# Reply to ''Scattering of very light charged particles''

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We respond to the preceding Comment by J. C. Taylor. [S0556-2821(96)01316-1]

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We welcome the comments [1] of Professor Taylor on our work. In this short response, we hope to clarify some points and indicate where more work needs to be done. We join him in the hope that his comments will provoke further discussion.

Professor Taylor raises two different doubts about our work [2–5] on initial-state collinear divergences. First, he questions whether one should ever have to take them into account for any particle of finite mass. Later, he questions whether our estimates for the opening angle are correct, although if he believes the former, this question seems moot.

Concerning matters of principle, for massless particles experiencing long-range forces, the usual formulation of the $S$ matrix in terms of asymptotic plane waves breaks down, both in potential theory and in field theory. Since the asymptotic states are simply not the conventional ones, we believe there is no question that the conventional formulation requires modification. There is no fundamental distinction between initial and final states in this regard, so we find it surprising that Professor Taylor accepts the usual treatment of final states but rejects the suggestion that initial states must also be treated in a similar manner. It certainly appears that Lee and Nauenberg had no doubts on this score, and we wonder what is to be done with initial-state mass singularities.

That being the case for massless particles, it is reasonable that, for a particle with sufficiently small mass, there may remain a vestige of these effects. It becomes a matter of the order of limits. Certainly, for a theory without massless particles, the usual $S$ matrix exists, and there is no problem of principle. However, the notion that we measure $S$-matrix elements is itself an idealization, since real measurements are conducted over finite times and distances. The physical question is whether the limit of infinite time and finite mass is a better approximation than finite time but negligible mass. Like Bloch and Nordsieck [6], we have argued that the massless limit is in fact smooth when phrased not in terms of the usual $S$ matrix but in terms of observables or a modified $S$ matrix.

We believe there is a misunderstanding in his reference to our remark that ''a complete resolution of this paradox requires a more careful analysis of the measurement process.'' We did not intend to cast doubt on our results, but it would be nice to see a derivation in which the same answer that we obtained via the asymptotic $S$ matrix was derived from a careful analysis of an idealized measurement over finite times and distances taking into account wave packets and instruments of finite resolutions. Our confidence in the relevance of initial-state sums is based on the fact that the asymptotic states for massless particles are not the usual momentum eigenstates. There is no doubt that for sufficiently small mass, some actual measurements will not be well approximated by the usual $S$-matrix elements. The challenge is to delineate the relevant experimental resolutions to compare with the mass.

This brings us to Professor Taylor's second point questioning our estimate of the angular resolution. In fact, we understood that an ultimate limitation would be set by the uncertainty principle in the sort of manner that he describes, and we mentioned this on p. 1311 of our paper.[1] However, we found that in every realistic case that we analyzed, the actual experimental resolution was far larger. We understand that he has doubts about the arguments leading to that conclusion, but does he admit that, in certain situations, it would be necessary to modify initial states? If not, his point of view would appear to leave unresolved matters of principle concerning evanescent processes, such as the nondecoupling of longitudinal photons or gluons from massless quarks or the nonrestoration of chiral symmetry in the limit that a massive fermion becomes massless limit. We prefer a formulation that implies that a massless theory is unique, independent of the manner in which these mass singularities are regulated. We tried to advance arguments why we believe that nature also acts in this manner.

Concerning his reference to our Appendix C [1], we admit that the derivation there is not completely convincing and requires further discussion. However, the paper by Morota, cited in our *Note added in proof*, suggests that this is a promising approach.

Concerning his remark about non-Abelian soft divergences, the initial state must of course contain soft gluons moving in all directions. A ''soft gluon,'' by definition, has such a long wavelength that it cannot be distinguished in the measurement. We discuss this to some detail in Appendix B,

[1]There is a typographical error in [2]: $\Delta E\hbar/T$ should of course read $\Delta E\approx\hbar/T$.

 

where we remark that ‘‘a soft photon has really no direction.’’ In the non-Abelian case, a quark always carries with it a cloud of soft gluons, so that it is meaningless to speak of a quark of a definite color. One simply must expand the incoming coherent state which, beyond zeroth order, involves a summation over quarks of different color. The difference between the non-Abelian and Abelian cases seems to be that, unlike Bloch and Nordsieck [6], it is not true that, so long as the initial-state resolution is smaller than the final-state resolution, one gets an answer independent of the initial-state resolution. This should be analyzed further, but, since realistic initial states always consist of colorless hadrons, it should sort itself out. We discuss this a bit in our concluding section, where we suggest that in QCD it is the confinement angle $\Lambda_{QCD}$ that should be identified with the initial-state energy resolution for partons.

[1] J. C. Taylor, preceding paper, Phys. Rev. D **54**, 2975 (1996).
[2] H. F. Contopanagos and M. B. Einhorn, Phys. Rev. D **45**, 1291 (1992).
[3] H. F. Contopanagos and M. B. Einhorn, Phys. Rev. D **45**, 1322 (1992).
[4] H. F. Contopanagos and M. B. Einhorn, Phys. Lett. B **277**, 345 (1992).
[5] H. F. Contoponagos, Nucl. Phys. **B343**, 571 (1990).
[6] F. Bloch and A. Nordsieck, Phys. Rev. **52**, 54 (1937).