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QCD Physics Lessons of Z^0 Decays*

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Abstract
This talk contains a subjective selection of interesting results on Z^0 decays, presented by the LEP and SLC groups. The emphasis is on soft and semi-hard QCD physics. Results are put in a theoretical context, and the limits of our current understanding are stressed. Topics covered include event measures, prompt photons, coherence and string effects, data and theory for particle rates and spectra, particle correlations and Bose–Einstein effects.

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1 Introduction

New QCD physics results continue to pour out from the ALEPH, DELPHI, L3, OPAL and SLD collaborations. Increased statistics, improved detectors and refined data analyses make for more precise tests of physics concepts. The task of the current minireview is not to cover everything we know, but only to comment on some of the results of the year. Other minireviews may be found in the proceedings[1, 2, 3, 4, 5, 6, 7]. Some attempts were made to avoid overlaps — for instance, hard QCD physics and α_s determinations are off limits — but it has not always been possible to define strict borders. Furthermore, the organizers requested that emphasis be put on the physics lessons we have learned, which means that I will take a more critical attitude to current QCD-inspired models than is normally done in the experimental papers. Therefore statements should not be accepted blindly, but hopefully they may help stimulate a fruitful debate.

In our current standard picture of hadronic Z^0 events it is assumed that the production process can be *factorized* into four steps:

1. creation of the primary $q\overline{q}$ pair (QFD);
2. additional parton production, described e.g. by parton showers with angular ordering (perturbative QCD);
3. hadronization, described e.g. by string or cluster fragmentation (nonperturbative QCD); and
4. secondary decays (QFD and nonperturbative QCD).

Even with such a simplified ansatz, the complexity makes Monte Carlo event generators the preferred realization of physics models.

2 Event Measures and Prompt Photons

Event shapes have been studied vigorously since the PETRA/PEP days, and extrapolations to Z^0 energies[8, 9] were presented long ago. Now when we sit with the answer in hand it is impressive how well measures such as thrust agree with predictions.

However, as emphasized by DELPHI[10], serious problems for models are seen in properties related to out-of-the-plane activity, such as aplanarity, four-jet rate and $p_{\perp\mathrm{out}}$ spectrum. Since models normally only are matched to $O(\alpha_s)$ matrix elements, not to $O(\alpha_s^2)$ ones, some discrepancies could have been expected and forgiven, but 30% is uncomfortably large.

The problems are even more glaring when one turns to events with prompt photons. Since $q \to q\gamma$ branchings compete with the $q \to qg$ ones, prompt photons probe the QCD evolution process. In the past we have learned that the JETSET[11] evolution, based on emissions ordered in mass, is not doing well, while the transverse-momentum-ordered ARIADNE[12] and the angularly-ordered HERWIG[13] do better though still not very well. Now new studies are presented, e.g. by ALEPH[14] based on a democratic jet finding algorithm, and further problems are found with models, especially in the description of energetic photons. It is less easy to find an excuse for these problems than for the out-of-the-plane ones, so further model development appears mandatory.

L3 has used prompt photons to study the properties of the remainder-system[15], to be compared with ordinary hadronic events at a reduced energy. Whereas many properties vary in the expected fashion, there are indications of a funny behaviour in the soft-photon region. Here events ought to be fairly similar to ordinary Z^0 decays without prompt photons; instead the data indicates that jets are narrower on the average. Once the photon is sufficiently energetic the expected behaviour is recovered, i.e. the scaled jet width is larger the smaller the hadronic mass, in accordance with the running of α_s and the character of nonperturbative contributions. This could indicate yet another problem in the description of photon emission, here for medium soft photons.

3 Coherence and String Effects

Interjet coherence is a perturbative phenomenon and the string effect a nonperturbative one, but both are based on the same respect for the colour flow topology of events, to leading order in $1/N_C^2$, where $N_C = 3$ is the number of colours.

OPAL[16] compares $q\overline{q}\gamma$ with $q\overline{q}g$ events. In the angular region between q and $\overline{q}$ the energy and particle flow is expected to be higher in the former than in the latter event class. This is indeed observed, and perturbative formulae[17] describe it qualitatively. However, the separation is larger in the data than expected by these formulae. Event generators describe the separation fully when the colour flow is respected both in the perturbative and the nonperturbative stages, but fail if either or both of these requirements are relaxed.

ALEPH[18] instead compares the qg and $q\overline{q}$ angular regions of $q\overline{q}g$ events. Again the former is expected to have a higher energy and particle flow, and this is confirmed by the data. In event generators that agree with data, about half the effect comes from the perturbative stage and half from the nonperturbative one. As above, models fail if colour flow effects are removed at either stage.

ALEPH further demonstrates that "jets are crooked": if a quark jet direction is reconstructed in $q\overline{q}g$ events, then there is a tendency for high-momentum particles to be found on the side away from the g jet and low-momentum ones on the side towards the g. The latter is what could be expected from the soft emission by the colour dipole spanned between the q and the g; the former then follows as a consequence of the jet direction being found as an average.

Also the particle–particle correlation and its asymmetry, defined by analogy with the more familiar energy–energy correlation measures, are good probes of colour topology effects. L3[19] and ALEPH[20] agree that models are required to have both perturbative and nonperturbative descriptions that respect this topology.

In summary, we now see that a peaceful coexistence should be possible between the perturbative coherence phenomenon and nonperturbative colour-topology-based fragmentation models. Both are needed for a complete description. The big loser may be the local parton–hadron duality philosophy. According to LPHD the energy and particle flows should be determined entirely by the perturbative stage, with no extra structure added in the nonperturbative stage. More about this in the next few paragraphs.

4 Particle Rates and Spectra

The collaborations have presented many new results on particle rates and spectra. An extensive discussion on the data, including a "world average" table of particle rates per Z^0 event, is found in the review by De Angelis[1].

Let us begin by a discussion on the shape of spectra, leaving aside absolute normalization. Generally these are well described by models. They are also well described by the MLLA+LPHD framework, i.e. modified leading-log approximation combined with local parton–hadron duality[21]. This applies both to the shape of the distribution and to the change of peak position (in the variable $\xi = \log(1/x_p)$) as a function of c.m. energy. A third prediction is that the peak position should vary in direct relation to the mass of a particle. Here OPAL[22] and DELPHI[23] compare a wide range of particles, from π to Ξ. The conclusion is unambiguous: peak positions do not agree with the expected mass dependence. Good general agreement is found with event generators, however, where secondary decays are major sources of the observed particles. Only if such generators are used to correct for the effects of secondary decays, i.e. if only primary produced particles are considered, is the MLLA+LPHD pattern visible.

The LPHD assumption is not part of the QCD framework, unlike MLLA, but an ad hoc ansatz that attempts to bypass the need for hadronization models and treatment of particle decays. As such, it has been given different interpretations by different authors, and in its milder formulations it is a very useful guiding principle. However, the hard-line approach, "one parton, one hadron", is now shown to be in direct conflict with data on several counts. It should be noted that programs such as HERWIG or JETSET are not consistent with the hard-line LPHD school, not only on the issue of secondary decays: in the programs the hadrons are not created at the positions of partons but in the colour fields (clusters/strings) spanned between partons. They agree with softer formulations of LPHD, however, in that they give clear correlations between the local phase-space density (and fluctuations) of partons and hadrons.

This does not mean that programs fully explain the shape of spectra. For instance, the proton fraction of all charged particles drops at large x, as demonstrated e.g. by SLD[24], and this runs counter to expectations. A possible explanation could be a suppression of diquark production at small proper times of the fragmentation process[25].

We now turn to the average particle production rate per hadronic Z^0 event. Here much progress has been achieved in the last year, but the picture still is not clear. For instance, many resonances are so broad that the background subtraction is a very delicate process. Therefore discrepancies may be found, for Δ^{++} between $0.22 \pm 0.04 \pm 0.04$ by OPAL[26] and 0.079 ± 0.015 by DELPHI[27]. Discrepancies such as these directly affect our physics conclusions. One of the cleaner tests of production dynamics is the relative rates of decuplet baryons, since these should be little affected by resonance decays and isospin issues. OPAL[26] here finds a pattern in bad disagreement with models, and also with a simple rule of a fixed suppression factor per extra s quark:

ratio	OPAL	JETSET	HERWIG	"world"
Σ^{*+}/Δ^{++}	0.086	0.206	0.373	0.177
Ξ^{*0}/Δ^{++}	0.029	0.029	0.089	0.049
Ω^-/Δ^{++}	0.023	0.004	0.024	0.013

If instead the "world average" numbers[1] are used, agreement with models improves significantly, and also a suppression factor of about 0.2 per s quark is a good approximation. But even the "world" numbers have experimental errors close to $\pm 50\%$, so maybe the main conclusion is that it is too early to jump to conclusions.

Turning to the (non-)theory of particle composition, the production rates could depend on several aspects, such as:

1. flavour content of hadrons (e.g. K vs. π),
2. flavour compensation requirement (e.g. no baryon without an antibaryon),
3. spin (e.g. ρ vs. π),
4. combined flavour+spin wavefunction (e.g. Σ^0 vs. Λ),

5. mass (e.g. η' vs. η),
6. phase space (e.g. cluster mass),
7. spatial shape of hadron wave function,
8. space–time overlap between adjacent wave functions,
9. topology of confinement field (e.g. g vs. q jets),
10. process type (e.g. ep vs e^+e^-),
11. thermodynamics (e.g. in heavy-ion collisions), and
12. Bose–Einstein and other collective effects.

There is no basic law to forbid either of these dependences, so at some level all of them should be expected. However, the hope is that some are more important than others, so that it is possible to find an efficient and simple first-order approximation.

Several approaches have been attempted; only a few are mentioned here.

- The Lund[28]/JETSET approach contains a large number of parameters related to flavour and spin, and this number has tended to increase over the years. One can more or less reproduce the data, but there is very little predictive power left. Higher resonances (tensor mesons) are more frequent in the data than expected; this could be reconciled if these resonances would be polarized and tend to decay along the global string direction, so that they could be viewed as intermediate string pieces.
- The UCLA model[29] is a variant of Lund in which the string area law is taken to give the rate of flavour production as well as the conventional kinematics dependence. It does a good job, given the small number of parameters. Problems appear in the baryon sector, however.
- The HERWIG cluster fragmentation approach also contains few parameters and does well. One would therefore consider this a very good first-order description, with the possibility of further refinements, if needed. The cluster approach is faced with other problems, however, as we will come to.
- Chliapnikov and Uvarov[30] have noted an interesting regularity in production rates, consistent with an exponential fall-off in m^2. This requires the introduction of ad hoc isospin factors, however, and does not take into account the effects of resonance feeddown, so it is difficult to draw any conclusions. What is presented is also more of a fit than a physics scenario.
- The most interesting new study is by Becattini[31], who takes a thermodynamical approach to the production rates. Only three parameters are required: a temperature, a volume and an s-quark suppression parameter. Within this constrained ansatz, impressive agreement with the data is achieved. Hidden in the ansatz is a number non-obvious assumptions, however, so the model is not fully as constrained as it might seem. One also assumes that hadrons reach complete thermal and chemical equilibrium, counter to conventional wisdom that an e^+e^- system is rapidly expanding and has a rather low hadronic density. It will therefore be interesting to see if new tests can be proposed to check the thermodynamics ideas.

In summary, today we do not have one unique explanation of particle production rates, but rather a set of mutually contradictory ideas. This reflects our uncertainty about which are the main mechanisms at play.

If there are some points in the list above that we would like not to involve in an ultimate explanation, it would be 9 and 10, since they break against such cherished notions as jet universality and factorization. It is therefore notable that discrepancies now are found in both areas. L3[32] has studied the η rate in three-jet events and observes a production in excess of expectations in the lowest-energy jet, i.e. likely the gluon jet. No anomaly is observed e.g. in the π^0 spectrum, and other studies have shown that the shape of gluon jets is very well predicted by models[33], so this is a singular occurence. It is too early to exclude a statistical fluctuation, but the effect would be consistent e.g. with glueball production, as allowed in some models[34, 35]. If so, even more spectacular discrepancies could be expected for the η'.

There also appears to be problems with strangeness production, i.e. mainly K and Λ. DELPHI[36] notes a deficit of strange particles in extreme two-jet events, i.e. events that are not resolved into three or more jets even for small jet resolution parameters. Worse, both ZEUS[37] and H1[38] require a s/u relative production rate of about 0.2, to be compared with 0.3 in e^+e^-. Similar numbers have been presented since many years, e.g. by neutrino experiments. Then it was at lower energies, so, rightly or wrongly, problems in part could be blamed on the poorly understood proton beam remnant. Now a low strangeness production rate is required in a broad range of rapidities and at large $p_\perp$. Potentially this can be a devastating observation for our current understanding of hadronization. Therefore this area should be watched closely in the future, to see if we can find some clue to what is going on.

5 Correlations and Bose–Einstein Effects

Once single-particle distributions begin to come under control, it is interesting to turn to correlations for further information.

ALEPH[39] studies the angle between the event axis and the $p\overline{p}$ momenta in the rest frame of the $p\overline{p}$ pair. Data show that baryon production is preferentially lined up along the event axis, in agreement with the string model but in sharp contrast to cluster models, where baryon-antibaryon pairs are produced in isotropic cluster decays. An even more precise test along these lines can be performed by SLD[24]: the large beam polarization implies that quarks preferentially are found in one hemisphere and antiquarks in the other. The data show that there are more energetic baryons than antibaryons in quark jets, and the opposite in antiquark jets. Again this is in in disagreement with the cluster picture. Also jet charge studies[40] indicate that isotropic cluster decays give the wrong flavour correlation pattern.

A hot topic at this meeting has been rapidity gaps at HERA and the Tevatron. Conventional wisdom is that gaps should be very rare in e^+e^- events, i.e. the rate should drop rapidly with increasing gap size. Even current models for colour rearrangement[41, 42] would agree with this, but one could conceive of models with enhanced rearrangement probability, which would then be disastrous for W mass determinations at LEP 2. Experimental studies fail to find any unexpected effects[43, 44].

The multiparticle production amplitude should be symmetrized for identical bosons. This can lead to a Bose-Einstein (BE) enhancement of particle production at small relative momentum separation. Often this enhancement is parametrized as $1 + \lambda \exp(-Q^2 R^2)$, where λ is a chaoticity parameter, $0 \leq \lambda \leq 1$, R is the source radius and $Q^2 = (p_1 - p_2)^2 = m_{12}^2 - 4m^2$. One could have expected a source elongated along the event axis, but actually e^+e^- data are well described by the spherical ansatz. The Gaussian shape is not in contradiction with data, but the tests are not particularly discriminating. Typical values are $R \approx 0.6$ fm and $\lambda \approx 1$, once effects of secondary decays have been taken into account. Some studies come up with $\lambda > 1$, which ought to be impossible. In a fitting procedure the

λ and R parameters are correlated, however, so the evidence still is not fully compelling, in particular not if also non-Gaussian shapes are considered. (One can observe $\lambda \gg 1$ in $\overline{\mathrm{p}}\mathrm{n}$ annihilation at rest, maybe related to interference between specific channels[45]. This is a warning signal that not all of the low-Q enhancement need be of BE origin.)

An experimental problem is that it is difficult to define a reference sample without BE effects. On the theory side little understanding exists of how exclusive event properties are affected, e.g. if BE effects can modify the multiplicity of events. A few explicit proposals have been made[46, 47], but tests are not yet sufficiently precise to discriminate.

Several new BE studies have appeared, see the review by Verbeure[7]. Especially nice is the first observation of nontrival three-body correlations by DELPHI[48]. The JETSET BE approach partly describes these effects, but not fully. Since the model was primarily based on two-particle correlations this is maybe not surprising, but indicates the primitive state of current modelling. An amazing aspect of this model is that it implies a significant change in the $\pi^+\pi^-$ mass spectrum, with a downwards shift of the ρ mass peak, as is now observed in the data[49]. However, the way this effect arises in the program is sufficiently subtle that one may worry whether the BE explanation is not a red herring.

If BE effects these days attract increased attention, it is partly due to the realization that BE correlations between the W^+ and W^- hadronic decay products at LEP 2 could affect the W mass determination[47], just as colour rearrangement could[41, 42].

6 Summary

The field of experimental QCD physics at the Z^0 is in impressively healthy shape. It appears there are more new results than ever, some improvements of previous studies but many breaking new ground. Apologies to the authors of all those works that should have been covered here but were not, for lack of space. Other interesting results include the observation of $\mathrm{g} \to \mathrm{c}\overline{\mathrm{c}}$ branchings at a slightly high but still reasonable rate[50], the first observation of Υ production[51, 52], the first attempts to measure a longitudinal polarization of the Λ[53, 54], the spin alignment of the phi[55], and much more.

Most of the data is understood not only qualitatively but also quantitatively. This is a success, not well reflected in this review. However, it is natural to concentrate on the failures, which are the ones that call out for more experimental and theoretical activity.

Possibly the most spectacular news is the potential breakdown of jet universality and factorization, in the enhanced η production rate in gluon jets compared with quark jets, and especially in the reduced strangeness production in ep events compared with $\mathrm{e}^+\mathrm{e}^-$ ones. These areas clearly need much further study, experimental and theoretical.

The area of flavour production in general is in a bit of a crisis, in that the models that served well for so many year now start to show cracks under the onslaught of high-precision data. Maybe we need a fresh outlook on the hadron production process.

Particle spectra still are reasonably well described by programs, with some problems for baryons. However, the hard-line interpretation of local parton–hadron duality now is in conflict with data: it is not possible e.g. to neglect the effects of unstable particle production and decay. In its more flexible interpretations, LPHD still offers useful guidelines, however.

The importance of the colour topology of events appears well established, and allows for a peaceful coexistence between perturbative and nonperturbative manifestations.

Alignment along the colour flow axis is also visible in particle correlations. Isotropically decaying clusters are excluded, at least so long as clusters do not carry baryon number.

While the soft radiation pattern seems under control, problems may be noted in the hard sector, both with respect to out-of-the-event-plane properties and the emission of prompt photons. It is too early to tell whether these are fundamental limitation or are solvable technical problems.

Finally, it should be said that the need for QCD studies has not decreased. On the contrary, there are many topics that deserve continued attention in their own right, and for their importance to other fields. As one such example, Bose-Einstein studies not only may teach us about the particle production process but also influence W mass determinations at LEP 2. There is therefore every reason to
Keep up the good work!

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