NAL PROPOSAL No. 41

Correspondent: V. E. Barnes
Department of Physics
Purdue University
Lafayette, Indiana 47907

Phone: Lafayette 317

VERY HIGH ENERGY PROTON PROTON INTERACTIONS: EXPLORATORY SURVEY IN A BUBBLE CHAMBER

F. J. Loeffler, V. E. Barnes, D. D. Carmony, R. S. Christian,
J. A. Gaidos, A. F. Garfinkel, L. J. Gutay, S. Lichtman,
R. L. McIlwain, D. H. Miller, T. R. Palfrey, R. B. Willmann,
D. Cords, J. Lamsa, K. Paler, K. Rangan, J. H. Scharenguivel

June 8, 1970

NAL Proposal

Very High Energy Proton Proton Interactions:
Exploratory Survey in a Bubble Chamber.

Abstract

We propose a bubble chamber study of the general features of proton proton interactions in the 200 to 500 GeV energy range in as much detail as measuring accuracy permits, starting with charged particle multiplicities, transverse and longitudinal momentum distributions, and detailed measurement of particle systems originating from the target proton, and extending to an exploration of the possibility of doing some four-constraint or equivalent kinematic analysis of complete events. A scanning search for any new or exotic phenomena is an important part of this proposal.

We request 100,000 pictures initially in a 2 meter or 14 foot hydrogen bubble chamber, with 200 GeV or greater proton beam, $\Delta p/p \leq .1\%$, $\Delta\theta \leq 2$ mrad, and both tolerances better, if possible.

Purdue High Energy Physics Group

F. J. Loeffler, V. E. Barnes, D. D. Carmony, R. S. Christian, J. A. Gaidos, A. F. Garfinkel, L. J. Gutay, S. Lichtman, R. L. McIlwain, D. H. Miller, T. R. Palfrey, R. B. Willmann, D. Cords, J. Lamsa, K. Paler, K. Rangan, J. H. Scharenguivel.

Date: June 8, 1970

Correspondent:

Virgil E. Barnes

Department of Physics
Purdue University
Lafayette, Indiana 47907

NAL Proposal

Exploratory Survey of Very High Energy Proton Interactions in a Medium or Large Size Hydrogen **Bubble Chamber**.

The aim of this experiment is an exploratory bubble chamber study of a new energy region with several points of interest:

1) To study gross features of multi hundred GeV p-p interactions, such as charged particle multiplicities, longitudinal and transverse momentum distributions, strange to non-strange particle ratios, and possibly s-dependence of these phenomena.

2) To study in greater detail the "target cone" of particles which are slow in the laboratory.

3) To search for fractionally charged quarks in directly observable production events.

4) To search for any other new or unexpected phenomena in this new region of observation.

5) To explore the possibility of doing some four-constraint physics.

It is proposed to expose a medium sized (2 meters) or large (14 foot) hydrogen bubble chamber to a flux of protons at the highest available NAL energy. For the full program we have outlined, even the large chamber may not be sufficient in terms of track momentum and angle accuracy. However, if a smaller chamber were available at a substantially earlier date, near to the date when extracted beams are first available, we would be interested in doing whatever subset of the proposed aims remains feasible in the smaller chamber on an initial, exploratory basis.

An initial exposure of 100,000 pictures at full available energy is requested, to be followed by 100,000 pictures at one-half the energy, and/or by an extension of the original exposure to several hundred thousand pictures if warranted by results of the initial exploratory analysis. On the assumption that one would limit the fiducial volume for measured primary interactions to about a meter of beam track length, in order to maximize secondary track measurement accuracy, the initial exposure would correspond to about 4 events/μb for measurement, and to at least 8 events/μb for the scanning parts of the proposal. A high magnetic field in the bubble chamber would be desirable but not crucial to most of the analysis. The beam momentum spread expected in Area 2, $\Delta p/p \simeq 0.1\%$, should be adequate for most of the intended types of analysis.

The beam angles should be known externally to a tolerance of $\Delta\theta_B \leq 2$mrad, either from beam optics or possibly from a hodoscopic or wire plane array. This is both (a) to permit use of events occuring near the beam entry window (these are, of course, the best events from the point of view of measurable length of fast secondary tracks), and (b) to make possible adequate accuracy in the measurement of transverse momenta of individual secondary particle, for Peyrou plots and related distributions. (See Appendix A.) To achieve aim 5, the beam momentum and angle tolerances could profitably be improved by a factor of 10.

A fast beam kicker would be desirable to limit the number of tracks per picture to a preset minimum and maximum, and would probably be desired by most chamber users as a general facility.

Explanation of Proposed Physics

1) Cross Features

Relative and absolute cross sections for $p + p \rightarrow 2, 4, 6$, etc. charged tracks can be obtained quickly and accurately, and will constitute new information.

Longitudinal and transverse momenta can be determined sufficiently well to make meaningful Peyrou plots or similar distributions, at least for particles traveling backward in the center of mass. The stated tolerance $\Delta\theta_B \lesssim 2$ mrad, will permit an accuracy $\Delta p_T < 50$ MeV/c for such particles. By symmetry, this provides complete information about the forward cone on a statistical basis. Most forward-cone tracks will also be useful, although less accurate.

Certain strange particle production rates may be estimated by measuring and fitting V^o's from the backward cone and applying statistical assumptions regarding, for example, relative rates for producing K^+K^-, K_sK_s, K_LK_L;[1] and for ΛK_s, ΛK^+. Initially, obvious decays of charged and neutral strange particles can be noted in scanning. It is probably true to first order that charged decaying tracks represent $\Sigma^{\pm}$, so that some strange particle extimates are possible even before measurements are made.

2) Backward or "Target Cone" Measurements.

Here, and to some extent in the gross features, we can check some aspects of the many models and ideas about high energy processes, such as, among many others, the two (or three) fireball model,[2] the hypothesis of limiting fragmentation,[3] the related idea of diffraction dissociation,[4] multi-Regge models particularly in the application by Chan, Loskiewicz and Allison,[5] a model with small Q value decays of peripherally produced nucleon resonances[6] closely related in spirit to the fireball and limiting fragmentation ideas, and the Hagedorn-Ranft thermodynamic model.[7]

In terms of studying resonances, a general feature which we expect is the opening up of very low momentum transfers to higher mass nucleon isobars. At a beam energy of 200 GeV, $t_{min} = (M_x^2 - M_p^2) / 2p_{inc} = 0.02\ \mathrm{GeV}^2$ for a 3 GeV/c^2 resonance, well within the range where diffractive mechanisms are important. Since the cross section for Pomeron exchange tends to be constant, while meson exchange processes decrease as some inverse power of the beam momentum, diffractive production mechanisms may be very important at these energies.

In each event, some of the outgoing particles travel backward in the center of mass. Neglecting transverse momentum, the laboratory energy of these particles must be less than $m\gamma_{c.m.}$, i.e. less than 10 or 16 times the particle mass at 200 or 500 GeV. At 200 GeV the upper limit for pions is about 1.5 GeV and for protons about 10 GeV. Of course, most backward protons will be fast in the center of mass, and therefore considerably slower than 10 GeV in the laboratory. Multibody effective masses can be computed for these slow particles, without the benefit of kinematic fitting. Identifying protons will be a problem unless they are slow. Dark protons can be scanned for and measured as a special class. For nucleon resonances excited very peripherally from the target proton, all decay products, including the decay nucleon, will be slow in the laboratory. Decays into $p\pi^o$ and $n\pi^+$ will not be very useful, but decays into $p\pi^+$ and π^- are plentiful for some $N^{*\frac{1}{2}}$ resonances[8] and could be analyzed without kinematic fitting. Visible decays into ΛK^+, Σ^+K^o, $\Sigma^+(1385)$ K^o, Y^{*o} K^+, etc. will similarly be fully analyzable. V^o escape corrections will be small and the K^+ will usually be identifiable by ionization measurements, readily obtainable if the events are measured on the Purdue POLLY.

3) Quarks

In the production process $p + p \rightarrow p + p + q + \bar{q}$, the quark mass must have a value $M_q \leq \frac{1}{2}W^* - m_p$ where W^* is the total center of mass energy. At 200 GeV this maximum mass is about 9 GeV/c^2 and at 500 GeV the mass can be as large as 14 GeV/c^2. These masses and beam energies are well beyond the regions where production experiments have set upper limits on the (fractionally charged) quark production cross section.[9] While various cosmic ray quark searches have proved either inconclusive or negative,[10] the upper limits which have been set for the flux of fractionally charged particles can be related only indirectly to production cross section limits.[11] It is interesting to note that a recent observation of an isolated faint high momentum cosmic ray track in a bubble chamber,[12] while not very convincing, is consistent with a "quark" mass of around 8 ± 3 GeV/c^2 for charge 1/3 or less than 6.5 GeV/c^2 for charge 2/3.

We reiterate that the proposed exposure will provide orders of magnitude more p-p interactions in this energy range than have been directly studied in cosmic ray interactions. If quarks have fractional charge, more than one quark must be produced in a given reaction. We would then see an event with at least two faint tracks in conjunction with a beam track of known ionizing power. If the q-$\bar{q}$ system had a net charge of ±1, the event would also contain an odd number of charged secondaries and the two faint tracks would have different ionizing powers, 1/9 and 4/9 minimum. Such configurations would be rather convincing. Non-observation of such processes will imply a cross section upper limit of $\sim 1/4$ μb (see final section on event rates).

4.) New and Unexpected Phenomena:

It is a very obvious point, that the bubble chamber with its large visible volume and good spatial resolution is capable of revealing a wide class of unanticipated phenomena. And we are working in an essentially unexplored energy range where particles with a mass of 10 or 20 GeV can in principle be produced. Metastable particles with lifetimes comparable to K_s, Λ, Ω^-, etc. will tend to decay within the visible volume, and one-half of the time such particles will tend to be slow, allowing the possibility to determine mass from measurement of the decay products. Abnormally heavy metastables would have large decay angles relative to the momenta of the decay tracks, which could be noticed by the use of templates or even by eye. Of course, bizarre patterns such as V^o with charged decaying track, V^o decaying into four instead of two tracks, long charged decay sequences, etc., would be readily noticed, manifestly interesting, and admittedly unexpected. The bubble chamber is ideally suited to observing and analysing such multi-vertex events, a point cogently put by Lach.[13]

Magnetic monopoles, if produced, would necessarily occur in pairs and would be extremely heavily ionizing if they had the Dirac or Schwinger values of magnetic charge. Ruderman and Zwanziger have presented arguments suggesting that the monopole mass would be at least 10 GeB/c^2 and that energy greatly in excess of the rest mass may be required to permanently separate a monopole-antimonopole pair after production[14]. The pair might instead manifest itself indirectly in the form of a shower of some 10^2 "soft" photons having center of mass energy too low to have come from π^o decays. The authors cite a number of anomalous photon showers observed in high altitude emulsions, which are compatible with the above picture. In the bubble chamber, ~ 10 such photons would convert within 1 meter of the production vertex, would be well collimated forward, and would have low energy (<20 MeV) in the lab (see Appendix B). Such patterns will be scanned for.

5) Exploration of the Possibility of Some 4-Constraint Kinematic Fitting:

We realize that the prospect is marginal, at best, of achieving a clean separation of 4C events from those with missing neutrals[15], and of sorting out track-mass assignment ambiguities at these high energies. These questions have been extensively discussed in the 1968 and 1969 NAL Summer Studies. Clearly, how far we can go with this approach at 200 GeV, much less at 500 GeV, will depend critically on the size of chamber available, the effective setting error (including large and small scale distortions of various sorts), the magnetic field strength, external beam angle and momentum tolerances, and the measuring precision of the Purdue POLLY. We anticipate high accuracy from POLLY, and the extensive sampling of track coordinates will be important in making optimal use of the inherent accuracy of the bubble chamber. Bubble density information routinely available will aid in reducing mass ambiguities. It will be important at least to attempt such an analysis on a real sample of events, since the gedanken estimates to date depend on a number of assumptions.

Although certainly not the whole answer, external beam tolerances on both ($\Delta P/P$) and ($\Delta\theta$) approaching 10^{-4} would reduce beam energy and momentum uncertainty to the comfortable level of 50 MeV at the highest beam momentum. We do not wish to make this proposal contingent on beam-defining equipment. We are nontheless willing to argue for such a facility as a standard adjunct of any bubble chamber used for high energy. A passive system using beam optics

---

is clearly preferable, and is more likely to prove feasible for a proton beam.

Event Rates and Analysis Effort

Assume for the moment 12 tracks per picture, 1 meter long primary interaction fiducial volume for measuring, an exposure of 100,000 pictures, and $\sigma_t = 38$ mb total p-p cross section. We then have 40 feet of track per picture, 2×10^6 feet in all, or 4 events/μb. This is 160,000 events total, 1.6 events per picture within the fiducial volume. For strikingly unusual phenomena which could be noticed easily in most of the chamber, we have greater effective exposure, ~ 8 events/μb, even in a 2 meter chamber.

Scanning for charged multiplicities, obvious strange particle decays, and unusual phenomena could proceed at 200 frames per shift, 25 shifts, ~ 2 man-years. This is 1.8 minutes per picture, or one event to be dealt with per minute. A search for dark protons and other particularly analyzable event types to be measured could be included in this pass. Any conventional measurement of common event types could proceed by scanning while measuring, because of the high density of events. POLLY is projected to come on stream by early 1972, in time for the earliest bubble chamber pictures from NAL. With POLLY we expect to achieve automatic scanning and measuring, at least for single vertex events, at rates approaching 100 events per hour. Thus, even a rather complete analysis of the proposed 160,000 events could be achieved in less than ½ year of the measuring shop, full time equivalent.

The Purdue group is also submitting a 1,000,000 picture neutrino proposal and a 500,000 picture $\pi^- p$ proposal to NAL, in addition to proposals involving triggered hybrid spectrometer/visual systems. We feel that these commitments are well within the capability of the group, over the anticipated time scale. We currently have some 20 scanning and measuring personnel. POLLY is expected to increase our measuring capability from 200,000events/year to 500,000 event/year. We currently have 7 scanning machines in operation at Purdue in Lafayette and 2 scanning machines at Purdue in Indianapolis. This latter group has been in active collaboration with us for the past year.

The Purdue High Energy Group consists of Professors F. J. Loeffler, V. E. Barnes, D. D. Carmony, R. S. Christian, J. Gaidos, A. F. Garfinkel, L. J. Gutay, S. Lichtman, R. L. McIlwain, D. H. Miller, T. R. Palfrey, and R. B. Willmann, Doctors D. Cords, J. Lamsa, K. Paler, L. Rangan, and J. Scharenguivel; and several students. In addition Professors F. T. Meiere and W. L. Yen at Purdue Indianapolis campus collaborate with the group.

APPENDIX A

Tolerance on Uncertainty of the Beam Angles

To obtain meaningful transverse momentum distributions, the beam direction must be known to within some limit, since for fast tracks the dominant comtribution to ΔP_T is $P\Delta\theta$. Specifically, it is the direction of the fast secondary particle relative to the beam which gives the transverse momentum of that single particle: $P_T \cong P$ secondary $(\theta_S - \theta_B)$. This argument is not applicable to the overall transverse momentum balance of an event, where the formula

$$(\Delta P_T)^2 = (P_B \Delta \theta_B)^2 - \sum_i (P_i \Delta\theta_i)^2$$

is appropriate and the first term will often dominate the error.

Assuming a setting error of 75μ in space and 1 meter measured track length, secondaries above 10 GeV/c have $\Delta\theta_s \sim 0.3$ mrad, and multiple scattering is relatively negligible [16]. Given that $\langle P_T \rangle \gtrsim 320$ MeV/c [17] we would want to obtain an accuracy of better than 50 MeV/c in the measurement of P_T. For $\Delta\theta_B \sim \Delta\theta_s \sim 0.3$ mrad this corresponds to track momenta less than 120 GeV/c. Most tracks in the fast forward cone would also have P_T adequately measured under these conditions. Relaxing the tolerance to $\Delta\theta_B \sim 2$ mrad corresponds to a maximum momentum of 25 GeV/c, which will include all particles in the backward hemisphere in the center of mass.

All backward-moving particles in the center of mass must have a laboratory velocity less than the velocity of the center of mass, to the extent that small transverse momenta may be neglected. The laboratory energy of these particles is then less than $m\bar{\gamma} = 16.4$ m at 500 GeV/c. For known particles m is less than 1.67 GeV/c^2, giving 27 GeV/c as an extreme limit on the laboratory momentum of particles from the backward hemisphere.

APPENDIX B

Soft Photon Showers From Abortive Magnetic Monopole Pair Production

At 500 GeV the velocity of the overall center of mass corresponds to $\gamma = 16.4$, $\bar{\beta} = (1 - 0.002)$, and total center of mass energy 30.6 GeV. A monopole-antimonopole pair of total rest mass 20 GeV/c^2 will be essentially at rest in the C.M. A photon of C.M. angle θ^* and C.M. energy E will have laboratory angle and energy respectively given by:

$$\tan \theta_L = (1/\bar{\gamma}) \sin \theta^* / (\bar{\beta} - \cos \theta^*)$$

$$E_L = E\, \bar{\gamma}\, (1 - \bar{\beta} \cos \theta^*)$$

90^o in the C.M. then corresponds to $\theta_L = 3.5^o$ and $15o^0$ C.M. is 26^o Lab. E_L is within a factor 2 of $E\bar{\gamma}$ for most photons. Ruderman and Zwanziger(6) cite "photon energies orders of magnitude too low to have π^o decays as their source". We take 0.6 MeV as an upper limit in the C.M., yielding a maximum laboratory energy of 20 MeV.

In addition to these bremsstrahlung photons, some annihilation products would have to be present to carry away the rest mass energy, possibly a pair of very hard photons. They would also tend to be forward collimated in the laboratory. In 1 or 2 meters of Hydrogen there would be a 20% to 40% chance of converting at least one of the hard photons.

REFERENCES

1.) J. W. Waters, W. D. Walker, A. R. Erwin and J. W. Elbert, Nuclear Physics B17, 445 (1970)

2.) For a recent model using both fireball and Regge ideas, and designed particularly for the 200 GeV region, see: R. Rajaraman, Phys. Rev. 1 D, 118 (1970)

3.) J. Benecke, T. T. Chou, C. N. Yang, and E. Yen, Phys. Rev. 188, 2159 (1969)

4.) M. L. Good and W. D. Walker, Phys. Rev. 120, 1857 (1960)

5.) Chan Hong-Mo, J. Loskiewicz, and W. W. M. Allison, Nuovo Cimento 57A, 93 (1968)

6.) E. Yen and E. L. Berger, Phys. Rev. Letters 24, 695 (1970)

7.) R. Hagedorn and J. Ranft, Suppl. Nuovo Cim. 6 169 (1968)

8.) V. E. Barnes, D. Bassano, S. U. Chung, R. L. Eisner, E. Flaminio, J. B. Kinson, and N. P. Samios, Phys. Rev. Letters 23 1516 (1969)

9.) Yu. M. Antipov, et. al., Phys. Letters 29B, 576 (1969)

10.) R. K. Adair and H. Kasha, Phys. Rev. Letters 23, 1355 (1969)

R. Gomez, H. Kobrak, A. Moline, J. Mullins, C. Orth, J. Van Puttan, and G. Zweig, Phys. Rev. Letters 18, 1022 (1967)

H. Kasha, R. C. Larsen, L. B. Leipuner, and R. K. Adair, Phys. Rev. Letters 20, 217 (1968)

11.) For example, quarks might be expected to remain in the cores of extensive air showers, where detecting devices will saturate and become ineffective. This and other reasons may be invited to explain non-observation of quarks in cosmic ray searches to date.

12.) W. T. Chu, S. Kim, W. J. Beam, and Kwak, Phys. Rev. Letters 24, 917 (1970)

13.) J. Lach, NAL 1969 Summer Study-Volume 2, P. 23

14.) M. Ruderman and D. Zwanziger, Phys. Rev. Letters 22, 146 (1969)

15.) M. Derrick, T. O'Halloran and R. Kraemer, NAL 1968 Summer Study, Volume 1, pp47 - 94

16.) Error formulae are taken from: D. Miller, NAL 1969 Summer Study, Volume 2, p. 39,

17.) N. Gelfand, A. Pevsner, and P. Slattery, NAL 1969 Summer Study, Volume 2, pp. 281 - 311