Fermi National Accelerator Laboratory

FERMILAB-Pub-78/96-EXP
7180.288

(Submitted to Phys. Rev. Lett.)

EVIDENCE FOR THE Υ'' AND A SEARCH FOR NEW NARROW RESONANCES

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December 1978

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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ABSTRACT

The production of the Υ family in proton-nucleus collisions is clarified by a six-fold increase in statistics. Constraining Υ, Υ′ masses to those observed at DORIS we find the statistical significance of the Υ″ to be 11 σ. The dependence of Υ production on p_t, y, and s is presented. Limits for other resonance production in the mass range 4-18 GeV are determined.

We report on further details of Upsilon[1,2] production in proton-nucleus collisions at Fermilab. In addition to data published previously,[1-4] we present here results from data taken in 1978. Our entire data sample can be divided into four subsets: I. published data with 400 GeV incident proton energy and 1200 ϒ(or ϒ') events, mass resolution ($\Delta M/M$) of 2.2% (rms)[1,2]; II. 200/300 GeV, 500 ϒ's, $\Delta M/M$ = 2.2% ; III. 400 GeV, 7000 ϒ's, $\Delta M/M$ = 2.2%; IV. 400 GeV, 500 ϒ's, $\Delta M/M$ = 1.7%. Except where noted all results hereafter are from 400 GeV data. The resolution improvement in data set IV was achieved by lowering the intensity of protons so that a multiwire proportional chamber could be installed and operated halfway between the target and the analysis magnet.

Table I lists apparatus and software efficiencies and corrections made to the data. Cross sections per Pt nucleus were converted to cross section per nucleon by dividing by A_{Pt} = 195. An isotropic decay angle distribution was assumed for resonances while $1 + \cos^2\theta$ (Gottfried-Jackson frame) was assumed for the continuum.

All the data from sets I, III, and IV between masses of 7.3 and 12.9 GeV were fit simultaneously. A linear exponential form was assumed for the continuum. This form fits the continuum well in this mass range.

The continuum shape, resonance mass separations, and relative cross sections were the same for all data sets but mass resolution, acceptance, normalization, and mass scale were particular to each set. Assuming three resonances and letting all parameters vary we obtain the first column in Table II.[6] This fit yields the spacing $m_{\Upsilon'} - m_{\Upsilon} = 0.57 \pm 0.03$ GeV. If we constrain $m_{\Upsilon'} - m_{\Upsilon}$ to the 0.555 ± 0.011 GeV value measured at DORIS[7] we obtain the result in the second column of Table II. In this case assuming two resonances instead of three increases χ^2 by 125 indicating a significance of 11 σ for the Υ''. We consider this convincing evidence for a third resonance. Data set III with continuum subtracted is plotted in Fig. 1 and compared with the fit constrained by the DORIS measurements. Table III gives the correlation matrices for the fits in Table II.

These results combined with the observation of Υ and Υ' at DORIS[7,8] strongly support the interpretation that the Υ, Υ' and Υ'' are the n^3S_1 $Q\bar{Q}$ states ($n = 1,2,3$) of a new heavy quark with charge 1/3 ("bottom"). Successful fitting of both J/ψ and Υ families with a common potential,[9,10] successful prediction of ≥ 3 states,[11] $m_{\Upsilon''} - m_{\Upsilon}$[9,10], Γ_{ee} (Υ and Υ')[7,8,11] and $B_{\mu\mu}\Upsilon$[12], all reinforce this interpretation.

In Fig. 2 we show the energy dependence of Υ production[13] and compare it to that for ψ production.[14] We see that they are similar.

Figure 3a shows the p_t dependence of the Υ cross section (continuum subtracted). The curve shows a fit to the continuum in adjacent mass bins. We see a significant difference particularly at the highest values of p_t. $\langle p_t \rangle_{\Upsilon}$ is 1.44 ± 0.04 GeV while $\langle p_t \rangle$ of the continuum is 1.20 ± 0.02 GeV. Figure 3b shows the y dependence of the Υ (also continuum subtracted) and a curve showing the expected continuum behavior based on interpolation from the surrounding continuum via the parton annihilation model. We see that in contrast to the continuum distribution the Υ distribution is symmetric about $y = 0$. $d\left[\ln(d^2\sigma/dm\,dy)\right]/dy|_{y=0}$ is 0.1 ± 0.2 for the Υ vs. 0.5 ± 0.1 for the continuum. This, together with the p_t dependence, the small ratio of Υ to continuum seen in our 200 GeV data (at $y = 0.4$),[4] and the large ratio of Υ to continuum seen at the ISR[13] ($\sqrt{s} = 60$ GeV), suggests that the Υ production mechanism differs from that of the continuum.

The observed mass spectrum (Fig. 4a), combined with knowledge of the mass resolution (confirmed by the observed resolution of $J/\psi, \psi'$ and Υ) allows us to determine upper limits for $B_{\mu\mu}\, d\sigma/dy$ for narrow resonances (independent of origin) in the mass range 4-18 GeV in proton-nucleus collisions. These are presented in Fig. 4b. Assuming resonance production is approximately proportional to the continuum and assuming a resonance production model, we can set limits on the masses of new quarkonium systems. Figure 4b compares the 95% confidence level upper limit for $B_{\mu\mu}\, d\sigma/dy$ (resonance)//$d\sigma/dm\,dy$ (continuum) with the predictions of two production models.[15,12] Following J. Ellis et al.,[15] we find $m_{1/3} > 15$ GeV and $m_{2/3} > 16.5$ GeV for charge 1/3 and charge 2/3 quarks respectively. Following R. Cahn and S. Ellis[12] we find $m_{1/3} > 15$ GeV and $m_{2/3} > 17.5$ GeV.

In summary, further data on Υ production in proton-nucleus collisions and the observation of Υ' at DORIS have increased the significance of the Υ'' to 11σ and supplied more evidence for the quarkonium interpretation of the Υ family. Assuming that only one additional narrow resonance above the Υ' contributes to our mass spectrum, we determine the Υ'' mass to be 10.41 ± .05 GeV. Differences in the dynamics of Υ and continuum production point to differing production mechanisms. Other quarkonium families with comparable resonance/continuum signals are unlikely in the mass range 4-14 GeV. A quarkonium family based on a charge 2/3 quark is unlikely below 16.5 GeV.

We wish to thank the staffs of our respective institutions, particularly the accelerator staff at Fermilab. This work was funded in part by grants from the National Science Foundation and the U. S. Department of Energy.

REFERENCES

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[5]The normalization of the data presented here differs from that of our previous publications. The primary cause of this change was the discovery that the Pt target used in data set I had partially melted. Other causes are changes in the decay angle and p_t distributions assumed in calculating the acceptance and the inclusion of nucleon-motion and radiative corrections.

[6]The mass scales in these fits were adjusted to yield the DORIS result $m = 9.46$ GeV. If this is not done our result is $m_T = 9.45 \pm 0.05$ GeV. The error is entirely systematic and arises from uncertainties in the magnetic field measurement and in knowledge of the energy loss in the hadron absorber.

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TABLE I

EFFICIENCIES, CORRECTIONS, AND ACCEPTANCE

Efficiencies	
Trigger	0.92 ± 0.04
Data compression	0.96 ± 0.01
Reconstruction	0.88 ± 0.03
Targeting	0.97 ± 0.03
Combined	0.76 ± 0.06
Corrections to cross section (multiplicative, at the T mass)	
Nucleon Motion	0.80 ± 0.10
Radiative (resonance)	1.10
Radiative (continuum)	1.03
A-dependence	1.00 ± 0.07[a]
Acceptance ($-.3 < y < .3$)	
$1 + \cos^2\theta$ (continuum)	0.0059±0.0003
Isotropic (resonance)	0.0065±0.0003
Overall normalization uncertainty	±0.15

[a] This represents the uncertainty in the calculation of the per "nucleon" cross sections from the per nucleus cross sections.

TABLE II

Resonance Fits[a]

Parameter	Number	($m_{\Upsilon'}-m_\Upsilon$ Free)	$m_{\Upsilon'}-m_\Upsilon$=.555±.011	Units
Continuum Parameters ($d^2\sigma/dmdy\|_{y=0} = Ae^{-b(m-m_\Upsilon)}$)				
A_I	1	0.262±.004(±.04)	0.262±.004(±.04)	pb/GeV
A_{III}	2	±.003 (b)	±.003(b)	"
A_{IV}	3	±.004 (b)	±.004(b)	"
b	4	0.954±.006(.015)	0.953±.006(±.015)	GeV^{-1}
Resonance Parameters				
m_Υ		9.46(fixed)	9.46(fixed)	GeV
R/C[c]	5	1.15 ±.03	1.14 ±.03	GeV
$Bd\sigma/dy\|_{y=0}$ Υ		0.30 ±.01(±.05)	0.30±.01(±.05)	pb
$m_{\Upsilon'}-m_\Upsilon$	6	0.574±.027	0.558±.011	GeV
$Bd\sigma/dy\|_{y=0}$ Υ'/Υ	7	0.32 ±.03	0.31 ±.03	-
$m_{\Upsilon''}-m_\Upsilon$	8	0.97 ±.05	0.95 ±.03	GeV
$Bd\sigma/dy\|_{y=0}$ Υ''/Υ	9	0.13 ±.029	0.15 ±.017	-
Common Parameters				
$\Delta m/m$(rms) I		0.022 fixed	0.022 fixed	-
$\Delta m/m$(rms) III		0.022 fixed	0.022 fixed	-
$\Delta m/m$(rms) IV	10	0.020±.002	0.020±.002	-
m factor I	11	0.998±.002	0.997±.002	-
m factor III	12	1.001±.001	1.001±.001	-
m factor IV	13	1.000±.002	1.000±.002	-
χ^2/DF		163/155	163/156	

(a) Where significant, systematic errors are given in parentheses.

(b) Since data sets III and IV have not been carefully normalized the precise values of these parameters are irrelevant.

(c) This parameter is $B_{\mu\mu}\, d\sigma/dy|_{y=0}$ for Υ production divided by $d^2\sigma/dmdy|_{y=0,\ m=m_\Upsilon}$ for the continuum.

TABLE III[a]

Correlation Matrices

$m_Y' - m_Y$ Free

	1	2	3	4	5	6	7	8	9	10	11	12
2	.452											
3	.250	.359										
4	-.481	-.703	-.345									
5	-.293	-.421	-.270	.306								
6	.368	.518	.220	-.408	-.207							
7	.057	.077	.049	-.079	-.677	-.118						
8	.164	.263	.156	-.190	-.540	.140	.613					
9	-.500	-.733	-.347	.654	.399	-.517	-.214	-.334				
10	-.098	-.156	-.034	.122	.218	.054	-.194	-.290	.145			
11	.057	.074	.038	-.021	.237	.072	-.232	-.234	.006	.092		
12	.183	.302	.096	-.215	.216	.222	-.381	-.212	-.256	-.066	.146	
13	.040	.102	.109	-.040	.016	-.063	-.054	.072	-.124	-.161	.011	.111

(cont'd)

TABLE III

Correlation Matrices (cont'd)

$m_T'-m_T = 0.555 \pm .011$	1	2	3	4	5	6	7	8	9	10	11	12
2	.476											
3	.268	.418										
4	-.508	-.727	-.420									
5	-.406	-.577	-.345	.446								
6	-.060	-.074	-.048	.109	.314							
7	-.239	-.325	-.191	.327	-.222	-.279						
8	-.322	-.428	-.244	.469	.264	-.031	.251					
9	.071	-.004	.008	-.033	-.369	-.328	.095	.032				
10	-.055	-.036	-.035	.039	.149	.108	-.071	.021	-.137			
11	.092	-.045	-.030	-.056	.028	.088	.032	.181	.053	-.058		
12	.072	.177	.071	-.087	.213	.164	-.339	-.166	-.328	.123	-.013	
13	-.020	-.015	.111	-.011	.120	.059	-.105	-.032	-.130	.044	.019	.126

[a] Parameter numbers as defined in Table II.

FIGURE CAPTIONS

Fig. 1: Mass spectrum in the Υ region with continuum subtracted (from data set III). The curve is the fit described in the second column of Table II.

Fig. 2: s dependence of Υ and ψ production. The Υ data are from this experiment and Ref. 13. The J/ψ data are from Ref. 14.

Fig. 3: (a) p_t dependence of Υ production (continuum subtracted). The curve shows the p_t dependence of the adjacent continuum (the continuum p_t spectrum is independent of mass in this mass range).

(b) y dependence of Υ production (continuum subtracted). The curve shows the continuuum y dependence based on interpolation from the adjacent continuum with a parton annihilation model.

Fig. 4: (a) Mass spectrum. The 4-6 GeV region is from data set (IV). The 6-20 GeV region is from data sets (I)+(III). The curve shows the mass resolution.

(b) Upper limits (95% CL) on $B_{\mu\mu}\, d\sigma/dy|_{y=0}$ for new resonance production.

(c) Upper limits (95% CL) on the ratio of resonance to continuum production. The dotted curves are the predictions calculated with the model of J. Ellis et al., (Ref. 15). The dashed curves are the predictions calculated with the model of R. Cahn and S. Ellis (Ref. 12).

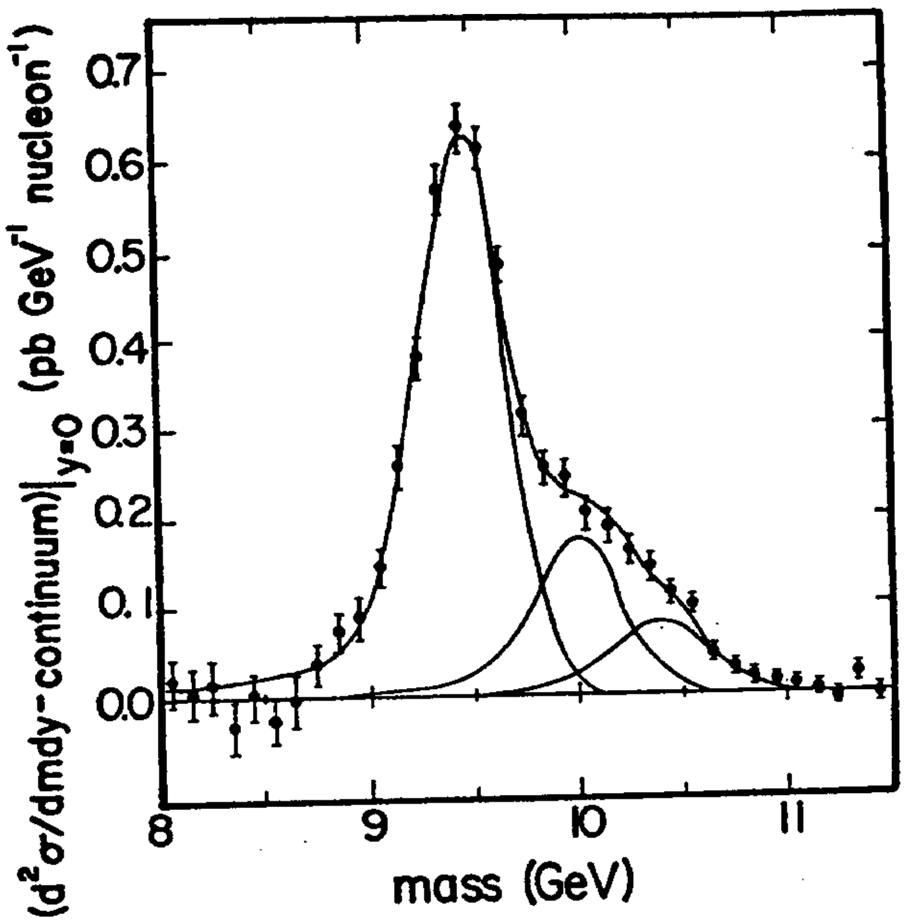
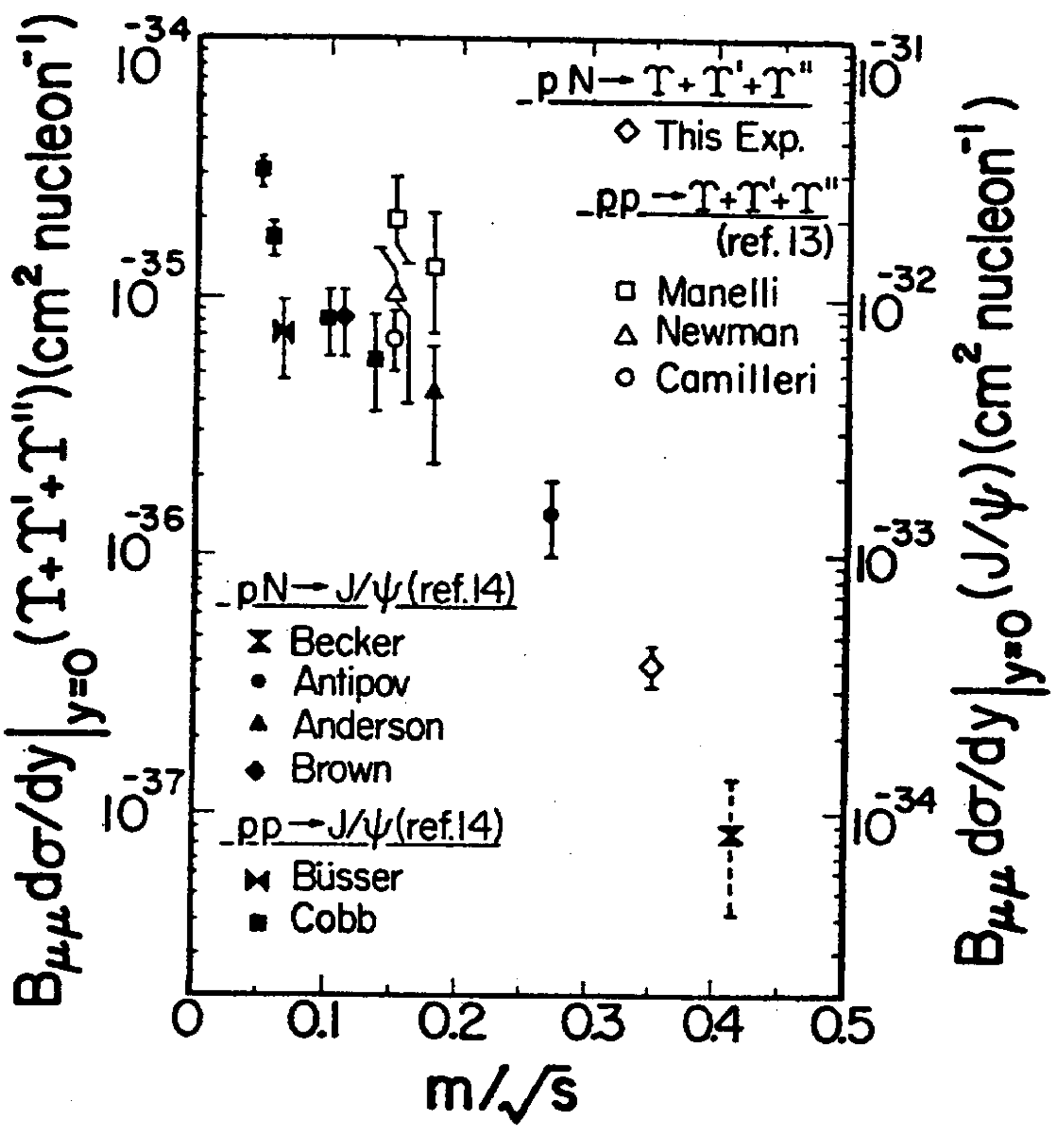
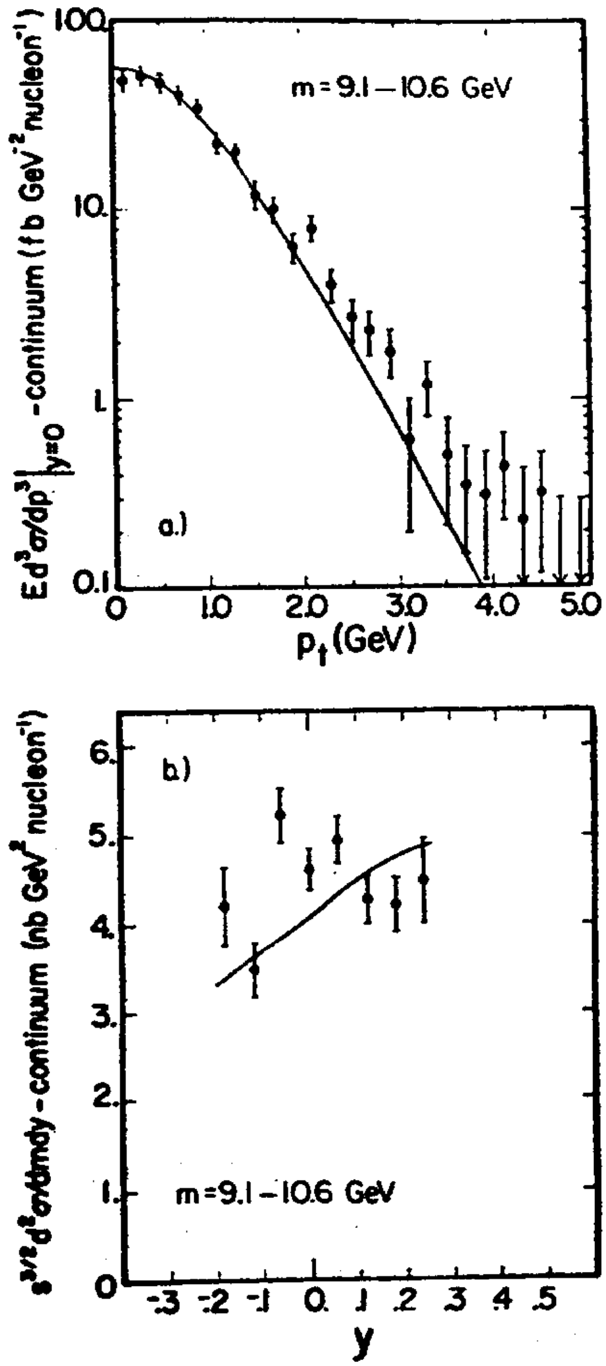

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
8
9
10
11
mass (GeV)
$(d^2\sigma/dmdy - continuum)|_{y=0}$ (pb GeV^{-1} nucleon^{-1})

Figure 1



pN → Υ+Υ'+Υ"
◇ This Exp.
pp → Υ+Υ'+Υ"
(ref. 13)
□ Manelli
△ Newman
○ Camilleri
pN → J/ψ (ref. 14)
Becker
Antipov
Anderson
Brown
pp → J/ψ (ref. 14)
Büsser
Cobb
$B_{\mu\mu} d\sigma/dy|_{y=0}$ (Υ+Υ'+Υ")(cm² nucleon⁻¹)
$B_{\mu\mu} d\sigma/dy|_{y=0}$ (J/ψ)(cm² nucleon⁻¹)
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-31}
10^{-32}
10^{-33}
10^{-34}
0
0.1
0.2
0.3
0.4
0.5
m/√s

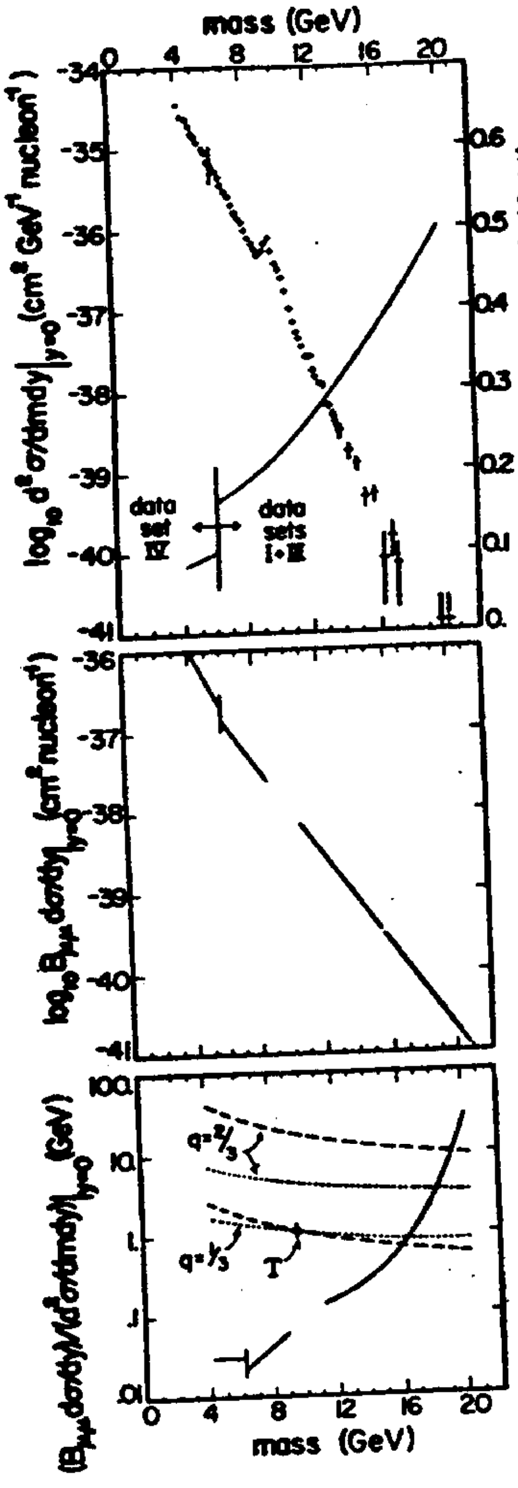
Figure 2



m = 9.1 – 10.6 GeV
a.)
Ed³σ/dp³|y=0 -continuum (f b GeV⁻² nucleon⁻¹)
p_t (GeV)
b.)
m = 9.1 – 10.6 GeV
s^3/2 d²σ/dmdy - continuum (nb GeV² nucleon⁻¹)
y

Figure 3

Figure 4


mass (GeV)
0 4 8 12 16 20
log₁₀ d²σ/dmdy|y=0 (cm² GeV⁻¹ nucleon⁻¹)
-34 -35 -36 -37 -38 -39 -40 -41
0.6 0.5 0.4 0.3 0.2 0.1 0.
mass resolution (r.m.s.) (GeV)
data set IV
data sets I + III
log₁₀ B_μμ dσ/dy|y=0 (cm² nucleon⁻¹)
-36 -37 -38 -39 -40 -41
(B_μμ dσ/dy)/(d²σ/dmdy)|y=0 (GeV)
100. 10. 1. .1 .01
q = 2/3
q = 1/3
Υ
0 4 8 12 16 20
mass (GeV)