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THE TOTAL NEUTRAL ENERGY SPECTRA IN THE CENTRAL REGION OF $\alpha\alpha$, dd AND pp INTERACTIONS AT $\sqrt{s}_{NN} = 31$ GeV PER NUCLEON PAIR AT THE CERN ISR

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ABSTRACT

The spectra in total neutral energy, E^0_{tot}, have been measured in $\alpha\alpha$, dd, and pp collisions at a centre-of-mass energy per nucleon pair, $\sqrt{s_{NN}}$, of 31 GeV. The range in E^0_{tot} covered was 1 to 19 GeV in pp, 18 to 24 GeV in dd, and 1 to 34 GeV in $\alpha\alpha$ interactions. The ratio of the $\alpha\alpha$ to the pp spectra rises monotonically from 7 at $E^0_{tot} = 1.5$ GeV to 10^5 at $E^0_{tot} = 19$ GeV. Since E^0_{tot} is the sum over many particles in the detector, it is directly sensitive to multiple nucleon–nucleon collisions in the interacting α particles. The $\alpha\alpha$ spectrum in the range $8 < E^0_{tot} < 17$ GeV is consistent with being described by a simple model of four simultaneous nucleon–nucleon collisions with a cross-section about equal to 10% of the observed $\alpha\alpha$ interaction cross-section. The spectrum of E^0_{tot} above 17 GeV is even flatter than this extreme case where four nucleon pairs are interacting.

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Inclusive particle production in proton–nucleus collisions and nucleus–nucleus collisions exhibits an enhancement relative to proton–proton collisions by a factor which has been parametrized as $(A_1A_2)^\alpha$, where A_1 (A_2) is the number of nucleons in one (the other) nucleus. The exponent α varies between 0.8 and 1.3 for inclusive single-particle production [1] in the central region and depends on the p_T and type of the produced particle as well as on the centre-of-mass energy of the collision [2].

The anomalous enhancement ($\alpha > 1$) has also been observed for the emission of transverse energy in the central region [3, 4], where the energy is summed over all the particles emitted into a fixed solid angle, typically $\Delta\Phi = 2\pi$, $\Delta y \approx \pm 1$. The variation of α is much larger in this class of experiment, with values as high as $\alpha = 2.0$ observed at transverse energies up to 80% of the available nucleon–nucleon centre-of-mass energy.

In this report, the total and transverse neutral energy spectra in the central region from $\alpha\alpha$, dd, and pp collisions at centre-of-mass energies of $\sqrt{s_{NN}} = 31$ GeV per nucleon pair are presented. The data were collected in the light-ion run at the CERN ISR during August 1983. The luminosity achieved for $\alpha\alpha$ collisions during this run was 10^{30} cm^{-2} s^{-1}, a factor of 5 higher than in the previous $\alpha\alpha$ run.

The apparatus, shown in Fig. 1, consisted of a superconducting solenoid providing a magnetic field of 1.4 T and enclosing a system of cylindrical drift chambers. Four modules of lead/scintillator shower counters were also located inside the magnet. Each module subtended 50° in azimuth and ± 1.1 units of rapidity y, centred on y = 0, and was segmented azimuthally into eight counters equipped with phototubes at both ends. The detection of electromagnetic showers was completed by two lead-glass modules located outside the magnet in the angular region not covered by the shower counters. The angular acceptance of each lead-glass array was 57° in azimuth and ± 0.7 units of rapidity, also centred on y = 0. The centre-of-mass acceptance in which the neutral energy was detected covered 90% of 2π in azimuth with an average rapidity acceptance inside this region of $\Delta y = \pm 0.9$. The thickness of the lead glass was 21 radiation lengths (r.l.) and that of the shower counters was 14 r.l. The r.m.s. energy resolutions were $(4.3/\sqrt{E} + 2)$% and $(16/\sqrt{E})$%, respectively, where E is measured in GeV. A hodoscope of 32 scintillation counters (A), also equipped with phototubes at both ends, was located between the first and second drift-chamber modules. The apparatus has been described in more detail elsewhere [5, 6].

To trigger the apparatus, all energies deposited in the shower counters and the lead glass were summed, and the total was required to be above threshold. The threshold was applied again in the off-line analysis, using more detailed calibration information.

Events due to the occurrence of more than one interaction during the apparatus recording time were rejected. This requirement was necessitated by the high interaction rate at the ISR, and the nature of the trigger which purposely placed little requirement on the pattern of energy deposition. All shower counters were equipped with time-to-digital converters (TDCs). In addition, the scintillator hodoscope (A) which surrounded the interaction region had TDCs capable of recording up to 14 hits per counter end in a time range of 300 ns before and after the nominal event time. The time data from the shower counters and the A scintillators were searched in a range of ± 200 ns (the longest gate time used in the calorimeter). A time cluster was defined as two or more counters firing within a 12 ns interval. If more than one distinct cluster was found, the event was rejected. This method has been shown to work [6] at interaction rates four times higher than those achieved for the $\alpha\alpha$ collisions.

Each event was required to contain at least two charged tracks, with two or more of these tracks intersecting at a point, the vertex, well within the interaction region in order to remove a small contamination of the event sample by interactions due to cosmic rays and stray beam particles.

A shower counter or lead-glass block was considered to be hit if it contained energy above a noise threshold of 70 MeV or 15 MeV, respectively. In each shower counter the longitudinal (along the colliding-beam axis) position of energy deposition was calculated from the time difference or energy difference between the phototube signals at each end. From each hit a momentum vector was constructed, assuming the hit was caused by a massless neutral particle emerging from the event vertex. Each momentum vector was Lorentz transformed from the laboratory system to the c.m. system of the colliding beams. The absolute values of these momentum vectors or their transverse components were then summed to give the total neutral energy E^0_{tot} or transverse neutral energy E^0_T for each event.

Data samples with six nominal thresholds were used for the $\alpha\alpha$ measurement: 1, 5, 10, 15, 20, and 25 GeV. For each data sample, the number of events per GeV of E^0_{tot} and E^0_T was divided by the integrated luminosity L to obtain the spectra $(1/L)(dN/dE^0_{tot})$ and $(1/L)(dN/dE^0_T)$, as shown in Fig. 2. Only the statistical errors are shown. The data from the different samples agree and cover a wide range in E^0_{tot} from 1 GeV to 34 GeV. It is noteworthy that the $\alpha\alpha$ data extend beyond the single nucleon pair kinematic limit of 31 GeV. The same spectra measured in pp and dd interactions at the same value of nucleon–nucleon centre-of-mass energy, $\sqrt{s_{NN}} = 31$ GeV, are also shown in the figure. The pp data extend from 1 to 19 GeV, but the dd data are available only in the limited range of 18 to 24 GeV. The integrated luminosities for the pp, dd, and $\alpha\alpha$ data are 5.3×10^{35} cm^{-2}, 4.2×10^{35} cm^{-2}, and 1.0×10^{35} cm^{-2}, respectively.

The spectra in Fig. 2 have been corrected for the energy deposited by charged particles in the electromagnetic shower detector. The effect of this correction was to make a small parallel displacement of the $\alpha\alpha$, dd, and pp spectra in energy for $E^0_{tot} > 3$ GeV in pp and $E^0_{tot} > 6$ GeV in $\alpha\alpha$ interactions. The logarithmic derivative, or exponential slope, of the $\alpha\alpha$, dd, and pp data changed by less than 1% owing to this correction. The uncertainty of this correction is estimated to be $\pm 50\%$ of itself. This introduces a systematic error in the $\alpha\alpha$ data for $E^0_{tot} > 6$ GeV and the pp data for $E^0_{tot} > 3$ GeV by which the $\alpha\alpha$ and pp data can be displaced together in E^0_{tot} by ± 0.45 GeV and ± 0.25 GeV, respectively. Other systematic errors in the data of Fig. 2 include an overall uncertainty on the E^0_{tot} scale of $\pm 5\%$. The data have not been corrected for resolution smearing or finite bin width, which would be equivalent to an overall energy scale shift of less than 1.8%. In addition, owing to a non-linearity introduced in the shower counter response by multiple hits within the same shower counter, the quoted E^0_{tot} values are high by 3% at $E^0_{tot} = 30$ GeV and 1.5% at $E^0_{tot} = 15$ GeV. This effect is three times larger in the E^0_T spectra because multiple hits cause an error in angle as well as energy.

The pp and $\alpha\alpha$ spectra shown in Fig. 2 both become exponentially decreasing for values of $E^0_{tot} > 5$ GeV and 12 GeV, respectively. The logarithmic derivatives are -1.26 ± 0.01 GeV^{-1} for pp and -0.83 ± 0.02 GeV^{-1} for $\alpha\alpha$, including all the systematic corrections mentioned above except for the scale error which introduces a common $\pm 5\%$ uncertainty in the values of the slopes. The ratio of the $\alpha\alpha$ to the pp spectra rises monotonically from a factor of 7 at $E^0_{tot} = 1.5$ GeV to 10^5 at $E^0_{tot} \approx 19$ GeV.

The existence of $\alpha\alpha$ data beyond the nucleon–nucleon kinematic limit indicates the inadequacy of the parametrization $R(\alpha\alpha/pp) = (A_1A_2)^\alpha$ for the E^0_{tot} spectrum. It is not surprising that the parametrization which worked for inclusive single-particle production should prove to be inadequate for the description of the total energy spectrum in $\alpha\alpha$ and pp interactions. E^0_{tot} is the sum over many particles in the detector, so it is directly sensitive to multiple nucleon–nucleon collisions in the interacting α particles. Single-particle spectra are thought to be the result of single hard collisions of nucleons and thus provide a different but complementary probe of nucleus–nucleus interactions.

It is therefore reasonable as a first approximation to try to understand the E^0_{tot} spectra in $\alpha\alpha$ interactions as the result of multiple nucleon–nucleon collisions with each collision producing an E^0_{tot} spectrum as shown in Fig. 2 for pp interactions. To do this, the pp spectrum is treated as the probability function for the collision of two protons. Repeated convolutions of this function are taken to represent the E^0_{tot} spectra which would result from two, three, four, and five such hypothetical simultaneous collisions. All spectra are normalized to the pp cross-section, implying an equal probability for any number of collisions (Fig. 3).

The maximum E^0_{tot} allowed in any single collision is 20 GeV. The pp spectrum has been extrapolated to zero using the shape measured for the charged E_T spectrum [4]. Only slight variations in the curves (a factor of $\approx$ 1.6 at E^0_{tot} = 30 GeV) can be obtained by varying the extrapolation to zero.

Several observations can be made from Fig. 3. With the above "equal probability" normalization, the E^0_{tot} spectrum from two simultaneous pp collisions is an excellent description of the available dd data and similarly the E^0_{tot} spectrum from four simultaneous pp collisions fits the $\alpha\alpha$ data over the range $8 \leq E^0_{tot} \leq 17$ GeV. At higher values of E^0_{tot} the slope of the $\alpha\alpha$ spectrum is too flat to be explained by four or even five nucleon-pair collisions. For instance, the curve for five collisions, with normalization adjusted downward by a factor of 4 from that shown in the figure, would fit the $\alpha\alpha$ data over the range $13 \leq E^0_{tot} \leq 25$ GeV. Above 25 GeV, however, the slope of the five-collision curve is $-1.00\ \mathrm{GeV}^{-1}$, which is 20% steeper than the slope of the $\alpha\alpha$ data in this E^0_{tot} range.

It should be noted that the interaction cross-section used for four collisions in Fig. 3 and in the above discussion is roughly equal to 10% of the observed $\alpha\alpha$ interaction cross-section.

In conclusion, the two-collision curve provides a reasonable description of the dd data in the limited range available, and the four simultaneous nucleon–nucleon collision curve is a good representation of the $\alpha\alpha$ data in the range $8 \leq E^0_{tot} \leq 17$ GeV, with the "equal probability" normalization described above. However, the E^0_{tot} spectrum in $\alpha\alpha$ does extend beyond the nucleon–nucleon kinematic limit of 31 GeV, and above 17 GeV it is even flatter than this extreme case in which four individual nucleon pairs are interacting.

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Figure captions

Fig. 1 : The apparatus viewed along the beam axis.

Fig. 2 : The neutral energy spectra for pp, dd, and $\alpha\alpha$ interactions at $\sqrt{s_{NN}} = 31$ GeV. a) Total neutral energy, E^0_{tot}. b) Transverse neutral energy, E^0_T.

Fig. 3 : The total neutral energy spectra of Fig. 2a together with curves representing the E^0_{tot} spectra produced by one, two, four, and five simultaneous pp collisions. All the curves have been normalized to the pp cross-section as explained in the text.

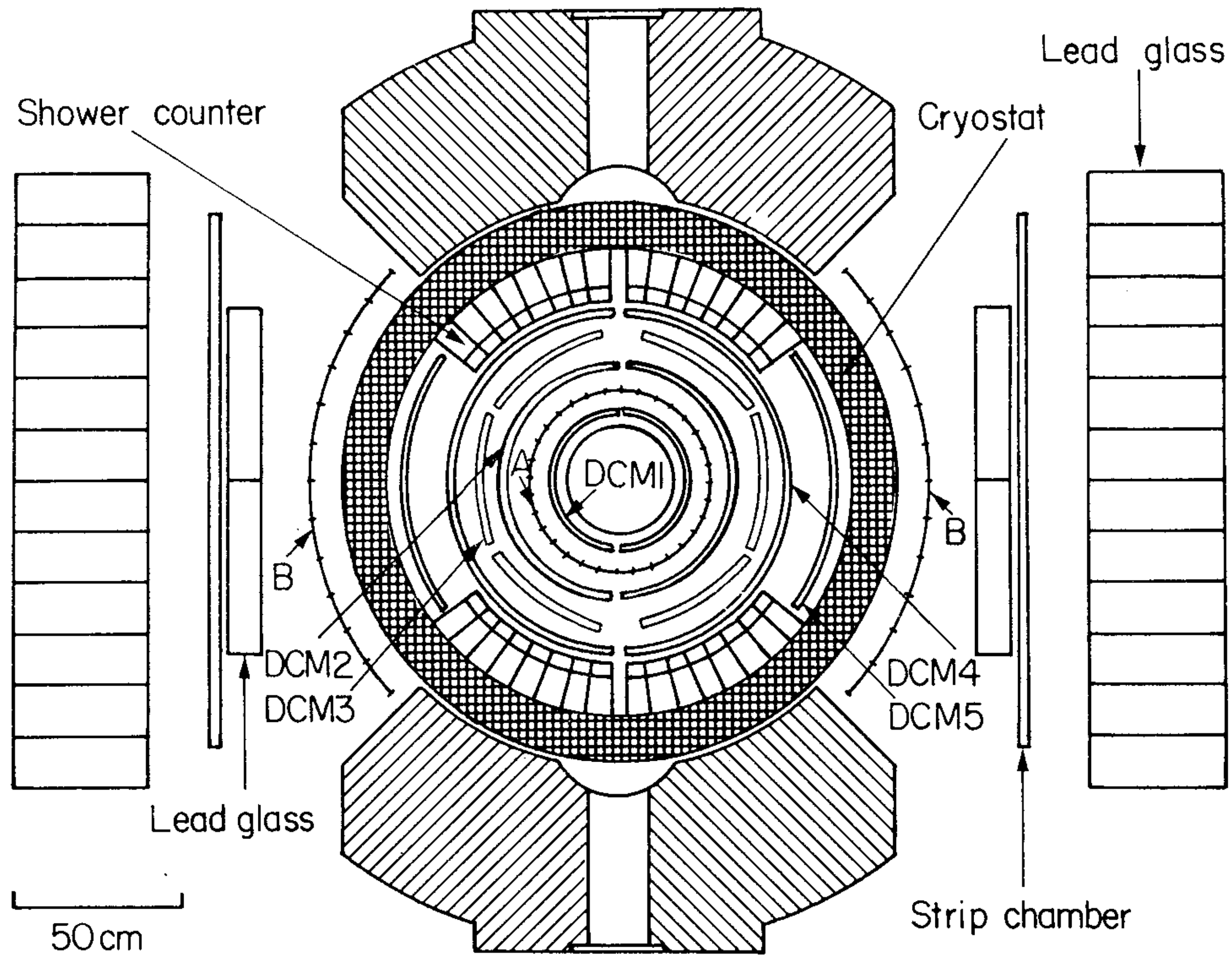

Lead glass
Shower counter
Cryostat
DCMI
A
B
B
DCM2
DCM3
DCM4
DCM5
Lead glass
Strip chamber
50 cm

Fig. 1

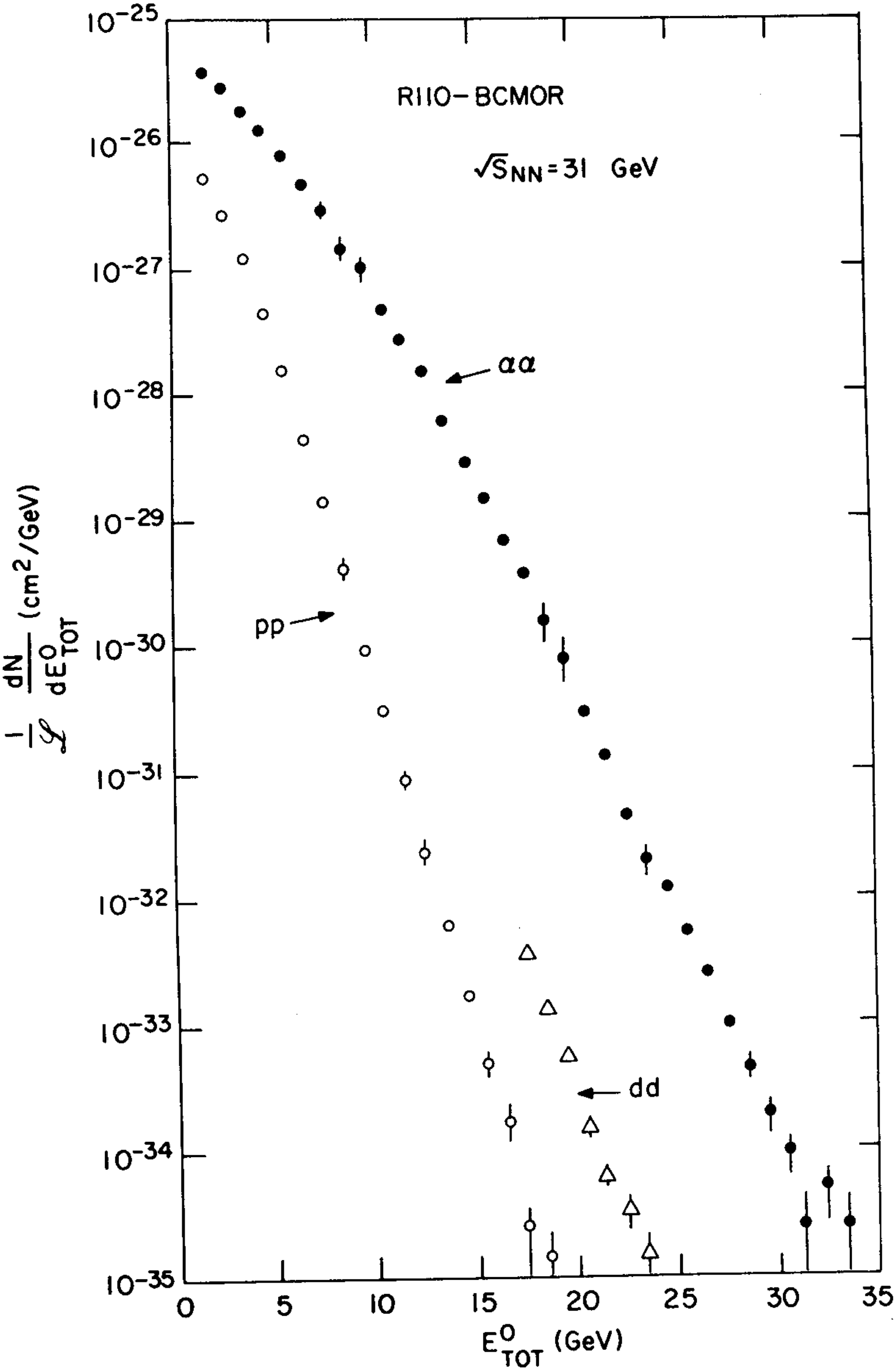
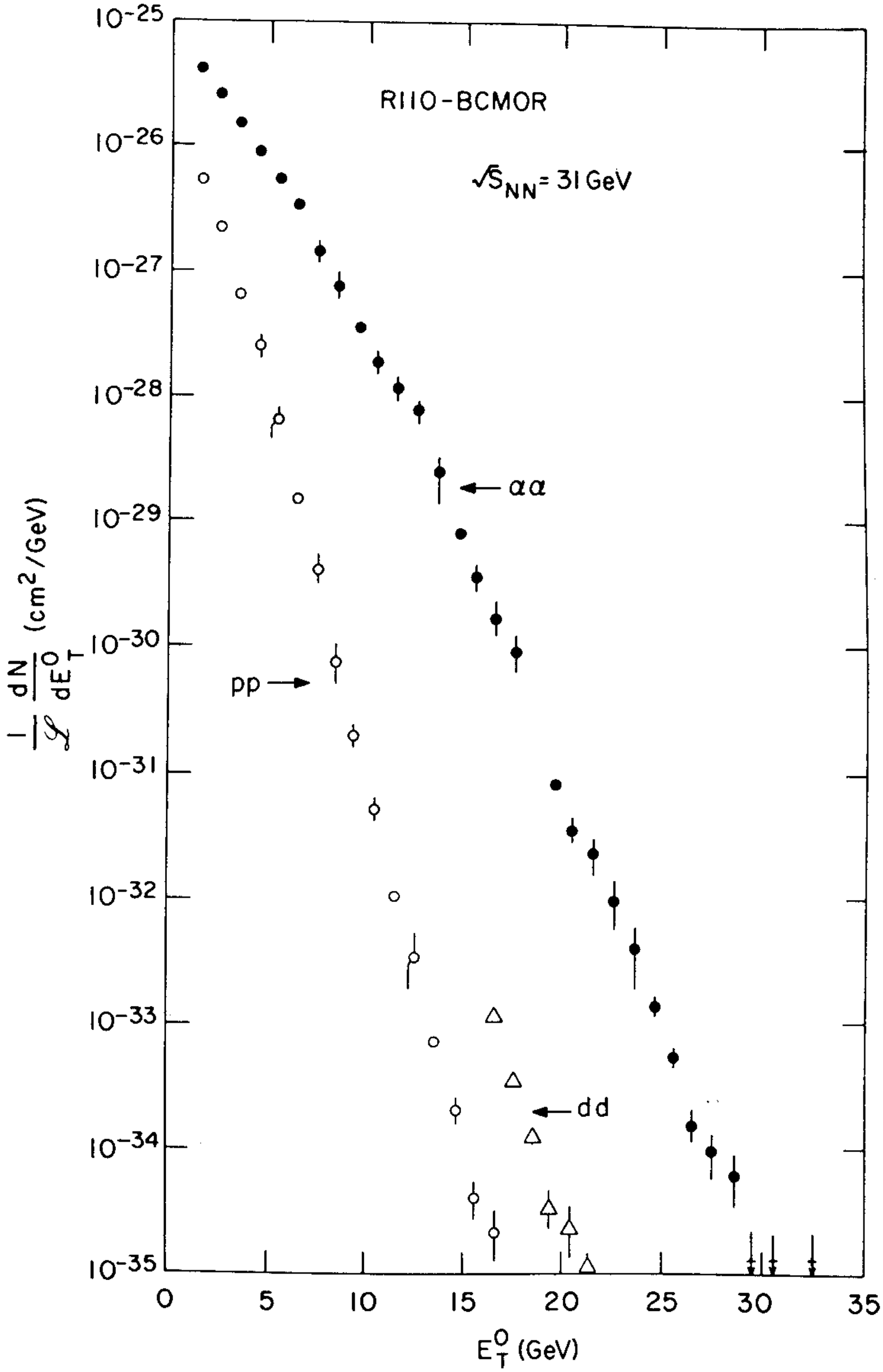
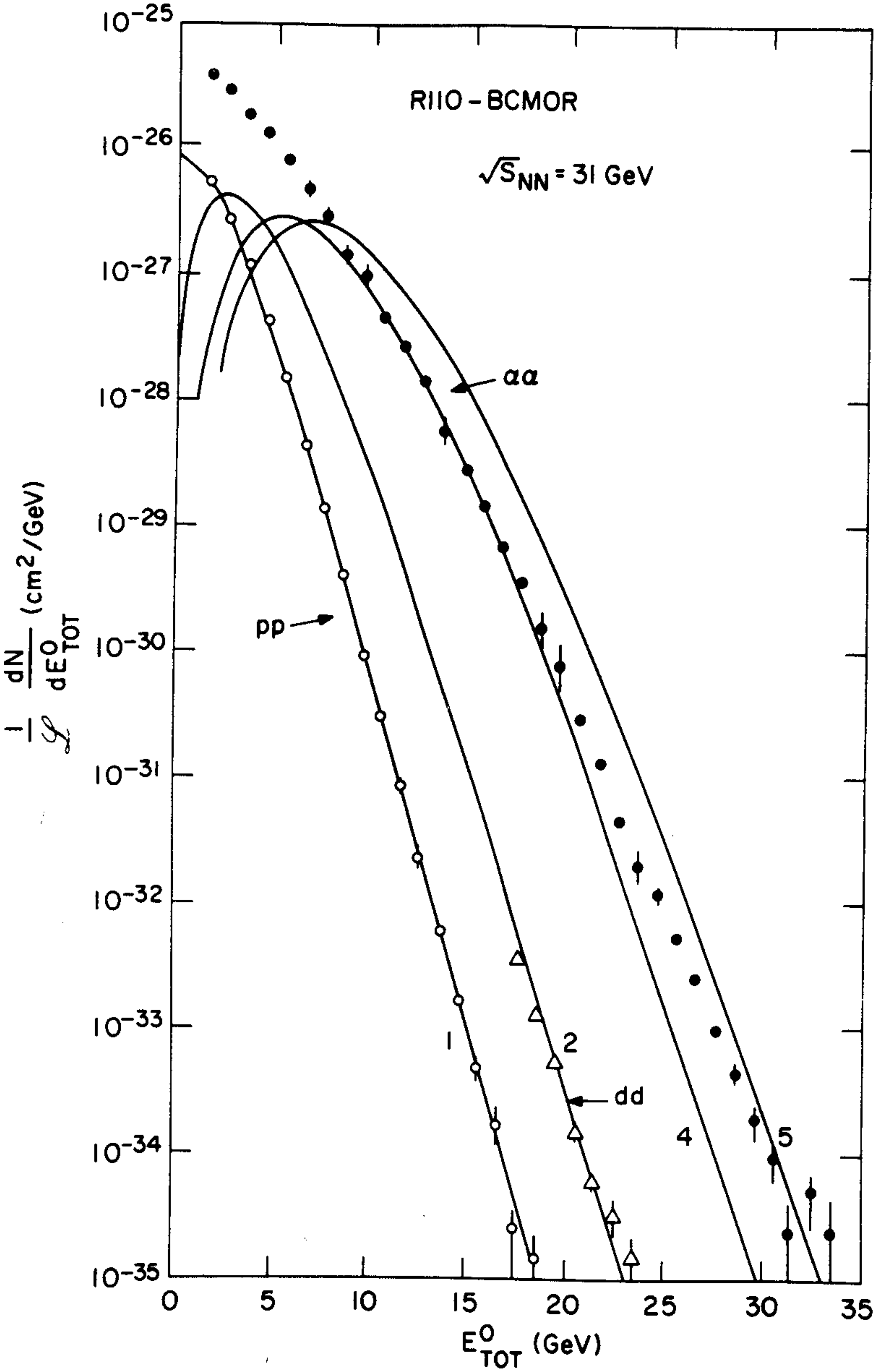

R110- BCMOR
√S NN = 31 GeV
αα
pp
dd
1/ℒ dN/dE⁰TOT (cm²/GeV)
E⁰TOT (GeV)
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
10⁻²⁹
10⁻³⁰
10⁻³¹
10⁻³²
10⁻³³
10⁻³⁴
10⁻³⁵
0
5
10
15
20
25
30
35

Fig. 2a



R110-BCMOR
$\sqrt{s}_{NN}$ = 31 GeV
αα
pp
dd
$\frac{1}{\mathscr{L}} \frac{dN}{dE_T^0}$ (cm²/GeV)
E_T^0 (GeV)

Fig. 2b



R110 - BCMOR
$\sqrt{S_{NN}}$ = 31 GeV
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
$\frac{1}{\mathcal{L}} \frac{dN}{dE^{0}_{TOT}}$ (cm^2/GeV)
αα
pp
dd
1
2
4
5
0
5
10
15
20
25
30
35
E^{0}_{TOT} (GeV)

Fig. 3