

the gauge is fixed up to boundary conditions, and the above results are encouraging. One may also argue that direct closed loop calculations will not produce a

cosmological term either, simply because dimensional regularization (which respects the gauge invariances) leads to vanishing of tadpole diagrams.

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

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Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

We have observed a strong enhancement at 9.5 GeV in the mass spectrum of dimuons produced in 400-GeV proton-nucleus collisions. Our conclusions are based upon an analysis of 9000 dimuon events with a reconstructed mass $m_{\mu^+\mu^-}$ greater than 5 GeV corresponding to 1.6×10^{16} protons incident on Cu and Pt targets:

$$p + (\text{Cu, Pt}) \rightarrow \mu^+ + \mu^- + \text{anything.}$$

The produced muons are analyzed in a double-arm magnetic-spectrometer system with a mass resolution $\Delta m/m$ (rms) $\approx 2\%$.

The experimental configuration (Fig. 1) is a modification of an earlier dilepton experiment in the Fermilab Proton Center Laboratory.¹⁻³ Narrow targets (~ 0.7 mm) with lengths corresponding to 30% of an interaction length are employed.

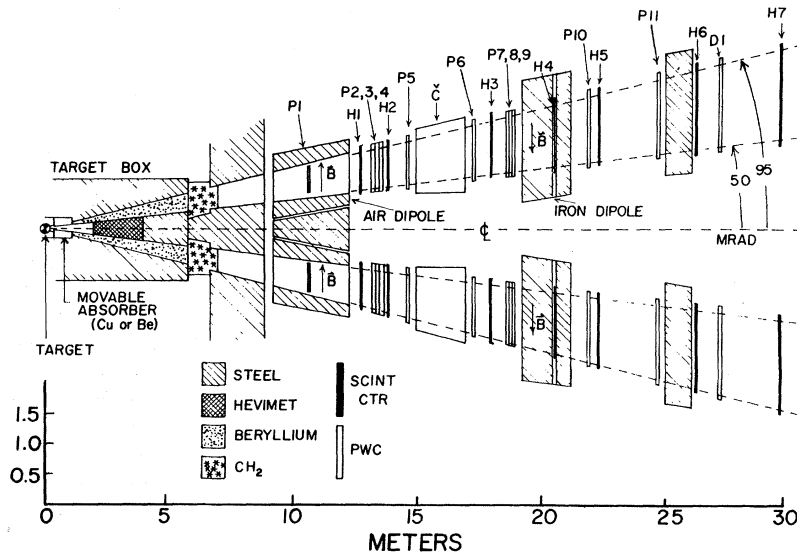


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1-P11, seven scintillation counter hodoscopes H1-H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

TABLE I. Yield of muon pairs for various running conditions.

Analyzing-magnet current (A)	Target	First 30 cm absorber	No. of incident protons	No. of events $m_{\mu^+\mu^-} \geq 5 \text{ GeV}$
1500	Cu	Cu	8.1×10^{15}	4093
1500	Pt	Cu	4.1×10^{15}	2076
1250	Cu	Cu	2.5×10^{15}	1891
1250	Pt	Be	1.6×10^{15}	911

Beryllium (18 interaction lengths) is used as a hadron filter, covering the 50–95-mrad (70–110° c.m.) horizontal and ± 10 -mrad vertical aperture in each arm. The Be is closely packed against steel and tungsten which minimize particle leakage from outside the aperture, especially from the tungsten beam dump located 2.2 m downstream of the target. Polyethylene (1.5 m) and a 2.2-m steel collimator complete the shielding. The first 30 cm of beryllium (starting 13 cm downstream of the target center) can be remotely exchanged for 30 cm of copper.

The spectrometer dipoles deflect vertically, decoupling the production angle of each muon

from its momentum determination. At full excitation (1500 A), the magnets provide a transverse momentum kick $p_t \approx 1.2 \text{ GeV}$. In order to maximize the usable luminosity, no detectors are placed upstream of the magnet. Conventional proportional wire chambers (PWC's) and scintillation hodoscopes serve to define the muon trajectory downstream of the air dipole. Following the PWC's is a solid iron magnet (1.8 m long, energized to 20 kG) used to refocus partially the muons vertically and to redetermine the muon momentum to $\pm 15\%$. A threshold Čerenkov counter on each arm also helps prevent possible low-momentum muon triggers. The apparatus is ar-

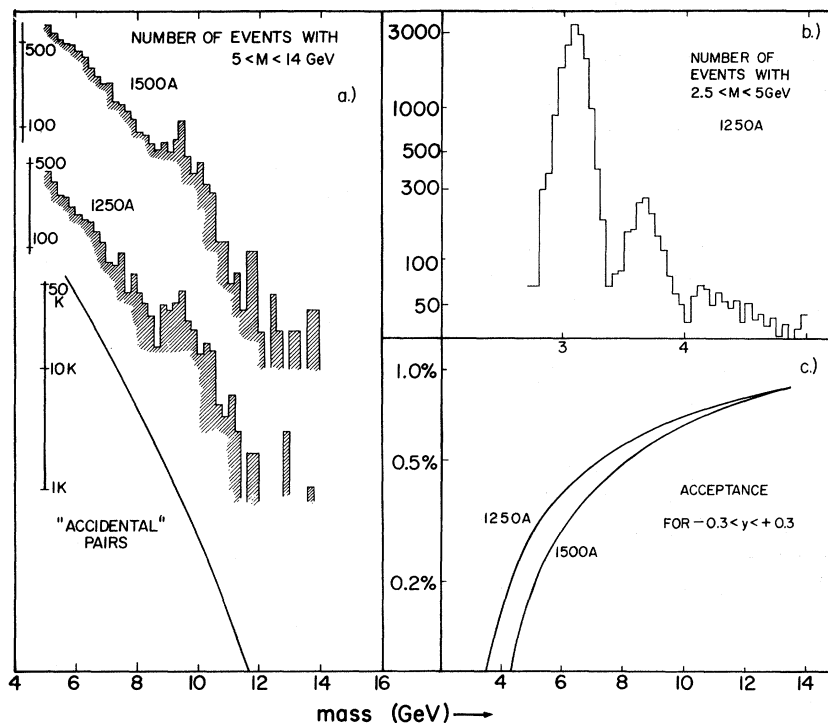


FIG. 2. (a) Dimuon yield at 1500 and 1250 A; the data with Cu and Pt targets have been combined. Also shown is the mass spectrum generated by combining two muons from different events. (b) Excess of opposite-sign over equal-sign muon pairs in the ψ, ψ' region. (c) Dimuon mass acceptance for the two excitations of the air dipole.

ranged symmetrically with respect to the horizontal median plane in order to detect both μ^+ and μ^- in each arm.

The data sets presented here are listed in Table I. Low-current runs produced $\sim 15\,000 J/\psi$ and 1000 ψ' particles which provide a test of resolution, normalization, and uniformity of response over various parts of the detector. Figure 2(b) shows the 1250-A J/ψ and ψ' data. The yields are in reasonable agreement with our earlier measurements.²

High-mass data (1250 and 1500 A) were collected at a rate of 20 events/h for $m_{\mu^+\mu^-} > 5$ GeV using $(1.5-3) \times 10^{11}$ incident protons per accelerator cycle. The proton intensity is limited by the requirement that the singles rate at any detector plane not exceed 10^7 counts/sec. The copper section of the hadron filter has the effect of lowering the singles rates by a factor of 2, permitting a corresponding increase in protons on target. The penalty is an $\sim 15\%$ worsening of the resolution at 10 GeV mass. Figure 2(a) shows the yield of muon pairs obtained in this work.

At the present stage of the analysis, the following conclusions may be drawn from the data [Fig. 3(a)]:

- (1) A statistically significant enhancement is observed at 9.5-GeV $\mu^+\mu^-$ mass.
- (2) By exclusion of the 8.8–10.6-GeV region, the continuum of $\mu^+\mu^-$ pairs falls smoothly with mass. A simple functional form,

$$[d\sigma/dm dy]_{y=0} = A e^{-bm},$$

with $A = (1.89 \pm 0.23) \times 10^{-33}$ cm²/GeV/nucleon and $b = 0.98 \pm 0.02$ GeV⁻¹, gives a good fit to the data for 6 GeV $< m_{\mu^+\mu^-} < 12$ GeV ($\chi^2 = 21$ for 19 degrees of freedom).^{4,5}

(3) In the excluded mass region, the continuum fit predicts 350 events. The data contain 770 events.

(4) The observed width of the enhancement is greater than our apparatus resolution of a full width at half-maximum (FWHM) of 0.5 ± 0.1 GeV. Fitting the data minus the continuum fit [Fig. 3(b)] with a simple Gaussian of variable width yields the following parameters (B is the branching ratio to two muons):

$$\text{Mass} = 9.54 \pm 0.04 \text{ GeV},$$

$$[Bd\sigma/dy]_{y=0} = (3.4 \pm 0.3) \times 10^{-37} \text{ cm}^2/\text{nucleon},$$

with FWHM = 1.16 ± 0.09 GeV and $\chi^2 = 52$ for 27

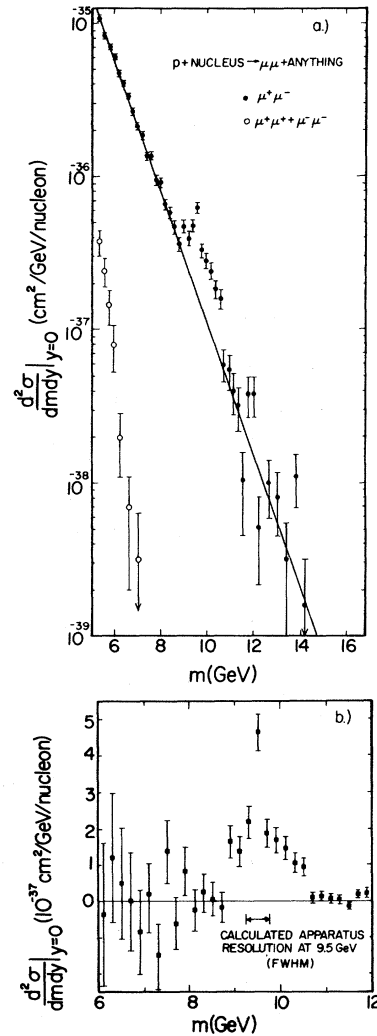


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign-dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

degrees of freedom (Ref. 5). An alternative fit with two Gaussians whose widths are fixed at the resolution of the apparatus yields

$$\text{Mass} = 9.44 \pm 0.03 \text{ and } 10.17 \pm 0.05 \text{ GeV},$$

$$[Bd\sigma/dy]_{y=0} = (2.3 \pm 0.2) \text{ and } (0.9 \pm 0.1)$$

$$\times 10^{-37} \text{ cm}^2/\text{nucleon},$$

with $\chi^2 = 41$ for 26 degrees of freedom (Ref. 5).

The Monte Carlo program used to calculate the acceptance [see Fig. 2(c)] and resolution of the

apparatus assumed a mass, p_t , rapidity and decay angular distribution of the $\mu^+\mu^-$ pair consistent with these data and previously published dilepton searches. It also included all multiple-scattering effects in the hadron absorber and detector resolutions. The conclusions stated above are insensitive to these assumptions. In particular we note that the acceptance is relatively flat in the 9–10-GeV region.

The following checks have been made to verify the validity of the conclusions reached above:

(1) The spectrum of $\mu^+\mu^+$ and $\mu^-\mu^-$ events in Fig. 3(a) constitute an upper limit on the combined effects of accidental coincidences and hadronic decays. Misidentified $\psi \rightarrow \mu^+ + \mu^-$ decays are prevented from producing background at high mass by the remeasurement of the muon momenta both downstream by the second magnet and also by the PWC at the center of the first magnet. This is confirmed by the clean separation of the ψ and ψ' peaks in Fig. 2(a). Their widths agree with the calculated apparatus resolution.

(2) Various subsets of the data were studied in order to search for possible apparatus bias. In addition to the subsets shown in Table I, data were studied as a function of magnet polarity and magnetic bend direction. All fits showed enhancements consistent with the values quoted above.

(3) To check our analysis software (and as a further check of the apparatus), we mixed muons from different events, yielding the smooth mass spectrum shown in Fig. 2(a). The geometrical distribution of events in the 9–10-GeV region at the various detector planes in the apparatus is consistent with that of events in neighboring mass bins.

(4) The longitudinal distribution of muon-pair vertices at the target (FWHM = 16 cm) is cleanly separated from events generated in the beam dump, 220 cm downstream. A separate target-out run with 6×10^{14} incident protons produced no acceptable $\mu^+\mu^-$ candidates above 6 GeV (an equivalent run with a Cu or Pt target would have yield-

ed about 200 events with 25 of these in the 9–10-GeV region).

In conclusion, the measured spectrum of $\mu^+\mu^-$ pairs produced in proton-nucleus collisions shows significant structure⁶ in the 9–10-GeV region on an exponentially falling continuum. The structure is wider than the apparatus resolution. The 9.5-GeV enhancement and the continuum are in agreement with our previous measurements.⁷

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¹D. C. Hom *et al.*, Phys. Rev. Lett. **36**, 1236 (1976).

²H. D. Snyder *et al.*, Phys. Rev. Lett. **36**, 1415 (1976).

³D. C. Hom *et al.*, Phys. Rev. Lett. **37**, 1374 (1976).

⁴Cu and Pt yields were reduced to cross sections per nucleon by assuming an atomic-number dependence of $A^{1.0}$.

⁵The errors quoted on the magnitude of the continuum and resonance cross sections and the resonance masses are statistical only. Systematic normalization effects are probably less than 25% and do not affect the conclusions drawn here. Systematic errors on the mass calibration are probably less than 1%.

⁶Following Ref. 1, a reasonable designation for this enhancement is $\Upsilon(9.5)$.

⁷We note that the 9–10-GeV mass bin in the e^+e^- and $\mu^+\mu^-$ spectra previously published by this group (Ref. 3) shows an excess of events, consistent with the statistically more significant results here. If we add our preliminary unpublished e^+e^- data to our published e^+e^- yield (Ref. 1), the spectrum contains a cluster of 6 e^+e^- events near 9.5 GeV where ~ 5 events would be expected on the assumption of μ - e universality.