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Dilepton Production at Intermediate Energy

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F-63177 AUBIERE CEDEX FRANCE

Invited talk presented at the 4th journées des théoriciens Saturne on Dilepton production in nucleon-nucleon and nucleon-nucleus collisions at relativistic energies
SACLAY - November 22-23 1990

PCCF RI 9015

Dilepton Production at Intermediate Energy.

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Abstract.

We discuss the DLS p-Be data at 1.0, 2.1 and 4.9 GeV, and model calculations that illustrate the various possible mechanisms of dilepton production at intermediate energy. It appears that the origin of dileptons is not presently understood, which is further supported by the recent DLS p-p and p-d preliminary results at 4.9 GeV. More thoughts and both theoretical and experimental works are needed.

Introduction.

The subject of my talk is centered around the Dilepton Spectrometer (DLS) program[1] at the LBL Bevalac. The program deals with dileptons (here, e^+e^- pairs or dielectrons) at intermediate energies, namely, about 1 GeV per nucleon incident energy. The main goal was to use dileptons as a probe of nucleus-nucleus collisions, and get information on nuclear matter at high temperature and density. However, we realized at the very beginning that we should understand proton-nucleus collisions before going to nucleus-nucleus, and more recently, we even realized that we should understand p-p and p-n.

In order to match better the topic of the meeting, I'll restrict myself mostly on that latter aspect of the DLS program. In fact, we'll see that p-p and p-A studies have their own interest. I'll present the first DLS data (1986 to 1989) and the model calculations done by several groups. Then I'll say a few words about π-nucleon and π-nucleus studies at Dubna, show preliminary DLS results in p-p and p-d, try to extract some conclusions, and end with possible developments of the program.

The first DLS data.

Table 1 gives the pair statistics for the data taken so far. The data is much cleaner for the lowest beam energy of 1.0 GeV per nucleon which allowed the use of looser cuts in the analysis (needless to say that the efficiency of the cuts is corrected for). The true to false ratio is about three times better for p-Be than for Ca-Ca collisions, independently of the analysis cuts and the incident energies. The existence of a dielectron signal down to 1 GeV per nucleon is established to a high level of statistical accuracy, which actually was the very first goal of the DLS program.

Table 1. DLS pair statistics.

OS= number of opposite sign pairs,
LS= number of like sign pairs,
F= number of false pairs in the OS sample (F=LS),
T= number of true pairs (T=OS−LS), $\sigma_T = \sqrt{OS + LS}$.
(for p-Be at 1.0 GeV, the stars refer to the same analysis as Ca-Ca at 1.0 A GeV)

Reaction	OS	LS	T	T/F	T/σ_T
4.9 GeV p-Be	732	201	531±31	2.6	17.4
2.1 GeV p-Be	567	148	419±27	2.8	15.7
2.0 A GeV Ca-Ca	94	45	49±12	1.1	4.2
1.0 GeV p-Be	111	19	92±11	4.8	8.1
	263*	111*	152±19*	1.4*	7.9*
1.0 A GeV Ca-Ca	731	476	255±35	0.5	7.3

Preliminary results, still under analysis

Reaction	OS	LS	T	T/F	T/σ_T
4.9 GeV p-Be	1003	318	685±36	2.2	18.8
2.0 A GeV Ca-Ca	400	318	82±28	0.3	3.1
1.0 A GeV Nb-Nb	263	200	63±22	0.3	2.9

Very preliminary results, on-line analysis

Reaction	Estimated number of true pairs
4.9 GeV p-d	2500
4.9 GeV p-p	1500

The cross section per nucleon (assuming an $A_t^{2/3}$ dependence, where A_t is the target mass) for p-Be as a function of the dielectron invariant mass is shown in Figure 1 for the three beam energies 4.9, 2.1 and 1.0 GeV. The general shape of the 4.9 and 2.1 GeV distributions for masses above 300 MeV are similar to that seen at higher energies. For comparison, the fit to the KEK 12 GeV p-Be data[(2)] is also shown in Figure 1(a). An enhancement in the ρ/ω region is seen in the mass spectrum at 4.9 GeV. At 2.1 GeV, the maximum energy available in the nucleon-nucleon center-of-mass frame is 850 MeV, just barely above the ρ/ω threshold. The total Dalitz decay contributions to the dielectron cross sections (see ref. (3) for details) are shown as dashed curves in Figure 1 for all three beam energies. The significant contributions are from π^0 and η at 4.9 and 2.1 GeV, while π^0 and $\Delta(1232)$ contribute at 1.0 GeV. At 4.9 and 2.1 GeV, the Dalitz decay background is approximately an order of magnitude smaller than the measured yield for masses above 200 MeV, in agreement with previous higher energy results and their interpretation. However, we just heard[(4)] that two recent experiments seem to show that the low mass dilepton continuum (the so-called "low mass dilepton anomaly") could be explained as originating from η and other meson Dalitz decays. For the 1.0 GeV data, the Dalitz decay contribution on Figure 1(c) is less accurate due to the uncertainty in the $\Delta(1232)$ production cross section and our systematical errors.

The structure observed at about 300 MeV (twice the pion mass) in the 4.9 and 2.1 GeV spectra has been discussed at various occasions (see ref. (5) for instance). Due to the uncertainty in the calculation of the tip of the DLS acceptance (the first mass bins), its magnitude is probably smaller than it appears on Figure 1. However, except for a quite large misunderstanding in the acceptance modeling, it should be there. The upcoming data analysis of the DLS p-p and p-d runs should help in the matter.

The cross section (per nucleon) for producing low mass dielectrons, $200 \lesssim M \lesssim 700$ MeV, is plotted in Figure 2 as a function of the available center-of-mass energy. The brackets around the DLS data points represent the systematic normalization errors of approximately +70/-20%. We first notice that the DLS cross sections are in agreement with the higher energy results from KEK[(2)] and SLAC[(6)], and probably also with the lower energy measurement at LAMPF[(7)]. The e^+e^- and $\pi^+\pi^-$ cross sections are found to have similar threshold behavior while the π^0 excitation function is much flatter in the same range of available center-of-mass energy. The dielectron to dipion ratio is about 10^{-5}.

Concluding on the experimental observation of both the mass structure at about twice the pion mass and the excitation function, we have suggested that *pion annihilation* is a possible dominant mechanism of dilepton production for proton beam energies above 2 GeV, though other mechanisms may also have significant contributions (e.g., Dalitz decay of the $\Delta(1232)$ resonance, bremsstrahlung). Let's see now what comes out of theoretical analyses.

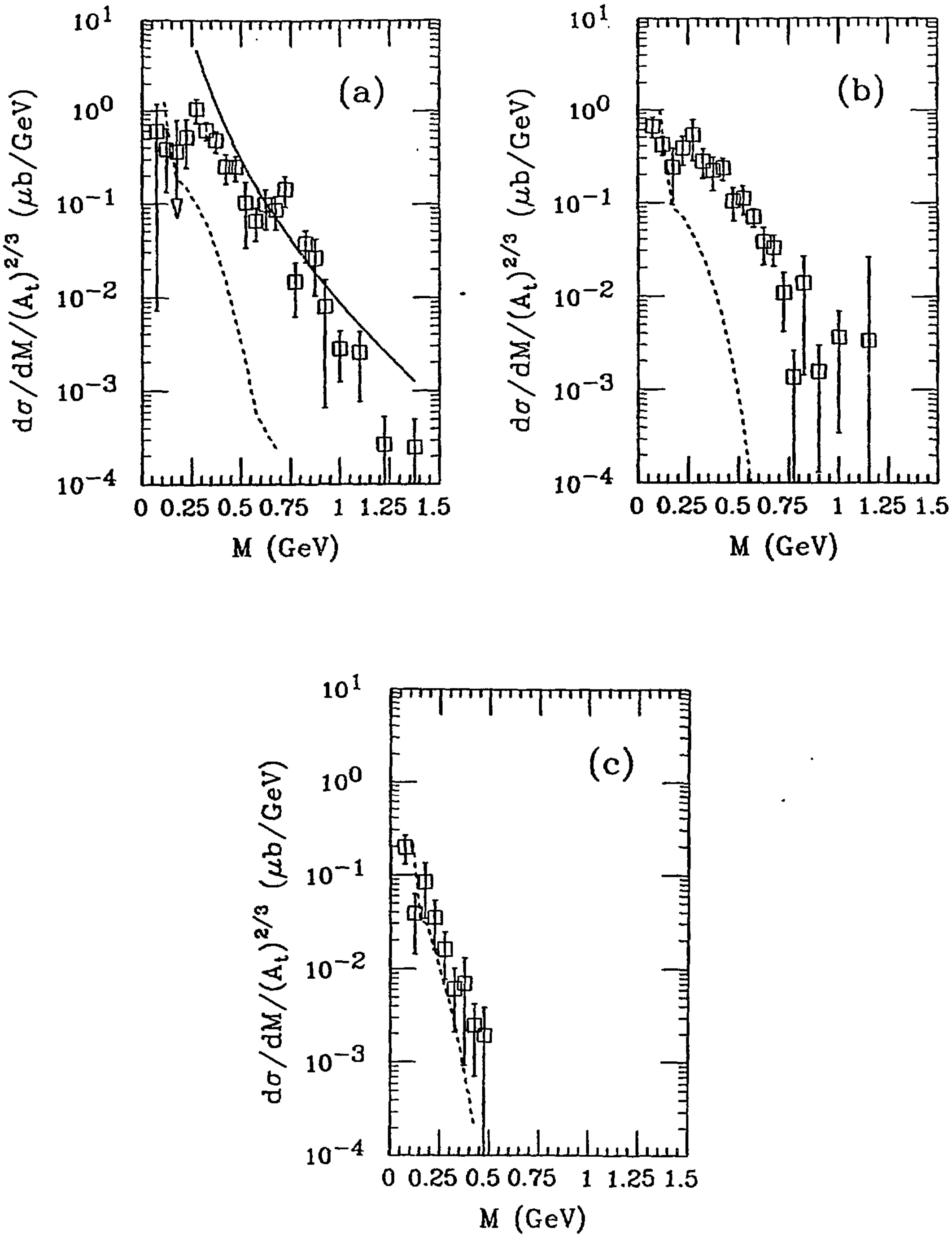

Fig. 1. The dielectron invariant mass spectra from the p-Be reaction at beam energies of (a) 4.9, (b) 2.1 and (c) 1.0 GeV. The first data point on all three spectra is qualitative. The dashed curves are the total Dalitz decay contributions. The solid curve is the fit to the KEK 12 GeV p-Be data[2] for comparison.

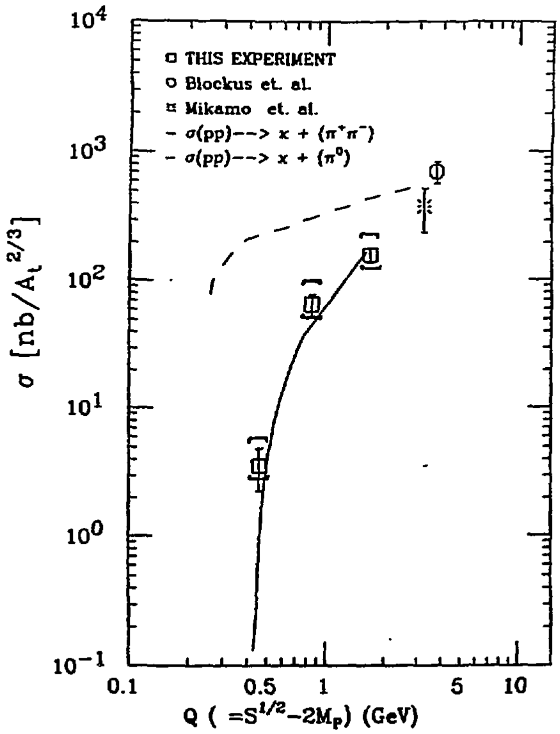

Fig. 2. The total dielectron production cross section as a function of the available NN center-of-mass energy: circle, D. Blockus *et al.*[6] π^-p at 16 GeV; star, S. Mikamo et al[2] p-Be at 12.1 GeV; squares, DLS data. The solid and dashed curves show the $\pi^+\pi^-$ and π^0 total cross sections[8] respectively, scaled down by 1.33×10^{-5}.

Model calculations.

Quite many theoretical calculations have been performed to interpret the DLS experimental data. I'll review the most recent ones that illustrate the various mechanisms possibly responsible for dilepton production at relativistic energies. However, the work by the Giessen Group will be presented in details by another speaker. Obviously, most of the contributions at the meeting discuss the same question, along with the issue of nuclear effects on the behavior of mesons and baryons.

In their cascade model, Xiong *et al.*[9] introduce dilepton production from p-n bremsstrahlung (treated in the soft-photon approximation with a phase-space correction), the Dalitz decay of the deltas, and pion annihilation on the nucleons. Figure 3 shows their calculated mass spectra and Figure 4 their excitation function. While their results at 1.0 GeV are in reasonable agreement with the DLS data, owing to in particular the rather poor statistics, there is significant discrepancy at 2.1 and 4.9 GeV. The magnitude of the mass spectrum is not really reproduced for masses above 300 MeV, at 2.1 GeV incident energy, and there is discrepancy in shape for the 4.9 GeV data. It is interesting to point out on both Figures that the p-n bremsstrahlung contribution is by far the highest at 4.9 GeV, which would indicate that p-p is supressed by a large factor at this energy (I'll come back to this later on). Of course their model is expected to brake down somewhere above 2 GeV, as indicated in the paper.

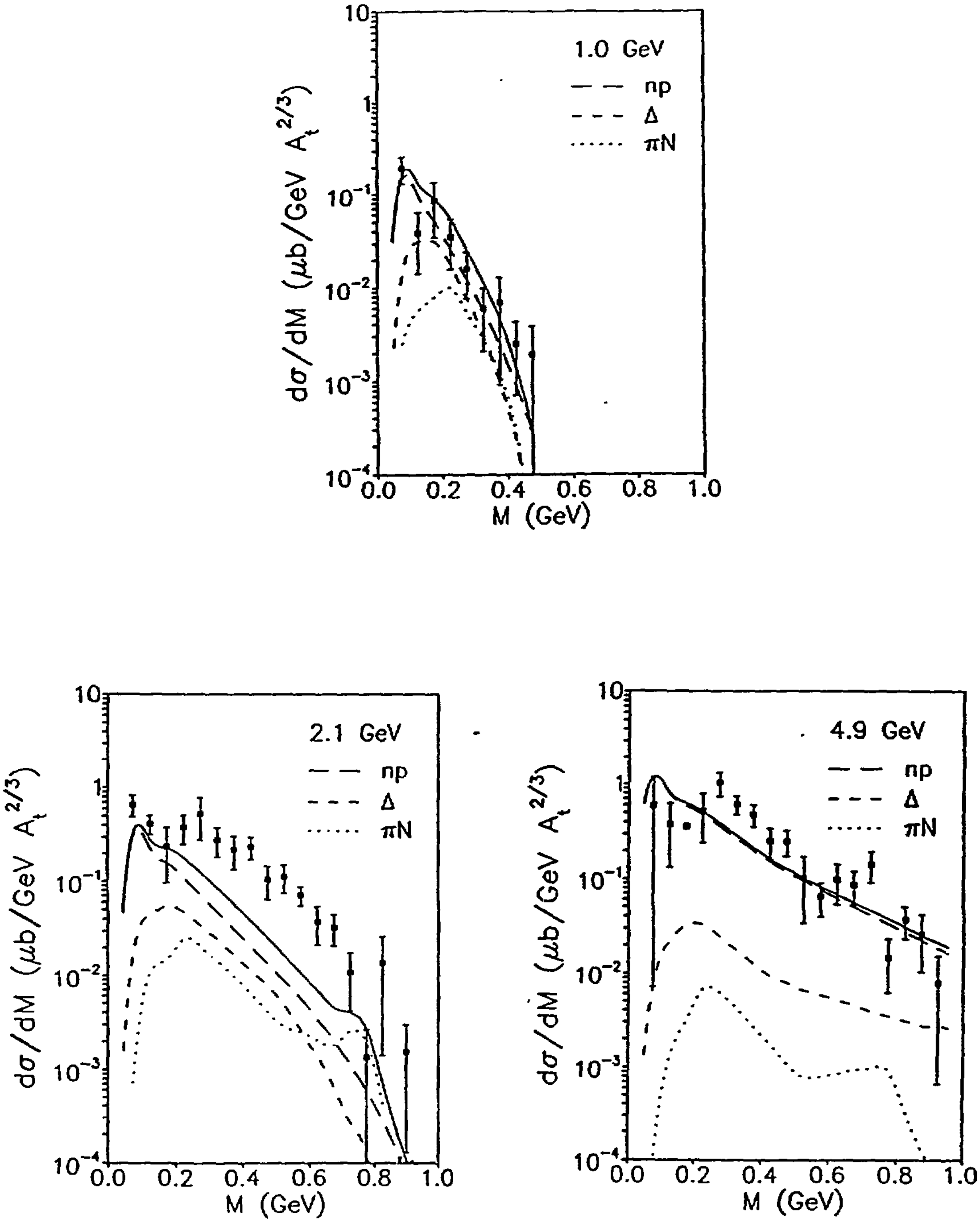

Fig. 3. Dielectron invariant mass spectra for p-Be reactions at 1.05, 2.1 and 4.9 GeV. The theoretical total yield is given by the solid curve. The figure is from ref. (9).

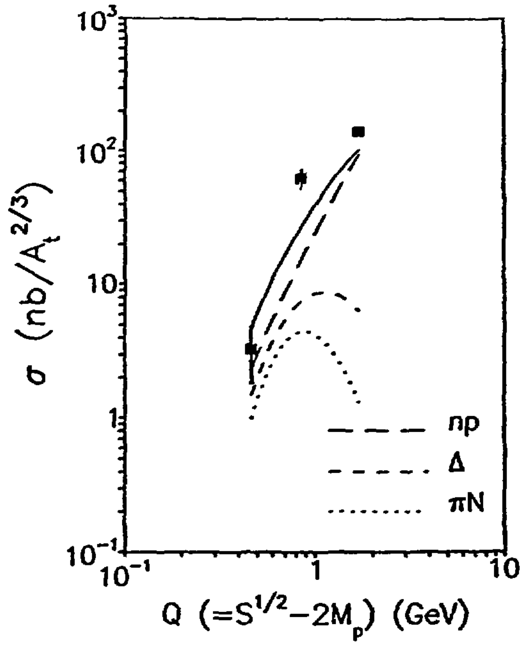

Fig. 4. Total integrated dielectron cross section for invariant masses $200 \lesssim M \lesssim 700$ MeV as a function of the available nucleon-nucleon center-of-mass energy Q. The figure is from ref. (9).

At this point, p-n bremsstrahlung seems to be a major issue. In the past, high energy measurement analyses above 10 GeV have always considered hadronic bremsstrahlung as a small contribution to low mass dilepton production. What is so different between 5 GeV and say 12 GeV, the KEK experiment energy? Haglin *et al.*[(10)] among others (see also Mosel's contribution at this meeting) have investigated the validity of the soft-photon approximation. They compute the e^+e^- cross section arising from OPE diagrams in p-n interaction. Their results are shown in Figures 5 for back-to-back pairs at an incident energy of 2.1 GeV. For dilepton masses above 300 MeV, the calculation for all the Feynman diagrams is much higher than the soft-photon approximation, and taking into account only the production from the external lines, "shake-off" diagrams, yields a result in between both. The "shake-off" diagrams calculation actually compares better with the experimental points.

Along the line of bremsstrahlung calculations, Figure 6 shows a result from a semiclassical treatment of the collective deceleration during the initial stage of central relativistic heavy ion collisions[(11)]. Dileptons are found to be produced incoherently (use of a incoherent charge density). The slope of the calculated spectrum strongly depends upon the assumed deceleration length parameter l. The computed curves are compared to the DLS Ca-Ca data at 2 GeV per nucleon.

Beside p-n bremsstrahlung, the next mechanism that has been first thought of as a possible source for dilepton production at intermediate energy is $\pi^+\pi^-$ annihilation (see for instance ref. (12)). More recently, Kapusta and Lichard[(13)] estimated this contribution in the elementary nucleon-nucleon interaction, thus without any nuclear medium effect. Figure 7 reproduces their calculated mass distribution integrated over all electron and positron momenta. The calculation fails to reproduce the DLS experimental data in the region of the bump at around $2m_\pi$ (p-Be at 4.9 GeV). Moreover, the estimated p_t dependence is in striking disagreement with the DLS data (see Figure 8). Thus, we may

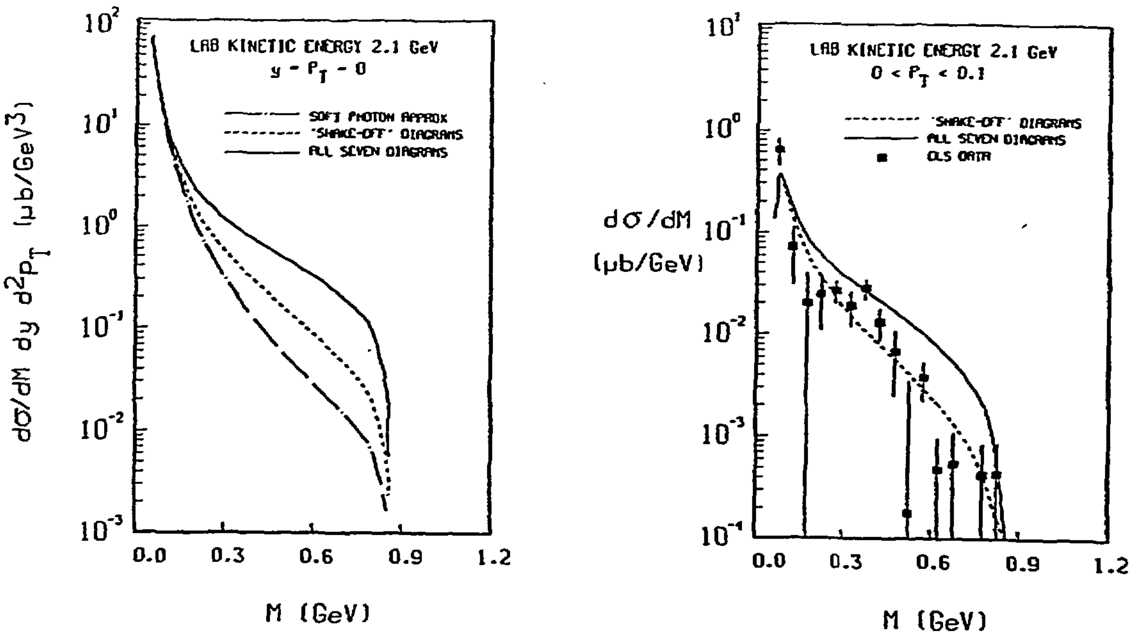

Fig. 5. Differential cross section for dilepton production versus invariant mass: (a) soft-photon approximation, "shake-off" diagrams, and all diagrams contributions; (b) comparison of all diagrams and "shake-off" diagrams calculations to DLS data. The figures are from ref. (10).

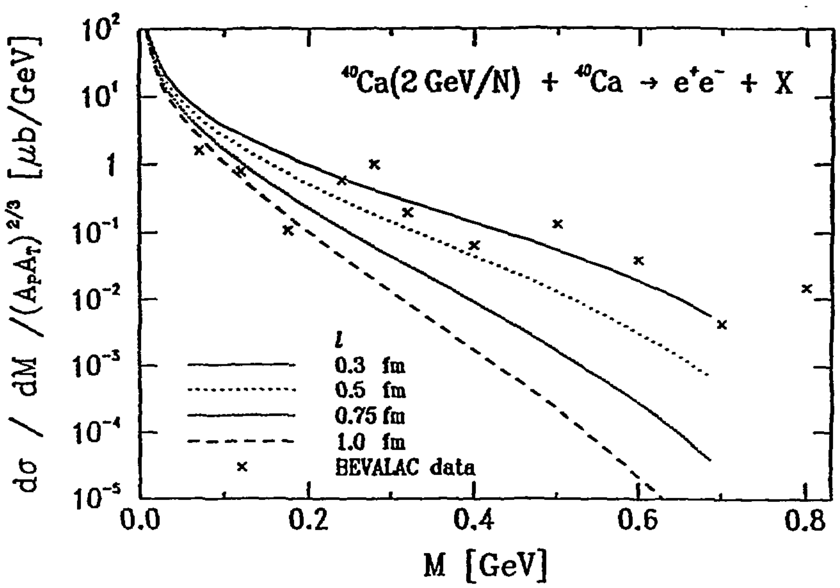

Fig. 6. Bremsstrahlung from the collective deceleration during the initial stage of relativistic heavy ion collisions. The figure is from ref. (11).

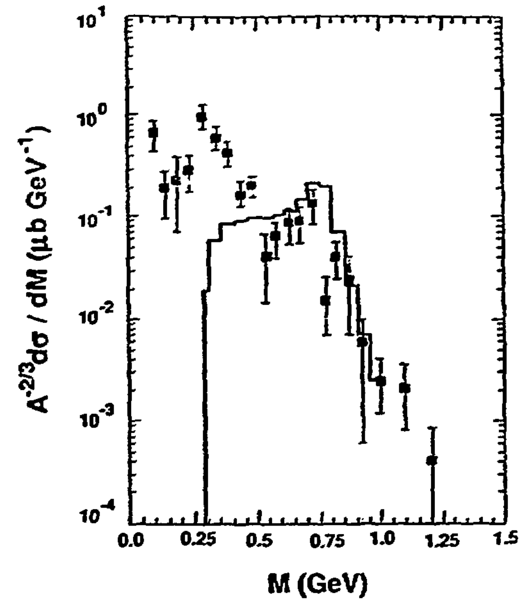

Fig. 7. The e^+e^- mass distribution (per nucleon) from p on Be at 4.9 GeV integrated over all electron and positron momenta. The data is from the DLS and the histogram is the result of the two-pion annihilation model. The figure is from ref. (13).

ask whether any medium effect would already take place in such a light system as p-Be? Gale and Kapusta[(12)], then Xia *et al.*[(14)], had predicted a bump at around $2m_\pi$, depending upon the softness of the pion dispersion relationship in the nuclear medium. However, a more recent work by Korpa and Pratt[(15)] indicates a strong reduction of the previously expected enhancement. More theoretical works are now in progress and some of them will be presented at the workshop.

At this stage of the DLS experimental data and the theoretical works, the source of dilepton production in the 1 GeV per nucleon energy range is not quantitatively understood. Before going to preliminary indications about the p-p and p-d DLS results, I'd like to mention earlier works on π-nucleon and π-nucleus reactions at intermediate energy, that are obviously related to the subject of the workshop, and in particular to the topic of my talk (remember the model calculation by Xiong *et al.*[(9)], for instance).

π-nucleon and π-nucleus studies.

Dilepton measurements at intermediate energy had actually been started at Dubna in the 70's, prior to the DLS program. The goal of these measurements was the determination of nucleon and pion form factors in the time-like region of 4-momentum transfers. The following reactions have been studied (details on the results can be found in the papers):

- $\pi^- + p \longrightarrow e^+e^- + n$ at 275 and 164 MeV, see ref. (16);
- $\pi^+ +^7 Li \longrightarrow e^+e^- +^7 Be(^7Be^*)$ at 380 MeV, see ref. (17);
- $\pi^- +^{12} C \longrightarrow e^+e^- + X$ at 164 MeV, see ref. (18).

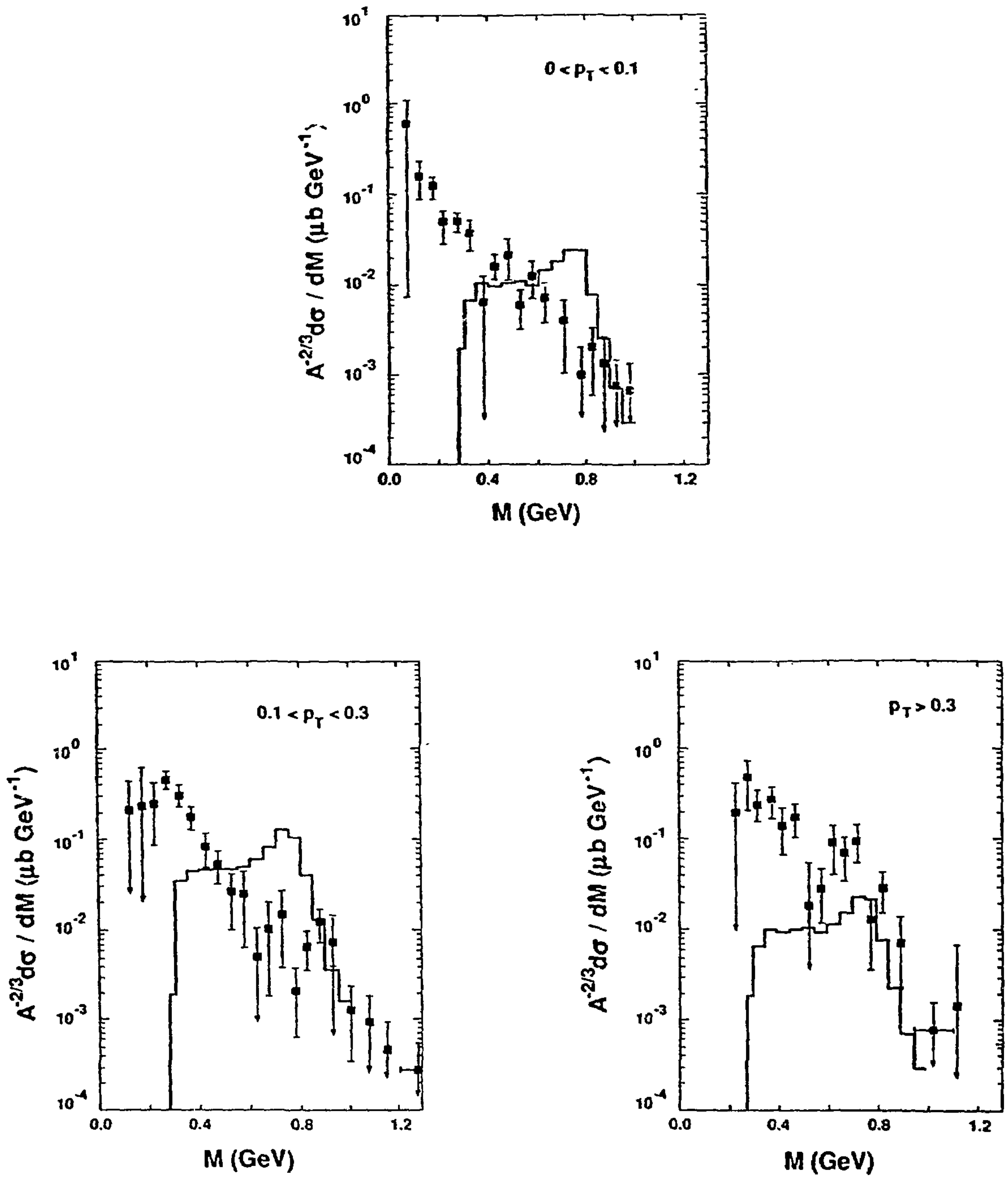

Fig. 8. Same as Fig. 7 except for the e^+e^- transverse momentum cuts indicated on the plots. The figures are from ref. (13).

About the subject, I'd like to quote G. Furlan *et al.*[19] in 1976: "Furthermore, the study of such a process" (here $\pi^- + p \longrightarrow l^+ l^- + n$) "on nuclei can represent a sensitive tool to probe the behaviour of pions (real and virtual) inside the nucleus". It is interesting to notice that the same kind of an argument has been brought again by Gale-Kapusta, other theoreticians, and the DLS Collaboration, trying to promote dilepton measurements at intermediate energy, about a decade later.

p-p and p-d DLS preliminary results.

As seen above, the origin of dilepton production in relativistic nuclear collisions is not presently understood. In order to help clarify concepts and models, the DLS Collaboration has undertaken a study of the elementary processes. Data have been collected in p-p and p-d collisions at 4.9 GeV last September-October. A full analysis must be done before reliable information on cross sections can be presented. However, we can already give some indications that are less likely to depend upon efficiency and/or calibration of the detectors. Table 2 shows the ratios of the p-d and p-p cross sections (per atom) to produce an e^+e^- pair, as a function of the low mass cut, the lowest cut value meaning the full mass acceptance. It is seen that the ratios are the same, about a value of two, independently of the mass cuts, with of course less statistical accuracy for higher masses. Therefore, the p-p and p-n cross sections are similar and, at least, p-p is not suppressed, which is in striking disagreement with the theoretical assumptions made so far.

Table 2. Very preliminary results in pp and pd at 4.9 GeV (on-line analysis):

σ_{pd}/σ_{pp} ratios (for about 30% of the whole data).

$M_{e^+e^-} > 0.05$ GeV	2.38 ± 0.21
$M_{e^+e^-} > 0.20$ GeV	2.39 ± 0.21
$M_{e^+e^-} > 0.30$ GeV	2.41 ± 0.24
$M_{e^+e^-} > 0.50$ GeV	2.52 ± 0.34
$M_{e^+e^-} > 0.70$ GeV	2.12 ± 0.37

Conclusions.

The first DLS data already established the existence of a dilepton signal down to 1 GeV per nucleon incident energy. For p-Be above 2 GeV, the mass distributions ($M_{e^+e^-} > 0.3GeV$), the p_t distributions, and the yields ($e^+e^-/\pi^+\pi^- \approx 10^{-5}$), are similar to those obtained at higher energies, above 10 GeV. The dominant mechanisms are not yet quantitatively understood: pion annihilation, pn bremsstrahlung... ???

Concerning the heavy ion results that I mostly skipped, I'll just mention here that they mainly show the *feasibility* and *interest* of experiments using dileptons as a probe of nucleus-nucleus collisions in the GeV per nucleon range.

The p-p and p-d preliminary results at 4.9 GeV further support the present difficulties in the understanding of the dilepton production origin. If it is confirmed that $\sigma_{pp} \approx \sigma_{pn}$, then important questions may have to be raised, in particular:

- hadronic origin of the dileptons?
- possibility for some common mechanism between 5 GeV and higher energies?

There is obviously need for more thoughts and work.

Developments of the program.

At the Bevalac (1991-94/95).

There should be ≈ 1000 hours per year for the DLS program that will be used to complete pp/pd studies[20] and collect data on Ca-Ca (≈ 4000 true pairs) and Nb-Nb (≈ 2000 true pairs), both heavy ion reactions at 1 GeV per nucleon. Furthermore, some heavier target/projectile examinations will be done.

A project for SIS.

A project for a high statistics study of nuclear collisions (up to Au-Au) at SIS with a Large Electromagnetic Spectrometer (both dilepton and real photon measurements) is under consideration. Some indications are given in a second presentation at the meeting.

Footnotes and references.

(1) The DLS Collaboration - Lawrence Berkeley Laboratory: J. Cailiu, H. Huang, G.F. Krebs, A. Letessier-Selvon, H.S. Matis, C. Naudet, L. Schroeder (Spokesperson), P.A. Seidl, A. Yegneswaran; University of California at Los Angeles: S. Beedoe, J. Carroll, G. Igo; The Johns Hopkins University: T. Hallman, L. Madansky, R. Welsh; Louisiana State University: P. Kirk, Z.F. Wang; Northwestern University: D. Miller; Université Blaise Pascal: M. Bougteb, P. Force, F. Manso, G. Roche; other contributors at earlier stages of the project: J. Bystricky, G. Claesson, J.-F. Gilot, J. Gordon, D. Hendrie, E. Lallier, G. Landaud, T. Mulera, J. Panetta, H. Pugh; engineers: R. Fulton and D. Nesbitt (LBL), P. Oillataguerre (UCLA).

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[20] Of course, this does not reduce the interest for more studies in p-p, p-d and p-nucleus collisions at Saturne, as will be discussed further during the workshop (see for instance Saudinos' talk).