hep-ph/9809564 28 Sep 1998

BHAM-HEP/98-01
28th September 1998

W^+W^- HADRONIC DECAY PROPERTIES

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Invited talk at ICHEP'98, $22-30^{th}$ July 1998, Vancouver, Canada.

Recent measurements of the properties of W^+W^- events produced in e^+e^- collisions at $\sqrt{s} \sim 183$ GeV at LEP are reviewed. The data are used to investigate the predicted effects of final state interactions, specifically "colour reconnection".

1 Motivation

Hadronic data in e^+e^- collisions can be characterised by event shape distributions and inclusive observables such as charged particle multiplicities and momentum spectra. In addition to tests of Monte Carlo models, measurement of the properties of the hadronic sector of W^+W^- decays allows the question of 'colour reconnection' [1] to be addressed experimentally. The decay products of the two W decays may have a significant space-time overlap as the separation of their decay vertices at LEP2 energies is small compared to characteristic hadronic distance scales. In the fully hadronic channel this may lead to final state interactions. Colour reconnection is the general name applied to the case where such final state interactions lead to a rearrangement of the colour flow between the two W bosons. At present there is general consensus that observable effects of interactions between the colour singlets during the perturbative phase are expected to be small. In contrast, significant interference in the hadronisation process is considered to be a real possibility. With the current knowledge of non-perturbative QCD, such interference can be estimated only in the context of specific models. [1,2,3,4] One should be aware that other final state effects such as Bose-Einstein correlations between identical bosons may also influence the observed event properties. The combined action of these two effects may be either to reduce or enhance possible characteristic signatures of their presence.

2 Event Properties

The results shown are based on $\sim$ 55 pb^{-1} data per LEP collaboration. [5] Simple observables such as the inclusive charged multiplicity are obvious candidates for study. There have been predictions [4] that the effects of colour reconnection may be $\sim 10\%$ on $\langle n_{\rm ch}^{\rm 4q}\rangle$, the mean charged multiplicity in $W^+W^-\to q\bar{q}q\bar{q}$ events. The reference sample against which such changes are gauged is typically taken to be twice the multiplicity of the hadronically decaying W in $W^+W^-\to q\bar{q}\ell\overline{\nu}_\ell$ events, $\langle n_{\rm ch}^{\rm qq\ell\nu}\rangle$.

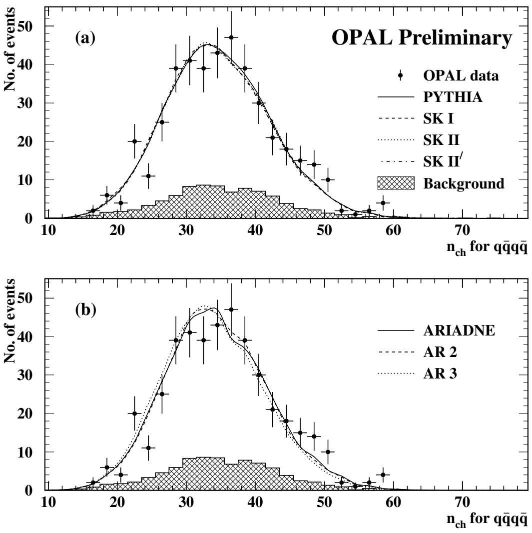

Figure 1: Observed track multiplicity, $W^+W^-\to q\bar{q}q\bar{q}$ events.

Charged particles associated with the leptonic component of such events are excluded. The difference is defined $\Delta\langle n_{\rm ch}\rangle = \langle n_{\rm ch}^{\rm 4q}\rangle - 2\langle n_{\rm ch}^{\rm qq\ell\nu}\rangle$. This reduces the dependence on the modelling of single W decays at the expense of a lower statistical significance of the test performed.

The observed (uncorrected) track multiplicities for selected $W^+W^-\to q\bar{q}q\bar{q}$ candidates are shown in Figure 1 by OPAL, together with the predictions from a variety of colour reconnection models. The mean charged particle multiplicities, $\langle n_{\rm ch}^{\rm 4q}\rangle$ and $\langle n_{\rm ch}^{\rm qq\ell\nu}\rangle$, may be extracted from such data, after subtraction of the predicted background, by employing a matrix-based unfolding procedure. This uses the event-by-event correlation, taken from Monte Carlo, between the charged multiplicity at hadron level and that observed in the detector after all analysis cuts have been applied. A subsequent correction for the effects of initial state photon radiation and to full acceptance is applied. Alternative methods for measuring $\langle n_{\rm ch}^{\rm 4q}\rangle$ and

Table 1: Mean charged particle multiplicities, errors are sum of statistical and systematic components. †: only partially unfolded.

Expt.	$\langle n_{\rm ch}^{\rm 4q} \rangle$	$\langle n_{\rm ch}^{{\rm qq}\ell\nu} \rangle$	$\Delta\langle n_{\rm ch} \rangle$
ALEPH†	35.33 ± 0.73	17.01 ± 0.37	$+1.31 \pm 0.83$
DELPHI	37.36 ± 1.00	19.48 ± 0.73	-1.6 ± 1.5
L3	36.3 ± 0.9	18.6 ± 0.6	-1.0 ± 0.9
OPAL	39.4 ± 1.0	19.3 ± 0.4	$+0.7 \pm 1.0$

$\langle n_{\rm ch}^{{\rm qq}\ell\nu} \rangle$ are the integration of any charged particle event shape, such as the distributions of momentum, rapidity or transverse momentum. Each collaboration uses more than one method to control possible systematic effects.

Changes in $\langle n_{\rm ch}^{\rm 4q} \rangle$ predicted vary with the colour reconnection model used, and the extent to which it may have been retuned. Representative shifts, defined as $\langle n_{\rm ch}^{\rm 4q} \rangle^{\rm reconnection} - \langle n_{\rm ch}^{\rm 4q} \rangle^{\rm normal}$ for each model, are:

$$\begin{aligned} \text{Sjöstrand-Khoze (SK) I} &\sim -0.3 \\ \text{SK II, SK II}' &\sim -0.2 \\ \textsc{Ariadne}\ 2 &\sim -0.1 \\ \textsc{Ariadne}\ 3\ (\text{AR } 3) &\sim -1.0 \end{aligned}$$

As unfolding the data may introduce a bias towards the model used, the procedure is repeated using a variety of models to estimate any associated systematic effect. L3 and OPAL also unfold their data using several colour reconnection models as part of such studies. ALEPH correct their data for experimental effects, such as finite detector resolution, but not for losses due to tracking inefficiency in the low momentum region ($p_T < 200$ MeV), or phase space and topological biases invariably present in experimental event selections. By using only a partial unfolding, their data should be less affected by model biases but cannot be compared directly with other experimental results, or to model predictions without passing through their detector simulation and analysis cuts.

The mean multiplicities, $\langle n_{\rm ch}^{\rm 4q} \rangle$, $\langle n_{\rm ch}^{{\rm qq}\ell\nu} \rangle$, and $\Delta\langle n_{\rm ch} \rangle$ measured by the LEP collaborations are shown in Table 1. Although the ALEPH mean multiplicities should not be compared directly with other data, the associated difference may be more meaningfully compared. The LEP average multiplicity difference obtained is:

$$\text{LEP} \quad \Delta\langle n_{\rm ch} \rangle = +0.20 \pm 0.50(\text{stat.} + \text{syst.}),$$

This is consistent with there being no change in the $\langle n_{\rm ch}^{\rm 4q} \rangle$ due to colour reconnection effects. As the systematics considered and the dominant source varied between the collaborations, this average assumes all systematics were uncorrelated. If, instead, the smallest overall systematic estimated by any collaboration is considered as fully correlated, the average value obtained is $\Delta\langle n_{\rm ch} \rangle = +0.15 \pm 0.80(\text{stat.} + \text{syst.})$. Performing the average while excluding the ALEPH results leads to the same conclusions.

Table 2: Dispersions of charged particle multiplicities, errors are sum of statistical and systematic components

Expt.	$\langle n_{\rm ch}^{\rm 4q} \rangle$	$\langle n_{\rm ch}^{{\rm qq}\ell\nu} \rangle$	$\Delta\langle n_{\rm ch} \rangle$
DELPHI	8.24 ± 0.51	5.76 ± 0.49	$+0.09 \pm 0.84$
OPAL	8.8 ± 0.7	6.1 ± 0.5	$+0.2 \pm 0.6$

All of the Sjöstrand-Khoze, Herwig and Ariadne models are consistent with data, although some more extreme models, such as the instantaneous reconnection scenarios in the Sjöstrand-Khoze model, and also the Ariadne model AR 3 [3] in which gluons having energies greater than $\Gamma_{\rm W}$ are allowed to interact, are disfavoured.

DELPHI and OPAL also measure the dispersions of the charged multiplicity distributions, $\rm D^{4q}$ and $\rm D^{q\overline{q}\ell\overline{\nu}_\ell}$, and the difference defined as $\Delta \rm D = D^{4q} - \sqrt{2} D^{q\overline{q}\ell\overline{\nu}_\ell}$. Their corrected results, shown in Table 2, are consistent with Monte Carlo expectations and there is no indication for differences in shape based on the first moments of the multiplicity distributions.

2.1 Ellis-Geiger Model

The Ellis-Geiger model, [4] implemented in the Monte Carlo program Vni, has been studied by the LEP collaborations. ALEPH and OPAL illustrate this by quoting some predictions from Vni. It is noted that the Ellis-Geiger model as implemented within Vni has not been tuned recently to describe $\rm Z^0$ data. ALEPH compared the predictions of Vni with other $\rm W^+W^-$ event generators, including detector simulation. Within the acceptance of their charged tracking and event selection criteria, ALEPH find Vni to give a charged track distribution that has $\langle n_{\rm ch}^{\rm 4q} \rangle \sim 2$ units higher than data and an r.m.s. ~ 1.7 units broader than in data. They also observe no dependence [4] of $\langle n_{\rm ch}^{\rm 4q} \rangle$ on the minimum angle between jets assigned to different W bosons. OPAL find from hadron level studies without detector simulation that Vni gives very high charged particle multiplicities, $\langle n_{\rm ch}^{\rm 4q} \rangle > 50$, and also does not reproduce the large predicted shifts in $\langle n_{\rm ch}^{\rm 4q} \rangle$ in any of the colour blind, colour singlet or colourful scenarios.[4] These studies were carried out at $\sqrt{s} = 183$ GeV, but the same conclusions hold at $\sqrt{s} = 166$ GeV, the lowest centre-of-mass energy allowed by Vni for $\rm W^+W^-$ production. For these reasons, the collaborations do not use the Ellis-Geiger model as currently implemented in Vni to estimate possible systematic effects on the W boson mass.

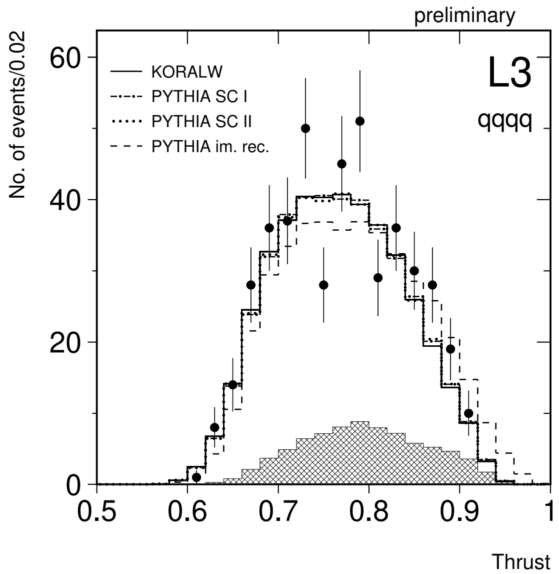

Figure 2: Observed thrust, $W^+W^- \to q\bar{q}q\bar{q}$ events.

2.2 *Thrust*

The thrust, T, distribution shown in Figure 2 from L3 illustrates how $W^+W^- \to q\bar{q}q\bar{q}$ events are more spherical than the $Z^0/\gamma \to q\bar{q}$ background, which is dominated by two-jet events. Qualitatively, colour reconnection effects are expected to be enhanced in W^+W^- events where the hadronic cascades from two W bosons overlap, but this is precisely the background dominated, two-jet like region generally excluded by the experimental event selections.

It is interesting to compare the hadron level predictions of a standard W^+W^- event generator such as KORALW with the VNI generator in its colour blind scenario. The distribution of $1-T$ is shown in Figure 3 for these two models. It can be seen that VNI predicts W^+W^- events to be more spherical than other models. While this might influence the efficiency with which such events are selected, they are topologically more distinct from the background than predicted by most models, so should fall well within the acceptance of the detectors.

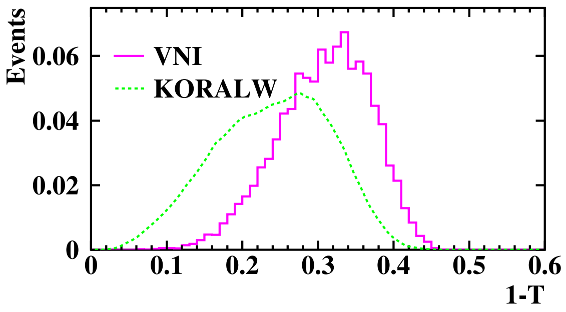

Figure 3: Hadron level predictions, $W^+W^- \to q\bar{q}q\bar{q}$ events.

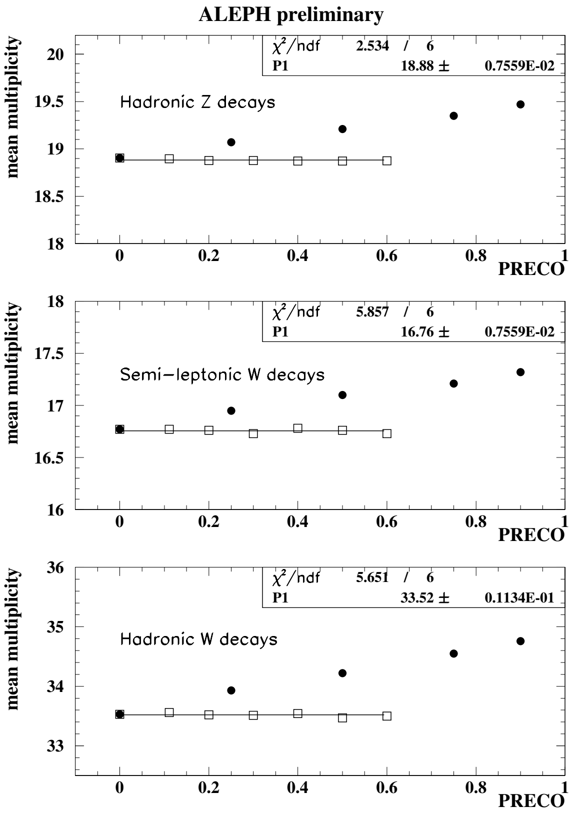

Figure 4: Tuning of HERWIG reconnection model.

2.3 *Model Tuning*

In general each model must be retuned to data after fixing reconnection related strength parameters or probabilities. The Sjöstrand-Khoze models do not require such retuning once the JETSET hadronisation model has been tuned. HERWIG, ARIADNE and the Ellis-Geiger model all require retuning. OPAL use a tuning of ARIADNE summarised in,[6] while ALEPH describe in detail their tuning of HERWIG. The mean charged multiplicities in HERWIG for Z^0/γ, $W^+W^- \to q\bar{q}\ell\bar{\nu}_\ell$ and $W^+W^- \to q\bar{q}q\bar{q}$ events as a function of the reconnection probability, `PRECO`, are shown in Figure 4 by ALEPH. The effect of retuning at each `PRECO`, and its necessity, is clear. A good description of the W^+W^- events may be achieved after suitable

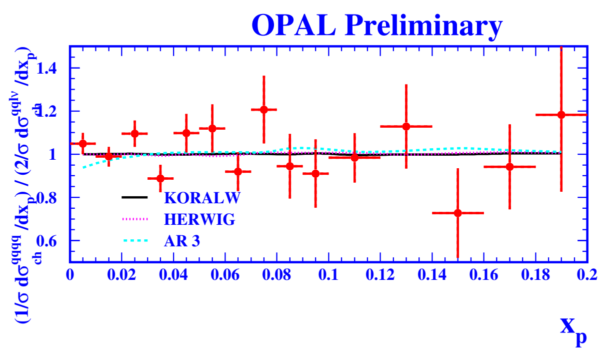

Figure 5: Momentum distribution ratio, $W^+W^-\to q\bar{q}q\bar{q}$ and $W^+W^-\to q\bar{q}\ell\overline{\nu}_\ell$.

retuning to Z^0 data.

2.4 *Alternative Observables*

The effects of colour reconnection are generally predicted to be enhanced in the soft particle region, therefore studies of fragmentation functions are interesting. Figure 5 shows the ratio of the corrected, scaled momentum distributions for $W^+W^-\to q\bar{q}q\bar{q}$ and $W^+W^-\to q\bar{q}\ell\overline{\nu}_\ell$ events, together with predictions of W^+W^- event generators and the colour reconnection model in which they found the largest effects, AR 3. Although this latter predicts differences which are as large as 5% in the lowest momentum interval, it is still consistent with data. OPAL also measure a variety of mean event shape variables, all of which are consistent with model predictions (neglecting VNI):

$$\begin{aligned}
\langle x_p^{4q}\rangle &= (3.16 \pm 0.05 \pm 0.04) \times 10^{-2}\\
\langle x_p^{q\bar{q}\ell\overline{\nu}_\ell}\rangle &= (3.25 \pm 0.07 \pm 0.04) \times 10^{-2}\\
\Delta\langle x_p\rangle &= (-0.09 \pm 0.09 \pm 0.06) \times 10^{-2}\\
\langle(1-T)^{4q}\rangle &= 0.240 \pm 0.015 \pm 0.009\\
\langle|y^{4q}|\rangle &= 1.017 \pm 0.016 \pm 0.016
\end{aligned}$$

DELPHI show in Figure 6 the transverse momentum distributions relative to the thrust axes for $W^+W^-\to q\bar{q}q\bar{q}$ and $W^+W^-\to q\bar{q}\ell\overline{\nu}_\ell$ events, and their ratio. In the semi-leptonic events the thrust axis is calculated taking the momentum imbalance in each event to be the neutrino momentum.There is no significant difference found between the data in the two channels.

3 Heavy Hadrons

It was recently predicted [7] that the effects of colour reconnection may be further enhanced by restricting analyses to heavier hadrons such as charged kaons and protons in the low momentum region, $0.2 < p < 1.2$ GeV.

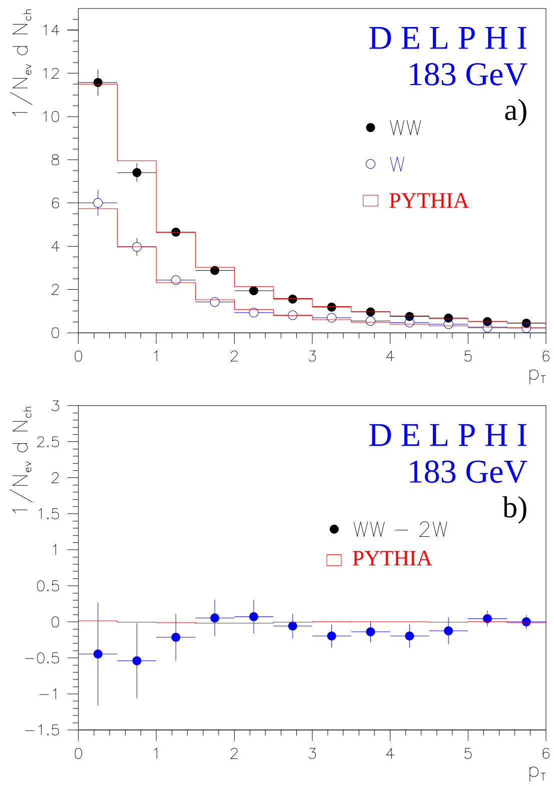

Figure 6: Transverse momentum distribution, $W^+W^-\to q\bar{q}q\bar{q}$ and $W^+W^-\to q\bar{q}\ell\overline{\nu}_\ell$.

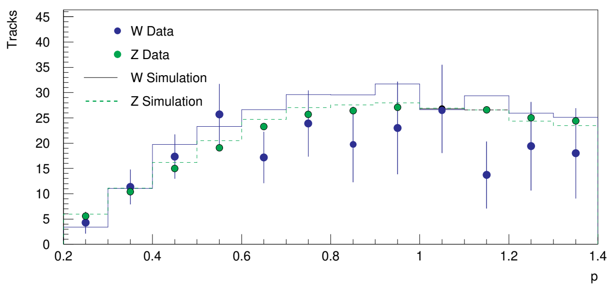

Figure 7: Comparison of W^+W^- and Z^0 pair data.

Numerically this increases the relative size of the effect, but taking into account the branching fractions to such species as well as experimental effects such as finite particle detection efficiency, background and modelling, it is not clear this will lead to an improved significance in the analyses. DELPHI use their TPC, RICH and vertex detector for particle identification, attaining tagging efficiencies for kaons and protons of order 90–50%, with purities in the range 90–75%. They observe 181 heavy hadrons in $W^+W^-\to q\overline{q}q\overline{q}$ events, 88 in $W^+W^-\to q\overline{q}\ell\overline{\nu}_\ell$. After unfolding for tagging effects this gives:

$$(q\overline{q}q\overline{q})/(2q\overline{q}\ell\overline{\nu}_\ell) = 1.03 \pm 0.15(\text{stat.}).$$

The statistical uncertainty on this measurement seems unlikely to be less than 5% even with the nominal LEP2 integrated luminosity of 500 pb^{-1}. To reduce the statistical uncertainty on these studies, they also use Z^0 calibration data as a reference sample. Pairs of Z^0 events, after boosting, are used to emulate $W^+W^-\to q\overline{q}q\overline{q}$ events, and a direct comparison is made with genuine $W^+W^-\to q\overline{q}q\overline{q}$ data. The two data samples and the corresponding Monte Carlo predictions are shown in Figure 7. The qualitative agreement is reasonable, although there may be differences between W^+W^- data and predictions for $p > 0.6$ GeV. The final result of their analysis is the ratio:

$$\langle n^{\text{heavy}}\rangle,\ \frac{W^+W^-}{Z^0Z^0} = 0.870 \pm 0.090(\text{stat.}) \pm 0.044(\text{syst.}).$$

4 W Mass Biases

Updated bias estimates for the effects of colour reconnection on the W mass measurement were presented by ALEPH, DELPHI and OPAL, as summarised in Table 3. It is noted that ALEPH and OPAL estimates are using their respective default M_W analyses, while the DELPHI results are a variant on their main M_W analysis. The bias estimates from Herwig and Ariadne are made after these models have been retuned to describe Z^0 data at $\sqrt{s} = 91$ GeV. As a cautionary note, there are non-negligible statistical uncertainties on all of these bias estimates which must be reduced for future analyses. No bias estimates are presented for the Ellis-Geiger model for reasons discussed earlier.

5 Summary

Studies of colour reconnection are maturing, in particular the area of Monte Carlo tuning is being addressed. There is no significant difference observed in the charged particle multiplicity of a single W boson produced in either a $W^+W^-\to q\overline{q}q\overline{q}$ or a $W^+W^-\to q\overline{q}\ell\overline{\nu}_\ell$ event. Most models are consistent with data based on an integrated luminosity of $\sim$ 55 pb^{-1} per collaboration. Identified particle studies in progress pose an interesting experimental challenge. The Ellis-Geiger model, as currently implemented and tuned, is not used for M_W bias estimates as it does not describe the data. Finally, the 1998 data should allow some models to be excluded leading to better control of the colour reconnection systematic on M_W measurements.

Table 3: Model dependent, colour reconnection bias estimates for M_W determination in $W^+W^-\to q\overline{q}q\overline{q}$ channel (statistical uncertainties). †: fast detector simulation, ‡: modified version of model.

Expt.	ALEPH	DELPHI†	OPAL
SK I	$+25 \pm 21^‡$	$+40 \pm 12$	$+50 \pm 17$
SK II	$+5 \pm 15$	–	$+17 \pm 17$
SK II′	$+17 \pm 15$	$+3 \pm 10$	$+18 \pm 17$
GH	–	$+13 \pm 18$	–
HW	-31 ± 25	–	
AR 2	–	–	$+73 \pm 18$
AR 3	–	–	$+146 \pm 18$

Acknowledgements

Work supported by PPARC grant GR/L04207. I would like to thank colleagues in the LEP collaborations, particularly R. Jones, B. Pietrzyk., P. de Jong, J. Mnich, C. Matteuzzi, N. Neufeld and M.F. Watson. It is with deepest sorrow that I note the recent, tragic death of Klaus Geiger, who will be missed by many.

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