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Observation of Coulomb Effects in Production of $\pi^+\pi^-$, $p\pi^-$, and K^+K^- Pairs in pp Collisions at 27.5 GeV/c *

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Abstract

In a study of collisions of 27.5 GeV/c protons in liquid hydrogen we have observed enhanced production of oppositely charged hadron pairs when the relative velocity of the two hadrons in the pair rest frame approaches αc. The scale and velocity dependence of the enhancement agree well with the effect of the attractive Coulomb interaction as described by the Gamow factor.

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The electromagnetic interaction has long been predicted to modify observed phase space densities for pairs of charged particles having relative velocity, β^*, in their rest frame of order αc[1-4]. This velocity-dependent effect is described by the Gamow factor, $G(q)=2\pi\eta/(e^{2\pi\eta}-1)$, where $\eta=\alpha Z^+Z^- 2\mu/q$, μ is the reduced mass ($1/\mu = 1/m^+ + 1/m^-$), Z^+ and Z^- are the particle charges, and **q** is the three-momentum difference in the rest frame of the pair. When $q \ll \mu$, β^* is simply $q/2\mu$. $G(q)$ has been used as an unobservable correction in same sign pair correlation studies[5]. The first direct observation of the final state Coulomb interaction in $\pi^+\pi^-$ pair production used 70 GeV/c protons on tantalum foil[6]. We report here the measurement of Coulomb effects in moderately high multiplicity pp collisions for $\pi^+\pi^-$, $p\pi^-$, and K^+K^- pair production.

We analyzed 300 million events containing on average 8 reconstructed charged particles that were produced in interactions of 27.5 GeV/c protons in liquid hydrogen at the BNL Alternating-Gradient Synchrotron. Experiment 766[7] used a large aperture spectrometer (Fig. 1) to measure complex interactions at high rates. Six drift chambers of ~~maximum~~ drift distance 1mm to 1.7mm measured charged particle trajectories in a non-uniform dipole magnetic field of central value 7.5 kG. Direct particle identification was provided by time-of-flight hodoscopes and by a 96-cell threshold Cherenkov counter (π/K/p thresholds of 2.5/9.0/17.0 GeV/c). Track reconstruction was performed by a special purpose hardware processor[8].

We investigate the β^* dependence of (+/-) pairs at small β^* using quantities that are independent of particle mass assignment.

We directly measure $q_\perp$, the relative momentum perpendicular to the pair momentum, and momentum asymmetry: $Y=(|P^+|-|P^-|)/(|P^+|+|P^-|)$ where P^+ and P^- are the particles' lab momenta. For relativistic small opening angle pairs,

$$Y = \frac{m^+-m^-}{m^++m^-} + \left(\frac{\beta_\parallel^*}{2}\right)\left(\frac{2\mu}{m^+}\right)\left(\frac{2\mu}{m^-}\right) \qquad (1)$$

For small $q_\perp$, a narrow peak in Y centered at $(m^+-m^-)/(m^++m^-)$ provides a signature of enhanced production at small β^*.

We selected 8.4 million (+/-) pairs with $q_\perp^2 < 250$ $(MeV/c)^2$, neither particle assigned to more than one pair, and both particles intersecting a vertex in the hydrogen formed by at least two additional tracks. These pairs are predominantly e^+e^- pairs from photons converting in material downstream of the primary vertex too close for the conversion to be resolved. These e^+e^- pairs have a softer momentum spectrum than hadron pairs, and an apparent q_x (the horizontal component of q) shifted by twice the magnetic field integral between the primary and actual conversion point. We used the Cherenkov counter to help select three samples: 1) h^+h^- candidates with $|P^++P^-| > 1$ GeV/c, $q_x<0$, and neither particle identified as an $e^+(e^-)$; 2) $p\pi^-$ candidates, with the positive track identified as heavier than a pion; and 3) e^+e^- candidates with at least one particle identified as an $e^+(e^-)$.

Fig. 2 shows the Y and $q_\perp^2$ distributions for the three samples. Four distinct Y peaks appear for the h^+h^- candidates (Fig. 2a); the peak at 0.0 is the Coulomb effect for same mass pairs (predominantly

$\pi^+\pi^-$), and the peak at $0.74 = (m_p - m_\pi)/(m_p + m_\pi)$ for $p\pi^-$ pairs. The other two peaks at 0.51 and 0.88 correspond to $p\pi^-$ pairs from unresolved axial Λ decays. The $p\pi^-$ peaks are more pronounced in the $p\pi^-$ sample (Fig. 2c). No sharp structure is present for the e^+e^- sample (Fig. 2e). (The shape is affected by momentum-dependence of electron identification.) The $q_\perp^2$ distributions (Fig. 2b,d,f) indicate e^+e^- pairs contaminate the h^+h^- sample at $q_\perp < 5$ MeV/c.

To simulate the experimental effects of phase space modified by the Gamow factor, we generated pairs isotropically in q out to 100 MeV/c with phase space density modified by the Gamow factor; $dN/dq = q^2 G(q)$. We then boosted the pairs into the lab using the momentum spectrum observed for the real data, added four tracks randomly selected from data to constrain the vertex position better, reconstructed the events including effects of material and digitization, and analyzed these simulated events in the same manner as the data. Our rms resolution for the $\pi^+\pi^-$ ($p\pi^-$) pairs in the h^+h^- ($p\pi^-$) sample is 3.5 (3.8) MeV/c in $q_\perp$ and 0.003 (0.002) in Y, considerably narrower than the dimensions of the enhancements. Note that the Y peaks from small β^* pairs are broader than those from unresolved Λ decays.

In Figs. 3, 4 we compare the observed and simulated Y distributions for three regions of $q_\perp$: 0-5, 5-10, 10-15 MeV/c. Except for h^+h^- candidates of $q_\perp < 5$ MeV/c which include e^+e^- pairs smoothly varying in Y, the data and the simulated distributions are very similar. In Table 1 we describe the $q_\perp$ dependence by listing the rms width and fraction of the excess for each peak as determined by fitting the wings to a quadratic (solid line), and extending the fitted curve through the Y region containing the peak (dotted line). We find excellent agreement between the data and simulation for both the $\pi^+\pi^-$ and the $p\pi^-$.

We also predict the absolute scale (# of pairs) of the observed excess by normalizing the simulated excess (MC peak) by the ratio of densities, (Data pairs/V)/(MC pairs/V), over a much larger phase space volume V outside the region contaminated by e^+e^- pairs or sharply modified by G(q). V extends in $q_\perp^2$ between 187.5 and 250 $(MeV/c)^2$, and in Y from -0.3 to +0.3 for $\pi^+\pi^-$ pairs and from 0.65 to 0.815 for $p\pi^-$ pairs. If we assume in V all h^+h^- candidates are $\pi^+\pi^-$, and all $p\pi^-$ candidates are $p\pi^-$, we obtain the results listed in Table 2. We note the normalization technique is sensitive to uncertainties in hadron identification. For example, the discrepancy for the $p\pi^-$ can be explained if 8.9% of these candidates are $K^+\pi^-$ or pK^-; such pairs also satisfy the selection. For the h^+h^-, the pairs in the enhancement and in V are mostly $\pi^+\pi^-$. Any K^+K^- pairs would contribute a factor of 2.3 more enhancement than $\pi^+\pi^-$, and pairs of unequal mass, such as $p\pi^-$, contribute no enhancement at Y=0.

Finally, we present Y distributions for small opening angle $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ pairs (Fig. 5) from fully reconstructed events in which the pair and the final state topology were identified by application of conservation laws and direct particle ID. For the $\pi^+\pi^-$ pairs we observed an enhancement of 53±20 pairs and predict 47. For the K^+K^- pairs we observe an enhancement in the central two Y bins of 10.2±3.8 pairs and predict 5.2. Limited statistics preclude drawing a conclusion for the $p\bar{p}$ pairs. (Central 2 bins contain 3 pairs total, with nearby average of 0.5 pairs/bin, compared to prediction of 2.7 and 0.45 pairs/bin.)

In summary, in a sample of 300 million reconstructed multiparticle events produced by collisions of 27.5 GeV/c protons in hydrogen, we have observed a sharp increase in the number of $\pi^+\pi^-$, $p\pi^-$, and K^+K^- pairs when the relative velocity of the two particles (in the pair rest frame) is of order αc. Our statistics and resolution for the $\pi^+\pi^-$ and $p\pi^-$ pairs are sufficient to show that this effect agrees in magnitude and dependence on relative velocity with phase space modified by the Gamow factor as predicted for the attractive electromagnetic force. With limited statistics, we observe the effect for K^+K^- pairs in fully reconstructed events.

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Tables

			$q_\perp$ range: 0-5 MeV/c	5-10 MeV/c	10-15 MeV/c
$\pi^+\pi^-$	Ex Fr	D	0.20 ± 0.014	0.36 ± 0.029	0.44 ± 0.035
		MC	0.17 ± 0.016	0.37 ± 0.032	0.45 ± 0.042
	rms	D	0.037	0.046	0.057
		MC	0.031	0.044	0.046
$p\pi^-$	Ex Fr	D	0.19 ± 0.022	0.38 ± 0.042	0.43 ± 0.056
		MC	0.16 ± 0.011	0.38 ± 0.023	0.46 ± 0.031
	rms	D	0.0085	0.012	0.014
		MC	0.0082	0.011	0.012

Table 1. The Y peaks at small β^* (see Figs. 3,4) for data (D) and Monte Carlo (MC) $\pi^+\pi^-$ and $p\pi^-$ pairs are compared as a function of $q_\perp$. Ex. Fr. denotes the fraction of total observed excess. Errors are statistical only.

	# Observed	# Predicted	MC peak	D/V	MC/V
$\pi^+\pi^-$	11697 ± 518	10811 ± 512	7574 ± 359	70460	49365
$p\pi^-$	2574 ± 161	2832 ± 98	7675 ± 265	10669	28912

Table 2. Absolute scale in numbers of pairs of observed and predicted excess at small β^* for pairs with $q_\perp$< 15 MeV/c. MC peak, Data/V, MC/V are used in the normalization (see text).

Figure Captions

FIG. 1. Experiment 766 magnetic field spectrometer.

Fig. 2. Y (momentum asymmetry) for h^+h^- (a), $p\pi^-$ (c), and e^+e^- (e) candidates with $q_\perp$ <10 MeV/c. This $q_\perp$ region is shaded in the corresponding $q_\perp^2$ distributions (b,d,f). The Y peaks at 0.0 in (a) and at 0.74 in (a,c) are evidence of enhanced production of same mass (mostly $\pi^+\pi^-$) and $p\pi^-$ pairs with relative velocity in the pair rest frame approaching αc. Photon conversions to e^+e^- cause the forward peaks in $q_\perp^2$ (b,f).

FIG. 3. Y (momentum asymmetry) for data h^+h^- candidates (a,c,e) and Monte Carlo $\pi^+\pi^-$ pairs (b,d,f) verses $q_\perp$.

FIG. 4. Y (momentum asymmetry) for data $p\pi^-$ candidates (a,c,e) and Monte Carlo $p\pi^-$ pairs (b,d,f) verses $q_\perp$.

Fig. 5. Y (momentum asymmetry) for $\pi^+\pi^-$ (a) K^+K^-(b) and $p\bar{p}$ (c) pairs with $q_\perp$<10 MeV/c from fully reconstructed events.

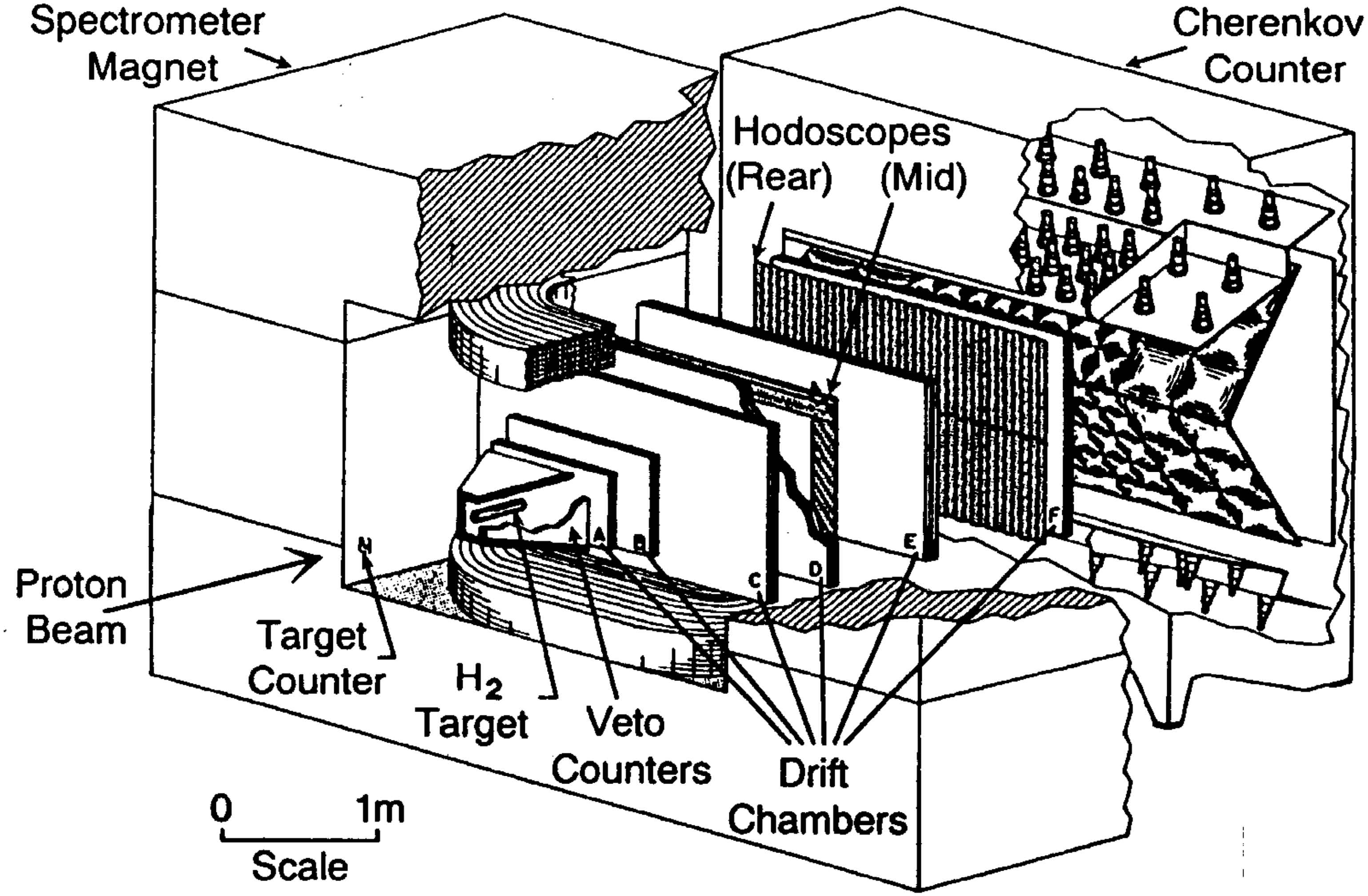
Spectrometer
Magnet
Cherenkov
Counter
Hodoscopes
(Rear)
(Mid)
Proton
Beam
Target
Counter
H_2
Target
Veto
Counters
Drift
Chambers
0
1m
Scale

Fig. 1

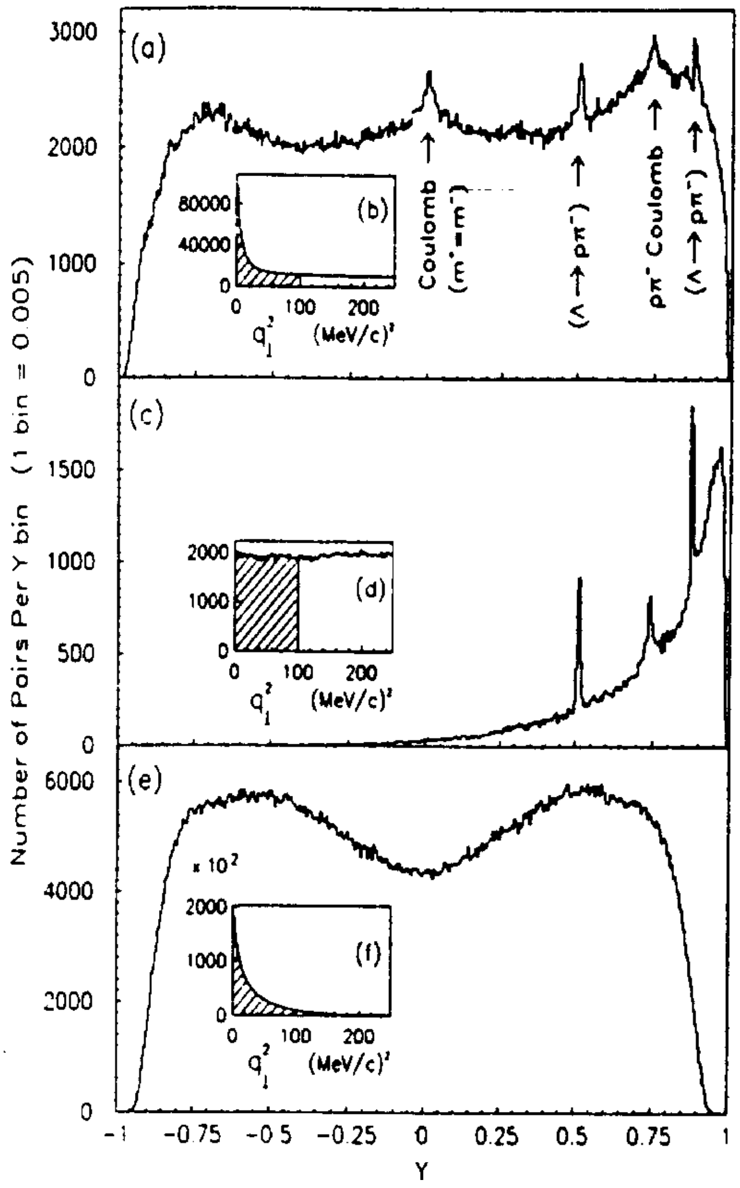
(a)
(b)
(c)
(d)
(e)
(f)
Coulomb
(m⁺=m⁻)
(Λ → pπ⁻)
pπ⁻ Coulomb
Number of Pairs Per Y bin (1 bin = 0.005)
q⊥²
(MeV/c)²
x 10²
Y

Fig. 2

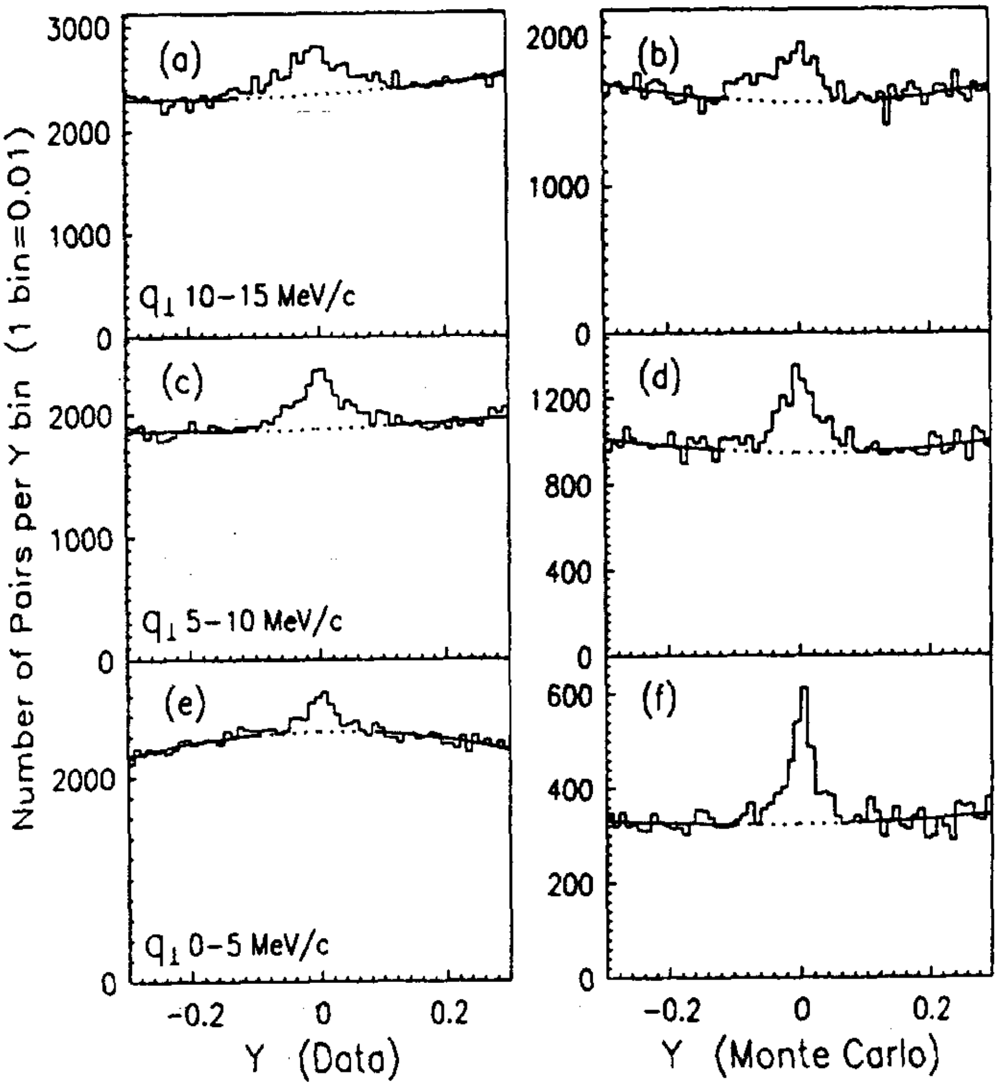
(a)
(b)
(c)
(d)
(e)
(f)
q⊥ 10–15 MeV/c
q⊥ 5–10 MeV/c
q⊥ 0–5 MeV/c
Number of Pairs per Y bin (1 bin=0.01)
Y (Data)
Y (Monte Carlo)

Fig. 3

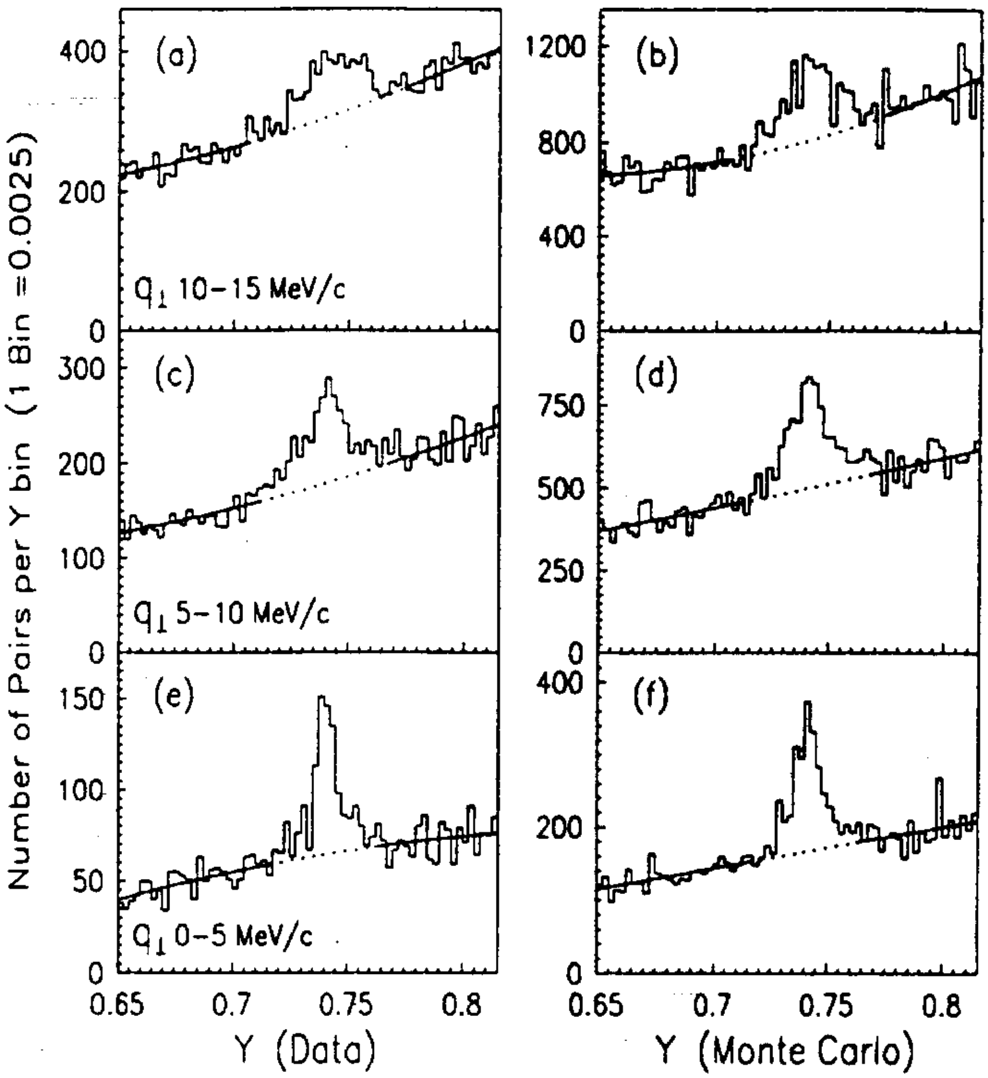
Number of Pairs per Y bin (1 Bin =0.0025)
(a)
q⊥ 10–15 MeV/c
(b)
(c)
q⊥ 5–10 MeV/c
(d)
(e)
q⊥ 0–5 MeV/c
(f)
Y (Data)
Y (Monte Carlo)

Fig. 4

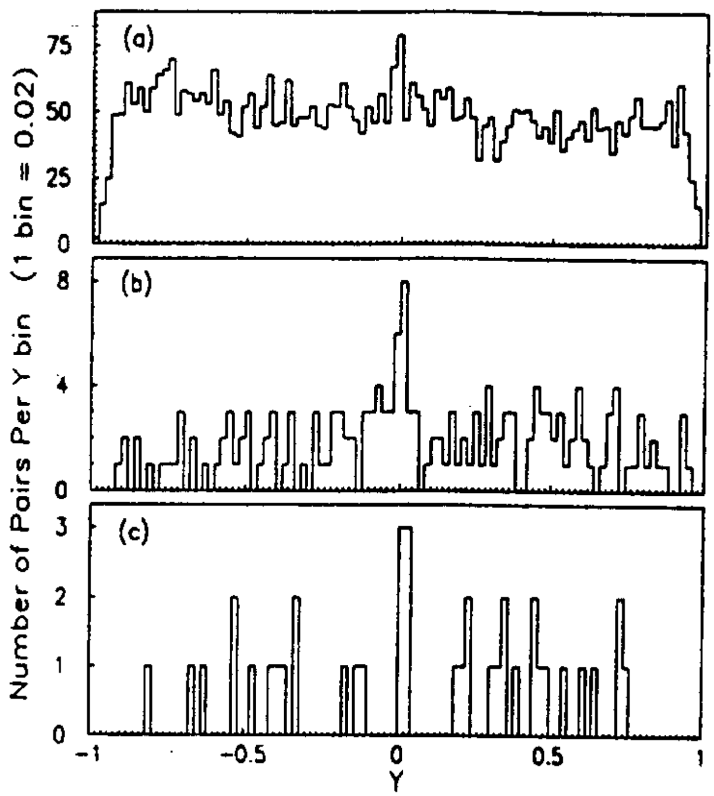
(a)
(b)
(c)
Number of Pairs Per Y bin (1 bin = 0.02)
0
25
50
75
4
8
1
2
3
-1
-0.5
0
0.5
1
Y

Fig. 5