<u>prediction of factorization</u> :

fragmentation is indep of rest of event (i.e. cares only about momentum of quark)

def: $Z_i \equiv \dfrac{p_i}{P}$ ← individual hadron, ← quark jet $\quad (0 \le Z_i \le 1)$

fragmentation functions : $f_{q\to i}(z)$.

e.g. $f_{u\to\pi^+}(z)$ probability of u quark to produce π^+ of momentum fraction $z = \dfrac{p_{\pi^+}}{p_u}$

(note : indep of P_i, P separately (follows from factorization and dim'l analysis, no other scale available)

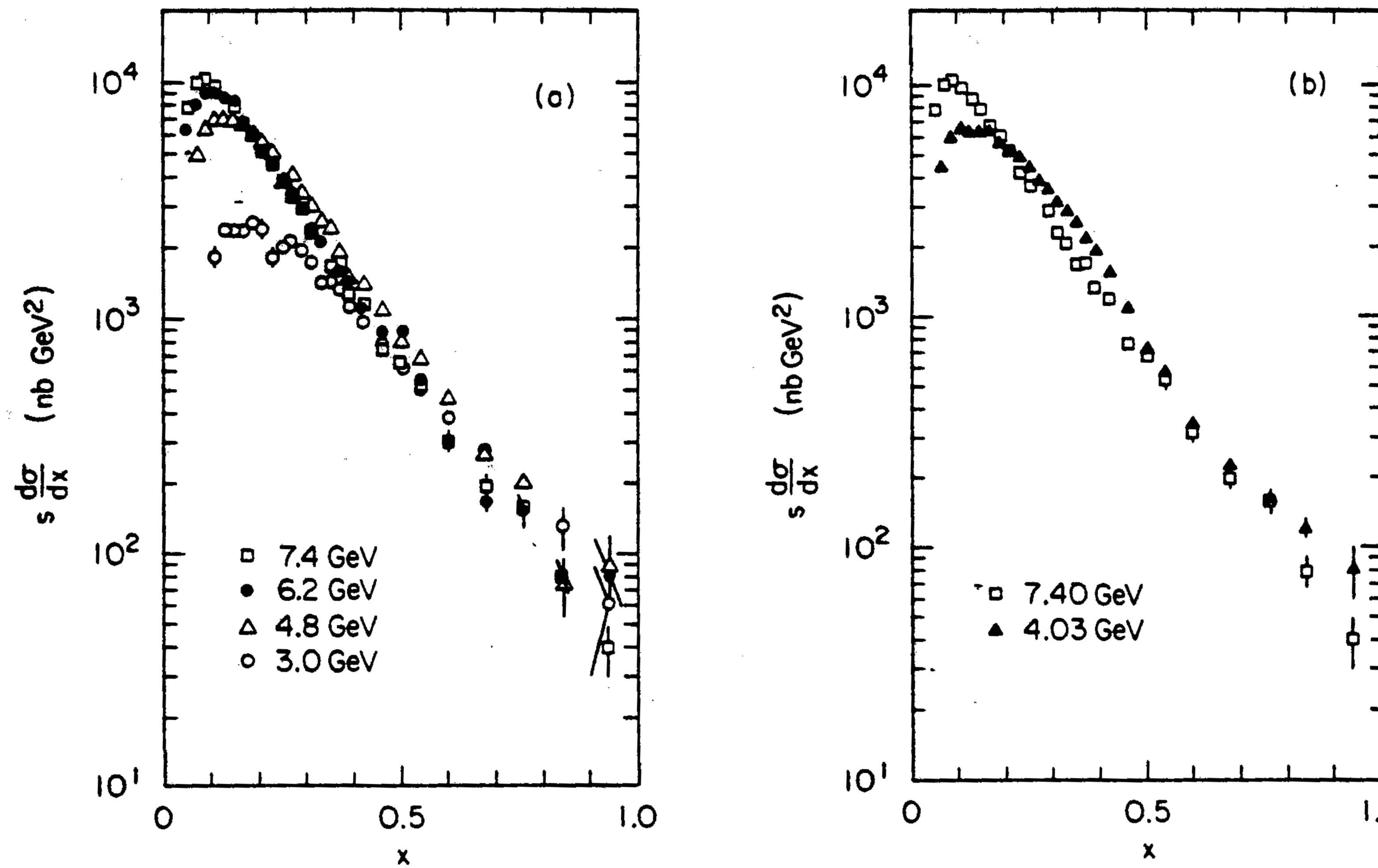
f are <u>universal</u> .

$\boxed{\text{PLOT Fig 12}}$

$$\underbrace{X = \frac{\hat{n}\cdot\vec{p}_\pi}{E_{CM}/2} \sim \frac{p_\pi}{P}}_{X\text{-axis}} = z \qquad \underset{E_{CM}^2}{s}\,\frac{d\sigma_\pi}{dx} \sim s\,\underbrace{\sigma_{q\bar{q}}}_{\text{const}} \cdot f_{q\to\pi}(x)$$

Fragmentation functions

J.L. Siegrist et al (Mark 1) Phys. Rev. D26, 969 (1980)

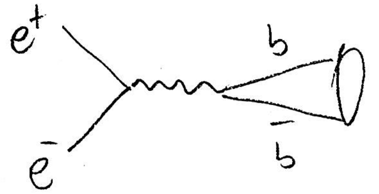


$$X = Z = \frac{\hat{n}\cdot\vec{P}_\pi}{(\frac{1}{2}E_{cm})}$$

$\hat{n}$ is the jet axis

bound states - spectroscopy

$\boxed{\text{PLOT 19}}$ $e^+e^- \to$ hadrons near $2m_b$

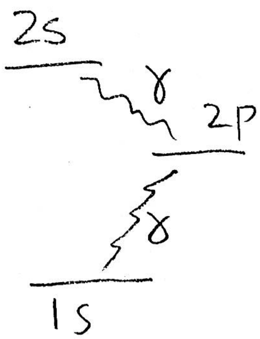


$b\bar{b}$ meson Υ

1s, 2s, 3s, 4s non-relativistic bound states

$r_\Upsilon \sim \alpha_s \frac{1}{m_b}$

$\Delta E_\Upsilon \sim \alpha_s^2 \frac{1}{m_b}$



spectroscopy to measure all energy levels

$\boxed{\text{PLOT 20}}$ $c\bar{c}$ E_γ continuum from $\pi^0 \to \gamma\gamma$ decays

spikes from "atomic" transitions

charmonium spectrum: Glashow - Lane

$\boxed{\text{PLOT 24}}$ $V(r)$ phenomenological models.

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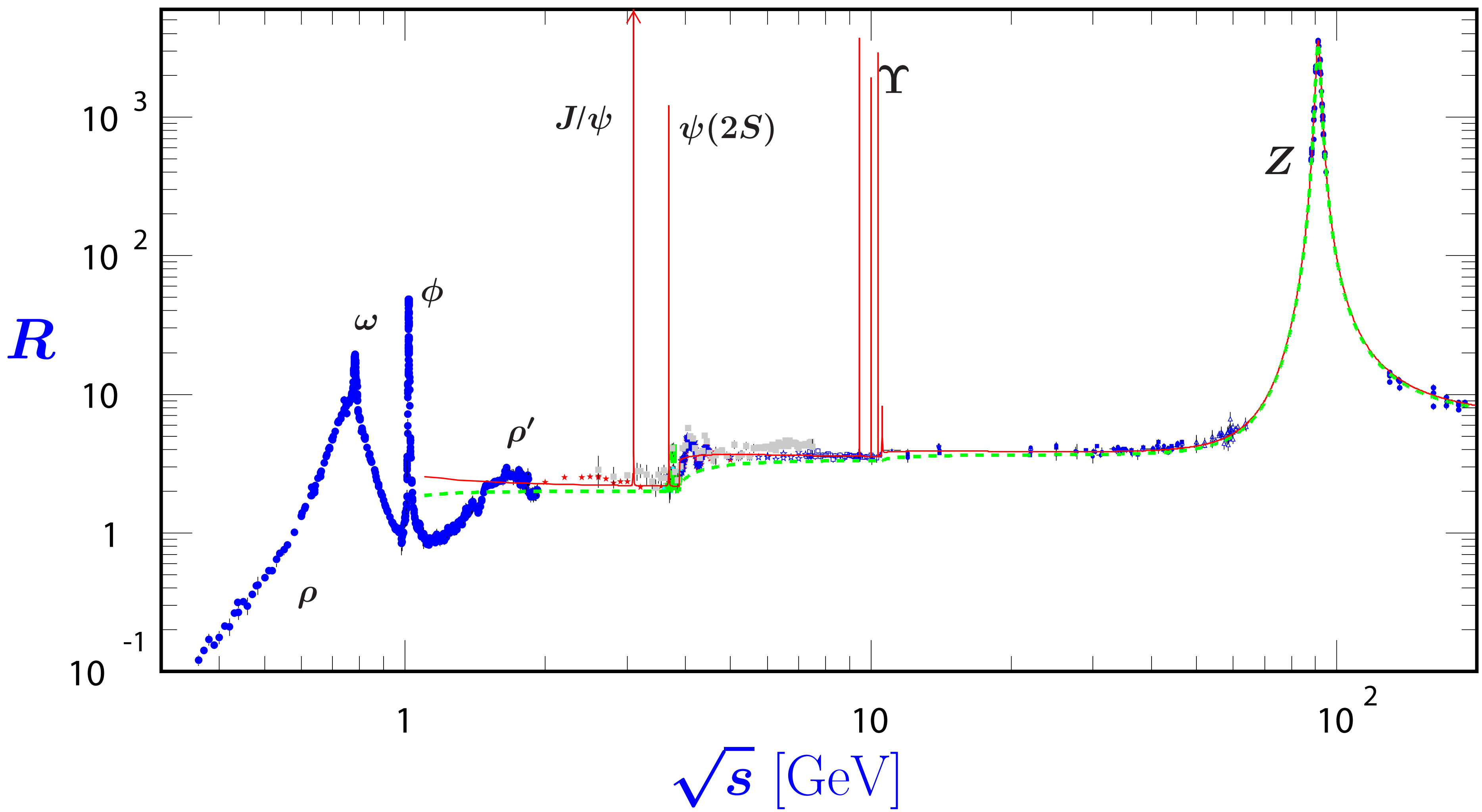
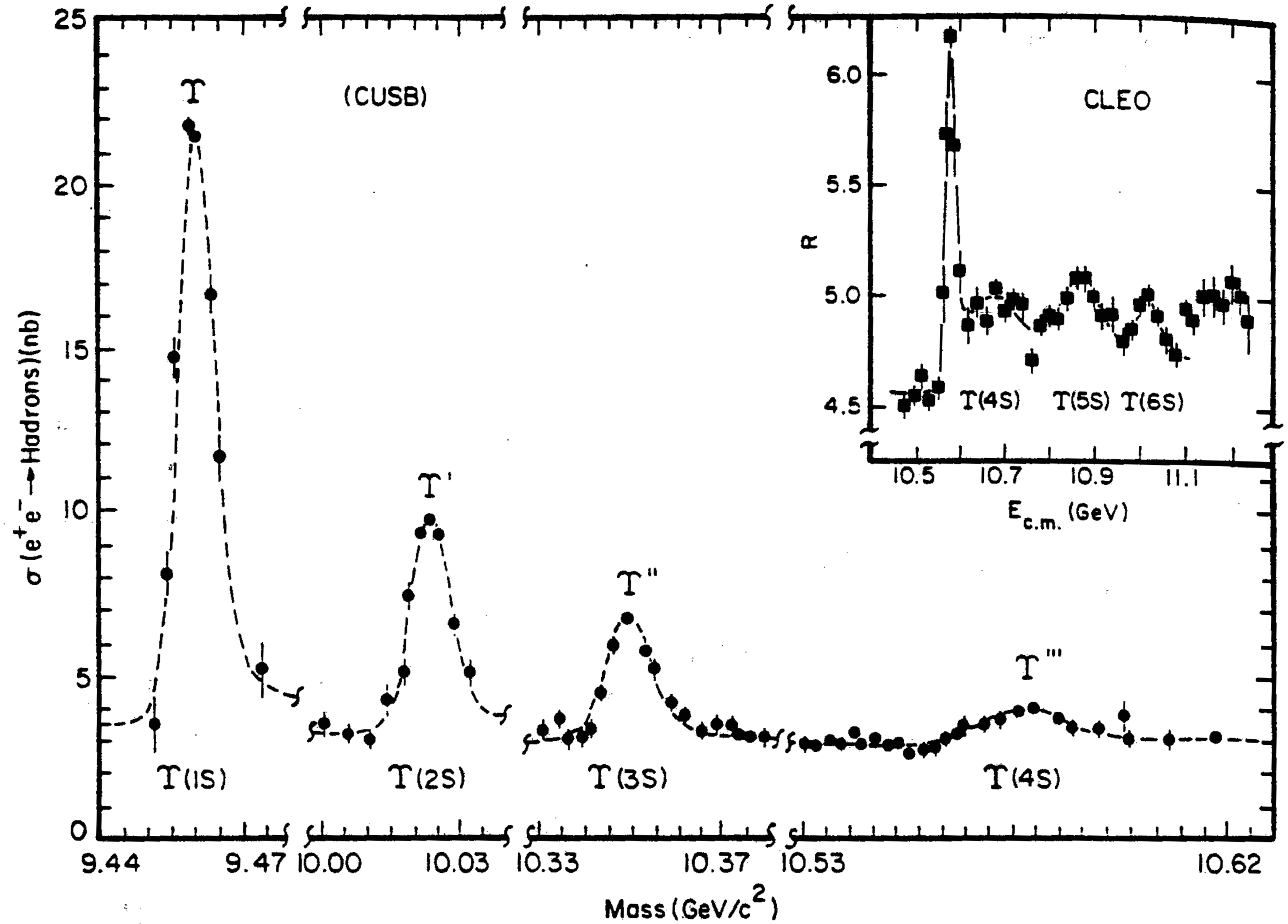
dual nature of QCD:
- hard scattering (QED-like)
- soft fragmentation, hadronization, bound states

R in e^+e^- Collisions



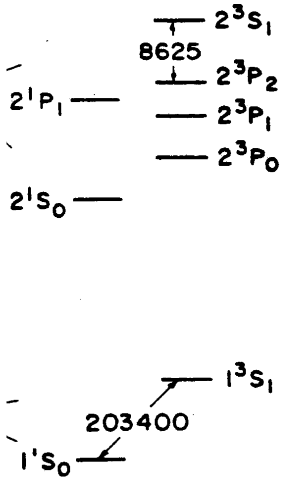
Particle Data Group compilation (2018)

Upsilon ~ bb* bound state resonances near e+e- > b b* threshold



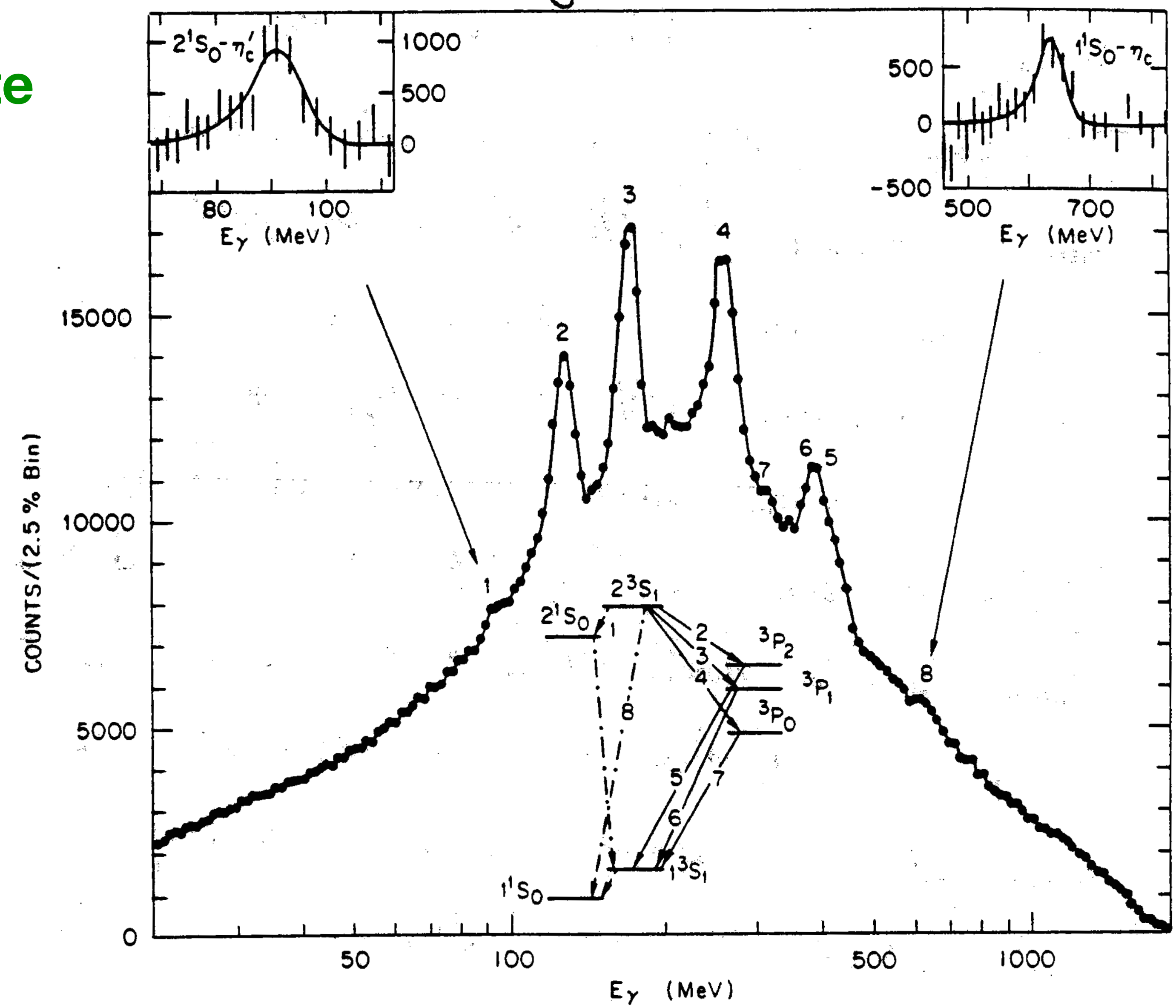
D. Besson and T. Skwarnicki
Ann Rev. Nucl. Part. Sci 43, 333 (1993)

c c* bound state
"charmonium"
spectroscopy



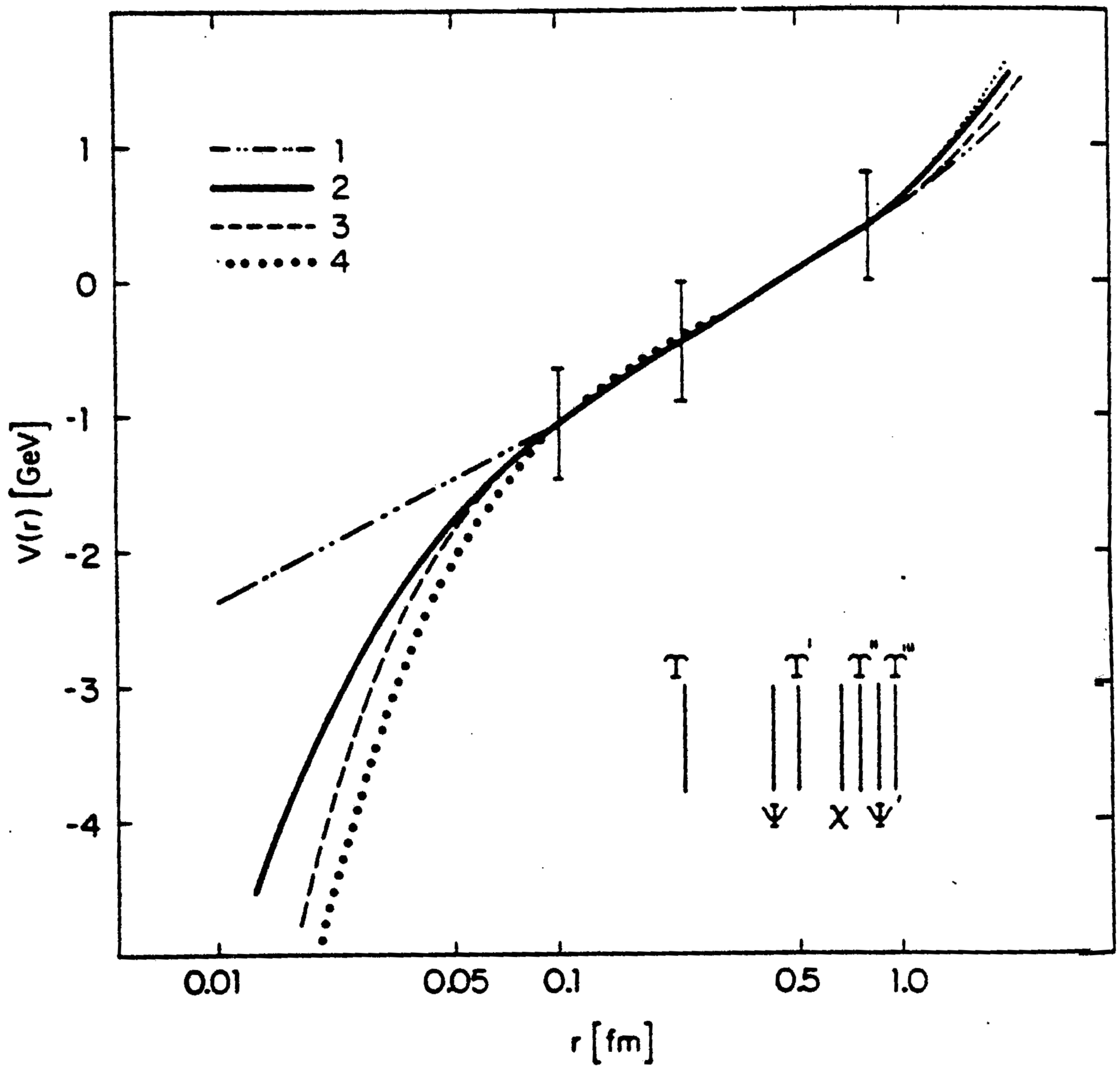
Positronium

Crystal Ball at $E_{cm} = m(\psi')$



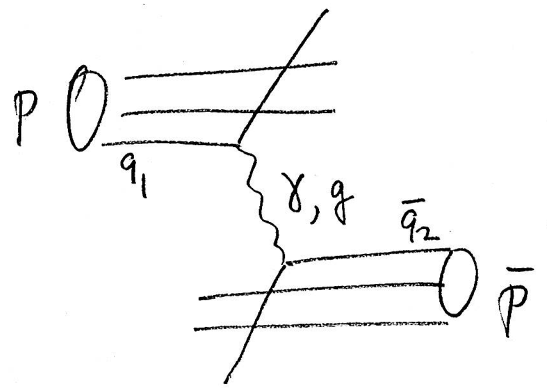
E. Bloom and C E Peck,
Ann. Rev. Nucl. Part. Sci. 33, 143 (1983)

Phenomenological non-relativistic QM potentials V(r) (models)



W. Buchmuller and S.-H. H. Tye
Phys. Rev. D 24, 132 (1981)

$P\bar{P}$ scattering $\quad E_{CM} \gg m_p \quad$ (in $P\bar{P}$-CM)



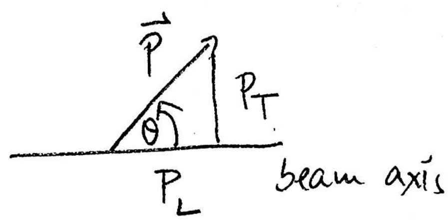
definitions:

1. $X = \dfrac{P_q}{P}$ momentum fraction carried by quark

   $X_1 \neq X_2$ in general $\Rightarrow$ "partonic CM" has unknown boost

2. $P_T = p \sin\theta$

   $P_L = p \cos\theta$



P_T is boost invariant $\Rightarrow$ measure of "hardness" of particle.

P_L not boost inv. $\quad$ P_L large when "nothing" happened

2.b. for $E \gg m$ $\quad p \sim E$

(E measured with calorimeters)

$\Rightarrow$ define $\quad E_{T_i} = E_i \sin\theta \quad$ (i-th particle)

$E_{T_{\text{event}}} = \sum_i E_{T_i}$ hardness of event

$\boxed{\text{PLOT 15}}$ most hadrons are soft $\quad 10^6 \sim \dfrac{N(1\,\text{GeV})}{N(8\,\text{GeV})} \ll 546\,\text{GeV}$

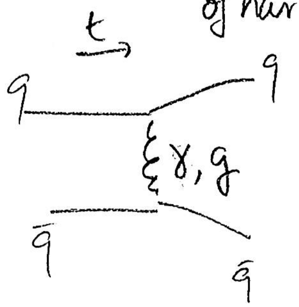
$\boxed{\text{PLOT 16}}$ events can be hard

two jets $\quad E(\theta,\varphi)$ "Lego plot"

$\boxed{\text{PLOT 17}}$ $\quad H_2 = \dfrac{E_T \text{ of leading jet}}{E_T \text{ total}}$

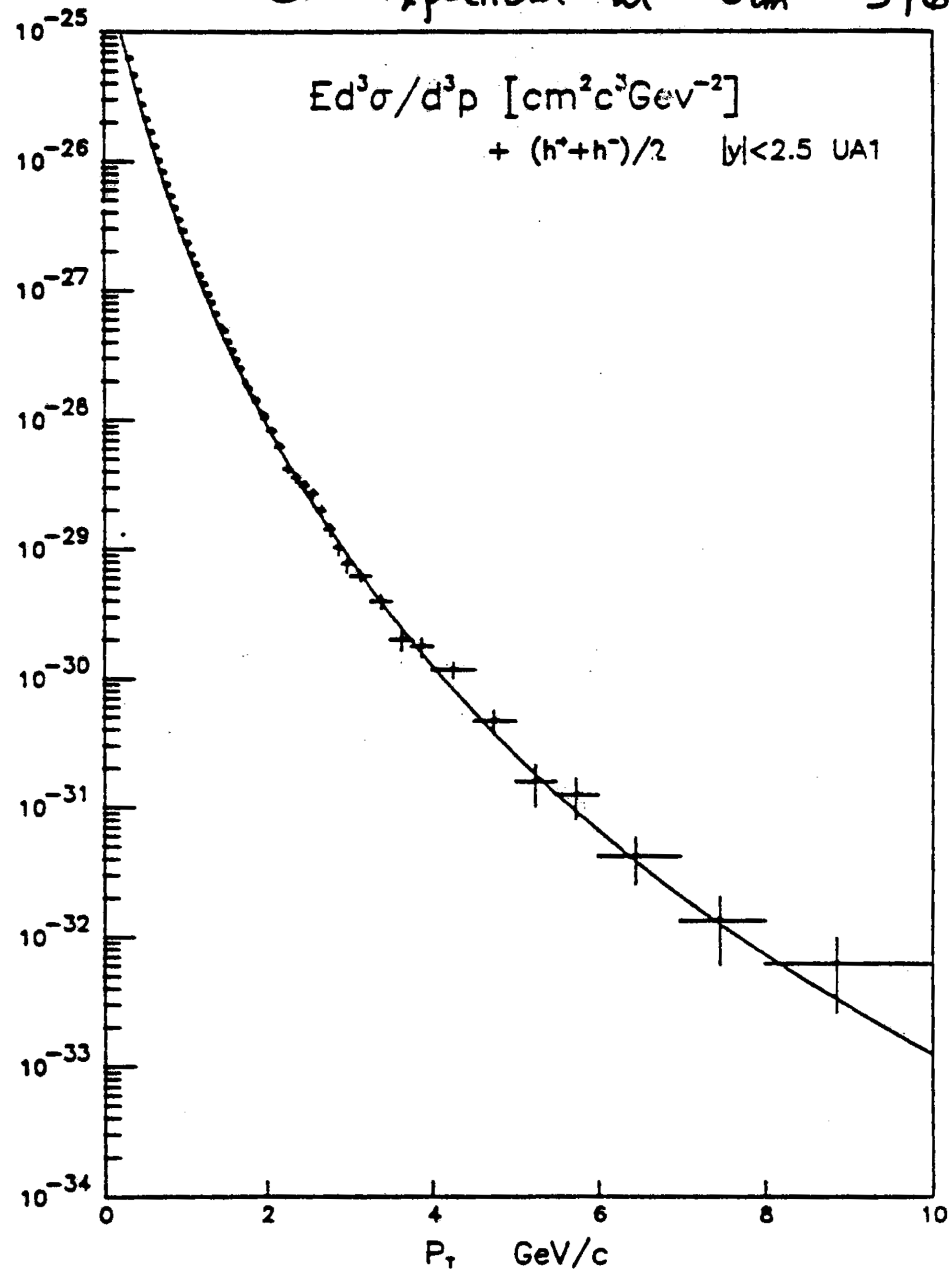
hardest events are 2-jet like.

$\boxed{\text{PLOT 18}}$ angular distribution? of hard jets $\quad \dfrac{d\sigma}{d\cos\theta_{CM}} \sim \dfrac{1}{\sin^4 \theta/2}$ coulomb scattering!



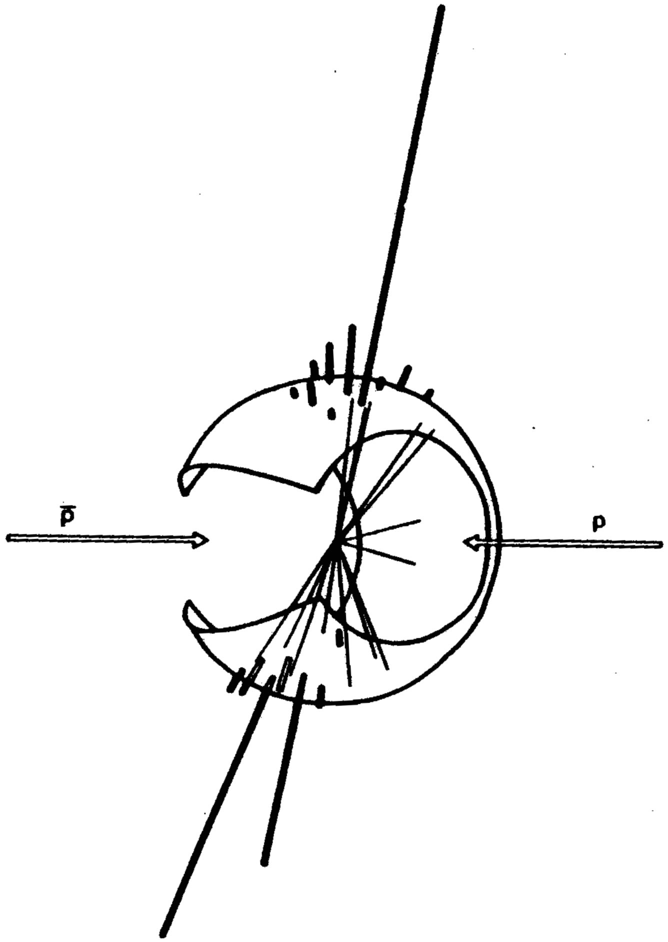
Most particles produced are "soft": $p_T \ll E_{CM}$

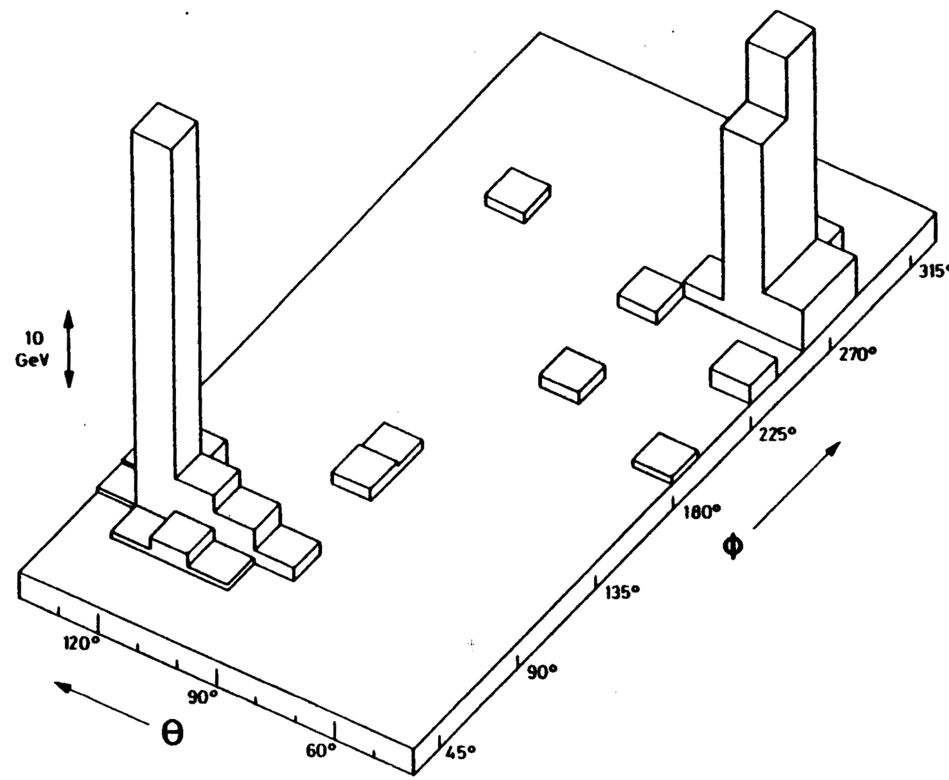
UA1 experiment at $E_{cm} = 546$ GeV



G. Altarelli and L. Di Lella,
Proton-Antiproton Collider Physics

Jets can be "hard"



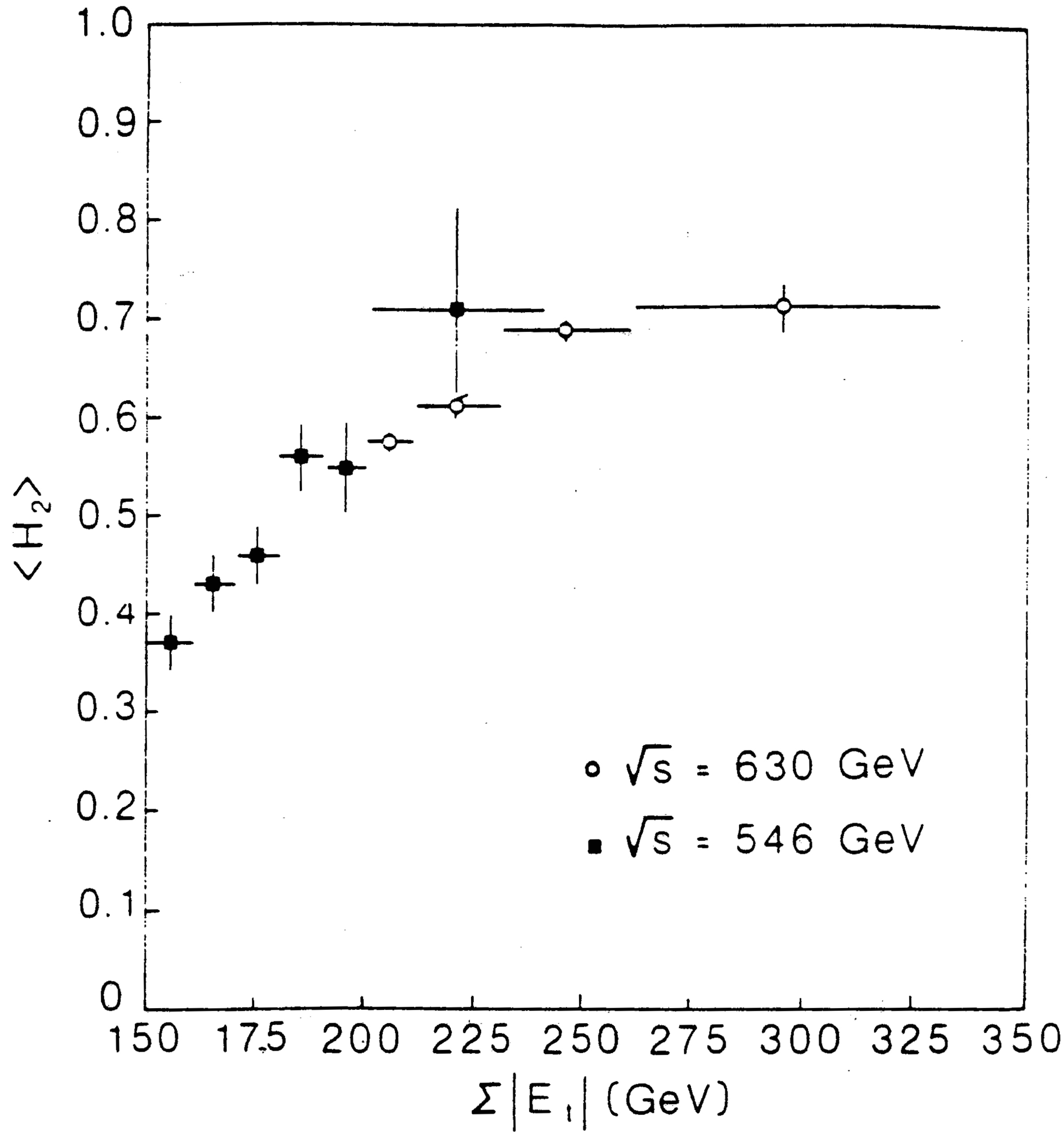


M. Banner et al (UA2)

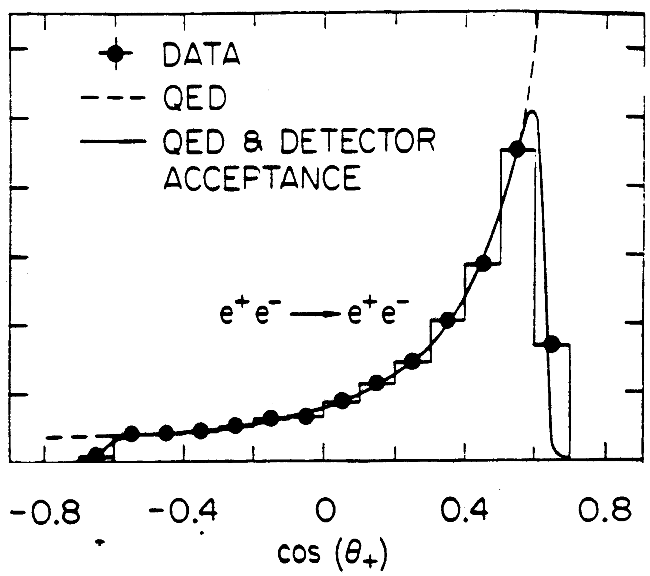
Phys. Lett. 118B, 203 (1982)

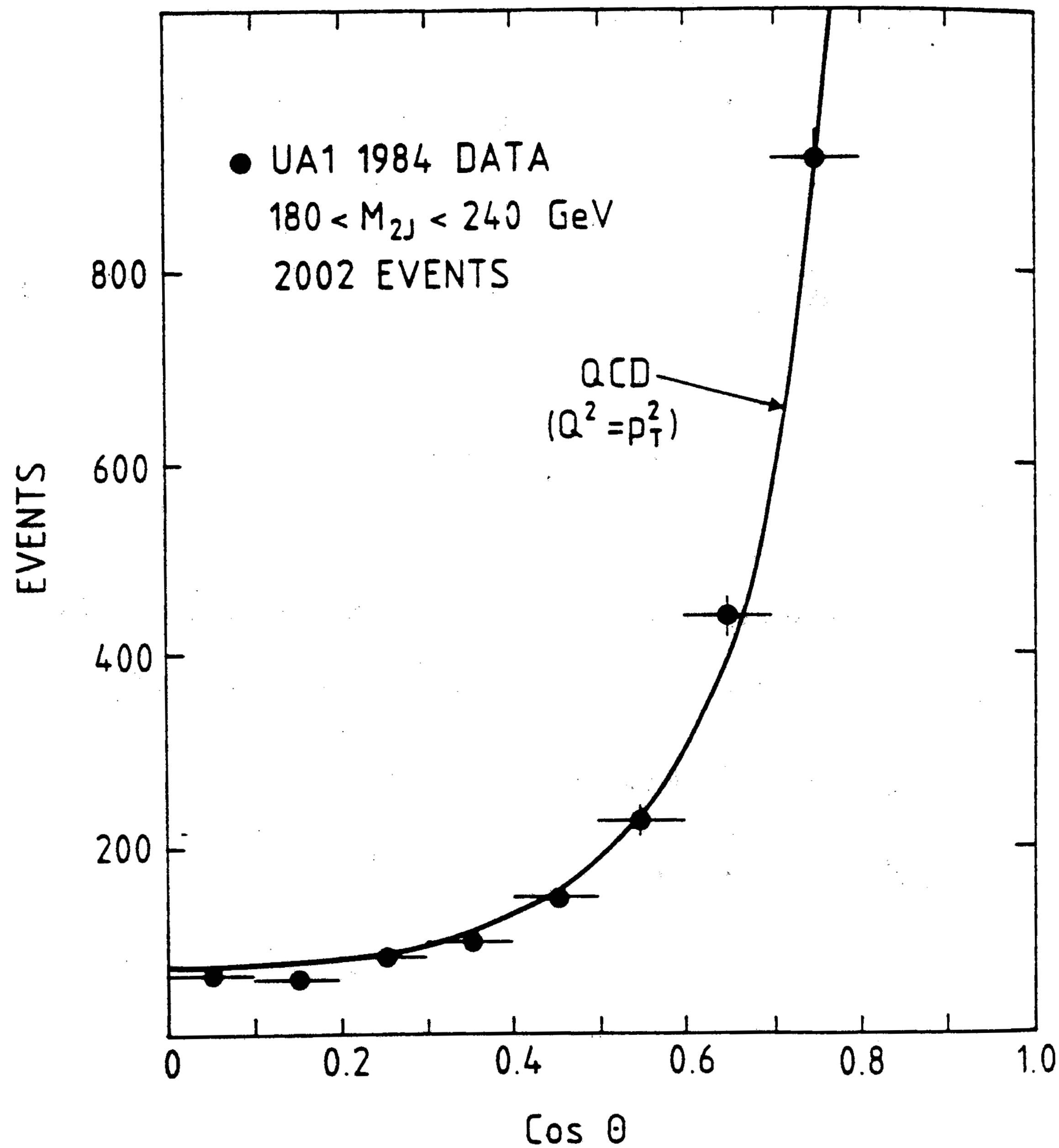
Fraction of E_T contained in the leading two jets

C. Albájar et al (UA1)
Z Phy. C 36, 33(1987)



Similarity of angular distributions of e+e- > e+e- versus q q* > q q* , Coulomb forward-scattering singularity





G. Arnison et al (UA1)

Phys. Lett. B177, 244 (1986)