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Review

Discovery of the *J* Particle at Brookhaven National Laboratory and the Physics of Electrons and Positrons

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Abstract: The 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.

Keywords: Charm; J Particle; AMS; L3; Gluons; Anti-matter

1. 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 (Figure 1). Most importantly, this experiment was independently confirmed by a group at the Cornell Electron Accelerator. Since those results touched 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 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].

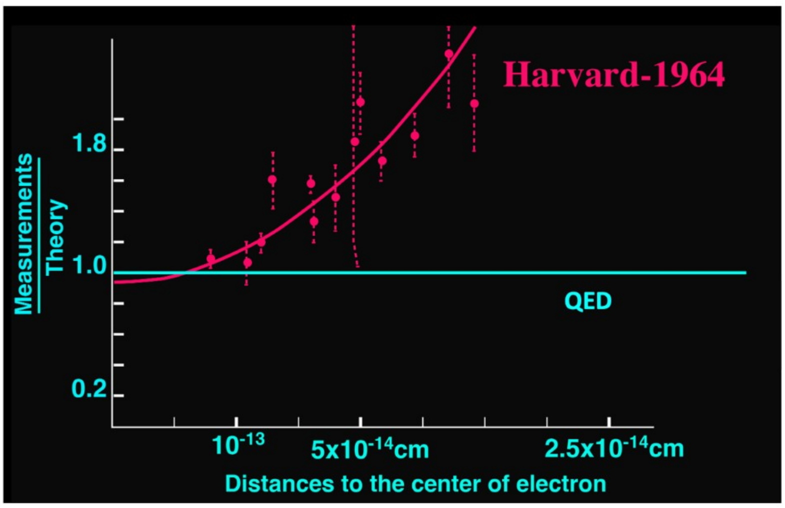


Figure 1. Results of the Harvard experiment showing that the electron has a radius of $\sim 10^{-13}$–10^{-14} cm.

The layout of my experiment at DESY (Figure 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 (Figure 2b) eventually led to the J-Particle experiment.

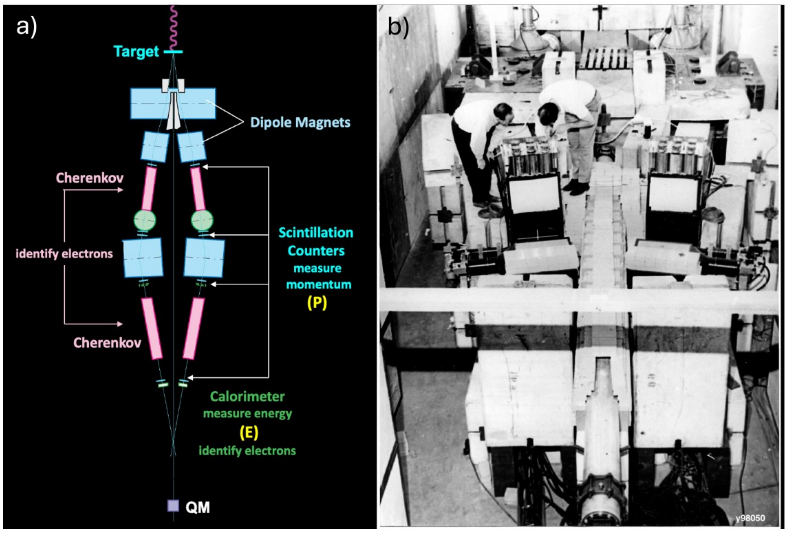


Figure 2. (**a**) Experimental layout of my experiment for electron size measurement at DESY; (**b**) Photo of the experiment for electron size measurement.

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] (Figure 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.

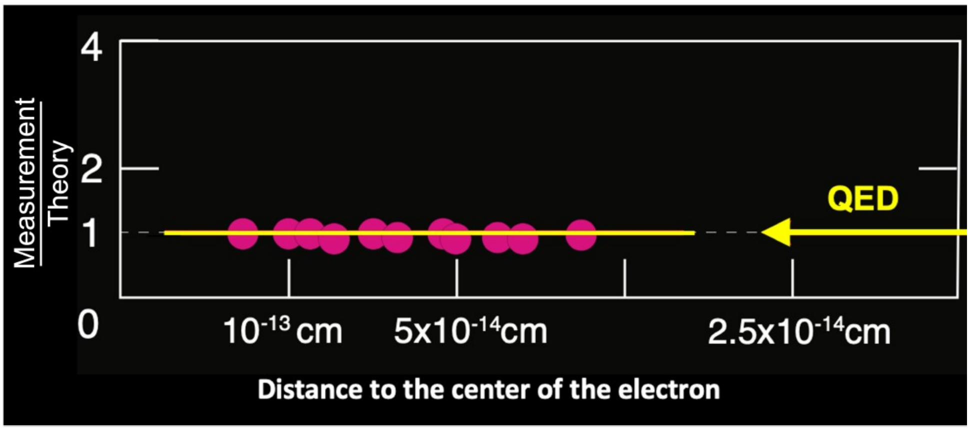


Figure 3. Results of our experiment showing that electron does not have measurable size up to 10^{-14} cm.

2. 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 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] (Figure 4). The observation of $\rho \to e^+e^-$ decays started a series of experiments by my group on massive photon-like particles [5–10].

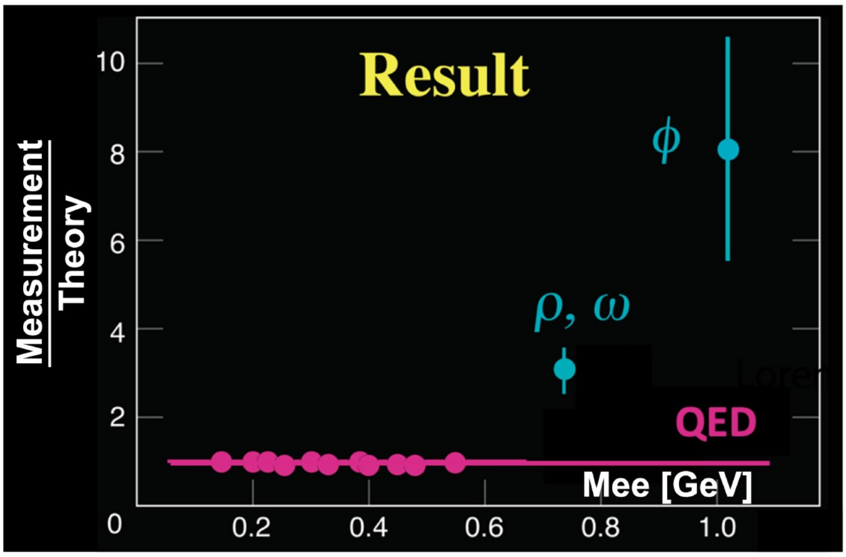


Figure 4. Deviation from QED due to heavy photon (ρ , ω and ϕ) production.

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} s. 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: $M_\rho = 760\,\text{MeV}$, $M_\phi = 783\,\text{MeV}$ and $M_\phi = 1020\,\text{MeV}$. Their interactions with hadrons are described by the Vector Dominance Model:

$$J_\mu(x) = \left[\frac{m_\rho^2}{2\gamma_\rho}\rho_\mu + \frac{m_\omega^2}{2\gamma_\omega}\omega_\mu + \frac{m_\phi^2}{2\gamma_\phi}\phi_\mu\right] \tag{1}$$

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 $\rho \to e^+e^-$ and $\omega \to e^+e^-$ decays (Figures 5 and 6) as well as forbidden $\omega \to \pi^+\pi^-$ decays, which at that time attracted significant attention [11–15] (Figures 7 and 8).

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

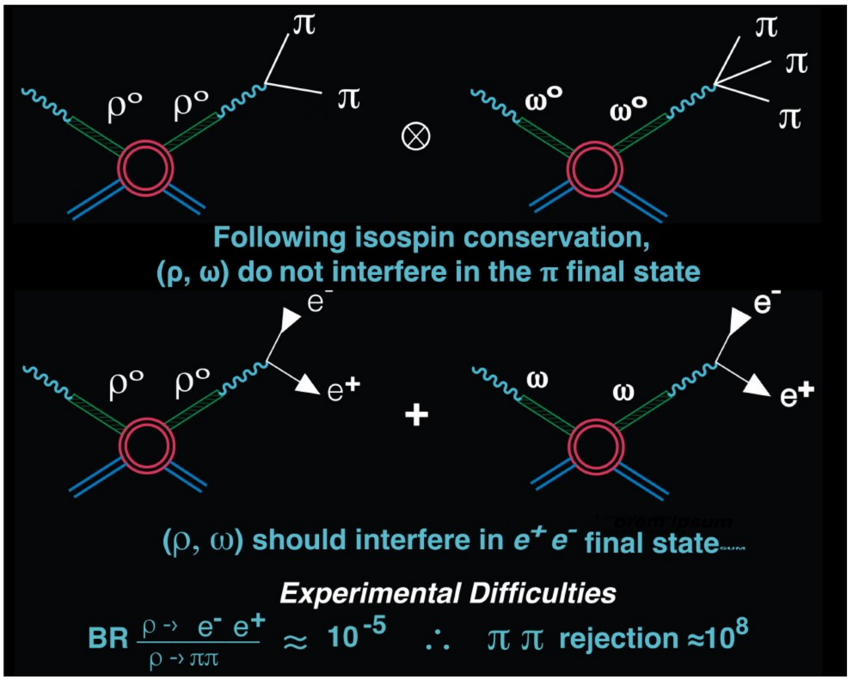


Figure 5. Feynman diagrams of $\rho - \omega$ coherent interference.

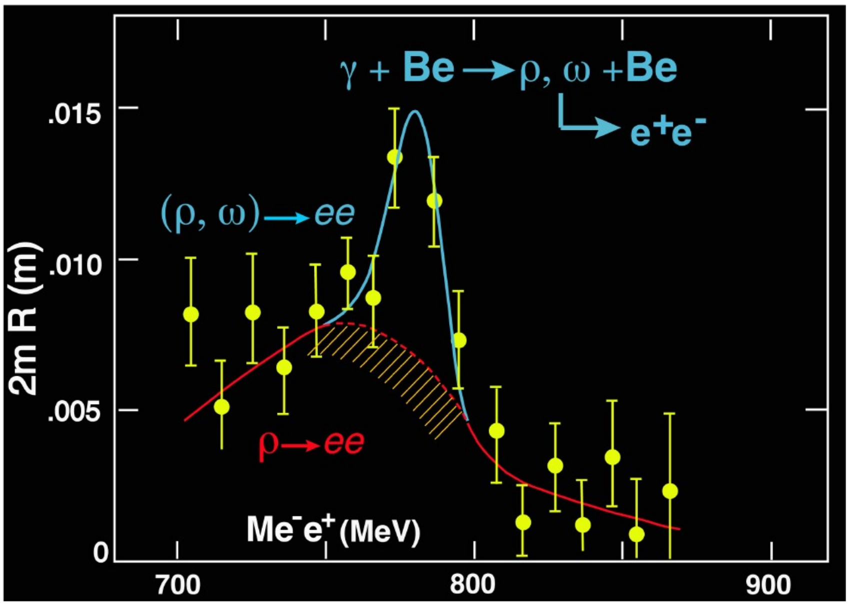


Figure 6. Observation of $\rho - \omega$ coherent interference in the e^+e^- final state.

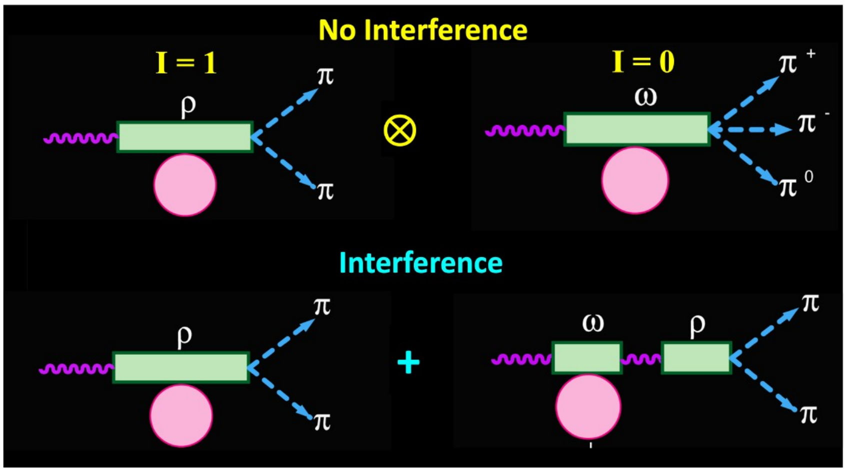


Figure 7. Feynman diagrams of forbidden $\omega \to \pi^+\pi^-$ decays due to isospin I violation.

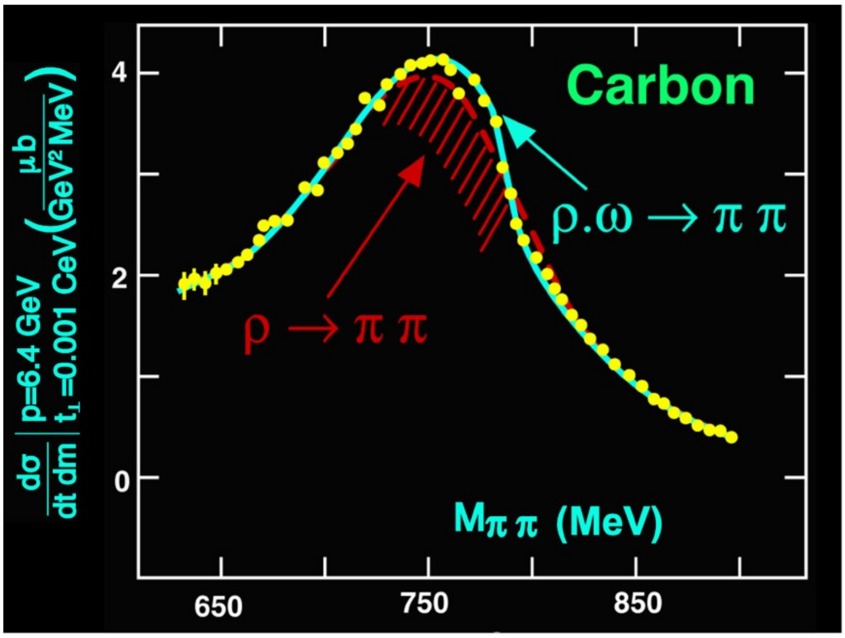


Figure 8. First observation of forbidden $\omega \to \pi^+\pi^-$ decays.

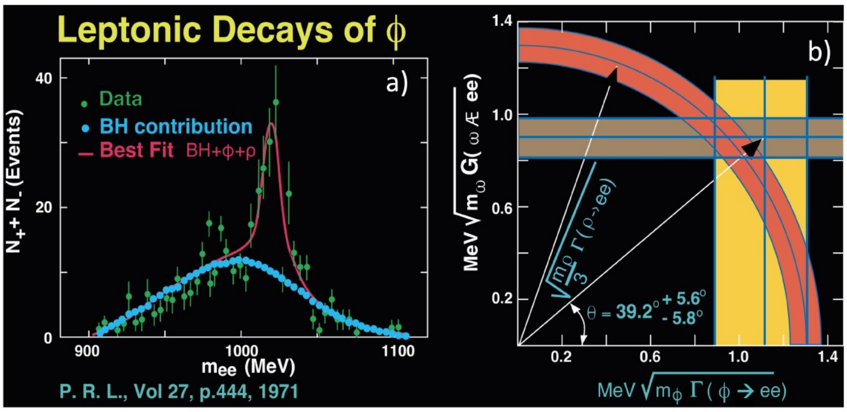
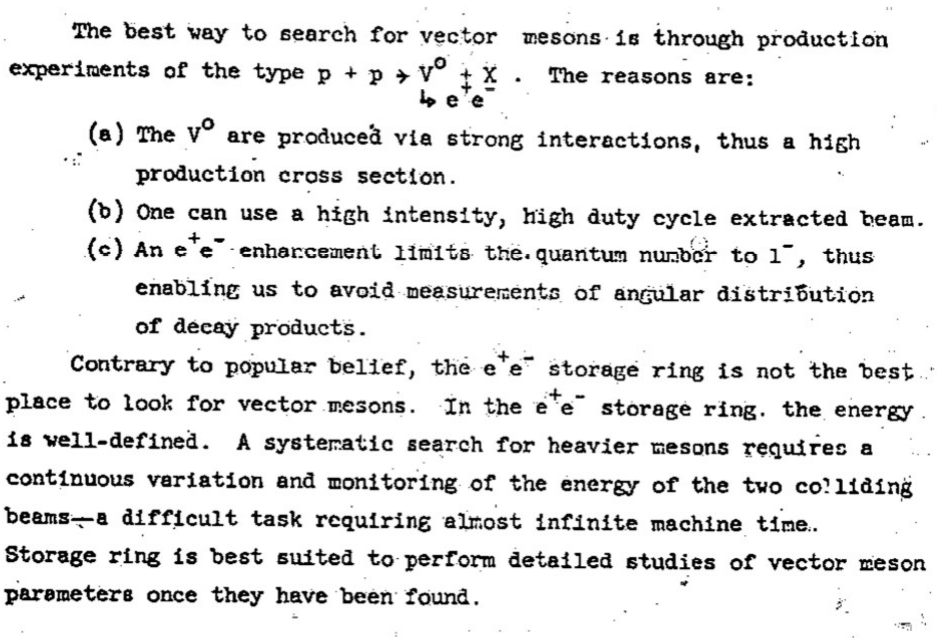


Figure 9. (a) invariant mass of e^+e^- pairs showing the ϕ meson peak; (b) first validation of Weinberg's first sum rule using our data on $\Gamma(\rho \to e^+e^-)$, $\Gamma(\omega \to e^+e^-)$ and $\Gamma(\phi \to e^+e^-)$.

3. 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. Figure 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 (Figure 11).


The best way to search for vector mesons is through production experiments of the type $p + p \to V^0 + X$, $V^0 \to e^+e^-$. 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.

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

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. Figure 12 shows the layout of the spectrometer and related detectors.

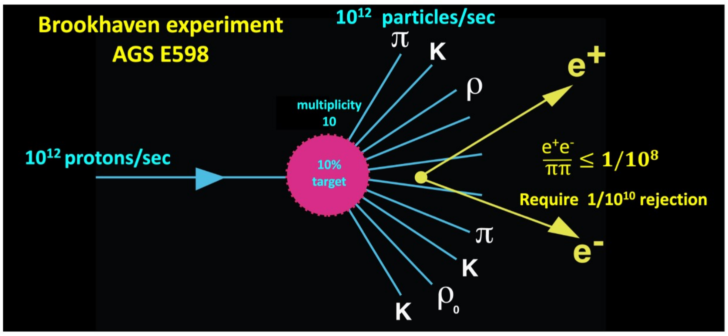


Figure 11. Concept of the AGS Experiment E598. The extracted beam of 10^{12} protons/s interact with a 10% target. The multiplicity is 10, resulting in 10^{12} particles/s from the target volume. The ratio $e^+e^-/\pi^+\pi^-$ is less than $1/10^8$, so a percent accuracy measurement requires $1/10^{10}$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

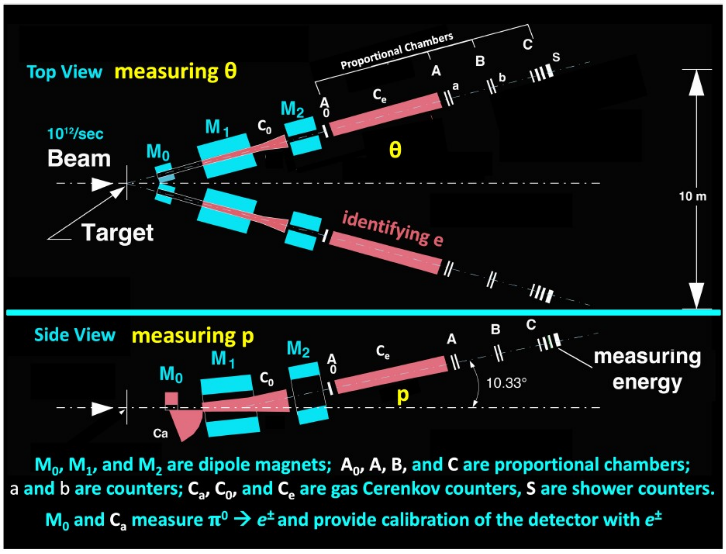


Figure 12. Layout of the AGS Experiment E598, which is an upgraded precision version of the DESY experiment.

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 (Figure 13).

Figure 13. Shielding arrangement with roof open.

(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 (Figure 14). This arrangement rejects accidental pairs by requiring both tracks come from the same origin.

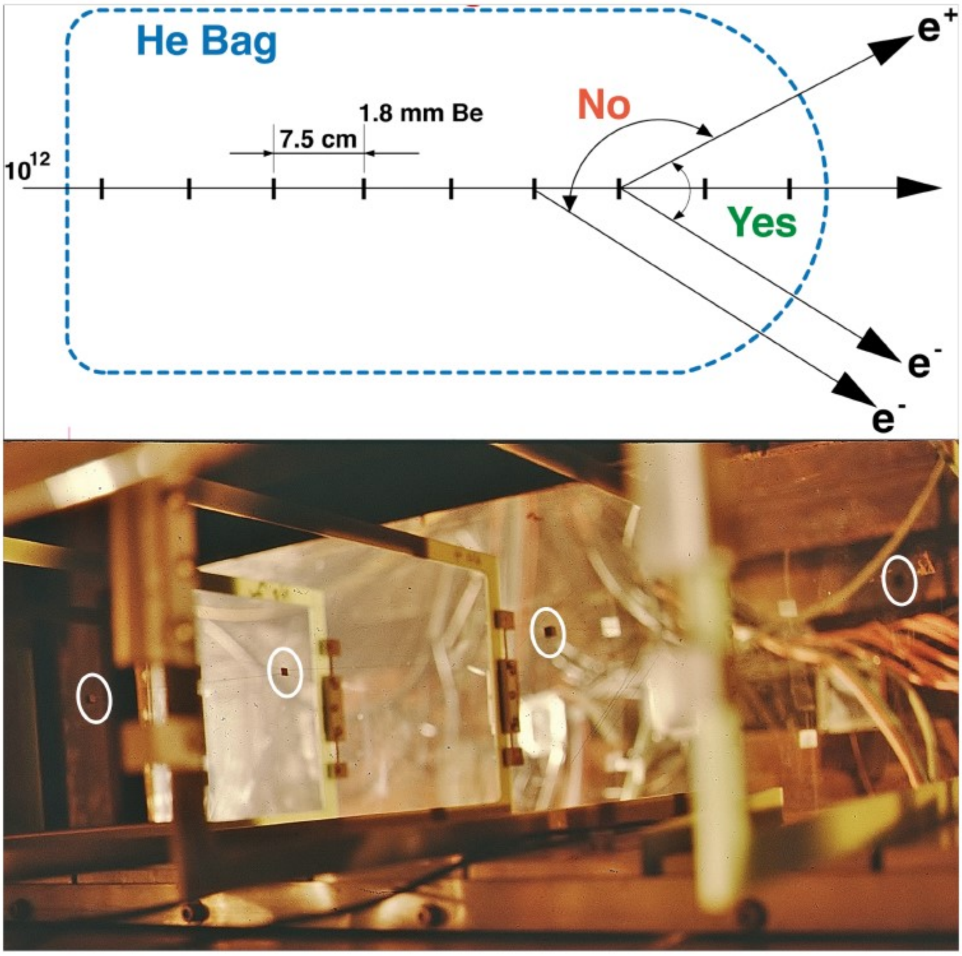


Figure 14. Nine separate targets to reduce the background.

(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 (Figure 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 $\pi^0 \to e^+e^-\gamma$ was performed (Figure 16).

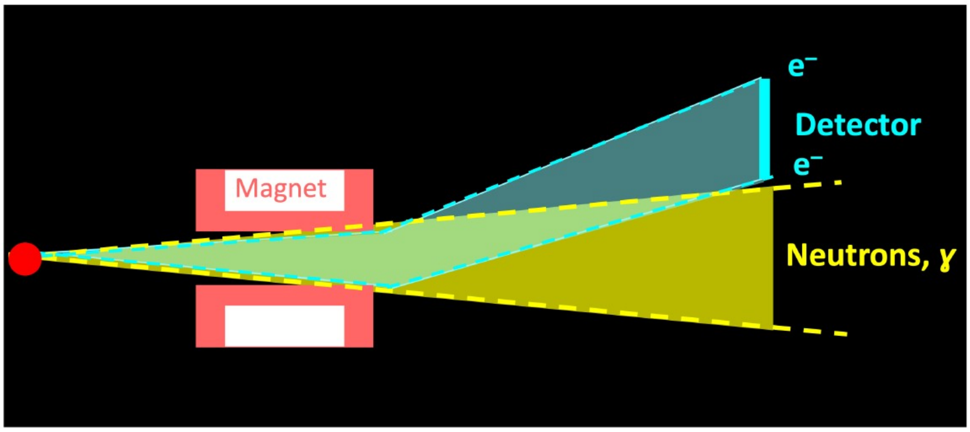


Figure 15. The magnets bend charged particles to an angle such that the detectors are not exposed to photons or neutrons from the target.

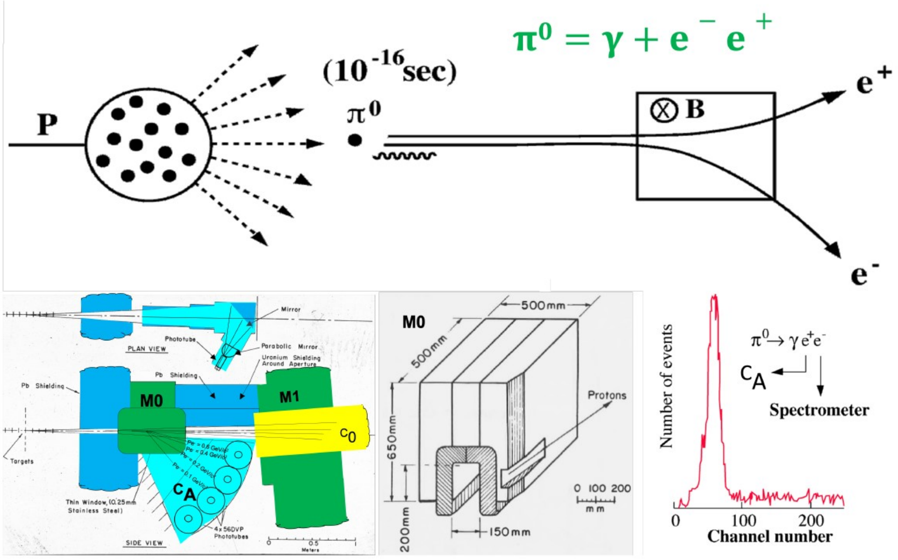


Figure 16. Detector calibration with a pure electron beam by placing a specially designed magnet M_0 close to the target followed by a special Cherenkov counter, C_A, to detect positrons from $\pi^0 \to \gamma e^+ e^-$ ensuring the electron entering the spectrometer.

(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—a unique feature for sorting out multi-hit events and rejecting backgrounds (Figure 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.

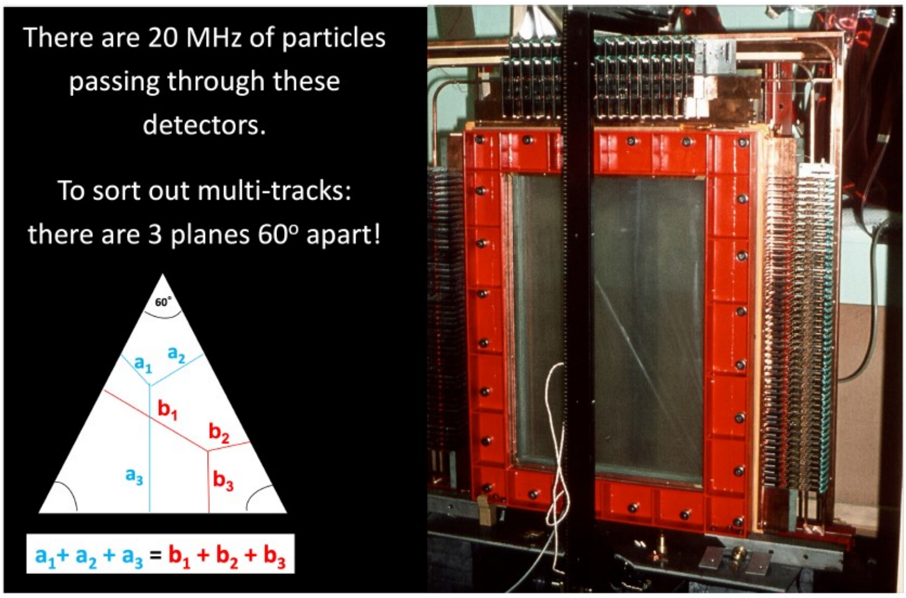


Figure 17. Precision position detectors, which were designed by the late Professor UJ Becker. The chamber, shown on the right, is on display in Smithsonian Institution in Washington, DC after completion of the experiment.

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

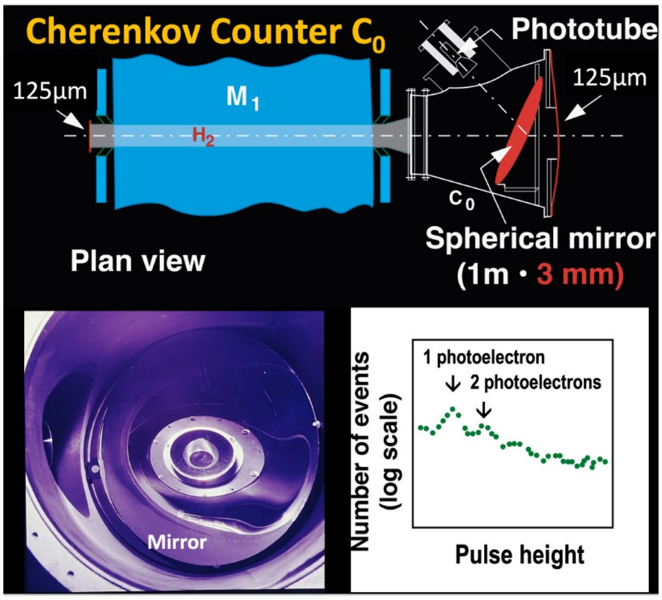


Figure 18. The $\pi - e$ separation was achieved by four extremely sensitive Cherenkov Counters C_o, C_e.

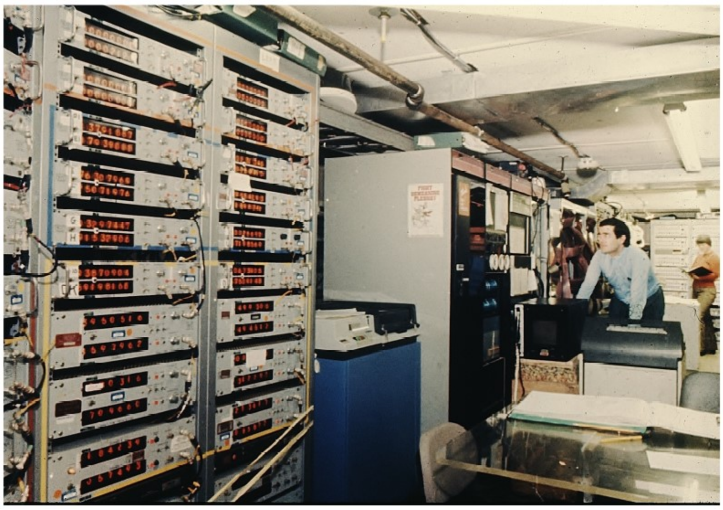


Figure 19. J. J. Aubert, Professor of Physics, University of Marseille, Director-General, IN2P3, France.

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 (Figure 20a). A more detailed analysis showed that the width was 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 (Figure 20b) showed right away that a real particle had been discovered [16,17].

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.

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.

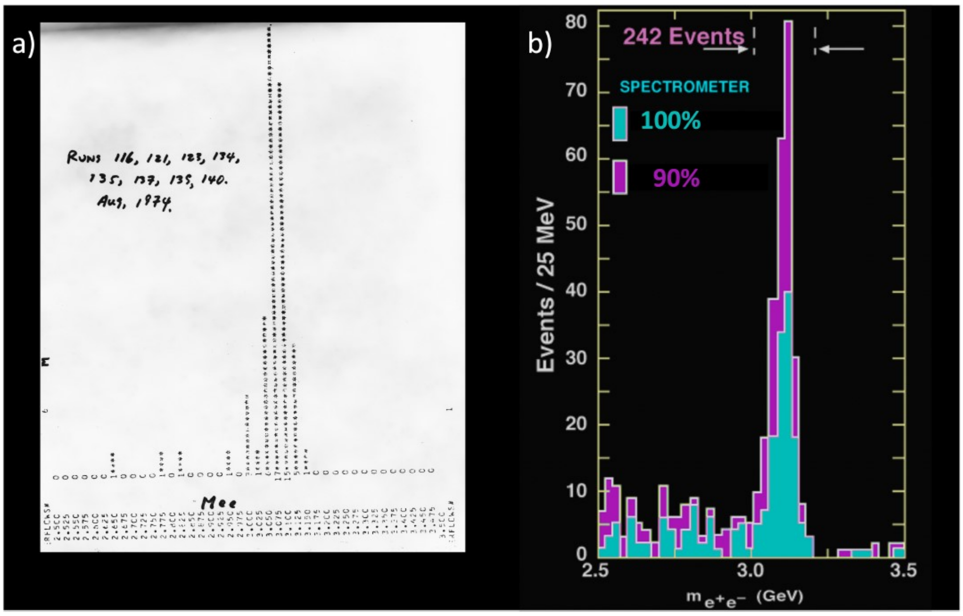


Figure 20. (**a**) First observation of the J particle peak in August 1974. (**b**) Stability of the peak position against the change of magnetic field strength.

Second, we realized that there were earlier Brookhaven measurements [18] 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 (Figure 21) to start the new experiment to search for more particles.

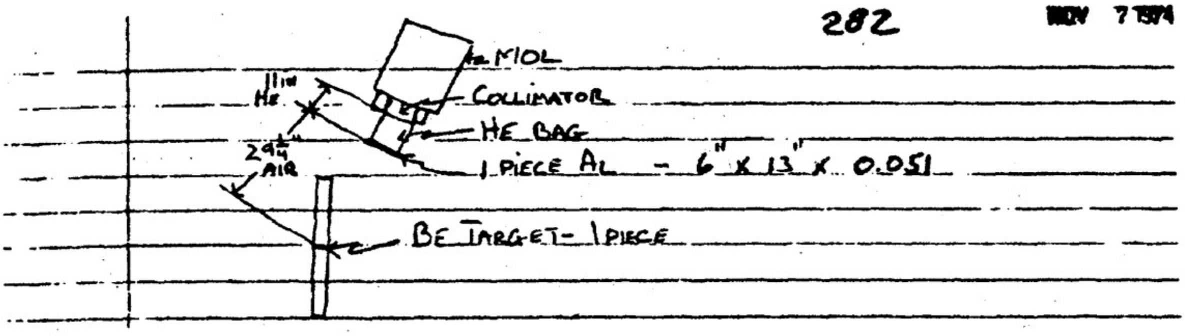


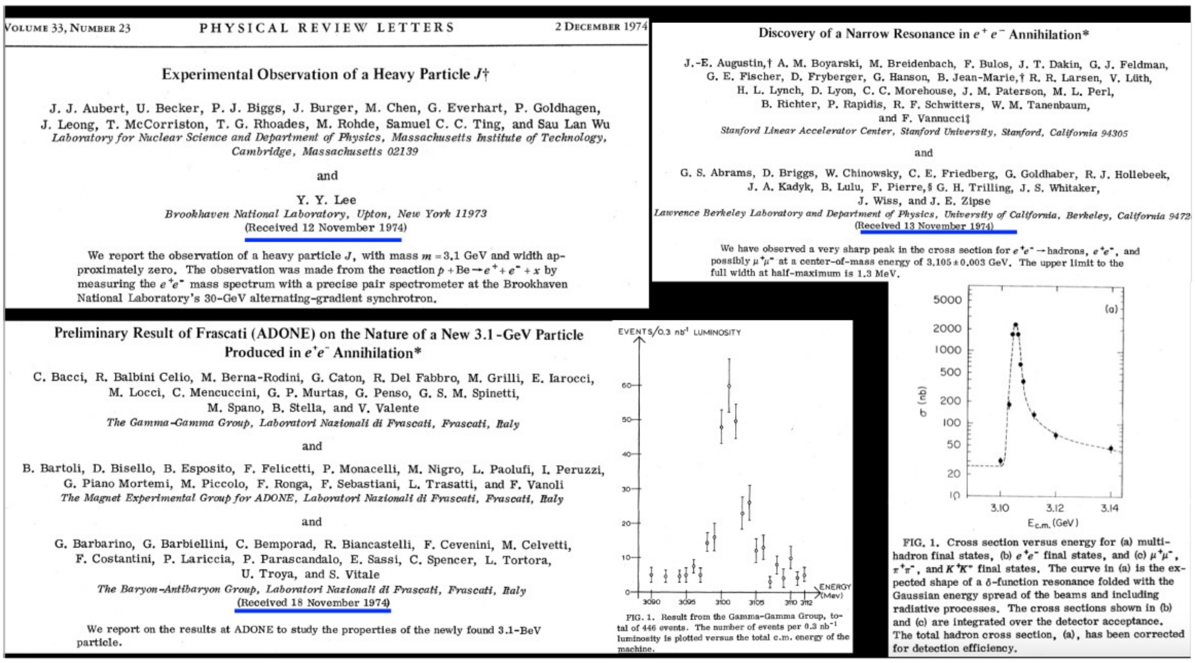
Figure 21. Aluminum foil arrangement in front of magnet M_0 in our new experiment to determine the e/π ratio. The converter was used to determine the electron background yield.

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 checks we made on the data. The group photo (Figure 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 [16,17,19]. 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 [20] in the same issue of *Physical Review Letters* as ours and the results from SLAC [21] (Figure 23). This discovery was widely discussed in the media [22] (Figure 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 (Figure 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 (Figure 26). Continuous, 40-year long studies were performed at the Beijing Electron-Positron Collider (Figures 27 and 28) where 30 new hadrons have been discovered from charmed meson production and decays by the BES detectors (Figure 29).

Figure 22. Members of the J-Particle Group.



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
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(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m=3.1$ GeV and width approximately zero. The observation was made from the reaction $p+\mathrm{Be}\to e^{+}+e^{-}+x$ by measuring the $e^{+}e^{-}$ mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

Discovery of a Narrow Resonance in $e^{+}e^{-}$ Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
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and

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Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 9472
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^{+}e^{-}\to$ hadrons, $e^{+}e^{-}$, and possibly $\mu^{+}\mu^{-}$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

Preliminary Result of Frascati (ADONE) on the Nature of a New 3.1-GeV Particle Produced in $e^{+}e^{-}$ Annihilation*

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(Received 18 November 1974)

We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

FIG. 1. Cross section versus energy for (a) multihadron final states, (b) $e^{+}e^{-}$ final states, and (c) $\mu^{+}\mu^{-}$, $\pi^{+}\pi^{-}$, and $K^{+}K^{-}$ final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

Figure 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*.

New and Surprising Type Of Atomic Particle Found
By WALTER SULLIVAN
New York Times (1857-Current file); Nov 17, 1974; ProQuest Historical Newspapers The New York Times (1851 - 2002)
pg. 1

New and Surprising Type Of Atomic Particle Found

By WALTER SULLIVAN

Experiments conducted independently on the East and West Coasts have disclosed a new type of atomic particle.

Its properties are so unexpected that there are differing views as to how it might fit into current theories on the elementary nature of matter.

The experiments were done at the Stanford Linear Accelerator in Palo Alto, Calif., by a team under Dr. Burton Richter and at the Brookhaven National Laboratory in Upton, L.I., by a group under Dr. Samuel C. C. Ting of the Massachusetts Institute of Technology.

In a statement yesterday, the two men said:

"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

"The theorists are working frantically to fit it into the framework of our present knowledge of the elementary particle. We experimenters hope to keep them busy for some time to come."

Some scientists believe that the new particle will prove to be the long-sought manifestation of the so-called weak force—one of the four basic forces in nature. The others are gravity, electromagnetism and the strong force that binds together the atomic nucleus.

It is also suspected that the particle may be related to a recently developed theory equating two of those forces — electromagnetism and the weak force— as manifestations of the same phenomenon. However, the properties of the newly discovered particle are not those predicted for either

Continued on Page 29, Column 1

Figure 24. (**left**) Article about discovery of a new form of matter in New York Times [22]; (**right**) Myself and Professor B.Richter in Stockholm two years later.

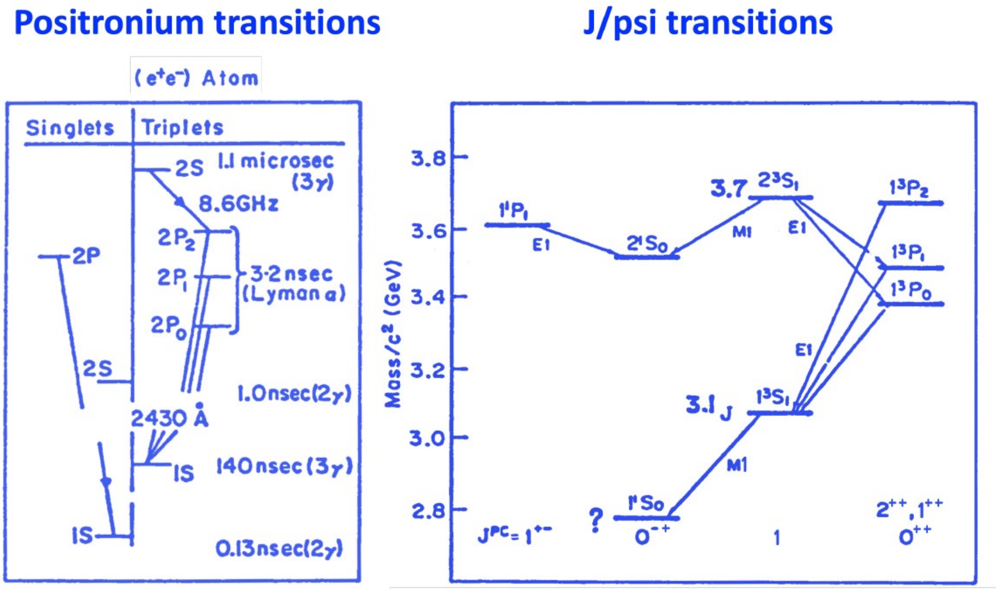


Figure 25. The transitions spectrum of the J particle is similar to positronium. This implies the existence of a new kind of matter made out of a new kind of quark-antiquark.

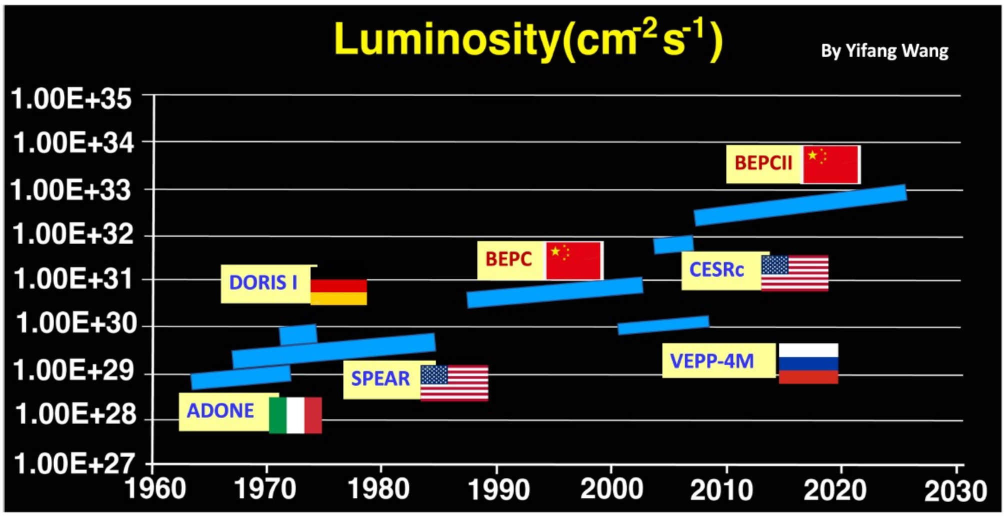


Figure 26. World tau-charm factories and their integral luminosities over time.

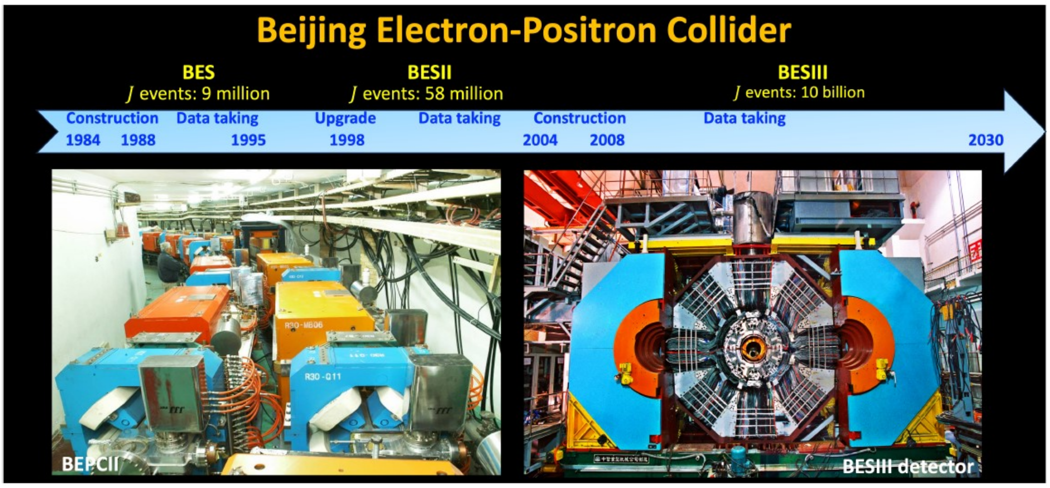


Figure 27. Beijing Electron-Positron Collider, BEPC and the BES detector running for 40 years at BEPC.

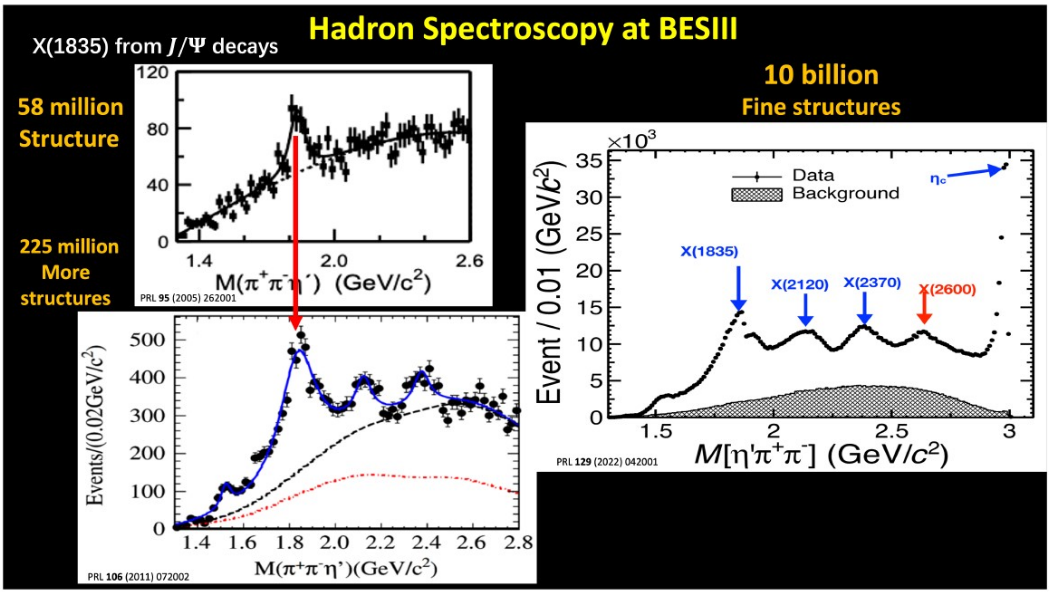


Figure 28. Hadron spectroscopy with the BES detectors at BEPC.

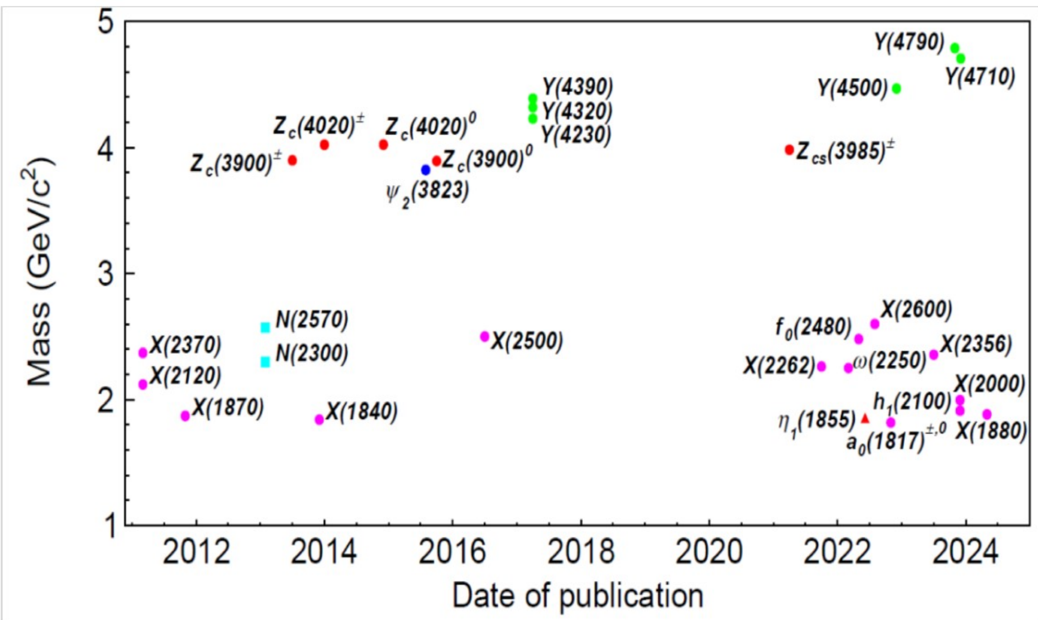
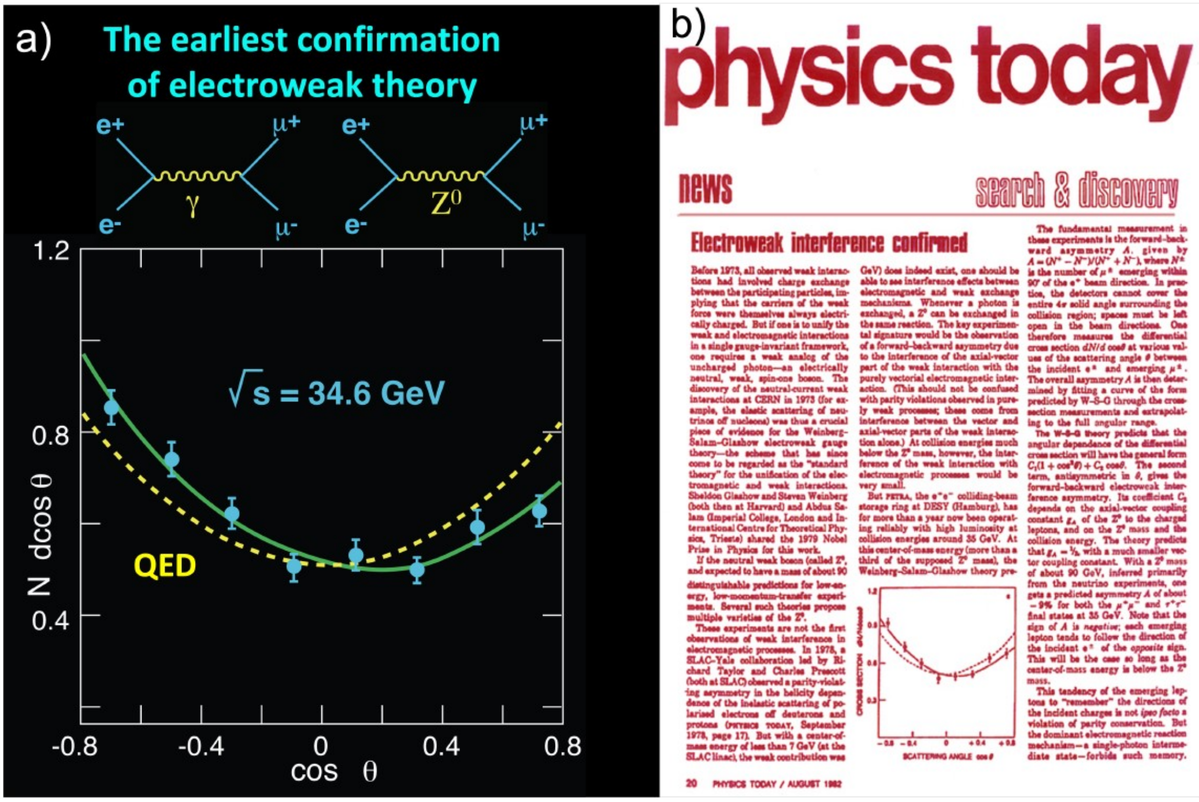


Figure 29. 30 new hadrons were discovered by the BES detectors from charmed meson production and decays [23].

4. MARK–J Experiment at DESY

In 1976 our group, in collaboration with institutes from the Europe and Asia, submitted to DESY a proposal for the MARK–J detector to measure e^+e^- reactions at high energies, eventually up to $E_{cm} = 46\,\text{GeV}$. 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.

The experiment, running at the PETRA e^+e^- collider, produced important results on the interference effects between weak and electromagnetic interactions by studying the charge asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ [24,25] (Figure 30a), clearly showing the contribution of the weak current, long before the discovery of the Z^0 boson at CERN [26]. This was the earliest confirmation of electroweak theory, which provided the first opportunity to distinguish between the Standard Model [27–29] and other models that yield indistinguishable predictions for low-energy, low-momentum-transfer experiments (Figure 30b).



Electroweak interference confirmed

Before 1973, all observed weak interactions had involved charge exchange between the participating particles, implying that the carriers of the weak force were themselves always electrically charged. But if one is to unify the weak and electromagnetic interactions in a single gauge-invariant framework, one requires a weak analog of the uncharged photon—an electrically neutral, weak, spin-one boson. The discovery of the neutral-current weak interactions at CERN in 1973 (for example, the elastic scattering of neutrinos off nucleons) was thus a crucial piece of evidence for the Weinberg–Salam–Glashow electroweak gauge theory—the scheme that has since come to be regarded as the "standard theory" for the unification of the electromagnetic and weak interactions. Sheldon Glashow and Steven Weinberg (both then at Harvard) and Abdus Salam (Imperial College, London and International Centre for Theoretical Physics, Trieste) shared the 1979 Nobel Prize in Physics for this work.

If the neutral weak boson (called Z^0, and expected to have a mass of about 90 GeV) does indeed exist, one should be able to see interference effects between electromagnetic and weak exchange mechanisms. Whenever a photon is exchanged, a Z^0 can be exchanged in the same reaction. The key experimental signature would be the observation of a forward–backward asymmetry due to the interference of the axial-vector part of the weak interaction with the purely vectorial electromagnetic interaction. (This should not be confused with parity violations observed in purely weak processes; these come from interference between the vector and axial-vector parts of the weak interaction alone.) At collision energies much below the Z^0 mass, however, the interference of the weak interaction with electromagnetic processes would be very small.

But PETRA, the e^+e^- colliding-beam storage ring at DESY (Hamburg), has for more than a year now been operating reliably with high luminosity at collision energies around 35 GeV. At this center-of-mass energy (more than a third of the supposed Z^0 mass), the Weinberg–Salam–Glashow theory pre-

distinguishable predictions for low-energy, low-momentum-transfer experiments. Several such theories propose multiple varieties of the Z^0.

These experiments are not the first observations of weak interference in electromagnetic processes. In 1978, a SLAC-Yale collaboration led by Richard Taylor and Charles Prescott (both at SLAC) observed a parity-violating asymmetry in the helicity dependence of the inelastic scattering of polarised electrons off deuterons and protons (PHYSICS TODAY, September 1978, page 17). But with a center-of-mass energy of less than 7 GeV (at the SLAC linac), the weak contribution was

The fundamental measurement in these experiments is the forward-backward asymmetry A, given by $A = (N^+ - N^-)/(N^+ + N^-)$, where $N^\pm$ is the number of $\mu^\pm$ emerging within 90° of the e^+ beam direction. In practice, the detectors cannot cover the entire 4π solid angle surrounding the collision region; spaces must be left open in the beam directions. One therefore measures the differential cross section $dN/d\cos\theta$ at various values of the scattering angle θ between the incident $e^\pm$ and emerging $\mu^\pm$. The overall asymmetry A is then determined by fitting a curve of the form predicted by W–S–G through the cross-section measurements and extrapolating to the full angular range.

The W–S–G theory predicts that the angular dependence of the differential cross section will have the general form $C_1(1 + \cos^2\theta) + C_2\cos\theta$. The second term, antisymmetric in θ, gives the forward–backward electroweak interference asymmetry. Its coefficient C_2 depends on the axial-vector coupling constant g_A of the Z^0 to the charged leptons, and on the Z^0 mass and the collision energy. The theory predicts that $g_A = ½$, with a much smaller vector coupling constant. With a Z^0 mass of about 90 GeV, inferred primarily from the neutrino experiments, one gets a predicted asymmetry A of about −9% for both the $\mu^+\mu^-$ and $\tau^+\tau^-$ final states at 35 GeV. Note that the sign of A is *negative*; each emerging lepton tends to follow the direction of the incident $e^\pm$ of the *opposite* sign. This will be the case so long as the center-of-mass energy is below the Z^0 mass.

This tendency of the emerging leptons to "remember" the directions of the incident charges is not *ipso facto* a violation of parity conservation. But the dominant electromagnetic reaction mechanism—a single-photon intermediate state—forbids such memory.

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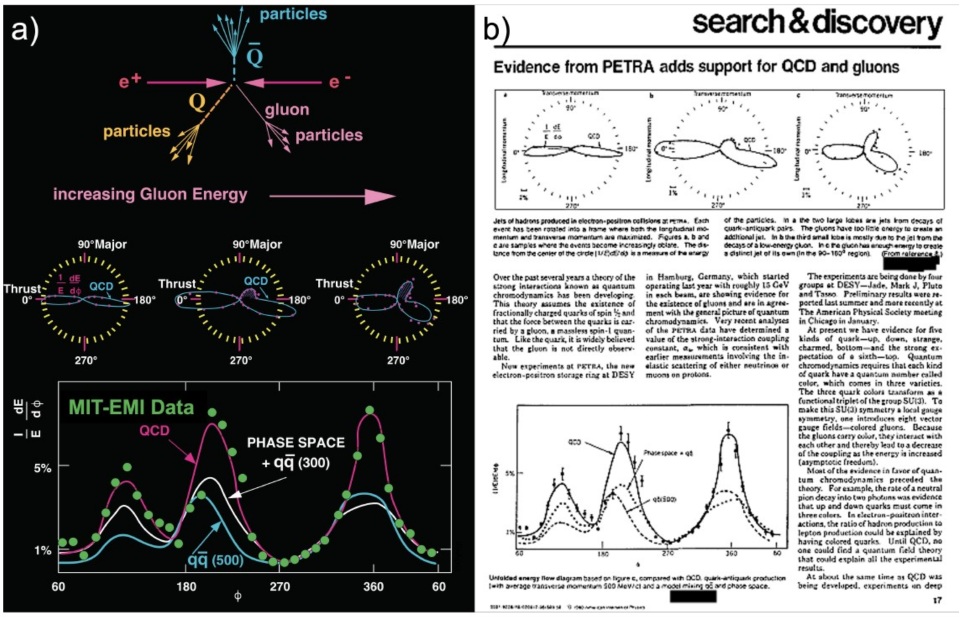
Figure 30. (**a**) Results on forward-backward asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ showing the contribution of the Z^0 boson. (**b**) Article in the August 1982 issue of *Physics Today* devoted to the observation of electroweak interference [26].

Most importantly, the experiment analyzed the properties of three-jet events, which led to the discovery of gluons [30]—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 (Figure 31a). MARK–J experiment was the first to report statistically significant evidence of the three-jet event pattern [31]. This observation was later confirmed by other PETRA experiments. This observation is the key in establishing the theory of the strong force [32], known as quantum chromodynamics or QCD (Figure 31b).



Evidence from PETRA adds support for QCD and gluons

Jets of hadrons produced in electron-positron collisions at PETRA. Each event has been rotated into a frame where both the longitudinal momentum and transverse momentum are maximized. Figures a, b and c are samples where the events become increasingly oblate. The distance from the center of the circle (1/E)dE/dφ is a measure of the energy of the particles. In a the two large lobes are jets from decays of quark-antiquark pairs. The gluons have too little energy to create an additional jet. In b the third small lobe is mostly due to the jet from the decays of a low-energy gluon. In c the gluon has enough energy to create a distinct jet of its own (in the 90–180° region). (From reference [redacted])

Over the past several years a theory of the strong interactions known as quantum chromodynamics has been developing. This theory assumes the existence of fractionally charged quarks of spin ½ and that the force between the quarks is carried by a gluon, a massless spin-1 quantum. Like the quark, it is widely believed that the gluon is not directly observable.

New experiments at PETRA, the new electron-positron storage ring at DESY in Hamburg, Germany, which started operating last year with roughly 15 GeV in each beam, are showing evidence for the existence of gluons and are in agreement with the general picture of quantum chromodynamics. Very recent analyses of the PETRA data have determined a value of the strong-interaction coupling constant, α_s, which is consistent with earlier measurements involving the inelastic scattering of either neutrinos or muons on protons.

The experiments are being done by four groups at DESY—Jade, Mark J, Pluto and Tasso. Preliminary results were reported last summer and more recently at The American Physical Society meeting in Chicago in January.

At present we have evidence for five kinds of quark—up, down, strange, charmed, bottom—and the strong expectation of a sixth—top. Quantum chromodynamics requires that each kind of quark have a quantum number called color, which comes in three varieties. The three quark colors transform as a functional triplet of the group SU(3). To make this SU(3) symmetry a local gauge symmetry, one introduces eight vector gauge fields—colored gluons. Because the gluons carry color, they interact with each other and thereby lead to a decrease of the coupling as the energy is increased (asymptotic freedom).

Most of the evidence in favor of quantum chromodynamics preceded the theory. For example, the rate of a neutral pion decay into two photons was evidence that up and down quarks must come in three colors. In electron-positron interactions, the ratio of hadron production to lepton production could be explained by having colored quarks. Until QCD, no one could find a quantum field theory that could explain all the experimental results.

At about the same time as QCD was being developed, experiments on deep

Unfolded energy flow diagram based on figure c, compared with QCD, quark-antiquark production (with average transverse momentum 500 MeV/c) and a model mixing $q\bar{q}$ and phase space. [redacted]

17

Figure 31. (**a**) Angular distribution of three-jet events showing bremsstrahlung emission of gluons. (**b**) Article in February 1980 issue of *Physics Today* showing the MARK–J results to the discovery of gluons [32].

5. L3 Experiment at CERN (1982–2003)

We spent 20 years, 1982–2003, building and operating the L3 experiment (Figure 32) 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 and muons. It was 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.

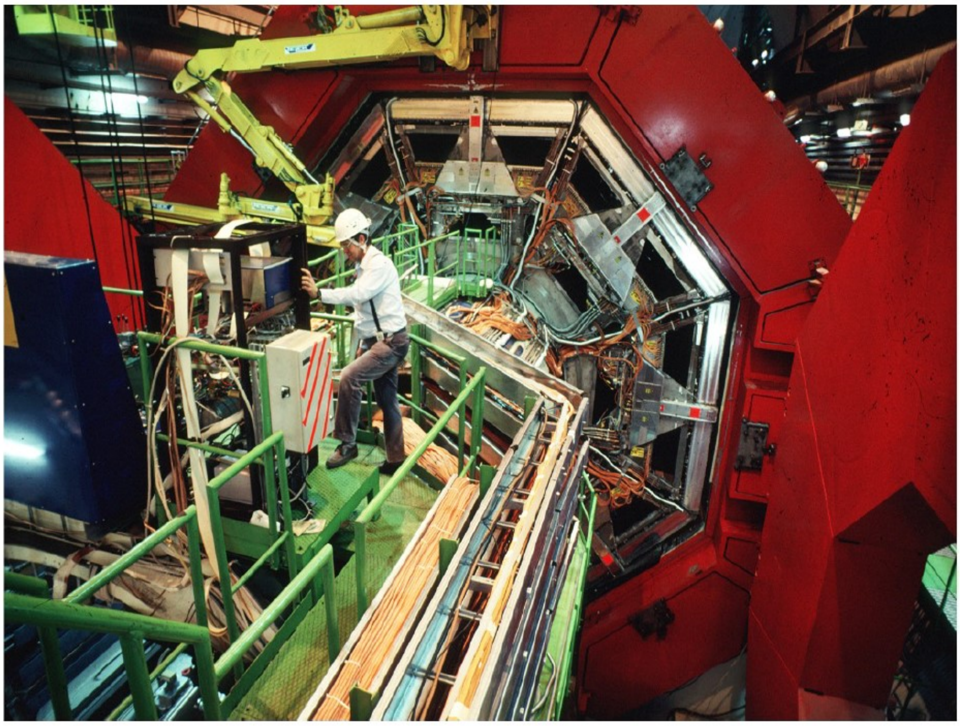


Figure 32. L3 detector at LEP.

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 a 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 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 ($\alpha(Q^2)$, $\sin\theta_W$, gauge couplings, ...); direct Higgs boson searches and Higgs mass constraints from precision electroweak measurements; QCD tests (evolution of the strong 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 models based on exotic particles.

We have published over 300 papers in Physics Letters. Our most notable results include studies of the energy evolution of the strong [33] (Figure 33a) and electromagnetic [34] (Figure 33b) coupling constants, as well as the model-independent determination of the number of light neutrinos [35] (Figure 34). All the results agreed with the standard model [36]. 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 more, obviously. After 20 years of precision measurements at LEP, we have found that the electron still has no measurable size, its radius is less than 10^{-17} centimeters.

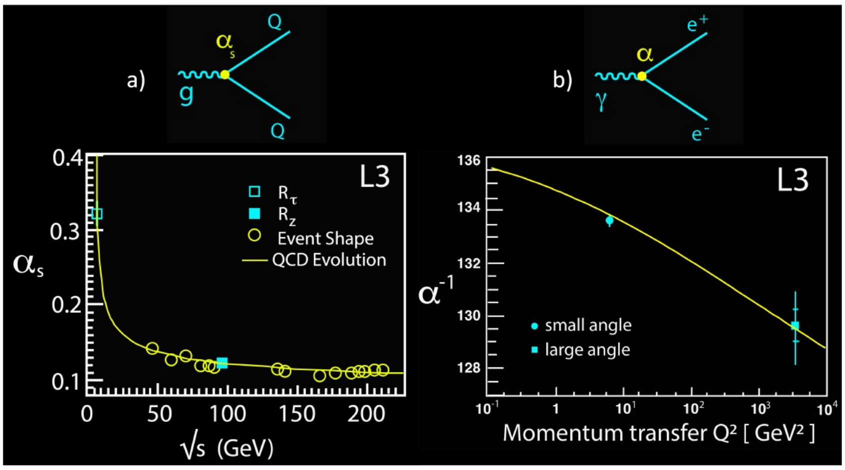


Figure 33. L3 experimental results: (**a**) dependence of the strong coupling constant, α_s, on center-of-mass energy $\sqrt{s}$; (**b**) dependence of the electromagnetic fine structure constant, α, on momentum transfer Q^2.

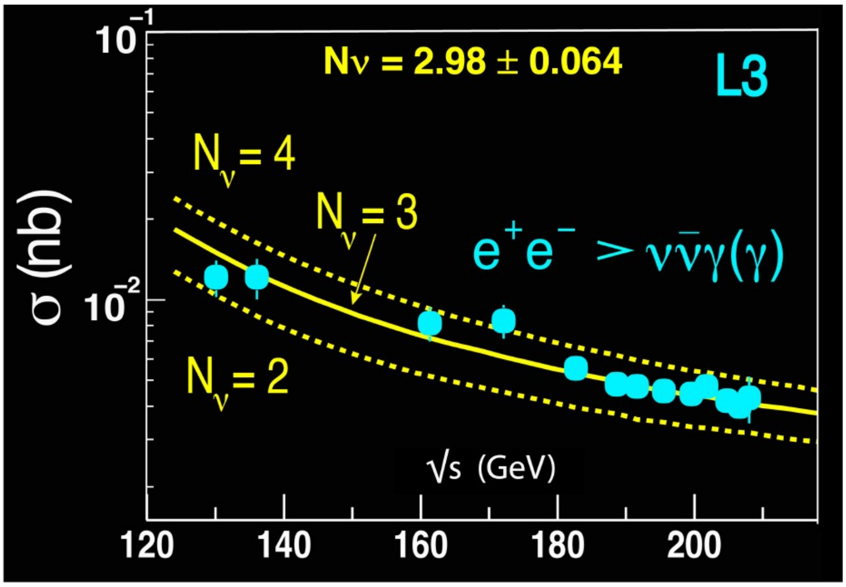


Figure 34. L3 experimental results: model independent determination of the number of light neutrino species using the reaction $e + e^- \to \nu\bar{\nu}\gamma$.

6. Alpha Magnetic Spectrometer (AMS)

The conceptual idea of AMS came to my mind when I was thinking about matter-antimatter asymmetry in the universe and related theoretical explanations. If the theory is wrong and antimatter exists in space then it can be detected experimentally. Despite having no prior experience of doing experiments in space, I decided that this is what I should do next: to look for antimatter, to study the origin of cosmic rays with a precision magnetic spectrometer in space. This is the origin of AMS.

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 (Figure 35) consists of a permanent magnet with $1.4\,\mathrm{kG}$ 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 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.

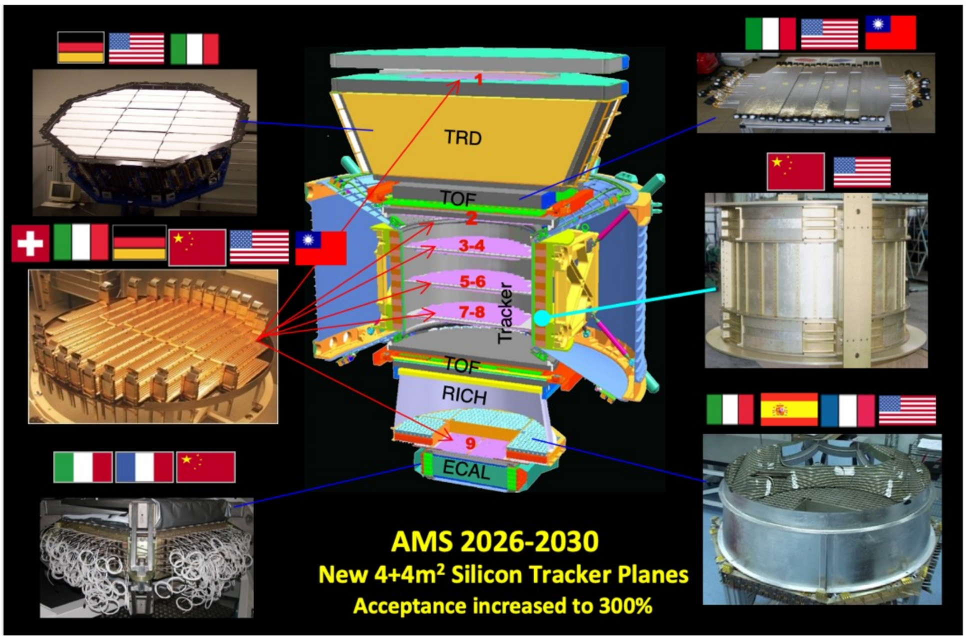


Figure 35. Layout of the AMS experiment showing the countries which participated in the construction of individual detectors.

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 [37], AMS was installed on the International Space Station, ISS, (Figure 36) 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 [38]. 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, $4 + 4\,\mathrm{m}^2$ silicon layer on top of the detector to increase the acceptance to 300%.

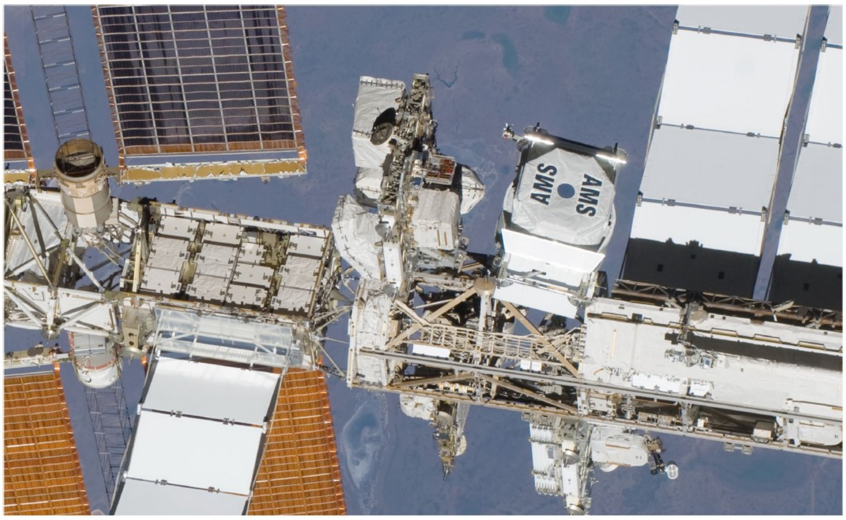


Figure 36. AMS on the International Space Station.

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 $\sim$25 to $\sim$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 $\sim$800 GeV. Significance of this measurement is 4.8σ (Figure 37). 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 (Figures 37 and 38a). With more data collected through 2030 with the upgraded detector (Figure 38b) we will be able to provide definitive answers concerning the physics nature of the positron source term.

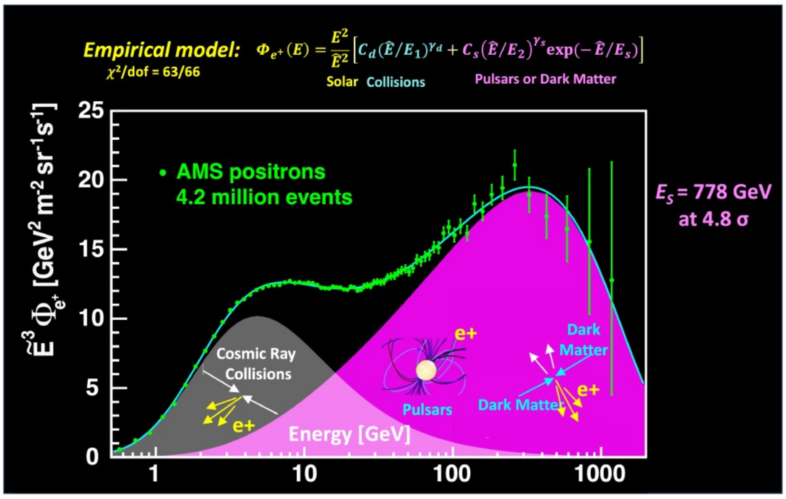


Figure 37. The positron flux is the sum of low energy part from cosmic ray collisions plus a high-energy term from pulsars or dark matter with a cutoff energy. The empirical formula (shown on top), which includes both cosmic ray collisions and new source term with an exponential cutoff is represented by a light blue line.

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 (Figure 39). 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.

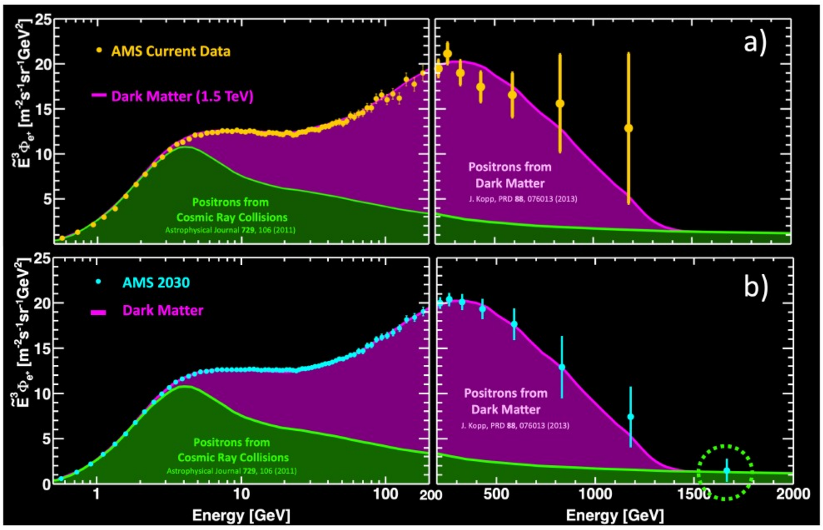


Figure 38. (**a**) Comparison of the AMS data with predictions of a dark matter model with $M_{\mathrm{DM}} = 1.5\,\mathrm{TeV}$. (**b**) The projection of AMS measurements to 2030 shows that we will not only improve the accuracy of current measurements but also provide a data point above the dark matter mass, where the contribution of cosmic ray collisions dominates.

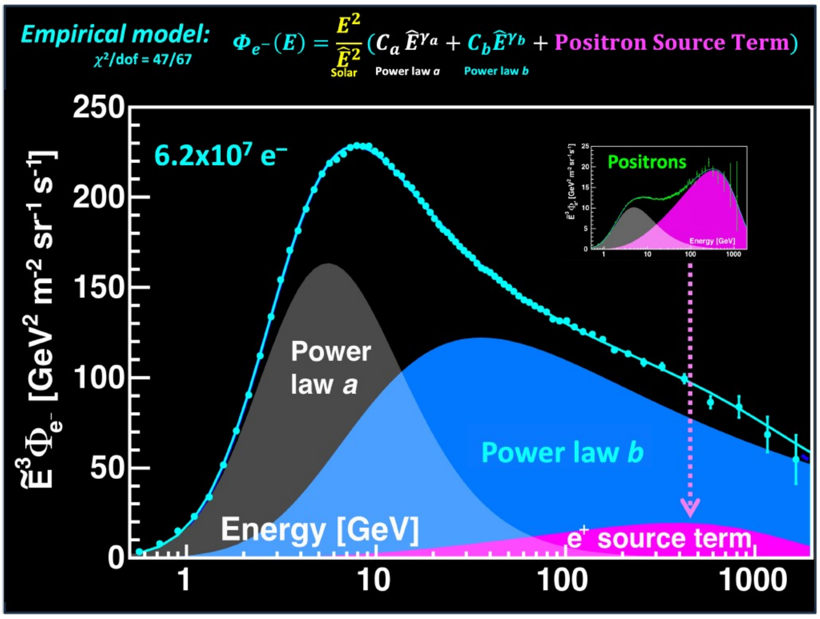


Figure 39. The electron spectrum with the fit results showing that the charge symmetric measured positron source term (from Figure 37) is needed to describe the behavior of the spectrum at high energies. The empirical formula (shown on top), which includes two power law functions and the positron source term with an exponential cutoff is represented by a light blue line.

For antiprotons we found that the spectrum is identical to the positron spectrum above 60 GeV (Figure 40). Indeed the ratio of the positron-to-antiproton fluxes above 60 GeV was determined to be $1.98 \pm 0.03\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})$. 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.

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 Figures 41 and 42). These phenomena were not predicted.

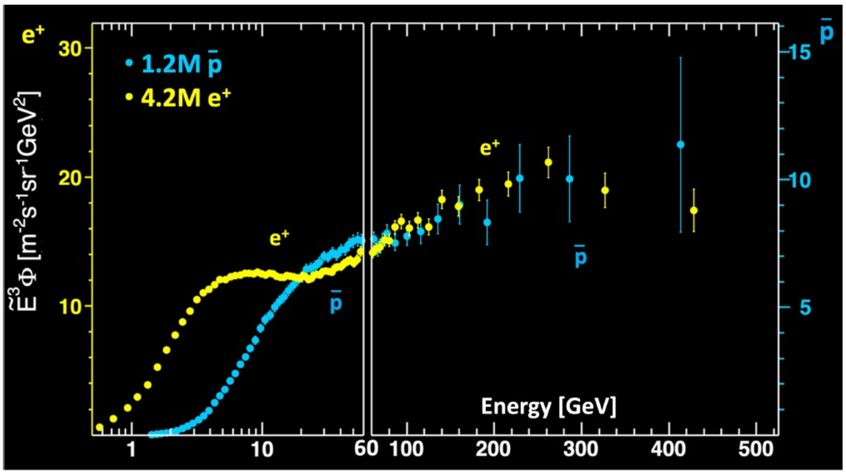


Figure 40. The antiproton spectrum (blue data points, right axis) and the positron spectrum (yellow data points, left axis) show identical behavior above 60 GeV.

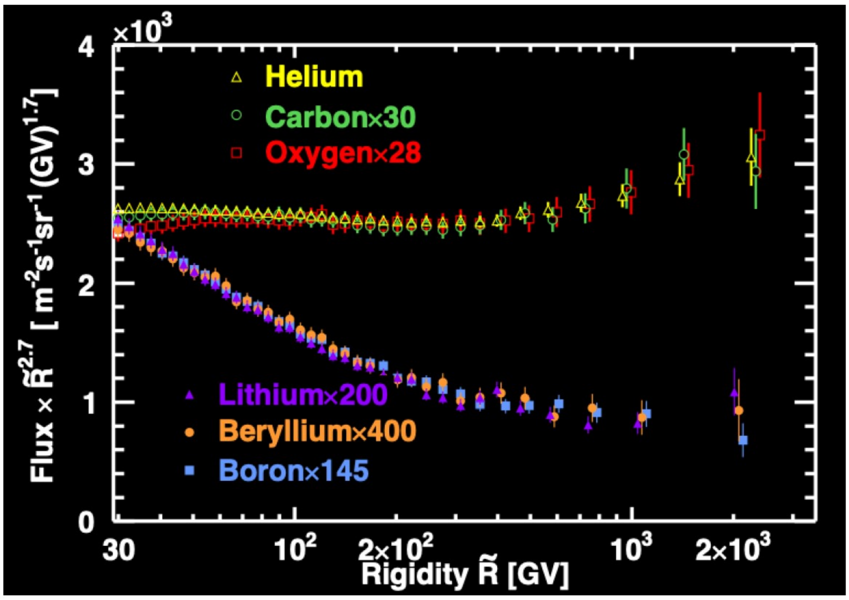


Figure 41. Class of light nuclei: $2 \le Z \le 8$ He-C-O primaries compared with Li-Be-B secondaries.

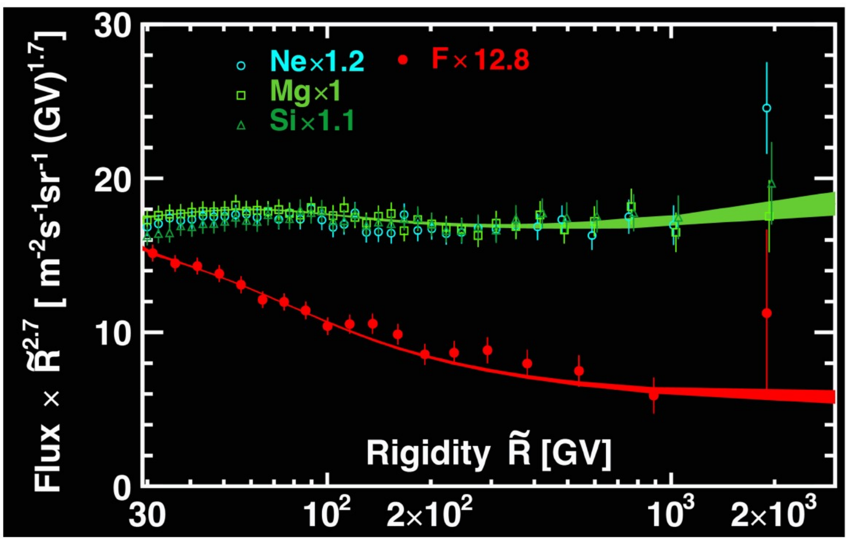


Figure 42. Class of heavier nuclei: $9 \le Z \le 14$ Ne-Mg-Si primaries compared with F secondaries.

Surprisingly, we found that any cosmic nuclei flux can be described as a linear combination of the corresponding primary and secondary fluxes (Figure 43). 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.

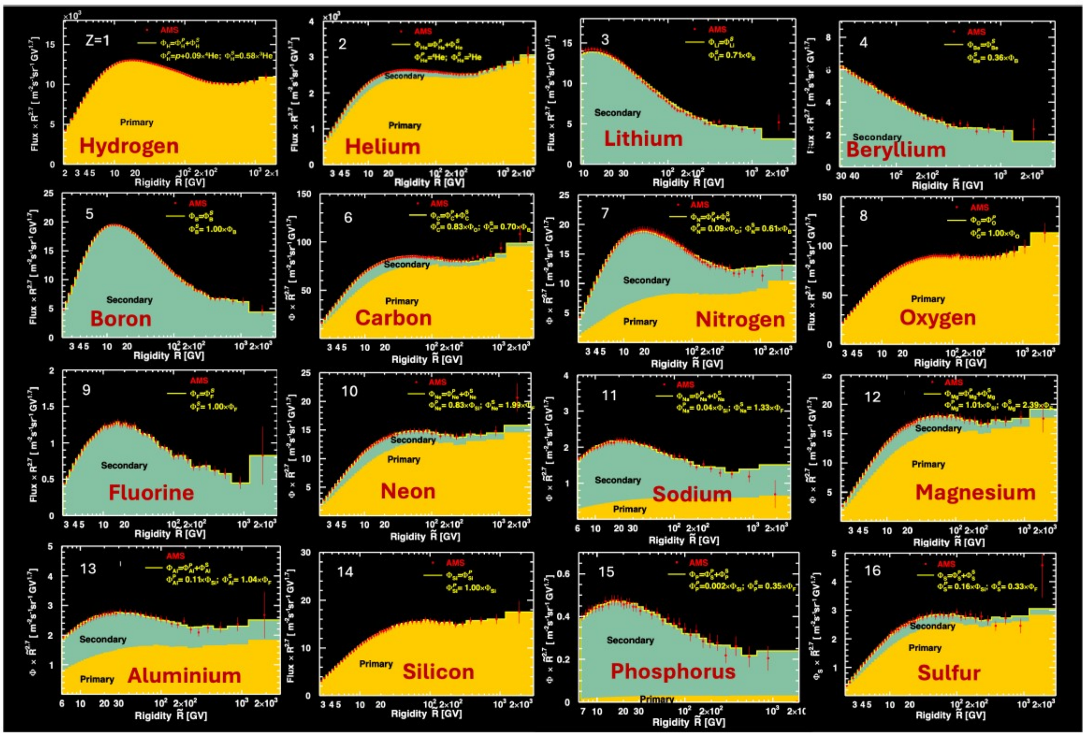


Figure 43. The fluxes of all cosmic nuclei from $Z = 1$ to $Z = 16$. In each plot the contributions of the primary and secondary components are indicated by the yellow and green shading, respectively.

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 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.

Acknowledgments

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Conflicts of Interest

The author declares no conflict of interest.

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