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New Hadronic Degree of Freedom, e^+e^- Annihilation and Deep Inelastic Scattering

by

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2 HAMBURG 52 · NOTKESTIEG 1

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Abstract:

Conjecturing "new duality" for e^+e^- into hadrons of a new degree of freedom, we show that presently known information on the particles at 3.105 and 3.7 GeV is compatible with $R \cong 4$. Scaling violations expected in deep inelastic scattering are related to the properties of $\psi(3105)$.

In a recent paper[1] it has been attempted to quantitatively analyze what to expect in deep inelastic scattering as a reflection of the approximate constancy of e^+e^- annihilation into hadrons[2] from about 3.5 to 5 GeV c.m. energy. Positive scaling violations, approximately linear in q^2, have been predicted[1] to show up in deep inelastic electron (muon) scattering in the large ω' diffraction region. First indications for such an effect of roughly the magnitude expected have been reported as a result[3] from the FNAL muon beam experiment. From the quantitative estimate of scaling violations to be expected in deep inelastic scattering, it has also been conjectured[1] that the present trend of an approximately constant behaviour of $\sigma(e^+e^- \to \text{hadrons}) \equiv \sigma_h$ should change rather soon beyond the presently explored energy range. A linear rise of $R \equiv \sigma_h/\sigma_{\mu^+\mu^-}$ beyond c.m. energies $\sqrt{s}$ of about $\sqrt{s} \sim 6$ or 7 GeV would seem to become incompatible with ep scattering data, even though scaling in the large ω' diffraction region has not been well tested due to obvious kinematical constraints.

The very recent discovery of the new particle J(3105), or ψ(3105), of width $\Gamma < 1$ MeV by the MIT Brookhaven group in p Be scattering[4] and by the SLAC-LBL collaboration in e^+e^- annihilation[5,*1)], seems to provide important insight into what is actually happening in the energy range above 3 GeV and may allow us to attempt drawing a more complete physical picture of e^+e^- annihilation and of its interrelation with deep inelastic scattering. As will be discussed subsequently, by relating the asymptotic behaviour of R to the properties of the new particle, scaling violations at large ω' may in fact be quantitatively predicted from the properties of ψ(3105).

Due to the small width of ψ(3105) into hadrons, an interpretation in terms of a new hadronic degree of freedom, like e.g. colour or hidden charm, $\psi(3105) \equiv \phi_c = c\bar{c}$, where c is a fourth (charmed) quark, seems appealing[*2)]. A small hadronic width of the new particle then appears natural, as the production threshold for e.g. charm anticharm pairs should lie[9] substantially above 3.1 GeV. We do not enter a discussion here on why the width[*3)] of the observed new particle even for an interpretation in terms of a new degree of freedom seems to be extraordinarily small, but rather persue the empirical consequences of the above conjecture as regards the value of R and as regards deep inelastic scattering.

With the mentioned interpretation of ψ(3105) as containing a new hadronic degree of freedom, it seems natural to postulate "new duality"[10,11] between scaling behaviour of e^+e^- annihilation into new hadronic states and the production cross section of the corresponding lowest lying vector meson, in the present case conjectured to be the $\psi(3105)$. We thus assume that e^+e^- annihilation behaves as $1/s$ as deduced from dimensional analysis[12], the scale being set by the prominent low lying resonances separately for each kind of hadronic matter coupled to the photon.

For the case of the $\psi(3105)$, let us thus first of all form the average of the production cross section into hadrons

$$\sigma^{average}_{e^+e^-\to\psi\to h} \equiv \frac{1}{\Delta m^2}\int_{m_\psi^2-\frac{\Delta m^2}{2}}^{m_\psi^2+\frac{\Delta m^2}{2}} \sigma_{e^+e^-\to\psi\to h}(s)\,ds \qquad (1)$$

over the mass interval Δm^2 to be fixed in magnitude later on. Inserting a Breit Wigner formula on the right hand side of (1), we obtain

$$\sigma^{average}_{e^+e^-\to\psi\to h} = \frac{(\alpha\pi)^2}{(\gamma_\psi^2/4\pi)}\,\frac{1}{\Delta m^2}\,, \qquad (2)$$

where $\gamma_\psi^2/4\pi$ is the photon $\psi(3105)$ coupling, related to the leptonic width by $\Gamma^{(\psi)}_{e^+e^-} = \alpha^2\pi m_\psi/3\gamma_\psi^2$. With scaling for $\sigma_{e^+e^-\to h}(s)\sim 1/s$ and the duality hypothesis that the low lying vector mesons, in our case the $\psi(3105)$, set the scale for the asymptotic magnitude of e^+e^- annihilation, we obtain for that part of R, which is dual to ψ

$$R_\psi = \sigma^{average}_{e^+e^-\to\psi\to h}\Big/\sigma_{\mu^+\mu^-}(s=m_\psi^2) = \frac{3\pi}{4}\,\frac{1}{(\gamma_\psi^2/4\pi)}\,\frac{m_\psi^2}{\Delta m_\psi^2}\,. \qquad (3)$$

Including the ρ^0, ω, ϕ pieces, the total value of R is given by[+4)]

$$R = \sum_{\rho^0,\omega,\phi,\psi} R_V = \frac{3\pi}{4}\sum_{\rho^0,\omega,\phi,\psi}\frac{1}{(\gamma_V^2/4\pi)}\,\frac{m_V^2}{\Delta m_V^2}\,\Theta\left(s-\left(m_V^2-\frac{\Delta m_V^2}{2}\right)\right). \qquad (4)$$

With the 9 : 1 : 2 ratio of the photon to ρ^0, ω, ϕ couplings, (4) simplifies to

$$R = \frac{\pi}{(\gamma_\rho^2/4\pi)}\,\frac{m_\rho^2}{\Delta m_\rho^2}\,\Theta\left(s-\left(m_\rho^2-\frac{\Delta m_\rho^2}{2}\right)\right) + \frac{3\pi}{4}\,\frac{1}{(\gamma_\psi^2/4\pi)}\,\frac{m_\psi^2}{\Delta m_\psi^2}\,\Theta\left(s-\left(m_\psi^2-\frac{\Delta m_\psi^2}{2}\right)\right). \qquad (5)$$

Thus ψ sets the scale for production of hadronic matter with the new hadronic degree of freedom (which for example would appear as $C\bar{C}$ production above production threshold), just as ρ^0, ω, ϕ set the scale for production of ordinary hadrons in e^+e^- annihilation. Let us add the remark that there is in fact no compelling reason for the sum in (4), (5) to stop exactly with $\psi(3105)$ and one may speculate on further surprises.

The numerical predictions obtained from (5) depend sensitively, of course, on the magnitude of Δm^2 chosen and the final experimental values for $\Gamma^{(\psi)}_{e^+e^-}$. For the case of a Veneziano type spectrum of levels, e.g. ψ, ψ' etc., Δm^2 is just identical to the level spacing. Fortunately enough we know from the Brookhaven experiment[4] that there are no indications for further sharp resonances coupled to e^+e^- below 3.5 GeV. Most recent information[14] from SPEAR indicates, however, the presence of a second narrow peak ($\Gamma \lesssim 3$ MeV) at 3.7 ± 0.02 GeV, and thus it may seem appropriate to chose Δm^2 accordingly to be $\Delta m^2 = (3.7^2 - 3.1^2)\ \mathrm{GeV}^2 = 4.1\ \mathrm{GeV}^2$. As for the leptonic width, $\Gamma^{(\psi)}_{e^+e^-}$, simple estimates on the basis of the available data[5] indicate[6] $\Gamma^{(\psi)}_{e^+e^-} \simeq 3$ keV, yielding $\gamma_\psi^2/4\pi \cong 4.6$ (to be compared with e.g. the ρ^0 coupling $\gamma_\rho^2/4\pi = 0.64 \pm 0.06$). With the usual $\Delta m_\rho^2 = 2\, m_\rho^2$ and $\Delta m_\psi^2 = 4.1\ \mathrm{GeV}^2$ one then obtains as an estimate for $R(s \gtrsim 15\ \mathrm{GeV}^2)$ a value of $R = R_{\rho,\omega,\phi} + R_\psi \cong 2.5 + 1.2 = 3.7$. A comparison with the available data on e^+e^- annihilation is presented in fig. 1. Should the object seen[13] at 3.7 ± 0.02 GeV really turn out to be a recurrence of $\psi(3105)$, from (3), the relative widths into leptons would be approximately determined by the respective mass ratios, i.e.
$\Gamma_{e^+e^-}(\psi'(3.7)) \simeq \Gamma_{e^+e^-}(\psi(3.1))(m_\psi/m_{\psi'}) \simeq 0.8\, \Gamma^{(\psi)}_{e^+e^-}$.

Let us now turn to deep inelastic scattering. The previous estimate[1] of the q^2 dependence of the proton structure function νW_2 for large ω' ($\equiv W^2/q^2 + 1$) had been based on simply fitting vector state photon couplings such as to yield approximate constancy of e^+e^- annihilation from about 3.3 to 5 GeV. Now, with more physical understanding in sight as regards the e^+e^- annihilation process, and with the analysis just presented, it seems appropriate to take into account e^+e^- annihilation beyond 3 GeV by simply incorporating the new threshold appearing in (5) into the prediction for νW_2 in the diffraction region. The prediction for νW_2 is then directly related to the properties of $\psi(3105)$.

Thus we simply have to include the piece of e^+e^- annihilation, which is dual to $\psi(3105)$, in the Generalized Vector Dominance[*5)] framework. Using the formula previously derived[14], the expression for the transverse part of the photon absorption cross section σ_T is given by (large ω')

$$\sigma_T(W, q^2) = \sum_V \frac{\overline{m}_V^2}{(q^2 + \overline{m}_V^2)}\, \overline{r}_V\, \sigma_{\gamma p}, \tag{6}$$

where the summation now extends not only over $\rho^0, \omega, \phi,$ but includes the new state $\psi(3105)$ as well. The constant

$$\overline{r}_V = \frac{1}{\sigma_{\gamma p}} \frac{\alpha \pi}{\gamma_V^2}\, \sigma_{Vp}\,(1 + \delta) \tag{7}$$

denotes the contribution to the total photon absorption cross section, which is induced by the vector meson $V(=\rho^0,\omega,\phi,\psi)$ and its higher mass partners. The small and only free parameter δ ($\cong 0.2$) in (7) is related[14] to the contribution from masses larger than m_V and is determined from the correct normalization of σ_T to photoproduction at $q^2 = 0$, which normalization implies

$$\sum_{\rho^0,\omega,\phi,\psi} \bar{r}_V = 1 . \tag{8}$$

The masses $\bar{m}_V$ are slightly smaller than the corresponding vector meson masses and are given by $\bar{m}_V^2 = ((1 + 2\delta)/(2 + 2\delta))\, m_V^2$.

Numerically, from ρ^0,ω,ϕ photoproduction, as is well known[1], one arrives at $\sum_{\rho^0\omega,\phi} (\alpha\pi/\gamma_V^2)\,\sigma_{Vp} \cong 0.68\, \sigma_{\gamma p}$. From the above mentioned estimate, $\gamma_\psi^2/4\pi \cong 4.6$, and from $\sigma_{\psi p} \cong \sigma_{\phi p}$ (as e. g. for $\psi = c\bar{c}$ might be suggested by the additive quark model), we obtain $(\alpha\pi/\gamma_\psi^2)\sigma_{\psi p} \cong 0.04$, yielding $\delta \cong 0.23$ from (8) and thus $\sum_{\rho^0,\omega,\phi} \bar{r}_V \cong 0.95$ and $\bar{r}_\psi \cong 0.05$, and finally $\bar{m}_V^2 \cong 0.6\, m_V^2$ *6). All quantities have now been fixed in (6) and the implications of (6) for scaling of the transverse part of $\nu W_2 \cong (q^2/4\pi^2\alpha)\sigma_T$(large ω') may be deduced.

From ($\omega' \gtrsim 10$)

$$\nu W_{2T} = \frac{1}{4\pi^2\alpha}\, \frac{q^2 \bar{m}_\rho^2}{(q^2+\bar{m}_\rho^2)} \Big(\sum_{\rho^0,\omega,\phi} \bar{r}_V\Big) \sigma_{\gamma p} \left(1 + \frac{\bar{m}_\psi^2\, \bar{r}_\psi}{\bar{m}_\rho^2 \sum_{\rho^0,\omega,\phi} \bar{r}_V}\, \frac{(q^2 + \bar{m}_\rho^2)}{(q^2 + \bar{m}_\psi^2)}\right), \tag{9}$$

a precocious scaling limit is reached for $q^2 \gtrsim 2\, m_\rho^2$, if the term due to $\psi(3105)$ is missing. Inclusion of the new term yields an approximately linear violation of precocity of scaling, until the true scaling limit of

$$\nu W_{2T}(\omega' \gg 10, q^2 \to \infty) \cong \bar{m}_\rho^2 \sigma_{\gamma p} \left(1 + \frac{m_\psi^2}{m_\rho^2}\, \bar{r}_\psi\right), \tag{10}$$

which is equal to $\nu W_{2T}(\omega' \gg 10, q^2 \to \infty) \cong 0.56$ for the above mentioned numerical values of the parameters, is finally reached for $q^2 \gg m_\psi^2$ only (see fig. 2). It is quite clear that experimentally verifying the approach to scaling (e.g. $\omega' \cong 30$, $q^2 \cong 30$) requires electron proton colliding beam energies. From the discussion given above, one should keep in mind that the numerical value of the true scaling limit is sensitively dependent upon $\gamma_\psi^2/4\pi$ which coupling is of course badly known at the moment, and on $\sigma_{\psi p}$ to be determined in ψ photoproduction.

Let us add a remark on νW_2 for small ω', where scaling has been very well tested[15] up to very large values of $q^2 \gtrsim 20$ GeV. For the case of e.g. $\psi(3105) \equiv \phi_c = c\bar{c}$, no scaling violations due to the new hadronic degree of freedom should show up for values of $\omega' \lesssim 5$, for which Pomeron exchange is strongly suppressed; as there is no c constituent quark in the proton, one cannot draw a duality diagram containing c, and the additional photon hadron interaction is irrelevant. The situation would then in rough approximation look like*7) fig. 3. The situation is not as simple, if the new hadronic degree of freedom is associated with e.g. colour. In this case substantial scaling violations have been predicted[16] also for small ω', which do not seem to be present in the data.

In summary, by supplementing the hypothesis that $\psi(3105)$ is a new vector meson indicating the existence of a new hadronic degree of freedom, with the "new duality" conjecture, we showed that present experimental information on the new particles is consistent with $R \cong 4$. Whether the coincidence with the value of R predicted[17] in the Han Nambu model is accidental will have to be resolved in the future. As regards deep inelastic scattering, we related breaking of scaling for large ω' to the properties of $\psi(3105)$. The mass, which sets the scale for the slow approach to the true scaling limit is then approximately equal to m_ψ. Due to our as yet very incomplete knowledge of the properties of the new particles, numerical estimates are likely to be subject to change in the near future. The hypothesis of the new particles setting the scale for production of new hadronic matter in e^+e^- annihilation, and the prediction of substantial scaling violations in deep inelastic scattering at large ω' may be likely, however, to stand the test of time.

Acknowledgement

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Footnotes

*1) The existence of $\psi(3105)$ has also been verified at DORIS (U. Timm and B. Wiik, private communication) and at ADONE (LNF-74/61(P)).

*2) Compare also R.P. Feynman, ref. 6. The hypothesis $\psi(3105) = \phi_c = c\bar{c}$ has been used in references 7 and 8.

*3) From the data[5] one estimates $\Gamma^{(\psi)}_{e^+e^-} \simeq 3$ keV and $\Gamma^{(\psi)} \simeq 80$ keV. See e.g. ref. 6.

*4) In a more sophisticated approach the Θ function in (4) should be smoothed out by an appropriate threshold factor.

*5) See ref. 1 for a recent review and a list of literature on GVD.

*6) Actually σ may depend on V. The factor 0.6 should thus be considered with some caution.

*7) V. Rittenberg has speculated on the possibility that the integral over νW_2 may rise compared to present values. (Private communication September 1974).

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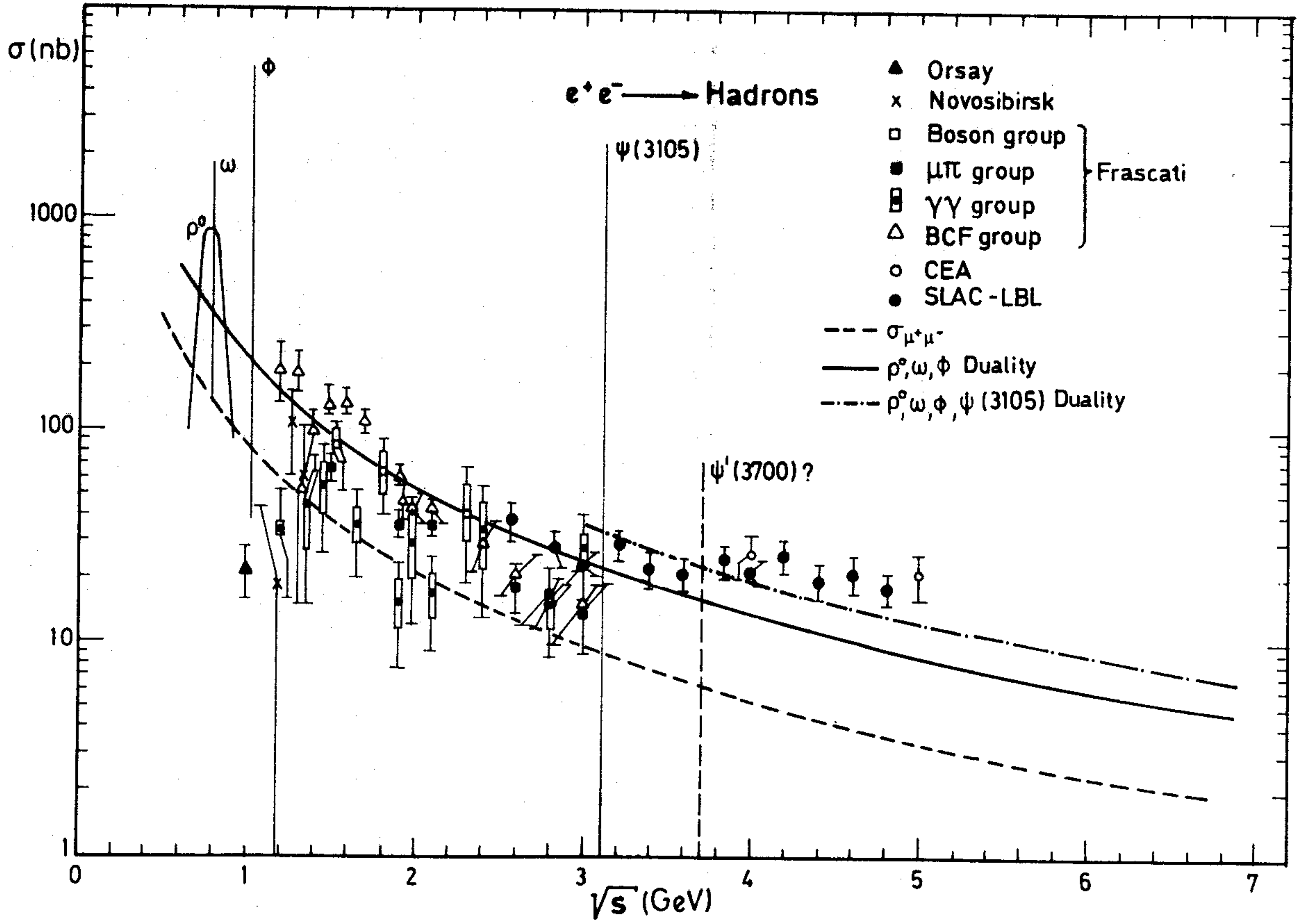
Figure Captions

Fig. 1 The cross section for $e^+e^- \rightarrow$ hadrons as a function of the c.m. energy, showing the prominent resonances setting the scale for the magnitude of the scaling cross section. (See ref. 1 for the list of references to the data).

Fig. 2 The transverse part of νW_2 as a function of q^2 at large ω' ($\omega' \gg 10, 30?$). Curve (a) shows the precocious approach to scaling corresponding to a smooth $1/s$ behaviour interpolating ρ^0, ω, ϕ. Curve (b) shows the effect of including the additional e^+e^- annihilation cross section beyond 3 GeV. (See ref. 1 for reference to data).

Fig. 3 Rough estimate of one possibility for the true scaling limit of νW_2. Compare text for details. (Data compilation taken from ref. 18).



σ (nb)
1000
100
10
1
0
1
2
3
4
5
6
7
√s (GeV)
e⁺e⁻ → Hadrons
ρ⁰
ω
Φ
ψ (3105)
ψ' (3700) ?
Orsay
Novosibirsk
Boson group
μπ group
γγ group
BCF group
Frascati
CEA
SLAC-LBL
σ μ⁺μ⁻
ρ⁰, ω, Φ Duality
ρ⁰, ω, Φ, ψ (3105) Duality

Fig. 1

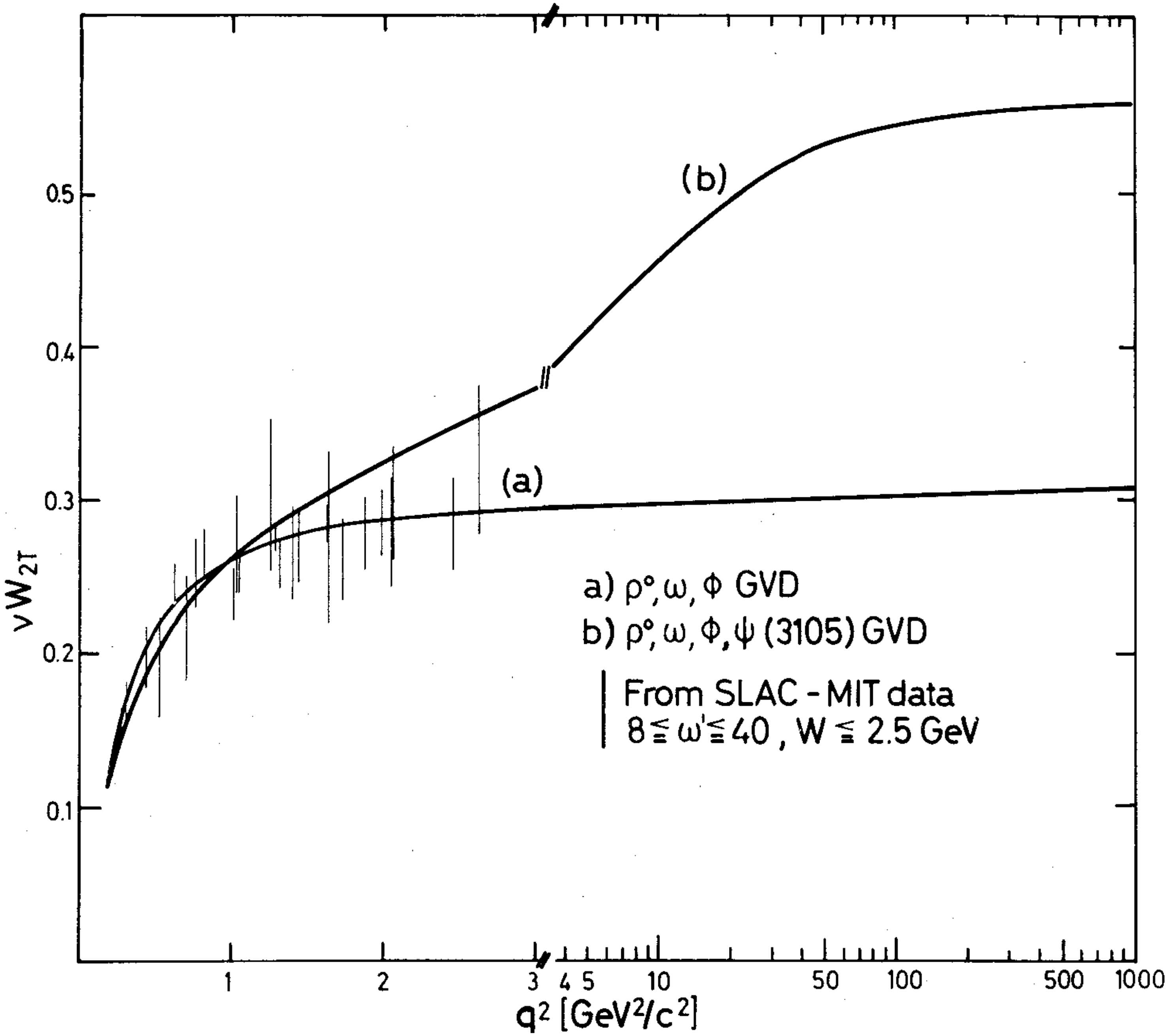
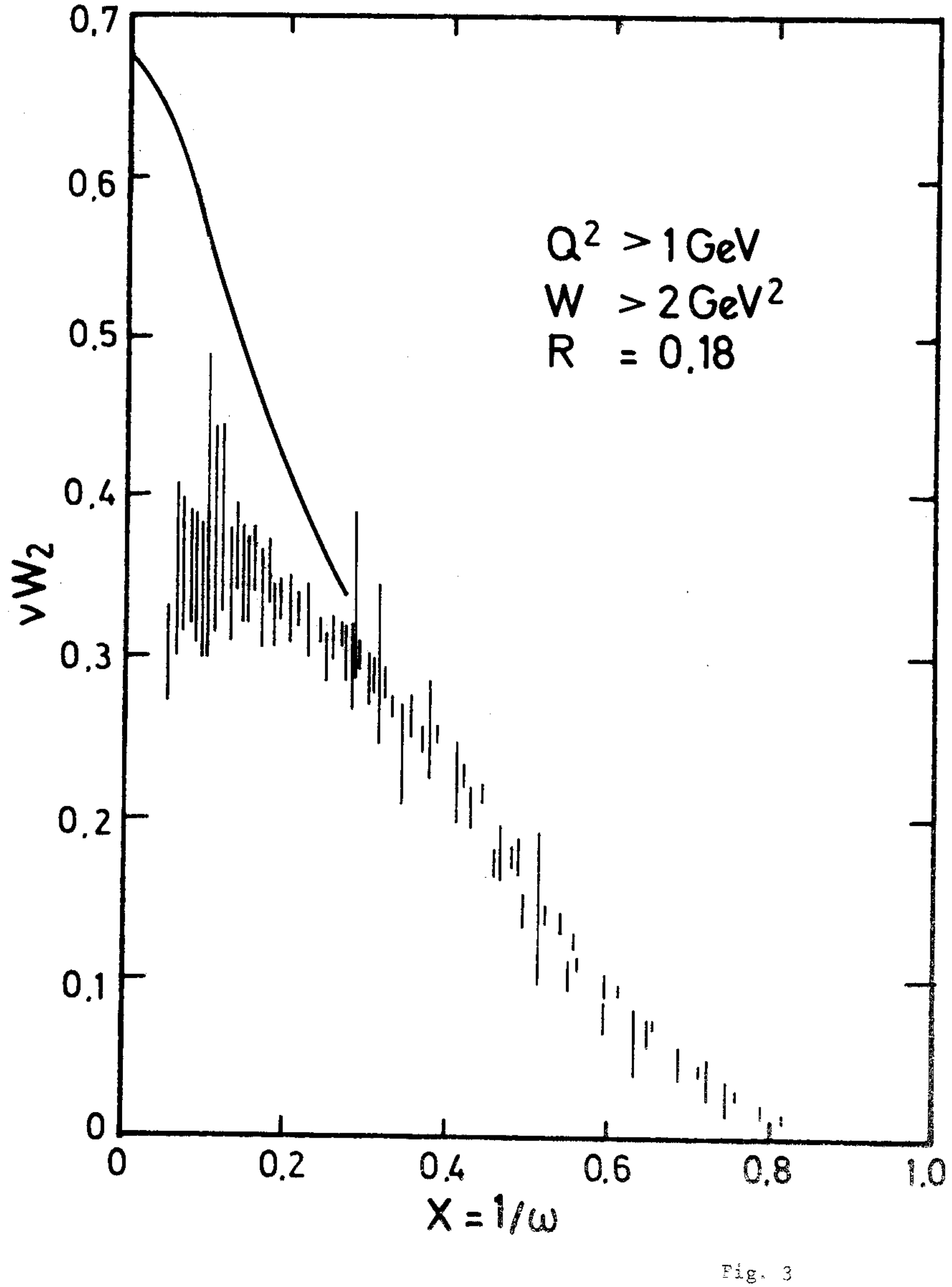

(b)
(a)
0.5
0.4
0.3
0.2
0.1
νW2T
a) ρ°, ω, Φ GVD
b) ρ°, ω, Φ, ψ (3105) GVD
From SLAC - MIT data
8 ≦ ω' ≦ 40 , W ≦ 2.5 GeV
1
2
3
4 5
10
50
100
500
1000
q² [GeV²/c²]

Fig. 2



0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
νW_2
$Q^2 > 1\,GeV$
$W > 2\,GeV^2$
$R = 0,18$
0
0,2
0,4
0,6
0,8
1,0
$X = 1/\omega$

Fig. 3