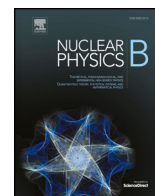




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Featured Article

Discovery of the J particle at Brookhaven National Laboratory and the physics of electrons and positrons [☆]Samuel Ting ^{ID},¹

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Editor's note

In celebration of the 50th anniversary of the discovery of J particle, the organizers of the International Symposium (October 20, 2024) invited Professor Samuel Ting for a plenary talk, together with a group of distinguished speakers. This article is based on his presentation at the symposium and it reviews the discovery of J particle in 1974 at the Brookhaven National Laboratory, which was referred as the “November Revolution of Particle Physics”. We publish this article of Professor Samuel Ting as a “Featured Article” to celebrate his groundbreaking discovery and achievement.

1. Encounters with particle physics

Discovery of the J particle in 1974 at Brookhaven National Laboratory led to the “November Revolution” in particle physics, fundamentally altering the Standard Model. In this article I review my experiments performed before, during, and after the “November Revolution” and their impact on modern physics.

2. First experiment: measuring the size of the electron (1966)

During my school years at Michigan and my years as a junior faculty member at Columbia University, I was very much interested in quantum electrodynamics (QED), particularly in various tests of QED at short distances using high-energy electron accelerators. QED, as formulated by Feynman, Schwinger, Tomonaga in 1948, assumes that electrons have no measurable radius. The theory agreed well with all experiments until the 6 GeV Cambridge Electron Accelerator (CEA) provided a most sensitive measurement of the size of the electron. At CEA, the Harvard experiment was done by the world's leading experts in the field who had spent many years to develop the technology [1]. Their results showed that the electron has a radius of $\sim 10^{-13} - 10^{-14}$ cm (Fig. 1). Most importantly, this experiment was independently confirmed by a group at the Cornell Electron Accelerator. Since those results touch upon the foundation of Modern Physics, I decided to perform an experiment with an independent method. At that time, I knew nothing about electron physics, so I received no support in the U.S. In 1965, I decided to leave Columbia University and move to the newly built 6 billion electron-volt electron accelerator (DESY) in Hamburg, Germany to re-measure the size of the electron. It was during this time

[☆] This article is based on the author's invited presentation given at the International Symposium of “50 Years Discovery of the J Particle”, Beijing, October 20, 2024.
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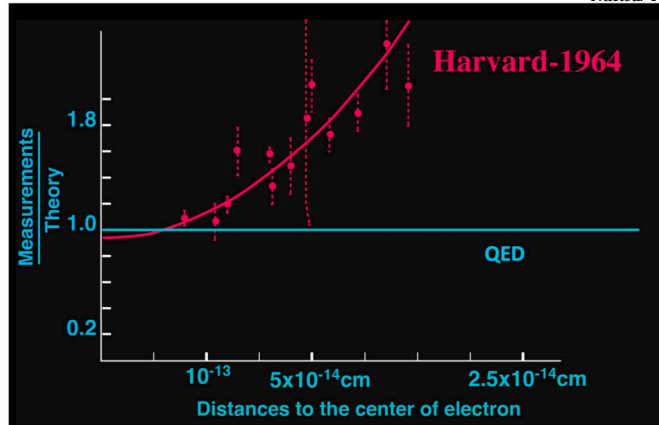


Fig. 1. Results of the Harvard experiment showing that the electron has a radius of $\sim 10^{-13} - 10^{-14}$ cm.

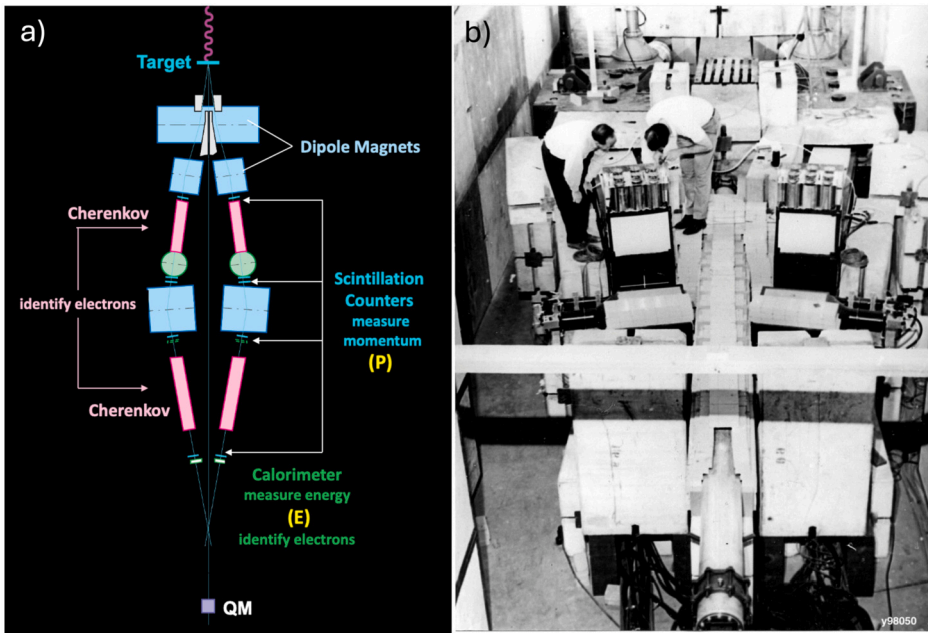


Fig. 2. (a) Experimental layout of my experiment for electron size measurement at DESY; (b) Photo of the experiment for electron size measurement.

at Columbia that I went to the Brandeis Summer School for Theoretical Physics and met with Luciano Maiani and have learnt a lot of physics from him, particularly the GIM mechanism [2].

The layout of my experiment at DESY (Fig. 2a) has the following unique features: use of dipole magnets and counters to measure the momentum (P); use of two Cherenkov counters separated by magnets on each arm to identify e^\pm , so that background e^\pm produced from interactions in the first counter are swept away by the magnet and the e^\pm identification of the two counters are independent; use of calorimeters to measure the energy (E); none of the detectors see the target so they are not exposed to neutron or gamma-ray backgrounds; the acceptance is defined by counters, not by the aperture of the magnet; require $E = P$ to reject large pion background. The development of this type of pair spectrometer (Fig. 2b) eventually led to the J-Particle experiment.

In 1966, after 8 months, our group completed the experiment at DESY and discovered that electron indeed has no measurable size $R_e < 10^{-14}$ cm [3] (Fig. 3). This result, which validated key aspects of QED, was first announced in 1966 at the ‘‘Rochester’’ conference at Berkeley (now known as the International Conference on High Energy Physics). On this occasion I met W.K.H. Panofsky, Dick Feynman, and I.I. Rabi. I maintained close contact with them for many years.

3. Studies on photons and heavy photons

The QED experiment set the foundation for further studies in particle physics, showing the importance of precision measurements in particle physics. When we tuned the spectrometer magnets so that the pair mass acceptance is centered near 750 MeV, we observed

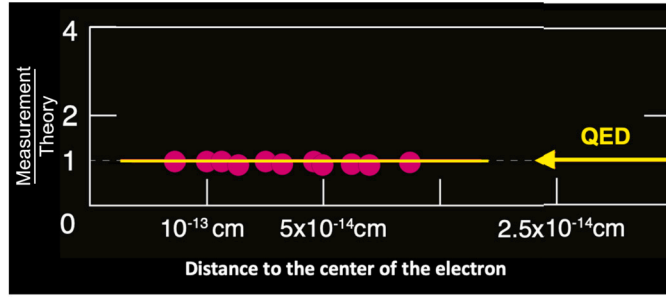


Fig. 3. Results of our experiment showing that electron does not have measurable size up to 10^{-14} cm.

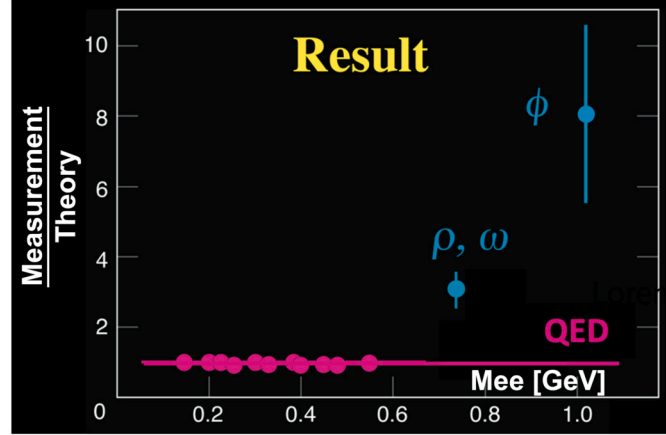


Fig. 4. Deviation from QED due to heavy photon (ρ , ω , and ϕ) production.

a large increase in the e^+e^- yield caused by an enhancement of the contribution to the e^+e^- yield of the ρ -meson – a massive photon-like particle, which decays into e^+e^- pairs [4] (Fig. 4). The observation of $\rho \rightarrow e^+e^-$ decays started a series of experiments by my group on massive photon-like particles [5].

The heavy photons ρ , ω , and ϕ are resonance states of $\pi^+\pi^-$ (ρ), $\pi^+\pi^-\pi^0$ (ω), and K^+K^- or $\pi^+\pi^-\pi^0$ (ϕ) with a rather short lifetime of typically between 10^{-24} and 10^{-23} sec. They are unique in that they all have quantum numbers J (spin) = 1, C (charge conjugation) = -1, P (parity) = -1. Thus, they are exactly like an ordinary light ray except for their heavy mass: $M_\rho = 760$ MeV, $M_\omega = 783$ MeV, and $M_\phi = 1020$ MeV. Their interactions with hadrons are described by the Vector Dominance Model:

$$J_\mu(x) = \left[\frac{m_\rho^2}{2\gamma_\rho} \rho_\mu(x) + \frac{m_\omega^2}{2\gamma_\omega} \omega_\mu(x) + \frac{m_\phi^2}{2\gamma_\phi} \phi_\mu(x) \right].$$

To carry out these experiments accurately, we improved the detector mass resolution to ~ 5 MeV and the background rejection to 10^8 . This allowed us to measure $\rho - \omega$ coherent interference using $\rho \rightarrow e^+e^-$ and $\omega \rightarrow e^+e^-$ decays (Figs. 5 and 6) as well as forbidden $\omega \rightarrow \pi^+\pi^-$ decays, which at that time attracted significant attention [6] (Figs. 7 and 8).

Precision measurements of the widths $\Gamma(\rho \rightarrow e^+e^-)$, $\Gamma(\omega \rightarrow e^+e^-)$ (Figs. 6 and 8), and $\Gamma(\phi \rightarrow e^+e^-)$ (Fig. 9a) resulted in verification of Weinberg's first sum rule (Fig. 9b).

4. Discovery of the J particle – the Brookhaven experiment (1972-1974)

From previous experiments we have learned that photons and heavy photons are almost the same. They transform into each other. We can now ask a simple question: how many heavy photons exist? And what are their properties? It was inconceivable to me that there should be only three of them, and all with a mass around 1 GeV. To answer these questions, I decided to perform the first large-scale experiment to search for more heavy photons by detecting their e^+e^- decay modes up to much higher mass. Fig. 10 shows the photocopy of a page of the proposal E598 to Brookhaven National Laboratory. It gives the reasons I presented, in the spring of 1972, for performing an e^+e^- experiment in a proton beam (Fig. 11).

This experiment was not popular with the physics community. Most theorists believed that the search for heavy photons was not the most interesting research subject. Few experimentalists believed that such a difficult experiment could be carried out successfully. The proposal was rejected by most of the leading laboratories. It was finally accepted by Brookhaven National Laboratory for 30 GeV proton accelerator, AGS.

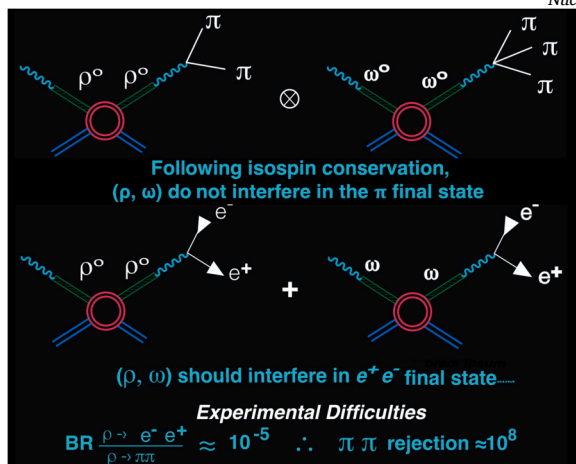


Fig. 5. Feynman diagrams of $\rho - \omega$ coherent interference.

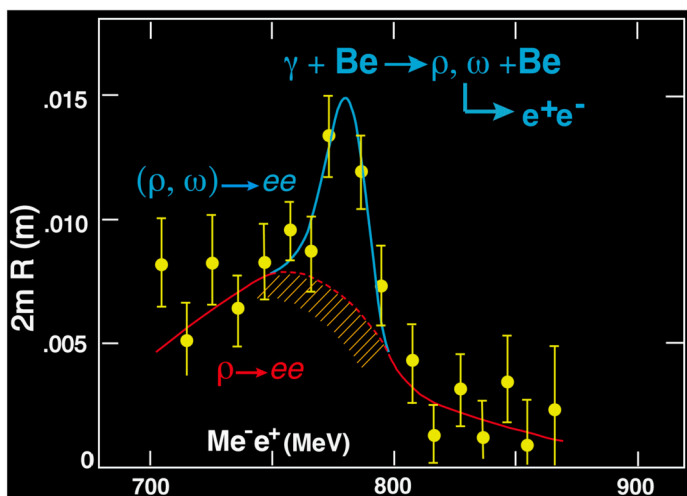


Fig. 6. Observation of $\rho - \omega$ coherent interference in the e^+e^- final state.

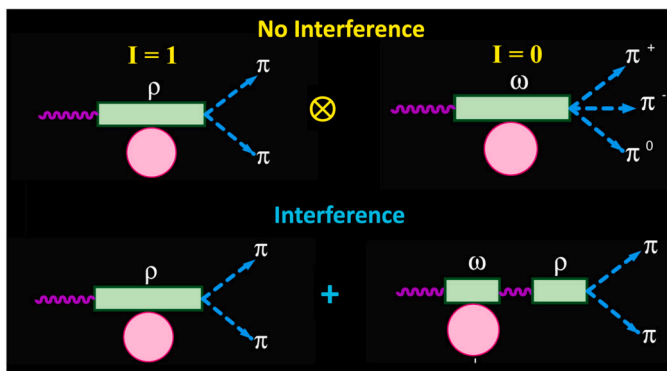
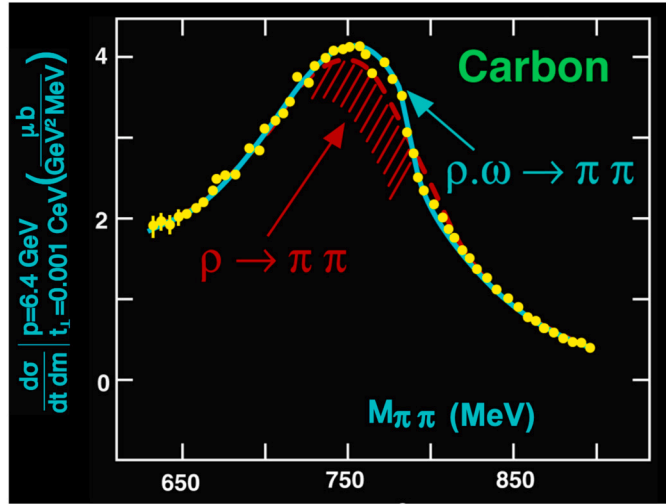
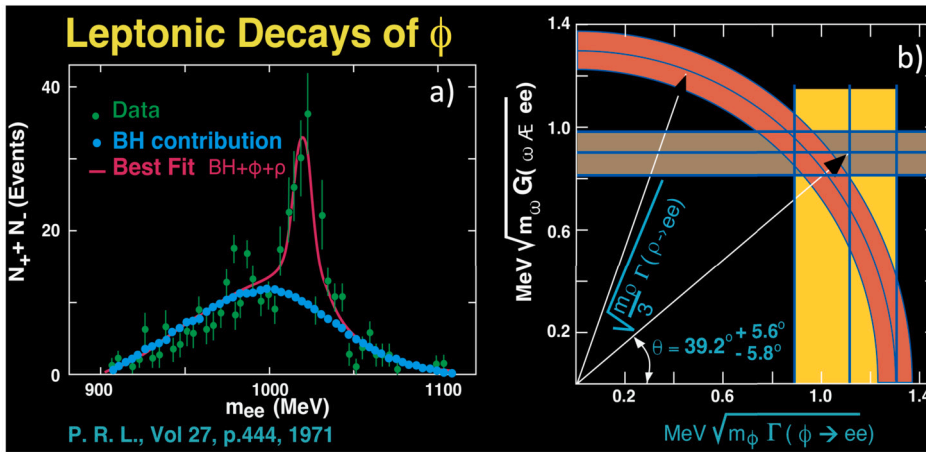


Fig. 7. Feynman diagrams of forbidden $\omega \rightarrow \pi^+ \pi^-$ decays due to isospin I violation.

Fig. 8. First observation of forbidden $\omega \rightarrow \pi^+ \pi^-$ decays.Fig. 9. (a) invariant mass of e^+e^- pairs showing the ϕ meson peak; (b) first validation of Weinberg's first sum rule using our data on $\Gamma(\rho \rightarrow e^+e^-)$, $\Gamma(\omega \rightarrow e^+e^-)$, and $\Gamma(\phi \rightarrow e^+e^-)$.

From our experience at DESY, we felt the best way to build an electron-pair spectrometer that could handle high intensities with high background rejection and at the same time have a large mass acceptance and a good mass resolution, is to repeat the concept of our spectrometer at DESY, i.e. a large double arm spectrometer and with all the detectors behind the magnets so they would not view the target directly and are not exposed to neutrons and gamma rays. To obtain the best mass resolution, we used magnets to bend the particles vertically for momentum measurement, while measuring production angles in the horizontal plane. Fig. 12 shows the layout of the spectrometer and detectors.

The main features of the spectrometer are the following:

(1) Shielding. Shielding the detector and the control room from 10^{12} particles per second generated in the experimental area was of the utmost importance. The total shielding used was approximately (a) 10 000 tons of concrete, (b) 100 tons of lead, (c) 5 tons of uranium, (d) 5 tons of soap – placed on top of C_0 , between M_1 and M_2 and around the front of C_e to stop soft neutrons (Fig. 13).

(2) The target. The target consists of nine pieces of 1.78-mm thick beryllium, each separated by 7.5 cm so that particles produced in one piece and accepted by the spectrometer do not pass through the next piece (Fig. 14). This arrangement rejects accidental pairs by requiring both tracks come from the same origin.

(3) The magnet system. The magnetic field is measured with 3-D Hall probe in 10^5 points. The bending power of the dipole magnets M_0 , M_1 , and M_2 are such that none of the counters sees the target directly (Fig. 15). The detector is smaller than the aperture of the magnets, so the detector itself defines the acceptance. Calibration of the detectors with pure electron beam produced in the target from $\pi^0 \rightarrow \gamma e^+ e^-$ was performed (Fig. 16).

(4) The position detectors. A_0 , A, B, and C are multiwire proportional chambers designed by the late Professor U.J. Becker. They consist of more than 8000 very fine, 20 μm , gold-plated wires, 2 mm apart, each with its own readout chain. Chambers A, B, and C have wire planes rotated 60° with respect to each other, so that for a given hit, the sum of distances to the wire planes is a constant

The best way to search for vector mesons is through production experiments of the type $p + p \rightarrow V^0 + X$. The reasons are:

- (a) The V^0 are produced via strong interactions, thus a high production cross section.
- (b) One can use a high intensity, high duty cycle extracted beam.
- (c) An e^+e^- enhancement limits the quantum number to 1^- , thus enabling us to avoid measurements of angular distribution of decay products.

Contrary to popular belief, the e^+e^- storage ring is not the best place to look for vector mesons. In the e^+e^- storage ring, the energy is well-defined. A systematic search for heavier mesons requires a continuous variation and monitoring of the energy of the two colliding beams—a difficult task requiring almost infinite machine time. Storage ring is best suited to perform detailed studies of vector meson parameters once they have been found.

Fig. 10. Page 4 of proposal E598 submitted to Brookhaven National Laboratory early in 1972 and approved in May of the same year.

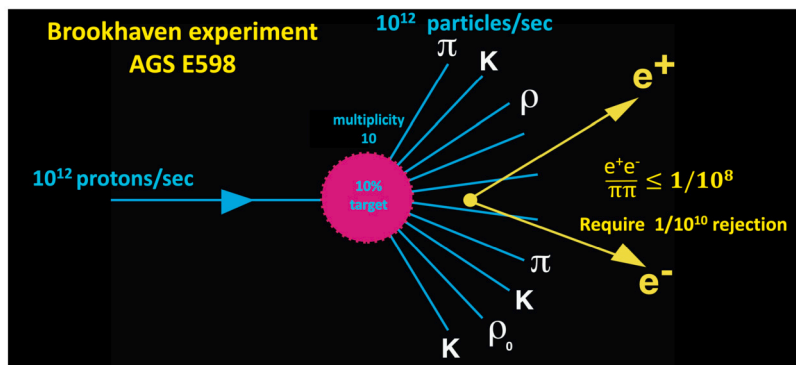


Fig. 11. Concept of the AGS Experiment E598. The extracted beam of 10^{12} protons/sec interact with a 10% target. The multiplicity is 10, resulting in 10^{12} particles/sec from the target volume. The ratio $\frac{e^+e^-}{\pi\pi}$ is less than $1/10^8$, so a percent accuracy measurement requires $1/10^{10}$ rejection.

— a unique feature for sorting out multi-hit events and rejecting backgrounds (Fig. 17). The chambers were operating at low voltage and with a special gas mixture such that they were able to operate at a rate of 20 MHz, and were also able to sort out as many as eight particles simultaneously in each arm.

(5) The $\pi - e$ separation was achieved by four extremely sensitive Cherenkov Counters C_0, C_e (Fig. 18), which were designed by M. Vivargent, J. J. Aubert and myself and manufactured at LAPP, Annecy, France. Fig. 19 shows a photo of J.J. Aubert in the control room.

In the early summer of 1974 we took some data in the high-mass region of 4-5 GeV. However, analysis of the data showed very few electron-positron pairs.

By the end of August 1974 we tuned the magnets to accept an effective mass of 2.5 – 4.0 GeV. Immediately we saw clean, real, electron pairs. But most surprising of all is that most of the e^+e^- pairs peaked narrowly at 3.1 GeV (Fig. 20a). A more detailed analysis showed that the width is less than 5 MeV.

To make sure the peak we observed was a real effect and not due to the instrumentation bias, we have performed several experimental checks on our data and on the data analysis. The most important one was to collect another set of data with the magnet current lowered by 10%. This has the effect of moving the particles into different parts of the detector. If the peak is false, it will shift away. The fact that the peak remained fixed at 3.1 GeV (Fig. 20b) showed right away that a real particle had been discovered [7].

I was considering announcing our results during the retirement ceremony for V. F. Weisskopf, who had helped us a great deal during the course of many of our experiments. This ceremony was to be held on 17 and 18 October 1974. I postponed the announcement for two reasons.

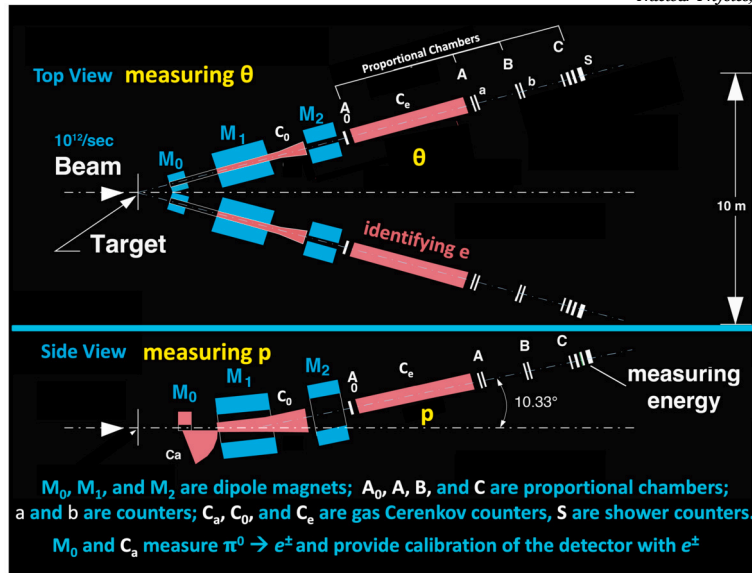


Fig. 12. Layout of the AGS Experiment E598, which is an upgraded precision version of the DESY experiment.



Fig. 13. Shielding arrangement with roof open.

First, there were speculations on high-mass e^+e^- pair production from proton-proton collisions as coming from a two-step process: $p + N \rightarrow \pi + \dots$, where the pion undergoes a second collision $\pi + N \rightarrow e^+e^- + \dots$. This could be checked by a measurement based on target thickness. The yield from a two-step process would increase quadratically with target thickness, whereas for a one-step process the yield increases linearly. This was quickly done.

Second, we realized that there were earlier Brookhaven measurements [8] of direct production of muons and pions in nucleon-nucleon collisions which gave the μ/π ratio as 10^{-4} , a mysterious ratio that seemed not to change from 2000 GeV of lab energy at the ISR down to 30 GeV.

This value was an order of magnitude larger than expected in terms of the three known vector mesons, ρ , ω , and ϕ , which, at that time, were the only possible “intermediaries” between the strong and electromagnetic interactions. We then added the J meson to the three and found that the linear combination of the four vector mesons could not explain the μ/π ratio either.

This I took as an indication that something exciting might be just around the corner, so I decided that we would make a direct measurement of this number. Since we could not measure the μ/π ratio with our spectrometer, we decided to look into the possibility of investigating the e^-/π^- ratio. On Thursday, 7 November, we made a major change in the spectrometer (Fig. 21) to start the new experiment to search for more particles.

On 6 November I paid a visit to G. Trigg, Editor of *Physical Review Letters*, to find out if the rules for publication without refereeing had been changed. Following that visit, I wrote a simple draft of a letter which emphasized only the discovery of J particle and the

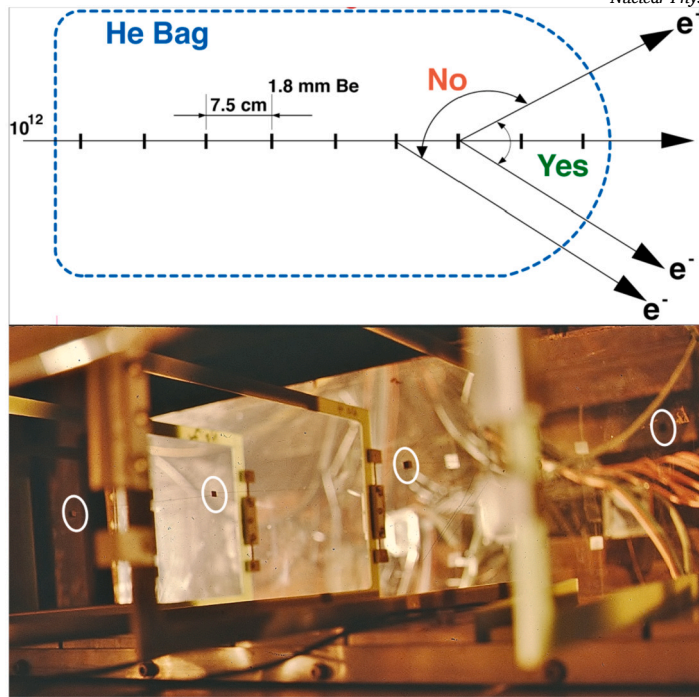


Fig. 14. Nine separate targets to reduce the background.

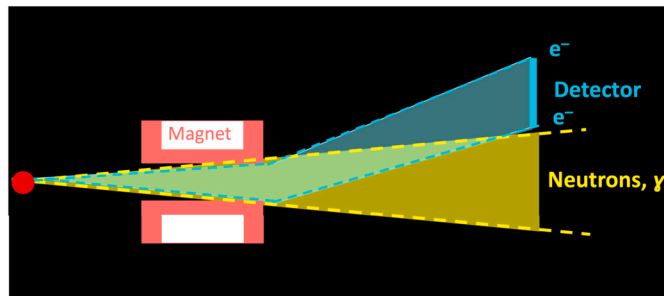


Fig. 15. The magnets bend charged particles to an angle such that the detectors are not exposed to photons or neutrons from the target.

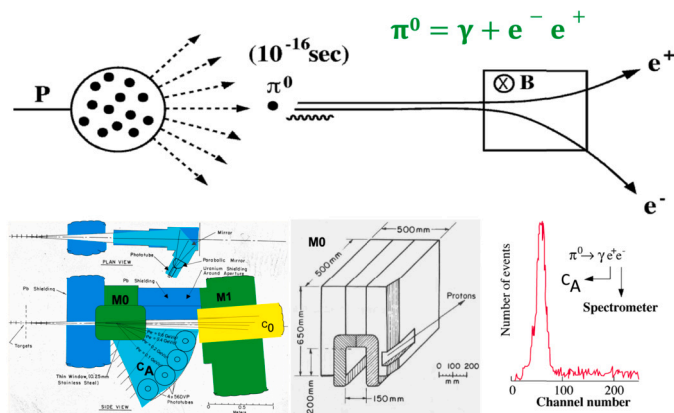


Fig. 16. Detector calibration with a pure electron beam by placing a specially designed magnet M_0 close to the target followed by a special Cherenkov counter, C_A , to detect positrons from $\pi^0 \rightarrow \gamma e^+ e^-$ ensuring the electron entering the spectrometer.

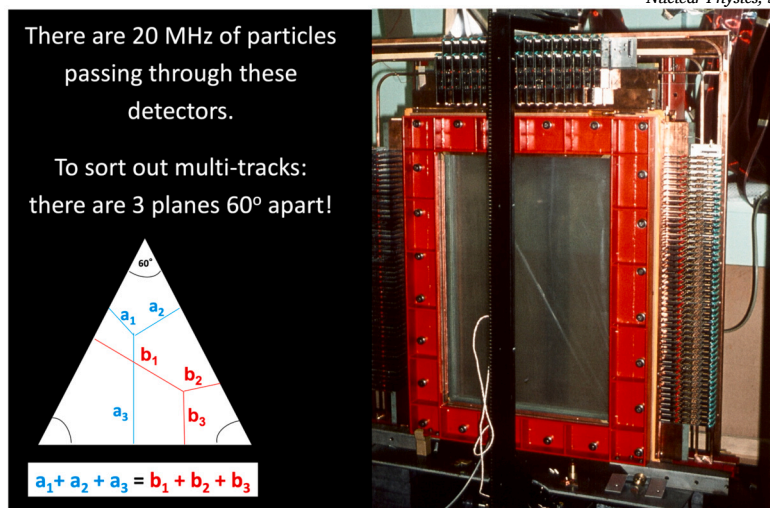


Fig. 17. Precision position detectors, which were designed by the late Professor UJ Becker. The chamber, shown on the right, is on display in Smithsonian Institution in Washington, DC after completion of the experiment.

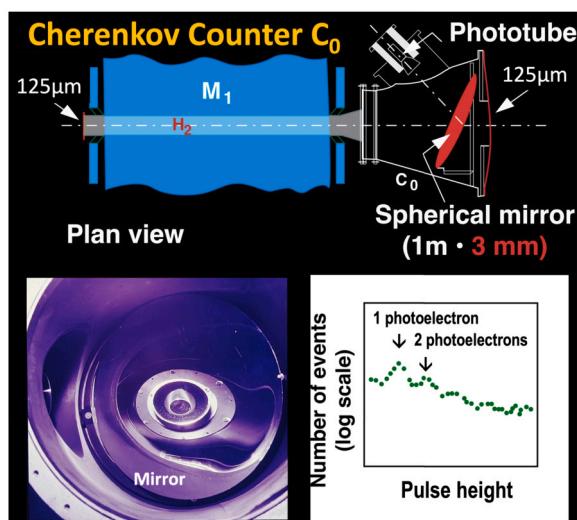


Fig. 18. The $\pi - e$ separation was achieved by four extremely sensitive Cherenkov Counters Co, Ce.

checks we made on the data. The group photo (Fig. 22) was taken when the paper was accepted for publication. On 11 November we telephoned G. Bellettini, the Director of Frascati Laboratory, informing him of our results [7,9]. At Frascati they started a search on 13 November, and called us back on 15 November to tell us excitedly that they had also seen the J signal. They were able to publish their results [10] in the same issue of *Physical Review Letters* as ours and the results from SLAC [11] (Fig. 23). This discovery was widely discussed in the media [12] (Fig. 24). The impact of these papers on our understanding of particle physics is known as the “November Revolution”.

The properties of the J particle are truly unique: its lifetime is 10,000 times longer than other hadronic particles. The significance of this is similar to suddenly discovering, in a remote region of the Earth, a village where people live to be, instead of 100 years old, about 1 million years old; its transitions spectrum is similar to positronium (Fig. 25). This implies the existence of a new kind of matter made out of a new kind of quark-antiquark.

Many accelerators were built to study the detailed properties of this particle (Fig. 26). Continuous, 40-year long studies were performed at the Beijing Electron-Positron Collider (Figs. 27, 28) where 30 new hadrons have been discovered from charmed meson production and decays by the BES detectors (Fig. 29).

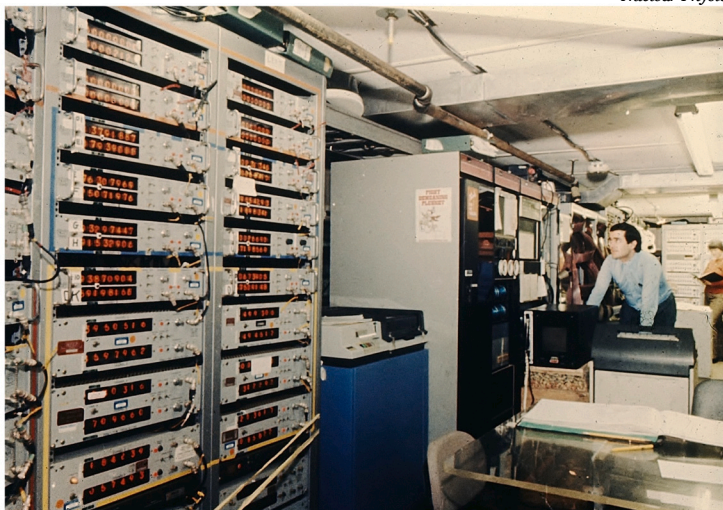


Fig. 19. J. J. Aubert, Professor of Physics, University of Marseille, Director-General, IN2P3, France.

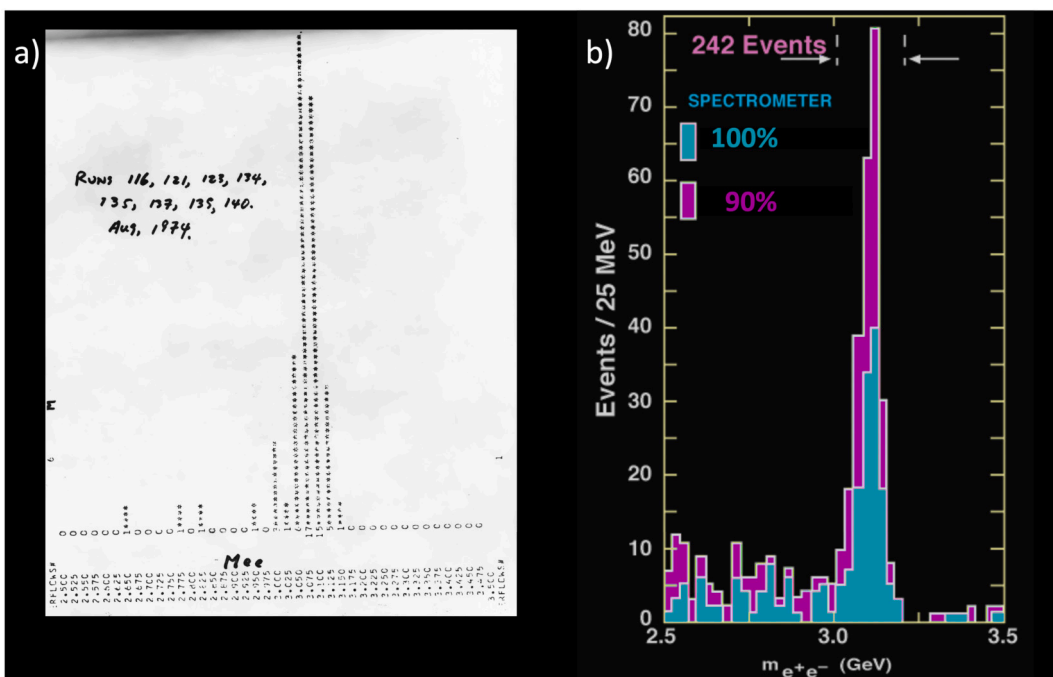


Fig. 20. (a) First observation of the J particle peak in August 1974. (b) Stability of the peak position against the change of magnetic field strength.

5. MARK-J experiment at DESY

In 1976 our group, in collaboration with institutes from Europe and Asia, submitted to DESY a proposal for the MARK-J detector to measure e^+e^- reactions at high energies, eventually up to $E_{cm} = 46$ GeV. The detector was designed to cover approximately 4π sr solid angle, and to measure and distinguish hadrons, electrons, neutral particles, and muons. The proposal was promptly accepted. With this detector we planned to do a wide range of studies including measurements of interference effects between weak and electromagnetic interactions, look for structures in the total hadronic cross section, searches for new quarks, vector mesons, and heavy leptons, study the structure of hadronic jets, etc.

It was also beginning of my long standing collaboration with Chinese research institutions. After the Cultural Revolution, in August 1977, Chairman Deng Xiaoping suggested sending 10 scientists each year to collaborate with me. In 1978, the first team of Chinese scientists joined the MARK-J experiment (Fig. 30). Since then, many Chinese scientists joined my team and have made contributions well recognized worldwide.

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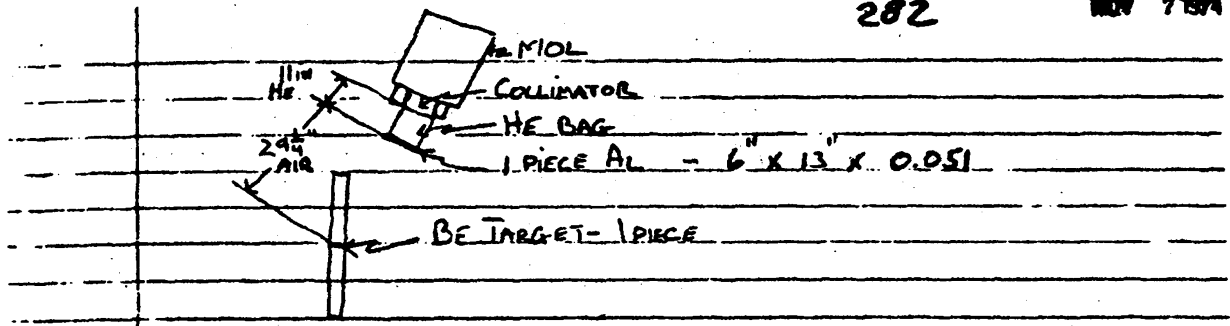


Fig. 21. Aluminum foil arrangement in front of magnet M_0 in our new experiment to determine the e/π ratio. The converter was used to determine the electron background yield.



Fig. 22. Members of the J-Particle Group.

The MARK-J experiment, running at the PETRA e^+e^- collider, produced important results on the interference effects between weak and electro-magnetic interactions by studying the charge asymmetry in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ [14] (Fig. 31a), clearly showing the contribution of the weak current, long before discovery of the Z^0 boson at CERN [15]. This was the earliest confirmation of electroweak theory, which provided the first opportunity to distinguish between the Standard Model [16] and other models that yield indistinguishable predictions for low-energy, low-momentum-transfer experiments (Fig. 31b).

Most importantly, the experiment analyzed the properties of three-jet events. This led to the discovery of gluon jets [17]. Gluons are the carriers of the strong force that “glue” quarks together into protons, neutrons, and other particles known collectively as hadrons. The three-jet topology was clearly visible and interpreted as $q\bar{q}$ gluon bremsstrahlung (Fig. 32a). Gluon jets become more pronounced with the increase of gluon energy. MARK-J experiment was the first to report statistically significant evidence of the three-jet event pattern originating from gluon emission [18]. As seen in Fig. 32a, three-jet events have many possible origins: QCD, Phase Space+ $q\bar{q}$ (300), $q\bar{q}$ (500), ... Note that each jet has approximately 1/2 of neutral particles, therefore, to study jet patterns, it was important to measure both charged and neutral particles at the same time, which was done only by MARK-J experiment at PETRA. The discovery of gluon jets was later confirmed by other PETRA experiments. This discovery is the key in establishing the theory of the strong force [19], known as quantum chromodynamics or QCD (Fig. 32b).

6. L3 experiment at CERN (1982-2003)

We spent 20 years, 1982-2003, building and operating the L3 experiment (Fig. 33) at the electron-positron collider LEP at CERN. The experiment was designed to study e^+e^- collisions in the center-of-mass energies ranging from 90 to 200 GeV with emphasis on high resolution energy measurements of electrons, photons, muons and hadron jets. It is an effort involving a worldwide collaboration of 600 physicists from 20 countries. It was the first large-scale scientific collaboration between the United States, China, the Soviet Union, India, East and West Germany.

The L3 detector conceptually differs from a standard e^+e^- collider detector by its emphasis on high resolution measurements of leptons, photons and jets. This is implemented in the experimental setup by an accurate tracking system, a high-resolution muon spectrometer, a precision electromagnetic calorimeter as well as 4π fine-grain hadron calorimetry. All the detectors were installed within a 10 thousand ton magnet providing a 0.5 T field. We have chosen a relatively low field in a large volume to optimize the muon

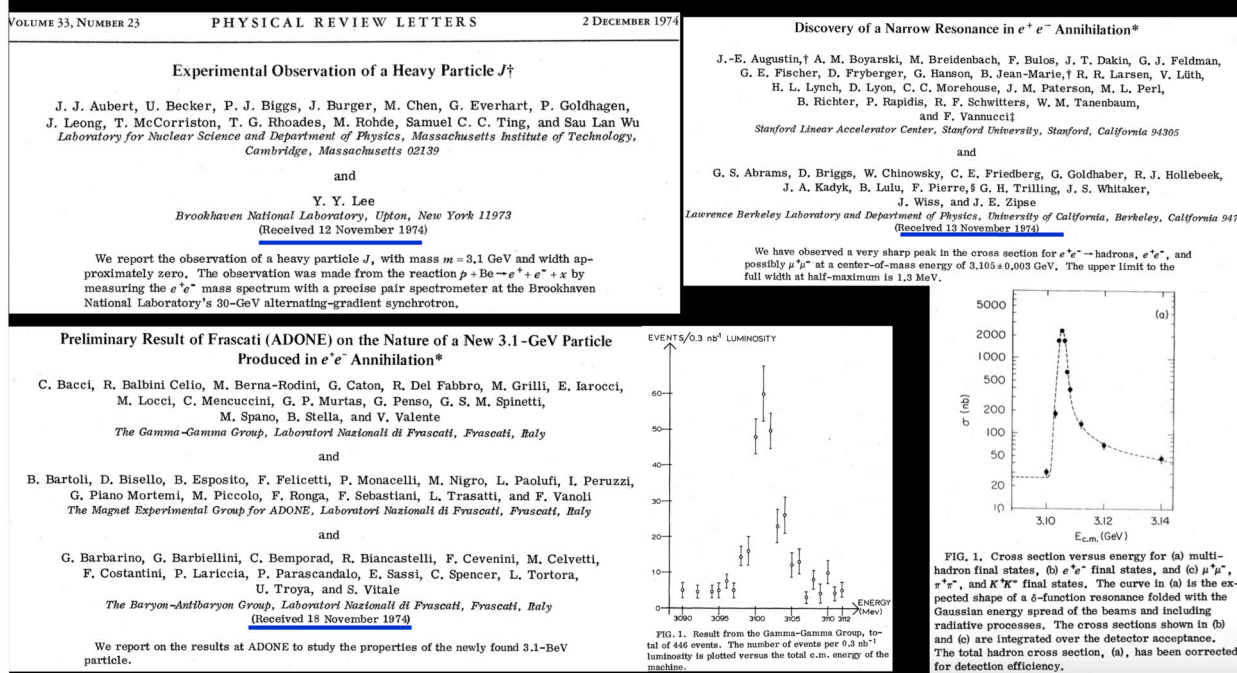


Fig. 23. The “November Revolution” - papers on a narrow hadronic resonance with a mass of 3.1 GeV published in the December 1974 issue of *Physical Review Letters*.



Fig. 24. (left) Article about discovery of a new form of matter in New York Times [12]; (right) Myself and Professor B. Richter in Stockholm two years later.

momentum resolution, which improves linearly with the field but quadratically with the track length. High resolution is essential for detecting rare new phenomena with sufficient signal-to-noise ratio; identifying exclusive and inclusive final states and rejecting backgrounds; and analyzing final state properties by measuring particle energy, momentum and reconstructing mass spectra. The construction of the experiment took eight years from its conception to the beginning of data taking in summer 1989.

Our research program at LEP was very broad: precision measurements of the Z boson properties (mass, width, and decay channels); determination of the number of light neutrino families; measurements of the electroweak force ($\alpha(Q^2)$, $\sin^2\theta_W$, gauge couplings, ...); direct Higgs boson searches and Higgs mass constraints from precision electroweak measurements; QCD tests (evolution of the strong

Positronium transitions

J/psi transitions

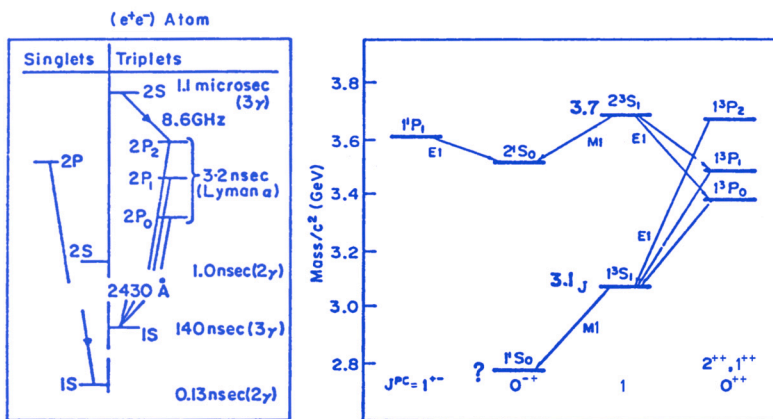


Fig. 25. The transitions spectrum of the J-particle is similar to positronium. This implies the existence of a new kind of matter made out of a new kind of quark-antiquark.

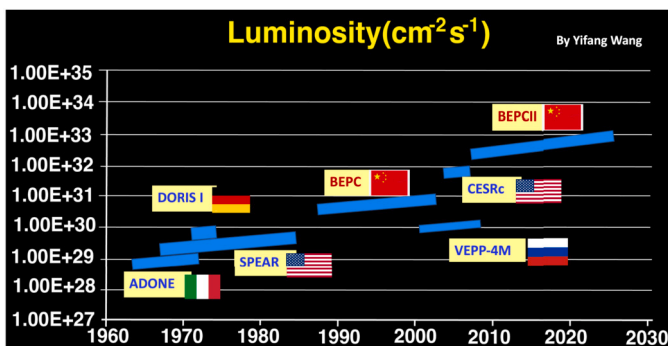


Fig. 26. World tau-charm factories and their integral luminosities over time.

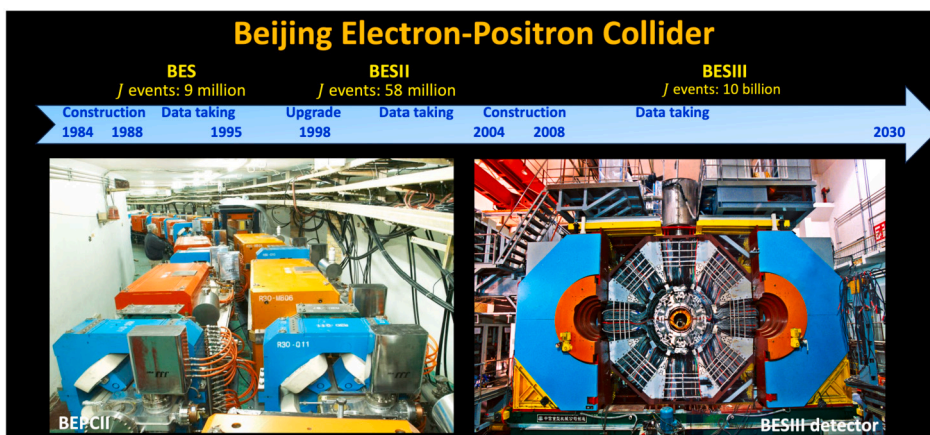


Fig. 27. Beijing Electron-Positron Collider, BEPC and the BES detector running for 40 years at BEPC.

coupling constant, $\alpha_s(\sqrt{s})$, and structure of gluon jets); physics of photon final states; study of two photon interactions; testing and constraining many theories beyond the Standard Model, including supersymmetry (SUSY) and other exotic particles.

We have published over 300 papers in Physics Letters. Our most notable results include studies of the energy evolution of the strong [20] (Fig. 34a) and electromagnetic [21] (Fig. 34b) coupling constants, as well as the model-independent determination of the number of light neutrinos [22] (Fig. 35). All the results agreed with the standard model [23]. That is rather unfortunate, because when an experiment agrees with the model, what you learn is limited. When an experiment disagrees with a model, you learn much

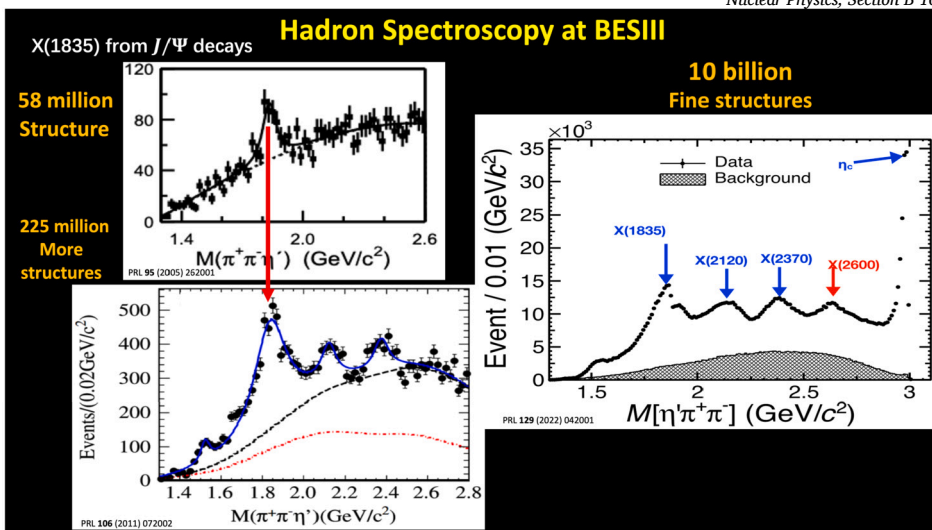


Fig. 28. Hadron spectroscopy with the BES detectors at BEPC.

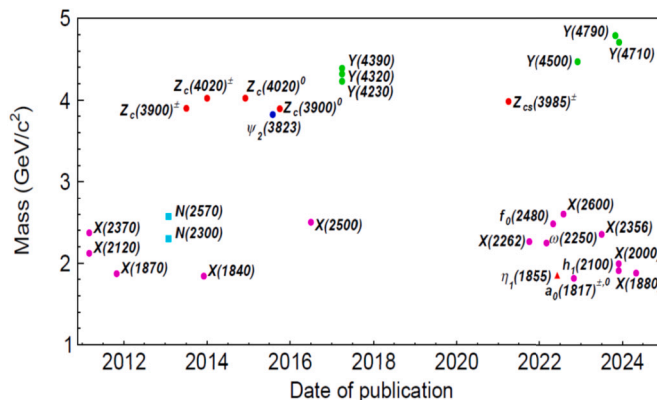


Fig. 29. 30 new hadrons were discovered by the BES detectors from charmed meson production and decays [13].



Fig. 30. The first group of Chinese scientists at DESY, Germany.



Fig. 33. IHEP director, academician Y.F. Wang (on the right), in front of the L3 detector at LEP.

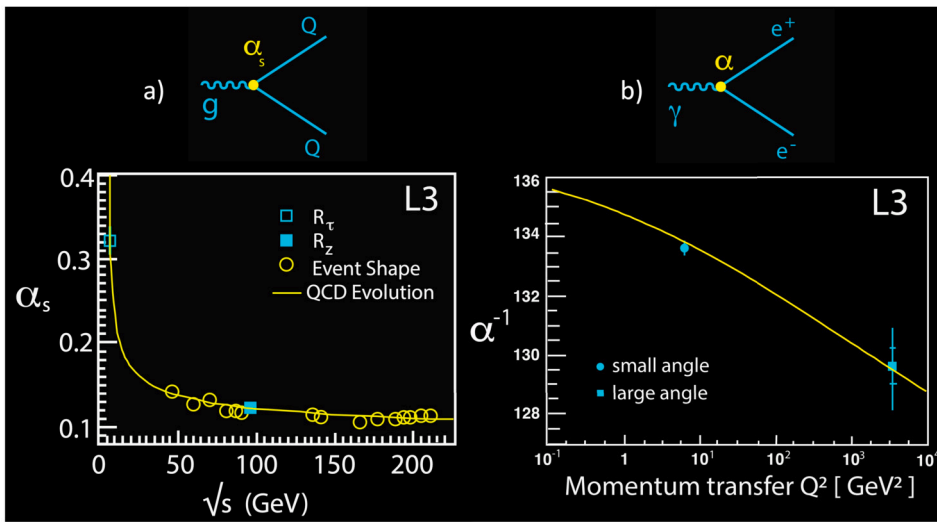


Fig. 34. L3 experimental results: (a) dependence of the strong coupling constant, α_s , on center-of-mass energy \sqrt{s} ; (b) dependence of the electromagnetic fine structure constant, α , on momentum transfer Q^2 .

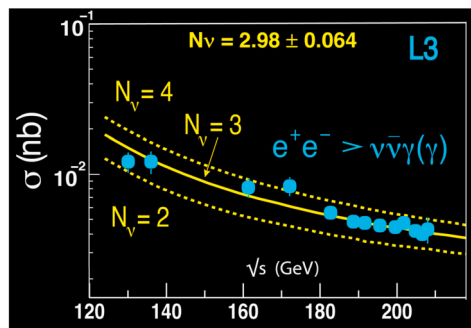


Fig. 35. L3 experimental results: model independent determination of the number of light neutrino species using reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$.

Since charged cosmic rays have mass, they are absorbed by the 100 km of Earth's atmosphere, therefore the properties (such as charge sign or momentum) of charged cosmic rays cannot be studied on the ground. The detector must be placed in space, it must be lightweight, without sizable external magnetic field, performing well in the harsh space environment.

The AMS detector (Fig. 36) consists of a permanent magnet with 1.4 kG field; nine planes of precision silicon tracker to measure the particle momentum, charge and sign; a transition radiation detector (TRD) to differentiate e^\pm from protons; four planes of



Fig. 36. Layout of the AMS experiment showing the countries which participated in the construction of individual detectors.



Fig. 37. AMS on the International Space Station.

time-of-flight (TOF) counters to measure the particle direction, charge, and velocity; an array of anticoincidence counters to reject particles entering the detector from the side; a ring imaging Cherenkov detector to measure particle charge and velocity; and a 3D electromagnetic calorimeter (ECAL) to measure energy and directions of electrons, positrons, and photons. The AMS Collaboration includes 47 universities and research institutes from 14 countries. NASA has organized an excellent AMS Project Office (APO) to ensure that the experiment is built according to space requirements and safety specifications. All the detectors of AMS were constructed in Europe and Asia, assembled at CERN and tested at the European Space Agency Test Facility in the Netherlands.

As a magnetic spectrometer, AMS is unique in its exploration of a new and exciting frontier in physics research. Following a 16-year period of construction and testing and a precursor flight on the Space Shuttle in 1998 [24], AMS was installed on the International Space Station, ISS, (Fig. 37) on 19 May 2011 to conduct a long duration mission of fundamental physics research in space. Its main physics objectives are the understanding of dark matter and complex antimatter in the cosmos, studies of the properties of primary and secondary cosmic rays as well as the search for new, unexpected phenomena [25]. The orders of magnitude improvement in accuracy over previous measurements is due to its precision, long exposure time in space, large acceptance, built-in redundancy and thorough calibration. In 2026 we will upgrade AMS with a new, $4+4\text{ m}^2$ silicon layer on top of the detector to increase the acceptance to 300%.

Studies of light cosmic ray antimatter species, such as positrons, antiprotons, and antideuterons, are crucial for the understanding of new phenomena in the cosmos, since the yield of these particles from traditional cosmic ray collisions is small. So far none of our results are what was expected when we first started the experiment. We found that the positron spectrum, based on 4.2 million events, exhibits complex energy dependence. Unexpectedly, after rising from ~ 25 to ~ 300 GeV, the spectrum suddenly cuts off and decreases quickly with energy. This means that there is a finite energy cutoff, which is measured to be ~ 800 GeV. Significance of this measurement is 4.8σ (Fig. 38). This complex behavior of the positron spectrum is consistent with the existence of a new source of high energy positrons with a characteristic cutoff energy, whether of dark matter or other new astrophysical origin. It is not consistent with the exclusive secondary production of positrons in collisions of cosmic rays with the interstellar media (Figs. 38 and 39a). With more data collected through 2030 with the upgraded detector (Fig. 39b) we will be able to provide definitive answers concerning the physics nature of the positron source term.

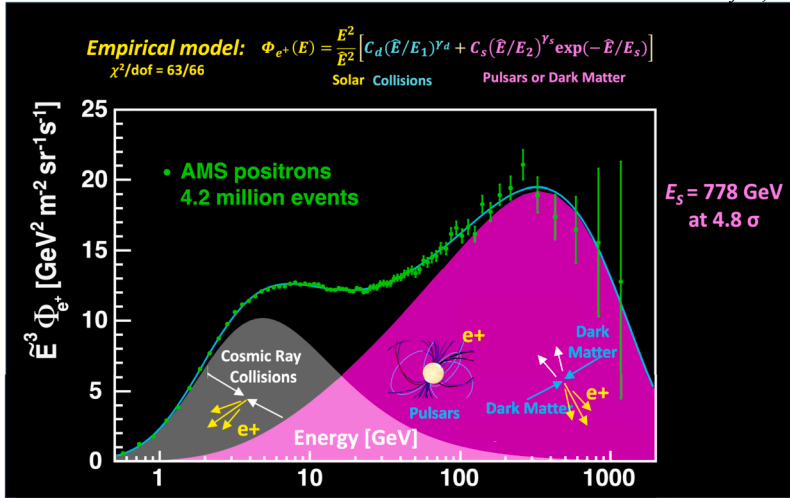


Fig. 38. The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy term from pulsars or dark matter with a cutoff energy. The empirical formula (shown on top), which includes both cosmic ray collisions and new source term with an exponential cutoff is represented by a light blue line.

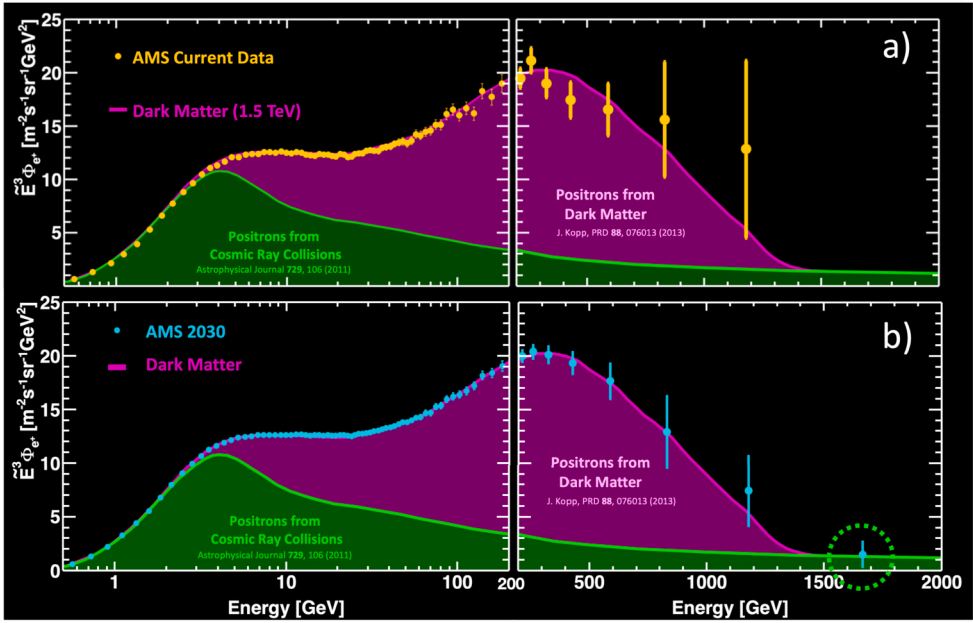


Fig. 39. (a) Comparison of the AMS data with predictions of a dark matter model with $M_{DM} = 1.5$ TeV. (b) The projection of AMS measurements to 2030 shows that we will not only improve the accuracy of current measurements but also provide a data point above the dark matter mass, where the contribution of cosmic ray collisions dominates.

For electrons, we have measured their spectrum from very low energy to a few TeV based on 62 million electrons. Note that the contribution of cosmic ray collisions to the electron flux is negligible. We have found that the spectrum can be described by two power law functions and the same source term observed in the positron spectrum (Fig. 40). This is consistent with the dark matter annihilation which produces equal amounts of high energy electrons and positrons. We determined the significance of the positron source term in the electron spectrum to be 2.6σ (99% CL) at present. With the AMS upgrade, we will determine the significance of the charge symmetric source term to 4σ .

For antiprotons we found that the spectrum is identical to the positron spectrum above 60 GeV (Fig. 41). Indeed the ratio of the positron-to-antiproton fluxes above 60 GeV was determined to be $1.98 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})$. This identical behavior of positrons and antiprotons excludes the pulsar origin of positrons.

For cosmic ray nuclei, we have measured the spectra of many different types, from helium up to iron, as a function of rigidity (i.e. momentum per unit charge). Before AMS, there were very limited measurements of cosmic rays with 30% or larger errors. Now, we can study cosmic rays with an accuracy of 1%. For each cosmic ray element we have collected tens of millions of events with energies up to multi-trillion electron volts.

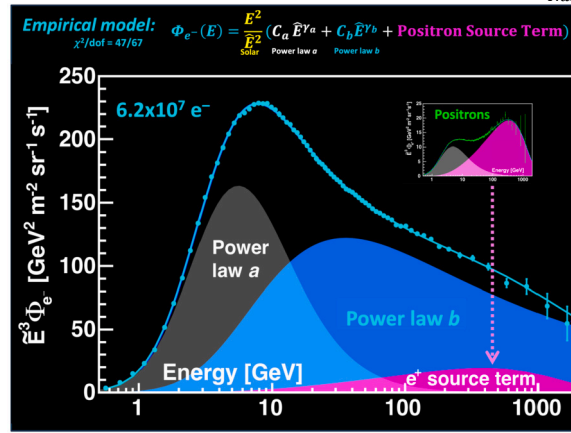


Fig. 40. The electron spectrum with the fit results showing that the charge symmetric measured positron source term (from Fig. 38) is needed to describe the behavior of the spectrum at high energies. The empirical formula (shown on top), which includes two power law functions and the positron source term with an exponential cutoff is represented by a light blue line.

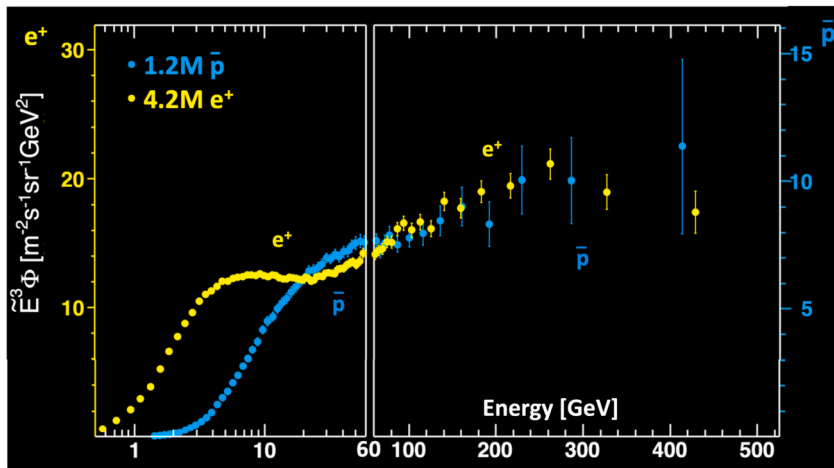


Fig. 41. The antiproton spectrum (blue data points, right axis) and the positron spectrum (yellow data points, left axis) show identical behavior above 60 GeV.

Before AMS, cosmic rays were believed to have two groups. The first group are primary cosmic rays (helium, carbon, oxygen, ...) which are produced from nuclear fusion in stars and accelerated by supernova explosions. Then there is another group of secondary cosmic rays (lithium, beryllium, boron, ...) which are produced from the collision of primary cosmic rays with the interstellar media. Unexpectedly, AMS discovered that at high rigidities, primary cosmic rays actually have two classes (light and heavy nuclei), each class contains elements with unique but identical rigidity dependence. AMS also found that the secondary cosmic rays have their own rigidity dependence also with two classes (light and heavy nuclei) which is very different from the two classes of primary cosmic rays (see Figs. 42 and 43). These phenomena were not predicted.

Surprisingly, we found that any cosmic nuclei flux can be described as a linear combination of the corresponding primary and secondary fluxes (Fig. 44). This is an important observation as it allows to determine for every cosmic nuclei the amount of its primary component at the source in a model-independent way. Most interesting, we found that the traditional primary cosmic rays He, C, S, Ne, and Mg all have sizable secondary components. We continue these studies aiming to definitively determine the nature of all high-energy cosmic rays from Z=1 to Z=26 and beyond.

One of the main physics research topics in the last half a century is the search for the explanation of the absence of heavy antimatter (known as baryogenesis). Baryogenesis requires strong CP symmetry breaking and a finite lifetime of the proton. To date, despite the efforts of many outstanding experiments, no evidence for strong CP symmetry breaking nor for proton decay has been found. Therefore, the observation of heavy antimatter events is of great importance. If the universe had come from the Big Bang, there should be equal amounts of matter and antimatter at the beginning. Now the universe is 14 billion years old, where is the other half of the universe made out of antimatter?

AMS is a unique precision magnetic spectrometer with large acceptance and long exposure time. We are studying anti-matter in space with highest priority and we have begun to see the anti-helium candidates. The observation of anti-helium events is the first

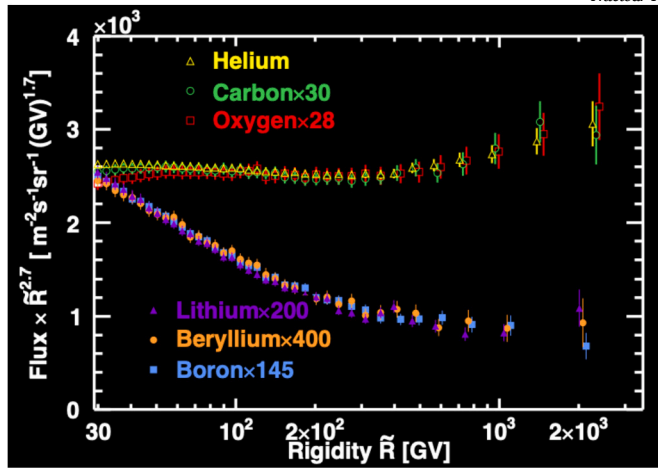


Fig. 42. Class of light nuclei: $2 \leq Z \leq 8$ He-C-O primaries compared with Li-Be-B secondaries.

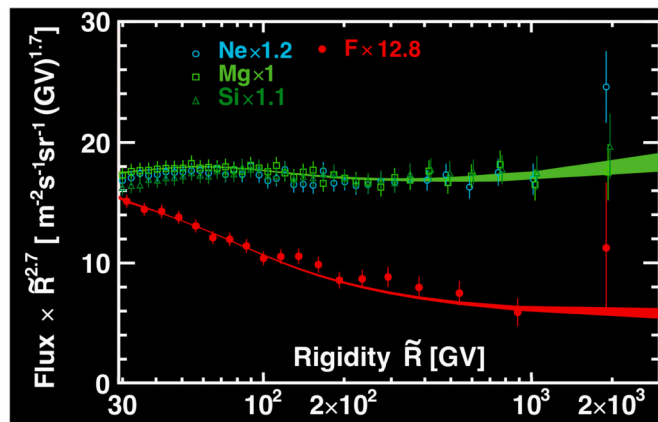


Fig. 43. Class of heavier nuclei: $9 \leq Z \leq 14$ Ne-Mg-Si primaries compared with F secondaries.

step for AMS to study heavy antimatter. We need to collect more data and investigate higher Z nuclei to see how many kinds of heavy antimatter nuclei we can find.

The latest AMS results on the fluxes of electrons, positrons, protons, antiprotons, and primary and secondary nuclei provide precise and unexpected information. The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, provide unique input to the understanding of cosmic ray production and propagation.

With data taking through the lifetime of the Space Station, we will explore the physics of complex anti-matter (anti-He, anti-C, ...), the physics of dark matter (anti-deuterons, anti-protons, and positrons), the physics of cosmic ray nuclei including isotopes and high- Z cosmic-rays for which there is only very limited data below 35 GeV/n, as well as the physics of the heliosphere. AMS is exploring uncharted territory and opening new domains of research. There is no plan by any country to launch another magnetic spectrometer into space. It is most important that we ensure that AMS data are precise and cover the highest energies and the highest Z continuously over an extended period of time.

Space is the ultimate laboratory. Space provides particles with much higher energies than accelerators. AMS provides a first step in uncovering the mysteries of cosmic rays. The unexpected nature of the AMS results requires a new and comprehensive astrophysical model of the cosmos.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

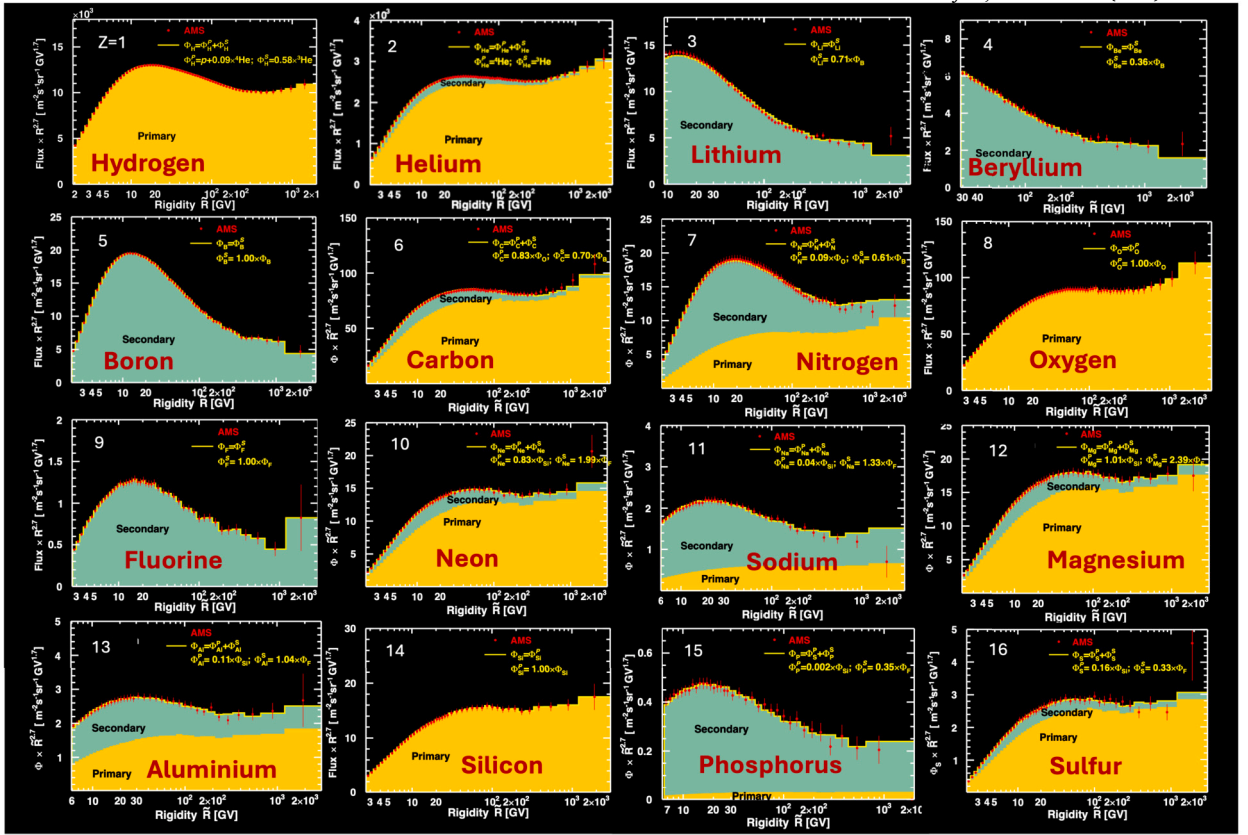


Fig. 44. The fluxes of all cosmic nuclei from $Z=1$ to $Z=16$. In each plot the contributions of the primary and secondary components are indicated by the yellow and green shading, respectively.

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Data availability

The data that has been used is confidential.

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