QCD IN $e^+ + e^- \rightarrow$ *Hadrons* IN THE EIGHTIES

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Festkolloquium Ahmed Ali
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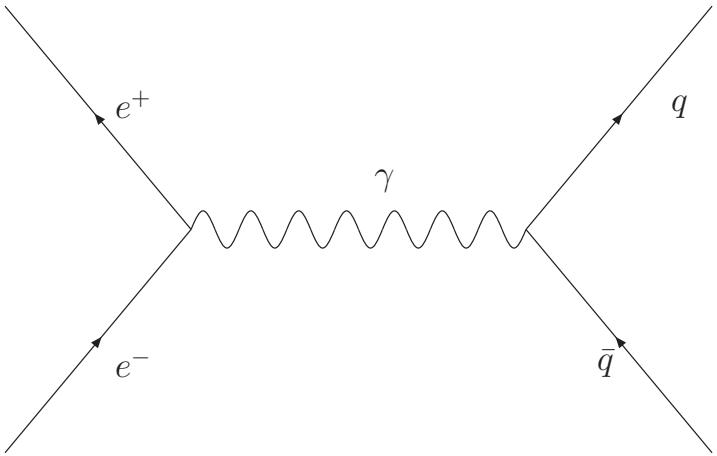
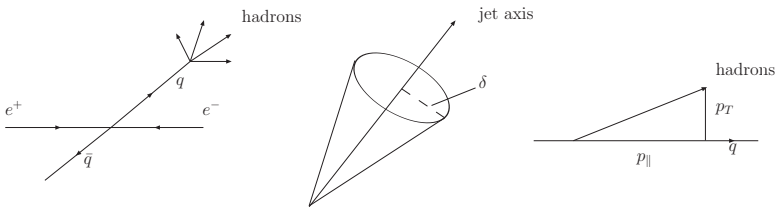
- Physics in the eighties most exciting time for experimentalists and theorists at DESY Discovery of three-jet events and establishing gluon jets

  Several detectors at PETRA: JADE, MARK J, PLUTO, TASSO (PLUTO replaced later by CELLO)

  On the theoretical side the development of MONTE CARLO programs for describing the final state in $e^+ + e^- \rightarrow hadrons$

- Results for simulating the two-jet final state in $e^+e^- \rightarrow hadrons$
  The influence of heavy quark production and hunting the top quark
  Description of the gluon jet in MONTE CARLO programs
  Higher QCD corrections and determination of the quark gluon coupling α_s





Born diagram for $e^+e^- \rightarrow \gamma \rightarrow q\bar{q}$

Final state in SPEAR experiment at SLAC
calculated either from phase space model
or a jet model in terms of limited transverse momentum
a la van Hove, 1969

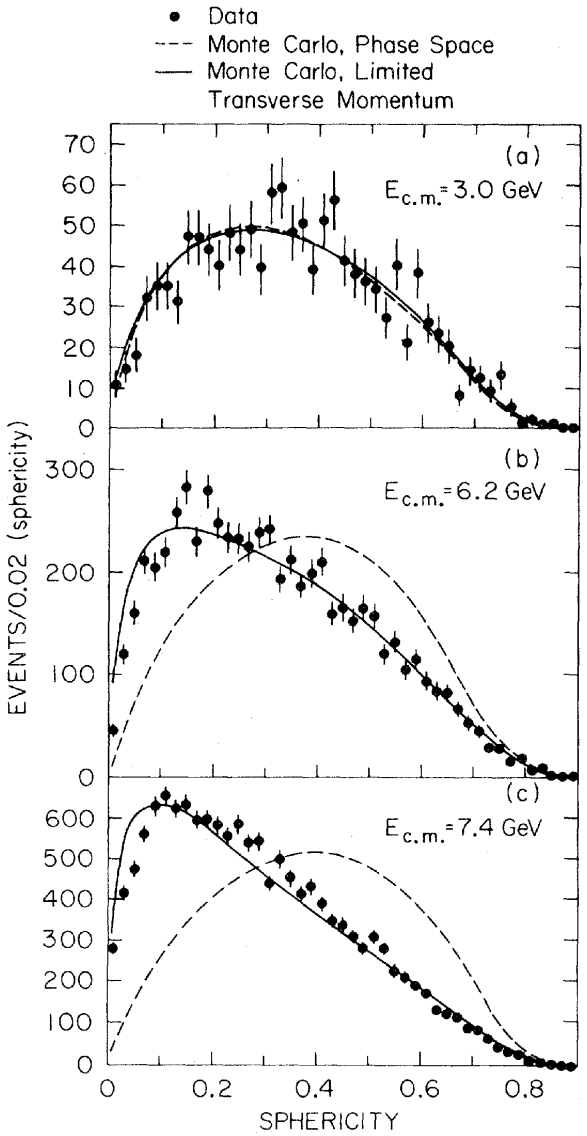
$M^2 = exp[-(\sum_i p_{iT}^2)/2b^2]$

Hanson et al. 1975, 1982

$< p_\parallel > \simeq < p > \simeq W/ < n >$
$W = E_{c.m.}$
half angle of jet cone $< \delta > \simeq < p_T > / < p > \simeq < p_T >< n > /W \sim 1/W$

$W = 4\ GeV$ and $< p_T > = 320\ MeV$
$< \delta > \simeq 30^o$

Underestimate, each of two jets broader than 60^o



jet model and phase space model

Data from MARK I detector at Spear

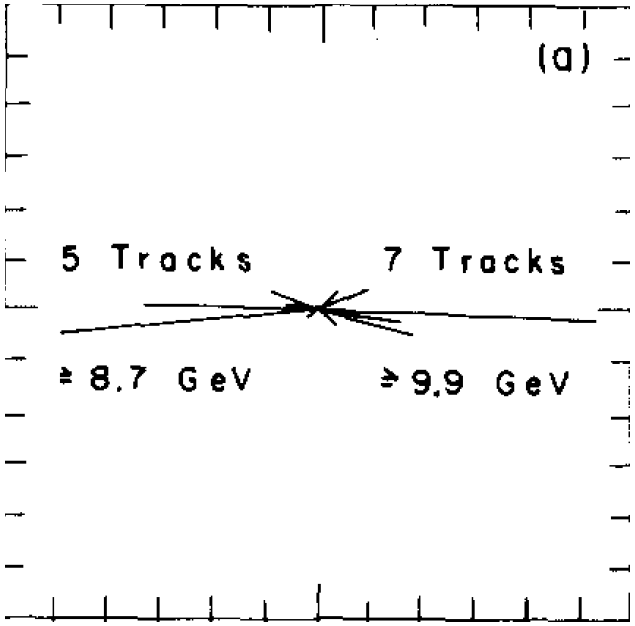
from G. Hanson et al. [SLAC-LBL Coll.] (1975)

full line jet model, dashed line phase space model

sphericity distribution

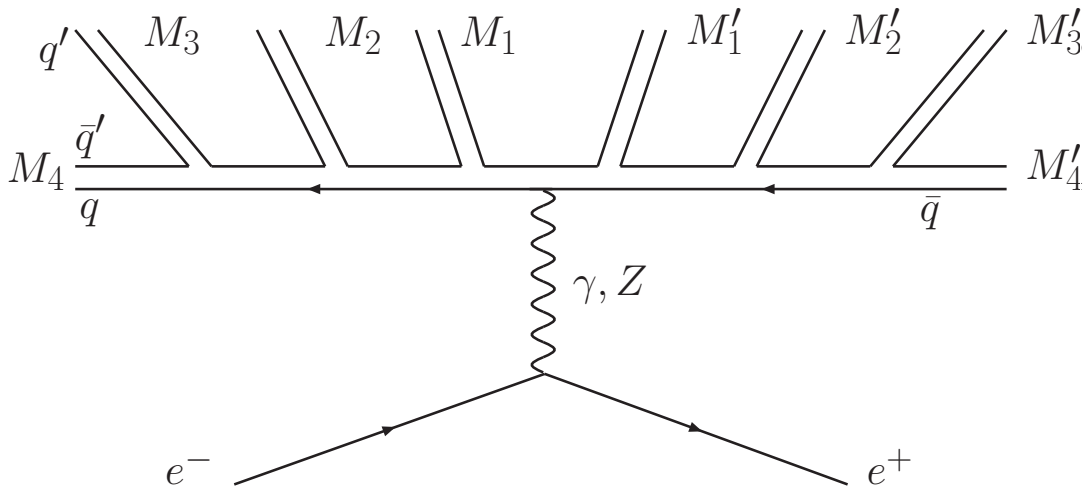
for $E_{c.m.} = 3.0,\ 6.2,\ 7.4$ GeV

$$sphericity = S = \frac{3}{2} min \frac{\sum_i |p_{iT}|^2}{\sum_i |p_i|^2}$$



Momentum-space drawing of two-jet event
from TASSO constructed with sphercity tensor
$E_{c.m.} = 31.6$ GeV

small tranverse monenta with respect to jet axis clearly visible



Quark fragmentation to hadrons induced by soft QCD a la Field and Feynman (1977)
initial quarks and antiquarks fragment independently in a cascade process
$q \to q + \bar{q}'q' \to h_{(q\bar{q}'} + q'$
charge and other flavour quantum number conserved ar each step

fragmentation $q \to h + q'$ desribed by primordial fragmentation function
$f_q^h(z) = 1 - a + 3a(1-z)^2, \;\; z = \frac{(E+p_{||})_h}{(E+p_{||})_q}$
'a' energy-independent parameter fixed fitted to data
p_T dpendence (p_T transverse momentum wit repect to jet axis)
$g(p_T^2) = (2\sigma_q^2)^{-1} \exp(-p_T^2/2\sigma_q^2)$
$\sigma_q \simeq 350\, MeV$

Two fragmentation models for $e^+ + e^- \to q + \bar{q} + g \to hadrons$
available around 1980

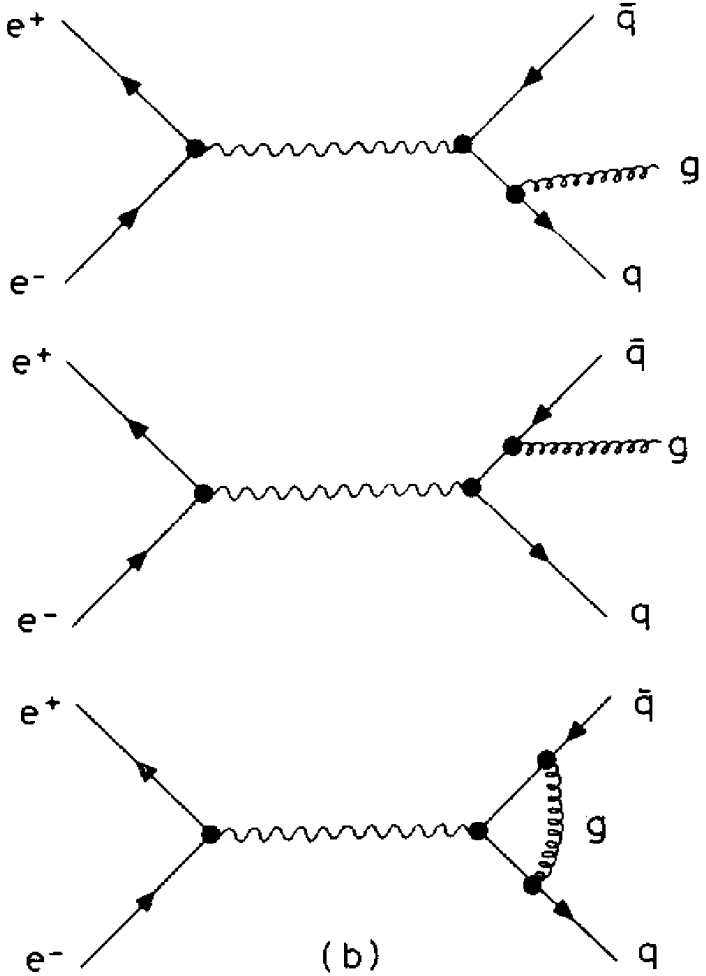
- Hoyer model: P. Hoyer, P. Osland, H. G. Sander, T. F. Walsh, P. Zerwas
  Nucl. Phys. B161 (1979) 349
- Ali model: A. Ali et al. Phys. Lett. 93B (1980) 155

Nothing known about gluon fragmentation
two different mechanism assumed
Hoyer model: frag(gluon) = frag (quark)
frag(quark) a la Feynman-Field

Ali model: $g \to q + \bar{q}$
$f_g(z) = [z^2 + (1-z)^2]/2$
frag(quark) a la Feynman-Field

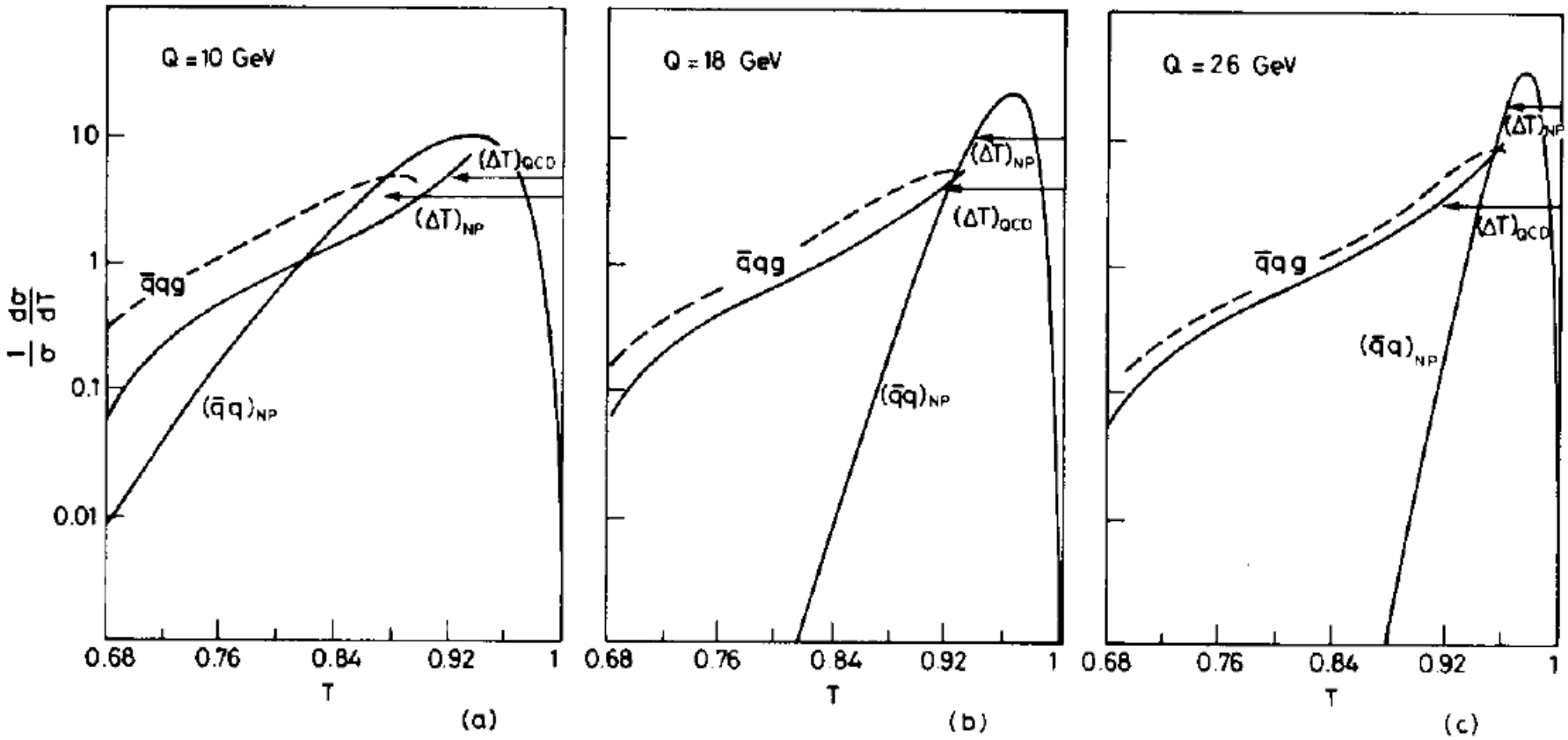
In addition: (i) frag(q) evolved a la Altarelli-Parisi to higher scales
(ii) decay of heavy quarks c, b and t
(iii) higher orders in quark-gluon coupling through
$e^+e^- \to q\bar{q}gg, q\bar{q}q\bar{q}$

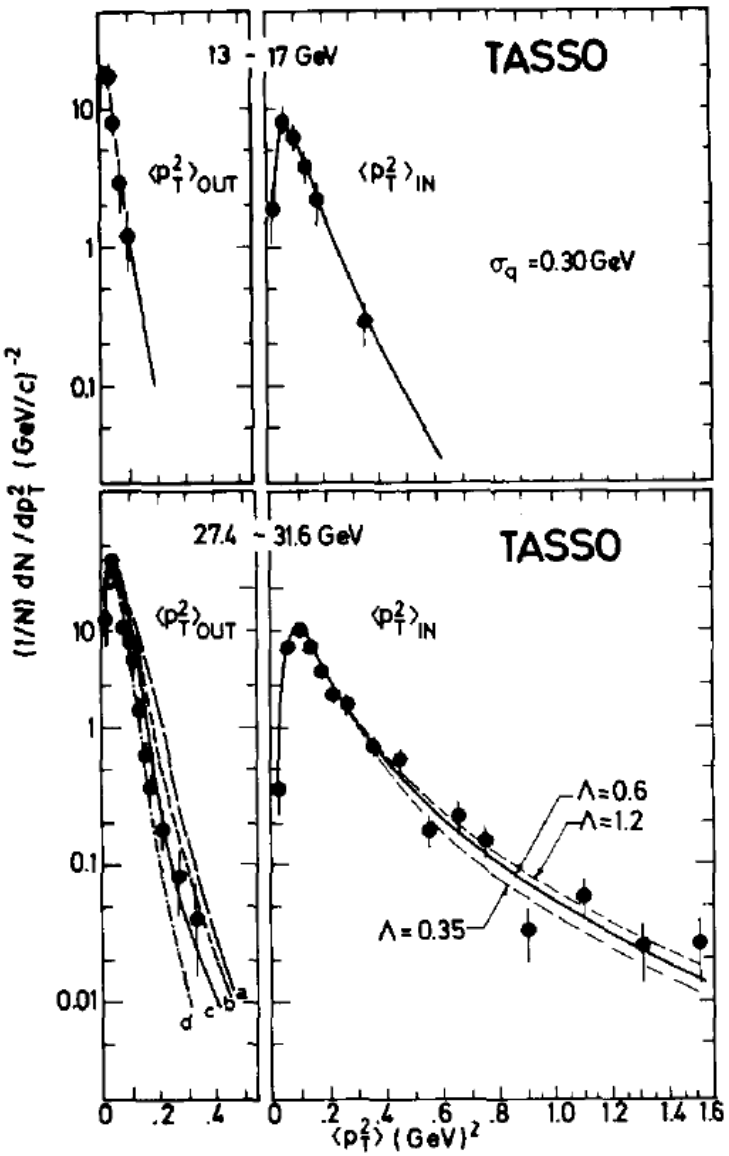
Lowest order diagrrams for $e^+e^- \to q\bar{q}g$ and vertex corrections in $e^+e^- \to q\bar{q}$

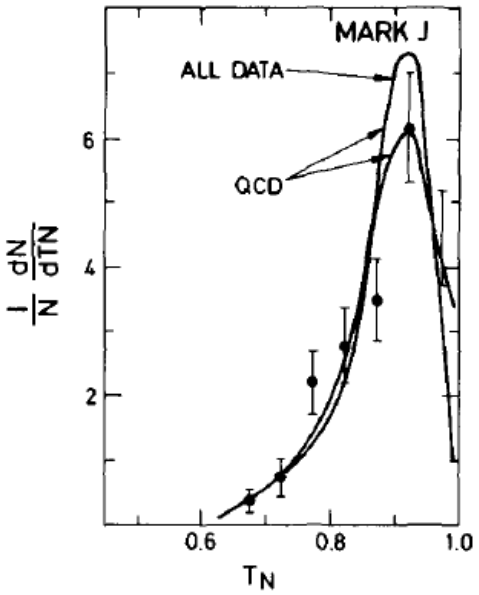


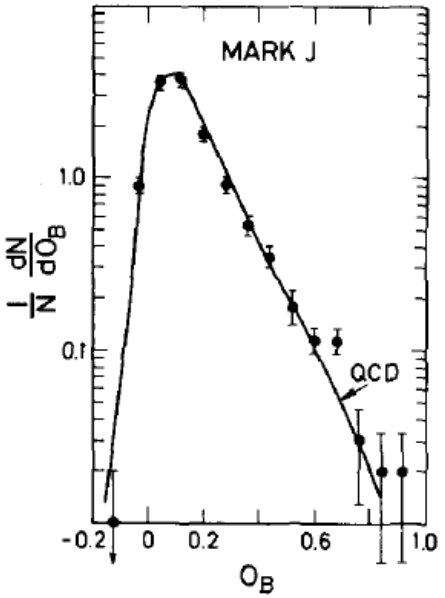
$$\frac{d^2\sigma}{dx1dx2} = \sigma_0 \frac{\alpha_s}{2\pi} C_F \frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)}$$

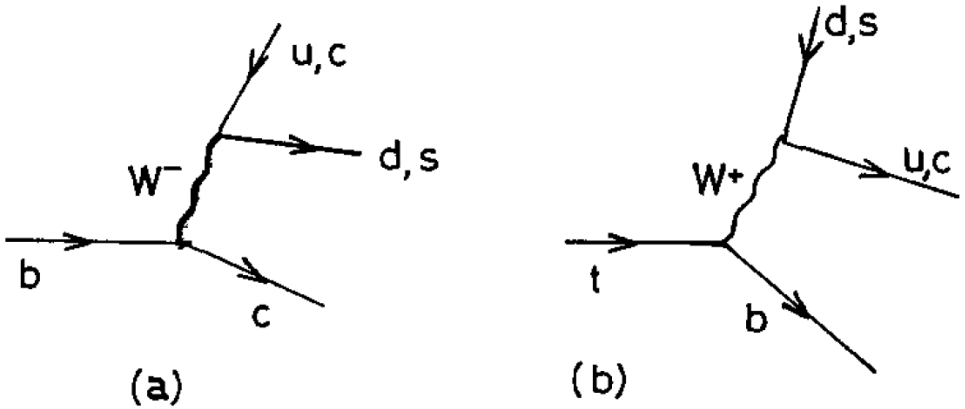
$$\textit{Thrust} \quad T = max \frac{\sum_i |p_{iL}|}{\sum_i |p_i|}$$


Q = 10 GeV
Q = 18 GeV
Q = 26 GeV
$\frac{1}{\sigma}\frac{d\sigma}{dT}$
10
1
0.1
0.01
$\bar{q}qg$
$(\bar{q}q)_{NP}$
$(\Delta T)_{QCD}$
$(\Delta T)_{NP}$
0.68
0.76
0.84
0.92
1
T
(a)
(b)
(c)


13 - 17 GeV
TASSO
$\langle p_T^2 \rangle_{OUT}$
$\langle p_T^2 \rangle_{IN}$
σ_q =0.30 GeV
27.4 - 31.6 GeV
TASSO
Λ=0.6
Λ=1.2
Λ = 0.35
a
b
c
d
$(1/N)\ dN/dp_T^2\ (GeV/c)^{-2}$
$\langle p_T^2 \rangle\ (GeV)^2$


MARK J
ALL DATA
QCD
$\frac{1}{N}\frac{dN}{dT_N}$
T_N


MARK J
QCD
$\frac{1}{N}\frac{dN}{dO_B}$
O_B



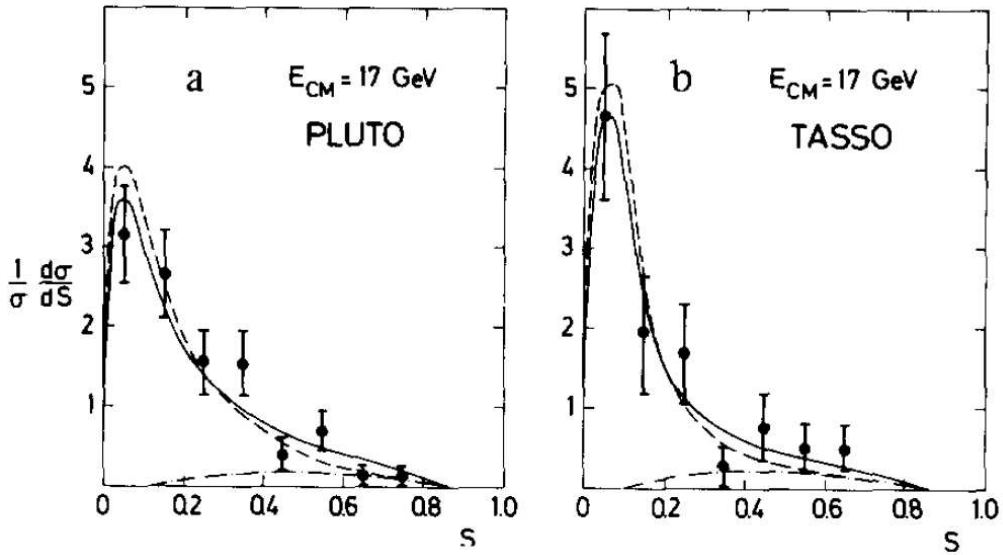
Four publication on heavy quark decay:

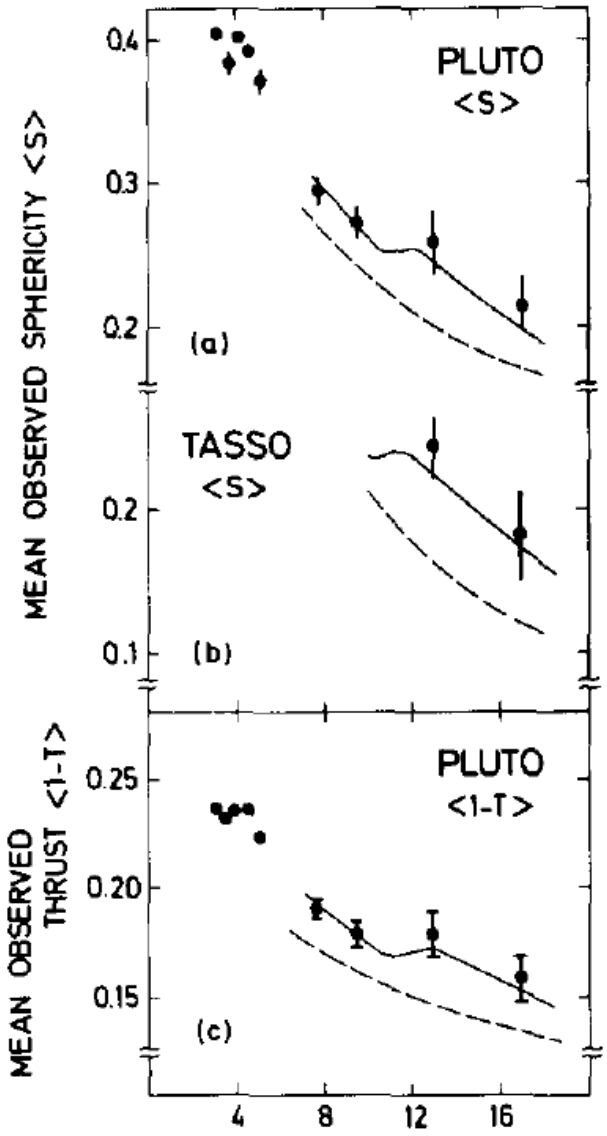
Jet-like Distributions for the Weak Decay of Heavy Quarks

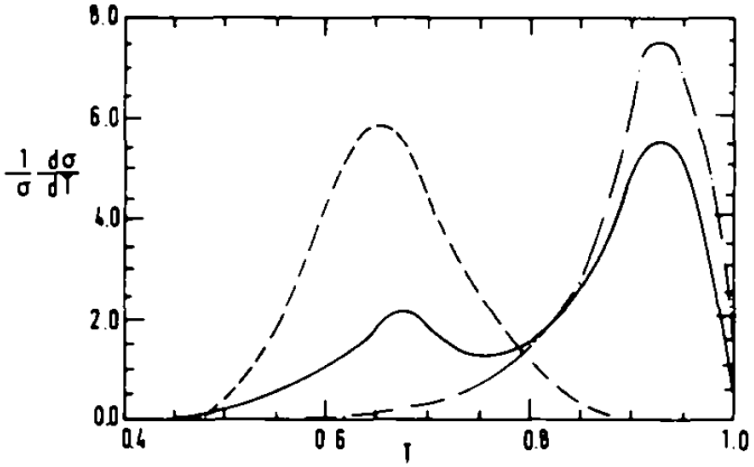
Non-leptonic Weak Decays of Heavy Mesons

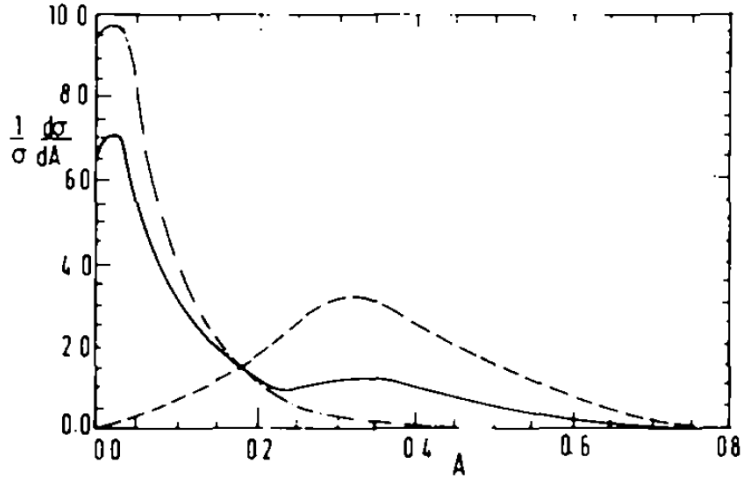
Final States in Non-leptonic Bottom Meson Decays

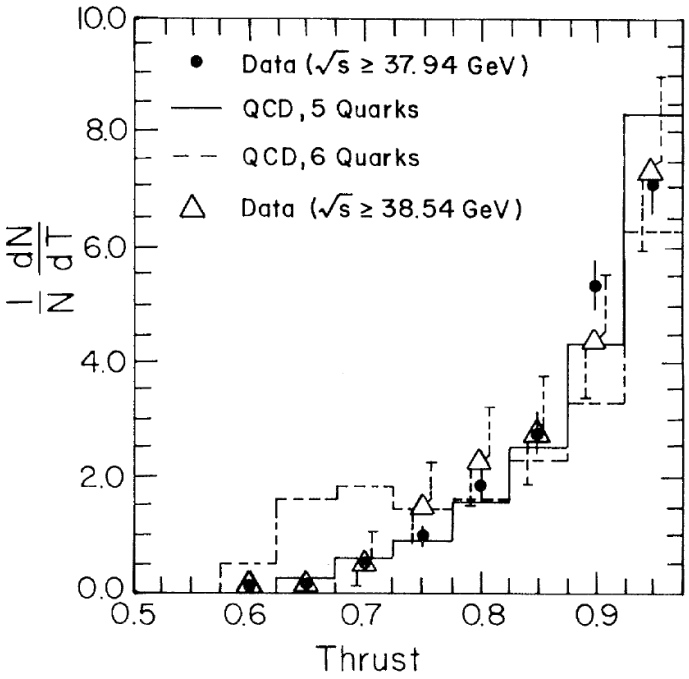
Heavy Quarks in e^+e^- Annihilation

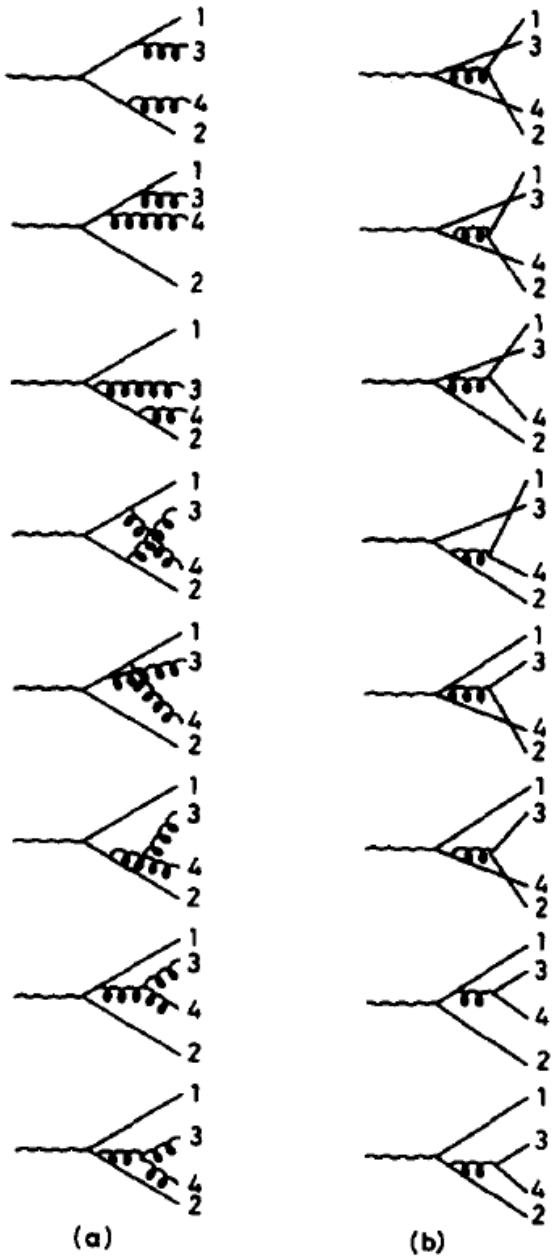

a
E_{CM} = 17 GeV
PLUTO
b
E_{CM} = 17 GeV
TASSO
$\frac{1}{\sigma}\frac{d\sigma}{dS}$
S
S


MEAN OBSERVED SPHERICITY <S>
PLUTO
<S>
(a)
TASSO
<S>
(b)
MEAN OBSERVED THRUST <1-T>
PLUTO
<1-T>
(c)

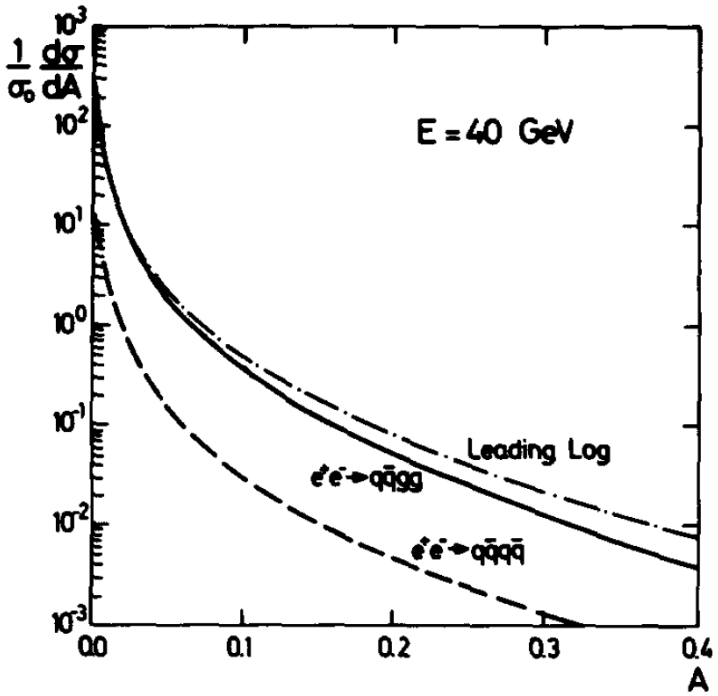

8.0
6.0
4.0
2.0
0.0
0.4
0.6
0.8
1.0
T
$\frac{1}{\sigma}\frac{d\sigma}{dT}$


10.0
8.0
6.0
4.0
2.0
0.0
0.0
0.2
0.4
0.6
0.8
A
$\frac{1}{\sigma}\frac{d\sigma}{dA}$

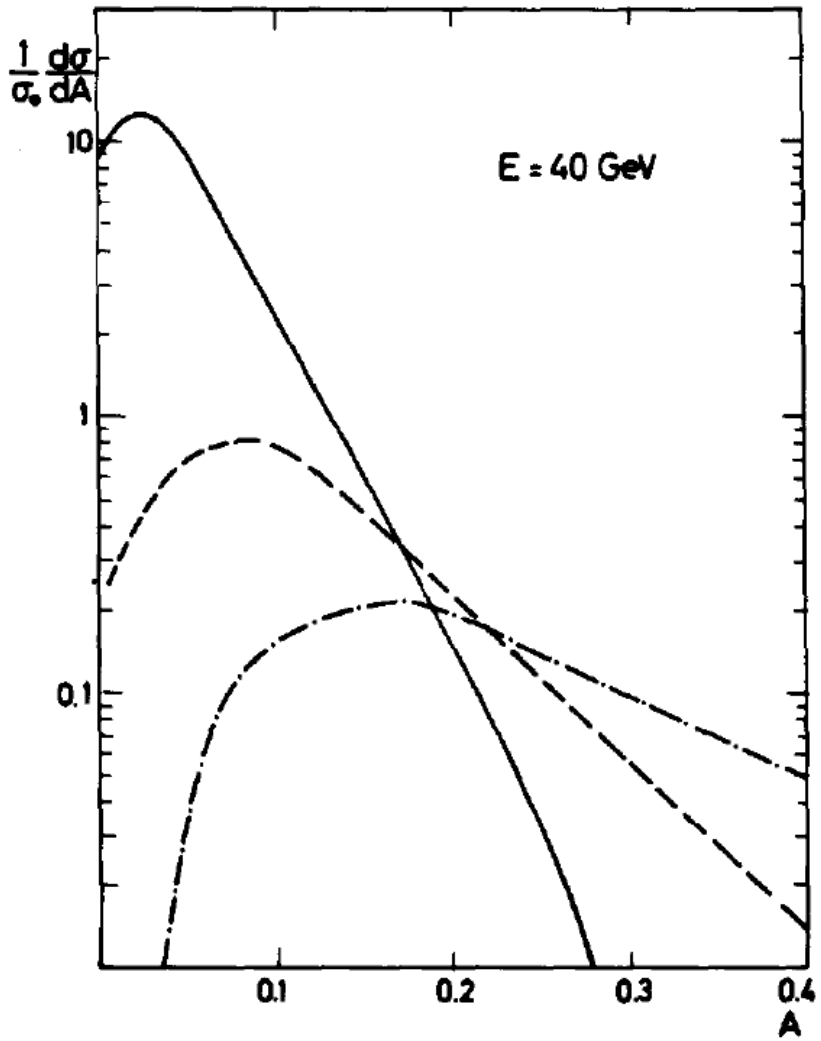

Data ($\sqrt{s} \geq 37.94$ GeV)
QCD, 5 Quarks
QCD, 6 Quarks
Data ($\sqrt{s} \geq 38.54$ GeV)
$\frac{1}{N}\frac{dN}{dT}$
10.0
8.0
6.0
4.0
2.0
0.0
0.5
0.6
0.7
0.8
0.9
Thrust



first contribution with three gluon coupling
$q\bar{q}q\bar{q}$ final state small compared to $qqgg$ state



$$A = 4min(\frac{\sum_i |p_{iT,out}|}{\sum_i |p_i|})^2$$



$$\sigma(4-jets) = (\frac{\alpha_s}{\pi})^2 C_F [C_F \sigma_{bb} + C_A \sigma_{gg} + n_f T_R \sigma_{qq}]$$

Results from LEP (OPAL collaboration,2001):

$$C_A/C_F = 2.29 \pm 0.06 \pm 0.14 \quad [QCD = 9/4, U(1) = 0]$$

$$T_R/C_F = 0.38 \pm 0.03 \pm 0.06 \quad [QCD = 3/8]$$

$$\frac{d\Sigma^{EEC}}{d\cos\chi} = \sum \int \frac{d^3\sigma}{dx_i dx_j d\cos\chi} x_i x_j dx_i dx_j$$

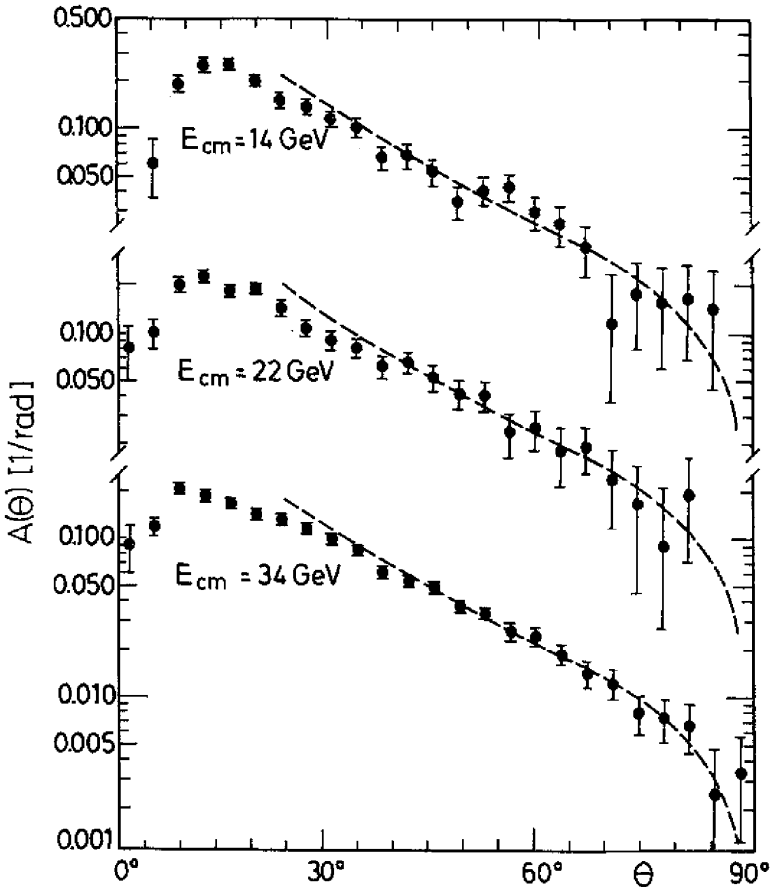
$$\frac{d\Sigma^{AEEC}}{d\cos\chi} = \frac{d\Sigma^{EEC}(\pi-\chi)}{d\cos\chi} - \frac{d\Sigma^{EEC}(\chi)}{d\cos\chi}$$

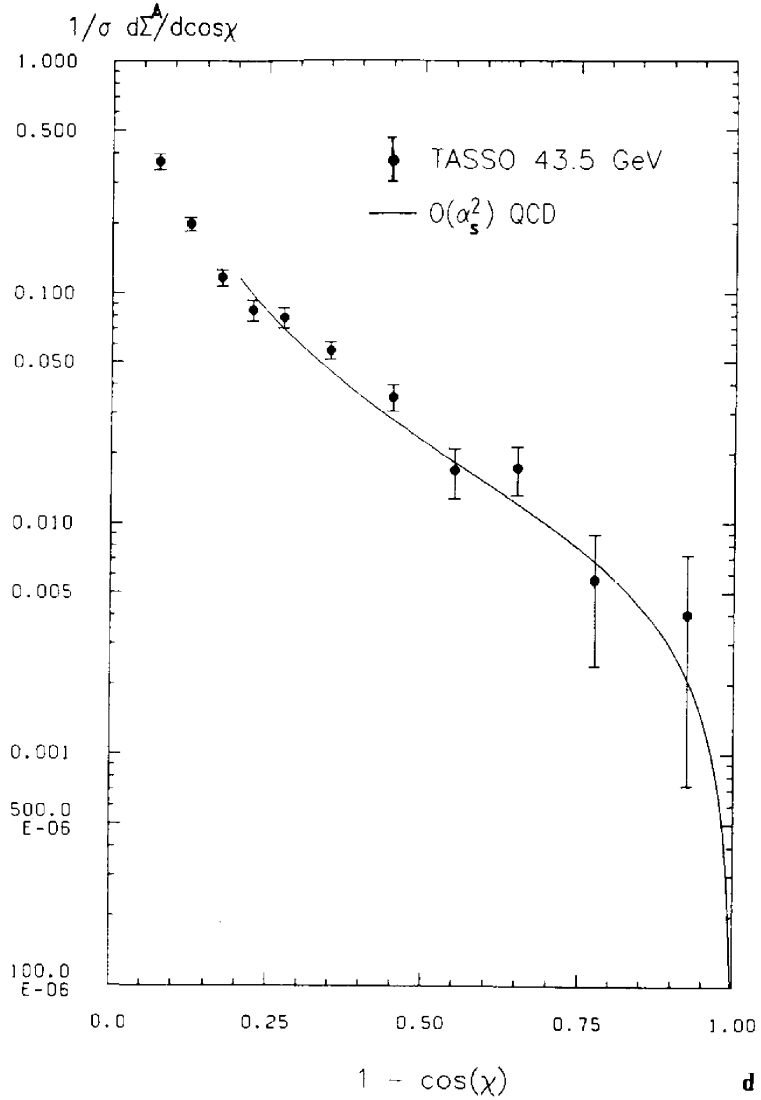
$$\frac{1}{\sigma_0}\frac{d\Sigma^{EEC}}{d\cos\chi} = \frac{\alpha_s}{\pi} F(\xi)$$

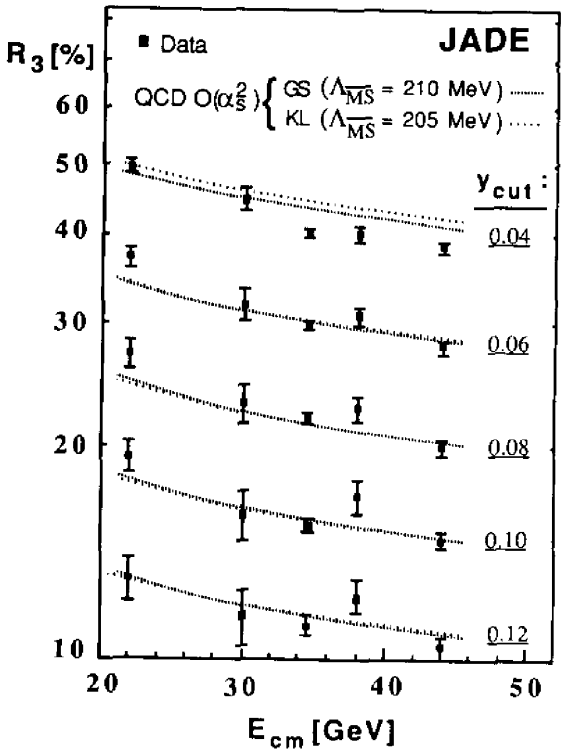
$$\xi = (1-\cos\chi)/2$$

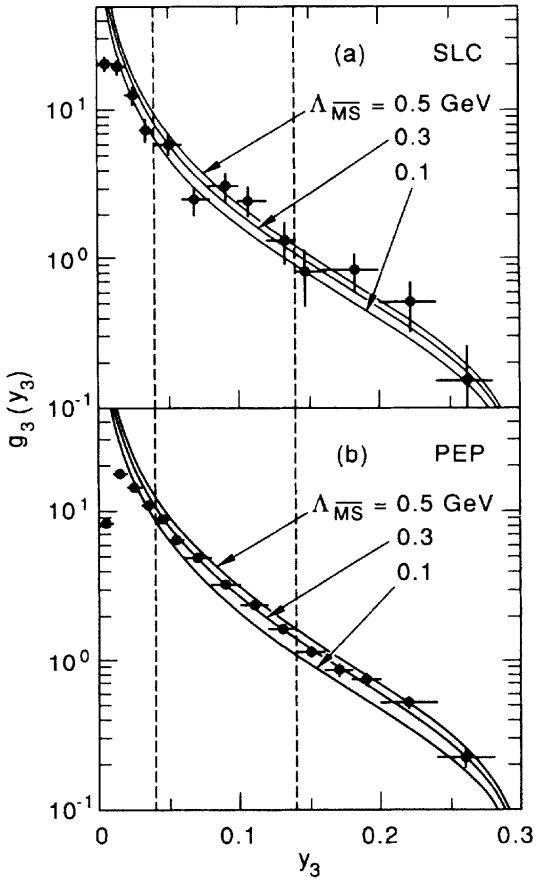
JADE: $\alpha_s(s = (34\ GeV)^2) = 0.115 \pm 0.005$

TASSO: $\alpha_s(s = (34.8\ GeV)^2) = 0.125 \pm 0.005$


A(Θ) [1/rad]
0.500
0.100
0.050
E_cm = 14 GeV
0.100
0.050
E_cm = 22 GeV
0.100
0.050
E_cm = 34 GeV
0.010
0.005
0.001
0°
30°
60°
Θ
90°


1/σ dΣ^A/dcosχ
1.000
0.500
0.100
0.050
0.010
0.005
0.001
500.0 E-06
100.0 E-06
TASSO 43.5 GeV
O(α_s^2) QCD
0.0
0.25
0.50
0.75
1.00
1 − cos(χ)
d





$y_{ij} = M_{ij}^2/s$

$$R_3(y_{min}, s) = C_1(y_{min})\alpha_s(s) + C_2(y_{min})\alpha_s^2(s)$$

JADE: $\Lambda_{\overline{MS}} = 205\ (210)$ MeV

$\alpha_s = 0.149 \pm 0.002 \pm 0.007$ MARKII(PEP)

$\alpha_s = 0.123 \pm 0.009 \pm 0.005$ MARKII(SLC)

Final Remarks

Collaborators of Ahmed Ali in the work I have mentioned:

- Energy-energy correlation: F. Barreiro
- Heavy quark production:
  J. G. Koerner, J. Willrodt, G. K.
- Ali Monte Carlo:
  E. Pietarinen, J. Willrodt, G. K.
- Four-jet final states:
  J. G. Koerner, Z. Kunszt, E. Pietarinen, G. Schierholz, J. Willrodt, G. K.
- Review Article: A. Ali and G. K.: Jets and QCD, to be published in Eur. Phys. J. H (H stands for history)