What is High Energy Physics?

Vittorio Del Duca
INFN LNF

Higgs Centre, 29 November 2024

Colloquium (Latin)
Conversation, discourse, interview

Hinc patriae proditiones, hinc rerum publicarum eversiones, hinc cum hostibus clandestina colloquia nasci…

Hence homeland betrayals, hence coups d’état, hence secret talks with the enemy are born…

M.T. Cicero - Cato Maior de Senectute

High-Energy Physics

ChatGPT

High-energy physics (HEP), also known as **particle physics**, is the branch of physics that deals with the study of fundamental particles (the basic building blocks of matter) and the forces that govern their interactions. These particles are typically studied at extremely high energies, where the effects of quantum mechanics and relativistic physics become significant.

Key Concepts in High-Energy Physics

The Standard Model:

- High-energy physics is primarily concerned with the **Standard Model of particle physics**, which describes three of the four known fundamental forces (electromagnetic, weak, and strong) and the particles that make up matter
- The **Standard Model** is a highly successful framework, explaining much of particle behavior and interactions, but it does not include **gravity** and leaves certain mysteries unexplained (e.g., dark matter, neutrino masses, etc.)

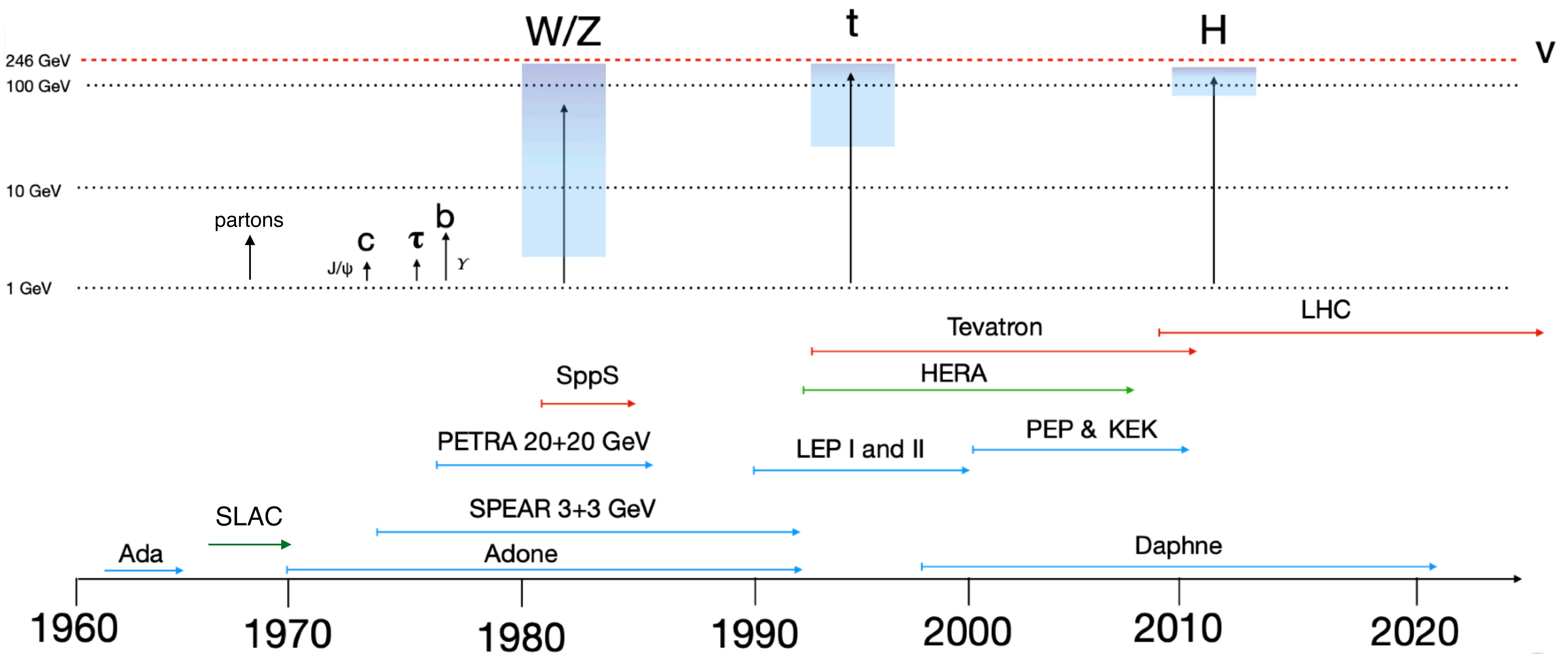
Accelerators:

- High-energy physics experiments often use **particle accelerators** to accelerate particles (such as protons, electrons, or ions) to extremely high speeds, close to the speed of light.
- These accelerated particles are then collided to observe the resulting interactions and produce new particles that may not be present under normal conditions.
- Examples of particle accelerators include:
  - **The Large Hadron Collider (LHC)** at CERN, the largest and most powerful accelerator in the world, which is famous for the discovery of the **Higgs boson** in 2012.

Brief history of collider physics

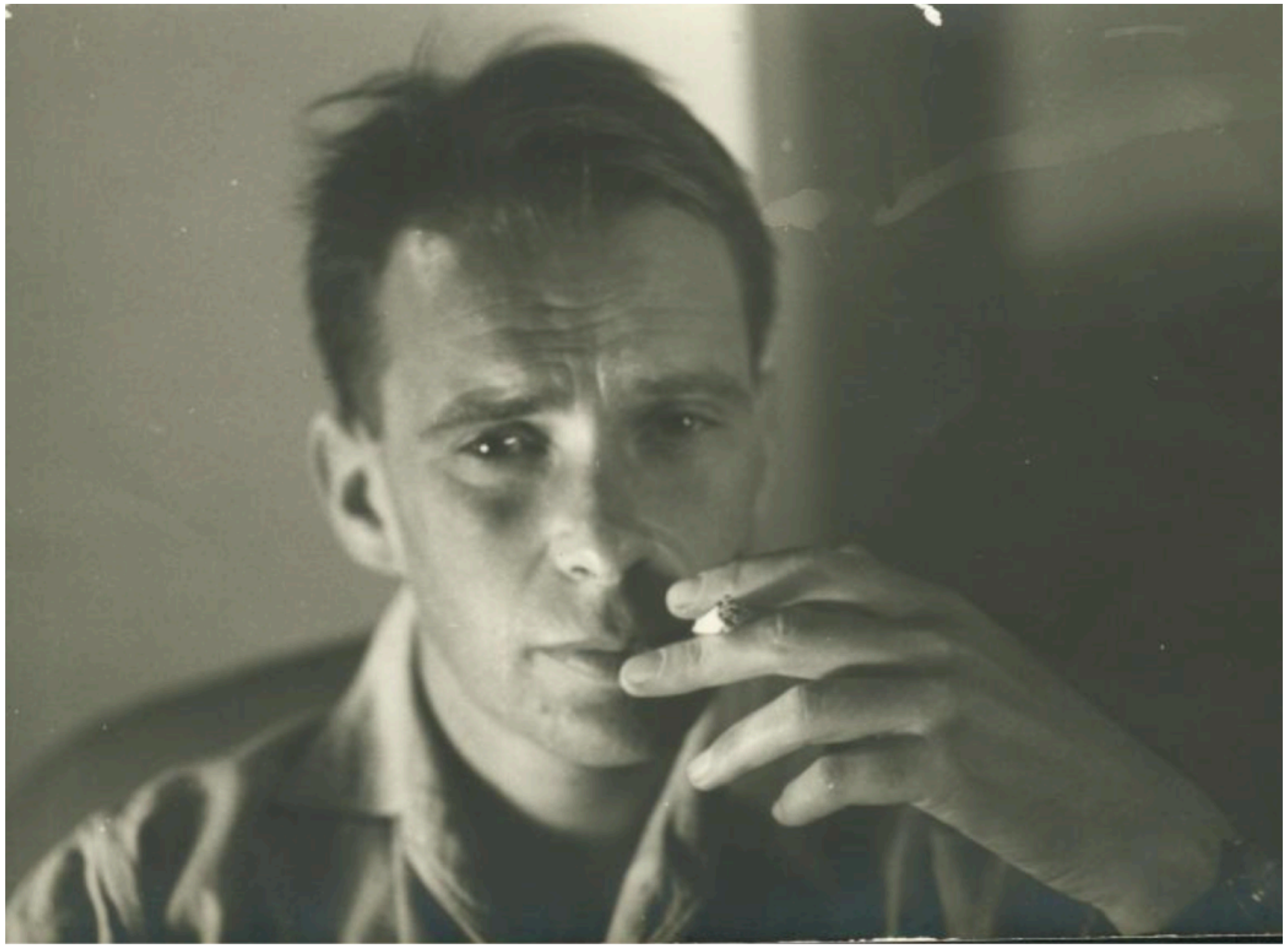
marked by colliders and particle discoveries

F. Maltoni at LFC24

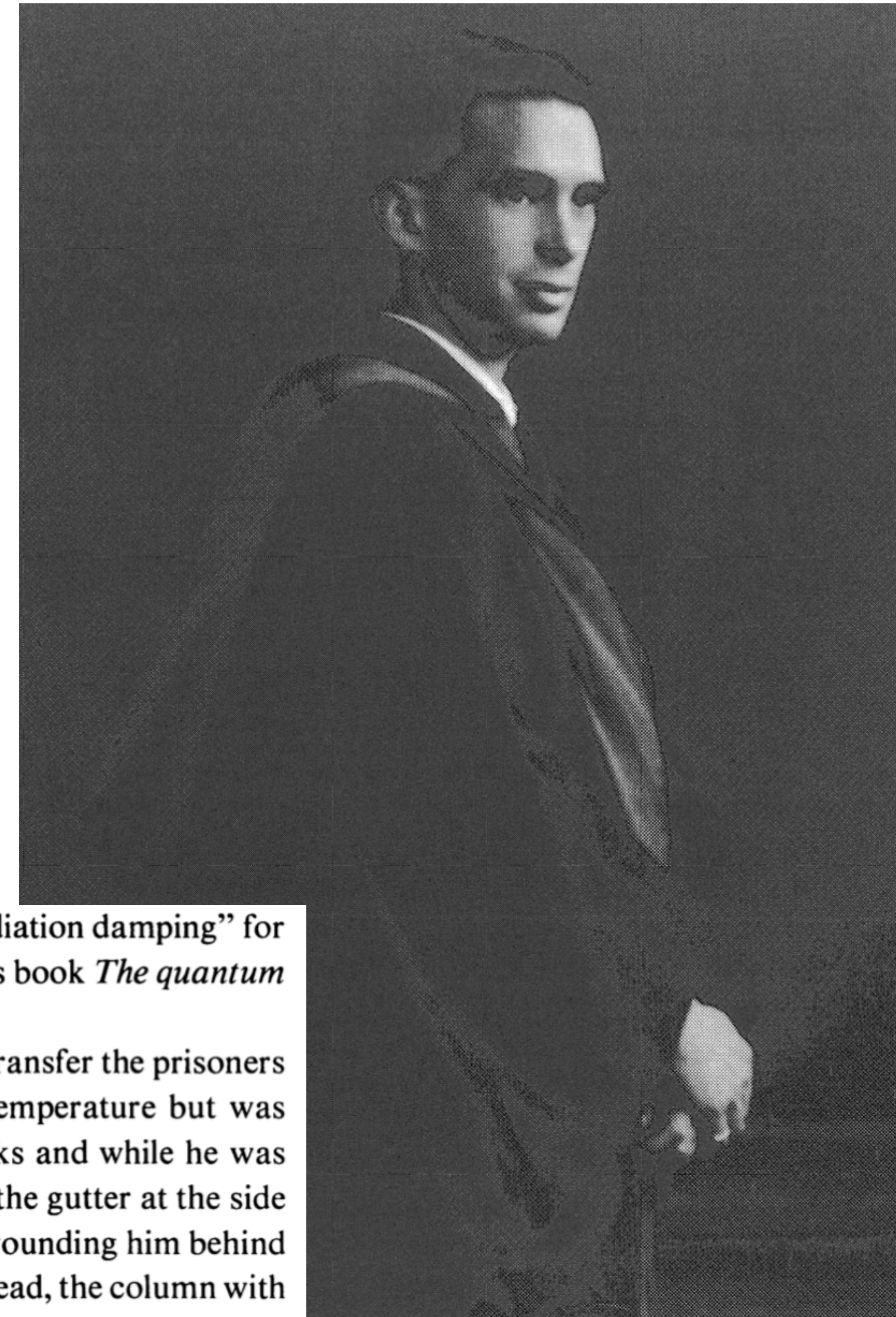


blue: lepton colliders
red: hadron colliders
green: lepton-hadron colliders

Bruno Touschek, designer and builder of the first collider: AdA



in Roma, 1955



in Glasgow, 1949

It was in prison that Touschek conceived the idea and developed the theory of "radiation damping" for electrons circulating in a betatron, which he wrote in invisible ink in the pages of Heitler's book *The quantum theory of radiation*[28)].

Around the end of February, or the beginning of March 1945, an order arrived to transfer the prisoners from Hamburg prison to a concentration camp in Kiel. Touschek had a very high temperature but was nevertheless ordered to leave the prison. He carried with him a heavy package of books and while he was marching, escorted by the SS, in the outskirts of Hamburg, he felt ill and collapsed into the gutter at the side of the street[29)]. An SS officer took out his pistol and, pointing at his head, shot at him, wounding him behind the left ear. It was not a serious wound but he lost a lot of blood. As they thought he was dead, the column with the SS guards went on. A short time after, a group of civilians gathered on the edge of the road, discussing whether the prisoner abandoned in the gutter was dead or not. Really Touschek was still conscious and could hear their conversation, but, as they went on for a long time, at a certain point he got up and to the general surprise asked where the nearest telephone was. They pointed to a building not far away and he went there. It proved to be a hospital, and he was treated there, but the Greek director told the police, who arrested him again and transferred him to the prison of Altona.

E. Amaldi
Bruno Touschek legacy 1981

Bruno Touschek, the Glasgow years

P.I. Dee

“My association with Bruno Touschek began in April 1947 when he was brought to my office (under guard!) for an interview. This had been arranged by Dr. Ronald Fraser[50)] (a friend of mine), who had met Bruno when serving on a post-war Allied commission which was visiting laboratories in Germany and elsewhere. Touschek had expressed a wish to work in a British laboratory, and Fraser knew that I had recently come to Glasgow to try to construct a nuclear physics centre in the university here.

“In the following five years Touschek took an active part in the expansion of the department and worked closely with Professor Gunn[51)] who, after his appointment in 1949, formed a strong theoretical team in parallel with the expansion of experimental work. Over this period Bruno became a close collaborator and personal friend. He was a person with immense vitality and enthusiasm. He was very clever and very original. He was also untiringly energetic and extrovert. Bruno led his life to the full extent in all situations and at all times. His enthusiasms were many and, although often brief, were exploited in a manner which most people would have found utterly exhausting.

“Bruno’s passion for novelty and independence knew no bounds. When he decided to have a desk made by a local carpenter he produced detailed drawings which the carpenter was forced to follow despite his strong reluctance. The end product was a desk having drawers with no backs and sides (to avoid dusty corners and edges) and which were to serve as withdrawable trays. This scheme might have been successful for a person of less ebullient character, but with Bruno’s rapidity of movement the result, in use, was a progressive and systematic transfer of the contents of all the drawers to the bottom level.

“On many occasions Bruno joined us in climbs on Scottish mountains. On these he would gradually discard and hide items of clothing, the final stage being completed in almost complete nudity. This also had the advantage that he could immerse himself in any small pools or burns which we came across on the way. He was an excellent swimmer with a dolphin like action, but here again he was rash and adventurous, once swimming to an island on Loch Lomond which even he felt to be too remote to risk the return swim. Fortunately he managed to hail a passing boat which returned him, blue with cold, to our picnic site.

Bruno Touschek, the Glasgow years

"Bruno's impatience with the slowness of behaviour of normal people often had very amusing consequences. Once having been allocated a new room in the laboratory and being unable to wait for a proposed redecoration, he embarked personally and without warning on this activity, during a weekend when the department was otherwise unoccupied. Apparently he soon found that proceeding systematically was very dull and boring, so he covered various areas at random as the spirit moved him. By Monday morning the room had a nightmarish patchwork appearance, whilst the fine teak block floor (left uncovered during the operation) was now coated with thousands of spots and streaks, so numerous as to give the impression that perhaps this had been intended. The situation was seemingly irrevocable and further exacerbated by a local contractor working in the department at the time, who took his friends and visitors to see the workmanship of what he claimed to be the university's own works department. This led to official protests and the placing of an embargo on any work on that room by university staff. My only course was to lock the room up for a period to allow passions to subside.

As Chisholm relates, in Glasgow Bruno had bought a motor cycle "which had a special feature, independent suspension of the front forks. During the first fortnight with this vehicle, he fell off it twice. He was convinced that he was not to blame for these accidents, and the evening after the second he settled down to make a complete study of the dynamics of the motor cycle. This took him about nine or ten hours, ending in the early hours of the next morning. His study showed that the new degree of freedom which had been introduced by the makers was unstable. He sent his full analysis to the manufacturers together with a letter beginning 'Dear Assassins, ...' The model was withdrawn from the market shortly afterwards. Some of those who suffered as a result of this accident were members of the first year Physics class, who had a lecture on Mechanics from Bruno the next day. Since he had prepared no other material they were treated to a lecture on Mechanics of the motor cycle and the bicycle; you can imagine that they would find this fairly difficult."

Bruno Touschek moves to Roma

In December 1952 Bruno Touschek moved to Rome, to which he had always been attracted owing to cultural and family ties. It was in Rome that his aunt Ada resided, having come there many years before. She was his mother's sister, and had married an Italian, Gaetano Vannini. Aunt Ada was the owner and joint

When Touschek moved to Rome, the main interest which he shared with Ferretti was the construction of a quantum field theory which would also include bound states, i.e. a theory which would go beyond perturbation methods.

In those early years of his life in Rome, Bruno Touschek owned a motor cycle which he called Josephine; he claimed that when he had been out late drinking in a pub or at a friend's Josephine knew how to bring him home safely.

In 1955, Bruno returned to Glasgow to marry Elspeth Yonge, the daughter of a well-known professor of Zoology at the University of Edinburgh, Sir (Charles) Maurice Yonge[60]. Elspeth gave Bruno two sons, Francis in 1958 and Stefan in 1961. The Touscheks first lived in a flat in Via Mancinelli (Piazza Vescovio),

On another occasion one night on his motor cycle he ran into the rear of a large car at a cross-roads, flew right over the top of it and injured his skull during the fall. He was immediately taken to the Neurological Clinic, which at that time was directed by Professor Ugo Cerletti.

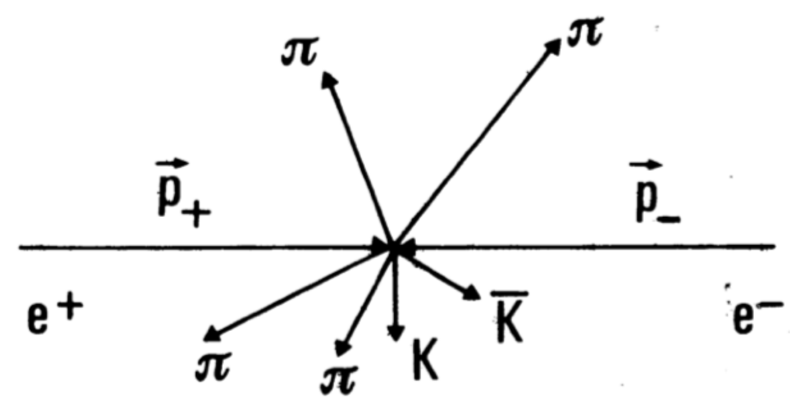
The injured person was in a state of great agitation and even if what he said was not understandable, he appeared to be of German tongue. The next morning, the doctor of the Psychiatric Section asked Dr. Valentino Braitenberg, of the Bolzano province, to go from the laboratory where he was working to fill in the hospital sheet for the newly admitted person. As Braitenberg relates "... a first superficial examination (that would not have lasted more than a few minutes) allowed my colleagues to determine that he was not Italian and to suspect psychosis. The injured man had declared he was a theoretical physicist, Vice-Director of the Scuola di Perfezionamento di Fisica Nucleare and a specialist in time reversal (see Section 6). I found Bruno sitting on his bed in the ward, still rather angry but already occupied in observing with interest the spectrum of mental alienations displayed by the surrounding patients. He wore a turban applied by the first-aid doctors when they treated the wound that he had received during the fall. The slight concussion which he suffered in combination with the high alcohol content in his blood had caused a state of agitation, as frequently happens, as a result of which the police decided to apply the rules of psychiatry rather than those of the Penal Code. We immediately became friends. His story was convincing and not at all psychotic, his German was delicious, rich and precise, his humour was uncontrollable even in such embarrassing circumstances. I wrote his clinical story with his help. The only slightly abnormal detail was the daily quantity of wine, but Bruno gave good reasons: tennis, the scarcity of water in aqueducts, etc. I thought it

Birth of collider physics

On 7 March 1960, Bruno Touschek held a seminar at the Laboratori Nazionali di Frascati, where he demonstrated for the first time the importance of a systematic and thorough study of electron-positron collisions (e^-e^+) and how this could be achieved, at least in principle, by constructing a single magnetic ring in which bunches of electrons and positrons circulate at the same energy E, but in opposite directions[94)]. By installing suitable particle detectors near to the parts of the ring where the bunches of opposite sign intersect, it is possible to study the particles emitted in all the reactions produced at the centre-of-mass energy $2E$, since the centre-of-mass of the two colliding particles is stationary in the laboratory reference frame

in fixed-target collisions: $s = \sqrt{2mE}$

in ee/pp colliders: $s = E_1 + E_2$



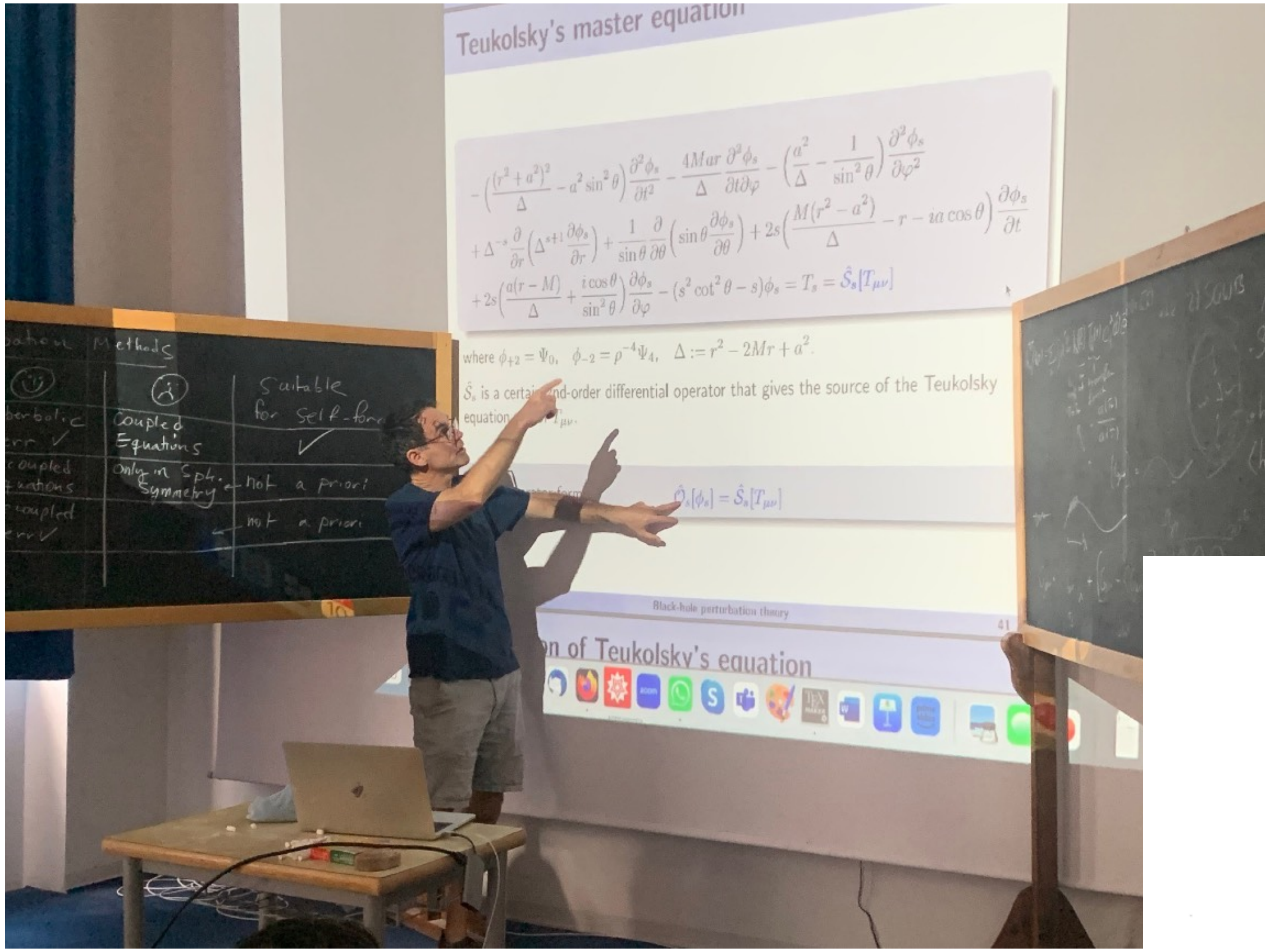
All of the arguments discussed by Touschek, and their brilliant exposition, made a considerable impression on everyone present, including the then Director of the Laboratori Nazionali di Frascati, Giorgio Salvini, and Carlo Bernardini, Gianfranco Corazza and Giorgio Ghigo.

During the same day, the three last-mentioned persons began to work with Touschek on a project for the first e^-e^+storage ring, essentially designed as a protype for checking the feasibility of accelerators based on the ideas set forth by Touschek during the seminar.

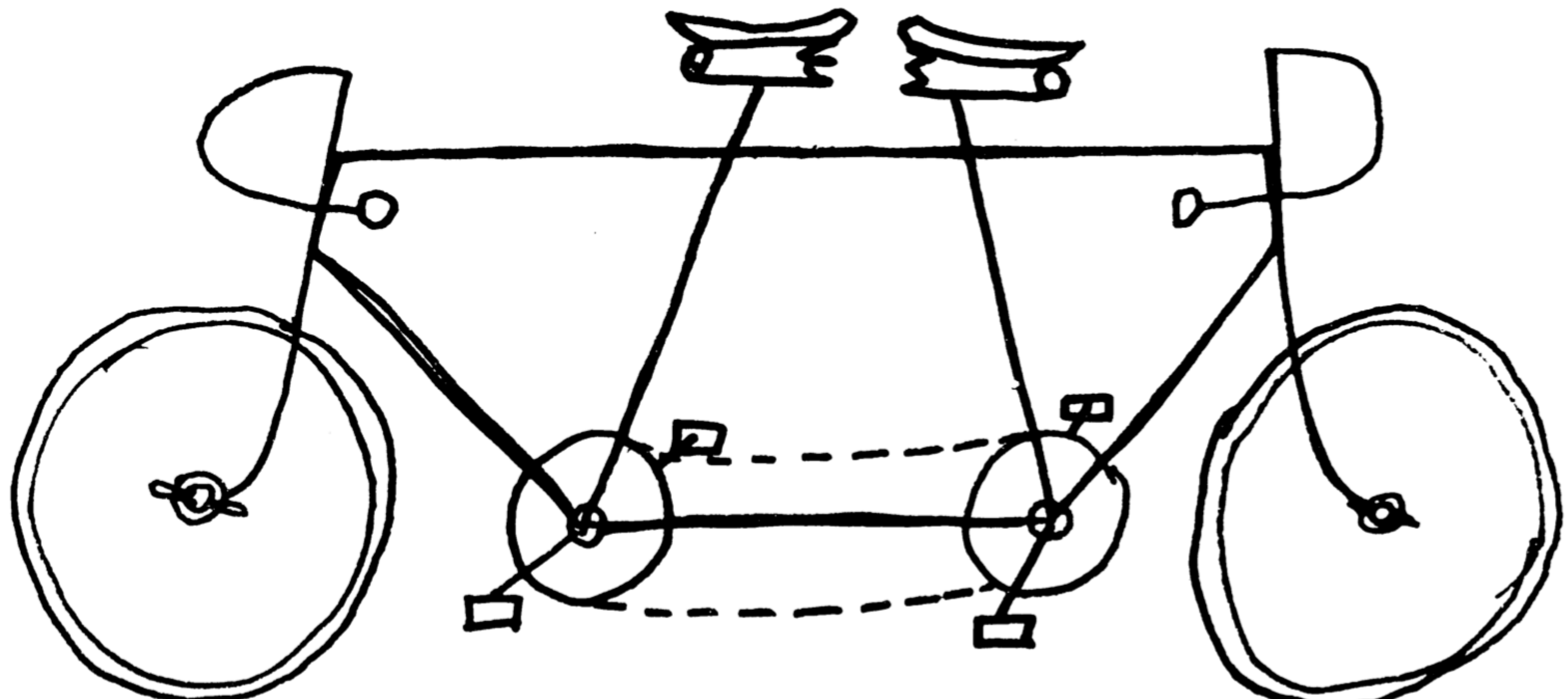
This first machine for the study of collisions between a particle and an antiparticle was known as AdA (Anello di Accumulazione e^+e^-). The story of its design, construction and use has already been written about

Touschek had, therefore, immediately found his first collaborators, but had also quickly found the financial resources. Giorgio Salvini, who had immediately realized the importance of the proposal, succeeded, shortly after this, in obtaining from the CNEN (of which Felice Ippolito was Secretary-General) an extraordinary grant of 20 million lire for the construction of the AdA prototype. This sum was almost entirely spent on the construction of the magnet, which was designed in a few days in a very original manner by Giorgio Ghigo[107)] and produced with the assistance of G. Sacerdoti. A description of the project is set out

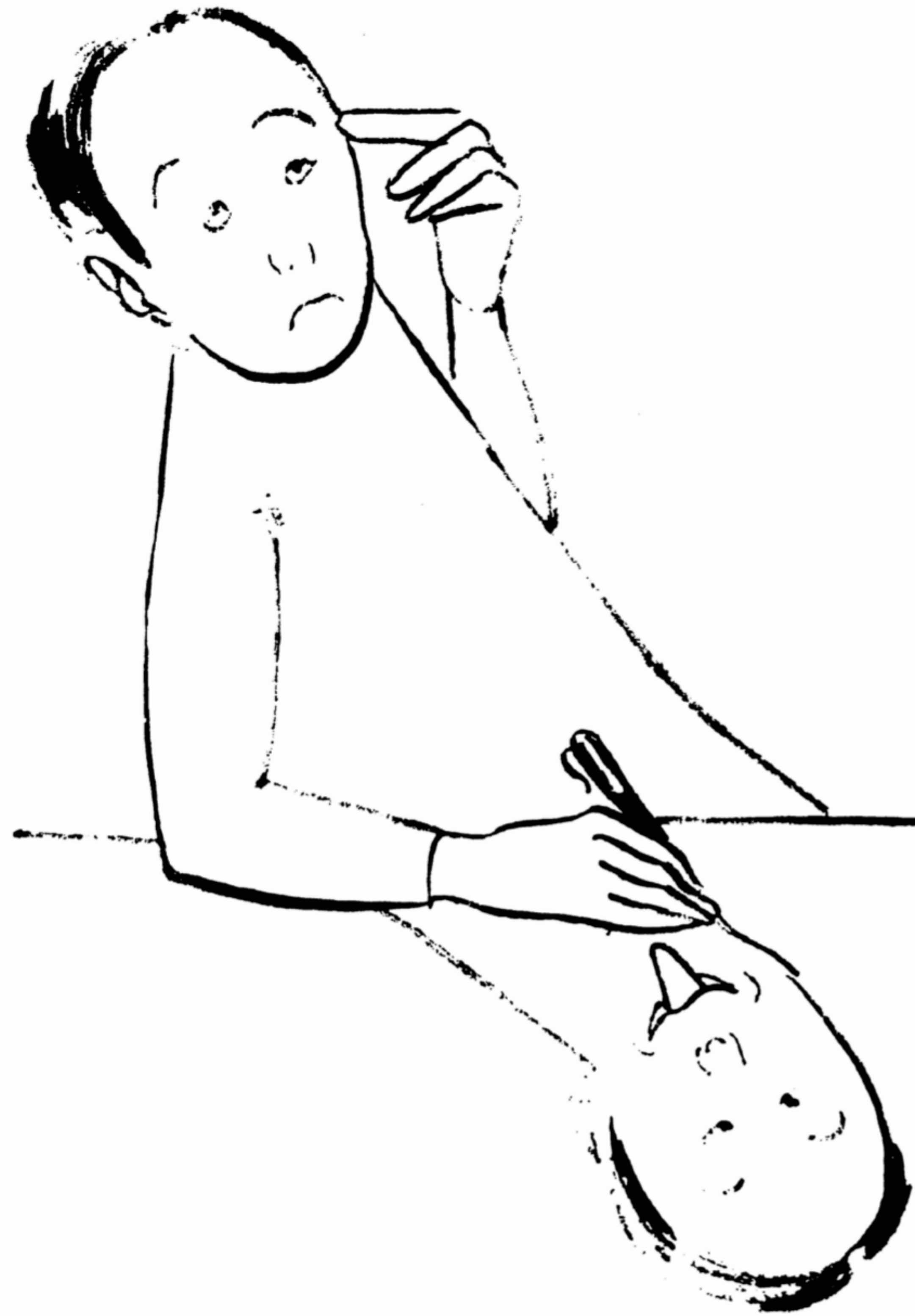
AdA began operation on 27 February 1961 [48], a date which had a special meaning for Bruno, since it was on that day a few years earlier that his aunt Ada had passed away.



MAGNETIC DISCUSSION



PROBARE ET REPROBARE !



ESAMI DI LAUREA

L'AUSCULTAZIONE DELLE TESINE

The **Standard Model** of particle physics is the theory that describes the fundamental particles and forces (except gravity) that make up the universe. It is one of the most successful and well-tested scientific theories, providing a comprehensive framework for understanding the electromagnetic, weak, and strong nuclear forces.

ChatGPT

$$\mathcal{L} = i\bar{\psi}\gamma^\mu D_\mu \psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

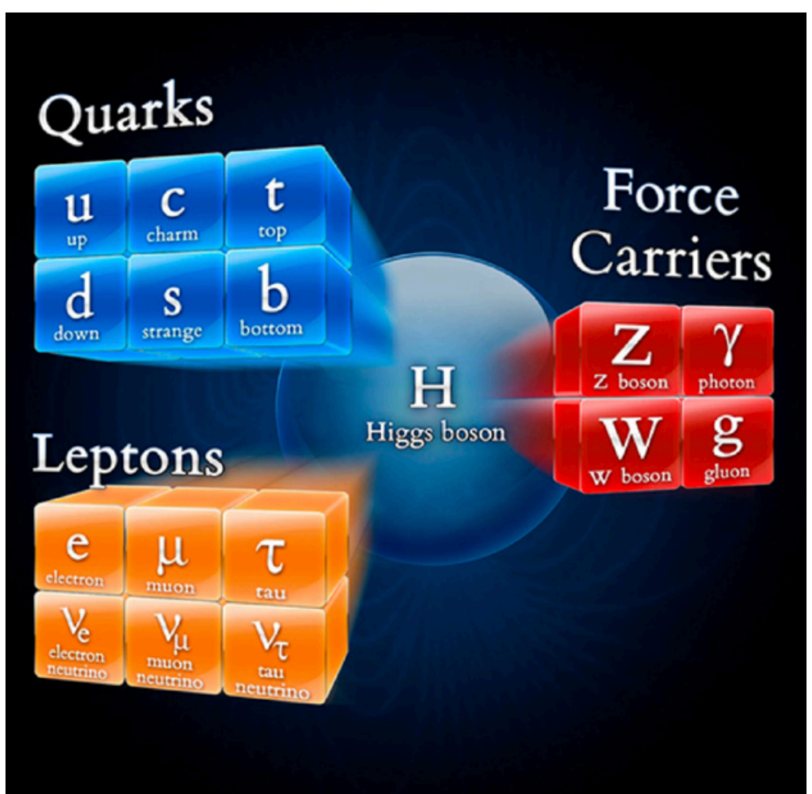
← gauge sector: depends on 3 coupling constants

$$+D^\mu H^\dagger D_\mu H - (\bar{\psi} Y H \psi + \text{h.c.}) - V_{SM}(H)$$

← scalar sector: 12 fermion masses
2 gauge boson masses
Higgs mass
vacuum expectation value
Higgs self-coupling
4 CKM parameters

Higgs potential

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$
$$= -\frac{M_H^2}{2}\left(|H|^2 - \sqrt{2} G_F |H|^4\right)$$



Type	Strength	Range	Mediator
strong	1	10^{-15} m	gluons (8)
electro-magnetic	10^{-2}	∞	photon
weak	10^{-5}	10^{-18} m	W^+, W^-, Z^0
gravity	10^{-38}	∞	graviton

Interview with
Peter Higgs
Edinburgh, 8 December 2008

Excerpts from the interview with Peter Higgs

www.lnf.infn.it/theory/delduca/higgsinterview.pdf

Peter Higgs talks about Nambu, Jona-Lasinio paper, Nambu mechanism, which governs the spontaneous symmetry breaking of a global symmetry, and implies (Goldstone theorem) the existence of massless spin-zero particles: the Goldstone bosons. Klein and Lee casted doubts about Goldstone theorem, but Walter Gilbert confirmed that it was correct: Goldstone bosons could not be evaded

… The crucial period, as far as I was concerned, was two weeks in July 1964. At the time, we didn't have an email subscription to Physical Review Letters, and it took a month to arrive. Gilbert's paper was, I think, published in the journal in the middle of June, and I saw it on July the 16th, before anybody else in Edinburgh because I was the member of staff who looked after the little departmental library, including the journals, and so ...

.. So I think it was Thursday, July the 16th (1964). I mean, I checked this once because one of my jobs as the guardian of the journals was to put a date on the cover as they came in, and to put them on the shelf for other people to read. And the cover of that issue of Physical Review Letters has been bound into the bound copy which went into the University Library, with my dating on it still. So, that's the evidence.

Anyway, when I read this paper by Gilbert, it seemed really to tidy things up completely: you couldn't evade the Goldstone theorem…

… So, during the weekend, it gradually occurred to me that I knew an exception to this statement of Gilbert's. The reason that I knew an exception to it, was that I'd been reading papers by Julian Schwinger, published in 1962 in Physical Review, under the title ``Gauge invariance and mass''. What Schwinger had done was to examine what had become folklore in the particle physics community: that in quantum electrodynamics the photon is massless because gauge invariance prevents any mass generation. Schwinger had shown this isn't true, that you could perfectly well have a gauge field theory, like quantum electrodynamics, in which the spin-one particle is massive. He wrote down some spectral functions for, I think, a commutator of vector potentials in a sort of Maxwell-type theory, and, because he was Schwinger, he used the Coulomb gauge. He thought that the way that people, you know, mutilated the Lagrangian and used a Lorentz gauge condition wasn't the right way to do it. You should start from Coulomb gauge which has no gauge freedom left in it, and if you want to get to a Lorentz gauge, which looks formally relativistically invariant, you transform all the things in the theory to this new gauge. And this had been spelled out in the very first issue of the Journal of Mathematical Physics by Zumino in 1960, I think. And I had read that too.

The thought which came to me that weekend in July was that if Schwinger can, in Coulomb gauge, write down the spectral function for the commutator of two four-vector fields which don't look properly Lorentz covariant, then you can do it in other places too. But it's the gauge freedom which is crucial there, this is how it can happen. If you don't have the gauge freedom, which in quantum field theory is a kind of embarrassment, because you have to fix the gauge before you have well defined quantum operators ... I mean: in anything but a gauge theory, you'll end with standard manifestly covariant formalism. But a gauge theory doesn't have to look manifestly covariant. As long as the physics which comes out at the end is relativistically invariant, it's all right. So, that's when I wrote the first short paper, which suggests a way out of the Goldstone theorem, and the way out is to combine spontaneous symmetry breaking with a gauge theory. In other words you have to have a gauge field coupled to the charges associated with the symmetry which you want to break spontaneously, and that was the trick…

Higgs mechanism governs spontaneous symmetry breaking of a local (gauge) symmetry (making particles to acquire mass)

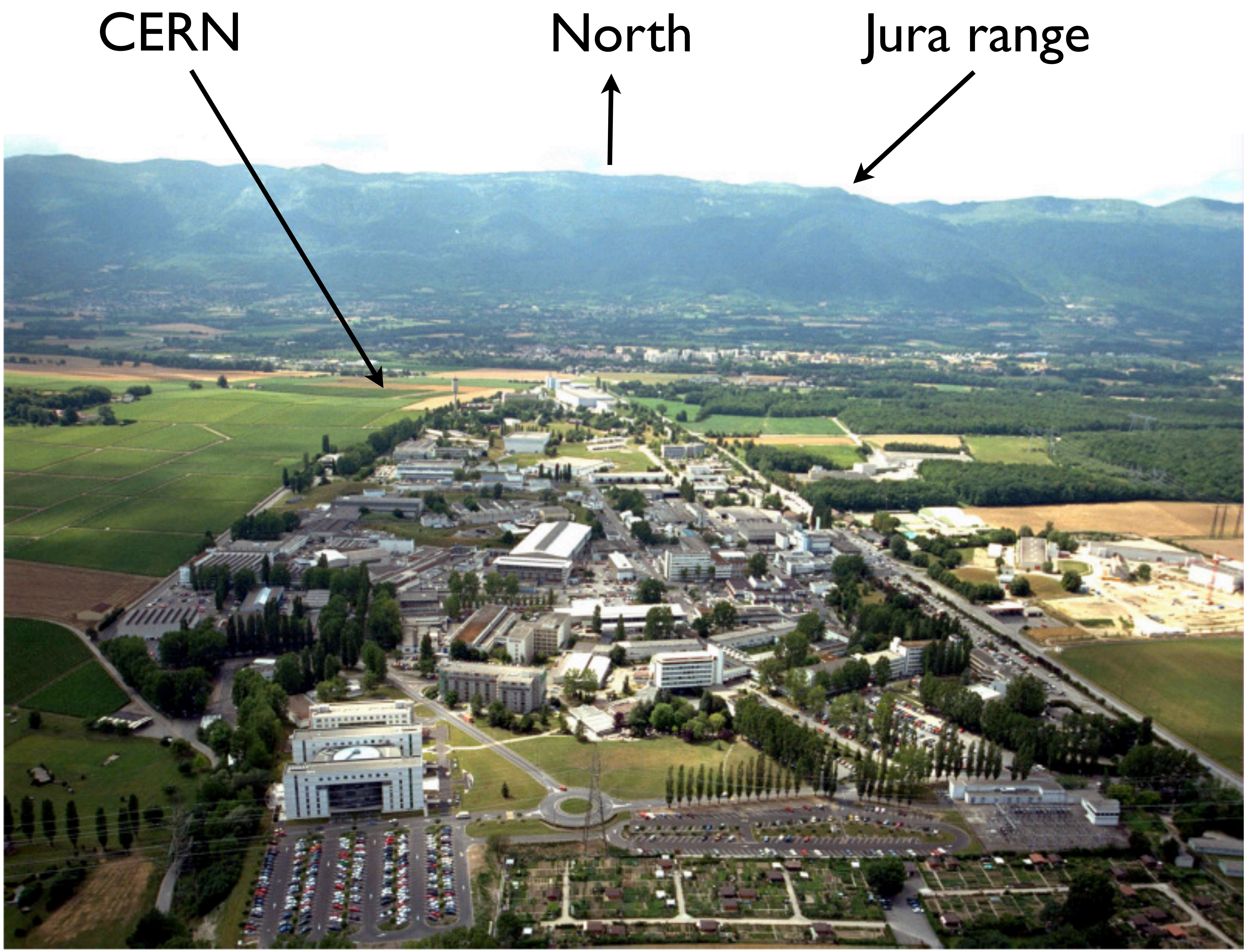
Present

recent past

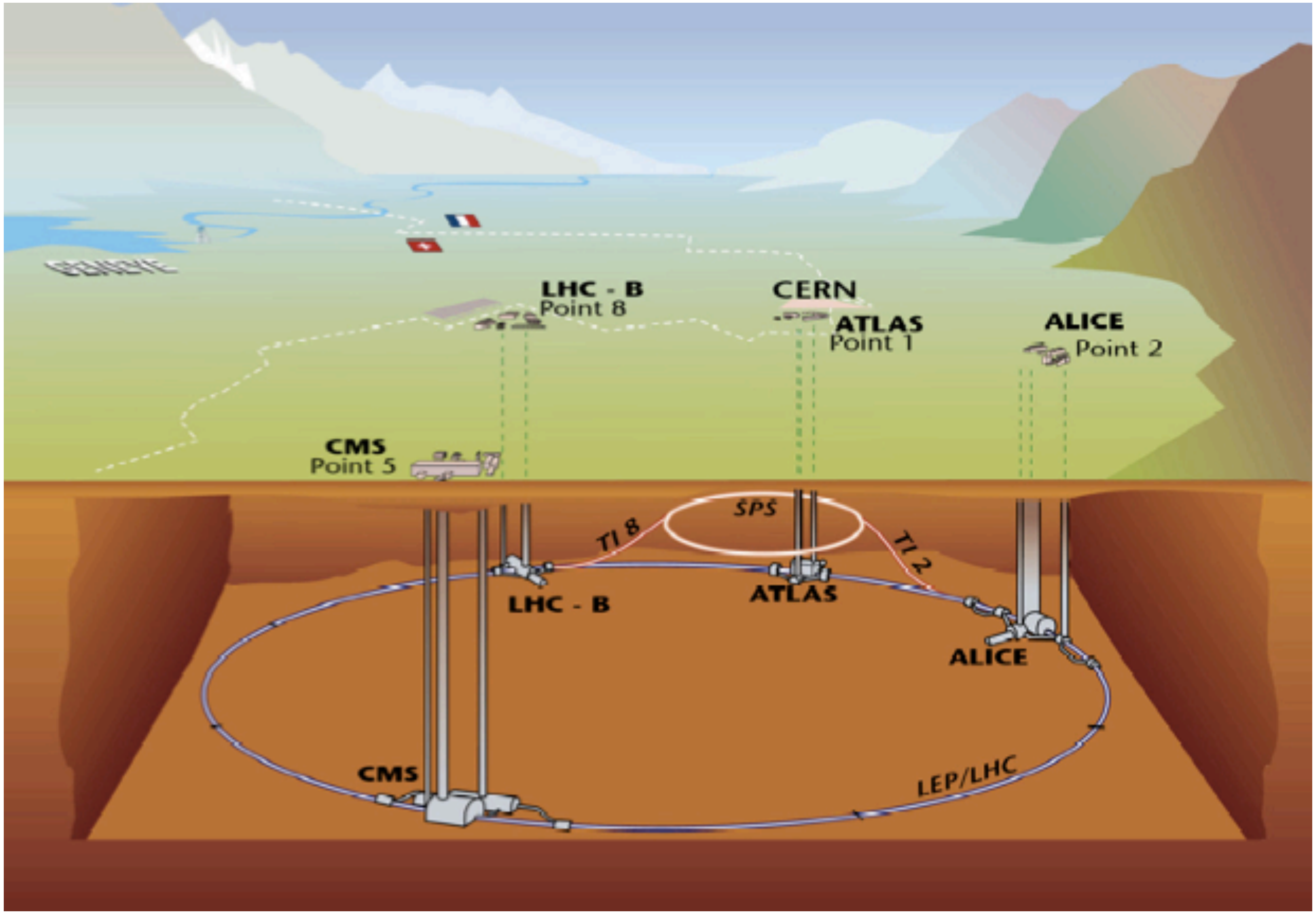
and near future

LHC

- Large Hadron Collider is a proton (ion) accelerator & collider
- It’s a ring-shaped tunnel (formed by 8 arcs connected by 8 small straight legs) 26,6 Km long and 3,8 m wide
- located at CERN, from 50 to 175 m underground at the French-Swiss border, between Geneva and the Jura range


CERN
North
Jura range

Sketch of LHC



→ North

Proton beams

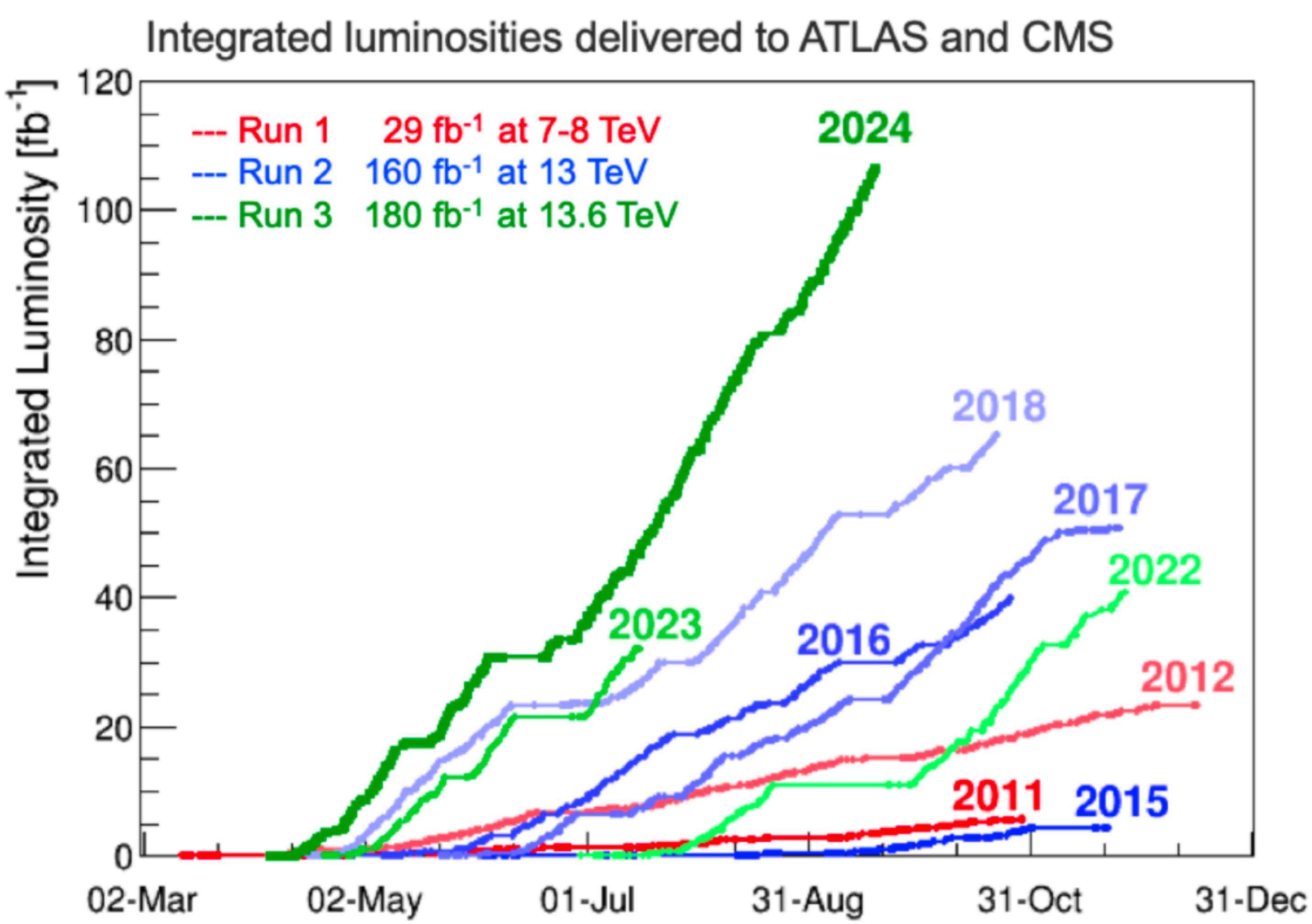
- In the tunnel are 2 tubes, each containing a proton beam, circulating one clock-wise and the other counter-clock-wise
- Each beam is narrower than a hair (about a micron) and is composed by 2808 proton bunches, each containing 115 billion protons

HL-LHC parameters

Parameter	Nominal LHC (design report)	HL-LHC 25ns (standard)
Beam energy in collision [TeV]	7	7
N_b	1.15E+11	2.2E+11
n_b [12]	2808	2760
Beam current [A]	0.58	1.1
Half Crossing angle [μrad]	142.5	250
Minimum β^* [m]	0.55	0.15
ε_n [μm]	3.75	2.50
Total loss factor R0 without crab-cavity	0.836	0.342
Total loss factor R1 with crab-cavity	-	0.716
Virtual Luminosity with crab-cavity: Lpeak*R1/R0 [$cm^{-2} s^{-1}$]	-	1.70E+35
Levelled Luminosity [$cm^{-2} s^{-1}$]	-	5.0E+34 [4]
Events / crossing (with leveling and crab-cavities for HL-LHC) [7]	27	131
Peak line density of pile up event [event/mm] (max over stable beams)	0.21	1.28
Leveling time [h] (assuming no emittance growth) [7]	-	7.3

L. Rossi
Accelerator Technologies for HiLumi & Hadron Colliders
Frascati, 1-2 October 2024

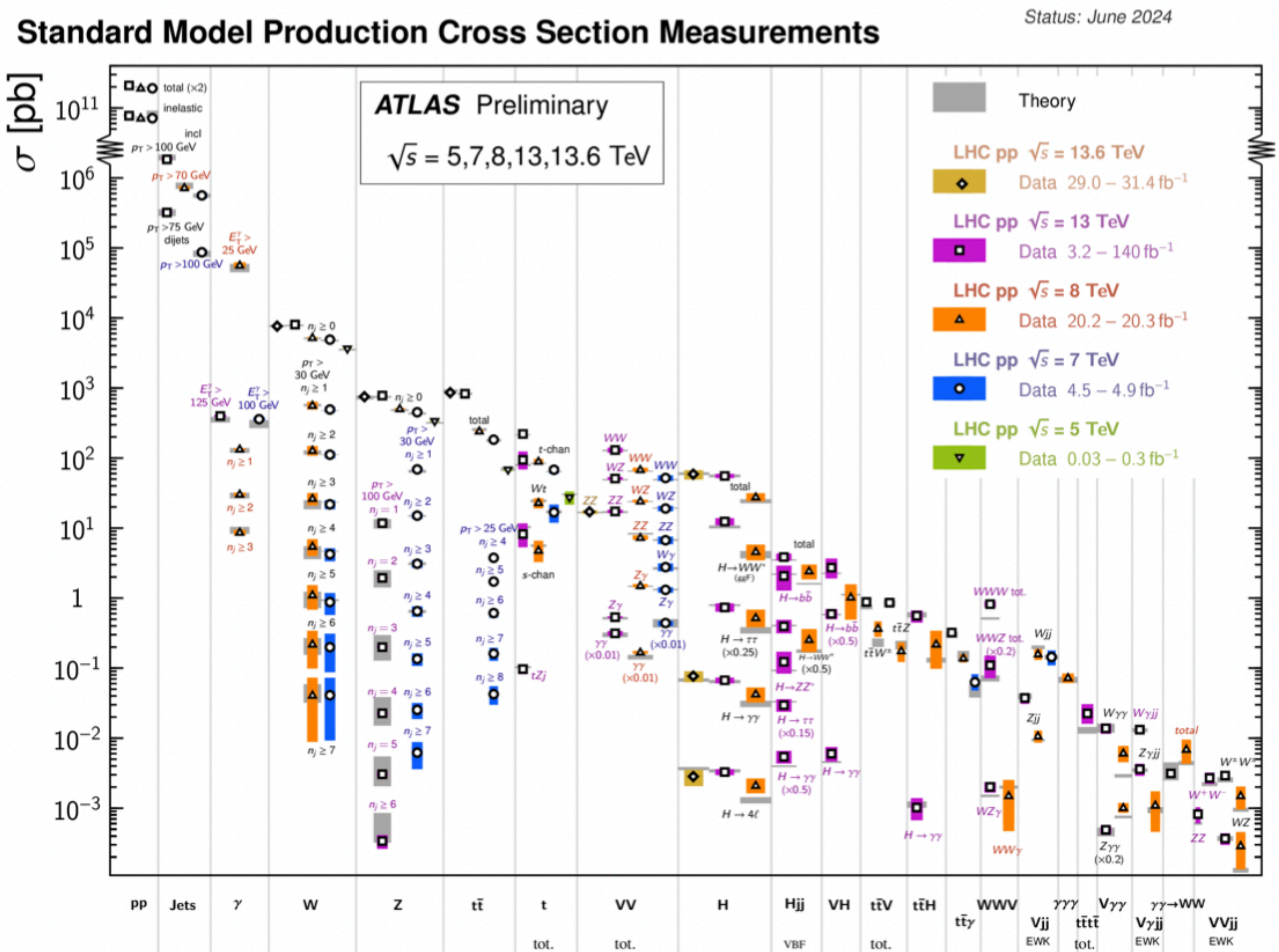
- The **Large Hadron Collider (LHC)** at CERN continues to explore the physics at unprecedented energy levels, probing the Higgs field, searching for supersymmetry, and investigating phenomena like **quark-gluon plasma** (a state of matter believed to have existed just after the Big Bang)



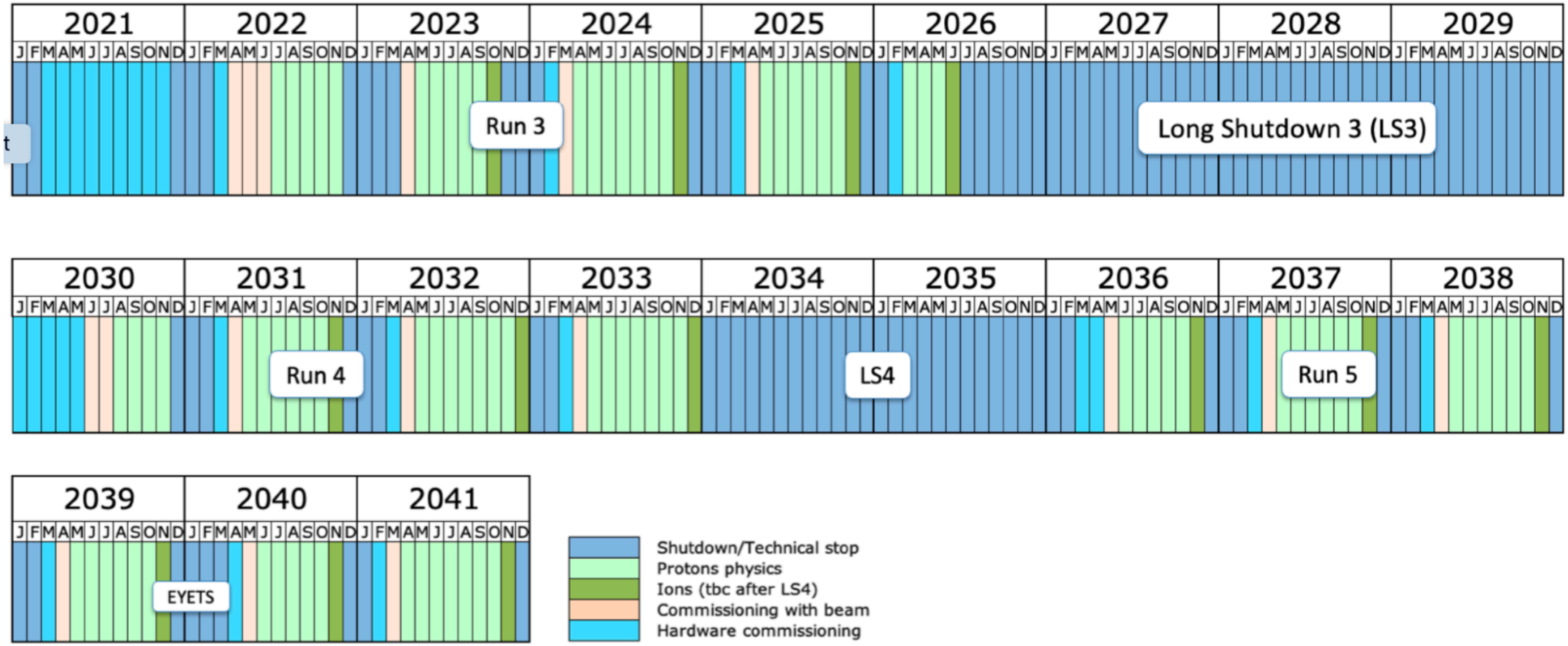
Time period	int. luminosity (fb^{-1})
Run1: 2010-12	29.2
Run2: 2015	4.2
Run2: 2016	39.7
Run2: 2017	50.2
Run2: 2018	66.0
Run1+Run2	189.3
Run3: 2022	42.0
Run3: 2023	33.0
Run 3 2024	110.0
Total lumi	**374.3**

Original goal of Run1+Run2 = 150 fb^{-1}: Δ = + 20%
Original goal of LHC before upgrade: 350 fb^{-1}
If we project 500 fb-1 by end of Run3 : Δ = + 40%

LHC production rates



LHC Schedule

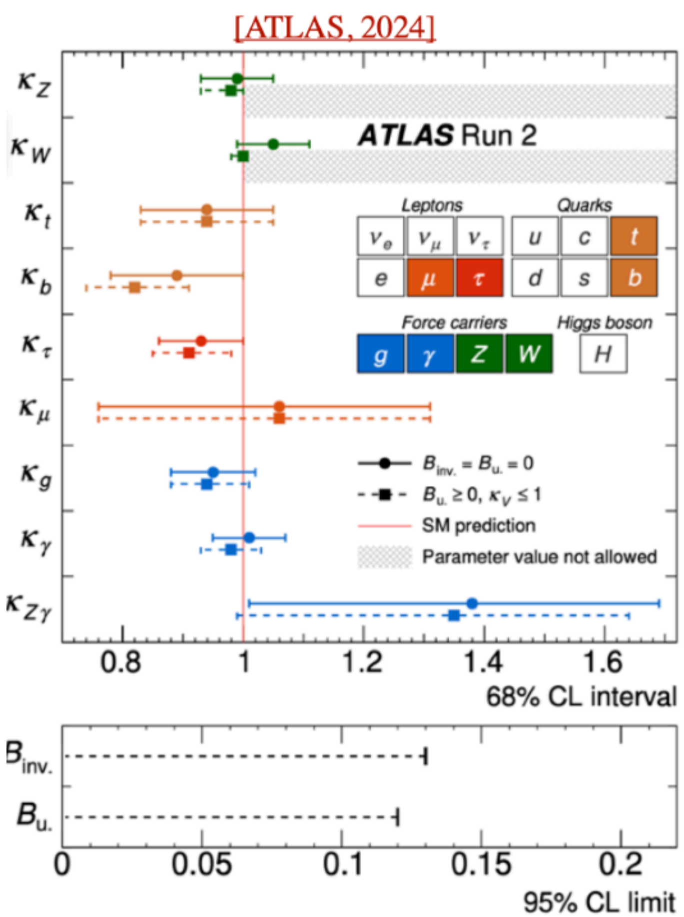


HL-LHC will increase ten-fold the statistics
it will improve the Higgs couplings
it will put bounds on the Higgs self-coupling

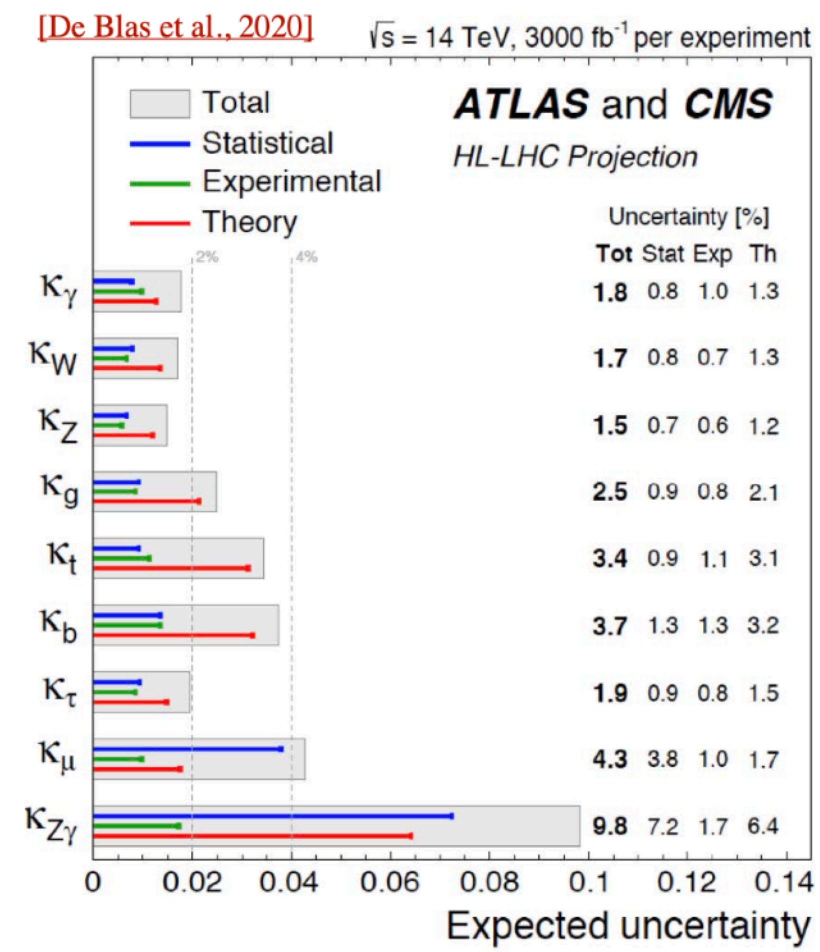
From LHC to HL-LHC

Higgs boson couplings

F. Maltoni at LFC24



10-20% → 2-4%



$$(\sigma\cdot \mathrm{BR})(i\to H\to f) = \frac{\sigma_i^{SM}\kappa_i^2\cdot\Gamma_f^{SM}\kappa_f^2}{\Gamma_H^{SM}\kappa_H^2} \quad\to\quad \mu_i^f \equiv \frac{\sigma\cdot \mathrm{BR}}{\sigma_{\mathrm{SM}}\cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2\cdot\kappa_f^2}{\kappa_H^2}$$

What is not in the Standard Model

- Neutrino Masses and Mixings
  Dark Matter
  Dark Energy
  Baryon-Antibaryon Asymmetry

  Dark Matter… *come l'Araba Fenice, che ci sia ciascun lo dice dove sia nessun lo sa*
  like the Phoenix, everyone says it exists, but no one knows where it is
  G. Marino *Adone*
  W.A. Mozart *Cosi fan tutte*

- Boson (photon & gluon) masses are protected by gauge symmetry
  Fermion (lepton & quark) masses are protected by chiral symmetry

  What protects the Higgs boson mass?
  Supersymmetry! (if it existed 😞)

  No supersymmetry? ☞ fine tuning ☞ "Naturalness" problem

  ☞ a lot of bemused model builders (a peculiar brand of theorists)

- SM must be modified at higher energies

After the shutdown of HL-LHC in 2041 what is next?

2026 update of the European Strategy for Particle Physics

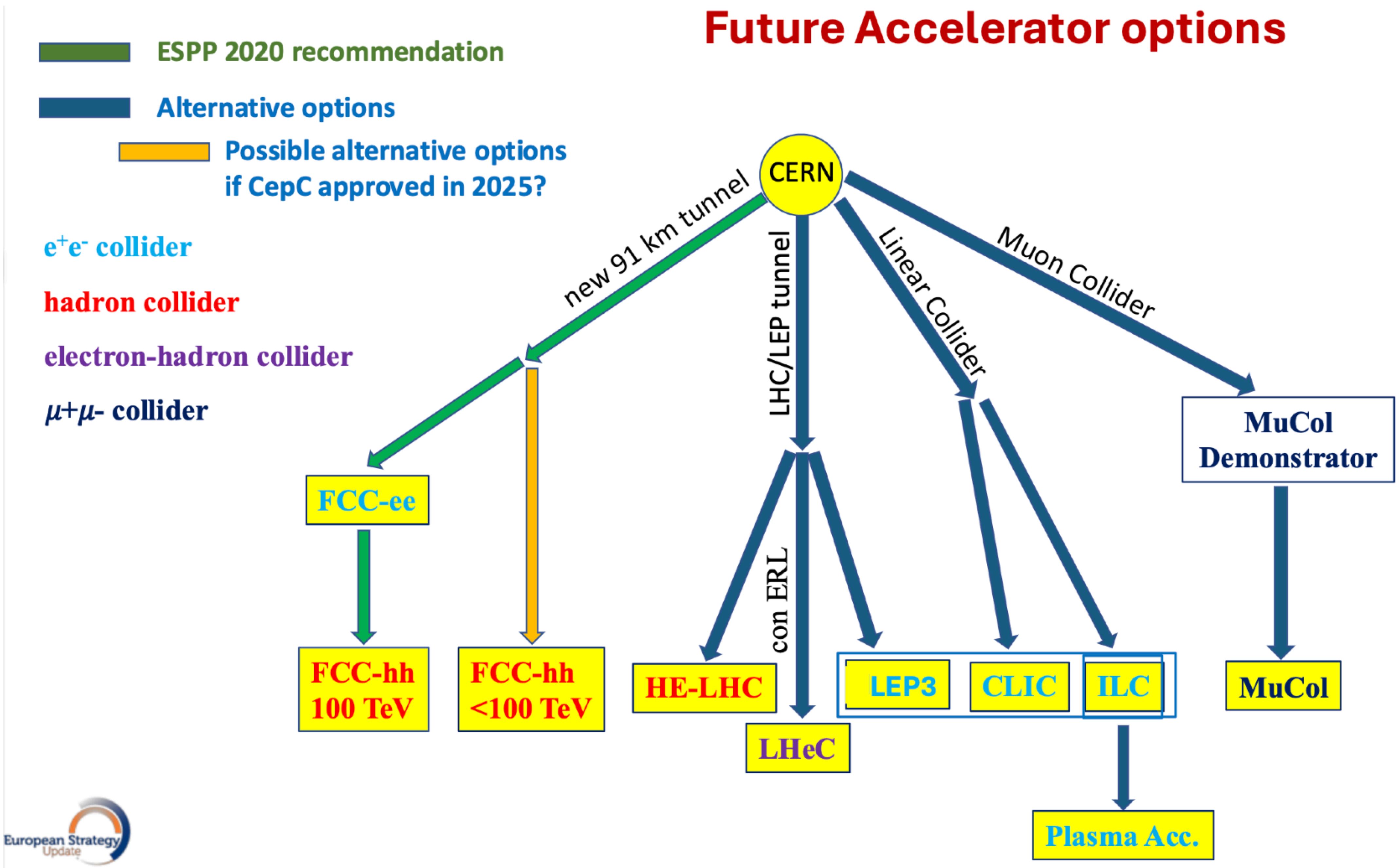
Previous Strategies:
2006: about the completion of LHC
2013: support HL-LHC & start looking at beyond LHC
2020: survey if FCC is viable and foster accelerator technology R&D

The remit of the European Strategy Group (ESG) specifies that it should take into consideration various aspects of the high-energy physics (HEP) landscape, including, very importantly, the input of the particle physics community.

- It is imperative that the European HEP community should provide explicit feedback on both the preferred and alternative options for this next collider at CERN, which will be the Laboratory's next flagship project, and an explanation of any specific prioritisation.

2026: approving the next collider at CERN

ECFA-INFN ECR meeting, 1 October 2024



S. Malvezzi, A. Nisati

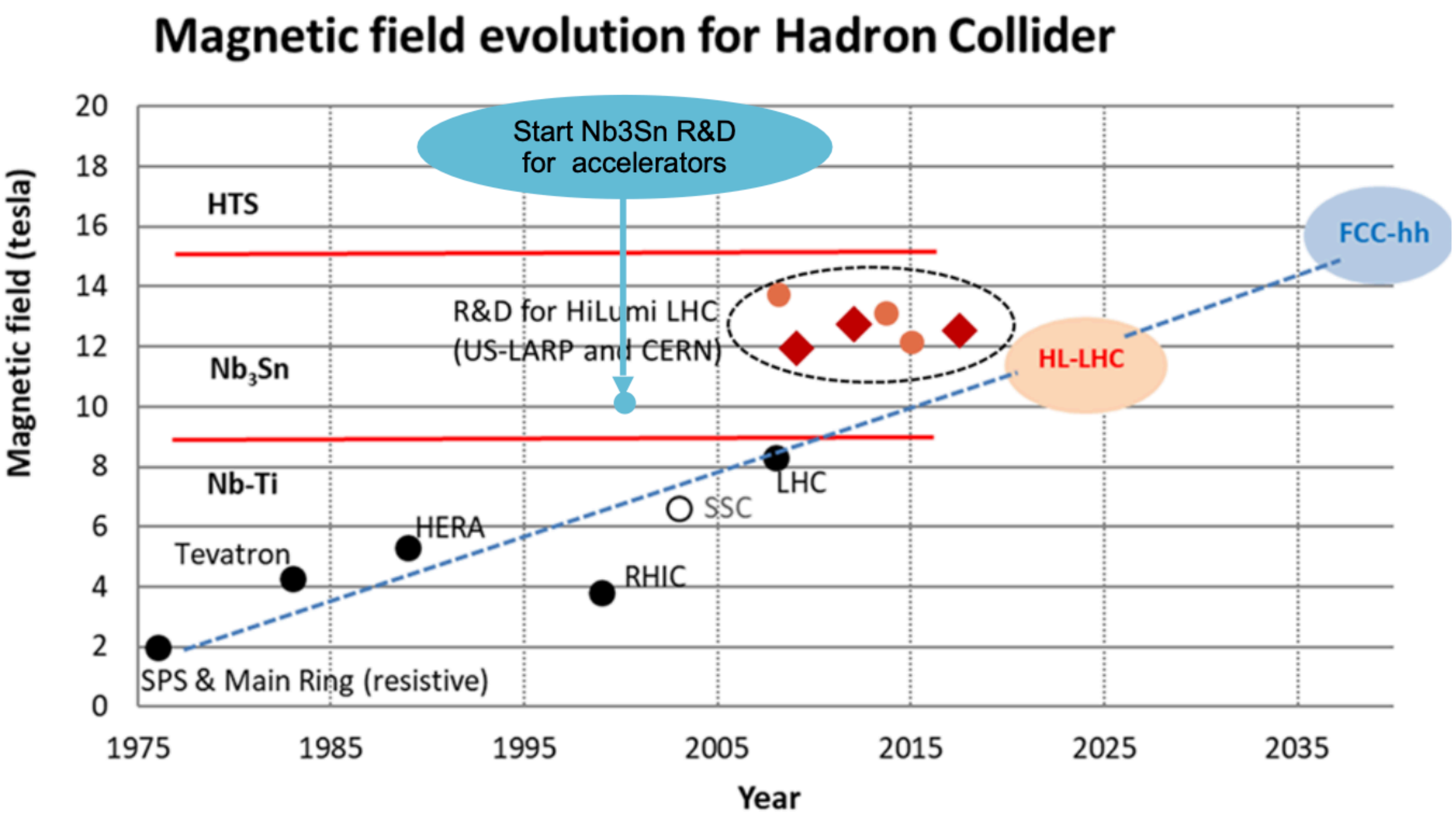
Future Circular Collider

- FCC is a *ee*/*pp* accelerator & collider
- It's a ring-shaped tunnel 91 Km long
- In the lepton phase (FCC*ee*), operating in the energy range, 91 GeV (Z pole) to 350 GeV (top-quark pair production)

synchrotron radiation power $P_\gamma \sim \frac{\gamma^4}{R^2} \simeq \left(\frac{E}{m}\right)^4 \frac{1}{R^2}$

- In the hadron phase (FCC*hh*), operating in the energy range, 70-95 TeV (depends on magnetic field strength)

Evolution of magnets for hadron collider



L. Rossi
Accelerator Technologies for HiLumi & Hadron Colliders
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A curiosity

Fermi's lecture at Columbia University, 29 January 1954

JAN. 29, 1954

FRIDAY AFTERNOON AT 2:00

McMillin Theatre

(H. A. BETHE AND P. E. KLOPSTEG presiding)

Joint Ceremonial Session of the APS and the AAPT

Retiring Presidential Address of the American Physical Society

P1. What Can We Learn with High-Energy Accelerators? ENRICO FERMI, *University of Chicago.*

Presentation of the Oersted Medal of the AAPT

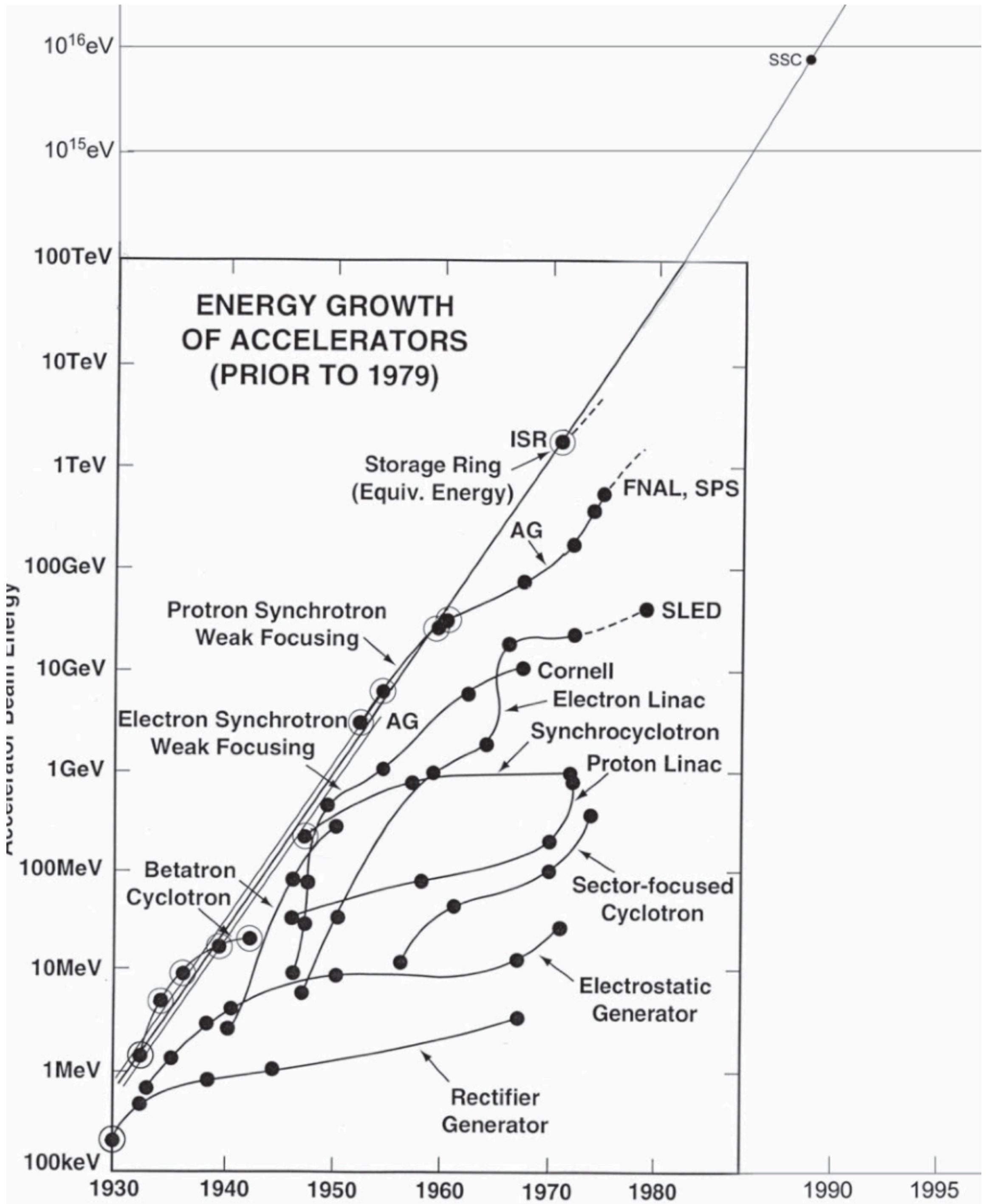
Response of the Oersted Medallist

P2. The Metaphysics of a Physics Teacher. C. N. WALL, *University of Minnesota.*

Twelfth Richtmyer Memorial Lecture of the AAPT

P3. Fields and Particles. J. A. WHEELER, *Princeton University.*

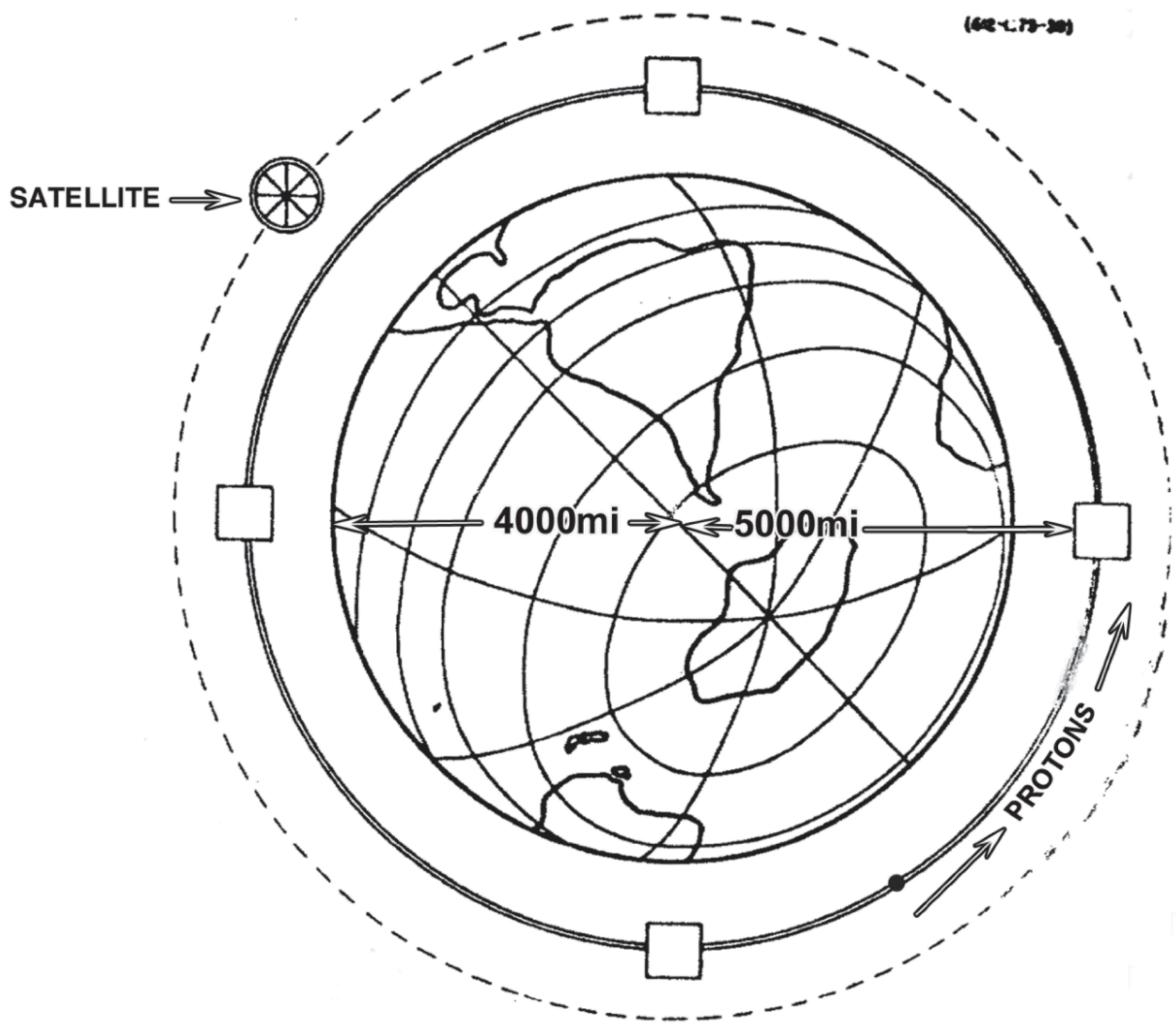
Fermi put accelerators on a log scale,
and predicted that by 1994 we would reach 5000 TeV



was Fermi right or wrong?

Fermi "ultimate accelerator"

5000 TeV proton collider



radius R = 8000 Km
magnets: 2 Tesla

fixed-target: corresponds to $\sqrt{s} \simeq 3$ TeV

Then what about future colliders?

It is said that in 1947 Fermi pronounced these words:

The research profession must return to its tradition of research for the love of discovering new truths, since in all directions we are surrounded by the unknown and the vocation of the man of science is to push forward the frontiers of our knowledge in all directions, not only in those that promise more immediate rewards or applause

The quoted phrase is attributed to Enrico Fermi and is mentioned in Giulio Maltese's biography, *Enrico Fermi in America*. However, the specific occasion and location where Fermi might have expressed these words are not directly clarified in the text. The phrase appears to reflect more of a summary of Fermi's thoughts and philosophy rather than a documented quotation from a single speech or statement

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The phrase fits Fermi's style, and the end of this talk