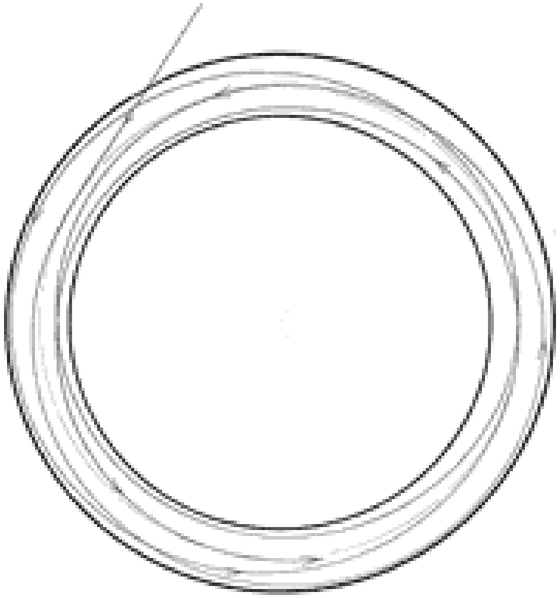
- A magnetic field can be used to deflect the particles.
- Lorentz force:
  $f = q(E + v \times B)$
- The LHC uses very strong magnets to keep its particles in a circular orbit.

LHC Dipole

http://lhc-machine-outreach.web.cern.ch

Focusing

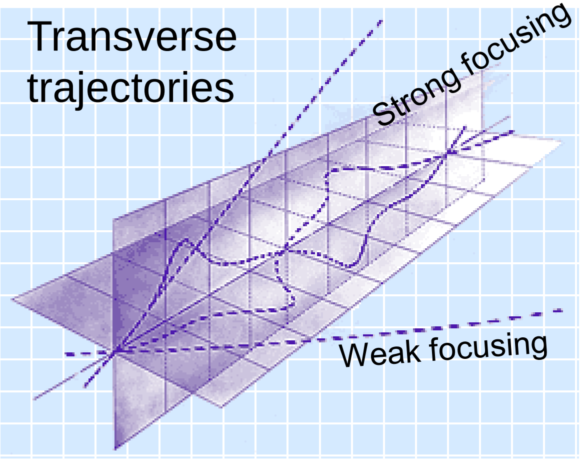
- Focusing is needed to confine the orbits.
- First accelerators had “weak focusing” – focusing period is larger than the perimeter.



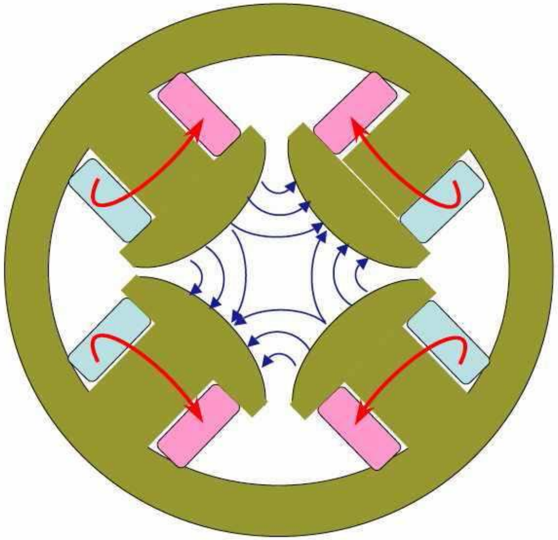
Weak focusing accelerator

10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful of its time. Its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

- “Strong focusing” alternates focusing-defocusing forces (provided by quadrupoles) to give overall focusing in both X & Y planes.



Strong focusing allows use of more compact magnets, thus achieving many times larger energy with the same cost.



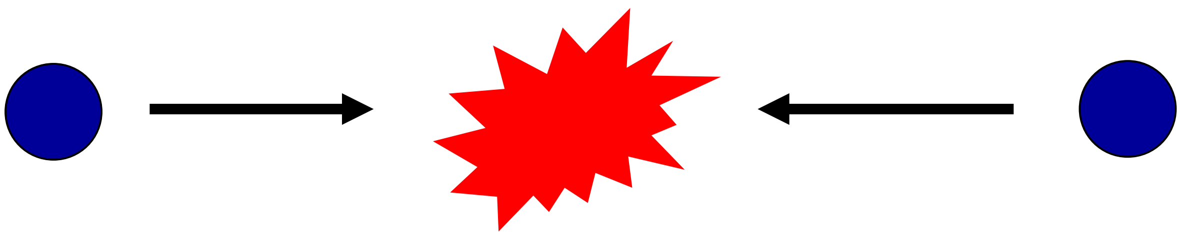
CERN's Proton Synchrotron, was the first operating strong-focusing accelerator.

200-m diameter ring, weight of magnets 3,800 tons

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?

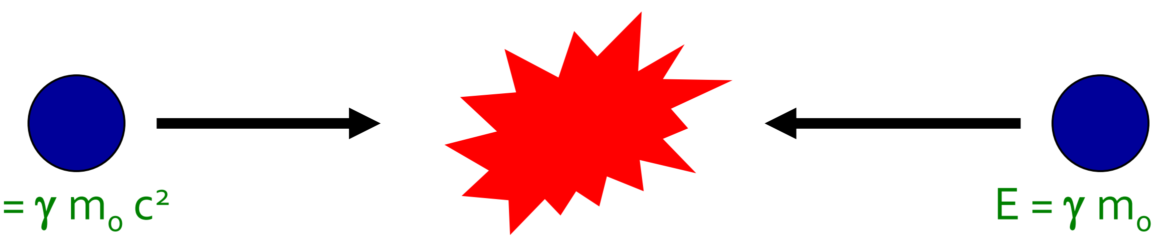
Fixed-target

$E = \gamma\, m_o\, c^2$

$P = \gamma\, m_o\, v$

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

Colliders



$E = \gamma\, m_o\, c^2$ $\qquad$ $E = \gamma\, m_o\, c^2$

Entire energy converted into the mass of new particles

De Broglie Wavelength

Momentum

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

Planck Constant

De Broglie wavelength

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"):

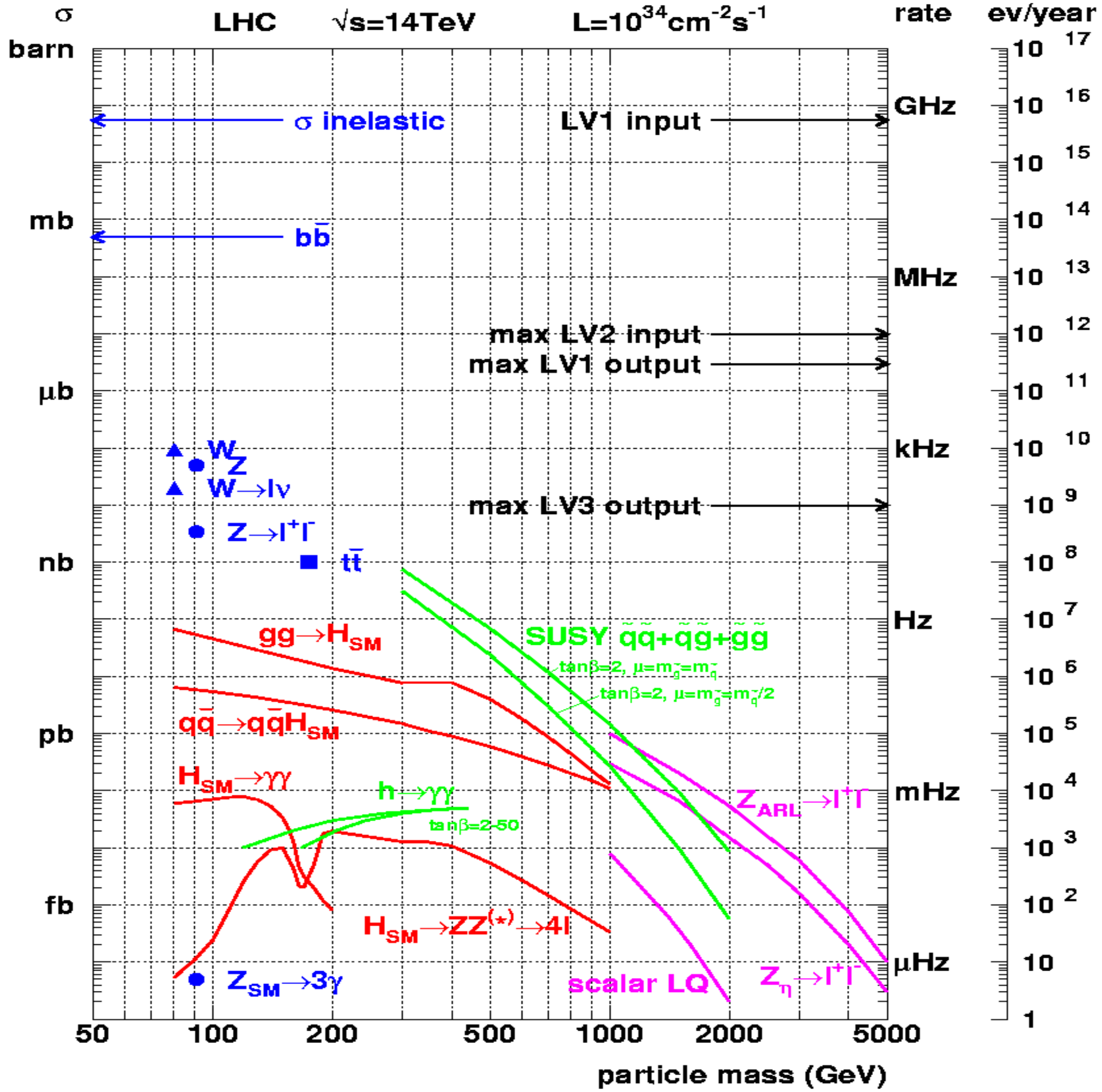
$$R = \mathcal{L}\sigma$$

For a Collider, instantaneous luminosity 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



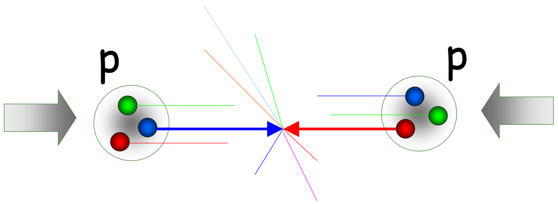
"Well known" processes. Don't need to keep all of them …

New Physics!!

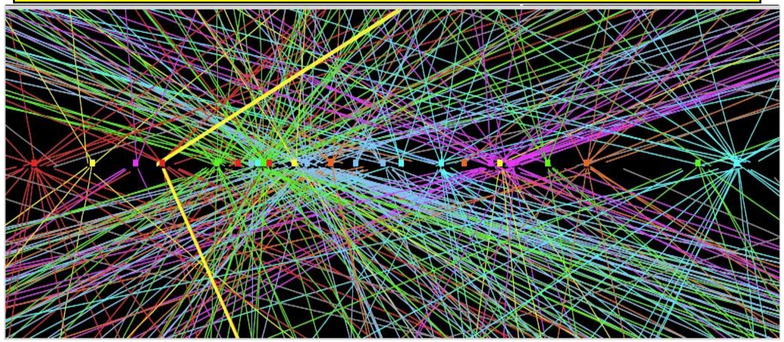
We want to keep!!

Collider Characteristics

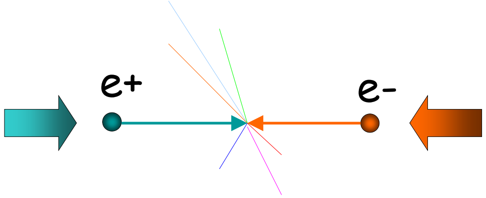
- Hadron collider at the frontier of physics
  - Huge QCD background
  - Not all nucleon energy available in collision

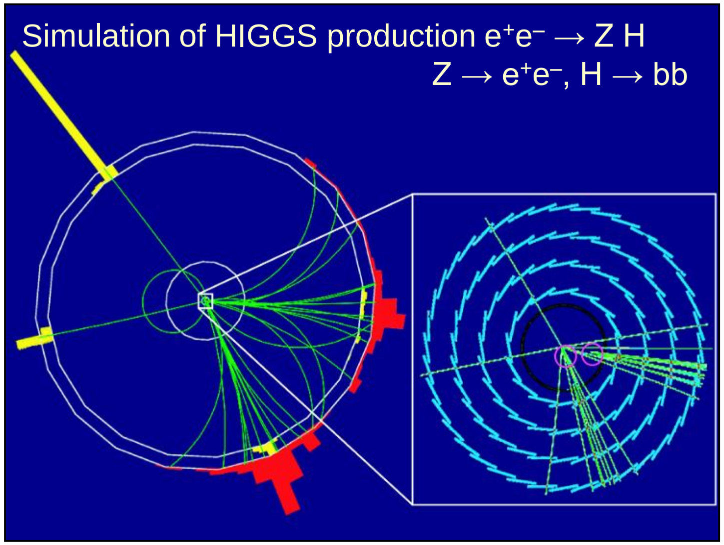


ATLAS Z → μμ event from 2012 data with 25 reconstructed vertices

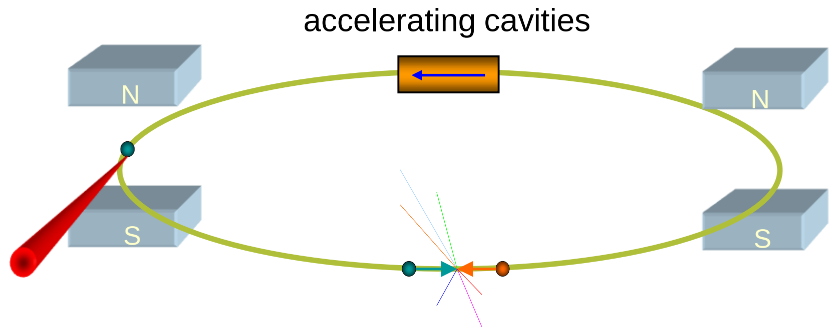


- Lepton collider for precision physics
  - Well defined initial energy for reaction
  - Colliding point like particles





Circular versus Linear Collider

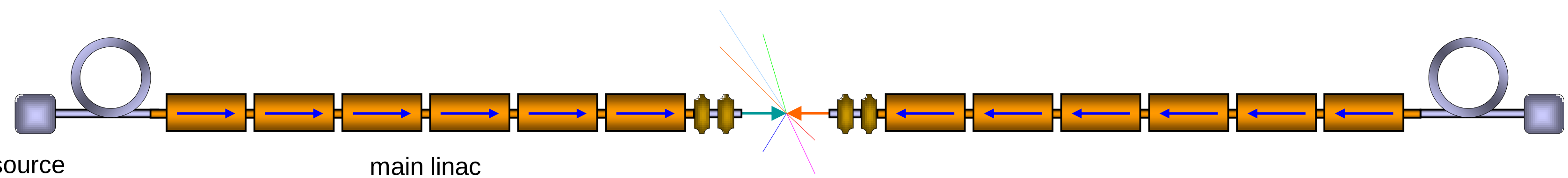


Circular Collider

many magnets, few cavities, stored beam

higher energy → stronger magnetic field

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



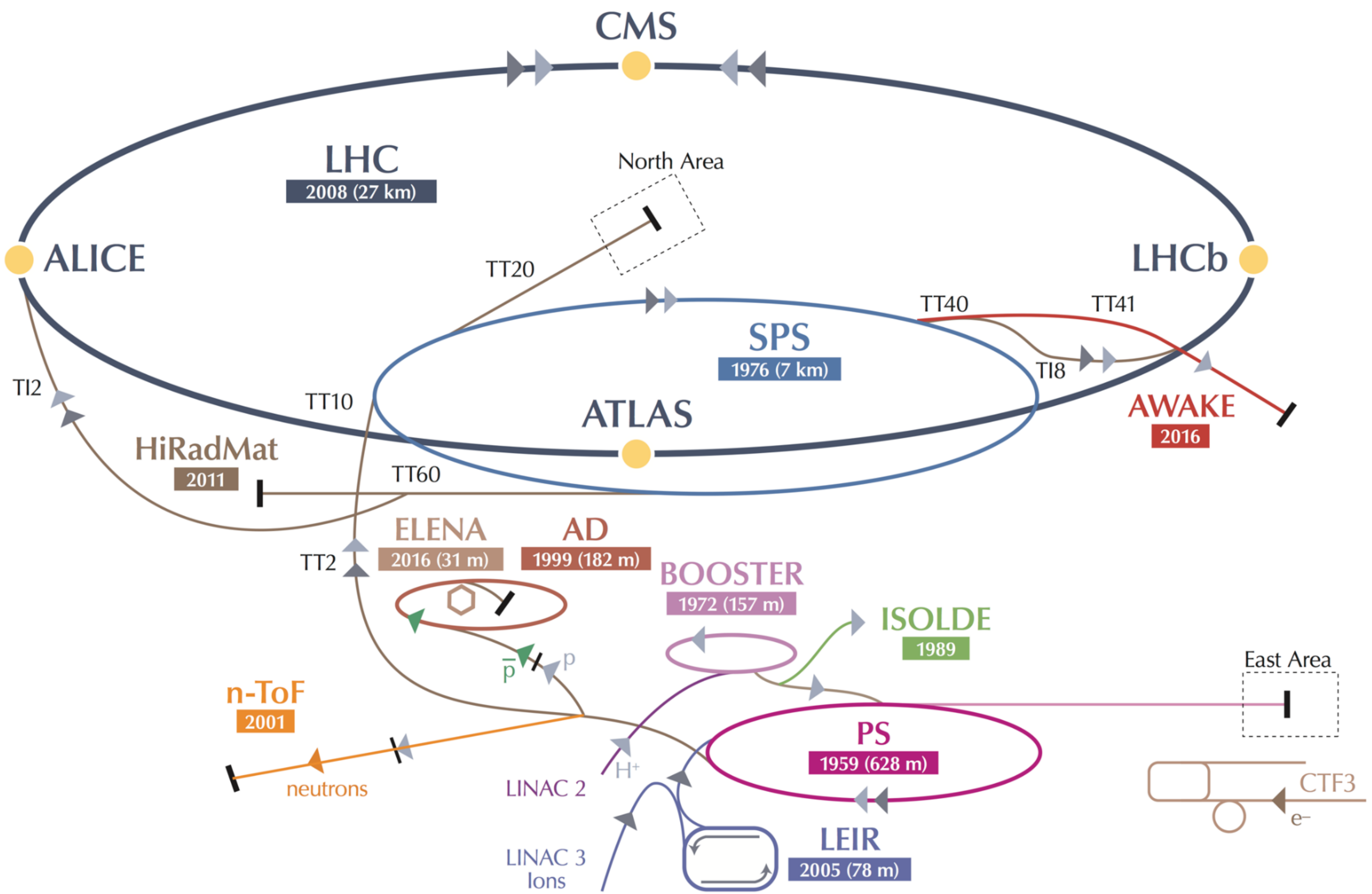
Linear Collider

few magnets, many cavities, single pass beam

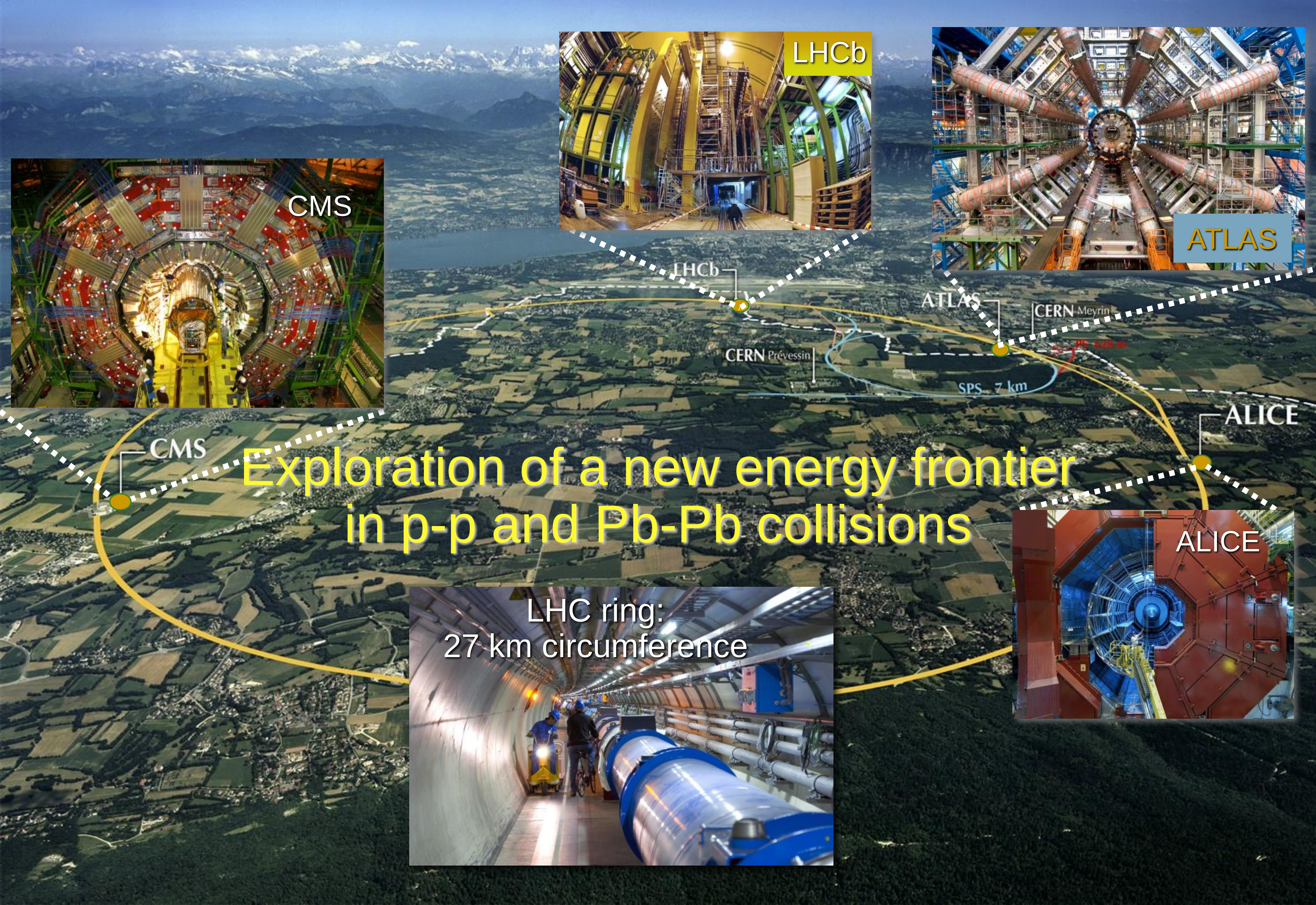
higher energy → higher accelerating gradient

higher luminosity → higher beam power (high bunch repetition)

CERN Accelerator Complex

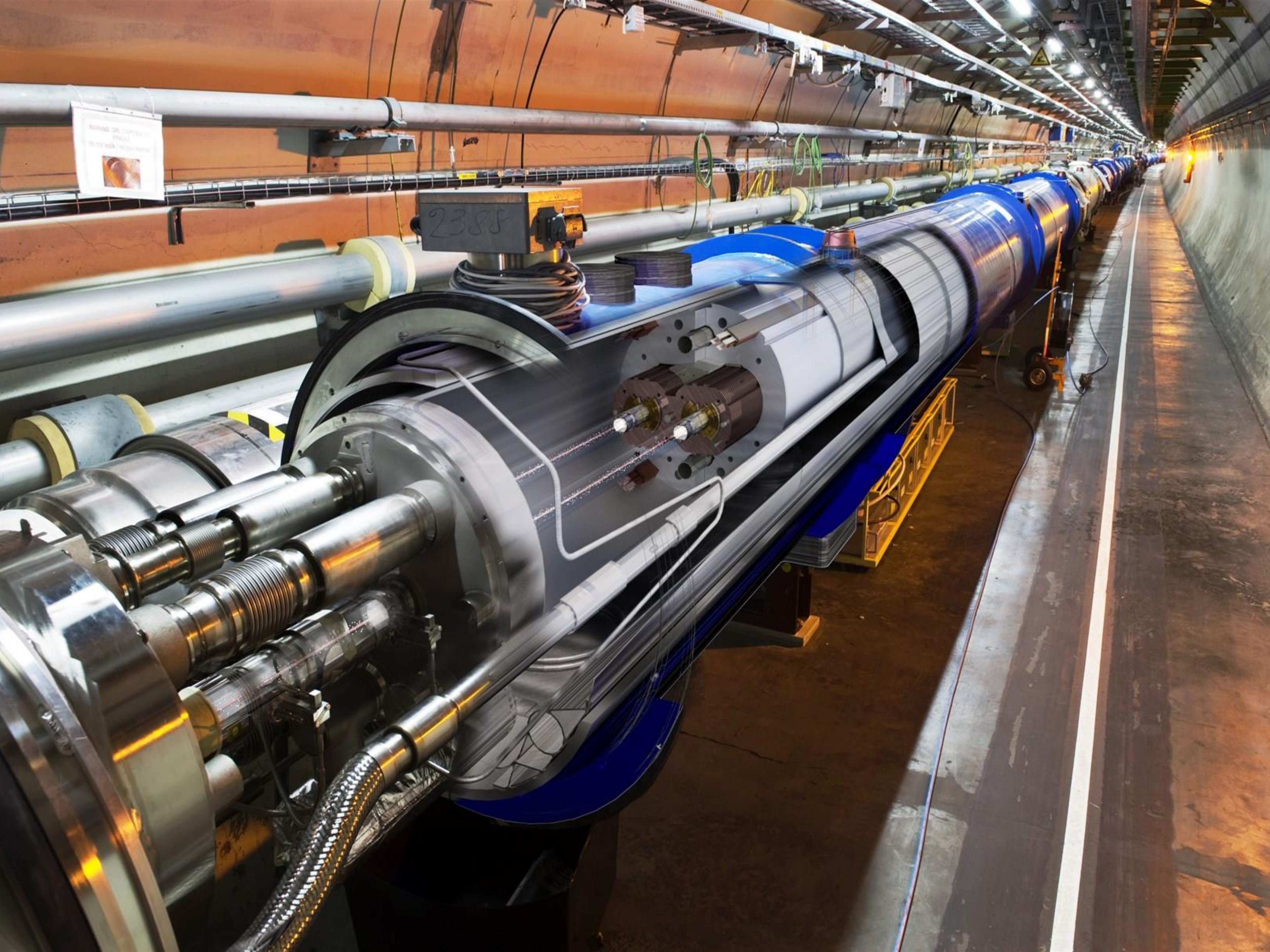


A New Era in Fundamental Science



Exploration of a new energy frontier
in p-p and Pb-Pb collisions

The LHC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The Predictable Future - *LHC Timeline*

2009

Start of LHC

Run 1: 7 and 8 TeV centre-of-mass energy, luminosity ramping up to several 10^{33} cm^{-2} s^{-1}, ~25 fb^{-1} delivered

2013/14

LS1 - LHC shut-down to prepare machine for design energy and nominal luminosity

Run 2: Ramp up luminosity to … cm^{-2} s^{-1}, ~50 to 100 fb^{-1}) and centre-of-mass energy (1…)

2018

LS2 - Injector and L… s to go to ultimate luminosity

Ru… p luminosity to 2.2 x nominal, reaching ~100 fb^{-1} / year acc… e few hundred fb^{-1}

Study of the properties of the Higgs Boson & physics beyond the Standard Model

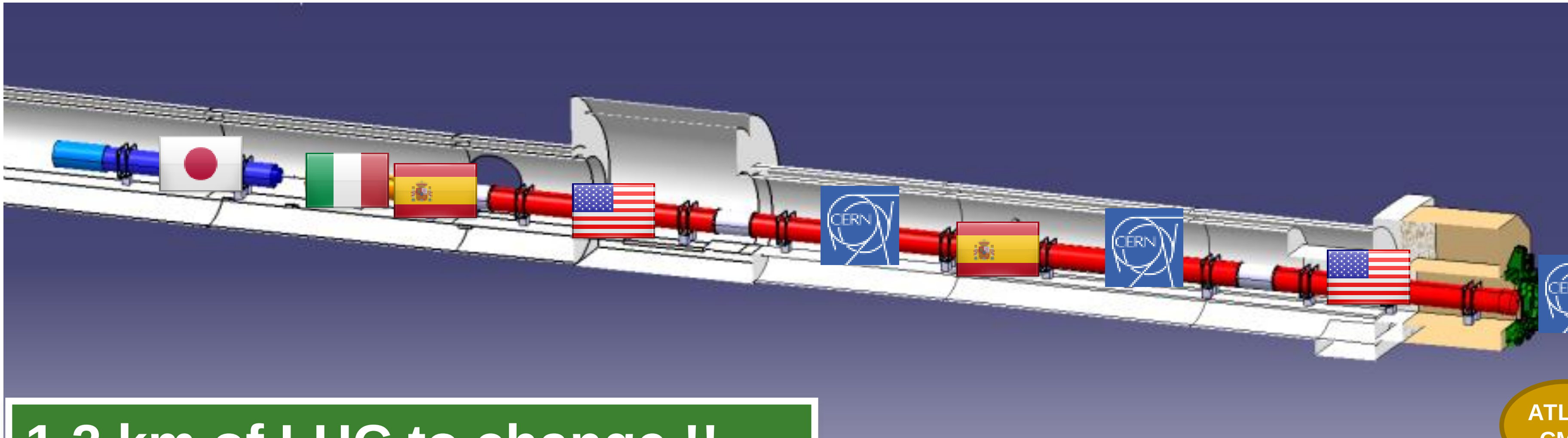
~2023

LS3 – High-luminosity LHC (HL-LHC). New focusing magnets and CRAB cavities for very high luminosity with levelling

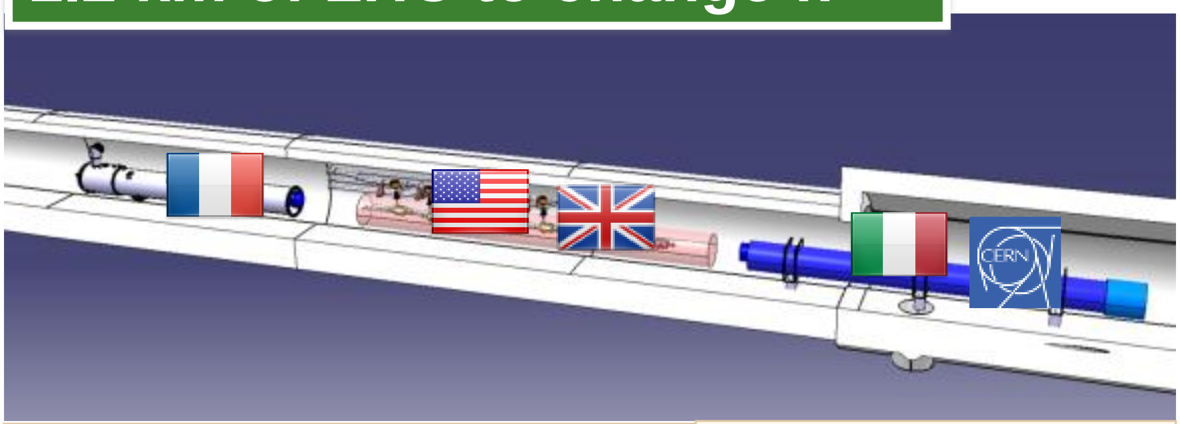
Run 4: Collect data until > 3000 fb^{-1}

>2035

HL-LHC: In-kind Contribution and Collaboration for Design and Prototypes



1.2 km of LHC to change !!

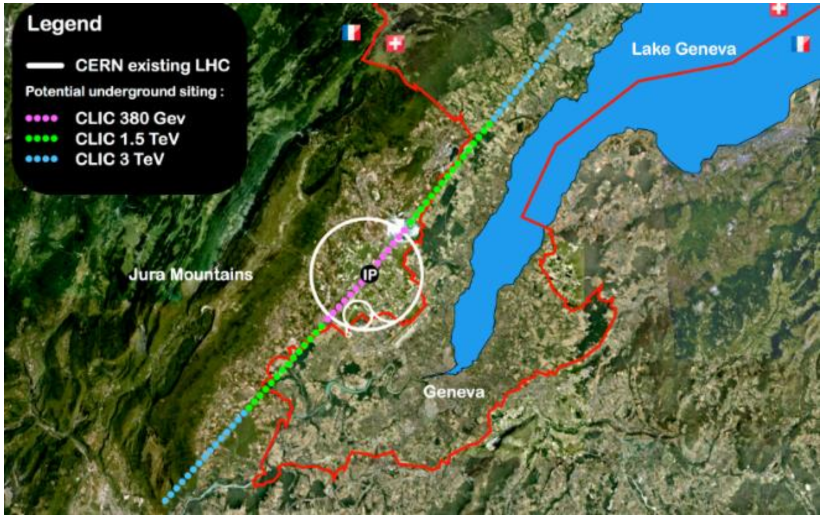


CC : R&D, Design and in-kind **USA**

CC : R&D and Design **UK**

Q1-Q3 : R&D, Design, Prototypes and in-kind **USA**
D1 : R&D, Design, Prototypes and in-kind **JP**
MCBX : Design and Prototype **ES**
HO Correctors: Design and Prototypes **IT**
Q4 : Design and Prototype **FR**

Future of Particle Physics

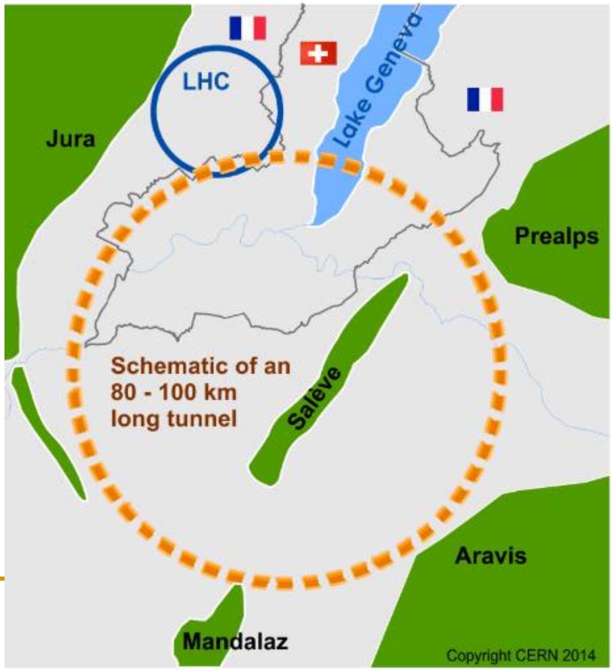


High Luminosity LHC until 2035

- Ten times more collisions than the original design

Studies in progress: Compact Linear Collider (CLIC)

- Linear e^+e^- collider $\sqrt{s}$ up to 3 TeV



Future Circular Collider (FCC)

- New technology magnets → 100 TeV pp collisions in 100km ring
- e^+e^- collider (FCC-ee) as 1st step?

European Strategy for Particle Physics

- Preparing next update in 2020

Future Circular Collider Study

Forming an international collaboration to study:

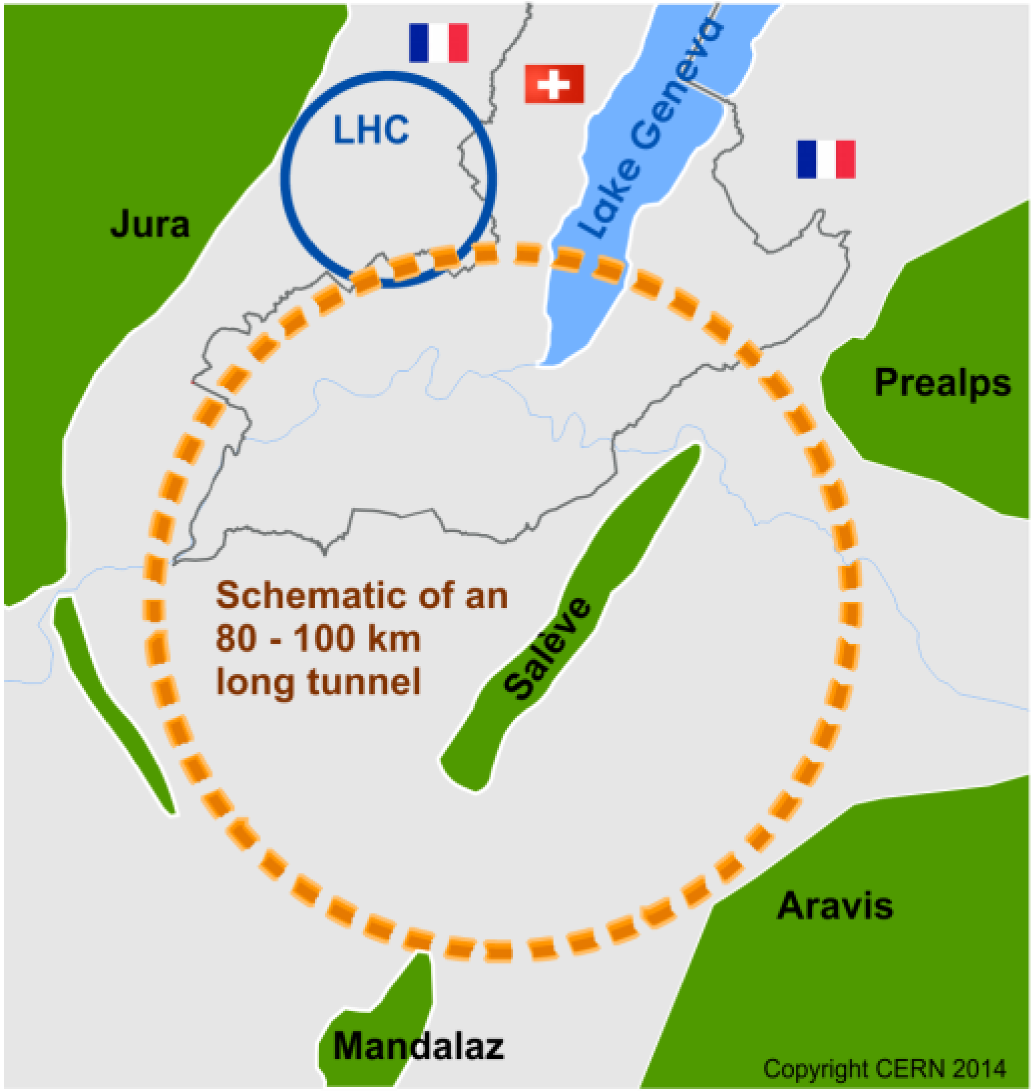
•***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

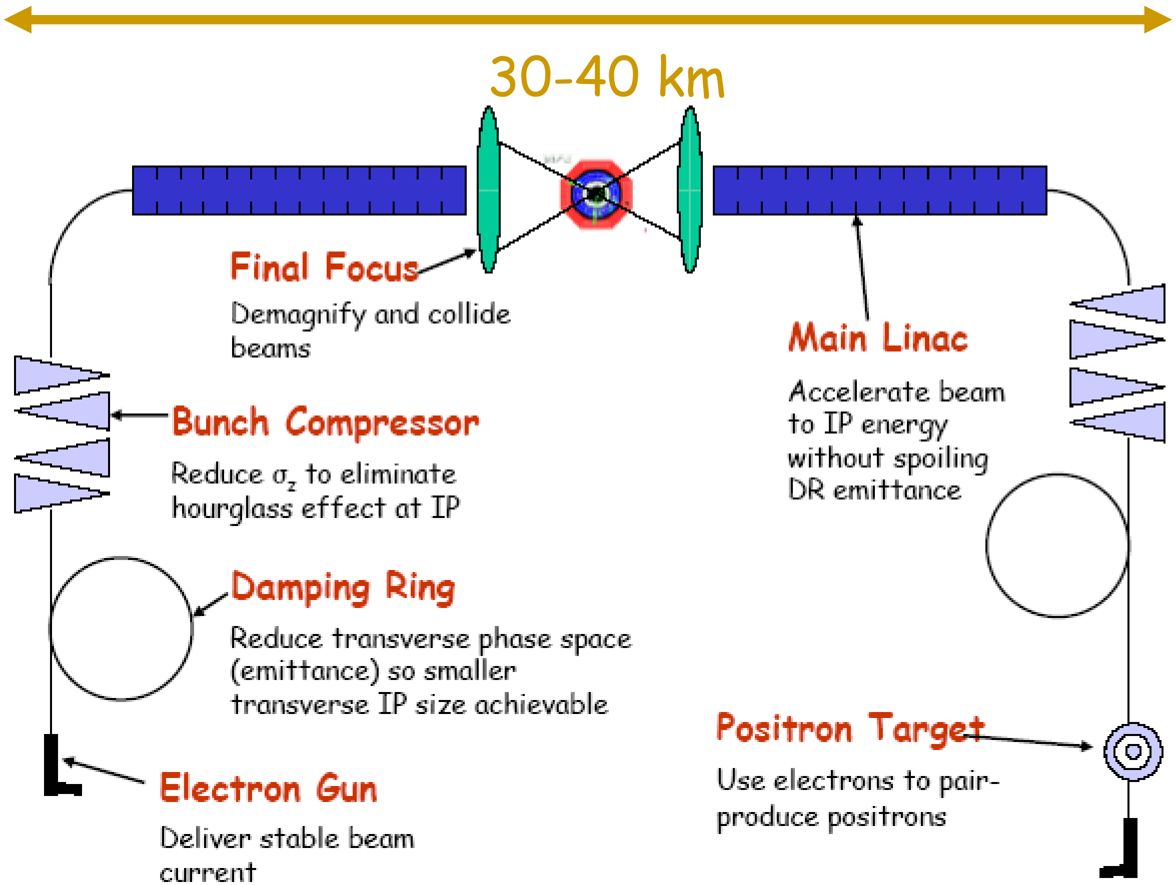
•**e^+e^- collider (*FCC-ee*)** as potential intermediate step

•***p-e* (*FCC-he*) option**

•**80-100 km infrastructure** in Geneva area



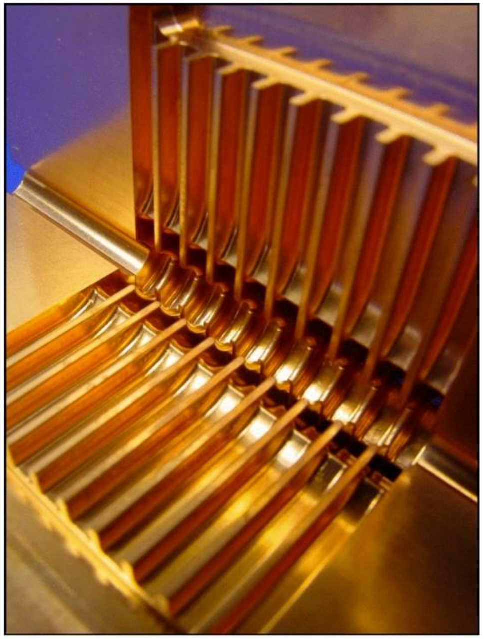
A Generic Linear Collider



The machine which will complement and extend the LHC best, and is closest to be realized, is a Linear e+e- Collider.

Linear Colliders

CLIC Compact Linear Collider

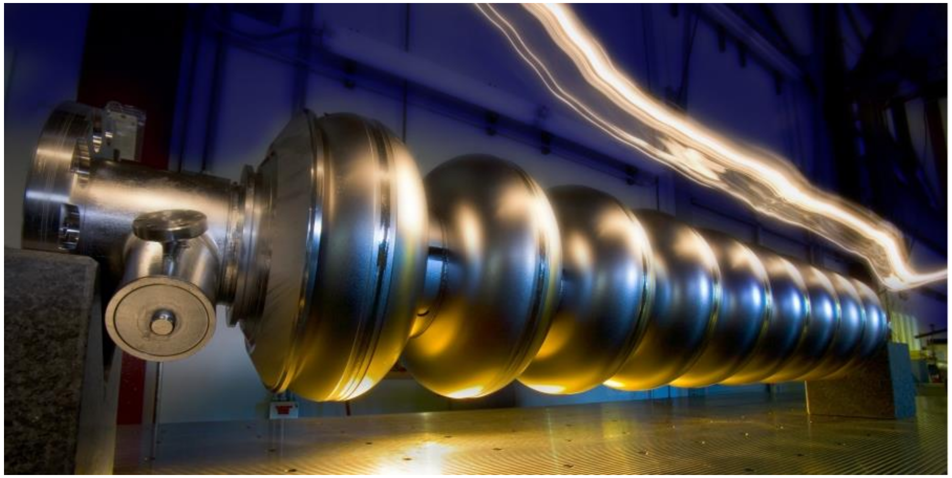


- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m
- √s up to 3 TeV
- Physics + Detector studies for 380 GeV - 3 TeV

Linear e^+e^- colliders

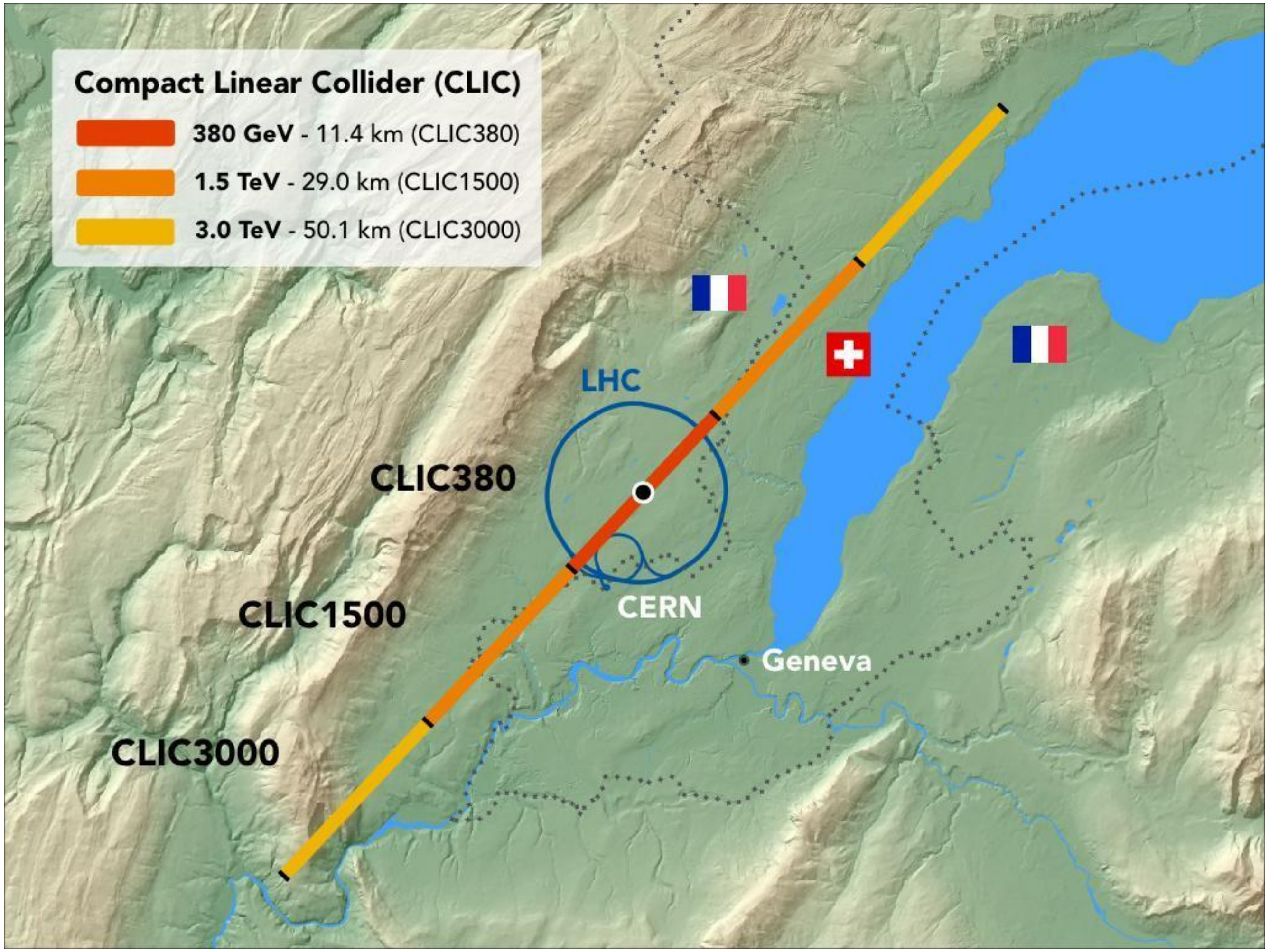
Luminosities: few 10^{34} $cm^{-2}s^{-1}$

ILC International Linear Collider



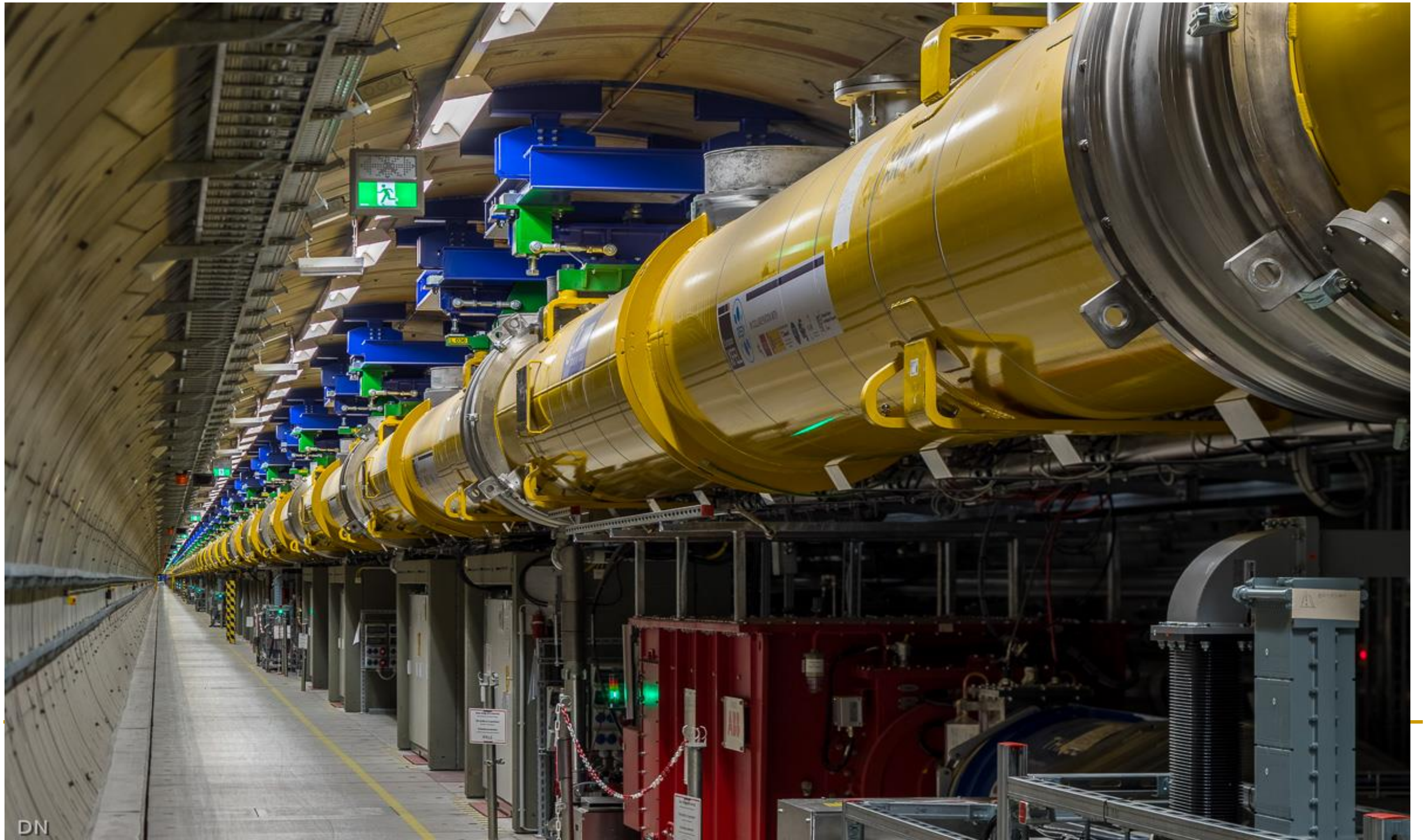
- Superconducting RF cavities (like XFEL)
- Gradient 32 MV/m
- √s ≤ 500 GeV (1 TeV upgrade option)
- Focus on ≤ 500 GeV, physics studies also for 1 TeV

CLIC Site Near Geneva

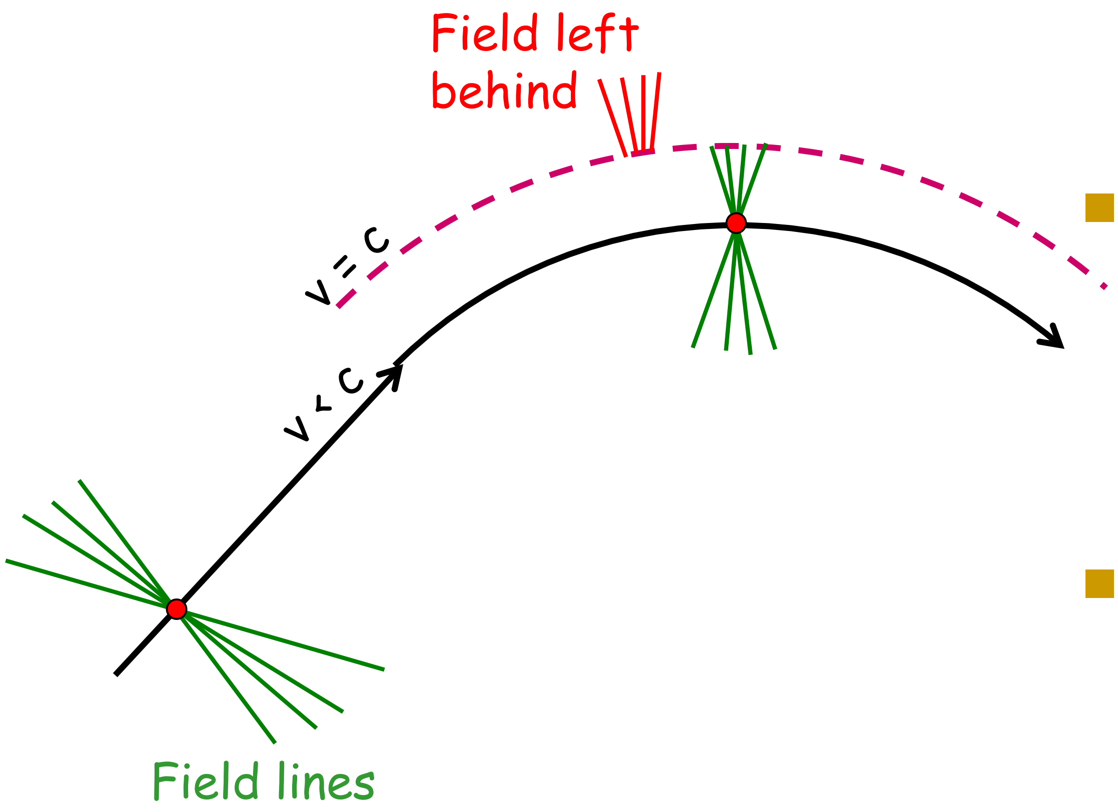


European XFEL

- **European XFEL at DESY is a large-scale proto-type for the ILC**
  - **100 cryomodules; 23.6 MV/m, accelerator length 2.1 km; 17.5 GeV**
  - **Sucessfully started operation in 2017**



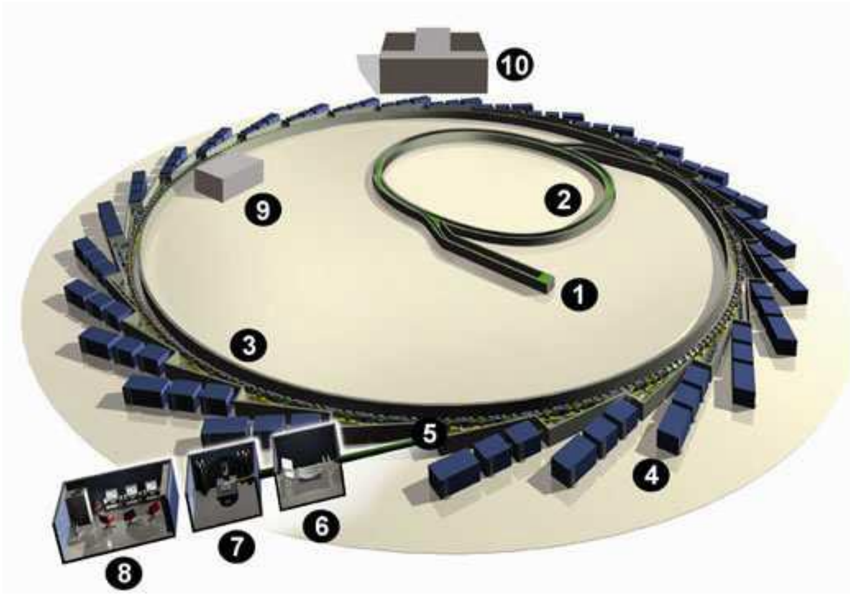
Synchrotron Radiation

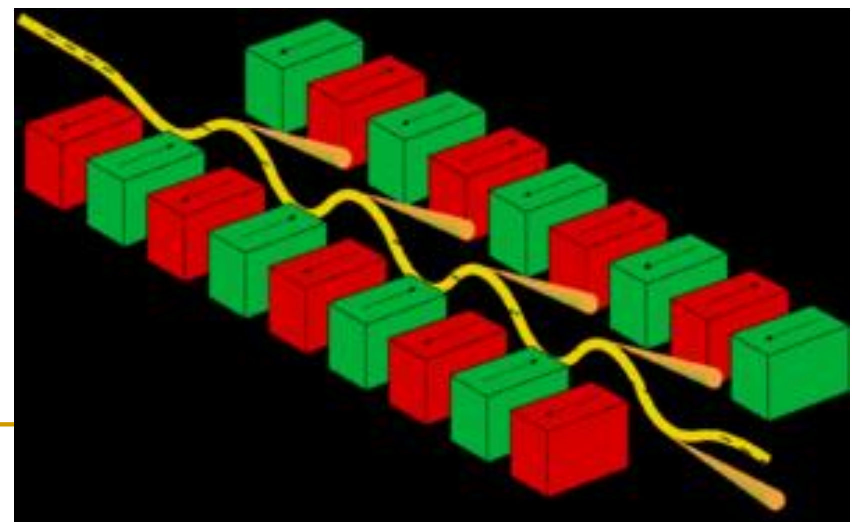


- Caused by field “left behind” during motion in a curved trajectory.
- Energy loss per meter is proportional to γ^4 and to $1/R^2$
- Can be both a nuisance and useful.

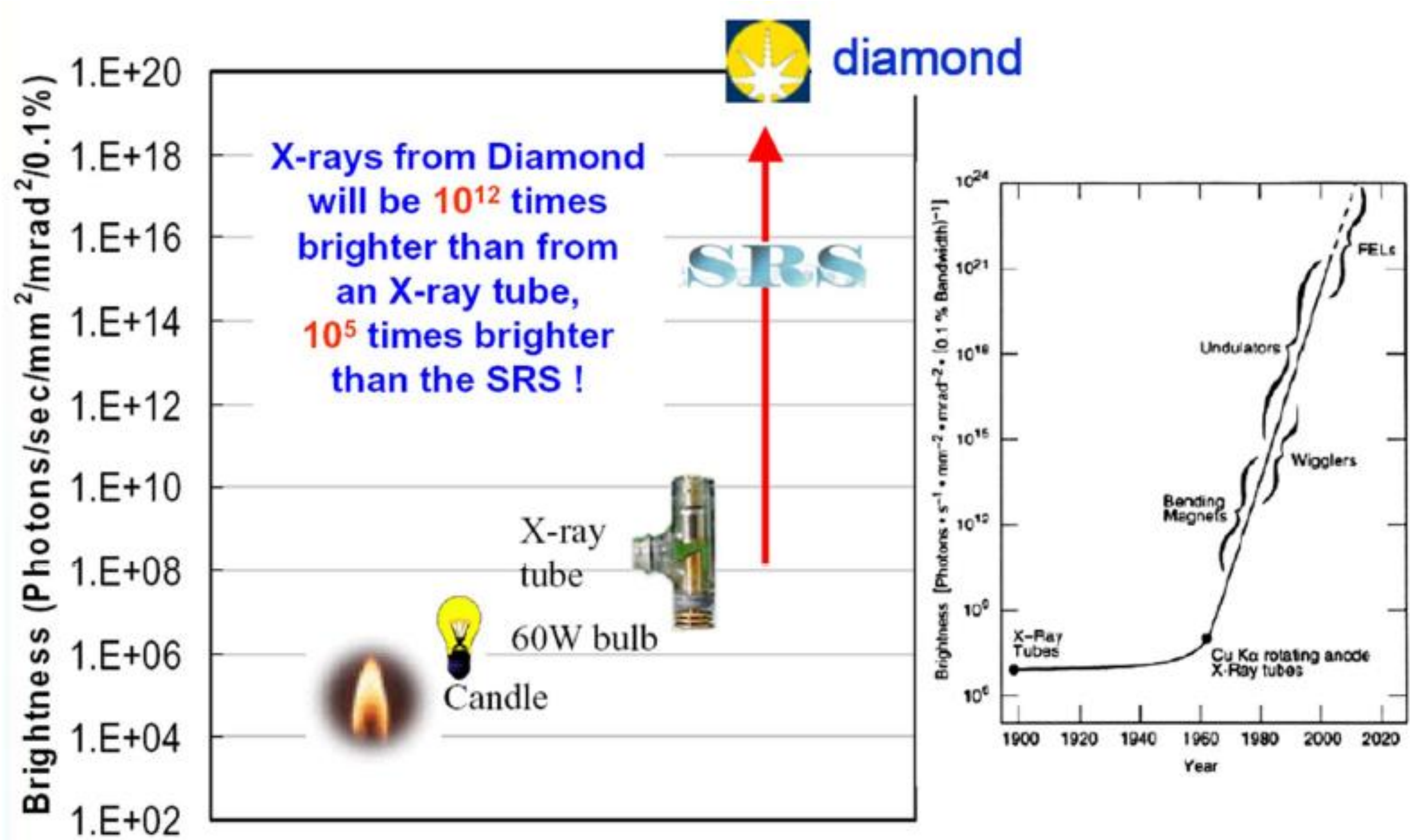
Use of Synchrotron Radiation

- Synchrotron radiation light sources exploit this feature to create scientific instruments.
- Special magnets (undulators) are inserted to further enhance the synchrotron radiation.

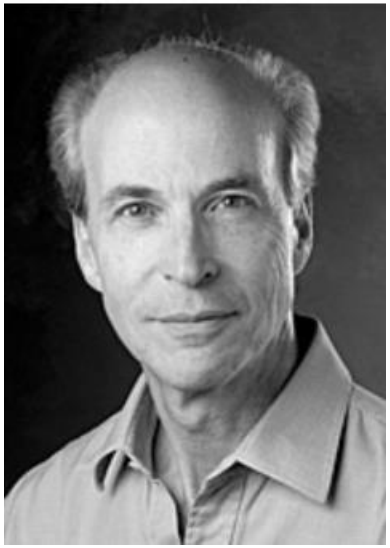




Accelerators for Synchrotron Light

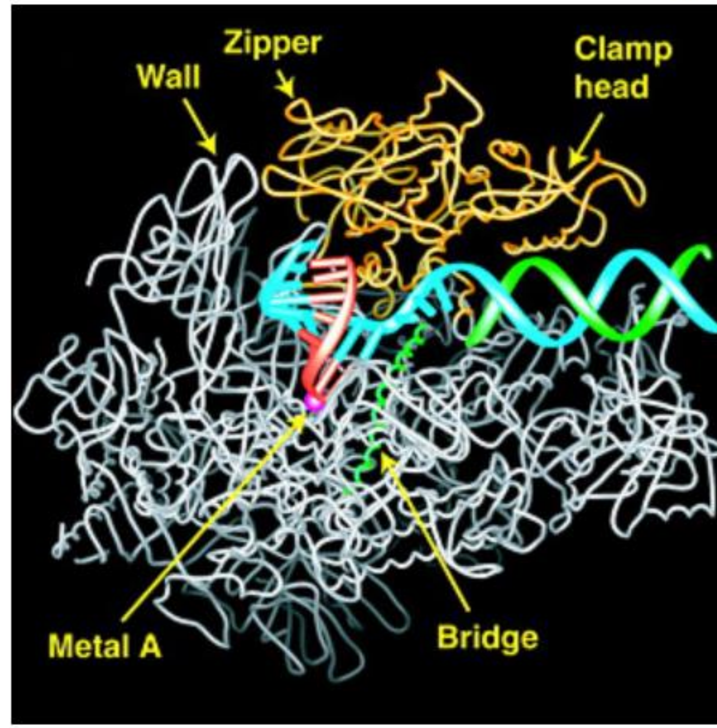


The Nobel Prize in Chemistry 2006
Roger D. Kornberg



Roger Kornberg's Nobel Prize-winning determination of the structure of RNA polymerase has been described as a "technical tour de force." The key to the visualization of this fundamental biological molecule in action was synchrotron radiation, supplied by the powerful X-ray crystallography instruments at the Stanford Synchrotron Radiation Laboratory.

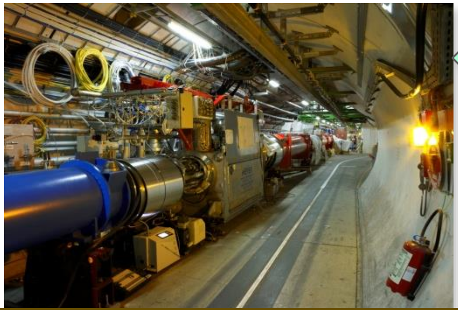
Science



The transcription process visualized by Roger Kornberg and his colleagues in his X-ray crystallography studies published online April 19, 2001, in *Science*. The protein chain shown in grey is RNA polymerase, with the portion that clamps on the DNA shaded in yellow. The DNA helix being unwound and transcribed by RNA polymerase is shown in green and blue, and the growing RNA stand is shown in red.

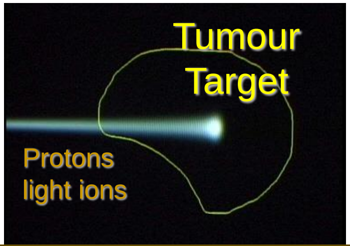
Medical Application as an Example of Particle Physics Spin-off

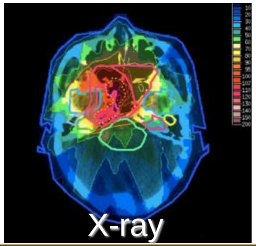
Combining Physics, ICT, Biology and Medicine to fight cancer

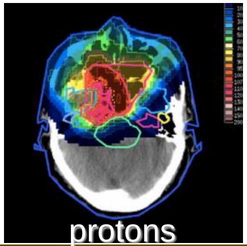


Accelerating particle beams
~30’000 accelerators worldwide
~17’000 used for medicine

Hadron Therapy

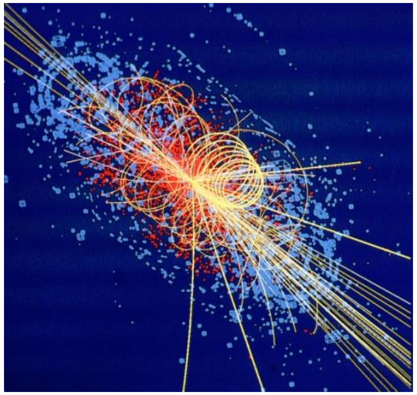






Leadership in Ion Beam Therapy now in Europe and Japan

>70’000 patients treated worldwide (30 facilities)
>21’000 patients treated in Europe (9 facilities)

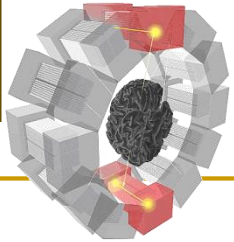


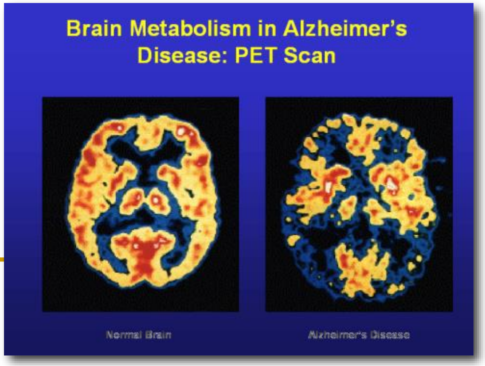
Detecting particles

Imaging

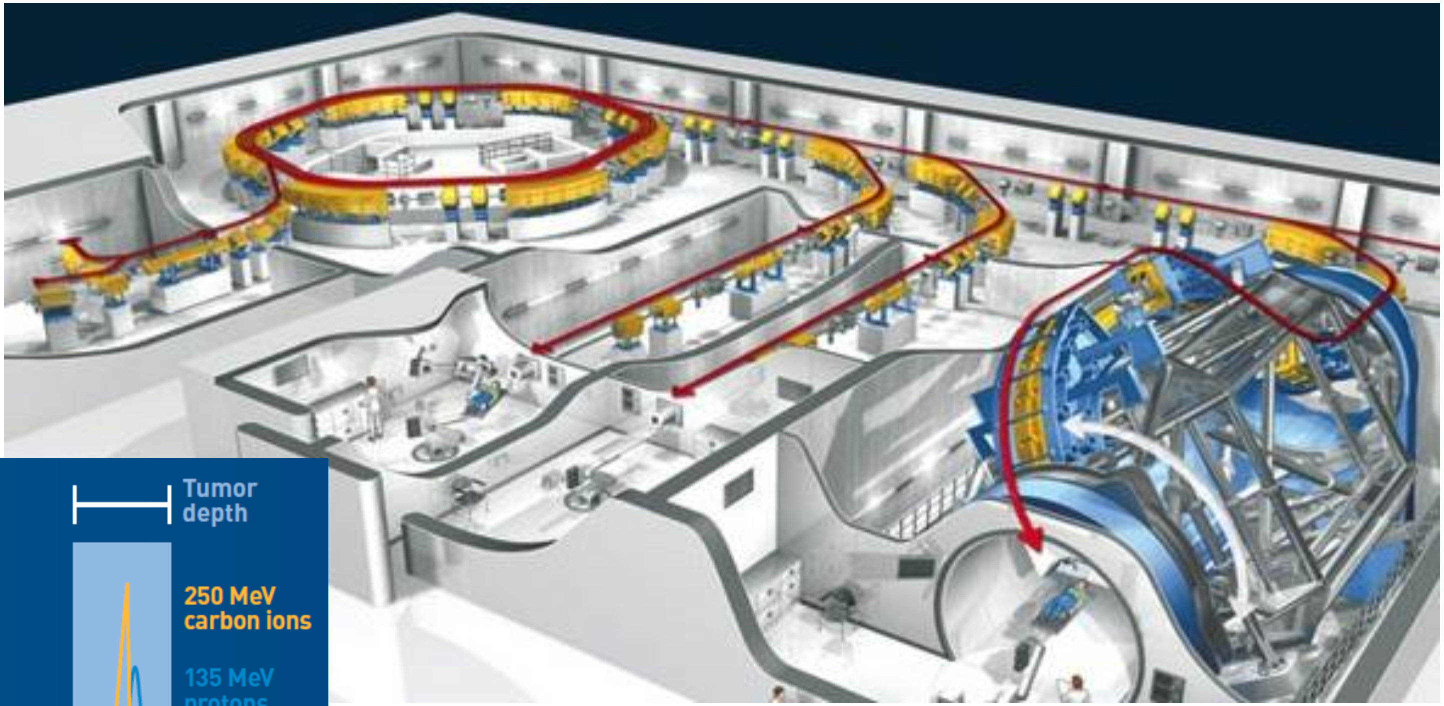
Clinical trial in Portugal for new breast imaging system (ClearPEM)

PET Scanner

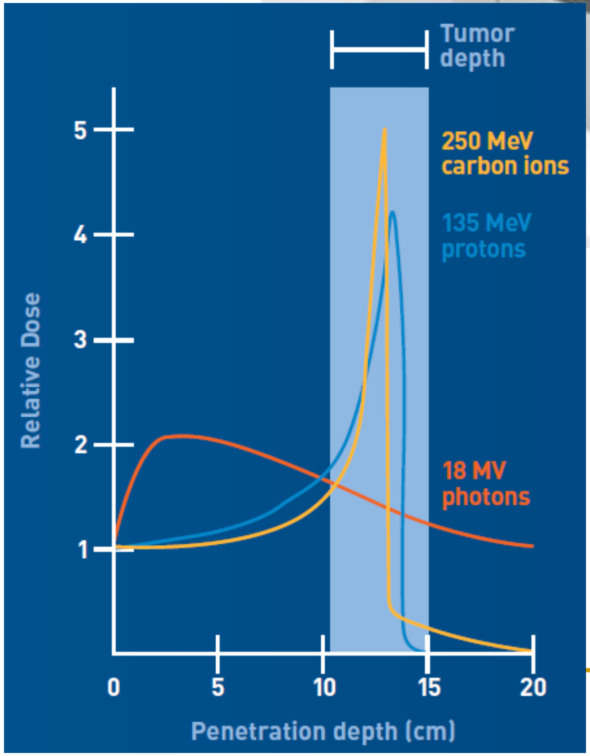


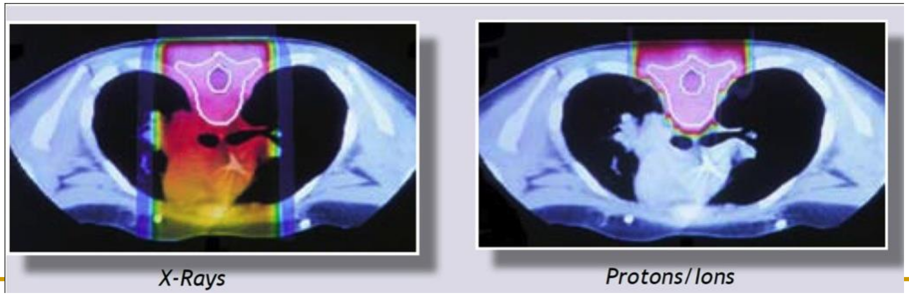


Hadrontherapy



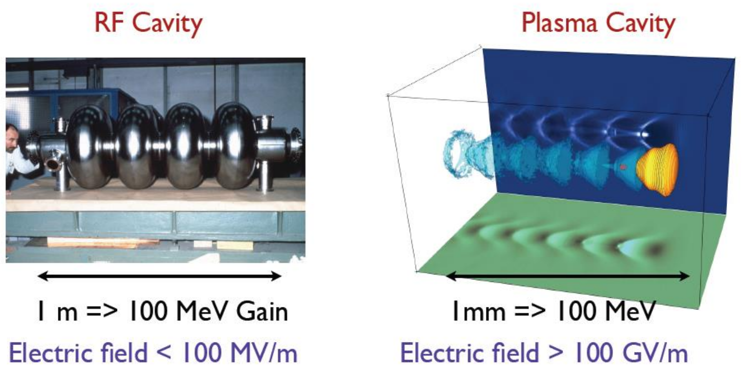
Heidelberg Ion Therapy Facility (protons & carbon)





Cancer therapy with x-rays and protons or heavier ions

Plasma Accelerators



V. Malka *et al.*, Science **298**, 1596 (2002)

e.g. AWAKE at CERN

Demonstration experiment to verify novel technique of p-driven plasma wakefield acceleration

Plasma accelerators:

Transform transverse fields into longitudinal fields.

Significantly higher accelereating gradients than conventional RF.

- **Laser driven**
- **e- driven**
- **p driven**
- **Dielectric wakefields**

Σας ευχαριστώ!