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Search for Strangelets and Free Quarks in Pb-Pb Collisions.

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1. Introduction.

In 1994, ultrarelativistic heavy ion beams will become available at the CERN SPS. The upgraded NA38 experiment will study dimuon spectra at the remarkable rate of 10^7 interactions per burst, i.e. $5\ 10^7$ Pb ions, nearly the total expected SPS beam flux, impinging on a 1 cm Pb target.

It is our intention to put this exceptional luminosity to use for a fully parasitic search for forward produced exotic particles. We expect the acceptance and the background conditions to be such that a sensitivity not far from the maximum one corresponding to the available luminosity can be reached. We also intend not to hamper in any way the experimental conditions for the main goal of the NA38 experiment, the study of the neutral vector mesons.

The upgraded NA38 layout will have a central, evacuated conical hole (see forthcoming Proposal), whose primary purpose will be to accommodate a Zero Degree Calorimeter (ZDC) which will provide an improved characterization of the dimuon events. A careful collimation is needed in order to limit the background in the muon spectrometer chambers. The beam, the beam fragments, and the particles produced at angles less than the 8 mrad subtended by the central hole of the toroidal magnet, will exit the NA38 layout. The charged particles will be bent away by a strong dipole magnet. A solid angle free of ordinary particles, also called the "region of unphysical momenta", is thus provided in between the neutral particles and the negative pions of maximum momentum. In this region, shown in Fig. 1, the wanted high sensitivity can be achieved for particles of magnetic rigidity -P/Z above 160 GeV/c.

If formed, both Strangelets and Free Quarks of charge -1/3 have a reasonable probability to be emitted at the corresponding small angles and large rigidities, and are therefore the prime objectives of the envisaged high luminosity search. Strangelets are small lumps of Strange Matter (SM) made of comparable amounts of u, d and s quarks contained in a single bag. We discuss the physics of the Strangelet in Section 2 and its detection and identification in Section 3. Section 4 is devoted to the Free Quarks. Strangelets and Free Quarks share three remarkable properties: their discovery is exceedingly improbable; the discovery of either would have a dramatic impact; and they both appear to be absolute signatures of the Quark-Gluon Plasma (QGP).

No other potentially interesting objects appear to be natural candidates of this type of high luminosity search. In particular, the antinuclei, whose production rate is thought to be an efficient indicator of QGP, are expected to be buried amidst the produced π^-; this holds even for antitritons, which reach the highest magnetic rigidity. We will not discuss these topics further.

Section 5 describes a possible layout, which achieves the wanted selectivity using relatively conventional detectors of modest size, and a trigger scheme. The trigger must be highly selective, since we intend to make full use of the available luminosity, without reducing the data acquisition rate of the dimuon experiment. Section 6 describes some aspects of the coexistence of the two experiments. The ZDC will have its operating conditions altered by the bending magnet. On the other side, the space left behind the present location of NA38 is rather limited, and the pro's and con's of a possible upstream move are discussed.

In Section 7, we conclude, and state our interest in finding new collaborators in view of preparing a Proposal.

2. The Physics of Strangelets.

E. WITTEN formulated back in 1984 the extravagant hypothesis that Strange Matter (i.e. matter formed by comparable amounts of u, d and s quarks) rather than Fe^{56} might be the ground state of matter [WIT84]. Strange Matter (SM) would come in bags clearly heavier than a single lambda, but neutral enough not to be limited in size by the Coulomb barrier. The Aarhus Workshop (May 20-24, 1991) came to the even more extravagant conclusion that this hypothesis has not been scathed by 7 years of intense and combined effort of cosmologists, astrophysicists and hunters of exotica ([MAD91; see also [ALC88]). Cosmologists tend to believe that primordial SM was either not formed in the early universe, or could not survive, basically because the quark-gluon world hadronized at a temperature above 100 MeV, while SM is stable only at temperatures below a few MeV. Astrophysicists still ponder whether some or all neutron stars might in fact be strange stars. And the lack of evidence from searches in bulk matter and in cosmic rays is contrasted by the two events recently found by T. Saito et al. [SAI90] in a balloon-borne counter experiment. Both have $A \geq 110$ and $Z = 14$. The latter value could be taken to indicate the charge of the lightest absolutely stable strangelet. [Lighter strangelets may be metastable, i.e. decay by weak interactions. Metastable SM had been conjectured even before 1984.]

Heavy ion collisions open a unique possibility for creation of strange matter in the laboratory [LIU84], [GRE87], [GRE88], [SHA89]. The arguments against SM formation in the early Universe do not apply here. But the production may be exceedingly small even if SM exists, since it requires a rather unusual succession of necessary conditions:

- formation of a baryon-rich quark-gluon plasma (a QGP containing more quarks than antiquarks);

- cooling by K^+ and K^0 emission, leading to an excess of u, d and s quarks over antiquarks;
- further cooling by photon emission, down to $T \sim 2$ MeV where strange matter becomes stable against boiling and evaporation.

The QGP is most likely to form near y=0, where pion production peaks (with a standard deviation $\sigma_y \approx 1.4$), and where the energy density is therefore highest. The traditional view, borne out by most models, e.g. FRITIOF, assumed that the colliding nuclei would loose no more than 1-2 units of rapidity, and that the central region would therefore be baryon-free, disfavouring somewhat our first condition. As Fig. 2 shows, recent NA35 data [STR91] lend more credit to the Frankfurt model (RQMD, [SOR91], [KEI91]), which naturally reproduces the flat baryon distribution found in central S-S collisions. For central Pb-Pb collisions at 160 A GeV, RQMD foresees that the baryon number peaks at $y = 0$, with a FWHM width of 3 rapidity units. *We assume in the following that the chances to form a baryon-rich QGP are best near $y=0$.*

A strangelet produced at the SPS would have the following properties:

- $<p_L> = 10 \cdot A$ GeV/c if produced at mid-rapidity ($\gamma = 10$);
- $<p_T> = (0.5 \div 0.9) \cdot \sqrt{A}$ GeV/c, possibly less if only selective cooling were to lead to strangelet formation;
- average production angles would therefore be rather small, of order 10 mrad for, say, $A = 25$;
- $<p^2_{L,c.m.}> = 6 \cdot A\ (\mathrm{GeV}/c)^2$, a random-walk parametrization which is compatible with the RQMD baryon production when $A = 1$, and is used to estimate the decreasing widths in y for Strangelets of increasing A (see Fig. 4a);
- a certain range of Z values clustering around $0.2 \cdot A$ [BER87], or even slightly negative Z, in the Frankfurt model, in which cooling proceeds both via K and nucleon emission [GRE91];
- formation probabilities have been estimated by Crawford et al. [CRA91] to be of order 10^{-6} per "isotope" for $Z = -1$, A between 15 and 30; here, QGP formation is postulated and a coalescence model tuned to reproduce nucleus and antinucleus formation is used;
- finally, the last two quoted models [GRE91], [CRA91] both give $10<A<30$ as the most likely range of strangelet sizes accessible in central Pb-Pb reactions.

3. Strangelets: Detectors.

Two strangelet search experiments have been approved recently at the AGS (E-864, J. Sandweiss et al.; and E-878, H.J. Crawford et al.). A search for neutral heavy objects including strangelets at the SPS is still under debate, after the recent withdrawal of Proposal P259 (K. Pretzl et al.).

Our goal is to search for charged strangelets at SPS energy, where QGP formation is more likely to occur than at the AGS. The setup must be highly selective to use effectively the huge available luminosity, by minimizing the background and identifying unambiguously the wanted objects of small Z, large A, provided their proper lifetimes exceed 10^{-8} sec. The detectors will be located well after the dipole magnet and keep clear of the region traversed by the beam and the beam fragments. The Lorentz factor γ and the total energy $\gamma \cdot A$ will both be measured twice, by independent detectors, namely (see also Fig. 3):

- scintillators SC to measure Z^2 and time-of-flight (TOF) to ±50 psec, so that a particle of $\gamma = 17$ will differ by 3 s.d. from a $\beta = 1$ particle (±100 psec were achieved under NA38 conditions; we will double the accuracy by using 4 already existing START counters, and 4 STOP scintillator hodoscopes SC);
- a high pressure threshold Cerenkov counter (threshold counter HPC or RICH) with threshold at $\gamma = 17$ and a measurement range extending to $\gamma = 27$ for the HPC or to $\gamma = 39$ in RICH alternative;
- proportional chambers (PC) for tracking, to reject those tracks which point back towards e.g. the pole pieces of the magnet, and to yield the bending angle and, hence, $Z/(A \cdot \gamma)$ for the particles coming from the target;
- a hadronic calorimeter HCAL which will measure $A \cdot \gamma$.

(The γ ranges vary when the length of the setup is changed). The agreement between the two $A \cdot \gamma$ measurements checks that the detected particle came from the target. The two γ measurements cover different γ ranges, but their efficiencies combine if a $\beta = 1$ background dominates.

4. Free Quarks.

The idea and the theory of confinement are based on the fact that no free quarks have been found so far. Confinement could be broken in the framework of higher symmetries. Theories with free quarks or diquarks have been described [RUJ78], [SLA81]. The confining potential has however been checked over several fermi, in particular by hadron trajectories and quarkonium spectroscopy. Heavy Ion collisions open a new window for free quark search in the following sense: When a QGP of the size of, say, colliding Pb nuclei hadronizes, some q and $\bar{q}$ could be left behind at distances where they do not feel/find each other any more.

There are basically two ways to perform a quark search in a heavy ion beam: looking by electronic means for objects of $Z^2 < 1$, in the "region of non-physical momenta" where the background conditions are favourable; or analyzing bulk material after it has been exposed to the beam. The latter method was applied by NA39 in the NA38 beam in 1986/87 [CAL89]. At least two modern tools for quark search in bulk matter are being developed (G. Shaw, private communication; R. Battiston, private communication). In all cases, an old remark by A. de Rújula still holds: being produced in a thick target, quarks would emerge after having swallowed nucleons, as proto-nuclear objects whose (non-integral) charge would most often be large, and whose range would be short.

While we hope that a quark search in bulk matter will eventually materialize in a proposal, we also intend to study the background-free region described above using the Z^2 measurement device, based on 4 or more layers of scintillators, in view of a high sensitivity search for $Z = -1/3$ quarks of momentum $p > 55$ GeV/c. The y distribution of quarks is rather wide, primordial $< p_T >$'s are small, and the free quark masses are expected to be well above the proton mass. The probability for a free quark to enter the high sensitivity region is therefore reasonable, provided it retains its $Z = -1/3$ charge.

5. Layout, Acceptance and Trigger.

Fig. 3 shows a schematic layout, which encompasses the goals outlined above. Its components have been described at the end of Section 3.

We have computed the acceptances first as a function of rapidity for strangelets of various masses (Fig. 4b) and for two magnetic field integrals. The convention was to accept a particle if it kept clear of the photon trajectories on one side, and of π^-'s of 140 GeV on the other, both in the Cerenkov counter and in the Calorimeter. In fact, if the lower rigidity cut were loosened down to 100 GeV, 5 events out of 6 would still be background free (as can be deduced from Fig. 1), and the acceptance for light Strangelets would improve.

The useful ranges of the γ measurement are indicated for the time-of-flight measurement by the multiple scintillator hodoscopes SC, and by the two Cerenkov alternatives under study, both pressurized to achieve a threshold γ as low as 17: the threshold counter HPC, and the RICH, for which pressure is a major complication.

The acceptances were then averaged over y using the Strangelet rapidity distributions exemplified in Fig. 4a. Results are shown in Fig. 5 for various magnets and for Strangelets of charge -1 and -2, as function of their mass number A, and requiring γ measurement using the two detector configurations, namely the HPC option (solid and dashed lines), and the RICH option (dotted lines). The RICH would improve the acceptance mainly for very low Strangelet masses ($A \leq 10$).

The trigger rate is limited by the requirement that it should not decrease the Dimuon acquisition rate. We need therefore both a highly selective trigger, and options to make it even more selective in the event of unforeseen backgrounds. The first level trigger will be given by a central Pb-Pb collision (signal supplied by the Dimuon logics) plus a charged track in the background free region. The second level trigger could be an OR of three conditions: at least 200 GeV in the hadron calorimeter or a TOF excluding $\beta = 1$ particles, signalling a minimal Strangelet, or a sum of pulse heights in the scintillators well below a minimum ionizing particle, the main Free Quark signal. The third level is given by the requirement that the track extrapolates back to the dipole magnet gap, rather than to pole pieces or collimators. The cuts in hadronic energy, time-of-flight and ionization can be fine tuned, if necessary.

6. Coexistence with the Dimuon Experiment.

We deal first with the two main constraints imposed by the NA38 layout as it stands on the envisaged Particle Search: the angular acceptance, limited to 8 mrad by the central hole of the muon spectrometer magnet; and the free space beyond the last NA38 detector (the hodoscope R4) which is only 20 m deep. Using the procedure outlined in the previous Section, we have found that the angular constraint reduces the acceptance by a factor of 2.1÷4.4 for the $<p_T>$ range given in Section 2. Lengthening the available space would increase the acceptance by a factor between 2.6 (for $A \approx 20$) and 3 (for $A = 10$ or 40), as shown in Fig. 4c and Fig. 5. It is in principle possible to move the NA38 experiment upstream by up to 50 m. This would however either require a lot of work of the most tedious and risky kind, if the electronics and the cables were also moved, or involve the risk of deteriorating the timing of the experiment, if the cables were lengthened. The experiment appears to be competitive even with the present layout. We would however use the forthcoming long shutdown to move the NA38 setup by the few meters compatible with existing supports and cables (as has been assumed in the acceptance calculations and in Fig. 3). Next, we discuss the coexistence with the ZDC, which is to be built for the Pb beam experiment, and which will be the only NA38 detector directly concerned by the Particle Search. This detector will act as a beam stop, and therefore as a major source of background. It will be best to bury it in a hole to be drilled in the wall. Hole dimensions of, say, 1 m diameter and 4 m depth should be adequate.

On the other hand, the ZDC will see the charged particles displaced by the field of the bending magnet. This may well turn out to be a substantial bonus, rather than a nuisance. Indeed, a ZDC without sweeping magnet needs to be preceded by a collimator which is always a source of trouble, and never fulfills well its purpose of recording the beam and all beam fragments but not the reaction products. The magnet will instead sweep the reaction products clear of an appropriately sized ZDC, which will instead see all charged beam fragments. The neutral particles need a special treatment: the γ's must be absorbed in a Pb block in front of the ZDC; the forward K^0's are the only reaction products which are seen by the ZDC and must be corrected for.

7. Conclusions.

We have expressed our wish to embark in a high sensitivity search of exotic particles, centered on strangelets and free quarks. The experiment would be done parasitically, using the high luminosity used by the NA38 dimuon study. The search would focus on the essentially background-free region between the neutral particles around 0 degrees, and the charged reaction products sweeped away by a strong dipole magnet. The experiment should find strangelets of small and negative charge and of suitable mass A and lifetime if their production rate exceeds 10^{-10} – 10^{-11} per Pb-Pb interaction, provided that the assumption of harmless background from secondary interactions of the primary reaction products is confirmed by the GEANT simulations which are now under way. This sensitivity corresponds to 1 - 10 detected events per "isotope" of given A and Z, in 100 days of beam time. A similar sensitivity is expected for a free, bare quark of charge $Z = -1/3$. The price to pay for the symbiosis with NA38 is at worst a factor 10 loss in acceptance when compared to an ideal stand-alone experiment relying on unrestricted means; the reward being an unsurpassable luminosity.

This search requires the construction of a number of detectors which are modest in size, non-trivial, and at the limit of the present state of the art. Also, the trigger requires an elaborate processor for track recognition and reconstruction. The arising work as well as the foreseeable running and analysis load are beyond the capabilities of the present NA38 collaboration. *We are looking* therefore *for new collaborators.*

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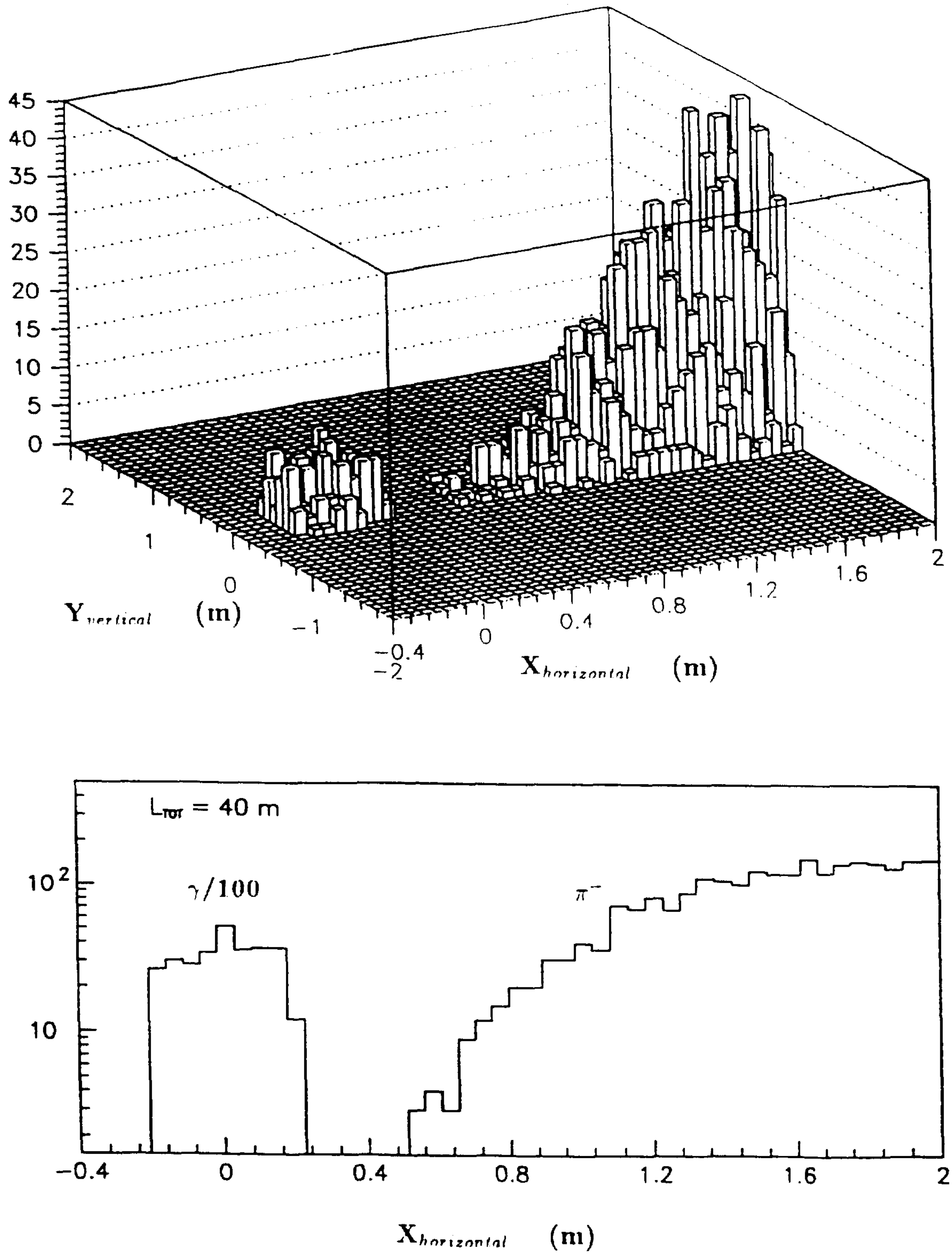

Fig. 1: Impacts on the wall 40 m dowmnstream of the target, of photons (left), and of negative pions magnetically deflected (1 Tm at 25 m from the target), from 1000 central Pb-Pb collisions at 160 A GeV simulated by VENUS. The virtually **background free region** used for the acceptance calculations extends from x = 23 to 70 cm and corresponds to rigidities between 420 and 140 GeV. Only one photon impact out of 100 is plotted.

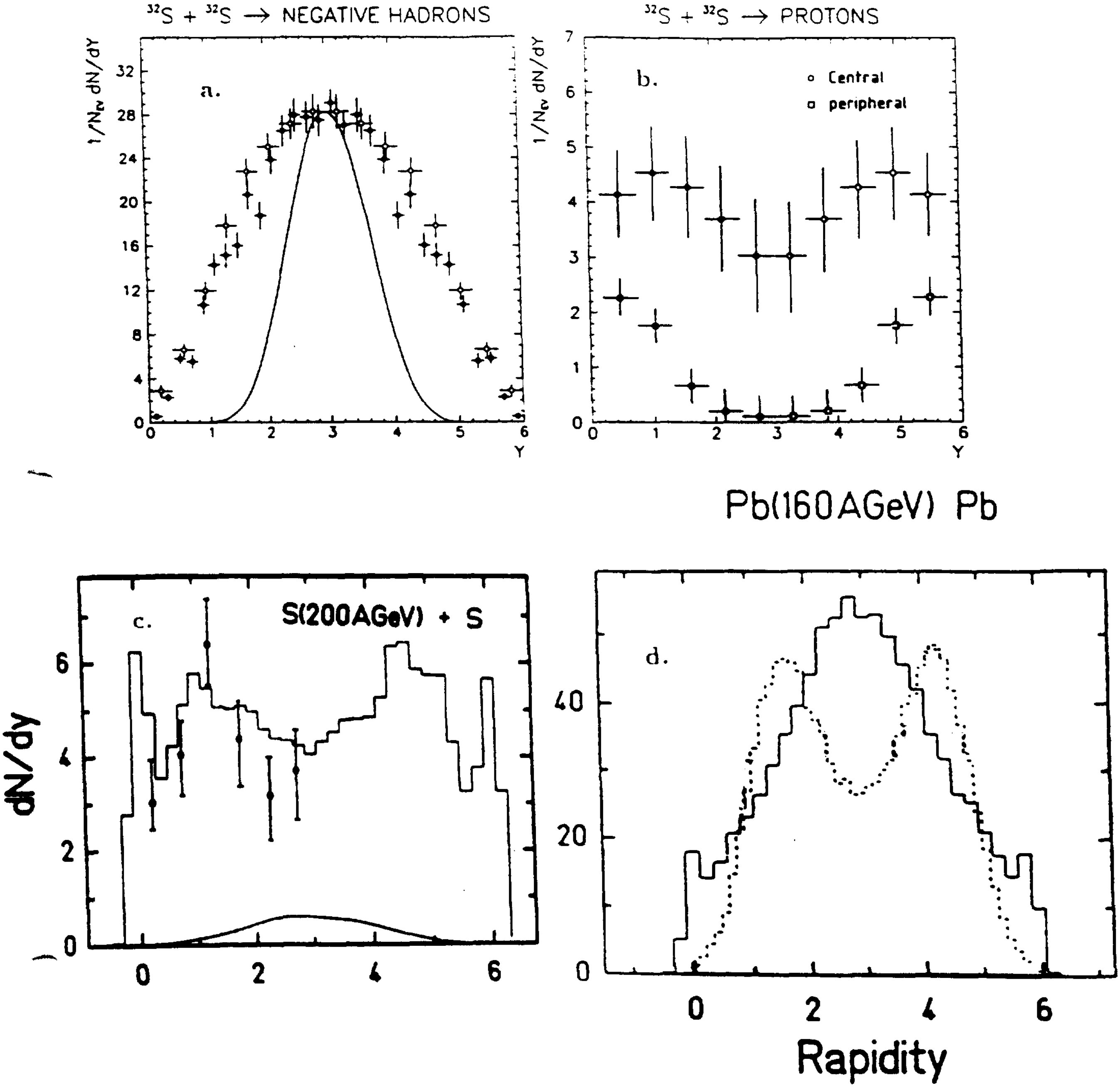

Fig. 2: Does the baryon density peak at y = 0 in Pb-Pb collisions ?
a. π^- and b. proton rapidity distributions measured by NA35 in S-S central and peripheral collisions [STR91]; c. the RQMD model (histogram) reproduces well the central S-S proton data [SOR91] and d. predicts, for central Pb-Pb collisions at the SPS, a proton distribution narrowly peaked at y=0 (solid line), in contrast to the central valley predicted bi FRITIOF (dotted line; adapted from [KEI91]; the RQMD data should be downscaled by 10 %).

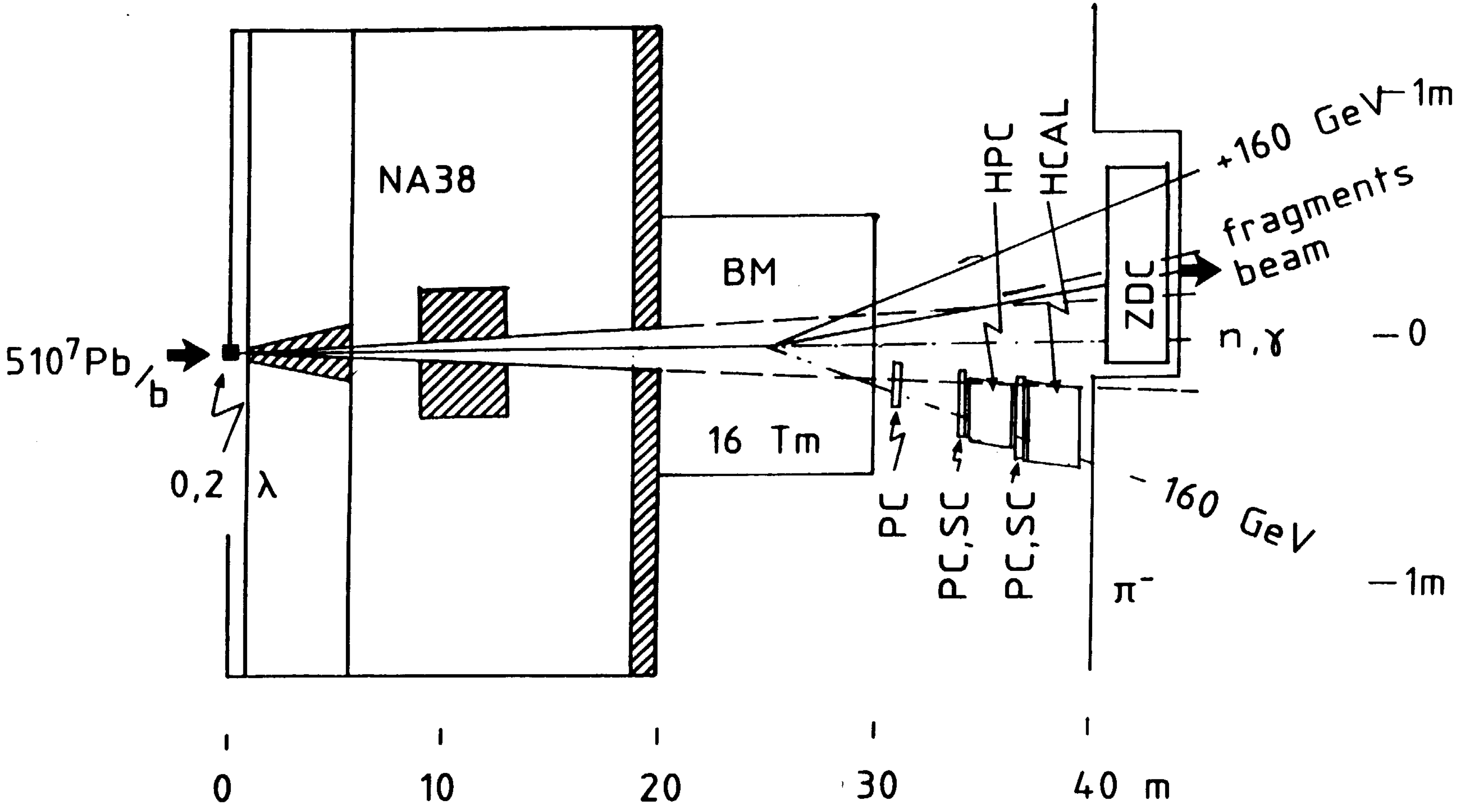

Fig. 3: A schematic layout for a particle search behind NA38.
The forward particles (< 7 mrad) traverse NA38 and a 16 Tm bending magnet BM. Beam, beam fragments and neutrals are collected by the Zero Degrees Calorimeter in its niche. The π^- are deflected by at least 30 mrad. If produced, Strangelets and $Z = -1/3$ Quarks have a good chance to traverse the narrow space free of photons and hadrons, which is well equipped for their detection and unambiguous identification.

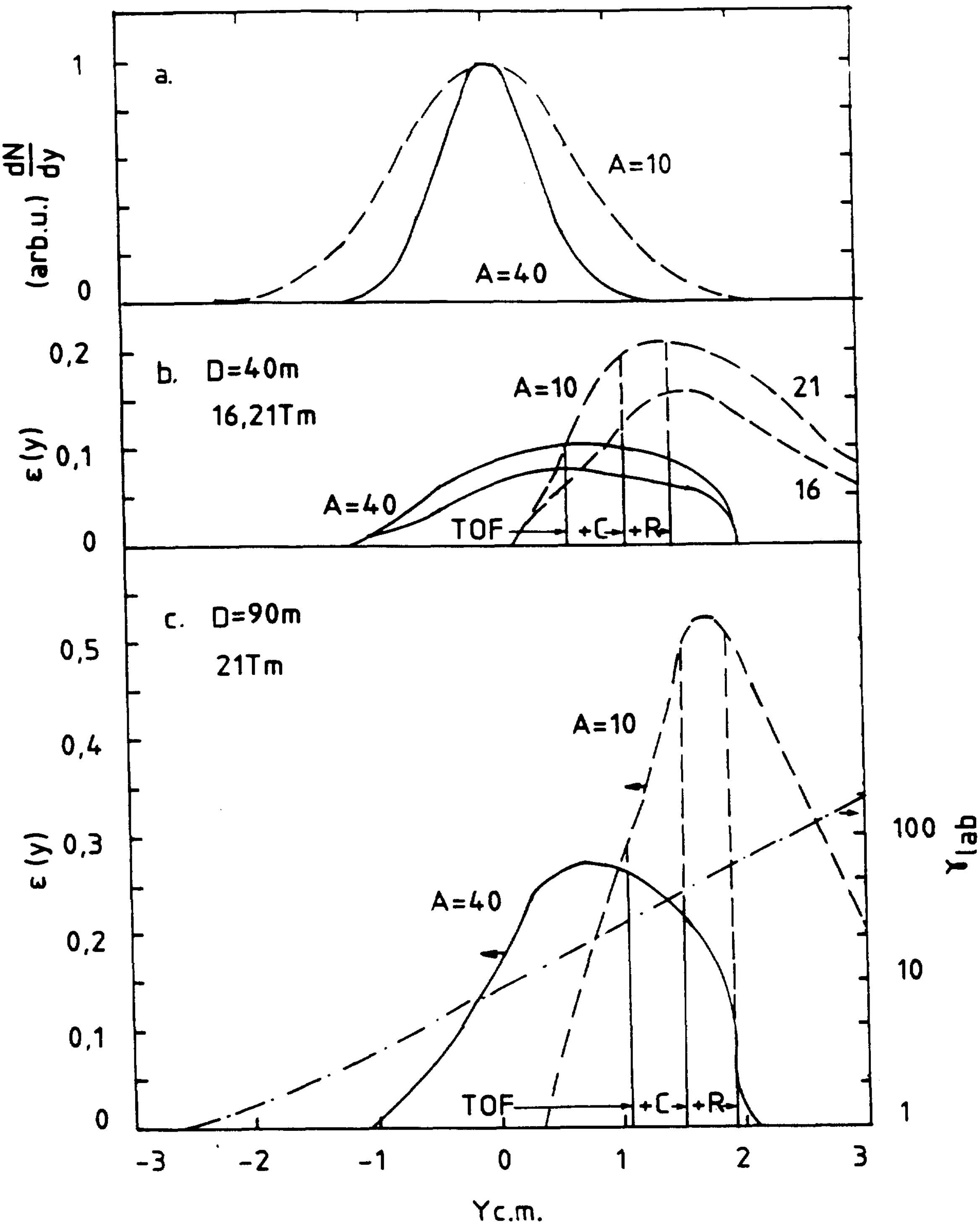

Fig. 4: **Rapidity distributions** of a. Strangelets of mass A=10 (dashed) and A=40 (solid) (assumed, see text); b. detection efficiencies at the NA38 site for magnets of 16 Tm (lower curves) and 21 Tm. The regions where γ is measured by time-of-flight (TOF), threshold Cerenkov (C) and RICH (R) are indicated. c. Same for a 50 m longer setup and a 21 Tm magnet. The dependence of γ on rapidity is indicated (right hand scale).

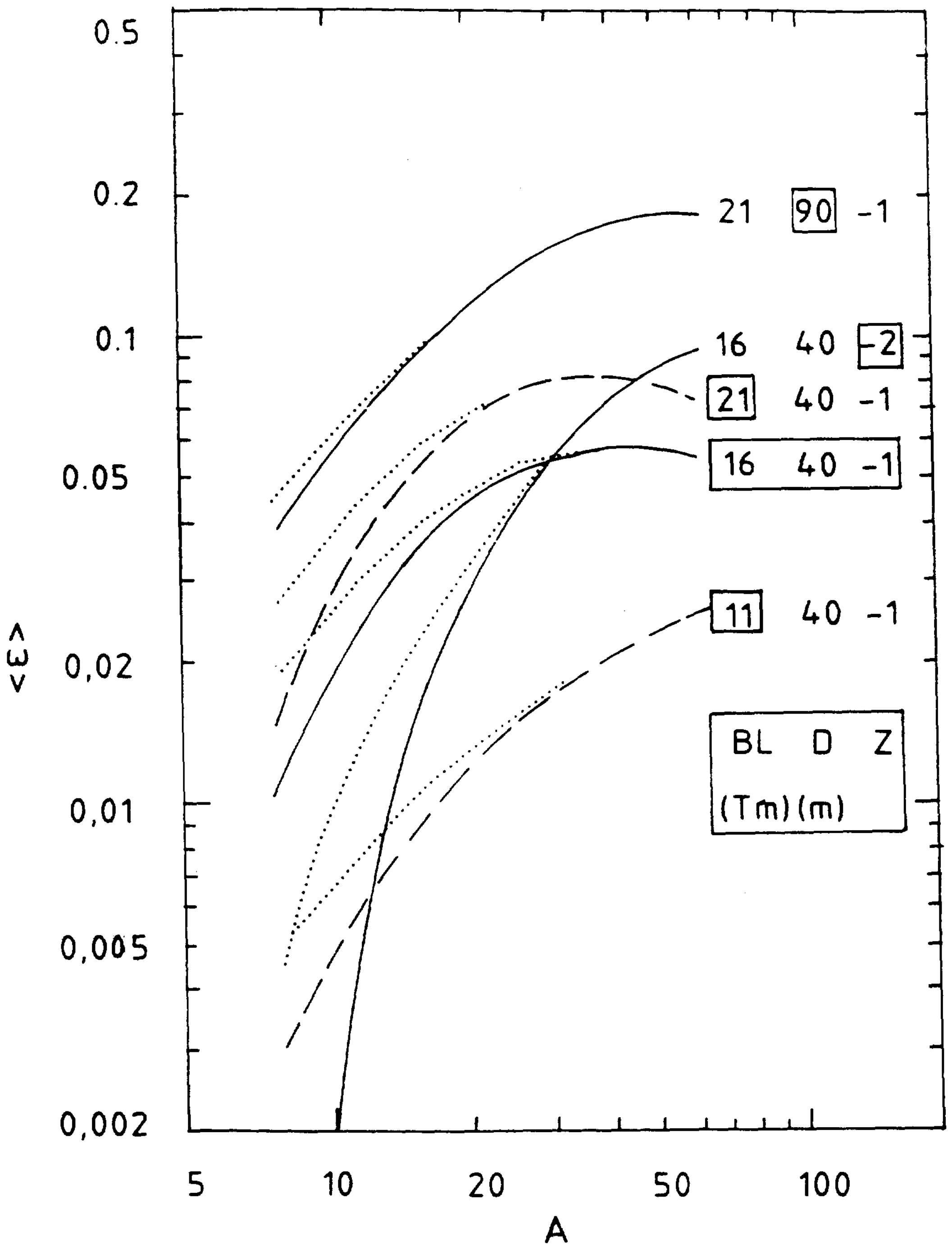

Fig. 5: Acceptances vs. mass number of produced Strangelets.
Solid lines: standard setup for Z=-1 and Z=-2 Strangelets, and long setup for Z=-1.
Dashed lines: same for standard setup, Z=-1, but different bending powers BL.
Lorentz factor γ measured using TOF and Threshold Cerenkov (solid and dashed lines), resp. TOF and RICH (dotted lines). The acceptances would double if $<p_T> = .5 \cdot \sqrt{A}$ were used instead of $.9 \cdot \sqrt{A}$.