FERMILAB-SLIDES-18-039-T

Fermilab's Greatest Hits:
Scientific Highlights of the First Fifty Years

Chris Quigg

DPF2017 · Fermilab · August 2, 2017 · APS | DIVISION OF PARTICLES & FIELDS

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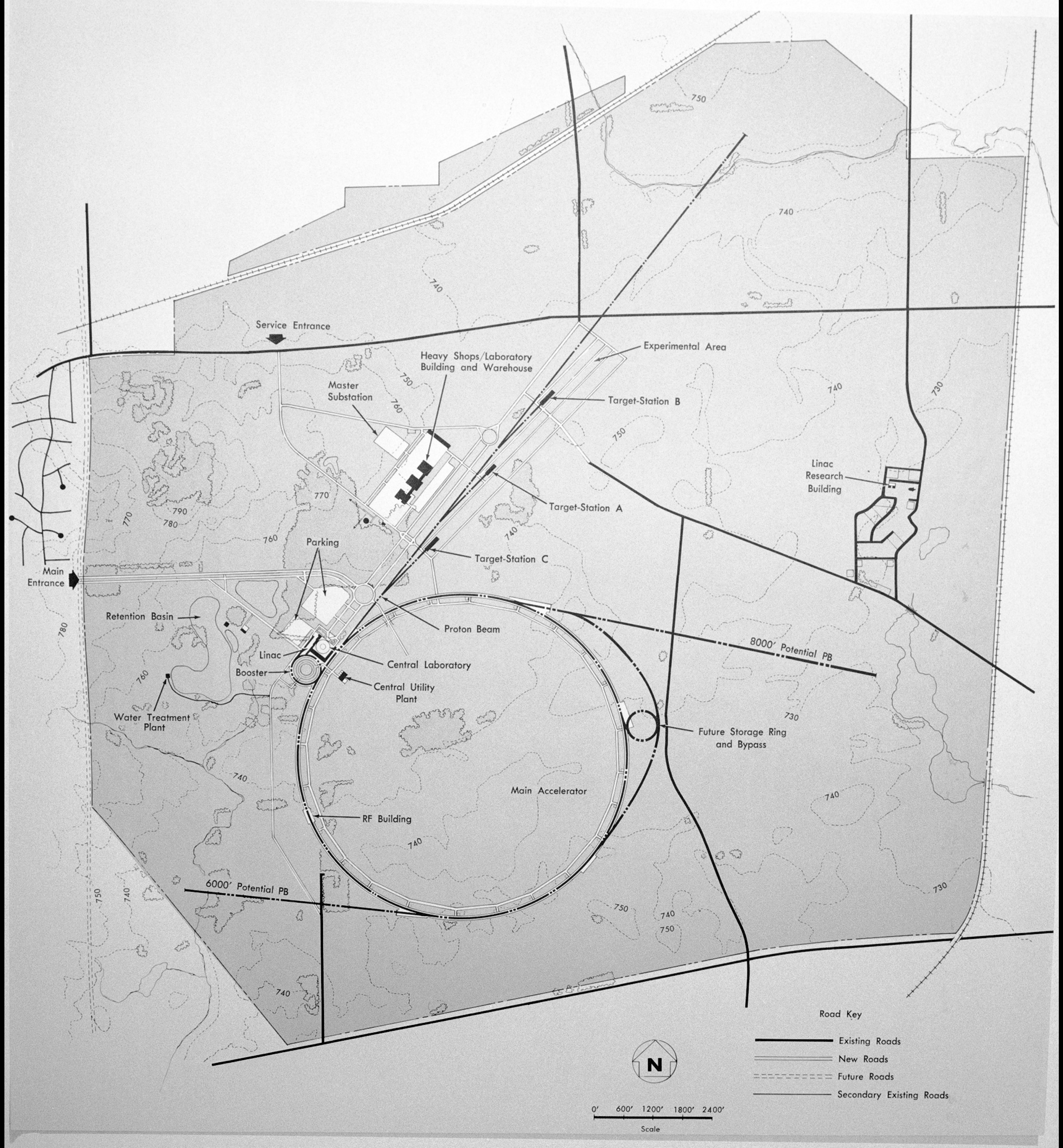

Service Entrance
Heavy Shops/Laboratory Building and Warehouse
Experimental Area
Master Substation
Target-Station B
Target-Station A
Target-Station C
Linac Research Building
Parking
Main Entrance
Retention Basin
Proton Beam
Linac
Central Laboratory
Booster
Central Utility Plant
8000′ Potential PB
Water Treatment Plant
Future Storage Ring and Bypass
Main Accelerator
RF Building
6000′ Potential PB
Road Key
Existing Roads
New Roads
Future Roads
Secondary Existing Roads
N
0′ 600′ 1200′ 1800′ 2400′
Scale

Public Lecture slides and video

Fermilab Ph.D. theses: 2281 and counting!

More than 170 “renowned” papers

10 Panofsky Prizes, 8 Wilson Prizes, 4 Sakurai Prizes

50 years ago: How little we knew

Problems of High-Energy Physics (NAL Design Report, January 1968)

We would like to have answers to many questions. Among them are the following:

Which, if any, of the particles that have so far been discovered, is, in fact, elementary, and is there any validity in the concept of "elementary" particles?

What new particles can be made at energies that have not yet been reached? Is there some set of building blocks that is still more fundamental than the neutron and the proton?

Is there a law that correctly predicts the existence and nature of all the particles, and if so, what is that law?

Will the characteristics of some of the very short-lived particles appear to be different when they are produced at such higher velocities that they no longer spend their entire lives within the strong influence of the particle from which they are produced?

Do new symmetries appear or old ones disappear for high momentum-transfer events?

What is the connection, if any, of electromagnetism and strong interactions?

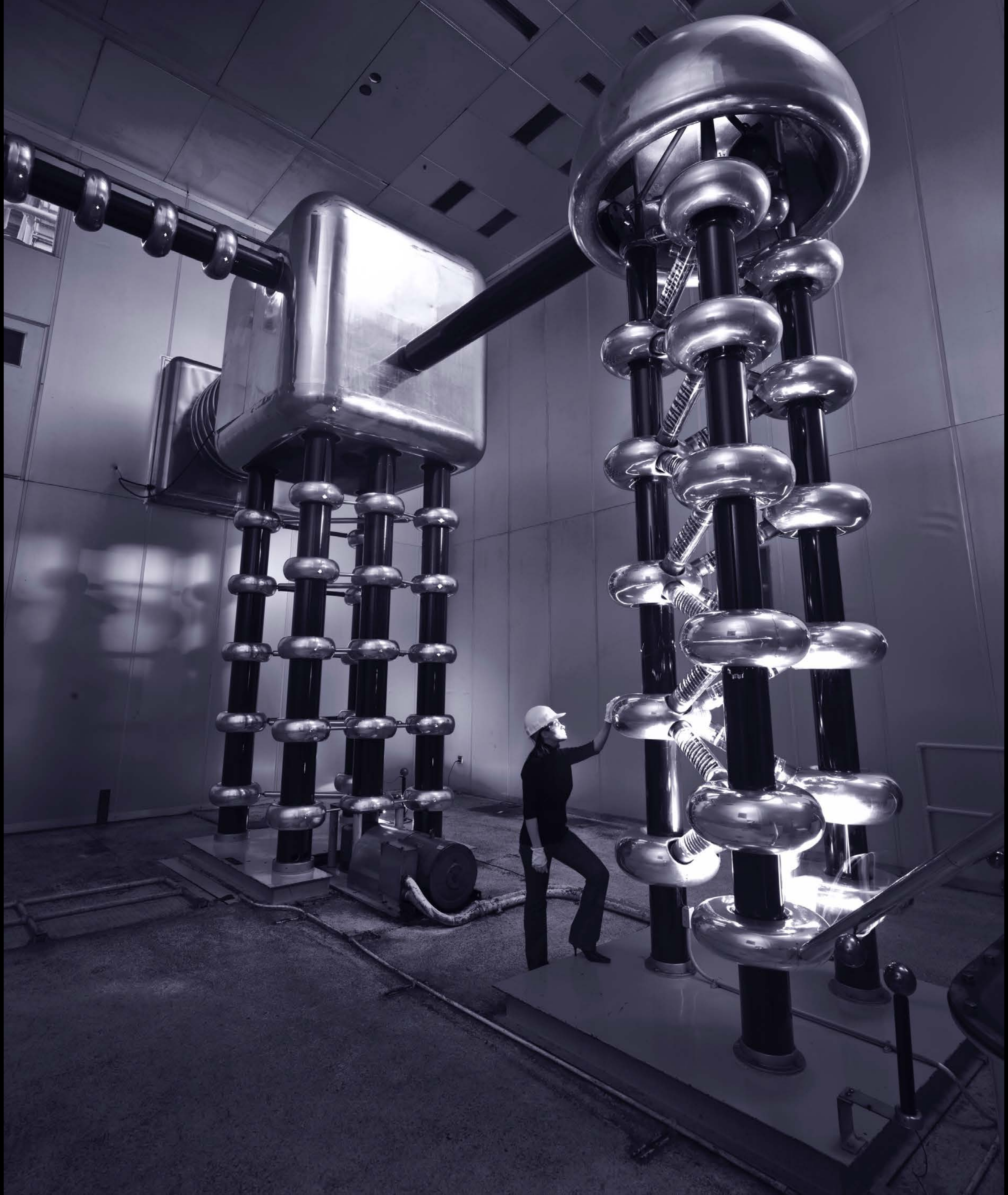
Do the laws of electromagnetic radiation, which are now known to hold over an enormous range of lengths and frequencies, continue to hold in the wavelength domain characteristic of the subnuclear particles?

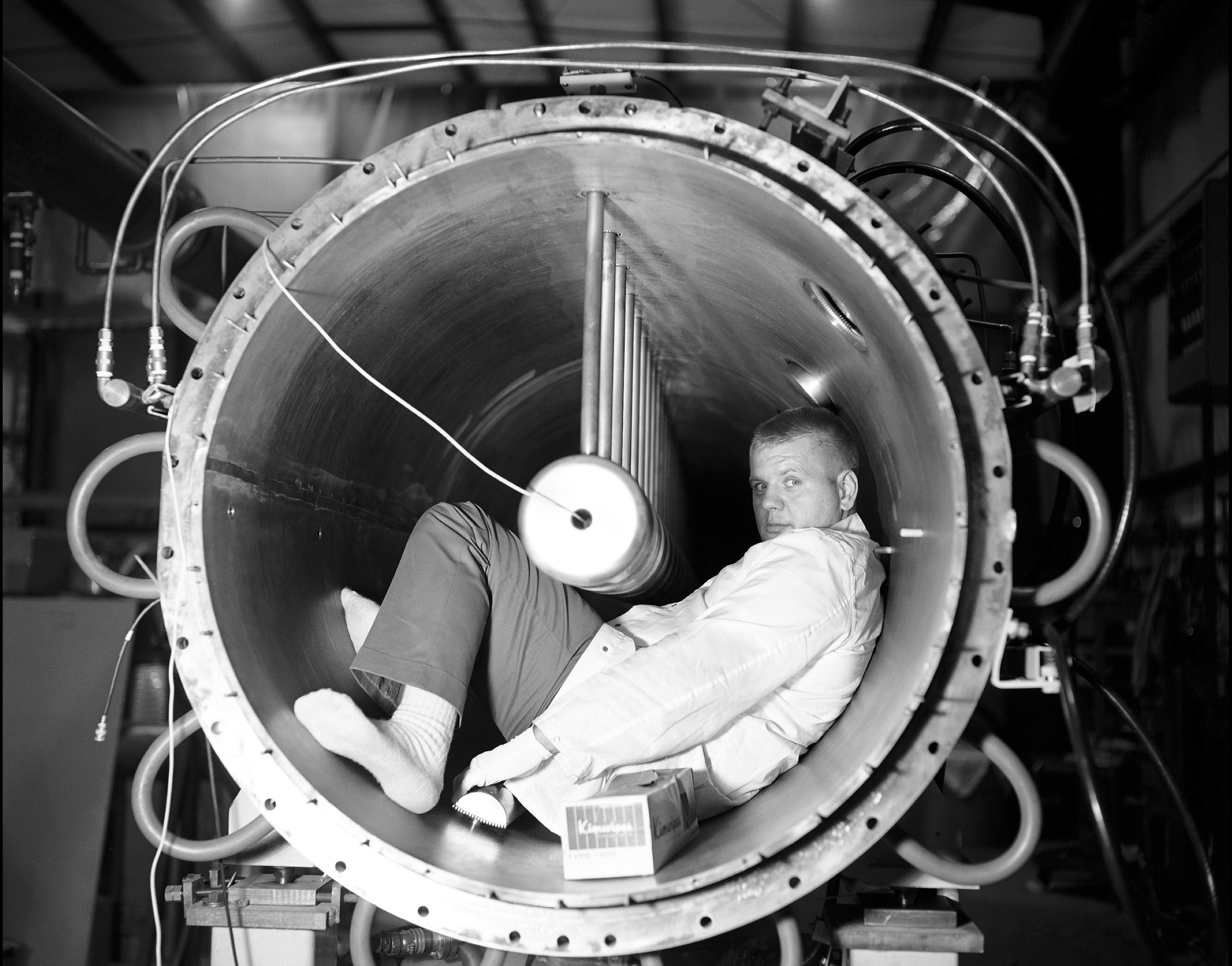
What is the connection between the weak interaction that is associated with the massless neutrino and the strong one that acts between neutron and proton?

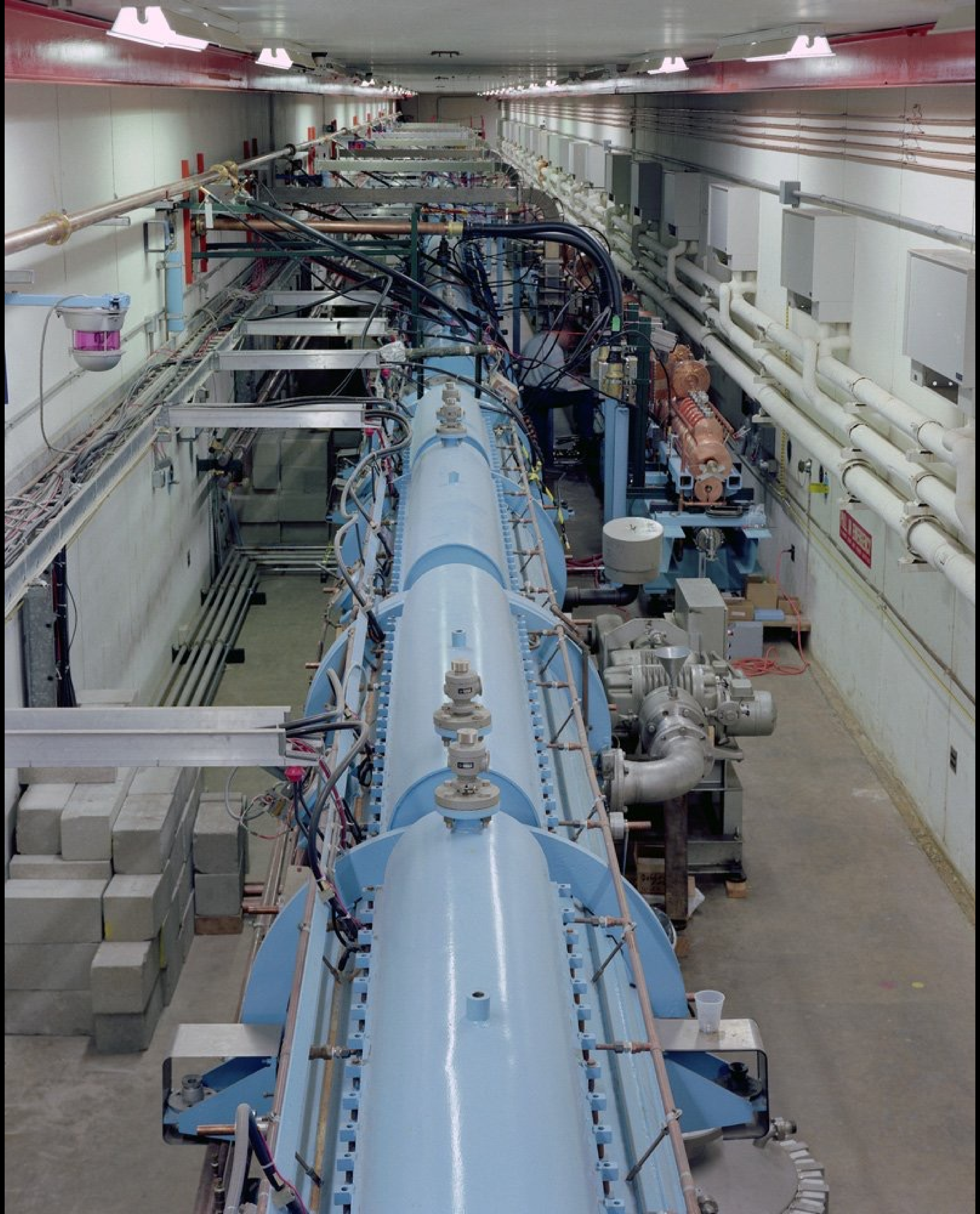
Is there some new particle underlying the action of the "weak" forces, just as, in the case of the nuclear force, there are mesons, and, in the case of the electromagnetic force, there are photons? If there is not, why not?

In more technical terms: Is local field theory valid? A failure in locality may imply a failure in our concept of space. What are the fields relevant to a correct local field theory? What are the form factors of the particles? What exactly is the explanation of the electromagnetic mass difference? Do "weak" interactions become strong at sufficiently small distances? Is the Pomeranchuk theorem true? Do the total cross sections become constant at high energy? Will new symmetries appear, or old ones disappear, at higher energy?


Angela Gonzales




Kimwipes



The Village Crier

national accelerator laboratory

Operated by Universities Research Association Inc.
Under Contract with the United States Atomic Energy Commission

Vol. 4 No. 8 February 24, 1972

....Broad smiles at NAL on February 11, 1972....(L to R) R. R. Wilson, D. Sutter, E. L. Goldwasser, T. Collins, S. Mori, E. Hubbard, and E. Malamud....

....Reason for the smiles.... 100 BeV on that date....

A DAY TO REMEMBER!!

There were indications in the NAL Main Control Room all day on Friday, February 11th, that it was going to be a good day. The elusive proton beam was more responsive than usual to the control system and to the crew working hard to train the beam into going to higher and higher energies around the four-mile NAL race track.

The entire Accelerator Section, under the guidance of Robert R. Wilson and Donald E. Young, had been marshalled all week -- all month, in fact, having attained 20 BeV on January 22nd and 53 BeV on February 4th. The experience and know-how they had gained in the past weeks spurred on their efforts to reach for further acceleration.

Ernest Malamud, Ryuji Yamada and Frank Nezrick led the day shift on Friday, the 11th. Transition energy (17 BeV) was achieved in the morning; tuning continued throughout the day, adjusting to get all of the component systems to function at the same time. Operations went very well during the day; some of the day shift people stayed on into the evening shift, hoping to see success before they left.

At 7:30 p.m. the evening crew, led by Shigeki Mori, Tom Collins, Dave Sutter and Chuck Schmidt, once again attained beam at transition energy, but for some time they could not get the energy to increase. Activity moved back and forth between the Main Control Room and the men on duty six blocks away in the Radio Frequency Building, Jim Griffin, Ray Stiening, K. C. Cahill, Ed Higgins and J. Hoelscher. The two groups continued adjusting and watching for results on the oscilloscope screens. At 9 p.m., after Jim Griffin made a simple adjustment of the B dot knob, the energy of the beam began to climb upward. Each additional pulse of the machine brought cheers from the Main Control Room on the inter-com to the R. F. building. In a very short time,

.....Gift from Dubna..
Photo by Tony Frelo, N

(Continued on Page 2)

A DAY TO REMEMBER (Continued from Page 1)

....(L to R) J. Griffin, K. C. Cahill, R. Stiening, E. Higgins in R.F. Building....

....(L to R) D. Sutter, F. Nezrick, D. Jovanovic, in the Main Control Room....

the beam touched 100 BeV.

A telephone call brought the Laboratory Director, Robert R. Wilson, to the Main Control Room. He was carrying a bottle of vodka, inscribed in handwriting on the label: "For Bob Wilson and colleagues when energy is greater than 76 BeV...A. A. Kuznetsov, Dubna." Wilson led a group to the R. F. Building, the scene of the breakthrough, where he shared the beverage and the undisguised joy of the occasion.

Tension gone, replaced by the inspiring realization that enormous efforts of countless persons and groups had begun to bear fruit, the crews shortly resumed their duties and the machine continued its magnificent performance throughout the night.

Experiment Number 36 personnel were called about 10 p.m., for they had been scheduled to test equipment installed in the Main Ring beam pipe beneath Service Building C-0 as soon as 100 BeV beam was achieved. Now, they had their chance to observe an accelerated beam react in their experimental apparatus, at 4 a.m. on February 12th.

Later, a shut-down was called for, to start unsplitting power supplies. By Monday morning, as word of the achievement spread like wildfire through the Laboratory, plans were already being posted for preparations that will lead to design energy (200 BeV) soon. The Accelerator Section obviously will be anxious to try for this new thrill, having so thoroughly enjoyed the last one!!

(Except as noted, all photographs in this article were taken by Ryuji Yamada, NAL.)

....(L to R) R. Flora, R. Cassel, H. Edwards at the console in the Main Control Room....

....T. Collins (L), Shigeki Mori shortly after reaching 100 BeV....


EXPT. 36
ROCKEFELLER
DUBNA
ROCHESTER
NAL
35
D

First experimental publication

Charged-Particle Multiplicity Distribution from 200-GeV *pp* Interactions*

G. Charlton, Y. Cho, M. Derrick, R. Engelmann, T. Fields, L. Hyman, K. Jaeger, U. Mehtani, B. Musgrave, Y. Oren,† D. Rhines, P. Schreiner, and H. Yuta
Argonne National Laboratory, Argonne, Illinois 60439

and

L. Voyvodic, R. Walker, and J. Whitmore
National Accelerator Laboratory, Batavia, Illinois 60510

and

H. B. Crawley
Iowa State University, Ames, Iowa 50010

and

Z. Ming Ma
Michigan State University, East Lansing, Michigan 48823

and

R. G. Glasser‡
University of Maryland, College Park, Maryland 20742

(Received 21 July 1972)

From 2728 events of 205-GeV *pp* interactions found in 15 000 pictures taken with the 30-in. hydrogen bubble chamber at the National Accelerator Laboratory, a total cross section of 39.5 ± 1.1 mb was measured. The mean charged-particle multiplicity for inelastic *pp* collisions was measured to be 7.65 ± 0.17. The prong distribution from 2 to 22 prongs is broader than a Poisson distribution and has a width parameter $f_2^- = \langle n_-(n_- - 1)\rangle - \langle n_-\rangle^2 = 0.95 \pm 0.21$.

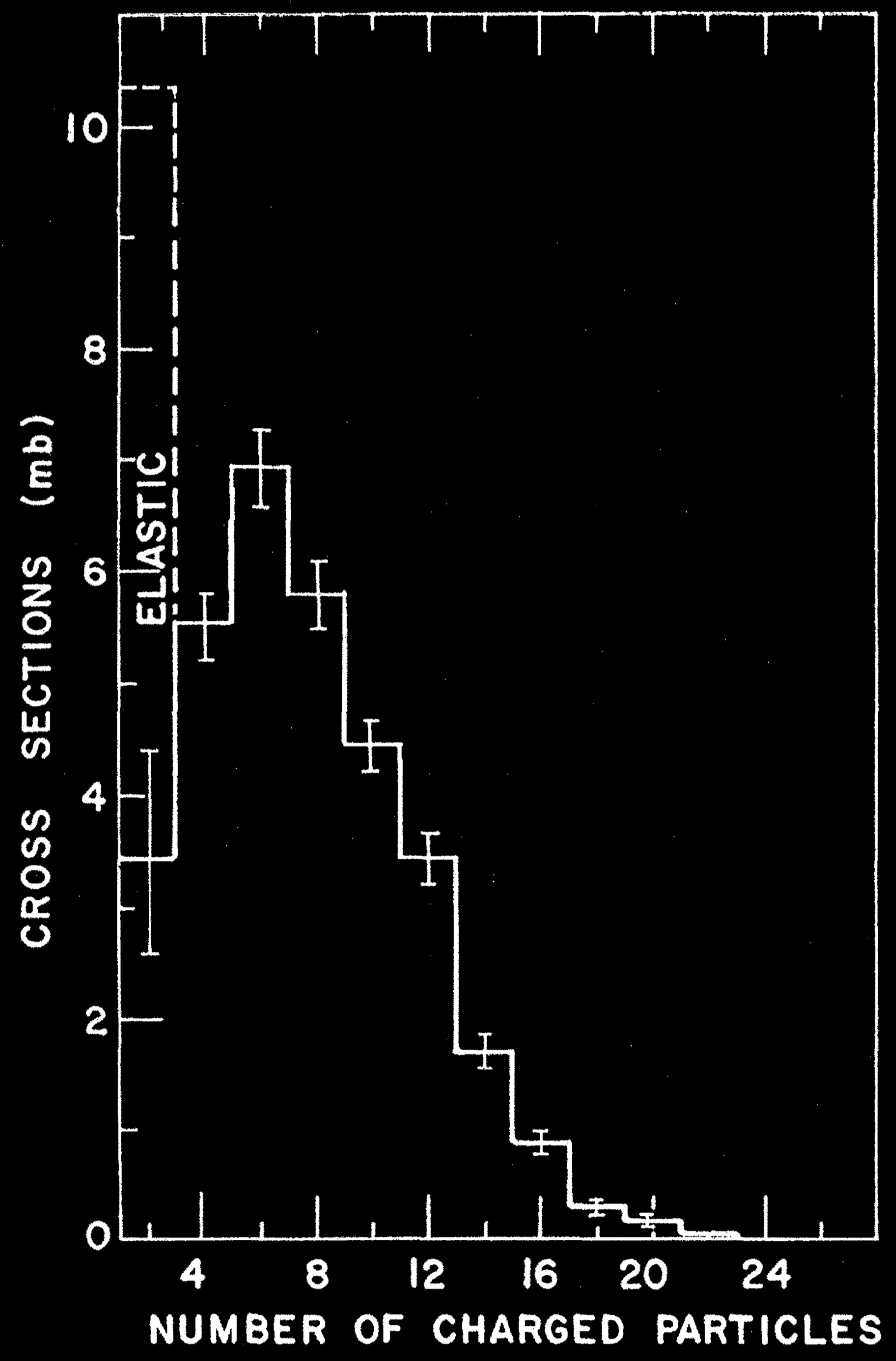


FIG. 1. Partial cross sections for events with 2 through 22 prongs. The dashed histogram shows the contribution of elastic scattering to the two-prong events.

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Vol. 3 No 28 July 15, 1971

NAL, CALTECH JOIN IN NEUTRINO STUDIES (EXPERIMENT 21)

NAL is about to undergo an interesting, significant and challenging transitional phase -- from early construction to operations; from building to research; from bricks and mortar to scientific investigation.

One of the first assignments before the world's most powerful particle accelerator will be to assist in the complex search for a new particle that would help describe nature's mysterious weak nuclear force.

...Frank Sciulli, one of the Caltech professors associated with Experiment 21...

Photo by Tim Fielding, NAL

Discovery of such a particle would indicate striking similarities between the weak force and at least two of the three other fundamental forces of nature -- the strong nuclear force and the electrical force. Both of these forces have specific particles associated with them, and perhaps the remaining one, gravity, does also.

Experiment 21, the goals of which are described in simple terms above, will be an NAL-California Institute of Technology collaboration. It is a novel experiment of Barry C. Barish, 35 years old, and Frank Sciulli, 32, associate and assistant professors, respectively, at Caltech. They are working with Alfred W. Maschke, head of NAL's Beam Transfer section, in what will be one of the first experiments to be undertaken on the proton synchrotron at NAL. They have been selected to investigate neutrino physics during the initial operation of the accelerator and continuing until January, 1973. The Caltech-NAL researchers plan to carry their studies on neutrinos up to about 300 BeV. Presently, data exists only up to about 10 BeV.

The nature of the weak force, which they will study, remains something of a mystery. It is associated with radioactive decay, and its interactions are many billions of times slower and weaker than those of the strong nuclear force, which binds together the protons and neutrons in an atom's nucleus.

It is the research team's plan to seek a particle that could carry the weak force. Although such a particle never has been found, it already has been named. It is called variously the "W," the "Uxl," or the "intermediate vector boson." One may exist, just as a particle -- the photon -- exists for carrying the electrical force.

If the W exists as a particle, present evidence suggests it will have a mass greater than that of two protons; this means that the weak force interacts over the extremely short distance of four quadrillionths of an inch or less. The higher the mass of the W, the more difficult it is to produce.

The Caltech-NAL experiment, supported by the U.S. Atomic Energy Commission, hopes to produce and detect the particle if its mass is less than about 20 proton masses. The high energy of NAL's new accelerator system makes this possible -- if the particle exists.

Says Dr. Sciulli: "We also will be able to probe more deeply than hitherto possible into the proton and the neutron. This could help us understand more about their structures and the forces associated with them. We may learn more about the electrical force because indications are that the weak force is related to it."

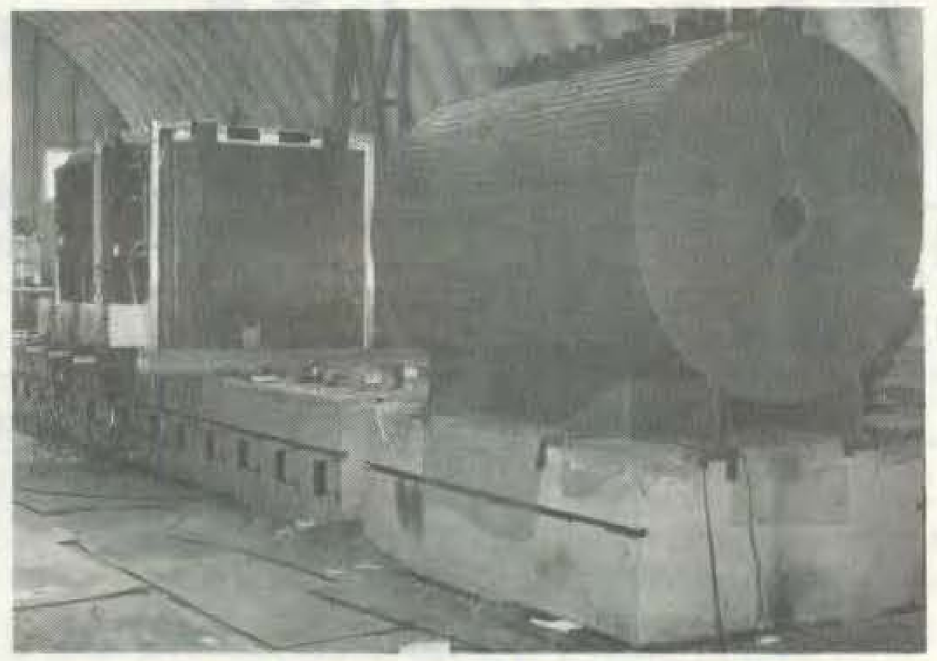
A small but distinguished group of physicists will conduct the experiment at NAL with

(Continued on Page 2)

NAL, CALTECH JOIN IN NEUTRINO STUDIES (EXPERIMENT 21) - Continued from Page 1

...An aerial view of the "Wonder Building" located near the intersection of Wilson and McChesney Roads, where Caltech experimenters are at work...

Photo by Tony Frelo, NAL



...Neutrino detectors (left) plus iron core toroidal magnet designed and being installed inside the Wonder Building by the Caltech group for initial measurements of neutrino interactions as soon as the NAL beam is available...

Photo by Tim Fielding, NAL

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Barish, Sciulli and Maschke. They include Les Oleksiuk of the NAL Beam Transfer section; and from Caltech: Charles Peck, associate professor of physics; Yorikiyo Nagashima, senior research fellow; William Ford, Dennis Shields (research fellow) and Tom Humphrey, thesis student. George Krafczyk, NAL technician, has been assisting in installing the experiment.

Members of the Caltech physics faculty and several Caltech students have been at NAL since March, preparing for this early experiment. They are housed in what was a cornfield between Batavia and McChesney Roads and to the east of Wilson Road. The lights rarely go off at the "Wonder Building"; they are on day and night, weekdays and weekends, as the team completes the special equipment designed and built for this experiment. The "Wonder Building" has a dirt floor, no framing, features bottled water and chemical toilets. It is truly an austere "Wonder Building" but it contains some of the most advanced scientific equipment for elementary particle research in the world.

During the school term at Caltech, the faculty members commuted from California to NAL, in order to maintain their teaching commitments and to prepare for the experiment at the same time. The Barish, Nagashima, and Sciulli families are now residing in the Surrey Hill apartments in St.Charles; the Caltech students working with the project are living at "The Pad" -- a dormitory-type facility located at 32 Sauk in the NAL Village. The professors and their families will return to California in the fall and will resume their commuting-teaching- experimenting schedule.

Robert R. Wilson, NAL Director, told the NAL Users' Organization, at their annual meeting, that the first aim of experiments on the NAL accelerator system will be at detection of a neutrino. "I feel that we then will be in business to do experiments on our accelerator, and I feel that this detection will come in the Caltech-NAL experiment. The Caltech installation excites my envy -- their enthusiasm and improvisation gives us a real incentive to provide them with the neutrinos they are waiting for."

The new accelerator will make it possible for the first time to observe the behavior of the weak nuclear force at high energies. Present knowledge of this force is based primarily on decays of heavy particles at low energies. Drs. Barish, Sciulli and Maschke will develop a very high energy beam of neutrinos -- a product of weak force interactions -- for this investigation. The beam will be unique in that its design allows the experimenters to specify the energy of the neutrinos that they wish to investigate.

Summarizing the progress of the NAL-Caltech experiment preparations, Barish commented, "We're on schedule; we'll be ready when the beam goes on, but not before, I hope, because it would be hard to wait."

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The Village Crier

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Vol. 5 No. 9 **March 1, 1973**

CAL TECH GROUP DETECTS NEUTRINOS

In 1971, NAL Director Robert R. Wilson told the Users' Organization that *"one of the first aims of experiments on the NAL accelerator system will be the detection of a neutrino. I feel that we then will be in business to do experiments on our accelerator..."*

Neutrinos, which have neither charge nor mass, are very difficult particles to detect experimentally. They play a very prominent role in the study of the weak interaction, because they only interact via the weak force, about which relatively little is known.

Months have passed since this comment was made, many long hours have been devoted to completing and refining the NAL accelerator, and Dr. Wilson's wish for the detection of a neutrino has been fulfilled. The Experiment 21 group, headed by Professors Barry Barish and Frank Sciulli, from the California Institute of Technology, detected neutrinos in their apparatus last November. They are presently making tests in the neutrino beam in anticipation of measurements they hope to pursue this year. It has been an exciting time for all those connected with the experiment. At the February 7th Director's Meeting, Dr. Barish described recent developments in the Wonder Building:

"As most people know, in November we first saw neutrinos, which at that point wasn't much more than proving to us that the accelerator really existed and something came out. We were set up in a mode where all we could do was see neutrinos interact -- we couldn't even attempt to look at the properties of high energy neutrino interactions. We were over-constraining ourselves in as many ways as possible, in order to make sure that we could really detect neutrinos and believe it.

By January...fortunately the energy of the machine went up to 300 GeV and we got something like 3 x 10^{16} protons on our target, which gave us our first opportunity to obtain a reasonable number of events. Quite a few people who were around here at the time actually saw events coming in. At one time, for example, we had two events on successive pulses, which seems to be a record.

Since then we've been looking very hard at what we have. We have seen some examples

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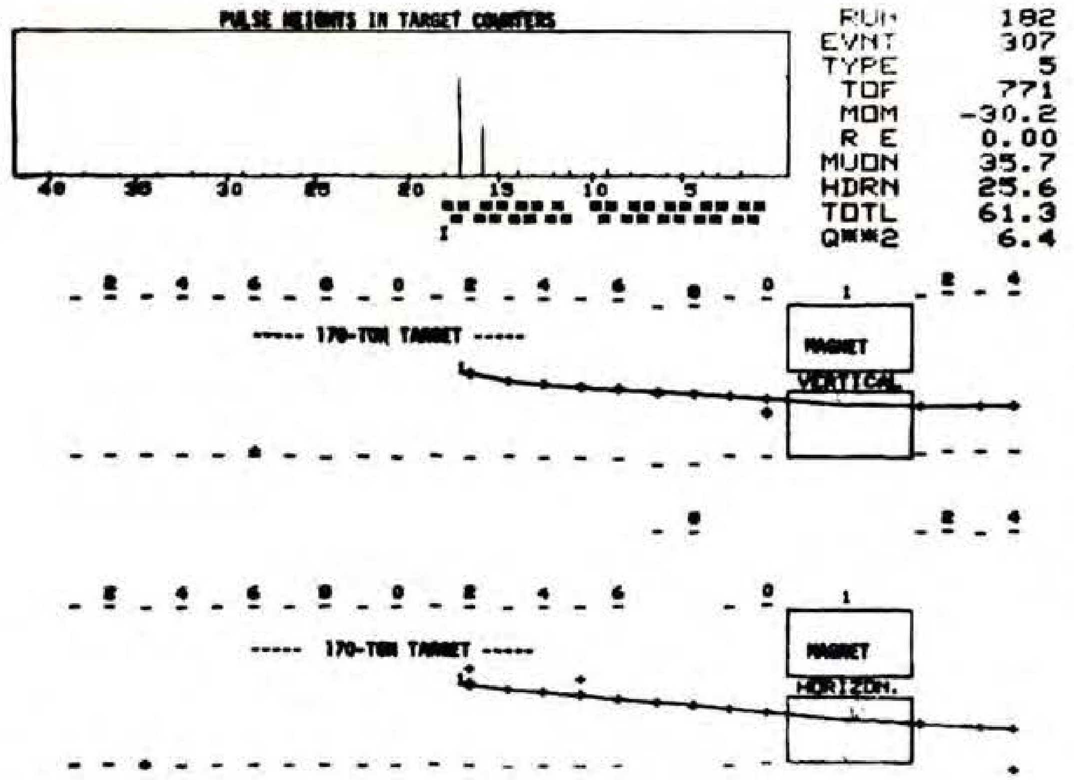

Vertical (side) and horizontal (top) views of the 170-ton Cal Tech detector, as seen by the on-line computer. A 61 GeV neutrino interacts near the center of the target, resulting in a μ minus visible in the spark chambers located in the target and downstream of the magnet. Simultaneously, a hadron shower occurs, as evidenced by large pulse heights in the target counter (shown at the top of the picture).

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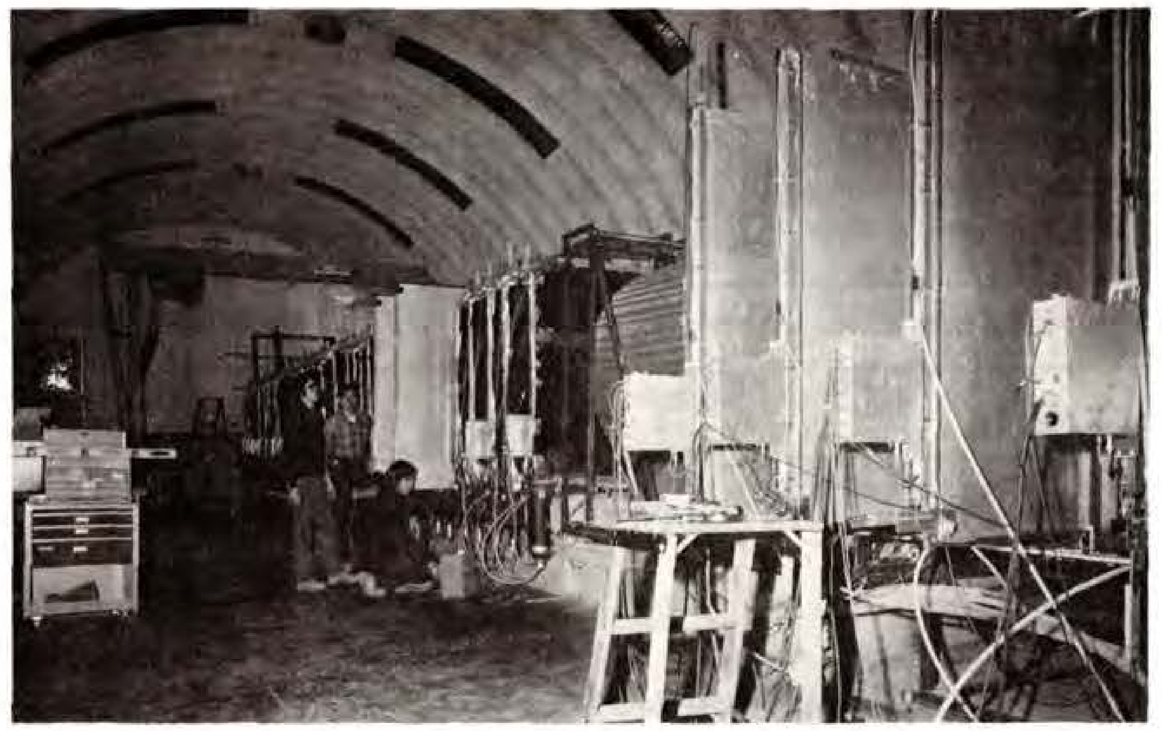
CAL TECH (continued)



...(L-R) Dave Buchholz, Henri Suter and Dennis Shields stand at the downstream end of the 170-ton neutrino target. The neutrino beam enters the apparatus through the wall at the rear of the photo.

...In the foreground are large-area spark chambers, used for the detection of muons resulting from the neutrino interaction...

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of neutrino interactions of over 100 GeV. Over half of our events are analyzable, and for a first attempt, that's encouraging. We know what we have to do to get at the rest, and we're just in the process of trying to understand and improve the apparatus, beam, and so forth. We have lots of tests to make, but I don't think it will be very long before we'll be able to say something. Right now, however, we remain very, very silent."

The Cal Tech group must now conduct more tests to be sure their apparatus is working properly and to determine which "pieces of physics" are sensible to pursue with it, and then finally, to complete an experiment.

Their experiment has been assembled with the help and support of the NAL Neutrino Section. The Cal Tech experimenters consist of a small, dedicated group. Dennis Shields built and installed much of the equipment one sees in the Wonder Building. The sophisticated ON-LINE data acquisition system used in the experiment was developed by Fritz Bartlett. George Krafczyk of NAL has made important contributions to almost every facet of the experiment. David Buchholz and Henri Suter, (a Cal Tech visitor from University of Geneva) have recently joined the experiment, adding both new stimulation and an international flavor to the group. Al Maschke, now at Brookhaven National Laboratory and Yori Nagashima, who has returned to Japan, have also contributed. Cal Tech thesis students, Tom Humphrey and Frank Merritt, are the real heart and soul of the experiment.

What the group hopes to investigate in the months ahead is the behavior of the weak interaction -- force -- at the very high energies possible with the NAL accelerator.

The weak interaction has been studied extensively in decays of unstable particles and radioactive nuclei, in which the energy released is in the range of approximately zero to 500 MeV. For a number of theoretical reasons, physicists expect that the picture of the weak interaction which has emerged from such particle decay experiments will change when higher energies are used, although the precise nature of the change remains conjecture. New phenomena, or even a new particle, may be discovered. No carrier of the force -- a field particle, so to speak -- has as yet been identified for the weak interaction, although the so-called W-particle or intermediate vector boson has been postulated. It just might be produced at higher energies. Nobody knows.

Experiments at CERN using neutrinos at energies up to 10 GeV showed no noticeable deviation from the known theory of weak interactions. Neutrino physics is so interesting and exciting that several other experiments have been approved, including those for the 15-foot Bubble Chamber.

Whether the NAL accelerator, which yields neutrino energies more than ten times greater than any studied to date, will provide enough energy to see any new phenomena or to prove the existence of the W-particle and thus, further explain this puzzling nuclear force, remains to be seen.

If it does, as Dr. Wilson enthusiastically remarked at that same Director's Meeting, *"just that one thing will make the whole Laboratory worthwhile."*

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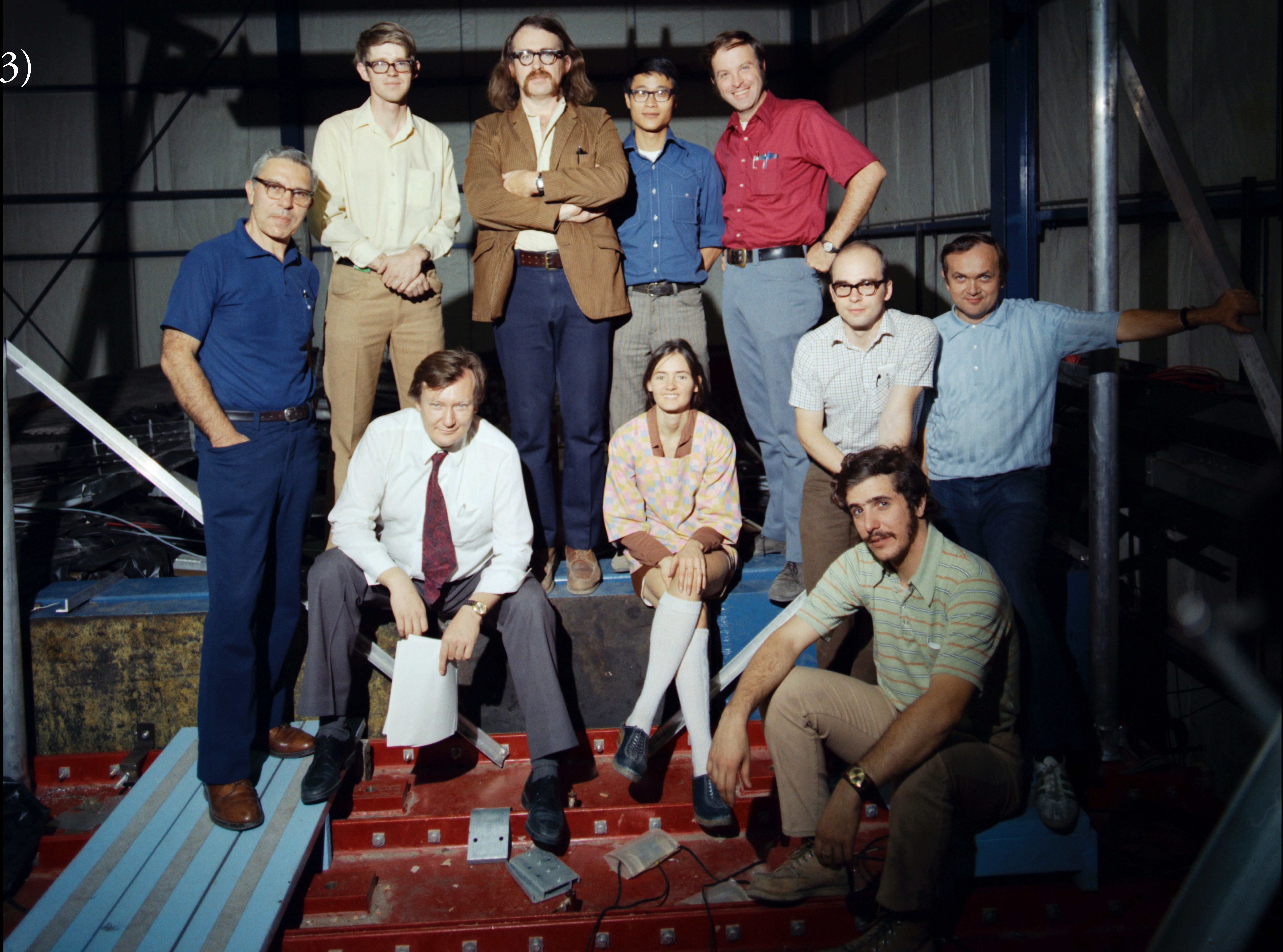
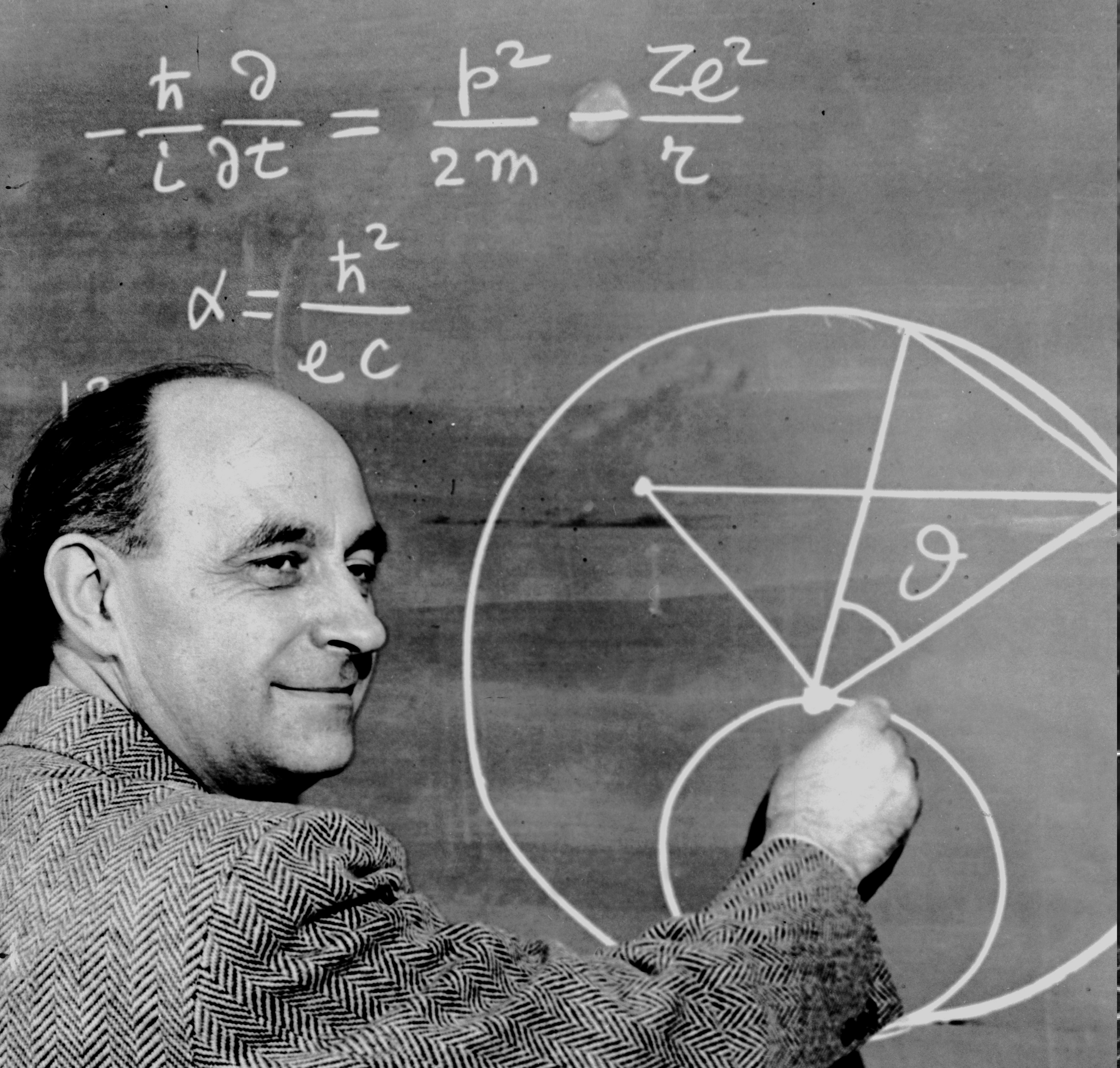
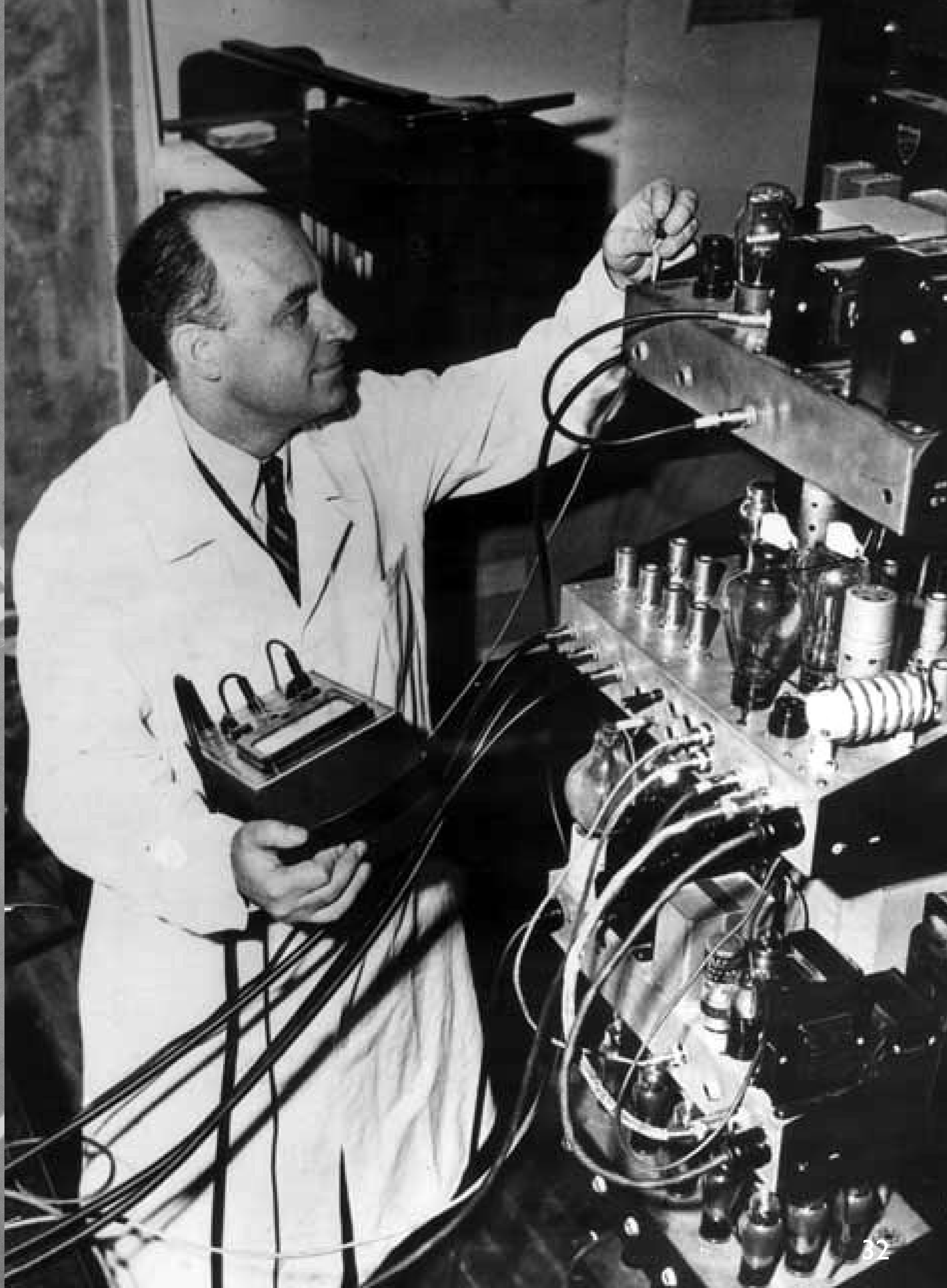
E1A (1973)



15-foot bubble chamber


$-\frac{\hbar}{i}\frac{\partial}{\partial t} = \frac{p^2}{2m} - \frac{Ze^2}{r}$
$\alpha = \frac{\hbar^2}{ec}$
ϑ



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PHYSICAL REVIEW D VOLUME 19, NUMBER 3 1 FEBRUARY 1979

Paper 1 conclusion (12/'74)

There does not appear to be any theory of high-$p_\perp$ particle production which fits these observations in a convincing fashion.

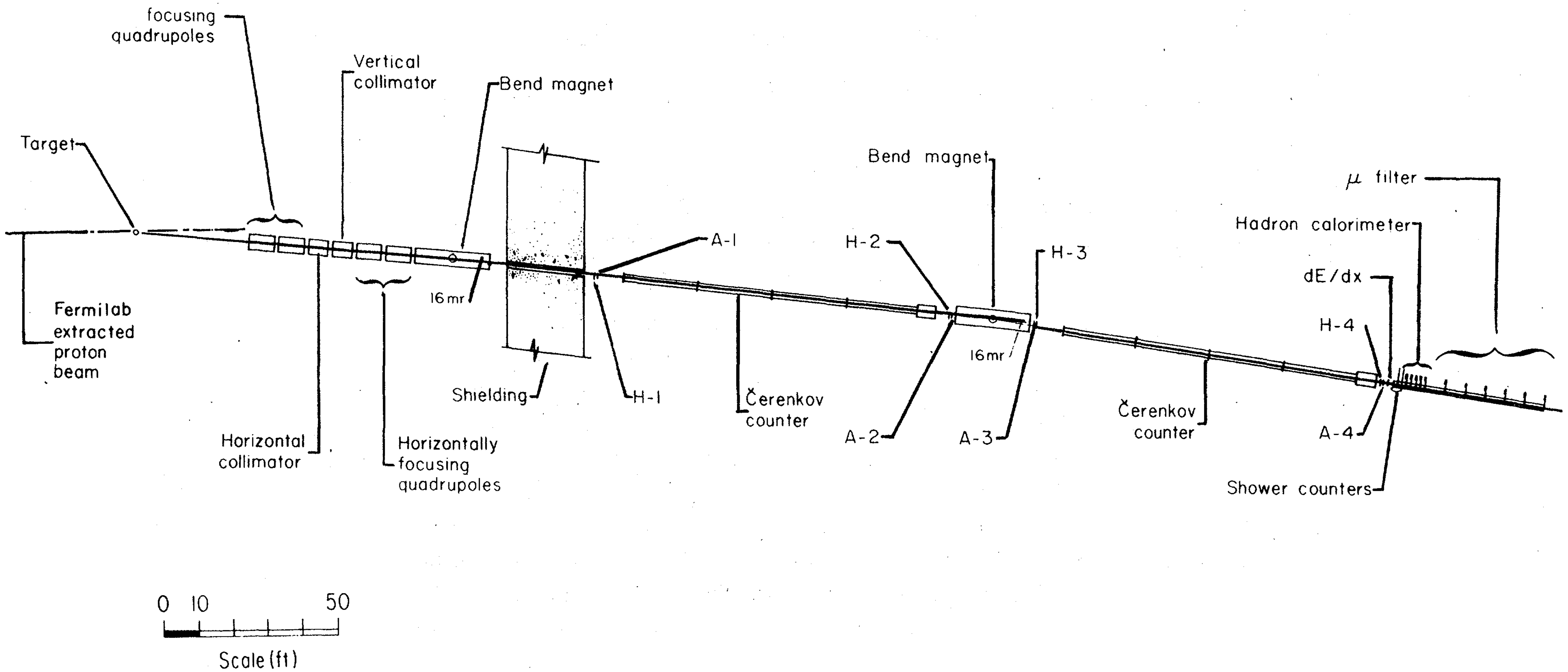
Production of hadrons at large transverse momentum in 200-, 300-, and 400-GeV p-p and p-nucleus collisions

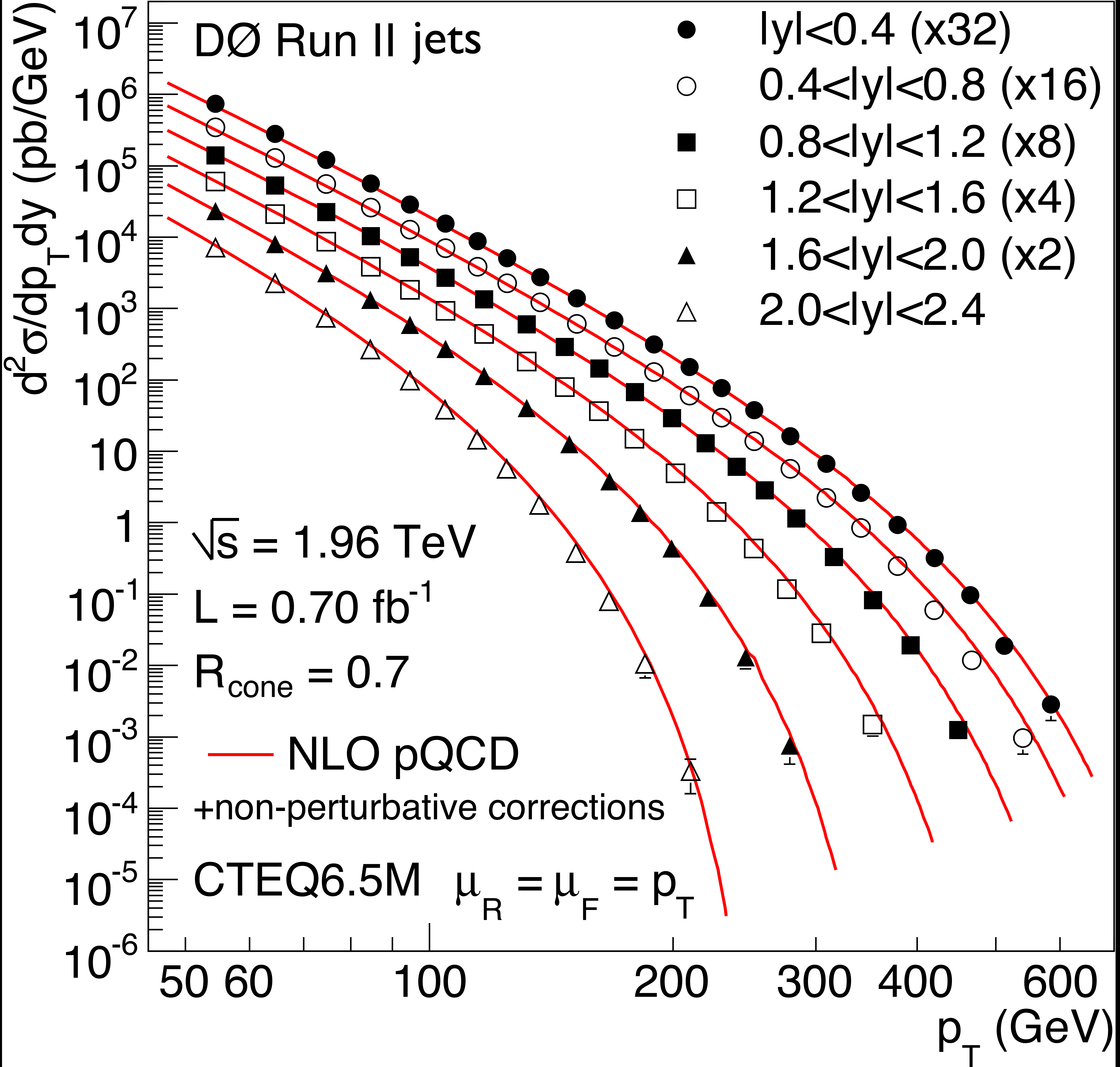
D. Antreasyan,* J. W. Cronin, H. J. Frisch, and M. J. Shochet
The Enrico Fermi Institute and Department of Physics, University of Chicago, Chicago, Illinois 60637

L. Kluberg,† P. A. Piroué, and R. L. Sumner
Department of Physics, Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

(Received 14 July 1978)

Measurements of the invariant cross section $Ed^3\sigma/d^3p$ are presented for the production of hadrons (π, K, p, and $\bar{p}$) at large transverse momentum ($p_\perp$) by 200-, 300-, and 400-GeV protons incident on H_2, D_2, Be, Ti, and W targets. The measurements were made at a laboratory angle of 77 mrad, which corresponds to angles near 90° in the c.m. system of the incident proton and a single nucleon at rest. The range in $p_\perp$ for the data is $0.77 \le p_\perp \le 6.91$ GeV/c, corresponding to values of the scaling variable $x_\perp = 2p_\perp/\sqrt{s}$ from 0.06 to 0.64. For p-p collisions, the pion cross sections can be represented in the region $x_\perp > 35$ by the form $(1/p_\perp{}^n)(1-x_\perp)^b$, with $n = 8$ and $b = 9$. The ratio of π^+ to π^- production grows as a function of $x_\perp$ to a value larger than 2 at $x_\perp \gtrsim 0.5$. The ratios of the production of K^+ and protons to π^+ and of K^- and antiprotons to π^- also scale with $x_\perp$ for p-p collisions. The $K^\pm$, p, and $\bar{p}$ fitted values for n and b are given. Particle ratios are also presented for D_2, Be, Ti, and W targets and the dependences on atomic weight (A) are discussed.




DØ Run II jets
|y|<0.4 (x32)
0.4<|y|<0.8 (x16)
0.8<|y|<1.2 (x8)
1.2<|y|<1.6 (x4)
1.6<|y|<2.0 (x2)
2.0<|y|<2.4
$d^2\sigma/dp_T dy$ (pb/GeV)
$\sqrt{s}$ = 1.96 TeV
L = 0.70 fb^{-1}
R_{cone} = 0.7
NLO pQCD
+non-perturbative corrections
CTEQ6.5M $\mu_R = \mu_F = p_T$
p_T (GeV)
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
50 60
100
200
300 400
600

Λ^0 Hyperon Polarization in Inclusive Production by 300-GeV Protons on Beryllium

G. Bunce, R. Handler, R. March, P. Martin, L. Pondrom, and M. Sheaff

Physics Department, University of Wisconsin, Madison, Wisconsin 53706*

and

K. Heller, O. Overseth, and P. Skubic

Physics Department,† University of Michigan, Ann Arbor, Michigan 48104

and

T. Devlin, B. Edelman, R. Edwards, J. Norem, L. Schachinger, and P. Yamin

Physics Department,† Rutgers University, New Brunswick, New Jersey 08903

(Received 1 December 1975)

Λ^0 polarization has been observed in $p+\mathrm{Be}\rightarrow\Lambda^0+$anything at 300 GeV. A total of 1.2×10^6 Λ^0 decays were recorded at fixed lab angles between 0 and 9.5 mrad, covering a range of kinematic variables $0.3\leqslant x\leqslant0.7$ and $0\leqslant p_\perp\leqslant1.5$ GeV/c. The observed polarization was consistent with parity conservation and increased monotonically with increasing $p_\perp$, independently of x, reaching $P_\Lambda=0.28\pm0.08$ at 1.5 GeV/c.

Precise Measurement of the Λ^0 Magnetic Moment

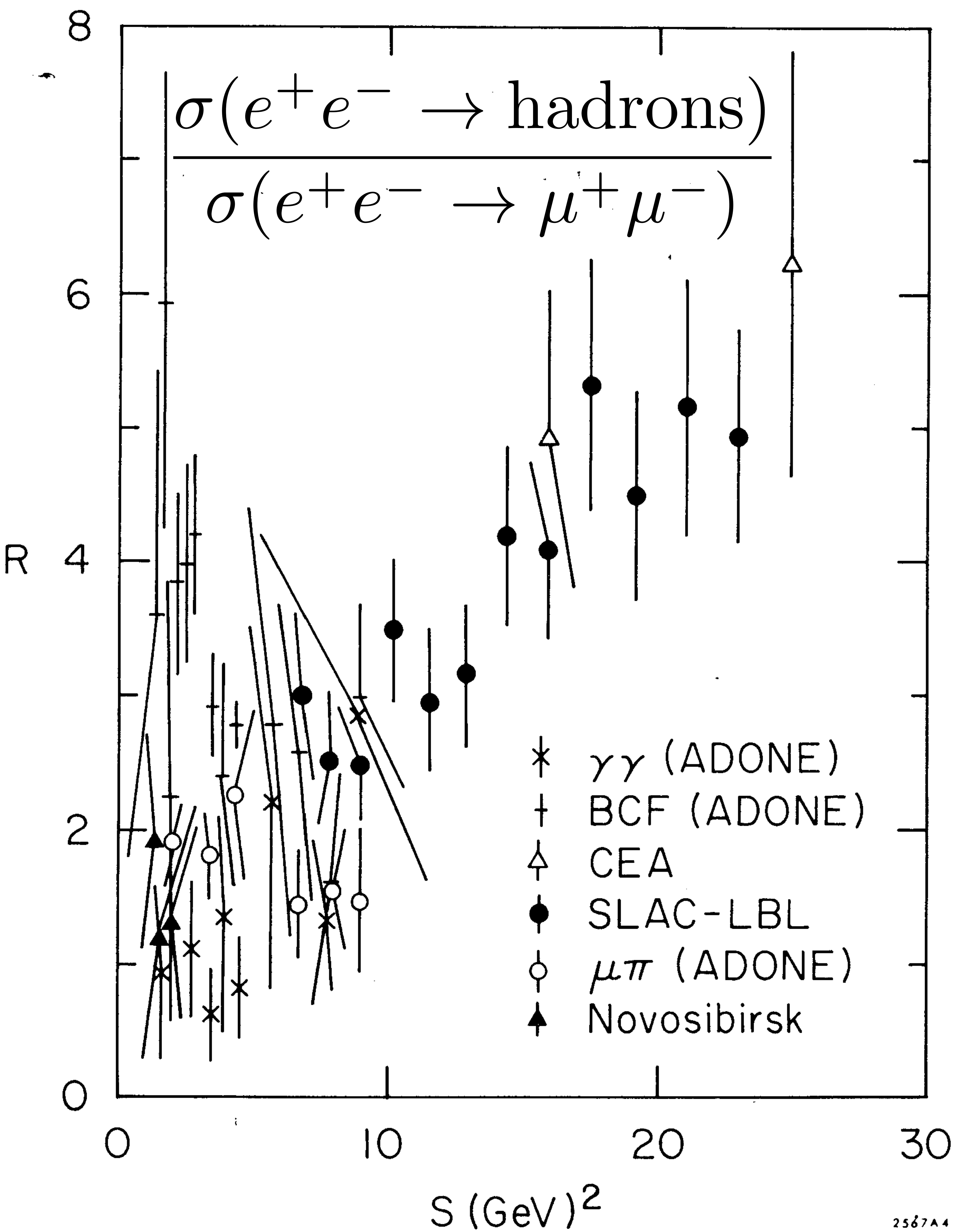
L. Schachinger,[a] G. Bunce,[b] P. T. Cox, T. Devlin, J. Dworkin, B. Edelman,[c] R. T. Edwards,[d] R. Handler, K. Heller,[e] R. March, P. Martin,[f] O. E. Overseth, L. Pondrom, M. Sheaff, and P. Skubic

Physics Department, University of Michigan, Ann Arbor, Michigan 48109, and Physics Department, Rutgers —The State University, Piscataway, New Jersey 08854, and Physics Department, University of Wisconsin, Madison, Wisconsin 53706

(Received 8 September 1978)

The magnetic moment of the Λ^0 hyperon has been measured to be $\mu_\Lambda = (-0.6138 \pm 0.0047)\mu_N$.

London ICHEP 1974



CHAIRMAN'S SUMMARY

L M Lederman

Columbia University

1. $\left(\frac{e}{\pi}\right)^+ \cong \left(\frac{e}{\pi}\right)^- \cong \left(\frac{\mu}{\pi}\right)^+ \cong \left(\frac{\mu}{\pi}\right)^- \cong 10^{-4}$
2. This is independent of P_T from 1.5 to 5 GeV/c.
3. This is independent of nucleon target size.
4. This is independent of CM viewing angle.
5. This is independent of s from $\sqrt{s}$ = 7 to $\sqrt{s}$ = 53 (See Fig. 1).

<u>All of these statements may be true to within a factor of 2 or so.</u>

(A BNL point is taken from a comment by R Adair). The implications are that leptons and pions have a common origin. Statement 5 implies the source mass <u>must be less than</u> 3-4 GeV (no threshold effects) for

$$p + p \to X + \text{anything}$$
$$\hookrightarrow \text{leptons}$$

or less than 1.5-2 GeV for pion production e.g. Charmed particles. Statement (1) in its lack of charge asymmetry is discouraging for charmed meson sources analogous to K-mesons. The agreement of the ISR with NAL rules out low masses (M_x > few hundred MeV) because narrow angle leptons are vetoed in the ISR measurements.

The ISR muons and NAL electrons set limits on the production of single leptons e.g. from $W^\pm$ up to the kinematic limit. However, it is out of fashion to convert these limits to mass limits because the necessary models are currently discredited.

The lack of $P_\perp$ "bumps" means there are no significant heavy objects (M from 3 → 10 GeV) decaying into <u>two leptons</u>.

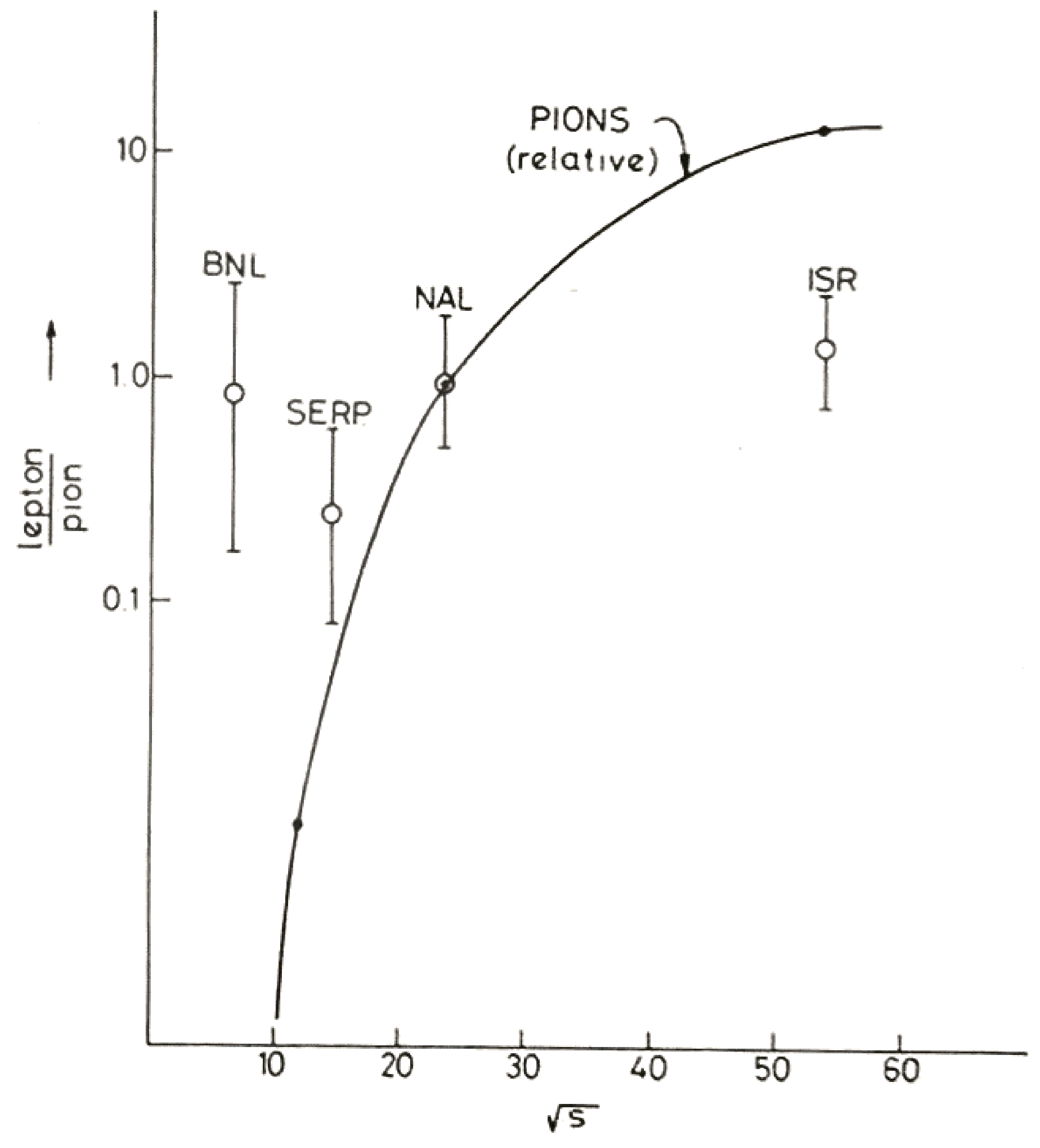
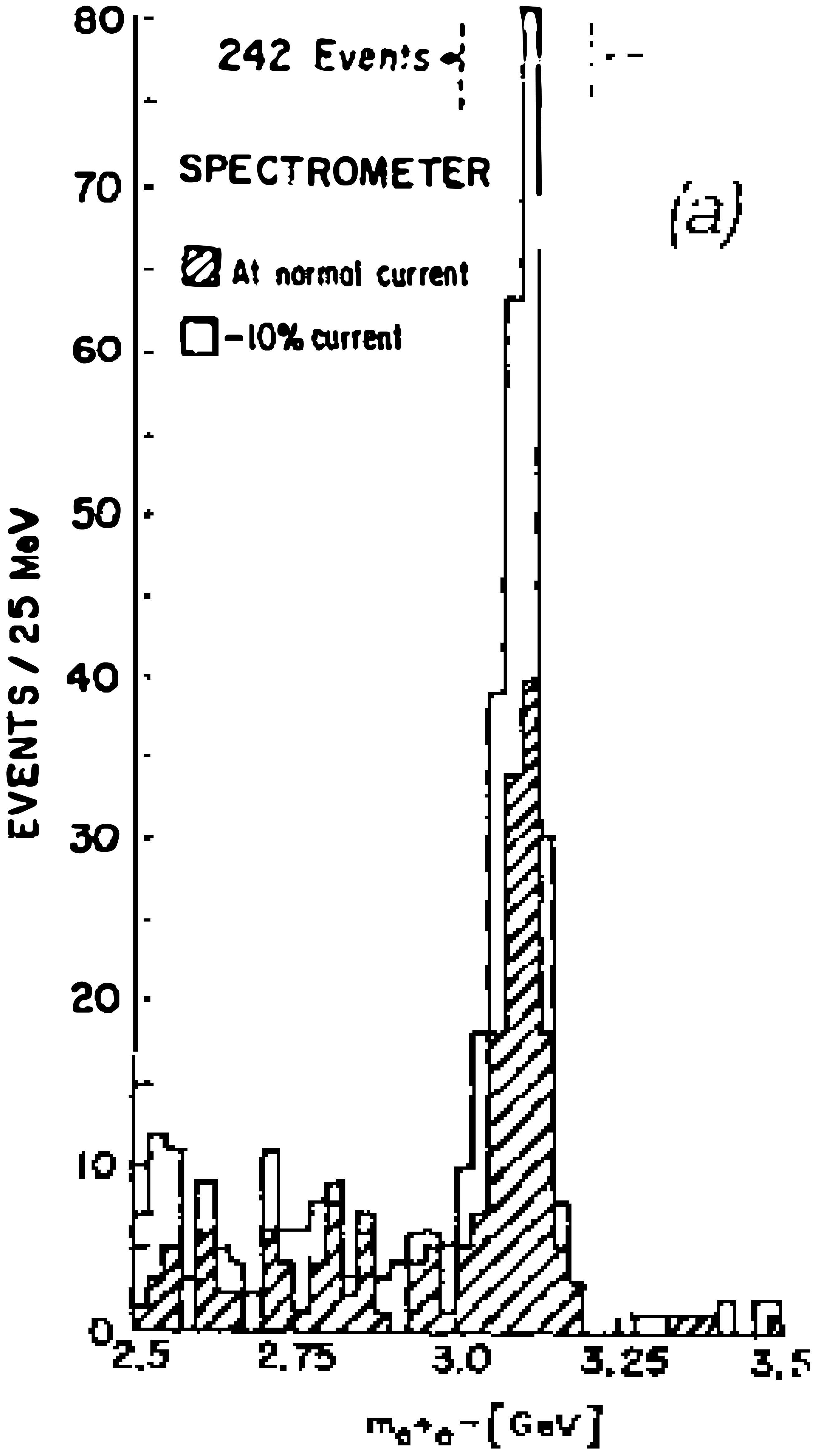
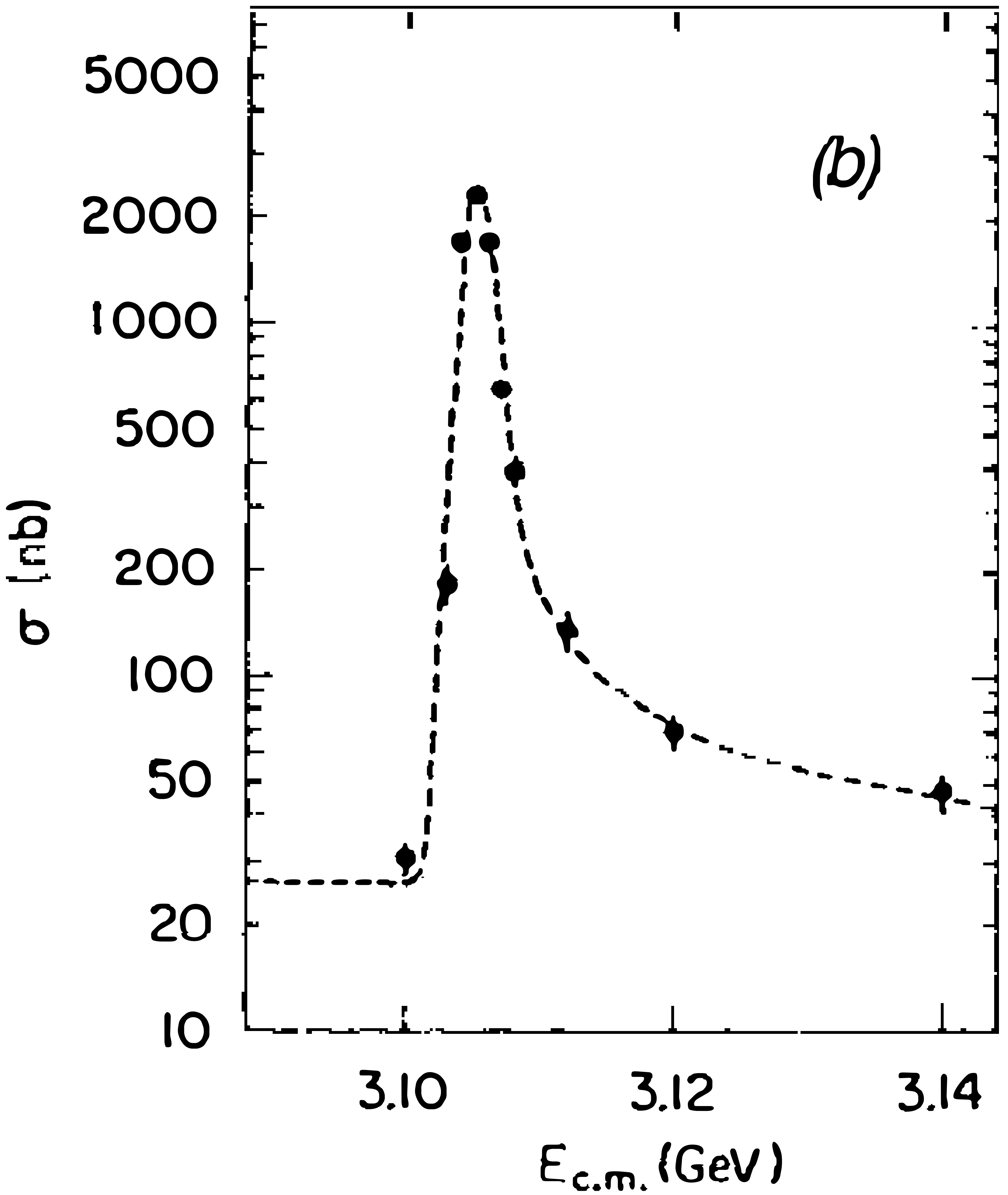


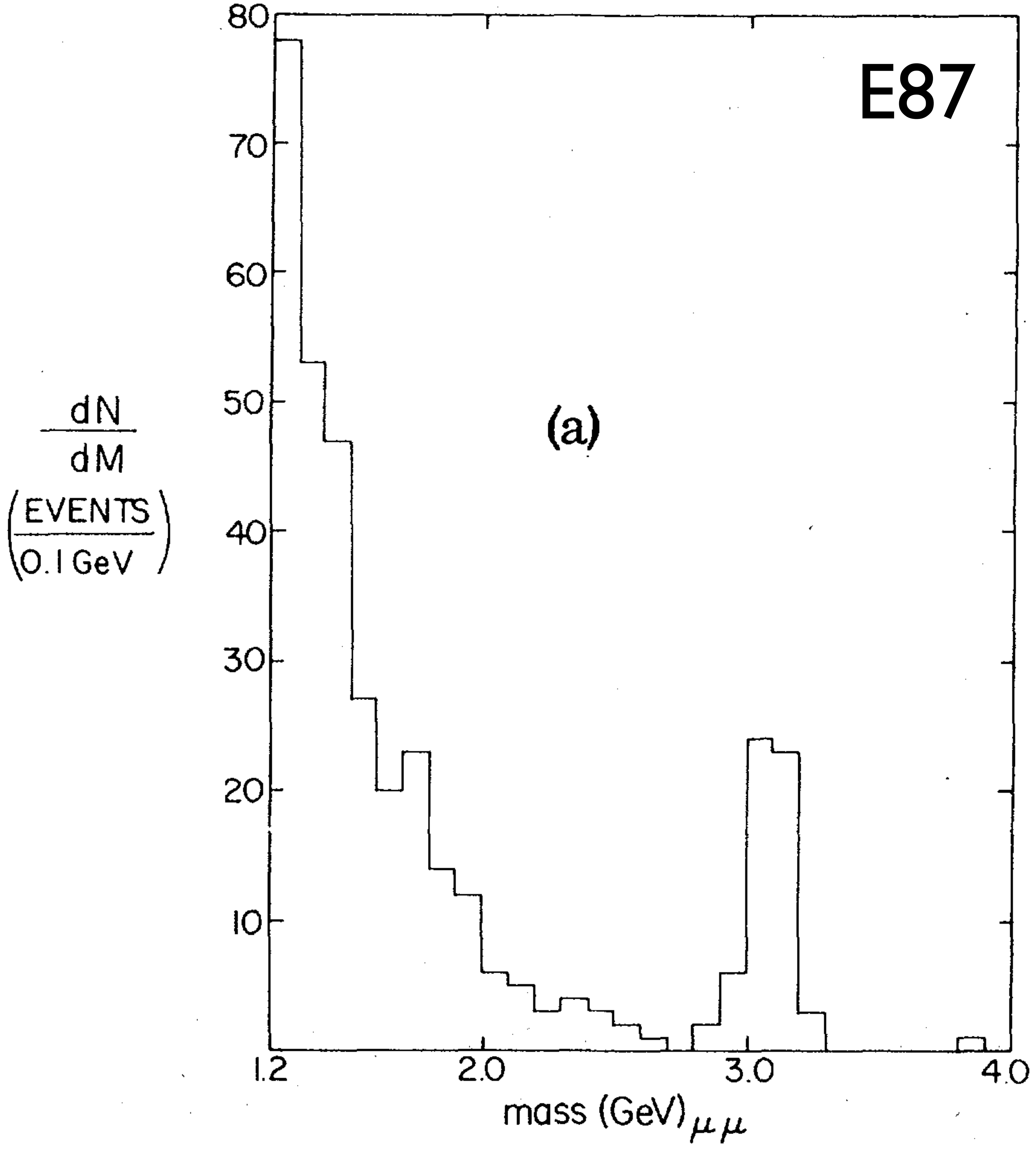
Fig. 1 lepton/pion ratio vs $\sqrt{s}$ compared to pion production ($P_\perp \sim 3$ GeV). Errors are estimated freely.



80
70
60
50
40
30
20
10
0
242 Events
SPECTROMETER
(a)
At normal current
-10% current
EVENTS / 25 MeV
2.5
2.75
3.0
3.25
3.5
$m_{e^+e^-}$ [GeV]



5000
2000
1000
500
200
100
50
20
10
(b)
σ (nb)
3.10
3.12
3.14
$E_{c.m.}$ (GeV)



dN/dM
(EVENTS / 0.1 GeV)
80
70
60
50
40
30
20
10
E87
(a)
1.2
2.0
3.0
4.0
mass (GeV)$_{\mu\mu}$

Theorists!

NAL PROPOSAL # 288

Scientific Spokesman:

L. M. Lederman
Physics Department
Columbia University
New York, New York 10027

FTS/Off-net: 212 - 460-0100
280-1754

A Study of Di-Lepton Production in Proton Collisions at NAL

J. A. Appel, M. H. Bourquin, D. C. Hom, L. M. Lederman, J. P. Repellin, H. D. Snyder, J. K. Yoh (Columbia University); B. C. Brown, P. Limon, T. Yamanouchi (NAL).

(Formerly #70 Phase III)

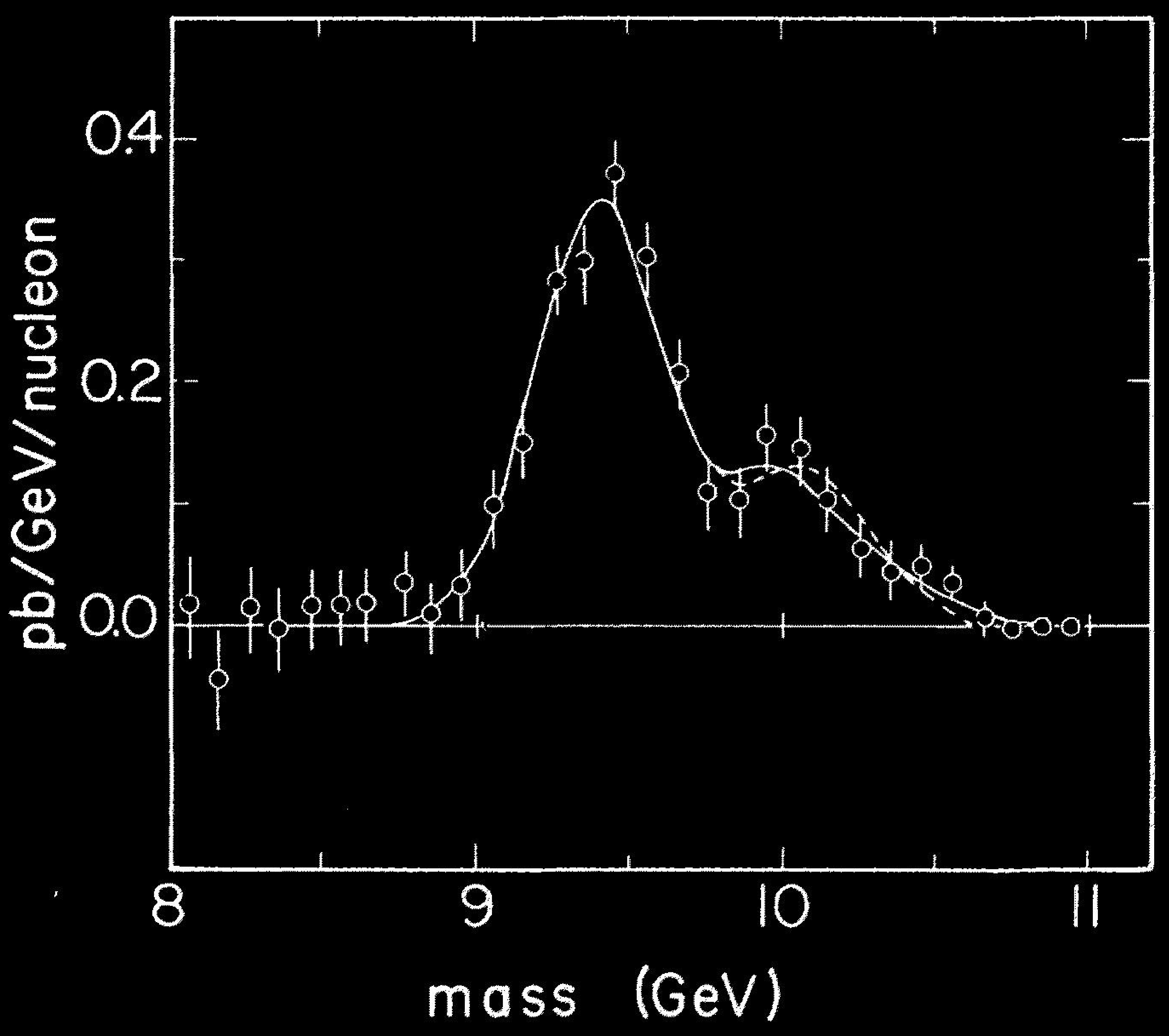
February 1974

AHR 5581

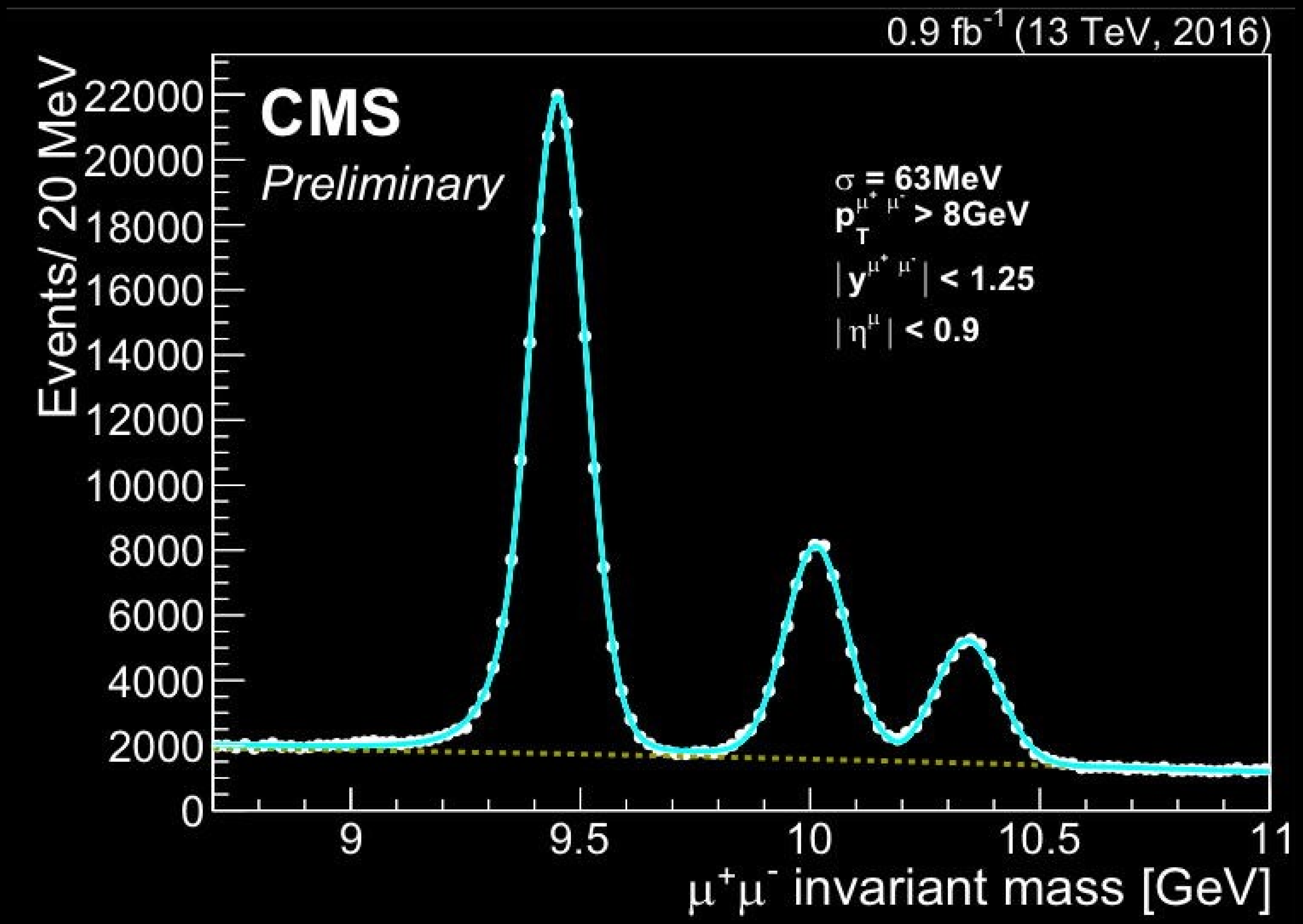
A Study of Di-Lepton Production in Proton Collisions at NAL

1. Observe and measure the spectrum of virtual photons emitted in p-nucleon collisions via the mass distribution of e^+e^- pairs: $p + p \to e^+ e^- +$ anything. (1) Study characteristics, e.g. parity violation, $p_\perp$ behavior.
2. Search for structures in the above spectrum, publish these and become famous, e.g. W°, B°.
3. Qualitatively study the mass spectrum of hadron pairs ($\pi\pi$, πp, etc). This is an interesting background for (1). It uses a crude hadron calorimeter, also required for hadron rejection in (1).
4. Check μe universality by looking, in the same arrangement but with the addition of a pion filter, at $\mu^+\mu^-$ pairs.
5. Extend the Experiment #70 study of single leptons in the double arm arrangement, i.e. $W^\pm$ etc. Publish these and become famous.
6. Look at $\pi^\circ\pi^\circ$ pairs by double conversion of π°- γ's in thin aluminum radiators. This data comes free since one adds 0.1 radiation length to enable an extrapolation to zero target thickness in (1).

Discovery



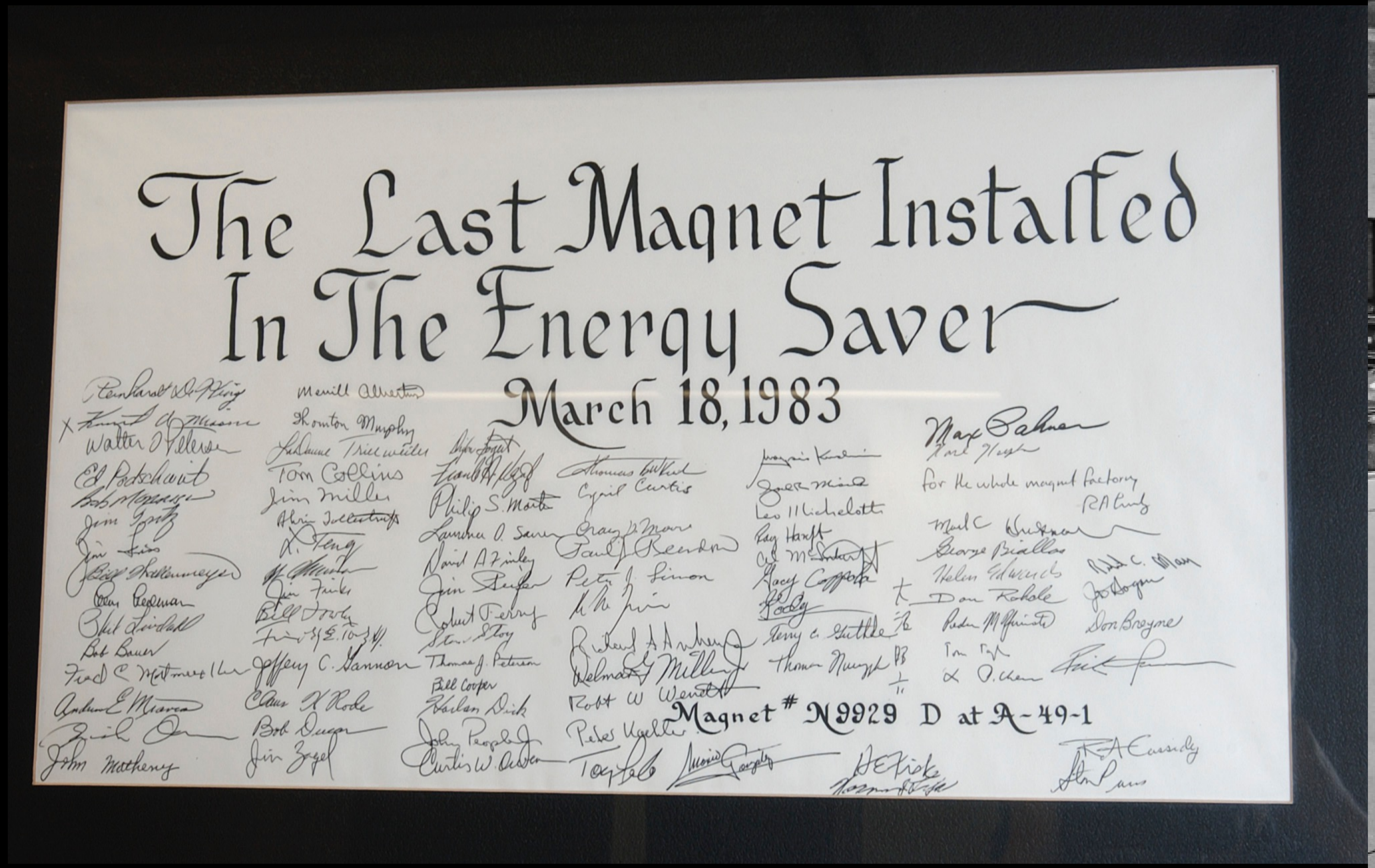
Calibration

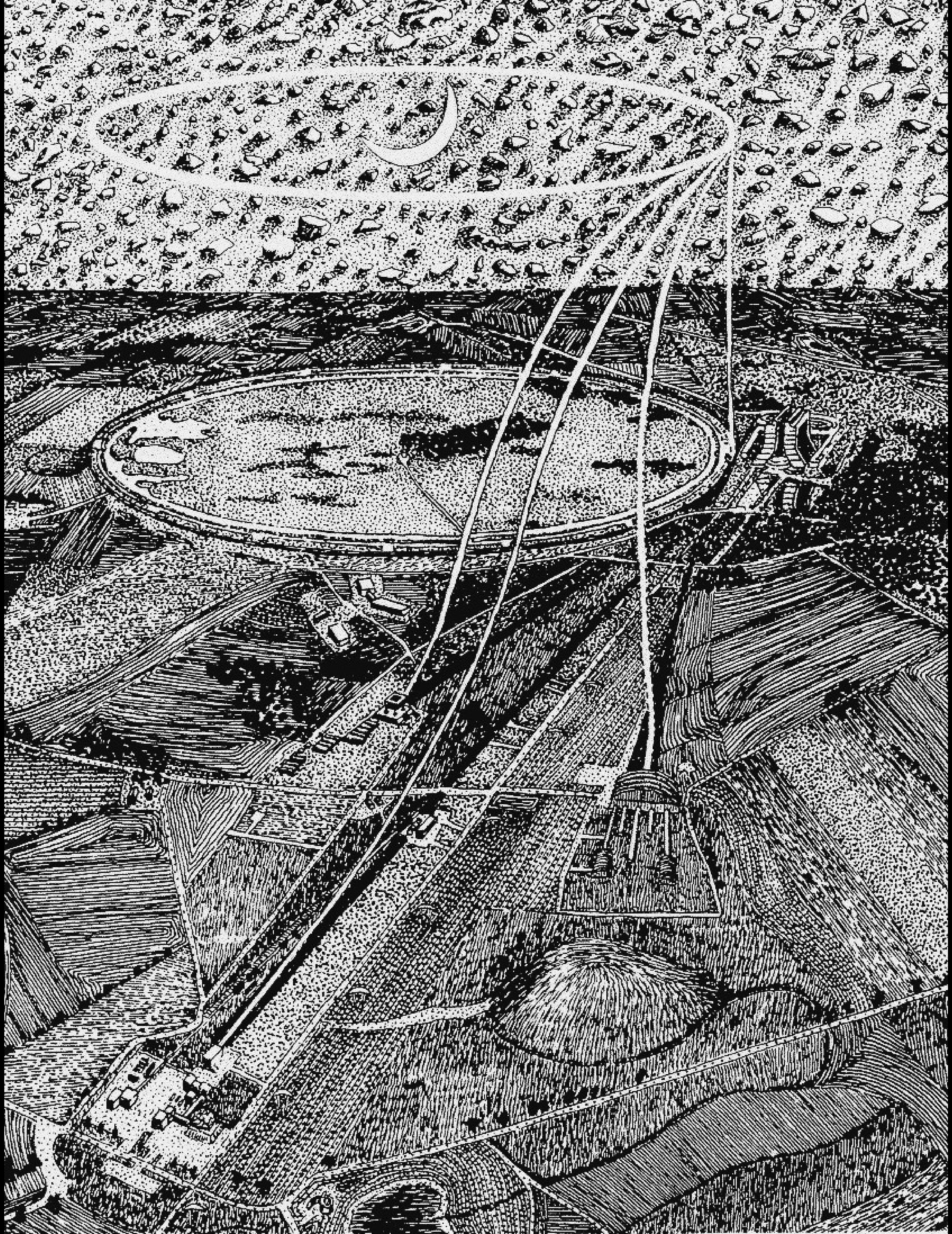


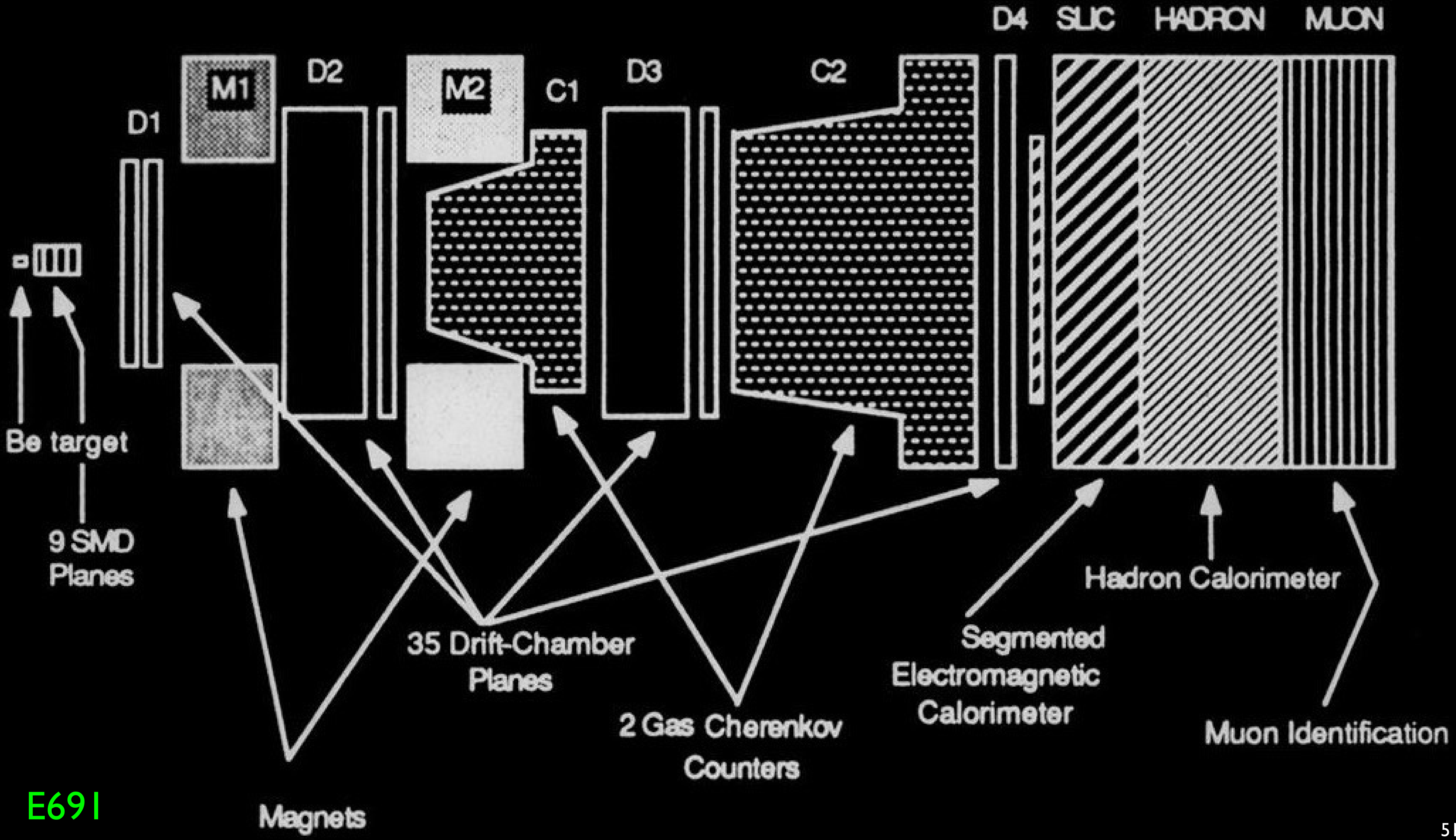
Comparative Quarkonium Spectroscopy

+ Richness of *b*-hadron studies

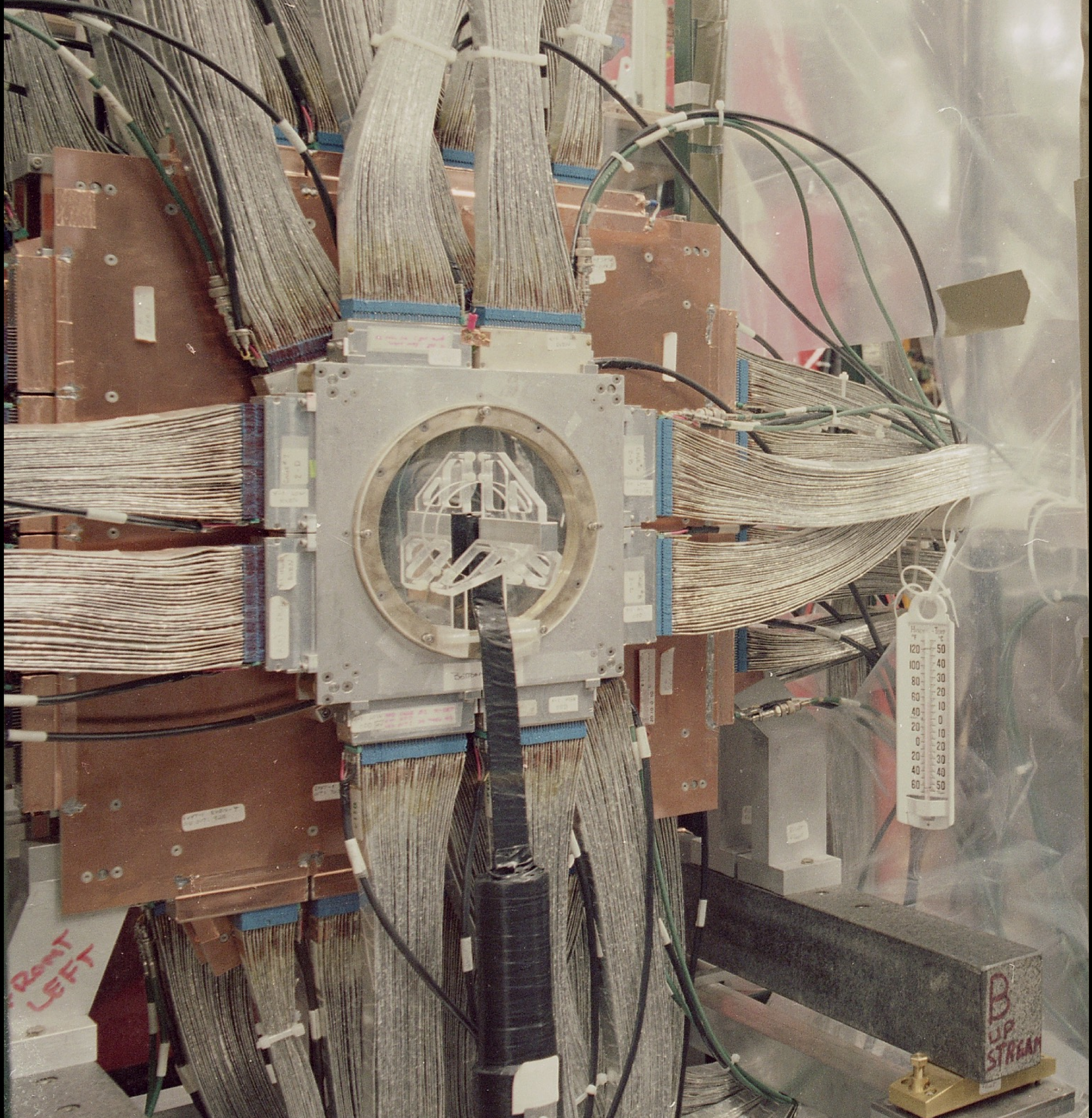

DIPOLE
QUADRUPOLE


The Last Magnet Installed
In The Energy Saver
March 18, 1983
Magnet # N9929 D at A-49-1

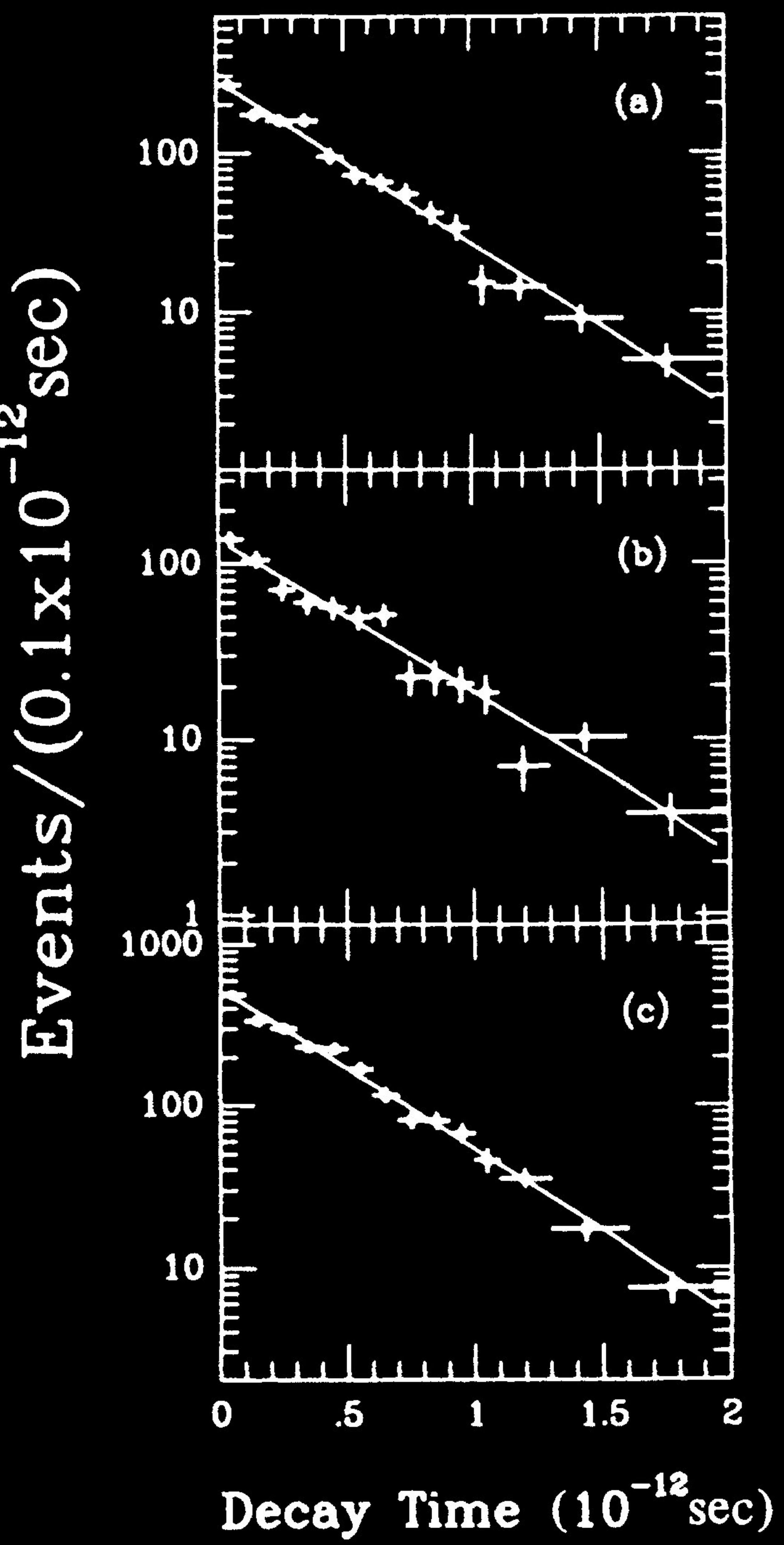



D4
SLIC
HADRON
MUON
M1
D2
M2
C1
D3
C2
D1
Be target
9 SMD
Planes
35 Drift-Chamber
Planes
2 Gas Cherenkov
Counters
Segmented
Electromagnetic
Calorimeter
Hadron Calorimeter
Muon Identification
Magnets

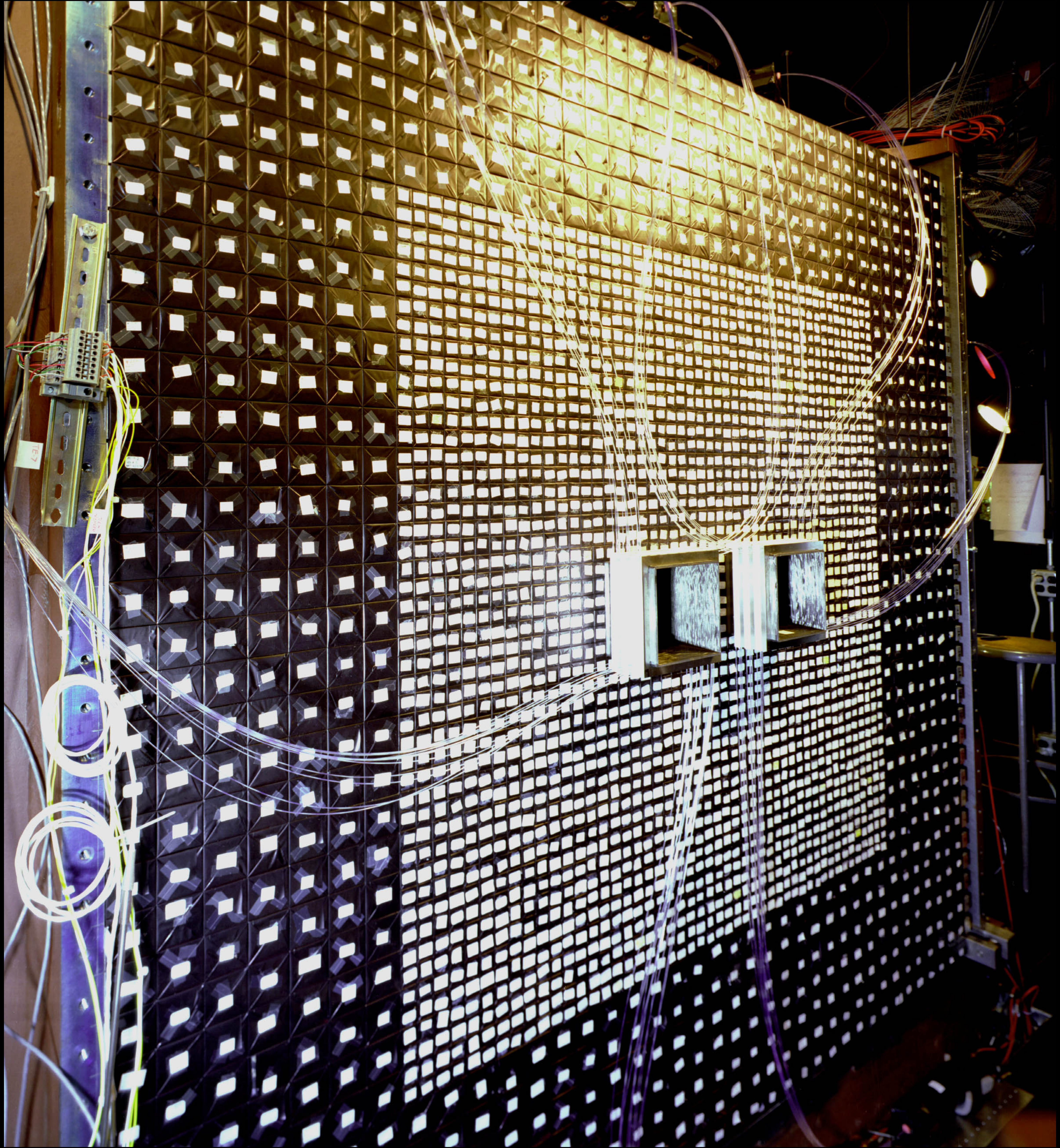
E691


B
UP
STREAM


A
B
C
D



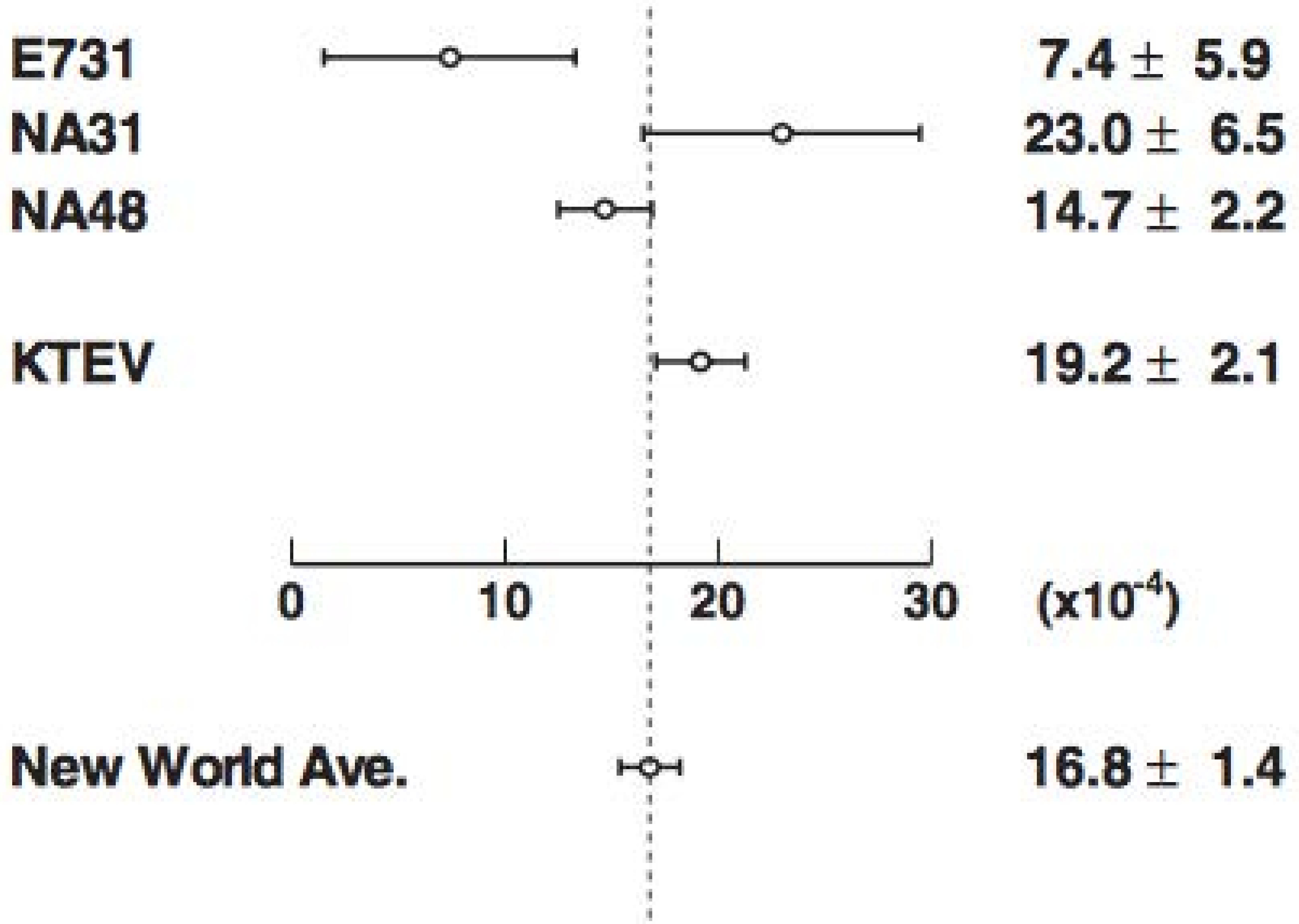
D^0 meson lifetime
~0.4 picoseconds
(4200 events)



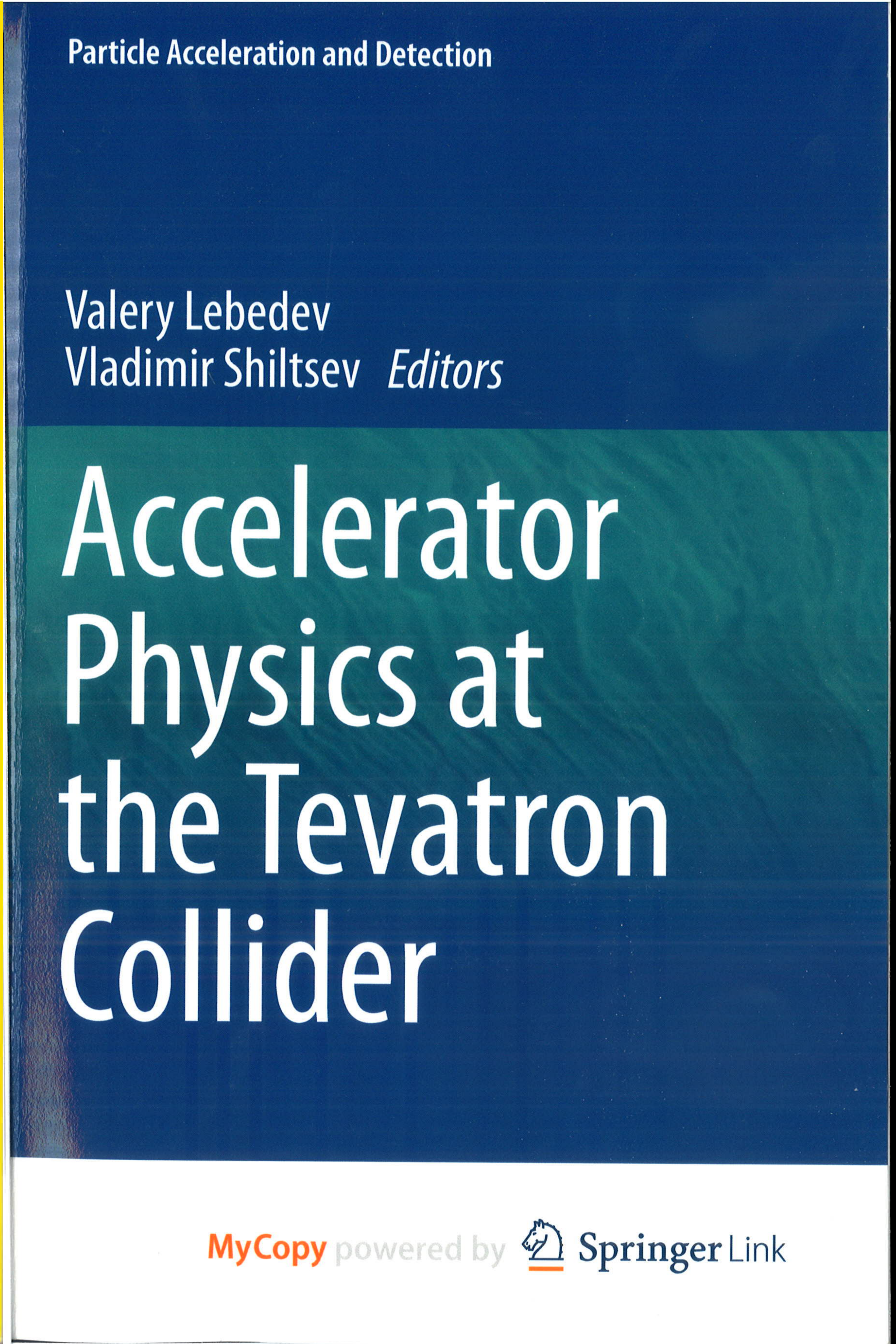
KTeV

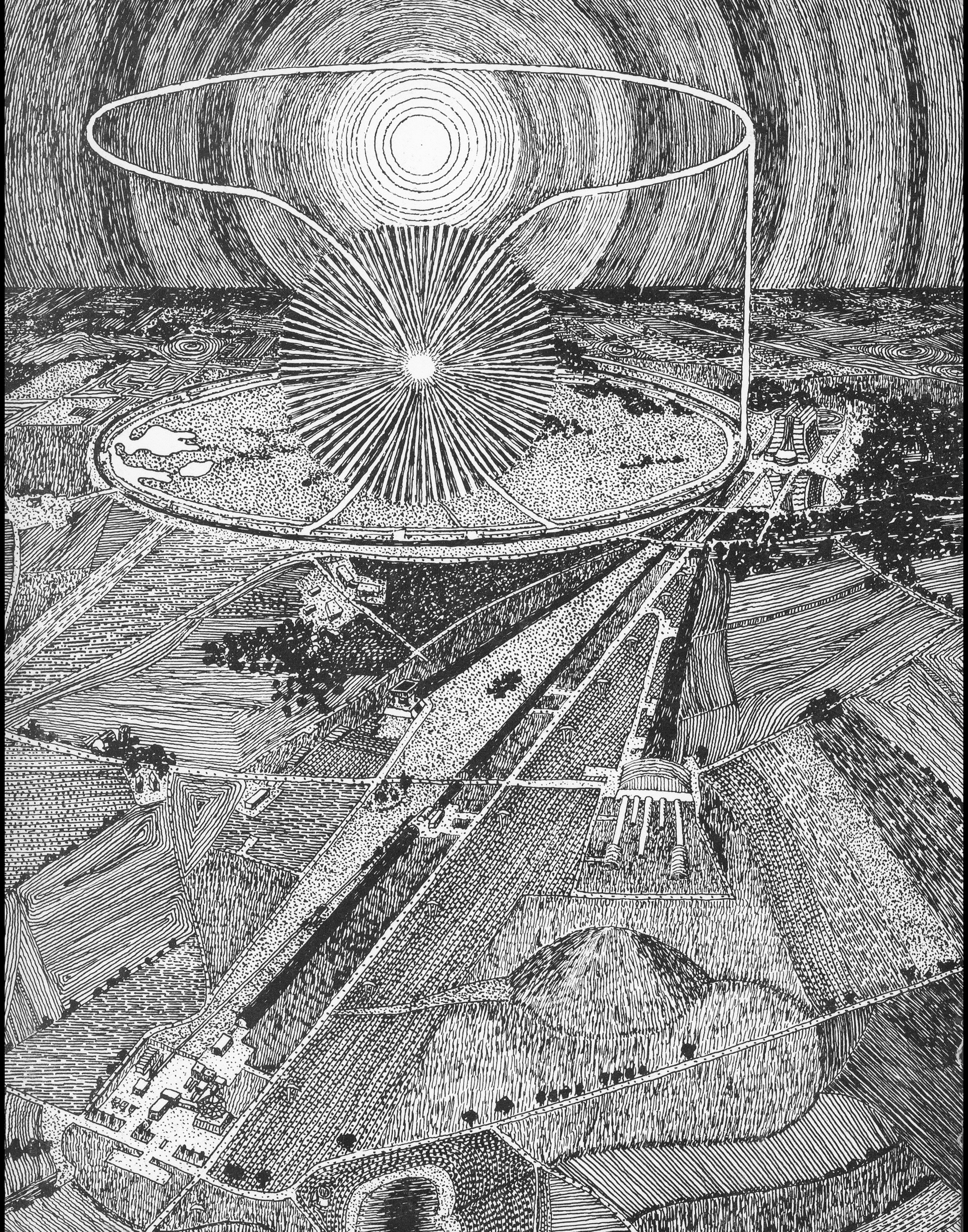
Re(ε′/ε)

$$K_{\mathrm{L}} \to \pi^0\pi^0, \pi^+\pi^-$$




Symposium in Celebration of the
Fixed Target Program with the
Tevatron
Fermilab Library
0 1160 0085443 4
Fermi National Accelerator Laboratory
June 2, 2000


Particle Acceleration and Detection
Valery Lebedev
Vladimir Shiltsev Editors
Accelerator
Physics at
the Tevatron
Collider
MyCopy powered by Springer Link




CDF
FERMILAB

D0

NY *Times*, January 5, 1993

315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

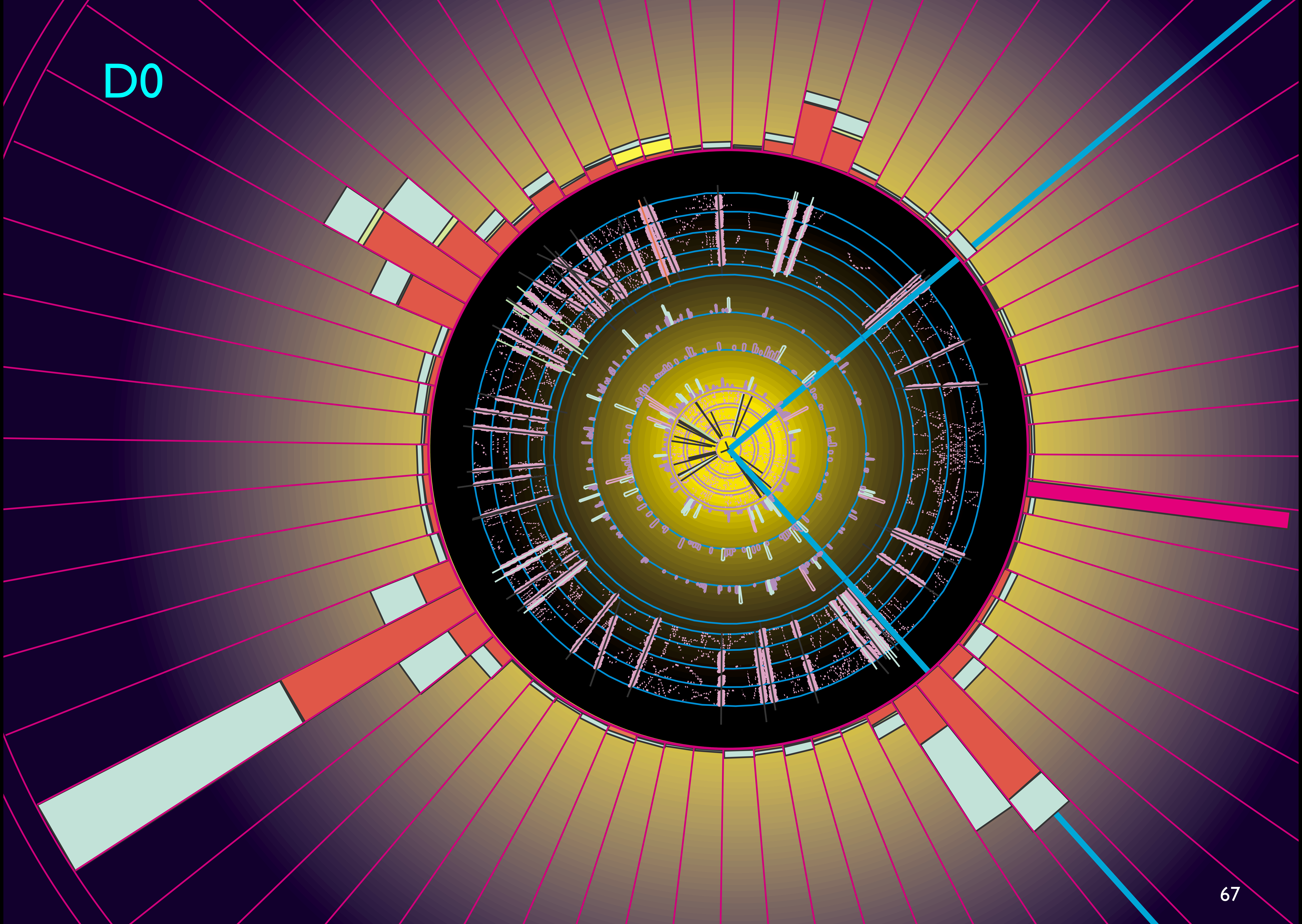
By MALCOLM W. BROWNE

THREE HUNDRED AND FIFTEEN physicists worked on the experiment.

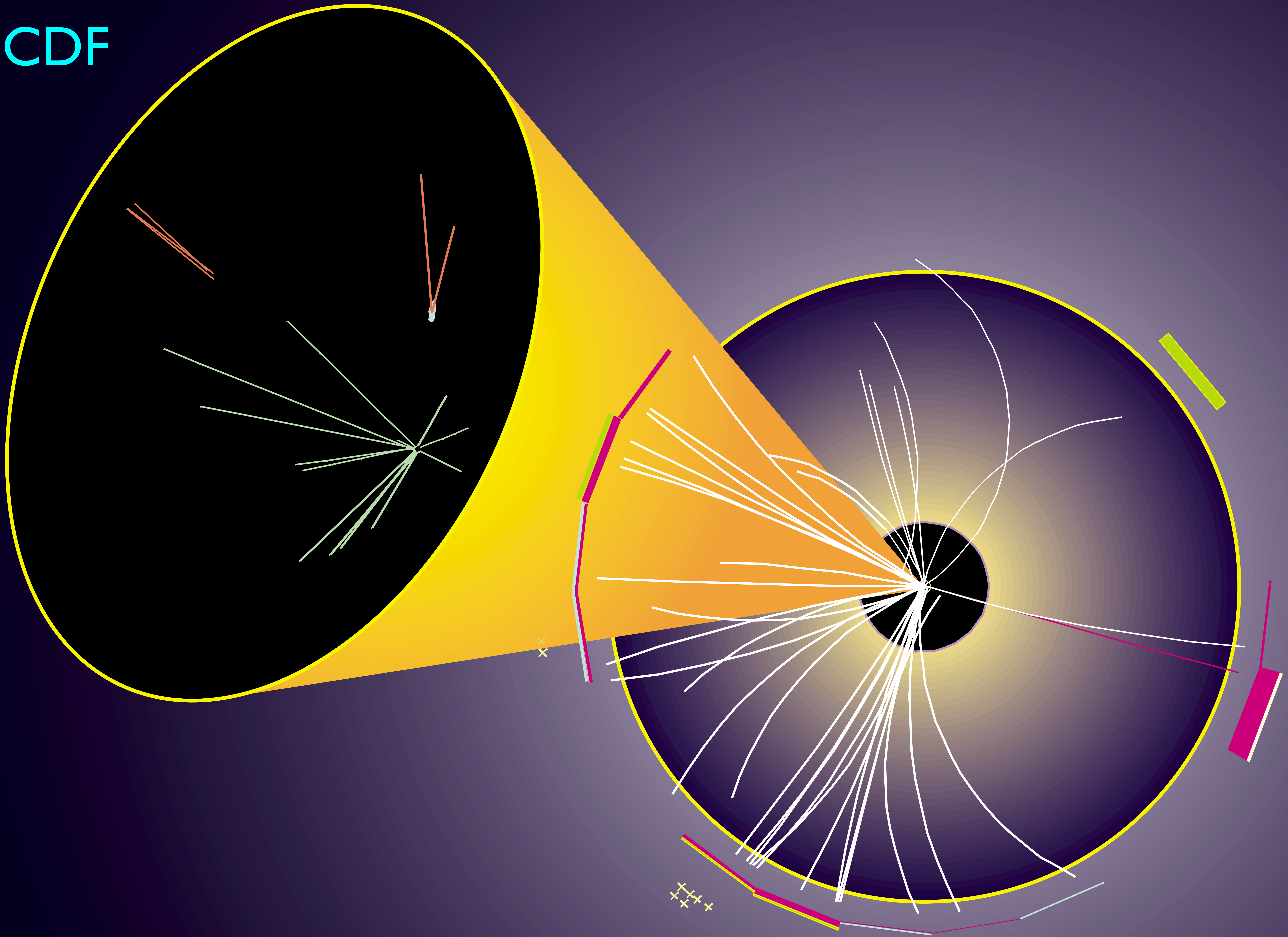
Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.


March 2, 1995

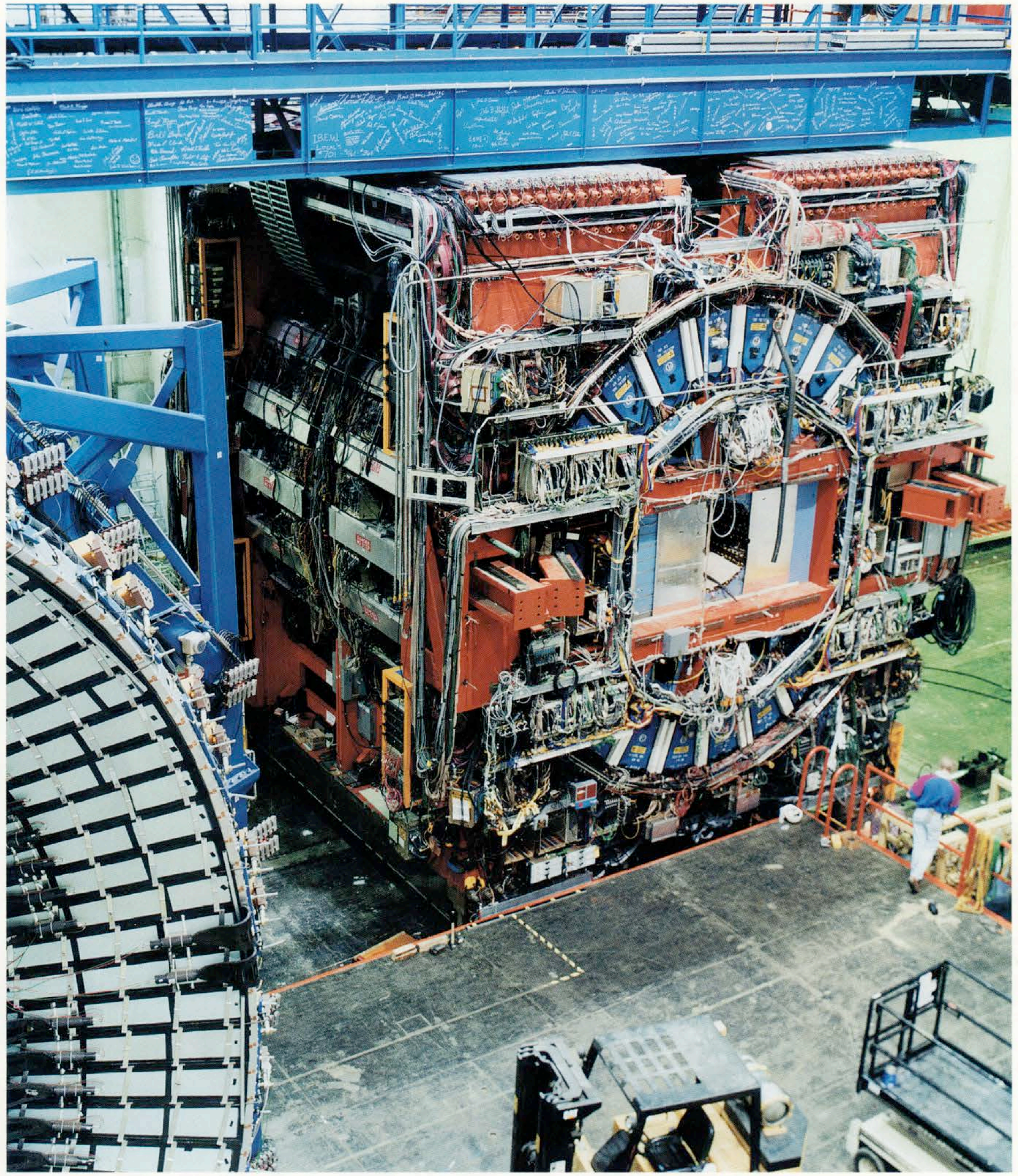

D0

CDF



PHYSICS TODAY

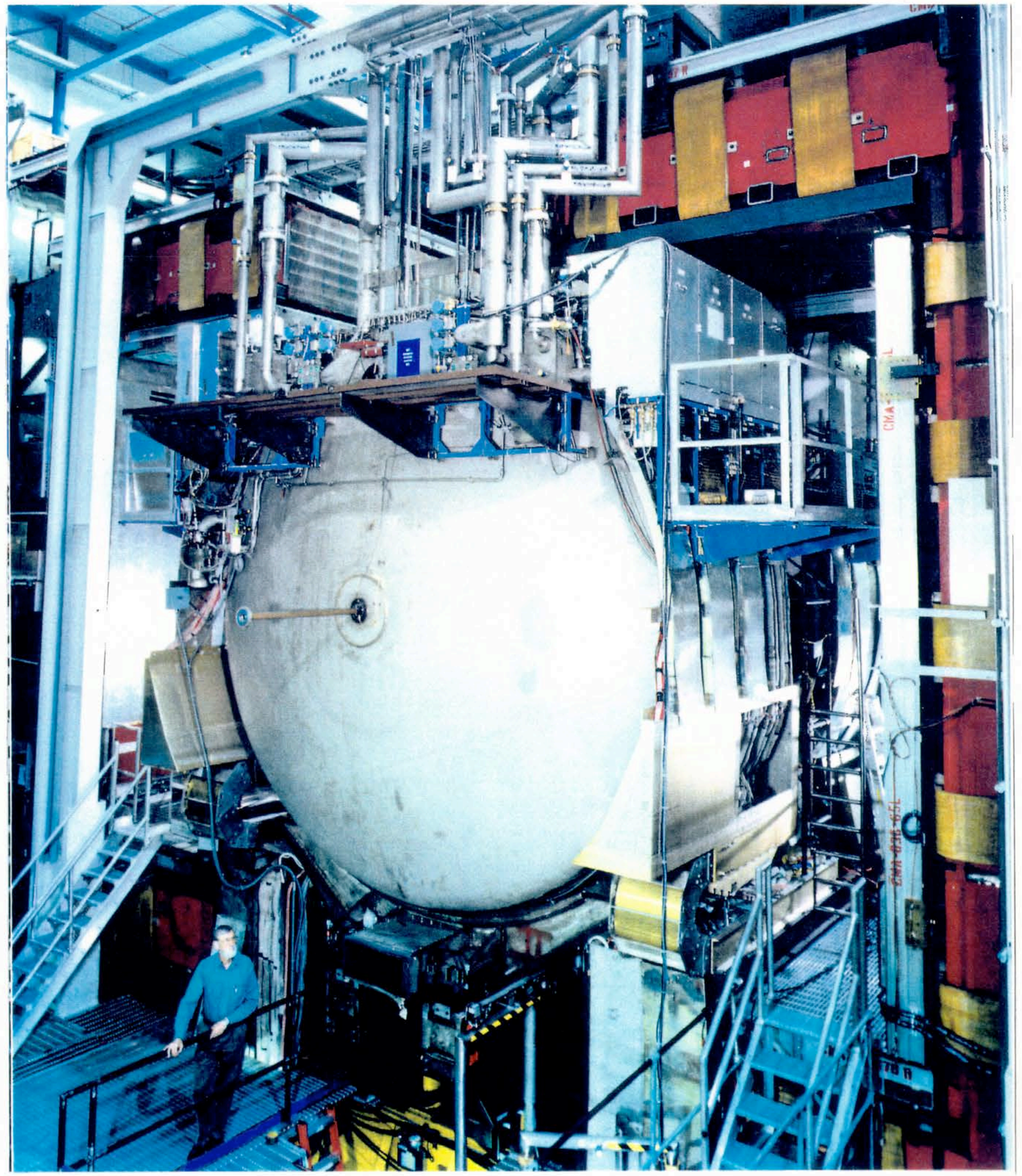
MAY 1997



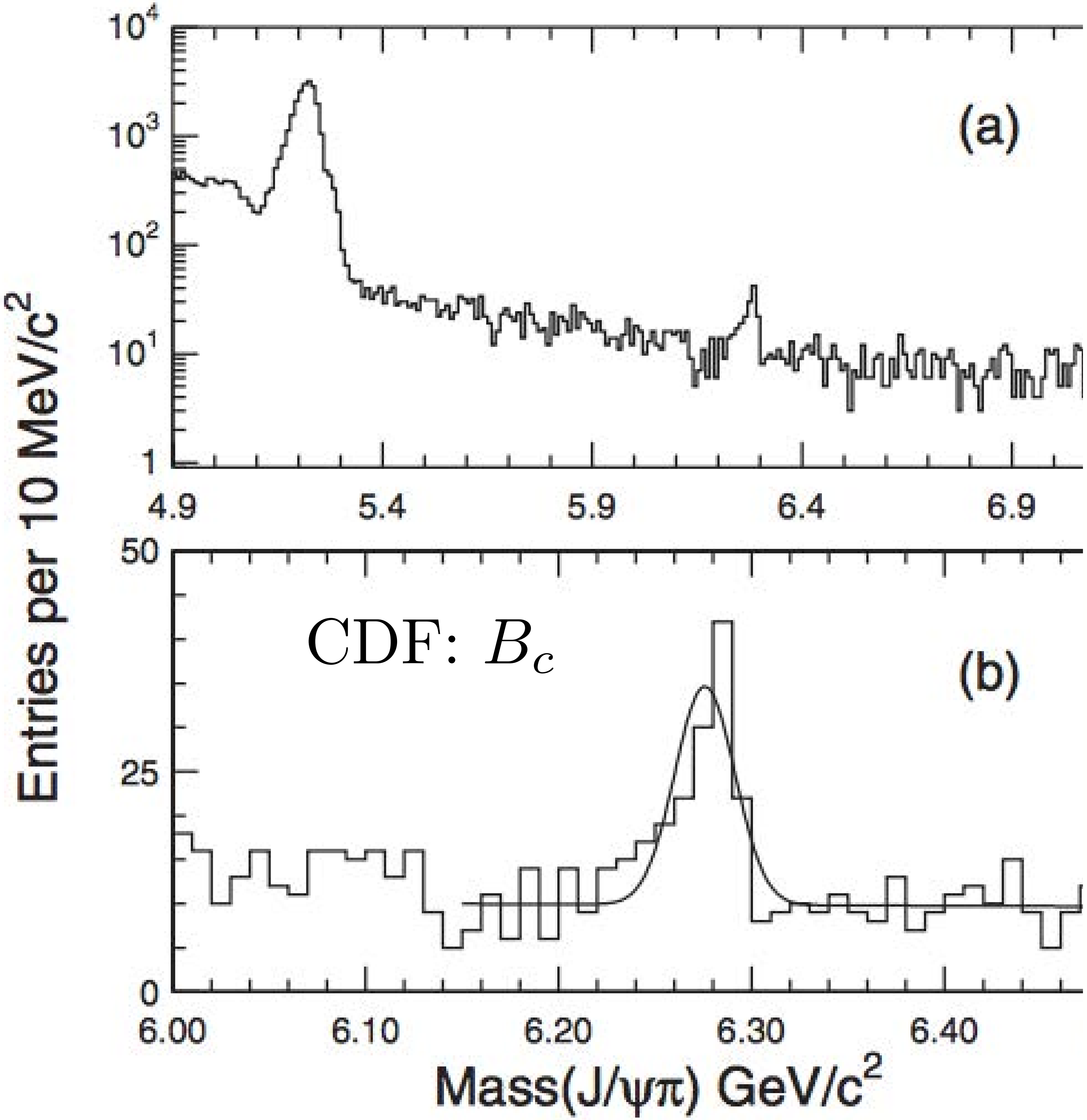
THE REMARKABLE TOP QUARK

PHYSICS TODAY

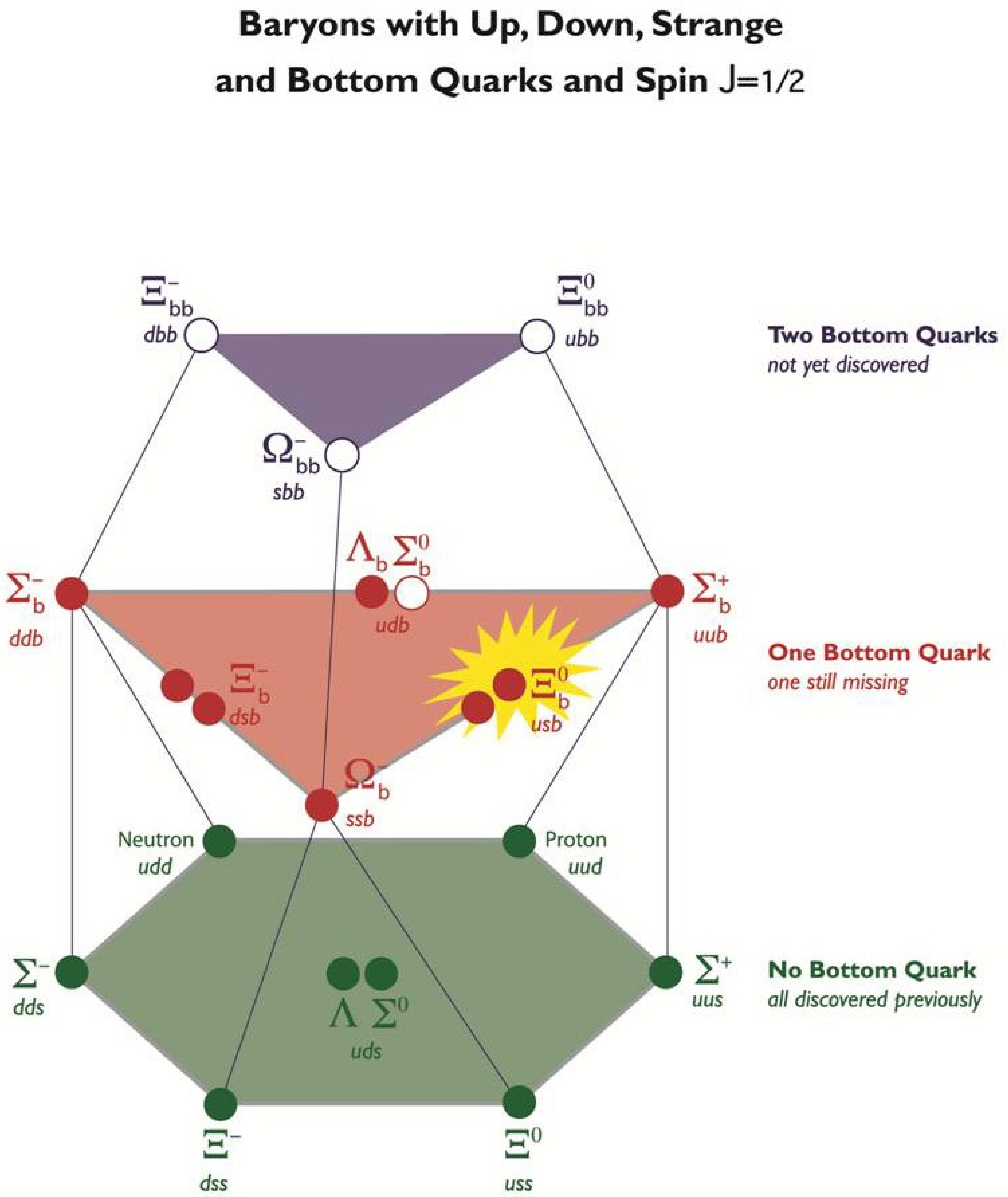
MAY 1997



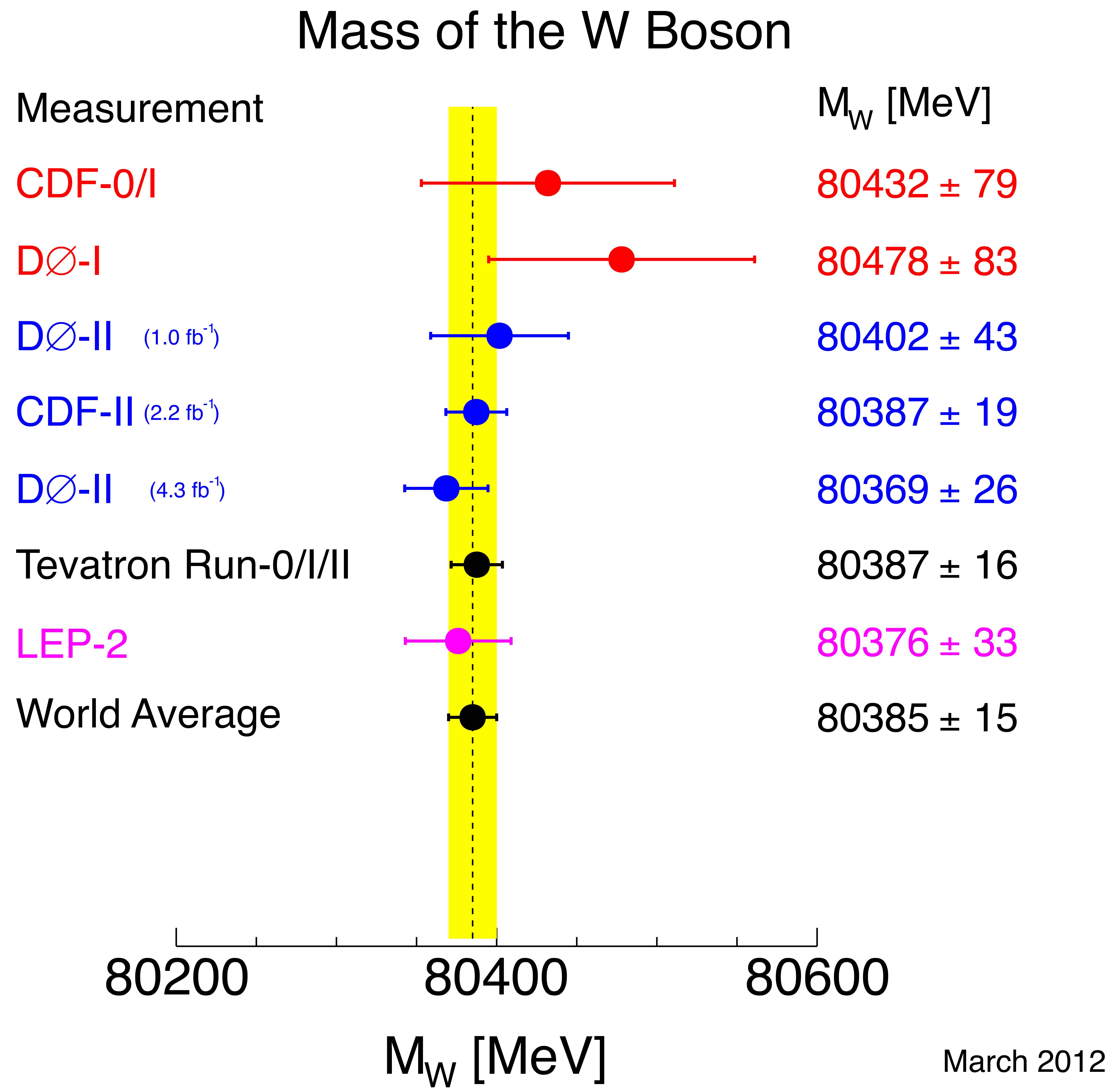
THE REMARKABLE TOP QUARK

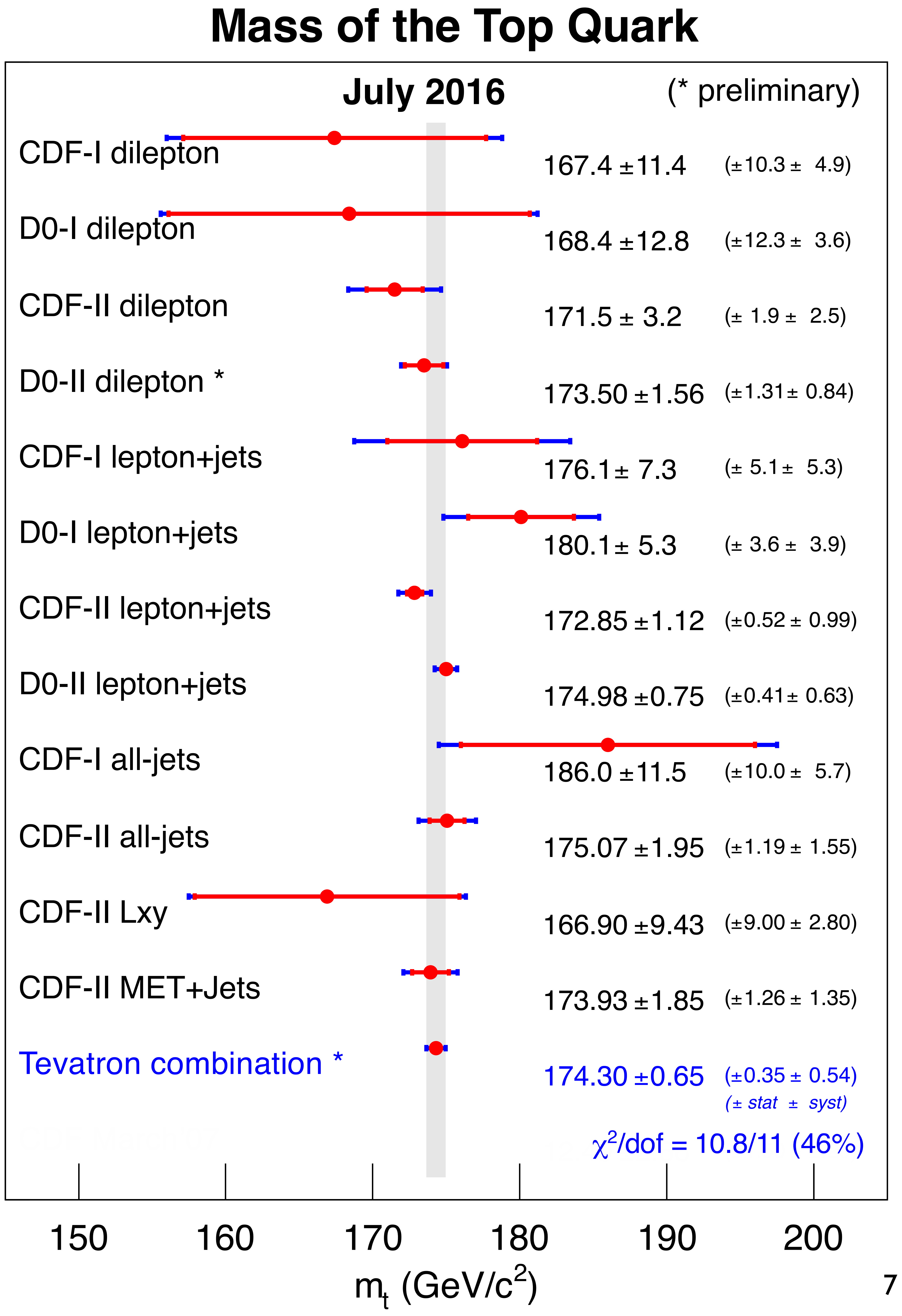


(a)
(b)
CDF: B_c
Entries per 10 MeV/c²
Mass(J/ψπ) GeV/c²



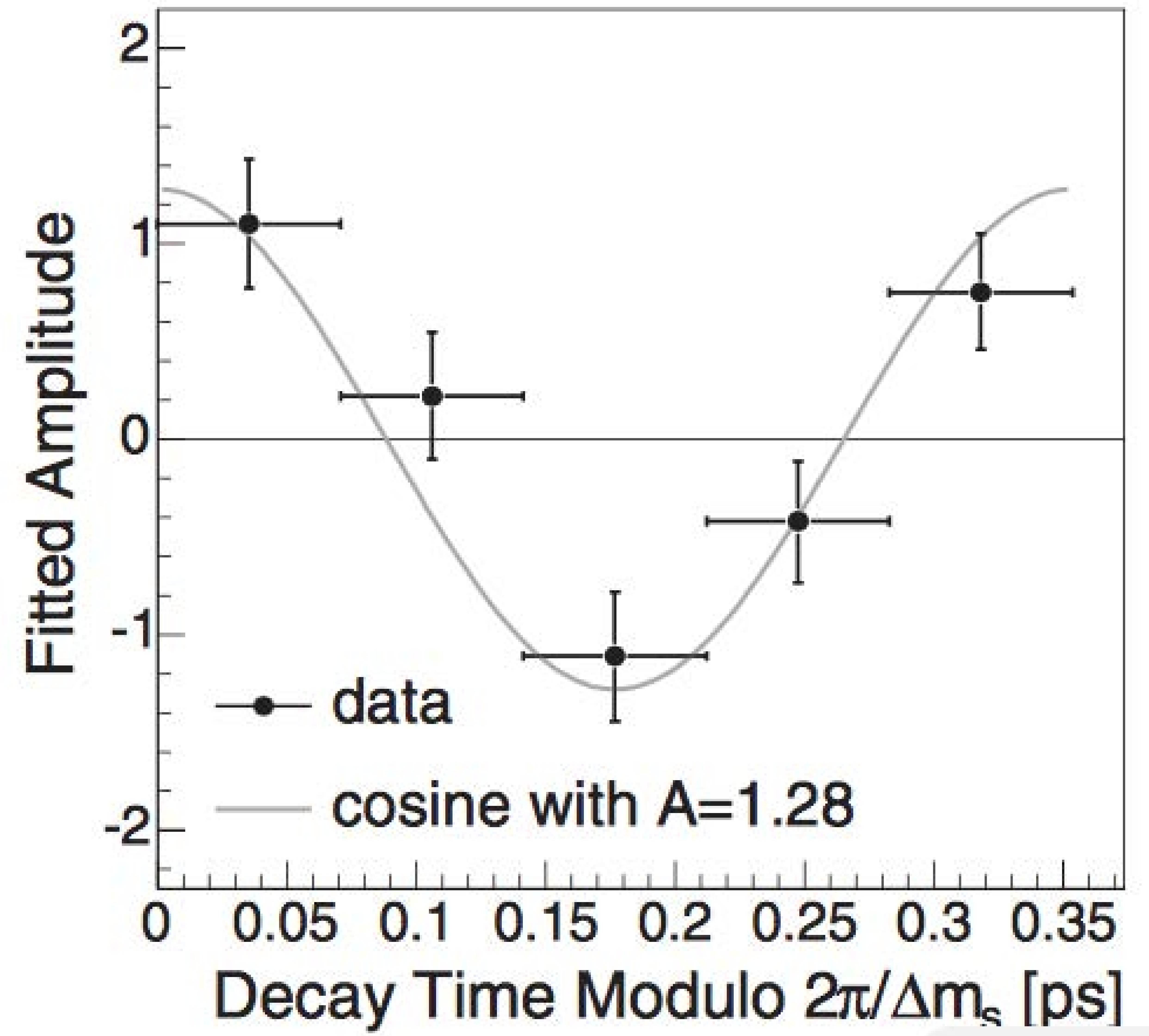
Baryons with Up, Down, Strange and Bottom Quarks and Spin J=1/2
Two Bottom Quarks
not yet discovered
One Bottom Quark
one still missing
No Bottom Quark
all discovered previously
Ξ^-_{bb} dbb
Ξ^0_{bb} ubb
Ω^-_{bb} sbb
Σ^-_b ddb
Λ_b Σ^0_b udb
Σ^+_b uub
Ξ^-_b dsb
Ξ^0_b usb
Ω^-_b ssb
Neutron udd
Proton uud
Σ^- dds
Λ Σ^0 uds
Σ^+ uus
Ξ^- dss
Ξ^0 uss

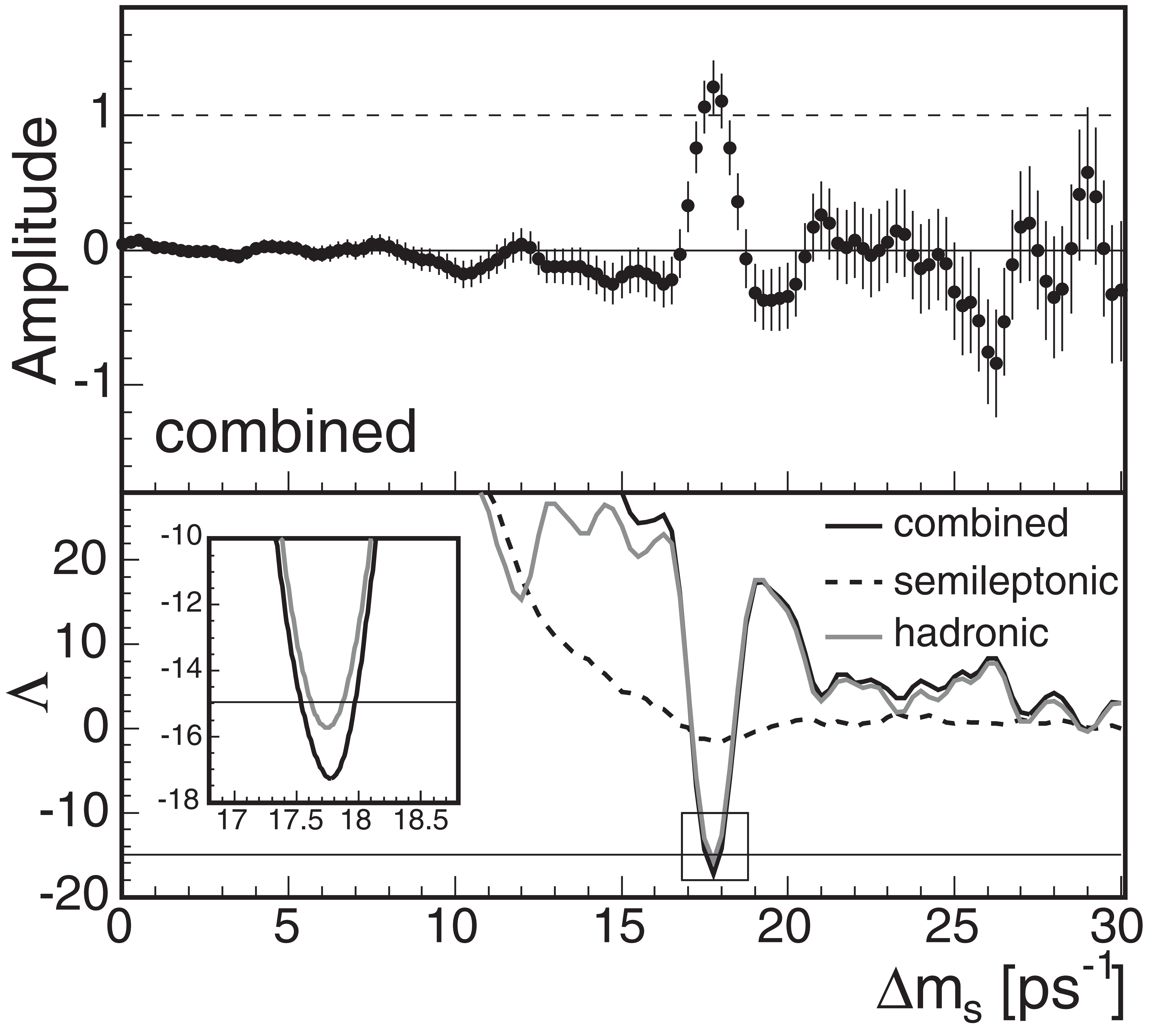

Mass of the W Boson
Measurement
M_W [MeV]
CDF-0/I
80432 ± 79
DØ-I
80478 ± 83
DØ-II (1.0 fb^{-1})
80402 ± 43
CDF-II (2.2 fb^{-1})
80387 ± 19
DØ-II (4.3 fb^{-1})
80369 ± 26
Tevatron Run-0/I/II
80387 ± 16
LEP-2
80376 ± 33
World Average
80385 ± 15
80200
80400
80600
M_W [MeV]
March 2012


Mass of the Top Quark
July 2016
(* preliminary)
CDF-I dilepton
167.4 ±11.4 (±10.3 ± 4.9)
D0-I dilepton
168.4 ±12.8 (±12.3 ± 3.6)
CDF-II dilepton
171.5 ± 3.2 (± 1.9 ± 2.5)
D0-II dilepton *
173.50 ±1.56 (±1.31± 0.84)
CDF-I lepton+jets
176.1± 7.3 (± 5.1 ± 5.3)
D0-I lepton+jets
180.1± 5.3 (± 3.6 ± 3.9)
CDF-II lepton+jets
172.85 ±1.12 (±0.52 ± 0.99)
D0-II lepton+jets
174.98 ±0.75 (±0.41± 0.63)
CDF-I all-jets
186.0 ±11.5 (±10.0 ± 5.7)
CDF-II all-jets
175.07 ±1.95 (±1.19 ± 1.55)
CDF-II Lxy
166.90 ±9.43 (±9.00 ± 2.80)
CDF-II MET+Jets
173.93 ±1.85 (±1.26 ± 1.35)
Tevatron combination *
174.30 ±0.65 (±0.35 ± 0.54)
(± stat ± syst)
χ^2/dof = 10.8/11 (46%)
150
160
170
180
190
200
m_t (GeV/c^2)

B_s oscillations: CDF

PRL **97,** 242003 (2006) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER 2006





Δm_s = 17.77 ± 0.10 (stat) ± 0.07 (syst) / ps ⇒ 2.8 THz

Fermilab

Accelerator Operations

Records

The following are performance records achieved by the AD accelerators.

Name	Value	Date	Description
Booster			
Hourly Beam Intensity	2.17 E17	April 19, 2017	Highest sum of protons through Booster in one hour.
Main Injector			
Beam Power Hour Average	727.1 kW	April 17, 2017	Main Injector one hour average beam power record at 120 GeV. Using 6+6 slip stacking in Recycler.
Beam Intensity (120 GeV)	55.1 E12	March 14, 2017	Highest intensity Main Injector pulse at 120 GeV. 12 batch slip-stacking.
Recycler			
Beam Intensity (8 GeV)	56.6 E12	January 30, 2017	Highest intensity Recycler pulse at 8 GeV. 12 batch slip-stacking.
Antiproton "Stash" Size	608 E10	March 21, 2011	Largest amount of antiprotons stored in the Recycler storage ring.
Sustained Antiproton "Stash" Time	49 days, 9 hours	August 15, 2008 - October 3, 2008	Longest uninterrupted amount of time antiprotons were stored in Recycler storage ring.
Anitprotons Delivered to the TeVatron (One week)	3977 E10	April 24, 2010 - May 1, 2010	Most amount of antiprotons delivered to the TeVatron for collider stores in one week.
Anitprotons "Stashed" (Floating week)	3980 E10	January 25, 2011 03:11:15 - February 1, 2011 03:11:15	Most amount of antiprotons stored in the Recycler storage ring in one week.
ECool			
Electron Cooling through entire Cooling Section	720 mA	October 19, 2005	Largest current ran through the ECool cooling section beam line.
Electron Cooling through UBend	1800 mA	April 9, 2006	Largest current ran through the UBend (Not delivered to the ECool cooling section beam line).
DC Electron Beam Power	7.8 MW	April 9, 2006	Electron DC beam power generated by ECool.
Accumulator			
Antiproton "Stack" Size	338.0 E10	April 15, 2011 04:43:21	Largest amount of antiprotons stored in the PBar accumulator ring.
Sustained Antiproton "Stack" Time	69 days, 10 hours, 18 minutes	March 26, 2004 - June 4, 2004	Longest uninterrupted amount of time antiprotons were stored in Accumulator storage ring.
Antiproton "Stacking" Rate (One hour)	28.56 E10/hr	December 19, 2008 17:43:37	Largest amount of antiprotons accumulated in one hour.
Antiproton "Stacking" Rate Average (One week)	25.65 E10/hr	January 30, 2011 00:00:00	Largest average amount of antiprotons accumulated in one hour for a week.
TeVatron			
Antiproton Beam Energy	980 GeV	2001 - 2011	The energy of antiprotons in the TeVatron.
"Store" Initial Luminosity	4.3107 E32 1/cm**2 sec	May 3, 2011 Store: 8709	Largest amount of integrated luminosity for proton/antiproton collisions in the TeVatron.
"Store" Integrated Luminosity	CDF: 12150.17 D0: 12048.1 1/nb	April 17, 2010 Store: 7748	Largest amount of integrated luminosity for proton/antiproton collisions in the TeVatron.
Integrated Luminosity (One week)	78.439 1/pb	March 2010	Largest average integrated luminosity for proton/antiproton collisions in the TeVatron in a week.
Sustained "Store" Duration	53.75 hours Store: 4862	July 29, 2006 - July 31, 2006	Longest amount of time proton/antiproton collisions in the TeVatron were sustained.

Last modified: April 20, 2017 - 11:08AM | email Beau Harrison

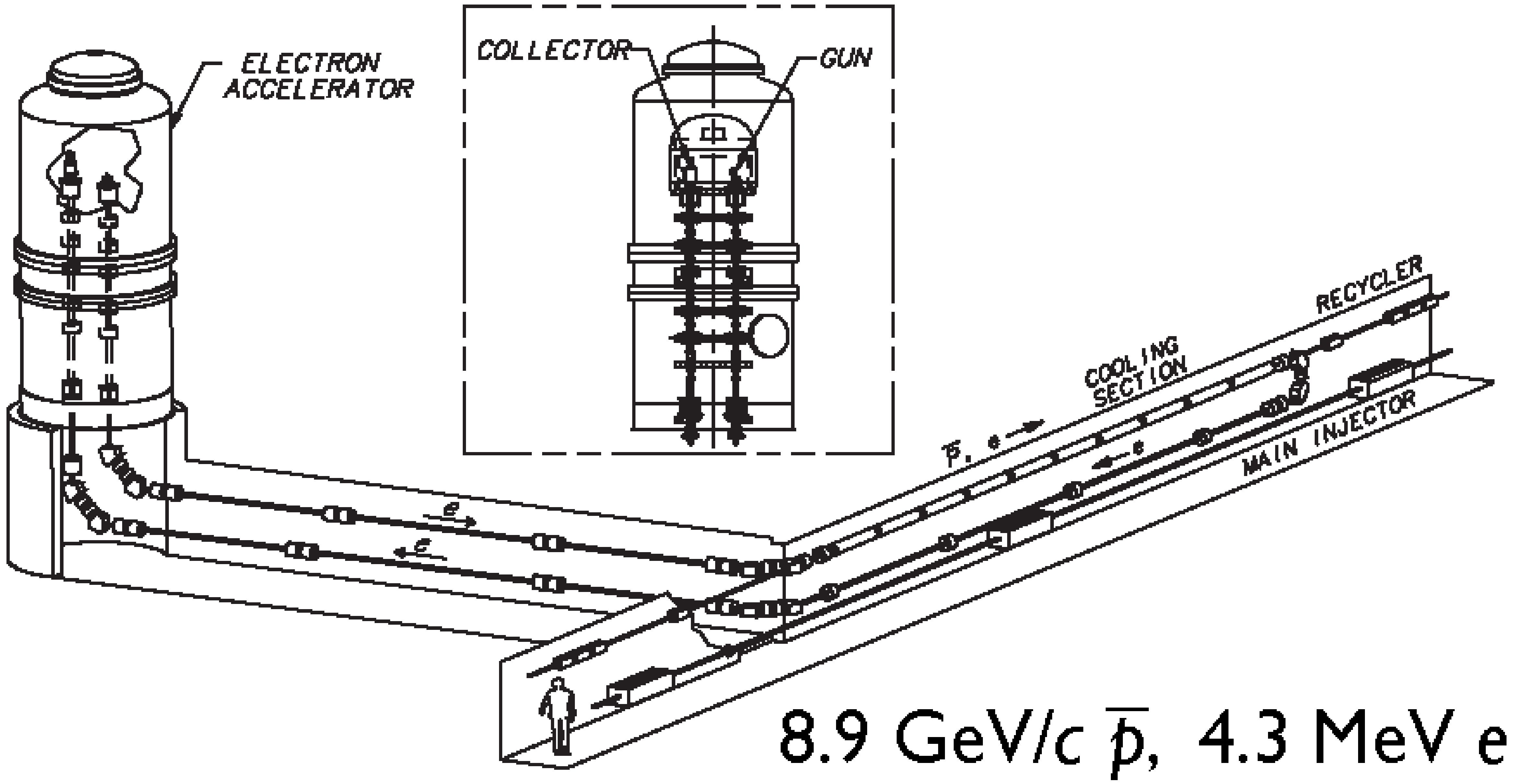
Experimental Demonstration of Relativistic Electron Cooling

Sergei Nagaitsev, Daniel Broemmelsiek, Alexey Burov, Kermit Carlson, Consolato Gattuso, Martin Hu, Thomas Kroc, Lionel Prost, Stanley Pruss, Mary Sutherland, Charles W. Schmidt, Alexander Shemyakin, Vitali Tupikov, and Arden Warner
FNAL, P.O. Box 500, Batavia, Illinois 60510, USA

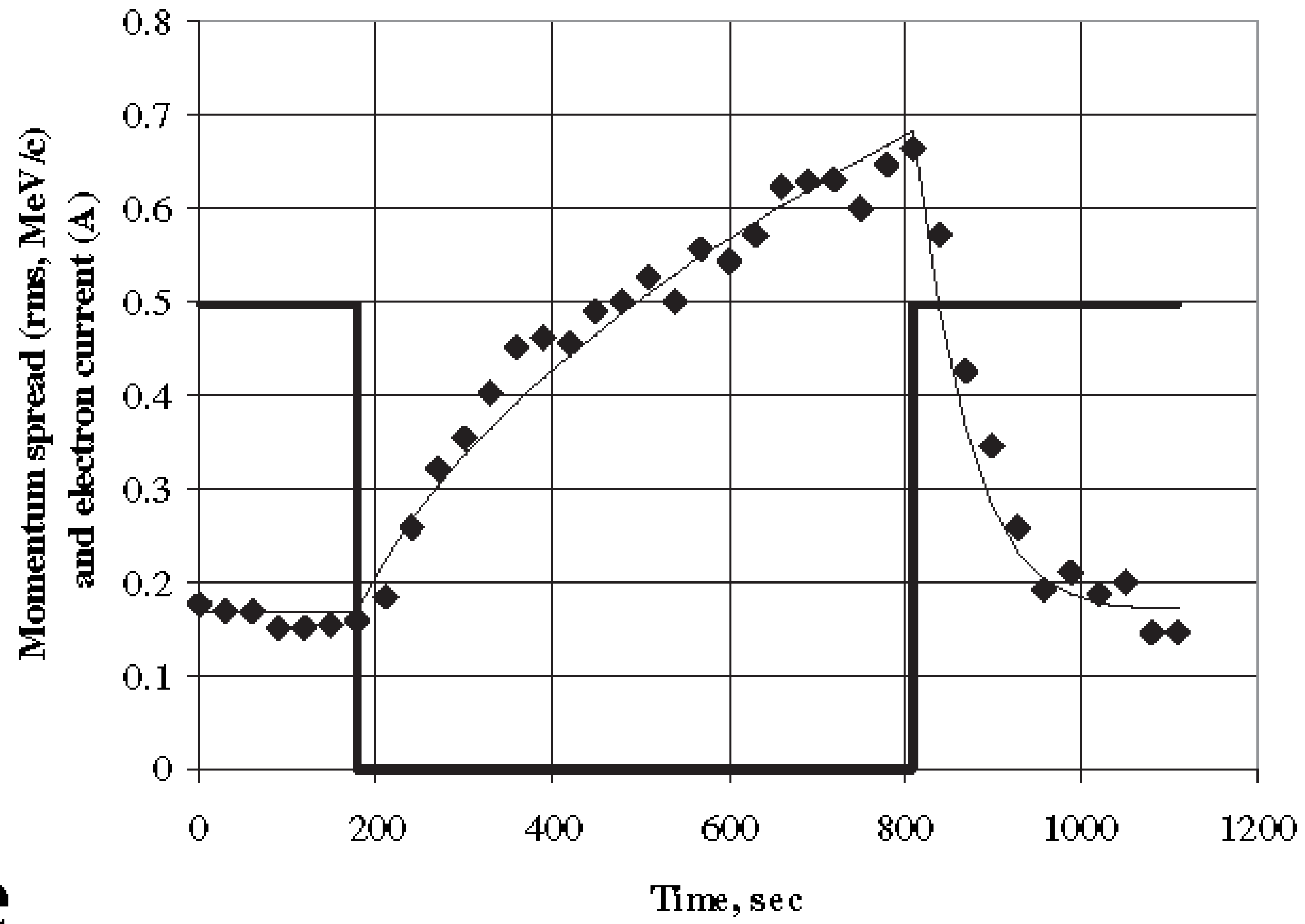
Grigory Kazakevich
Budker INP, Novosibirsk 630090, Russian Federation

Sergey Seletskiy
University of Rochester, Rochester, New York 14627, USA
(Received 22 November 2005; published 30 January 2006)

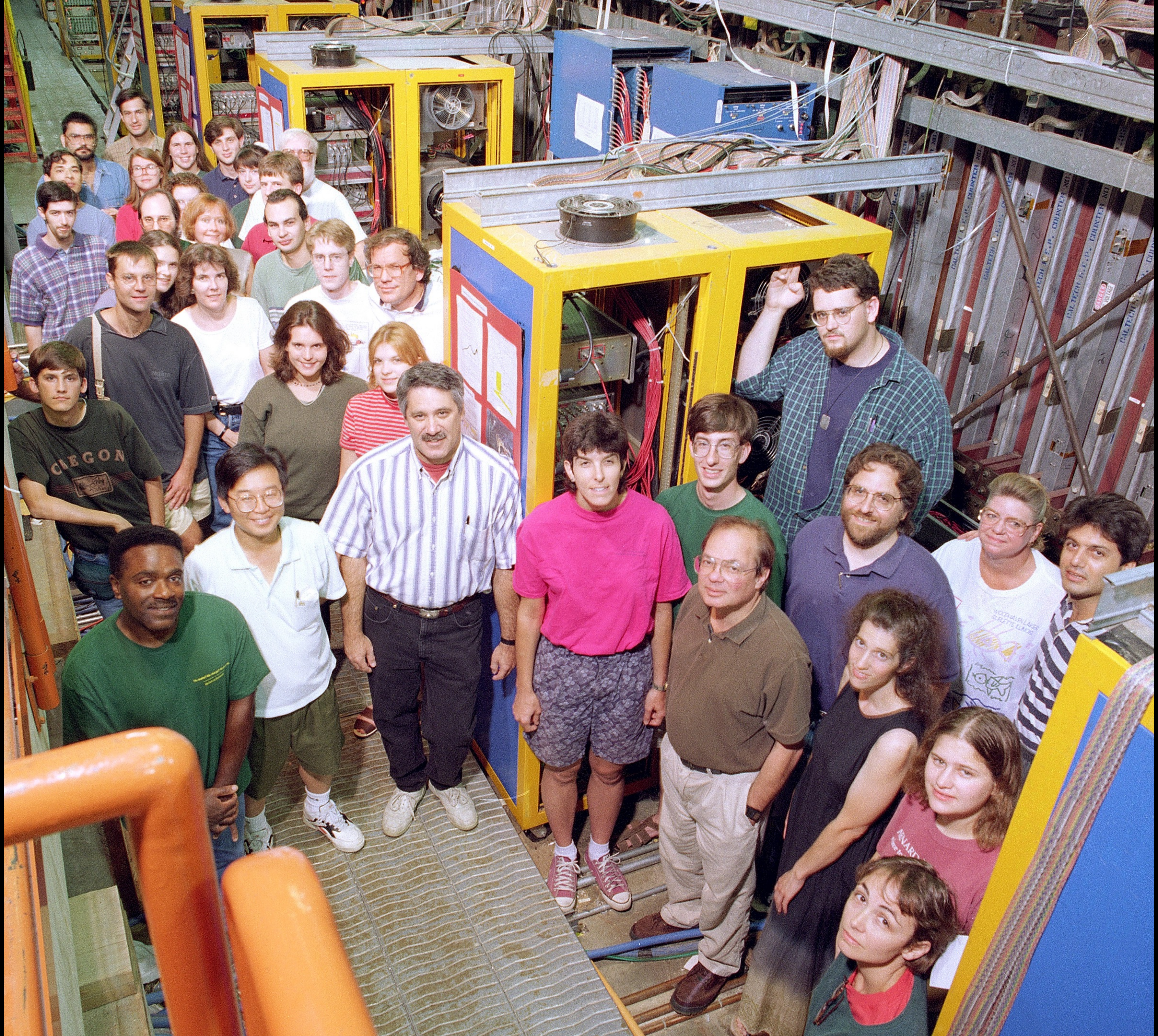
We report on an experimental demonstration of electron cooling of high-energy antiprotons circulating in a storage ring. In our experiments, electron cooling, a well-established method at low energies (<500 MeV/nucleon), was carried out in a new region of beam parameters, requiring a multi-MeV dc electron beam and an unusual beam transport line. In this Letter, we present the results of the longitudinal cooling force measurements and compare them with theoretical predictions.

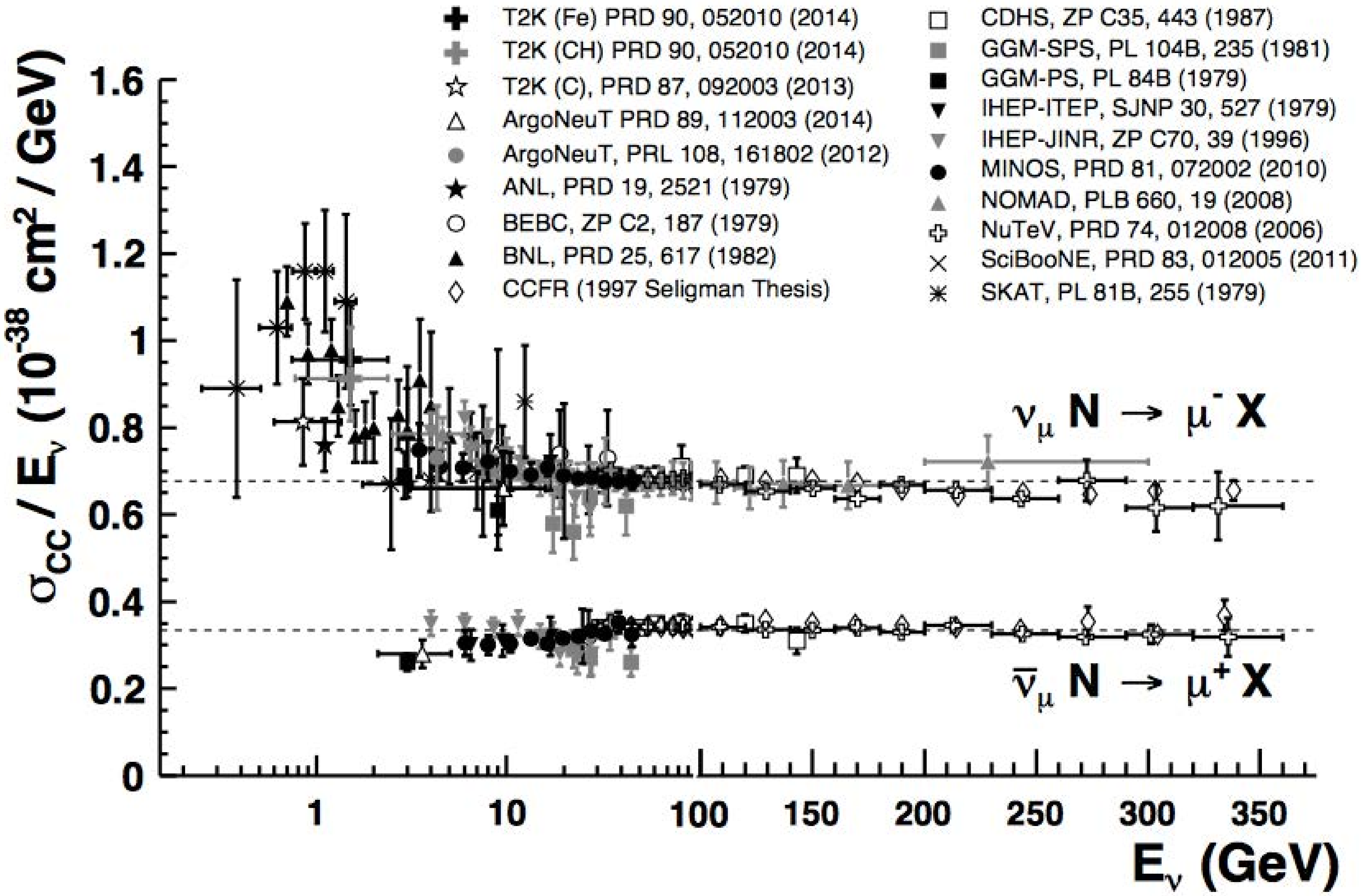


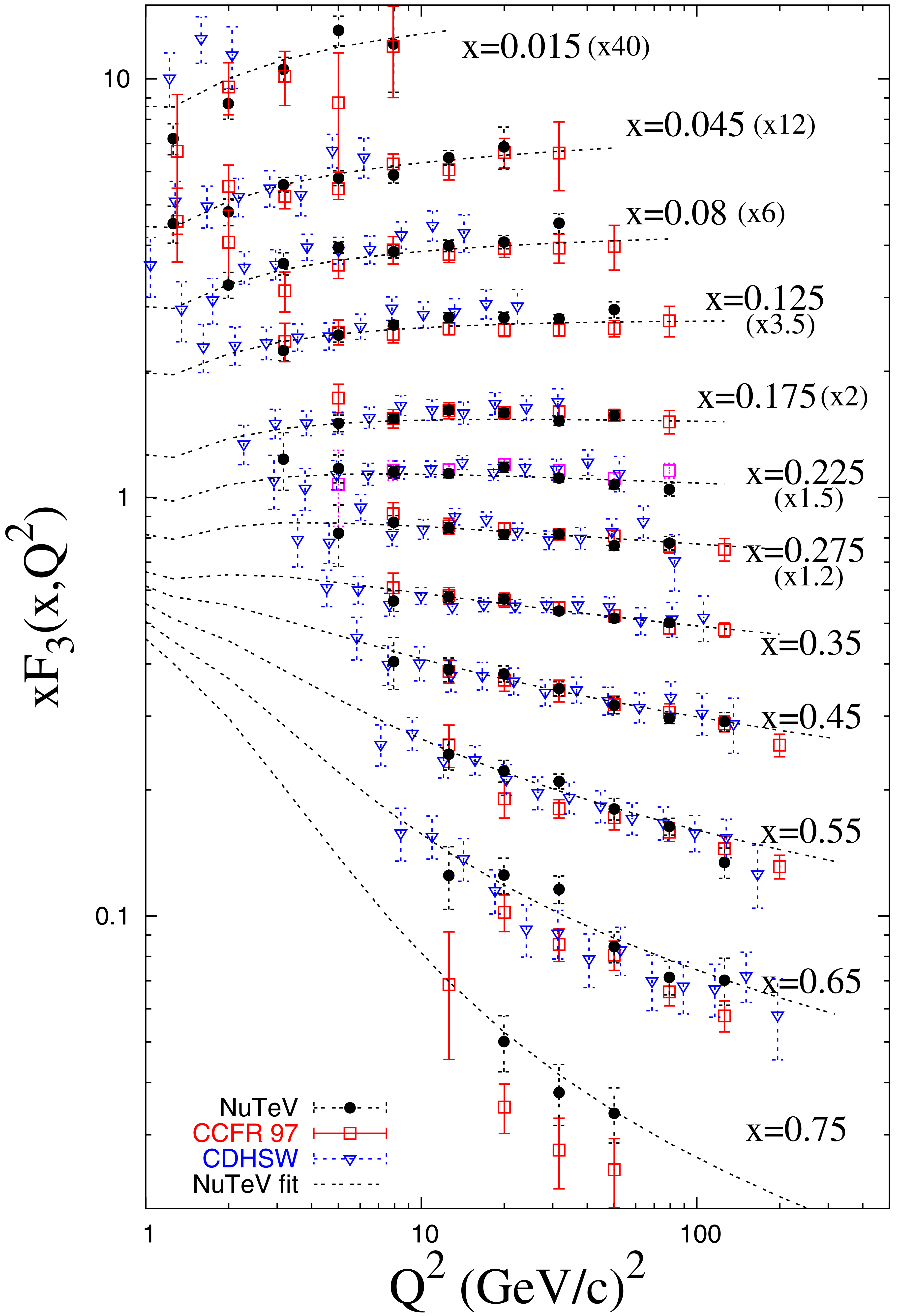
8.9 GeV/c $\bar{p}$, 4.3 MeV e



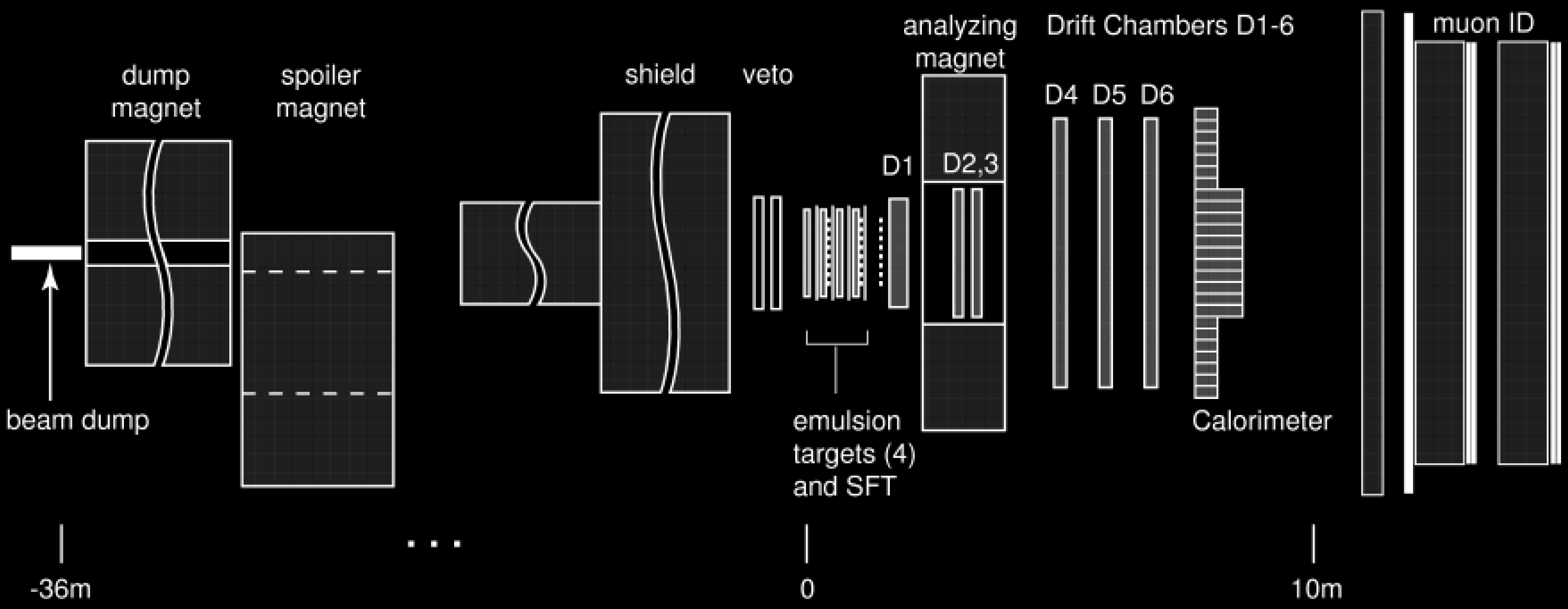
NuTeV

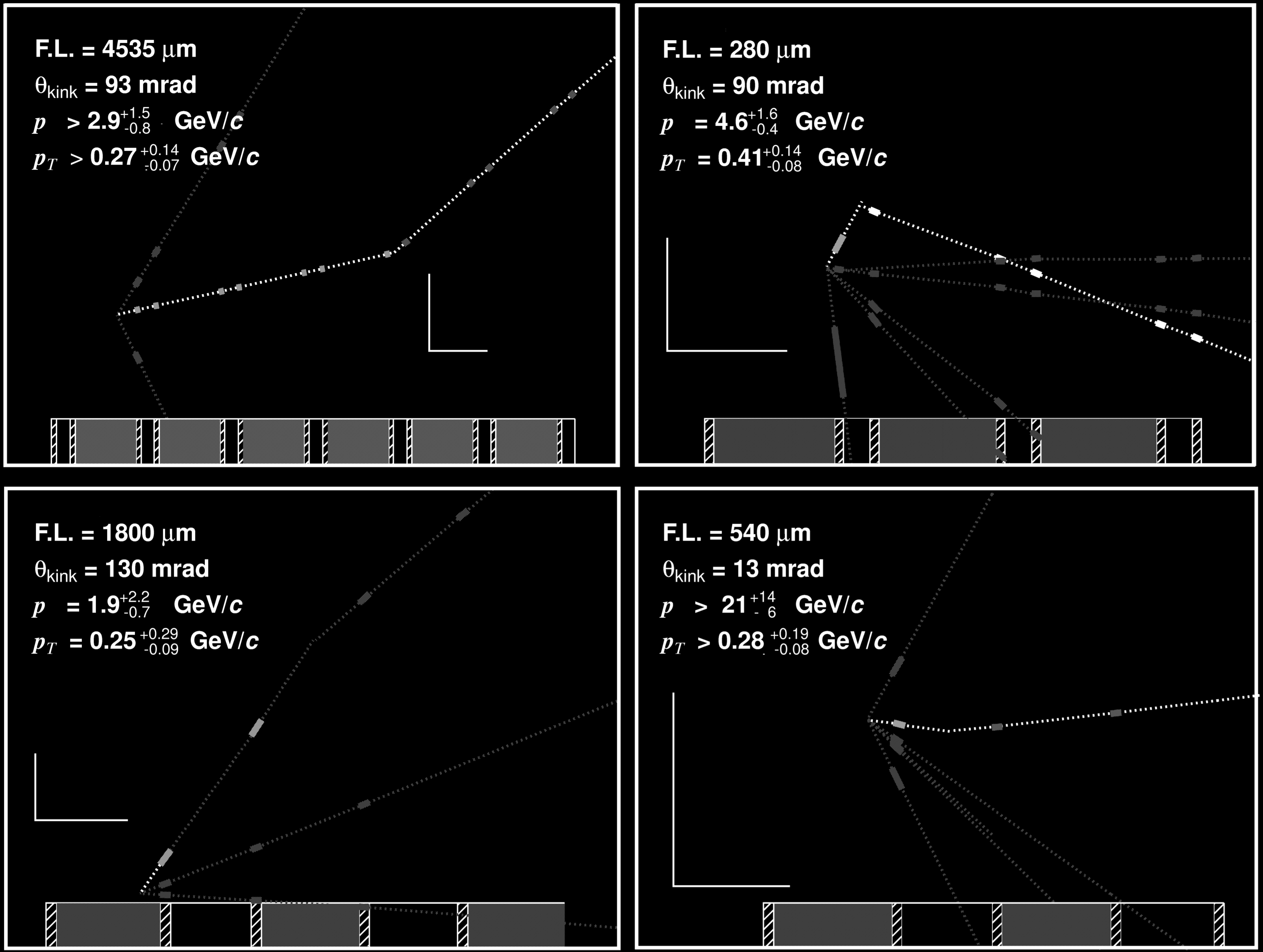



T2K (Fe) PRD 90, 052010 (2014)
T2K (CH) PRD 90, 052010 (2014)
T2K (C), PRD 87, 092003 (2013)
ArgoNeuT PRD 89, 112003 (2014)
ArgoNeuT, PRL 108, 161802 (2012)
ANL, PRD 19, 2521 (1979)
BEBC, ZP C2, 187 (1979)
BNL, PRD 25, 617 (1982)
CCFR (1997 Seligman Thesis)
CDHS, ZP C35, 443 (1987)
GGM-SPS, PL 104B, 235 (1981)
GGM-PS, PL 84B (1979)
IHEP-ITEP, SJNP 30, 527 (1979)
IHEP-JINR, ZP C70, 39 (1996)
MINOS, PRD 81, 072002 (2010)
NOMAD, PLB 660, 19 (2008)
NuTeV, PRD 74, 012008 (2006)
SciBooNE, PRD 83, 012005 (2011)
SKAT, PL 81B, 255 (1979)
ν_μ N → μ^- X
$\bar{\nu}_\mu$ N → μ^+ X
σ_{CC} / E_ν (10^{-38} cm^2 / GeV)
E_ν (GeV)

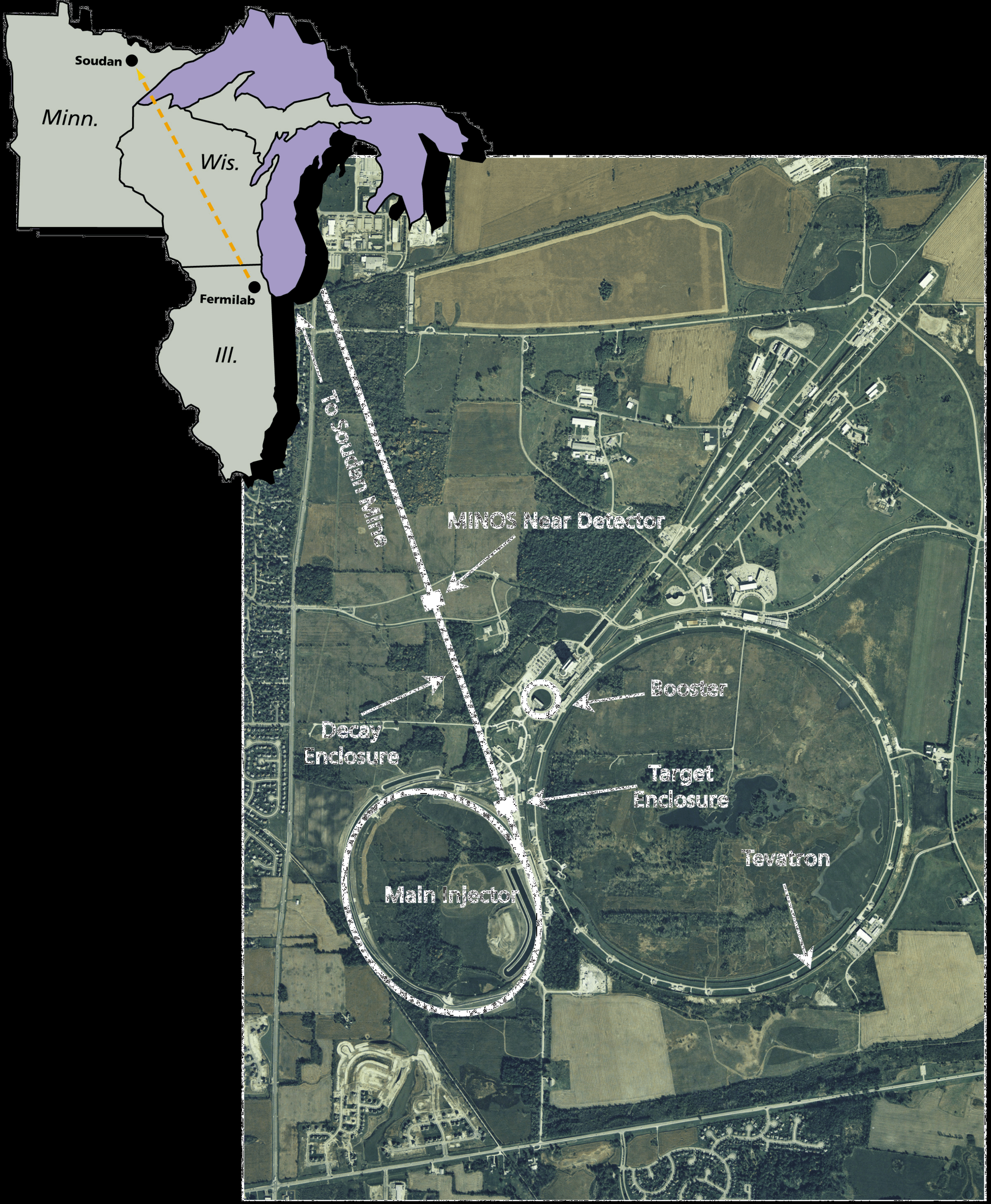

x=0.015 (x40)
x=0.045 (x12)
x=0.08 (x6)
x=0.125 (x3.5)
x=0.175 (x2)
x=0.225 (x1.5)
x=0.275 (x1.2)
x=0.35
x=0.45
x=0.55
x=0.65
x=0.75
NuTeV
CCFR 97
CDHSW
NuTeV fit
$xF_3(x,Q^2)$
Q^2 (GeV/c)^2

Direct Observation of the tau neutrino

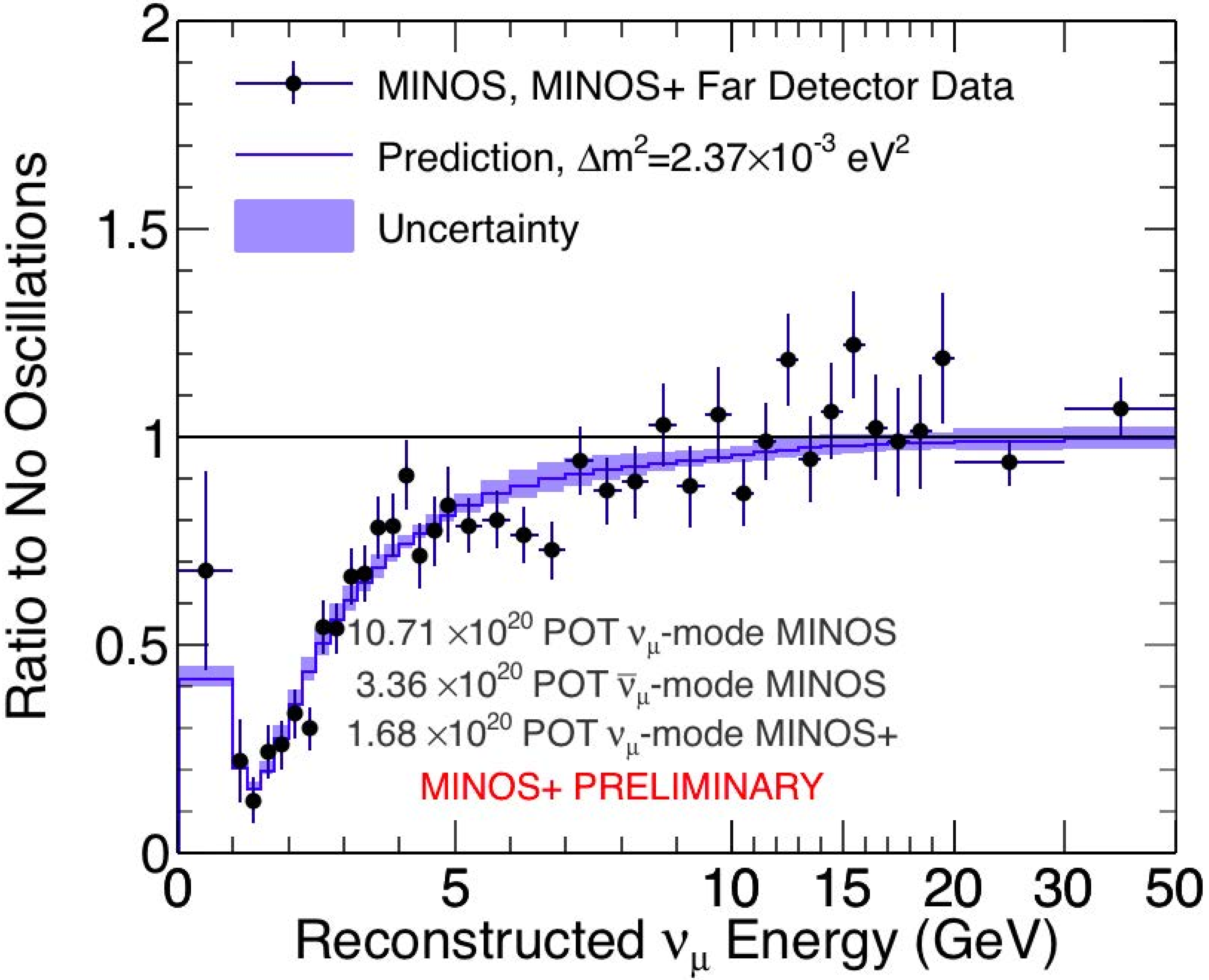


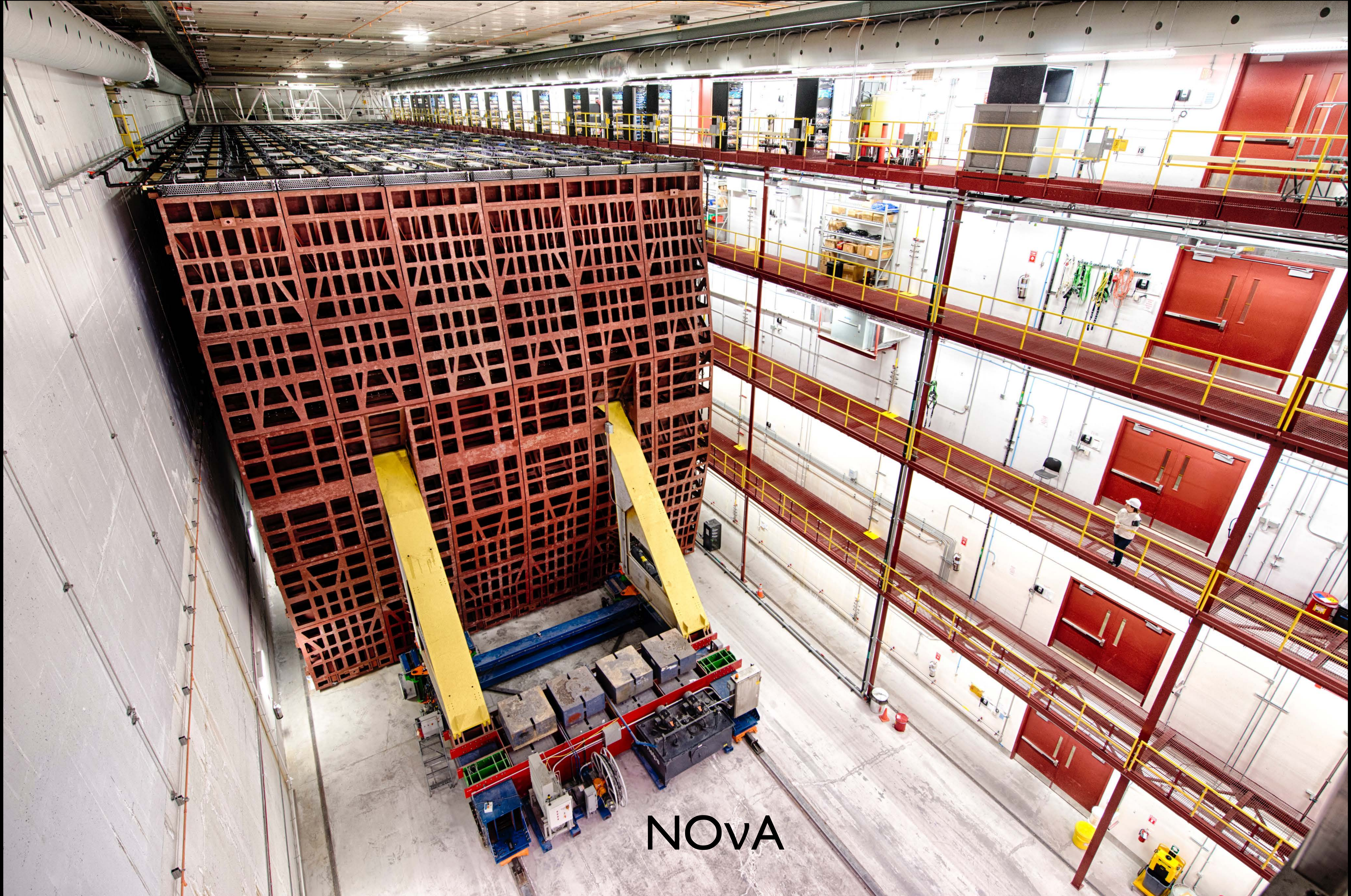

F.L. = 4535 μm
θkink = 93 mrad
p > 2.9 +1.5 -0.8 GeV/c
pT > 0.27 +0.14 -0.07 GeV/c
F.L. = 280 μm
θkink = 90 mrad
p = 4.6 +1.6 -0.4 GeV/c
pT = 0.41 +0.14 -0.08 GeV/c
F.L. = 1800 μm
θkink = 130 mrad
p = 1.9 +2.2 -0.7 GeV/c
pT = 0.25 +0.29 -0.09 GeV/c
F.L. = 540 μm
θkink = 13 mrad
p > 21 +14 -6 GeV/c
pT > 0.28 +0.19 -0.08 GeV/c


EXIT


Soudan
Minn.
Wis.
Fermilab
Ill.
To Soudan Mine
MINOS Near Detector
Booster
Decay Enclosure
Target Enclosure
Tevatron
Main Injector

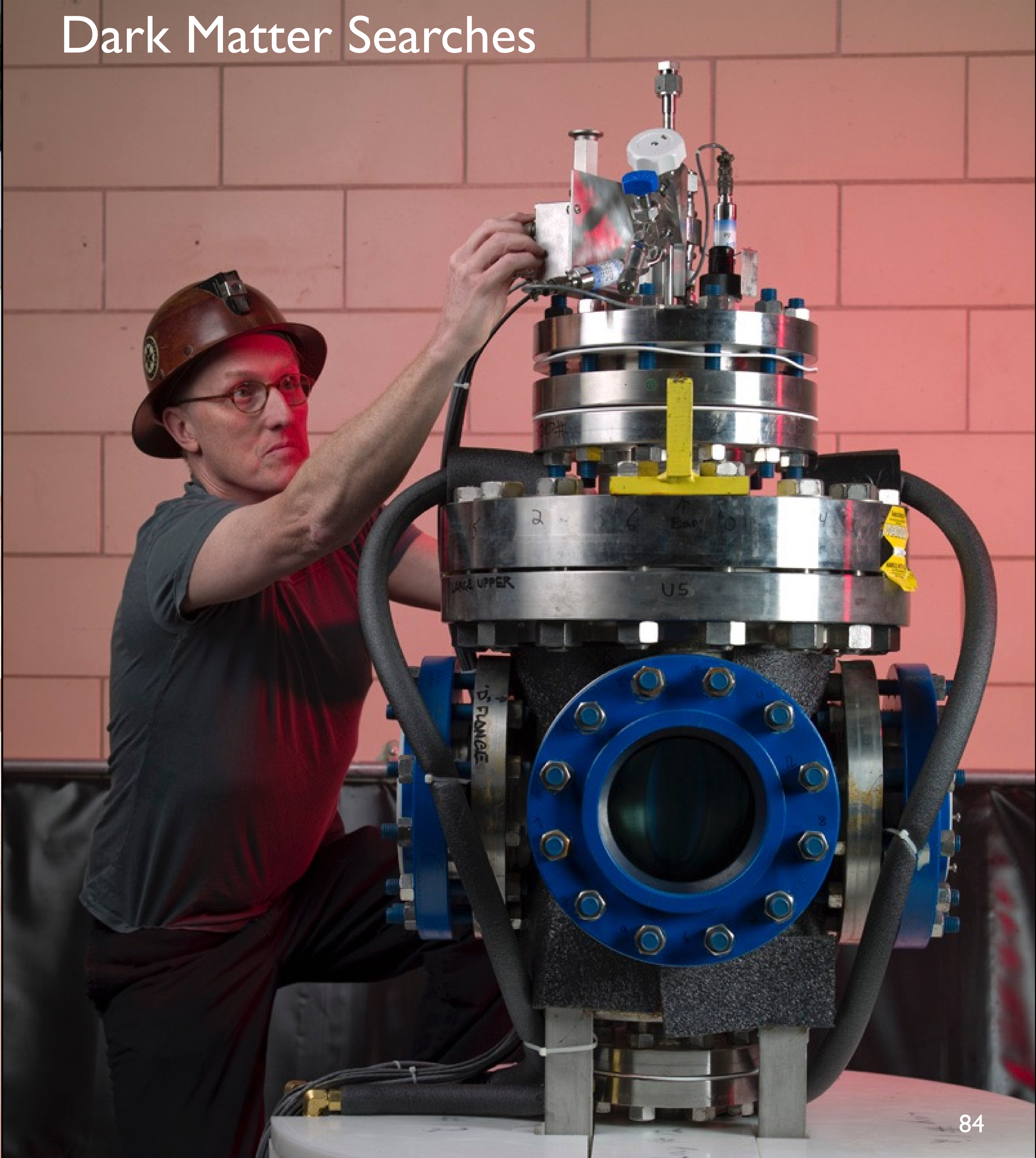

485


MINOS, MINOS+ Far Detector Data
Prediction, Δm^2=2.37×10^{-3} eV^2
Uncertainty
10.71 ×10^{20} POT ν_μ-mode MINOS
3.36 ×10^{20} POT $\bar{\nu}_\mu$-mode MINOS
1.68 ×10^{20} POT ν_μ-mode MINOS+
MINOS+ PRELIMINARY
Ratio to No Oscillations
Reconstructed ν_μ Energy (GeV)
0
0.5
1
1.5
2
0
5
10
15
20
30
50



NOvA

Dark Matter Searches



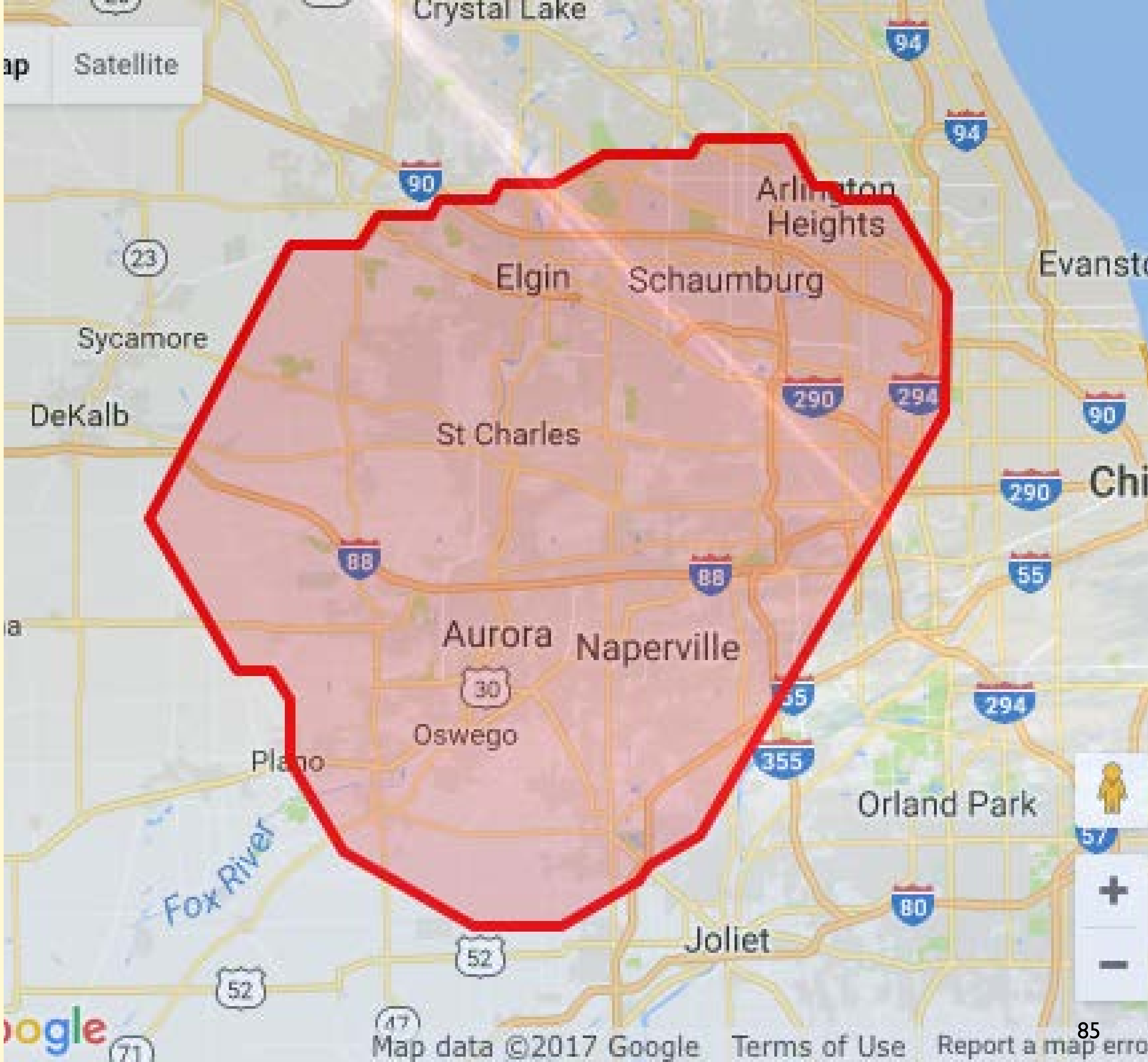
WHAT ARE COSMIC RAYS?

Revised and Enlarged American Edition

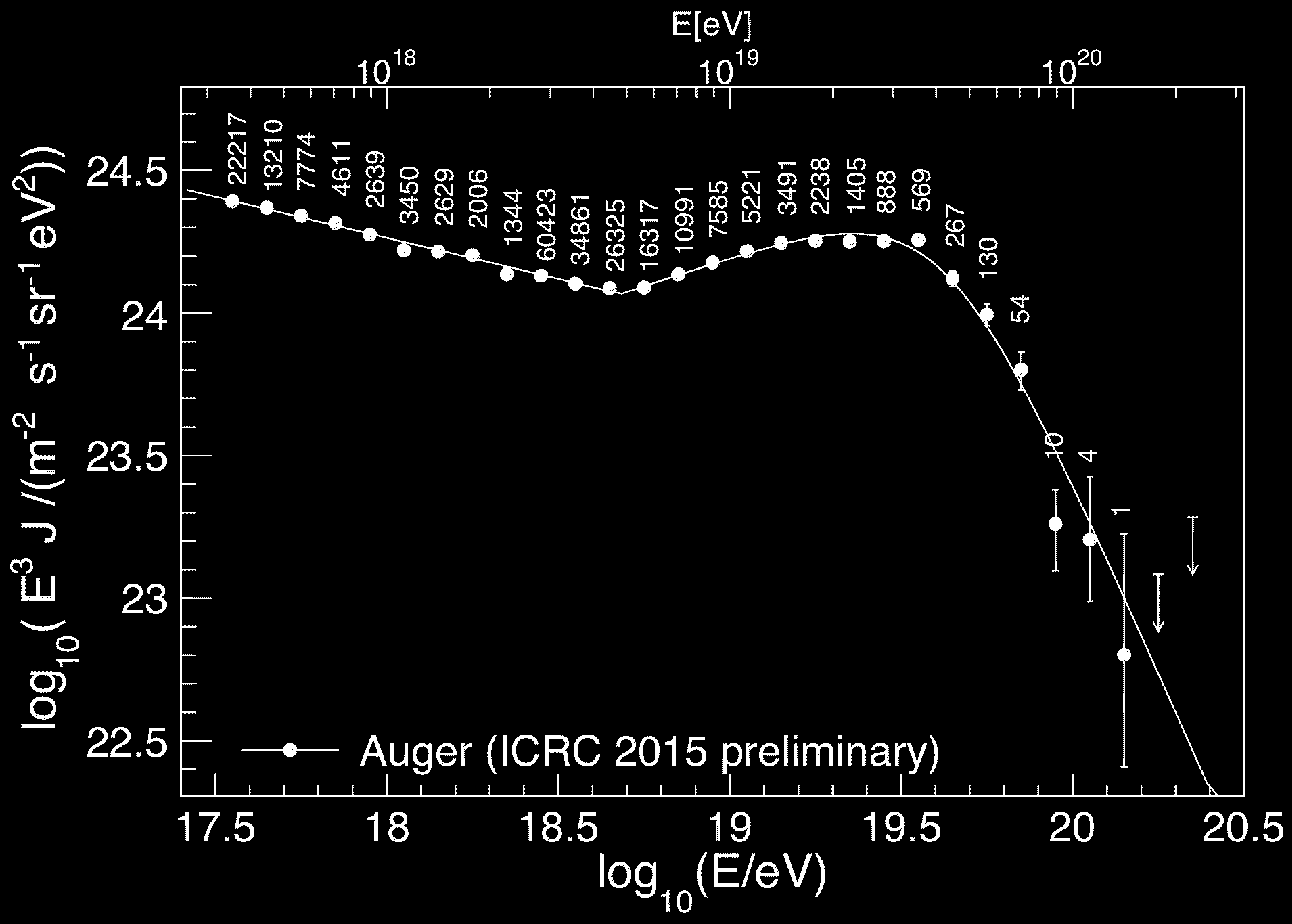
BY PIERRE AUGER

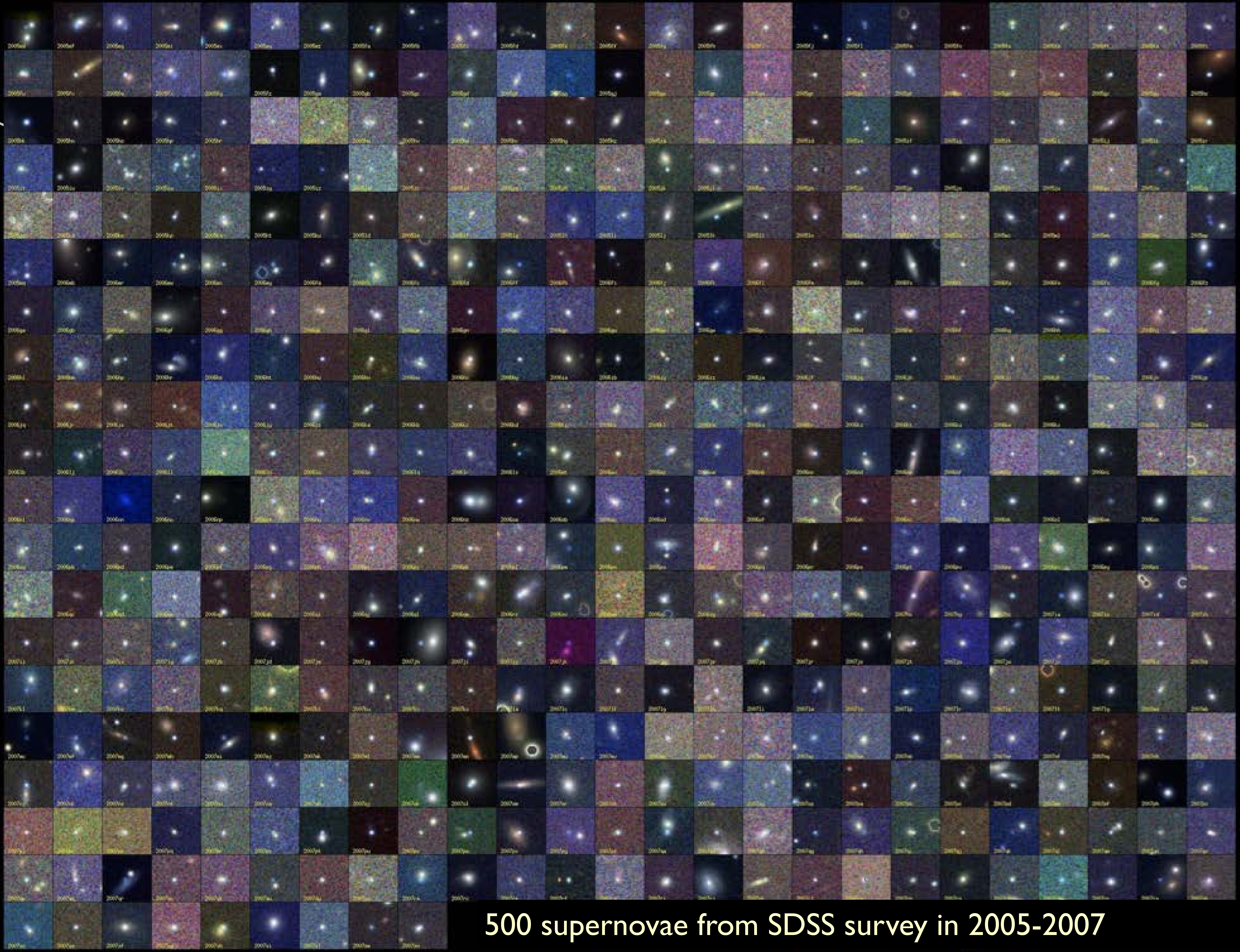
TRANSLATED FROM THE FRENCH
by
MAURICE M. SHAPIRO

UNIVERSITY OF CHICAGO PRESS · CHICAGO




Malargüe


E[eV]
10^{18}
10^{19}
10^{20}
22217
13210
7774
4611
2639
3450
2629
2006
1344
60423
34861
26325
16317
10991
7585
5221
3491
2238
1405
888
569
267
130
54
10
4
1
24.5
24
23.5
23
22.5
$\log_{10}(E^3 J / (m^{-2}\ s^{-1}\ sr^{-1}\ eV^2))$
Auger (ICRC 2015 preliminary)
17.5
18
18.5
19
19.5
20
20.5
$\log_{10}(E/eV)$



500 supernovae from SDSS survey in 2005-2007

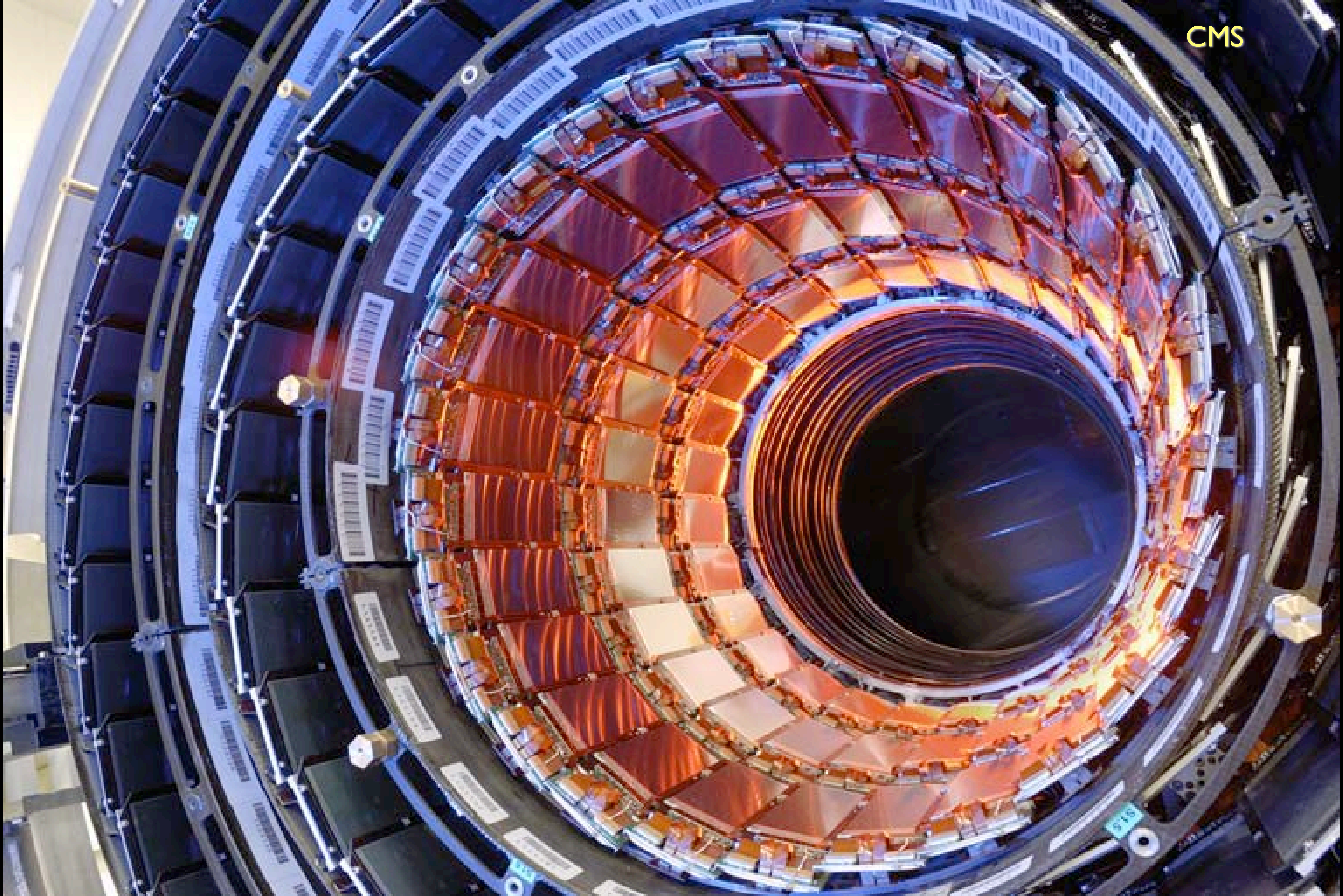
B. Dilday

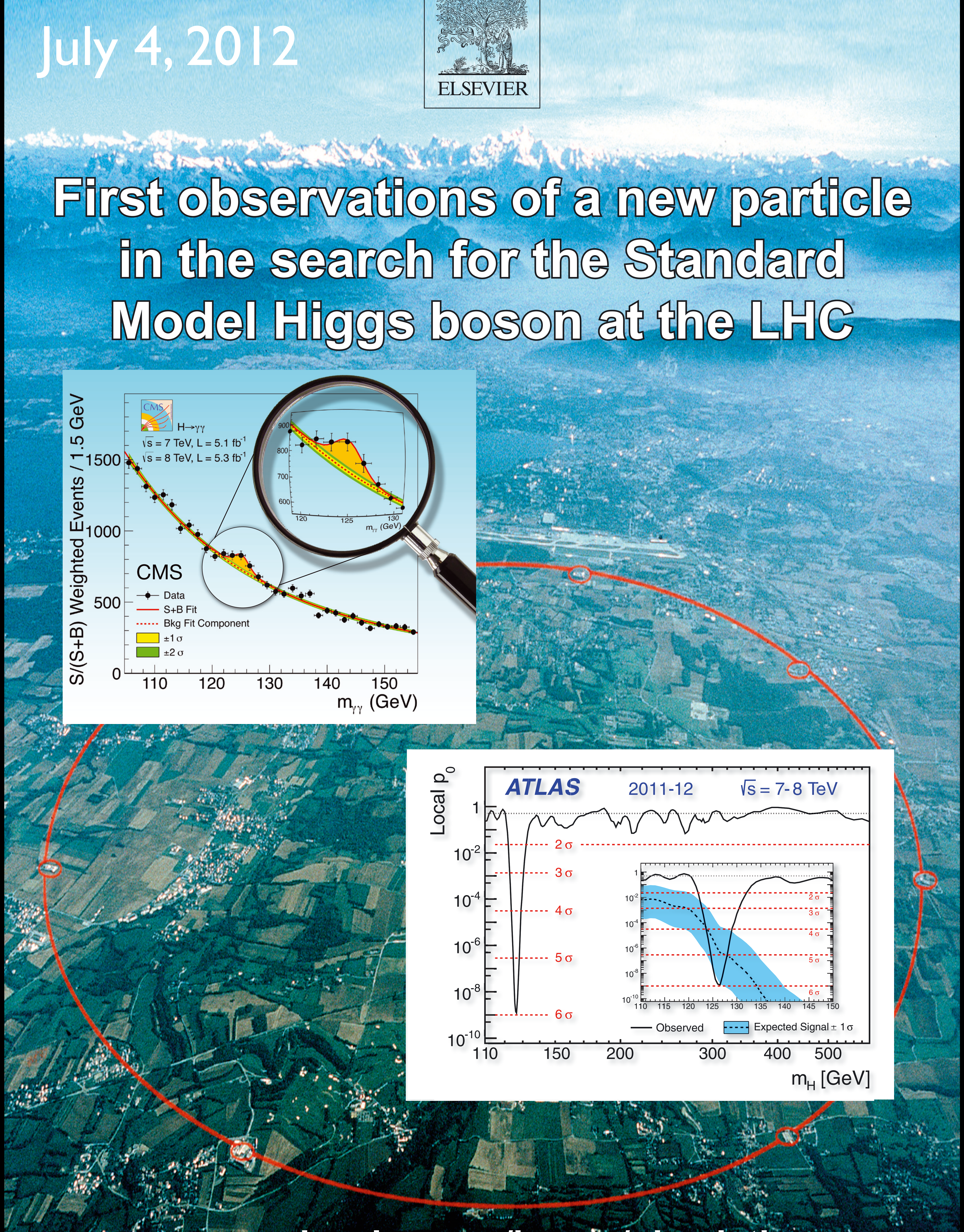
Reticulum II

Dark Energy Survey


fermilab
MAGNET TEST FACILITY

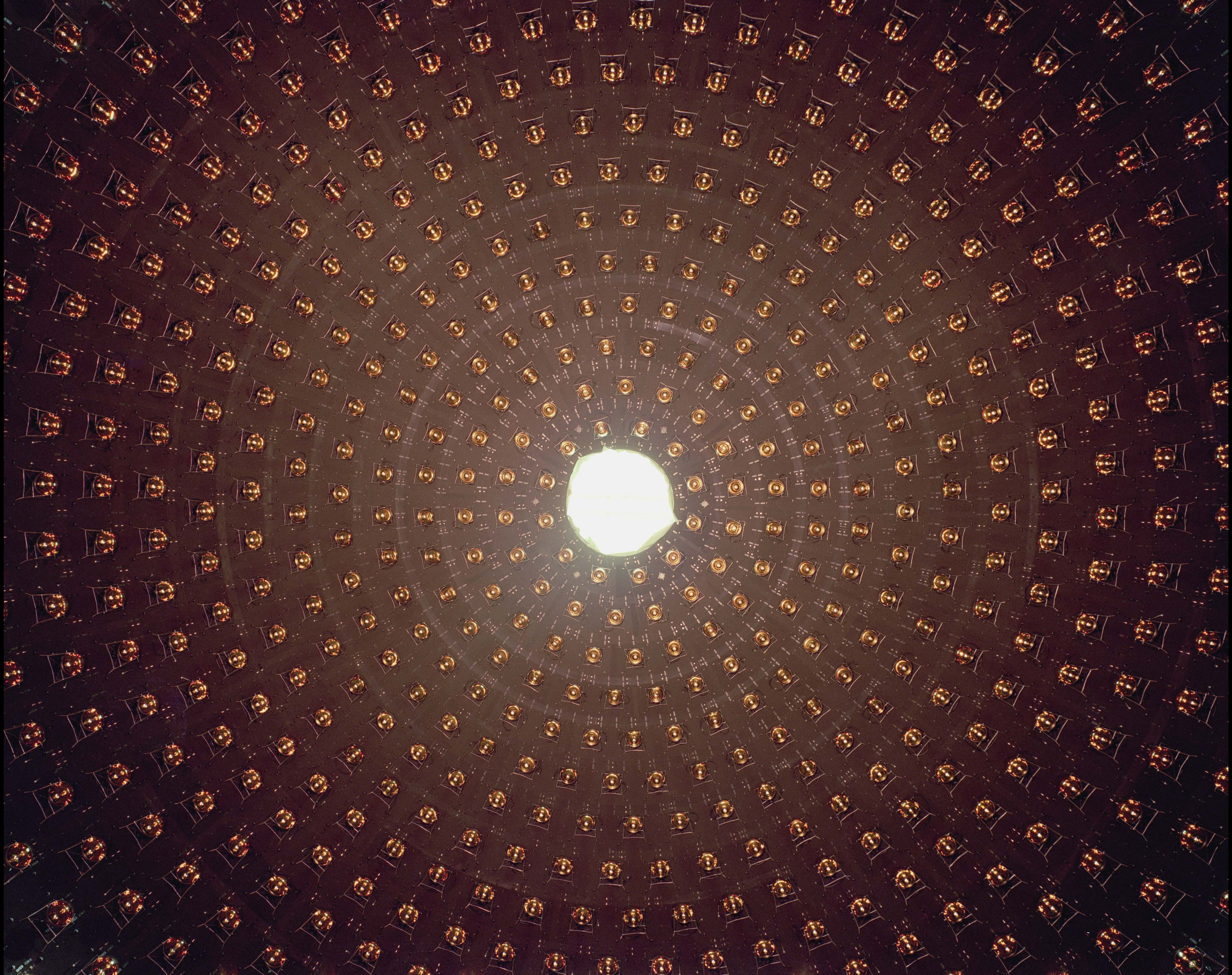

CMS

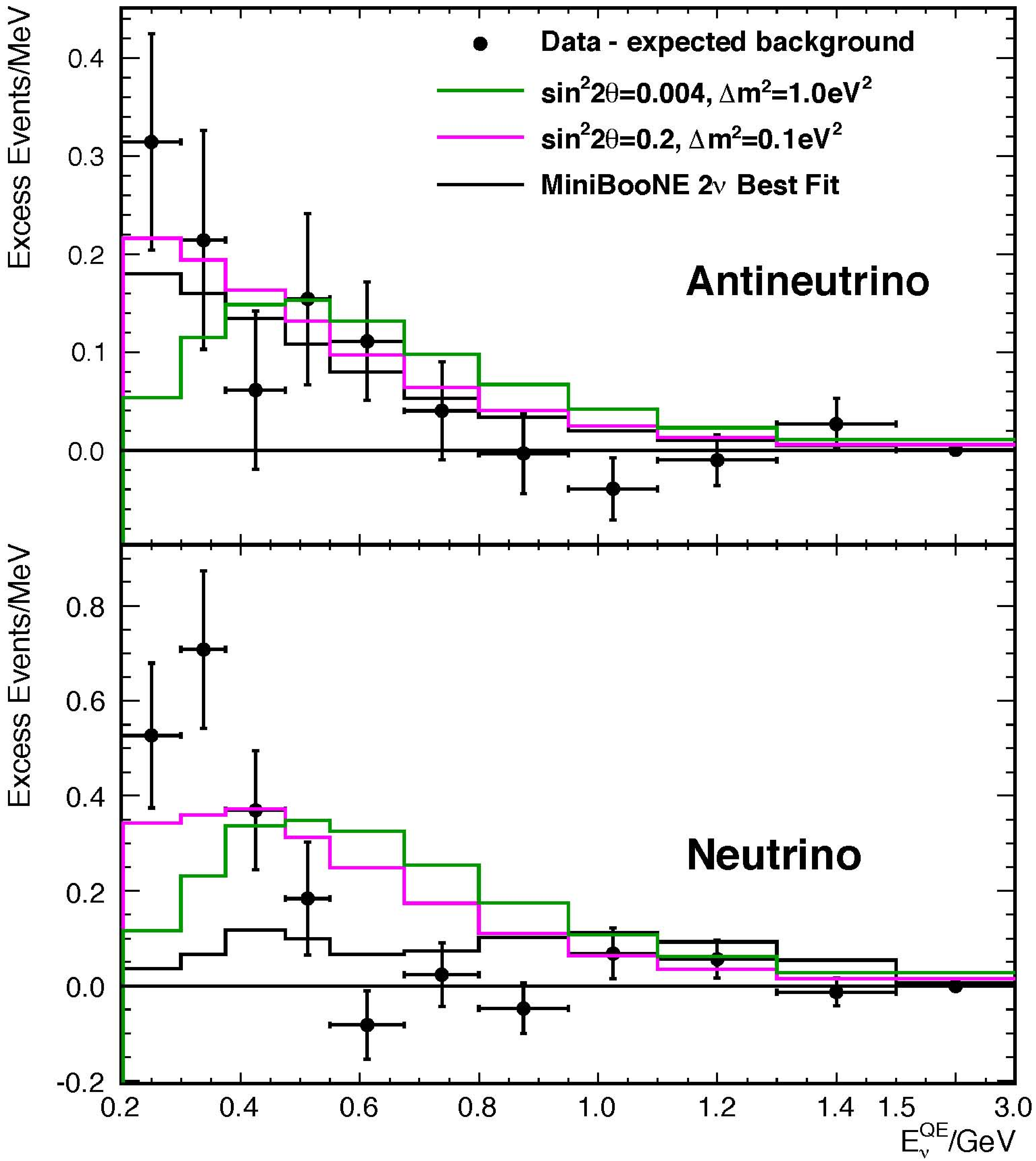

CMS



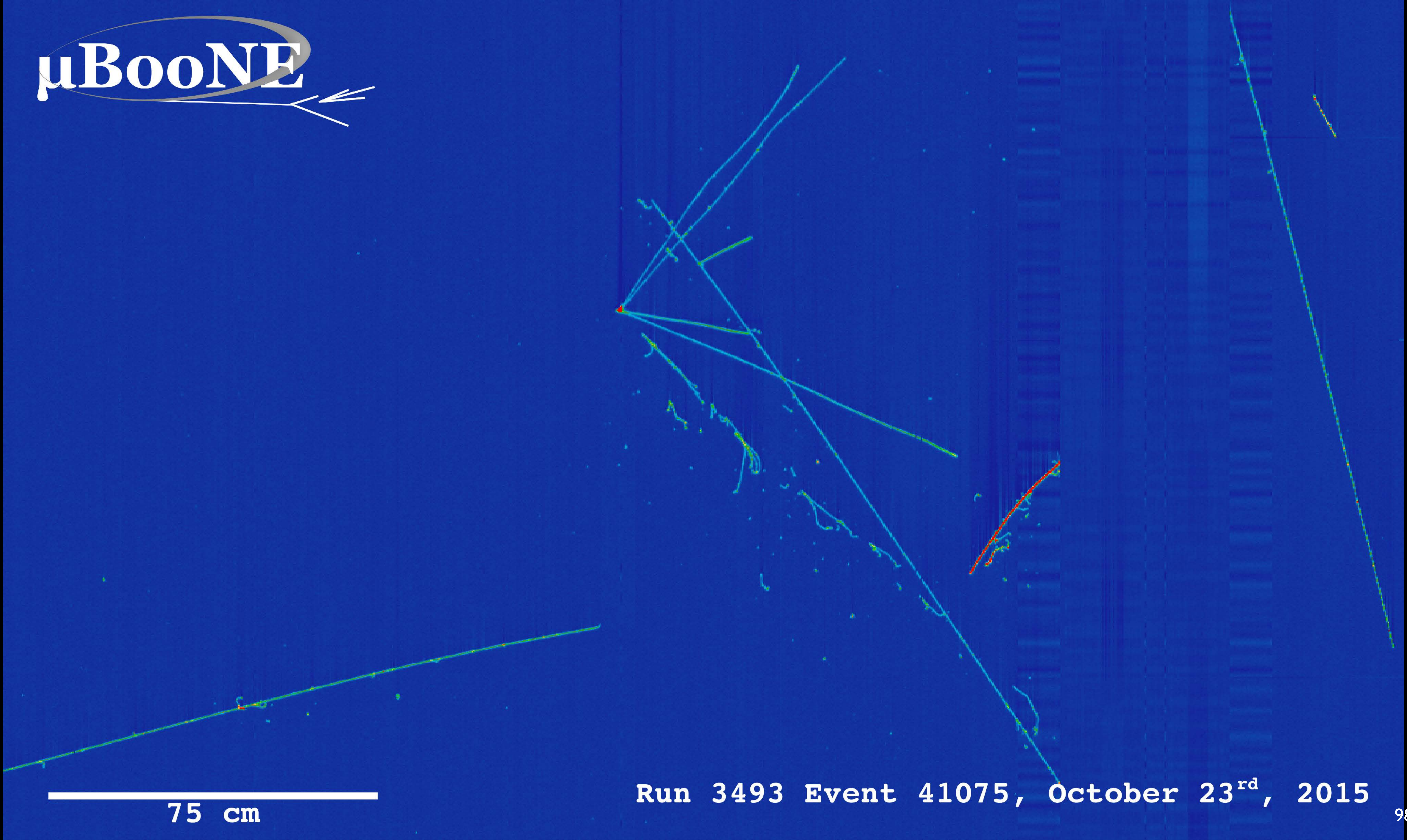
July 4, 2012
ELSEVIER
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC
CMS
H→γγ
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/(S+B) Weighted Events / 1.5 GeV
Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
m_γγ (GeV)
ATLAS
2011-12
√s = 7-8 TeV
Local p_0
2σ
3σ
4σ
5σ
6σ
Observed
Expected Signal ± 1σ
m_H [GeV]

Mini-BooNE





Data - expected background
sin²2θ=0.004, Δm²=1.0eV²
sin²2θ=0.2, Δm²=0.1eV²
MiniBooNE 2ν Best Fit
Antineutrino
Neutrino
Excess Events/MeV
Excess Events/MeV
0.0
0.1
0.2
0.3
0.4
-0.2
0.0
0.2
0.4
0.6
0.8
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.5
3.0
E_ν^QE/GeV


μBooNE
75 cm
Run 3493 Event 41075, October 23rd, 2015

DEEP UNDERGROUND NEUTRINO EXPERIMENT


EP
T BERN

DPF/APS Prizes Associated with Work at Fermilab

Panofsky Prize

Mike Witherell 1990

Tom Devlin & Lee Pondrom 1994

Frank Sciulli 1995

Paul Grannis 2001

Ari Bodek 2004

Bruce Winstein 2007

Luciano Ristori & Aldo Menzione 2009

Stan Wojcicki 2016

Wilson Prize

Alvin Tollestrup 1989

Tom Collins 1994

Helen Edwards 2003

Lee Teng 2007

John Peoples 2010

Hassan Padamsee 2015

Bj Bjorken & Sekazi Mtingwa 2017

Sakurai Prize

Bill Bardeen 1996

Keith Ellis 2009

Estia Eichten, et al. 2011