The Birth of Relativistic Heavy Ion Physics

W.A. Zajc
Columbia University

Symposium Celebrating the Scientific Career of Bill Willis
April 26th, 2012

Acknowledgments

"Intellectual debts differ from all others,
in that they are a pleasure to acknowledge."

(paraphrasing Horace Freeland Judson,
from his preface to *The Eighth Day of Creation*.)

- I am personally indebted to Bill Willis
- As are so many others
- *As is the entire field of relativistic heavy ion physics*

- *Thanks to Gabor David, Chris Fabjan, Barbara Jacak, David Lissauer, Tom Ludlam, Shoji Nagamiya, Ed O'Brien, Nick Samios, Helio Takai, and Craig Woody for help in preparing this talk*

1974: The Start of It All

Report of the Workshop on

BEV/NUCLEON COLLISIONS OF HEAVY IONS – HOW AND WHY

NATIONAL SCIENCE FOUNDATION

AND

NEVIS LABORATORIES, COLUMBIA UNIVERSITY

NOVEMBER 29-DECEMBER 1, 1974

BEAR MOUNTAIN, NEW YORK

A Lot of Intriguing Ideas…

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One Truly Compelling Insight

A Possible New Form of Matter at High Density*

T.D. Lee
Columbia University, New York, New York 10027

I. INTRODUCTION

In this talk, I would like to discuss some of my recent theoretical speculations, made in collaboration with Gian-Carlo Wick. Over the past year, we have tried to investigate the structure of the vacuum. It is through this investigation that the possibilities of vacuum excitation states and abnormal nuclear states have been suggested. Before coming to the main topic, whether or not there may be the possibility of a new form of matter at high density, perhaps I should first digress on questions related to the vacuum.

In physics, one defines the vacuum as the lowest energy state of the system. By definition, it has zero 4-momentum. In most quantum field-theoretic treatments, quite often the vacuum state is used only to enable us to perform the mathematical construct of a Hilbert space. From the vacuum state, we build the one-particle state, then the two-particle state, . . . ; hopefully, the resulting Hilbert space will eventually resemble our universe. From this approach, different vacuum state means different Hilbert space, and therefore different universe.

Nevertheless, one may ask: What is this vacuum state? Does it have complicated structure? If so, can a part of this structure be changed? Ever since the formulation of relativity, after the downfall of the classical aether concept, one learns that the vacuum is Lorentz invariant. At least, one knows that just running around and changing the reference system won't alter the vacuum. However, Lorentz invariance alone does not insure that the vacuum is necessarily simple. For example, the vacuum can be as complicated as the product or sum of any scalar field or other scalar object at the zero 4-momentum limit:

$$\text{vacuum} \sim \phi^n \quad \text{or} \quad (\bar{\psi}\psi)^m \quad \text{at} \quad k_\mu = 0\,. \tag{1}$$

From Dirac's hole theory, one knows that the vacuum, though Lorentz-invariant, can be rather complicated. That this complicated structure of the vacuum may in part be changeable is suggested by the large variety of broken symmetries, found especially over the past two decades.

If we consider symmetry quantum numbers such as the isospin **I**, the strangeness S, the parity P, . . . , we find

$$\frac{d}{dt}\begin{Bmatrix} \mathbf{I} \\ S \\ P \\ C \\ CP \\ \vdots \end{Bmatrix}_{\text{matter}} \neq 0\,. \tag{2}$$

---

*This research was supported in part by the U.S. Atomic Energy Commission.

1974 Was a Busy Year for T.D.

Chairman Mao has a conversation with Dr. Li Cheng-tao.
On May 30, 1974, Chairman Mao Tsetung met and had a very cordial conversation with American physicist Dr. Li Cheng-tao who had come to China to see his relatives and for a visit.
Present on the occasion were Chu Kuang-ya, Lo Ching-chang, Wang Hai-jung and Tang Wen-sheng.

Photo courtesy of Ann Therrien

When Did Bill Willis Come Into the Picture?

- I don't know.

- Perhaps we can gain insight today from friends and colleagues gathered to celebrate his enormous scientific legacy.

- Best estimate (courtesy of Tom Ludlam):
  Early 1979, upon receipt of Lee-Wick paper.
  "Bill was a towering influence … amazingly prescient"

Sample of Bill's 112(!) Publications from 1974 to 1981

16. High-energy Nucleus-nucleus Collisions: Ideal And Real Experiments
W. Willis (CERN). Sep 1981. 13 pp. CERN-EP-81-120, C81-07-09-28

19. Experiments On Very High-energy Heavy Ions
W.J. Willis (CERN). Mar 1981. 29 pp. CERN-EP-81-21

26. Applications Of Wire Chambers In High-energy Physics
W. Willis (CERN). Jun 1980. 17 pp. Published in **Nucl.Instrum.Meth. 176 (1980) 61**, CERN-EP-80-90, C80-02-27-26

30. A Measurement of Direct Photon Production at Large P(T) at the CERN ISR
M. Diakonou, C. Kourkoumelis, L.K. Resvanis (Athens U.), T.A. Filippas, E. Fokitis, C. Trakkas (Natl. Tech. U., Athens), A.M. Cnops, E.C. Fowler, D.M. Hood, R.B. Palmer (Brookhaven) *et al*.. *Jan 1980. 12 pp.* Published in **Phys.Lett. B91 (1980) 296-300**, CERN-EP/80-02

44. The Large Spectrometers
W.J. Willis (CERN & Brookhaven). 1978. Published in **Phys.Today 31N10 (1978) 32-39**

53. Use of Transition Radiation Detectors at the ISR
W. Willis (CERN). 1977. Published in **In *Erevan 1977, Proceedings, Transition Radiation Of High Energy Particles*, Erevan 1977, 245-255**

54. Measurement of Reactions Producing Neutrinos
D. Cundy, P. Darriulat, F. Palmonari, W. Willis. 1977.
Published in **In *CERN 76-18, Physics With High Energy E+ E- Colliding Beams*, Geneva 1076, 145-168**

67. Novel Mechanisms for Particle Acceleration
W.J. Willis (CERN). 1975. Published in **In *Conf.Brookhaven 1975, Isabelle Summer Study*, Brookhaven 1975, 170-181**

83. Σ Production in High-Energy Proton Interactions
V. Hungerbuehler, R. Majka, J.N. Marx, P. Nemethy, J. Sandweiss, William M. Tanenbaum, W.J. Willis (Yale U.), M. Atac, S. Ecklund, P.J. Gollon (Fermilab) *et al*.. *1973.* , Published in **Phys.Rev.Lett. 30 (1973) 1234-1237, Erratum-ibid. 31 (1973) 141**

In The Beginning

- *Experiments on Very High Energy Heavy Ions*, CERN-EP-81-21, published in *Proceedings of the Workshop on Future Relativistic Heavy Ion Experiments*, GSI Darmstadt, October 1980

- *"in equilibrium with matter above a certain temperature, the physical vacuum must necessarily undergo a phase transition to the simple, or perturbative, vacuum."*

- Invention(?) of the phrase "cold nuclear matter": *"proton-nucleus collisions are probably not very effective for such studies: the narrow hot region is immersed in wet blanket of cold nuclear matter…"*

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/81-21
18 March 1981

EXPERIMENTS ON VERY HIGH ENERGY HEAVY IONS

W.J. Willis
CERN, Geneva, Switzerland

Talk given at the
Workshop on Future
Relativistic Heavy Ion Experiments,
GSI Darmstadt, 7-10 October 1980

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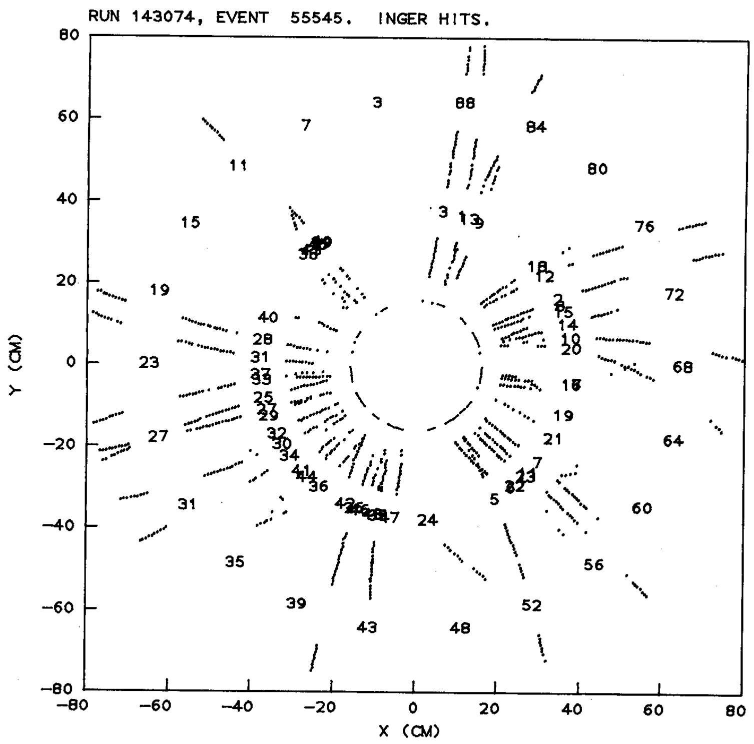

Fig. 6

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In The Beginning

- *High-Energy Nucleus-Nucleus Collisions, Ideal and Real Experiments*, CERN-EP-81-120, talk given at EPS International Conference on High Energy Physics, Lisbon, July 1981.

- *"It is a happy circumstance that calorimetric detectors … actually perform better under conditions of high-energy deposit by numerous particles. Also, such detectors lend themselves to spatial subdivision into a large number of cells, particularly the electromagnetic part, which is just what is needed to study photons and electrons under conditions of high particle multiplicity."*

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Some questions do require detailed measurement of the momentum of charged particles as well as energy flow measurement in calorimeters. Two approaches to this problem have been discussed (12). First, an inspection of these questions seems to show that if 4π coverage by a calorimetric detector is provided, the questions requiring charged-particle measurement can generally be satisfied by measuring particles over a restricted solid angle whose energy flow configuration has been identified, or selected by a trigger, using the calorimeter. The multiplicities in the detector can then be made to conform with those ordinarily handled in present detectors. Figure 3 shows how one

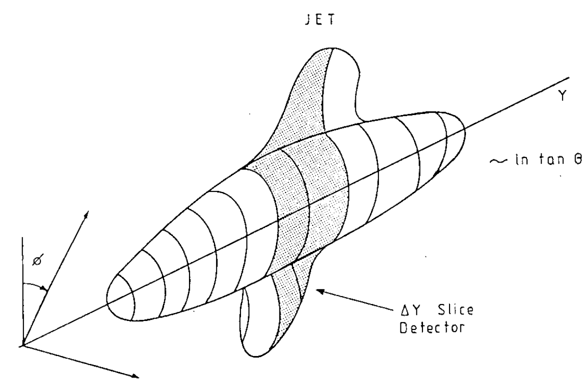
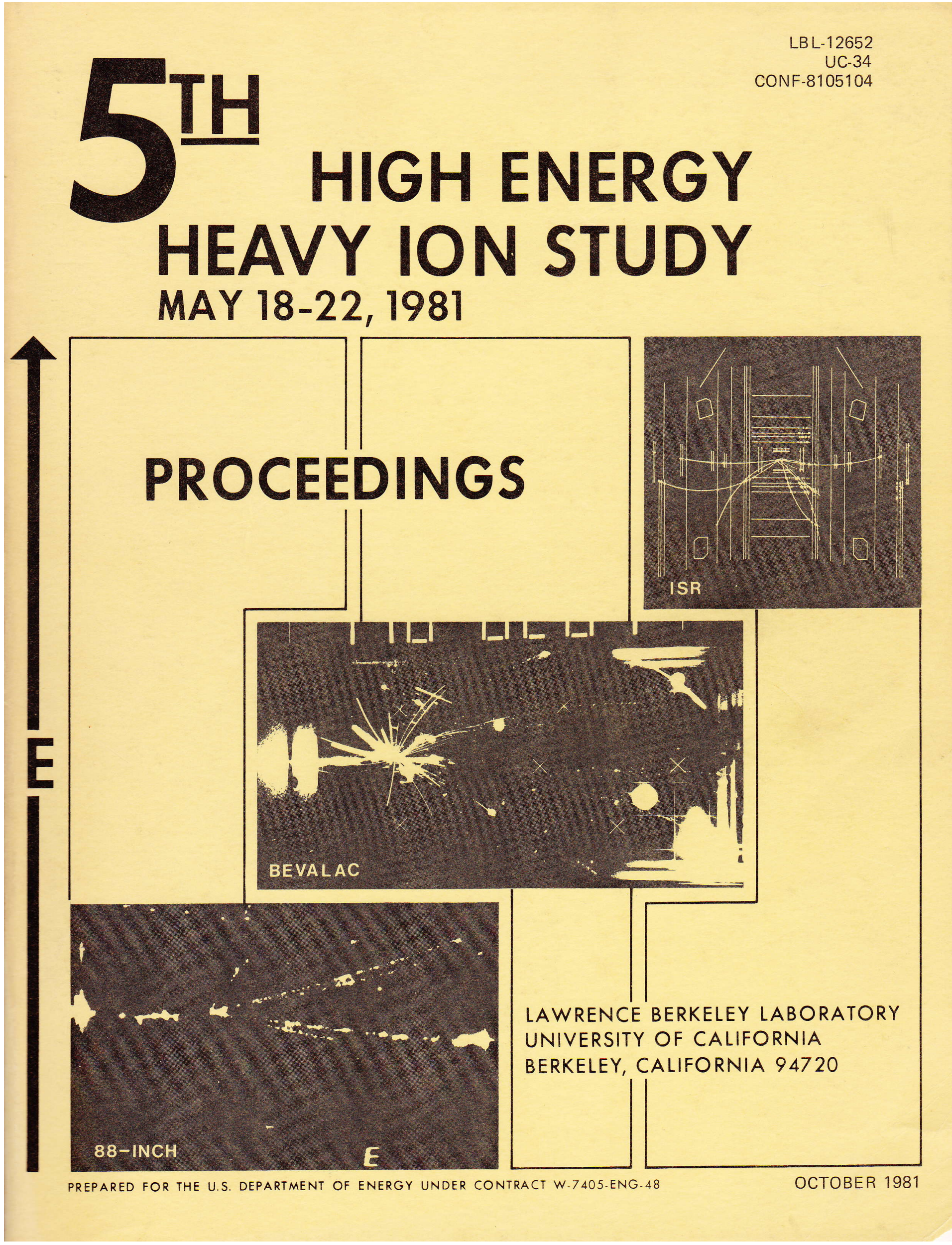
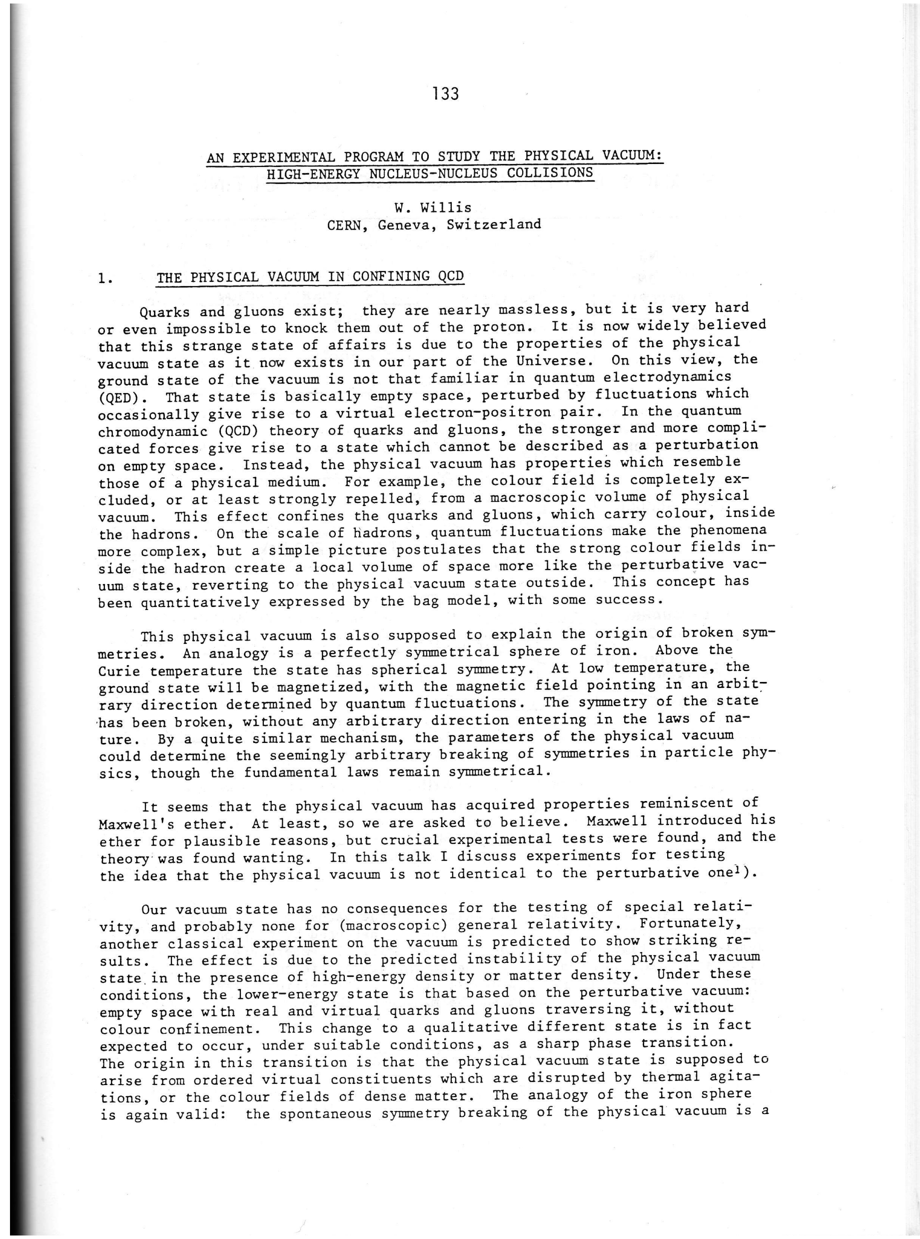


Fig. 3 A contour plot of energy flow in rapidity and transverse energy variables. The rapidity coverage of a track detector is indicated, showing how a small interval can be used to sample the jet selected by the large-solid-angle calorimeter.

can do this. The picture illustrates the energy flow in a hypothetical event, in rapidity versus transverse energy space. This event has been selected by a calorimeter trigger to have a "super-jet" in a special rapidity interval of small extent. There is a cylindrical drift chamber covering that rapidity interval only, but the whole azimuth. The energy flow is measured by the calorimeter over the whole solid angle.

In The Beginning





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AN EXPERIMENTAL PROGRAM TO STUDY THE PHYSICAL VACUUM:
HIGH-ENERGY NUCLEUS-NUCLEUS COLLISIONS

W. Willis
CERN, Geneva, Switzerland

1. THE PHYSICAL VACUUM IN CONFINING QCD

Quarks and gluons exist; they are nearly massless, but it is very hard or even impossible to knock them out of the proton. It is now widely believed that this strange state of affairs is due to the properties of the physical vacuum state as it now exists in our part of the Universe. On this view, the ground state of the vacuum is not that familiar in quantum electrodynamics (QED). That state is basically empty space, perturbed by fluctuations which occasionally give rise to a virtual electron-positron pair. In the quantum chromodynamic (QCD) theory of quarks and gluons, the stronger and more complicated forces give rise to a state which cannot be described as a perturbation on empty space. Instead, the physical vacuum has properties which resemble those of a physical medium. For example, the colour field is completely excluded, or at least strongly repelled, from a macroscopic volume of physical vacuum. This effect confines the quarks and gluons, which carry colour, inside the hadrons. On the scale of hadrons, quantum fluctuations make the phenomena more complex, but a simple picture postulates that the strong colour fields inside the hadron create a local volume of space more like the perturbative vacuum state, reverting to the physical vacuum state outside. This concept has been quantitatively expressed by the bag model, with some success.

This physical vacuum is also supposed to explain the origin of broken symmetries. An analogy is a perfectly symmetrical sphere of iron. Above the Curie temperature the state has spherical symmetry. At low temperature, the ground state will be magnetized, with the magnetic field pointing in an arbitrary direction determined by quantum fluctuations. The symmetry of the state has been broken, without any arbitrary direction entering in the laws of nature. By a quite similar mechanism, the parameters of the physical vacuum could determine the seemingly arbitrary breaking of symmetries in particle physics, though the fundamental laws remain symmetrical.

It seems that the physical vacuum has acquired properties reminiscent of Maxwell's ether. At least, so we are asked to believe. Maxwell introduced his ether for plausible reasons, but crucial experimental tests were found, and the theory was found wanting. In this talk I discuss experiments for testing the idea that the physical vacuum is not identical to the perturbative one[1]).

Our vacuum state has no consequences for the testing of special relativity, and probably none for (macroscopic) general relativity. Fortunately, another classical experiment on the vacuum is predicted to show striking results. The effect is due to the predicted instability of the physical vacuum state in the presence of high-energy density or matter density. Under these conditions, the lower-energy state is that based on the perturbative vacuum: empty space with real and virtual quarks and gluons traversing it, without colour confinement. This change to a qualitative different state is in fact expected to occur, under suitable conditions, as a sharp phase transition. The origin in this transition is that the physical vacuum state is supposed to arise from ordered virtual constituents which are disrupted by thermal agitations, or the colour fields of dense matter. The analogy of the iron sphere is again valid: the spontaneous symmetry breaking of the physical vacuum is a

Vacuum Melting & Novel Effects in Peripheral Collisions

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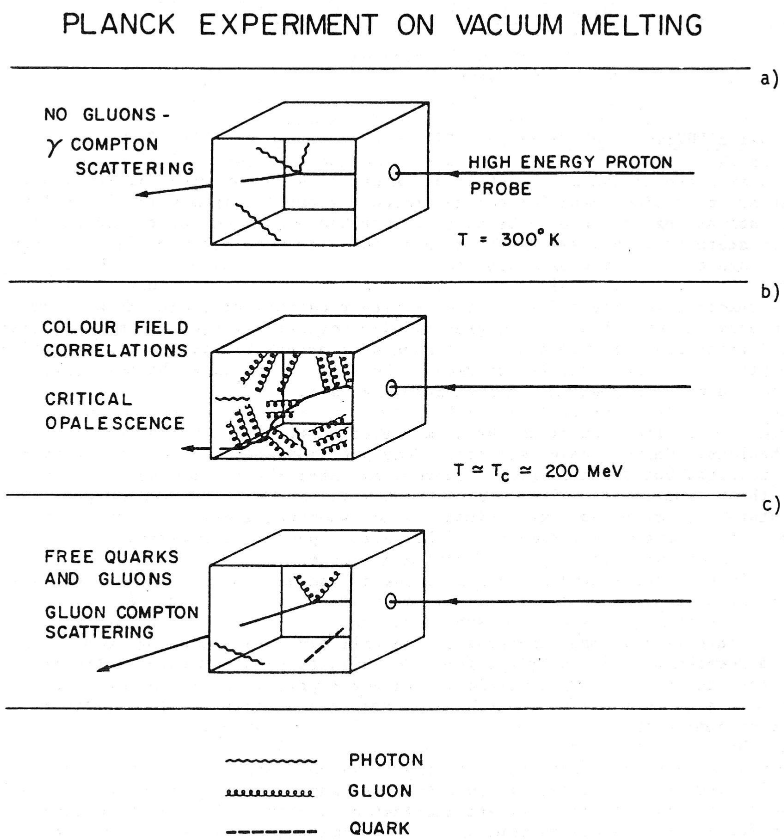

Fig. 1 Idealized experiment on "melting of the vacuum": a) Box at ambient temperature, showing thermal photons detected by Compton scattering of high-energy protons; b) at critical temperature, with large-scale fluctuations of the colour dielectric constant, and critical opalescence for protons; c) above transition, free gluons and quarks are detected in the middle of the box.

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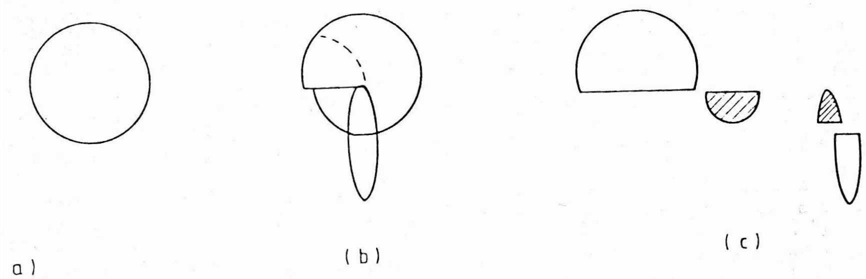


. 2 A picture of the evolution of a glancing collision of a very high rgy heavy nucleus, in the rest frame of the target nucleus, at three ferent stages.

Though only a small fraction of all pions traverse the non-interacting on of the target, the number can easily reach ten or more. The wavelength ese pions will be of the same order as the nuclear size. The effects of a intense wave of strongly interacting pions may produce an interesting ing in the nuclear matter, which may be detectable by observing the nu-s, which are unlikely to have the characteristics expected for "specta-, or by observations of the pions with velocities near that of the target.

THE PROBLEM OF OBSERVABLES

The literature on this subject does not provide many good discussions of uantities to be observed. One of the weaknesses, as well as strength, of hermodynamical method is that one can proceed happily in a discussion the thermodynamic variables without the necessity of explaining how they o be measured. The problem becomes acute when there are strong temporal patial variations. A correct procedure would be to perform a Monte Carlo ation at the constituent and vacuum level, but that is out of reach for oment. We cannot yet renounce thermodynamical considerations.

My Own Beginning

- *CERN Courier,* January 1982, pp. 17-20

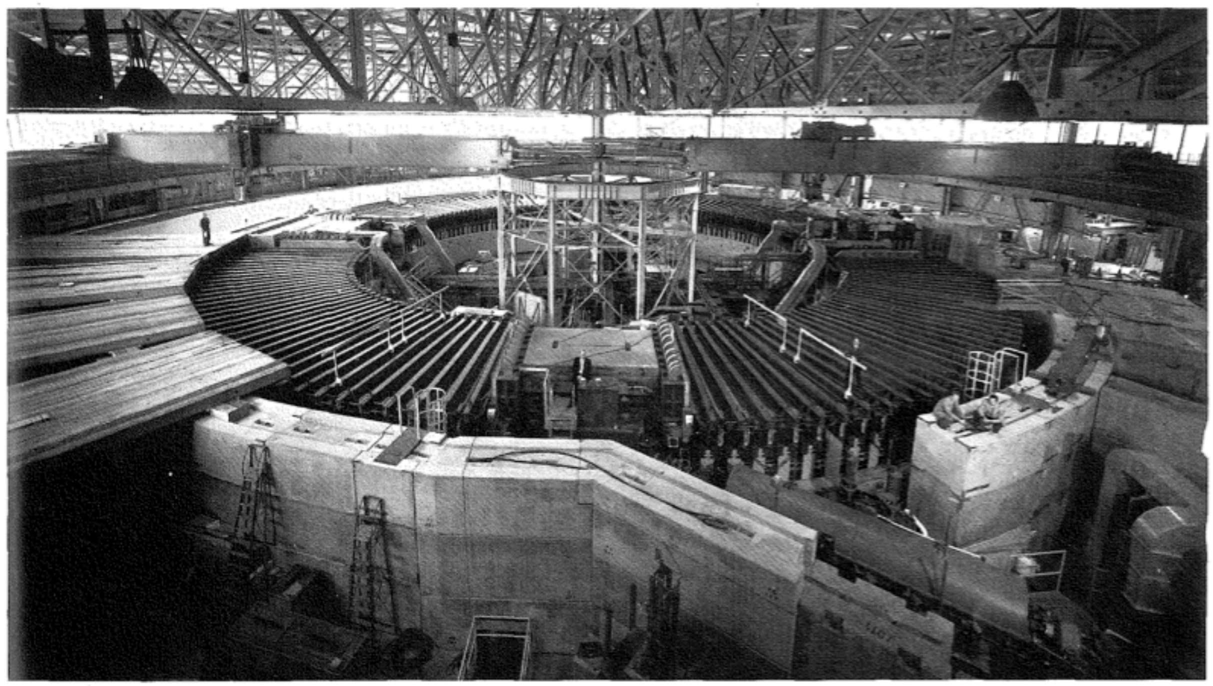
  (a condensed version of his contribution to the proceedings of the May 1981 workshop at LBL)

New possibilities with nucleus-nucleus collisions

by W. Willis

The Bevatron at Berkeley, now part of the Bevalac and scene of experiments with high energy heavy ion beams. However these energies of several GeV per nucleon may be insufficient to reveal important phenomena in nucleus-nucleus collisions.

(Photo LBL)



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The symmetry of the state has been broken, without any arbitrary direction entering in the laws of nature. By a quite similar mechanism, the parameters of the physical vacuum could determine the seemingly arbitrary breaking of symmetries in particle physics, though the fundamental laws remain symmetrical.

Bill’s Scientific Insight

- “*Most hadrons will have at last scattered near the surface of the interaction volume, largely erasing the information about their previous history. It is not sensible to go to such trouble to provide a good surface-to-volume ratio, and then selectively to observe the surface. Weakly interacting probes are called for.*”

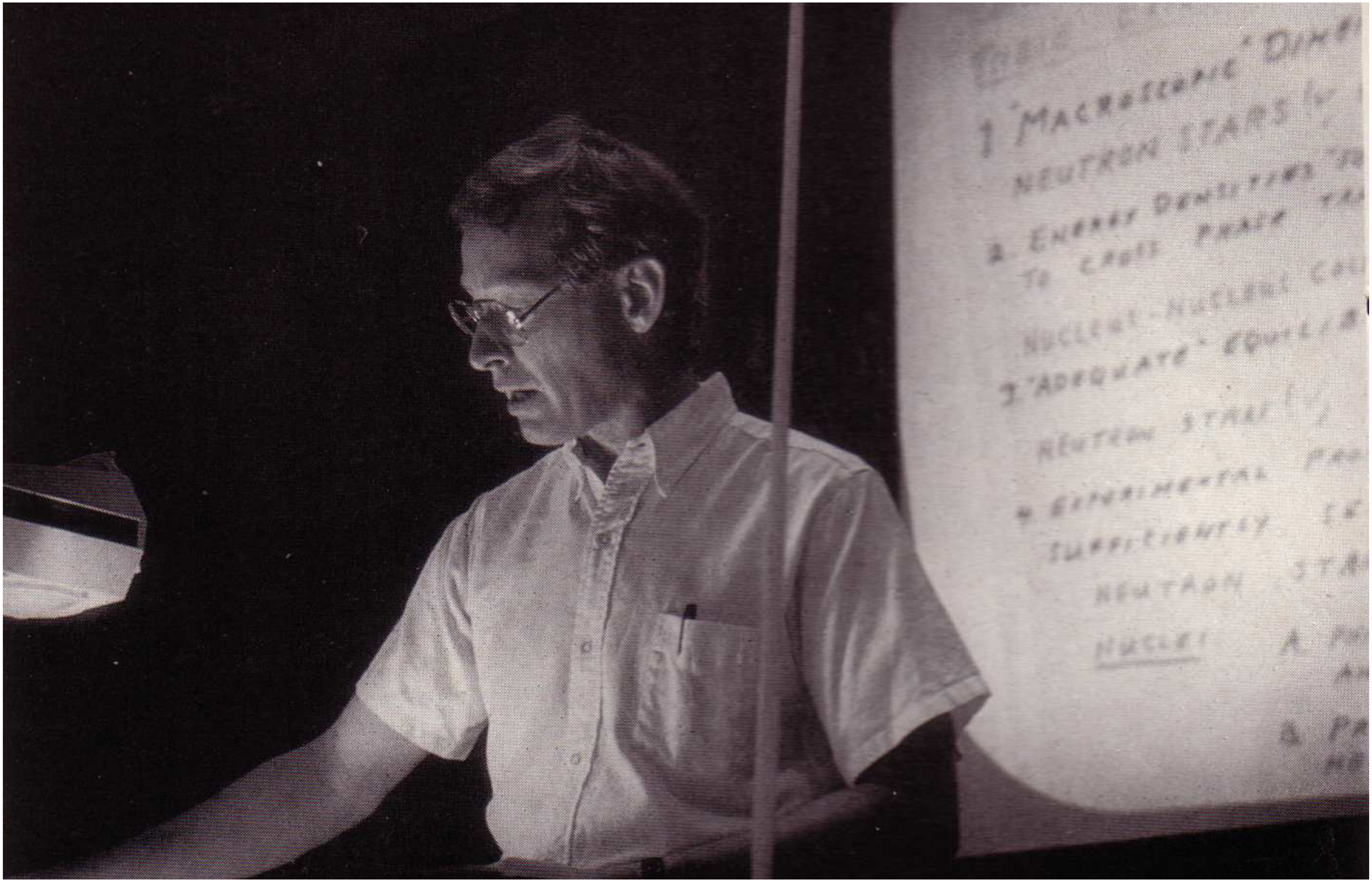
From That Inspirational Article

- *"The effect is due to the predicted instability of the vacuum in the presence of high energy or matter density."*

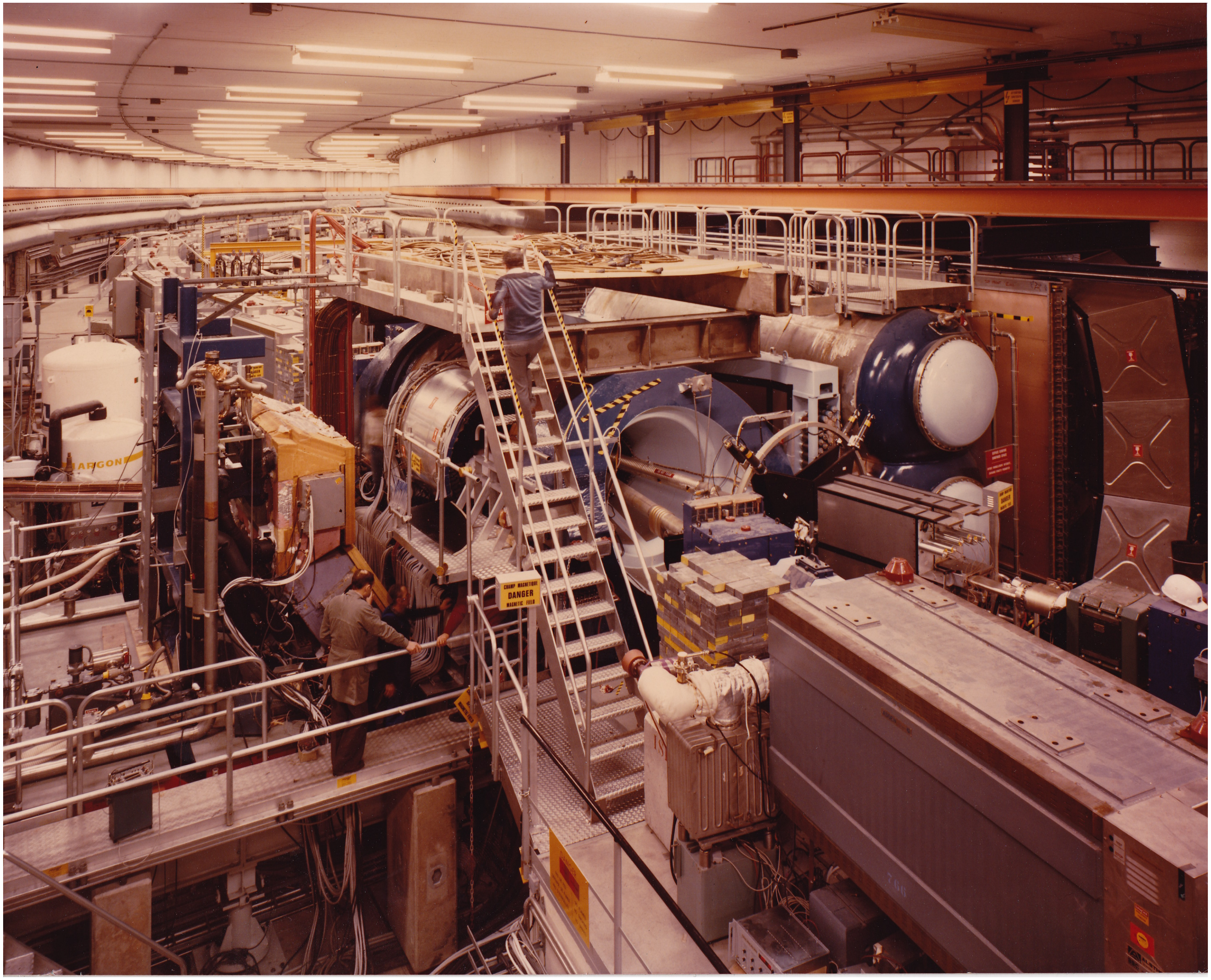
- *"The 'Curie temperature' of the vacuum is of the order of the QCD scale parameter."*

- *"It seems clear that the energies investigated at Berkeley and Dubna, a few GeV per nucleon, are not sufficient and the further investigation of these phenomena must await the availability of much higher energy nuclear collisions."*

From That Inspirational Article

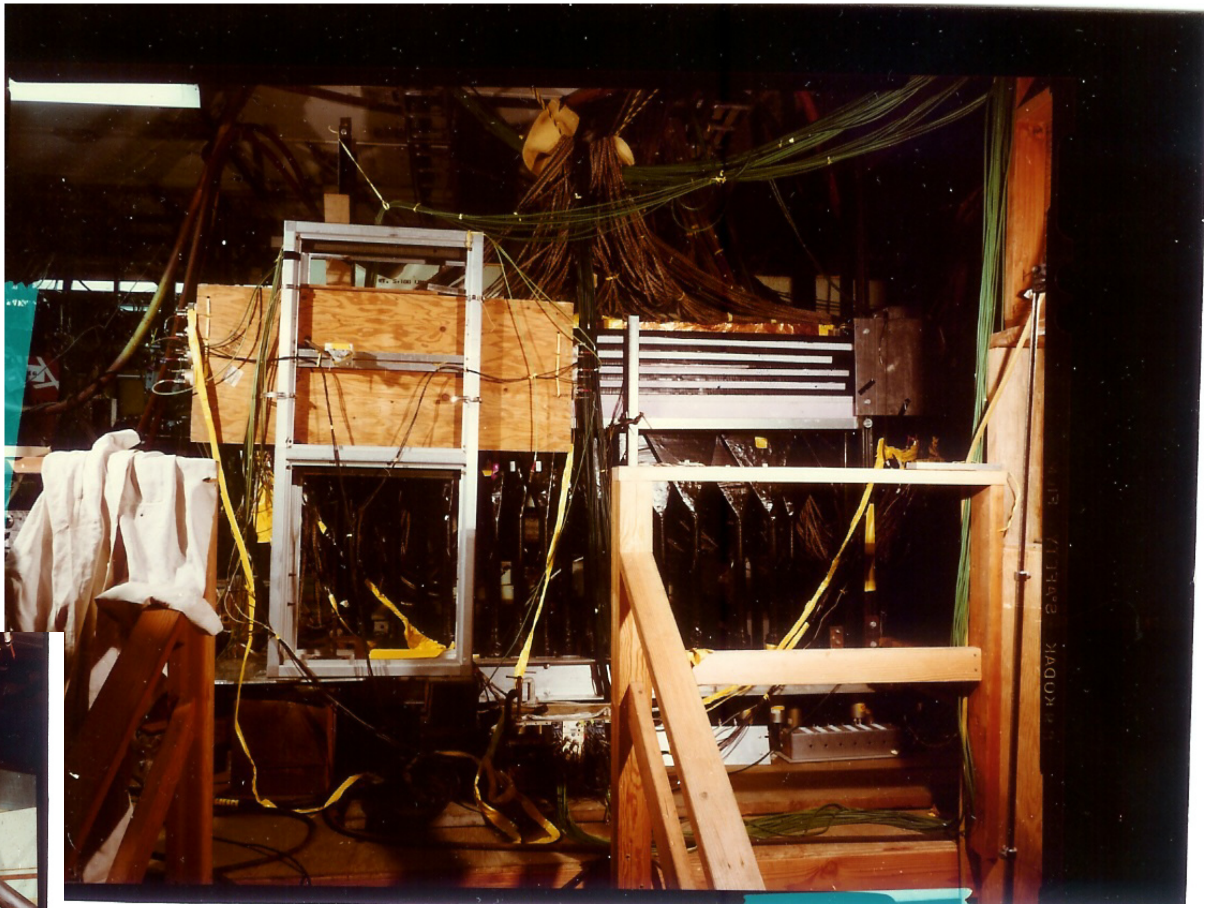


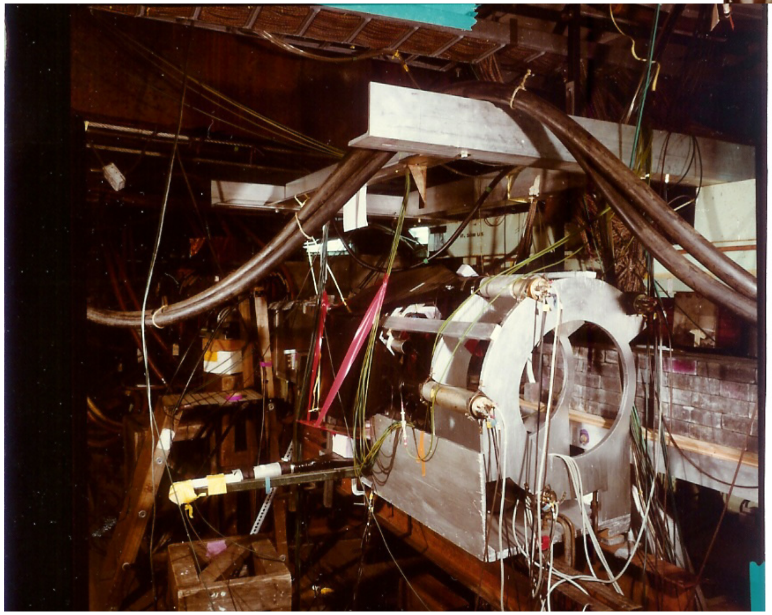
The AFS at the ISR



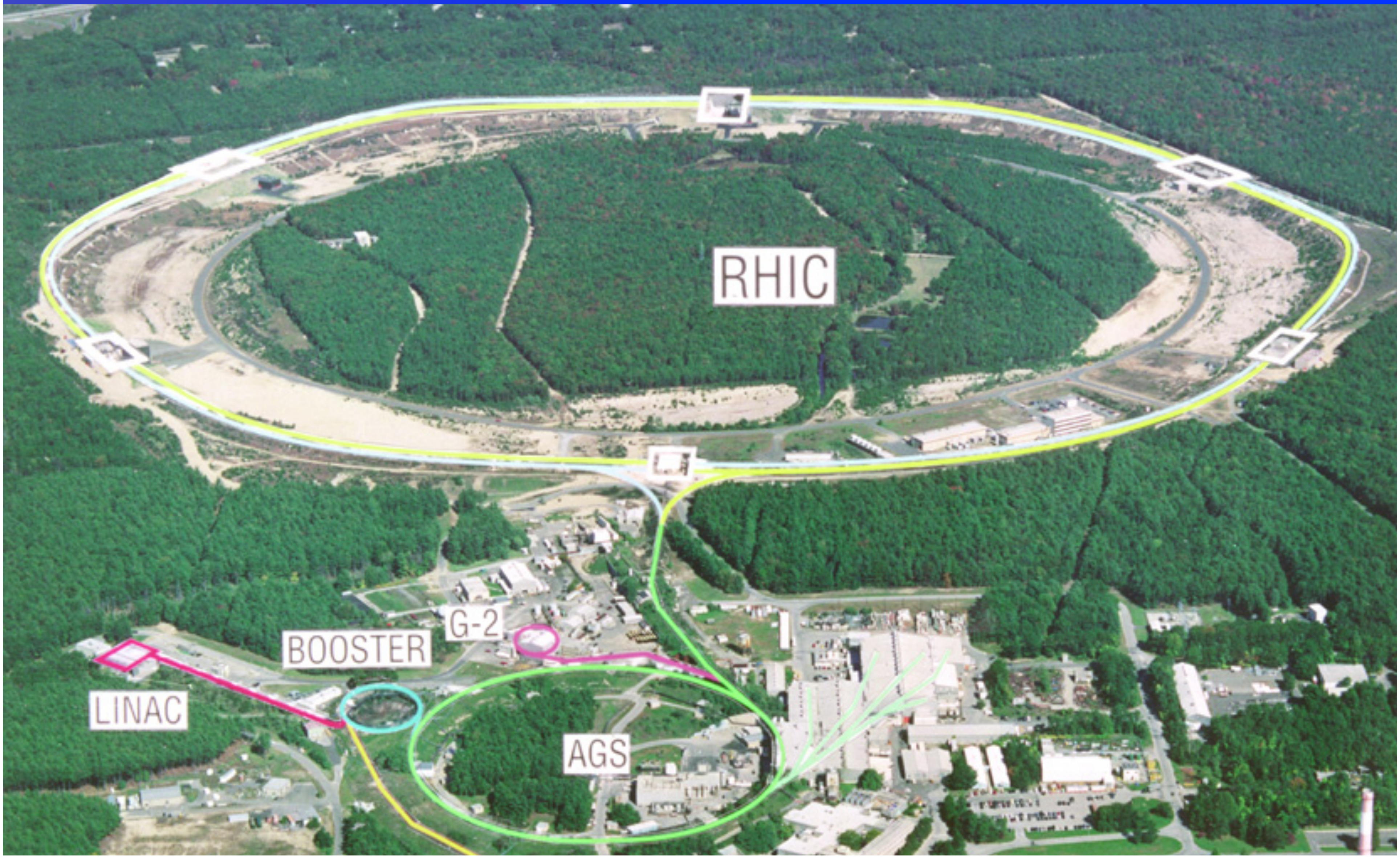
Emerging from a Bevalac Cave

- CERN, and the beautiful AFS apparatus, beckoned like the shining city on the hill…

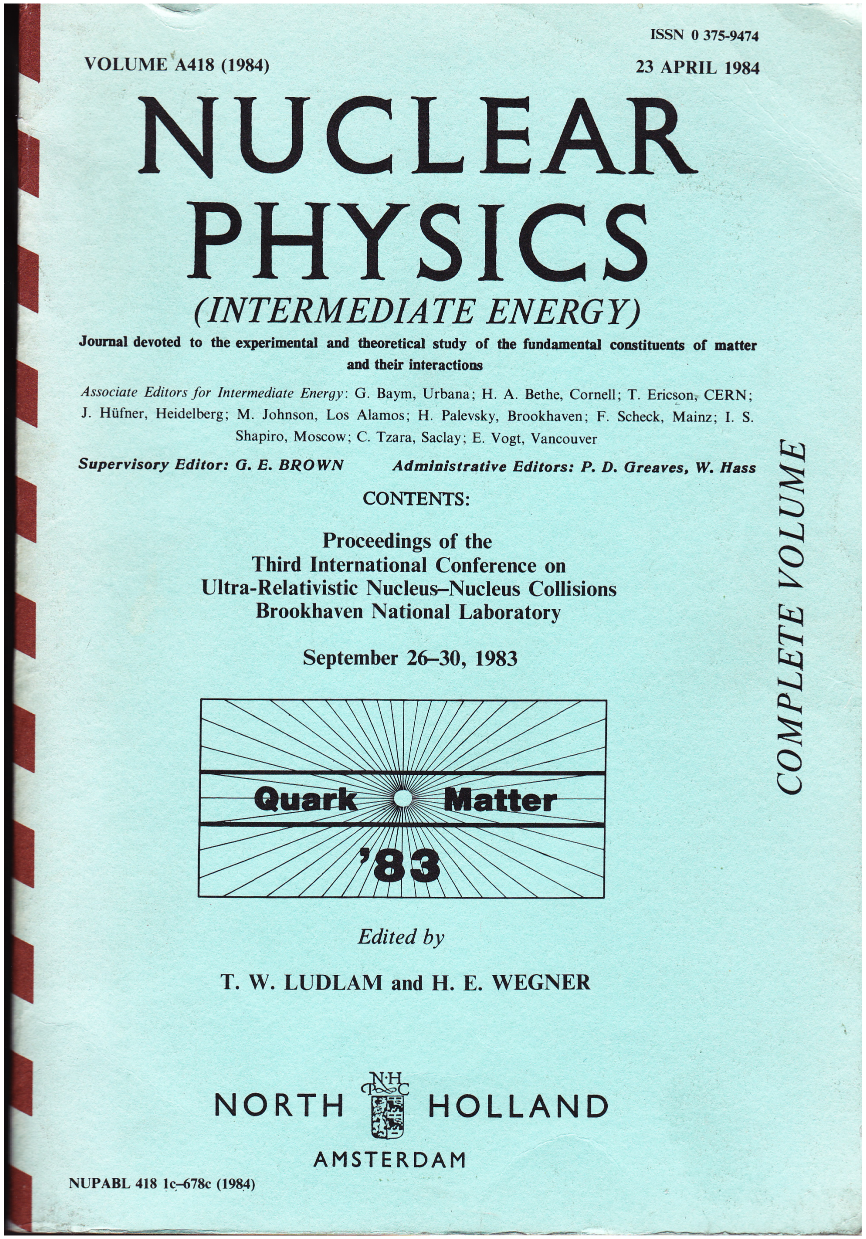




1983: Another Shining City is Proposed



1983: The First *Named* "Quark Matter" Conference



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(INTERMEDIATE ENERGY)

Journal devoted to the experimental and theoretical study of the fundamental constituents of matter and their interactions

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COMPLETE VOLUME

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Proceedings of the
Third International Conference on
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Brookhaven National Laboratory

September 26–30, 1983

Quark Matter '83

Edited by

T. W. LUDLAM and H. E. WEGNER

NORTH HOLLAND
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North-Holland, Amsterdam

SUMMARY OF PARALLEL SESSIONS ON EXPERIMENTS

W. Willis and C. Chasman, Organizers

I. INTRODUCTION

These sessions began with a number of "mini reviews" of recent efforts to design experiments and detectors for very high energy heavy ion collisions. These include last year's Bielefeld Workshop,[1] the SPS Workshop on Fixed Target Experiments[2] and some experimental proposals which are presently being developed.[3,4] The mini-review topics and speakers are listed in Table I. Some of the talks, for which the material is not published elsewhere, are reproduced in this volume (see Experimental Discussions).

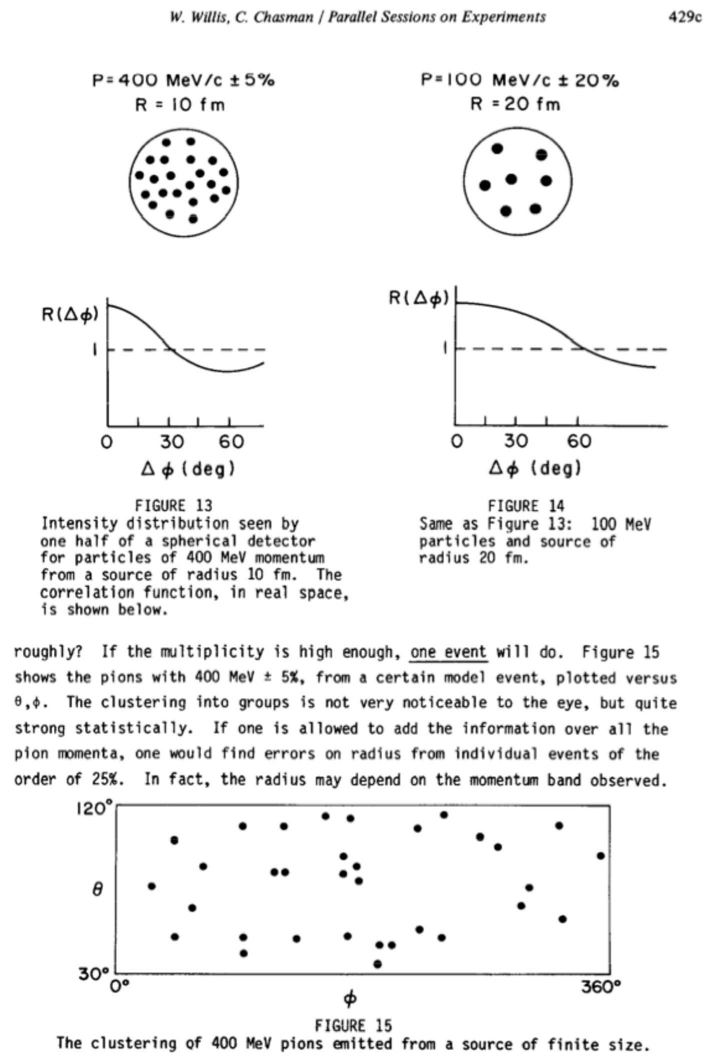
Following these mini-reviews three discussion groups were formed to attempt to develop further the existing ideas. In particular, since previous work has dealt primarily with fixed target experiments, we aimed here to extend the thinking to include the possibilities and requirements for a very high energy colliding beam facility. Time was short for this process-- the working time for our discussion groups being about 1/20 that of the Bielefeld and SPS workshops. Many new ideas emerged, and many opinions were aired, without sufficient time to reach fully coherent conclusions. There was time for a certain evolution of ideas, however. For example, the 4π discussions led many members to favor constructing a "few particle" detector, while the few particle detector group came out in favor of a 4π detector.

We summarize here the results of each of the 3 discussion groups, and then present some new approaches to the problem of track measurement in a very high multiplicity environment. Finally, we discuss some possible new kinds of measurements which become possible if the extraordinarily high multiplicities are successfully dealt with. New kinds of measurements which offer the chance of new discoveries independent of theoretical wisdom regarding the quark plasma (in keeping with Prof. Nakai's remarks in the panel discussion), and which are also fun to contemplate for their intellectual and technical challenge.

0375-9474/84/$03.00 © Elsevier Science Publishers B.V.
(North-Holland Physics Publishing Division)

Also Speckle Interferometry (!)

- *“In the high multiplicity events we are describing, we approach the other limit, where there often are more than two particles in the same volume. It is then very bad to neglect the part of the information carried by more than two particle correlations. The correct formalism to use in the many particle limit is known from optical studies. The analog is that of "speckle interferometry," so called because coherent light scattered from a rough surface produces "speckles" familiar to anyone who has seen an ordinary object illuminated with a Ne-He laser, with its characteristic grainy appearance.”*



W. Willis, C. Chasman / Parallel Sessions on Experiments 429c

FIGURE 13
Intensity distribution seen by one half of a spherical detector for particles of 400 MeV momentum from a source of radius 10 fm. The correlation function, in real space, is shown below.

FIGURE 14
Same as Figure 13: 100 MeV particles and source of radius 20 fm.

roughly? If the multiplicity is high enough, one event will do. Figure 15 shows the pions with 400 MeV ± 5%, from a certain model event, plotted versus θ,ϕ. The clustering into groups is not very noticeable to the eye, but quite strong statistically. If one is allowed to add the information over all the pion momenta, one would find errors on radius from individual events of the order of 25%. In fact, the radius may depend on the momentum band observed.

FIGURE 15
The clustering of 400 MeV pions emitted from a source of finite size.

An Intellectual Debt

PHYSICAL REVIEW D VOLUME 35, NUMBER 11 1 JUNE 1987

Monte Carlo calculational methods for the generation of events with Bose-Einstein correlations

William A. Zajc*
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 17 November 1986)

The momentum-space correlations for n bosons emitted by a source distributed in space and time are discussed in the context of intensity interferometry for identical pions. The Metropolis algorithm is used to generate events containing such correlations to all orders via a Monte Carlo technique. Direct calculation of the probability for multiparticle correlations is practicable for n-body states up to $n \sim 20$. Beyond this, a method which samples the symmetrized n-body probability must be used. It is observed that the traditional pair-correlation function is distorted for events with high phase-space density in a fashion consistent with the results of a simple model calculation.

I. INTRODUCTION

The use of intensity interferometry to study hadronic-source sizes is by now a well-established technique of high-energy physics. Typically, the two-particle correlation function is generated as a function of the relative momentum between the two (like) particles. This quantity is directly related to the Fourier transform of the density distribution for the source of these particles, thus permitting the extraction of the source size and lifetime.

In principle, the extension of such methods to more than two particles is straightforward. Experimentally, this is seldom done, since pion multiplicities in typical reactions are sufficiently low that the probability of finding three or more like-charged pions in the same region of phase space is negligible. (Given that the pion is the most abundant boson produced in hadronic reactions, I will confine my attention to pions in this paper.) Recently Willis[1] has emphasized that pion abundances in the collision of two large nuclei at high energies are sufficiently large that multipion correlations (that is, correlations that are not the product of simpler pairwise correlations) are no longer small. In the limit of very large multiplicities, the appropriate technique then becomes *speckle interferometry*, i.e., the study of phase-space clustering of large numbers of pions.

It is therefore of some interest to have a method whereby typical multipion events can be generated that explicitly exhibit all correlations induced by Bose statistics. Previous efforts[2,3] while dealing with much more complicated dynamical systems than the simple source considered here, have typically limited themselves to producing only the pairwise correlations by weighting events. This paper presents two Monte Carlo procedures for generating events of unit weight that incorporate these correlations to all orders.

The organization is as follows. Section II provides a simple introduction to the relevant features of the n-pion state. Section III describes both the algorithm used to generate the n-pion state, and methods by which the various probabilities may be efficiently calculated. Results are presented in Sec. IV, while potential methods for analyzing the correlated events are discussed in Sec. V. Conclusions and indications for future research appear in Sec. VI. Analytic results for the distortion of the pairwise correlation function by the higher-order correlations are presented in an appendix. An earlier version of this work appeared in Ref. 4; this paper extends and to some extent supersedes the material presented there.

II. n-BOSON INTENSITY INTERFEROMETRY

This section reviews the basic properties of a n-pion state arising from a source distributed in space and time. Although some portions of this discussion have been presented elsewhere (see, e.g., Ref. 5), it is included both for completeness as well as for clarity in establishing notational conventions. We begin with the canonical derivation for the case of two pions, then consider the appropriate generalizations for multipion states.

Assume that a pion of momentum p_1 is detected at x_1 and momentum p_2 at x_2. If the source of these pions has a space-time distribution given by $\rho(\mathbf{r},t) \equiv \rho(r_1)$, the probability of such an event is given by

$$\mathscr{P}_{12} = \int |\Psi_{p_1p_2}(x_1x_2;r_1r_2)|^2 \rho(r_1)\rho(r_2) d^4r_1 d^4r_2 , \quad (1)$$

where $\Psi_{p_1p_2}(x_1x_2;r_1r_2)$ is defined as the amplitude for a pion pair produced at r_1 and r_2 to register in the detectors in the prescribed fashion. In general we are unable to determine which pion was emitted at r_1 and which at r_2, so that we are required by Bose statistics to add the amplitudes for the alternative histories, as shown in Fig. 1. Regardless of the production mechanisms for the pions, if we assume that their emissions are uncorrelated and that they propagate as free particles after their last strong interaction, we have, for $\Psi_{p_1p_2}(x_1x_2;r_1,r_2)$,

$$\Psi_{p_1p_2}(x_1x_2;r_1r_2) = \frac{1}{\sqrt{2!}}\left(e^{ip_1(x_1-r_1)}e^{ip_2(x_2-r_2)} + e^{ip_1(x_1-r_2)}e^{ip_2(x_2-r_1)}\right) . \quad (2)$$

Evaluating the squared wave function and performing the integration in Eq. (1) leads to

those calculated assuming Poisson statistics on the number of entries in each bin. Such a scaling, of course, does not change the fitted value of the k, but does scale the error on this quantity to the value $k = 3.08 \pm 0.22$. The factor of 6 is chosen to produce a χ^2 per degree of freedom of order unity, providing us with further evidence that successive events generated via the CCK algorithm are not statistically independent, but instead have a "correlation length" in event space of order 6–10 events. (This conclusion is clearly a strong function of n_π, as indicated by Figs. 10–12.) It is important to note that the negative-binomial shape for the multiplicity distribution, along with an appropriate value for k, are produced *automatically* by the Bose correlations resulting from the finite source size; it is not an additional input into our event-generating procedure. We regard this, and the scaling of the multiplicity fluctuations with $\bar{n}$, as stringent tests for the applicability of our model.

We now discuss the extraction of source parameters from the Bose events. To motivate this, we consider the expression for the signal-to-noise ratio obtained for speckle interferometry in the optical regime:[8]

$$\frac{S}{N} = N_{ev}{}^{1/2} n_{\pi/s} N_s{}^{1/2} , \quad (26)$$

where N_{ev} is the number of frames of data, or events, $n_{\pi/s}$ is the number of bosons per speckle (pions in our case), and N_s is the number of speckles per event. (The ratio S/N is defined as the rms value of the image density to the error on the same, and thus corresponds roughly to the ratio of the R to the error in measuring the radius.) Following the considerations of Sec. II, the expression for S/N may be written as

$$\frac{S}{N} = \left[N_{ev} \left[\frac{2\pi}{p_0 R}\right]^2 n_{\text{pairs/ev}} \right]^{1/2} , \quad (27)$$

where $n_{\text{pairs/ev}}$ is the number of boson pairs per event. Thus, the determination of the source parameters via the canonical speckle methods depends on the total number of pairs of relative momentum measured, just as for the usual two-particle correlation function. Note also that the expression for the signal-to-noise ratio is inversely proportional to the pion phase-space density.

These results may be understood by recalling that optical speckle interferometry is simply a special case of intensity interferometry, which exploits the correlations $\langle I_1 I_2 \rangle$ between the intensities of the received wave fronts. For instance, the Fourier transform of the image-plane correlation function

$$C_1(x_1) \equiv \frac{\langle I(x+x_1)I(x)\rangle - \langle I \rangle^2}{\langle I \rangle^2} \quad (28)$$

is equal to the autocorrelation of the source function, as shown in Ref. 8. Translated into the particle regime, this

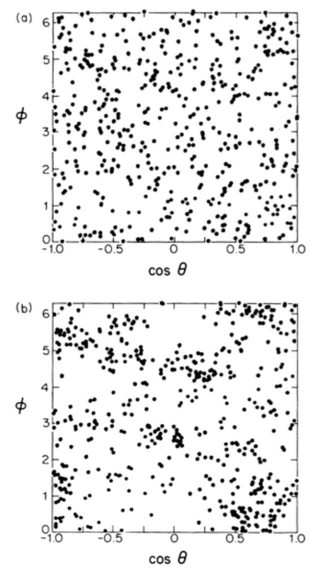


FIG. 15. Angular phase-space distributions with $n_\pi = 500$ for (a) uncorrelated and (b) Bose-correlated events. The points in (b) are assumed to be emitted from a source of (Gaussian) radius = 6 fm with $p_0 = 300$ MeV/c.

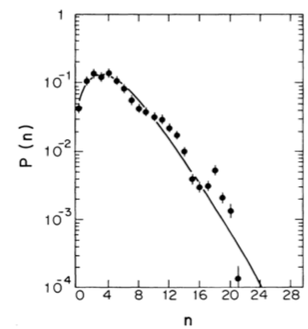


FIG. 16. The probability distribution for cell occupancies in Bose-correlated events with $n_\pi = 500$, along with a fit to a negative-binomial distribution. The errors have been increased by a factor of 6 relative to those calculated assuming Poisson statistics.

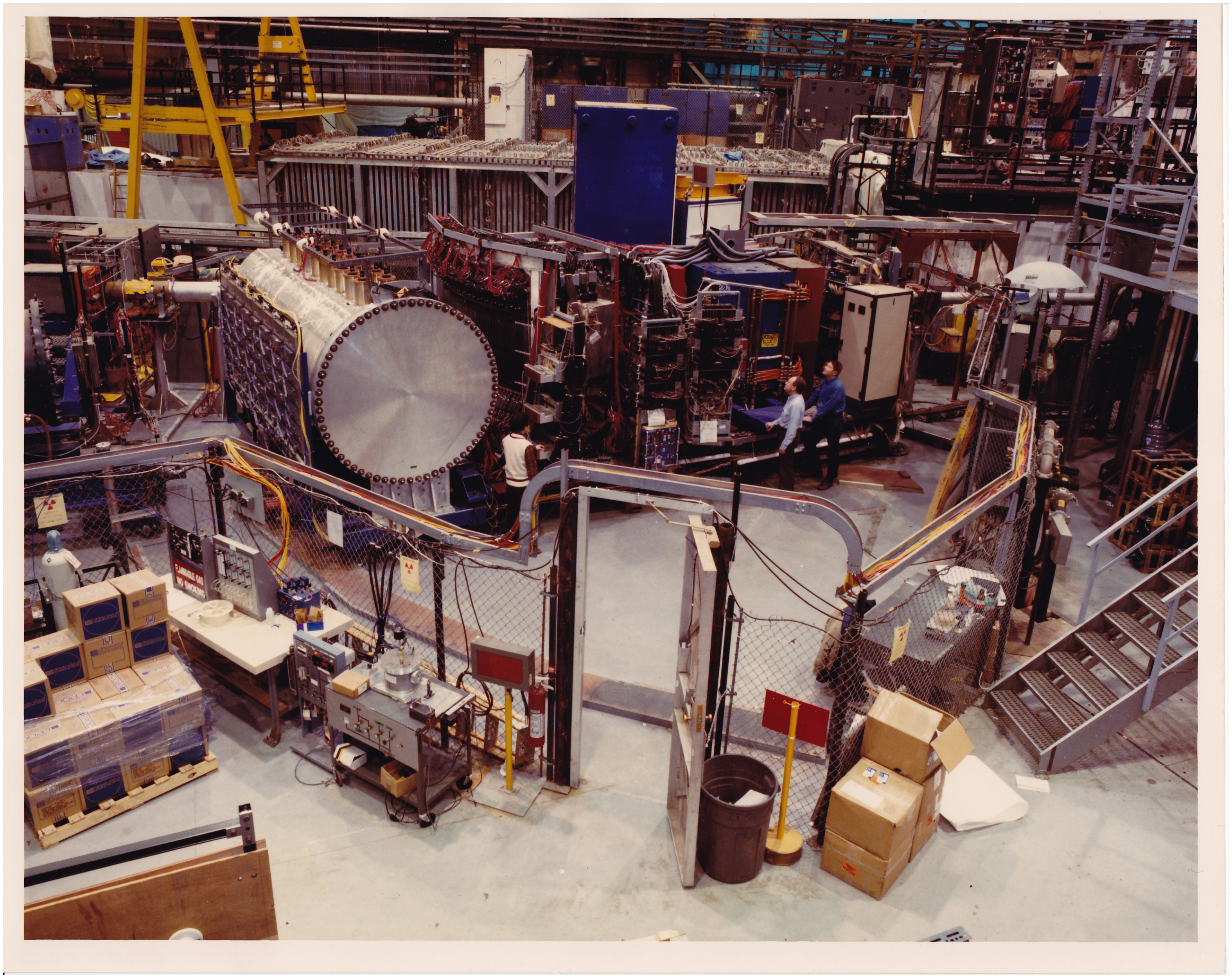
RHIC Advisory Committee: 1985-1997

Bill was a charter member, and served the entire duration of the committee – *Nick Samios*

The RHIC Policy Committee at its meeting on Feb. 28, 1991.

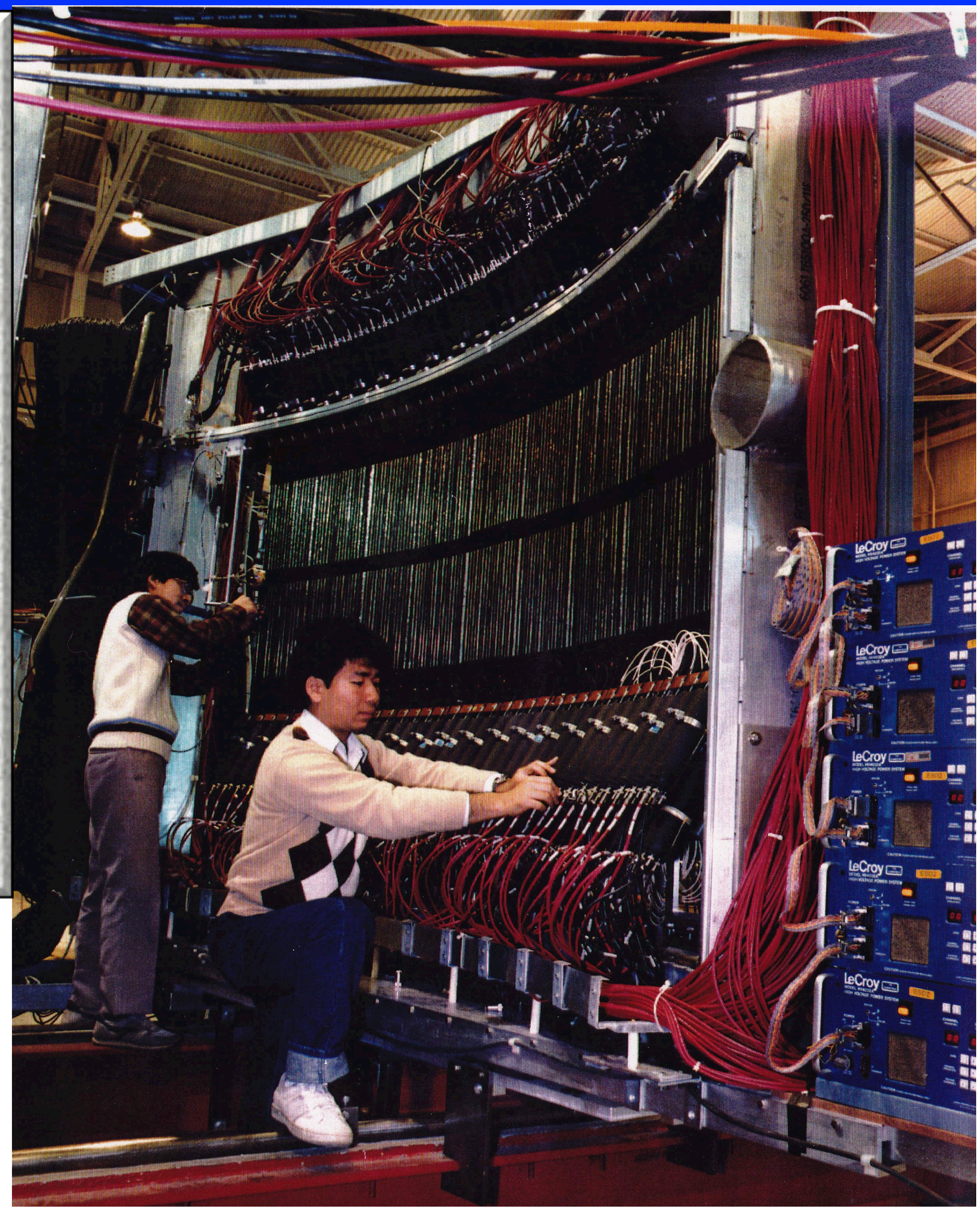
Standing, from left: Satoshi Ozaki (BNL, RHIC Project Head), Rudolf Bock (GSI, Germany), Nicholas Samios (Brookhaven Laboratory Director), John Schiffer (Argonne National Laboratory), Gordon Baym (University of Illinois), Pierre Darriulat (CERN), Mel Schwartz (BNL, Assoc. Director for High Energy and Nuclear Physics), Arthur Kerman (MIT); seated, from left: James Ball (Oak Ridge National Laboratory), Jack Sandweiss (Yale University), T.D. Lee (Columbia University), James Symons (Lawrence Berkeley Laboratory), Ernest Henley (University of Washington), Satio Hayakawa (Nagoya University), William Willis (Columbia University), Herman Feshbach (MIT), Chairman; not present: Hermann Grunder (CEBAF).

~1986: Fixed Target Program (E802)



From Shoji Nagamiya

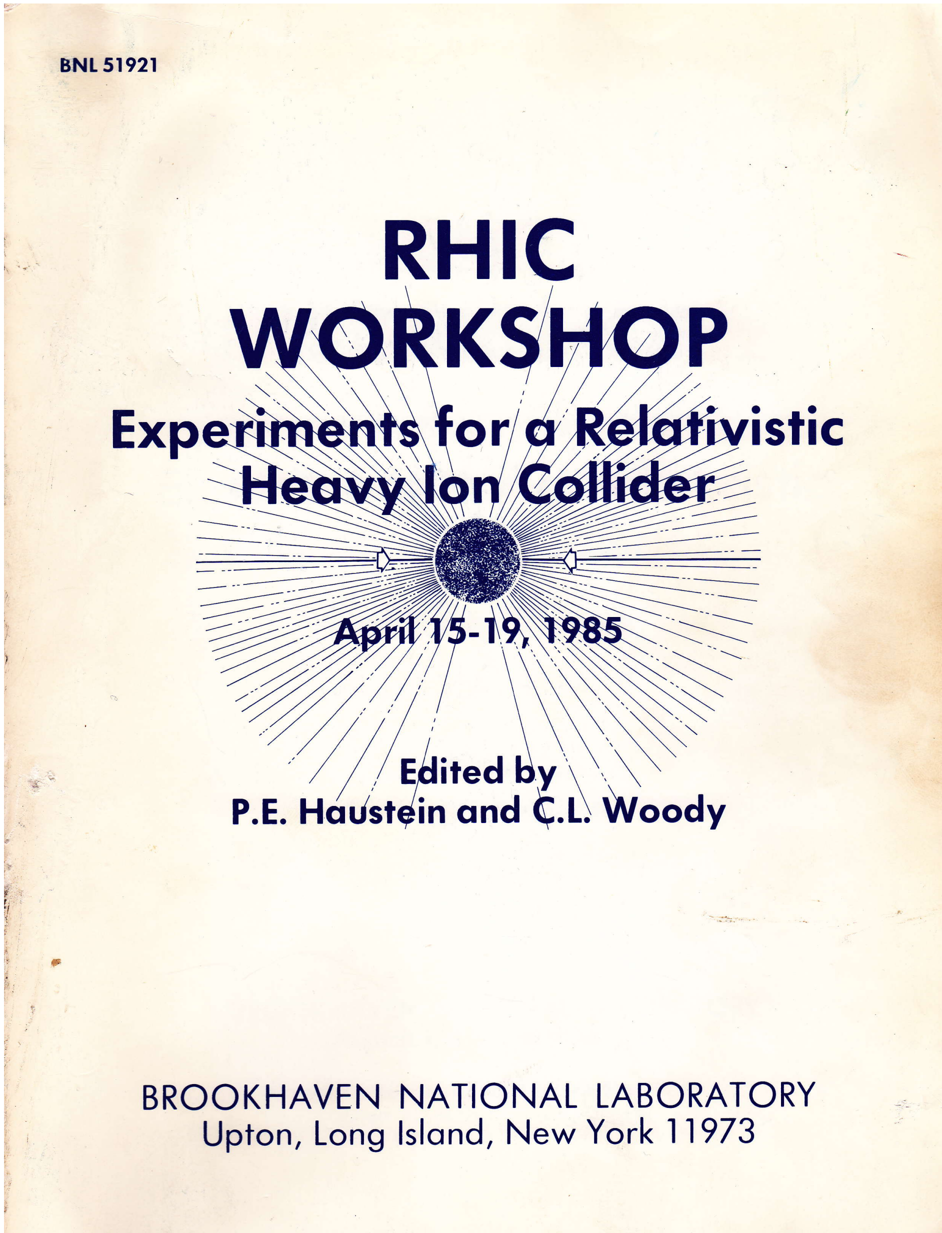
"(Bill) was deeply impressed by our technologies to resolve kaons from pions by having TOF resolution of about 70 ps. Therefore, he asked me to join the NA44 experiment and bring our technologies of high resolution TOF."



~1988: E814

- (From David Lissauer)
- "*Study of extreme peripheral collisions and of the transition from peripheral to central collisions in reactions induced by relativistic Heavy Ions*"
- Recycled from R806/R807:
  - NaI crystals
  - Ur-Scint calorimeter
- (Photos courtesy of Helio Takai)

1985: Making It Happen



BNL 51921

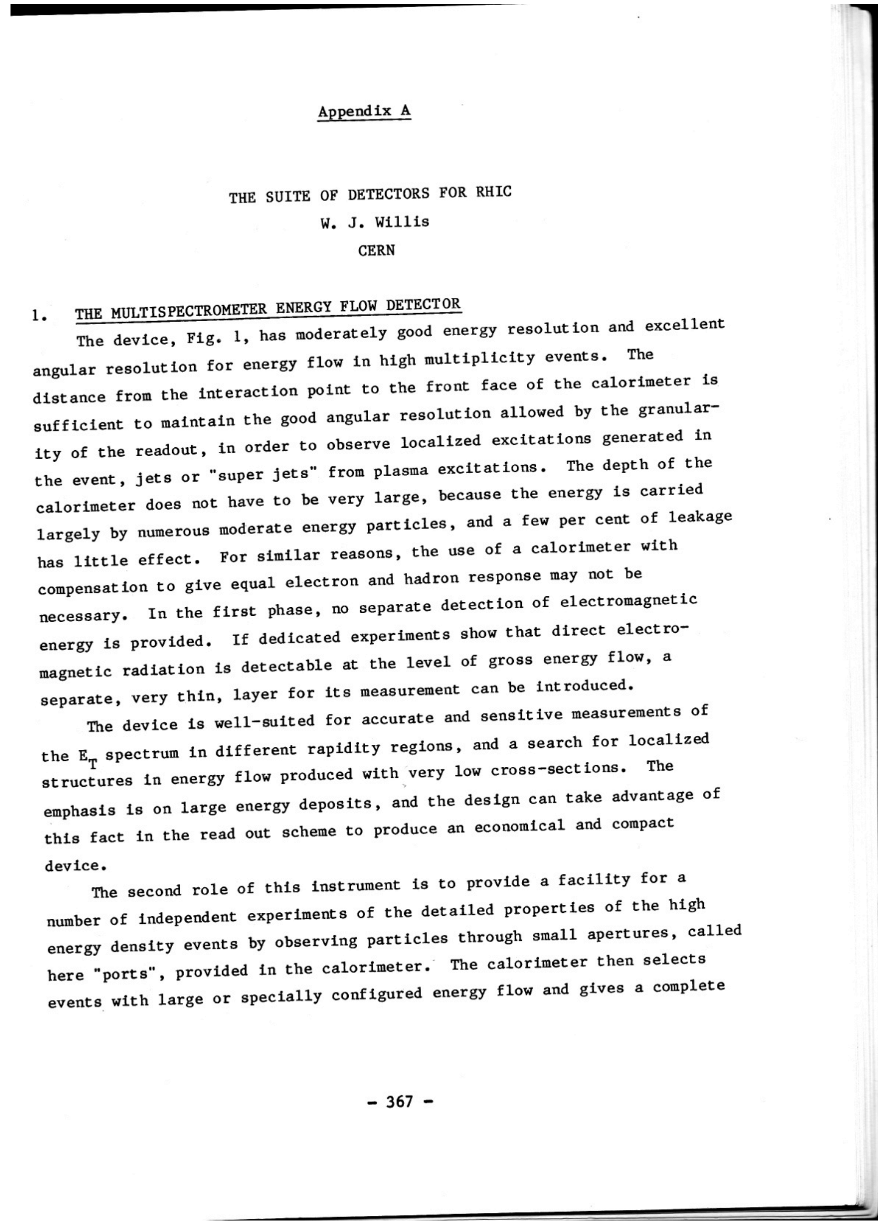
RHIC WORKSHOP

Experiments for a Relativistic Heavy Ion Collider

April 15-19, 1985

Edited by
P.E. Haustein and C.L. Woody

BROOKHAVEN NATIONAL LABORATORY
Upton, Long Island, New York 11973



Appendix A

THE SUITE OF DETECTORS FOR RHIC
W. J. Willis
CERN

1. THE MULTISPECTROMETER ENERGY FLOW DETECTOR

The device, Fig. 1, has moderately good energy resolution and excellent angular resolution for energy flow in high multiplicity events. The distance from the interaction point to the front face of the calorimeter is sufficient to maintain the good angular resolution allowed by the granularity of the readout, in order to observe localized excitations generated in the event, jets or "super jets" from plasma excitations. The depth of the calorimeter does not have to be very large, because the energy is carried largely by numerous moderate energy particles, and a few per cent of leakage has little effect. For similar reasons, the use of a calorimeter with compensation to give equal electron and hadron response may not be necessary. In the first phase, no separate detection of electromagnetic energy is provided. If dedicated experiments show that direct electromagnetic radiation is detectable at the level of gross energy flow, a separate, very thin, layer for its measurement can be introduced.

The device is well-suited for accurate and sensitive measurements of the E_T spectrum in different rapidity regions, and a search for localized structures in energy flow produced with very low cross-sections. The emphasis is on large energy deposits, and the design can take advantage of this fact in the read out scheme to produce an economical and compact device.

The second role of this instrument is to provide a facility for a number of independent experiments of the detailed properties of the high energy density events by observing particles through small apertures, called here "ports", provided in the calorimeter. The calorimeter then selects events with large or specially configured energy flow and gives a complete

- 367 -

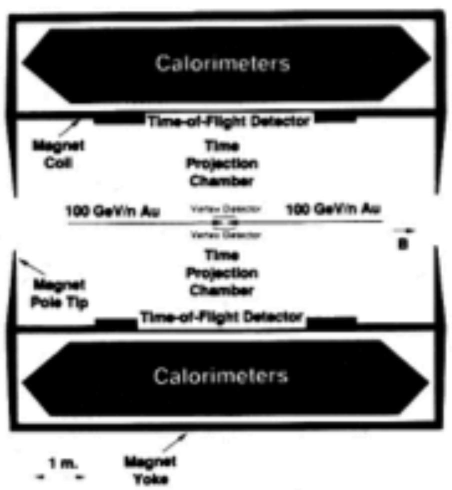
From Shoji Nagamiya

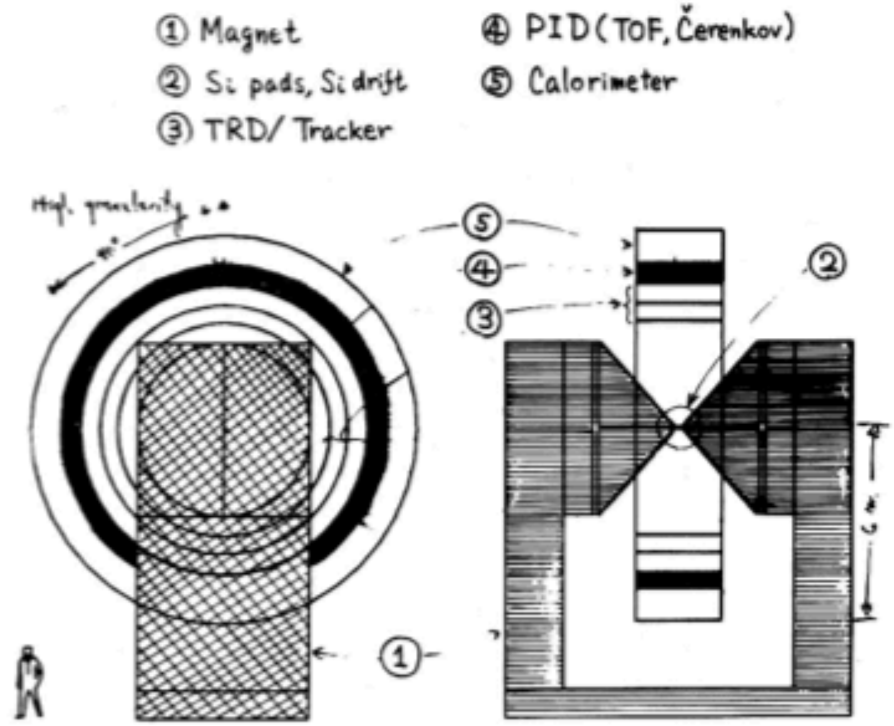
"(Bill) was deeply impressed by our technologies to resolve kaons from pions by having TOF resolution of about 70 ps. Therefore, he asked me to join the NA44 experiment and bring our technologies of high resolution TOF."

"I stayed at CERN for short time. There, I started to know Bill more in depth. For example, when we were talking, he suggested axial field arrangement for RHIC, since his design at ISR was based on the axial field magnet. I finally adopted this idea for both OASIS and later for PHENIX."

1990: Initial OASIS Design

Sketches from the Workshop: 3 New Detector Concepts





Left, large-acceptance detector for charged particles and jets, with a solenoidal magnet. Right, toroidal magnet spectrometer for large transverse momentum photons, charged particles and jets.

An "open focussing spectrometer", with axial field magnet.

1991: OASIS → RE2

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Office of the Director

September 9, 1991

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Dear Peter, Shoji and Glenn:

This is to confirm the discussion we had on Tuesday, September 3, 1991 regarding the decisions made by the Program Advisory Committee with respect to your RHIC Letters of Intent.

1. The Committee decided to reject all three of the Letters of Intent because of what were felt to be major deficiencies in each of them.

2. The Committee decided to place the emphasis on a detector designed to study electrons and photons emerging from the QGP. In this regard, it will address some of the basic physics interests of each of your groups.

3. The Laboratory has appointed Sam Aronson as Spokesman and Project Director with the charge of developing a new collaboration to design and build such a detector. We strongly urge each of you and your current respective collaborators to join in this effort. Those of you who are primarily interested in hadron physics will be welcomed by the STAR collaboration which has been empowered to build a large TPC detector.

4. The Laboratory is prepared to contribute at most $30 million to the design and construction of this detector. Hopefully, you can find resources outside of the Laboratory to augment this sum.

5. It is hoped that the new collaboration can present a conceptual design to the Technical Advisory Committee in mid December. Sam Aronson will have final authority as to the technical and scientific content of the proposal. He is in the process of forming an advisory committee composed primarily of the leadership of the three former collaborations to assist in the conceptual design.

Although I realize that each of you is very disappointed, I hope that you will find it possible to become a part of this effort. We need all of you in order to maximize our probability of success.

Sincerely,

Mel

Mel Schwartz
Associate Director
High Energy and Nuclear Physics

MS:laz
cc: HENP PAC Membership

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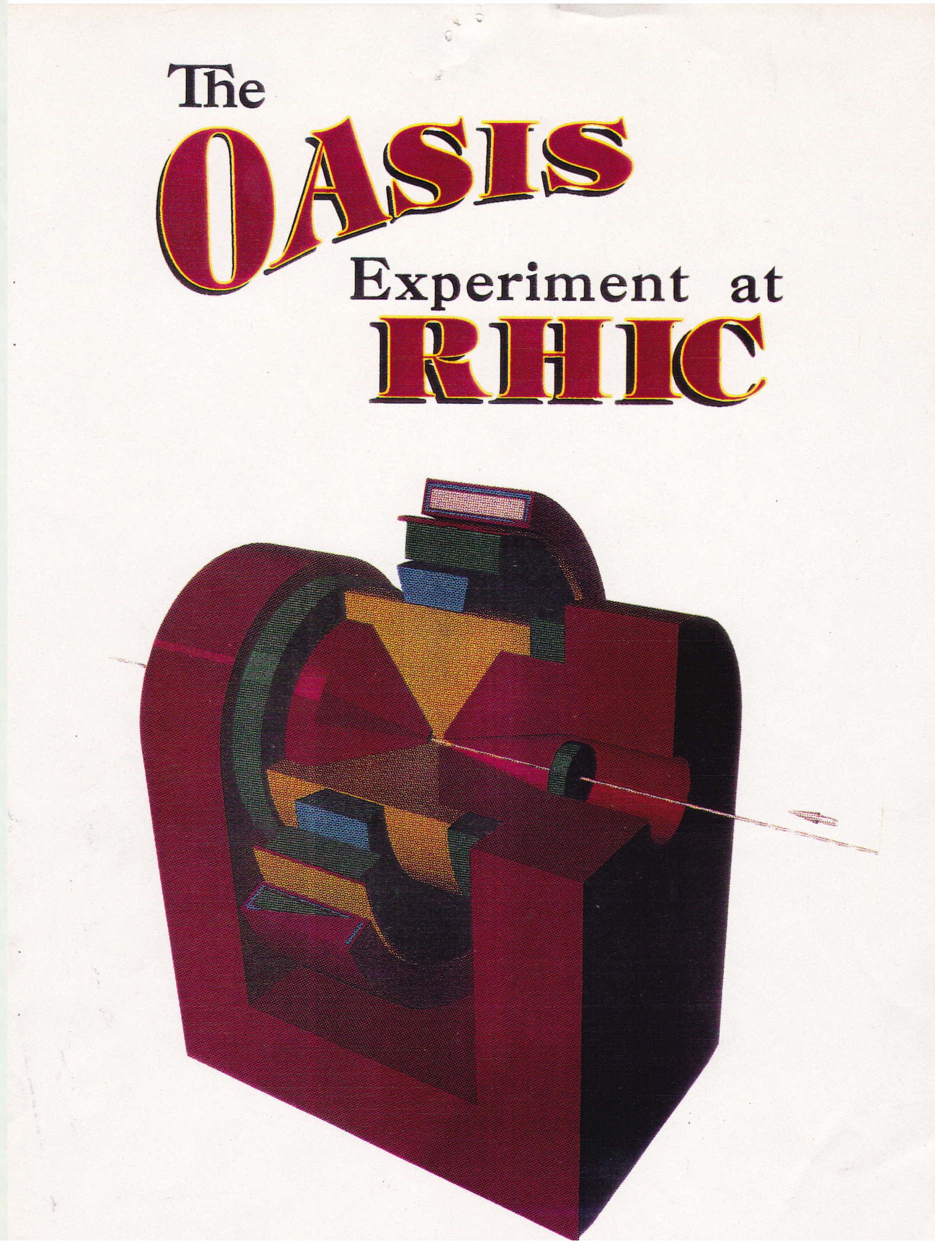
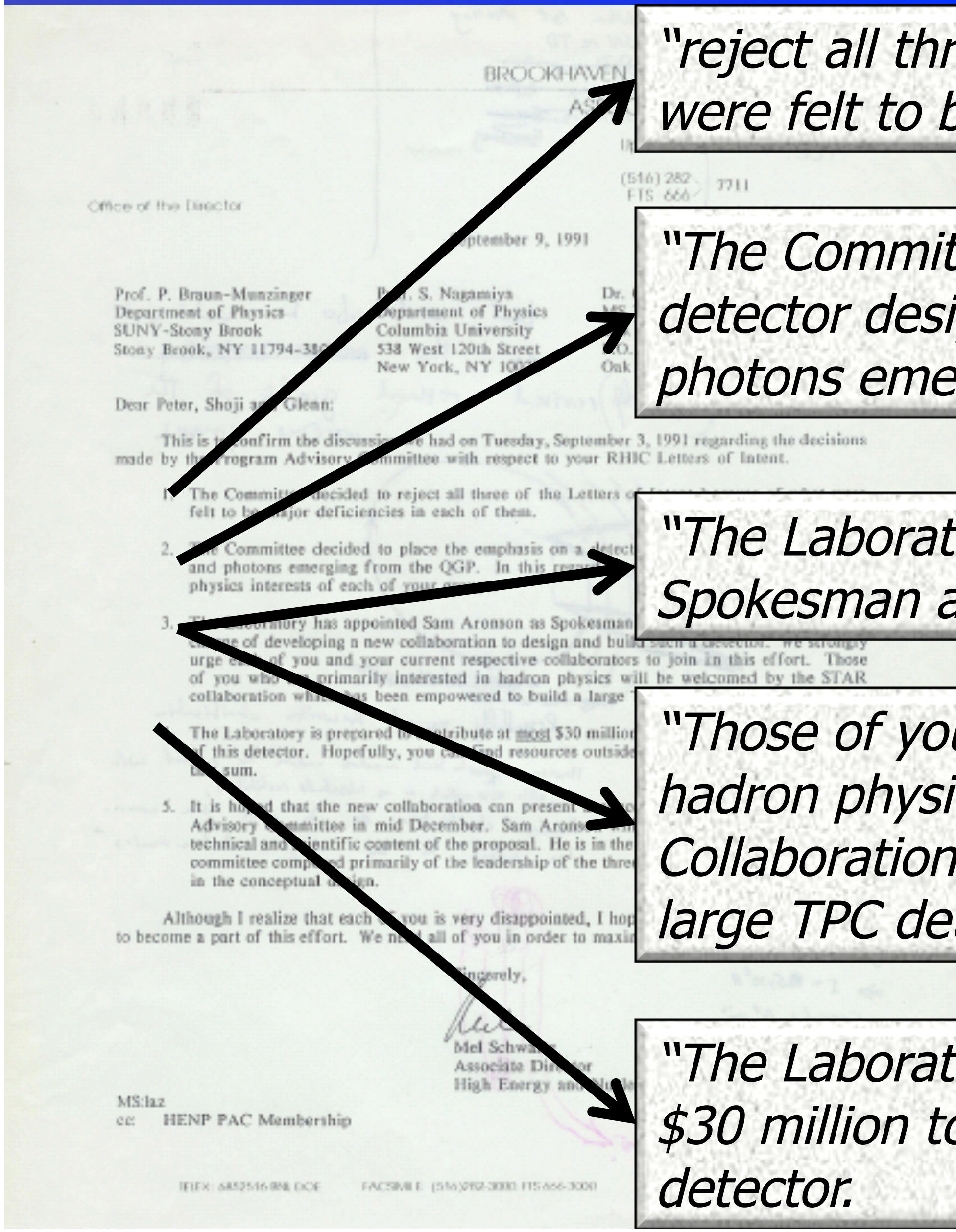


1991 Labor Day Massacre



"reject all three Letters of Intent because of what were felt to be major deficiencies in each of them."

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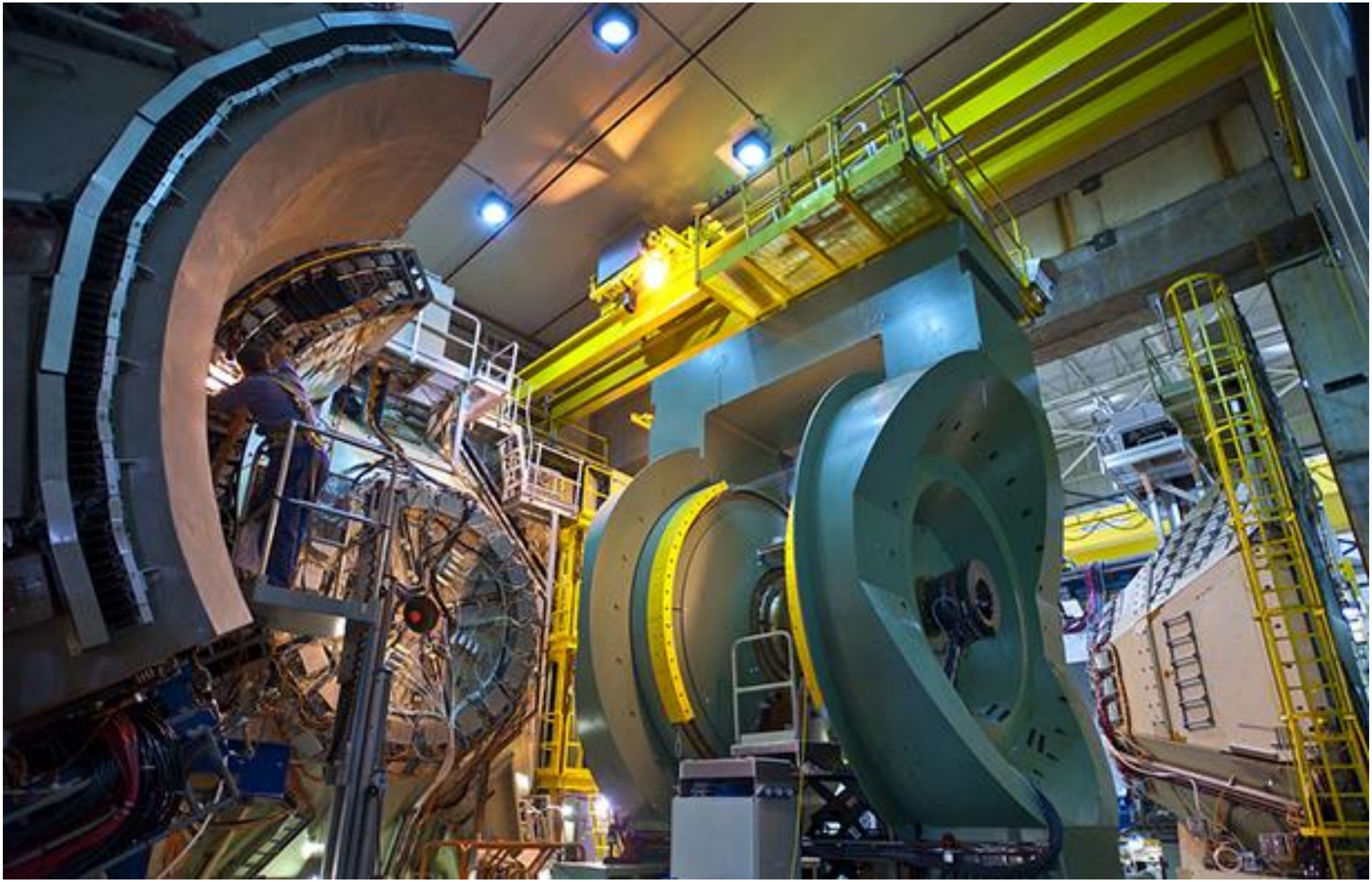
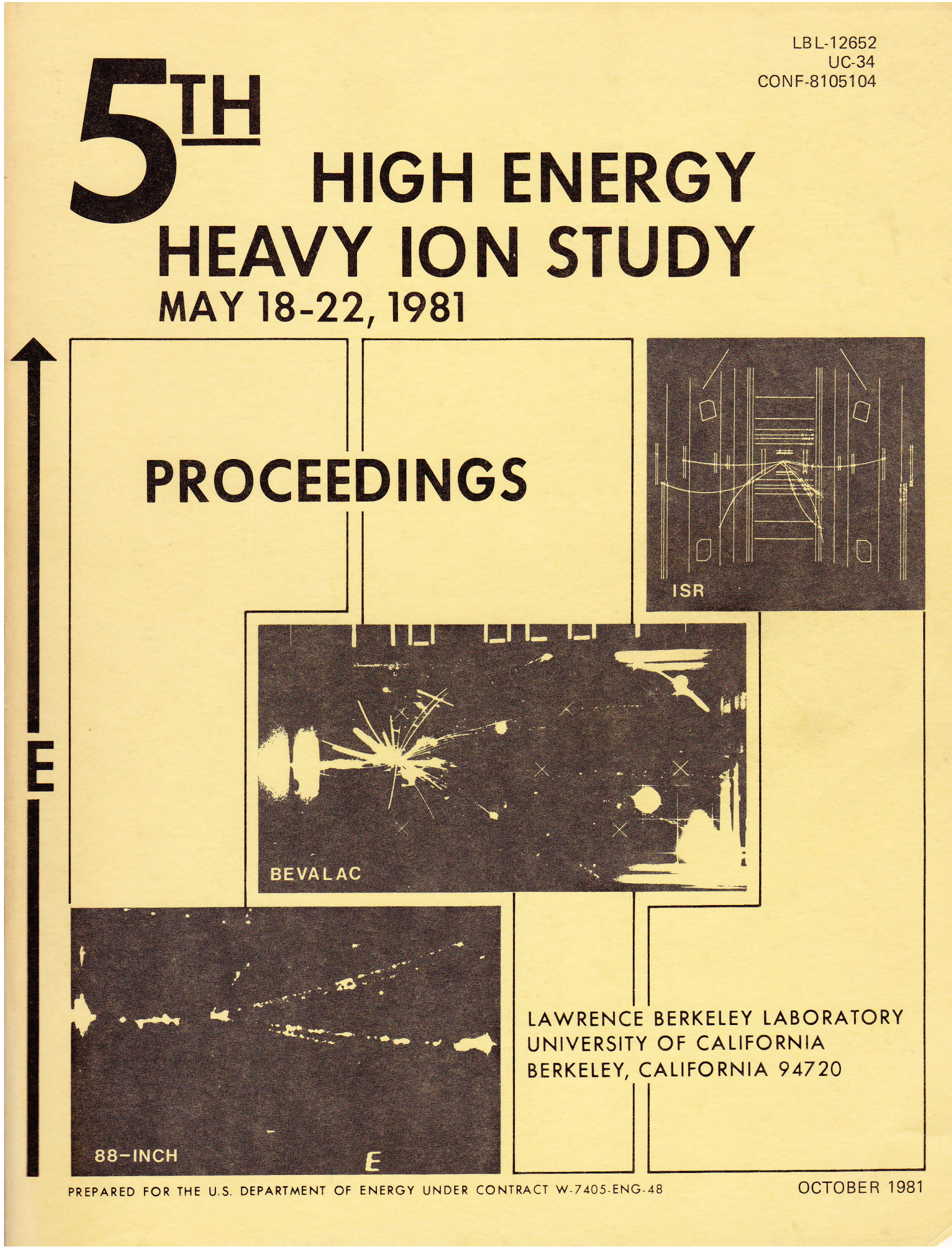
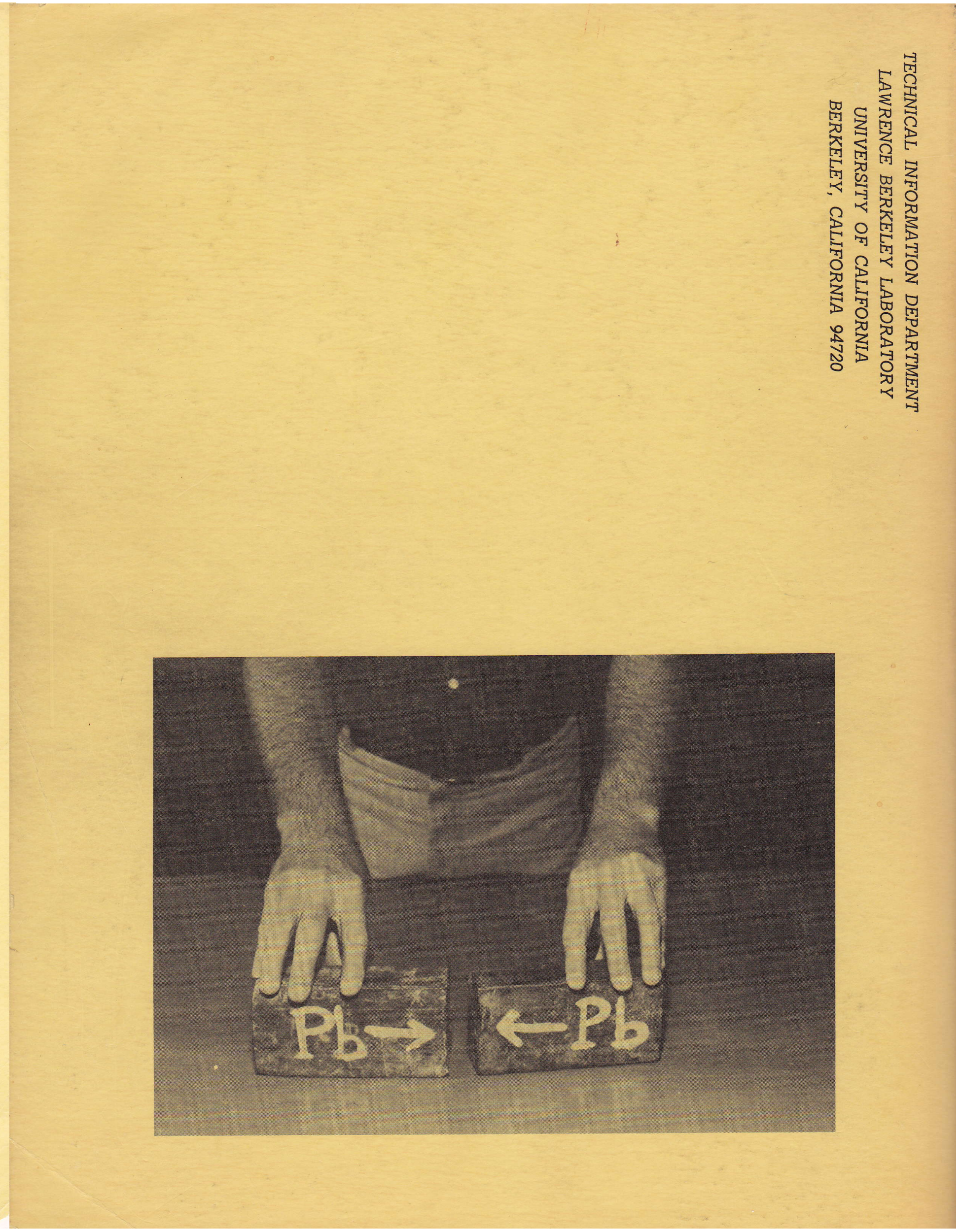
"The Laboratory is prepared to contributed at most $30 million to the design and construction of this detector.

RE2 → PHENIX → 120+ Publications

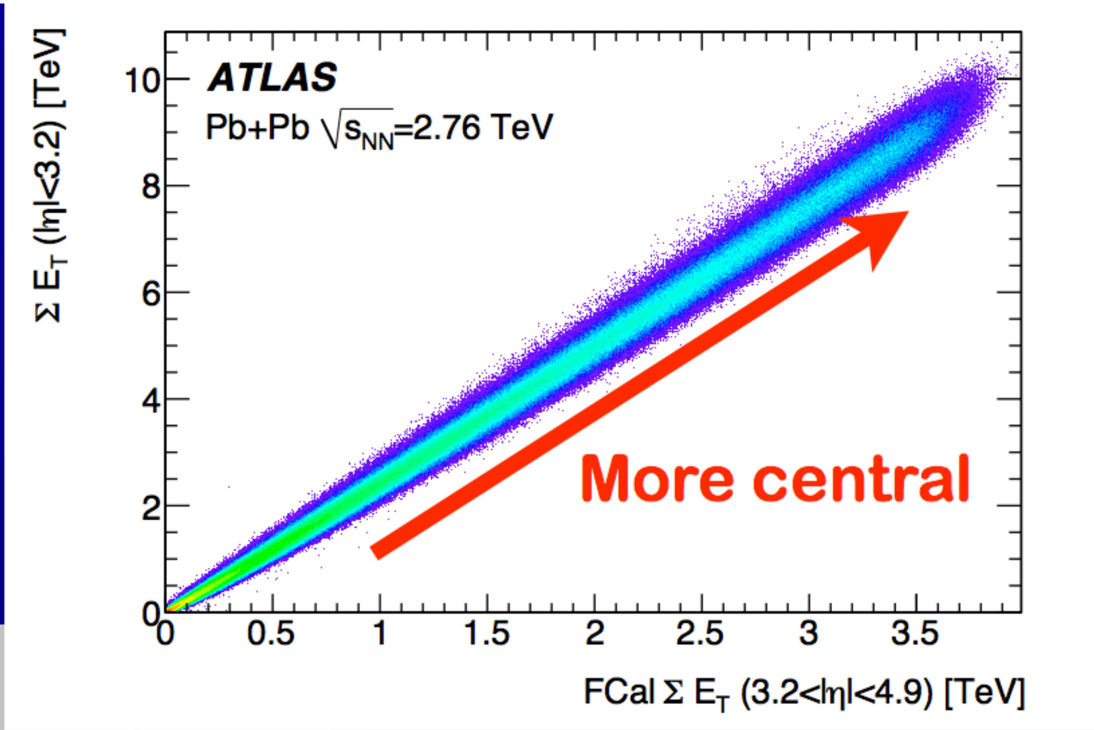


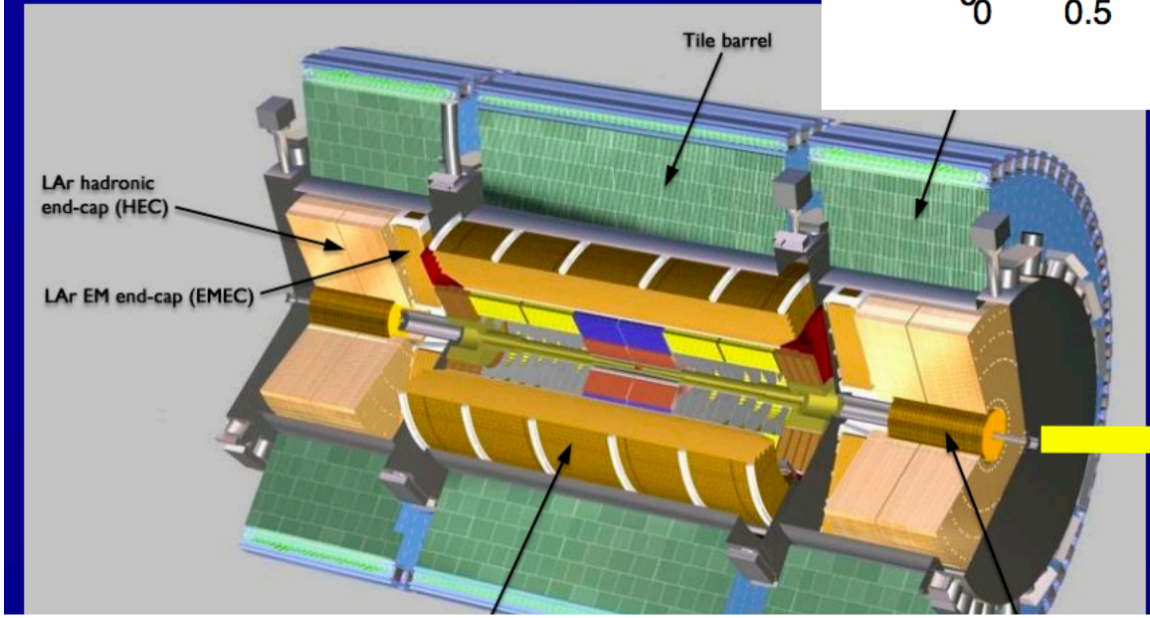
In The Beginning



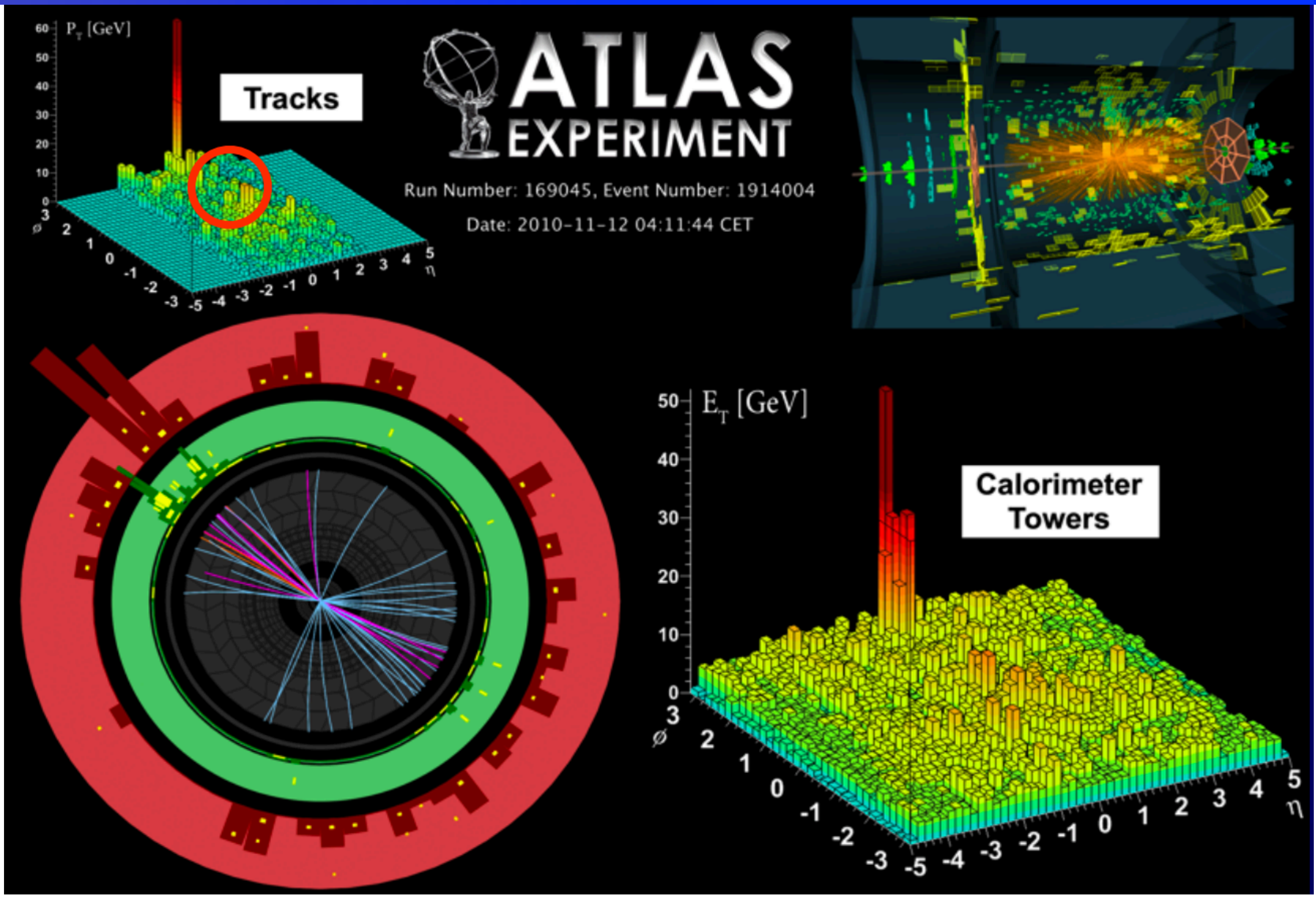


Liquid Argon over 10 units of η !



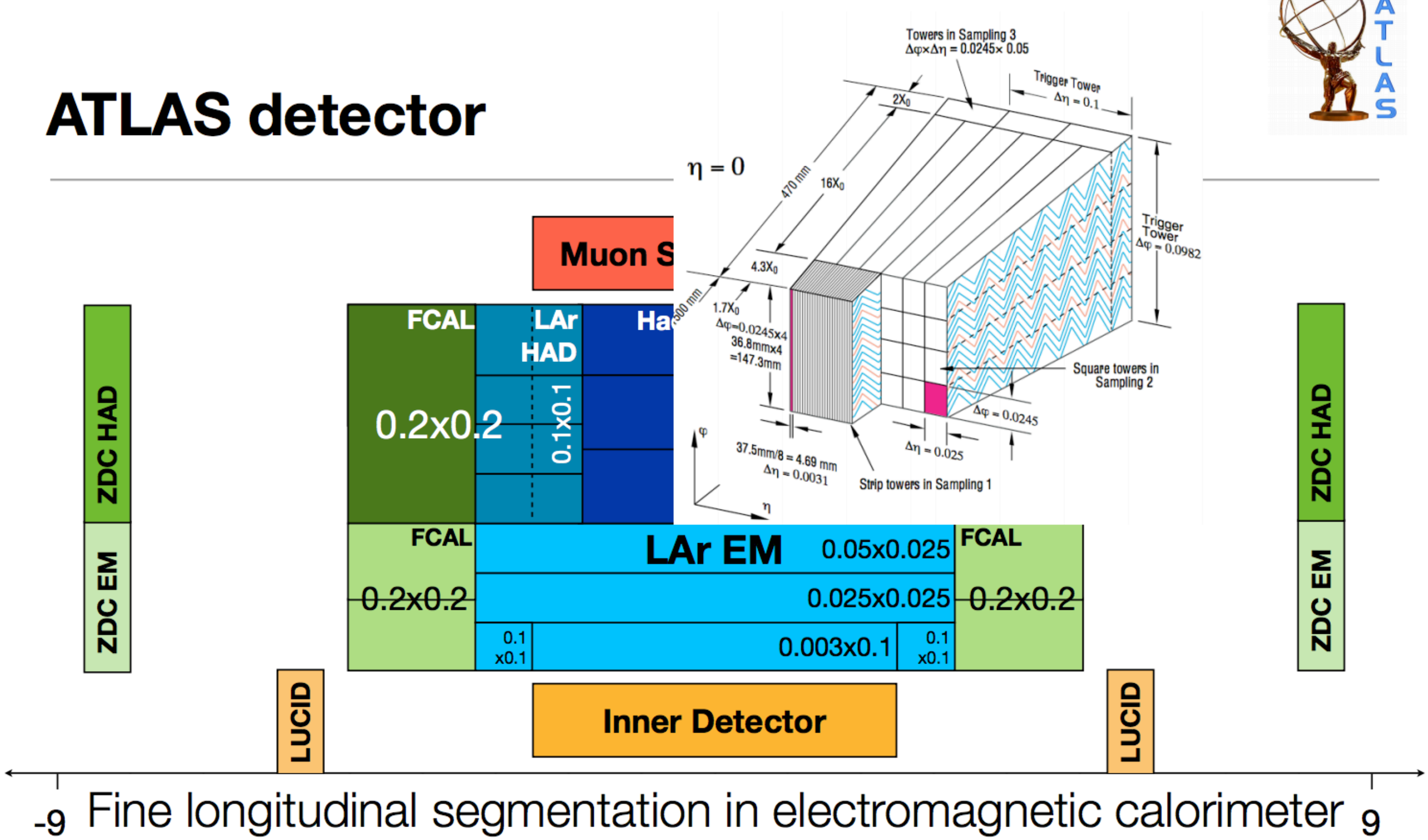


2010: Discovery of Jet Asymmetry



Bill’s Suggestion: Very Fine η Segmentation

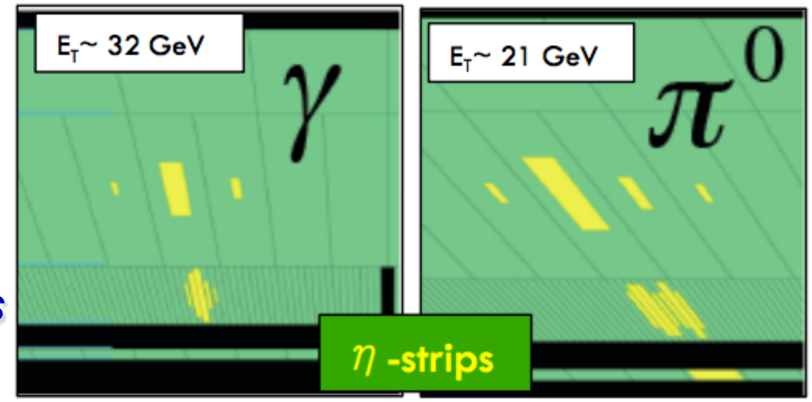
ATLAS detector



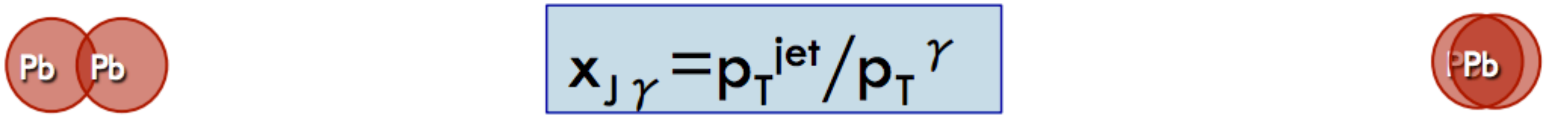
Fine longitudinal segmentation in electromagnetic calorimeter (|Δη|=0.0031) can distinguish direct photons from hadronic decay photons based on shower shape

Physics from Bill's Suggestion

- ATLAS Direct Photon measurements in Pb+Pb made possible by fine η strips:

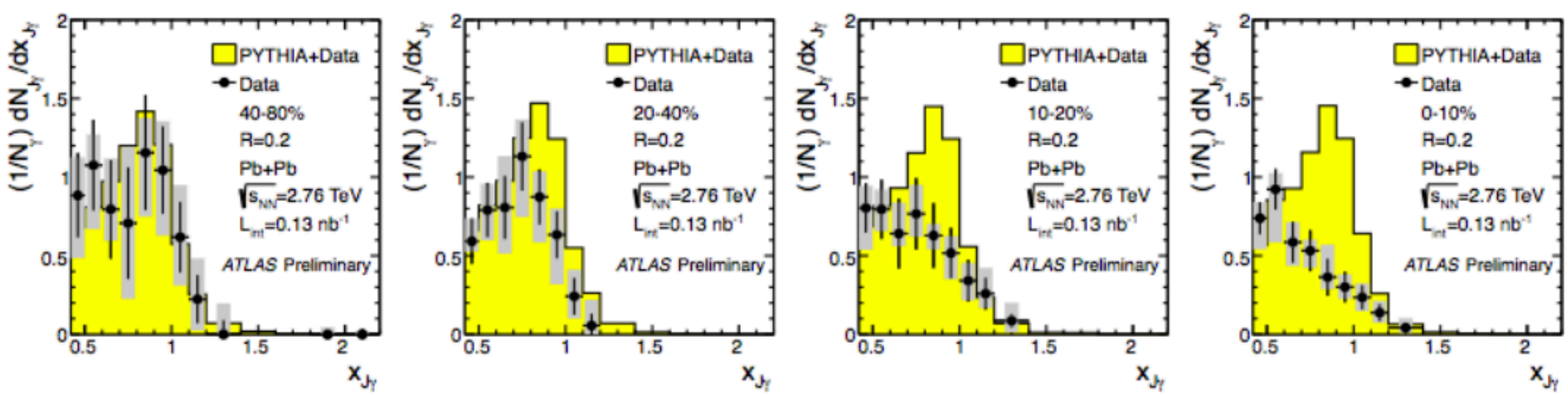


- Iwona Grabowska-Bold, *Isolated Direct Photons in Pb+Pb Collisions at 2.76 TeV,* QM2012
- Peter Steinberg, *Z and γ-jet Measurements in Pb+Pb Collisions in ATLAS*, QM2012



$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$

R=0.2



It Is A Pleasure To Acknowledge Our Intellectual Debt