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Use of the $\Delta\phi$-Angle Test to Rule Out Neutral Heavy Leptons

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ABSTRACT

The strong energy dependence of the $\Delta\phi$ distribution signal for neutrino production of neutral heavy leptons is pointed out in an effort to clarify the use of these distributions to suggest or rule out the existence of such leptons.

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The present limits on the mass of a hypothetical neutral heavy lepton are at best rather tenuous. On the one hand a lower limit of 10 GeV/c^2 was placed on such a heavy M^o muon as the sole source of neutrino-induced dimuon events by the HPWF group[1] in 1975. Subsequent experiments[2] have revealed that the major (if not total) portion of the signal is due to single charm production by the charged weak current, so the former limit is negated by the copious background signals. More recent evidence bearing on this issue comes from a SPEAR experiment[3] which looked for L^o's resulting from the pair production of charged heavy leptons $L^{\pm}$, the L^o's being identified by their decay into the exclusive $e\pi$ and $\mu\pi$ channels. The null result obtained suggested a lower bound of 1.2 GeV/c^2 on the mass of such an L^o. A beam dump experiment[4] at Fermilab also failed to detect L^o's decaying into $\mu\pi$ or $e\pi$ modes (unaccompanied by μ's with $p_\mu > 10$ GeV/c) with a mass less than 1 GeV/c^2 and a lifetime in the range $10^{-10} - 10^{-8}$ seconds.

A relatively light (1.5 - 3 GeV/c^2) mass neutral muon is not inconsistent with the present Aachen-Padova and CDHS data.[5,6] Indeed, it has been suggested by the Aachen-Padova group that of the order of 10 "quiet" $\mu^- e^+$ events (little hadron energy) best fit the characteristics of the reaction

$$\nu_\mu + N \rightarrow M^o + X$$
$$\hookrightarrow \mu^- + \nu_e e^+ (\nu_\mu \mu^+) \quad . \tag{1}$$

The CDHS trimuon data can partially be understood with an L^o of mass 1.5 GeV/c^2 being produced in association with a heavy quark. Preliminary evidence from the BEBC group even suggested that an M^o with mass 1.8 GeV/c^2 had been identified by its decay into the $\mu\pi$ mode.[7] Subsequent experimental searches have not borne this out.

Clearly there is need for sensitive tests which can pinpoint the presence of an M^o heavy lepton at the level of 10%, or less, of the substantial charm background reaction

$$\begin{array}{l} \nu_\mu + d(s) \to \mu^- + c \\ \qquad\qquad\qquad \hookrightarrow s\,(d) + \nu_\mu \mu^+ (\nu_e e^+) \end{array} \qquad (2)$$

The Pais - Treiman test[8] requiring the muon average energy ratio to be in the range $0.5 \lesssim (\langle E_{\mu^+}\rangle / \langle E_{\mu^-}\rangle) \lesssim 2.0$ is not very useful in the presence of a large charm background. The α parameter test,[9] where $\alpha = (E_{\mu^-} - E_{\mu^+})/(E_{\mu^-} + E_{\mu^+})$, is better but suffers from any antineutrino contamination in the neutrino beam. In a previous letter[10] we suggested the combined use of the transverse momentum and opening azimuthal angle tests to signal M^o production followed by the charged dilepton decay mode. While reaction (2) exhibits a strong backward peaking of the aximuthal opening angle ($\Delta\phi$) distribution of the two leptons measured in a plane perpendicular to the beam direction, in reaction (1) both charged leptons originate from the decay of the M^o and the $\Delta\phi$ distribution tends to be peaked forward at the higher energies.

The purpose of this note is to point out that the shape of the $\Delta\phi$ distribution for reaction (1) is very energy dependent, so the phi angle test must be used with caution. The critical variable is E/E_{th}, where $E_{th} = \left[(M+m)^2 - m^2\right]/(2m)$ is the threshold energy for production of an M^o of mass M and m is the nucleon mass. For typical neutrino beam energies $\lesssim 2\,E_{th}$, the $\Delta\phi$ distribution can, in fact, be slightly peaked in the backward hemisphere,[11] since the M^o tends to be produced almost directly forward in the laboratory. Only at energies $\gtrsim 5\,E_{th}$ does the pronounced forward peaking occur when the M^o can be produced at sizable angles relative to the neutrino beam direction.

These features are clearly illustrated in Fig. 1a where the distributions are drawn for a 2 GeV M^o heavy lepton ($E_{th} \simeq 4$ GeV) produced in a double horn experiment at the CERN PS and in a double horn experiment at Fermilab (or the SPS) with 400 GeV primary protons. The results are somewhat helicity dependent and curves are drawn for both $(V-A)\cdot(V-A)$ and $(V-A)\cdot(V+A)$ decay matrix elements. In the latter case more so than in the former case, the two charged leptons tend to be emitted back-to-back in the heavy lepton rest frame so that the $\Delta\phi$ distributions reflect this fact.

As cited earlier, the Aachen-Padova neutrino group has reported[5] finding of the order of 10 "quiet" $\mu^- e^+$ events which fit the characteristics of reaction (1). In particular the $\Delta\phi$ distribution for this small sample of events exhibits a plateau in the backward hemisphere. But we see from

Fig. 1 that with a considerably harder neutrino energy spectrum, a pronounced peaking should occur in the forward hemisphere; moreover, the cross section for a 2 GeV/c^2 M^o produced in reaction (2) should no longer be suppressed by threshold effects. Hence the heavy lepton signal should compete more favorably with the charm background and peaks at both $\Delta\phi = 0$ and 180° should be observed. This has not been confirmed,[12] and the possibility that such M^o's are produced by neutrinos is small.

The situation is not all all clear for heavier neutral leptons, however. In Fig. 1b we show $\Delta\phi$ distributions for both 5 GeV/c^2 and 8 GeV/c^2 M^o's with the Fermilab double horn beam. Note that with $E_{th} \simeq 20-40$ GeV and $\langle E/E_{th}\rangle \simeq 2$, the $\Delta\phi$ curves are again higher in the backward hemisphere. With the 8 GeV/c^2 M^o contribution suppressed by threshold factors and superposed on the charm background curve, it is clear that the $\Delta\phi$ curve will only exhibit a backward peak.

One can also plot $\Delta\phi'$ distributions, where $\Delta\phi'$ represents the azimuthal opening angle between the two charged leptons projected onto a plane perpendicular to the hadron jet direction. We show such plots in Fig. 2a for a 2 GeV/c^2 M^o lepton and both CERN PS and Fermilab horn beams;in Fig. 2b we give the $\Delta\phi'$ distributions for 5 and 8 GeV/c^2 M^o's with the Fermilab horn beam only. In nearly every case, these curves are peaked forward. Dileptons from charm production would tend to exhibit rather flat $\Delta\phi'$ distributions, so these plots can help to unravel a heavy lepton signal on a substantial charm background. We remark that $\Delta\phi'$ distributions in general are subject to larger experimental errors than $\Delta\phi$ distributions, since the error in determining the "apparent" hadron jet direction is non-negligible. This is especially true in bubble chamber experiments where hadrons can escape the chamber without being detected.

In summary, we have attempted to clarify the sensitivity of $\Delta\phi$ distributions to M^o heavy lepton production and decay through leptonic modes yielding dilepton events. It appears that current experiments will not be able to place a higher mass limit than 4-5 GeV/c^2 on M^o's produced with full strength couplings. This contrasts rather sharply with corresponding limits[13] of 7.5 GeV/c^2 and 12 GeV/c^2 recently placed on M^- and M^+ heavy leptons.

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FOOTNOTES AND REFERENCES

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FIGURE CAPTIONS

Fig. 1: $\Delta\phi$ distributions expected for (a) $M = 2$ GeV/c^2 neutral heavy leptons produced by the CERN PS and Fermilab 400 GeV double horn beams. In (b) the $\Delta\phi$ distributions pertain to $M = 5$ and 8 GeV/c^2 neutral heavy leptons produced by the Fermilab horn beam. The solid (dashed) curves refer to LL (LR) helicity couplings in the M^o decay matrix element.

Fig. 2: $\Delta\phi'$ distributions corresponding to Fig. 1.

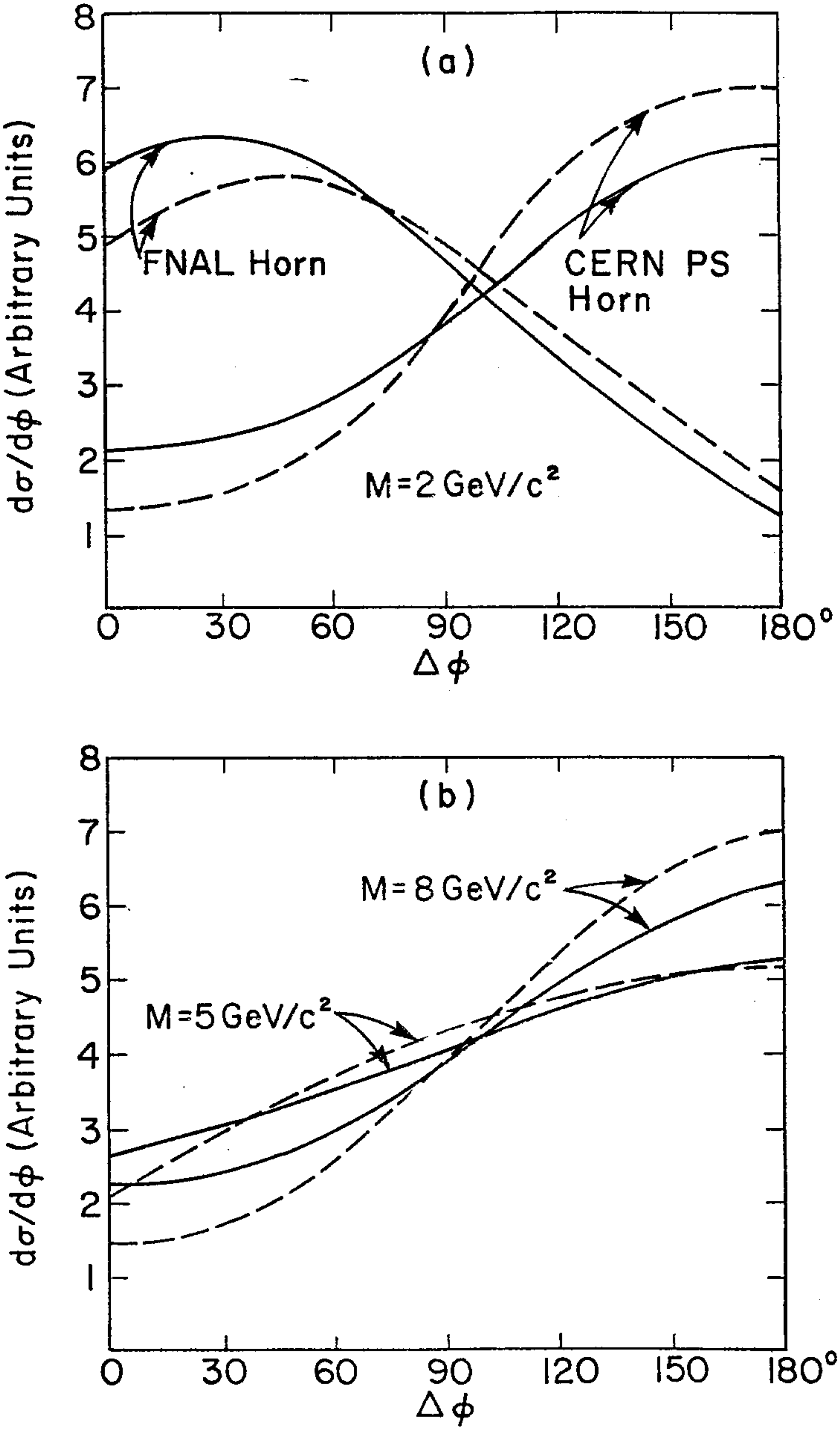
(a)
FNAL Horn
CERN PS
Horn
M=2 GeV/c²
dσ/dφ (Arbitrary Units)
Δφ
0
30
60
90
120
150
180°
1
2
3
4
5
6
7
8
(b)
M=8 GeV/c²
M=5 GeV/c²
dσ/dφ (Arbitrary Units)
Δφ
0
30
60
90
120
150
180°
1
2
3
4
5
6
7
8

Fig. 1

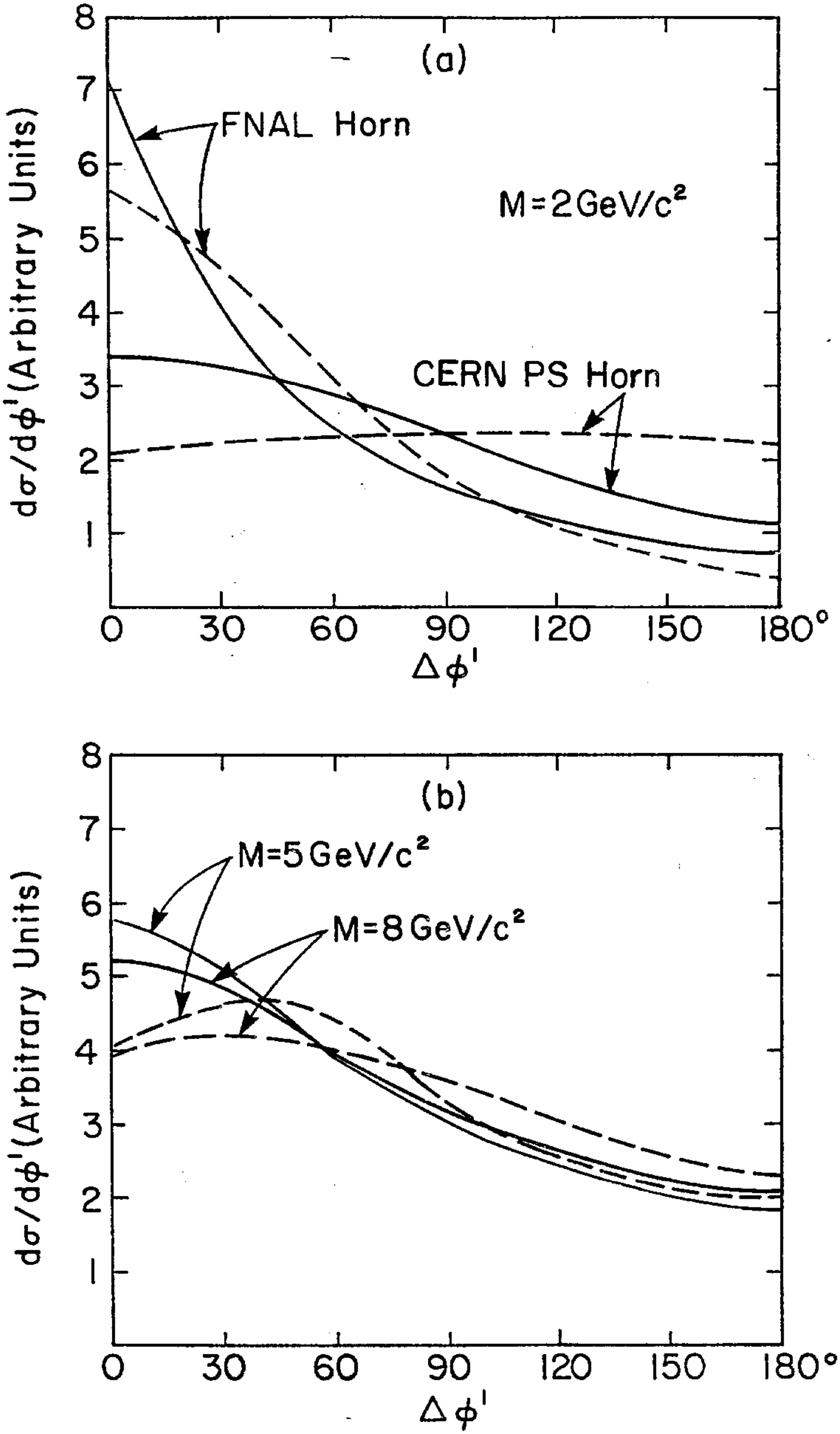
(a)
FNAL Horn
M=2GeV/c²
CERN PS Horn
dσ/dφ'(Arbitrary Units)
Δφ'
0
30
60
90
120
150
180°
1
2
3
4
5
6
7
8
(b)
M=5GeV/c²
M=8GeV/c²
dσ/dφ'(Arbitrary Units)
Δφ'

Fig. 2