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Colour reconnection at LEP2

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Abstract. Two measurements are presented of estimators sensitive to the Colour Reconnection effect in W^+W^- events at LEP2. The results are compared with various phenomenological Monte Carlo implementations of the effect. A feasibility study is performed to reduce the total uncertainty in the direct m_W measurement at LEP2 by use of the inferred information about the Colour Reconnection effect.

PACS. 14.70.Fm W bosons – 13.38.Be Decays of W bosons

1 Introduction

Colour Reconnection is the term used for strong interactions between colour singlet parton systems of different origin [1]. The effect can influence the evolution of two nearby parton showers. The kinematics of the hadrons coming from both systems can therefore be perturbed. In the reaction $e^+e^- \to W^+W^- \to q_1\bar{q}_2q_3\bar{q}_4$ the colour singlets $q_1\bar{q}_2$ and $q_3\bar{q}_4$ formed by the decay products of both W bosons, could rearrange themselves to new colour singlets $q_1'\bar{q}_4'$ and $\bar{q}_2'q_3'$. Because the flow of the colour quantum numbers, reflecting the particle dynamics at short distances, controls the particle distributions in the final state, one could expect a change in these distributions after the colour rearrangement. In these W^+W^- events produced at LEP2, the separation distance between the $W^\pm$ decay vertices is around $\tau_W \sim 1/\Gamma_W \simeq 0.1$ fm, while the fragmentation scale of the W bosons is around 1 fm. Hence there is a significant space-time overlap of both W hadronization regions where Colour Reconnection could occur. The resulting kinematic structure of a W^+W^- event will be different from the situation without this reconnection. The presence of similar effects was found in hadronic B meson decays $B \to J/\psi + X$ where the colour interference between the two original colour singlets ($\bar{c} + s$ and c+spectator) suppresses this decay [1].

The probability to rearrange can be enhanced by gluon exchange between both W decay systems. Within the perturbative parton shower model it was shown that the Colour Reconnection or interference probability is negligible [2]. Colour transmutations between partons from different W bosons can only occur from the interference of at least two emitted gluons. This interference piece is suppressed by the effective number of colours as $1/N_c^2 = 1/9$ compared to the $\mathcal{O}(\alpha_s^2)$ non-reconnection emissions. Also the effects of a finite W width restrict the energy range of primary gluons generated by the alternative rearranged dipoles, because both W bosons do not necessarily decay at the same time.

Within the framework of the Lund string fragmentation implemented in JETSET the colour fields of both W boson strings can overlap in space-time. When the strings are described in their simplest Lorentz invariant way by a linear confinement potential, the event probability $\mathcal{P}_i$ to reconnect is related to the volume, $\mathcal{O}_i$, of the string overlap as:

$$\mathcal{P}_i = 1 - e^{-\kappa \cdot \mathcal{O}_i} \quad . \tag{1}$$

The SK1 model parameter κ, with a fixed value for each event, is unknown and can only be tuned or measured from experimental data. For simplicity only one reconnection per event was allowed.

Within ARIADNE the Dipole Cascade Model is also followed by a string fragmentation according to the Lund model. As a criterion for Colour Reconnection one can therefore use the string length Λ defined in the momentum space

$$\Lambda = \sum_{i=1}^{n-1} \frac{\ln(p_i + p_{i+1})^2}{m_0^2} \tag{2}$$

where the sum covers all $n-1$ string pieces for a string connecting n partons and m_0 is a typical hadronic mass scale (usually Γ_W). Reconnection is allowed when the string length after reconnection is shorter than the original one. In the ARIADNE 2 (AR2) model, reconnection between strings from different W bosons only happens below a fixed energy scale (usually Γ_W), while in the ARIADNE 3 (AR3) version reconnection is allowed at all energy scales which includes the perturbative phase. Therefore it is only the AR2 model which is relevant for this

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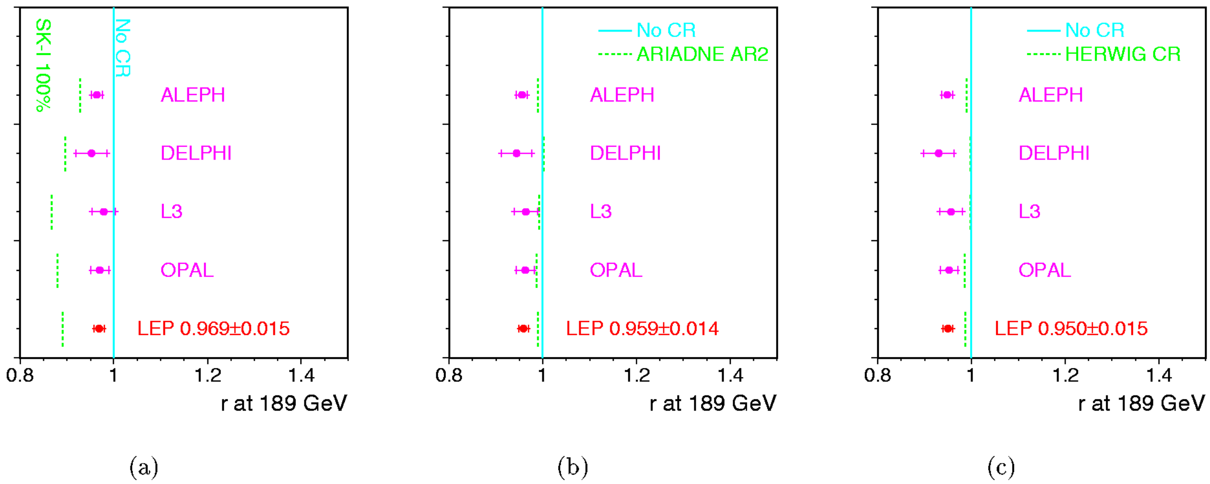

Fig. 1. Preliminary particle flow results on $r = R^{data}/R^{no-CR}$ using all LEP2 data. In plot **a** both hypotheses without and with full (100%) SK1 Colour Reconnection are shown, in plot **b** and **c** the ARIADNE and HERWIG Colour Reconnection models are tested, based on the predicted sensitivity. The *dashed lines* indicate the predicted values of $r = R^{CR}/R^{no-CR}$ for the analysis of each experiment. For comparison all values are interpolated to a centre-of-mass energy of 189 GeV and the LEP combined values are shown on the bottom of each plot

study. Within an event multiple inter-string reconnections and self-reconnections inside a single string could occur.

Before the formation of the clusters in the HERWIG fragmentation process, reconnection is allowed with a fixed probability ($\simeq 1/9$) when it reduces the sum of the squared sizes of the formed clusters. The size of a cluster is defined as the space-time separation of the production vertices of the partons forming the cluster. Multiple reconnections and self-reconnections within a single parton shower are allowed.

2 Particle flow measurement

The string effect predicts a higher particle production rate in the region between jets originating from the same $W \to q\bar{q}$ decay ('intra' region), compared to the regions between jets from different W decays ('inter' region). When Colour Reconnection is present, particles tend to migrate from the intra-W to the inter-W region. Therefore an observable which counts the particles in these different regions could be sensitive to the different Colour Reconnection algorithms. The ratio R of the integrated particle density or particle flow in the intra region to the integrated density in the inter region quantifies this behavior.

The value obtained from the LEP combined data is compared to the different models in Fig. 1. In the SK1 interpretation of Colour Reconnection the data prefers a value of $\kappa = 1.18$, and the 68% confidence level lower and upper limits are 0.39 and 2.13 respectively. This corresponds to a reconnection probability of 49% in this model at $\sqrt{s} = 189$ GeV. The extreme SK1 scenario with 100% reconnection probability disagrees with the data at a level of 5.2 σ. The log-likelihood as a function of κ is shown in Fig. 2. All four experiments have observed a very weak sensitivity to the ARIADNE and HERWIG Colour Reconnection models, which does not coincide with the SK1 prediction of the effect. The expected value of R from those fragmentation models in the hypothesis that no Colour Reconnection is present, differs from the measured LEP combined data value by 3.1 and 3.7 σ for the ARIADNE and HERWIG models, respectively. This may indicate an underestimation of the systematic uncertainties in these particle flow analyses. The dominating systematic uncertainties are the fragmentation modeling in the simulation and the possibility for Bose-Einstein Correlations in the final state.

3 The Δm_W method [3]

It has been shown that the m_W observable [4] inferred from hadronic decaying W^+W^- events at LEP2 by the method of direct reconstruction, is influenced when changing the value of κ. A second method is therefore based on the observation that two different m_W estimators have different sensitivity to the parametrized Colour Reconnection effect. Hence the difference between them is an observable with information content about κ.

It is observed that mostly low momentum particles and particles in inter-jet regions are affected by Colour Reconnection and hence influencing the the value of, m_W. An alternative analysis was designed which neglects these particles in the reconstruction of the momenta of the four primary partons. This by applying an optimized cone algorithm to cluster the particles in jets, rather than using inclusive clustering algorithms like DURHAM.

An indirect measurement of the SK1 model parameter κ is possible from the direct measurement of the difference $\Delta m_W(i,j)$ in reconstructed m_W between the CR-sensitive standard (i) and CR-less-sensitive alternative (j) analysis. The observable $\Delta m_W(\mathrm{std}, R_{cone})$ where R_{cone} is around 0.5 rad, was found to be most sensitive (4.3 σ sensitivity to the full SK1 model). The systematic uncertainty

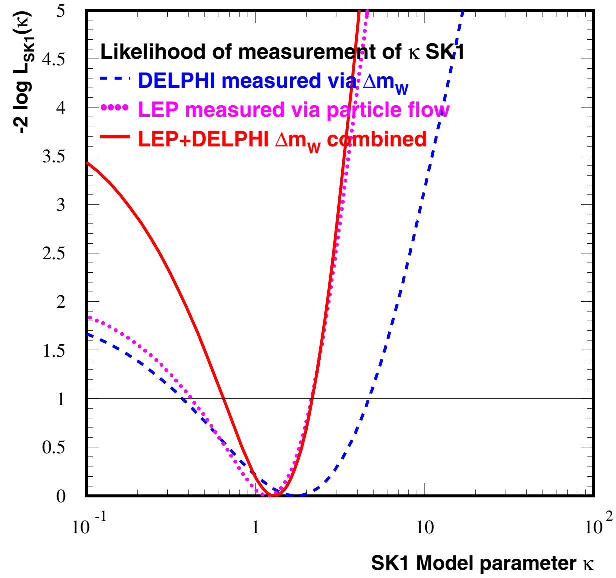

Fig. 2. Combined log-likelihood information on κ from both measurement assuming they are uncorrelated

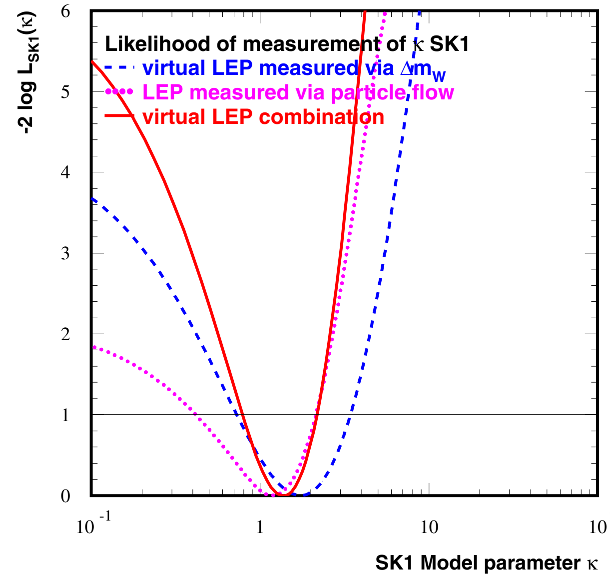

Fig. 3. Feasible log-likelihood information about Colour Reconnection to be extracted by the LEP2 data in WW events. The DELPHI Δm_W log-likelihood is rescaled to four times more luminosity

is dominated by possible effects like Bose-Einstein Correlations or detector related discrepancies in the energy flow reconstruction. The log-likelihood as a function of κ obtained by DELPHI is shown in Fig. 2.

After rescaling the effect according to the overall reconnection probability difference between the SK1 and the HERWIG model, also similar sensitivities were observed for both models. Only a negligible sensitivity to the ARIADNE implementation was found.

The correlation between the $\Delta m_W(\mathrm{std}, R_{cone} = 0.5\mathrm{rad})$ and standard m_W estimators was found to be around 11%.

4 Feasibility study for the m_W measurement

The log-likelihood information about κ from both measurements is combined in Fig. 2. Within the SK1 model a significant amount of Colour Reconnection is found.

The m_W estimators applied by the four LEP Collaborations are equally sensitive to the effect of Colour Reconnection. Therefore one can expect to infer the same amount of likelihood information from all four datasets. In this hypothesis and assuming that the Δm_W analysis would reveal the same most likely value for κ, the total log-likelihood obtained by LEP2 would be Fig. 3. For m_W measured in the fully hadronic channel the minimum of this log-likelihood corresponds to a shift of 106 MeV/c^2 at $\sqrt{s} = 200$ GeV with a 68% CL of [77;144] MeV/c^2 (where -2log$\mathcal{L}$=1). These numbers should be compared with the statistical uncertainty of 28 MeV/c^2 in the absence of systematic uncertainties [5]. Assuming that the SK1 model is the true model of Colour Reconnection, could calibrate for this shift. The oneremaining uncertainty due to Colour Reconnection would be about 35 MeV/c^2 (neglecting ARIADNE and HERWIG). This would reduce the total uncertainty on m_W measured in the fully hadronic channel from about 110 to 60 MeV/c^2 and increase the relative weight of this channel from 9 to 29% in the combination with the semi-leptonic channel.

5 Conclusion

Two basically uncorrelated measurements observe the same amount of Colour Reconnection in the LEP2 data according to the SK1 phenomenological model. Within the direct measurement of m_W this effect was not corrected for and therefore induced a significant systematic uncertainty. A simple but efficient calibration method was proposed to benefit from the inferred information about the Colour Reconnection effect in the m_W measurement. The uncertainty on the LEP2 value of the direct measurement of m_W would reduce from 42 to 39 MeV/c^2.

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