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Heavy Quark Fragmentation*

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Abstract

Recent developments in the field of charm and bottom quark fragmentation are reviewed. Results derived from direct charm meson reconstruction and from inclusive lepton analyses are shown. Two experimentally related topics, semileptonic branching ratios and the weak asymmetry of heavy quarks are also discussed.

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Fragmentation is the process by which primarily produced quarks dress themselves up as the hadrons which are observed experimentally. Bjorken[1)] and Suzuki[2)] were the first to put forward the kinematic argument that a heavy quark would retain a larger fraction of its momentum during hadronization and therefore have a harder fragmentation function. Since then several authors have proposed fragmentation functions in order to quantify this. The single parameter form given below was proposed by Peterson et al.[3)] and is widely used by many experiments to parameterize their data.

$$D_q(z) = \frac{N}{z\,[\,1 - 1/z - \varepsilon/(1 - z)\,]^2}$$

$$z = (E + p_{||})_{hadron} / (E + p)_{quark}$$

N is a normalization constant[4)] and $p_{||}$ is the component of the meson momentum parallel to that of the fragmenting heavy quark. The parameter to be fit is ε, and it is expected to have a value of about $(m_{light\ quark}/m_{heavy\ quark})^2$. More recently, the Lund group[5)] has proposed the form:

$$D_q(z) = (N/z)(1 - z)^a \exp(-bm^2/z)$$

The two parameters a and b are to be determined experimentally, and m is the mass of the meson being formed from the fragmenting quark.

The variable z is convenient for theoretical treatments of fragmentation, and Monte Carlo simulations have been developed according to those theoretical ideas. Unfortunately the energy and momentum of quarks aren't observed before fragmentation. Experiments at e^+e^- colliders often express their data in terms of the variable $x = E_{hadron}/E_{beam}$ or $x_p = p_{hadron}/\sqrt{E^2_{beam} - m^2_{hadron}}$. In general one expects x to be smaller than z since the energy of the fragmenting quark is not E_{beam}, but it is diminished by the effects of intial state photon radiation and gluon bremsstrahlung. The JADE group estimates that for charm quarks pairs produced at $\sqrt{s}$ = 34 GeV these are 5% and 11% effects respectively[8]. Some experiments have elected to correct x for the effects of intial state radiation, denoted here by "x+Y", and some have attempted to deduce the primordial z distribution. For any meson, $z \geq x+Y \geq x$.

Charm Fragmentation

The most direct way to measure the fragmentation of charm quarks is to reconstruct charm mesons. The easiest method has been to use the $D^{*+} - D^{0}$ mass difference trick to tag decays of the $D^{*\pm}$. MARK II[6], TASSO[7], JADE[8], HRS[9], DELCO[10] and TPC[11] have done this at the electron-positron colliders PETRA and PEP, and CLEO[12] and ARGUS[13] have done likewise at CESR and DORIS II. In addition, CLEO and HRS have reconstructed D^{0}'s directly, and HRS has reconstructed $D^{\pm}$'s. Some of these charm signals are shown in fig. 1. Table 1 summarizes the world sample of charm mesons reconstructed in the 10 GeV and the 30 - 34 GeV regions. Almost all of this information is less than two years old! The PETRA/PEP $D^{*\pm}$ scaled differential cross section measurements are shown fig. 2, and those from CLEO and ARGUS follow in fig 3. There is reasonably good agreement among the experiments within each energy region, but notice that the 10 GeV data is plotted as a function of x_p. At this beam energy the mass of the D meson is still a significant fraction of the beam energy, and threshold effects play an important role. Using x_p hides the threshold issue since its values can range from 0 to 1. Table 2 contains Peterson ε_c values obtained by fitting the data of figs. 2 and 3. Remember that $\varepsilon_c(x)$ and $\varepsilon_c(x_p)$ are not directly comparable, and that neither directly represents $\varepsilon_c(z)$ which describes the underlying fragmentation process. This is illustrated by the two curves in fig 4. The solid curve relates the observable quantity $\langle E_D*/E_{beam}\rangle$ to $\varepsilon_c(x)$ while the broken curve has relied on an independent jet Monte Carlo[14] to infer $\varepsilon_c(z)$. Other Monte Carlo models would give slightly different curves for $\varepsilon_c(z)$ as would different values of α_s.

Another aspect of charm fragmentation is the ratio of vector to pseudoscalar mesons produced. A first piece of information comes from the total cross section for charm production. One expects for the charm to μ pair cross section ratio, $\sigma_{all\ charm}/\sigma_{\mu\mu}$ = $2 \times 4/3 \times (1 + \alpha_s/\pi) \approx 2.8$. The measurements of $\sigma_{D^{*\pm}}/\sigma_{\mu\mu}$ found in Table 2 and the assumption of isospin invariance, i.e. $\sigma_{D^{*\pm}} = \sigma_{D^{*0}}$ indicate that charm production is supersaturated by D^{*}'s. More direct evidence came from HRS and CLEO which were able to reconstruct D^{0}'s and $D^{\pm}$'s without relying on a $D^{*\pm}$ tag. If r is the ratio of D's to D^{*}'s produced directly, then the ratio of the numbers of each specie observed would be r+1 since all D^{*} decay modes involve a D meson. If simple spin state counting holds, then r+1 would equal 1.33. If there were no direct D^{0} or $D^{\pm}$ production, then r+1 would equal 1. HRS[9] measured:

$$\frac{D^{0}\text{observed} + D^{\pm}\text{observed}}{2 \times D^{*\pm}\text{observed}} = \begin{array}{ll} 1.1 \pm 0.4 & \text{for all } x \\ 1.0 \begin{array}{l} +0.3 \\ -0.2 \end{array} & \text{for } x > 0.5 \end{array}$$

CLEO[12] found:

$$D^{0}\text{direct} / D^{*\pm}\text{direct} = 0.18 \pm 0.24 \pm 0.25 \quad \text{for } x_p > 0.55$$

Since neither experiment detected D^{*0}'s, they both relied upon D^{*} isospin invariance in order to interpret their data. D^{*}'s were produced more plentifully than D's, but the data were consistent with both no direct D production and with the predictions of spin counting.

The transverse momentum of $D^{*\pm}$'s is generated during first rank charm fragmentation. Fig. 5 shows TASSO's plot of the p_T^2 of $D^{*\pm}$'s with respect to the fragmenting charm quark direction where a Monte Carlo was used to correct p_T^2 measured with respect to the thrust axis[16]. The data were well described by the form $dN/dp_T^2 \sim \exp(-p_T^2/(2\sigma_c))$ with $\sigma_c = 0.36 \pm 0.02 \pm 0.04$ GeV/c. The value of σ_c agreed well with the value $\sigma_q = 0.355 \pm 0.010$ GeV/c obtained by fitting the entire event sample. Fig. 6 shows JADE's measurement of the p_T^2 of $D^{*\pm}$'s and charged tracks with respect to the sphericity axis[8]. Only particles with $x > 0.4$ were used. Fits to these and a similar Λ distribution yielded $\langle p_T^2 \rangle_{D^{*+}} = 0.62 \pm 0.08$, $\langle p_T^2 \rangle_\Lambda = 0.56 \pm 0.07$ and $\langle p_T^2 \rangle_{charged} = 0.52 \pm 0.05$. Within errors these numbers are compatible.

TASSO used tagged $D^{*\pm}$ as "triggers" and studied the unbiased charm jets in the opposite thrust hemisphere. Fig. 7 contains the corrected scaled momentum, rapidity, p_T^2, sphericity and thrust distributions for charm jets at W = 34.4 GeV and the same for the average jet containing a charm contribution of 4/11. No statistically significant differences were found. TASSO has also studied the particles remaining in the D^* trigger jet after the D^* daughters were removed. The mean residual jet energy was 6.2 ± 0.4 GeV which suggested comparison with W = 14 GeV data. Fig 8. shows the momenta of trigger jet particles scaled by the residual energy and the scaled particle momenta from $\sqrt{s}$ = 14 GeV data. Good agreement was found. Rapidity and p_T^2 also agreed well.

In QCD, the coupling of the gluon to quarks is independent of the flavor of the quark and characterized by a single constant α_s. TASSO has studied the "perturbative tail" of the $p_{T_{in}}$ distribution, i.e. $p_{T_{in}} > 0.7$ GeV/c for their charm-tagged sample as seen in fig. 9. TASSO found $\alpha_s^c = 0.153 \pm 0.031 \pm 0.030$ within the context of their second order QCD, independent jet fragmentation model. A more significant result came from the ratio α_s^c/α_s since much of the model dependence cancelled out. They found $\alpha_s^c/\alpha_s = 1.00 \pm 0.20 \pm 0.20$[16]. JADE[8] compared their $D^{*\pm}$ events with multihadronic events containing at least one track with an $x > 0.4$. They found 13 ± 4% of the $D^{*\pm}$ events and 10 ± 1% of the multihadronic events are "3 jet" events. Using the Lund Monte Carlo they inferred $\alpha_s^c = 0.13 \pm 0.08$.

A candidate for the charm-strange F meson was reported last year at 1.97 GeV by the CLEO[17] group, and has been confirmed by TASSO[18],

ARGUS[19] and HRS[20]. All four experiments detected it via its decay $F^+ \to \phi\pi^+$ and ARGUS also has seen $F^+ \to \phi\pi^+\pi^-\pi^+$. Invariant mass distributions can be found in fig. 10. Differential cross sections are shown in fig. 11, and each experiment's results are summarized in Table 3. While the F fragmentation function has not been as well measured as that of D cousins, it is clearly softer. Qualitatively this is expected because the fragmenting charm quark has to split its momentum with a heavier strange quark. The HRS's preliminary differential cross section contained an unexpected large and "unfragmentation-like" enhancement at low x. An alternative source for F mesons with low x would be from decays of B mesons, but CLEO limits would seem to exclude such a large enhancement[21]. The situation will become clearer shortly since HRS already has 60% more data in hand for which results will be available shortly. Also, TASSO data would indicate a higher cross section than is seen at 10 GeV or by HRS's $x > 0.4$ data.

One of the first measurements of the charm fragmentation unhampered by threshold effects came from the observation of the semimuonic decay of charmed particles induced by neutrino scattering. At CERN, CDHS[22] observed dimuon events of the type shown in fig. 12. By studying $(p_{\mu^+})/(p_{\mu^+} + E_{shower})$ they were able to deduce $\langle x_c \rangle = 0.68 \pm 0.05 \pm 0.06$ for some unmeasured mixture of charm particle species. More recently experiment E531[23] at Fermilab has been able to reconstruct directly the charmed particles produced via the same mechanism. They found $\langle x_c \rangle = 0.59 \pm 0.03 \pm 0.03$ for the data shown in fig. 13.

Inclusive Leptons

Studies of inclusive leptons produced in e^+e^- annihilations have revealed a surprising amount of information[11,24-34]. Leptons can come from the following processes:

1) $b \to c\,\ell\,\nu_\ell$ semileptonic bottom decays
2) $c \to s\,\ell\,\nu_\ell$ semileptonic charm decays
3) $b \to c\,X \to s\,\ell\,\nu_\ell\,X$ "cascade decays"
4) backgrounds such as π^0 Dalitz decays, converted photons, hadrons that fake leptons

Each source is characterized by a distinctive p and p_T distribution. In particular, as a heavy meson decays, it daughters tend to be given a transverse kick relative to the jet axis. Therefore it has been possible to perform fits to lepton p and p_T and to extract semileptonic branching ratios and fragmentation function mean values for both charm and bottom. Fig. 14 contain TASSO's inclusive electron data and their fit which was broken down to show the contributions from the three "interesting" sources plus backgrounds. Note that the spectrum of electrons from bottom is quite different from the others, and that the differences between electrons from charm and those of background processes are not so marked. Semileptonic branching ratio measurements from inclusive analyses can be found in Table 4 along with measurements made near threshold for open charm and bottom production. The experiments are all in good agreement, and when combined (statistical and systematic errors taken in quadrature) give 8.8 ± 0.6% for charm and 12.0 ± 0.8% for bottom. The charm branching ratio is in good agreement with the world average[32] on the ψ'' (8.1 ± 1.0%) and the region above the ψ'' (8.1 ± 1.4%). These might have been expected to differ since the ψ'' data contained no F mesons, and the continuum range just above the ψ'' could have been a different mixture of charm particles than were produced at PETRA and PEP. The bottom branching ratio also agreed well with the 11.8 ± 0.6% determined for Υ(4S) data[32]. These measurements might also have been expected to differ since the Υ(4S) does not produce B_s mesons.

Table 5 contains a summary of charm fragmentation measurements from inclusive leptons, D^*'s and neutrinos. They are also plotted in fig. 15. The inclusive lepton measurements are not in wonderful agreement.

The experiments may have been overconfident of their understanding of "background" leptons and underestimated systematic errors accordingly. To confuse matters further, some groups have presented results in terms of x_c and others in terms of $x_c^{+\gamma}$ or z_c. The safest conclusion to draw from the inclusive analyses is that the mean lies somewhere between 0.5 and 0.7. The D^* measurements were self consistent and found $\langle x_c \rangle$ = 0.57 ± 0.02, corresponding to ε_c = 0.30 ± 0.04. The neutrino experiments were also in agreement and found $\langle x_c \rangle$ = 0.61 ± 0.04.

The bottom fragmentation results are found in Table 6 and are represented graphically in fig. 16. Experiments have chosen to present $\langle x_b \rangle$, $\langle x_b^{+\gamma} \rangle$ and/or $\langle z_b \rangle$. With the assumption (guess) that $\langle z_b \rangle \approx 1.05 \times \langle x_b \rangle$, the world average is $\langle z_b \rangle$ = 0.80 ± 0.03. Each experiment has quoted corresponding ε_b values, but it would be senseless to average them since in this range the errors are asymmetric and nonlinear. While these analyses have determined $\langle z_b \rangle$ remarkably well, they had no sensitivity to the shape of the bottom fragmentation function.

Weak Quark Asymmetry

Charm-tagged D events and flavor-enhanced lepton events have been used to determine the electroweak quark asymmetry. If θ is the angle defined by the momenta of the incoming e^+ and the outgoing quark, then

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \frac{8}{3}A\cos\theta + \cos^2\theta$$

For center of mass energy W much less than the mass of the Z^0, M_Z the standard model predicts

$$A = \frac{3}{2}\,\frac{g_A^e\, g_A^Q}{e_Q}\,\frac{G_F}{2\sqrt{2}\pi\alpha}\,\frac{W^2}{1-(W/M_Z)^2}$$

In the standard model the values of the axial vector coupling constants are $g_A^e = -1/2$, $g_A^c = 1/2$ and $g_A^b = -1/2$. The quark charge, e_Q in the denominator leads to larger asymmetries than are found for lepton pairs. All experiments assumed $g_A^e = -1/2$ when calculating g_A^c or g_A^b. Individual measurements of g_A^c and g_A^b are listed in Tables 7 and 8, and they are represented graphically in figs. 17 and 18 respectively. The world averages are $g_A^c = 0.57 \pm 0.16$ and $g_A^b = -0.49 \pm 0.10$ in good agreement with the standard model. One should regard averages of many measurements of small statistical signifcance with a certain amount of caution, but it's encouraging that there are now measurements that can stand alone.

Conclusions

The data showed clearly that the charm quark has a hard fragmentation function with $\langle x_c \rangle = 0.57 \pm 0.02$. Charm jets aren't very different from the average jet, and charm quarks couple to the gluon with a strength similar to that of all quarks produced at PETRA/PEP. Better D branching ratios which should be available shortly from MARK III will reduce the systematic errors for total charm cross section and the ratio of D's to D^*'s. Statistical errors are approaching the point where the detailed shape of the fragmentation function can be studied. The effect of thresholds needs to be better understood for lower energy data, and the contributions to the charm cross section from decays of B mesons needs to be understood for high energy data.

The picture for fragmentation of charm into F mesons is just starting to emerge. Much more data is needed but it is already clear that the F spectrum is softer than that of D mesons. HRS's low x enhancement, if confirmed will bear some explanation.

Inclusive lepton measurements have given $\langle z_b \rangle = 0.80 \pm 0.03$ for the fragmentation function of the bottom quark, but nothing else is known about its shape. A quantum leap will occur if and when PETRA and PEP experiments learn how to reconstruct B mesons.

The correction from x to z needs to be better understood. The data of different experiments can be compared directly in terms of x, but z is needed to reach the underlying physics. At present there are many fragmentation Monte Carlos, values of α_s and QCD generators in use. All lead to slightly different mappings of x onto z. The combined world error for z measurements can not be improved much further until this is clarified.

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References

[1] J.D. Bjorken, Phys. Rev D17 (1978) 171

[2] M. Suzuki, Phys. Lett. 71B, (1977) 139

[3] C. Peterson et al., Phys. Rev. D27 (1983) 105

[4] N is defined such that $\int_{z_{threshold}}^{1} D_q(z)dz = 1$. Letting $2\alpha = c$,

$$\frac{1}{N}\int D_q(z)dz = \frac{1}{2}\ln\left(\frac{z^2 - 2(1-\alpha)z + 1}{\alpha(2-\alpha)}\right) + \frac{2\alpha(1-\alpha)}{z^2 - 2(1-\alpha)z + 1}$$

$$+ \frac{1 - 3\alpha + \alpha^2}{\sqrt{\alpha}(2-\alpha)^{3/2}}\tan^{-1}\left(\frac{z - 1 + \alpha}{\sqrt{\alpha(2-\alpha)}}\right)$$

$$- \left(\frac{1 - 4\alpha + 2\alpha^2}{2 - \alpha}\right)\left(\frac{z - 1 + \alpha}{z^2 - 2(1-\alpha)z + 1}\right)$$

[5] B. Andersson et al., Z. Phys. C - Particles and Fields 20, (1983) 317

[6] J.M. Yelton et al. (MARK II), Phys. Rev. Lett. 49 (1982) 430. Also see Proceedings of the XXII International Conference on High Energy Physics, Leipzig, July 19-25, 1984 for a MARK II D^* update with higher statistics.

[7] M. Althoff et al. (TASSO), Phys. Lett. 126B (1983) 493

[8] W. Bartel et al. (JADE), DESY Report 84-059, submitted to Physics Lett.

[9] S. Ahlen et al. (HRS), Phys. Rev. Lett. 51 (1983) 1147
M. Derrick et al. (HRS), preprint HRS-PR-84-1, to be published in Phys. Rev. Lett.
M. Derrick et al. (HRS), preprint HRS-PR-84-2, to be published in Phys. Lett.

[10] J. Dorfan, Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, Ithaca, NY, August 4-9, 1983

[11] R.J. Madaras (TPC), proceedings of XIX Rencontre de Moriond, La Plagne, France, March 4-10, 1984
W. Hofmann, private communication

[12] C. Bebek et al. (CLEO), Phys. Rev. Lett. 49 (1982) 430
P. Avery et al. (CLEO), Phys. Rev. Lett. 51 (1983) 1139

[13] H. Albrecht et al. (ARGUS), DESY Report 84-073 to be published in Phys. Lett.

[14] The independent jet model described in M. Althoff et al. (TASSO), DESY Report 84-057 to be published in Z. Phys. C.

[15] M. Althoff et al. (TASSO), Phys. Lett. 135 (1984) 243

[16] M. Althoff et al. (TASSO), Phys. Lett. 138B (1984) 317

[17] A. Chen et al. (CLEO), Phys. Rev. Lett. 51 (1983) 634

[18] M. Althoff et al. (TASSO), Phys. Lett. 136B (1984) 139

[19] H. Albrecht et al. (ARGUS), "Production and Decay of the F-Meson in e^+e^- - Annihilation at 10 GeV Centre-of-Mass Energy", submitted to the XXII International Conference on High Energy Physics, Leipzig, July 19-25, 1984

[20] M. Derrick et al. (HRS), preprint HRS-CP-84-3 submitted to the XXII International Conference on High Energy Physics, Leipzig, July 19-25, 1984

[21] A. Silverman, Proceedings of the XXII International Conference on High Energy Physics, Leipzig, July 19-25, 1984

[22] H. Abramowicz et al. (CDHS), Z. Phys. C 15 (1982) 19

[23] N. Ushida et al. (E531), Phys. Lett. 121B, (1983) 292

[24] M.E. Nelson et al. (MARK II), Phys. Rev. Lett. 50 (1983) 1542

[25] E. Fernandez et al. (MAC), Phys. Rev. Lett. 50 (1983) 1542

[26] B. Adeva et al. (MARK J), Phys. Rev. Lett. 51 (1983) 443
B. Adeva et al. (MARK J), MIT-LNSR-131, December 1983

[27] H.J. Behrend et al. (CELLO), Z. Phys. C 19 (1983) 291

[28] M. Althoff et al. (TASSO), Z. Phys. C 22 (1984) 219

[29] D.E. Koop et al. (DELCO), Phys. Rev. Lett. 52 (1984) 970

[30] H. Aihara et al. (TPC), LBL-17545, UT-HE-84/03, March 1984
W. Hofmann, private communication

[31] M. Althoff et al. (TASSO), DESY Report 84-061, submitted to Phys. Rev. Lett.

[32] For a recent compilation see M. Sakuda, Proceedings of the Symposium on High Energy e^+e^- Interactions, Vanderbilt University, Nashville, Tennessee, April 5-7, 1984

[33] B. Naroska, Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, Cornell University, Ithaca, NY, August 4-9, 1983.

[34] W. Bartel et al. (JADE), DESY Report 84-068, submitted to Phys. Lett.

Table 1. World Charm Sample (e^+e^-)

	$D^{*\pm}$	D^0	$D^\pm$
CLEO/ARGUS	674	644	---
PEP/PETRA	~450	144	123

Table 2. D Mesons

Experiment		E_{CM}	ε_c	$\sigma_D/\sigma_{\mu\mu}$	
JADE	$D^{*\pm}$	34.4	0.24 ± 0.08	$1.9 \pm 0.3 \pm 0.4$	$(x > 0.4)$
TASSO	$D^{*\pm}$	34.4	$0.25 \pm ^{0.13}_{0.08}$	$1.57 \pm 0.31 \pm 0.55$	$(x > 0.3)$
MARK II	$D^{*\pm}$	29	~0.25	3.2 ± 1.6	$(x > 0.2)$
TPC	$D^{*\pm}$	29	0.28 ± 0.11		(preliminary)
HRS	$D^{*\pm}$	29 }	$0.35 \pm ^{0.07}_{0.06}$	1.35 ± 0.45	
	D^0	29		1.8 ± 0.5	
	$D^\pm$	29		1.2 ± 0.4	
CLEO	$D^{*\pm}$	10.5	0.10 ± 0.02	$1.11 \pm 0.13 \pm 0.35$	
	D^0	10.5		$2.0 \pm 0.4 \pm 0.4$	
ARGUS	$D^{*\pm}$	10	0.19 ± 0.03		

PEP/PETRA experiments fit x, CLEO and ARGUS fit x_p.
PEP/PETRA use $Br(D^{*+} \to D^0\pi^+) = 44 \pm 10$ %, $Br(D^0 \to K^-\pi^+) = 3.0 \pm 0.6$ %
CLEO uses $Br(D^{*+} \to D^0\pi^+) = 60 \pm 15$ %, $Br(D^0 \to K^-\pi^+) = 3.0 \pm 0.6$ %

Table 3. F Mesons

Exp.	Mode	E_{CM}	ε	$R_F \cdot Br$	
CLEO	$\phi\pi$	10.5		0.015 ± 0.004	$(p > 2.5)$
ARGUS	$\phi\pi$	10	$0.47 \pm^{0.27}_{0.17}$	$0.017 \pm 0.005 \pm 0.005$	
	$\phi\pi\pi\pi$	10		$0.033 \pm 0.011 \pm 0.012$	
TASSO	$\phi\pi$	34.7	0.45 ± 0.25	$0.061 \pm 0.012 \pm 0.018$	$(x > 0.3)$
HRS	$\phi\pi$	29		0.071 ± 0.017	

Table 4. Semileptonic Branching Ratios

Experiment		$Br(c \to \ell)$ (%)	$Br(b \to \ell)$ (%)
CELLO	μ	$12.3 \pm 2.9 \pm 3.9$	$8.8 \pm 3.4 \pm 3.5$
	e		$14.1 \pm 5.8 \pm 3.0$
MARK J	μ	$11.5 \pm 1.0 \pm 1.7$	$10.5 \pm 1.5 \pm 1.3$
TASSO	μ	$8.2 \pm 1.2 \pm^{2.}_{1.}$	$11.7 \pm 2.8 \pm 1.0$
	e	$9.2 \pm 2.2 \pm 4.0$	$11.1 \pm 3.5 \pm 4.0$
DELCO	e	9.1 ± 1.3	14.6 ± 2.8
MAC	μ	$9. \pm 3.$	$12.3 \pm 1.8 \pm (^{1.7}_{1.8} \pm 0.8)$
	e	$8. \pm 3.$	$11.3 \pm 1.9 \pm 3.0$
MARK II	μ	$8.3 \pm 1.3 \pm 1.8$	$12.6 \pm 5.2 \pm 3.0$
	e	$6.6 \pm 1.4 \pm 2.8$	$13.5 \pm 2.6 \pm 2.0$
TPC	μ	$7.2 \pm 1.4 \pm 0.5$	$13.2 \pm 1.8 \pm 1.0$
	e	$9.1 \pm 0.9 \pm 1.3$	$11.0 \pm 1.8 \pm 1.0$
AVERAGE		8.8 ± 0.6	12.0 ± 0.8
ψ'' (no F's)		8.1 ± 1.0	SLAC-LBL-LGW/DELCO/MARK II/DASP
Above ψ''		8.1 ± 1.4	SLAC-LBL-LGW/DASP
$\Upsilon(4S)$ (no B_s)		CLEO/CUSB	11.8 ± 0.6

Table 5. Charm Fragmentation Function

Experiment		Variable	Mean	ε_c
MARK J	μ	z	$0.46 \pm 0.02 \pm 0.05$	$0.8 \pm 0.1 \pm 0.2 = \sqrt{\varepsilon_c}$
TASSO	μ	z	$0.77 \pm^{0.05}_{0.07} \pm^{0.03}_{0.11}$	$0.006 \pm^{0.017}_{0.005} \pm^{0.052}_{0.003}$
	μ	x	$0.71 \pm^{0.05}_{0.07} \pm^{0.04}_{0.11}$	
	e	z	$0.57 \pm^{0.10}_{0.09} \pm^{0.05}_{0.06}$	$0.24 \pm^{0.35}_{0.16} \pm^{0.17}_{0.08}$
DELCO	e	x+Y	0.69 ± 0.06	$0.05 \pm^{0.06}_{0.03}$
	e	x	0.66 ± 0.06	$0.071 \pm^{0.076}_{0.038}$
TPC	e	x+Y	$0.55 \pm 0.07 \pm 0.03$	$0.26 \pm^{0.24}_{0.13} \pm^{0.09}_{0.04}$
AVERAGE	e,μ		0.5 - 0.7	
JADE	D^*	x	0.64 ± 0.05	0.24 0.08
TASSO	D^*	x	0.59 ± 0.04	$0.25 \pm^{0.13}_{0.08}$
HRS	D^*, D^0	x	0.53 ± 0.03 (D^*)	$0.35 \pm^{0.07}_{0.06}$ (D^*, D^0)
MARK II	D^*	x	0.58 ± 0.06	~0.25
TPC	D^*	x+Y	$0.58 \pm 0.03 \pm 0.05$	0.28 ± 0.11 (preliminary)
AVERAGE		x	0.57 ± 0.02	0.30 ± 0.04
CDHS	ν	x	$0.68 \pm 0.05 \pm 0.06$	
E531	ν	x	$0.59 \pm 0.03 \pm 0.03$	
AVERAGE		x	0.61 ± 0.04	

Table 6. Bottom Fragmentation Function

Experiment		Variable	Mean	ε_b
MARK J	μ	z	$0.75 \pm 0.03 \pm 0.06$	$0.15 \pm 0.03 \pm 0.05 = \sqrt{\varepsilon_b}$
TASSO	μ	z	$0.85 \pm^{0.10}_{0.12} \pm^{0.02}_{0.07}$	$0.0025 \pm^{0.029}_{0.0025} \pm^{0.011}_{0.0013}$
	μ	x	$0.81 \pm^{0.04}_{0.09} \pm^{0.02}_{0.05}$	
	e	z	$0.84 \pm^{0.15}_{0.10} \pm^{0.15}_{0.11}$	$0.005 \pm^{0.022}_{0.005} \pm^{0.020}_{0.005}$
DELCO	e	x+Y	0.78 ± 0.05	$0.018 \pm^{0.024}_{0.011}$
		x	0.76 ± 0.06	$0.025 \pm^{0.034}_{0.015}$
MAC	μ	z	0.8 ± 0.1	$0.008 \pm^{0.037}_{0.008}$
MARK II	μ	z	$0.73 \pm 0.15 \pm 0.10$	$0.042 \pm^{0.218}_{0.008} \pm^{0.12}_{0.035}$
	e	z	$0.79 \pm 0.06 \pm 0.06$	$0.015 \pm^{0.022}_{0.011} \pm^{0.023}_{0.011}$
TPC	μ	x+Y	$0.83 \pm 0.05 \pm 0.03$	$0.0065 \pm^{0.0096}_{0.0041} \pm^{0.0181}_{0.001}$
	e	x+Y	$0.74 \pm 0.05 \pm 0.03$	$0.033 \pm^{0.037}_{0.019} \pm^{0.019}_{0.012}$
AVERAGE		x	0.80 ± 0.03	

Table 7. Charm Axial Vector Coupling Constant

Experiment	Method	g_A^c
MARK J	μ	0.6 ± 0.3
JADE	D^*	0.5 ± 0.32
TASSO	D^*	0.45 ± 0.35
TASSO	e	-0.18 ± 0.86
MAC	μ	0.8 ± 1.8
TPC	D^*	1.2 ± 0.7
TPC	e	$1.15 \pm 0.7 \pm 0.5$
HRS	D^*	0.63 ± 0.42
AVERAGE		0.57 ± 0.16

Table 8. Bottom Axial Vector Coupling Constant

Experiment	Method	g_A^b
TASSO	μ,e	-0.60 ± 0.36
JADE	μ	$-0.45 \pm 0.12 \pm 0.05$
MARK J	μ	-0.4 ± 0.4
MAC	μ	-0.3 ± 0.35
MARK II	μ,e	$-0.75 \pm^{0.35}_{0.30}$
TPC	e	$-1.0 \pm 0.95 \pm 0.25$
AVERAGE		-0.49 ± 0.10

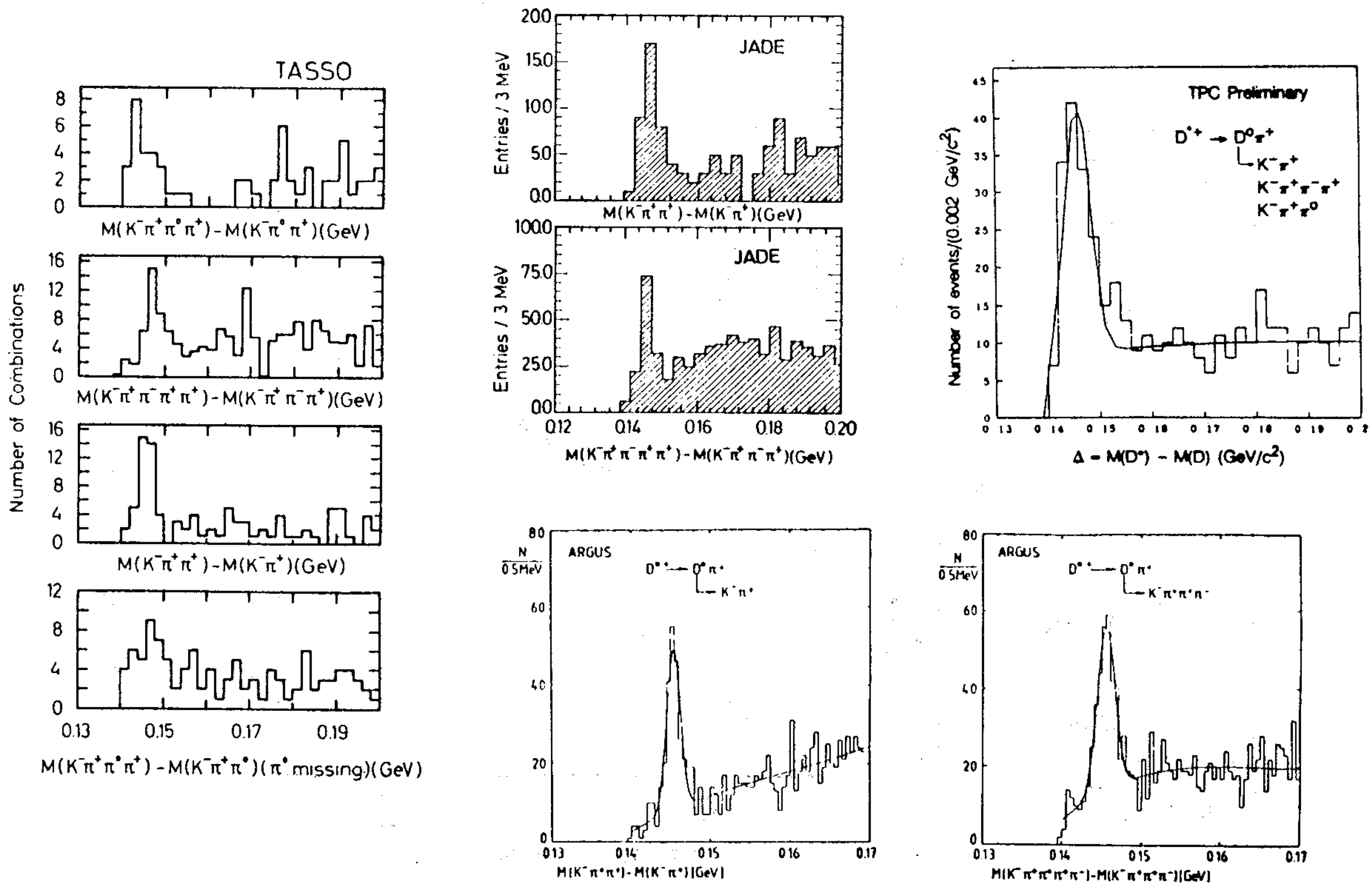


Fig. 1a $M_{D^{*\pm}} - M_{D^0}$ distributions.

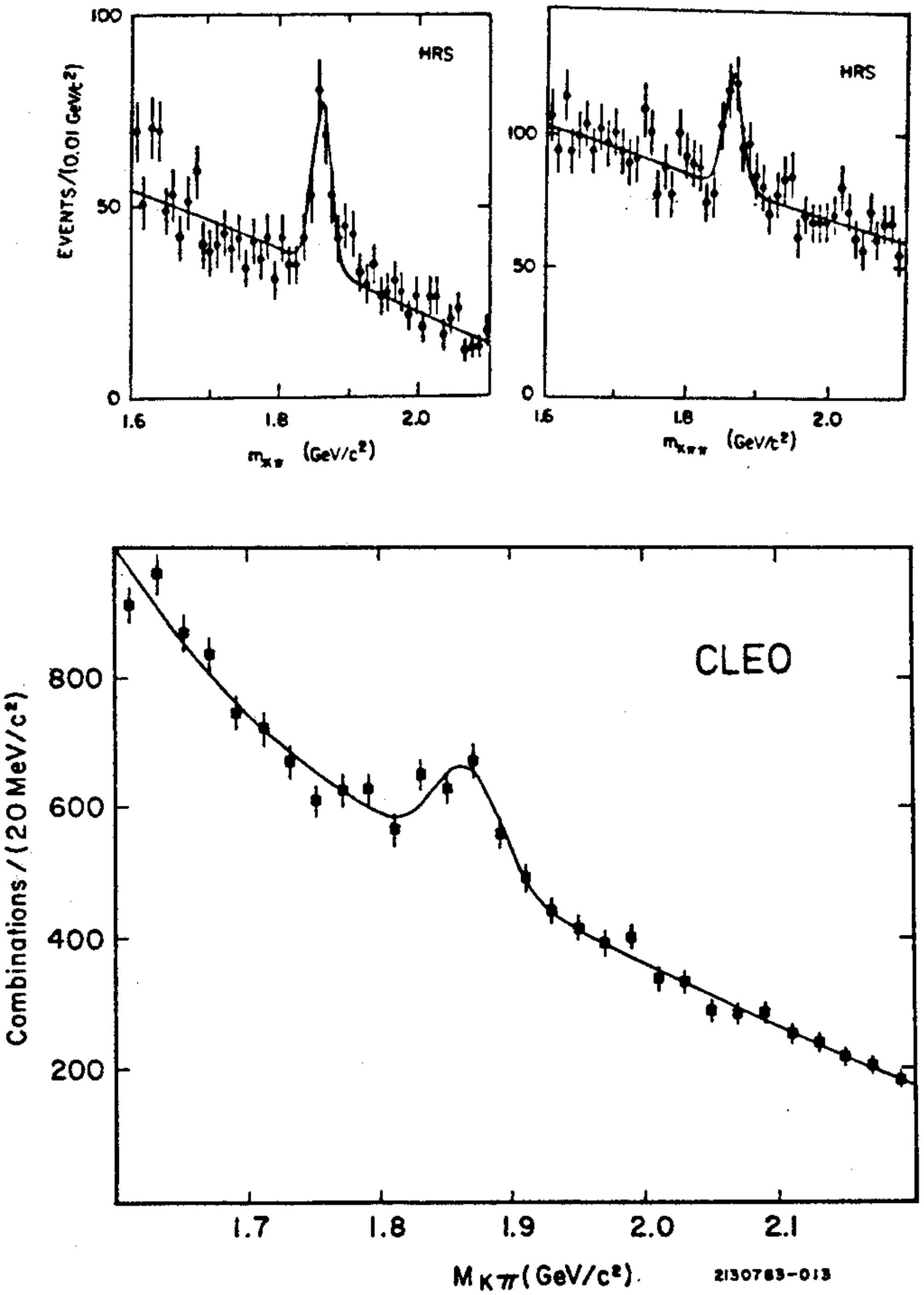


Fig. 1b D meson invariant mass distribution

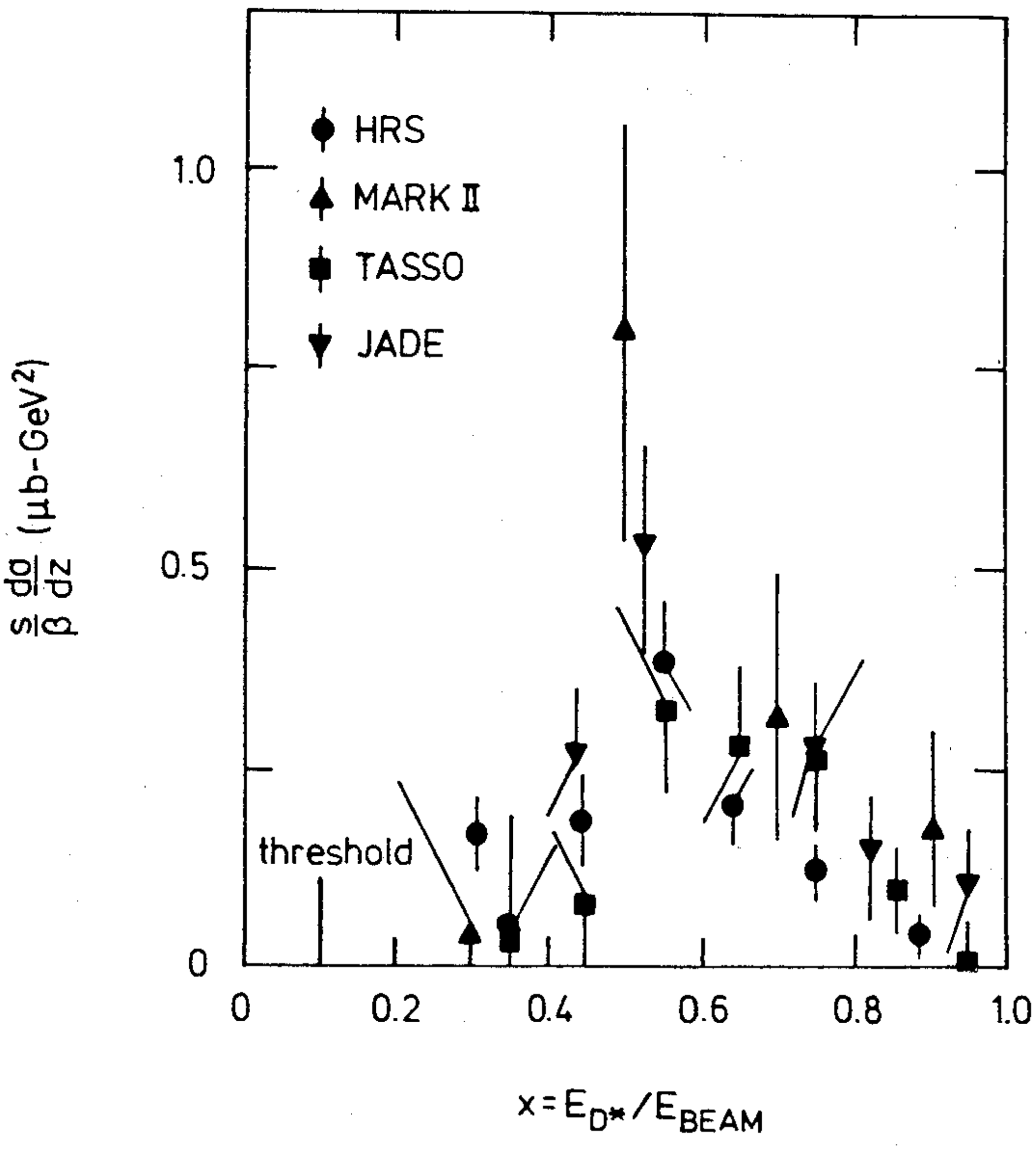


Fig. 2 PEP/PETRA $D^{*\pm}$ scaled differential cross section.

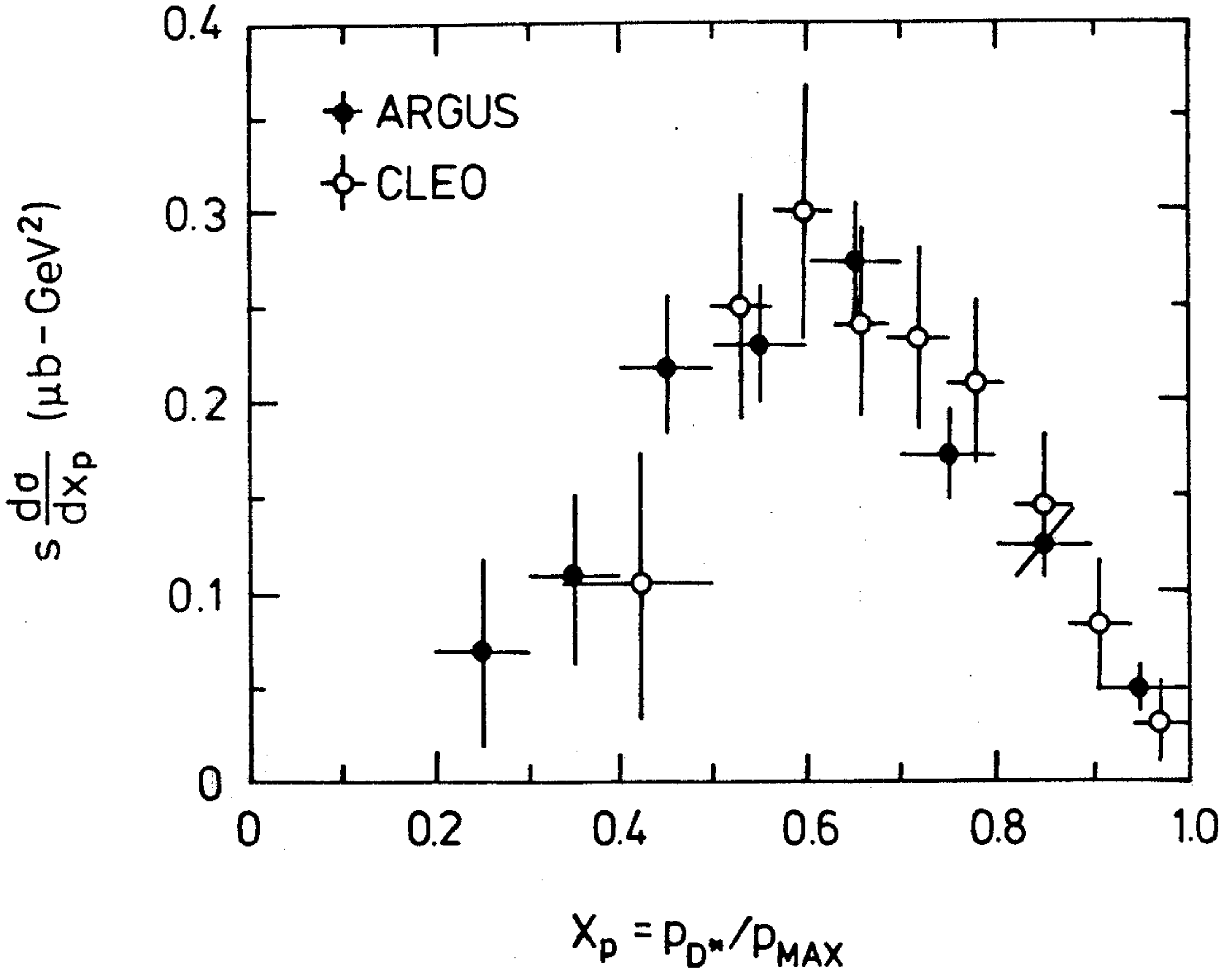


Fig. 3 CLEO/ARGUS $D^{*\pm}$ scaled differential cross section using $Br(D^{*\pm} \to D^0\pi^\pm) = 0.64 \pm 0.11$, $Br(D^0 \to K^-\pi^+) = 0.024 \pm 0.004$, $Br(D^0 \to K^-\pi^+\pi^-\pi^+/Br(D^0 \to K^-\pi^+) = 2.17 \pm 0.28 \pm 0.23$.

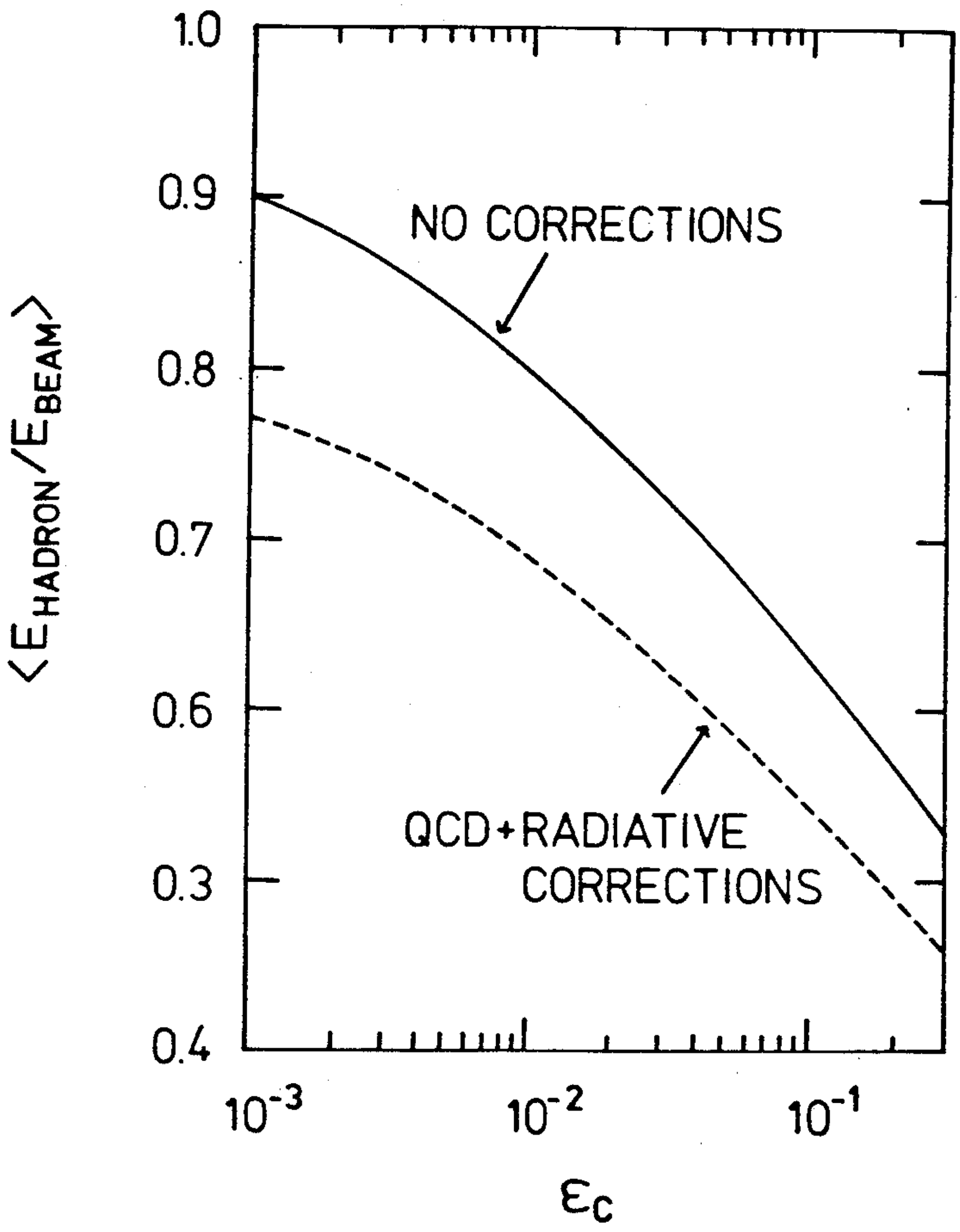


Fig. 4 Mean value of Peterson fragmentation function at 34 GeV. Solid curve is for $\varepsilon_c(x)$. Broken curve is for $\varepsilon_c(z)$.

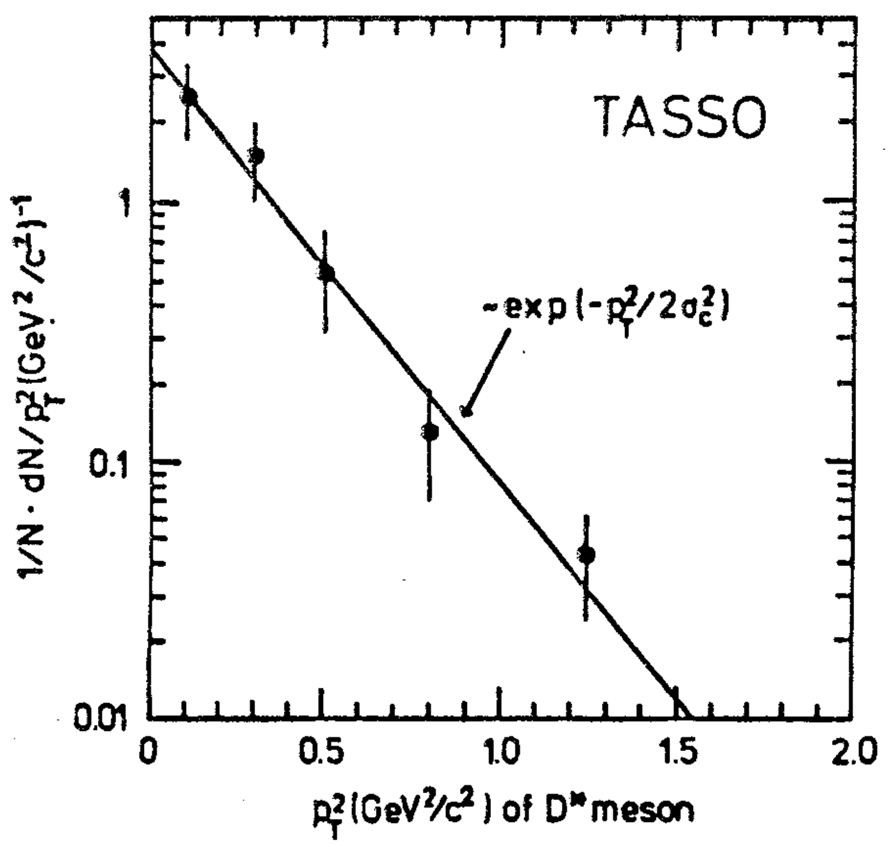


Fig. 5 p_T^2 for $D^{*\pm}$'s relative to the original charm quark direction.

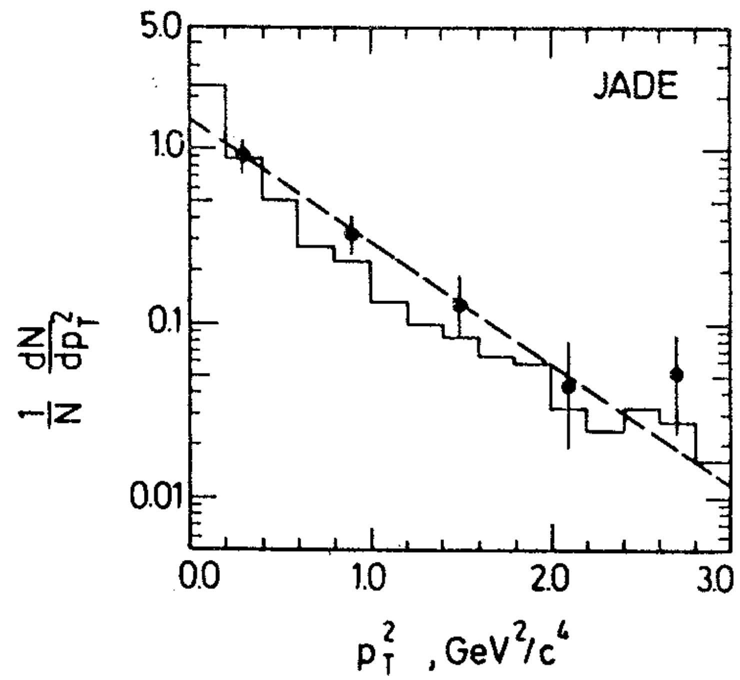
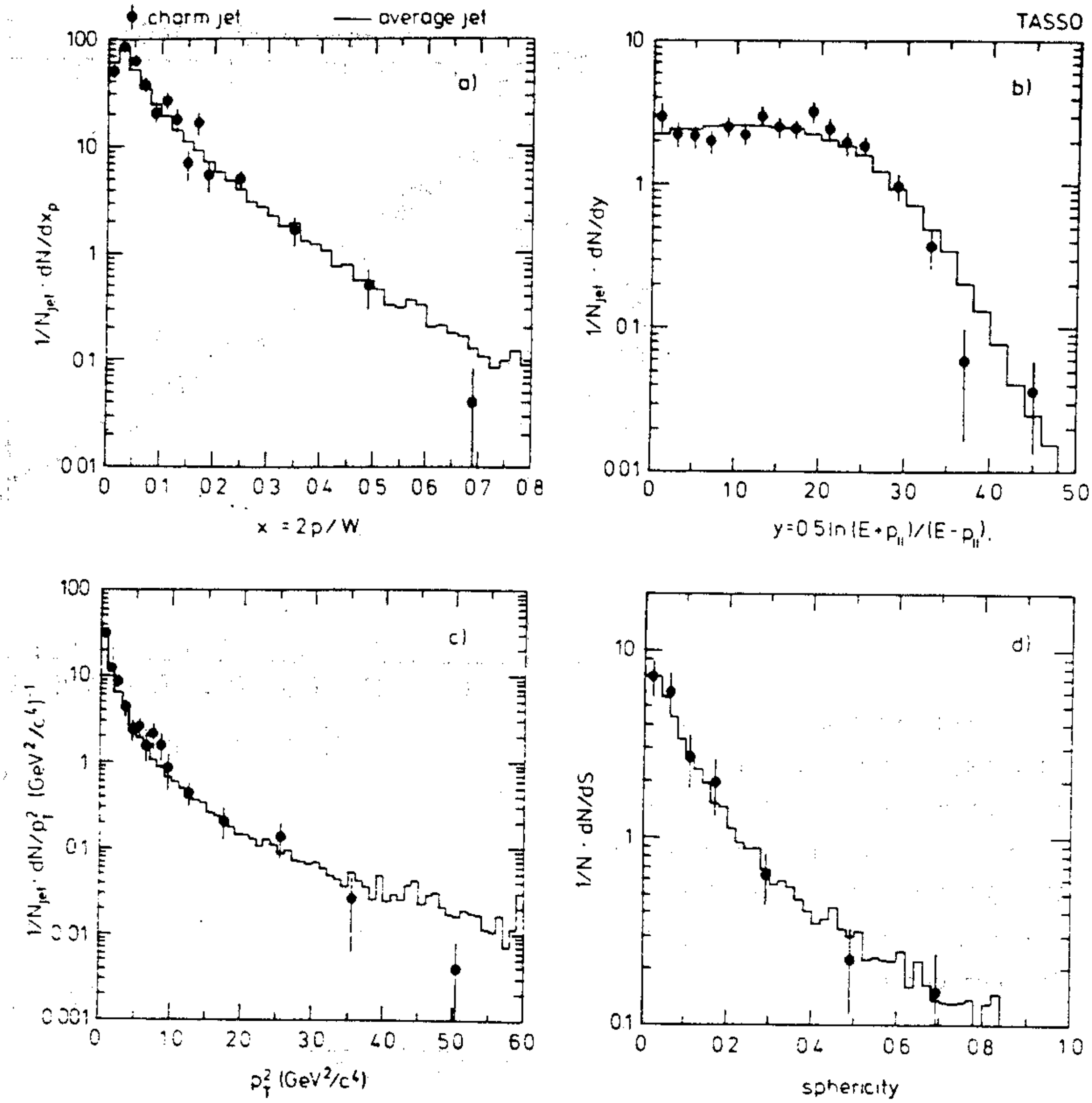


Fig. 6 p_T^2 with respect to sphericity axis for $D^{*\pm}$, $x > 0.4$ (circles), charged tracks, $x > 0.4$ (histogram)



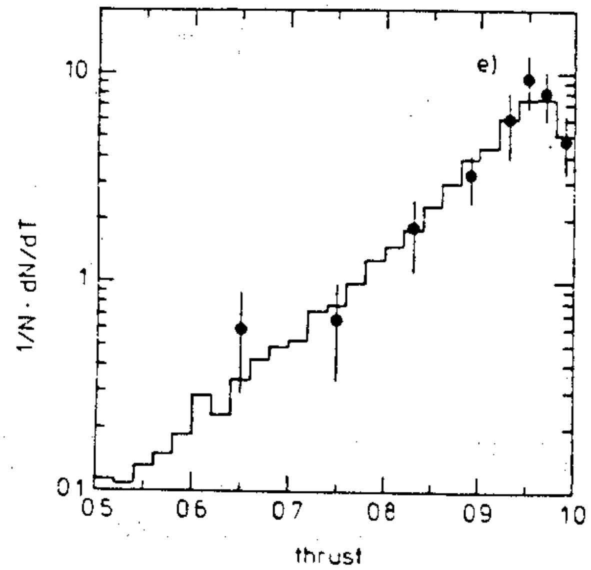


Fig. 7 Charged particle spectra of charm jets (circle) and average jets (histogram): scaled momentum, rapidity, transverse momentum, jet sphericity and jet thrust.

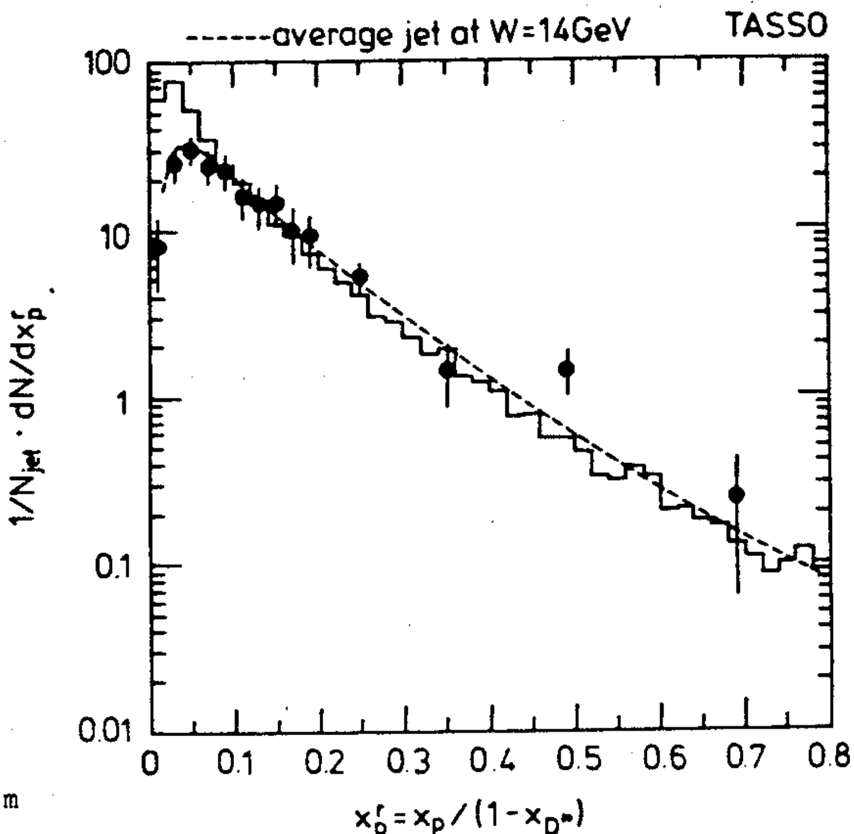
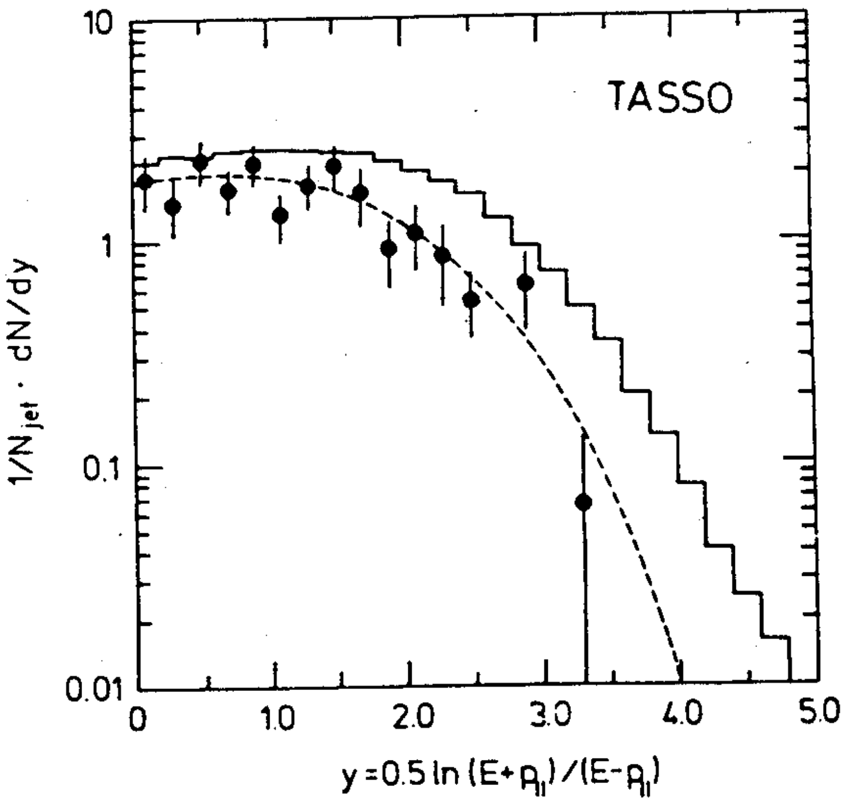


Fig. 8 Renormalized scaled momentum and rapidity for charged particles accompanying $D^{*\pm}$'s (circles), average jets at W = 34.4 GeV (histogram) and average jets at W = 14 GeV (broken curve).



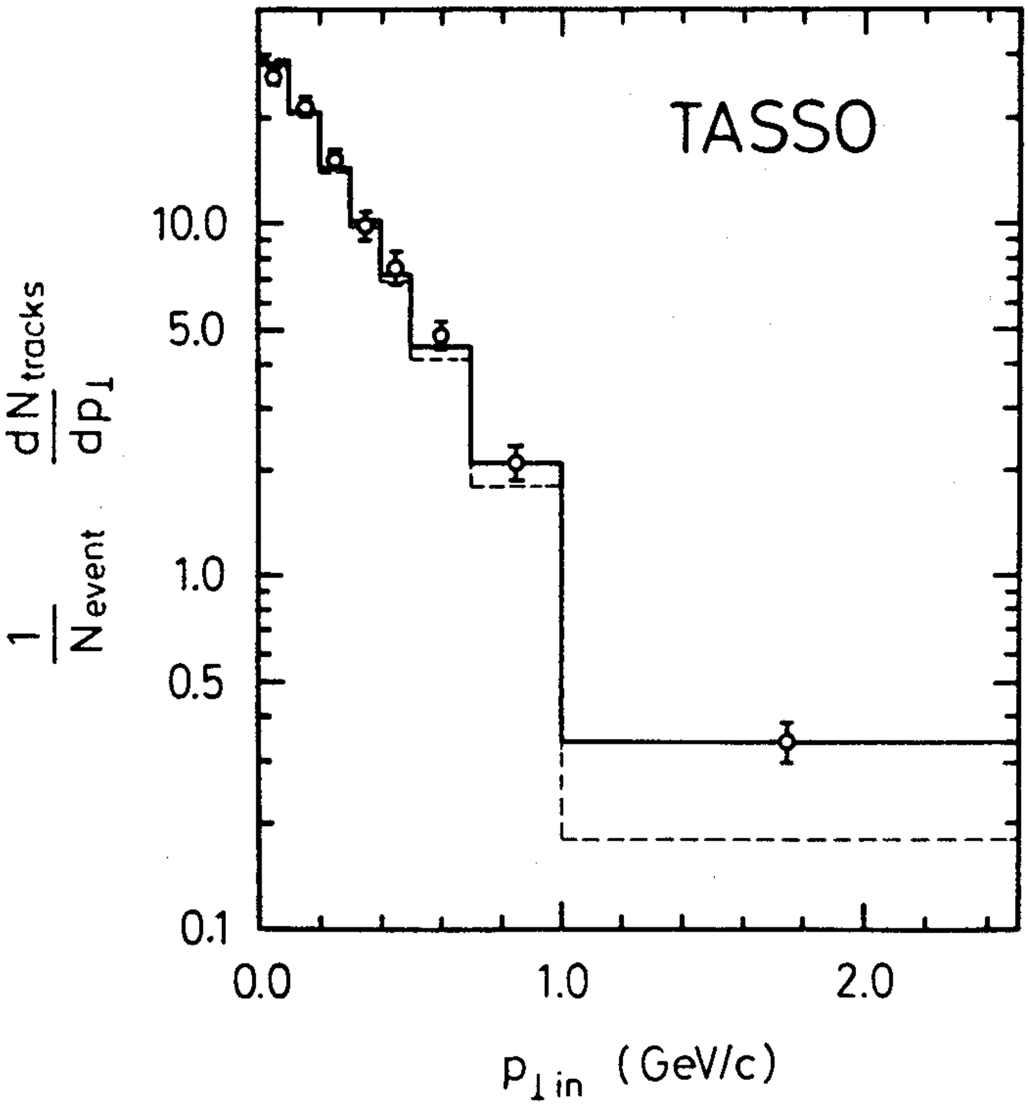


Fig. 9 Normalized transverse momentum with respect to the sphericity axis for $D^{*\pm}$ events (circles), fit with $\alpha_s^c = 0.153$ (solid histogram) and $\alpha_s^c = 0$ (broken histogram).

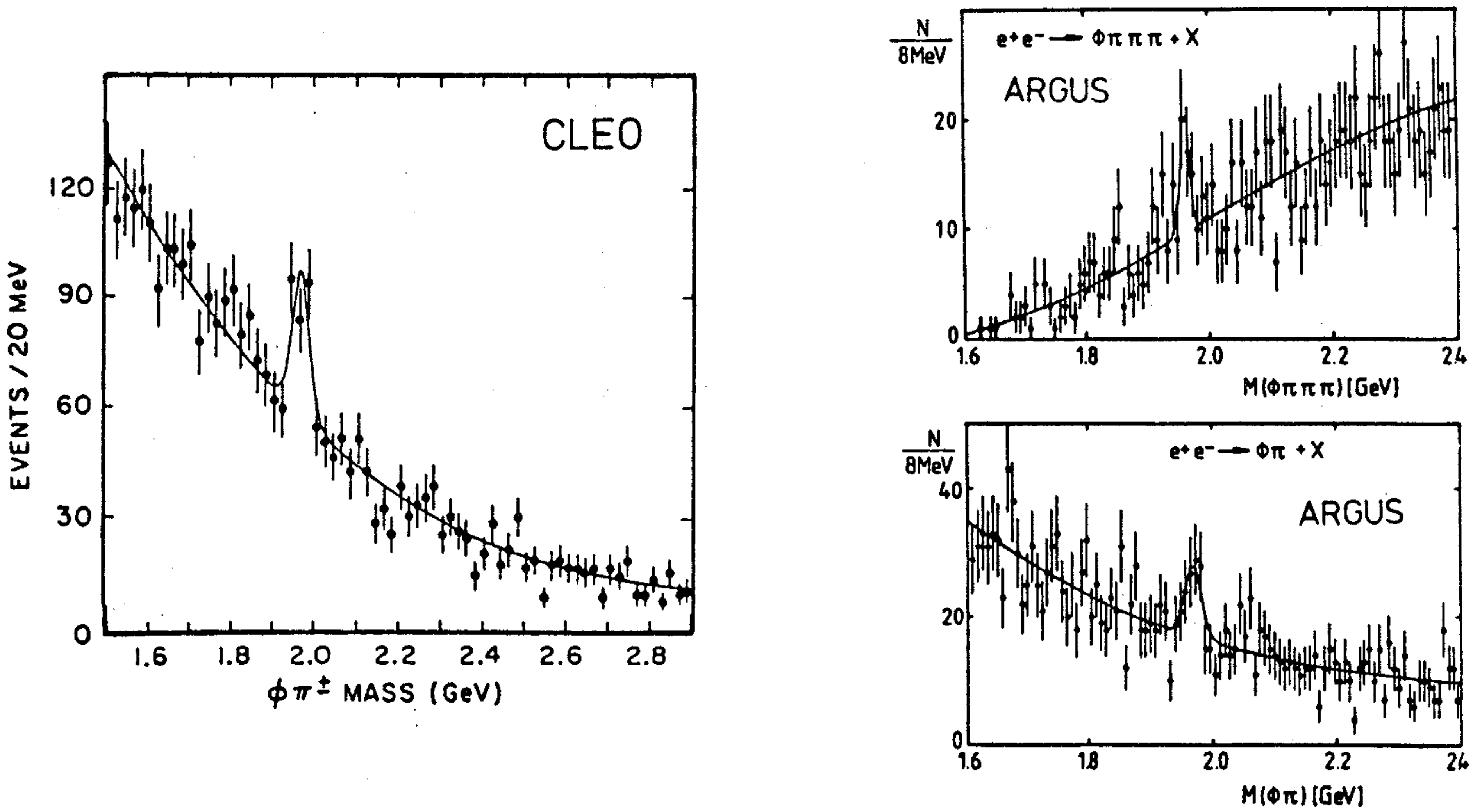


Fig. 10a F meson invariant mass plots of CLEO and ARGUS

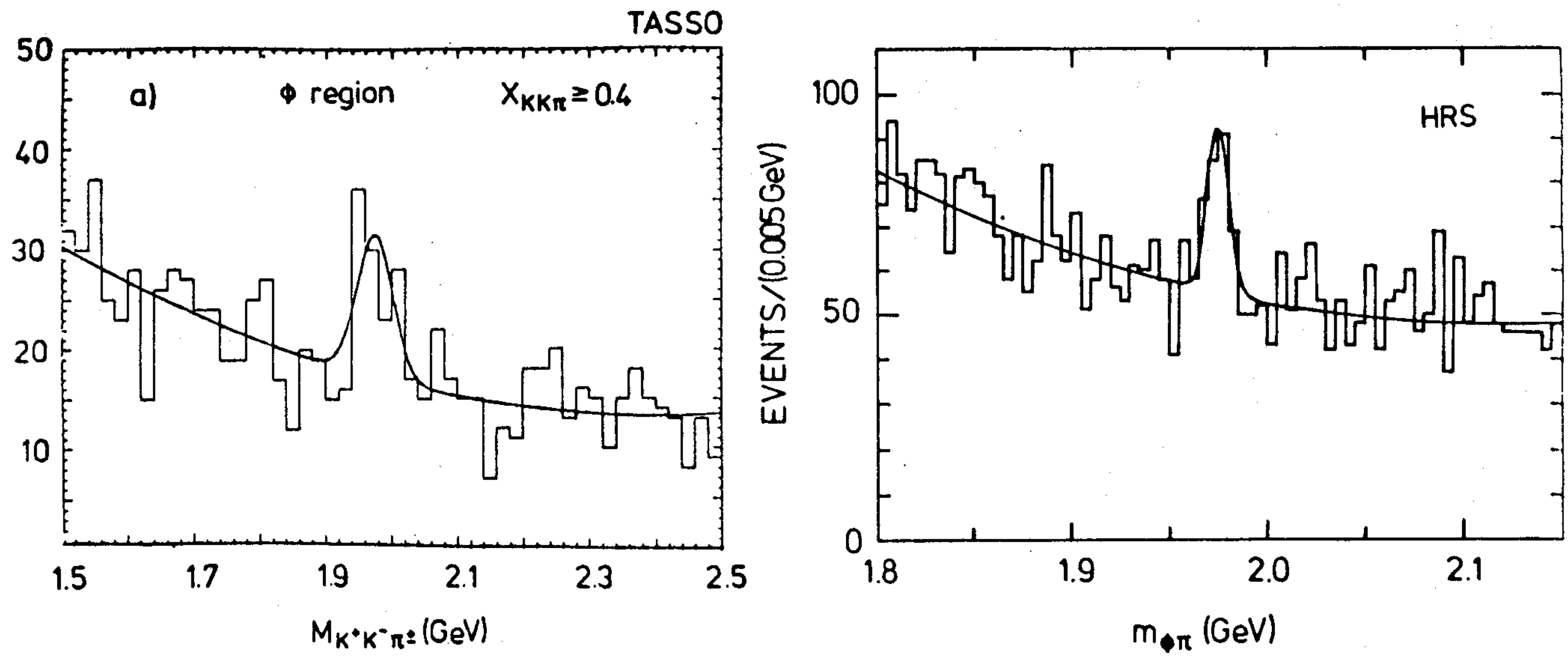


Fig. 10b F meson invariant mass plots of TASSO and HRS

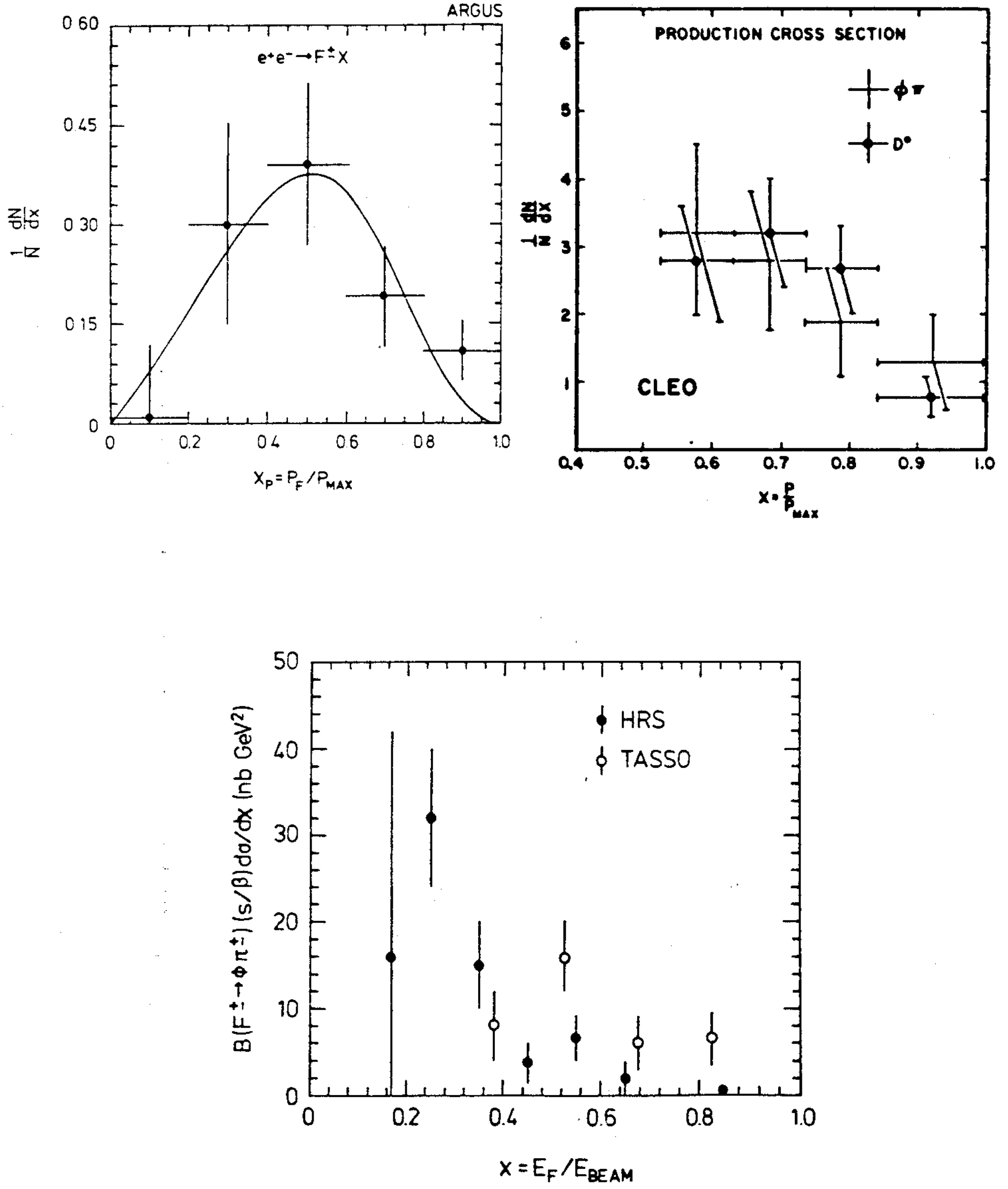


Fig. 11 F fragmentation function.

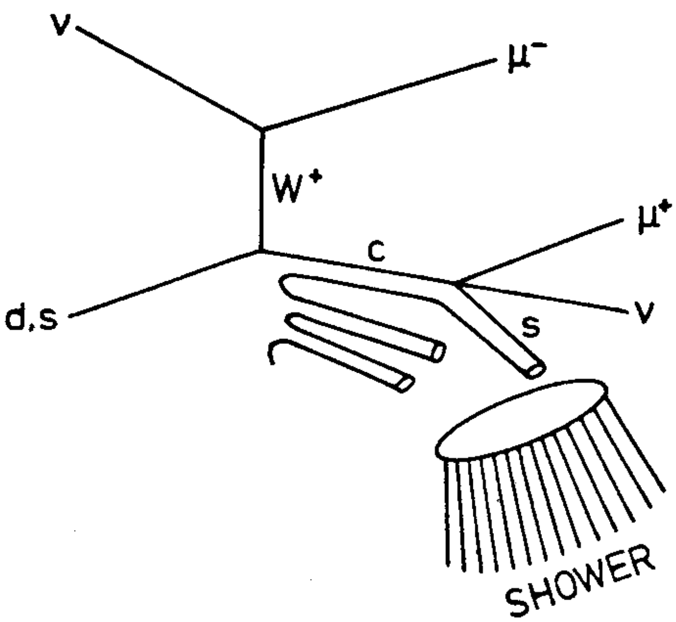


Fig. 12 Charm production by ν scattering followed by a semileptonic decay.

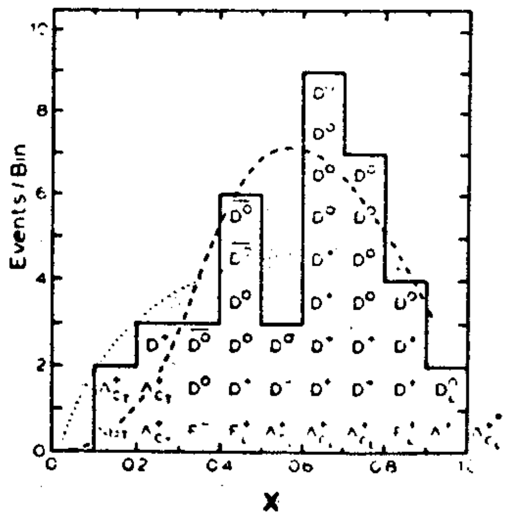


Fig. 13 E531's fragmentation distribution.

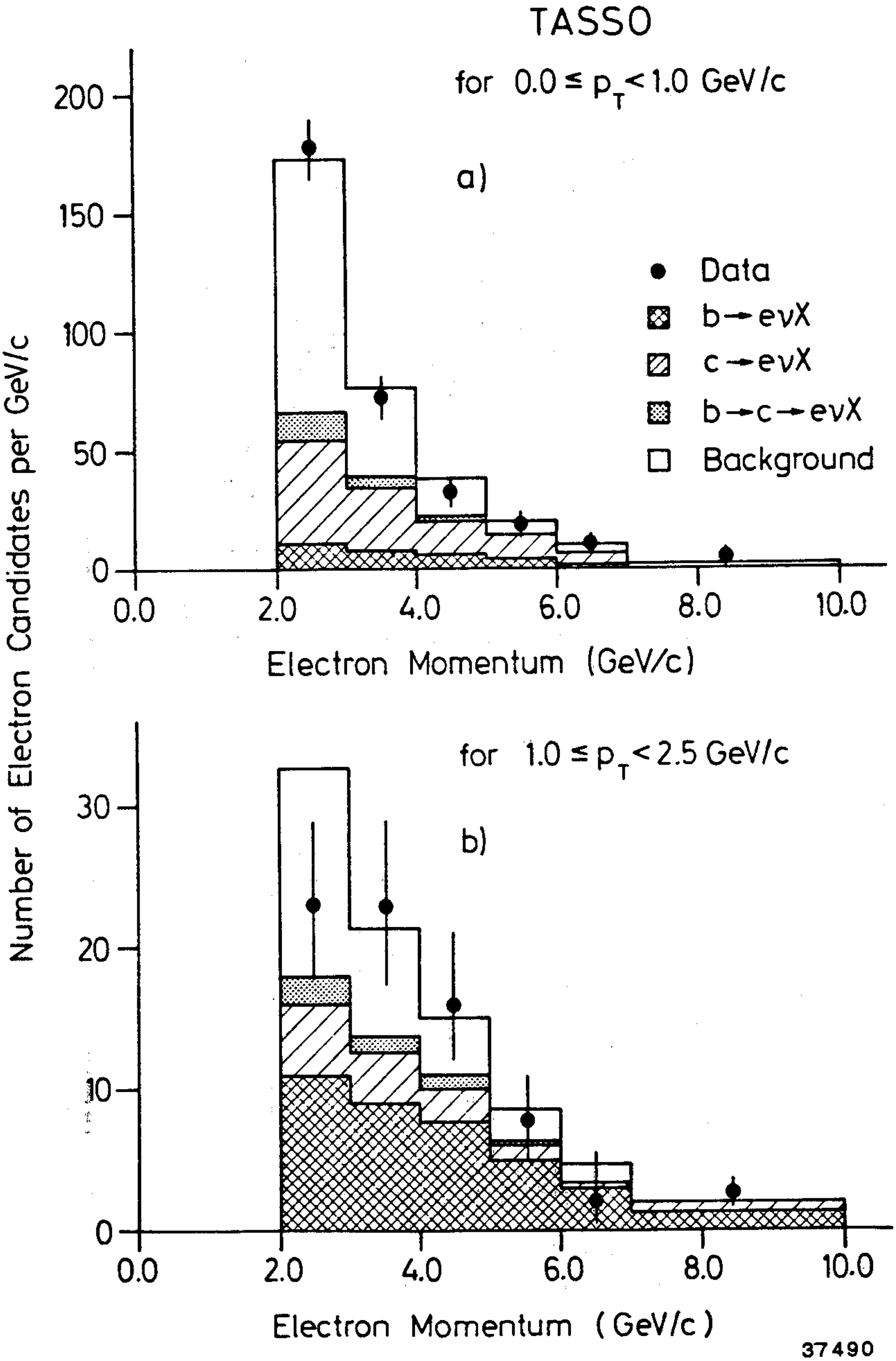


Fig. 14 Fit to momentum spectra of electron candidates. Circles are data points

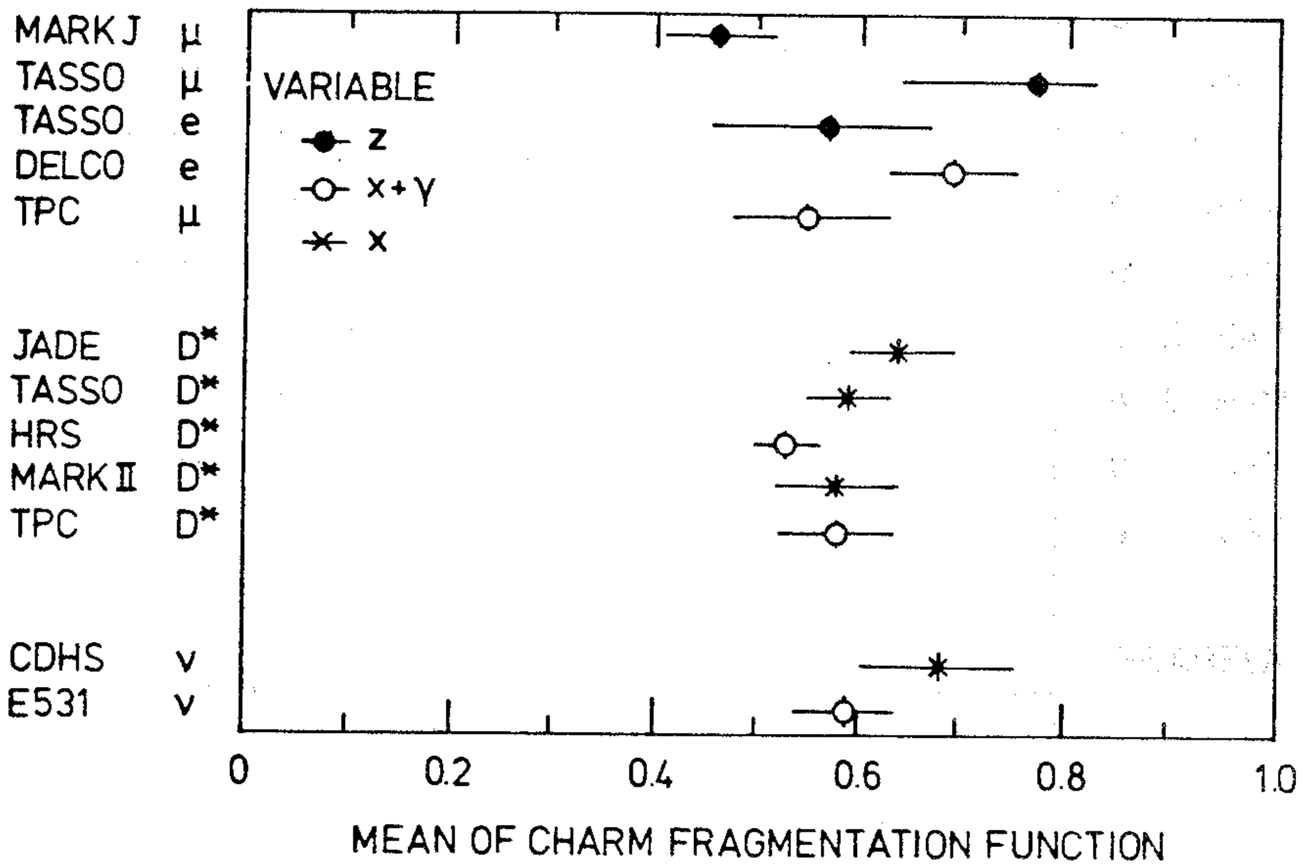


Fig. 15 Summary of charm fragmentation results.

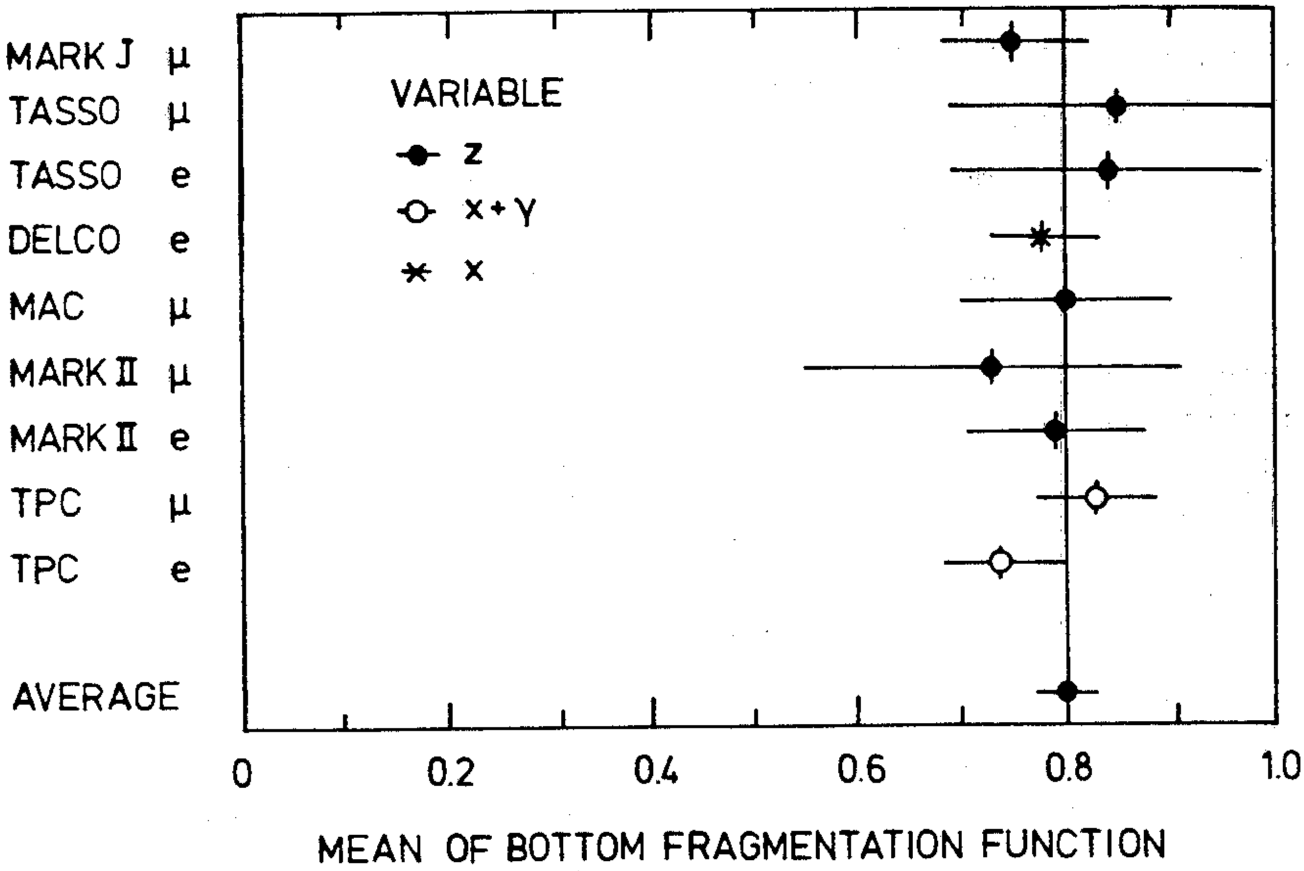


Fig. 16 Summary of bottom fragmentation results.
The solid line is the average of all data.

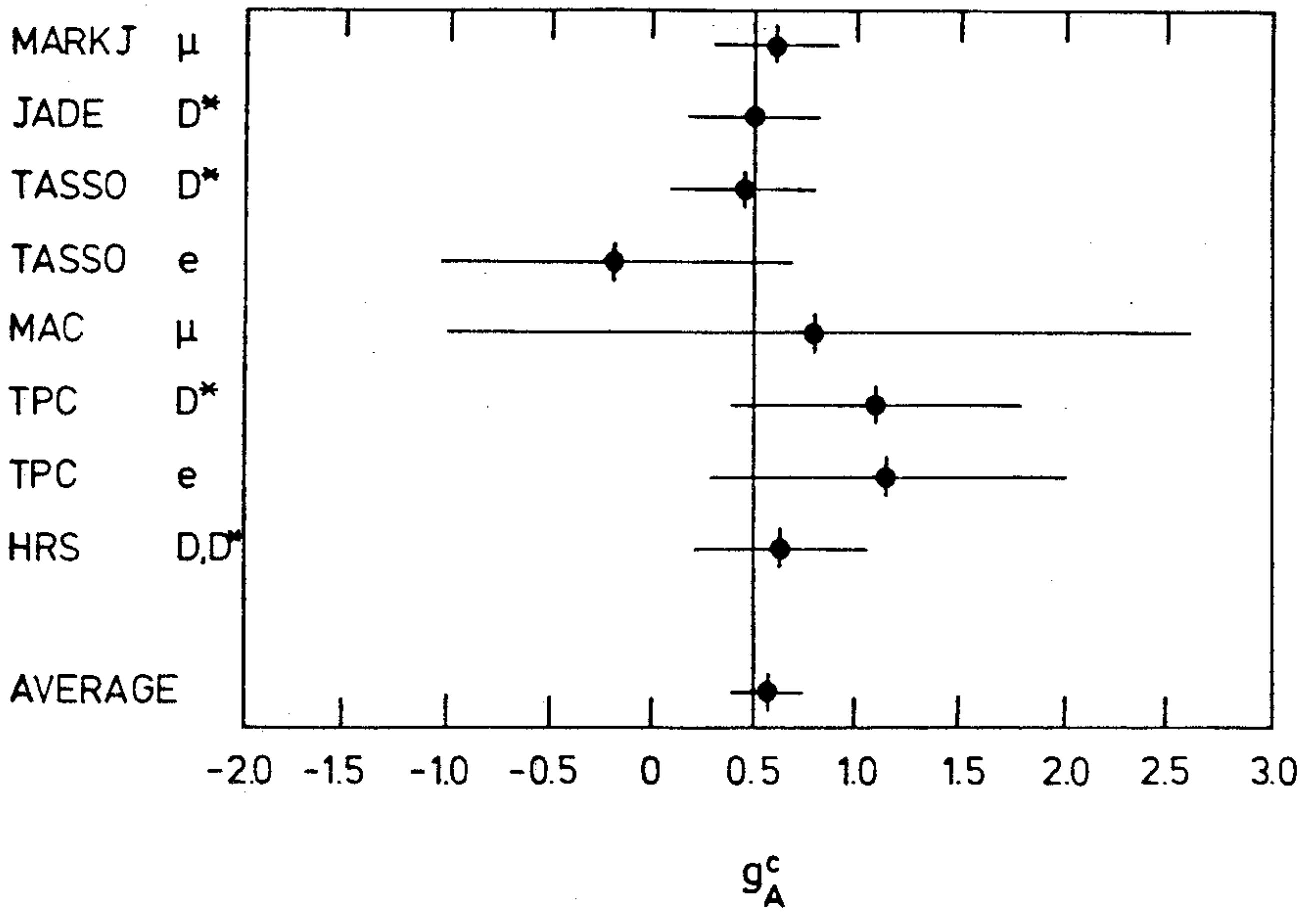


Fig. 17 Charm weak axial vector coupling constant. The line shows the prediction of the standard model.

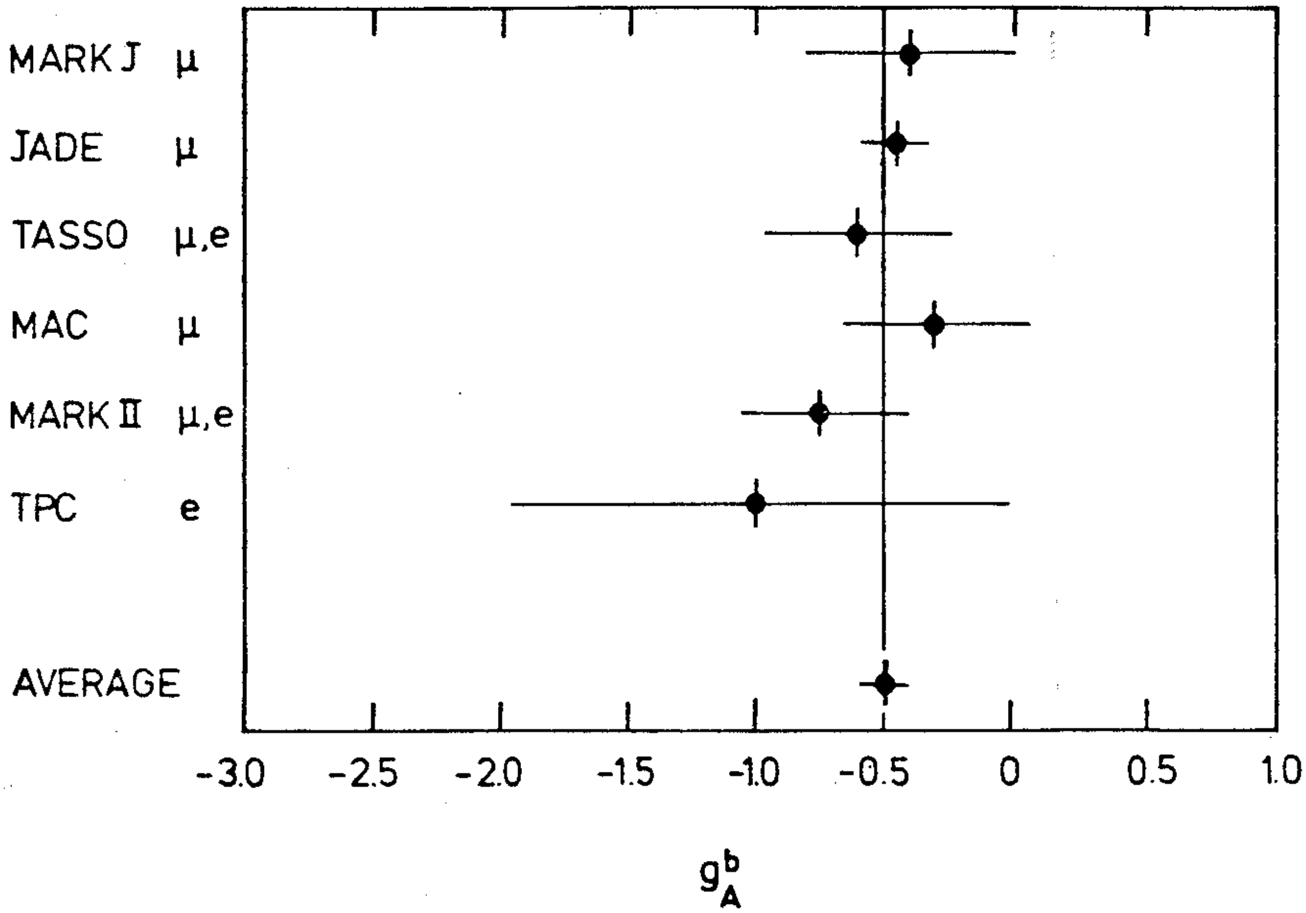


Fig. 18 Bottom weak axial vector coupling constant. The line shows the prediction of the standard model.