DIMUON PRODUCTION AT THE TEVATRON

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Introduction

We consider the Drell-Yan process of dimuon production in high-energy hadron collisions (Fig. 1). We write the dimuon momentum as

$$q^{\mu} = x_1 \, p_1{}^{\mu} + x_2 \, p_2{}^{\mu} + q_T{}^{\mu}, \tag{1-1}$$

with $p_1 q_T = 0$. The dimuon will generally come from decay of a single virtual photon. If we let θ and ϕ be the polar angles on one muon with respect to some axes in the dimuon rest-frame, then

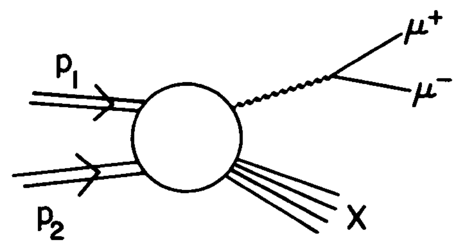

Fig. 1

the main object of interest is the inclusive cross section

$$\frac{d\sigma}{d^4q \; d\Omega} \tag{1-2}$$

which is a function of s, x_1 x_2, q_T, θ, and ϕ. It is also of interest to measure properties of the hadronic final state X.

Measurements of the process are important because it provides a good test of QCD. There is a standard set of perturbative calculations which express the cross section (1-2) in terms of quark and gluon distributions in the incident hadrons. Since all of the distributions can be measured in deep inelastic scattering (though only with difficulty for the gluons), it is of interest to verify that the same distributions appear in a totally different process.

The main theoretical uncertainties are to do with the effect of higher-order corrections and with the precise slope of the cross section at low transverse momentum. These two problems are in fact related to each other! Higher order corrections should be small if perturbation theory is to be useful; unfortunately the one-loop corrections are not small. Even so, the largest part of the correction amounts to a change of the normalization. It appears[1] that this large correction is caused by emission of soft gluons and that the large parts of the correction can be summed to all orders of perturbation theory. Indeed[2] the experimental cross section is a factor $K \approx 2$ higher than the lowest order prediction.

At low transverse momentum [i.e., $q_T \ll (s)^{1/2}$] the simplest methods of calculation are inapplicable, primarily because of soft gluon effects. Much theoretical work[5,6,8] has been done, and the situation is probably under control.

Many experimental measurements remain to be done--especially at large transverse momentum, where the statistics available at a fixed-target machine are important. The Tevatron is particularly useful for its improved secondary beams. A factor of two increase in s is helpful for reducing non-Drell-Yan mechanisms (which are non-leading by a power of s), while the q^2-dependence of predicted higher-twist effects at $x_F \equiv x_1 - x_2 \to 1$ can also be tested.

In Section 2, we discuss the possibilities at low transverse momentum, in Section 3 we describe large transverse momentum, and in Section 4 we investigate jet measurements, etc.

Low Transverse Momentum

Many measurements have already been made[2] of $d\sigma/dx_1dx_2$, the cross section integrated over transverse momentum and the muon angles θ and ϕ. These have resulted in a determination of the valence quark distributions for the pion and kaon, and a check has been made that the cross section for proton and antiproton induced events is consistent with the Drell-Yan form

$$\frac{d\sigma}{dx_1 dx_2} = K \frac{4\pi\alpha^2}{9q^2} \sum_q e_q^2 \; f_{q/1}(x_1) \; f_{\bar{q}/2}(x_2). \qquad (2.1)$$

Here the f(x)'s are quark probability distributions, and K is a constant which in the simplest version of the theory is unity. Experiments[2] suggest that $K \approx 2$, while in QCD there are higher order corrections whose main effect[1] is to induce such a value for K.

Antiproton-induced dimuons provide the cleanest test of the theory, since annihilation of valence quarks and antiquarks dominates. However $\bar{p}$ beams are the lowest in energy and intensity. The increase in energy (to 200 GeV) and in intensity at the Tevatron will be important in improving these results.

There are a number of areas where improved measurements are needed. The first is $x = x_F \to 1$. For pions (but **not** protons) it is predicted[3] that the valence quark distribution is effectively

$$f_{q/\pi}(x) \sim (1 - x)^2 + \frac{2}{9}\frac{K_T^2}{q^2} , \qquad (2.2)$$

as $x \to 1$, while the angular distribution goes to $\sin^2\theta$. There are experimental indications of this[2,4], but with large errors. Both the θ-distribution and the q^2-dependence need to be checked. (The region should be explored with both pion and proton beams.)

The A-dependence of cross sections (A = mass of target nucleus), especially at large x_F, needs to be measured better. Although the usual expectation is a linear A-dependence, it is **conceivable** (and, at some low enough level, necessary) that nuclear binding effects change the proton distributions, particularly at small x. (Small x is explored by $x_F \sim 1$ when q^2 is fixed.) Furthermore, non-perturbative and/or higher-twist corrections do not have to have linear A-dependence.

Low q_T Distributions

The conventional methods of calculating in QCD apply to the case that either

(1) q_T is integrated over

or

(2) $x_T = q_T/(s)^{1/2}$ is treated as a scaling variable.

When one attempts to compute $d\sigma/dx_1\, dx_2\, d^2q_T$ with $q_T \ll (s)^{1/2}$, serious problems arise. Soft gluon emission becomes very important and a summation of certain contributions to the cross section to all orders of perturbation theory is necessary [5,6,8] before meaningful comparison with experiment can be made. The effects are related to the "Sudakov form-factor," and they result in a substantial modification to naive expectations. Figure 2 is suggested by Refs. 6 and 8. Comparison of experimental data[7] at beam energies of 200 GeV and 400 GeV supports this picture.

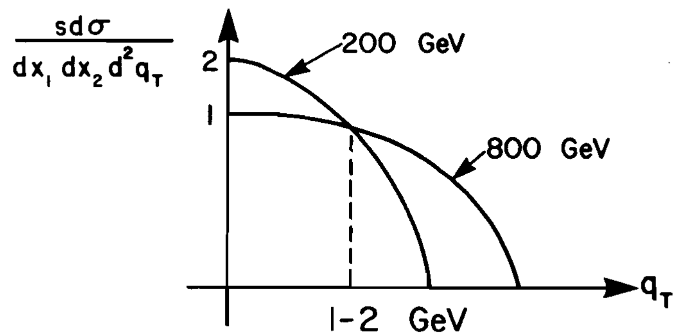

Fig. 2

Further measurements of these effects at a range of energies are important. They probe some complicated high order corrections. Moreover,[9] Sudakov form factors are also crucial to an understanding of problems like

1. Structure functions at $x \to 1$,
2. Nucleon form factors at large q^2,
3. Elastic wide-angle scattering,
4. $e^+ + e^- \to h_1 + h_2 + x$.

The long lever arm (with good statistics) obtained by going from 200 GeV to 800 GeV at a fixed-target machine is clearly important (regardless of whose theoretical calculations are considered).

Event Rates at the Tevatron

For the primary beam used at full intensity, a factor 5 is lost in intensity because of the increased cycle time. Large aperture experiments, however, would use much less of the beam, so this factor is not necessarily important. The secondary beams are more intense, so that the longer cycle time is compensated for.

At **fixed x_1 and x_2** the cross section $d\sigma/dx_1dx_2$ is reduced by a factor of 2 because of scaling in going from a 400-GeV beam to 800 GeV. However, the region in which scaling occurs is extended so that it is relevant to consider what happens at fixed q^2. For incident protons we expect[7] a cross section proportional to $e^{0.7M}$ at a beam energy of 800 GeV. (This is obtained by scaling 400-GeV data.) For example, if $M = 15$ GeV this results in a $d\sigma/dx_1dx_2$ that is a factor 40 higher at 800 GeV than at 400 GeV.

Large Transverse Momentum

When $q_T{}^2$ is of order q^2, dimuon production should be well described by the graphs of Fig. 3. Only the $q\bar{q}$ graphs of Fig. 3

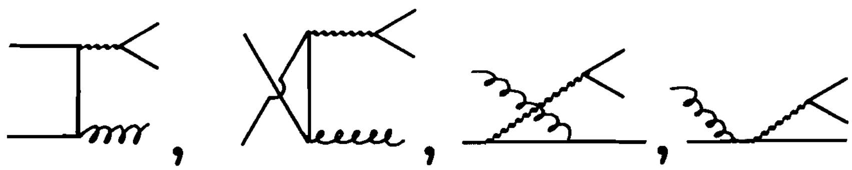

Fig. 3

(a) should be important in pion- or antiproton-induced dimuon production. But in proton-induced events, the gluon-quark graphs of Fig. 3(b) are at least as important.[10]

Many people[10] have performed the calculations which give the cross section as a function of x_1, x_2, q_T, θ, and ϕ, in terms of quark and gluon distribution functions. We have a good test of QCD (modules a possible K-factor). The predictions are written as an integral over parton distributions. For example, the $q\bar{q}$ graphs of Fig. 3(a) give

$$\frac{d\sigma}{dx_1dx_2d^2q_T} = \frac{8\alpha^2\alpha_s}{27\pi q^2q_T^2}\sum_q e_q^2\int\frac{d\xi_1d\xi_2}{\xi_1{}^2\xi_2{}^2}\,\delta\,[(\xi_1-x_1)(\xi_2-x_2)-q_T^2/s] \tag{3.1}$$

$$f_{q/1}(\xi_1)\,f_{\bar{q}/2}(\xi_2)\,[\frac{q^4}{s^2}-\frac{2q_T^2}{s}\xi_1\xi_2+\xi_1^2\xi_2^2],$$

where the $f(\xi)$'s are the parton **probability** distributions (so that $\sum_q\int dxf_q(x) = 3$ for valence quarks in a proton), and the δ-function puts the final-state gluon on its mass-shell. (The integration is over

$$x_1 + [q_T^2/s(1-x_2)] < \xi_1 < 1,$$

$$x_2 + [q_T^2/s(1 - x_1)] < \xi_2 < 1,$$

The predictions should be checked by high acceptance experiments (at large q_T). Expected event rates can be obtained from (3.1). For example, let us use sea and valence distributions $1.75x^{-0.5}\ (1-x)^{3.54}$ and $0.15\ x^{-1}(1-x)^7$ respectively. In pp scattering with $(s)^{1/2} = 40$ GeV, $M = 12$ GeV, $q_T = 6$ GeV, and $x_F = 0$, the cross section into a $0{\cdot}1\times0{\cdot}1$ square of x_1 and x_2 and a 1-GeV gin in q_T is roughly 3×10^{-14} mb. This gives about 10^{-15} events per proton. (Compare with the expectations of ~10^{13} protons per pulse.) Normal estimates of gluon distributions increase this by a factor of a few,[10] and the number is consistent with a scaled version of Fig. 12 of Ref. 7. Event rates at lower dimuon masses are of course much higher, even in regions where the theory should be applicable.

Angular distributions are also predicted by the theory. For example $q\bar{q}$ scattering under the same conditions as above (viz. $q_T/q = 1/2$) gives $1 + 7/11\ \cos^2\theta$ (in the Collins-Soper frame). This is very different from the $1 + \cos^2\theta$ seen at low q_T. The deviation from $1 + \cos^2\theta$ in the gluon-quark case is even larger.[10] Measurements of both θ and ϕ distributions need to be made.

Jets, Higgs and Electromagnetic-weak Interference

There is a jet associated with the final-state parton in Fig. 3 when a large transverse momentum dimuon is produced. Such dimuons therefore give one a hadronic final state known to contain a jet. In particular in πp or $\bar{p}p$ collisions the jet is almost a pure gluon jet (admittedly with low statistics). These topics were discussed in the jets section of this workshop. The Tevatron is important in enabling the jet to be at large enough transverse momentum to be observable.

In pion-induced dimuon production the spectator quark of the pion provides one with an example of a single quark jet. Experimental data on such a jet would be interesting.

The Drell-Yan process can occur via a Higgs' boson instead of a virtual photon, and the possibility of seeing the Higgs in this way was discussed in the Higgs section of the workshop.

Interference exists between Z^0 and γ exchange in the Drell-Yan process with essentially the same physics as in e^+e^- annihilation. In particular there is an asymmetry proportional to q^2. It would be interesting to look for this in an experiment with enough statistics (at low q_T) and with low enough systematic error. The extra energy at the Tevatron is very important, both in itself for allowing higher q^2 and at fixed q^2 for greatly increasing event rates. However e^+e^- machines can give higher q^2.

References

1. See, for example, C. Llewellyn-Smith's talk at the Madison conference.

2. See, for example, J. LeFrancois's talk at Madison.

3. E. L. Berger and S. Brodsky, Phys. Rev. Lett. **42**, 940 (1979).

4. K. J. Anderson et al., Phys. Rev. Lett. **43**, 1219 (1979).

5. Yu. L. Kokshitsev, D. I. Dychonov, and S. I. Troyan, Phys. Reports **58**, 269 (1980).

6. G. Parisi and R. Petronzio, Nucl. Phys. **B154**, 427 (1979), especially the Appendix.

7. A. S. Ito et al., Fermi National Accelerator Laboratory Preprint Fermilab-Pub-80/19-EXP, February 1980.

8. J. Collins and D. Soper, talks at Madison.

9. See, for example, A. Duncan and A. H. Mueller, Phys. Rev. **D21**, 1636 (1980).

10. See, for example, K. Kajantie and R. Raitio, Nucl. Phys. **B139**, 72 (1978); C. S. Lam and W. K. Tung, Phys. Lett. **80B**, 228 (1979); R. L. Thews, Phys. Rev. Lett. **43**, 987 (1979); J. C. Collins, Phys. Rev. Lett. **42**, 291 (1979).

Many of these papers contain errors in formulae. Debugged formulae for $d\sigma/d^4q$ are in E. L. Berger, at Vanderbilt Conference, 1978. Errors in the formulae are a potential source of systematic error--in one known case a factor of 6! Hence, **all** formulae [including, e.g., (3.1)] should be checked before use.