R Measurement at BES and Hadronic Production in BEPC Energies

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R Working Group, BES Collaboration

- R Experiment
- Lund Area Law
- Hadronic Spectrum
- Summary

Experiment Formula

R values are measured by following way

$$R = \frac{\sigma^0_{had}}{\sigma^0_{\mu\mu}} = \frac{N^{obs}_{had} - N_{bg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma^0_{\mu\mu} \cdot \varepsilon_{had} \cdot \varepsilon_{trg} \cdot (1+\delta) \cdot \mathcal{L}}$$

N_{obs} : the observed hadronic events

N_{bg} : beam-associated backgrounds

N_{ll} : lepton pair backgrounds

$N_{\gamma\gamma}$: two-photon process events

$\mathcal{L}$: integrated luminosity

$(1+\delta)$: radiative correction

ε_{had}: detection efficiency

ε_{trg}: trigger efficiency

Previous status of R values

R has been measured in the energy region from hadron production threshold to the Z^0 pole.

Table 1: Uncertainties of R in different energy region

E_{cm}(GeV)	$1-5$	$5-10$	$10-m_Z$
$\Delta R/R(\%)$	$15-20$	$5-10$	$2-7$

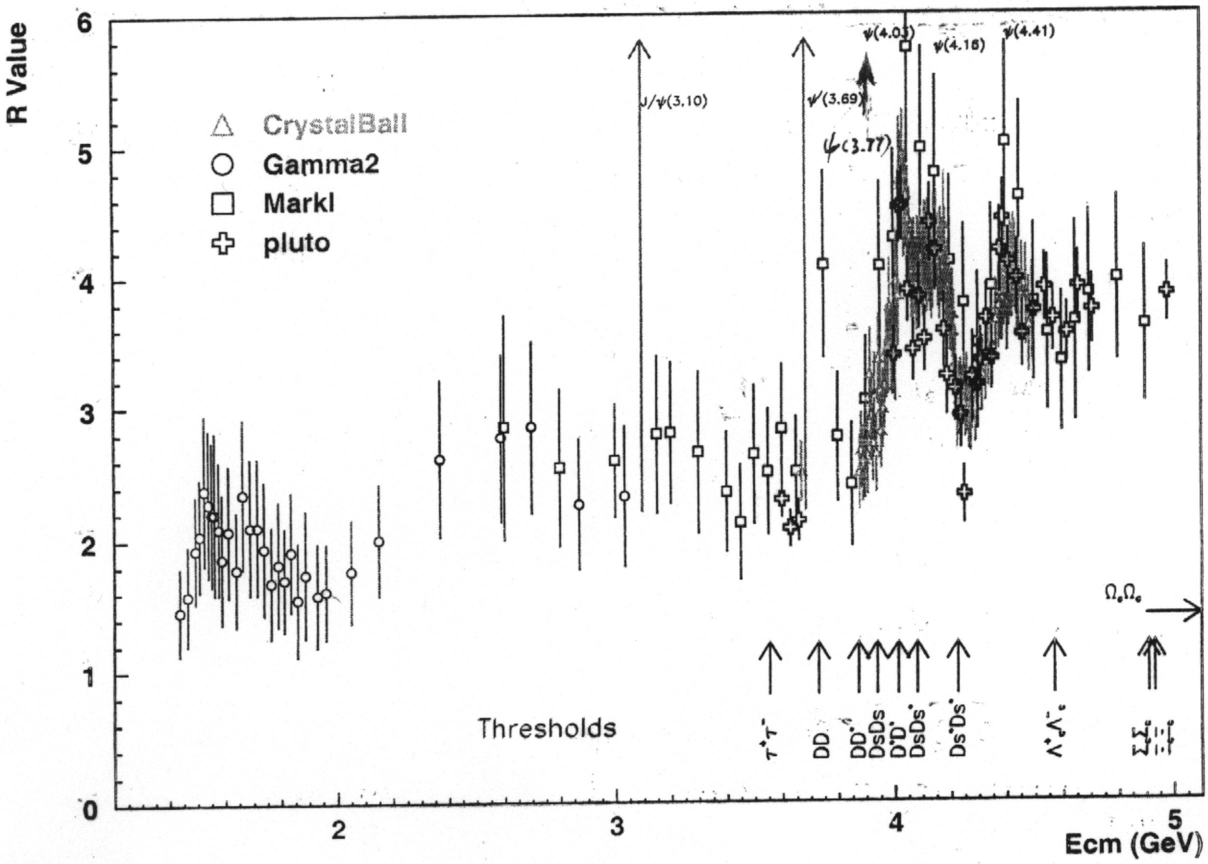


Figure 1: Previous R measurements below 5 GeV, last experiment carried out almost 20 years ago.

The First Run (Spring '98)

- 6 energy points scaned
- Results published in PRL 84(2000)594-597

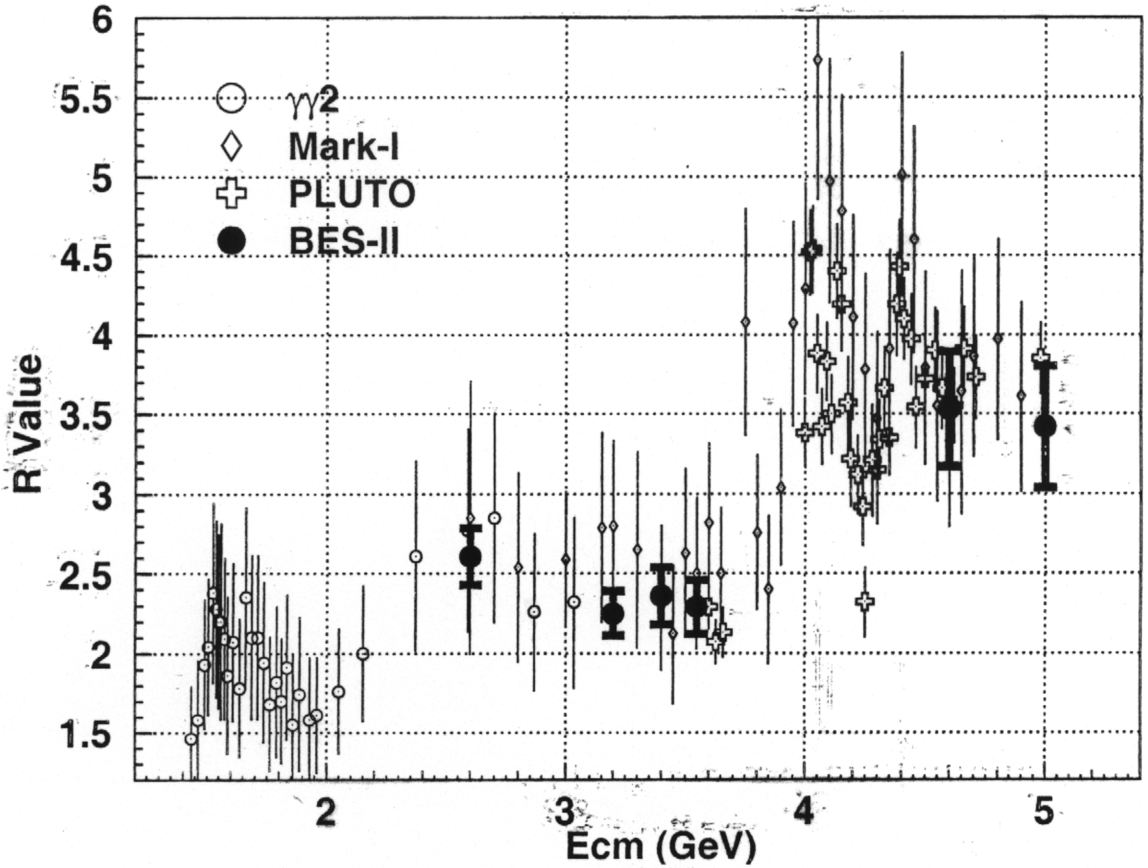


Figure 2: Plot of R values vs E_{cm}.

The Second Run (Spring '99)

- 85 energy points,

  24 points with separated-beam data

  7 points with also single-beam data

- The results will be published in PRL 88 (2002) 101802

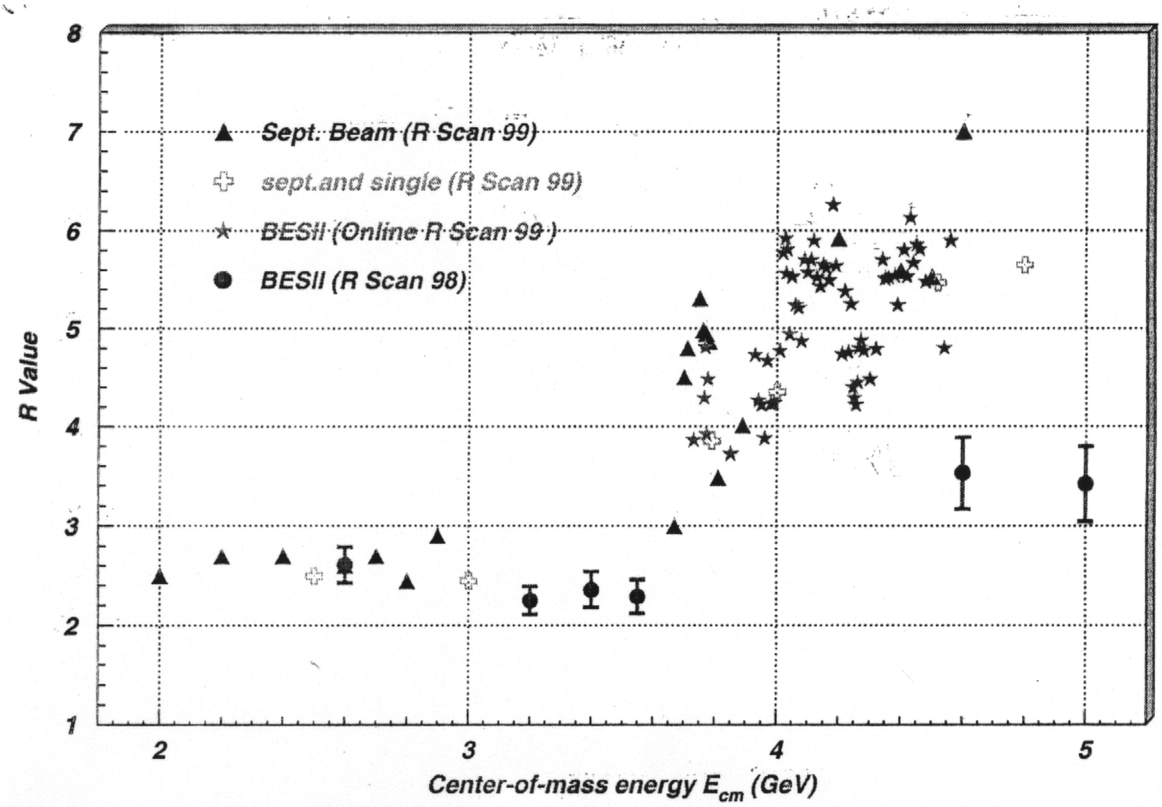


Figure 3: Data status of R scan ('98 and '99 runs)

Final Results

BEPC/BES obtained R values at 6 + 85 energy points in $2-5$GeV region with uncertainties of $\underline{5\sim10\%}$ (the average is 6.6%).

Table 2: Error Contributions at Several Typical Energies

E_{cm}(GeV)	had.sel.	L	had.eff.	trig.	rad.corr.	sys.	stat	tot.
2.000	7.07	2.81	2.62	0.5	1.06	8.13	3.16	8.72
3.000	3.30	2.30	2.66	0.5	1.32	5.02	2.49	5.61
4.000	2.64	2.43	2.25	0.5	1.82	4.64	4.44	6.42
4.800	3.58	1.74	3.05	0.5	1.02	5.14	3.79	6.38
average	3.5	2.3	2.5	0.5	1.2	5.1	4.2	6.6

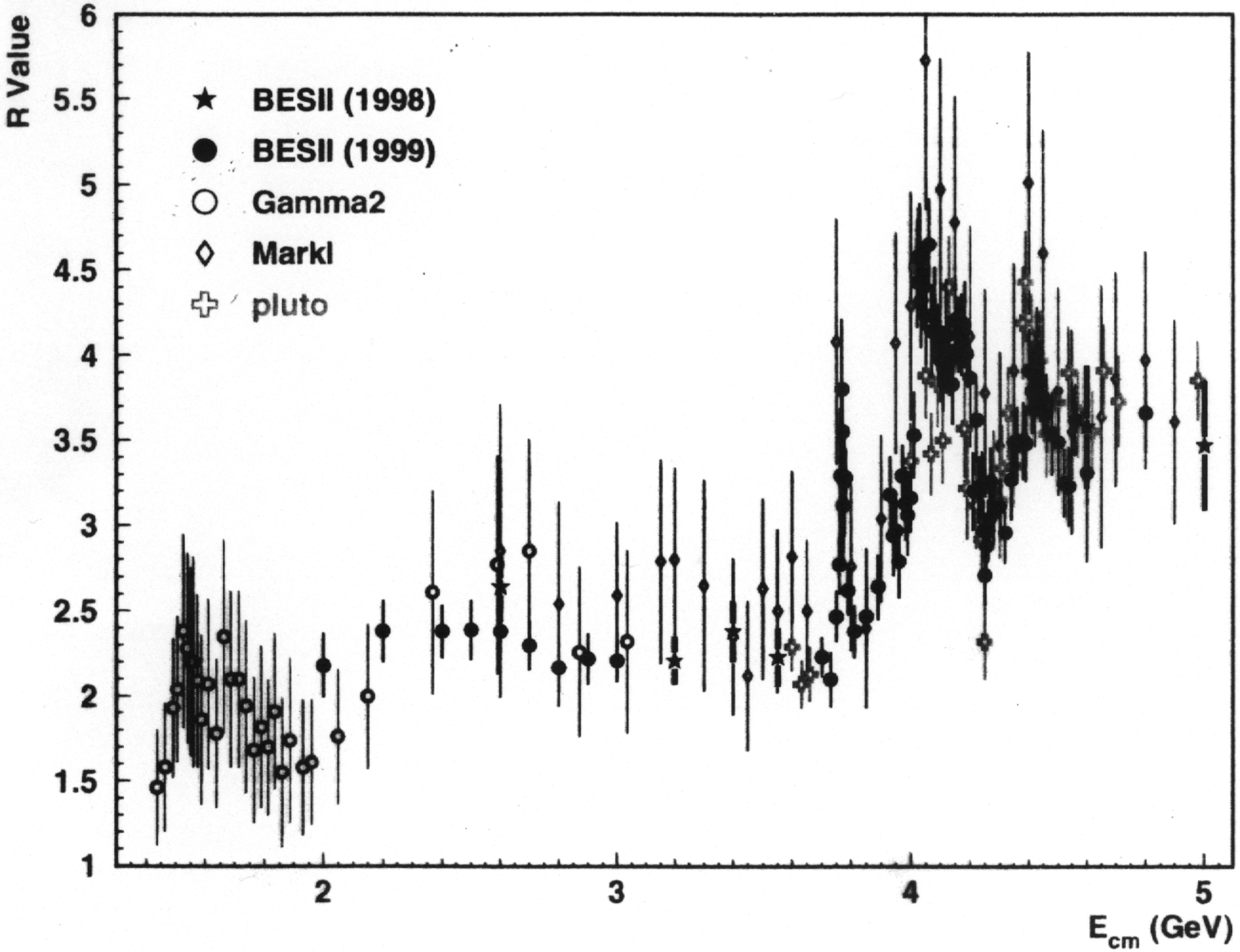


Figure 14: R values in $1-5$ GeV energy region

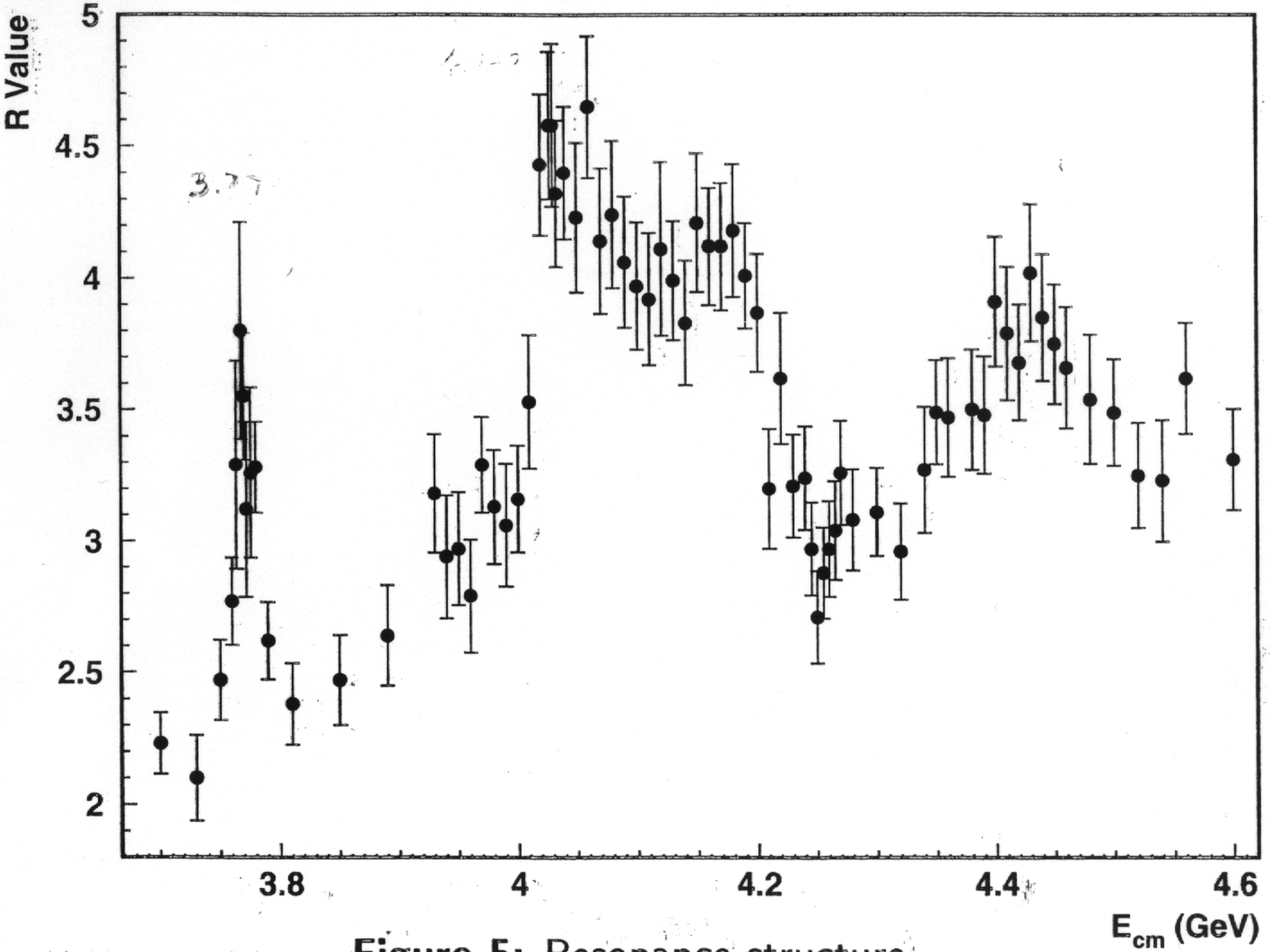
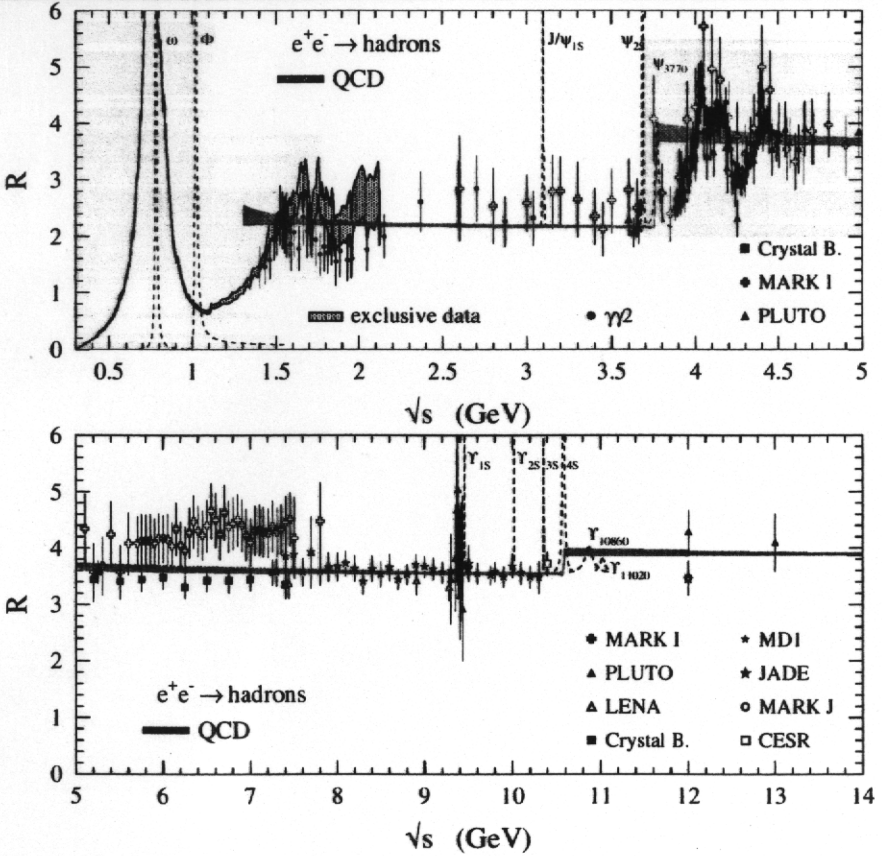


Figure 5: Resonance structure



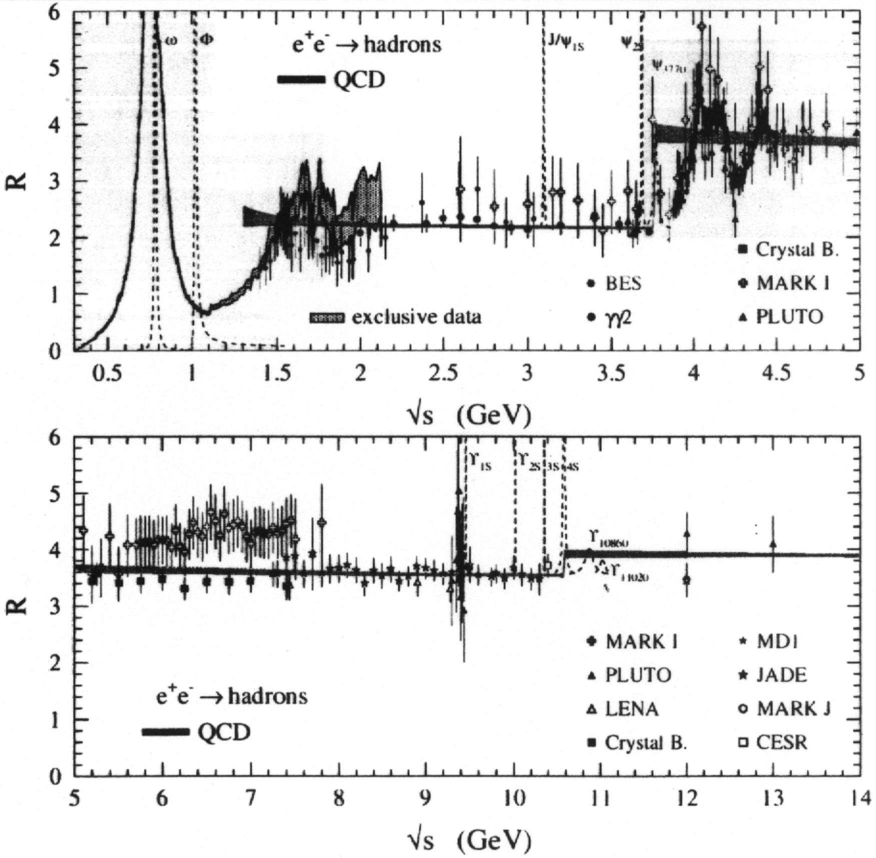


Figure 18: R values and pQCD prediction without BES R results

Figure 19: R values and pQCD prediction with BES R results

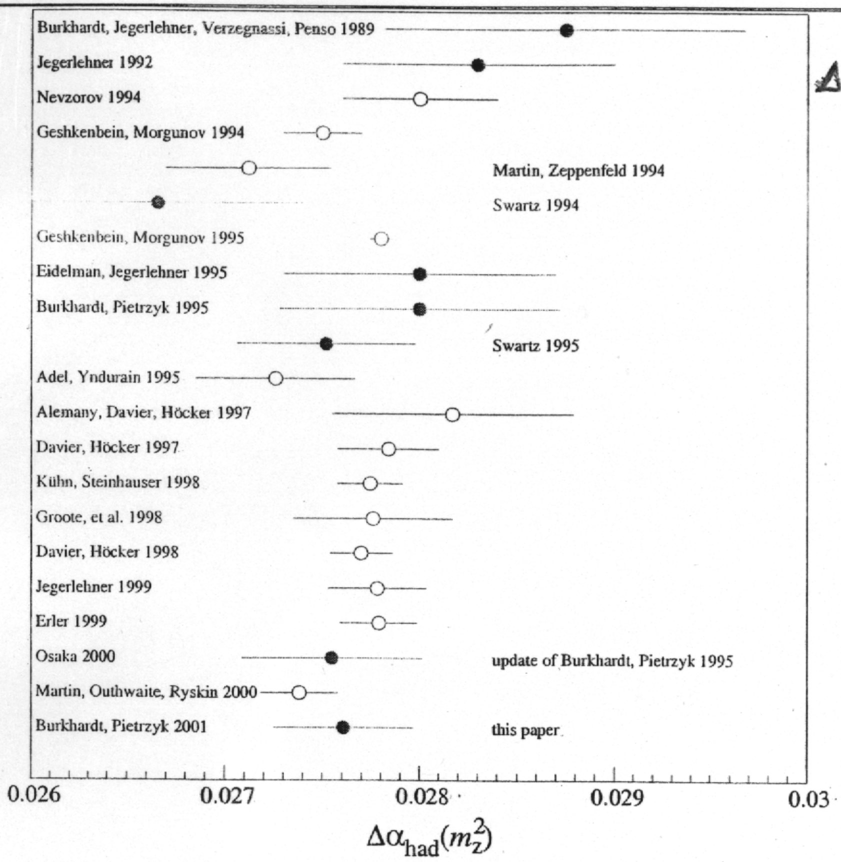


Figure 11: Recent evalutions of $\Delta\alpha^{(5)}_{had}(m_Z^2)$, including BES R results

$\Delta\alpha_h^{(5)}(M_Z^2)$

$\delta(\Delta\alpha^{(5)}_{had}(M_Z^2))$

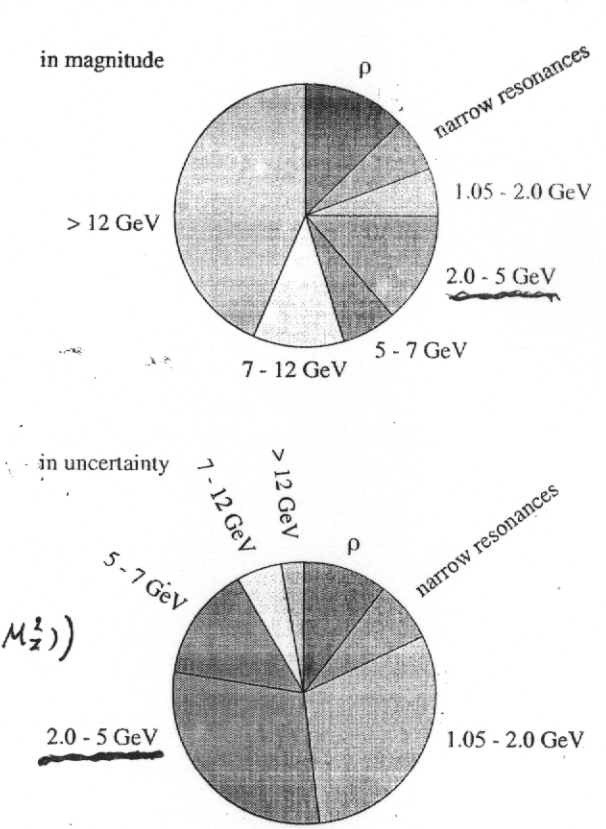


Figure 12: Relative contributions to $\Delta\alpha^{(5)}_{had}(m_Z^2)$ in magnitude and uncertainty

A higher precision measurement of R will have a significant impact on the test of electroweak and QCD predictions.

The R values from BES have an average uncertainty of about 6.6%, which represents a factor of 2/3 improvement compared to previous experiments between $2-5$ GeV.

One of the most difficult problems in R measurement is getting a reliable hadronization model in intermediate energies.

A special joint effort was made by Lund group and the BES collaboration to develop the generator LUARLW, which uses a formalism based on the Lund area law.

LUND AREA LAW

1. Problem of Hadronization
2. Lund string fragmentation scheme
3. Derivation of the area law
4. Solution of the area law
5. Multiplicity of primary hadron
6. Exclusive probability
7. Monte Carlo results and BES data

Problem of Hadronization

Hadronization processes belong to nonperturbative QCD problem and have not theoretical calculation available yet. This phase is even more prominent at intermediate and low energies.

Some hadronization models were built up. The famous Lund string fragmentation model is one of the most successful hadronization scheme. It has been tested well at high energies.

But JETSET is not built in order to describe few-body states at the few GeV level in e^+e^- annihilation.

The application of Lund model at intermediate energies has being blank. A direct way to solve this problem is to start from the basic assumptions of Lund model and find the solutions of the area law.

At intermediate energies, the emitted gluons from initial qurk and antiquark are usually soft. The gluon jets do not significantly change the topological shapes of final states, and therefore no observable jet effect.

Lund string fragmentation scheme

The hadron production picture is that string fragmentation by a set of new pairs $(q\bar{q})$ and $(q\bar{q}q\bar{q})$ production, hadrons form at vertices.

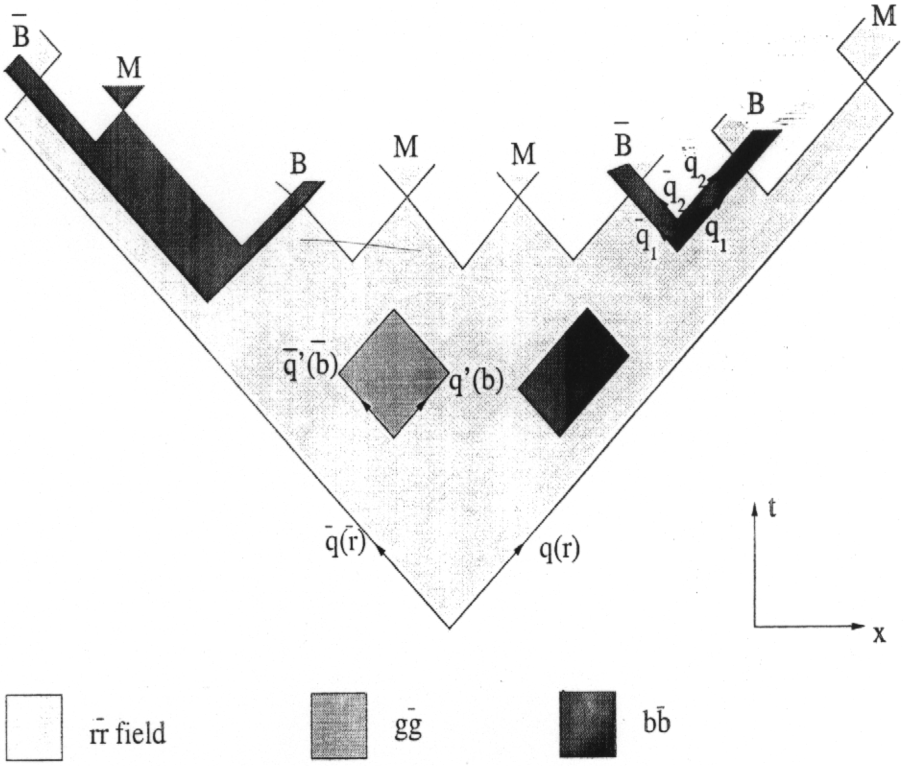


Figure 15: *String fragmentation in $t-x$ space. The produced new pairs $(q\bar{q})$ and $(q\bar{q}q\bar{q})$ may form mesons and baryons if they carry with the correct flavor quantum number, othewise they just behave like the vacuum fluctuations and do not lead any observable effects in experiments.*

Under the following three assumptions:

- Very high energy approximation
- Left-right symmetry in fragmentation
- Iterative fragmentation

Lund fragmentation function has the unique form

$$f(z) = \frac{N}{z}(1-z)^a exp(-\frac{bm^2}{z})$$

a and b are parameters, z is the fraction of light-cone momentum.

$f(z)$ is used in JETSET to govern string fragmentation, its applicable region is the remnant string still has large invariant mass.

At intermediate energies, the string usually fragments into $2 \sim 6$ direct hadrons, the assumptions used to derive $f(z)$ are too much rough.

The string fragmentation have to be treated as exclusive one instead of inclusive like in JETSET.

Derivation of the area law

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

The processes occurring in subsystem is the same as it be a complete system starting at the some original energy s.

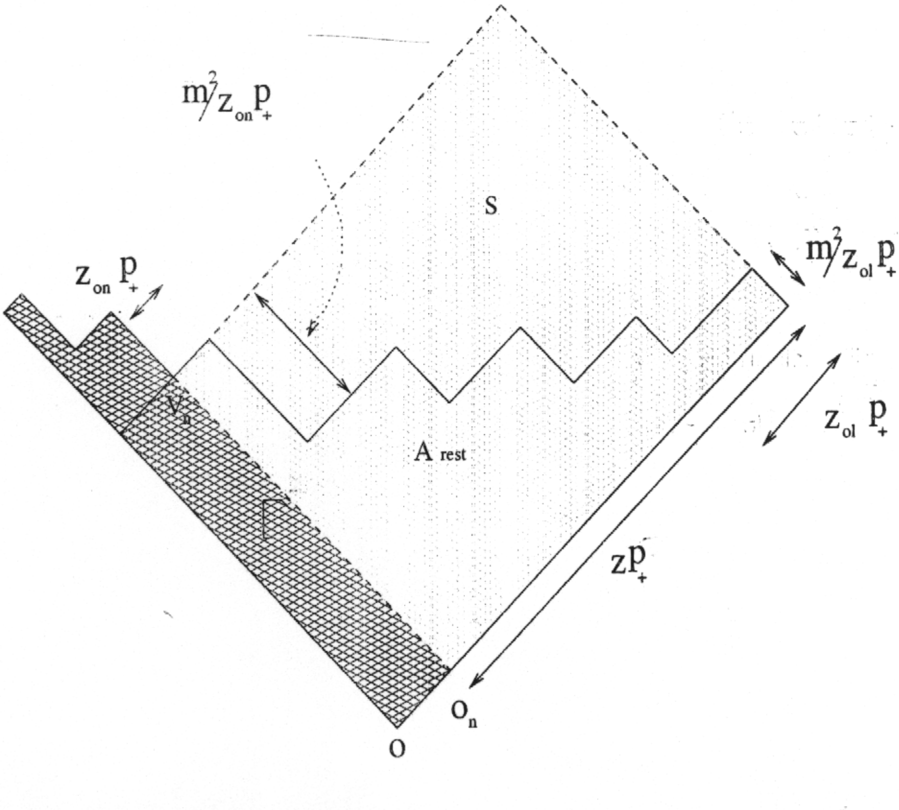


Figure 16: *The situation after n steps fragmentation. s is the squared invariant mass of the n-hadrons subsystem, $\mathcal{A}_{rest} = \mathcal{A}_n$ is the area enclosed by the quark and antiquark light-cone momentum lines of n particles.*

According to the general properties of iterative cascade, the combined distribution is

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

The external part

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

corresponds to the probability that the cluster will occur. The internal part (area law)

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

corresponds to exclusive probability that the cluster will decay into n-particle channel.

The factor

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

may be viewed as the squared matrix element, $\mathcal{A}_n$ is the area enclosed by the quark and antiquark light-cone momentum lines of n particles.

Solution of the area law

Finishing the integral of area law, the exclusive distribution for producing just n particles has following form

$$d\wp_n(s,\mathcal{A}) = F_n(s,\mathcal{A})d\mathcal{A}.$$

- String ⇒ 2 hadrons

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

- String ⇒ 3 hadrons

$$d\wp_3 = \frac{C_3}{\sqrt{\Lambda}}exp(-b\mathcal{A}_3)d\mathcal{A}_3,$$

•String ⇒ $4, 5, 6$ hadrons

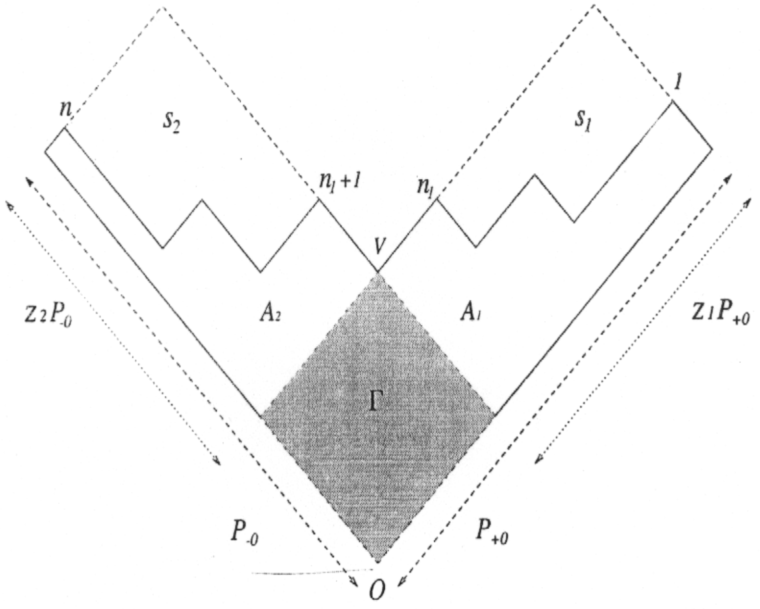


Figure 17: *The vertex V divides the n-body string fragmentation into two clusters which contain n_1 and n_2 hadrons and with squared invariant masses s_1 and s_2 separately*

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

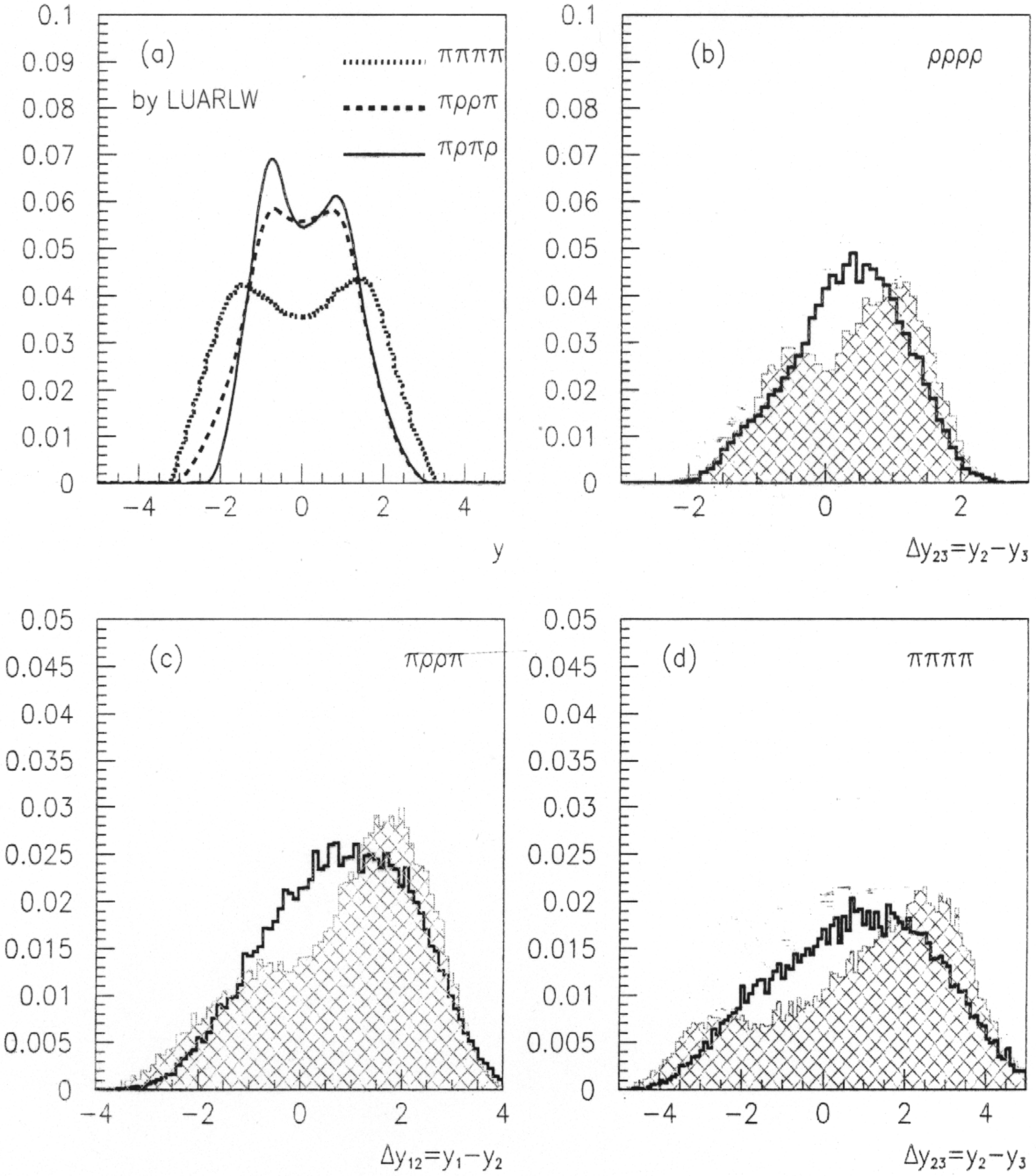


Figure 18: *The distributions of rapidity and rapidity differences for some special final states at* $\sqrt{s} = 4\ GeV$ *predicted by JETSET (the hatched regions) and LUARLW (the solid lines).*

Multiplicity of primary hadrons

Define dimensionless n-particle partition function

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

where, dR_n is the n-particle phase space element.

The relation between multiplicity distribution and Z_n is

$$\tilde{P}_n = \frac{Z_n}{\sum Z_n},$$

which has the approximative expression

$$\tilde{P}_n = \frac{\mu^n}{n!} \cdot exp[c_0 + c_1(n-\mu) + c_2(n-\mu)^2], \quad (c_2 < 0).$$

Free parameters

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

or

$$\mu = a + b\ ln(s) + c\ ln^2(s).$$

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

Exclusive probability

There are different production channels for n-particle states. Such as 4-body state may be

$$\pi^+\pi^-\pi^+\pi^-, \quad \pi^+\pi^-\pi^\circ\pi^\circ, \quad \rho^+\rho^-\pi+\pi^-, \quad \text{etc.}$$

The probability for the special channel is

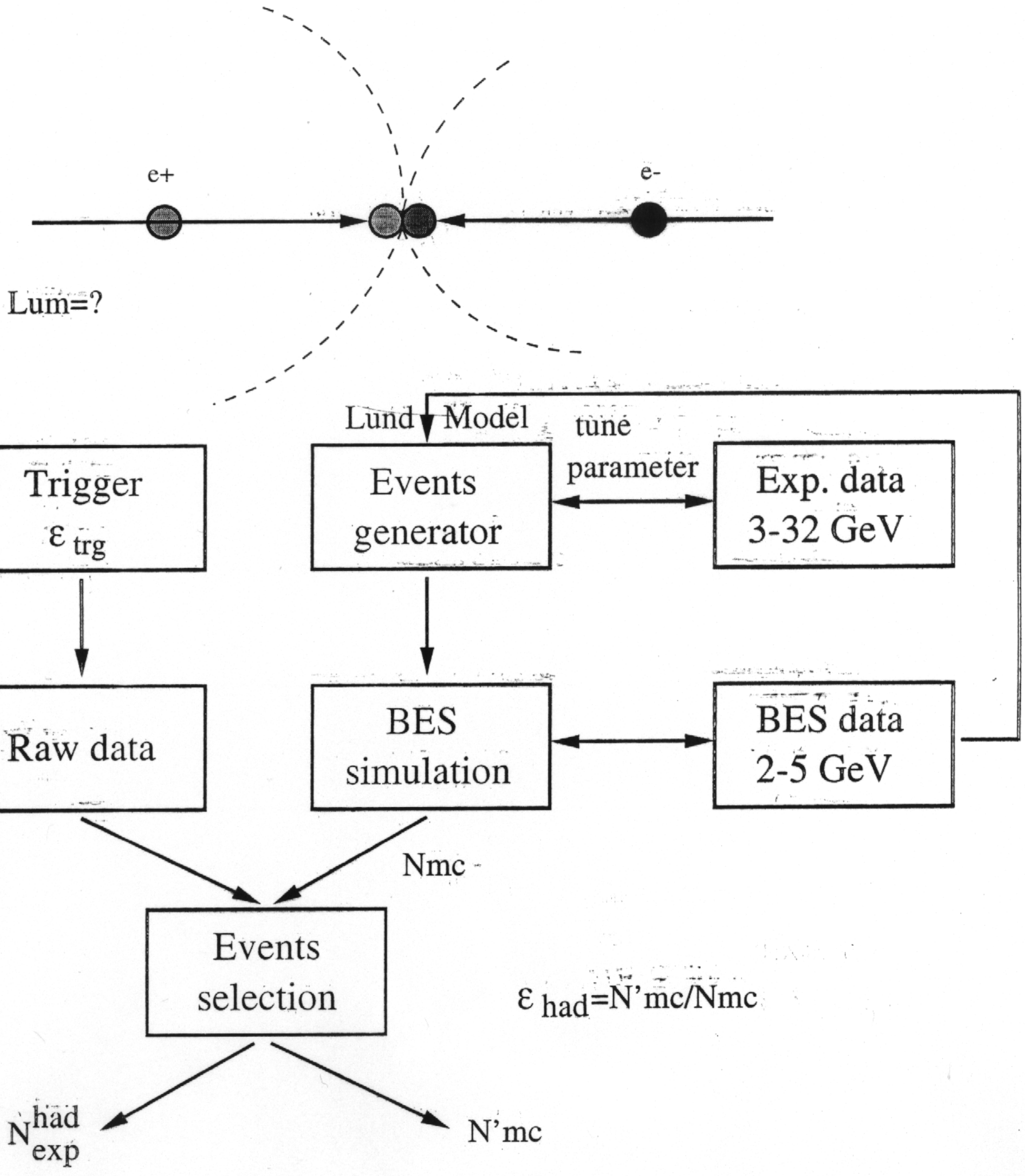
$$\hat{P}_n = B_n \cdot (VPS) \cdot (SUD) \cdot \wp_n(m_{\perp 1}, \cdots, m_{\perp n}; s).$$

- B_n is the combinatorial number stemming from may be more string configurations lead to the same state.

- (VPS) is the vector to pseudoscalar rate.

- (SUD) is the strange to up and down quark pair probability.

Flow Chart of Data Analysis



e+

e-

Lum=?

Lund Model

tune parameter

Trigger ε_{trg}

Events generator

Exp. data 3-32 GeV

Raw data

BES simulation

BES data 2-5 GeV

Nmc

Events selection

$\varepsilon_{had} = N'mc/Nmc$

N^{had}_{exp}

N'mc

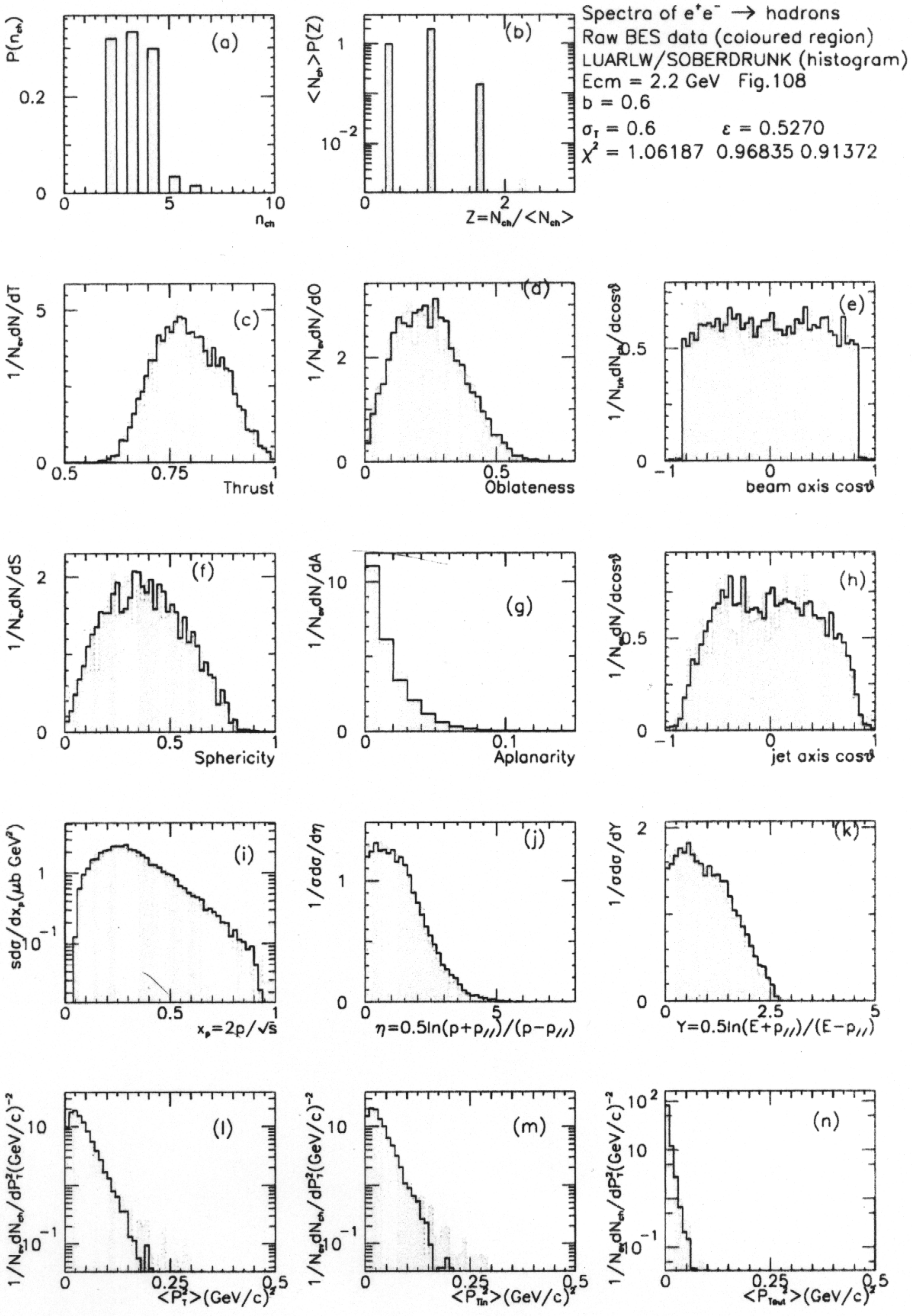


Figure 10: Event shapes at 2.2 GeV, Lund AreaLaw

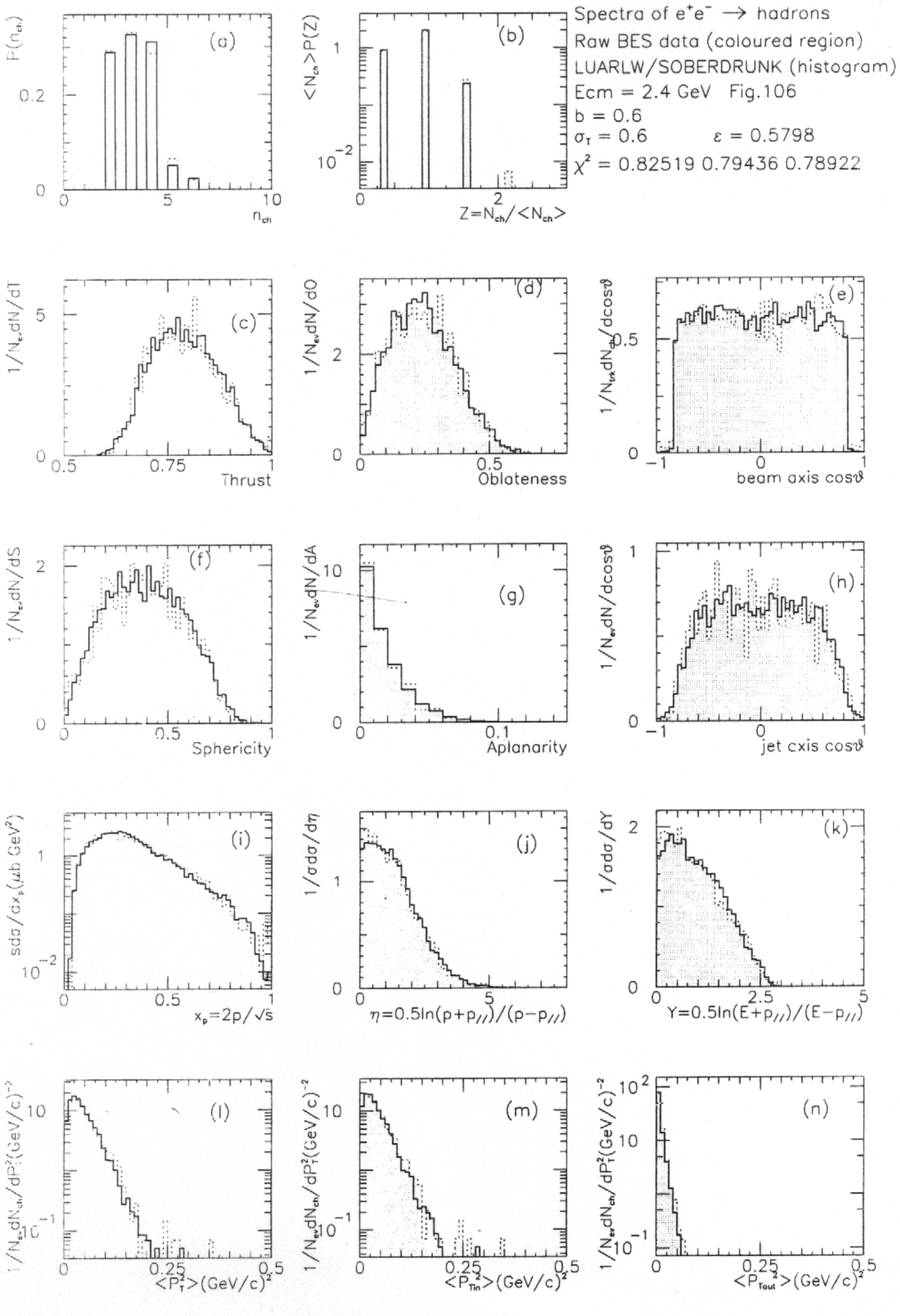


Figure 7: $e^+e^- \rightarrow$ *hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at* $Ecm = 2.4$ *GeV.*

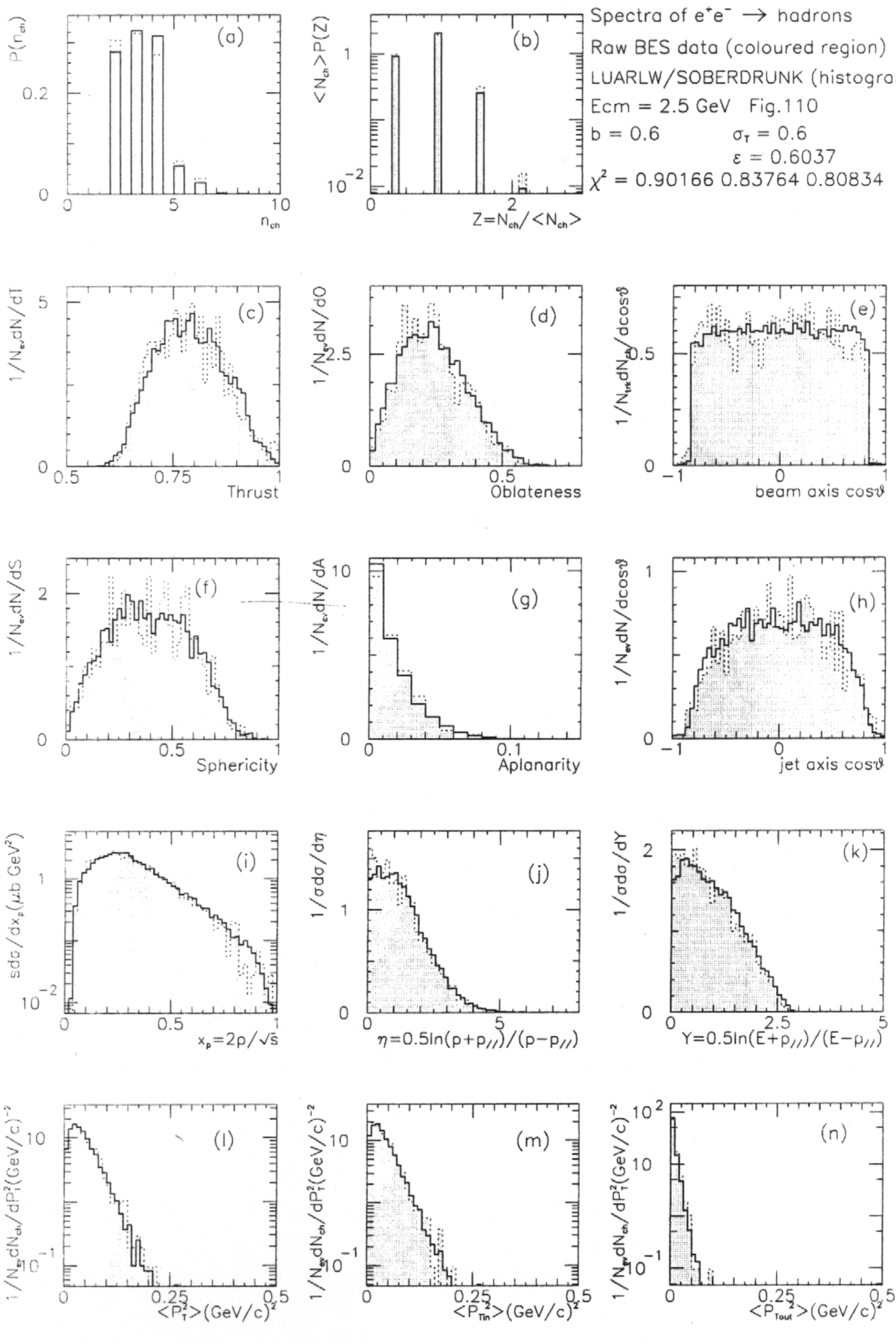


Figure 8: $e^+e^- \to$ *hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at* $Ecm = 2.5$ *GeV.*

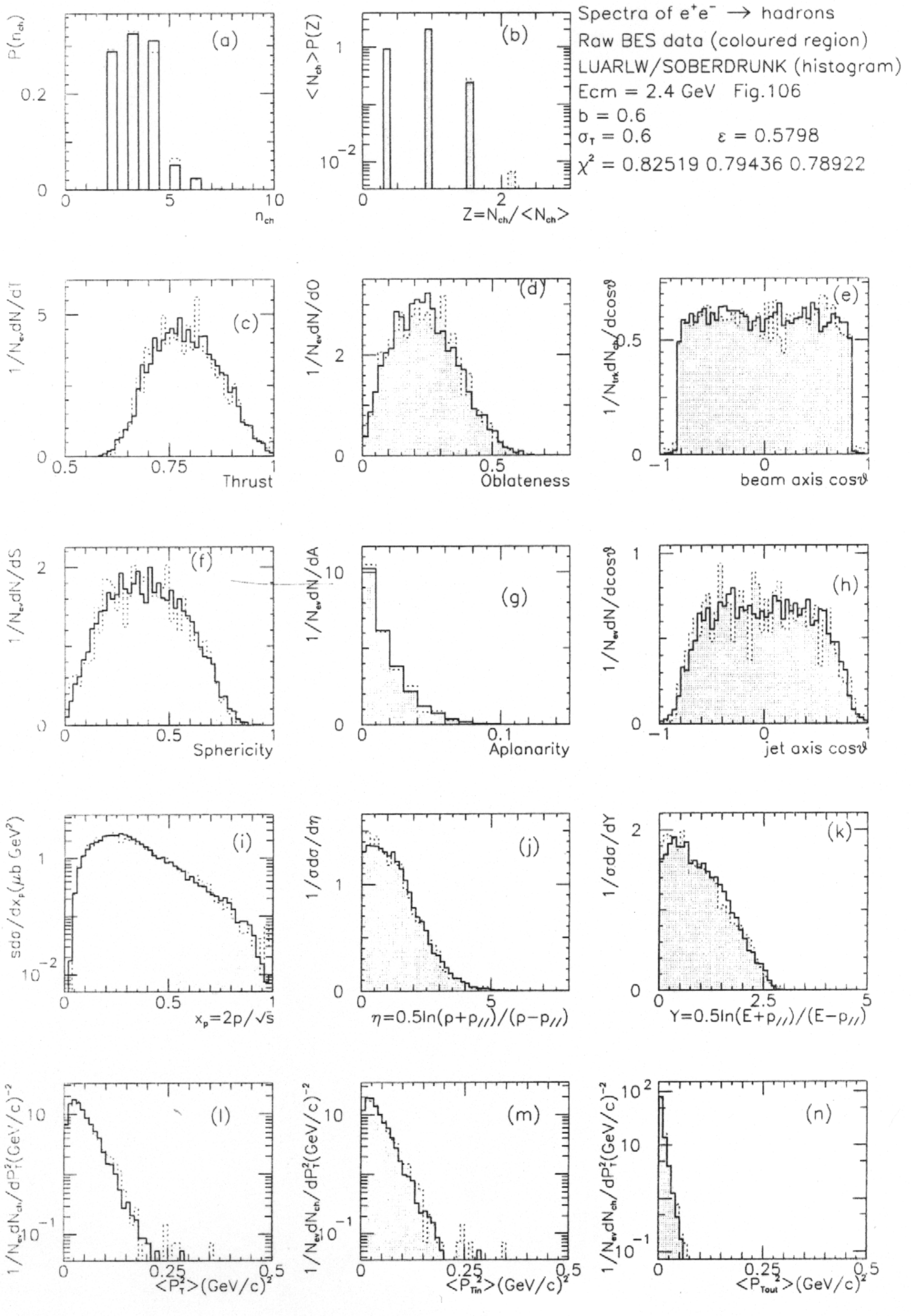


Figure 9: $e^+e^- \to$ *hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at* $Ecm =$ 2.6 *GeV.*

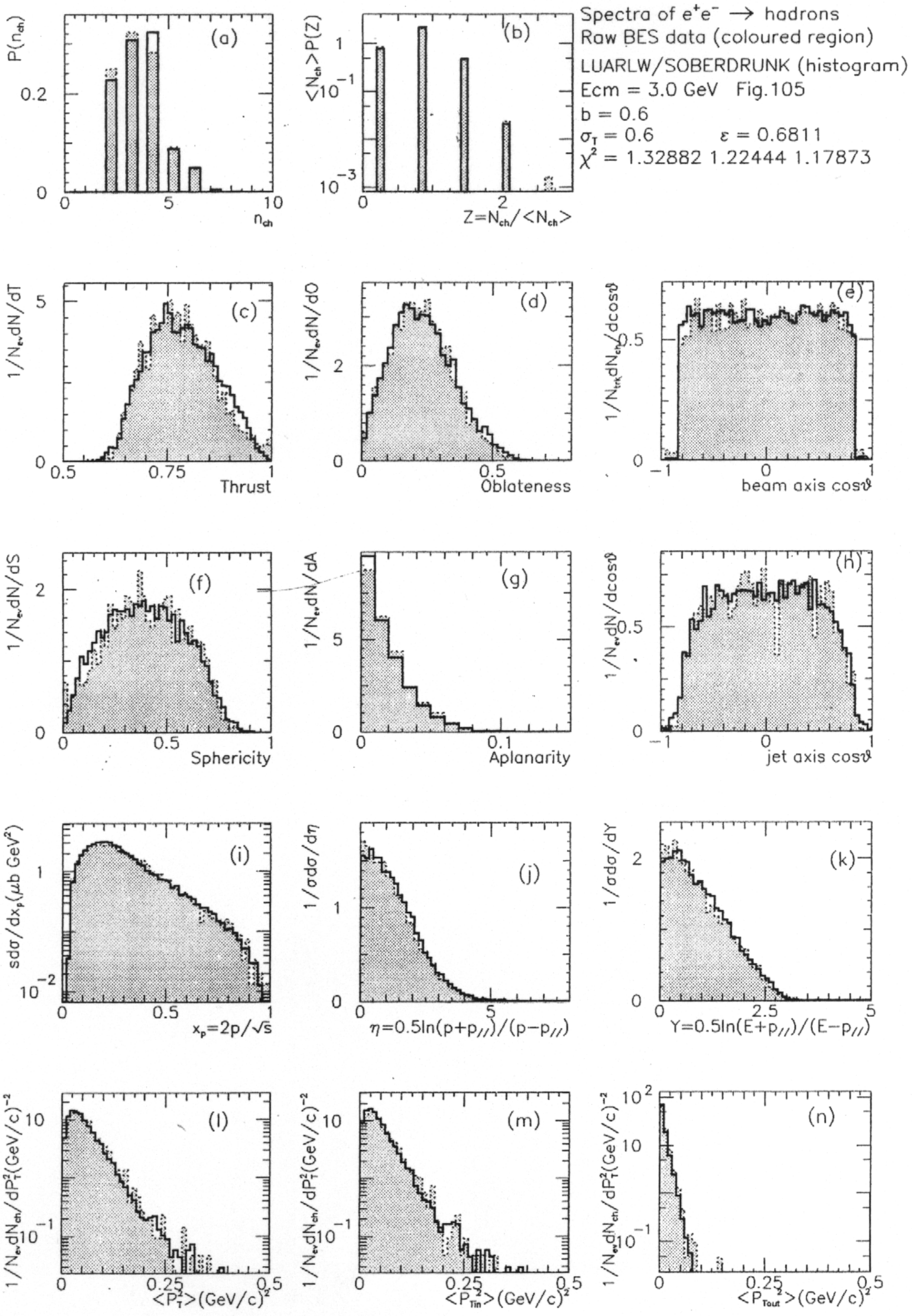


Figure 11: $e^+e^- \to$ *hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at* $Ecm = 3.0$ *GeV.*

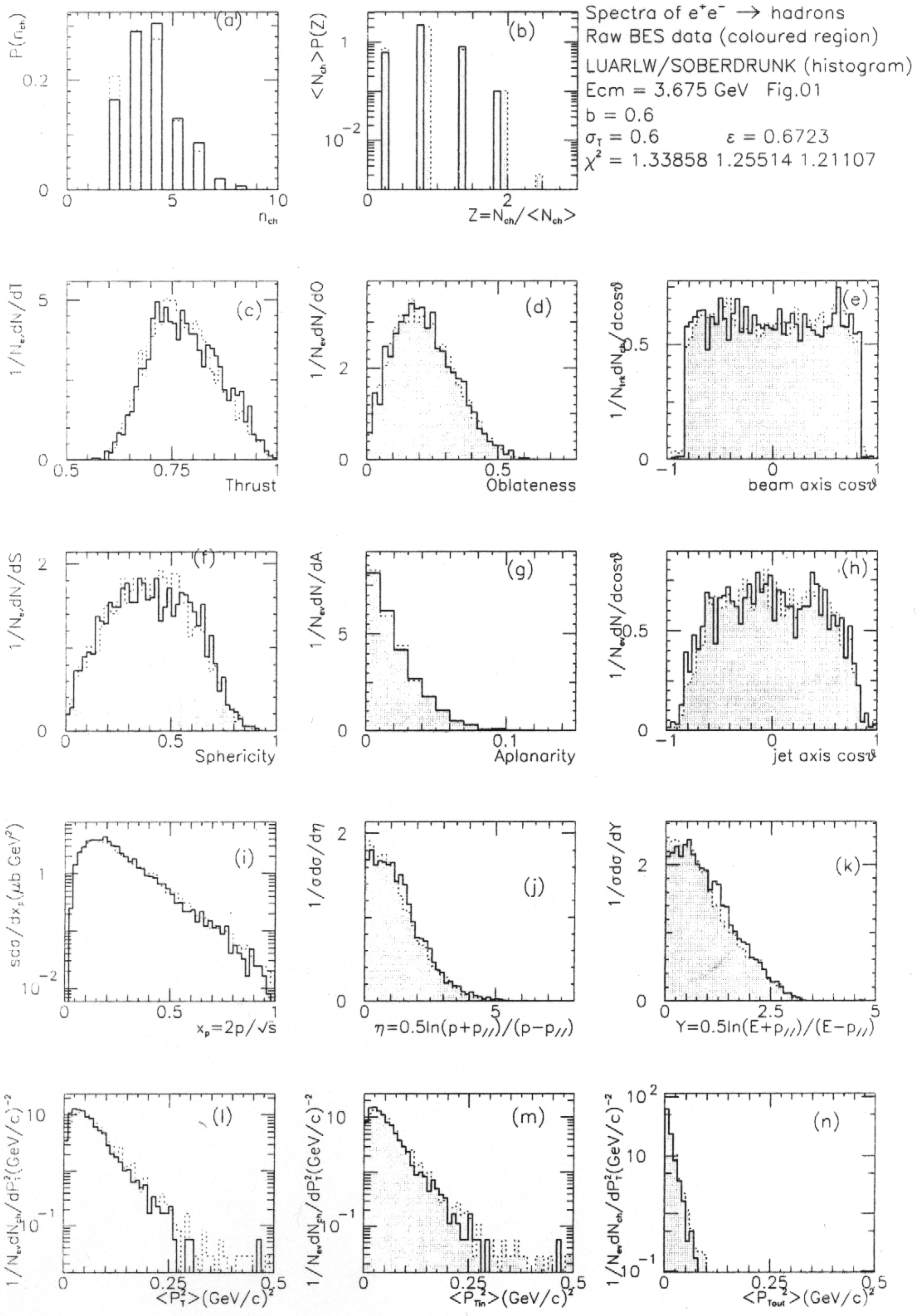


Figure 12: *$e^+e^- \rightarrow$ hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at $Ecm = 3.675$ GeV.*

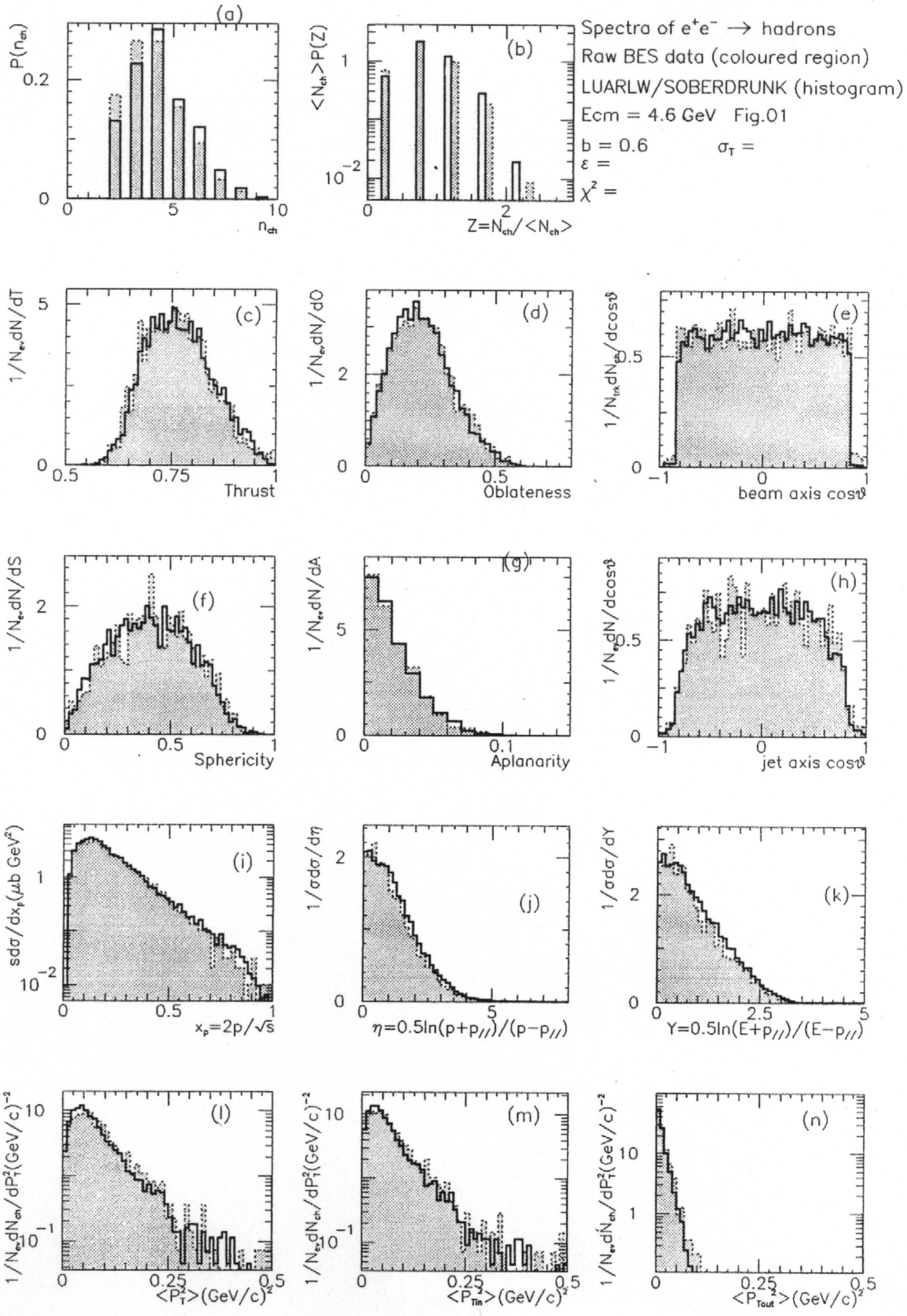


Figure 13: *e^+e^- → hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at $Ecm = 4.6$ GeV.*

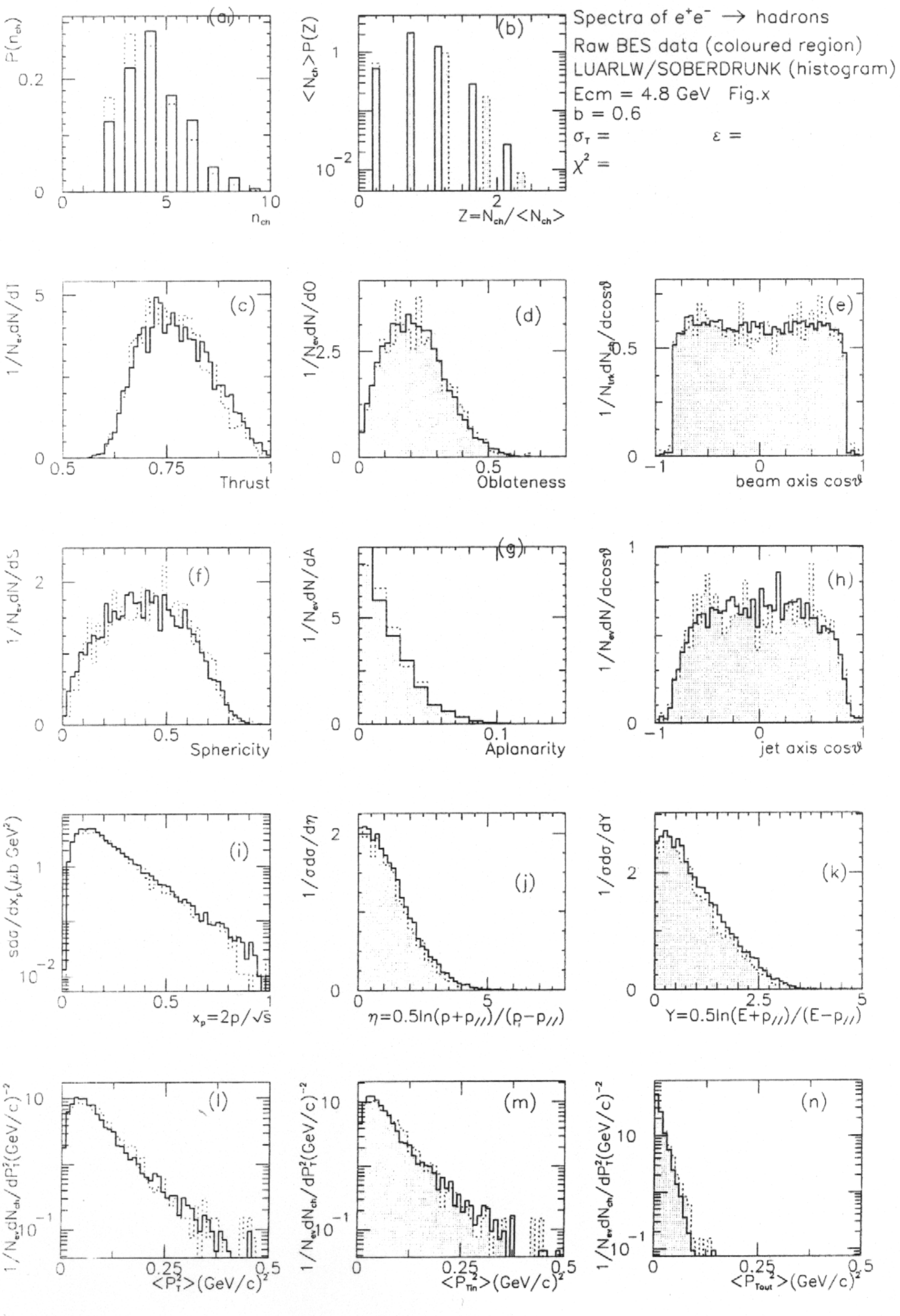


Figure 14: e^+e^- $\rightarrow$ *hadrons spectrum of raw BES data (grey region) and LUARLW/SOBDRUNK (black line) at* $Ecm = 4.8$ *GeV.*

Summary

- BEPC/BES measured R values in $2-5$ GeV region successfully;
- First R scan: test run with 6 energies, results published in PRL;
- Fine R scan: complete run with 85 energies, results to be published in PRL;
- Uncertainties of R values reduce down to $6 \sim 10\%$ (a factor of 2 improvement).
- BES R values have significant impact on the evaluation of α_{QED} and a_μ.

- $$\textbf{Lund MC}\left\{\begin{array}{ll}\textbf{JETSET} & \textbf{high energy}\\ \textbf{Area Law} & \textbf{intermediate energy}\end{array}\right.$$

- The formalism based on the Lund Model area law is directly developed into Monte Carlo program LUARLW, which is satisfied to treat 2-body up to 6-body states.

- The LUARLW predicts more than 14 distributions totally agree with BES data well.