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

Sept. 23, 2024

S. Ting

Encounters with Particle Physics

First Experiment: Measuring the size of electrons

QED requires that electrons have no measurable radius

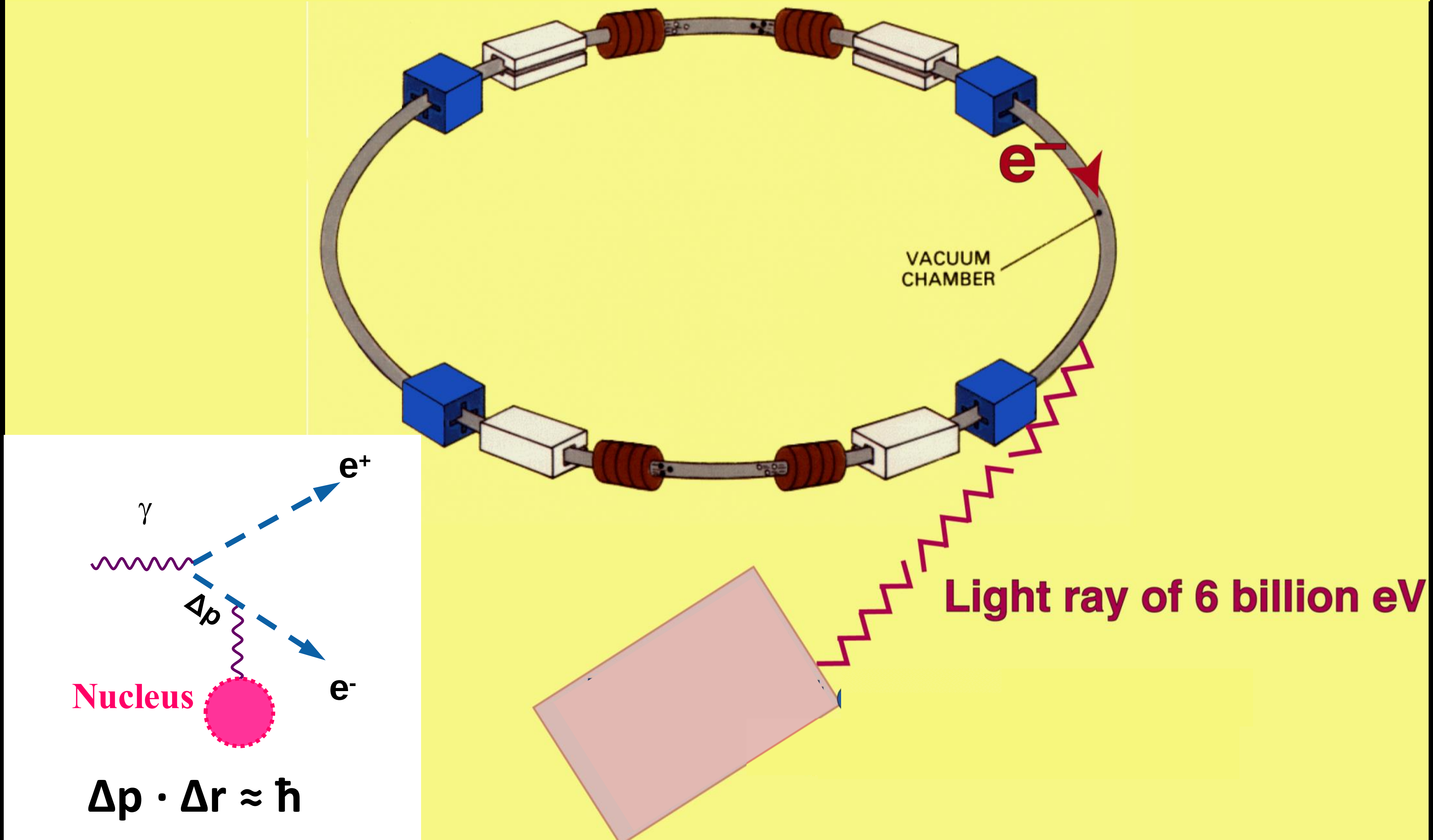
(Feynman, Schwinger, Tomonaga - 1948)

The theory agreed well with all experiments until a 6 GeV electron accelerator provided a most sensitive measurement of the size of the electron.

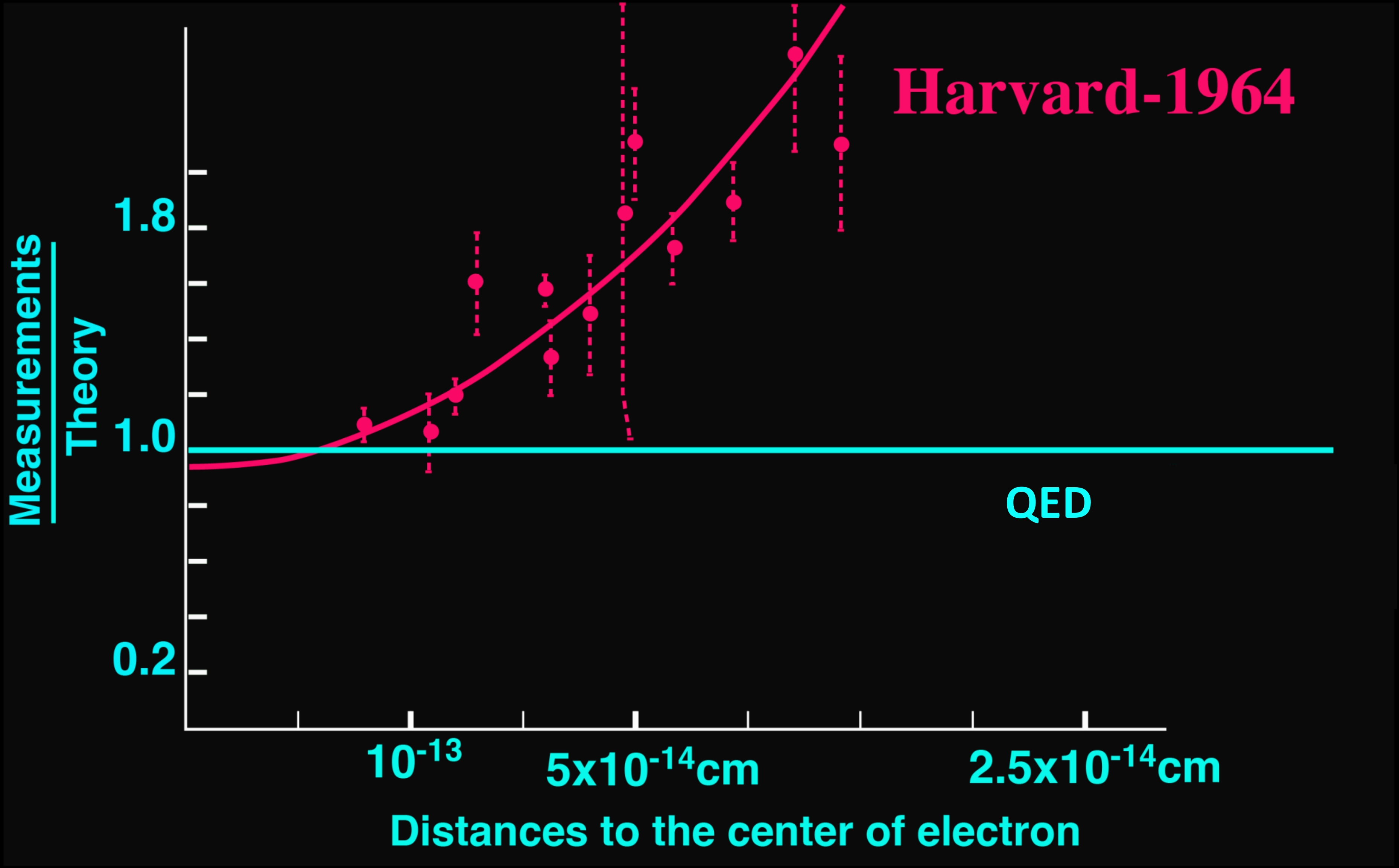
The Harvard experiment was done by the world's leading experts in the field who had spent many years to develop the technology.

Harvard experiment measuring the size of the electron at the Cambridge Electron Accelerator

Circumference 300 meters



$$\Delta p \cdot \Delta r \approx \hbar$$



This data shows that the electron has a radius of ~ 10^{-13} to 10^{-14} cm.

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 the experiment with an independent method

At that time, I knew nothing about electron physics,
so I received no support in the U.S.

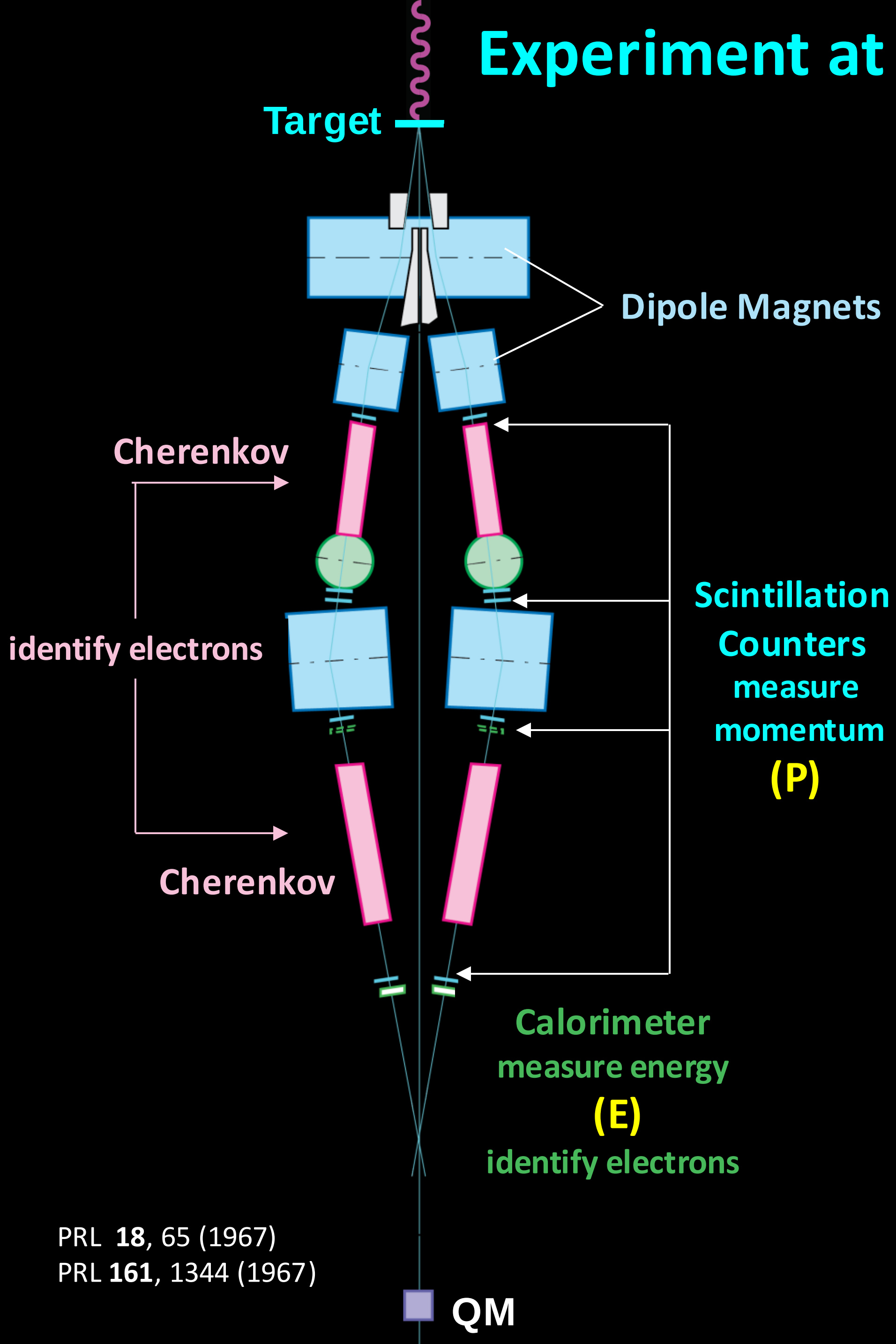
In 1965, I decided to leave Columbia University and move to
the newly built 6 billion electron-Volt electron accelerator (DESY)
in Hamburg, Germany
to re-measure the size of the electron

It was during this time at Columbia that I went to
the Brandeis Summer School for Theoretical Physics
and met with Luciano Maiani and Nicola Cabibbo

Luciano and I
in New York
and Columbia
University

1965-1972: First set of experiments at DESY

Experiment at DESY measuring electron-positron pairs (1966)



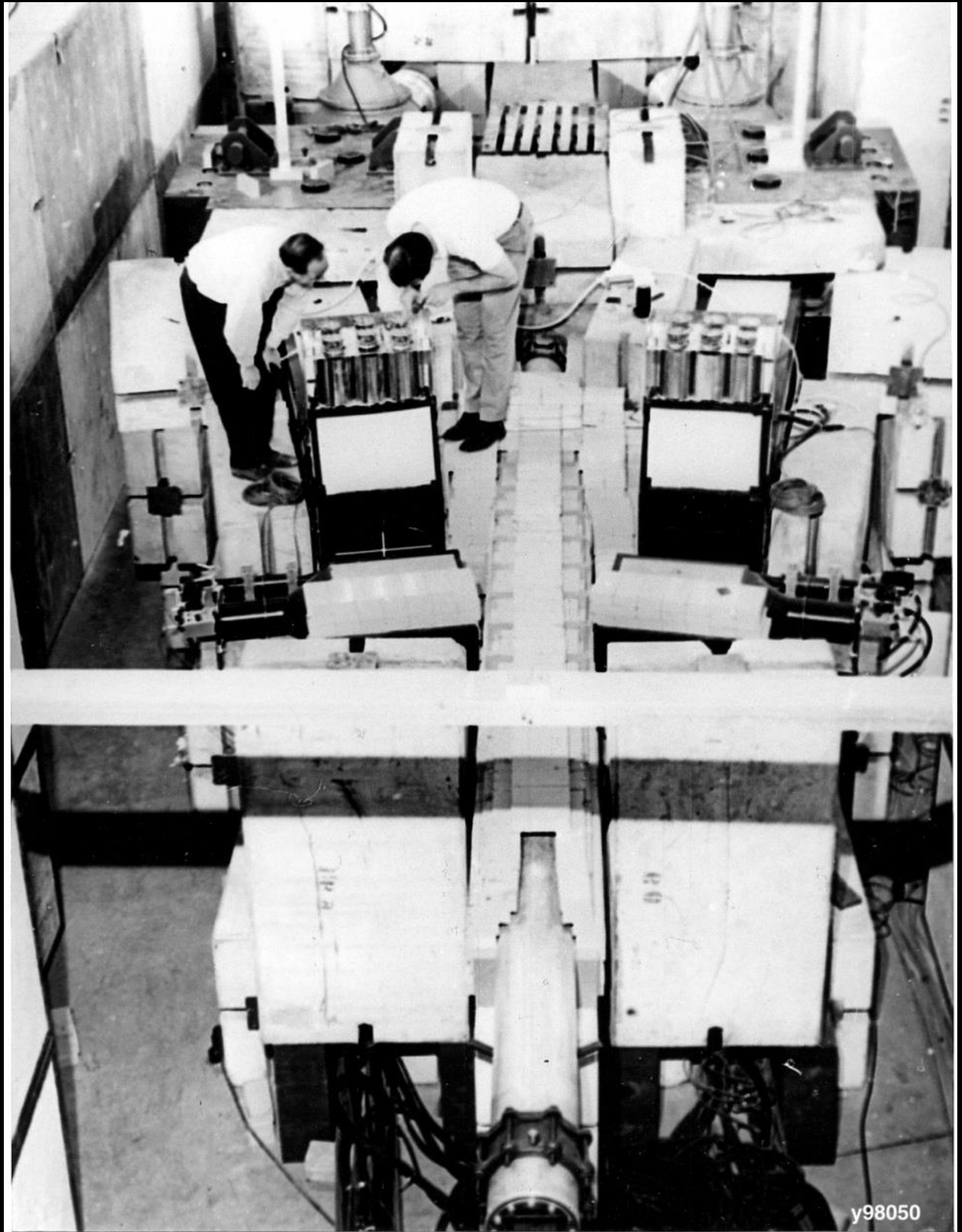
PRL **18**, 65 (1967)
PRL **161**, 1344 (1967)

Unique features

1. Using Dipoles magnets and counters to measure the momentum (P).
2. Using 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.
3. Using calorimeters to measure the energy (E).
4. None of the detectors see the target so they are not exposed to neutrons or gamma-rays backgrounds.
5. The acceptance is defined by counters,
   not by the aperture of the magnet.
6. To reject large pion background, require E=P

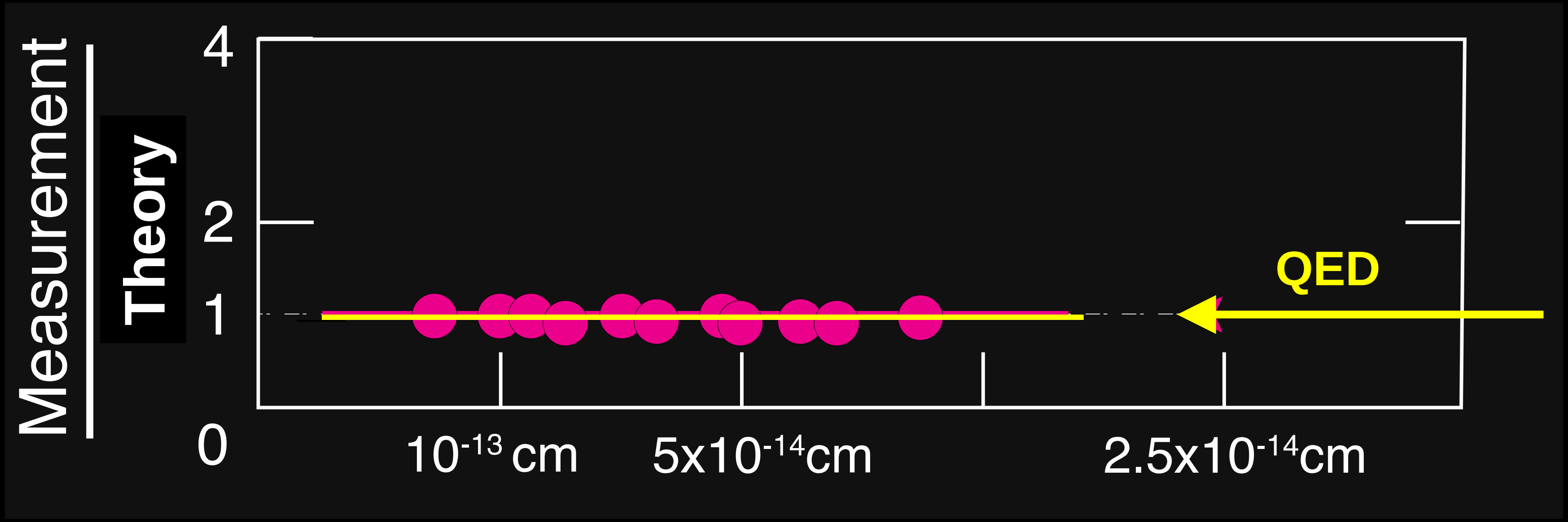
Experiment at DESY measuring electron-positron pairs (1966)

The development of
this type of
pair spectrometer
eventually led to the
J-Particle experiment.


y98050

In 1966, after 8 months, our group completed the experiment at DESY and discovered that:

The electron indeed has no measurable size: Radius < 10^{-14} cm

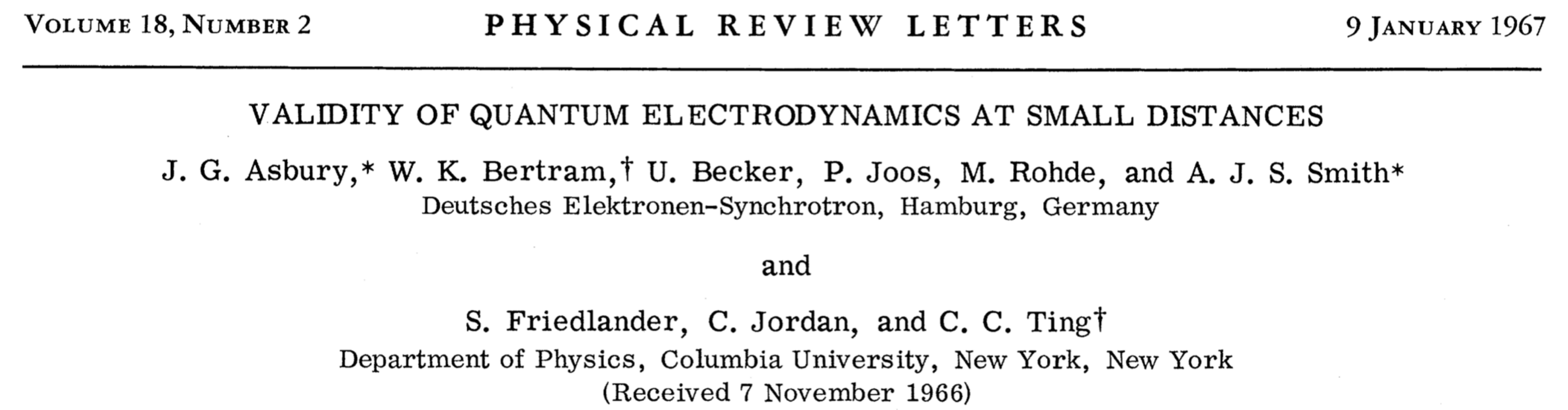


Distance to the center of the electron

This result 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.

First Publication



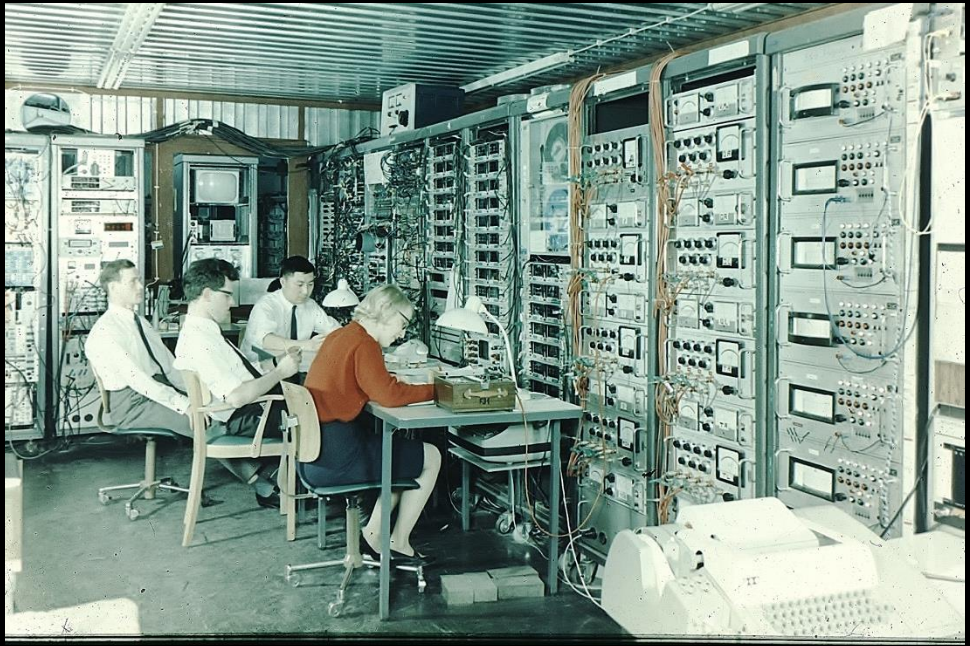
VOLUME 18, NUMBER 2 PHYSICAL REVIEW LETTERS 9 JANUARY 1967

VALIDITY OF QUANTUM ELECTRODYNAMICS AT SMALL DISTANCES

J. G. Asbury,* W. K. Bertram,† U. Becker, P. Joos, M. Rohde, and A. J. S. Smith*
Deutsches Elektronen-Synchrotron, Hamburg, Germany

and

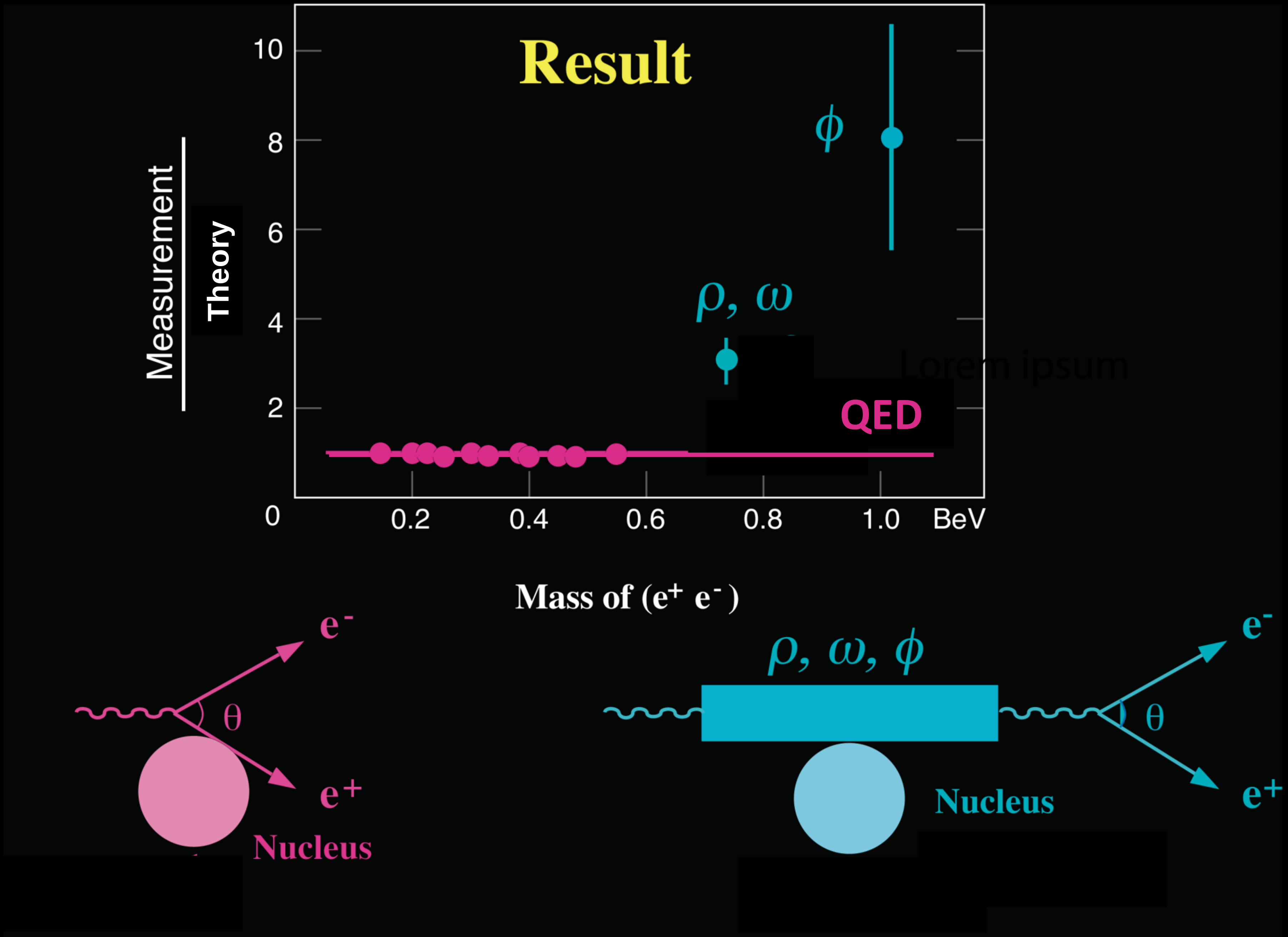
S. Friedlander, C. Jordan, and C. C. Ting†
Department of Physics, Columbia University, New York, New York
(Received 7 November 1966)



Early Control room at DESY
with Miss I. Schulz,
Graduate Students U. Becker, and M Rohde.

The group was solely supported by DESY

Experimental Results on Photons and Heavy Photons



Second Experiment: Photons and Heavy Photons

γ ∿∿∿ $m = 0$

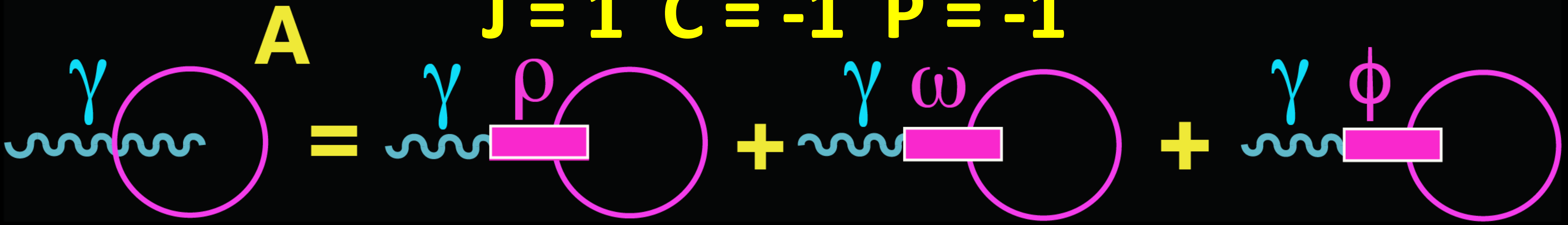
$\rho \rightarrow \pi\pi$ $m = 760$ MeV

$\omega \rightarrow \pi\pi\pi$ $m = 785$ MeV

$\phi \rightarrow kk$ $m = 1020$ MeV

Photons and Heavy Photons have the same quantum numbers

$J = 1 \quad C = -1 \quad P = -1$



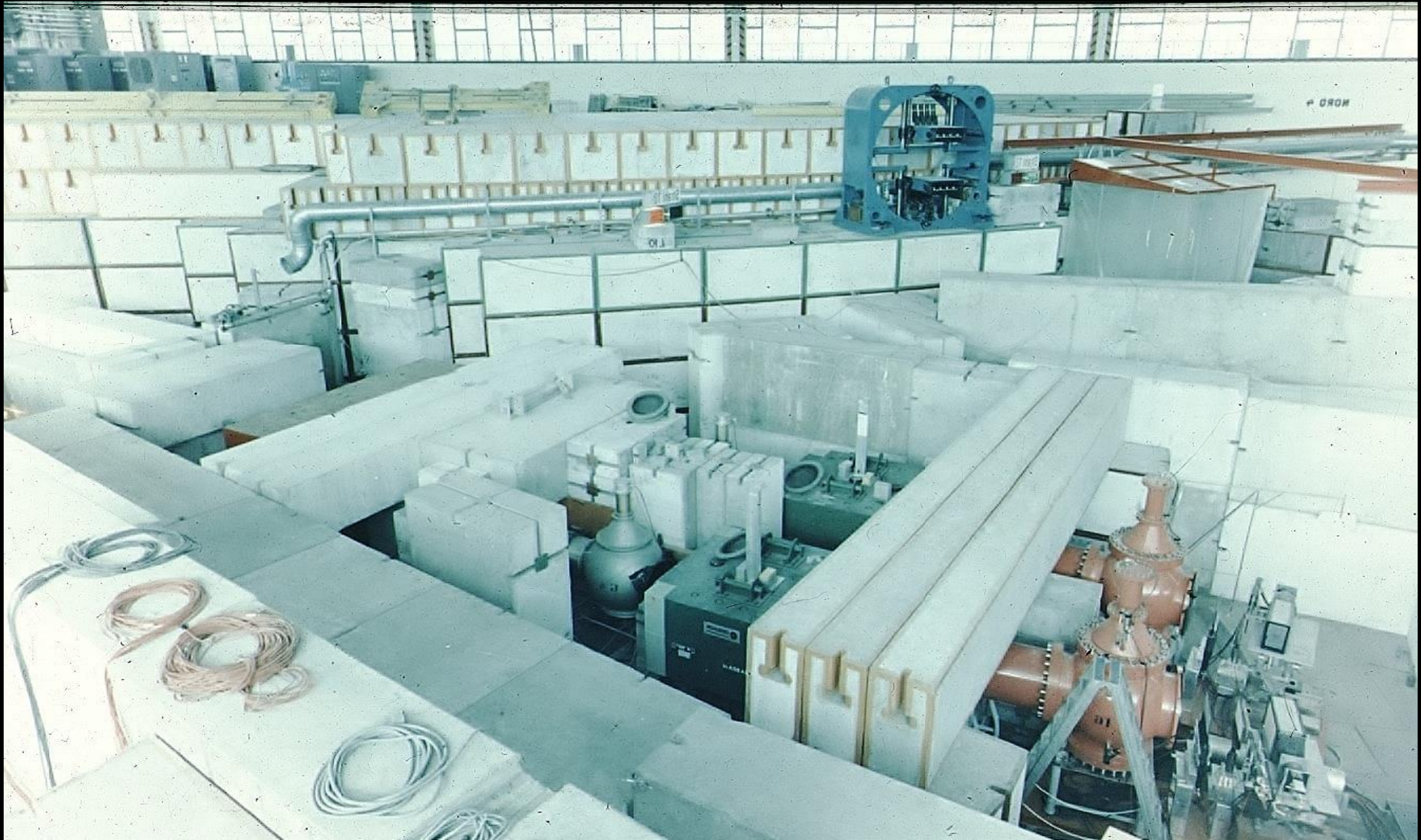
$$J_\mu(x) = -\left[\frac{m^2{}_\rho}{2\gamma_\rho}\rho_\mu(x) + \frac{m^2{}_\omega}{2\gamma_\omega}\,\omega_\mu(x) + \frac{m^2{}_\phi}{2\gamma_\phi}\,\phi_\mu(x)\right]$$

This is known as the Vector Dominance Model

Experimental question: what is the relationship between Photons & Heavy Photons?

MIT Heavy Photon Experiments at DESY

with major improvements in coordinate and momentum resolution and in particle identification

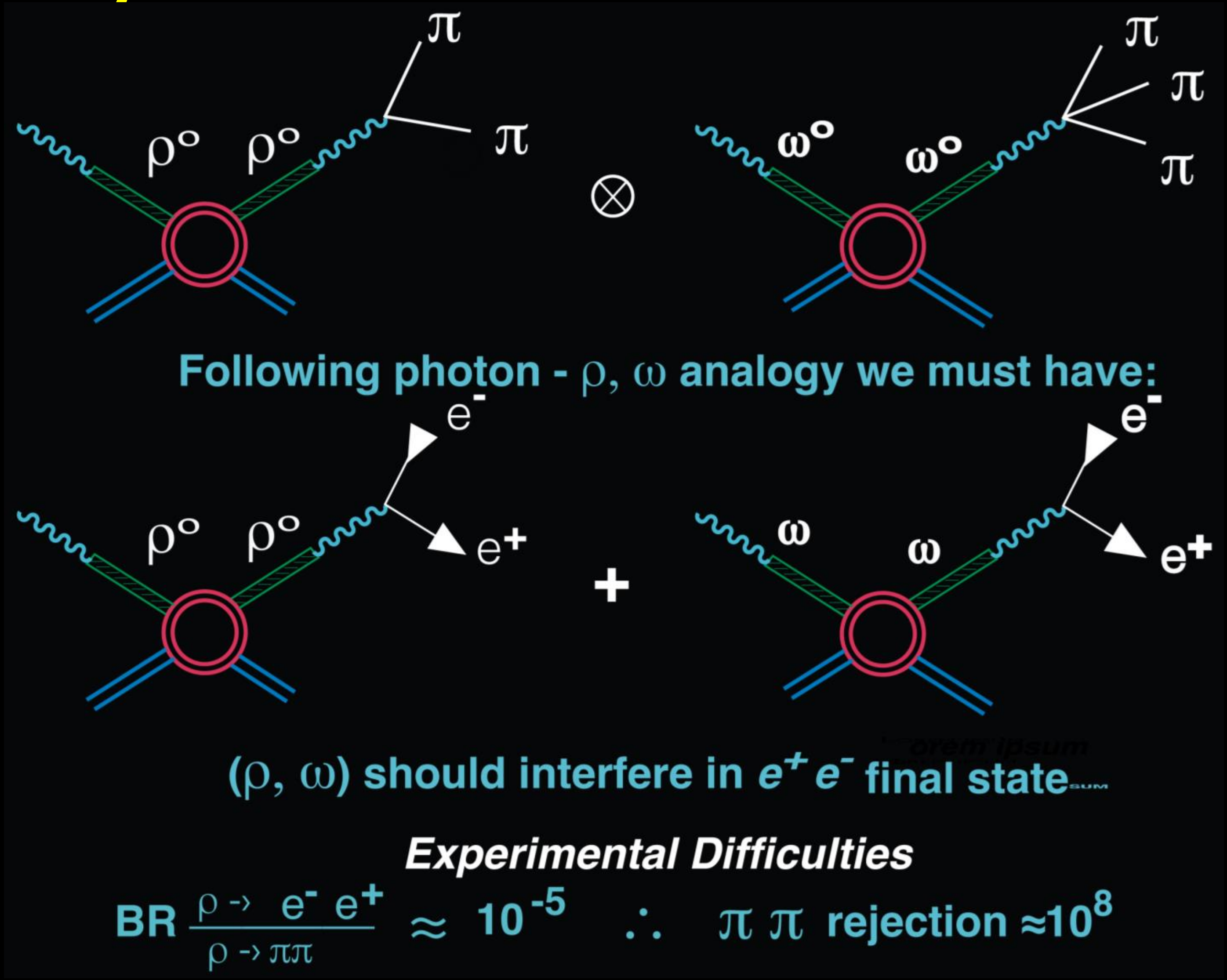


Observation of Coherent interference Pattern between ρ and ω Decays

(P.R.L. 25, 1373 1970)

ρ is a 2π resonance, ω is a 3π resonance

they do not interfere in the π final state



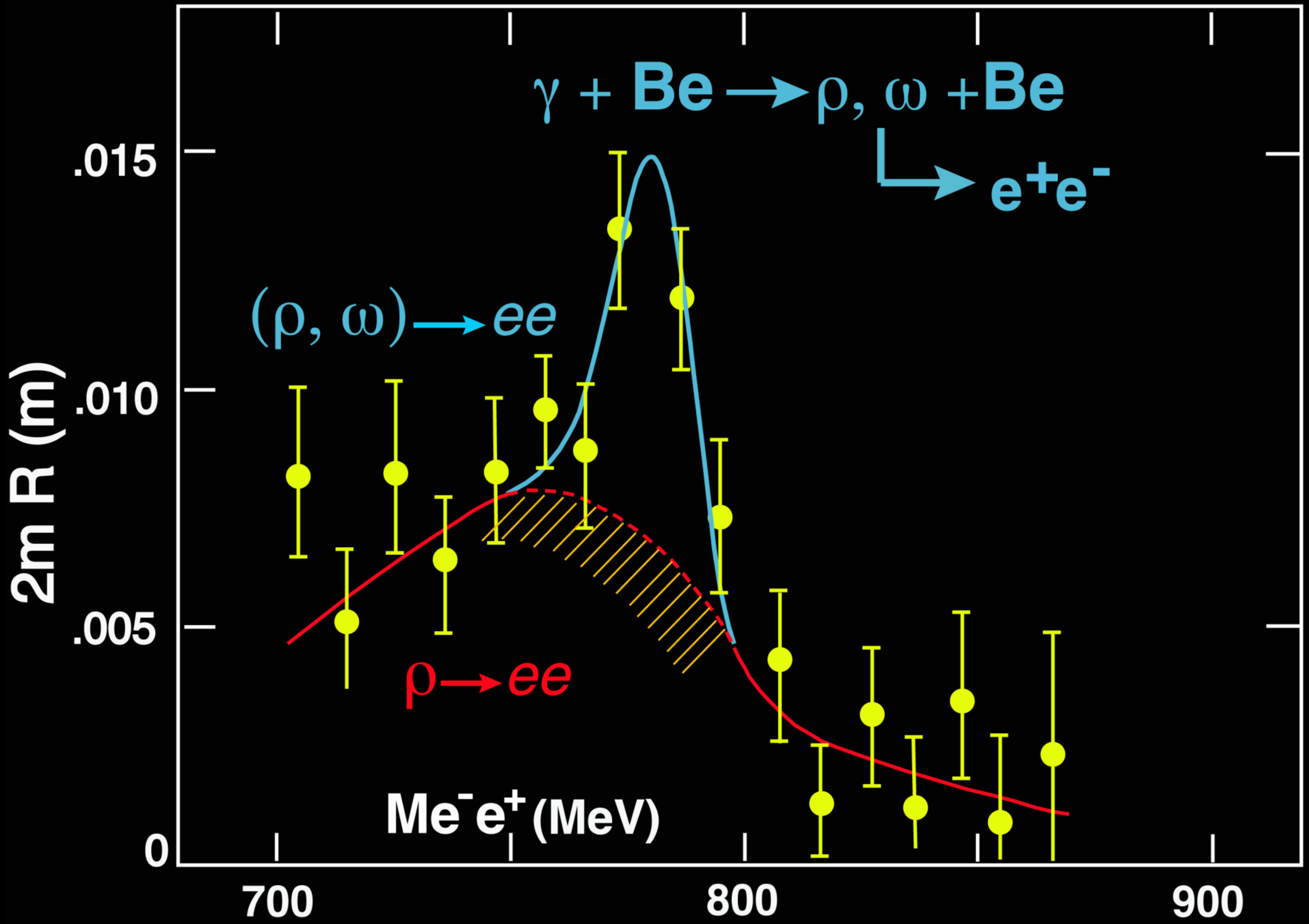
Following photon - ρ, ω analogy we must have:

(ρ, ω) should interfere in $e^+ e^-$ final state

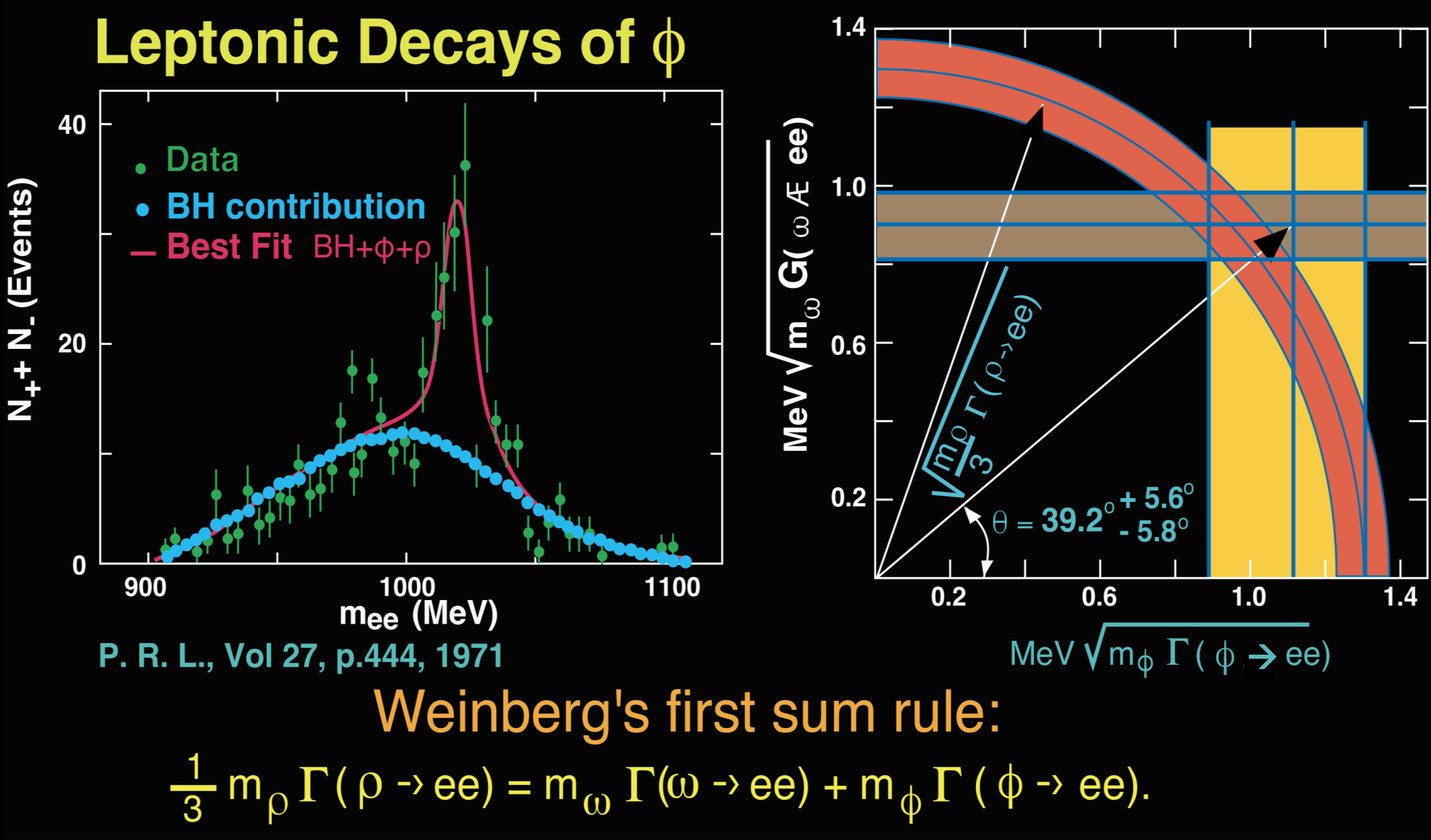
Experimental Difficulties

BR $\frac{\rho \to e^- e^+}{\rho \to \pi\pi} \approx 10^{-5}$ ∴ $\pi\pi$ rejection $\approx 10^8$

Observation of Coherent interference Pattern between ρ and ω Decays



Verification of Weinberg’s first sum rule



Leptonic Decays of φ

P. R. L., Vol 27, p.444, 1971

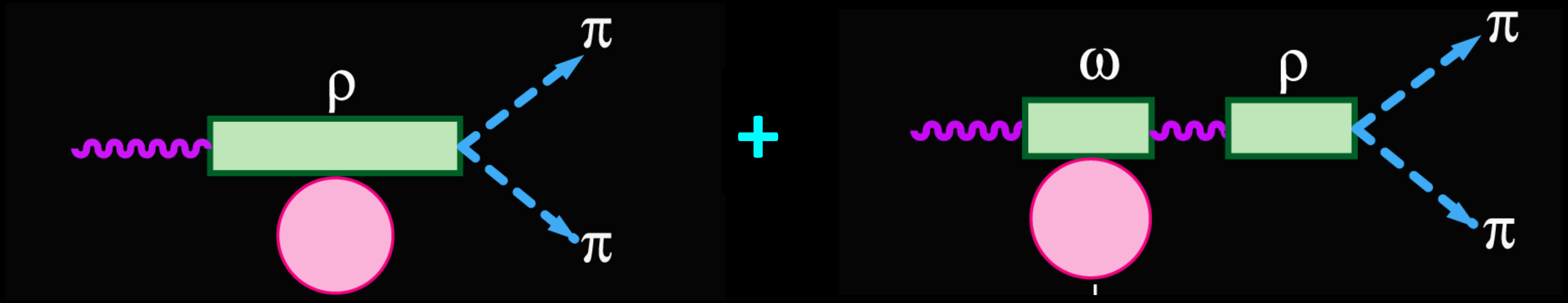
Weinberg's first sum rule:

$$\frac{1}{3} m_\rho \Gamma(\rho \to ee) = m_\omega \Gamma(\omega \to ee) + m_\phi \Gamma(\phi \to ee).$$

Observation of Forbidden $\omega \rightarrow 2\pi$ Decays

No Interference

Interference



S. L. Glashow, P.R.L. 7, 469 (1961),

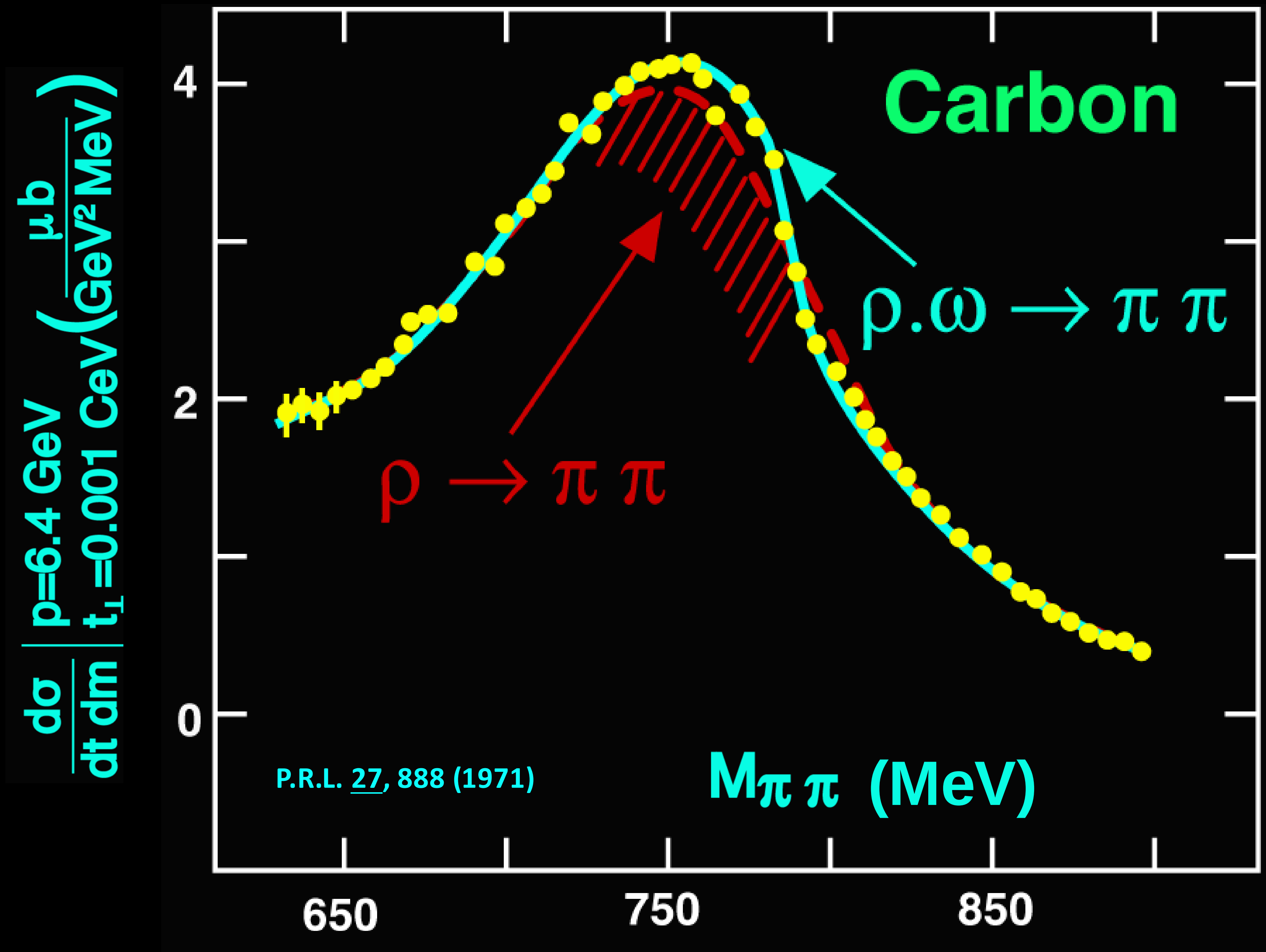
J. Bernstein and G. Feinberg, Nuovo Cimento 25, 1343

M. Gordin, P.L. 30B, 347 (1969)

R. G. Sachs, P.R. D2, 133 + …

J. Steinberger, P.R.L. 12, 517 (1964), **BR< 0.1%**

Observation of Forbidden $\omega \to 2\pi$ Decays



P.R.L. 27, 888 (1971)

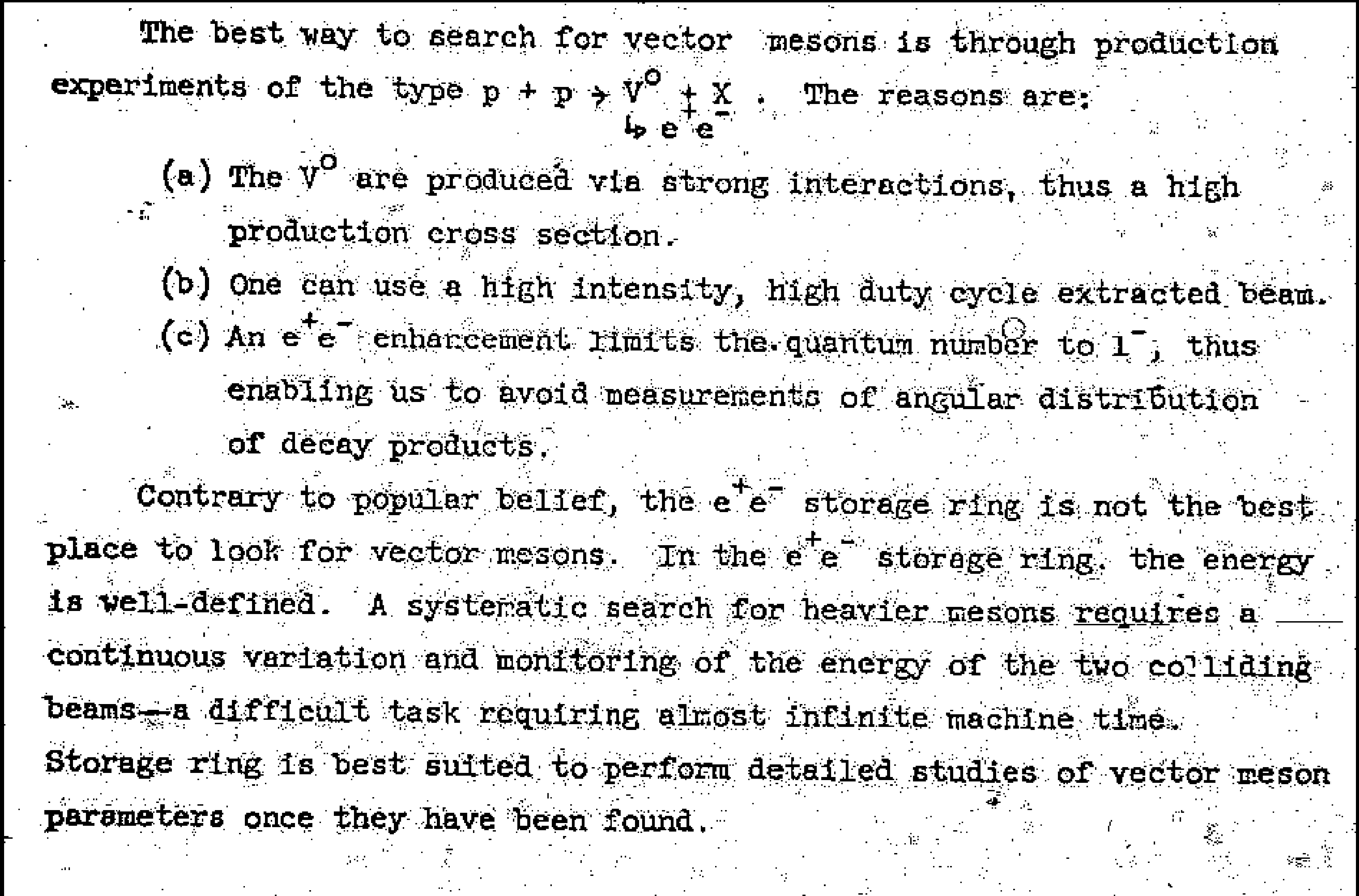
Third Experiment: Discovery of the J particle

We learned that photons and heavy photons
are almost the same.
They transform into each other.

Question: Why should there be only three heavy photons
all at mass ~ 1 GeV?

To go to higher mass we moved to a higher energy accelerator

Page 4 of Proposal AGS E598 (1972) to Brookhaven National Lab



The best way to search for vector mesons is through production experiments of the type $p + p \to \underset{\hookrightarrow e^+e^-}{V^0} + X$. The reasons are:

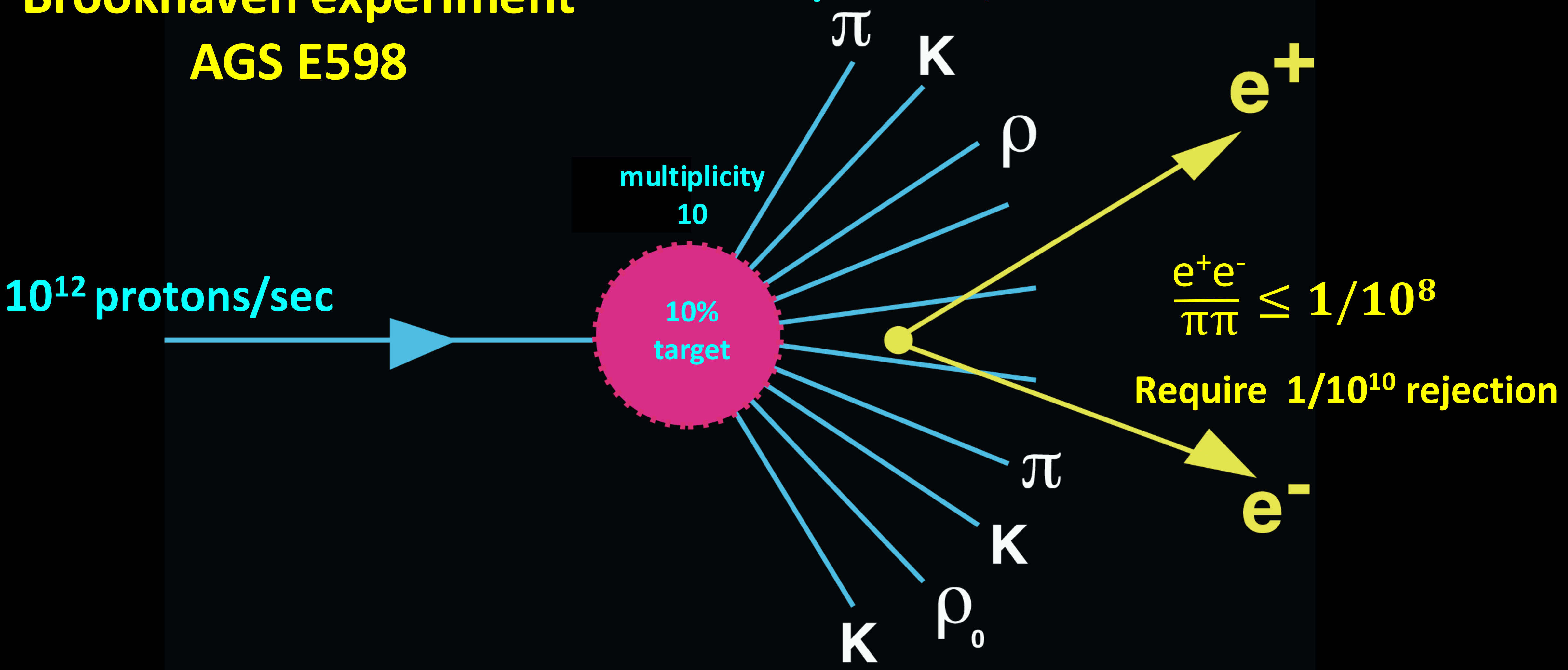
(a) The V^0 are produced via strong interactions, thus a high production cross section.

(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 <u>requires</u> 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.

Brookhaven experiment
AGS E598



$$\frac{e^+e^-}{\pi\pi} \leq 1/10^8$$

Require $1/10^{10}$ rejection

During a rainstorm over **Rome** there are 10 billion rain drops/sec.

Try to find the one drop that is red.

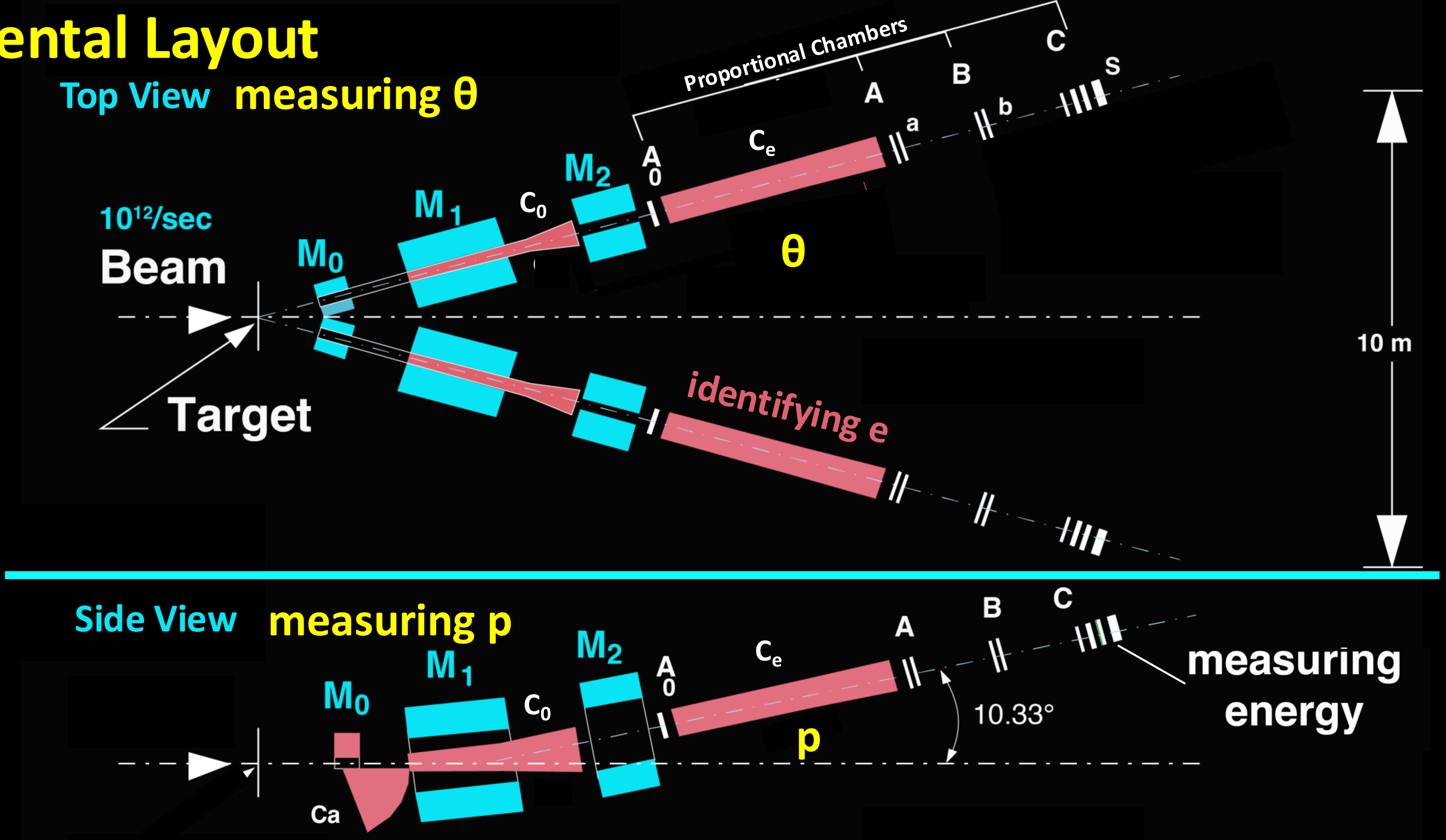
This experiment was not popular with the physics community:

(1) Most physicists believed that the search for heavy photons was not the most interesting research subject

(2) Few 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

Experimental Layout



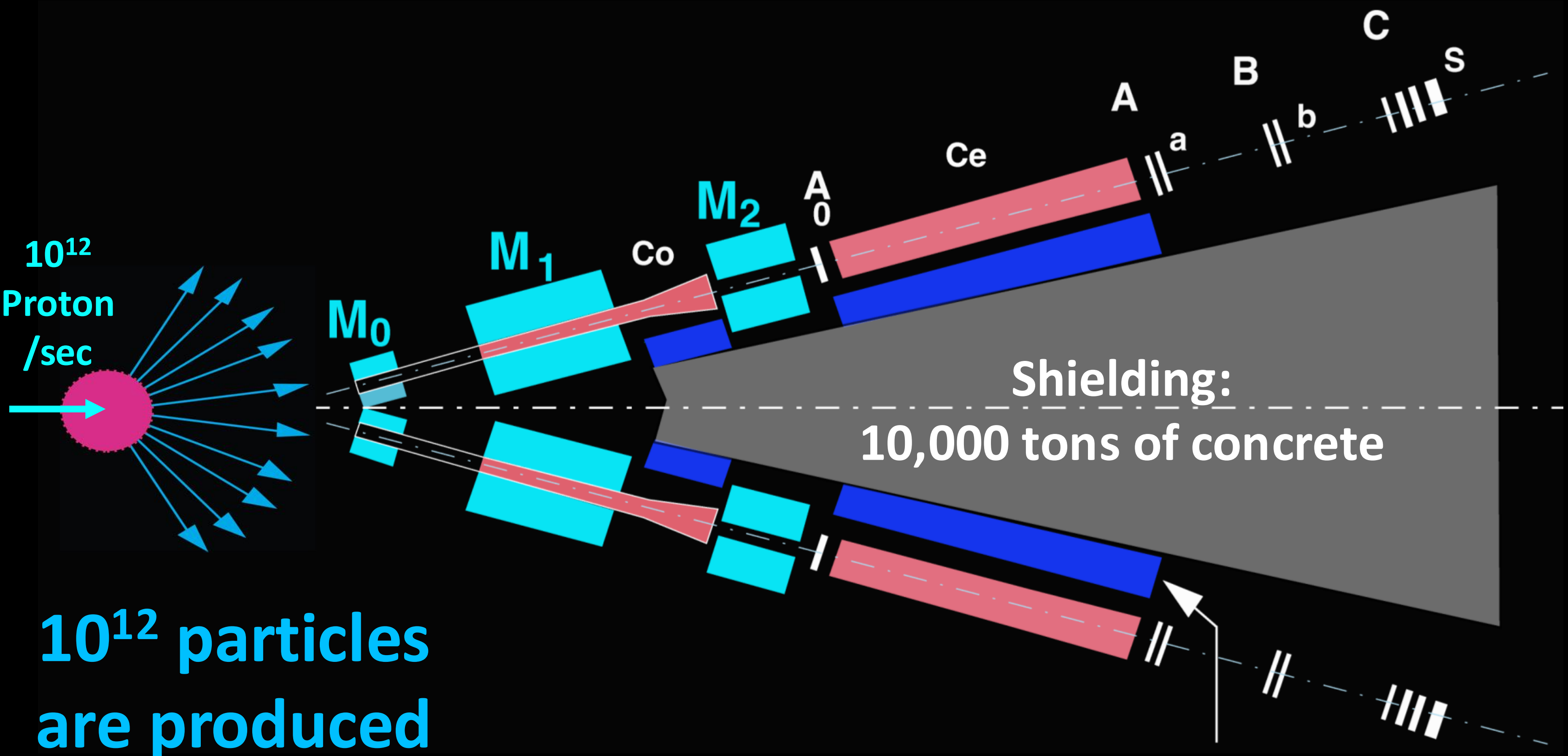
M_0, M_1, and M_2 are dipole magnets; A_0, A, B, and C are proportional chambers; a and b are counters; C_a, C_0, and C_e are gas Cerenkov counters, S are shower counters.

M_0 and C_a measure $\pi^0 \rightarrow e^{\pm}$ and provide calibration of the detector with $e^{\pm}$

The detector follows the design of the first experiment at DESY

Brookhaven e^+e^- magnetic pair spectrometer

Radiation Protection

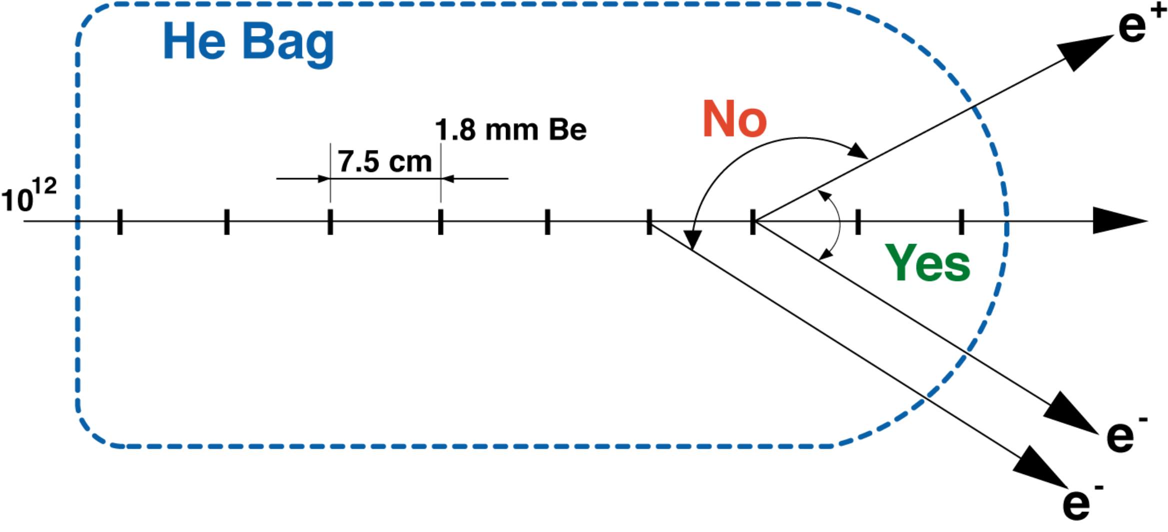


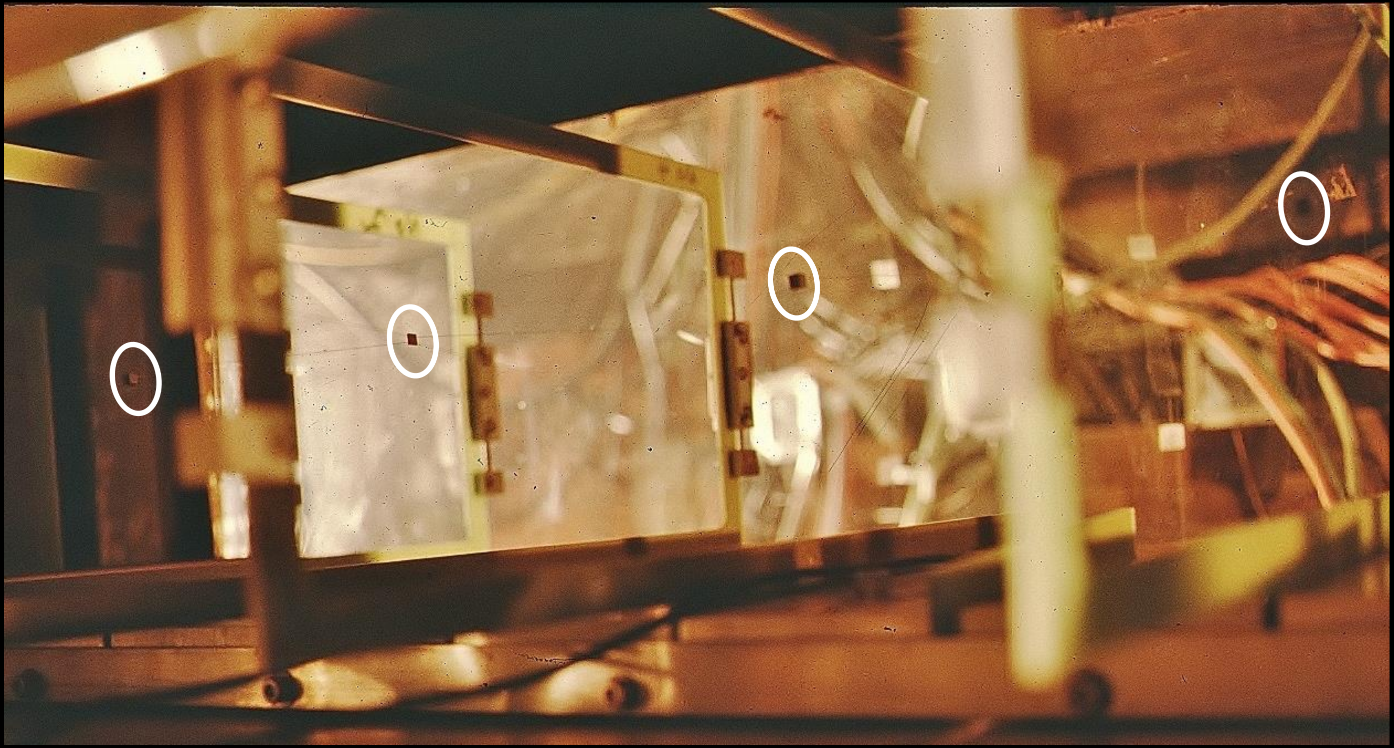
10^{12} particles are produced each second

+ 5 tons of ^{238}U
+ 100 tons of lead
+ 5 tons of soap

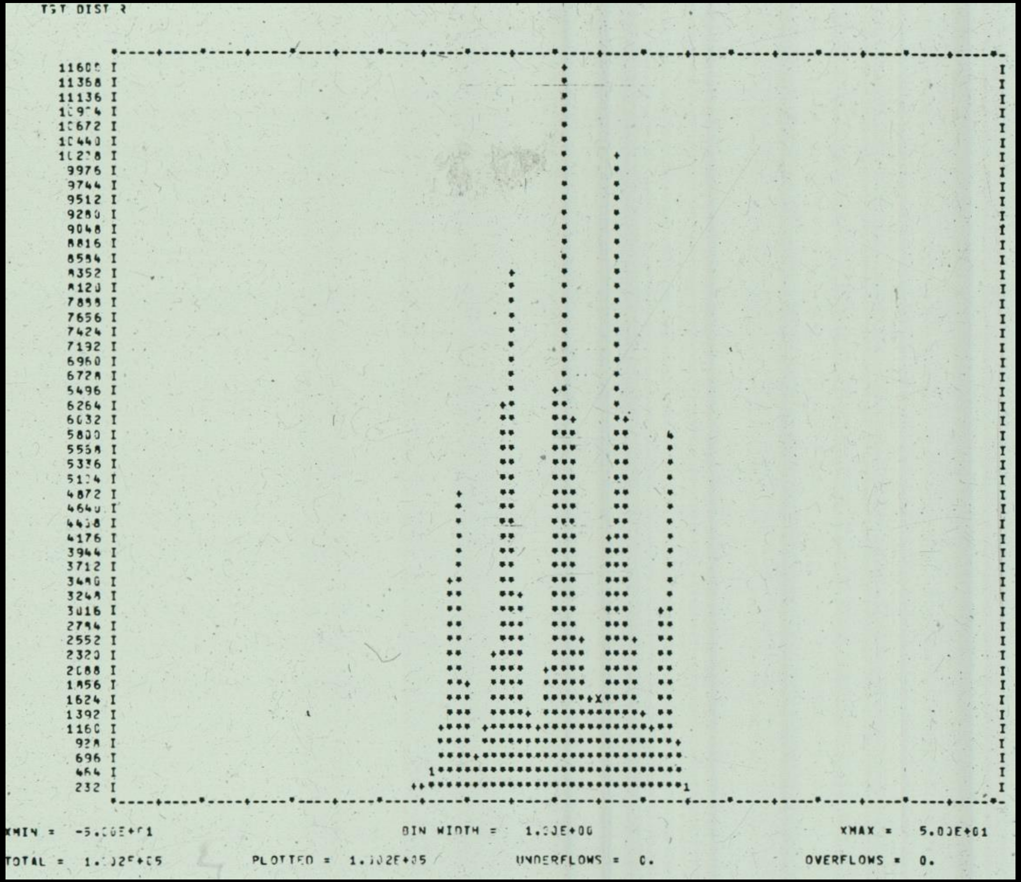
Shielding Arrangement with roof open

Separate targets to reduce the background



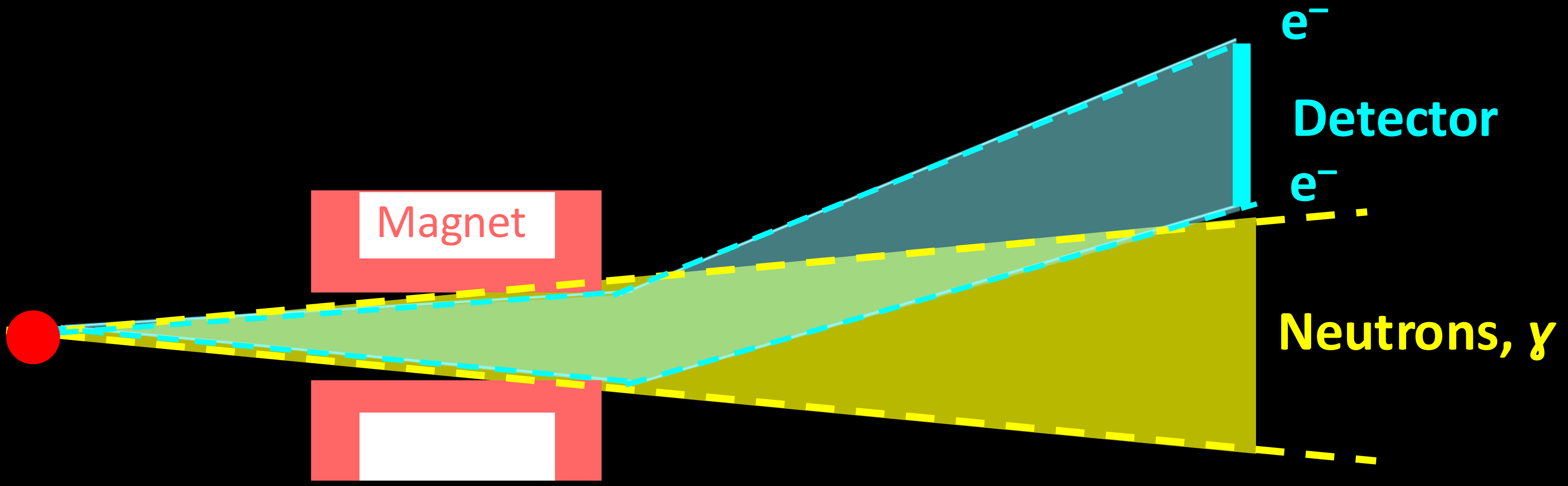


Event distribution

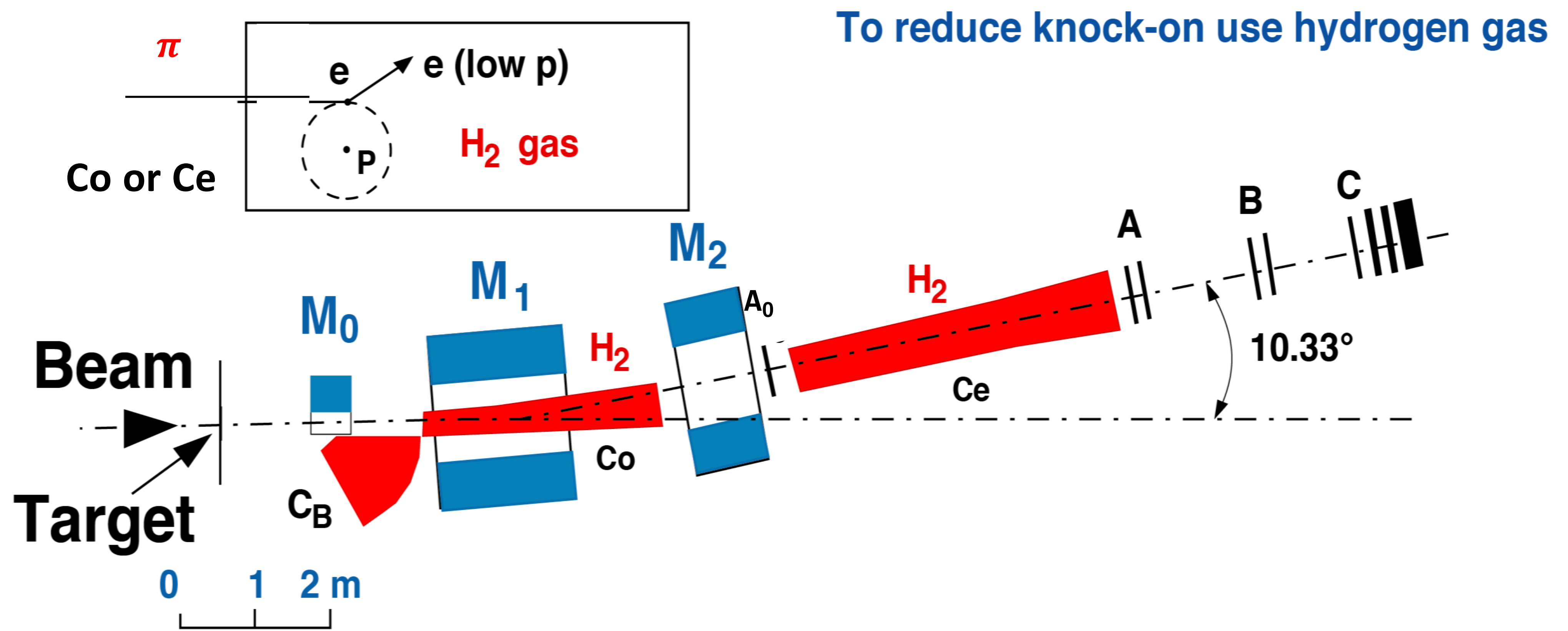


The Magnets

1. The field is measured with 3-D Hall probe, a total of 10^5 points.
2. The detector is smaller than the magnets aperture, the detector defines the acceptance.
3. The magnets bend charged particles to an angle such that the detectors are not exposed to photons or neutrons from the target.



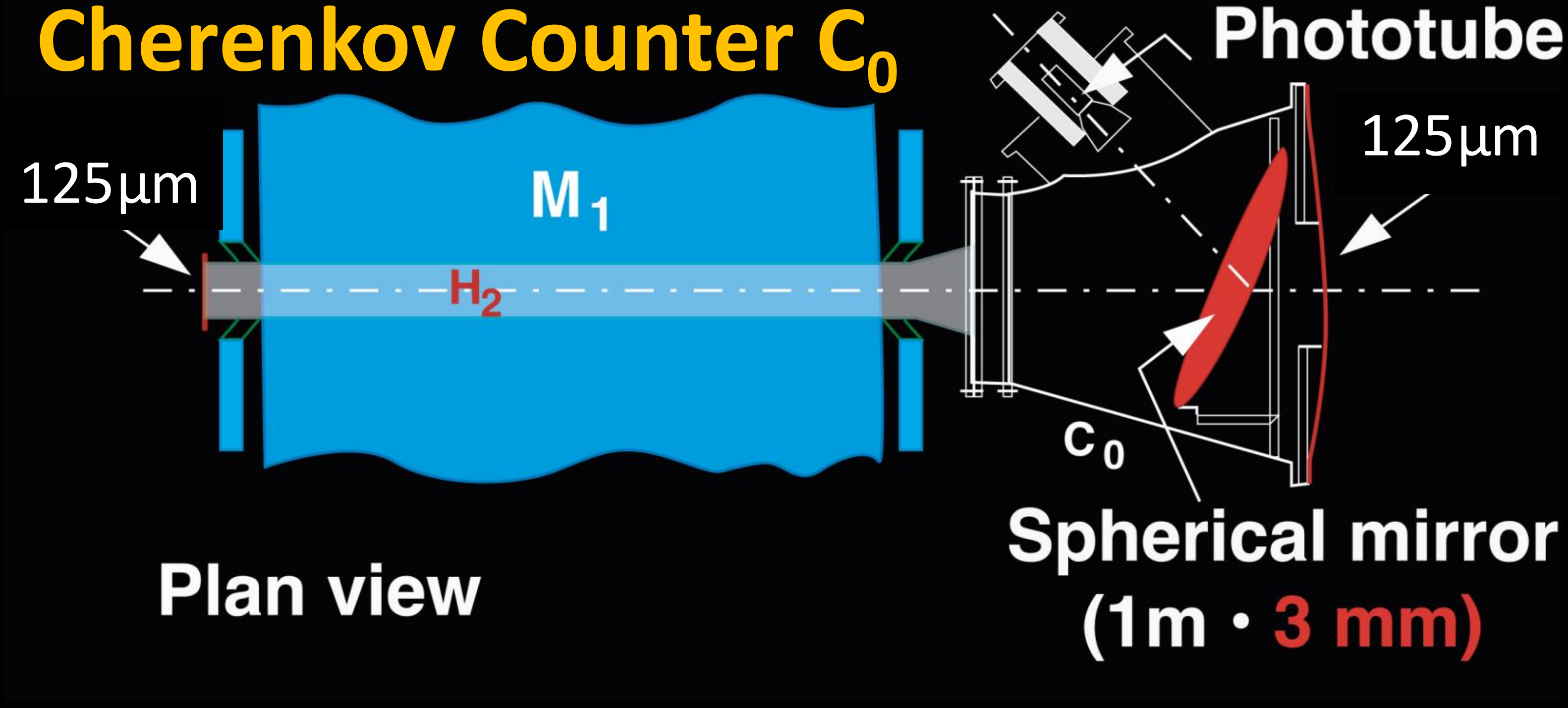
Hadron Rejection of 10^{10}



The Cherenkov counter in the magnet has large spherical mirror with a diameter of 1 m. This is followed by another Cherenkov counter behind the second magnet

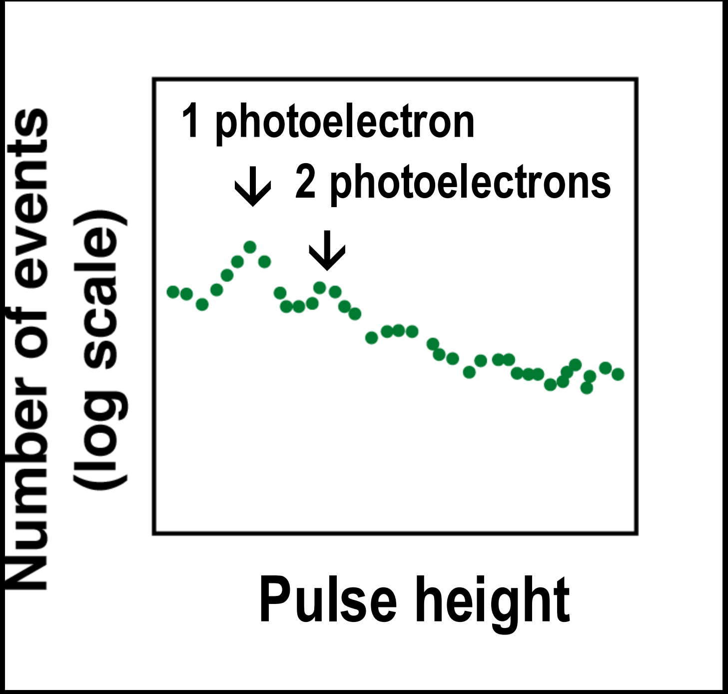
The separation of the two counters by strong magnetic fields ensures that the minute number of knock-on electrons produced in the first counter are swept away and do not enter the second counter

Cherenkov Counter C_0

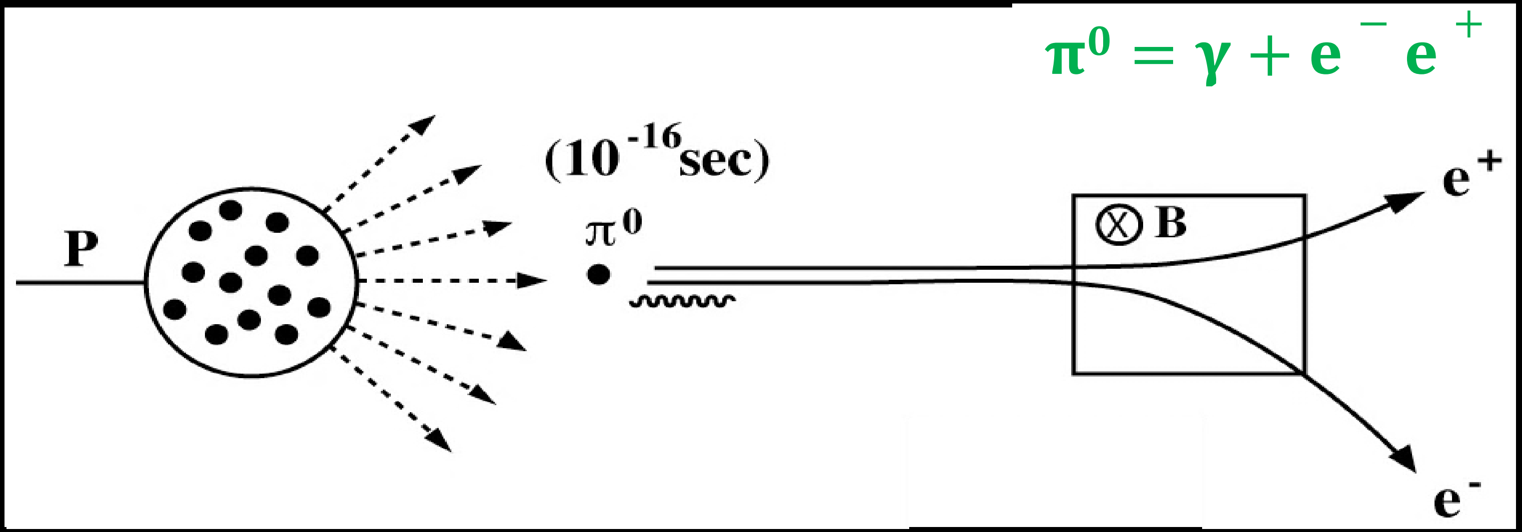


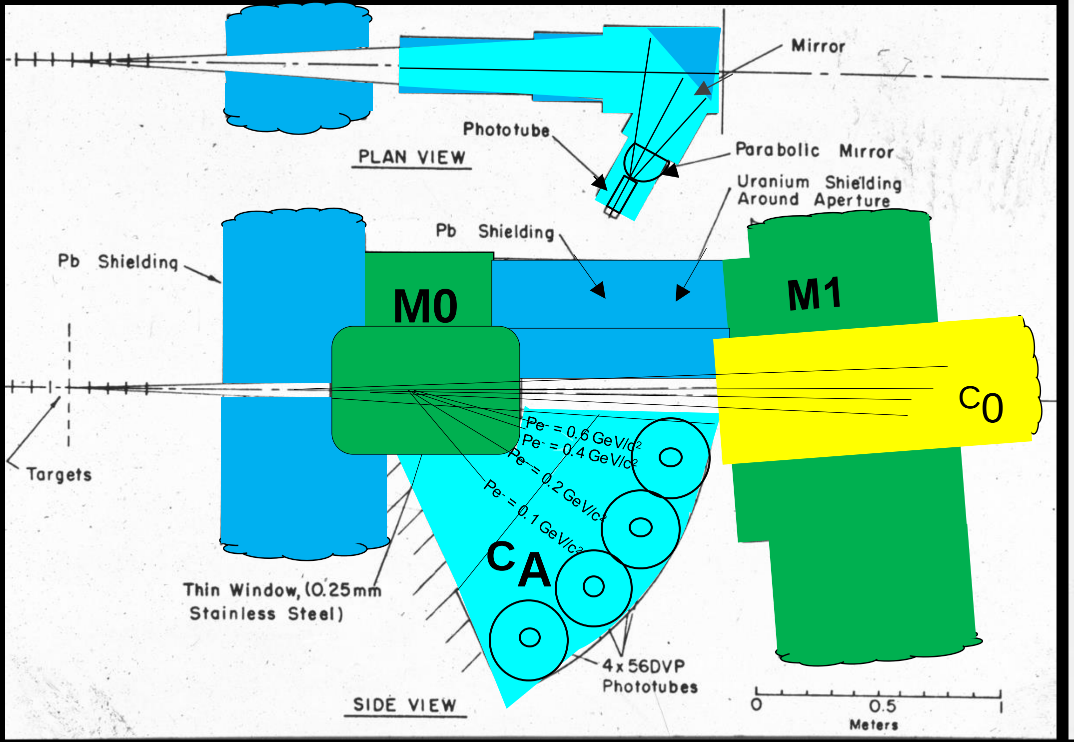
The π-e separation was achieved by four extremely sensitive Cherenkov Counters Co, Ce

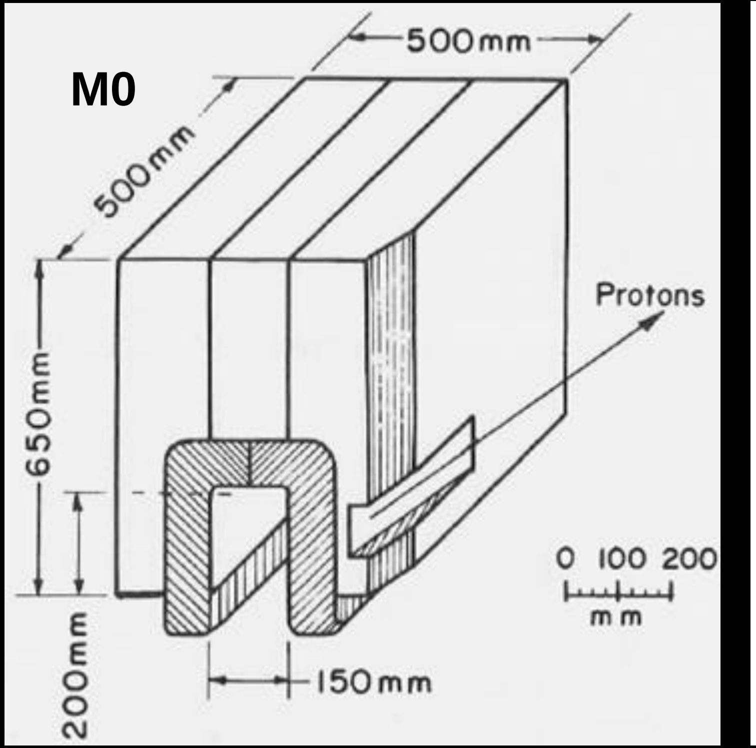
Designed by M. Vivargent, J. J. Aubert and S. Ting and manufactured at LAPP, Annecy, France

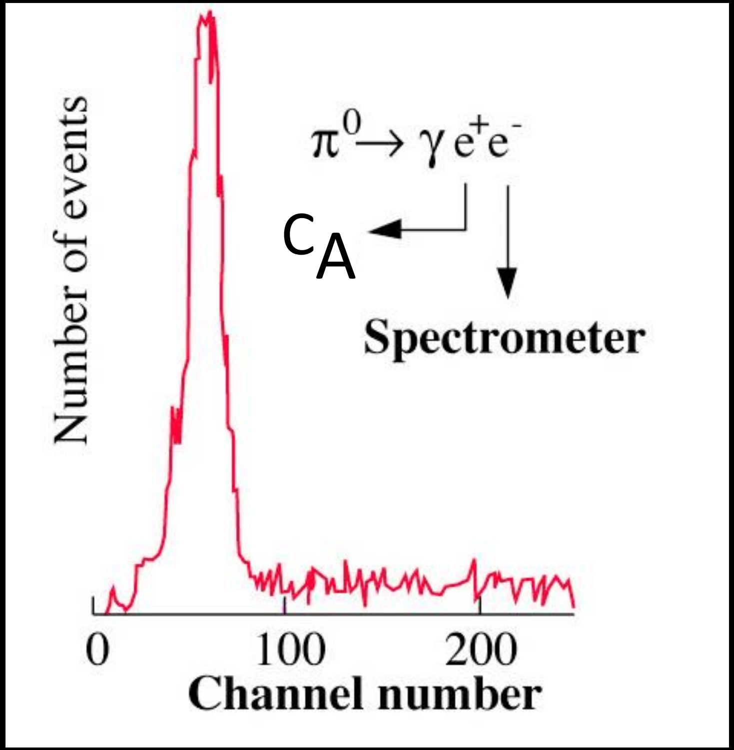


Detector calibration with a pure electron beam

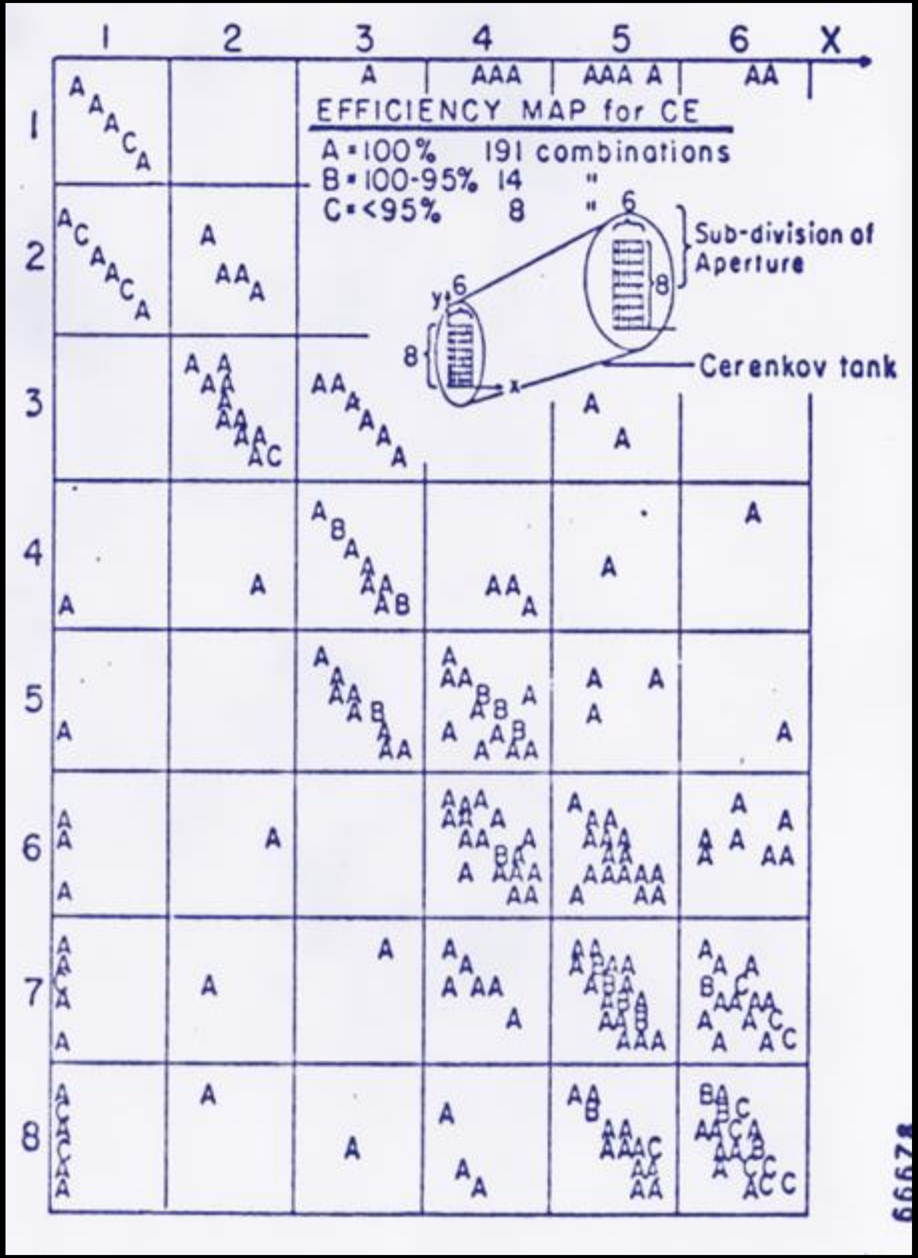






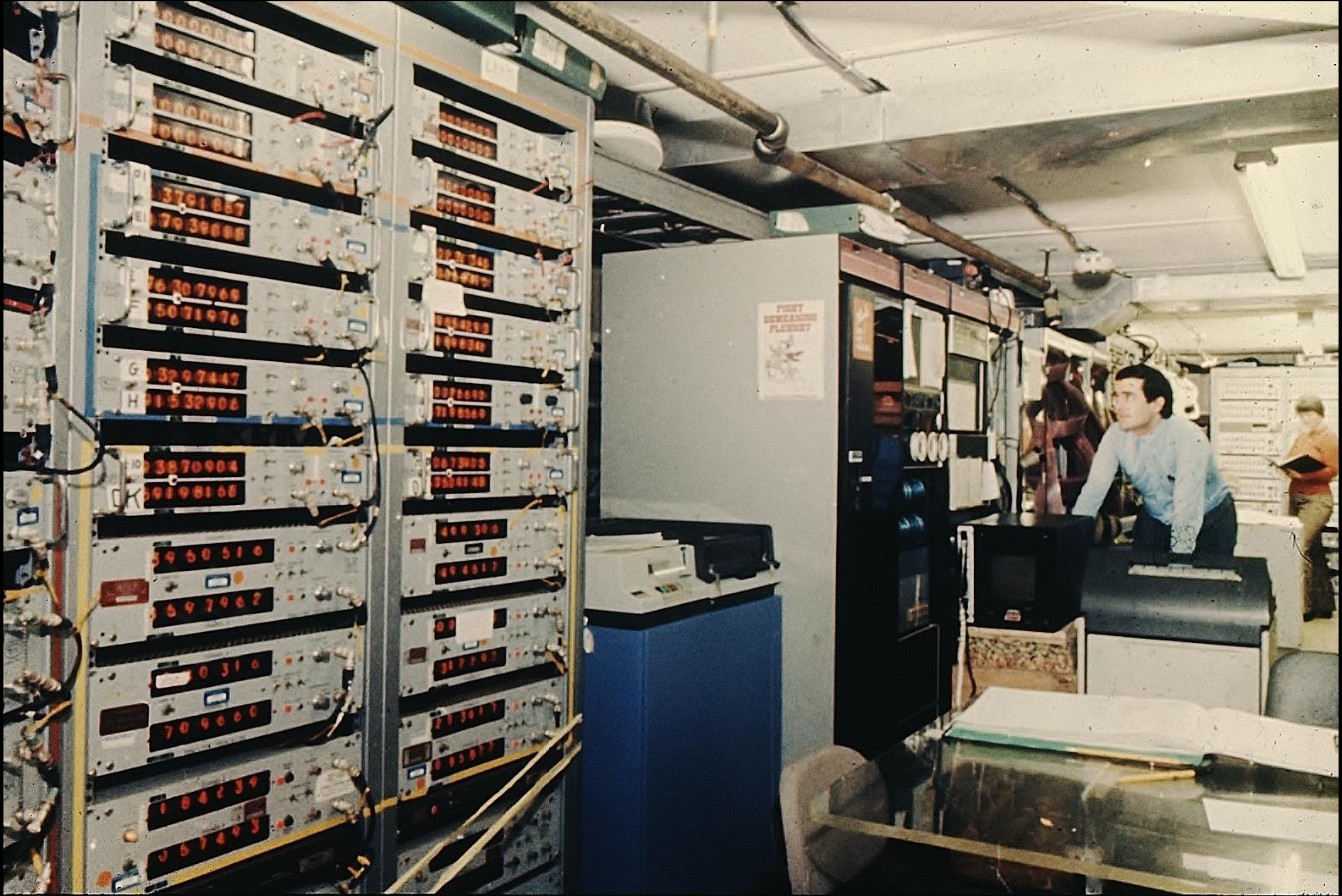


Ensure the efficiency of the Cherenkov counter is 100%


EFFICIENCY MAP for CE

A = 100% 191 combinations
B = 100-95% 14 "
C = <95% 8 "

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

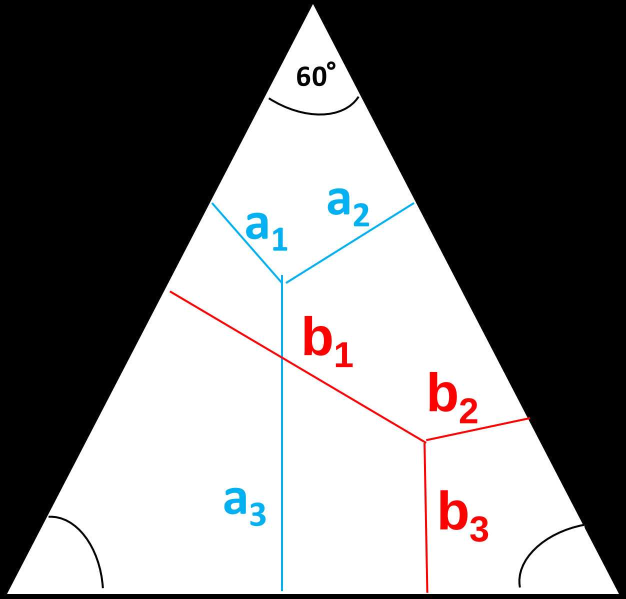


Position Detectors

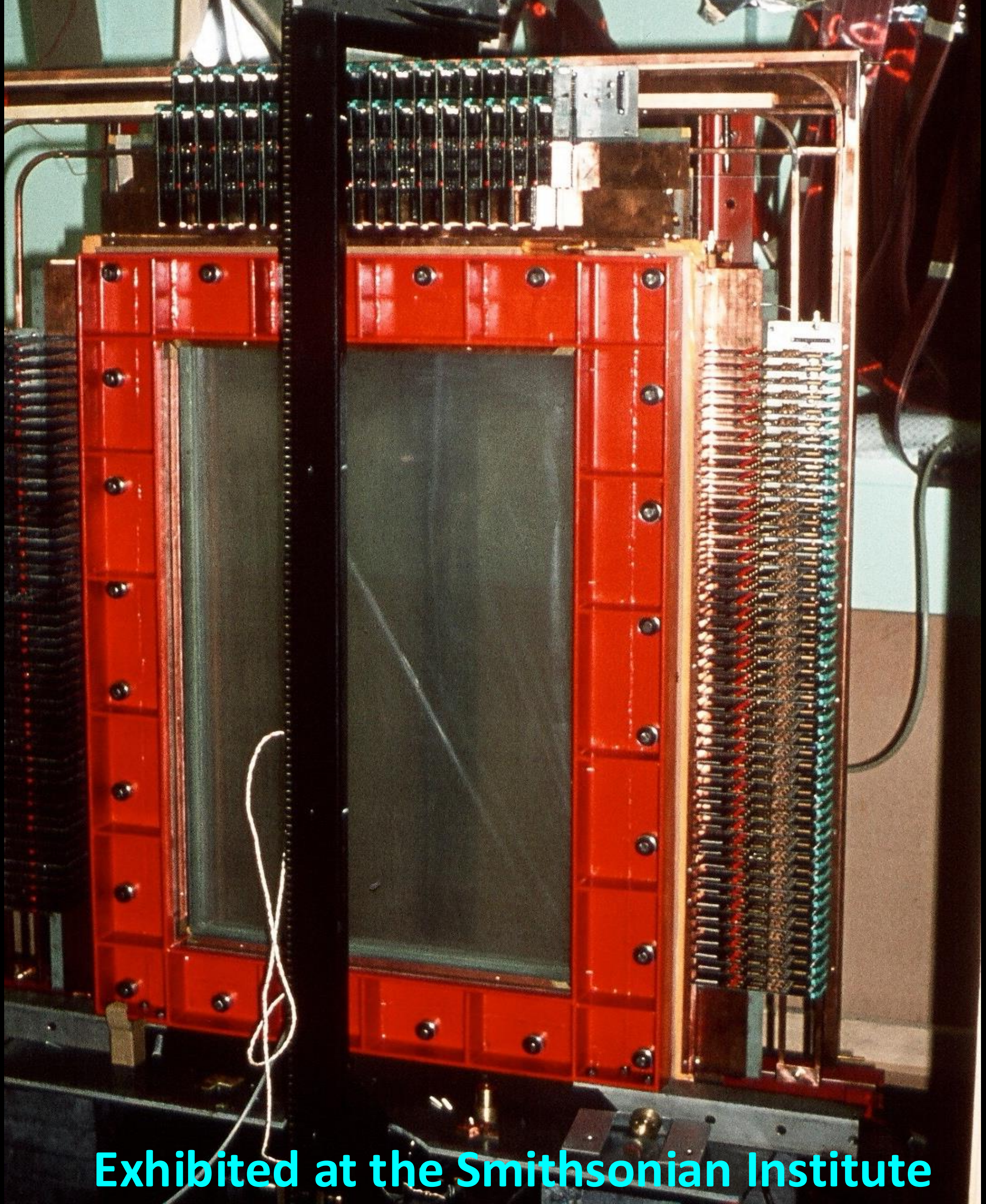
designed by the
late Professor UJ Becker

There are 20 MHz of particles passing through these detectors.

To sort out multi-tracks:
there are 3 planes 60^o apart!



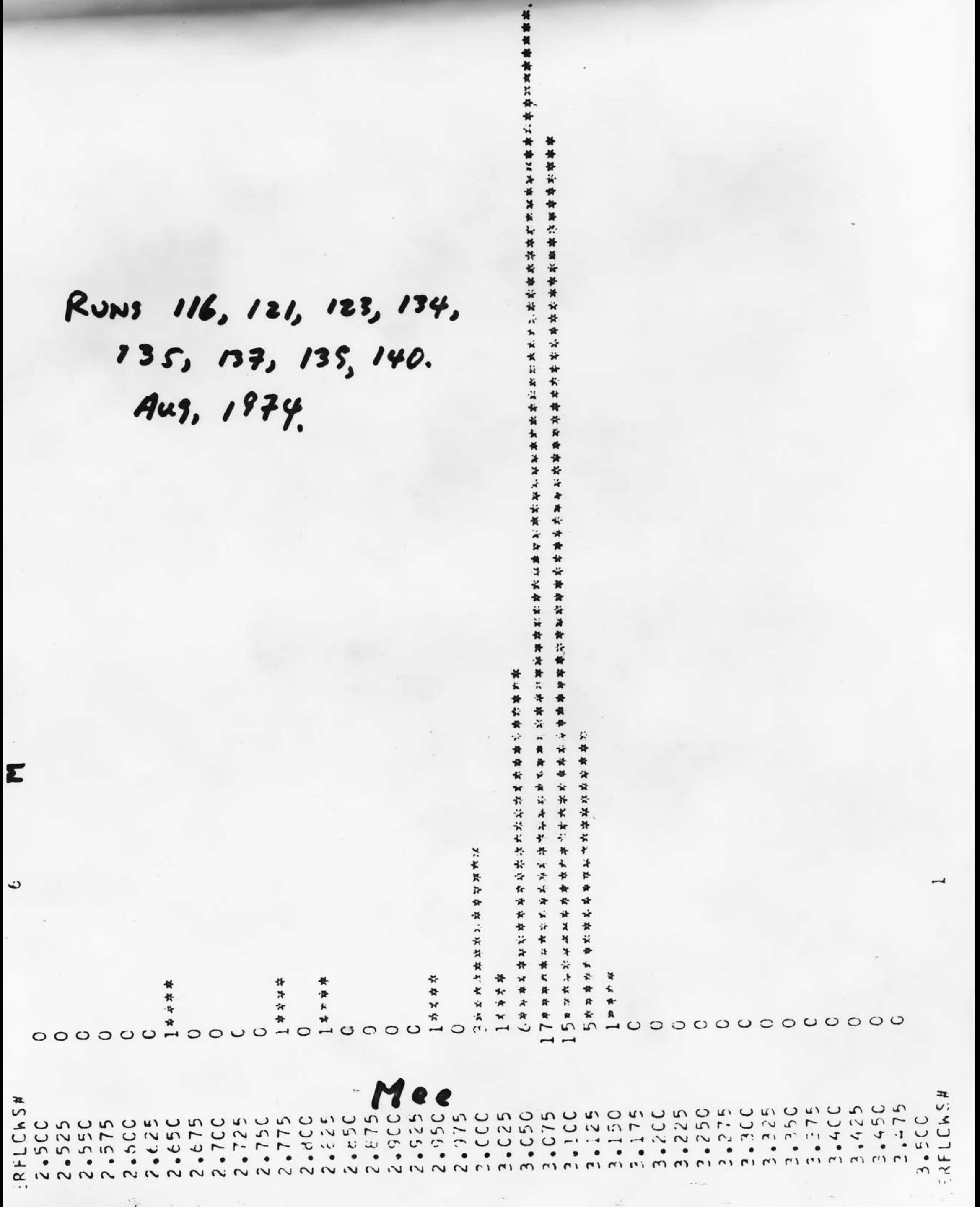
$$a_1 + a_2 + a_3 = b_1 + b_2 + b_3$$



Exhibited at the Smithsonian Institute

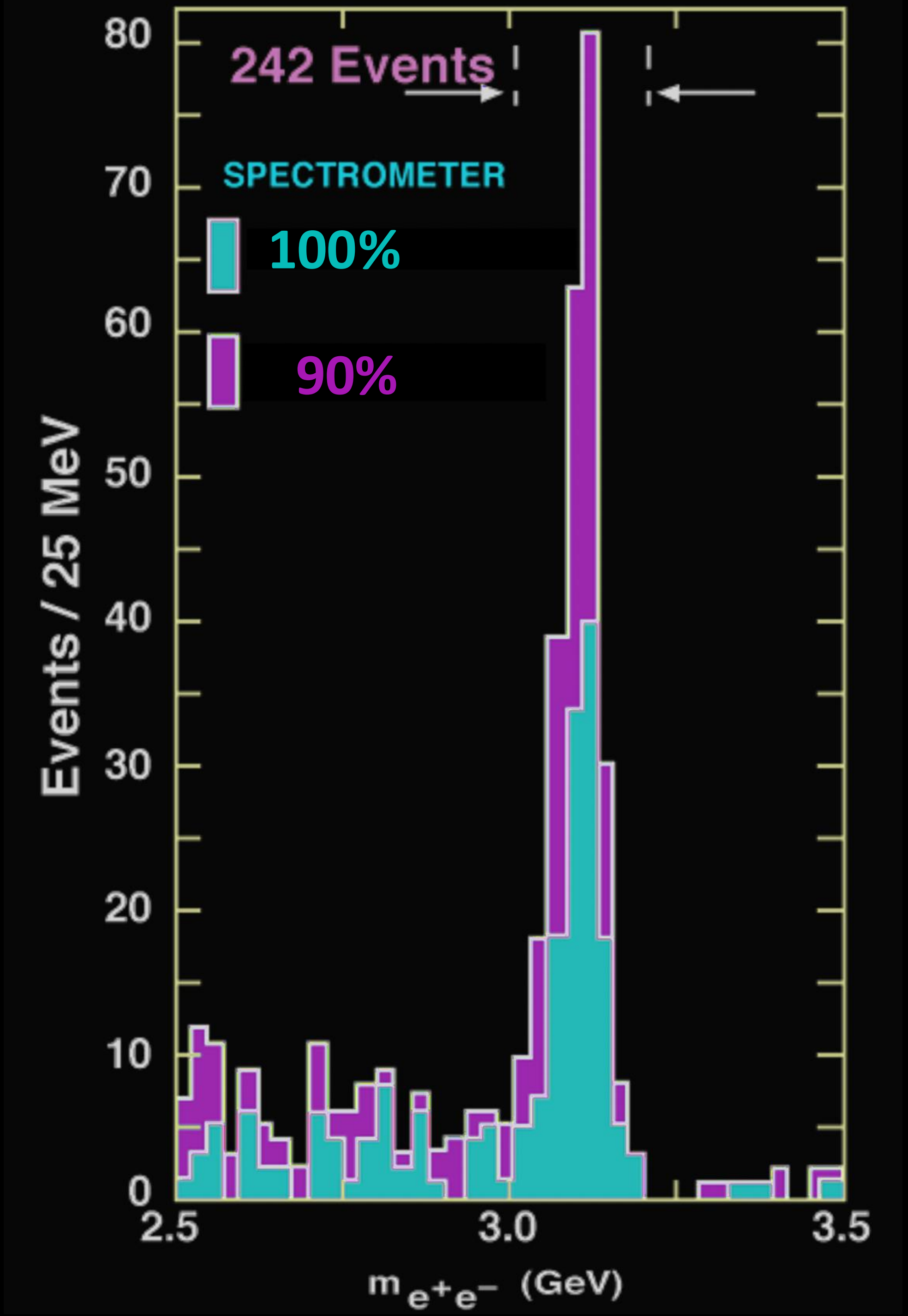
Position Detectors

First data showing an unexpected peak at 3.1 GeV



Runs 116, 121, 123, 134, 135, 137, 139, 140.
Aug, 1974.

Important Check of the Detector



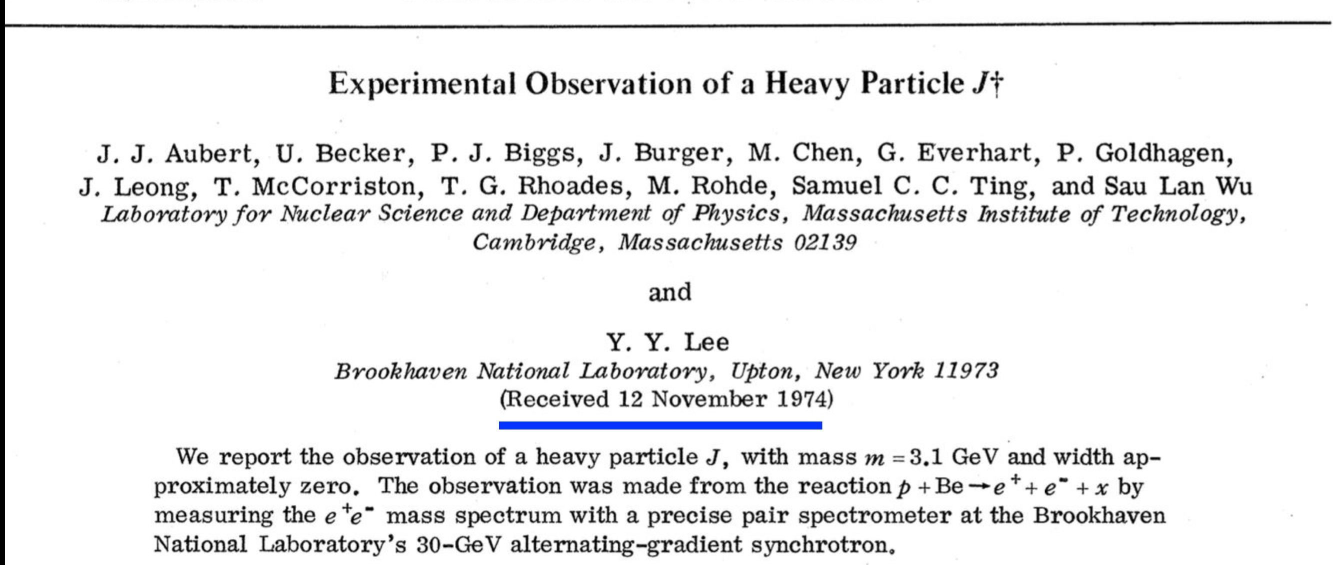
Lower the magnetic field by **10%**:
Particles bend into different parts of the detector.

If the peak is false, it will shift away, but it did not.

The discovery is verified.

Members of the J-Particle Group

November Revolution 1974



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

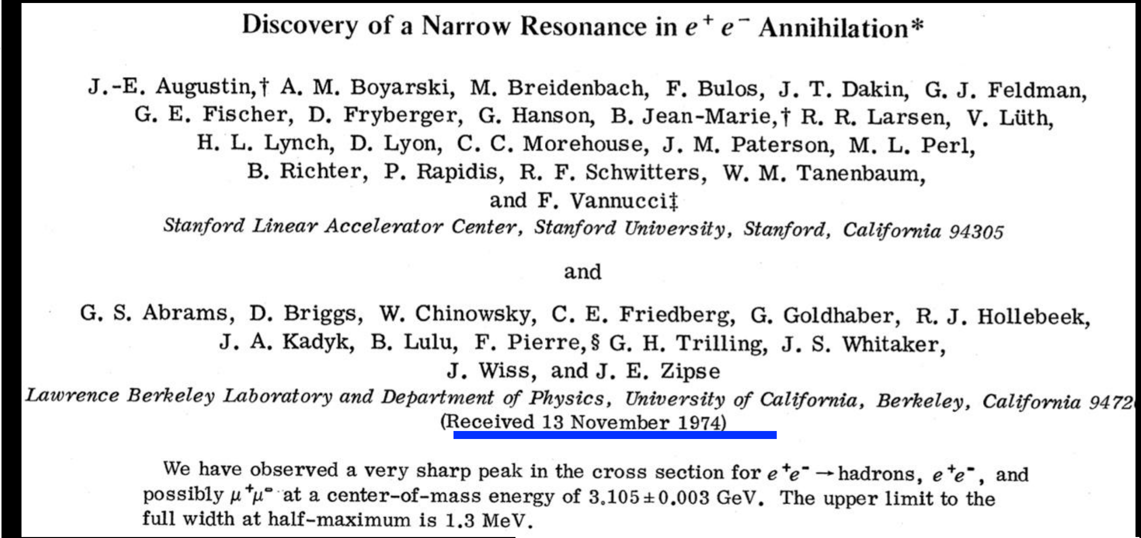
J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973

(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*

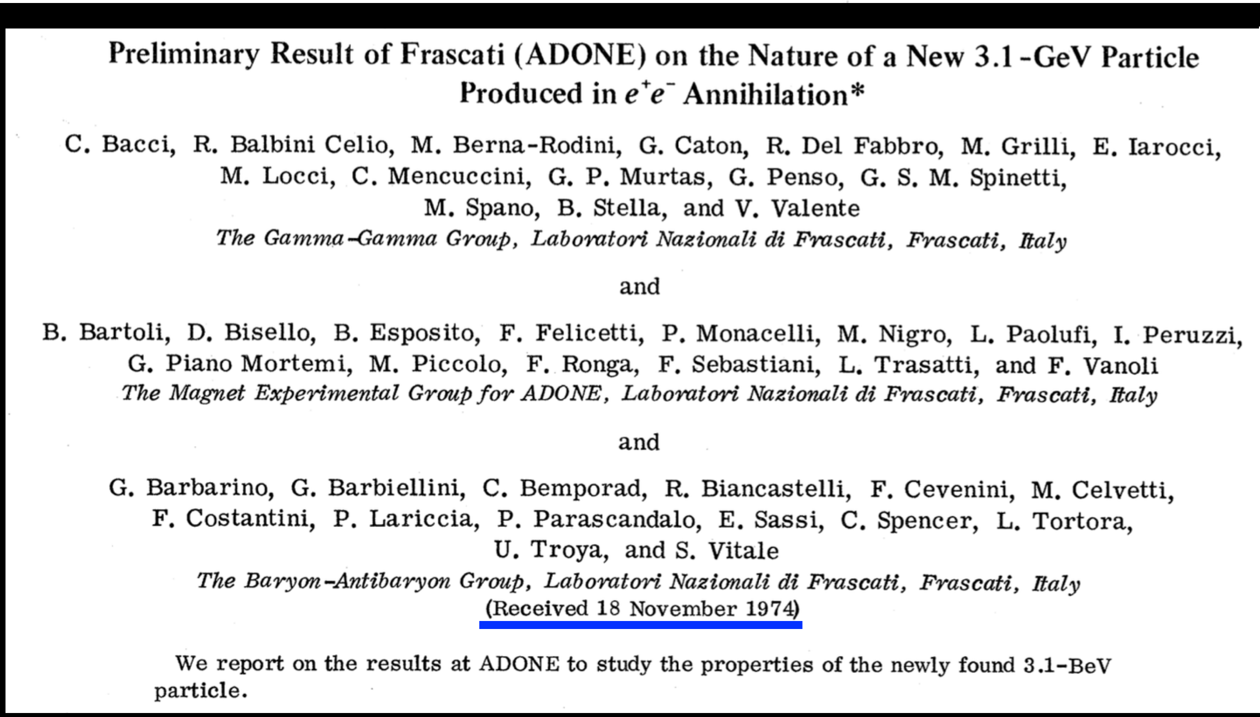
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
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*

C. Bacci, R. Balbini Celio, M. Berna-Rodini, G. Caton, R. Del Fabbro, M. Grilli, E. Iarocci,
M. Locci, C. Mencuccini, G. P. Murtas, G. Penso, G. S. M. Spinetti,
M. Spano, B. Stella, and V. Valente
The Gamma-Gamma Group, Laboratori Nazionali di Frascati, Frascati, Italy

and

B. Bartoli, D. Bisello, B. Esposito, F. Felicetti, P. Monacelli, M. Nigro, L. Paolufi, I. Peruzzi,
G. Piano Mortemi, M. Piccolo, F. Ronga, F. Sebastiani, L. Trasatti, and F. Vanoli
The Magnet Experimental Group for ADONE, Laboratori Nazionali di Frascati, Frascati, Italy

and

G. Barbarino, G. Barbiellini, C. Bemporad, R. Biancastelli, F. Cevenini, M. Celvetti,
F. Costantini, P. Lariccia, P. Parascandalo, E. Sassi, C. Spencer, L. Tortora,
U. Troya, and S. Vitale
The Baryon-Antibaryon Group, Laboratori Nazionali di Frascati, Frascati, Italy

(Received 18 November 1974)

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

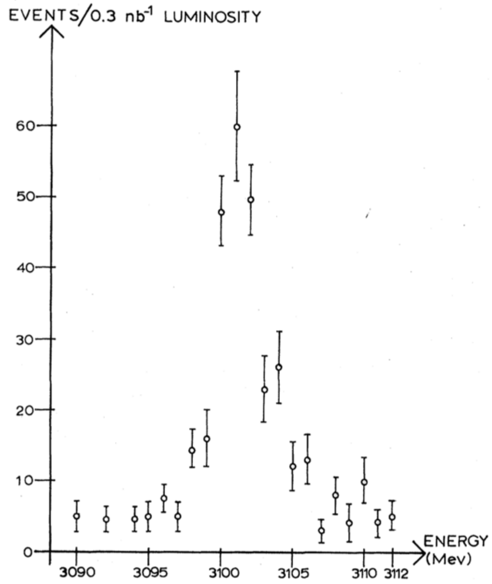


FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

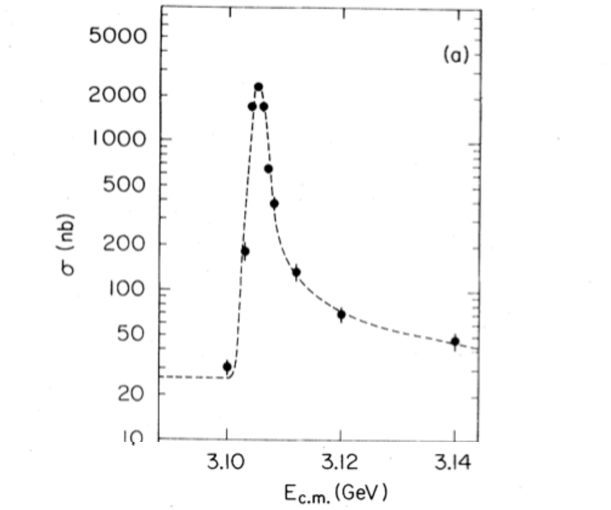
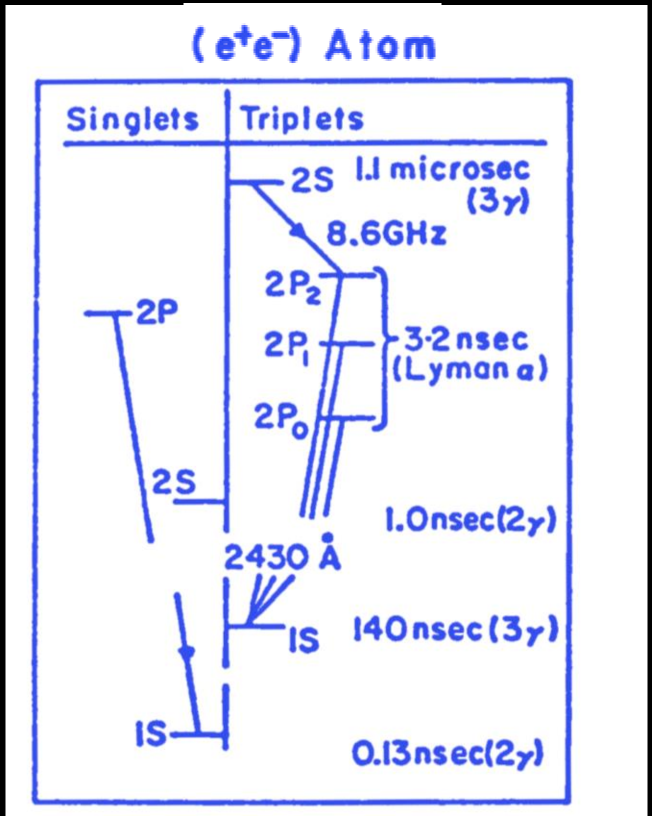


FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. 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.

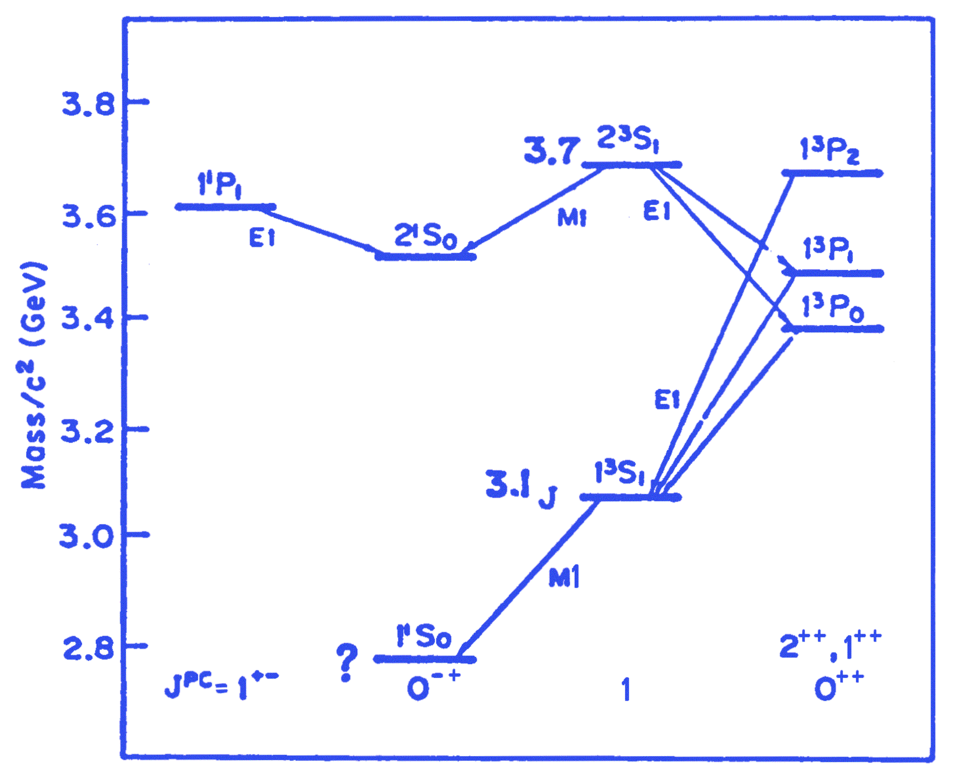
The unique properties of the J particle are:

1. Its lifetime is 10,000 times longer than other 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.
2. The spectrum is similar to positronium
   This implies the existence of a new kind of matter made out of a new kind of Quark-Antiquark.

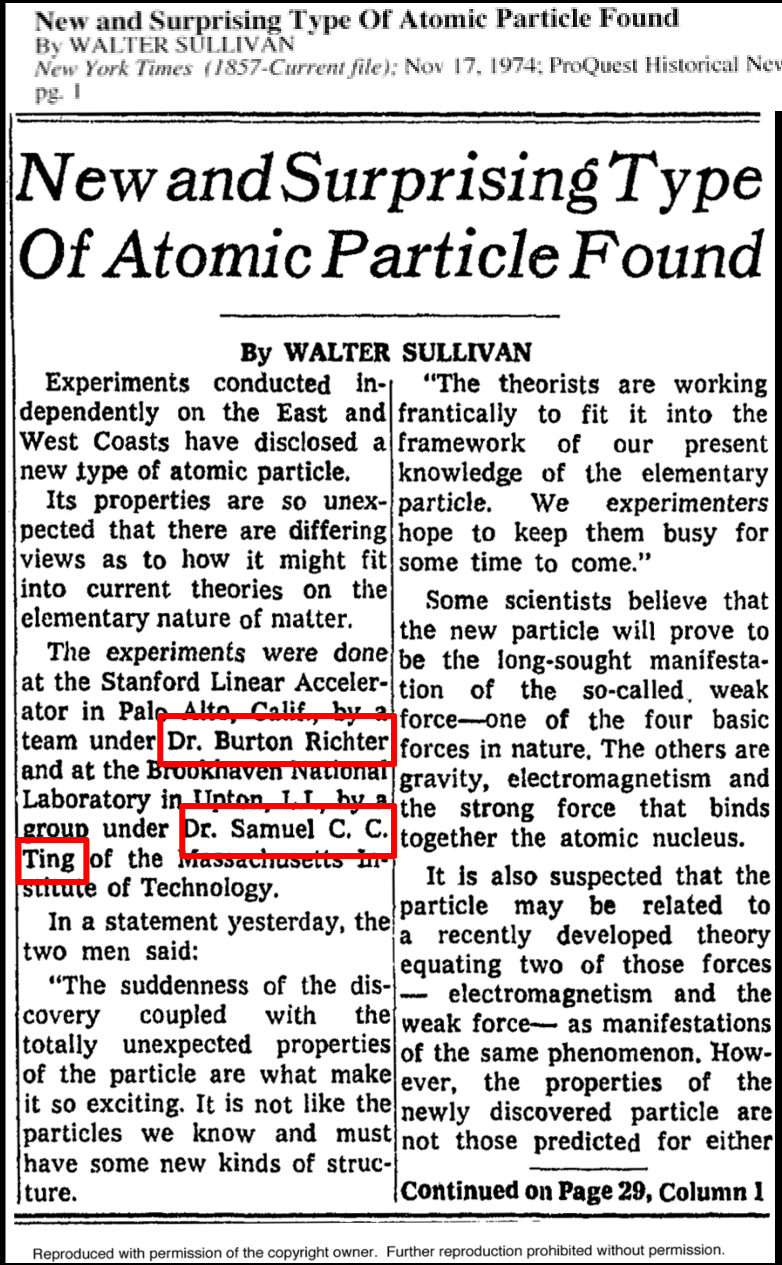
Positronium transitions



J/psi transitions



It has been 50 years since: The discovery of a new form of matter
New York Times, Nov 17, 1974, page 1.



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:

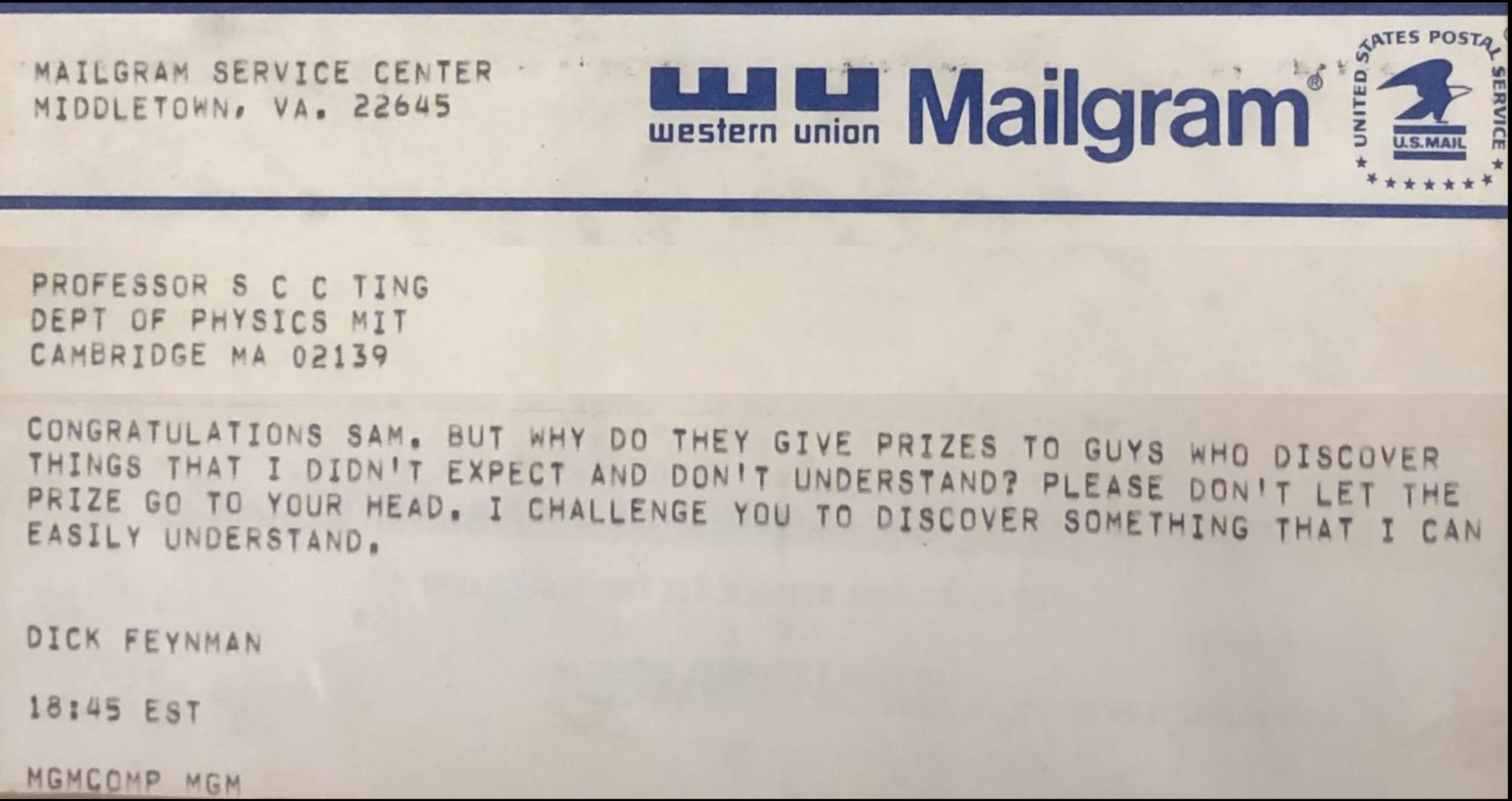
"The suddenness of the discovery coupled with the totally unexpected properties of the particle are what make it so exciting. It is not like the particles we know and must have some new kinds of structure.

"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



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PROFESSOR S C C TING
DEPT OF PHYSICS MIT
CAMBRIDGE MA 02139

CONGRATULATIONS SAM. BUT WHY DO THEY GIVE PRIZES TO GUYS WHO DISCOVER THINGS THAT I DIDN'T EXPECT AND DON'T UNDERSTAND? PLEASE DON'T LET THE PRIZE GO TO YOUR HEAD. I CHALLENGE YOU TO DISCOVER SOMETHING THAT I CAN EASILY UNDERSTAND.

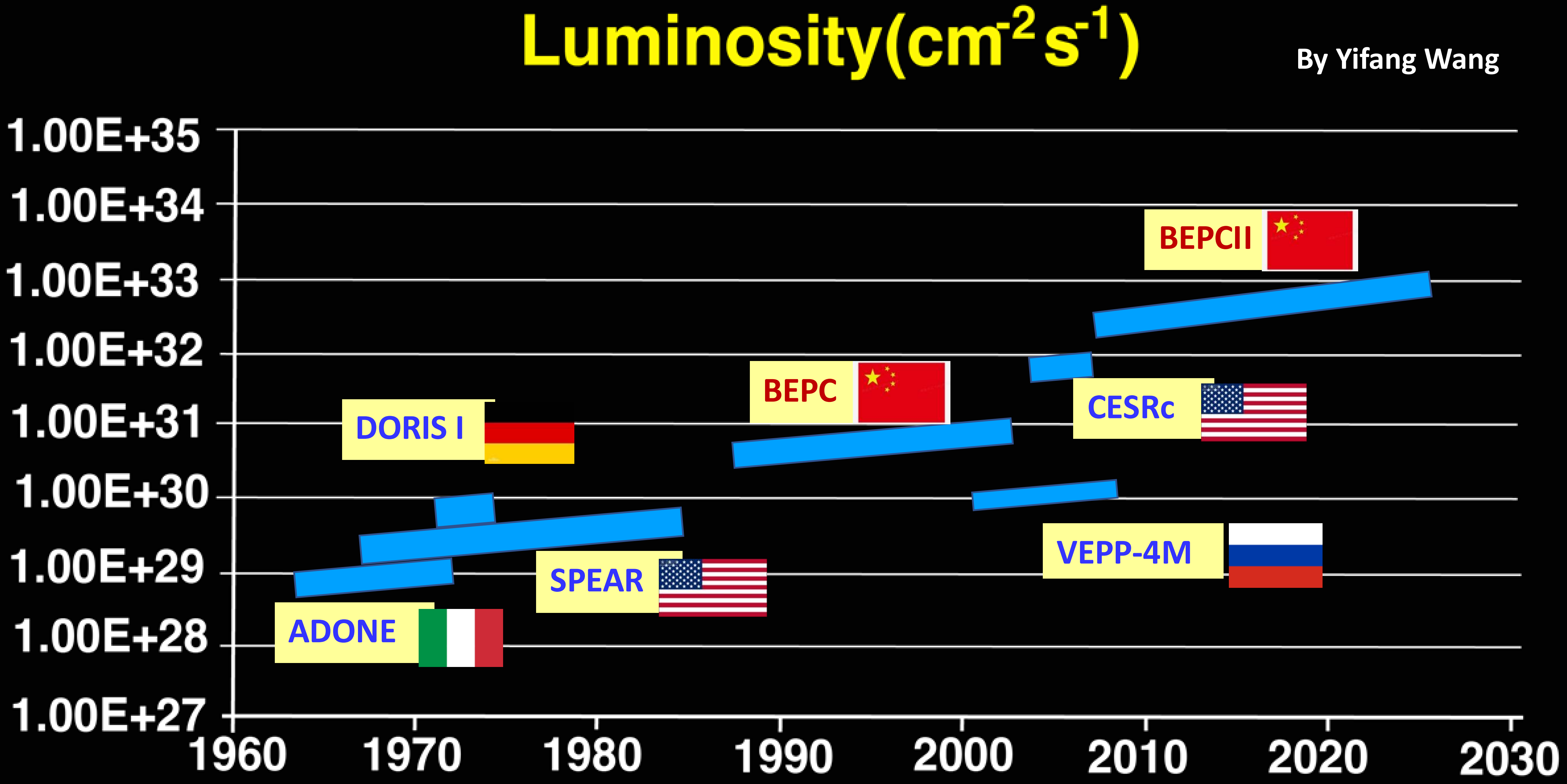
DICK FEYNMAN

18:45 EST

MGMCOMP MGM

Tau-Charm Factories in the World

By Yifang Wang



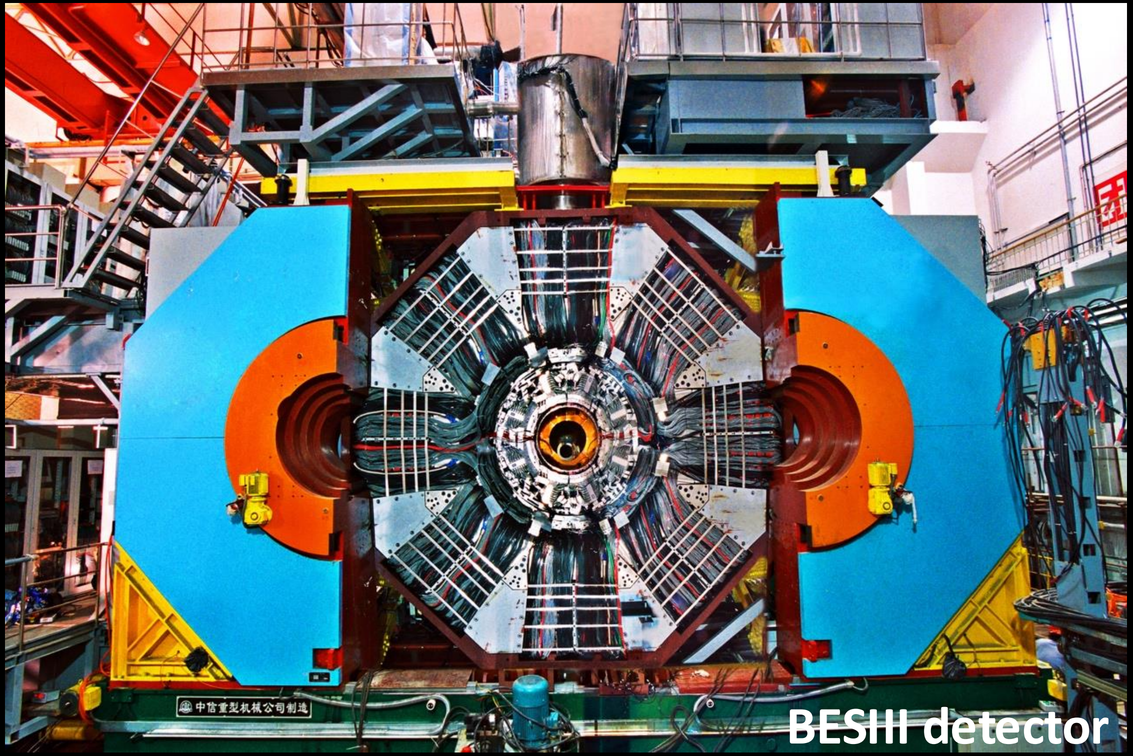
J/Ψ Continuously Studied for 40 years at BEPC
(Beijing Electron-Positron Collider)

BES
J events: 9 million

BESII
J events: 58 million

BESIII
J events: 10 billion

Construction 1984 1988
Data taking 1995
Upgrade 1998
Data taking 2004
Construction 2008
Data taking
2030

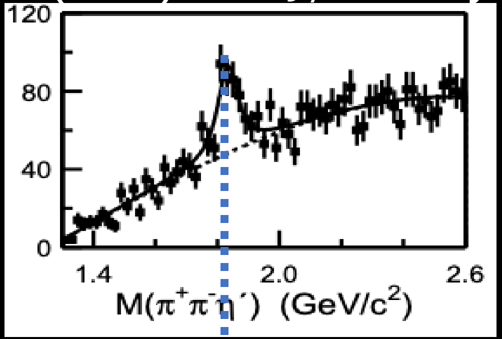


BESIII Project leader: Academician Yifang Wang

Hadron Spectroscopy at BESIII

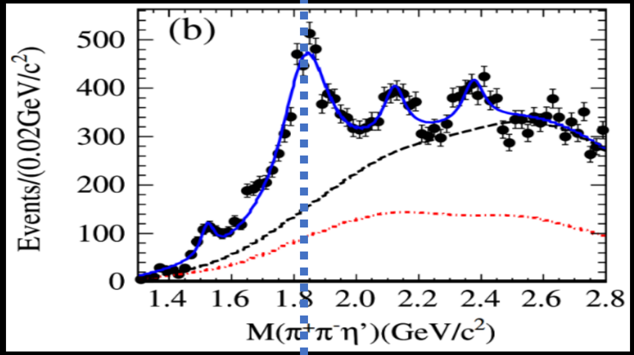
X(1835) from J/Ψ decays

58 million



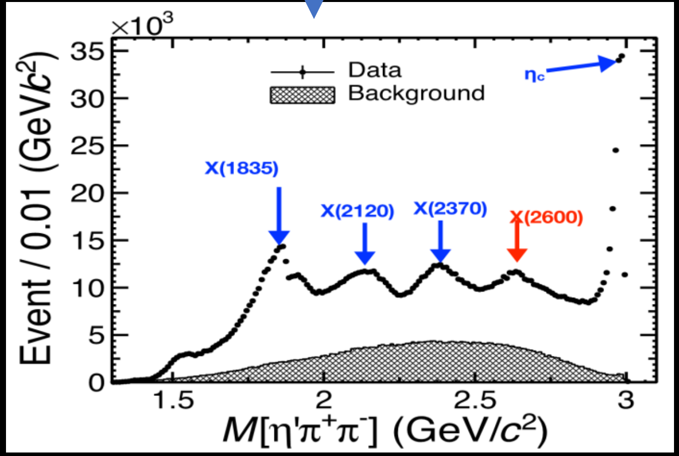
Structure PRL **95** (2005) 262001

225 million



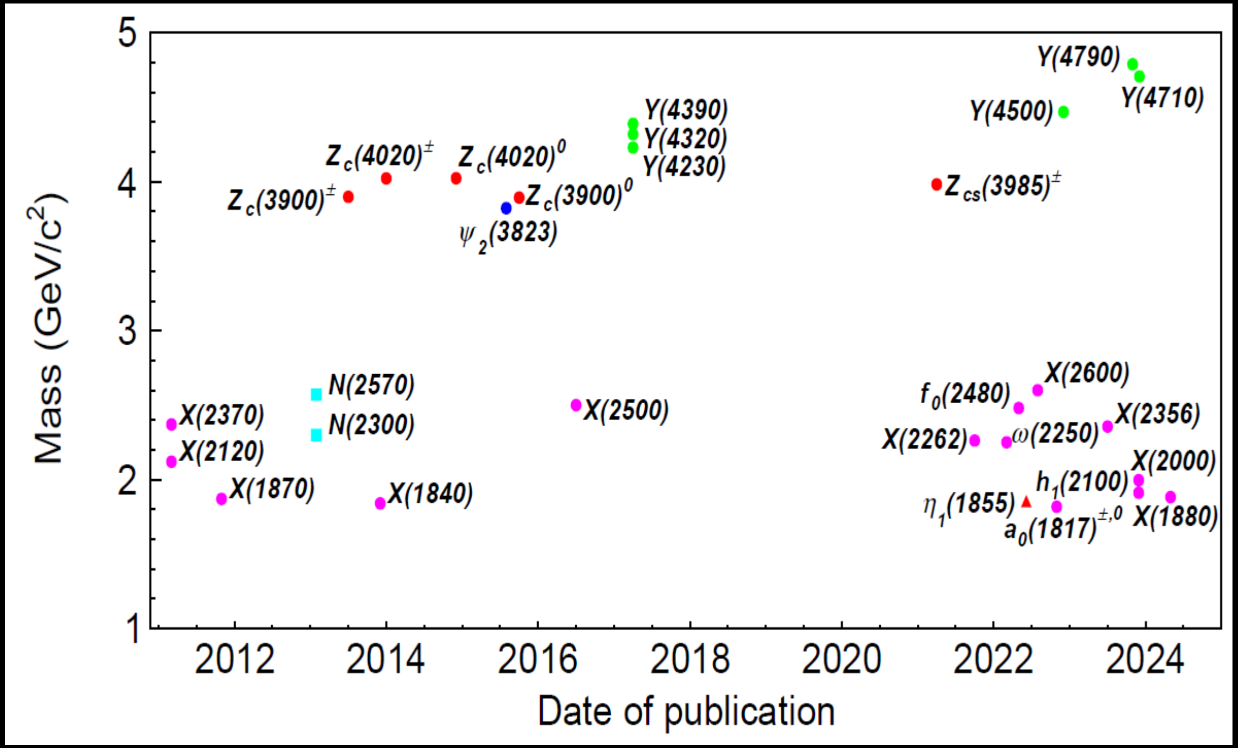
More structures PRL **106** (2011) 072002

10 billion



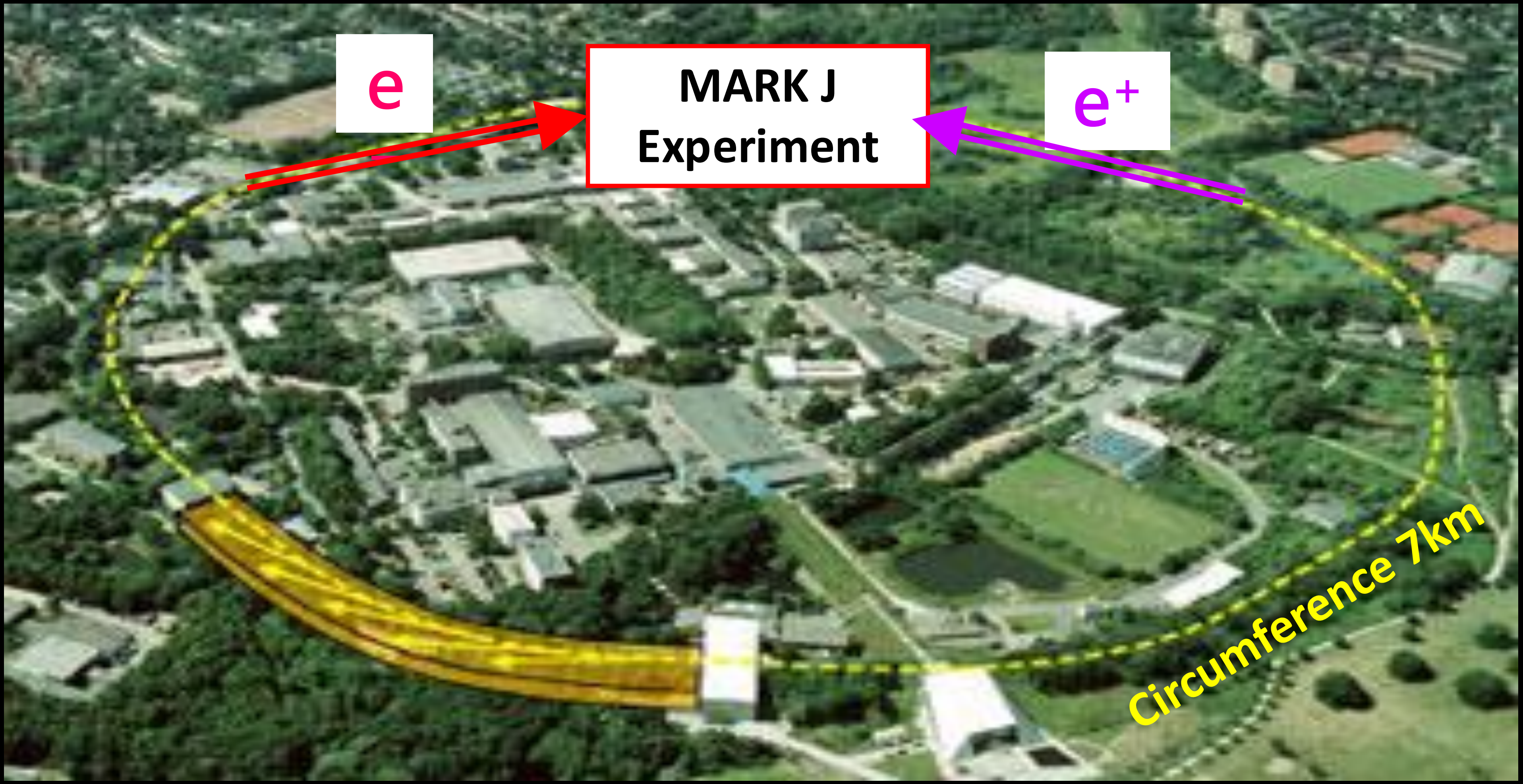
Fine structures PRL **129** (2022) 042001

30 new hadrons discovered at BESIII from charmed meson production and decays

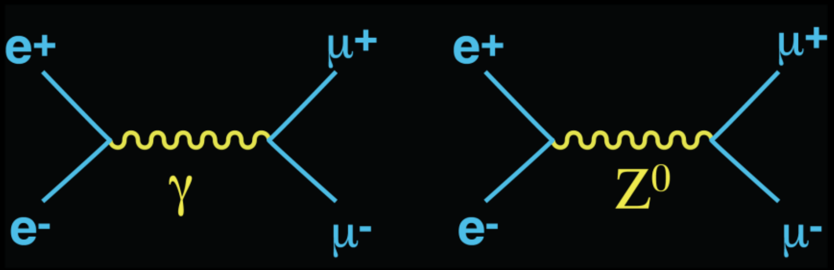


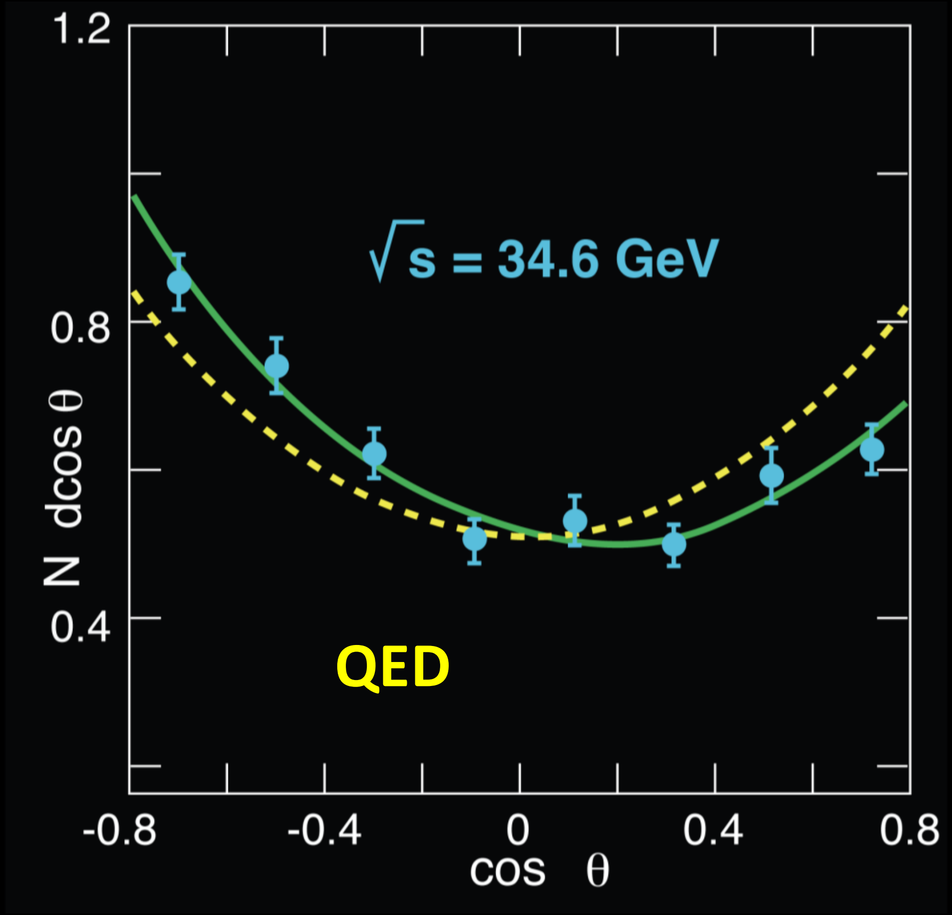
Electrons at Higher Energy

46 Billion Electron Volt Collider at DESY, Germany

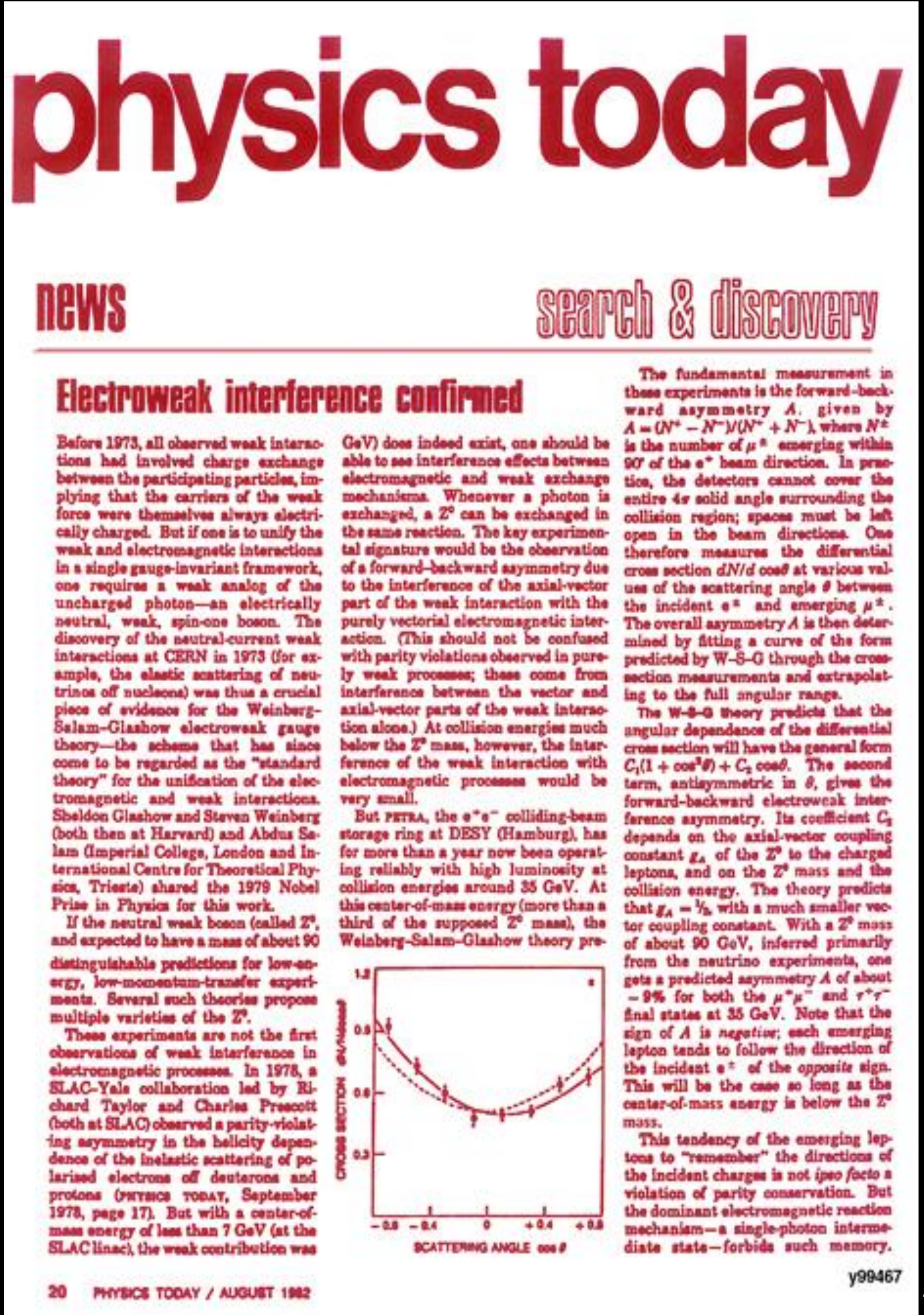


The earliest confirmation of electroweak theory





P.R.L. 48, 25 (21 June 1982)



physics today

news

search & discovery

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 polarized 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 $g_A = -\frac{1}{2}$, 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.

20 PHYSICS TODAY / AUGUST 1982

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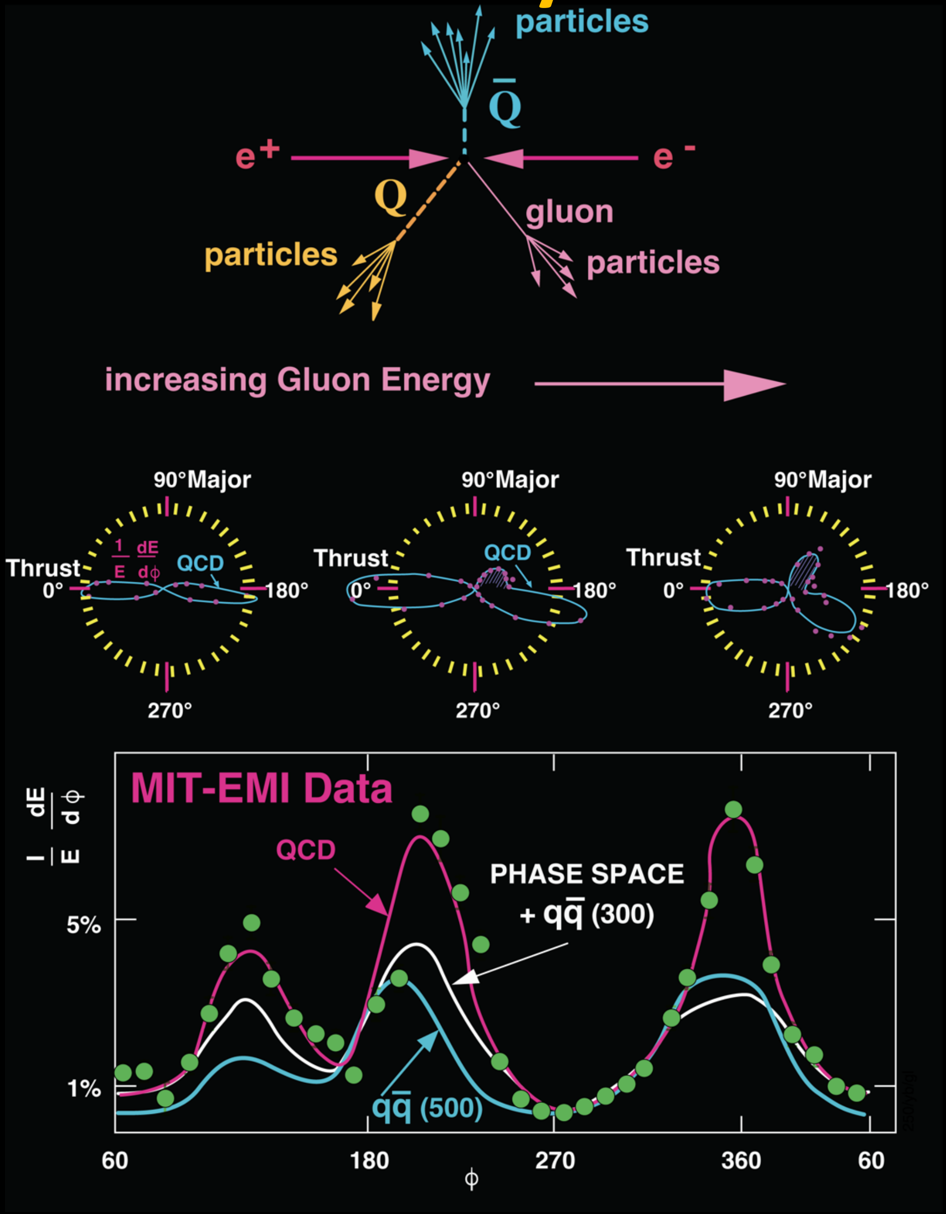
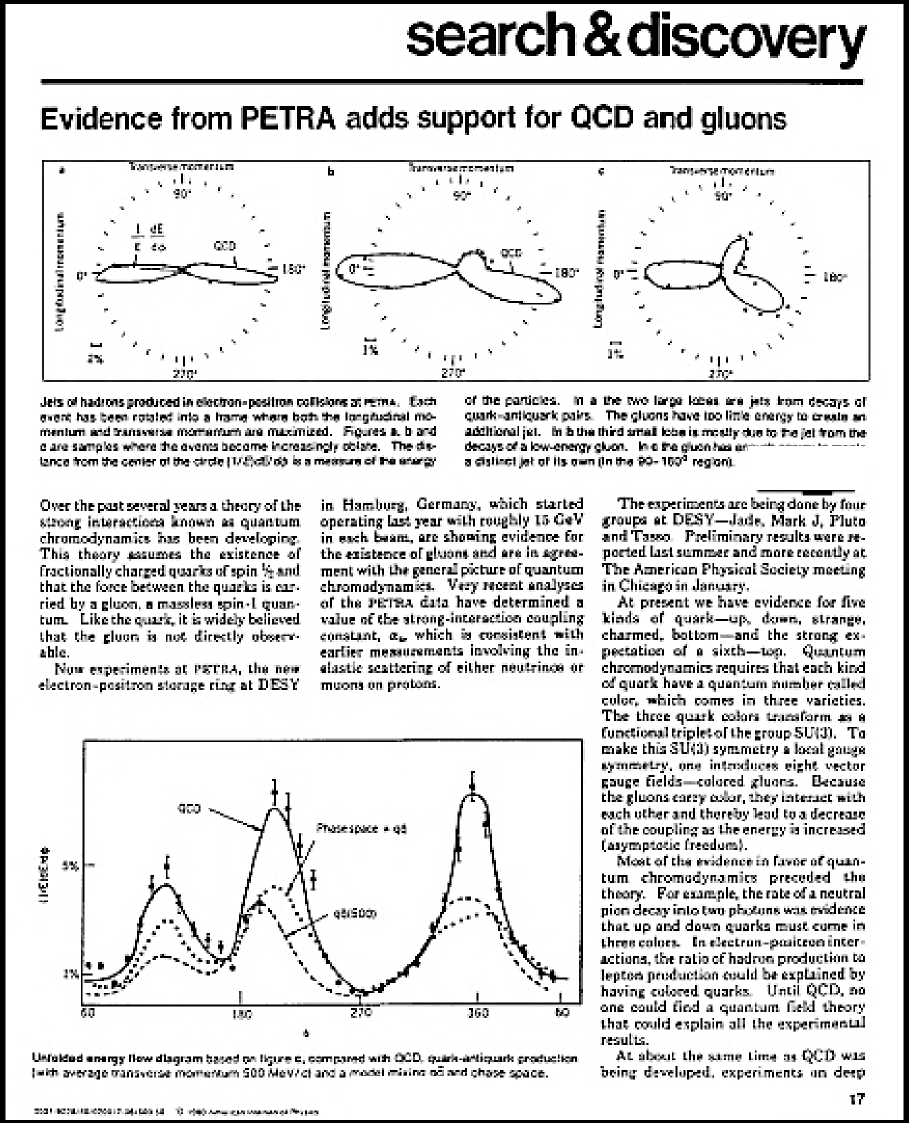
Discovery of Gluons at PETRA, Germany

Physics Today, February 1980 (p.17)





search & discovery

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 en[illegible] a distinct jet of its own (in the 90–180° region).

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.

Now 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.

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.

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).

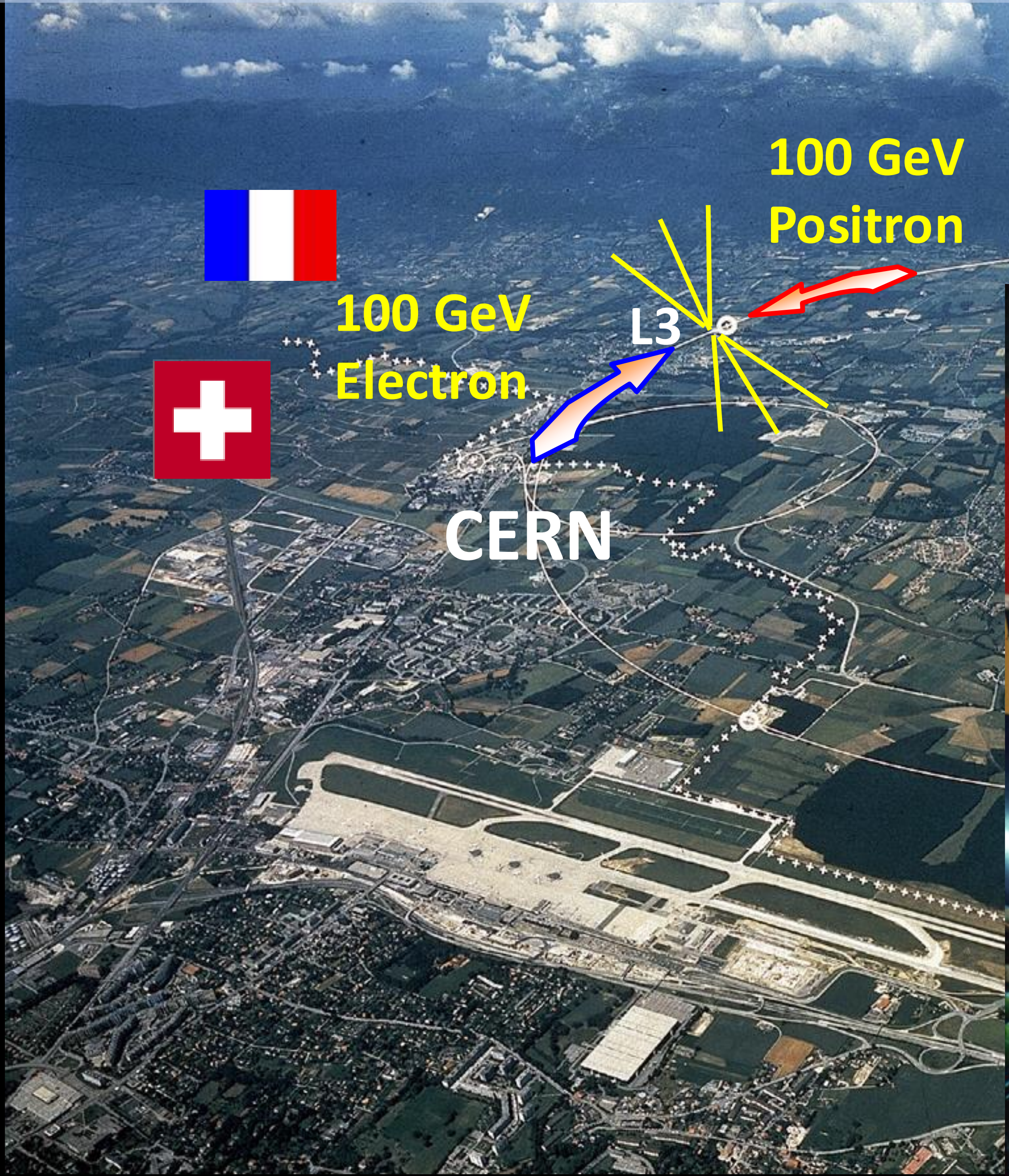
Most of the evidence in favor of quantum chromodynamics preceded the theory. For example, the rate of a neutral pion decay into two photons was evidence that up and down quarks must come in three colors. In electron–positron interactions, the ratio of hadron production to lepton production could be explained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

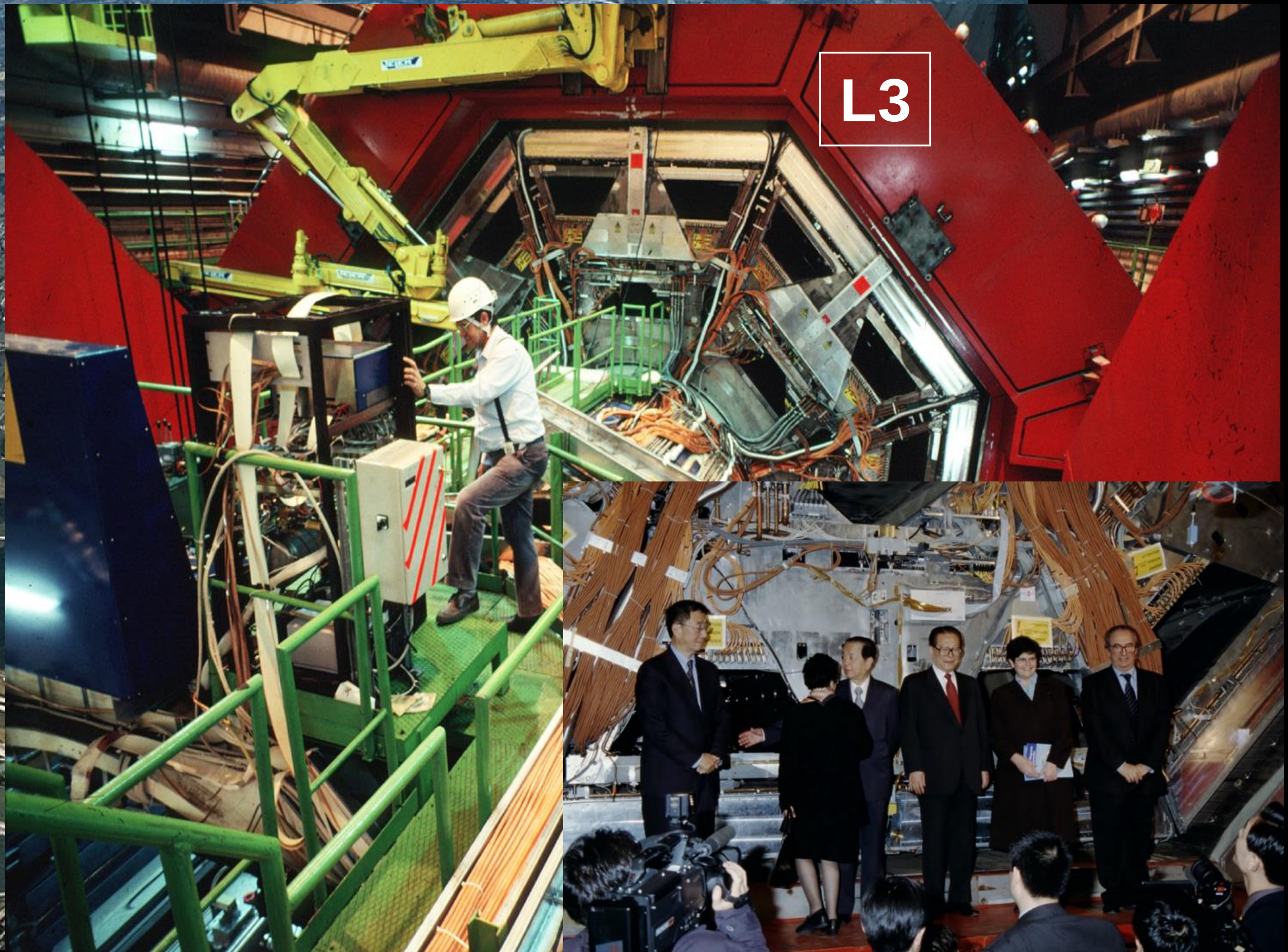
At about the same time as QCD was being developed, experiments on deep

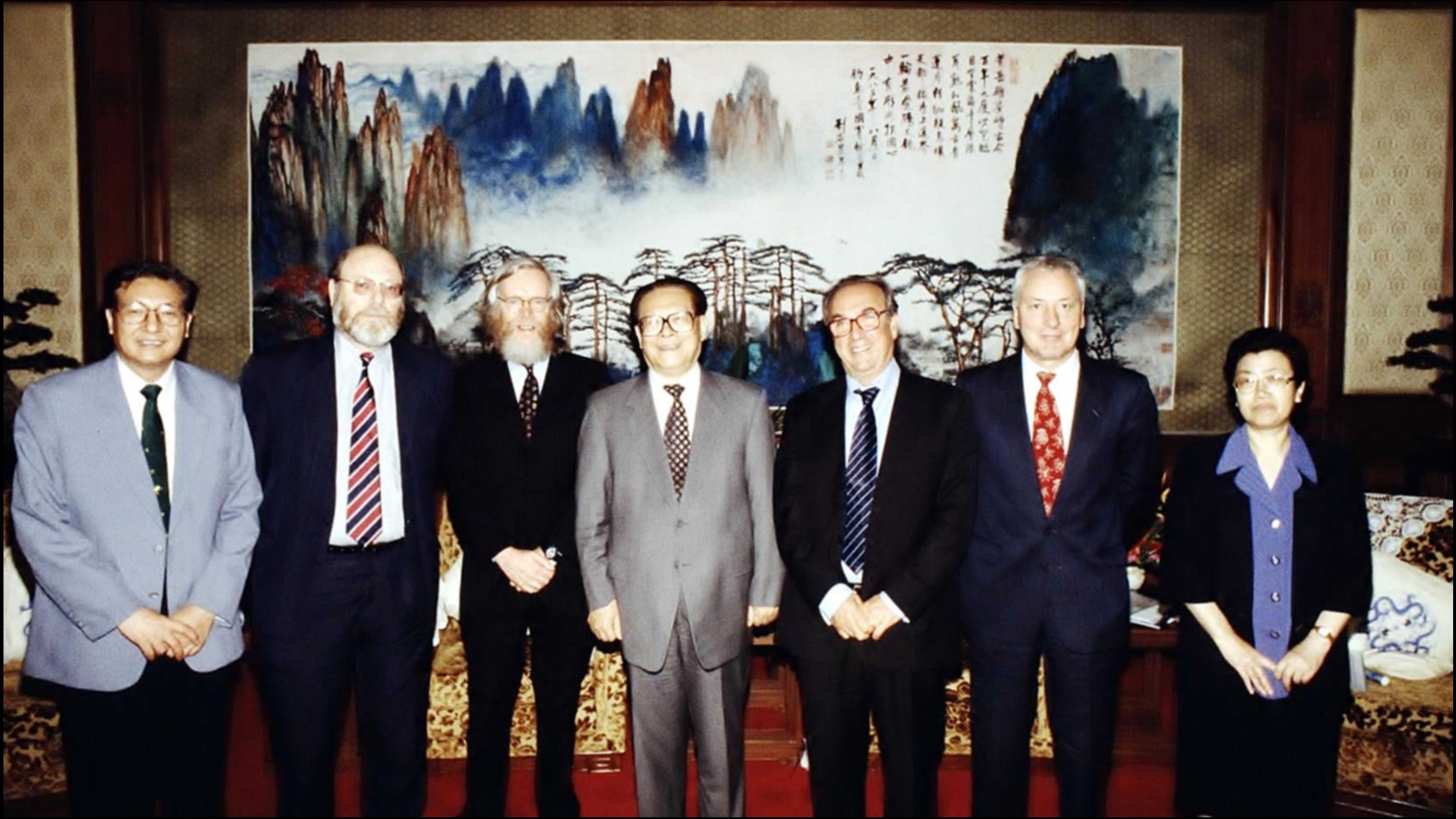
There are many sources of three jets events

By measuring many three jets events, we discovered that their distribution agrees with QCD predictions

L3 Experiment at CERN (1982-2003)

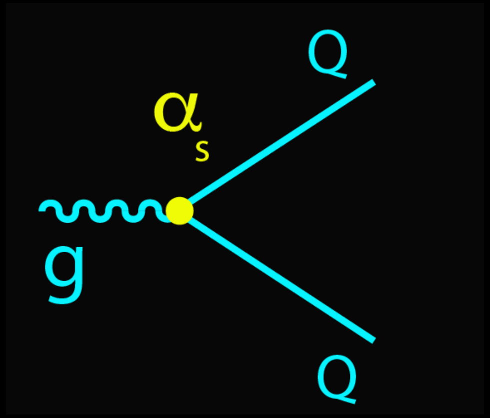


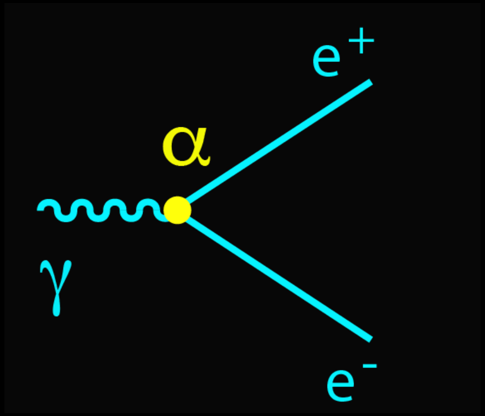


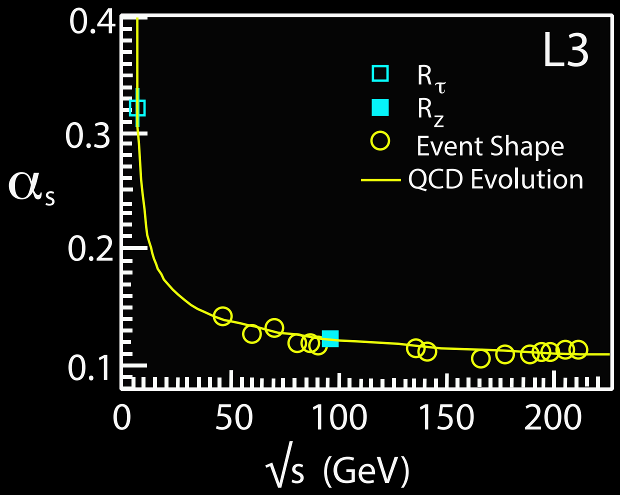


L3 Publications

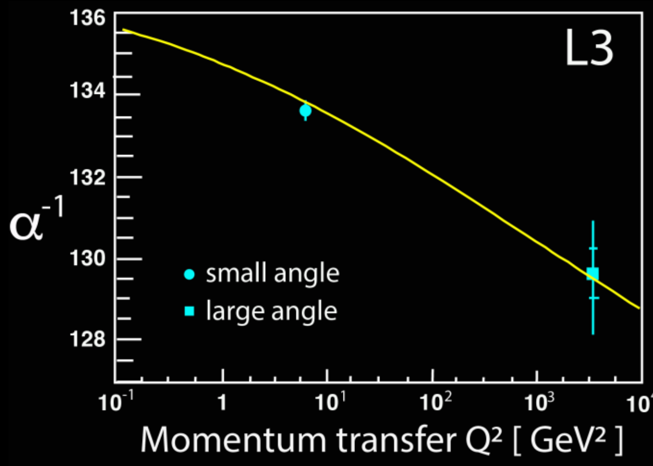
Dependence of the coupling “constants” on energy







Phys. Lett. B 476 (2000) 40

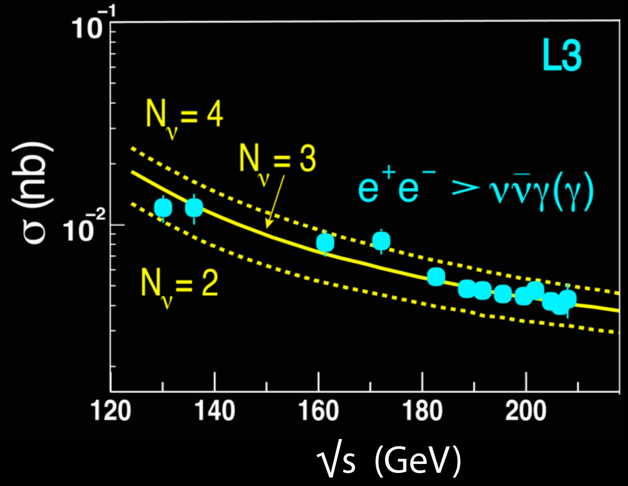


Phys. Lett. B 536 (2002) 217

Model independent measurement of the number of neutrinos

$$e^+ e^- \rightarrow \nu\bar{\nu}\gamma$$

$N_\nu = 2.98 \pm 0.064$

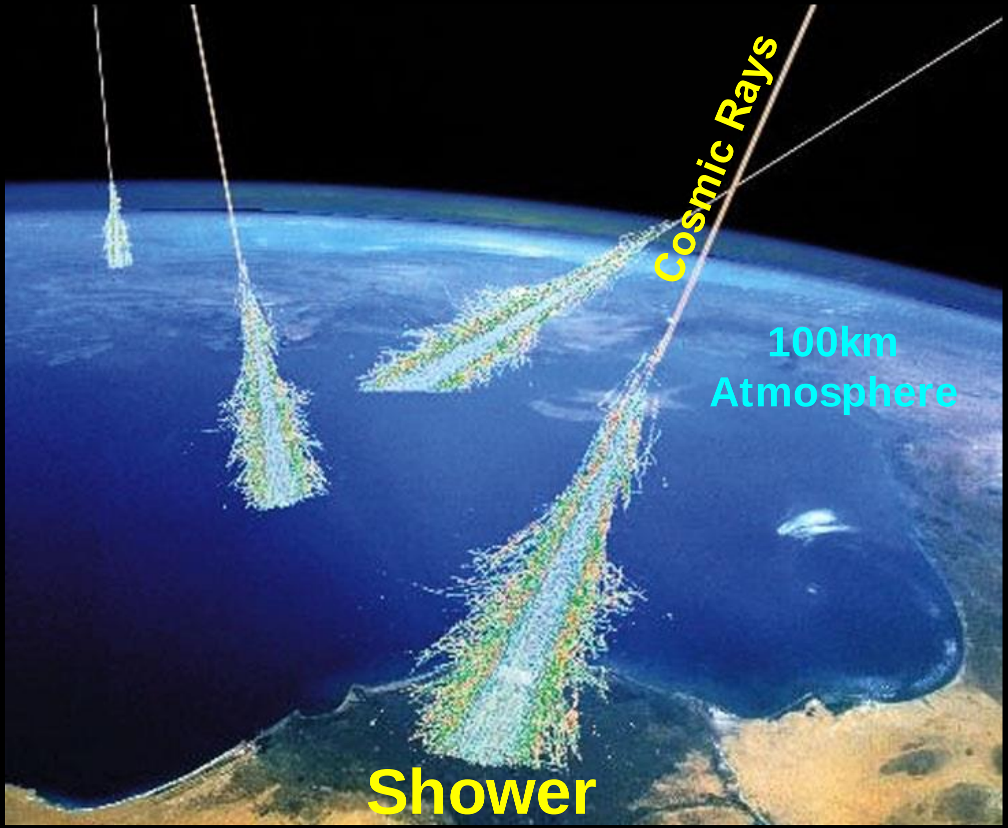


Phys. Lett. B 587 (2004) 16

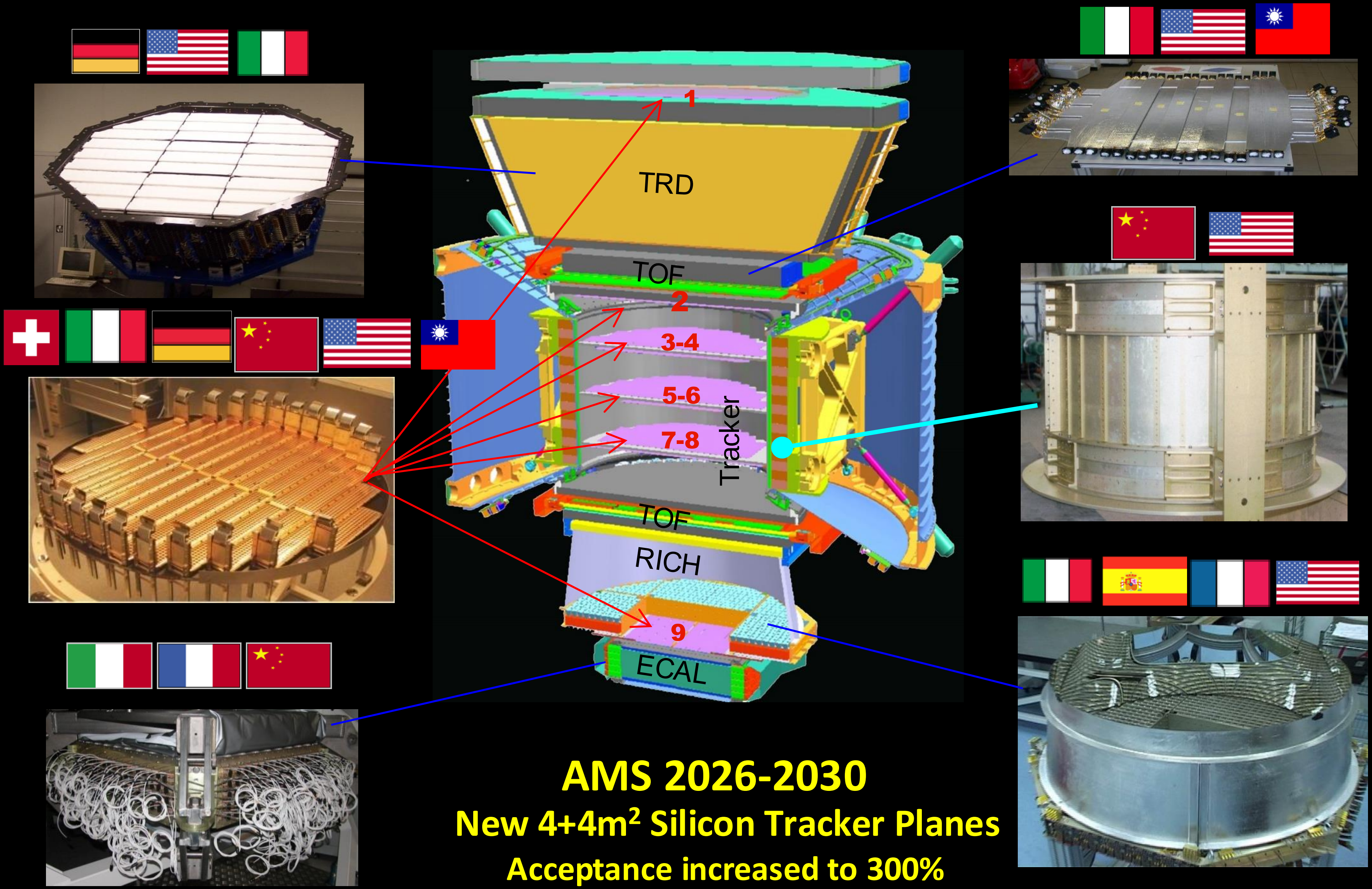
Electrons and Positrons in the Cosmos: AMS on the Space Station:

Charged cosmic rays have mass,
they are absorbed by the 100 km of Earth's atmosphere
(10m of water)
The properties (±*Z, P*) of charged cosmic rays cannot be studied on the ground.

To measure cosmic ray
charge and momentum requires
a magnetic spectrometer in space



AMS was constructed in Europe and Asia, assembled and tested at CERN and ESA with NASA support

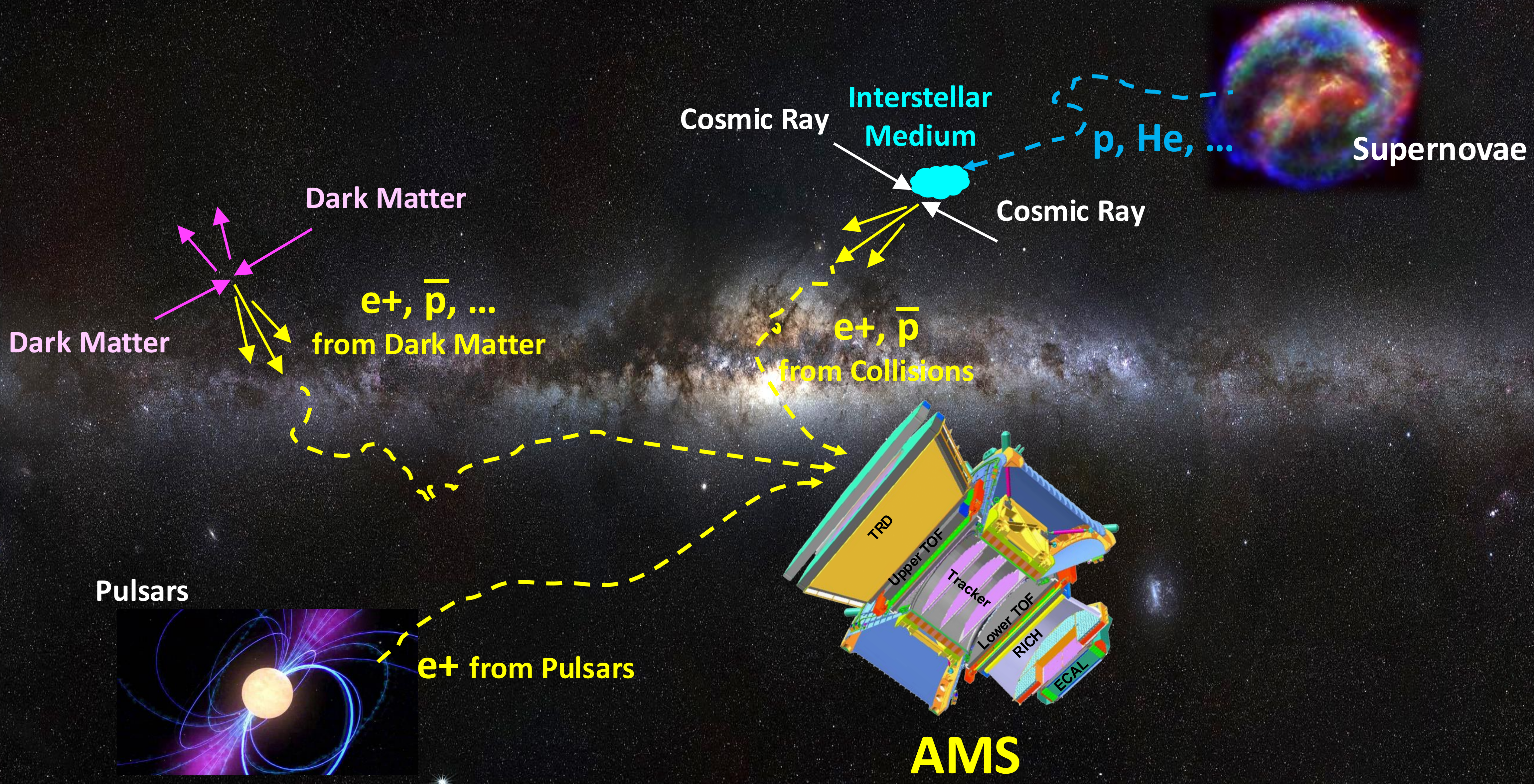


AMS 2026-2030

New 4+4m^2 Silicon Tracker Planes

Acceptance increased to 300%

Latest Results on cosmic elementary particles: e+, e−, and $\bar{p}$



Supernovae

p, He, …

Interstellar Medium

Cosmic Ray

Cosmic Ray

Dark Matter

Dark Matter

e+, $\bar{p}$, … from Dark Matter

e+, $\bar{p}$ from Collisions

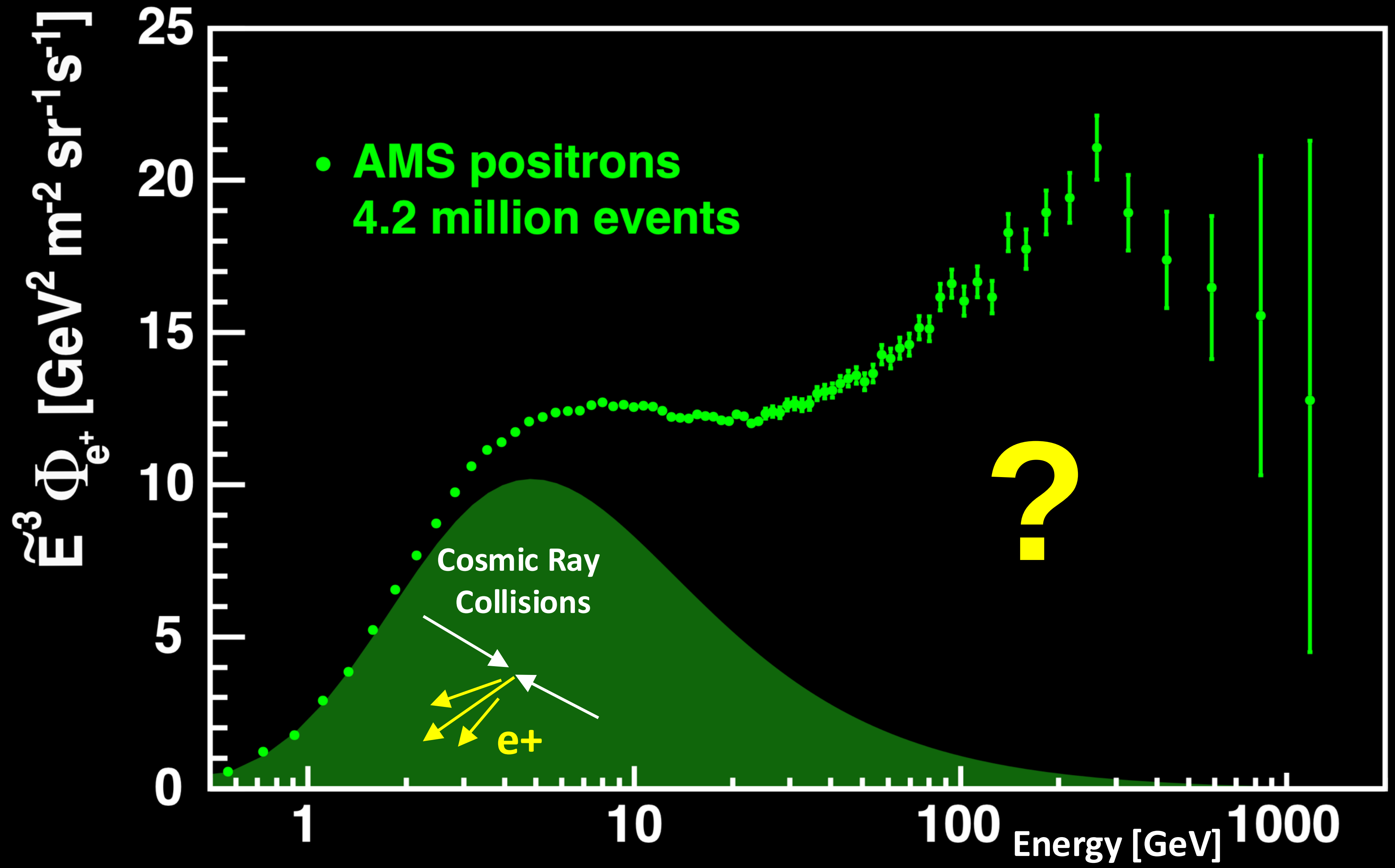
Pulsars

e+ from Pulsars

AMS

Low-energy positrons come from cosmic ray collisions

High-energy positrons must come from a new source

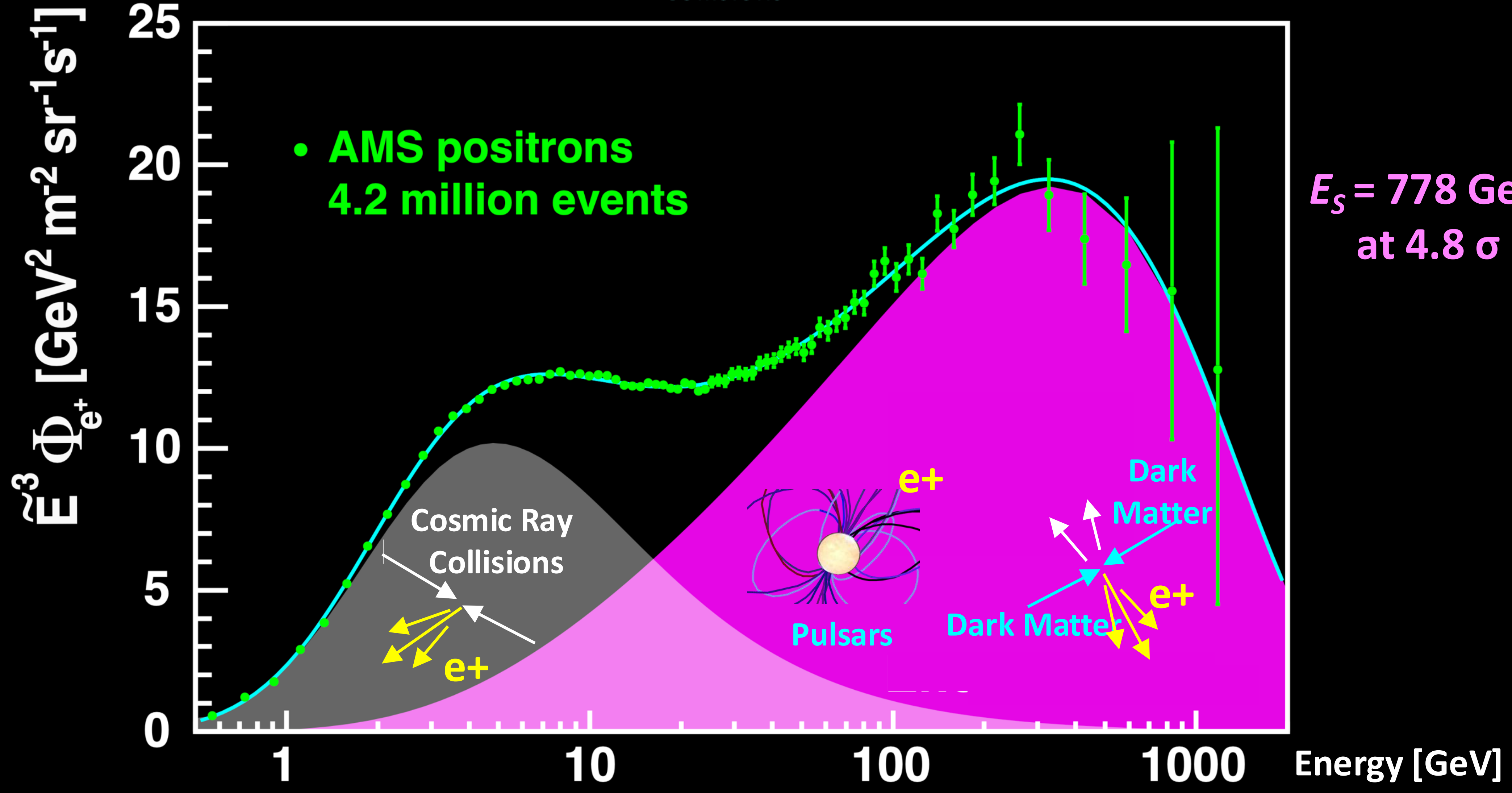


The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from pulsars or dark matter with a cutoff energy

Empirical model: $\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$

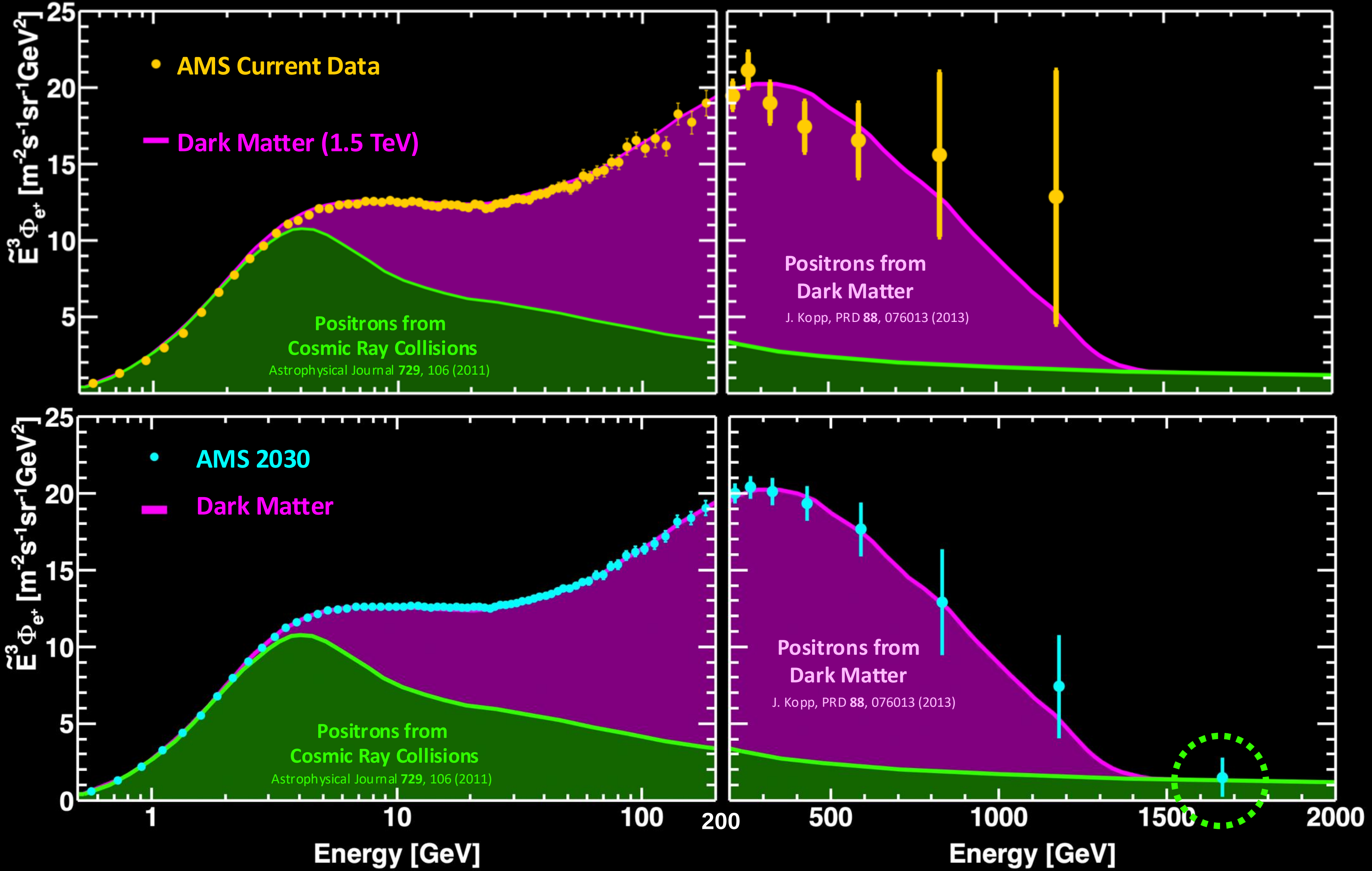
$\chi^2/\text{dof} = 63/66$

Solar Collisions Pulsars or Dark Matter



E_S = 778 GeV
at 4.8 σ

Positron spectrum to 2030



By 2030, AMS will ensure that the high energy positron spectrum drops off quickly in the 0.2-2 TeV region and the highest energy positrons only come from cosmic ray collisions as predicted for dark matter collisions

AMS Result on the electron spectrum

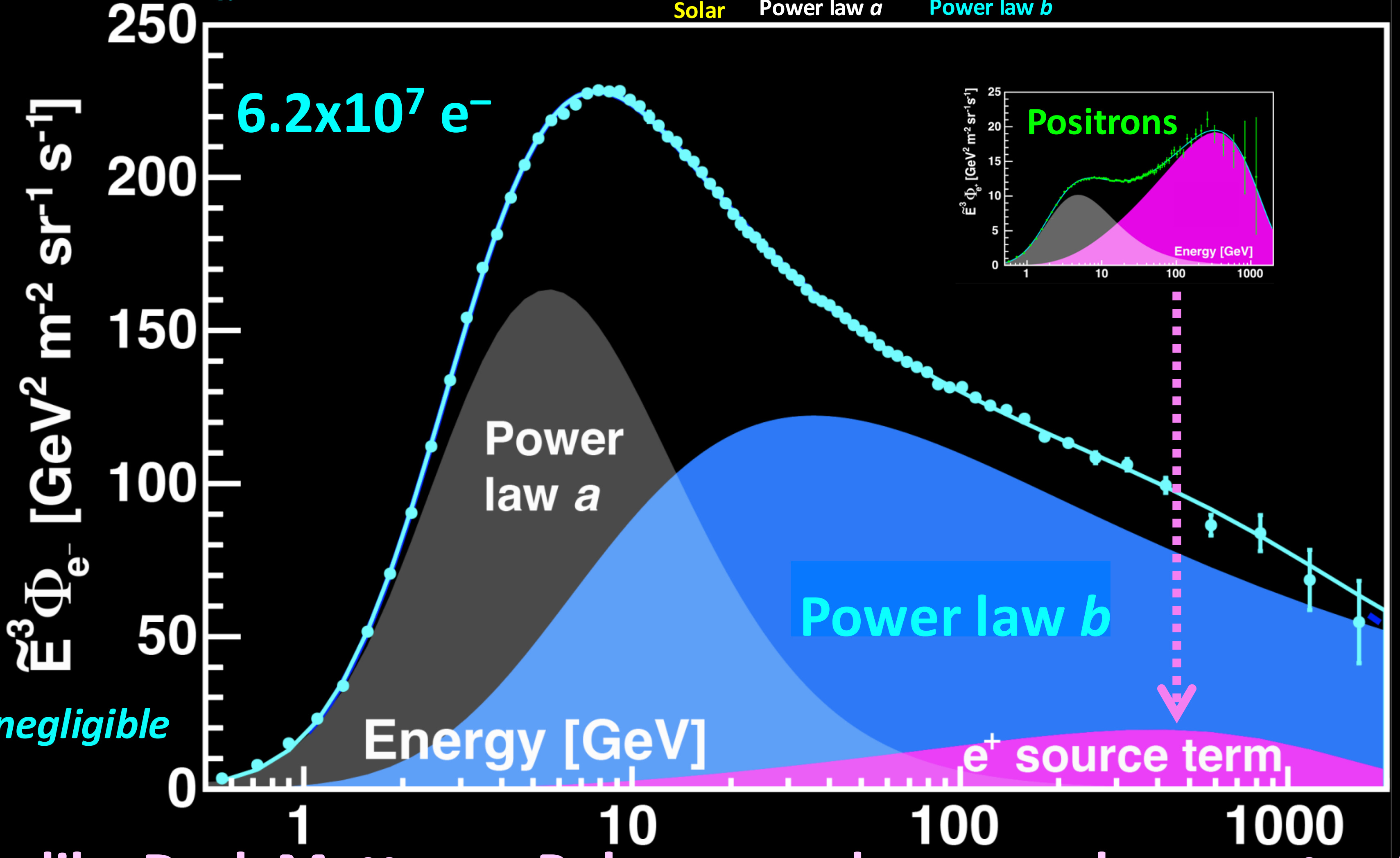
The spectrum fits well with two power laws (*a*, *b*) and a source term like positrons

Empirical model:

$\chi^2/\text{dof} = 47/67$

$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}\left(C_a \hat{E}^{\gamma_a} + C_b \hat{E}^{\gamma_b} + \text{Positron Source Term}\right)$$

Solar Power law *a* Power law *b*



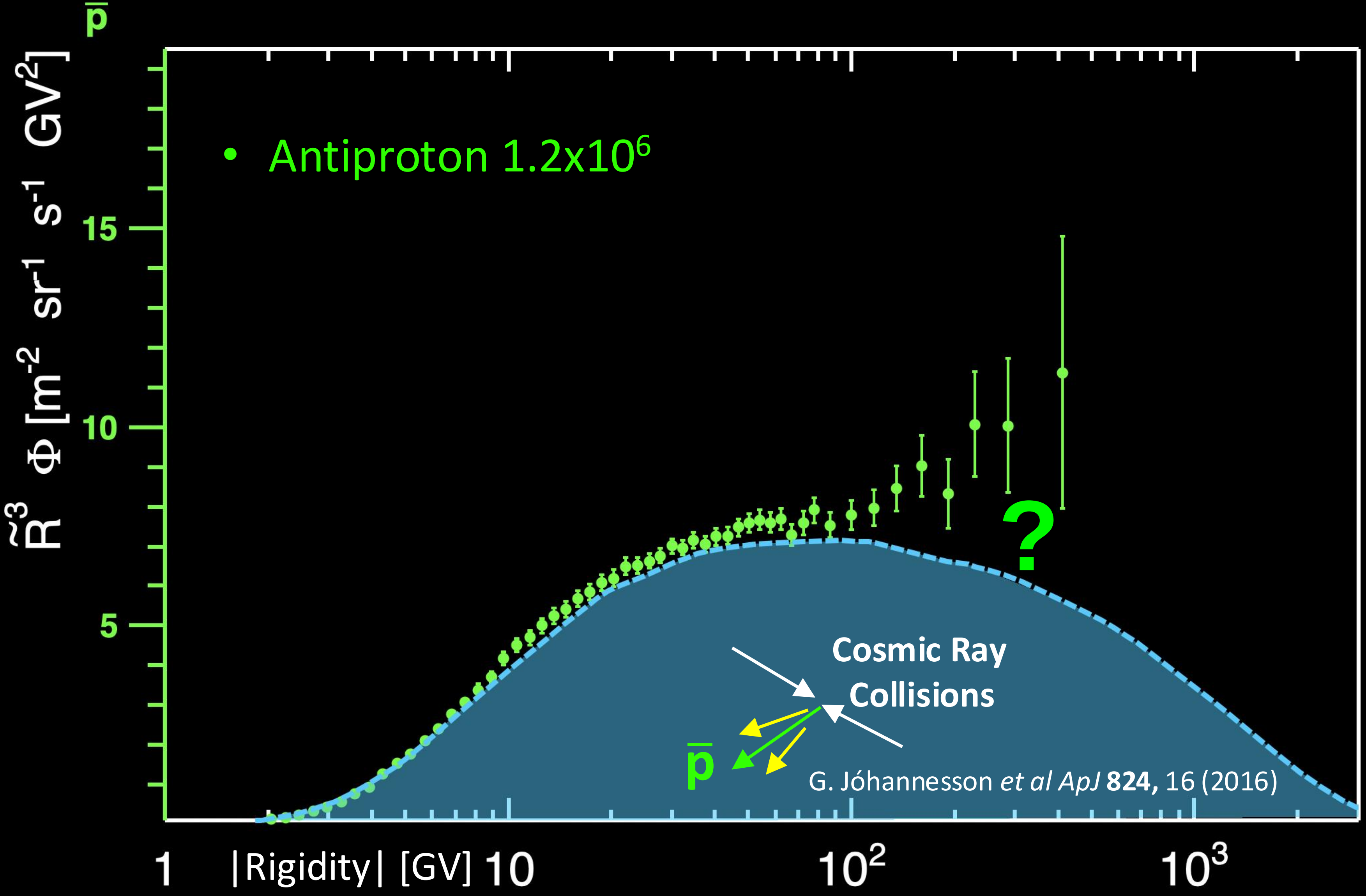
e⁻ from collisions negligible

98.8% CL

99.99% CL
by 2030

New sources, like Dark Matter or Pulsars, produce equal amounts of e+ and e−

Cosmic Antiprotons

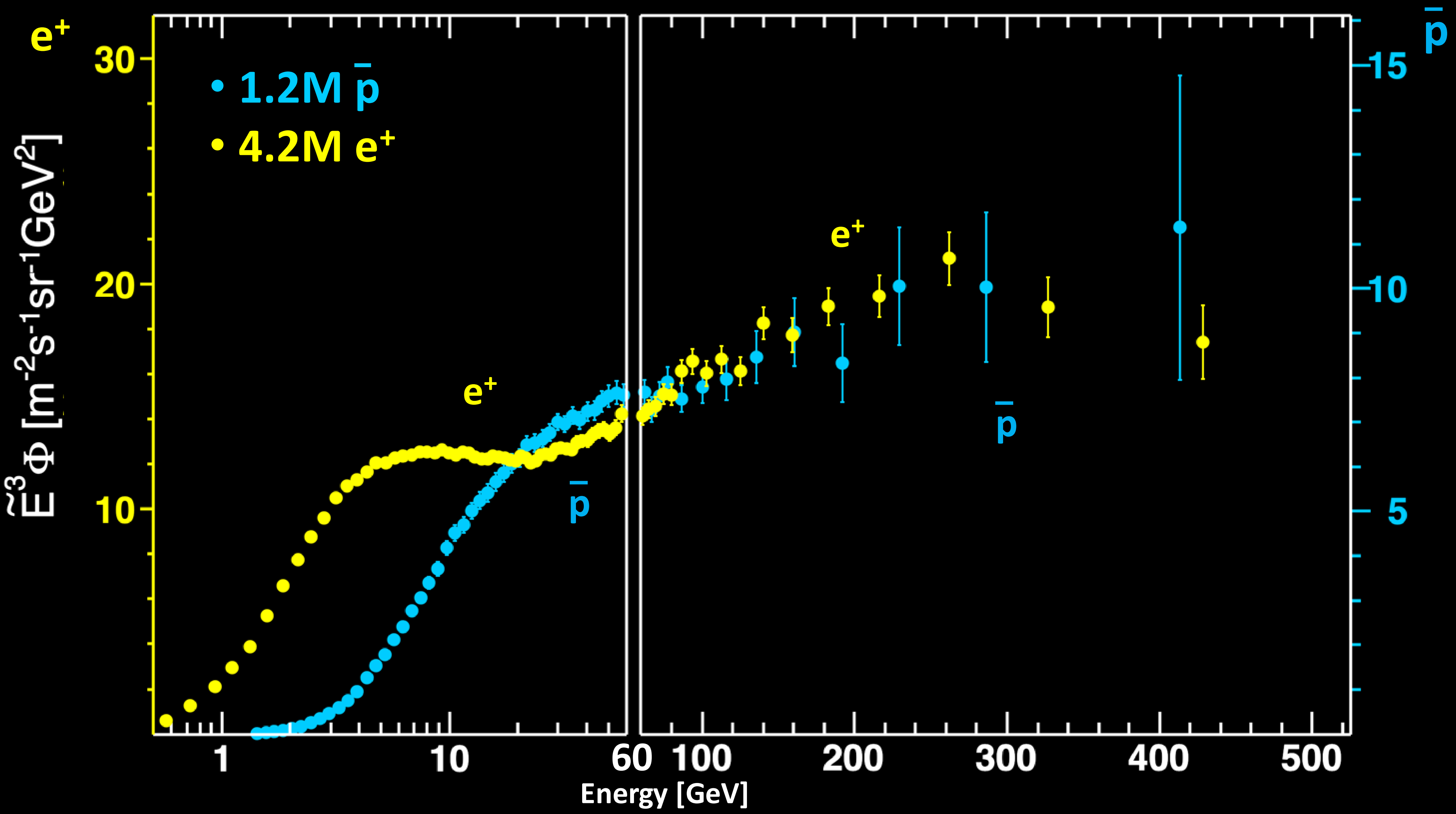


G. Jóhannesson *et al ApJ* **824,** 16 (2016)

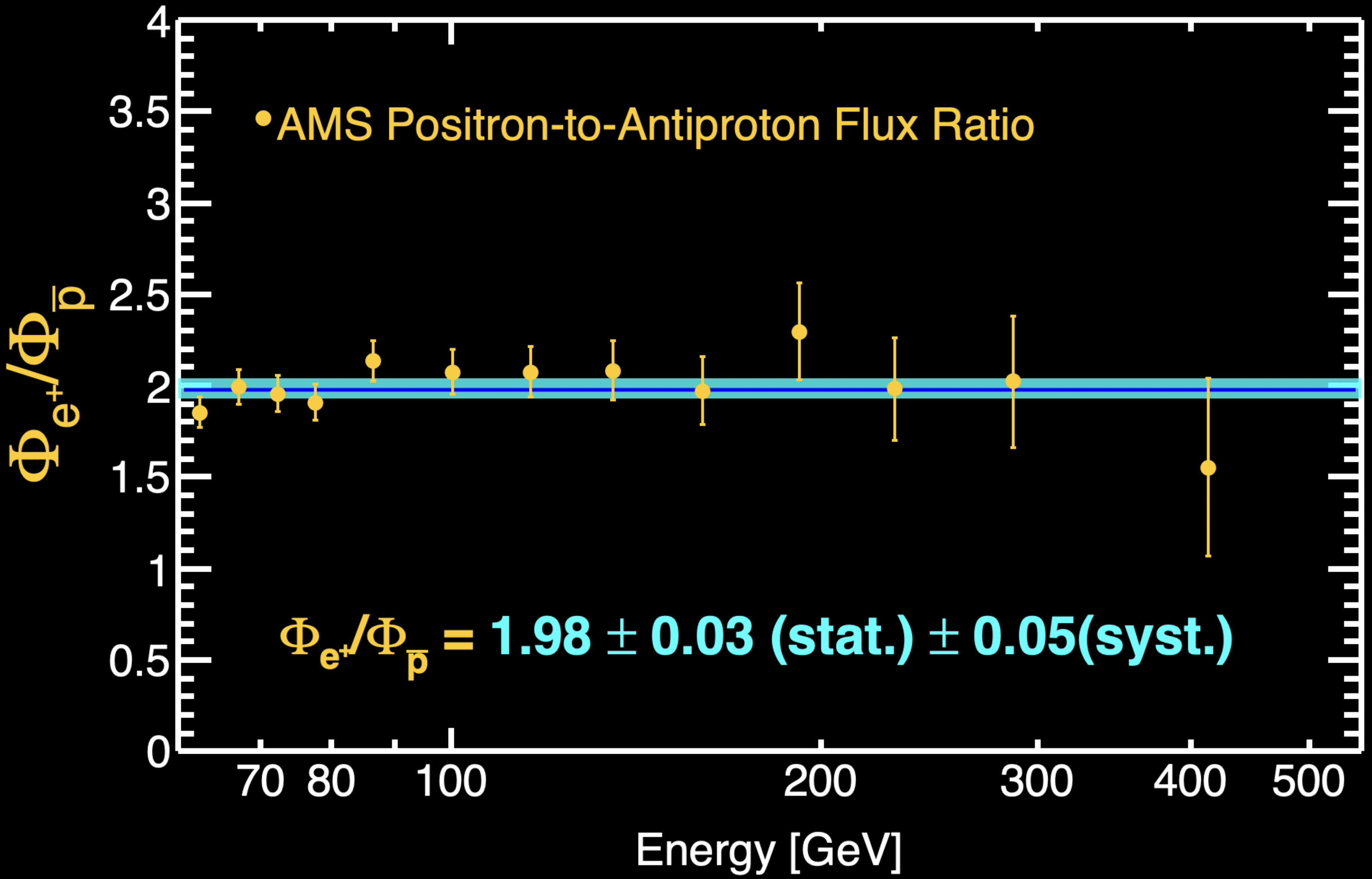
p̄ are not produced by pulsars nor by cosmic ray collisions above 60 GV

Cosmic Antiprotons and Positrons

Above 60 GeV, the $\bar{p}$ and e^+ fluxes have identical rigidity dependence

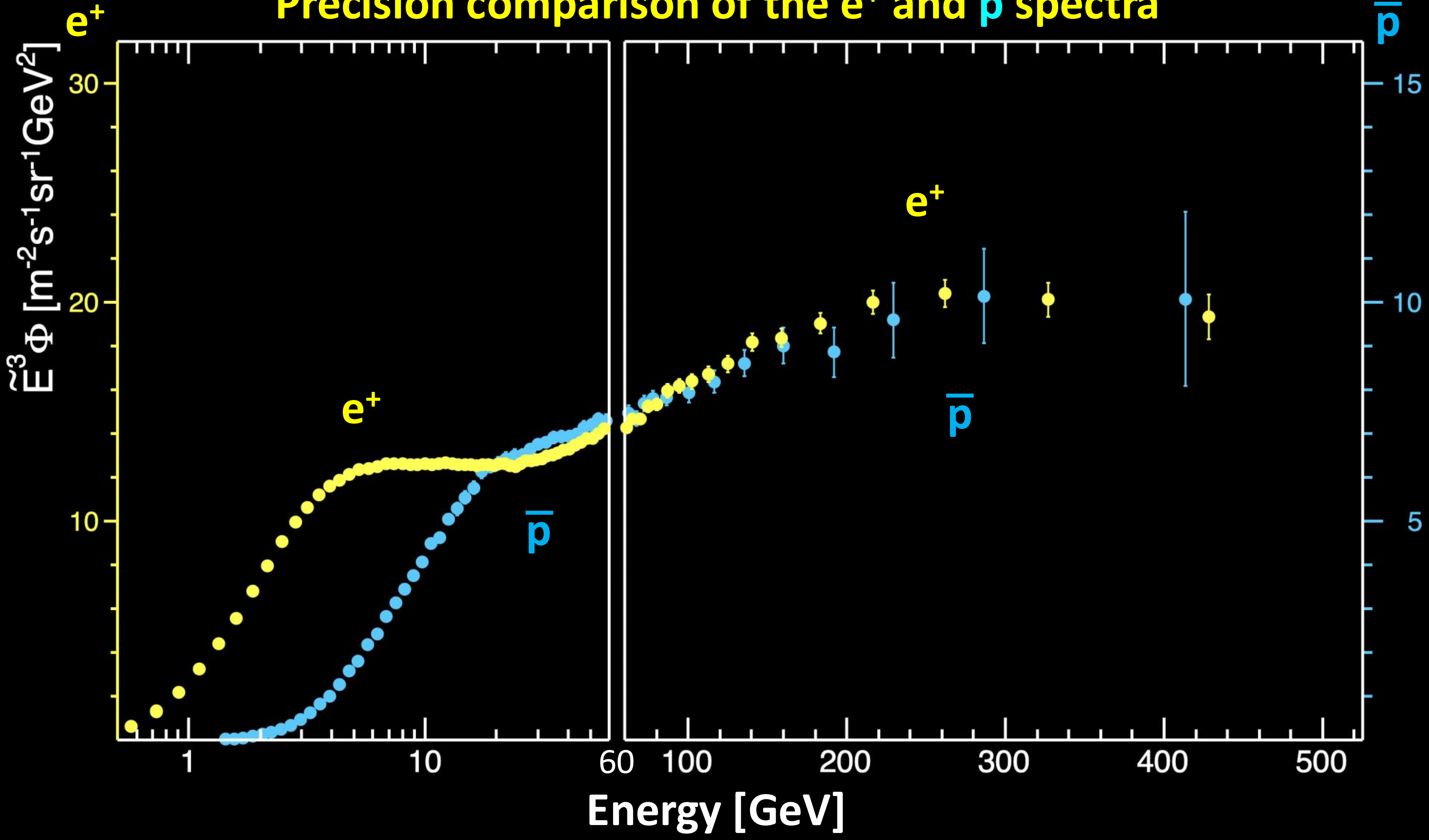


The positron-to-antiproton flux ratio is independent of energy.



Antiproton to 2030

Precision comparison of the e^+ and $\overline{p}$ spectra

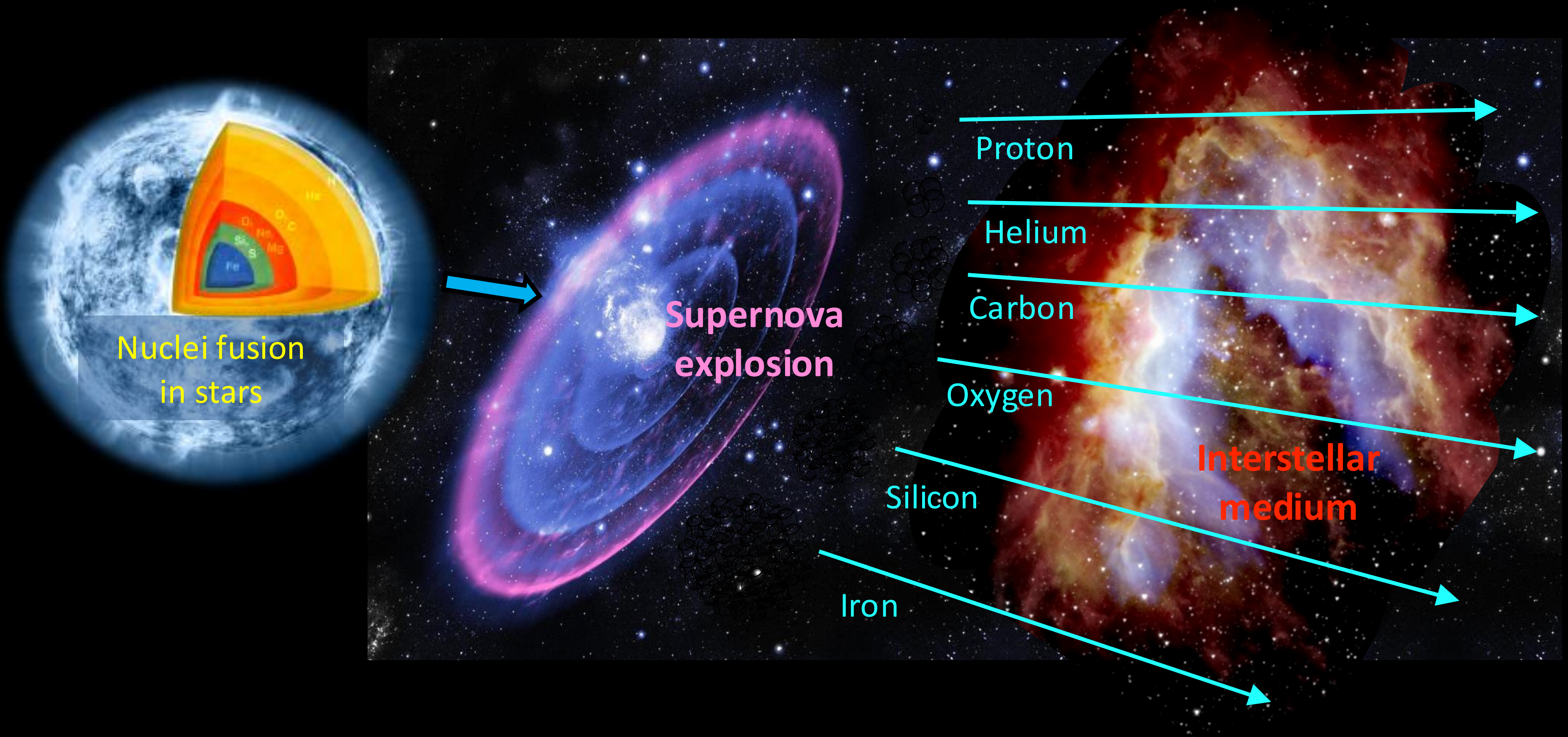


The identical behavior of positrons and antiprotons above 60 GeV excludes the pulsar origin of positrons

AMS Results on Primary Cosmic Rays

Primary cosmic rays p, He, C, O, ..., Si, ..., Fe

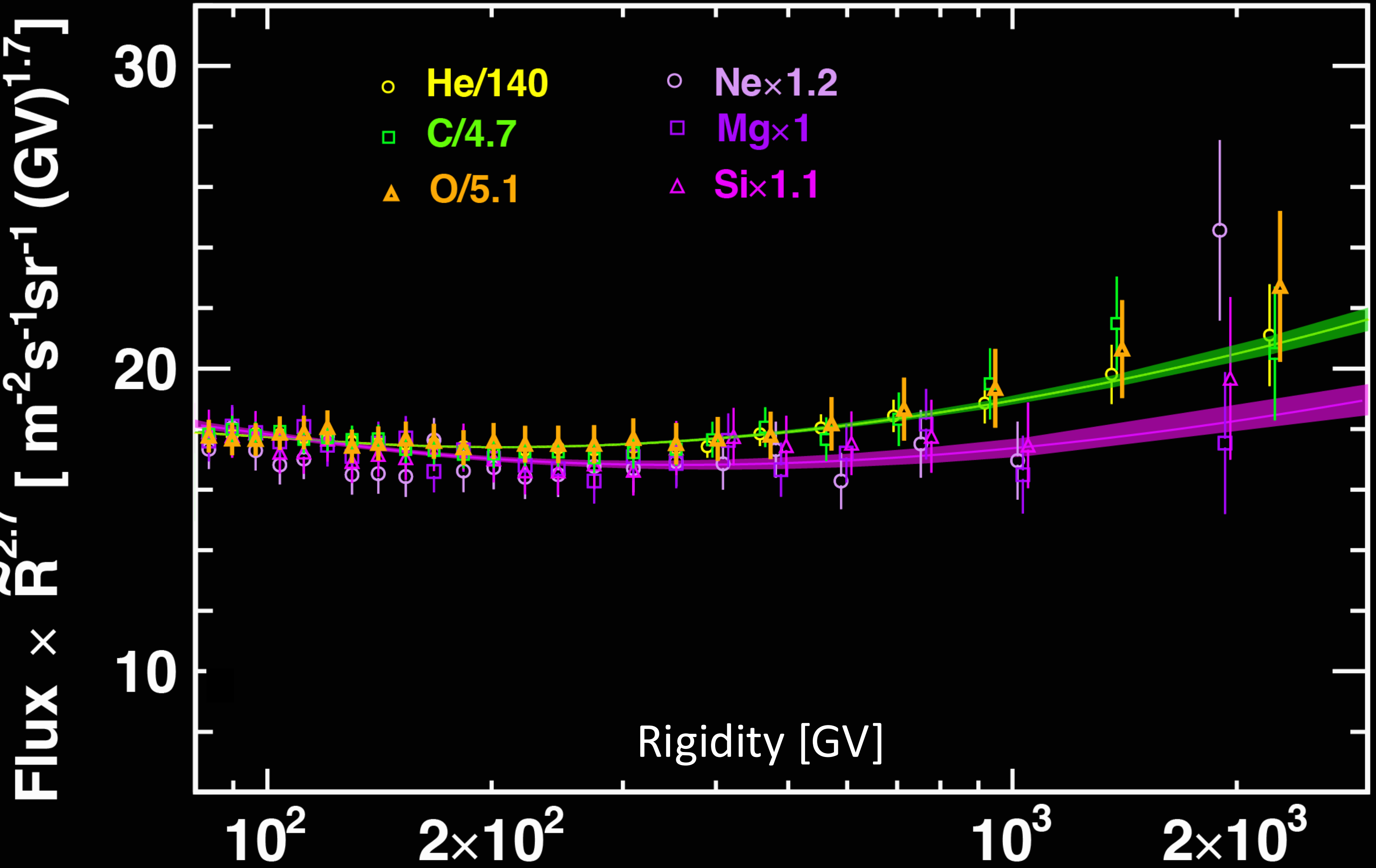
are produced during the lifetime of stars and accelerated by supernovae.
They propagate through interstellar medium before they reach AMS.



Measurements of primary cosmic ray fluxes are fundamental to understanding the origin, acceleration, and propagation processes of cosmic rays in the Galaxy.

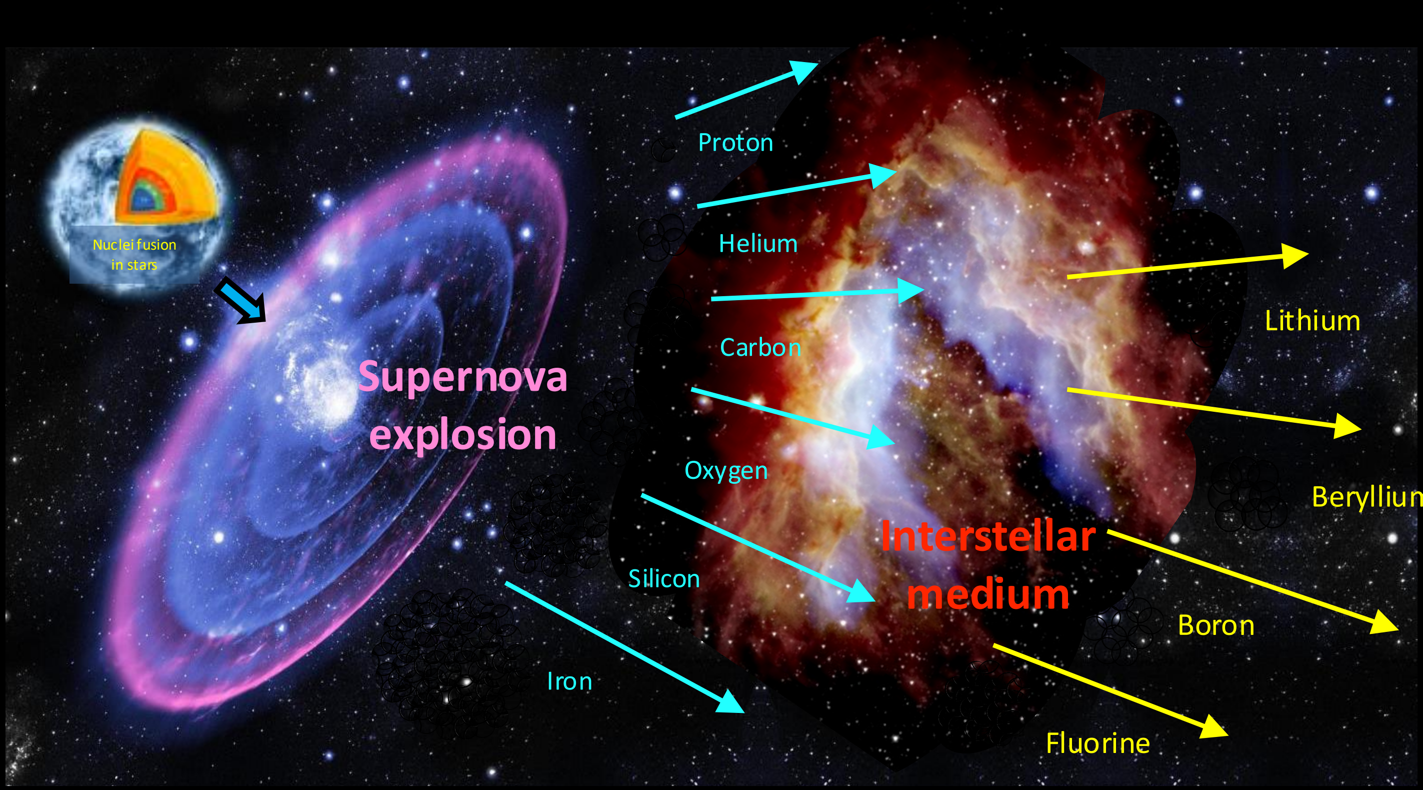
Primary cosmic rays have two classes

Light elements He-C-O and Heavier elements Ne-Mg-Si each have their own rigidity dependence



AMS Results on Secondary Cosmic Ray Nuclei

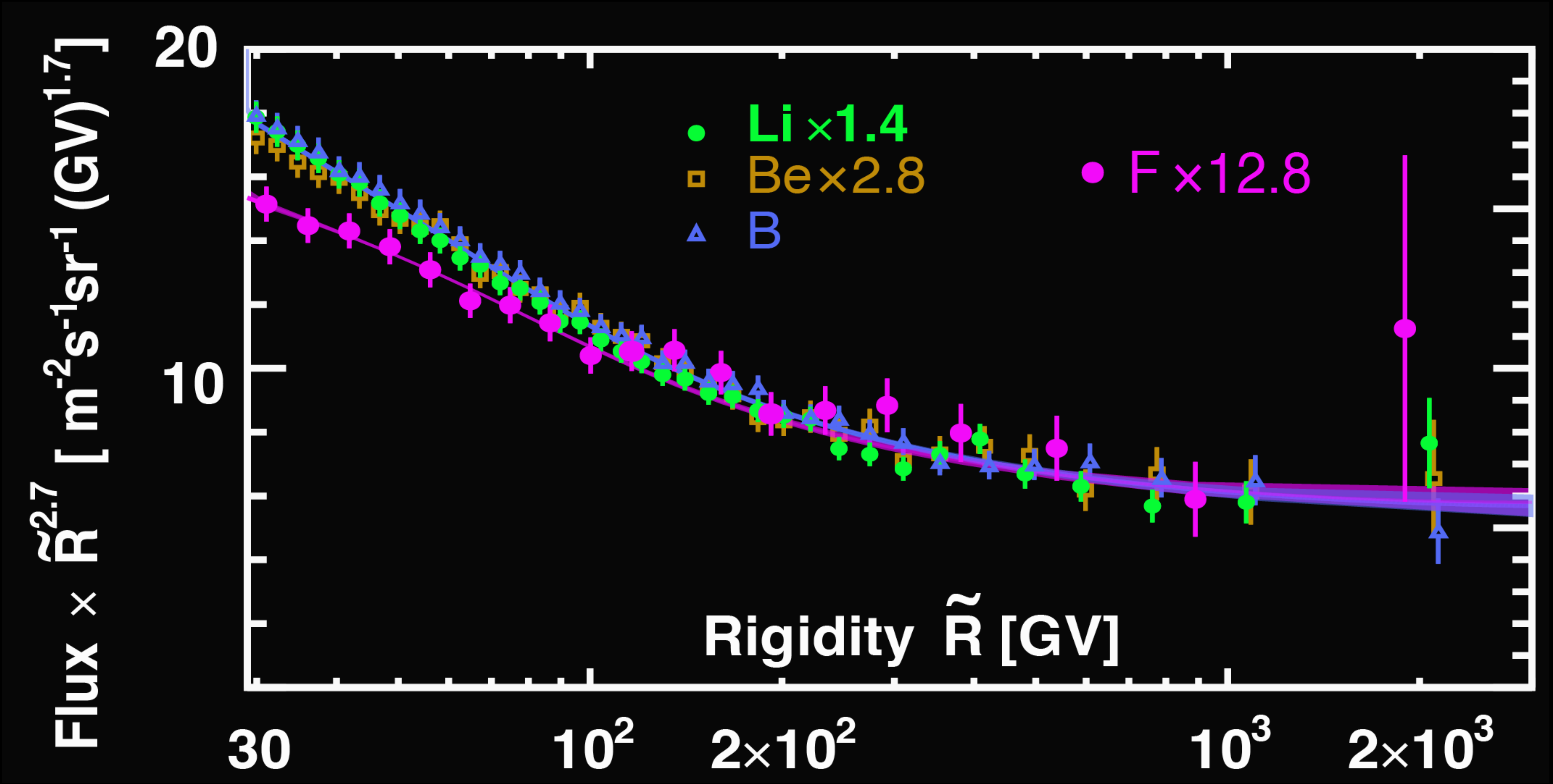
Secondary Li, Be, B, and F nuclei in cosmic rays are produced by the collision of primary cosmic rays C, O, Ne, Mg, Si, …, Fe with the interstellar medium.



Measurements of the secondary cosmic ray nuclei fluxes are important in understanding the propagation of cosmic rays in the Galaxy.

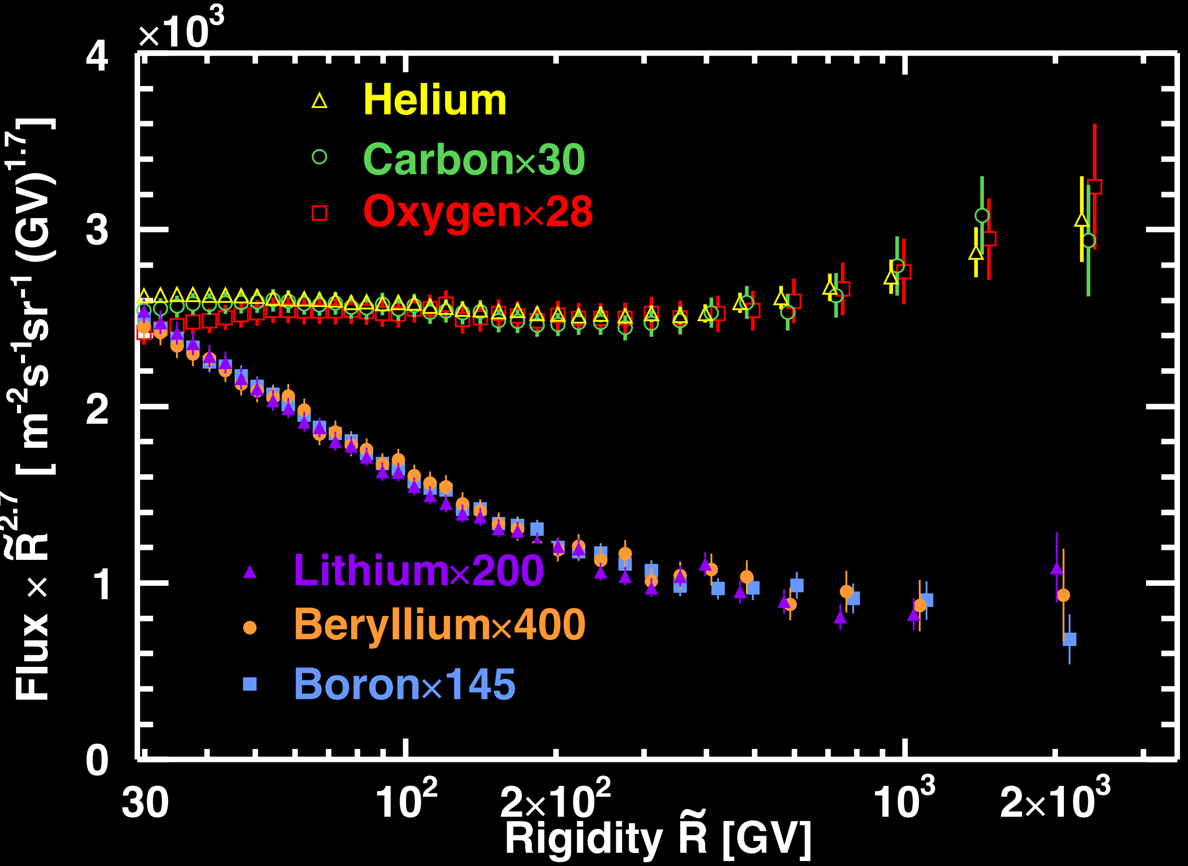
Secondary cosmic rays have two classes of rigidity dependence

Li-Be-B and F



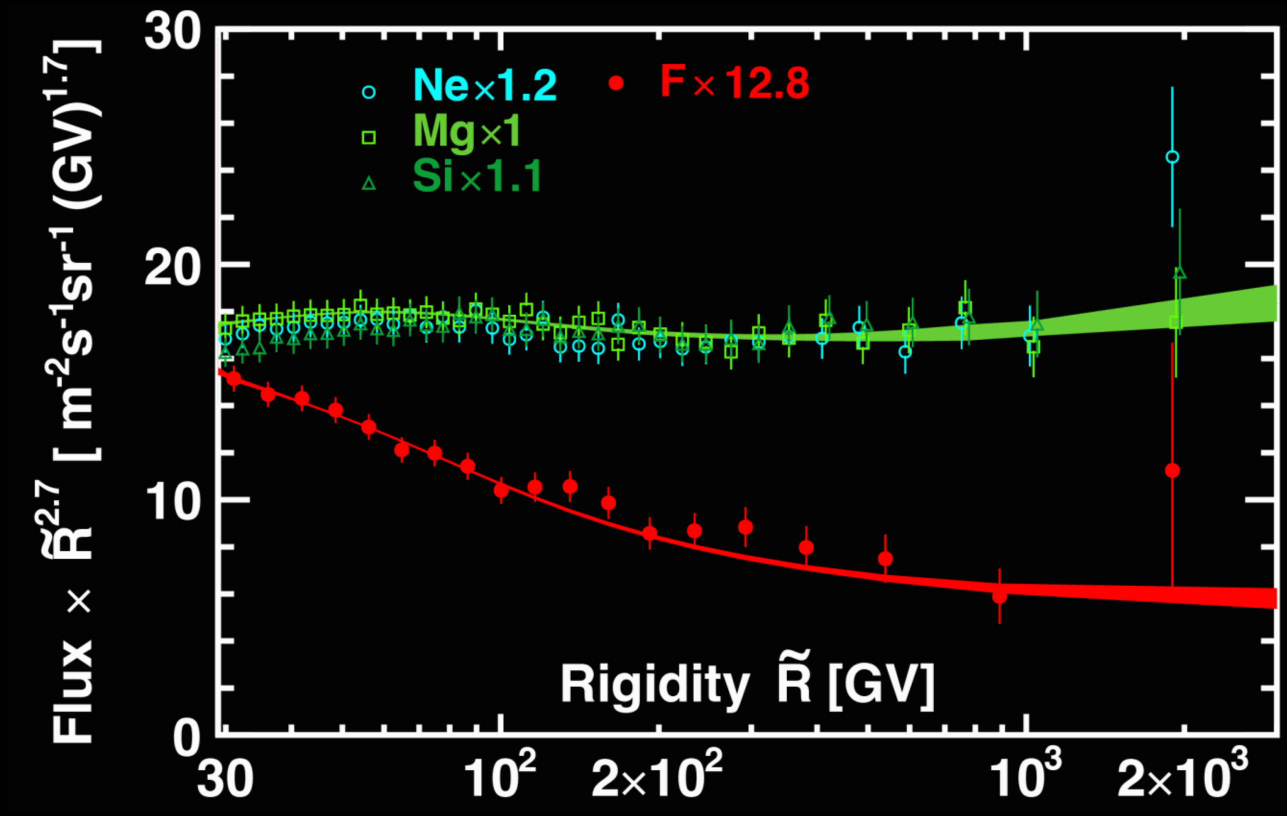
Light Nuclei 2 ≤ Z ≤ 8

He-C-O primaries compared with Li-Be-B secondaries



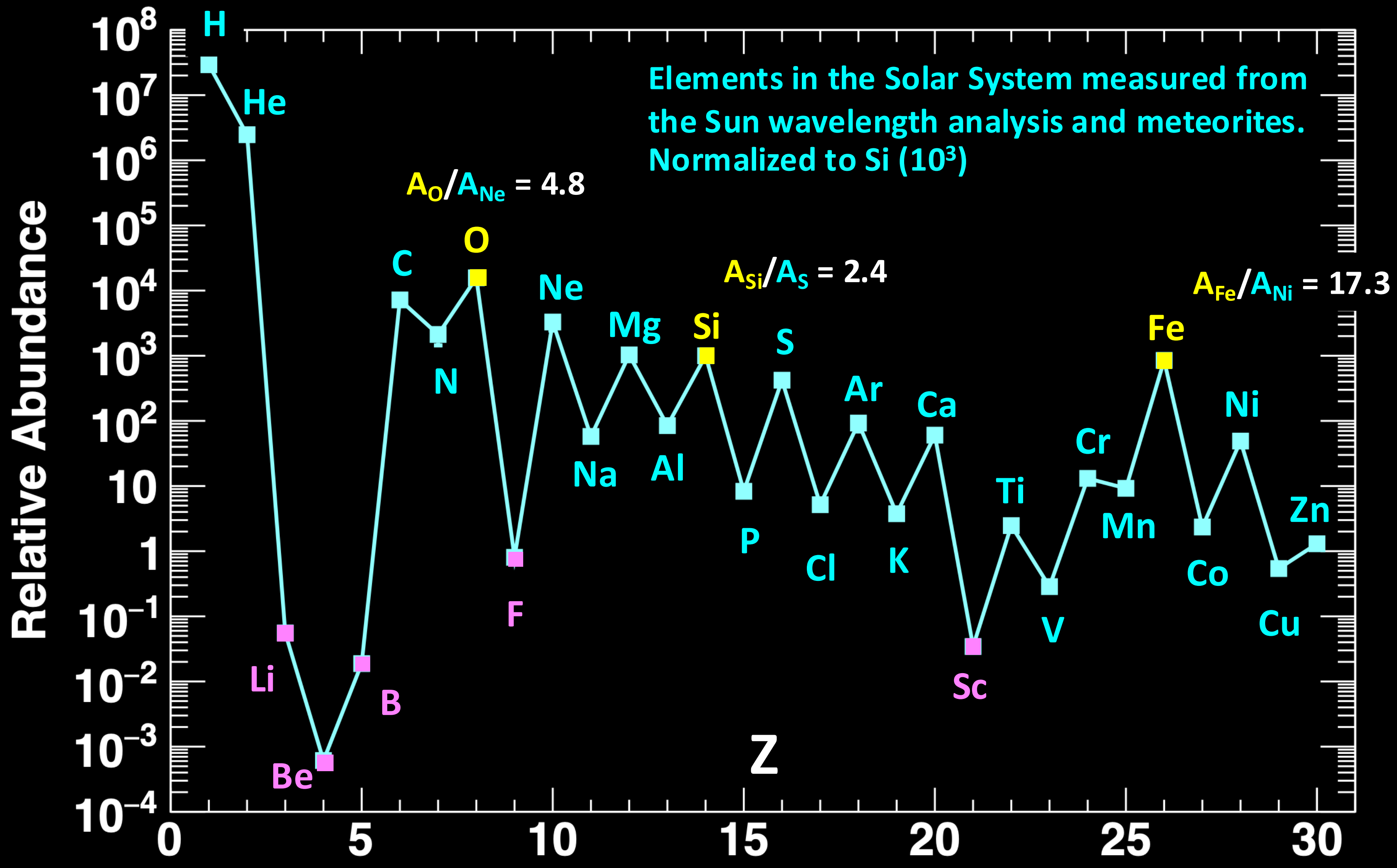
Heavier Nuclei 9 ≤ Z ≤ 14

Ne-Mg-Si primaries compared with F secondaries



Light and heavy nuclei each have two distinct classes

Abundance of elements in the Solar System

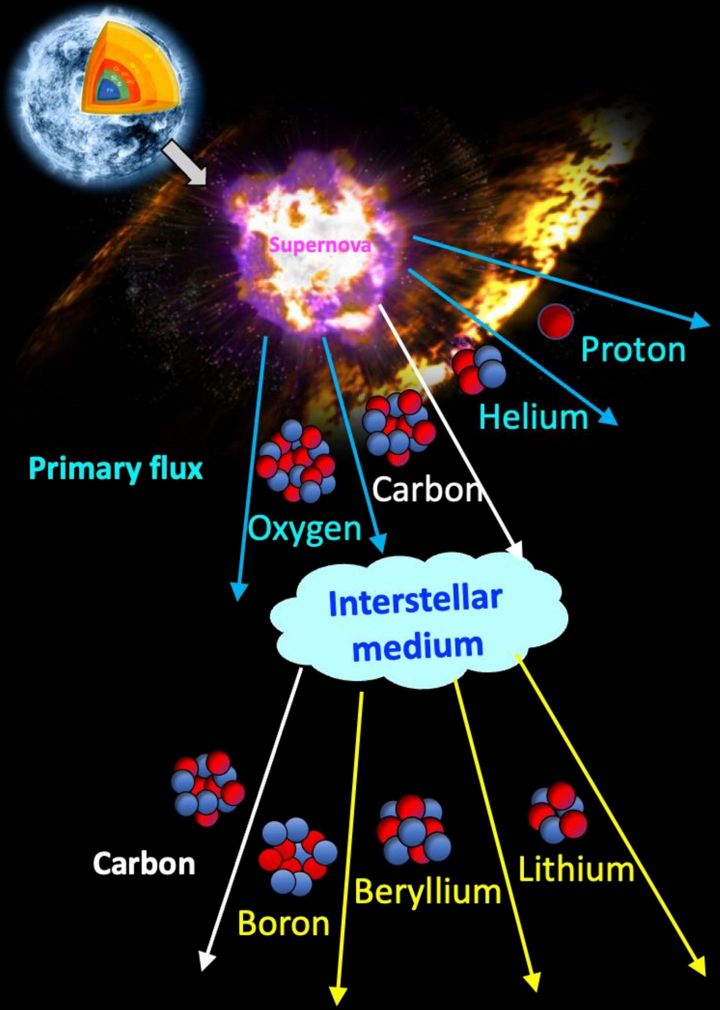


O, Si, and Fe are characteristic primary cosmic rays

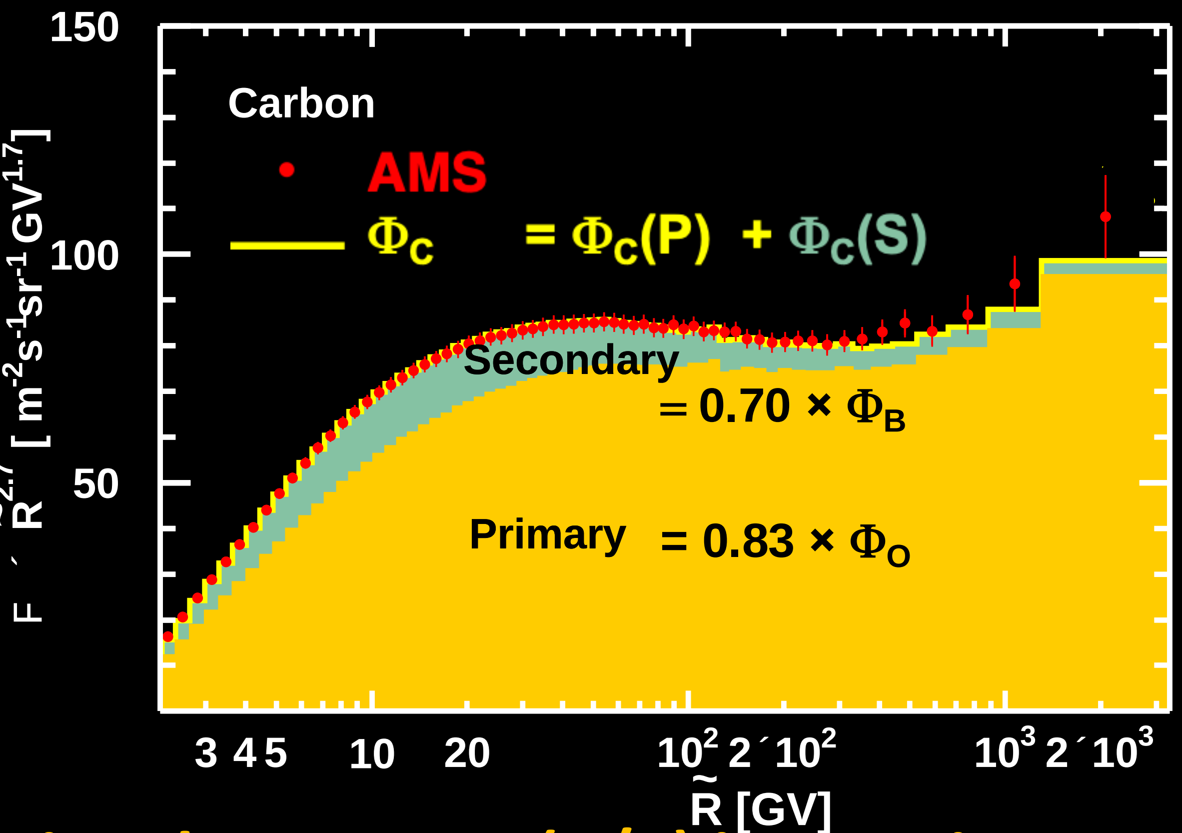
Li, Be, B, F, and Sc are characteristic secondary cosmic rays

Further Surprising Results:

Before AMS, taking into account the long-standing idea that C is pure primary and B is pure secondary, the (B/C) ratio has been used in models to describe cosmic ray propagation

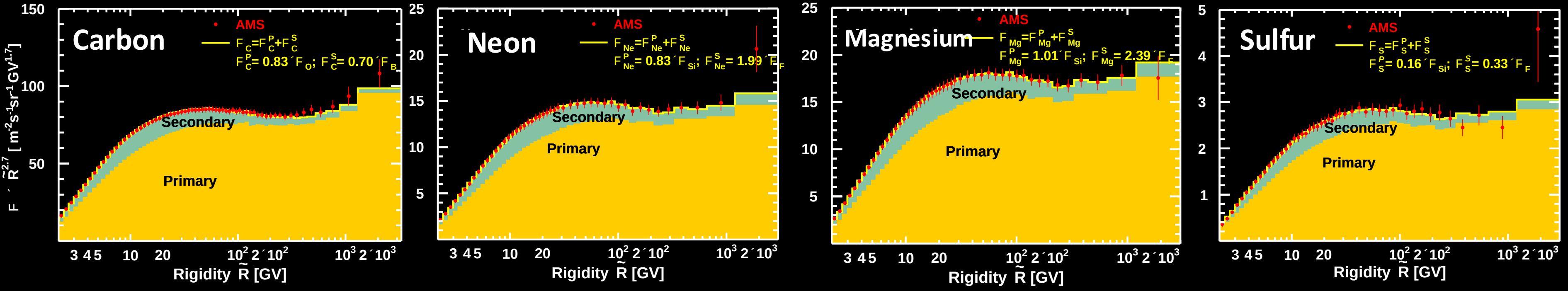


The spectrum of carbon Φ_C is the composition of a primary flux $\Phi_C(P)$ identical to $0.83 \times \Phi_O$ oxygen and a secondary flux $\Phi_C(S)$ identical to $0.70 \times \Phi_B$ boron

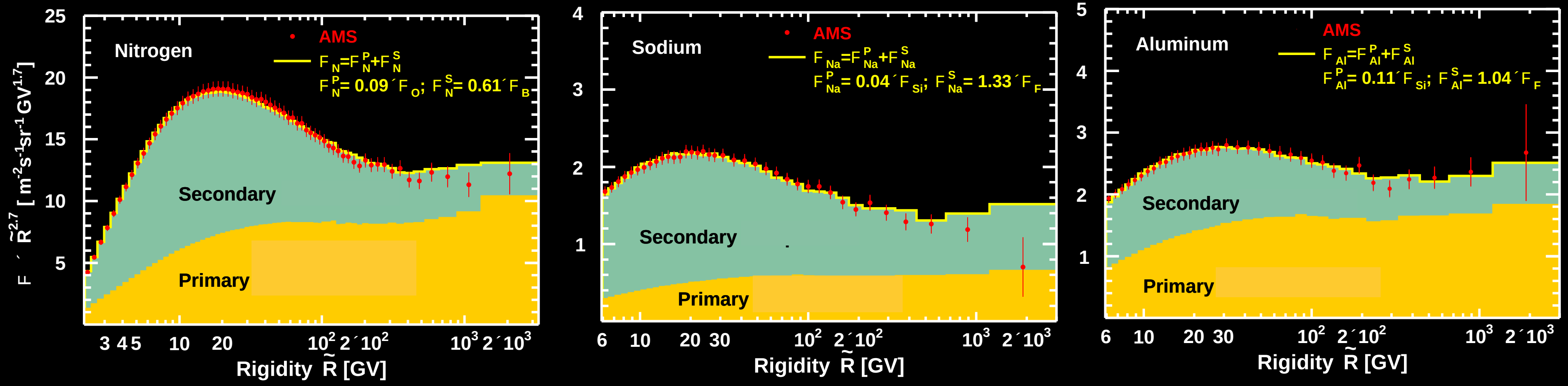


But C is NOT pure primary. Question: how to use (B/C) in cosmic ray models?

Even-Z nuclei and Odd-Z nuclei have distinctly different primary and secondary composition

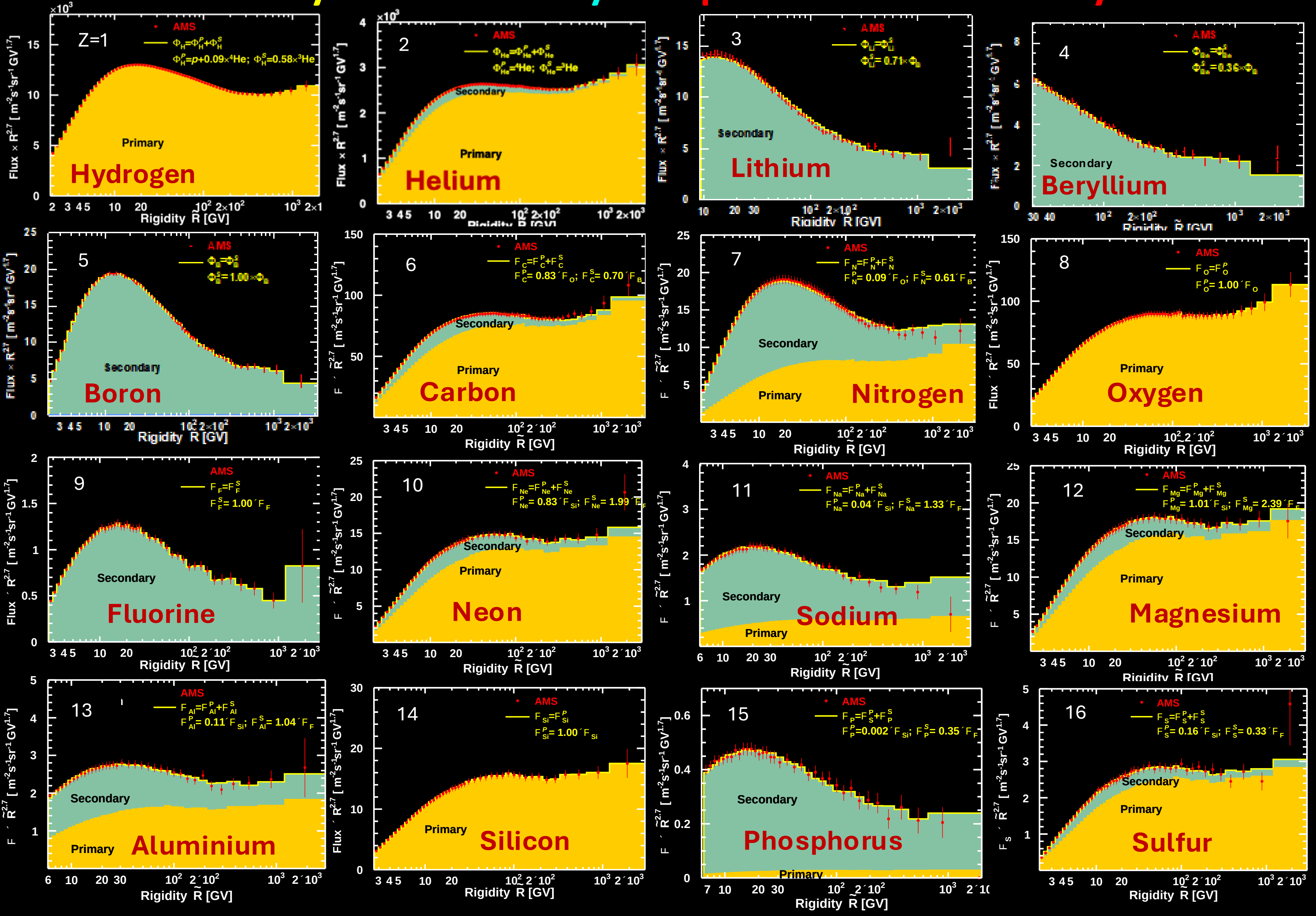


Even-Z nuclei are dominated by primaries



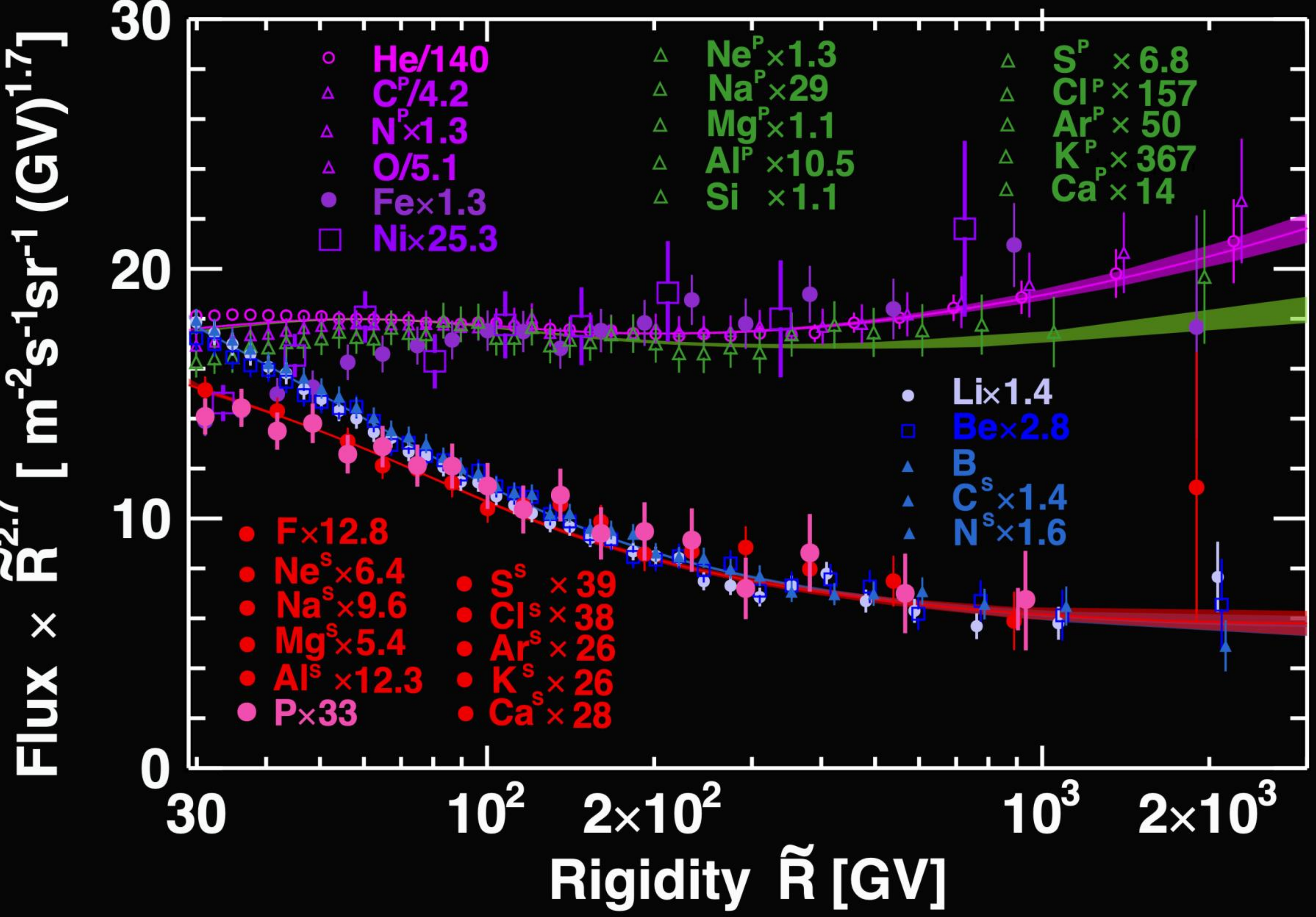
Odd-Z nuclei have more secondaries than even-Z

Primary and Secondary Composition of Cosmic Rays

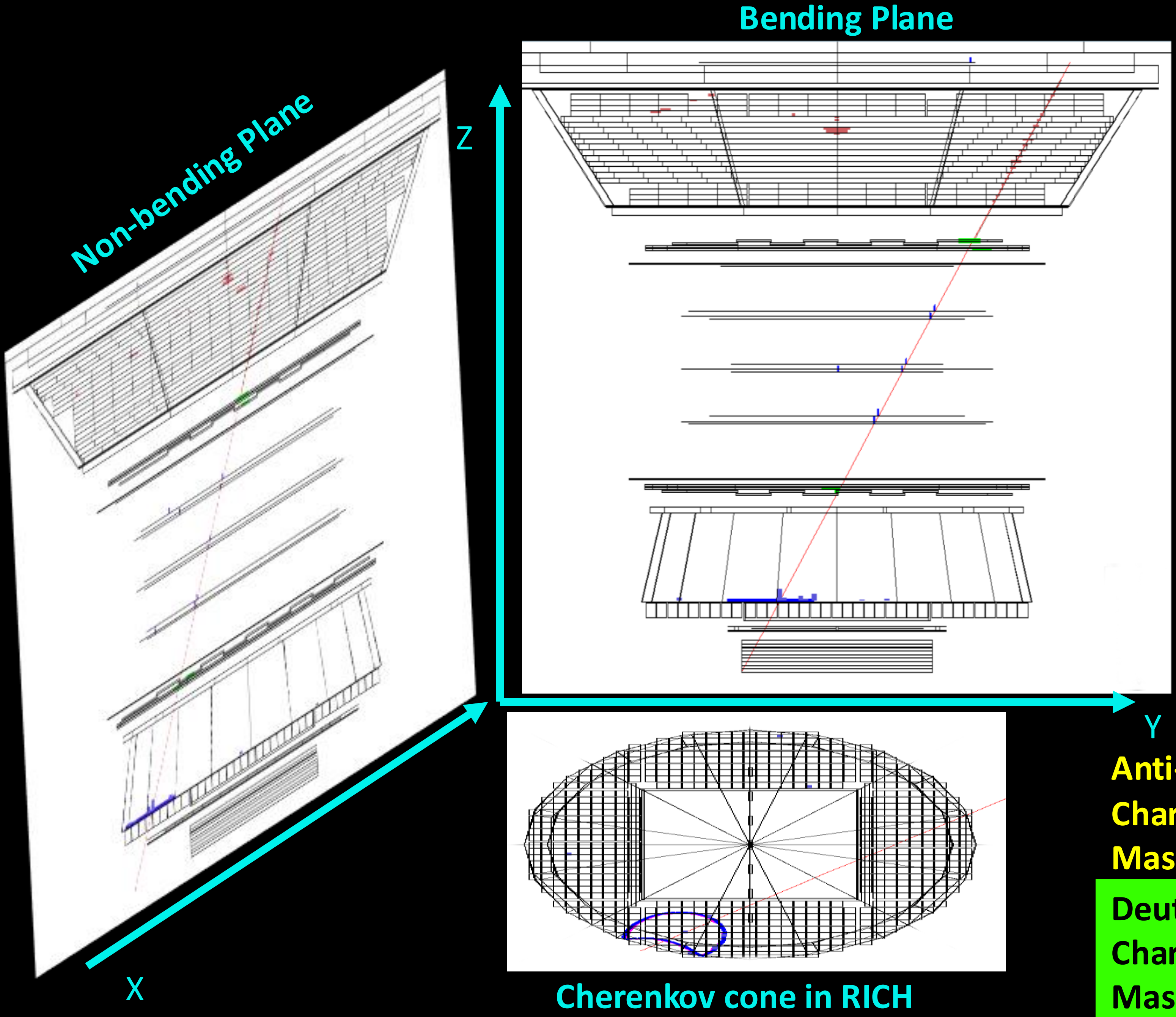


Progress on 21 of 28 elements:

Decomposition of Primary and Secondary Cosmic Ray Fluxes



An Anti-Deuteron Candidate from ~100 million deuterons and ~10 billion protons



Anti-deuteron Candidate

Charge = −1.02 ± 0.05

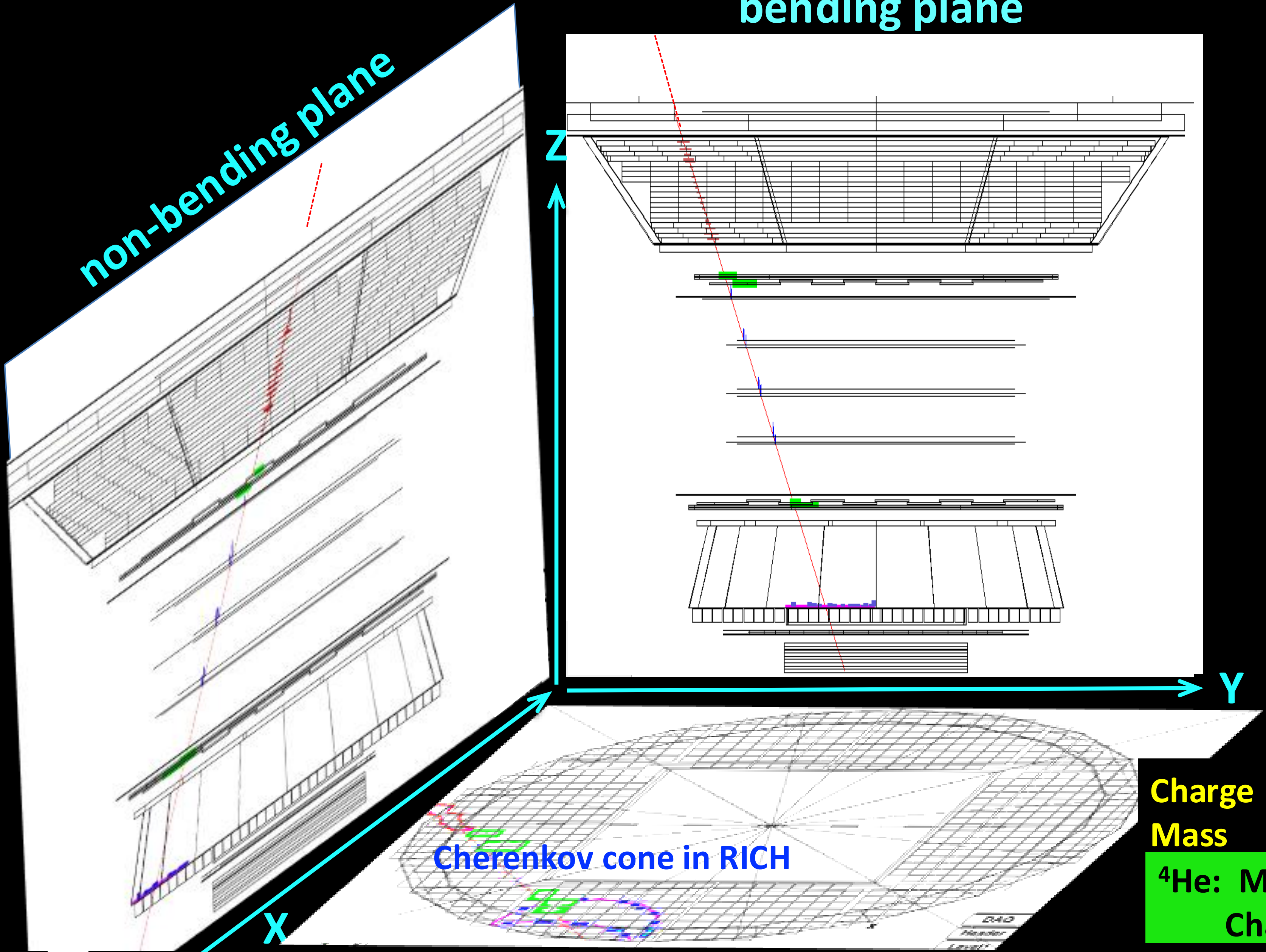
Mass = 1.9±0.1 GeV/c^2

Deuteron

Charge = +1

Mass = 1.88 GeV/c^2

Anti-^{4}HeliumCandidate

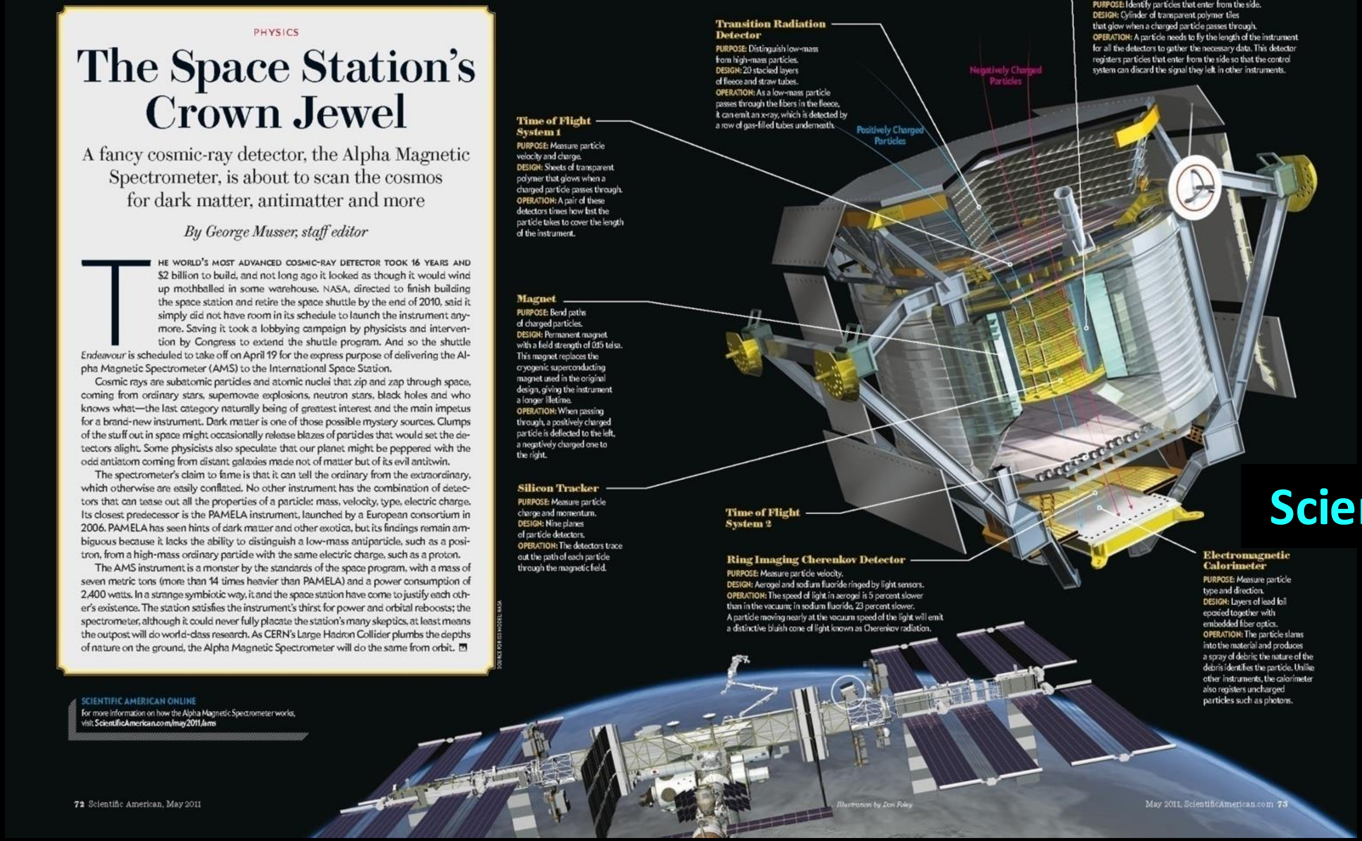


Charge = -2.05 ± 0.05

Mass = 3.81 ± 0.29 GeV/c^2

^{4}He: Mass = 3.73 GeV/c^2

Charge = +2



PHYSICS

The Space Station's Crown Jewel

A fancy cosmic-ray detector, the Alpha Magnetic Spectrometer, is about to scan the cosmos for dark matter, antimatter and more

By George Musser, staff editor

THE WORLD'S MOST ADVANCED COSMIC-RAY DETECTOR TOOK 16 YEARS AND $2 billion to build, and not long ago it looked as though it would wind up mothballed in some warehouse. NASA, directed to finish building the space station and retire the space shuttle by the end of 2010, said it simply did not have room in its schedule to launch the instrument anymore. Saving it took a lobbying campaign by physicists and intervention by Congress to extend the shuttle program. And so the shuttle *Endeavour* is scheduled to take off on April 19 for the express purpose of delivering the Alpha Magnetic Spectrometer (AMS) to the International Space Station.

Cosmic rays are subatomic particles and atomic nuclei that zip and zap through space, coming from ordinary stars, supernovae explosions, neutron stars, black holes and who knows what—the last category naturally being of greatest interest and the main impetus for a brand-new instrument. Dark matter is one of those possible mystery sources. Clumps of the stuff out in space might occasionally release blazes of particles that would set the detectors alight. Some physicists also speculate that our planet might be peppered with the odd antiatom coming from distant galaxies made not of matter but of its evil antitwin.

The spectrometer's claim to fame is that it can tell the ordinary from the extraordinary, which otherwise are easily conflated. No other instrument has the combination of detectors that can tease out all the properties of a particle: mass, velocity, type, electric charge. Its closest predecessor is the PAMELA instrument, launched by a European consortium in 2006. PAMELA has seen hints of dark matter and other exotica, but its findings remain ambiguous because it lacks the ability to distinguish a low-mass antiparticle, such as a positron, from a high-mass ordinary particle with the same electric charge, such as a proton.

The AMS instrument is a monster by the standards of the space program, with a mass of seven metric tons (more than 14 times heavier than PAMELA) and a power consumption of 2,400 watts. In a strange symbiotic way, it and the space station have come to justify each other's existence. The station satisfies the instrument's thirst for power and orbital reboosts; the spectrometer, although it could never fully placate the station's many skeptics, at least means the outpost will do world-class research. As CERN's Large Hadron Collider plumbs the depths of nature on the ground, the Alpha Magnetic Spectrometer will do the same from orbit. ■

SOURCE FOR ISS MODEL: NASA

SCIENTIFIC AMERICAN ONLINE
For more information on how the Alpha Magnetic Spectrometer works, visit **ScientificAmerican.com/may2011/ams**

PURPOSE: Identify particles that enter from the side.
DESIGN: Cylinder of transparent polymer tiles that glow when a charged particle passes through.
OPERATION: A particle needs to fly the length of the instrument for all the detectors to gather the necessary data. This detector registers particles that enter from the side so that the control system can discard the signal they left in other instruments.

Transition Radiation Detector
PURPOSE: Distinguish low-mass from high-mass particles.
DESIGN: 20 stacked layers of fleece and straw tubes.
OPERATION: As a low-mass particle passes through the fibers in the fleece, it can emit an x-ray, which is detected by a row of gas-filled tubes underneath.

Time of Flight System 1
PURPOSE: Measure particle velocity and charge.
DESIGN: Sheets of transparent polymer that glows when a charged particle passes through.
OPERATION: A pair of these detectors times how fast the particle takes to cover the length of the instrument.

Magnet
PURPOSE: Bend paths of charged particles.
DESIGN: Permanent magnet with a field strength of 0.15 telsa. This magnet replaces the cryogenic superconducting magnet used in the original design, giving the instrument a longer lifetime.
OPERATION: When passing through, a positively charged particle is deflected to the left, a negatively charged one to the right.

Silicon Tracker
PURPOSE: Measure particle charge and momentum.
DESIGN: Nine planes of particle detectors.
OPERATION: The detectors trace out the path of each particle through the magnetic field.

Time of Flight System 2

Ring Imaging Cherenkov Detector
PURPOSE: Measure particle velocity.
DESIGN: Aerogel and sodium fluoride ringed by light sensors.
OPERATION: The speed of light in aerogel is 5 percent slower than in the vacuum; in sodium fluoride, 23 percent slower. A particle moving nearly at the vacuum speed of the light will emit a distinctive bluish cone of light known as Cherenkov radiation.

Electromagnetic Calorimeter
PURPOSE: Measure particle type and direction.
DESIGN: Layers of lead foil epoxied together with embedded fiber optics.
OPERATION: The particle slams into the material and produces a spray of debris; the nature of the debris identifies the particle. Unlike other instruments, the calorimeter also registers uncharged particles such as photons.

Illustration by Don Foley

Scientific American, May 2011

Space is the ultimate laboratory. Space provides particles with much higher energies than accelerators. AMS provides a first small step in uncovering the mysteries of cosmic rays.

AMS results contradict current cosmic ray theories and require the development of a new Standard Model of the cosmos.