Fermi National Accelerator Laboratory

FERMILAB-Pub-92/140-E

E705

Production of J/Ψ via ψ' and χ Decay in 300 GeV/c Proton and $\pi\pm$ Nucleon Interactions

E705 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

May 1992

Submitted to *Physics Review Letters*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

Production of J/Ψ via Ψ' and χ Decay in 300 GeV/c Proton and $\pi^{\pm}$ Nucleon Interactions

The E705 Collaboration

L. Antoniazzi[3], M. Arenton[9], Z. Cao[8],T. Chen[5], S. Conetti[4], B. Cox[9], S. Delchamps[3], L. Fortney[2], K. Guffey[7], M. Haire[4], P. Iaonnou[1], C.M. Jenkins[3], D.J. Judd[7], C. Kourkoumelis[1],A. Manousakis-Katsikakis[1], J. Kuzminski[4], T. LeCompte[6], A. Marchionni[4], M. He[8], P. O. Mazur[3], C. T. Murphy[3], P. Pramantiotis[1], R. Rameika[3], L. K. Resvanis[1], M. Rosati[4], J. Rosen[6], C. Shen[8], Q. Shen[2], A.Simard[4], R. P. Smith[3], L. Spiegel[3], D. G. Stairs[4], Y. Tan[6], R. J.Tesarek[2], T. Turkington[2], L. Turnbull[7], F. Turkot[3], S. Tzamarias[6],G. Voulgaris[1], D. E. Wagoner[7], C. Wang[8], W. Yang[3], N. Yao[5], N. Zhang[8], X. Zhang[8], G. Zioulas[4], B. Zou[2]

(1) University of Athens, Athens, Greece
(2) Duke University, Durham, NC 27706
(3) Fermi National Accelerator Laboratory, Batavia, IL 60510
(4) McGill University, Montreal, PQ, Canada H3A 2T8
(5) Nanjing University, Nanjing, People's Republic of China
(6) Northwestern University, Evanston, IL 60208
(7) Prairie View A&M University, Prairie View, TX 77445
(8) Shandong University, Jinan, Shandong, People's Republic of China
(9) University of Virginia, Charlottesville, VA 22901

The production of the 1P χ_1 and χ_2 states of charmonium has been observed in 300 Gev/c $\pi^{\pm}$N and pN interactions. The ratio of direct to total inclusive J/Ψ production has been determined for the different beam types by measuring the contributions to the J/Ψ production due to Ψ' and radiative χ decay. Combining this experiment's measurements of J/Ψ and the ratio of $\chi_1 + \chi_2$ to J/Ψ production with previous measurements of the ratios of χ_1/Ψ and χ_2/Ψ, total cross sections for χ_1 and χ_2 production in 300 GeV/c π^-N interactions have been determined.

PACS numbers: 13.40.H

A considerable fraction[1] of the $J^{PC} = 1^{--}$ J/Ψ's produced in hadronic interactions results from the production of the $J^{PC} = 1^{++}$ (χ_1) and 2^{++} (χ_2) states of charmonium followed by their radiative decays into $\gamma\Psi$. The $J^{PC} = 0^{++}$ (χ_0) state has a small branching ratio to J/Ψ and is not expected to contribute appreciably to J/Ψ production. In the color singlet model[2], the direct production of the J/Ψ must proceed (because of conservation of angular momentum, charge conjugation and parity) by three gluon or quark annihilation processes. Alternatively, within the color singlet model, the production of J/Ψ's can proceed indirectly via production of the χ states with relatively large cross sections by the two gluon fusion, followed by the decay of the χ states into final states containing J/Ψ's. A second production process is provided by the color evaporation model[3] in which the $c\bar{c}$ pair is initially produced in a colored, unbound state and the final non colored singlet state is reached via the emission of a gluon. Therefore, an important facet of the untangling of the hadronic production mechanisms for hidden charm states is the determination of the fraction of the J/Ψ production resulting from decays of the χ states. In order to ascertain the formation mechanisms for these charmonium states and, ultimately, to extract the gluon structure functions from the study of their production by various beam types, we have performed an experiment to measure the fraction of J/Ψ arising from the χ radiative decays. In the process, we have determined the cross section for production of the χ states, by combining our measurement of the J/Ψ cross section together with our high statistics measurement of the ratio of $(\chi_1 + \chi_2)/\Psi$ production and a previous measurement[4] of the ratios of χ_1/Ψ and χ_2/Ψ production.

Our experiment, Fermilab E705, was performed with 300 GeV/c $\pi^{\pm}$, proton and antiproton beams incident on a 5 cm radius, 33 cm long ^{7}Li target [0.21 radiation lengths; 0.24 and 0.175 interaction lengths for protons and pions respectively] in the P-West High Intensity Laboratory at Fermilab. The beam particles were tagged with two gas Cerenkov counters operated in the threshold mode; the 300 GeV/c negative beam was 98% π^- and 2% antiprotons and the positive beam was 55% protons and 45% π^+. Small charged K components estimated to be less than 6% were present in both the positive and negative beams.

The χ states produced by the four beam types were observed via their radiative decays

$$p^{\pm},\pi^{\pm}\,N \longrightarrow \chi_1,\chi_2 \longrightarrow J/\Psi + \gamma \longrightarrow \mu^+\mu^-$$

using a large aperture open geometry spectrometer[5], a component of which was a large EM detector composed of approximately 400 lead (PbO) and scintillating (BaO loaded with Ce_2O_3) glass elements. The EM detector also incorporated a photon preconverter consisting of an eight layer lead sheet/extruded aluminum channel sandwich in the beam region and a hodoscope of scintillating glass counters followed by a conducting plastic gas tube layer at large angles. The preconverter identified photons and determined

their positions. This choice of EM detector[6] offered a reasonable compromise between the need to operate at high rates without significant radiation damage and the desire to maintain good photon energy resolution for photons of quite low energy (down to 2 GeV).

An equally important aspect of the spectrometer was a two level dimuon trigger. The first level required that two or more muons penetrate 0.40 meters of Cu, 3.7 meters of steel and 0.91 meters of shielding concrete, causing appropriate triple coincidences between the elements of three banks of scintillation counters placed at various depths in the absorbing material. The second level consisted of a trigger processor[7] which processed hits from drift chambers downstream of the spectrometer analysis magnet to find tracks pointing at the muon counter triple coincidences. These tracks were used to form a crude dimuon mass under the assumption that each track originated in the target. All events passing a mass cut of 2.4 GeV/c^2 were written to tape. The suppression of the total cross section by this trigger system was approximately a factor of 3×10^{-4}. Over 140 million dimuon triggers were accumulated in this manner at interaction rates of up to 1.5 MHz.

The mass spectra of all opposite charge muon pairs obtained by these triggers are shown in Fig. 1 for the four different beam types, $p^{\pm}$ and $\pi^{\pm}$. A clear J/Ψ signal is seen with the expected resolution of $\sigma \approx$ 60 Mev/c^2 in each of the four spectra. Differential and total cross sections for production of the J/Ψ and Ψ' as measured in this experiment are given in Ref. 8 for the four beam types.

Approximately 32,150 J/Ψ ->$\mu\mu$ candidate events with mass between 2.88 and 3.28 GeV/c^2 yielded approximately 24,440 J/Ψ events in total for all four beam types after background subtraction. These J/Ψ events were used in the search for the radiative decays of the charmonium χ states. For this purpose, the muon pairs were combined with all photons in a given event other than those from reconstructed π^0 decays. The difference between the invariant mass of $\mu^+\mu^-\gamma$ and $\mu^+\mu^-$ combinations is shown in Fig. 2 for our $\pi^{\pm}$ N and pN data. Use of the mass difference spectra allows us to eliminate part of the experimental error in the mass resolution of the $\gamma\Psi$ final states; the resulting mass distributions show a clear peak in the region of the $\chi_1-\Psi$ and $\chi_2-\Psi$ mass differences (expected values 414 and 459 Mev/c^2). The numbers of events in the χ peaks were 590±50, 300±35 and 250±35 for the π^-, π^+ and proton data respectively after subtraction of background. These χ's are associated with the 12470±160, 5560±90, and 6090±90 J/Ψ's obtained after background subtraction from the π^-, π^+, and proton induced J/Ψ data samples respectively.

Uncorrelated $\gamma\Psi$ backgrounds were constructed by pairing photons and J/Ψ from different events, provided that both the photon and the J/Ψ could have contributed to the difference mass spectra. Correlated $\gamma\Psi$ backgrounds due to Ψ' decays (such as Ψ'-> J/$\Psi\pi^0\pi^0$,$\Psi\eta^0$, or $\chi\gamma$) were also estimated and are included in background distributions superimposed on the mass difference spectra shown in Fig. 2. These background distributions were fitted to the mass region above the χ because of the uncertainties associated with the inclusion of the Ψ' decays and the possibility that the backgrounds below the χ_1,χ_2 region might include some $\chi(0^{++})$ decays into $\gamma\Psi$.

The acceptance of the electromagnetic spectrometer for the photons in the χ events was determined to be 0.60±0.01 for both pion and proton data. The photon reconstruction and pattern recognition efficiency for the photons in the acceptance of the EM detector was 0.27±0.01±0.03. The first error is due to the statistics of the Monte Carlo χ events used in the determination of the efficiencies and the second to the systematics of using e^+e^- pairs to estimate the efficiency of the χ photon pattern recognition and reconstruction. The width of the reconstructed χ peaks are greater than our resolution of $\sigma \approx$ 30±3 Mev/c^2 for a single χ state (based on electromagnetic calorimeter resolution fixed by the experimentally observed E/p distributions for electrons and the observed width of the π^0) , indicating the production of both χ_1 and χ_2.

The fraction of J/Ψ production due to χ decay was determined from the total number of background subtracted χ's, corrected for acceptance and reconstruction efficiencies. Table I lists the fractions of χ contribution to Ψ production for our pion and proton data.

Table I

Fraction of Total J/Ψ Production due to Radiative χ_1 and χ_2 Decay

	π^+	π^-	proton
Fraction	0.40±0.04	0.37±0.03	0.30±0.04

These data are compared in Fig. 3 with data from other experiments[1] at different $\sqrt{\tau} = M\chi/\sqrt{s}$. As can be observed from Fig. 3b, the π^+ and π^- fractions measured in this experiment are consistent with each other and with previous π- measurements at approximately the same $\sqrt{\tau} = M\chi/\sqrt{s}$. Our proton data as shown in Fig. 3a has a somewhat smaller value than that obtained in other proton experiments at different $\sqrt{\tau}$.

In addition to radiative χ decay, another contribution to J/Ψ production, for which there have been no previous estimates to date, is Ψ' production followed by decay into final states containing J/Ψ's. Combining our measurement[8] of J/Ψ andΨ' production, determined using the branching ratio[9] for $\Psi' \rightarrow \mu\mu$ (0.077±0.017), the recently redetermined branching ratio[10] for $\Psi \rightarrow \mu\mu$ (0.0591±0.0011±0.0020), and our observation of the J/$\Psi \rightarrow \mu\mu$ and$\Psi' \rightarrow \mu\mu$ channel, with the measured inclusive branching ratio[11] $\Psi' \rightarrow$J/Ψ+anything (0.55±0.07), we find that 7.6±2.3%, and 8.0±2.2% of the J/Ψ signal in 300 GeV/c π^-N and π^+N interactions respectively comes from Ψ' production followed by decay into J/Ψ. In the same manner, the fraction of J/Ψ from Ψ' is found to be 5.5±1.6% for the pN interactions at 300 GeV/c.

Since we have measured J/Ψ, Ψ' and χ production in a single experiment, it is possible to obtain a cross section for direct production of J/Ψ. If we assume that the only sources of J/Ψ other than direct production are the decays of the χ_1 , χ_2 and Ψ', then the fraction of directly produced J/Ψ is 49.2±4.9%, 45.4±5.4% and 60±4.8% in in π^-N, π^+N and pN interactions respectively at 300 GeV/c. While other indirect sources of J/Ψ such as χ_0 or B meson decay can contribute, a small branching ratio

(0.0066±0.0018 for χ_0->J/$\Psi\gamma$ from Ref. 12) and the combination of an expected small cross section for B production at 300 GeV/c (in the range of 10->20 nb/nucleon[13]) and small branching ratios (0.0112±0.0018 for B->J/Ψ inclusive decays[14]) make these sources negligible compared to production via χ_1, χ_2 and Ψ' decay. Combining the above fractions of direct J/Ψ production with our measurement[8] of the inclusive J/Ψ production, we obtain direct J/Ψ production cross sections of 97.7±6.4±11.8, 86.4±6.1±8.7 and 97.4±6.4±11.8 nb/nucleon for the π^-N, π^+N and pN interactions respectively, where the first error is statistical and the second systematic. We have assumed an $A^{0.92}$ atomic number dependence to extract the cross section per nucleon . The large percentage of directly produced J/Ψ, unexpected in the color singlet model, indicates that processes other than simple quark and/or two gluon fusion must be involved in hadroproduction of hidden charm at these energies.

The CERN WA11 experiment[4] has measured the ratios χ_1/Ψ and χ_2/Ψ in 185 GeV/c π^-Be interactions by reconstructing the charmonium states in the subset of the χ->$\gamma\Psi$ decays in which the radiated photons converted. They obtain 17.7±3.5% and 12.8±2.3% for the $\chi_1/\Psi$and χ_2/Ψ ratios respectively. These measurements together with our measurement of 0.37±0.03 for the ratio of the combined χ_1 and χ_2 to J/Ψ production at 300 GeV/c are shown in Fig. 4. Ignoring the possibility of an energy dependence of the ratio of χ states to J/Ψ production (none is required by the data of Fig. 3b), the new best values for these ratios from a fit to these three available pieces of data are indicated in Fig. 4 and shown in Table II below.

Table II
χ_1/Ψ, χ_2/Ψ and $\chi_1+\chi_2/\Psi$ Ratios for π-N Interactions
from a Fit to the Combined WA11 and E705 Data

	χ_1/Ψ	χ_2/Ψ	$\chi_1+\chi_2/\Psi$
Ratio	0.201±0.024	0.143±0.020	0.344±0.031

Combining the ratios of $\chi_1/\Psi$and χ_2/Ψ determined in this manner together with the absolute cross section for J/Ψ production in 300 GeV/c π^- nucleon interactions (178±6±20 nb/nucleon), as measured in our experiment[8], and using branching ratios of 0.273±0.016 and 0.135±0.11 for χ_1->$\gamma\Psi$ and χ_2->$\gamma\Psi$ respectively[15], we obtain the following cross sections for χ_1 and χ_2 production in π^- nucleon interactions at 300 GeV/c:

$$\sigma(\pi^-N->\chi_1 +x) = 131\pm18\pm14 \text{ nb/nucleon}$$
$$\sigma(\pi^-N->\chi_2 +x) = 188\pm30\pm21 \text{ nb/nucleon}$$

where the first error is statistical and the second systematic, and the cross sections are for x_F>0..

In conclusion, we have determined the fraction of J/Ψ production due to the radiative decays of the χ_1 and χ_2 charmonium states in $\pi^\pm$ and proton interactions with ^{7}Li at 300 GeV/c. Using our measurement of J/Ψ from the decay of the Ψ', we have also determined the cross section for direct J/Ψ

production. Combining our measurement of the ratio of $\chi_1 + \chi_2$ to J/Ψ production with previous measurements of the χ_1/Ψ and χ_2/Ψ ratios and using our measurement of the total cross section for J/Ψ at 300 GeV/c, we have obtained values for the cross section for χ_1 and χ_2 production in π^- nucleon interactions. Both the large fraction due to direct J/Ψ production and the approximately equal cross sections for χ_1 and χ_2 production, indicate that processes in addition to the color singlet processes are necessary to explain the data.

We wish to thank the U.S. Department of Energy, the Natural Sciences and Engineering Research Council of Canada, the Quebec Department of Education, and the Scientific Affairs Division of the North Atlantic Treaty Organization for their support of this experiment. In particular, we wish to acknowledge the administration and staff of the Fermi National Accelerator Laboratory for their help.

References

[1]J.H. Cobb et al., R806 Collaboration, Phys. Lett. **72B**, 497(1978); C. Kourkoumelis et al., R806 Collaboration, Phys. Lett. **81B**, 405(1979); Y. Lemoigne et al., WA11 Collaboration, Phys. Lett. **113B**, 509(1982); F. Binon et al., GAMS2000 Collaboration, Nucl. Phys. **239B**, 311(1984); S.R. Hahn et al., E673 Collaboration, Phys. Rev. **D30**, 671(1984); D.A. Bauer et al.,E673 Collaboration, Phys. Rev. Lett. **54**, 753(1985).

[2]C.E. Carlson and R. Suaya, Phys. Rev **18D**, 760(1978); C.H. Chang, Nucl. Phys. **172B**,425(1980); R. Baier and R. Ruckl, Z. Phys. **C19**, 251(1983); J.H. Kuhn, Phys. Lett. **89B**, 385(1979).

[3]H. Fritzsch, Phys. Lett. **67B**, 217(1977); M. Gluck et al., Phys. Rev. **D17**, 2324(1978).

[4]Y. Lemoigne et al., Phys. Lett. **113B**, 509(1982)

[5]"The Experiment 705 Spectrometer: A Large Aperture Spectrometer at Fermilab to Study High Mass Dimuons and High Transverse Momentum Photons", L. Antoniazzi et al., submitted to Nucl. Inst. and Methods.

[6]B. Cox et al., Nucl. Inst. and Methods **219**, 487(1984); B. Cox et al. Nuclear Inst. and Methods **219**, 491(1984); D. Wagoner et. al. Nuclear Inst. and Methods **A238**, 315(1985), B. Cox et al., Nuclear Inst. and Methods **A238**, 321(1985); "The Experiment 705 Electromagnetic Calorimeter", L. Antoniazzi et al, submitted to Nucl. Inst. and Methods.

[7]H. Areti et al., Nucl. Inst. and Meth. **212,** 135(1983)

[8]"A Measurement of J/Ψ and Ψ' Production in 300 GeV/c Proton, Antiproton and $\pi^{\pm}$ Nucleon Interactions", L. Antoniazzi et al., submitted to Physical Review D.

[9]Particle Data Group, "Review of Particle Properties", Phys. Lett. **239B**, VII.153(1990).

[10]D. Coffman et al., MARK III Collaboration, "A Direct Measurement of the J/Ψ Leptonic Branching Fraction", SLAC-PUB-5592, (1992).

[11]Particle Data Group, "Review of Particle Properties", Phys. Lett. **239B**, VII.153(1990).

[12]Particle Data Group, "Review of Particle Properties", Phys. Lett. **239B**, VII.149(1990).

[13]P.Nason, S. Dawson and R.K. Ellis, Nuclear Phys. **B327**, 49(1989).

[14]Particle Data Group, "Review of Particle Properties", Phys. Lett. **239B**, VII.132(1990).

[15]Particle Data Group, "Review of Particle Properties", Phys. Lett. **239B**, II.15(1990).

Figure Captions

Fig. 1 E705 $\mu+\mu-$ mass spectra for a)$\pi-$, b)$\pi+$, c)proton and d)antiproton ^{7}Li interactions at 300 GeV/c

Fig. 2 E705 $M(\mu^+\mu^-\gamma)$ - $M(\mu^+\mu^-)$ mass difference spectra for a)all beam types, b)$\pi+$, c)$\pi-$ and d)proton ^{7}Li interactions at 300 GeV/c. The backgrounds superimposed on the mass difference spectra are generated from pairing photons and J/Ψ's from different events. Ψ' decays resulting in J/Ψ final states are also included in the background estimates.

Fig. 3 Fraction of J/Ψ produced via radiative χ in 300 GeV/c a)proton and b) $\pi^{\pm}$ ^{7}Li interactions

Fig. 4 Composite WA11 and E705 results for ratio of χ_1/Ψ and χ_2/Ψ in π^-N interactions.

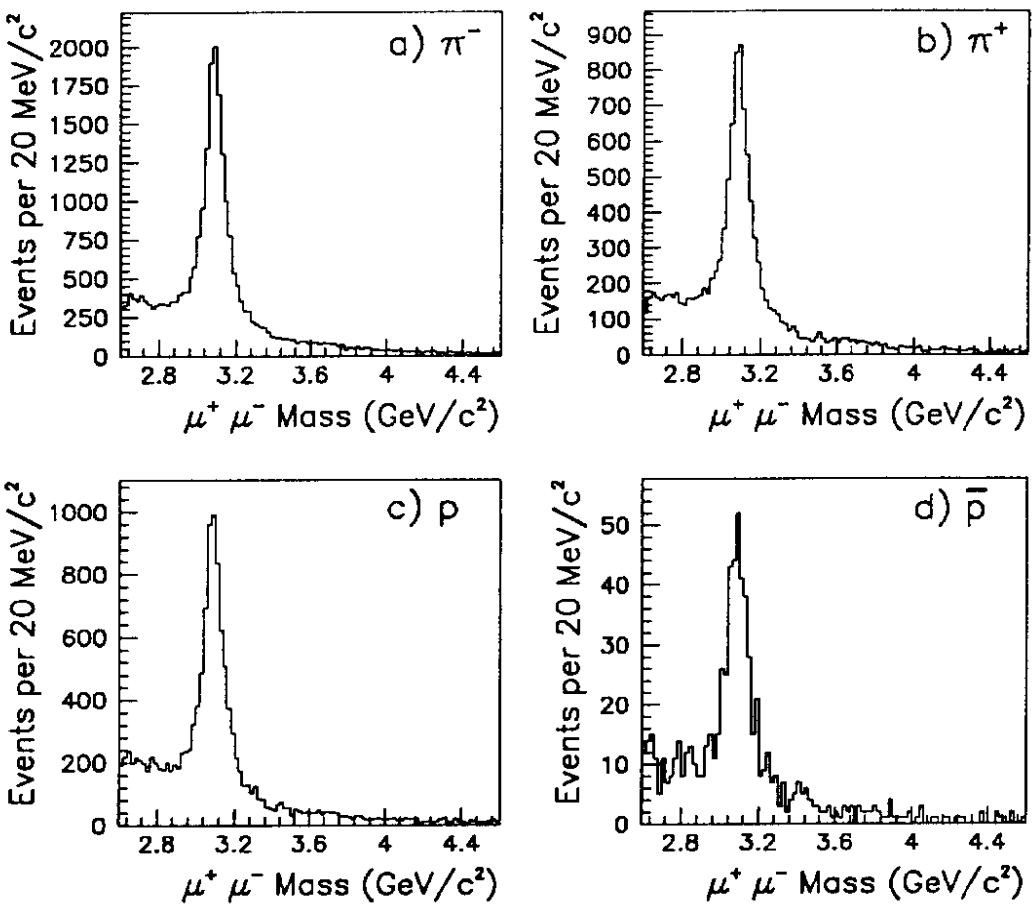
a) π^-
b) π^+
c) p
d) $\bar{p}$
Events per 20 MeV/c^2
$\mu^+\mu^-$ Mass (GeV/c^2)
2.8
3.2
3.6
4
4.4

Fig. 1

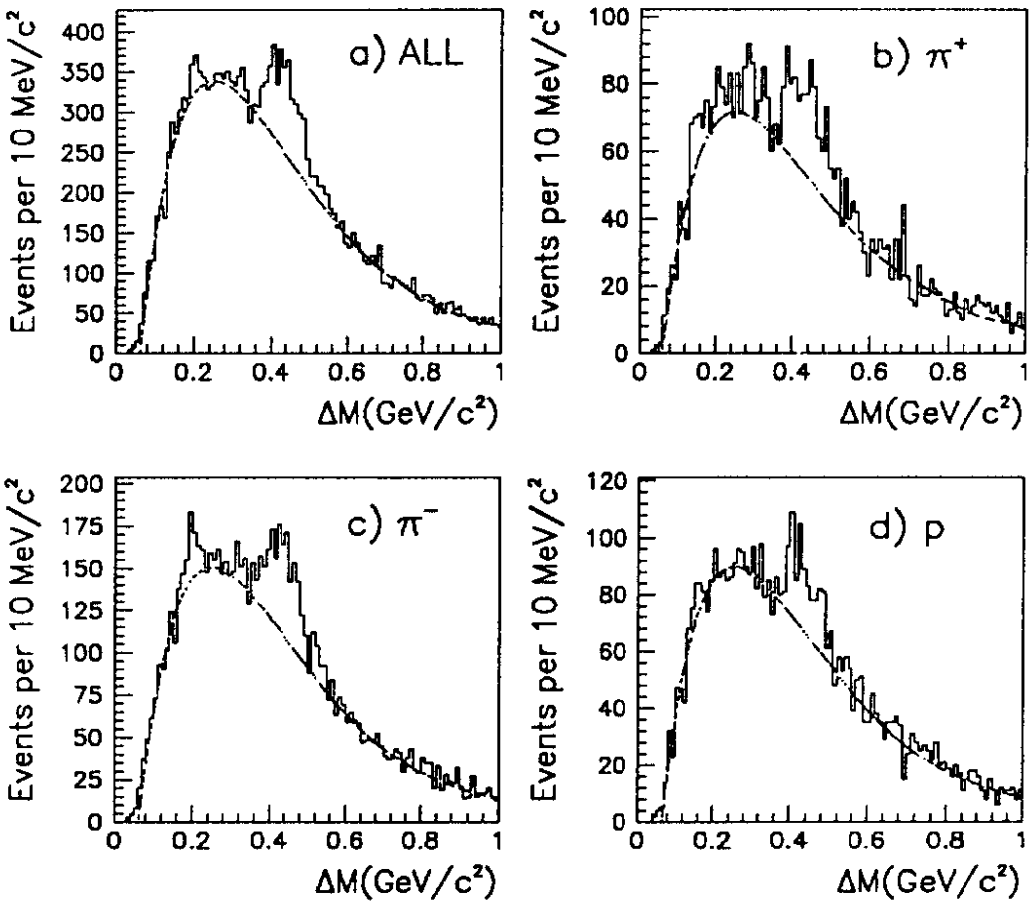

Fig. 2

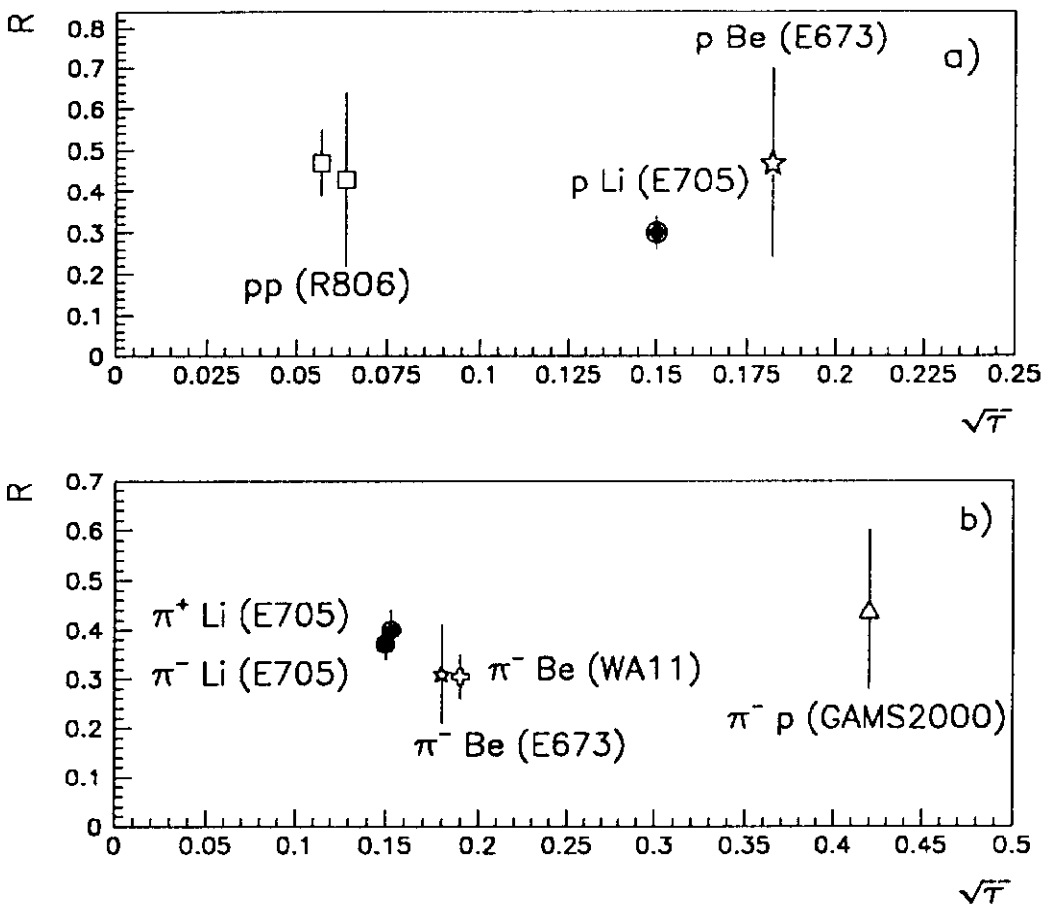
R
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0.225
0.25
$\sqrt{\tau}$
p Be (E673)
a)
p Li (E705)
pp (R806)
R
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
$\sqrt{\tau}$
b)
π^+ Li (E705)
π^- Li (E705)
π^- Be (WA11)
π^- Be (E673)
π^- p (GAMS2000)

Fig. 3

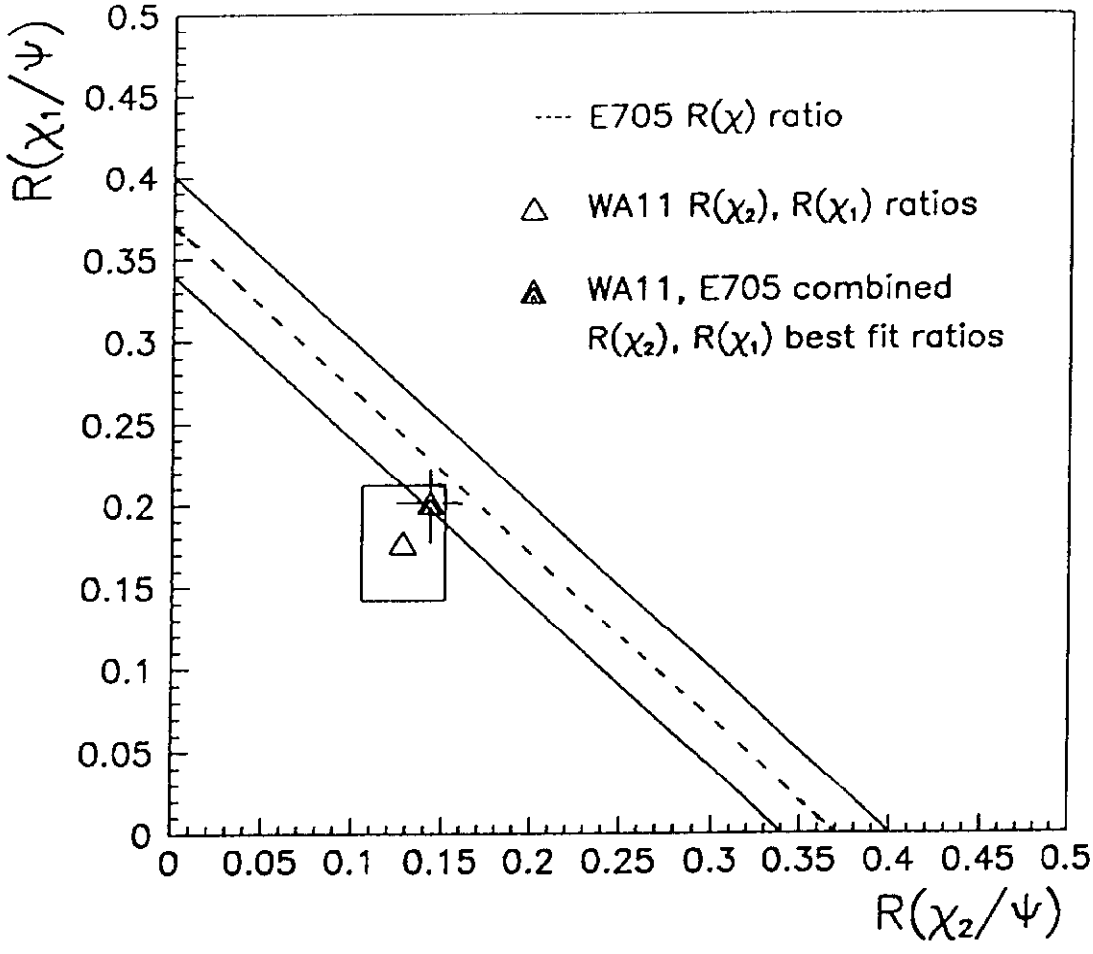
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5
R(χ1/ψ)
R(χ2/ψ)
E705 R(χ) ratio
WA11 R(χ2), R(χ1) ratios
WA11, E705 combined
R(χ2), R(χ1) best fit ratios

Fig. 4