EUROPEAN LABORATORY FOR PARTICLE PHYSICS

Study of prompt J/ψ production in hadronic Z decays

The ALEPH Collaboration

A measurement of prompt J/ψ production with low model dependence is performed on 3.9 million hadronic Z decays collected by the ALEPH detector. The sample of J/ψ at short decay-length shows an excess of 46 ± 12 prompt J/ψ on a background of 57 B decay and 18 combinatorial events, yielding the branching ratio

$$Br(\mathrm{Z} \to \mathrm{prompt\ J}/\psi\mathrm{X}) = (3.00 \pm 0.78_{\mathrm{stat}} \pm 0.30_{\mathrm{syst}} \pm 0.15_{\mathrm{theo}}) \times 10^{-4}.$$

This result is consistent with a theoretical prediction allowing for color-octet gluon$\to$ J/ψ as well as c quark fragmentation.

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1 Introduction

If most of the J/ψ production at LEP is through B decays, a small prompt component has since long been predicted, within various models. A few years, the CDF collaboration reported a prompt J/ψ production much higher than any predictions. This has triggered theory developments, the most relevant being probably the "color-octet" model for gluon splitting in J/ψ. In short, the color octet model does not require the $c\bar{c}$ quarks to be matched in color for the production of a J/ψ (as the usual color-singlet models) but rather factorizes it in the production of a color octet state, which then decays non perturbatively in a J/ψ and soft gluons. The first part can be calculated perturbatively in the framework of non-relativistic QCD (NRQCD), while the matrix elements of the second part are determined on data. Although the resulting fit does predict correctly (with two free matrix elements) the shape of the p_T spectrum of J/ψ at CDF, it is of great interest to test the model with the same matrix elements but on different processes. The advantage of Z decay with this respect is that gluon production is better understood there than at low energy e^+e^- colliders, at ep or $p\bar{p}$ colliders or in B decay.

The following analysis proceeds in two steps. The first is to estimate the amount of prompt J/ψ production in a model-independent way. This is done by evaluating simply the excess of J/ψ at short decay-length, compared to the B decay contribution. The second step is to compare in a qualitative way some variables sensitive to the different mechanisms of J/ψ production, mainly the gluon component and the c quark fragmentation component using topology and flavor tagging. The delicate task of actually measuring the proportion of the two components is postponed to a future work, because it relies more on the details of the Monte Carlo event generation.

This paper is organised as follows. First a brief overview of the theoretical and experimental status is given, and the generation of Monte Carlo samples is explained. Then the J/ψ selection is described, the prompt J/ψ production is measured and its uncertainties are evaluated. Finally, an attempt is made to separate the main two contributions.

2 Theoretical and experimental overview

The processes for J/ψ production at LEP are listed below:

- B decays is obviously the dominant process, and is characterised by the long J/ψ apparent decay-length. The corresponding branching ratio is $Br(\mathrm{Z} \to \mathrm{B} \to J/\psi \mathrm{X}) = 3.4 \times 10^{-3}$

- c quark fragmentation to J/ψ occurs when a primary c quark emits a gluon, which splits in a secondary $c\bar{c}$ pair. Then, if the $\bar{c}$ is approximately collinear to the primary c quark and of opposite colour, a colorless state can be formed. Due to the necessary collinearity of the two c's, this is a typical process that can be evaluated in NRQCD [1]. For completeness, a similar colour octet process exists for this scheme, but is not dominant. The branching ratio is predicted to be [2]

$$Br(\mathrm{Z} \to c\bar{c} \text{ prompt } J/\psi) = 0.8 \times 10^{-4}.$$

In this topology, the J/ψ is accompanied by a nearby soft charmed jet; a second charm jet exists also in the opposite hemisphere.

- in the gluon color-octet contribution, a gluon emitted in the parton shower splits into a color octet charmonium state, which decays subsequently in a J/ψ and soft gluons. The matrix elements for the second part are fit to CDF data on prompt J/ψ production [2, 3, 4, 5]. The predicted branching ratio in [2] is

$$Br(\mathrm{Z} \to \mathrm{q\bar{q}g} \to \text{ prompt J}/\psi) = 1.9 \times 10^{-4},$$

  with an uncertainty of a factor of at least two due to the difficult description of gluon in $\mathrm{p\bar{p}}$ collisions. At least two additional jets containing the primary quarks of random flavor are present.

- other processes are at least two orders of magnitude smaller than the previous ones.

Excited charmonium states are also produced with the relative rates for J/ψ:ψ(2S)):χ_c estimated to be in the ratios 0.5:0.2:0.3 [2].

Up to now the only significant experimental measurement was done by OPAL [6]. In their case the prompt J/ψ are tagged by their short decay-length, and by the isolation energy, being defined as the energy in a 30° cone around the J/ψ direction. They see an excess of $13.8 \pm 4.9 \pm 2.0$ events on a background of 10.2 ± 2.0 events in a sample with decay-length between -4σ and +4σ and isolation energy below 4 GeV/c^2. They obtain the following branching ratio:

$$Br(\mathrm{Z} \to \text{prompt J}/\psi \text{ X}) = (1.9 \pm 0.7_{\mathrm{stat}} \pm 0.5_{\mathrm{syst}} \pm 0.5_{\mathrm{theory}}) \times 10^{-4}.$$

This is in good agreement with the theoretical predictions quoted above. It should be noted that the 25% theoretical uncertainty is due to the fact that the isolation energy is very dependent on the process considered.

3 Monte Carlo generation

3.1 B decays

17000 $\mathrm{Z} \to \mathrm{B} \to J/\psi\mathrm{X}$ events were generated using JETSET 7.4 [7] and fully simulated in the ALEPH detector. Since the following analysis relies on the relative rate of J/ψ at short decay-length and long decay-length, care was taken to reweight the events for the lifetime of each B species [8]. The B fragmentation was also reweighted to the measured value $< x_B >= 0.715 \pm 0.15$ [10]. The error on decay-length (reconstructed decay-length minus true decay-length) is multiplied by 1.1 ± 0.2 before applying any decay-length cut, to take into account the somewhat worse resolution on data compared to Monte Carlo simulation.

3.2 Gluon component

The gluon component is not implemented in JETSET 7.4. This sample is generated by using an analytical formula [2] for the partial width of the $q\overline{q}J/\psi$ final state. The $q\overline{q}$ pair is then handed over to the usual JETSET parton shower and fragmentation. The production of $\psi(2S)$ and χ_c decaying into J/ψ is done the same way. With this method the basic topology of the event and the momentum spectrum of the J/ψ is generated correctly. However, it does not take into account the soft gluons radiated when the colour-octet state decays into a J/ψ.

3.3 c fragmentation

The c fragmentation sample was obtained by running JETSET 7.4 [7] with $c\bar{c}$ events only. The J/ψ momentum spectrum obtained is in agreement with theoretical expectation [1]. It also does not depend critically on the tuning of parameters driving the parton shower.

For cross-check purposes, an alternate sample was also generated (as in [6]) using the fragmentation approach formula [1] to produce the $c\overline{c}J/\psi$ final state, which is then handed over to the usual parton shower and fragmentation as in the previous section. The J/ψ momentum spectrum is in this sample similar to the previous one, but the topology is rather different as shown in section 6.3.

4 J/ψ selection

The J/ψ selection follows closely the one of a previous ALEPH paper [9], with the additional requirements to have the highest efficiency down to low momentum (to reduce model dependance), and to have a precise vertex reconstruction. Throughout this note the cuts were optimized to have the best signal significance for a predicted prompt J/ψ branching fraction of 3×10^{-4} .

The electrons are identified with momentum above 1.3 GeV/c from the shower profile in the electromagnetic calorimeter and the specific ionisation in the TPC. Photon conversions and electrons which have underwent a hard bremsstrahlung are rejected. The muons are identified above 2.2 GeV/c from the hit pattern in the HCAL and the muon chambers.

The two leptons should form an angle less than 90°. No cut is applied on the visible energy in the J/ψ hemisphere, since it would affect a part of the gluon component, when the J/ψ is recoiling against the two quarks. The vertex probability is required to be in excess of 1%. Each lepton should have at least one VDET hit. No momentum cut is applied to the J/ψ.

The efficiency of these cuts is $(24.1 \pm 0.2)\%$ for J/ψ from B decay, $(23.6 \pm 0.8)\%$ for J/ψ from c quark fragmentation and $(21.4 \pm 0.7)\%$ for J/ψ from gluon. These efficiencies were obtained using the Monte Carlo simulations described in section 3, with a correction measured on data for the VDET hit and vertex probability requirements.

The lepton pair mass spectra are shown in Fig. 1. The mass window used is $3 - 3.2$ GeV/c^2. The background is estimated the following way: the $e^+\mu^-$ mass spectrum is

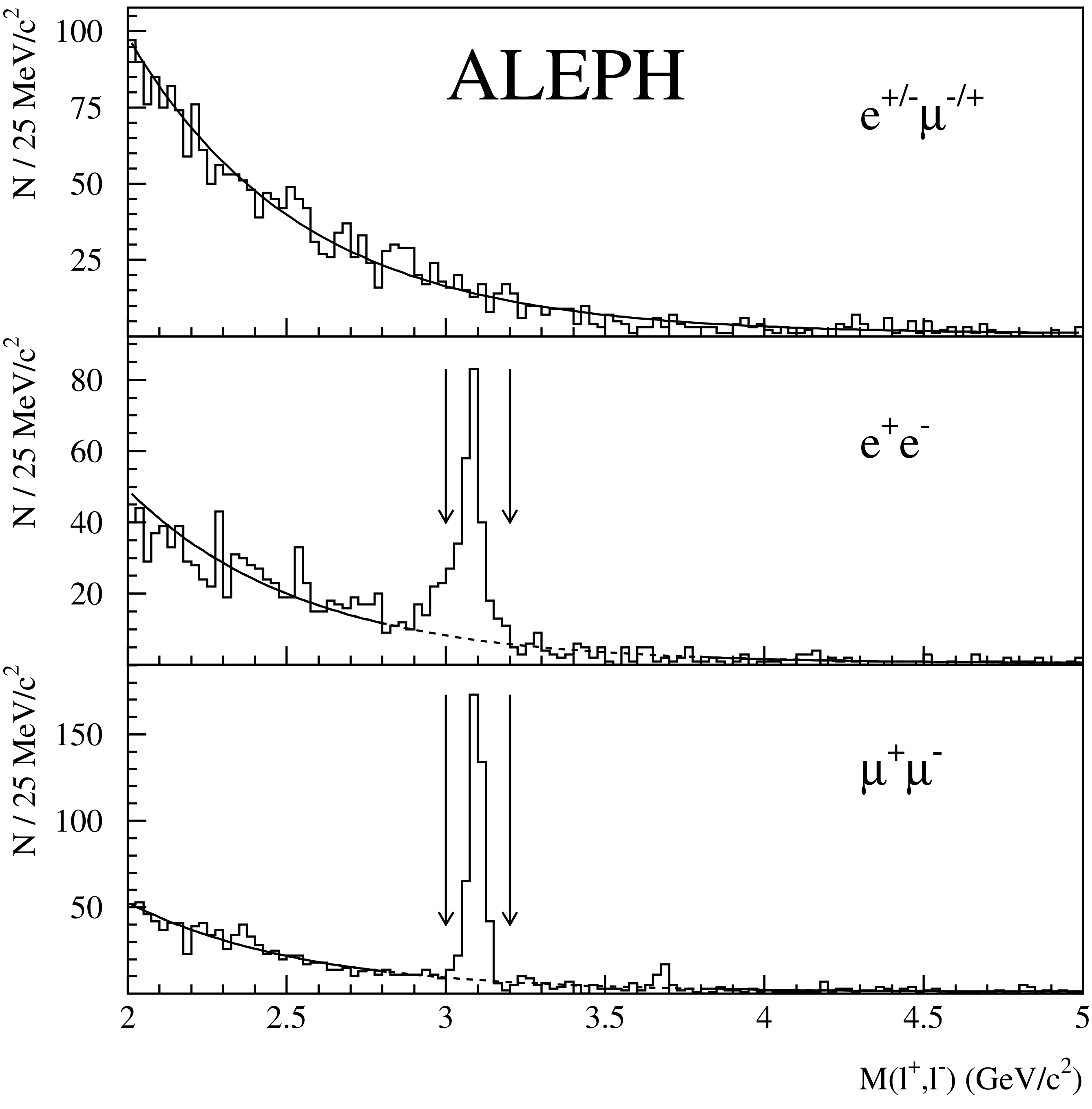

Figure 1: Invariant mass of selected $e^{\pm}\mu^{\mp}$, e^+e^- and $\mu^+\mu^-$ pairs. The arrows define the mass window for the J/ψ signal. The curves show the fit used to estimate the background below the J/ψ peak.

Channel	signal	background
e^+e^-	197± 16	39± 3
$\mu^+\mu^-$	366± 20	42± 3

Table 1: Detail of data sample used.

fitted by an exponential plus a constant term. Then fits to the e^+e^- and $\mu^+\mu^-$ mass spectra between 2 and 2.8 GeV/c^2 and between 4 and 5 GeV/c^2 are performed with the same function, but the slope being fixed to the value found in the first fit. The function is then integrated over the mass window to evaluate the background. The number of signal and background events in each channel are reported in Table 4.

5 Prompt J/ψ signal extraction

The prompt J/ψ signal is searched for by looking for an excess of events at 0 decay-length, which does not depend of the details of the Monte Carlo simulation. The decay-length is calculated from the distance between the primary and J/ψ vertex, projected onto the J/ψ momentum.

5.1 Method

The J/ψ sample defined above is divided into a "long decay-length" sample ($l > 3\sigma_l$) which only contains J/ψ from B decays and a "short decay-length" sample ($-3\sigma_l < l < 2\sigma_l$) which contains almost all the prompt J/ψ and a contribution of J/ψ from B decays. The number N_{pr} of prompt J/ψ is determined using the formula:

$$N_{pr} = N^{short} - N^{long} \times \frac{\epsilon_B^{short}}{\epsilon_B^{long}},$$

where N^{short} (N^{long}) is the number of J/ψ events in the short (long) decay length sample, ϵ_B^{short} (ϵ_B^{long}) is the efficiency to find a J/ψ from B decays in the short (long) sample.

To estimate the number of signal events in both samples, each sample is further divided into seven bins of J/ψ momentum between 5 and 40 GeV/c, the first and last bins containing possible underflows and overflows. The fit of the mass estimates is done separately in each bin of each sample. This procedure allows for a change of the shape of the background with the momentum and is necessary to obtain the prompt J/ψ component down to the lowest momentum. If it had been applied in the previous section, the total number of J/ψ events would have increased by 2%.

The mass spectra for the two samples are shown in Fig. 2 after summing over the momentum bins. The composition of each bin for the short sample is shown in Fig. 3. Resumming over the bins, the number of J/ψ event in the short decay-length sample is

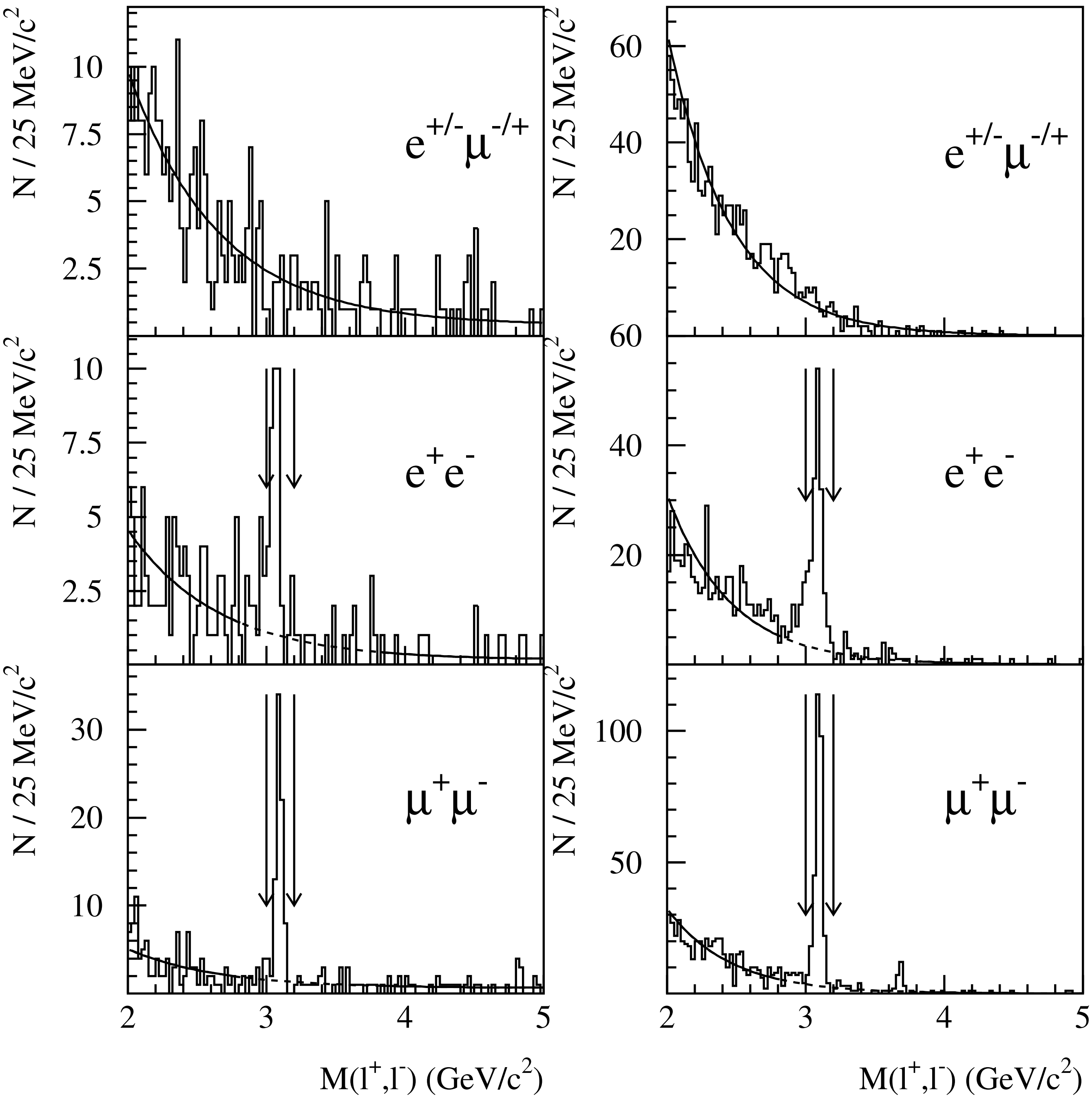

Figure 2: Invariant mass of selected $e^\pm\mu^\mp$, e^+e^- and $\mu^+\mu^-$ pairs, for the short decay-length sample (left) and the long decay-length sample (right).

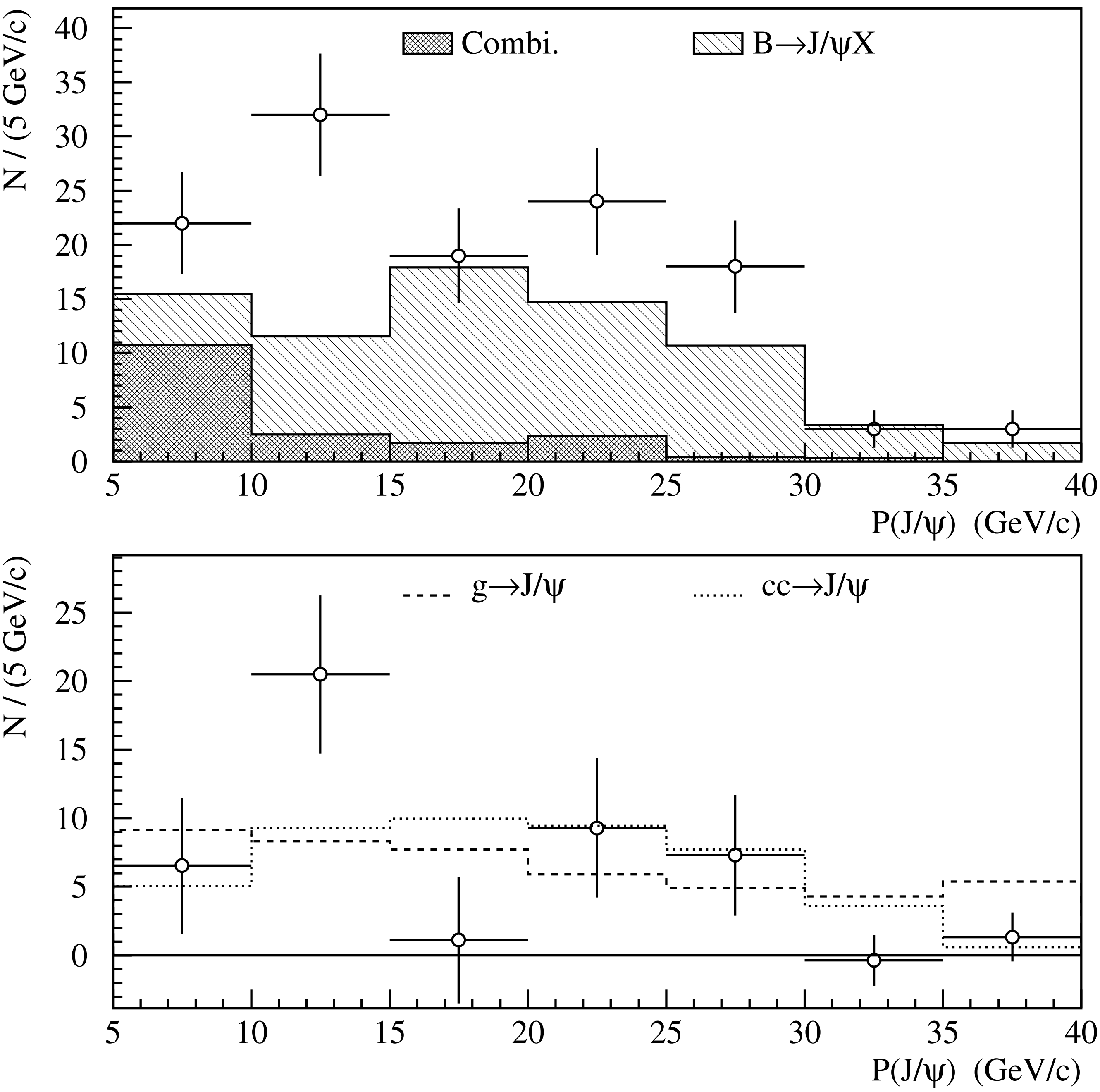

Figure 3: The top plot shows the momentum of the $\ell^+\ell^-$ pairs in the mass window of the short decay-length sample (circles). The shaded histogram is the combinatorial background and the hatched histogram the B decay contribution. The bottom plot shows the momentum of the prompt J/ψ in data (circles). The shape of the two possible contributions are superimposed with the same area with dashed line (gluon) or dotted line (c quark fragmentation).

$N^{short} = 103 \pm 11$ on a background of 18 ± 2 events and in the long decay-length sample $N^{long} = 442 \pm 22$ on a background of 45 ± 3 events (with statistical uncertainty only). The ratio $\frac{\epsilon_B^{short}}{\epsilon_B^{long}}$ is estimated to be (13.0±0.6)%, yielding finally

$$N_{pr} = 46 \pm 12.$$

The branching ratio of Z to prompt J/ψ is determined through the formula

$$Br(\mathrm{Z} \to \text{prompt } \mathrm{J}/\psi\mathrm{X}) = \frac{N_{pr}\epsilon_{\mathrm{q\bar{q}}} Br(\mathrm{Z} \to \mathrm{q\bar{q}})}{2N_{\mathrm{q\bar{q}}} Br(\mathrm{J}/\psi \to \ell^+\ell^-)\epsilon_{pr}^{short}},$$

where $N_{\mathrm{q\bar{q}}} = 3.9$ millions is the number of $\mathrm{Z} \to \mathrm{q\bar{q}}$ events used, $Br(\mathrm{J}/\psi \to \ell^+\ell^-) = (6.02 \pm 0.19)\%$ [8] is the J/ψ leptonic branching ratio, $Br(\mathrm{Z} \to \mathrm{q\bar{q}}) = (69.90 \pm 0.15)\%$ is the Z hadronic branching ratio, $\epsilon_{\mathrm{q\bar{q}}} = (97.40 \pm 0.24)\%$ is the hadronic Z decay efficiency and ϵ_{pr}^{short} is the efficiency for prompt J/ψ selection. For J/ψ from c quark fragmentation $\epsilon_{pr}^{short} = (23.3 \pm 0.8)\%$ while for gluon $\epsilon_{pr}^{short} = (21.1 \pm 0.7)\%$. The value used is the average of the two, the remaining difference being quoted as an uncertainty due to model dependence: $\epsilon_{pr}^{short} = (22.2 \pm 0.5_{stat} \pm 1.1_{theo})\%$. The uncertainty of the efficiency due to the presence of cascade decay from heavier charmonium states is negligible.

The branching ratio is then calculated to be

$$Br(\mathrm{Z} \to \text{prompt } \mathrm{J}/\psi\mathrm{X}) = (3.00 \pm 0.78_{\mathrm{stat}} \pm 0.15_{\mathrm{theo}}) \times 10^{-4}.$$

5.2 Systematic uncertainties

The systematic uncertainties are listed in Table 5.2. They are described in more details below.

To check the stability of the number of prompt J/ψ events determination, the analysis is repeated not splitting further the samples in bins of J/ψ momentum, or by splitting them using different variables like minimum lepton momentum, isolation energy; the maximum departure from the central value is 5%. The B lifetimes and B fragmentation parameter used to reweight the Monte Carlo were changed within errors, since they might affect the ratio $\epsilon_B^{short}/\epsilon_B^{long}$. Also a possible $\mathrm{B_c}$ component with $f(\mathrm{b} \to \mathrm{B_c}) = 0.1\%$, $Br(\mathrm{B_c} \to \mathrm{J}/\psi\ \mathrm{X}) = 10\%$ and lifetime 0.4 ps is allowed; it is the dominant lifetime related uncertainty. The pull on decay-length was varied by 20% and affects mainly ϵ_{pr}^{short}. The uncertainty on lepton efficiency is set to 2% per lepton (based on [11]). The VDET and vertex efficiency correction is varied within its 2% error. The uncertainty due to Bremsstrahlung is evaluated by decreasing the lower value of the mass window to 2.95 GeV/c^2 and taking the full change of the branching ratio as the uncertainty.

The final branching ratio, clearly dominated by the statistical uncertainty, is then

$$Br(\mathrm{Z} \to \text{prompt } \mathrm{J}/\psi\mathrm{X}) = (3.00 \pm 0.78_{\mathrm{stat}} \pm 0.30_{\mathrm{syst}} \pm 0.15_{\mathrm{theo}}) \times 10^{-4}.$$

Source	uncertainty
Stability	5%
B lifetime	5%
B fragmentation	1%
Pull on decay-length	3%
Lepton efficiency (2% per lepton)	4%
VDET and vertex efficiency	2%
$(\ell^+\ell^-)$ mass	2%
J/ψ leptonic branching ratio	3%
Total systematic error	10%

Table 2: Source of systematic uncertainties on prompt J/ψ production.

5.3 Checks

5.3.1 Shape of the excess in decay-length significance

The decay-length significance of the J/ψ candidates is shown in Fig. 4. After subtraction of the background component (obtained from the side-band) and of the B decay component normalized to the long decay-length sample, the excess of events due to prompt J/ψ is clearly seen at 0. The fit of a gaussian to the excess gives a mean of 0.14±0.28 and a width of 1.02±0.23 in perfect agreement with the expectation for an excess of events produced at the primary vertex.

5.3.2 General Monte Carlo

The analysis is repeated on a sample of 4 million $q\bar{q}$ Monte Carlo events from which prompt J/ψ were explicitly removed. The number of prompt J/ψ measured is -2 ± 10, corresponding to a branching ratio $Br(\mathrm{Z} \rightarrow \text{prompt } \mathrm{J}/\psi\mathrm{X}) = (-1.3 \pm 6.6) \times 10^{-5}$. The fraction of $b\bar{b}$ events in the short decay-length sample is 80%.

Carrying out the same test on 2.56 million $b\bar{b}$ Monte Carlo events yields 9 ± 20 prompt J/ψ measured, corresponding to a branching ratio $Br(\mathrm{Z} \rightarrow \text{prompt } \mathrm{J}/\psi\mathrm{X}) = (2.0 \pm 4.3) \times 10^{-5}$.

No significant excess is seen in both cases, as expected.

5.3.3 B→ J/ψX branching ratio

All the J/ψ in the long decay-length sample come from B decay, allowing the inclusive branching ratio of B to J/ψ to be measured:

$$Br(\mathrm{B} \rightarrow \mathrm{J}/\psi\mathrm{X}) = (1.00 \pm 0.05_{\mathrm{stat}})\%.$$

This is in good agreement with $\Upsilon(4S)$ measurement of $(1.14 \pm 0.06)\%$[8].

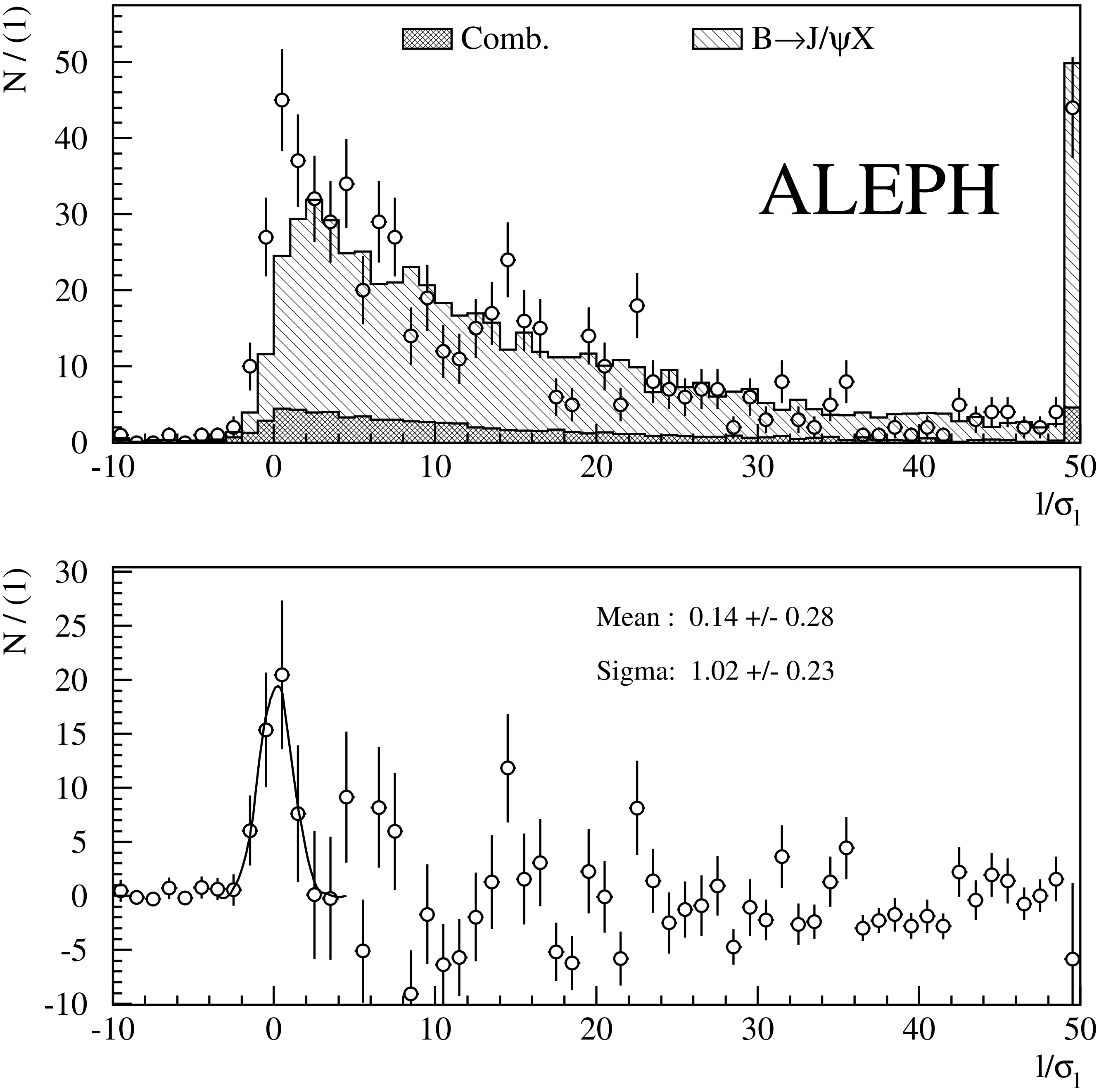

Figure 4: The top plot shows the decay-length significance for all J/ψ candidates in the data (circles), the B decay component (hatched) and the combinatorial background component (shaded). The bottom plot shows the gaussian fit of the excess at small decay-length.

6 Process separation

Several variables with the potential of separating the two main contribution have been studied. For each of them, the estimation of the combinatorial background and of the B decay contributions was estimated bin by bin.

6.1 J/ψ momentum

The momentum spectrum of prompt J/ψ was shown in Fig. 3. There is reasonable agreement between data and Monte Carlo, except maybe above 30 GeV/c where very few events are observed. The shape is similar for the two prompt J/ψ contribution, except below 10 GeV/c and above 35 GeV/c^2.

6.2 b tag

Fig. 5 shows the logarithm of the uds probability of the event calculated with an impact parameter tag, the two leptons being excluded from the calculation. It is clear that the prompt J/ψ sample has a relatively low content of b quarks (when compared to the B decay component), but it is not possible to distinguish the $c\bar{c}$ contribution of the c fragmentation process from the udscb contribution of the gluon process.

6.3 Isolation energy

The isolation energy is defined as in OPAL paper [6] to be the visible energy in a cone of 30° half angle centered on the J/ψ (the J/ψ being excluded). If the J/ψ is isolated the isolation energy is close to 0. However this variable is also sensitive to the details of the Monte Carlo event generation, because, for example, the cone will most likely contain the energy of the soft gluons emitted by the color-octet state or by the higher order charmonium states decaying to J/ψ. There is a clear excess between 0 and 4 GeV in data as in the gluon Monte Carlo, but corresponding to little more than $\frac{1}{3}$ of the total excess. The remaining excess is evenly distributed at higher isolation energy, as in the c quark Monte Carlo. This variable is the most promising for separating the processes, but maybe also the most difficult to handle. As an example of this, the shape of the c quark contribution in [6] is rather different from the one shown here. In particular, the average isolation energy is half smaller than in our case. This is due to a different method for generating the c quark Monte Carlo (see Section 3.3). Our measurement being only somewhat sensitive to the J/ψ momentum spectrum and not to the topology of the events, is not affected within the theoretical uncertainty quoted.

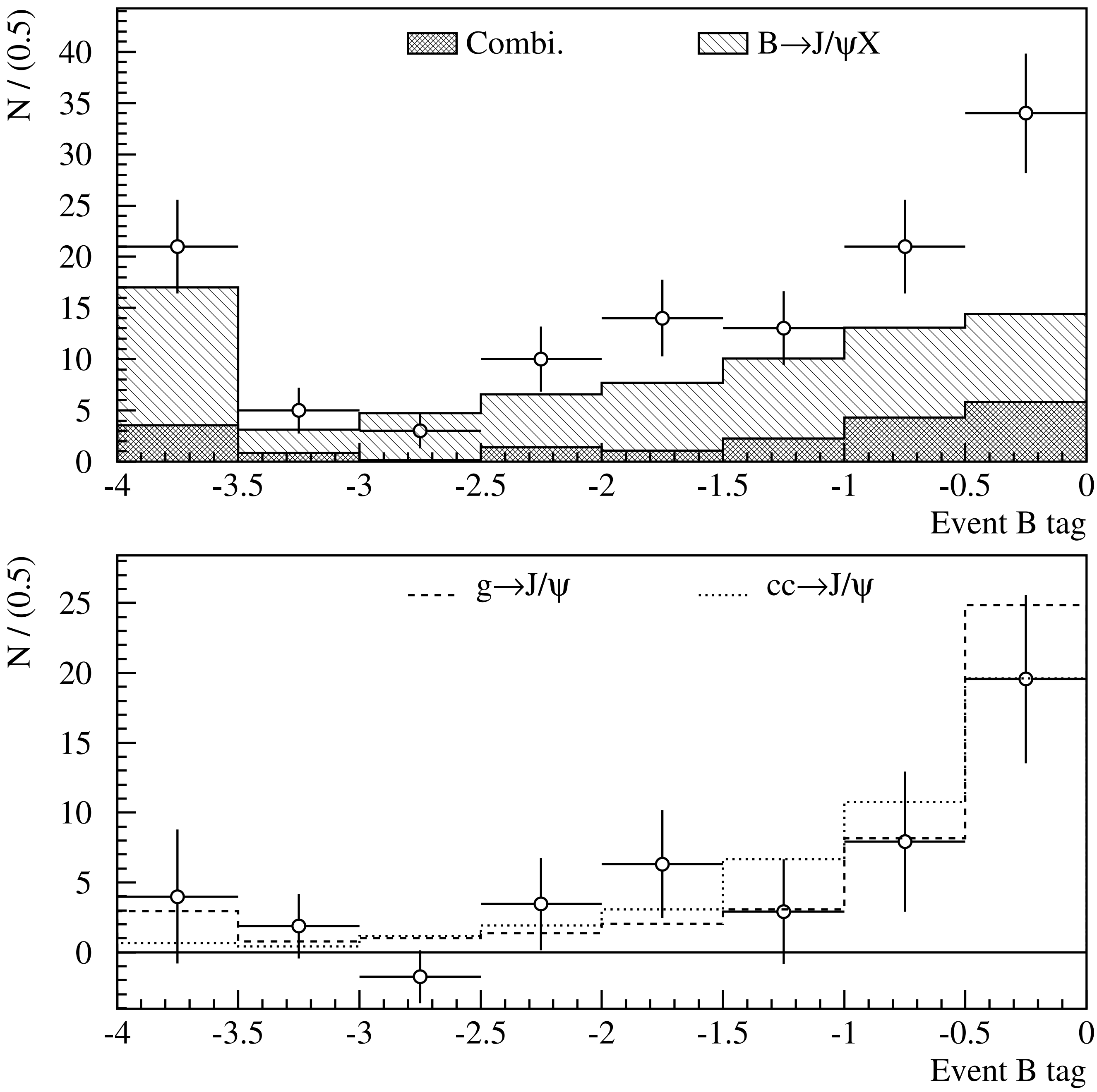

Figure 5: The top plot shows the logarithm of the uds probability of the events for the short decay-length sample (circles). The shaded histogram is the combinatorial background and the hatched histogram the B decay contribution. The bottom plot shows the distribution for the prompt J/ψ in data (circles) after backgrounds subtraction. The shape of the two possible contributions are superimposed with the same area with dashed line (gluon) or dotted line (c quark fragmentation).

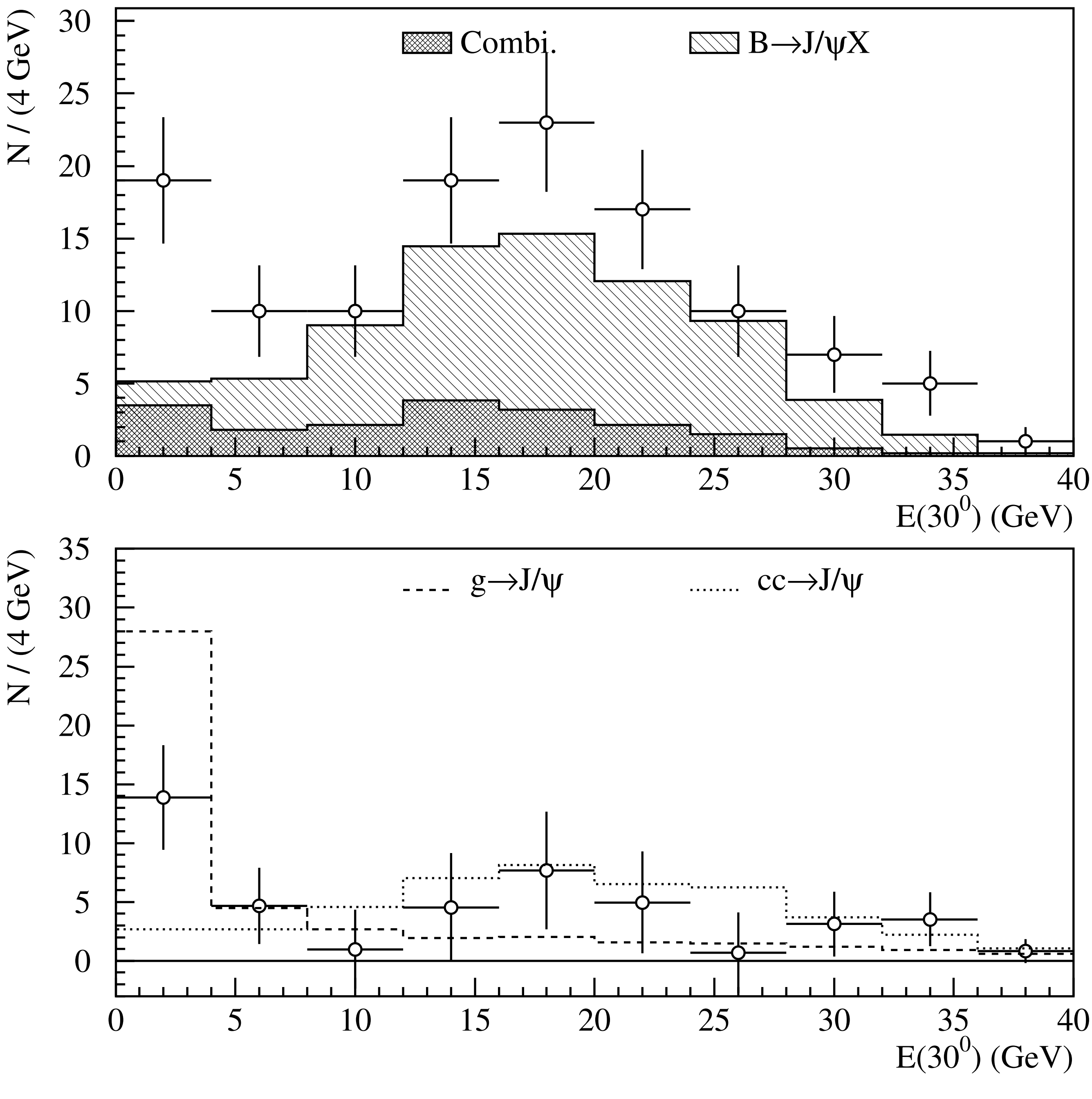

Figure 6: The top plot shows the energy in a 30° cone around the J/ψ direction for the short decay-length sample (circles). The shaded histogram is the combinatorial background and the hatched histogram the B decay contribution. The bottom plot shows the distribution for prompt J/ψ in data (circles) after background subtraction. The shape of the two possible contributions are superimposed with the same area with dashed line (gluon) or dotted line (c quark fragmentation).

7 Conclusion

A clear excess of 46 ± 12 prompt J/ψ events is seen, from which a branching ratio is measured

$$Br(\mathrm{Z} \to \text{prompt J}/\psi\mathrm{X}) = (3.00 \pm 0.78_{\mathrm{stat}} \pm 0.30_{\mathrm{syst}} \pm 0.15_{\mathrm{theo}}) \times 10^{-4}.$$

This is in good agreement with the theoretical predictions (see Section 2), and, in particular, seems to require the presence of the color-octet gluon contribution. This is also in agreement with OPAL measurement with a lower uncertainty due to model dependence, thanks to the only use of decay-length as a tagging variable. Several process-dependent variables were compared. The isolation energy indicates the presence of two components. Further work is needed to assess the impact of the details of the Monte Carlo generation on such variable, before separate measurement of the two components is possible.

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