Colliders: Evolution and Promise

Chris Quigg
Fermilab

GGI Workshop · *Exploring the Energy Frontier with Muon Beams* · July 28, 2025

Modern e^+e^- Colliders

SPEAR (SLAC)
DORIS (DESY)
PETRA (DESY)
PEP (SLAC)
TRISTAN (KEK)
VEPP-2000 (Novosibirsk)
VEPP-4M (Novosibirsk)
BEPC (Beijing)
BEPC-II (Beijing)

DAΦNE (Frascati)
CESR (Cornell)
CESR-C (Cornell)
LEP (CERN)
SLC (SLAC)
KEKB (KEK)
PEP-II (SLAC)
Super KEK-B (KEK)

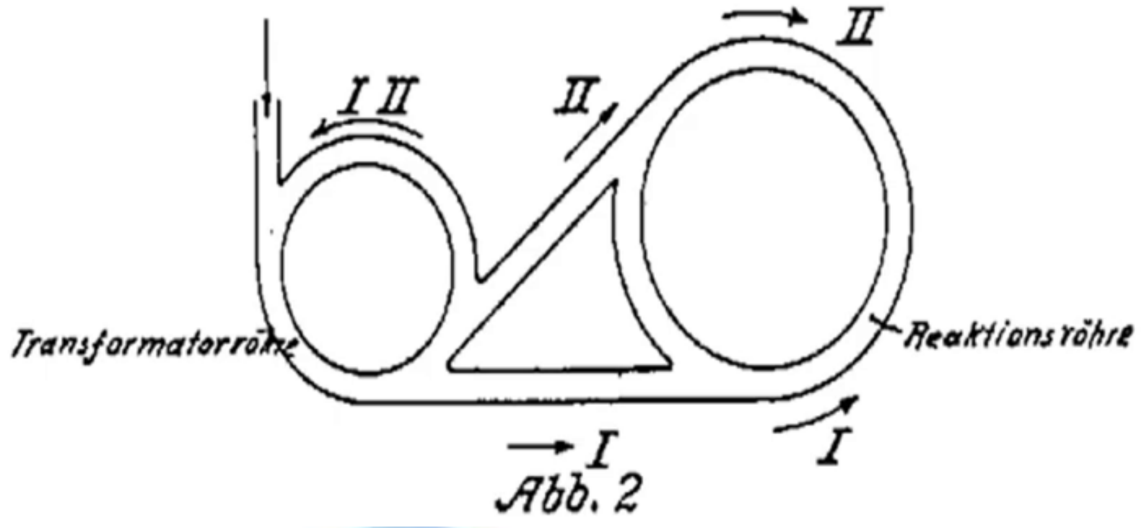
Hadron Colliders

$Sp\bar{p}S$ Collider (CERN)
Tevatron (Fermilab)
(SSC)
RHIC (Brookhaven)
LHC (CERN)

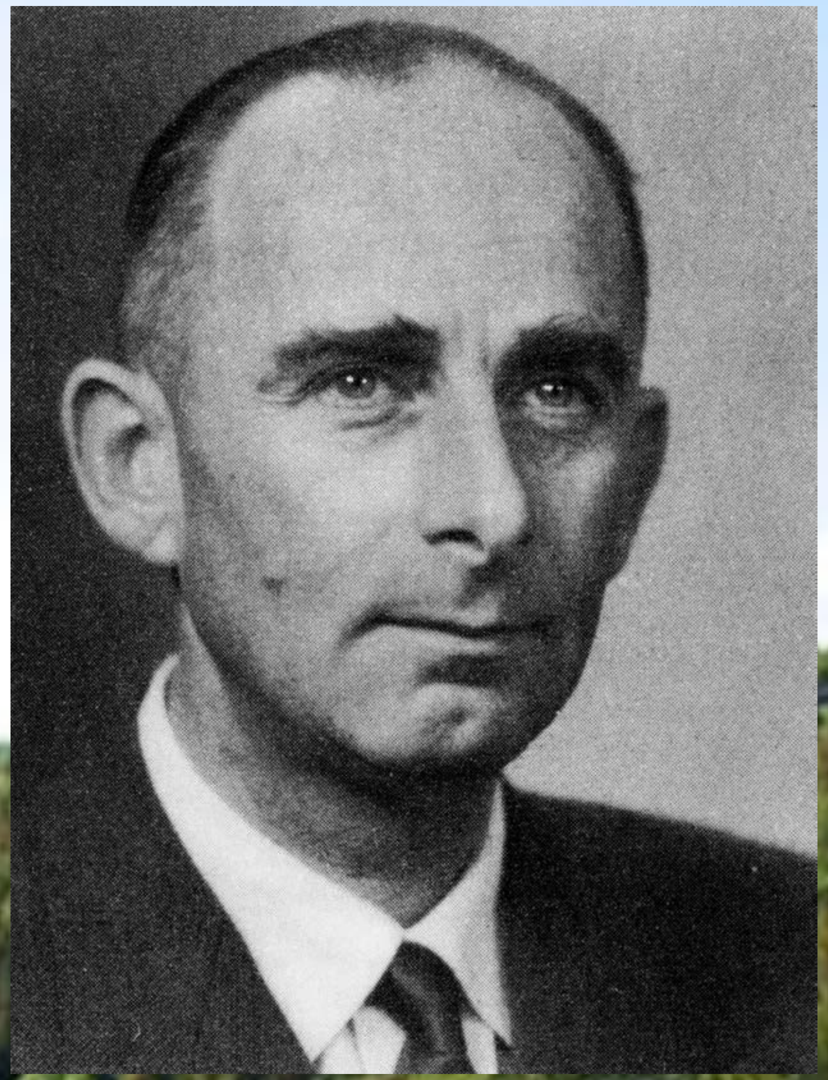
$e^{\pm}p$ Collider

HERA (DESY)

Lists from Particle Data Group: Defunct and Recent



Rolf Widerøe (1943), Tuddal (Telemark) NO:
colliding clouds inspire colliding beams
Kernmühle German patent issued 1953



8 The Invention of the Storage Ring

At this point I would like to recall an important event of my Hamburg period. It happened during the autumn of 1943, on one of my vacation trips back to Norway. Ragnhild and I were staying in a hotel in a forest in Tuddal, near Telemarken, and Ragnhild unfortunately took rather ill with pneumonia.

I was lying on a grassy hill one day, observing the clouds in the sky, when I noticed two clouds moving towards each other, as if they were about to collide. This started me thinking about cars in frontal collisions and inspired me to make the following consideration: On frontal impact, most of the kinetic energy of both cars is transformed into destructive energy. On the other hand, if a car collides against one which is at rest, only part of the kinetic energy contributes to the destruction. Quite a considerable amount of it is used up to hurl the previously stationary car away and therefore is not available to destroy the two cars. This is a result of the laws of mechanics.

I had thus come upon a simple method for improving the exploitation of particle energies available in accelerators for nuclear reactions. As with the cars, when a target particle (at rest) is bombarded, a considerable portion of the kinetic energy is used to hurl it (or the reaction products) away. Only a relatively small portion of the accelerated particle's energy is used to actually split or destroy the colliding particles. However, when the collision is frontal, most of the available kinetic energy can be exploited. For nuclear particles, relativistic mechanics must be applied, and this would cause the effect to be even greater.

However, it is not so easy to achieve head-on collisions of very small particles against each other. A large number of particles are required and they have to be tightly bundled in order for any two to stand any chance of ever colliding with each other. At the time, I was thinking of atomic nuclei. Since Rutherford's experiments

their approximate size was known and I could therefore estimate the probability of a collision. However, given the particle beams available at that time this was an utterly hopeless venture.

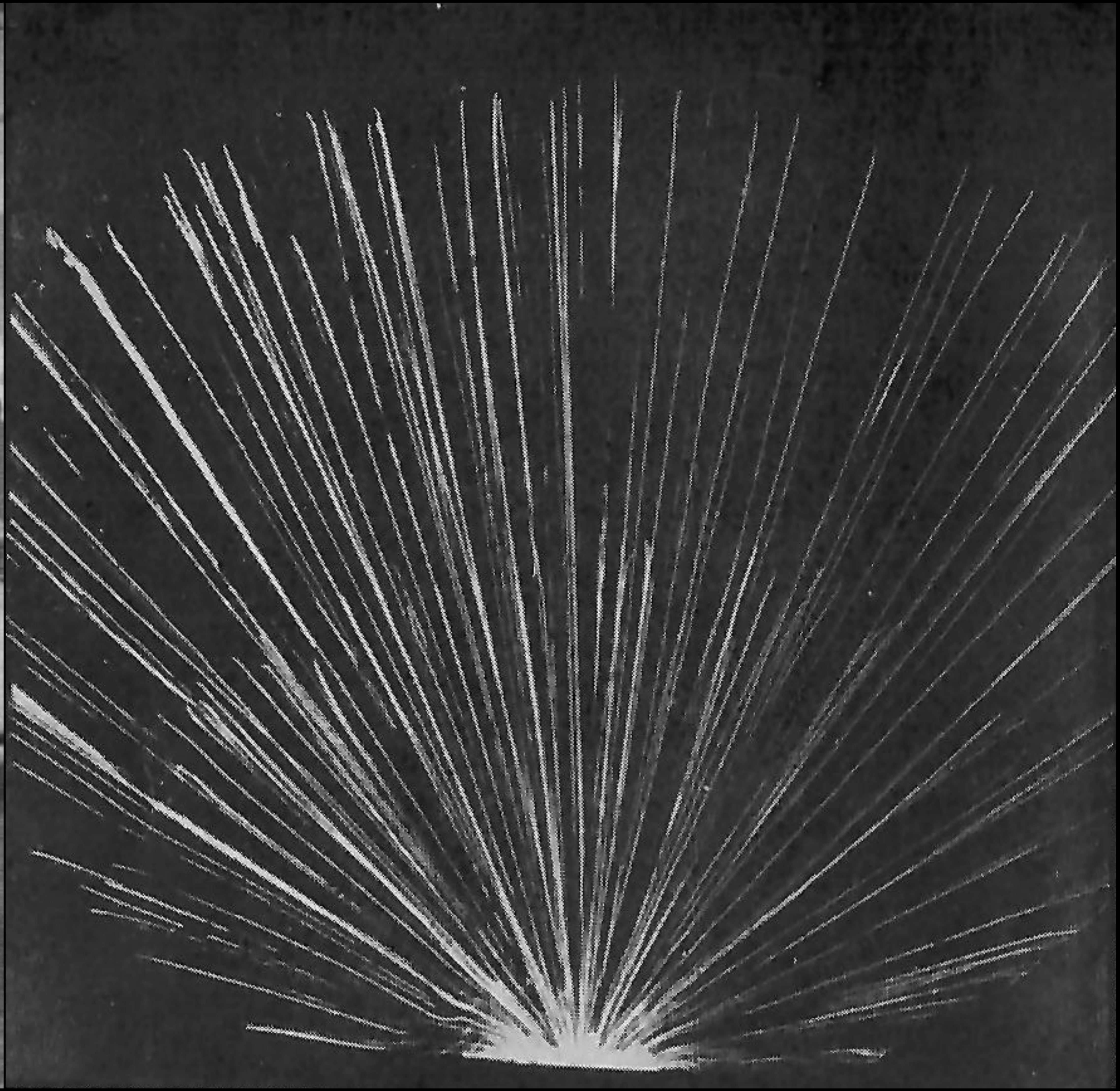
And this is where I had my second idea. If it were possible to store the particles in rings for longer periods, and if these 'stored' particles were made to run in opposite directions, the result would be one opportunity for collision at each revolution. Because the accelerated particles would move very quickly they would make many thousand revolutions per second and one could expect to obtain a collision rate that would be sufficient for many interesting experiments. I gave the name 'nuclear mill' to this storage ring, or rings, in which the collisions were to take place.

This exceedingly simple principle was not conceived of again until 1956, i.e. thirteen years later, in the USA [Ke56] [O'N56], when it was developed further and eventually put into practice. Also, in the USSR, at Novosibirsk, similar ideas appeared. However, the first storage ring was put into operation in 1961, and it was not in either the USA or the USSR, but in Italy. Many storage rings used in high energy physics were built in accordance with the principle of this first Italian machine.

After I returned to Hamburg I spoke with Touschek about my ideas and he said that they were obvious, the type of thing that most people would learn at school (he even said 'primary school') and that such an idea could not be published or patented. That was fine, but I still wanted to be assured of the priority of this idea, and I thought the best way to do this would be to submit a patent. I telephoned my friend Ernst Sommerfeld in Berlin and we turned it into a very nice and quite useable patent which we submitted on September 8, 1943 (see facsimile in Appendix 1). This was given the status of a 'secret patent'. It was not until 1953 that it was retrospectively recognized and published [Wi43a].

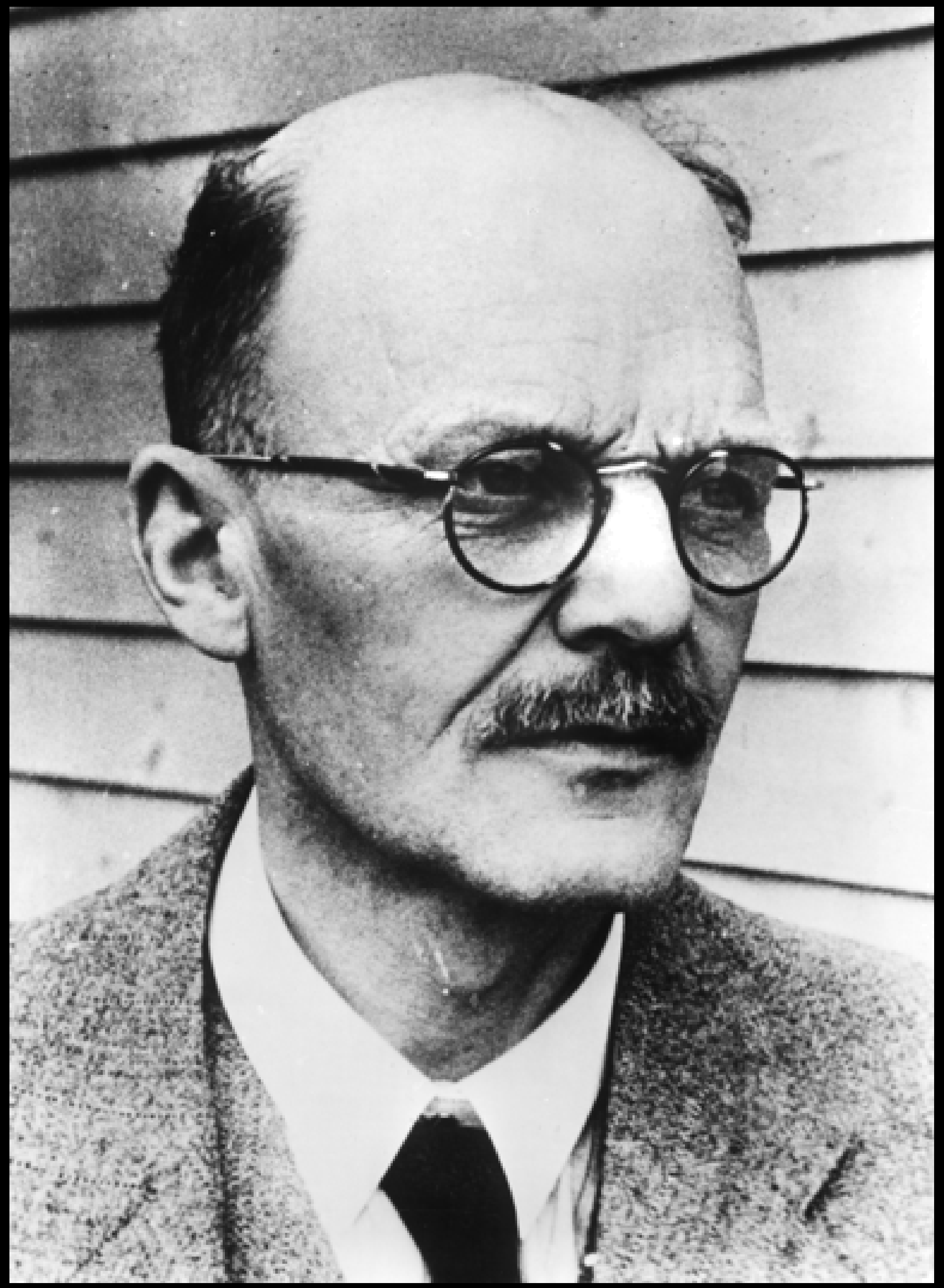
But we had taken Touschek's objections into consideration and did not state anything about the favourable balance of energy during a frontal collision in the patent, as this was considered a well known fact. Even so, Touschek was pretty offended.

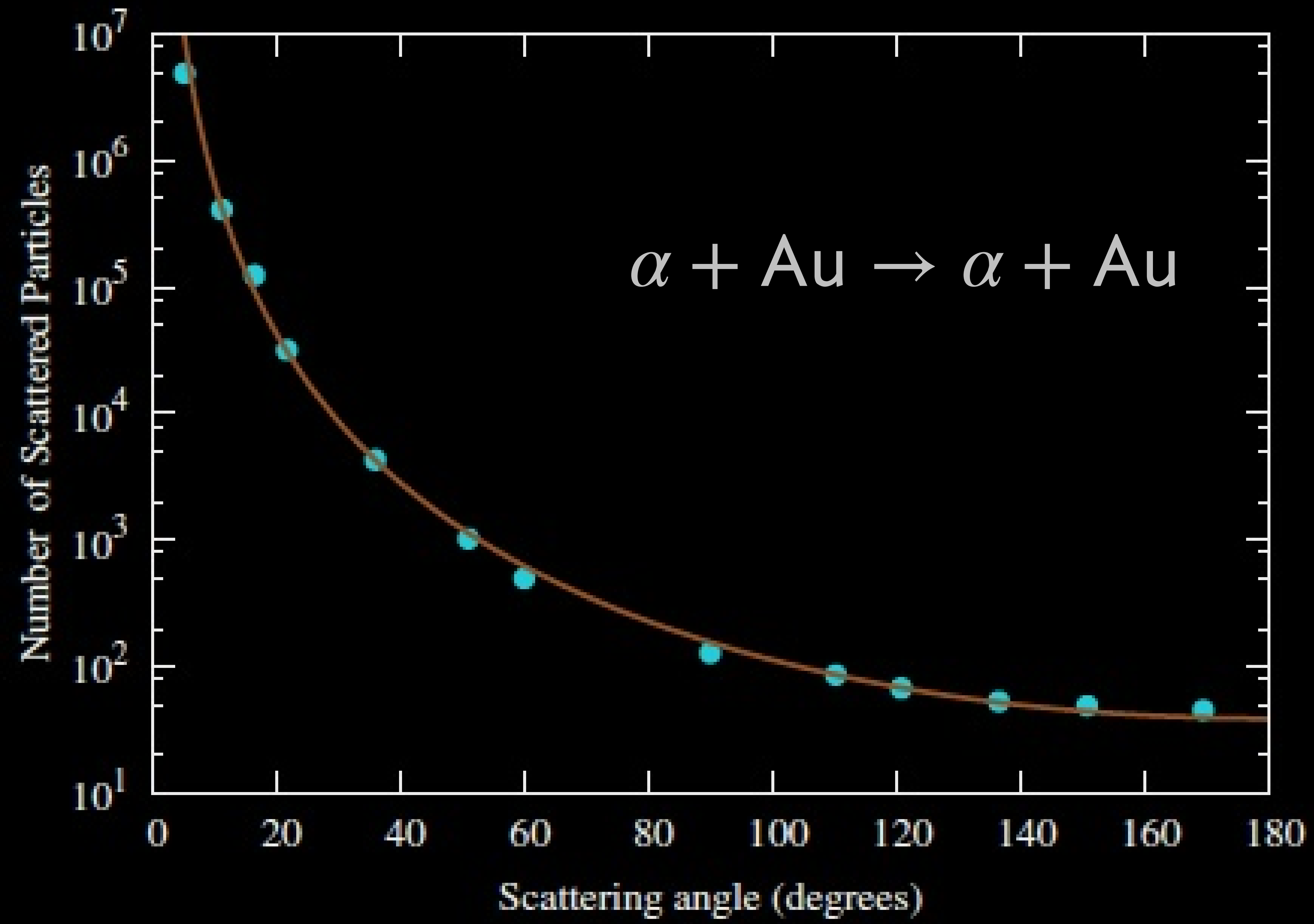
Found Beams!



Thorium C = ^{212}Bi: 6.208 MeV; C' = ^{212}Po: 8.784 MeV

Maria Skłodowska-Curie & Pierre Curie (Paris, 1898–1902)





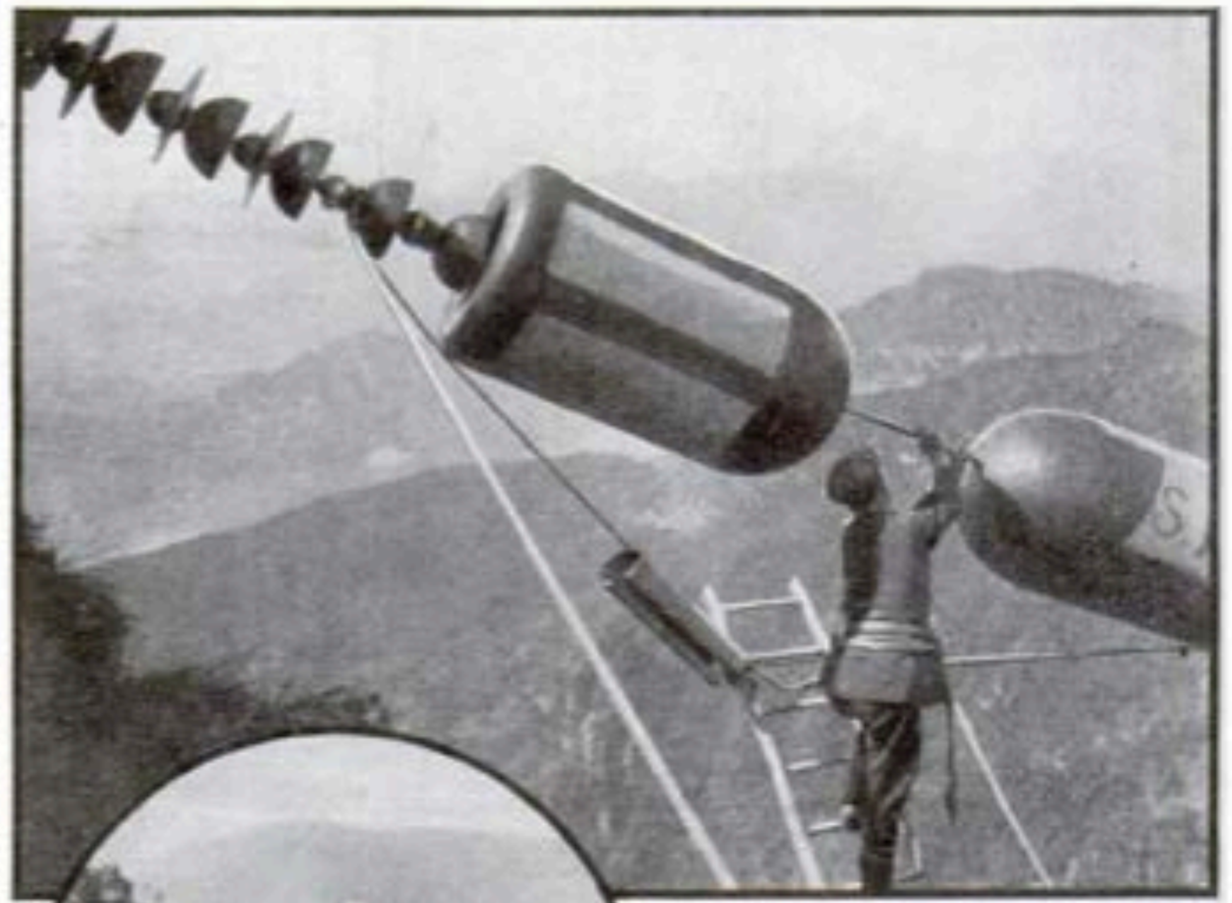
Hans Geiger, Ernest Marsden, *Ernest Rutherford* (Manchester, 1908–1913)

Arno Brasch, Fritz Lange, Kurt Urban: Monte Generoso (1927–1928)

18,000,000 Volts Captured *from the* Sky

Cable, Strung between Mountains, Acts as Antenna to Gather up Lightning

Dr. Kurt Urban, most shocked man in the world, on roof of Mt. Generoso lightningproof cabin.



Workmen installs metal "corona cylinders" in the Mt. Generoso cable to keep the high-voltage current from leaking into the air.

This apparently small spark is really one of several million volts, drawn from the sky, and leaping across a fifteen-foot gap in a preliminary test by experimenters at the Mt. Generoso station in Switzerland.

High-voltage currents, knowing no bonds, do strange things. Here is an arc that is leaping between two high-tension wires.

AT THE peril of their lives, three young Germans have just succeeded in drawing electric currents of 18,000,000 volts from the skies during a violent display of lightning. On the slopes of Mt. Generoso in Switzerland they duplicated Benjamin Franklin's famous experiment of catching atmospheric electricity with a kite and key, on a scale which that pioneer never dreamed of.

From the side of Generoso's bony-ridged slope, they stretched, as an aerial, a metallic cable across a chasm to a neighboring peak. Threaded through cylinders of galvanized metal, this antenna resembled a string of beads for a giantess. Its knobs were designed to keep the currents from leaping from the ends. Instead, an escape was provided in an adjustable spark gap, from which the electricity could be carried to a lightning-proof cabin sheathed with metal beneath the brow of the mountain. Here were meters and other instruments to gage the force of the electricity.

ONE day not long ago the daring three, Drs. A. Brasch, F. Lange, and Kurt Urban, of the University of Berlin, saw a storm of unusual intensity brewing. The sky became pitch dark. Peals of thunder hurried the scientists as they threw switches and tested instruments. Then with a rush of wind up the valley that almost swept away the aerial, the fury of the storm broke.

Tongues of electric flame played about the rocks of the mountain's face near the summit. Filled with metallic ore, it was a natural lightning rod. Great yellow sparks snapped every second across the spark gap. The pointers of the voltmeters within the cabin were doing a dance. There came a brief lull, ominous in its calm.

Suddenly a terrific thunderclap seemed to shake the whole mountain. The valley was lit up as by a million arc lights, and fantastic reflections danced over the white faces of the scientists. A bolt of flame crashed across the spark gap. For the first time, an eighteen-million-volt thunderbolt had been caught. The scientists had tapped the power of the lightning.

NOW that they know how to obtain voltages infinitely greater than any man-made machine has been able to produce, their dream is to apply the titanic forces to an apparatus like an X-ray tube and see what will happen. The ordinary glass X-ray tube would have to be half a mile long, an impossible constructional feat, to withstand such electrical pressure. But the experimenters have already built a strange tube, less than a dozen feet long, of alternate rings of aluminum, rubber, and paper, that will stand electric forces up to 2,600,000 volts—by a considerable margin the most powerful ever made.

The rays from this tube far exceed in power those of all the radium in the world. They easily penetrate a wall of lead a yard thick, an impassable barrier to all ordinary X-rays. Next the experimenters plan to build a 7,000,000-volt tube of similar

design. Only lightning can run it, for the greatest electrical tension ever produced in a laboratory is 5,000,000 volts.

How can such staggering forces be put to use? No one knows exactly, yet. But there are several long-awaited tests for which the power of lightning may be tried.

One of these is the dream of alchemists of old—the "transmutation of elements," such as turning base metals into gold. In recent years science has conceded that metals and other substances once held unchangeable can actually be transformed into entirely different ones under certain circumstances, requiring tremendous forces.

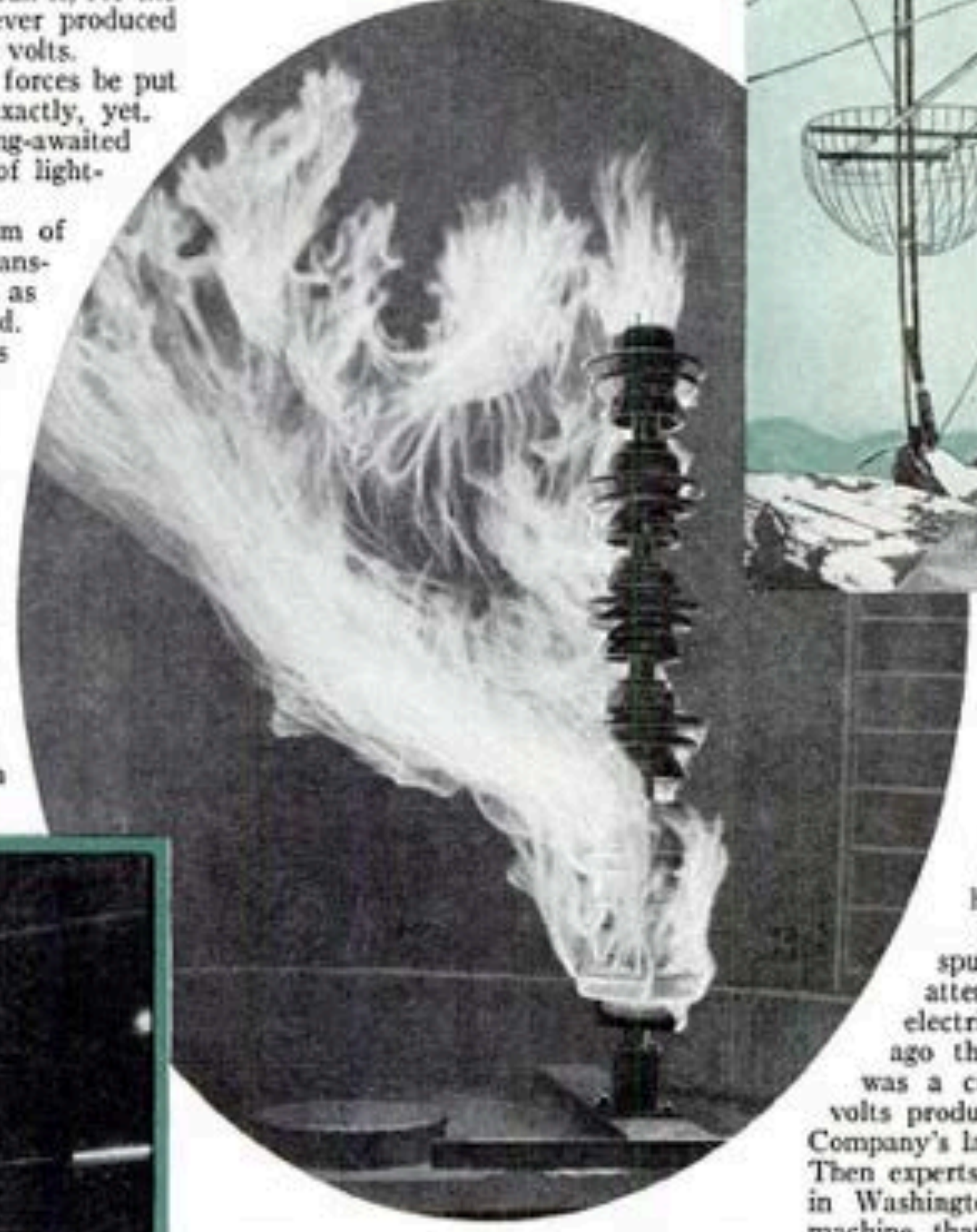
So far the only proved cases of transmutation have been done with the mysterious power of radium; thus, minute quantities of aluminum, phosphorus, and other things have been turned into hydrogen. Perhaps lightning's power may permit more useful transformations of other elements, when harnessed in a vacuum tube.

Then there is the question of unlocking the power of the atom. Some scientists hold that the energy contained in a single spoonful of water, for example, is sufficient to drive a modern steamship across the ocean. But this energy, if it does exist, is so securely locked up that no way has yet been found to release it. Should lightning's force break an entrance into this stronghold of power, the world might see a new era of industrial greatness based upon free atomic energy.

LASTLY, the rays from an electric tube operated by lightning's power may well have the most profound effect upon human beings. Whether beneficial or not, it is too early to say. Perhaps the audacious experimenters will find a curative ray more effective against cancer than any instrument hitherto known to science. On the other hand it may be a "death ray."

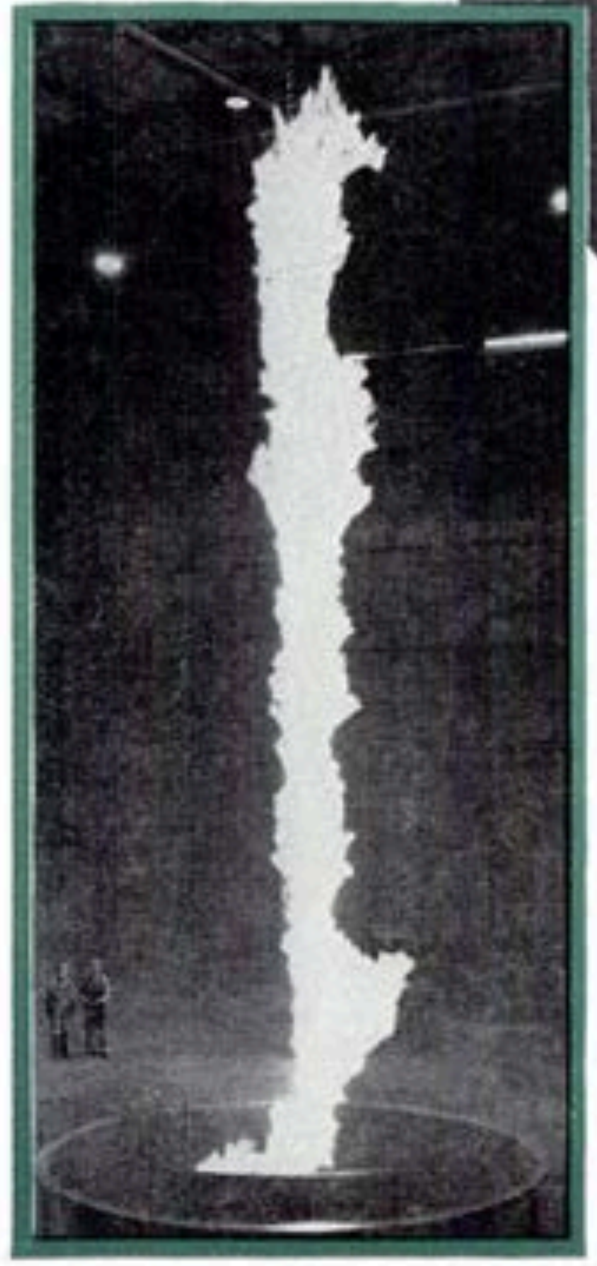
Such fascinating possibilities spur man's advance in his attempt to harness stupendous electric forces. Only a few years ago the pinnacle of these efforts was a crackling spark of 3,600,000 volts produced at the General Electric Company's laboratory in Pittsfield, Mass. Then experts at the Carnegie Institution in Washington, D. C., built a mighty machine that could command 5,000,000 volts. Meanwhile the German experimenters had already installed a preliminary apparatus on Mt. Generoso, a peak famed for the frequency and violence of its electric storms, and were drawing two-million-volt sparks (P. S. M., Jan. '29, p. 23). A higher, rebuilt antenna made their recent feat possible. One of the experimenters, Dr. Urban, has acquired the sobriquet of "most shocked man in the world" from being knocked unconscious by sky currents.

IT MUST be understood that their antenna is not directly struck by lightning, for if it were, despite an electrical "safety valve" they have provided, they would probably all be killed. The aerial takes current from the clouds in two ways. Electricity in the air itself leaks down the cables in steady sparks. But the greatest voltages are obtained when a lightning bolt passes close to the aerial and a sympathetic surge of electricity is induced in the wire. In this way they have now captured 18,000,000 volts, and even greater voltages, up to thirty million, are in sight!



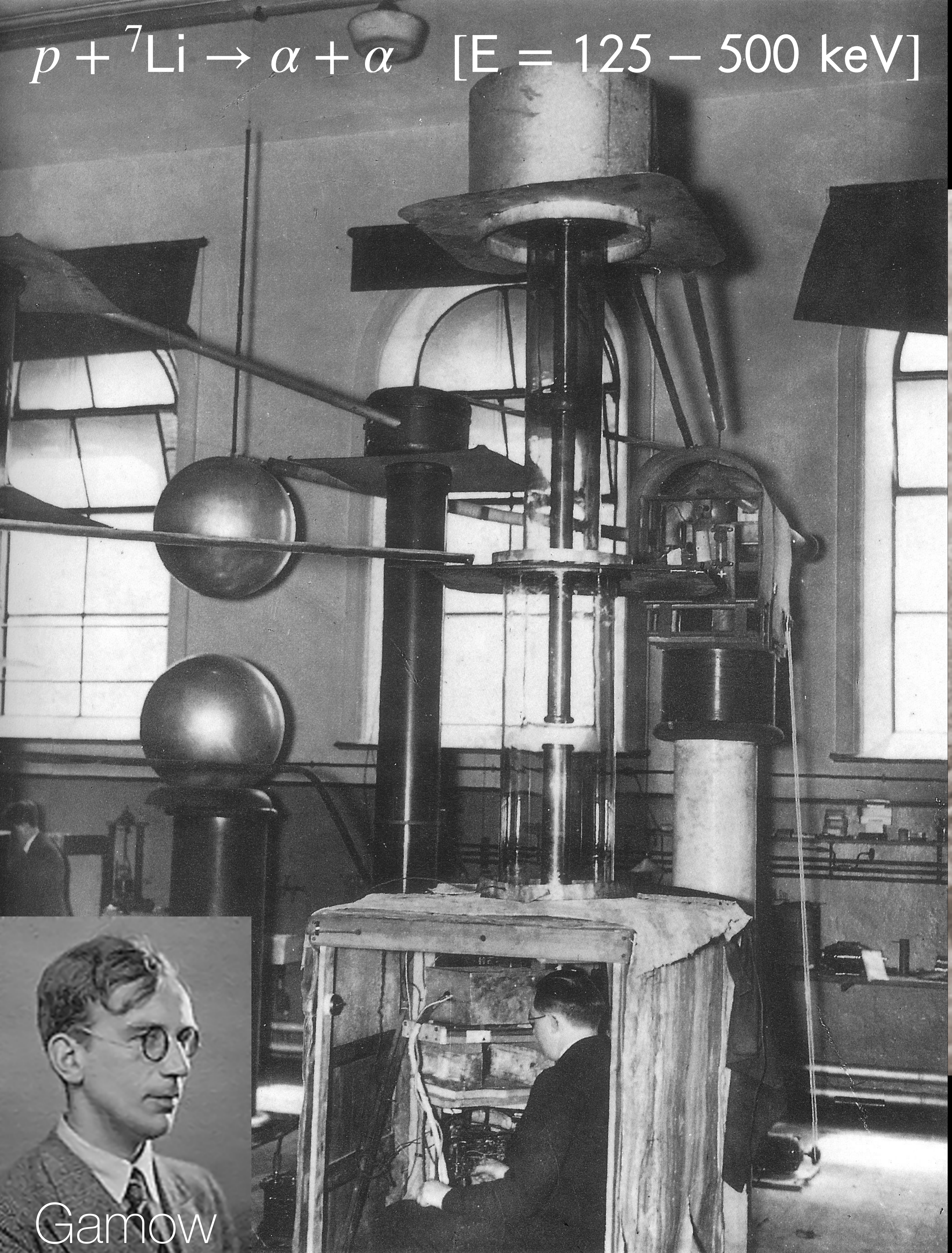
This is not lightning, but a discharge of laboratory electricity leaping from insulators. It shows why extraordinary apparatus is required in harnessing 18,000,000 volts.

Here is part of the apparatus that was used in the Mt. Generoso tests. This strange network was designed to carry the enormous voltage to the laboratory where the scientists waited in danger of instant death.



This 55-foot man-made arc was drawn out in Westinghouse laboratory in recent test.

$p + {}^{7}\mathrm{Li} \rightarrow \alpha + \alpha$ [E = 125 – 500 keV]



Walton · Rutherford · Cockcroft (Cambridge, 1932)

Lawrence & Livingston Cyclotron (Berkeley, 1931–2)

60” cyclotron magnet frame (1938)

16-MeV deuterons from Lawrence’s 60” cyclotron

LIFE, February 5, 1940

TRIUMF Cyclotron: 18-m diameter, 520 MeV, 10^{15} *p*/sec

vacuum chamber 46 cm high

Cosmic Rays (Hess, 1911–); Disintegration stars (Blau & Wambacher, 1937)

Disintegration Processes by Cosmic Rays with the Simultaneous Emission of Several Heavy Particles

On photographic plates which had been exposed to cosmic radiation on the Hafelekar (2,300 m. above sea-level) near Innsbruck for five months, we found, apart from the very long tracks (up to 1,200 cm. in length) which have been reported recently in a note in the Wiener Akademie-Berichte, evidence of several processes described below.

From a single point within the emulsion several tracks, some of them having a considerable length, take their departure. We observed four cases with three particles, four with four and 'stars' with six, seven, eight and nine particles, one of each kind.

The longest track corresponded to a range in air (15°, 760 mm. Hg) of 176 cm. The ionization produced by the particles is different in the different cases. Most of the tracks show much larger mean grain-distances than α-particles and slow protons.

In Fig. 1 a 'star' with eight tracks is reproduced. On account of the rather steep angles at which some of the particles cross the emulsion-layer (approximately 70 μ thick) it is not possible to have all the tracks of a 'star' in focus simultaneously. Fig. 2 shows a sketch of the same 'star'. Measurement of the tracks gives the results in the accompanying table.

Track	Length in cm. of air (15°, 760 mm.)	Number of grains	Position of the end of the track
A	30·0 cm.	113	Within the emulsion
B	11·0 ,,	15	,, ,, ,,
C	44·6 ,,	71	Glass
D	6·2 ,,	11	,,
E	7·0 ,,	22	,,
F	1·2 ,,	5	Within the emulsion
G	13·6 ,,	67	Surface of the emulsion
H	23·9 ,,	58	Glass

Centre of the 'star' 25 μ under the surface of the emulsion.

We believe that the process in question is a disintegration of an atom in the emulsion (probably Ag or Br) by a cosmic ray. The striking feature about it is the simultaneous emission of so many heavy particles with such long ranges, which excludes any confusion with 'stars' due to radioactive contamination. A similar configuration of tracks by chance is equally out of question. Brode and others[1]

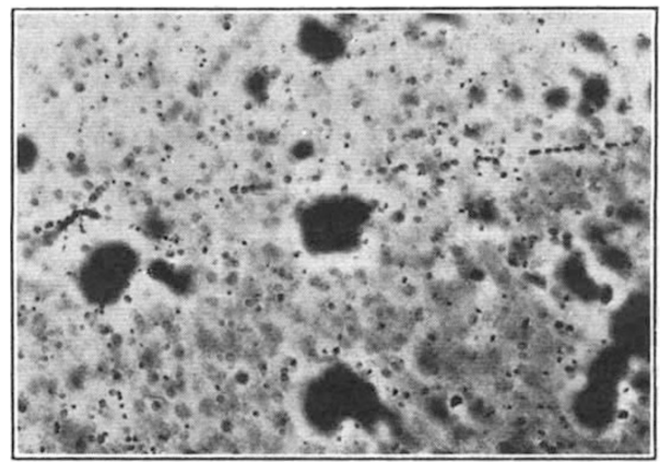


Fig. 1.

observed a single case of a disintegration with three heavy particles in a Wilson cloud chamber. The phenomenon which Wilkins believes was a shower of protons is perhaps a similar process, but he did not observe a centre[2].

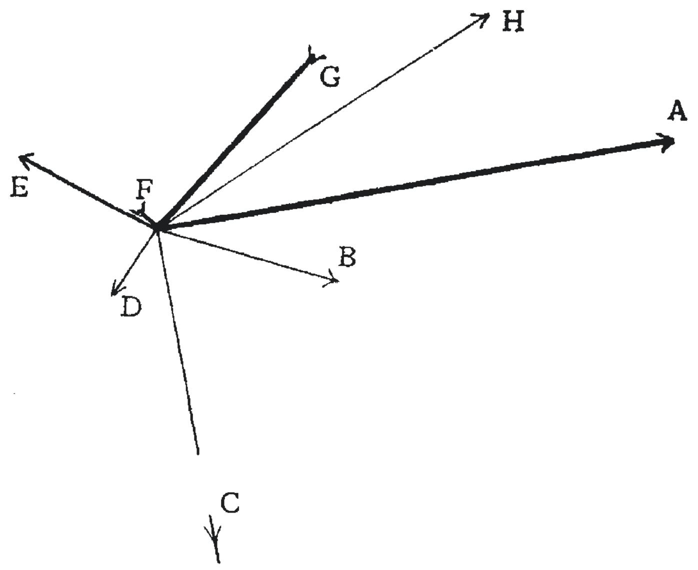


Fig. 2.

Thick lines indicate a comparatively large number of grains per unit of length of the track. An interrupted line means that the track is too long to be reproduced on the same scale. The arrows indicate the direction from the surface of the emulsion to the glass.

The total energy involved in the process cannot as yet be calculated as most of the particles do not end in the emulsion.

We hope to give further details before long in the Wiener Akademie-Berichte.

M. Blau.
H. Wambacher.

Radium Institut
u. 2 Physik. Institut,
Wien.
Aug. 25.

[1] Brode, R. L., and others, *Phys. Rev.*, **50**, 581 (October, 1936).
[2] Wilkins, *Nat. Geog. Soc.*, Stratosphere Series, No. 2, 37 (1936).

Positron, muon, pion, strange particles, …

Eur. Phys. J. H **36**, 183–201 (2011)
DOI: 10.1140/epjh/e2011-20014-4

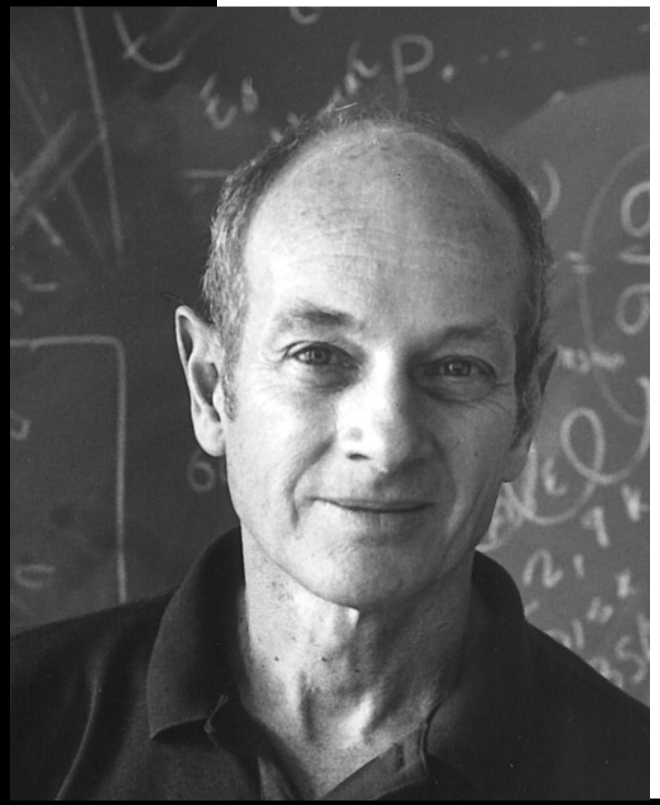
THE EUROPEAN PHYSICAL JOURNAL H

The 1953 Cosmic Ray Conference at Bagnères de Bigorre: the Birth of Sub Atomic Physics

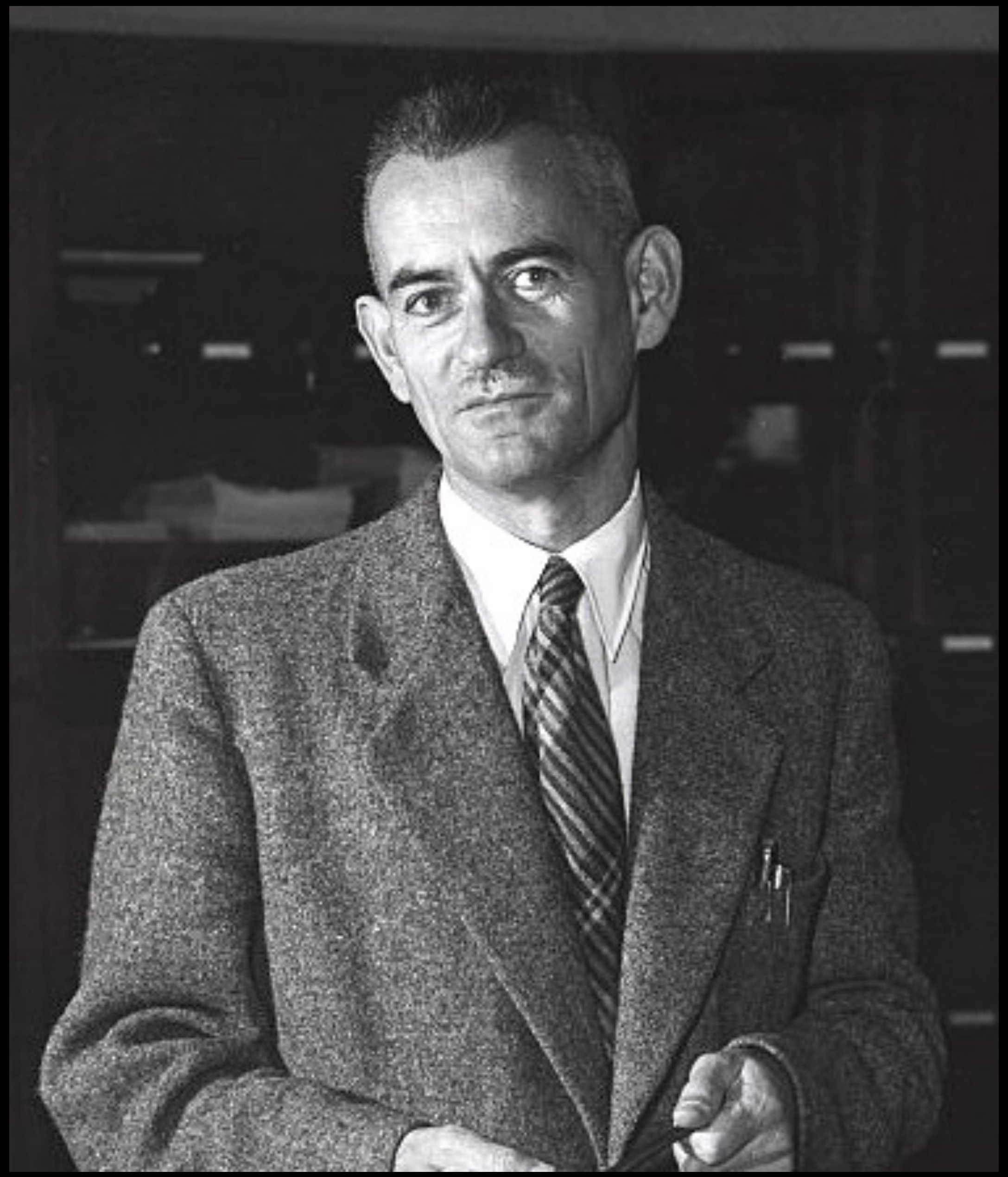
J.W. Cronin[a]

Department of Astronomy and Astrophysics, Enrico Fermi Institute, University of Chicago, 5640 South Ellis Ave., Chicago, IL 60637, USA

Received 2 March 2011
Published online 29 August 2011



Abstract. The cosmic ray conference at Bagnères de Bigorre in July, 1953 organized by Patrick Blackett and Louis Leprince-Ringuet was a seminal one. It marked the beginning of sub atomic physics and its shift from cosmic ray research to research at the new high energy accelerators. The knowledge of the heavy unstable particles found in the cosmic rays was essentially correct in fact and interpretation and defined the experiments that needed to be carried out with the new accelerators. A large fraction of the physicists who had been using cosmic rays for their research moved to the accelerators. This conference can be placed in importance in the same category as two other famous conferences, the Solvay congress of 1927 and the Shelter Island Conference of 1948.



Louis Leprince-Ringuet
Bagnères-de-Bigorre (1953)
« Mais nous devons aller vite, nous devons courir sans ralentir notre cadence : nous sommes poursuivis … nous sommes poursuivis par les machines ! »

Phase stability (Veksler (1944)–McMillan (1945)) ↪ Synchrotrons

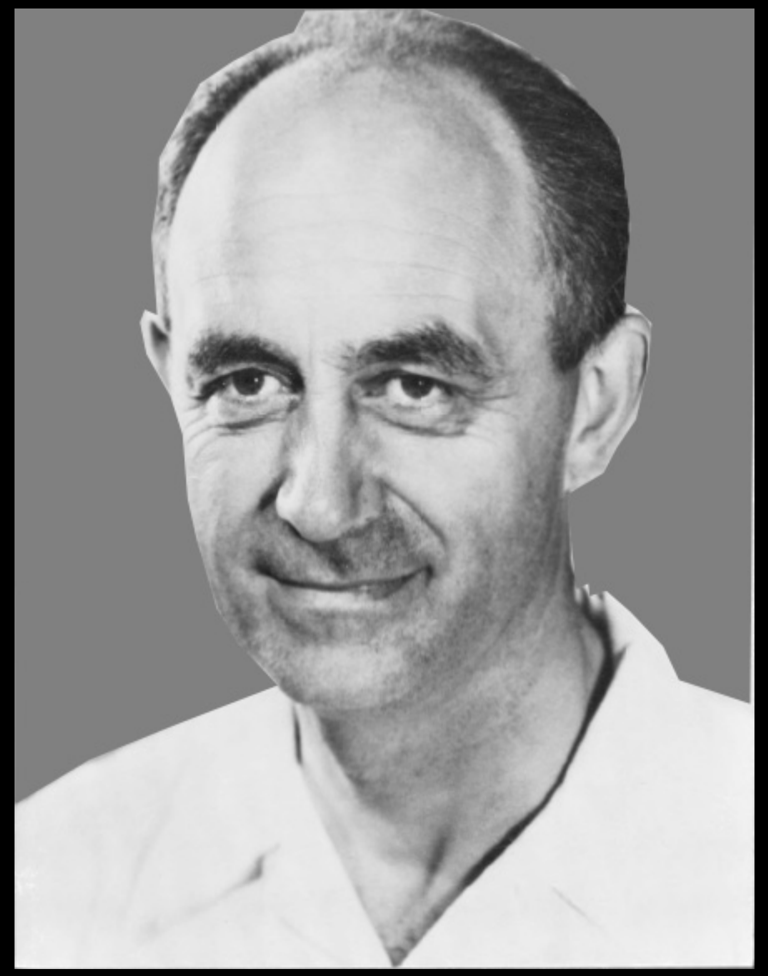
Brookhaven Cosmotron, 3+ GeV (1952–4)

Berkeley Bevatron, 6.2 GeV (1954)

Fermi's Dream Machine (1954): 5000-TeV p ~ E_{cm} = 3 TeV

2-tesla magnets at radius ≈ 8000 km

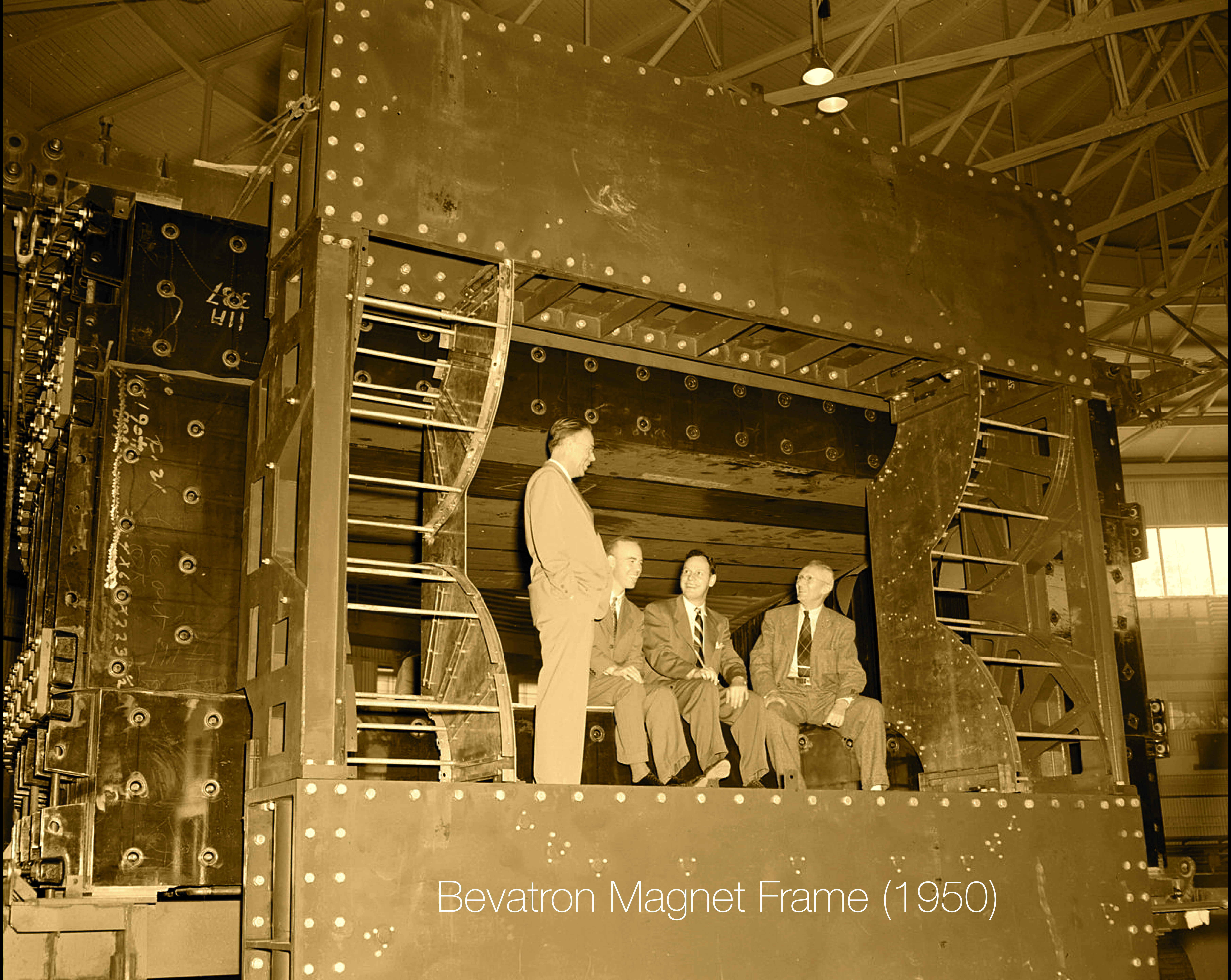
Projected operation 1994
cost $170 Billion
1954 inflation rate 0.75%



Why must accelerators be so large?

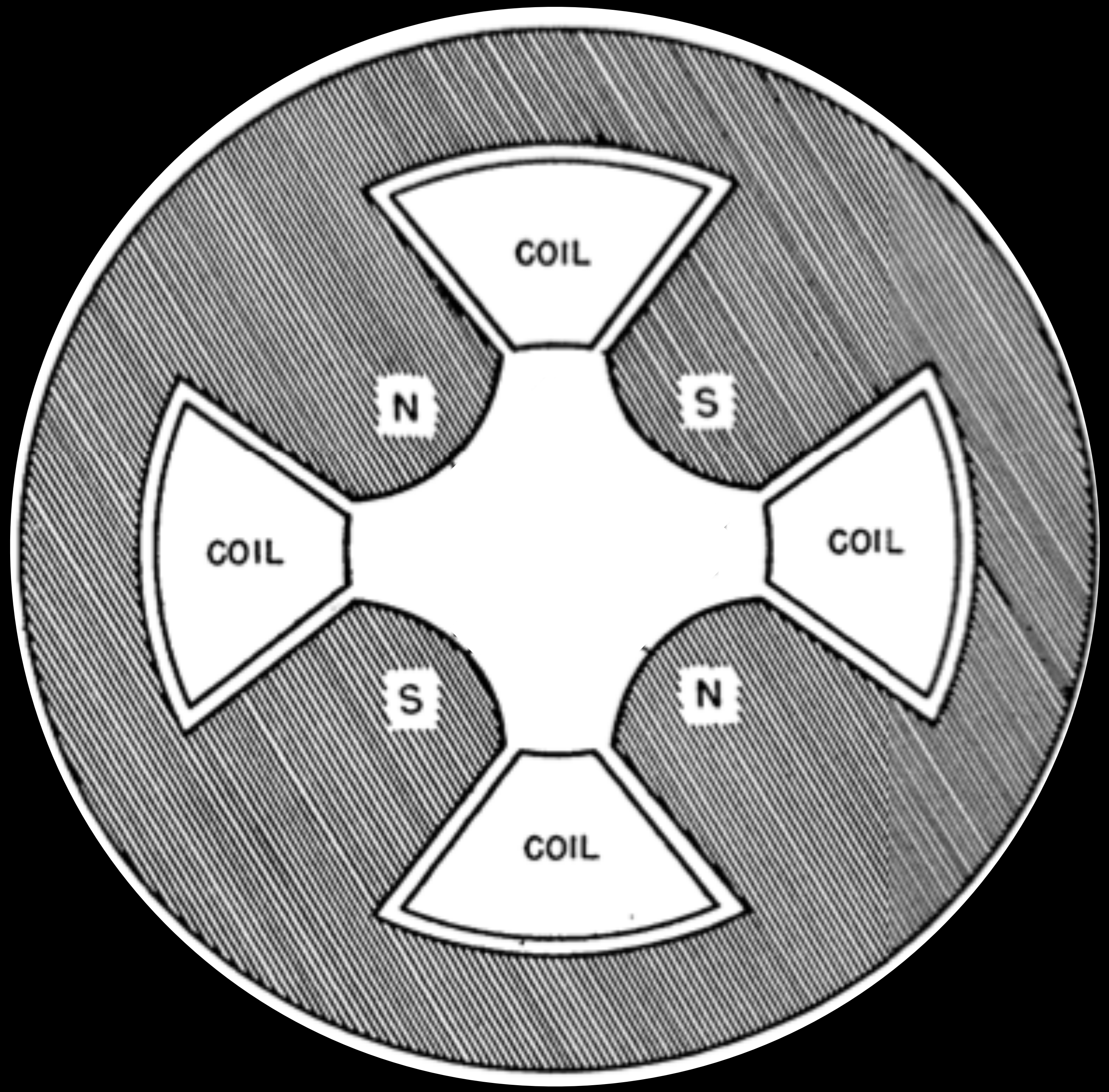
$$\text{radius} \approx \frac{10\ \text{km}}{3} \cdot \left(\frac{\text{Energy}}{1\ \text{TeV}}\right) \Big/ \left(\frac{\text{Magnetic Field}}{1\ \text{tesla}}\right)$$

+ aperture to contain unruly beam

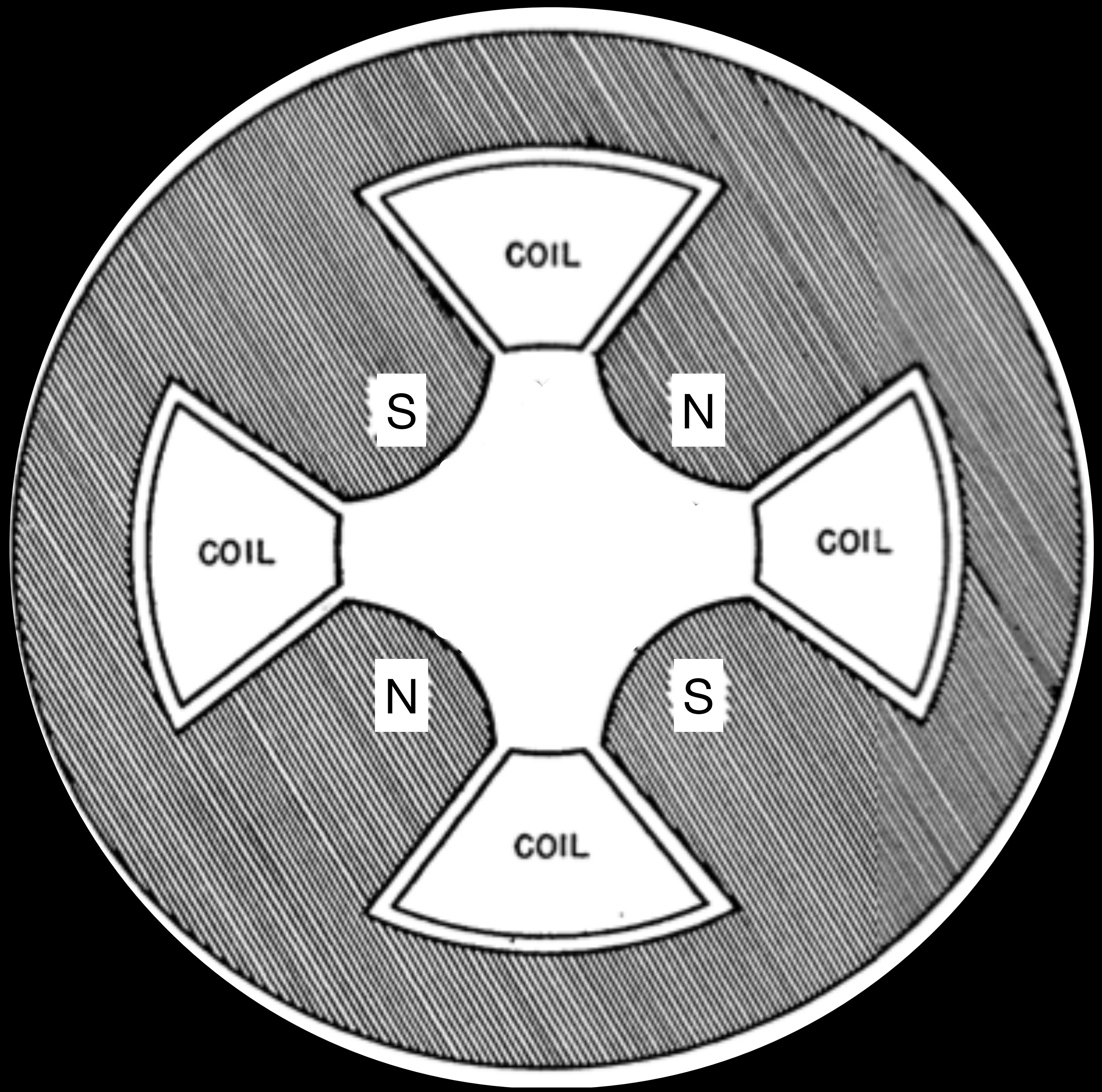


Bevatron Magnet Frame (1950)

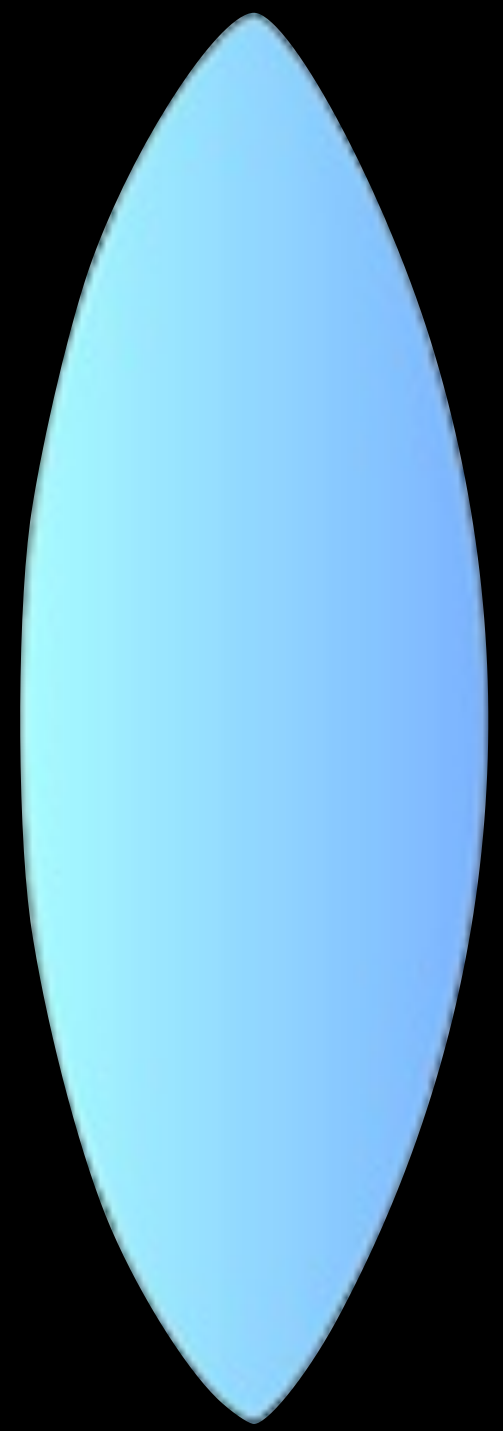
Alternating-gradient (strong) focusing



+



≈



Christofilos (Athens, 1949)

Courant, Livingston, Snyder (Brookhaven, 1952)

Impact of alternating-gradient (strong) focusing

Synchrotron (circumference, *E*)	Beam Tube	Magnet Size
Cosmotron (230 ft, 3 GeV)	9 in x 3 ft	8 ft x 8 ft
Bevatron (400 ft, 6.2 GeV)	1 ft × 4 ft	9-1/2 ft × 20-1/2 ft
Brookhaven AGS (0.5 mi, 30 GeV)	2.7 in × 6 in	33 in × 39 in
Fermilab Main Ring (2π km, 400 GeV)	2 in × 4 in	14 in × 25 in
Fermilab Tevatron (≈ 1 TeV)	70 mm	4.3 T (SC, 4.2 K)
CERN LHC (27 km, → 7 TeV)	56 mm	8.3 T (SC, 1.3 K)

Main Ring's volume under vacuum < Bevatron's

NY *Times*, March 11, 1965: “Atom-Smasher Test Shows Way to Save on Energy”

Attainment of Very High Energy by Means of Intersecting Beams of Particles

D. W. Kerst,* F. T. Cole,† H. R. Crane,‡ L. W. Jones,‡ L. J. Laslett,§ T. Ohkawa,‖ A. M. Sessler,¶ K. R. Symon,** K. M. Terwilliger,‡ and Nils Vogt Nilsen††

Midwestern Universities Research Association,‡‡ University of Illinois, Champaign, Illinois

(Received January 23, 1956)

The Frascati Storage Ring.

C. Bernardini, G. F. Corazza, G. Ghigo

Laboratori Nazionali del CNEN - Frascati

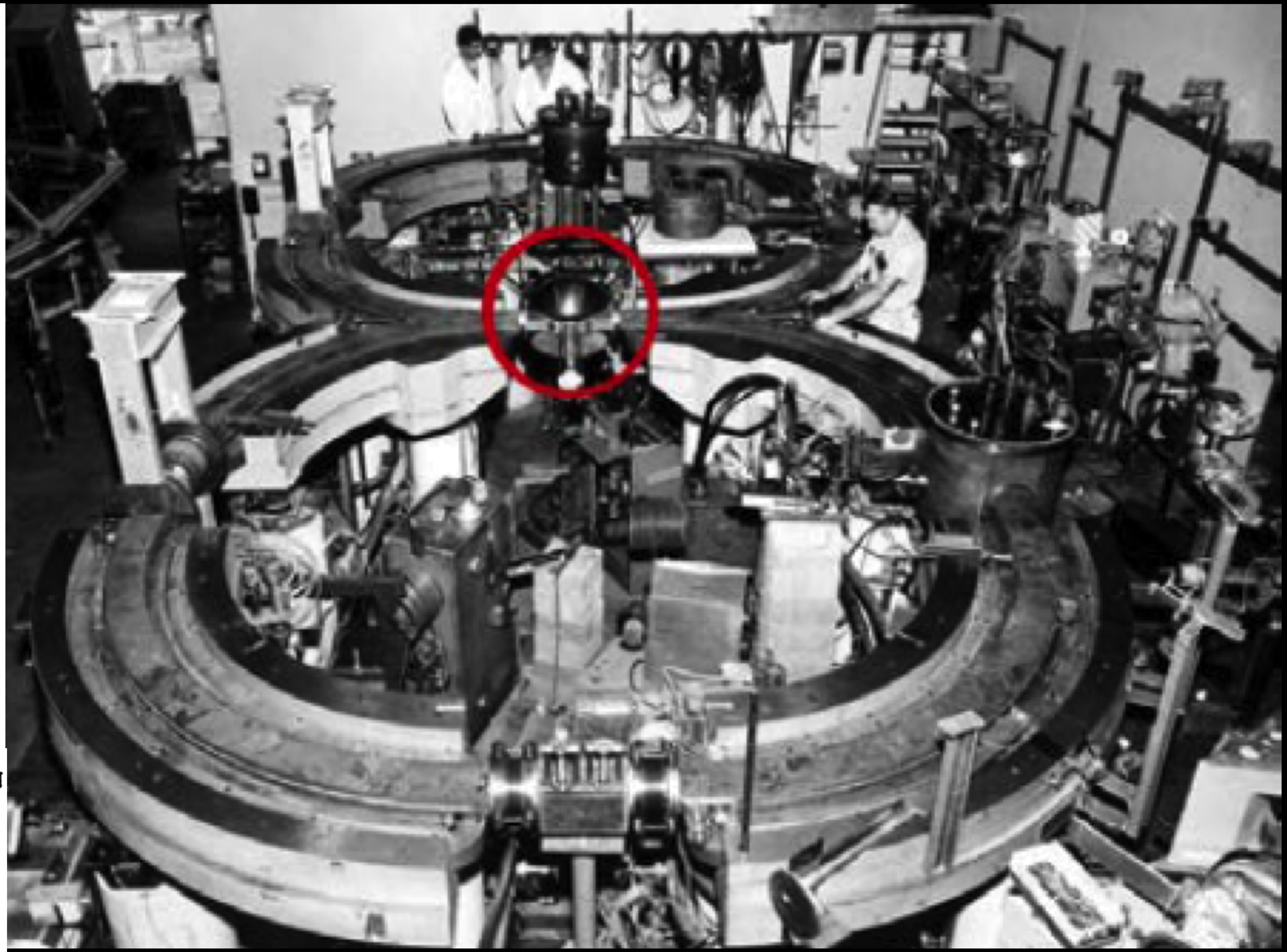
B. Touschek

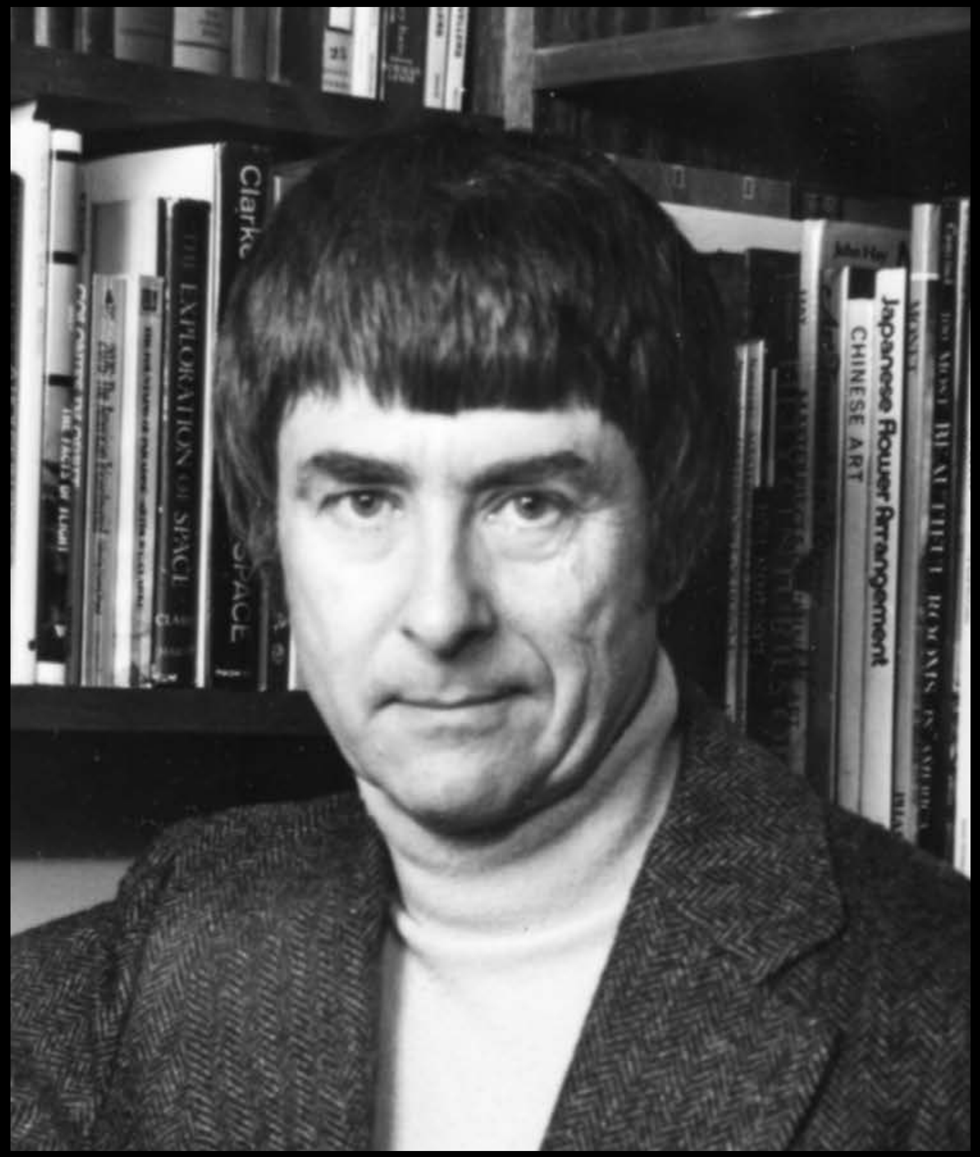
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare - Sezione di Roma

(ricevuto il 7 Novembre 1960)

STUDIES OF COLLIDING ELECTRON-ELECTRON, POSITRON-ELECTRON AND PROTON-PROTON BEAMS AT THE INSTITUTE FOR NUCLEAR PHYSICS, THE SIBERIAN BRANCH OF THE U.S.S.R. ACADEMY OF SCIENCES

G.I. Budker, A.A. Naumov, and co-workers



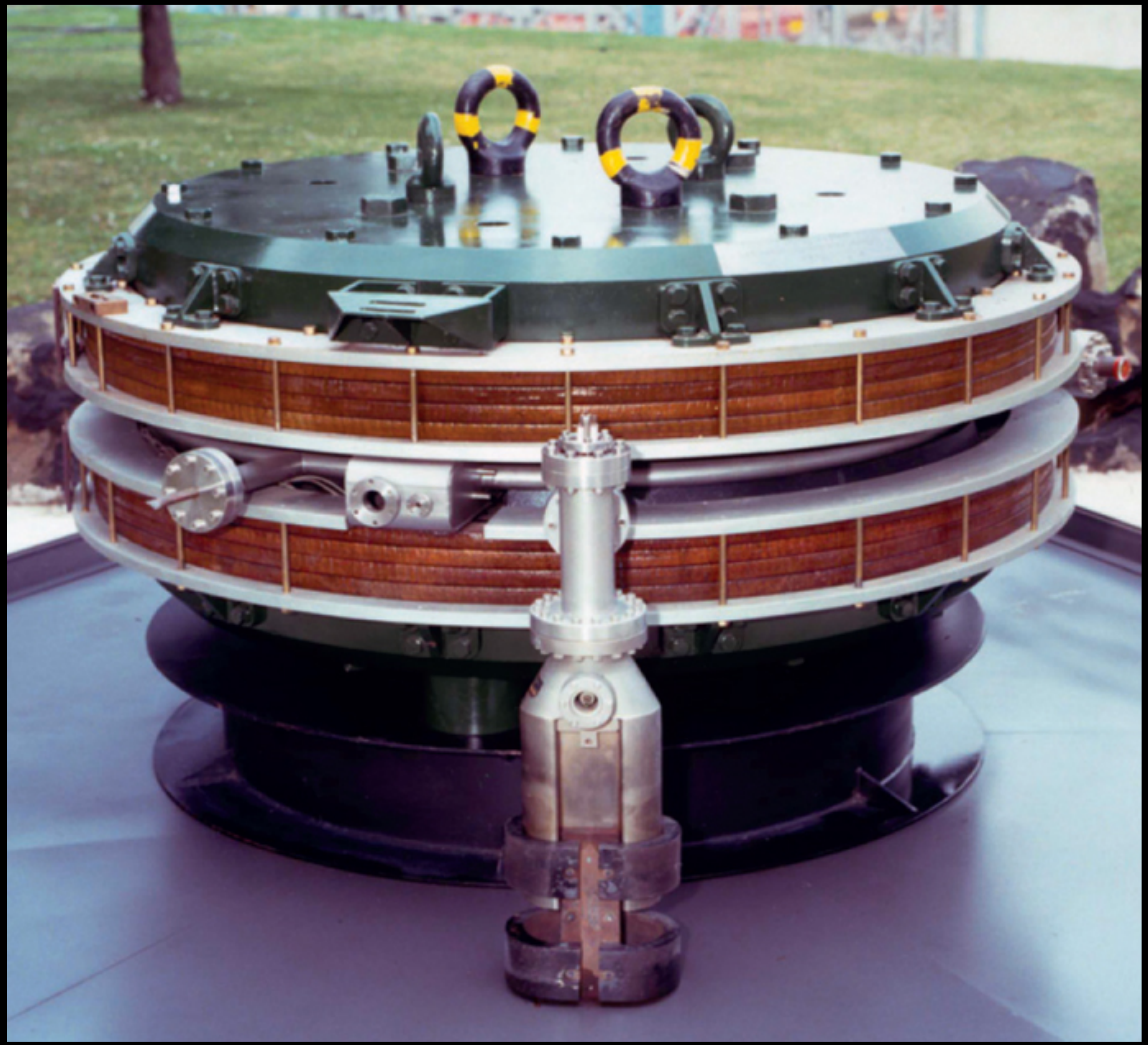


O’Neill (1956)
25⊗25-GeV *pp*
~1.3 TeV fixed target

Carl Barber, Bernard Gittelman, G. K. O’Neill, Burton Richter: CBX

300-MeV electrons in collision ⇒ 350 GeV fixed-target

First e^+e^- Collisions: AdA
Anello di Accumulazione, Frascati
↪ ACO, Orsay



Bruno Touschek and AdA

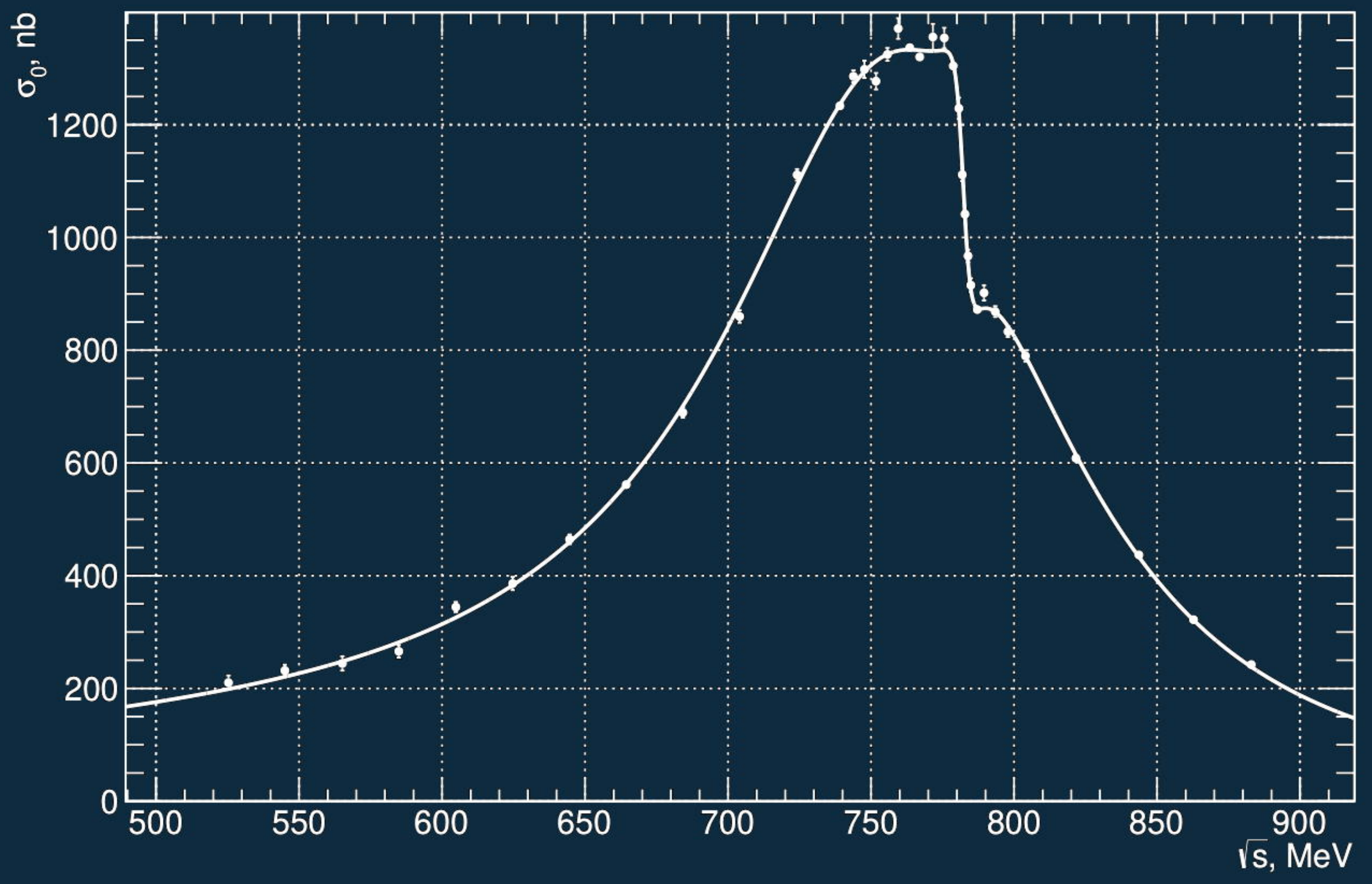
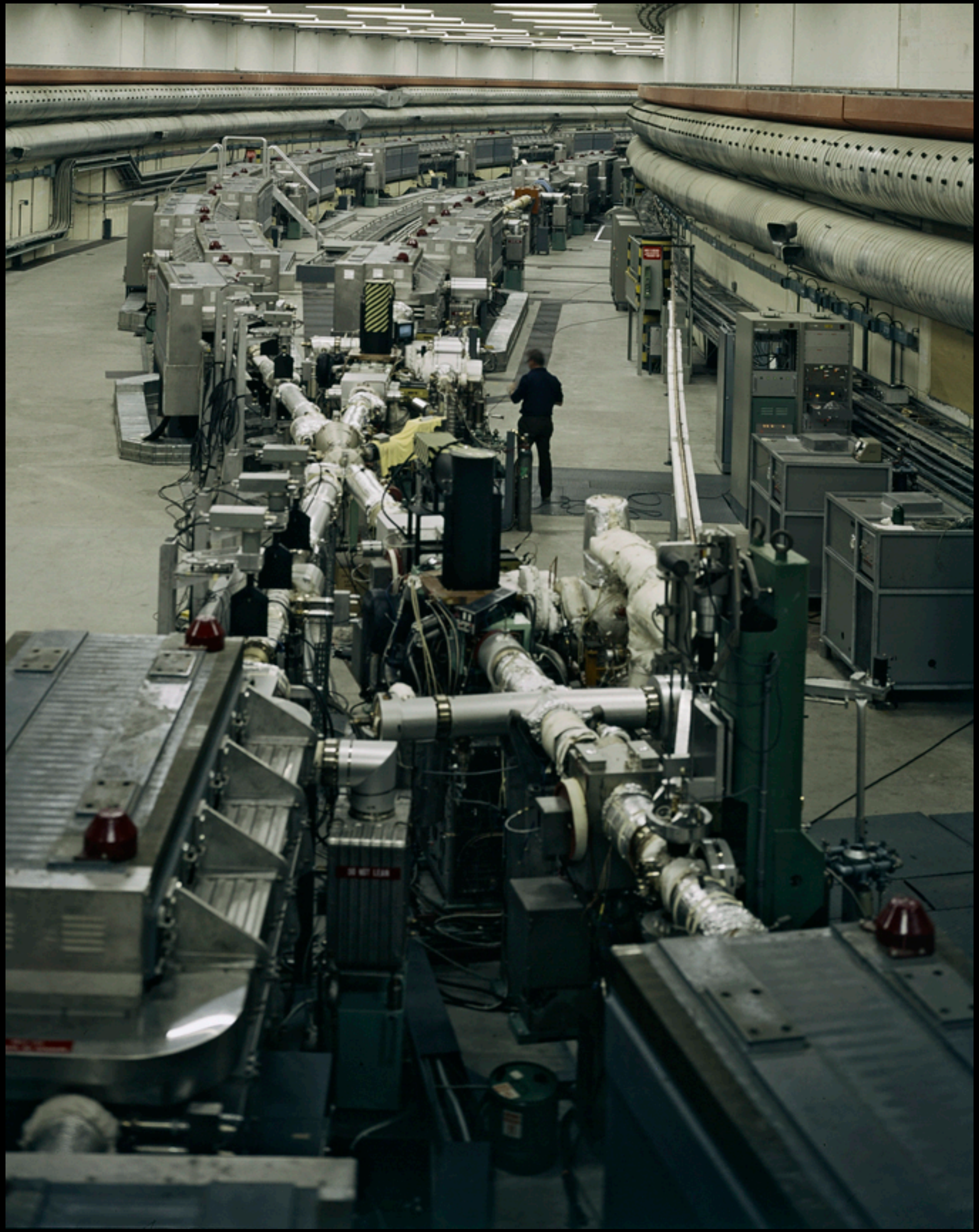


Figure 12. The dependence of the Born cross section of the $e^+e^- \to \pi^+\pi^-$ process on energy, dots with errors are data, curve is the fit result.

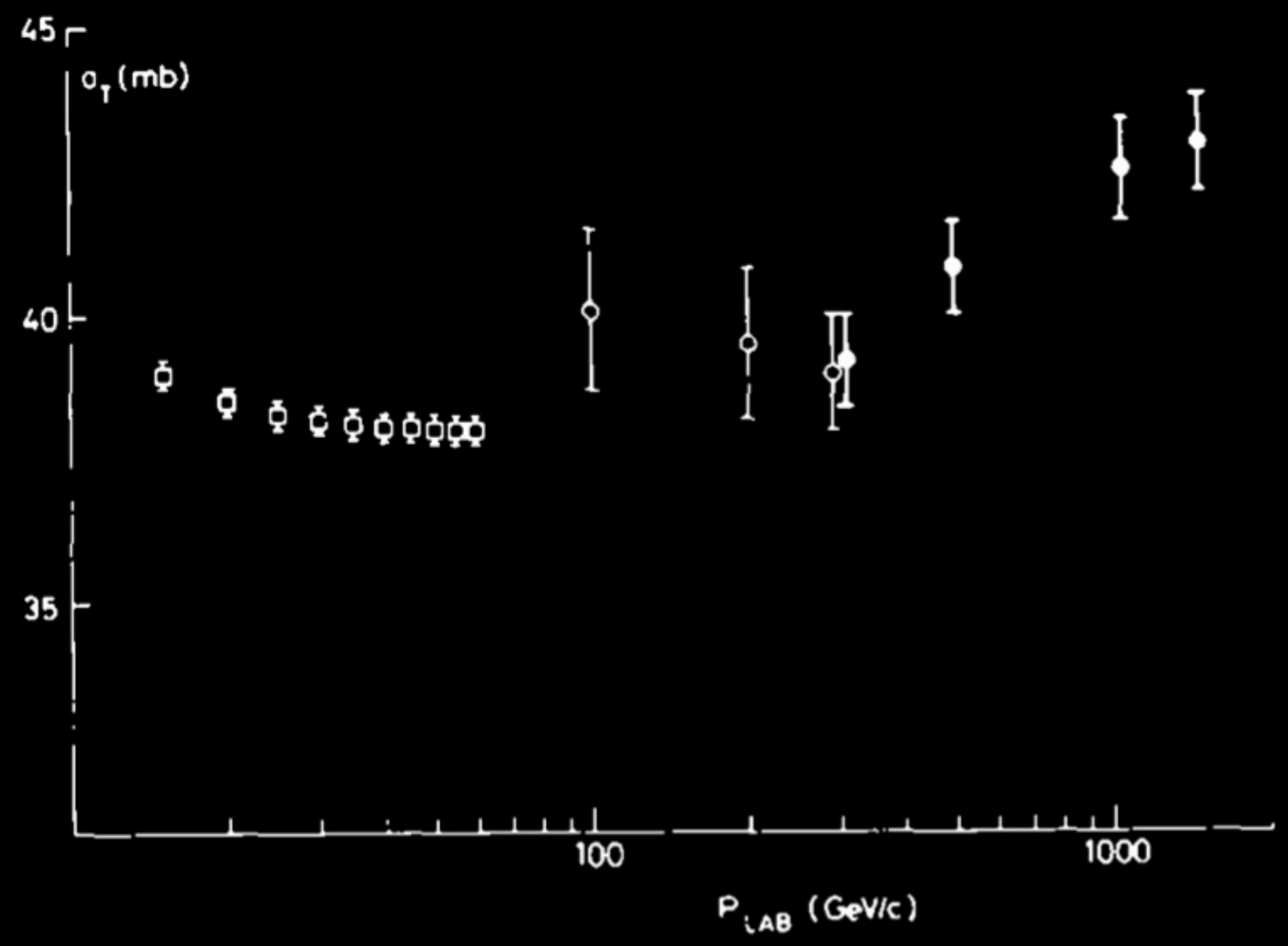
SND, VEPP-2000 Collider (Novosibirsk, 2021)

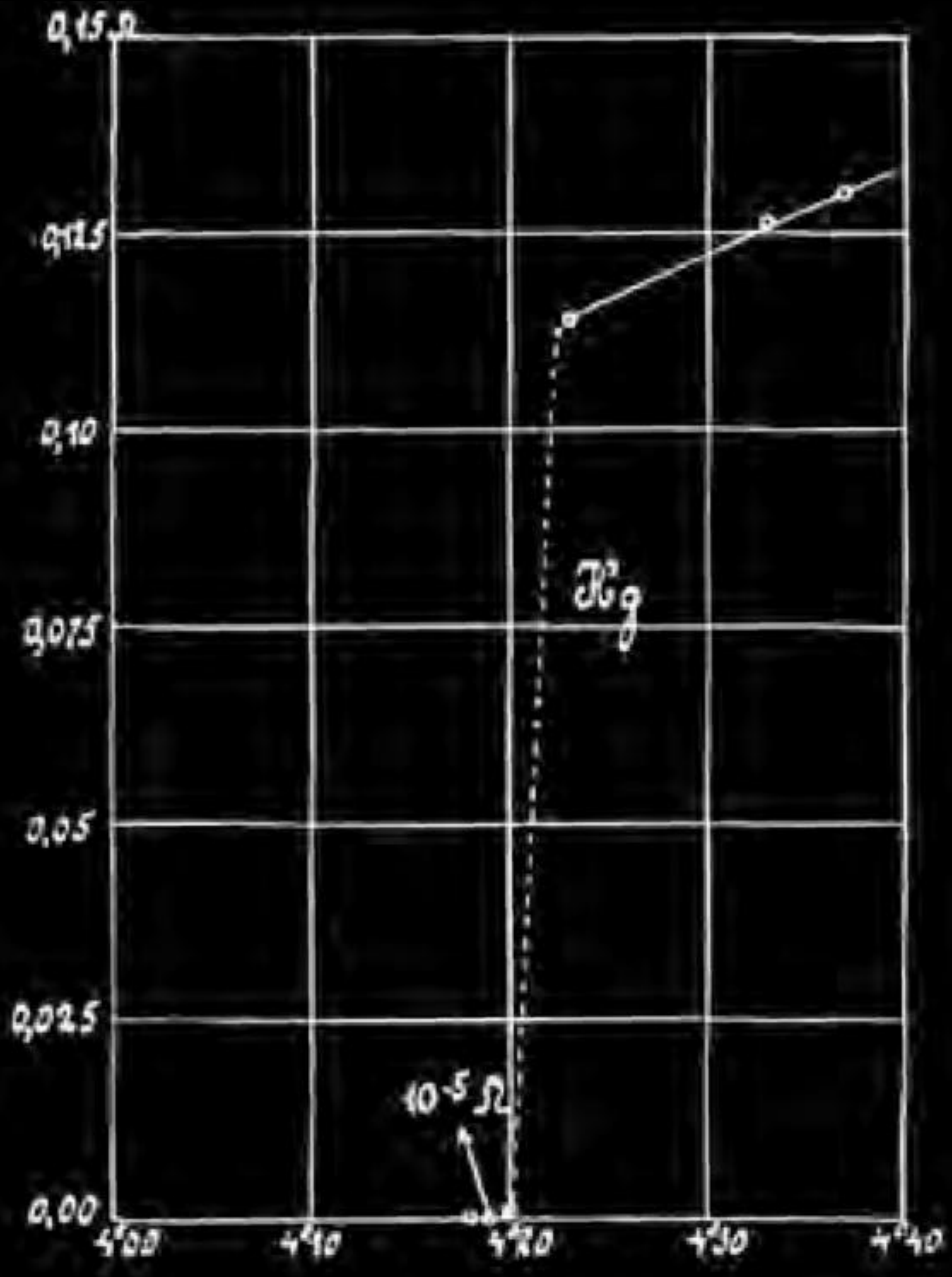
CERN Intersecting Storage Rings (1971)—Kjell Johnsen:
“the finest instrument one can imagine for research in accelerator physics”

0.3π km circumference
two independent rings
1.33-T dipoles
pp @ E_{cm} → 62 GeV
~ 2 TeV fixed-target
millions events/sec
also stored d, α, $\bar{p}$



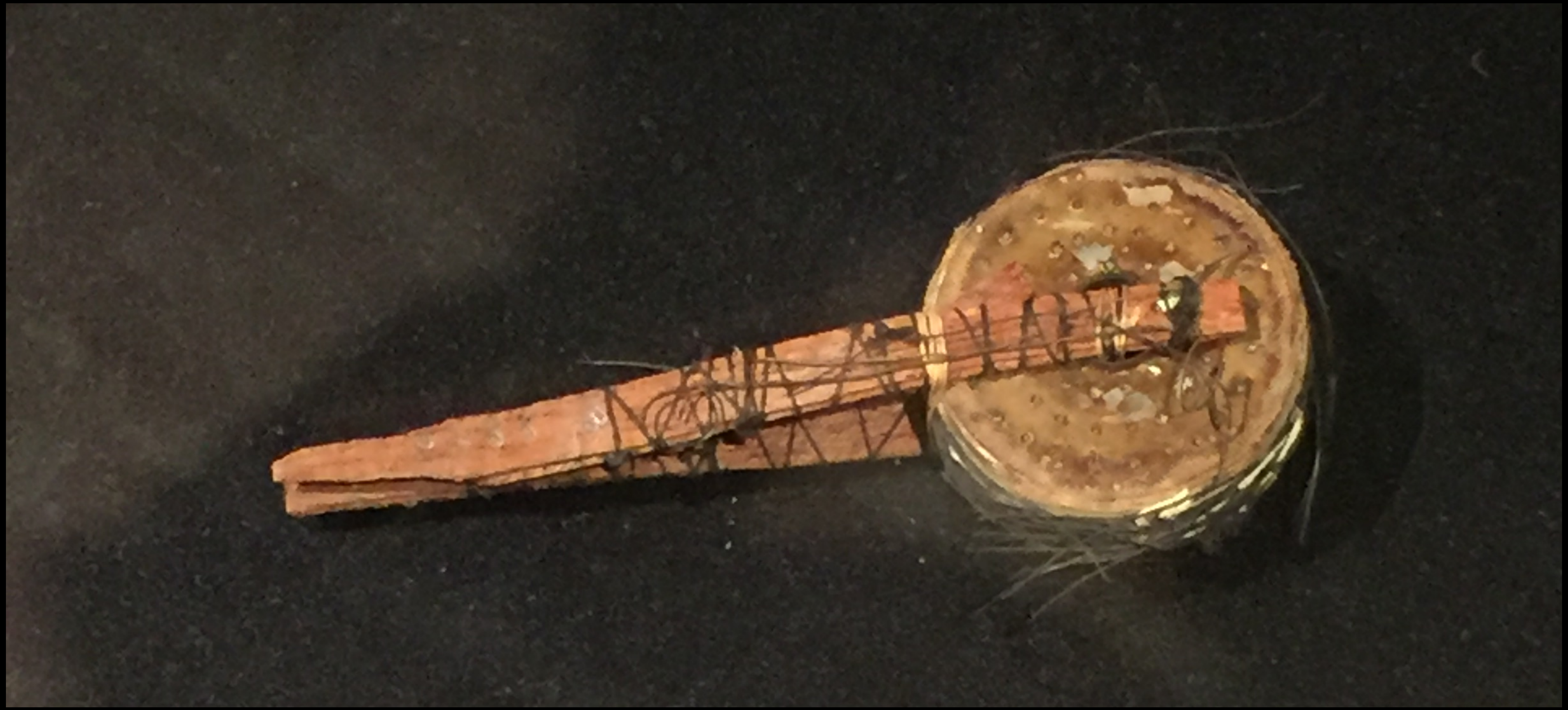
Underinstrumented!
discovered rising σ_t
CERN–Rome,
Pisa–Stony Brook
hints of *qq* scattering
Missed *J*/ψ, Υ
A learning experience





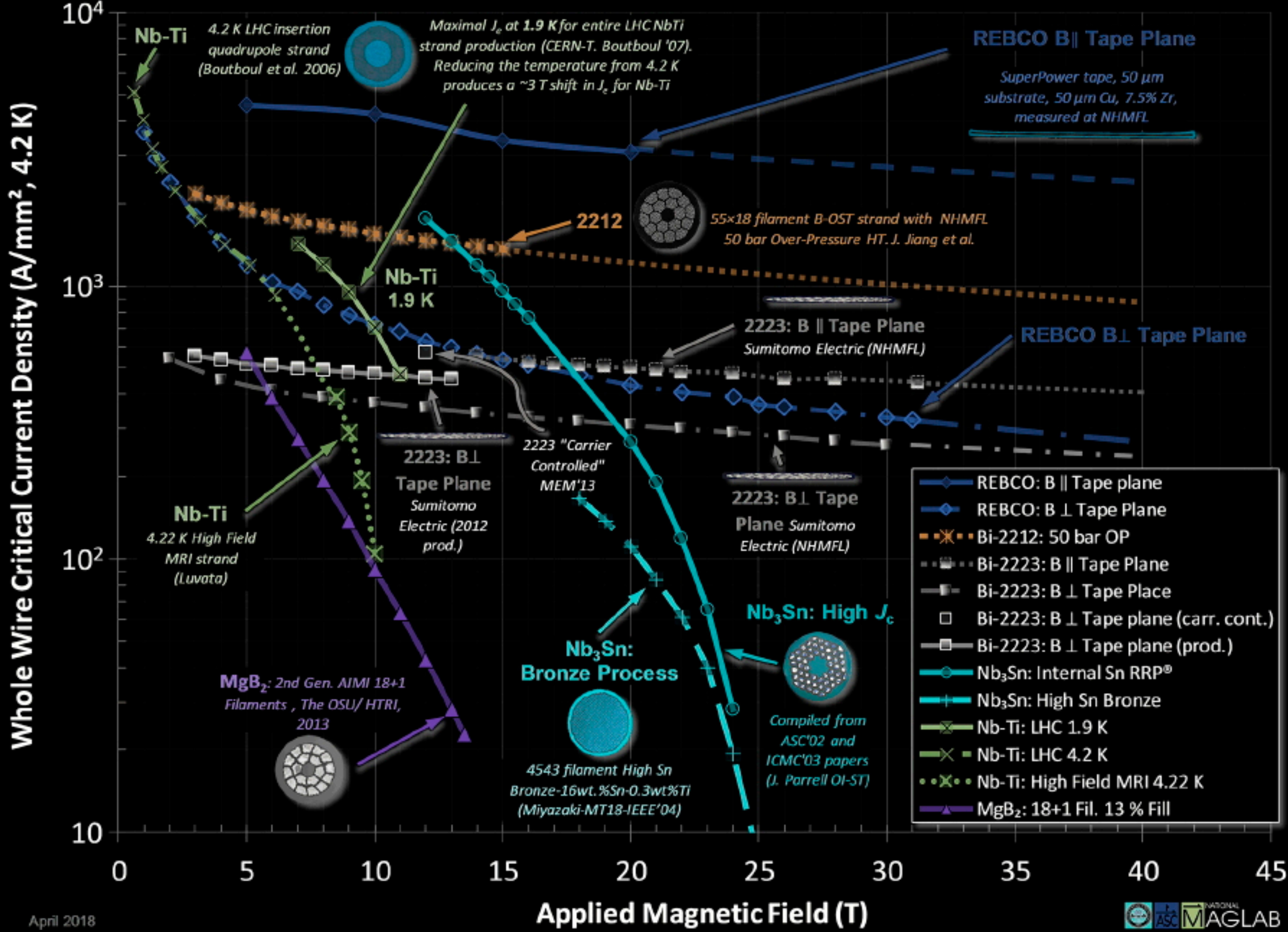
Heike Kamerlingh Onnes (Leiden, 1908)

Door meten tot weten



First superconducting magnet: Pb wire, 600 gauss (< 7.2 K)
Museum Boerhaave, Leiden

Superconducting accelerator magnets based on Type-II superconductors



How can accelerators be so small?

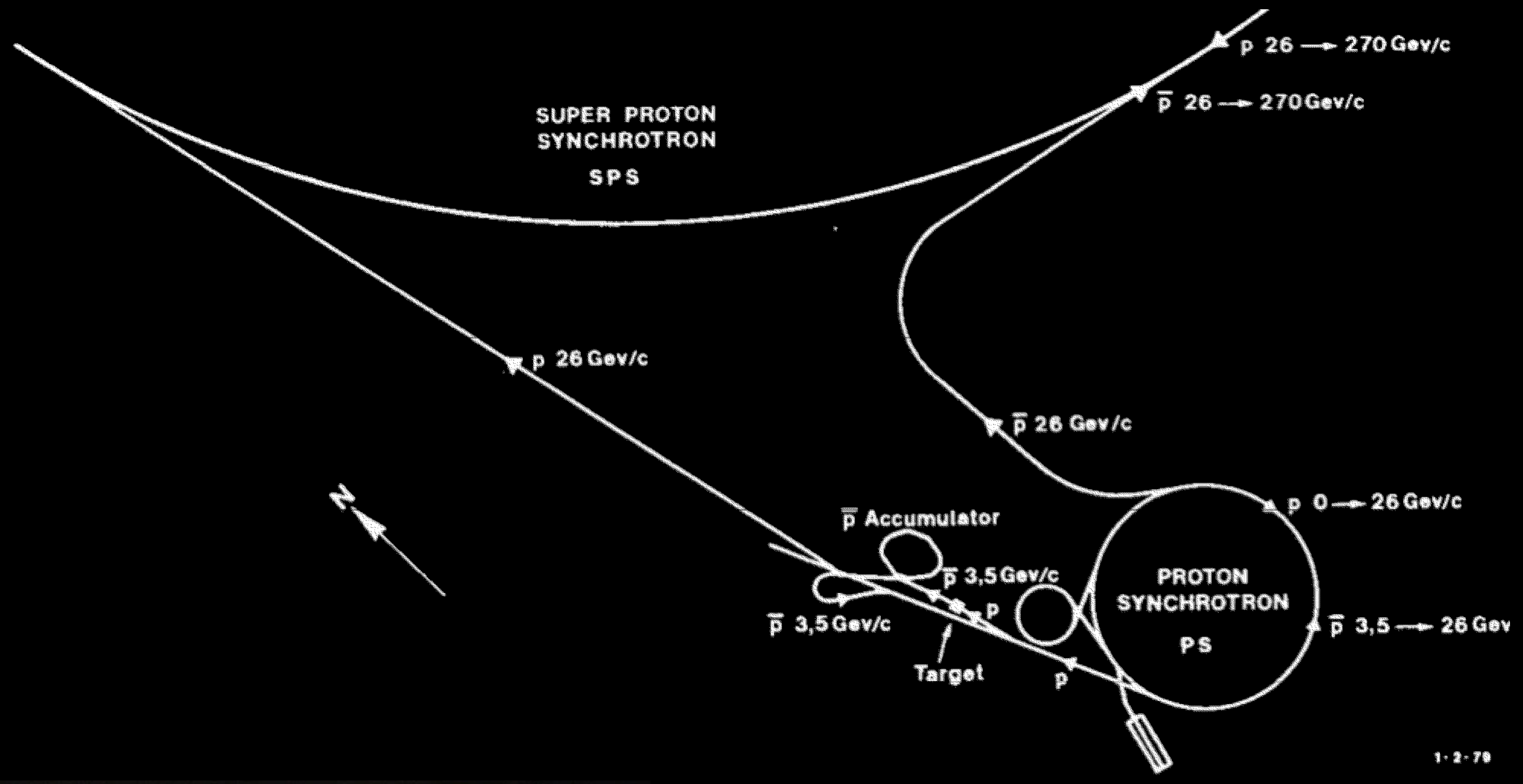
Development of large-scale cryogenic technology,
to maintain many km of magnets at a few kelvins.

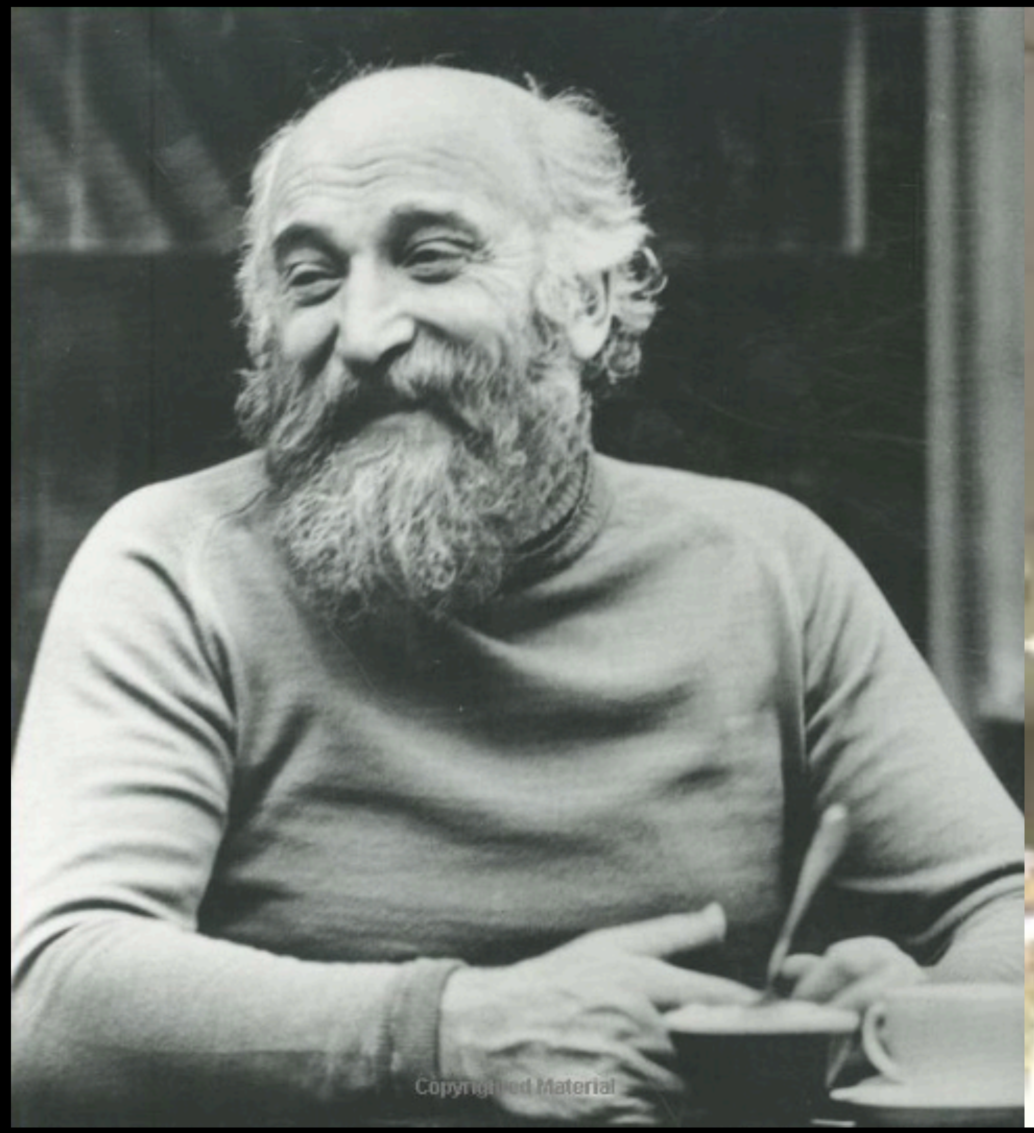
Active optics to achieve real-time corrections of orbits
enables reliable, highly tuned accelerators with small-aperture magnets.
Also “cooling,” or phase-space compaction, of stored (anti)protons.

Evolution of vacuum technology.
Beams stored for approximately 20 hours travel
~ 2×10^{10} km, about 150 times the Earth–Sun distance,
without encountering a stray air molecule. LHC: 10^{-13} atm.

Improvements in accelerating gradient
through efficient (superconducting) RF cavities

Simon van der Meer, Carlo Rubbia: *Sp$\bar{p}$S* Collider (1981); “active optics”



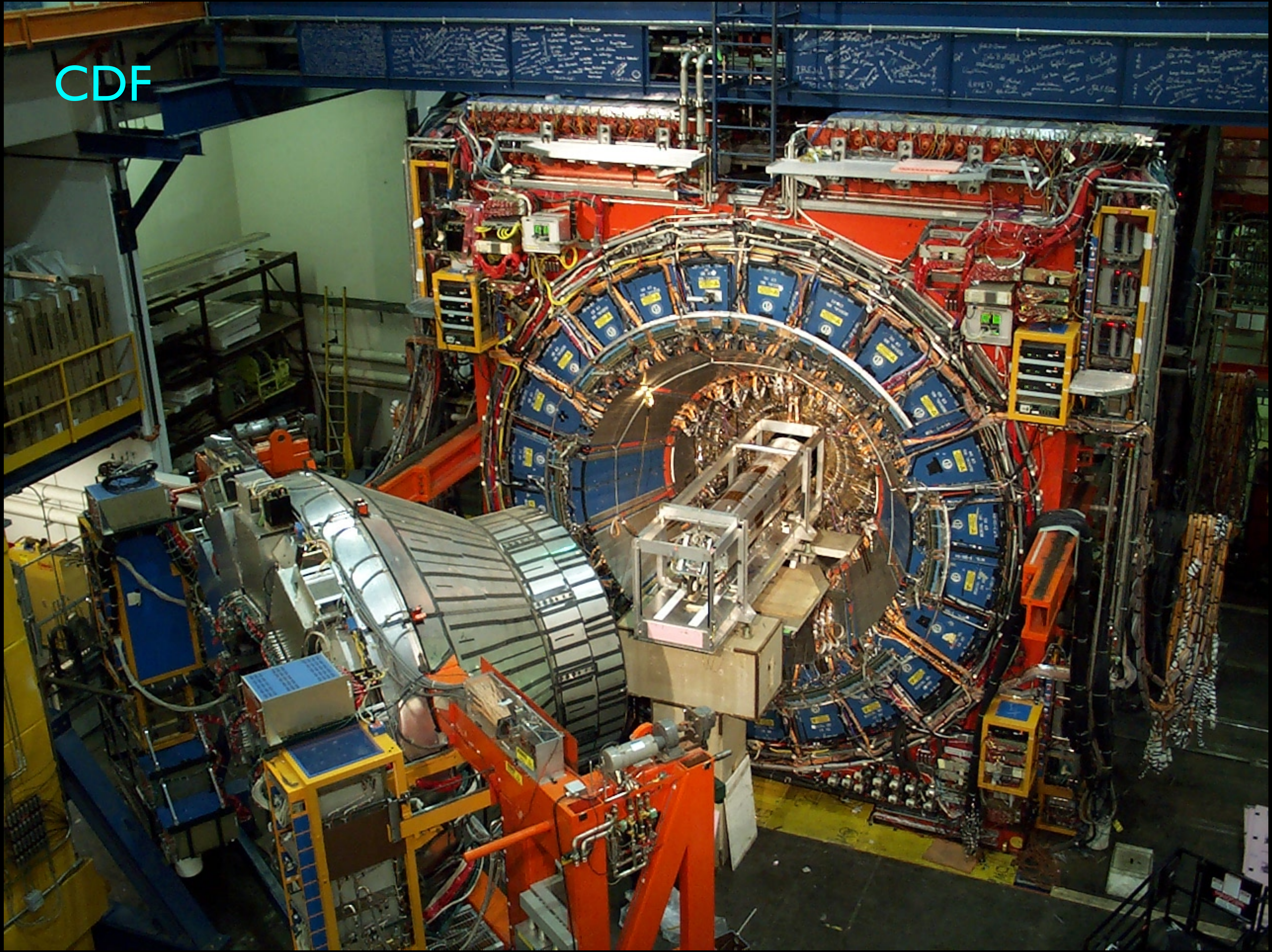


G. I. Budker, A. N. Skrinsky (Novosibirsk, 1970s)

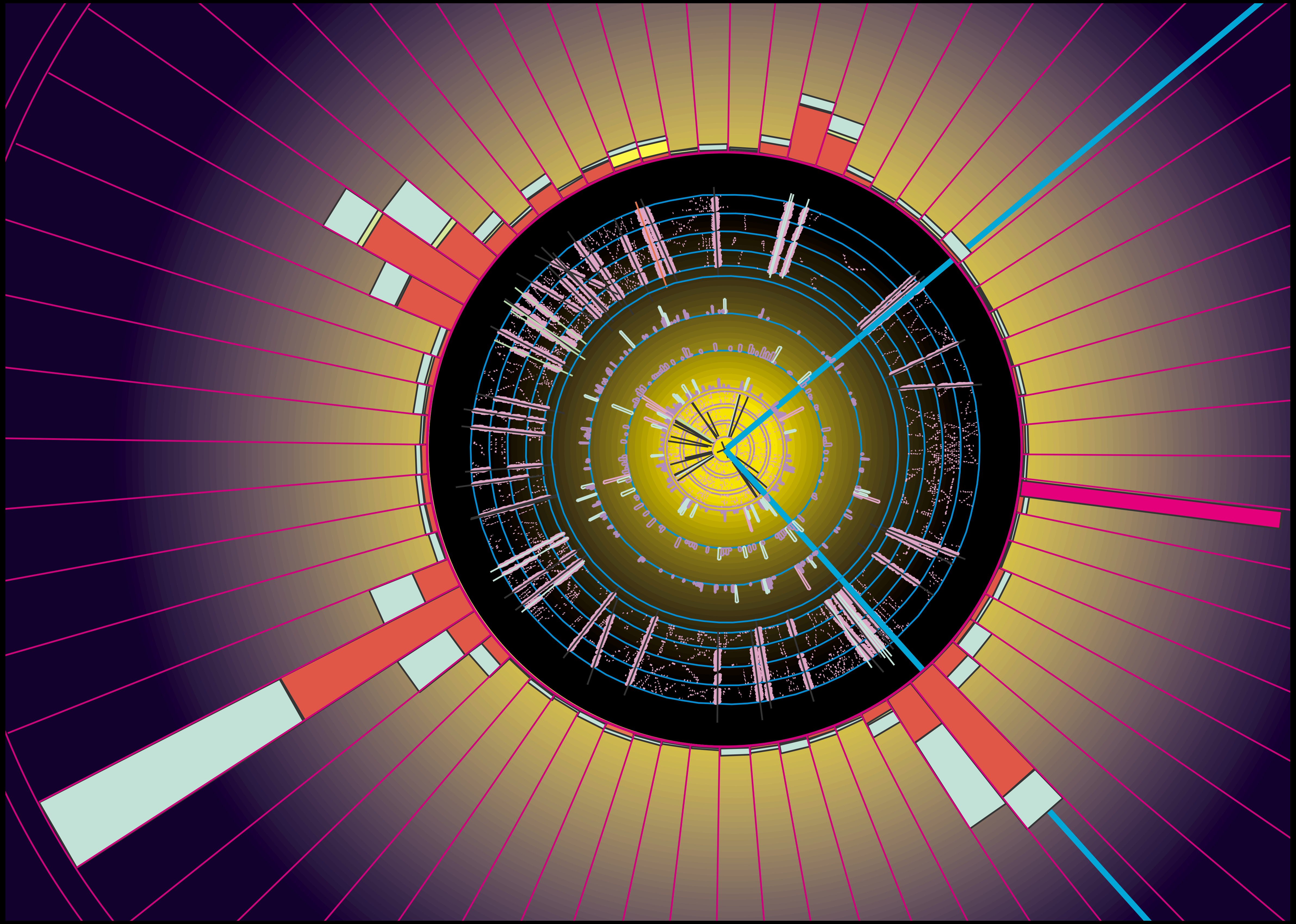
UA1: $Z^0 \rightarrow e^+e^-$


Tevatron superconducting proton-antiproton collider
CDF
D0


DIPOLE
QUADRUPOLE


CDF

CDF/D0 (1995)
top quark:
mass ≈ 173 GeV ≈ 186 u
lifetime ≈ 0.4 ys



The Tevatron (1983–) showed SC magnets in reach

HERA $e^{\pm}p$ Collider

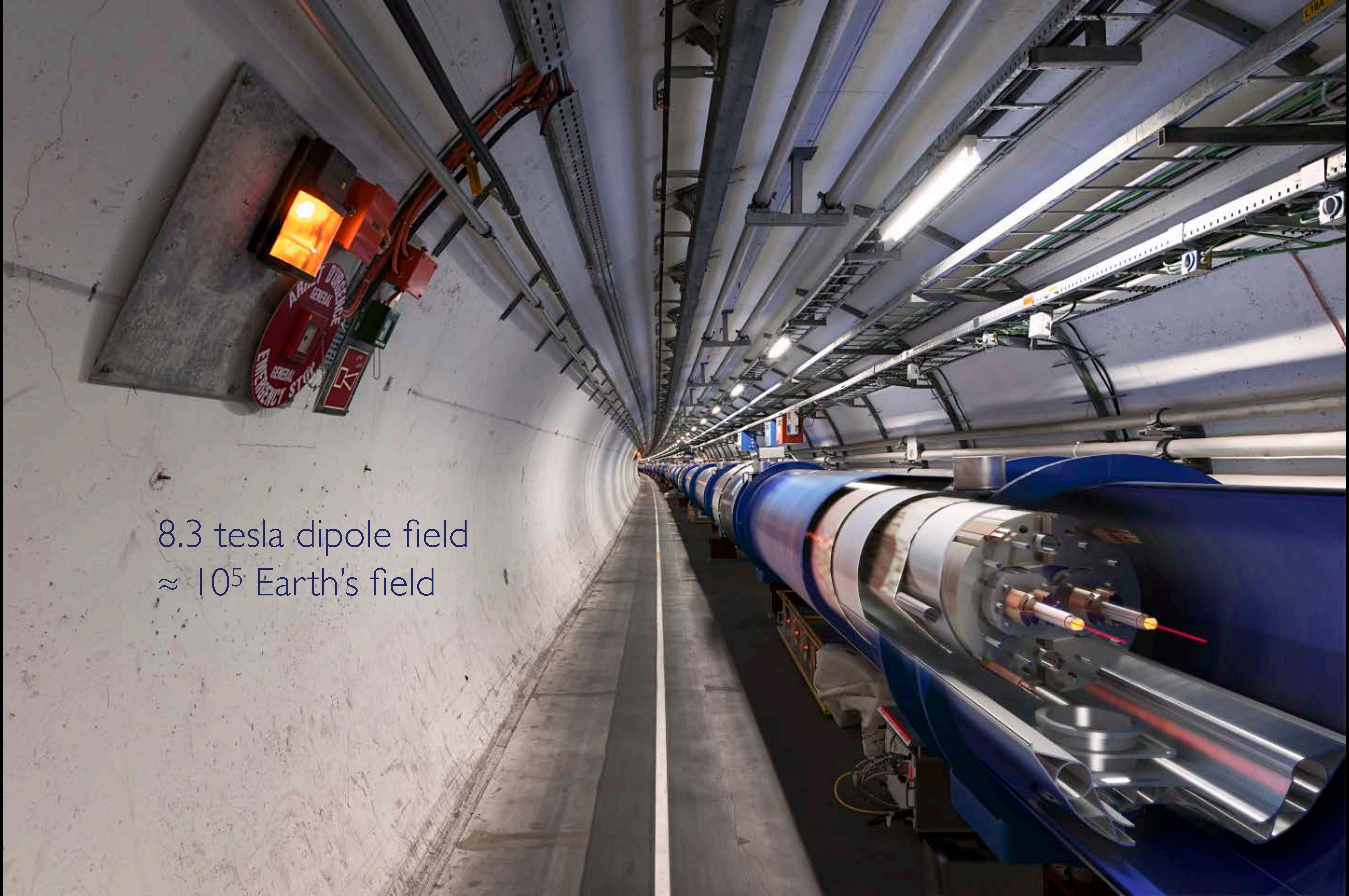
Thought experiment (1977) considering *WW* scattering had revealed

$$\left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} \approx 1\ \text{TeV}$$

energy scale to discover the mechanism
of electroweak symmetry breaking

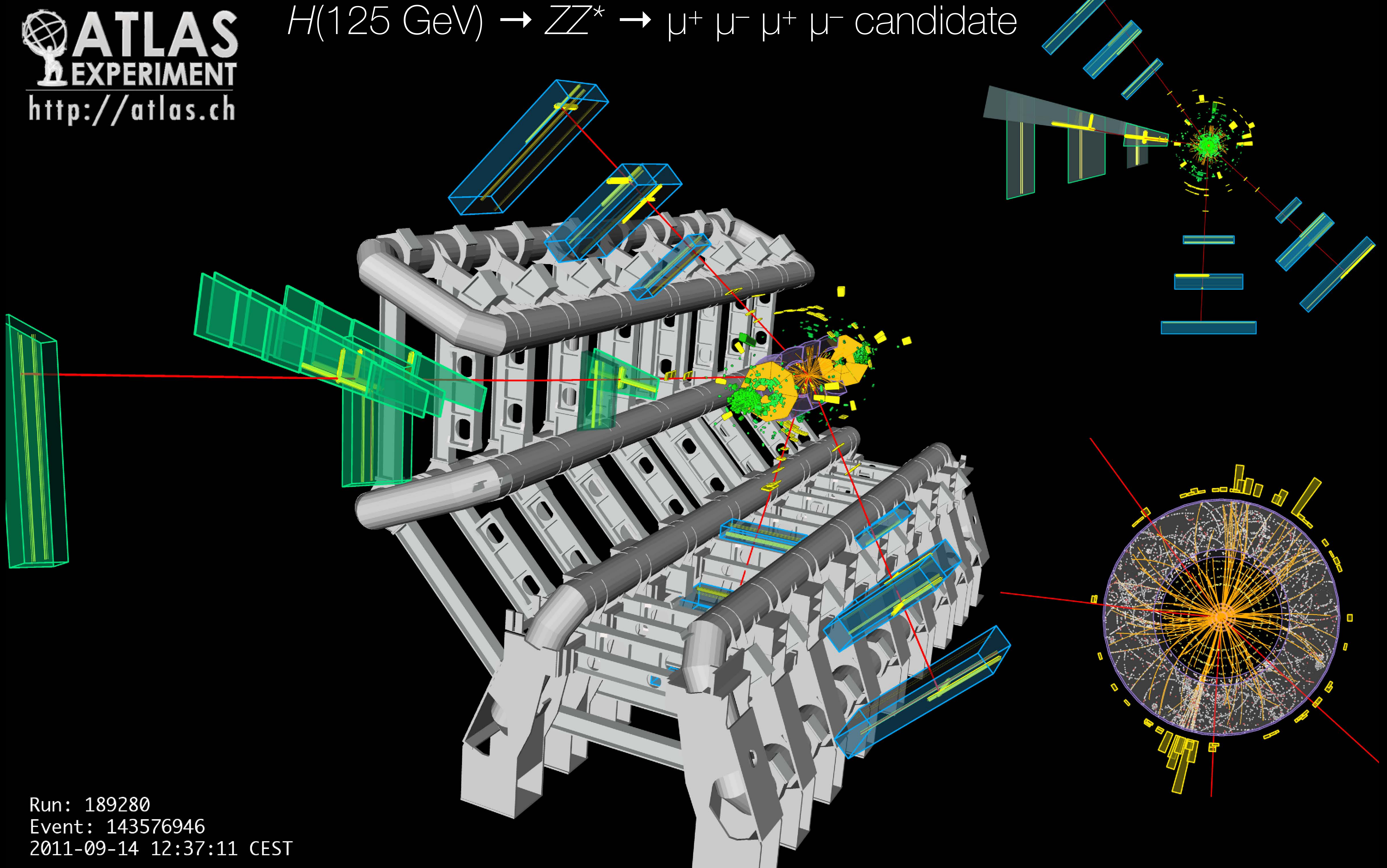
LEP → Large Hadron Collider

pp, E_{cm} = 1 TRy = 13.6 TeV



8.3 tesla dipole field
≈ 10^5 Earth's field

$H(125\ \text{GeV}) \rightarrow ZZ^* \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ candidate



patrick.koppenburg@cern.ch 2025-07-04

Higgs discovery follow-ups

Refine Higgs-boson properties: (HL)-LHC, "Higgs Factory"

$e^+e^- \rightarrow H + Z$

Is *H* source of all quark, charged-lepton masses? Neutrino masses?

Does H have partners?

How does *H* interact with itself?

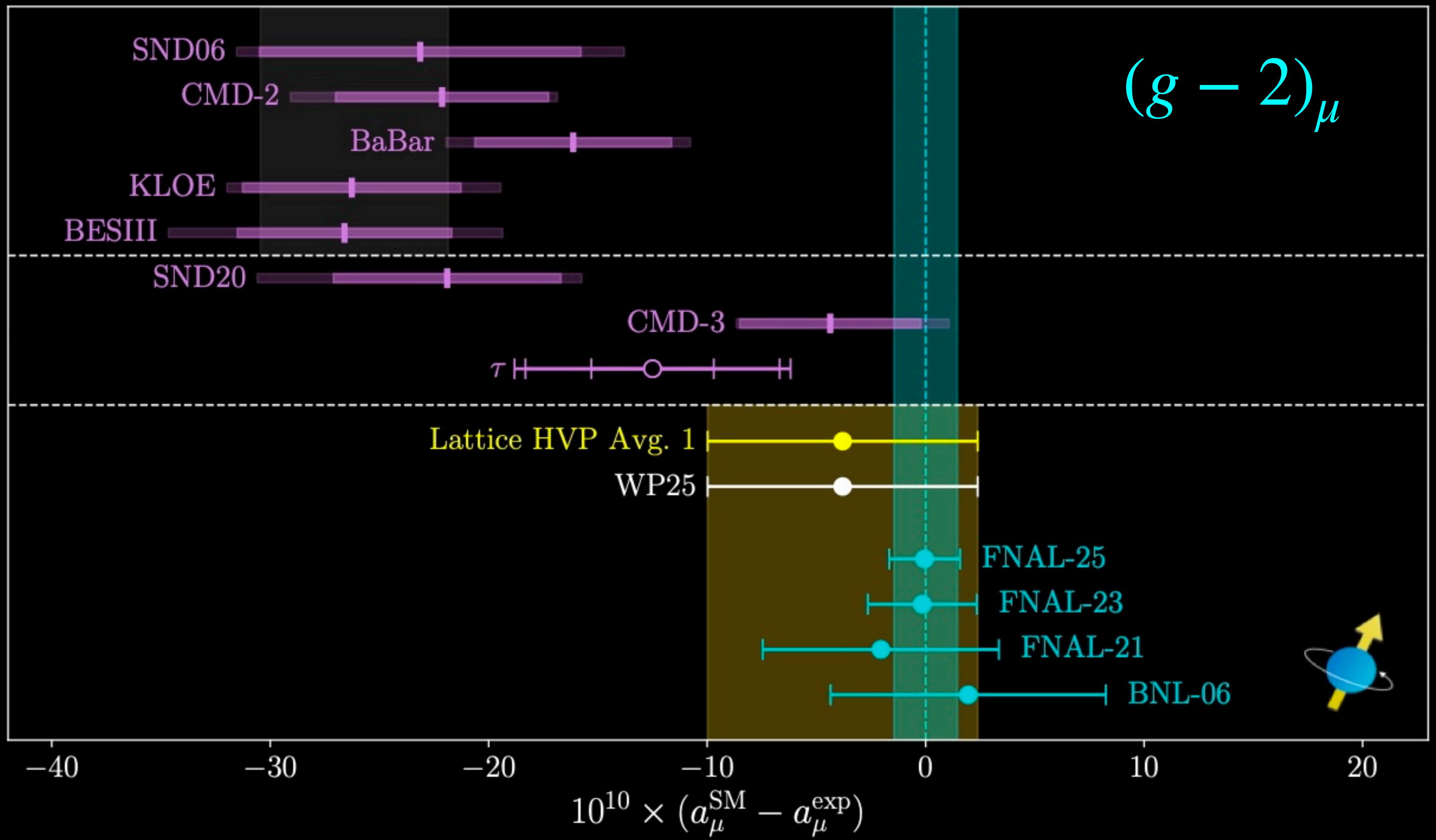
Does *H* fully regulate *WW* scattering?

Vacuum-energy problem: $10^{-3}\,M_\odot$ in each of us???

→ Perspectives & (120^+) Questions

→ Gedanken Worlds without Higgs

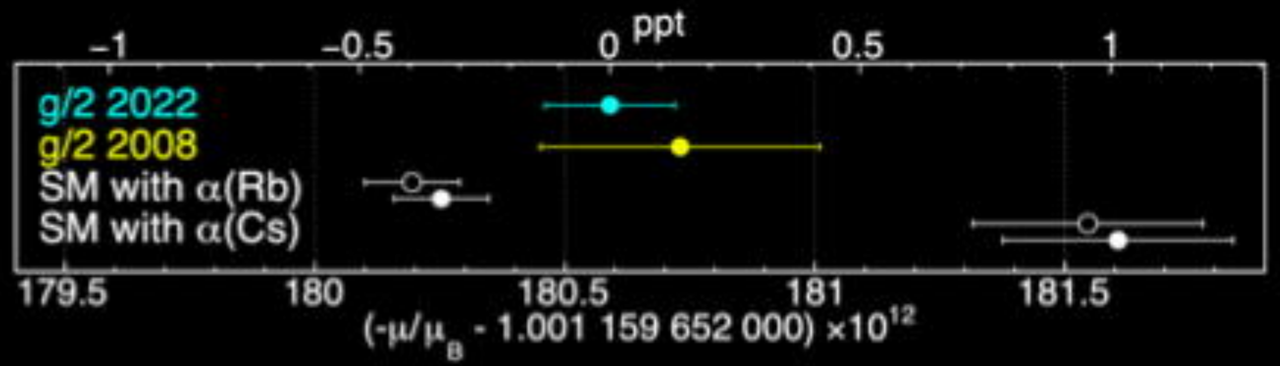
"sixth place of the decimal" and beyond …



CMS (2024): $a_\tau = 0.0009^{+0.0032}_{-0.0031}$

e magnetic dipole moment measured to 0.13 ppt

$$-\mu_e/\mu_B = 1.00115965218059(13)$$



Gabrielse: Harvard–NU

fine structure constant

Berkeley: $\alpha^{-1}(\mathrm{Cs}) = 137.035\,999\,046(27)$

Paris: $\alpha^{-1}(\mathrm{Rb}) = 137.035\,999\,206(11)$

(differ by 5.4 s.d.)

(Anti)proton magnetic moments: CPT test

$$\mu_{\bar{p}} = -2.792\,847\,344\,1(42)\ \mu_N$$

vs.

$$\mu_p = +2.792\,847\,344\,62(82)\ \mu_N$$

BASE Collaboration @CERN Antiproton Decelerator

Next steps for accelerators and colliders: more interactions, higher energy, better control

Improved techniques to accelerate and manipulate standard particles

Novel acceleration schemes

Accelerate novel particle species, combinations

$e^{\pm}p$ · heavy ions · rare isotopes · β-emitters/EC · μ

High-luminosity e^+e^-, up to $t\bar{t}$ threshold

Future Circular Collider
~ 89 km

↪ "100-TeV" *pp* for exploration

e^+e^- Linear Collider

A 10-TeV μ+μ− Collider for the Nuclear Mill Centennial?

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

and/or ν Factory?

16.5 km

10 km

Applications beyond our research agenda

>30,000 accelerators worldwide
few hundred for research
industrial processes,
medical imaging, isotopes, hadron therapy, …
food irradiation, cross-linking polymers, …