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Hadron Production at Intermediate Energies and Lund Area Law

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The Lund area law was developed into a Monte Carlo program LUARLW, which agrees well with the BEPC/BES R scan data.

1. INTRODUCTION

The hadron production mechanism in particle collisions is one of the important subjects in the study of strong interaction. In standard model (QCD), hadronization processes belong to a nonperturbative problem for which no practicable calculation is available. Some phenomenological hadronization models were built up, which play important roles in the studies toward the final understanding of strong interaction. The famous Lund string fragmentation model is one of the successful hadronization schemes, which contains several nontrivial dynamical features and describes the general semi-classical picture of hadron production. At high energies, Lund generator JETSET can simulate the processes of hadron production via single photon annihilation well, and predicts the correct properties of the final states. But the application of the Lund model at intermediate energies has been blank. A direct solution is to start from the basic assumptions of Lund model and find the solutions of the area law without adopting any high-energy approximation. Based on the Lund area law, a new generator LUARLW was compiled, which agrees well with BES data between 3–5 GeV (see Figure 1 on page 186).

2. LUND STRING FRAGMENTATION

The foundations of the Lund model (relativity, causality and quantum mechanics) are universal. The basic hadron production picture is string fragmentation. The produced new pairs ($q\bar{q}$) and ($q\bar{q}q\bar{q}$) may form mesons and baryons if they carry with the correct flavor quantum numbers, otherwise they just behave like the vacuum fluctuations and do not lead any observable effects in experiments (see Figure 1). Using the assumptions of very high energy approximation (the remaining string always has large energy scale), left–right symmetry (fragmentation from q_0 end or $\bar{q}_0$ end are identical) and iterative fragmentation (string fragmentation may be treated

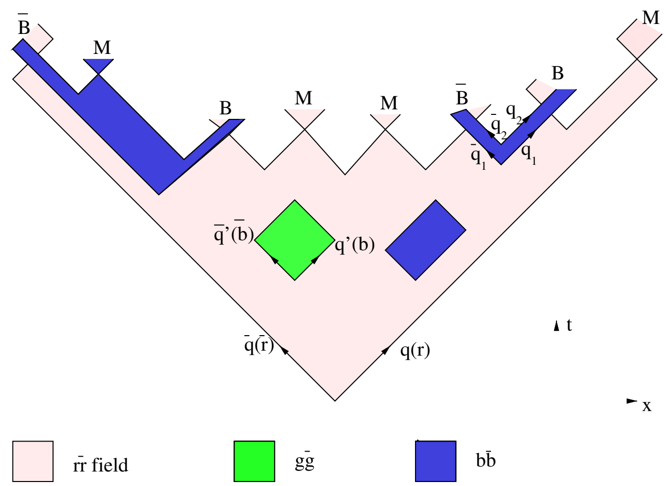

Figure 1: String fragmentation by a set of new pairs ($q\bar{q}$) and ($q\bar{q}q\bar{q}$) production, hadrons form at vertices

iteratively), Lund fragmentation function $f(z)$ was derived uniquely, which is used in JETSET to govern string fragmentation. The fragmentation function $f(z)$ has the characteristics of inclusive distribution, and the single particle production is independent of anything else before and after. The applicable region of $f(z)$, the remnant string, still has large invariant mass. At intermediate energies, the mass-shell conditions should be the component part of the fragmentation dynamics, therefore the string fragmentation has to be treated as an exclusive one instead of inclusive like in JETSET.

3. LUND AREA LAW

The Lund string fragmentation process is Lorentz invariant and factorizable. The finite energy (s) system containing n hadrons may be viewed as a cluster of infinite string fragmentation system with energy ($s_0 \to \infty$)

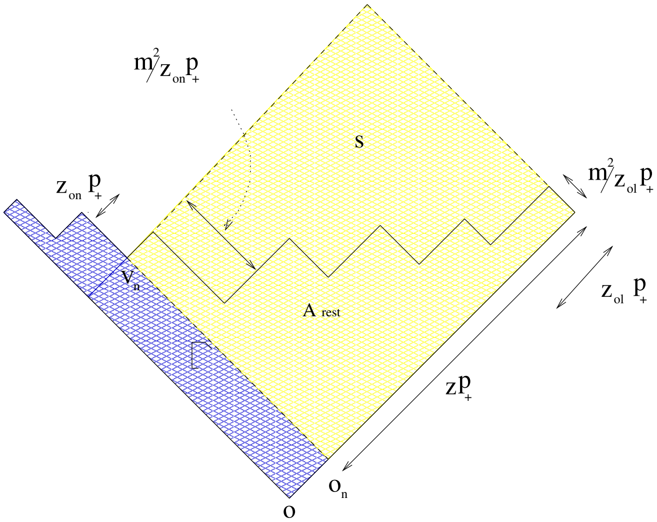

Figure 2: The situation after n steps fragmentation.

(see Figure 2). According to the general properties of iterative cascade, the combined distribution is

$$\begin{aligned} d\tilde{\wp}_n &= \prod_{j=1}^{n} f_j(z_j)dz_j \\ &= C_n \cdot d\wp_{\rm ext}(s,z) \cdot d\wp_n(u_1,\cdots,u_n), \end{aligned} \tag{1}$$

where, C_n is normalization constant. We know from (1) that a subsystem may be split up from the total system, the processes occurring in the subsystem is the same as a complete system starting at the some original energy s. The external part

$$d\wp_{\rm ext}(s,z) = ds\frac{dz}{z}(1-z)^a \cdot \exp(-b\Gamma) \tag{2}$$

corresponds to the probability that the cluster will occur. The internal part

$$\begin{aligned} d\wp_n(u_1,\ldots,u_n) = \delta^2(P_n - \sum_{j=1}^{n} p_{\circ j}) \\ \prod_{j=1}^{n} d^2p_{\circ j}\delta(p_{\circ j}^2 - m_{\perp j}^2)\exp(-b\mathcal{A}_n) \end{aligned} \tag{3}$$

corresponds to the exclusive probability that the cluster will decay into the particular channel containing the given n particles with energy-momentum $\{p_{\circ j}\}$ and nothing else. $\mathcal{A}_{\rm rest} = \mathcal{A}_n$ is the area enclosed by the quark and antiquark light-cone energy-momentum lines of n particles. The factor

$$|M|^2 \equiv \exp(-b\mathcal{A}_n) \tag{4}$$

may be viewed as the squared matrix element, the other parts are phase-space elements. In formulas, b is fundamental color-dynamical parameters. Distribution (3) is called Lund area law. The total area

$$\mathcal{A}_{\rm tot} = \sum_{j=1}^{n} \mathcal{A}_j = \mathcal{A}_n + \Gamma, \qquad \Gamma = \frac{s(1-z)}{z} \tag{5}$$

and

$$\mathcal{A}_n = \sum_{j=1}^{n} \frac{m_{\perp j}^2}{z_j} \cdot \left(\sum_{k=j}^{n} z_k\right). \tag{6}$$

Finishing the integral over kinematic variables, area law has the following forms:

- String $\Rightarrow$ 2 hadrons

$$\wp_2 = \frac{C_2}{\sqrt{\lambda}}\left[\exp(-b\mathcal{A}_2^{(1)}) + \exp(-b\mathcal{A}_2^{(2)})\right]. \tag{7}$$

- String $\Rightarrow$ 3 hadrons

$$d\wp_3 = \frac{C_3}{\sqrt{\Lambda}}\exp(-b\mathcal{A})d\mathcal{A}. \tag{8}$$

- String $\Rightarrow 4,5,6$ hadrons

$$\begin{aligned} d\wp_n(s) &= \frac{ds_1 ds_2}{\sqrt{\lambda(s,s_1,s_2)}}\exp(-b\Gamma) \\ &\quad \wp_{n_1}(s_1,\mathcal{A}_1)\wp_{n_2}(s_2,\mathcal{A}_2). \end{aligned} \tag{9}$$

In above fragmentation distributions, the gluon effects are neglected. At intermediate and low energies, the emitted gluons from initial quark or antiquark are usually soft, most of which will stop before the string starts to break, the effect of the gluon will then essentially be a small transverse broadening of a two-jet system, the gluon and quark will then look as a single quark jet. The gluon emissions do not significantly change the topological shapes (sphericity and thrust) of final states, and therefore no observable jet effects.

4. MULTIPLICITY

Define dimensionless n-particle partition function

$$Z_n = s\int dR_n \cdot \exp(-b\mathcal{A}), \tag{10}$$

where dR_n is the n-particle phase space element. The relation between Z_n and the multiplicity distribution $\tilde{P}_n$ for primary hadrons is

$$\tilde{P}_n = \frac{Z_n}{\sum Z_n}. \tag{11}$$

$\tilde{P}_n$ has the approximative expression

$$\begin{aligned} \tilde{P}_n &= \frac{\mu^n}{n!}\cdot\exp[c_0 + c_1(n-\mu) \\ &\qquad + c_2(n-\mu)^2], \qquad (c_2 < 0). \end{aligned} \tag{12}$$

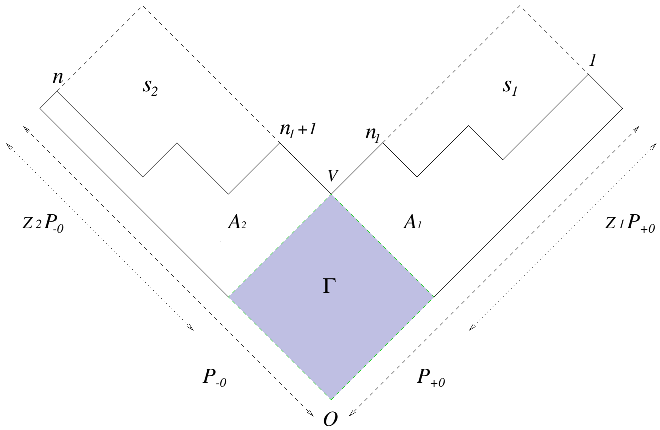

Figure 3: The vertex V divides the n-body string fragmentation into two clusters which contain n_1 and n_2 hadrons and with squared invariant masses s_1 and s_2 separately.

Quantity μ may be written as the energy-dependent form

$$\mu = a + b \cdot \exp(c\sqrt{s}), \tag{13}$$

or

$$\mu = a + b\ln(s) + c\ln^2(s). \tag{14}$$

All parameters a, b, c, c_0, c_1, and c_2 need to be determined by experimental data and were tunned with BES data samples of R scan.

5. EXCLUSIVE DISTRIBUTION

There are some different production channels for n-particle states, such as 4-body states may be $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-\pi^\circ\pi^\circ$, $\rho^+\rho^-\pi+\pi^-$, etc. The exclusive probability for the special channel is

$$\hat{P}_n = B_n \cdot (VPS) \cdot (SUD) \cdot \wp_n(m_{\perp 1}, \ldots, m_{\perp n}; s). \tag{15}$$

- B_n is the combinatorial number stemming from may be more than one string configurations lead to this state.
- (VPS) is the vector to pseudoscalar rate.
- (SUD) is the strange to up and down quark pair probability.

6. TRANSVERSE MOMENTUM DISTRIBUTION

The above results are obtained when the transverse momentums of all primary hadrons have given. In the Lund model, the quantum mechanical tunneling effect was used to explain the production of new pairs $q_i\bar{q}_i$. The particles obtain their transverse momenta from the constituents. At each production point the $(q_i\bar{q}_i)$-pair is given $\pm\mathbf{q}_i$ and the particle momenta are

$$\mathbf{p}_{\perp 1} = \mathbf{q}_1, \ldots \mathbf{p}_{\perp j} = \mathbf{q}_j - \mathbf{q}_{j-1}, \ldots \mathbf{p}_{\perp n} = -\mathbf{q}_n. \tag{16}$$

From the Lund model, the following distribution with forward–backward symmetric correlation was derived

$$\begin{aligned} &F^{(n)}(\mathbf{q}_1, \ldots, \mathbf{q}_n) \\ &\quad = C_n \exp\left\{-\frac{1}{2\sigma^2}\left[\mathbf{q}_1^2 + \frac{(\mathbf{q}_2 - \rho_2\mathbf{q}_1)^2}{1-\rho_2^2}\cdots\right]\right\} \\ &\quad = C_n \exp\left\{-\frac{1}{4\sigma^2}\left[\mathbf{q}_1^2 + \mathbf{q}_n^2\right.\right. \\ &\qquad\quad \left.\left. + \sum A_j(\mathbf{q}_j^2 + \mathbf{q}_{j-1}^2 - 2\varepsilon_j\mathbf{q}_j \cdot \mathbf{q}_{j-1})\right]\right\}, \end{aligned}$$

with

$$A_j = \frac{(1+\rho_j^2)}{(1-\rho_j^2)}, \qquad \varepsilon_j = \frac{2\rho_j}{(1+\rho_j^2)}.$$

The correlations ρ_j are phenomenological parameters, which in general are small.

ACKNOWLEDGEMENT

This work was done under the instruction of Professor Bo Andersson. All the knowledge about Lund model may be found in The Lund Model by Bo Andersson, Cambridge University Press, Cambridge, 1998.

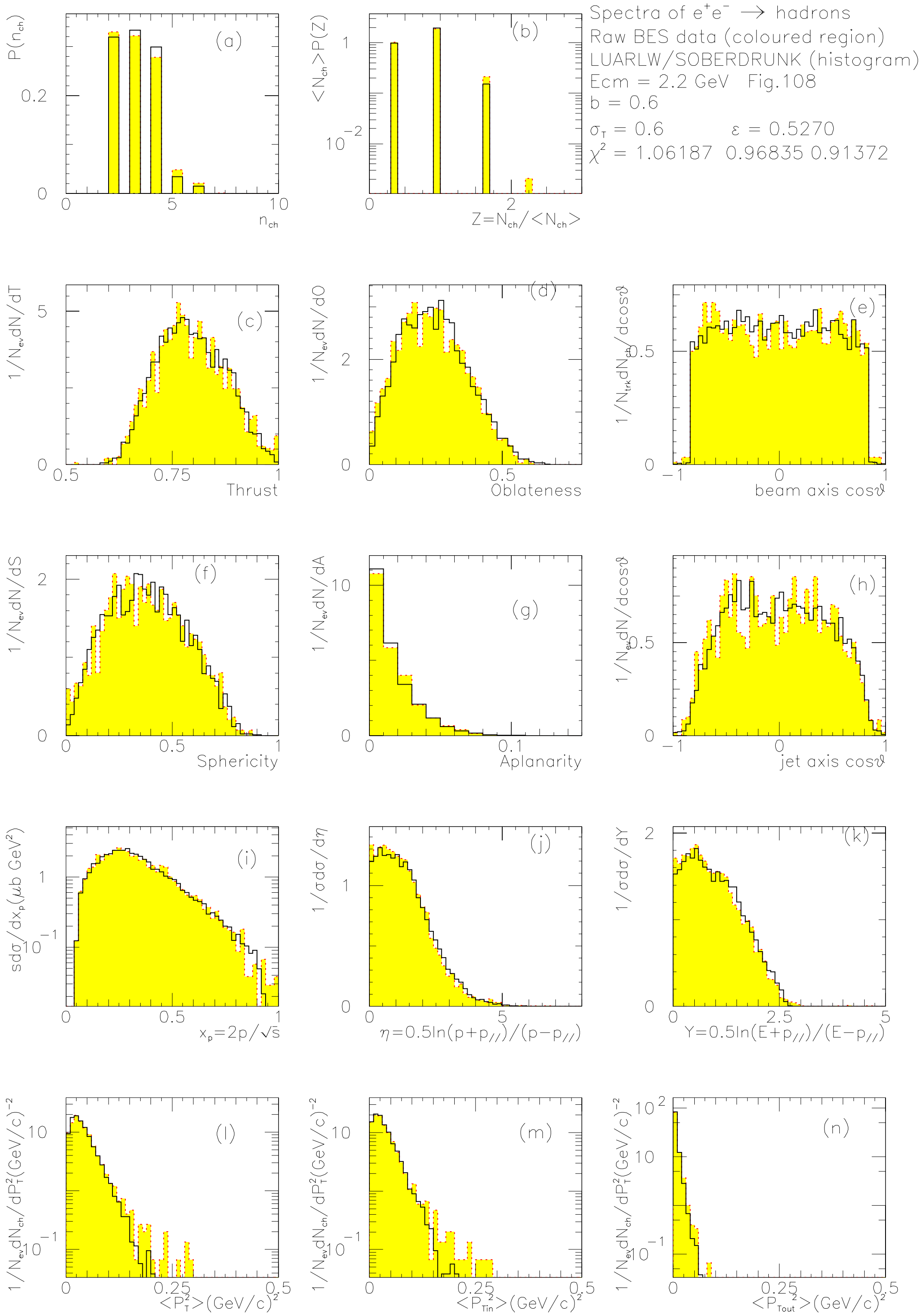

Figure 1: $e^+e^- \to$ hadrons spectrum of raw BES data (hatched region) and LUARLW/SOBDRUNK (black line) at $Ecm = 2.2$ GeV.