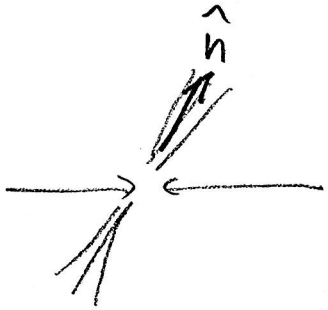
$E_{CM} > m_g$? $R \to 0$ very fast

but $R_h = \dfrac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \sim \text{const} \sim 2$ (Lesson 1)

typical events have many hadrons [Plot pg 8] ($e^+e^- \to \pi^+\pi^-$ = wrong question)

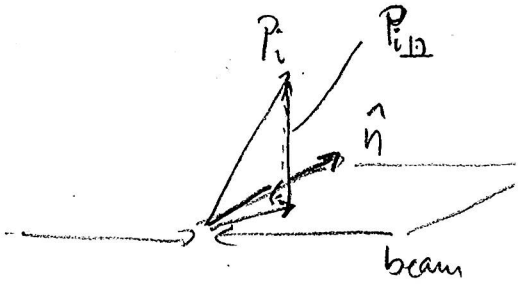
typical events have "Thrust axis" [Plot pg 10] (Lesson 2)

Thrust: $T(\hat{n}) = \sum_{\substack{\text{all} \\ \text{particles } i}} \dfrac{|\hat{n} \cdot \vec{p}_i|}{|\vec{p}_i|} \in [1/2, 1]$



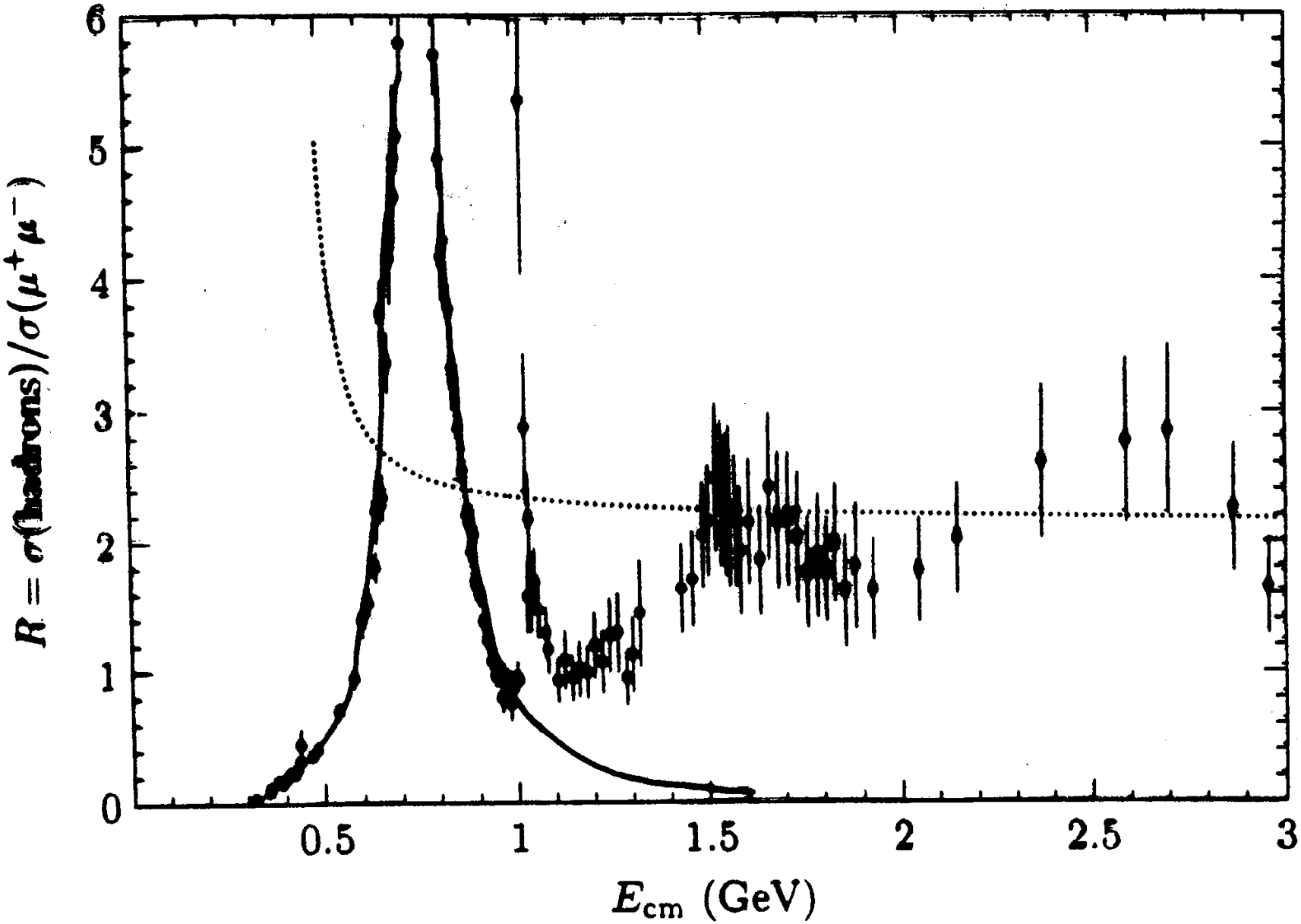
$\hat{n}_{max}$ = "thrust axis" maximizes $T(\hat{n})$

Acoplanarity: $A(\hat{n}) = \sum_i \dfrac{|p_{i\perp}|}{|\vec{p}_i|}$



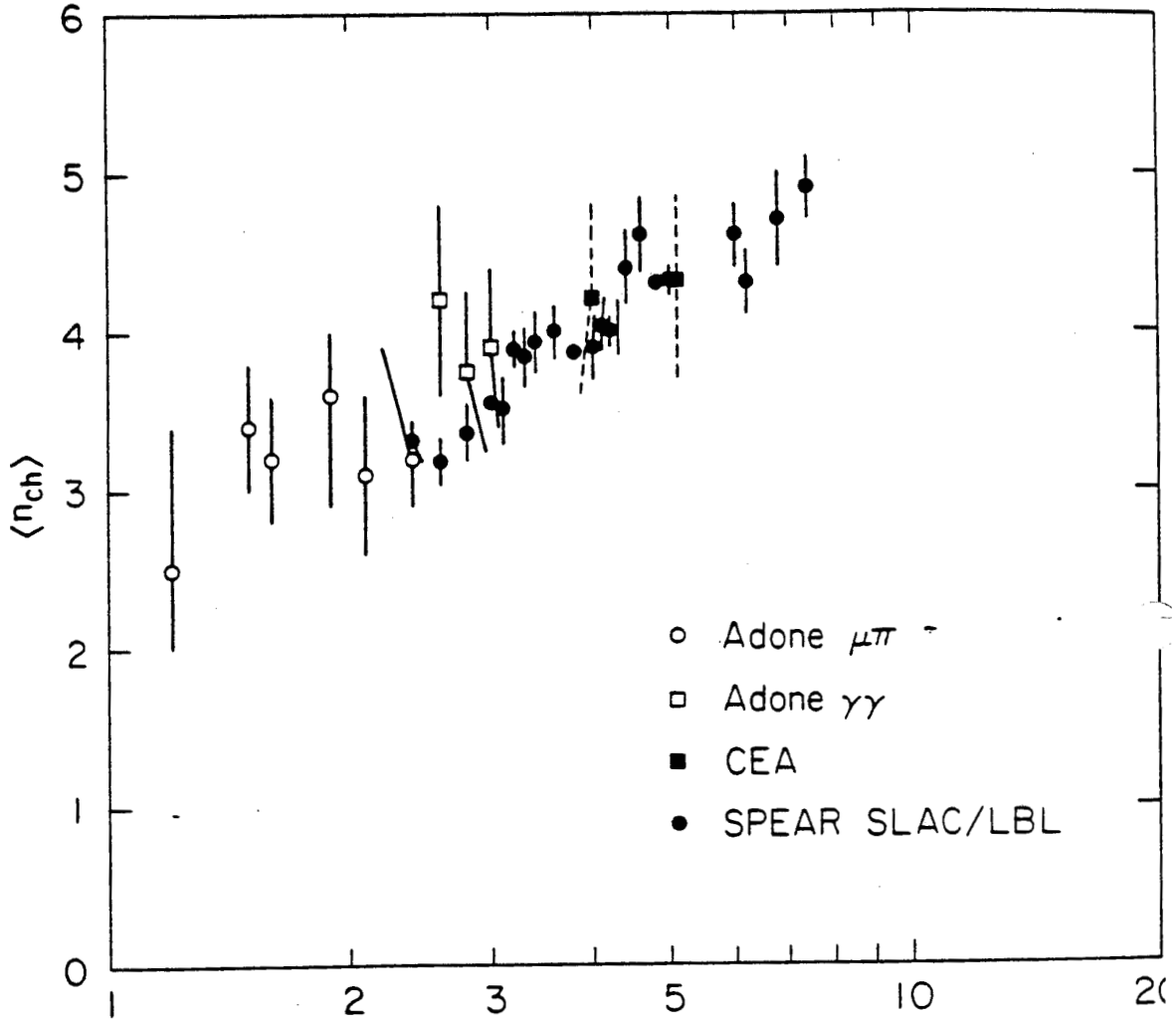
[Plot Fig 8] small acoplanarity, more so at large E_{CM}

Acoplanar: neither close to beam, nor thrust axis particle


$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$
0
1
2
3
4
5
6
0.5
1
1.5
2
2.5
3
E_{cm} (GeV)

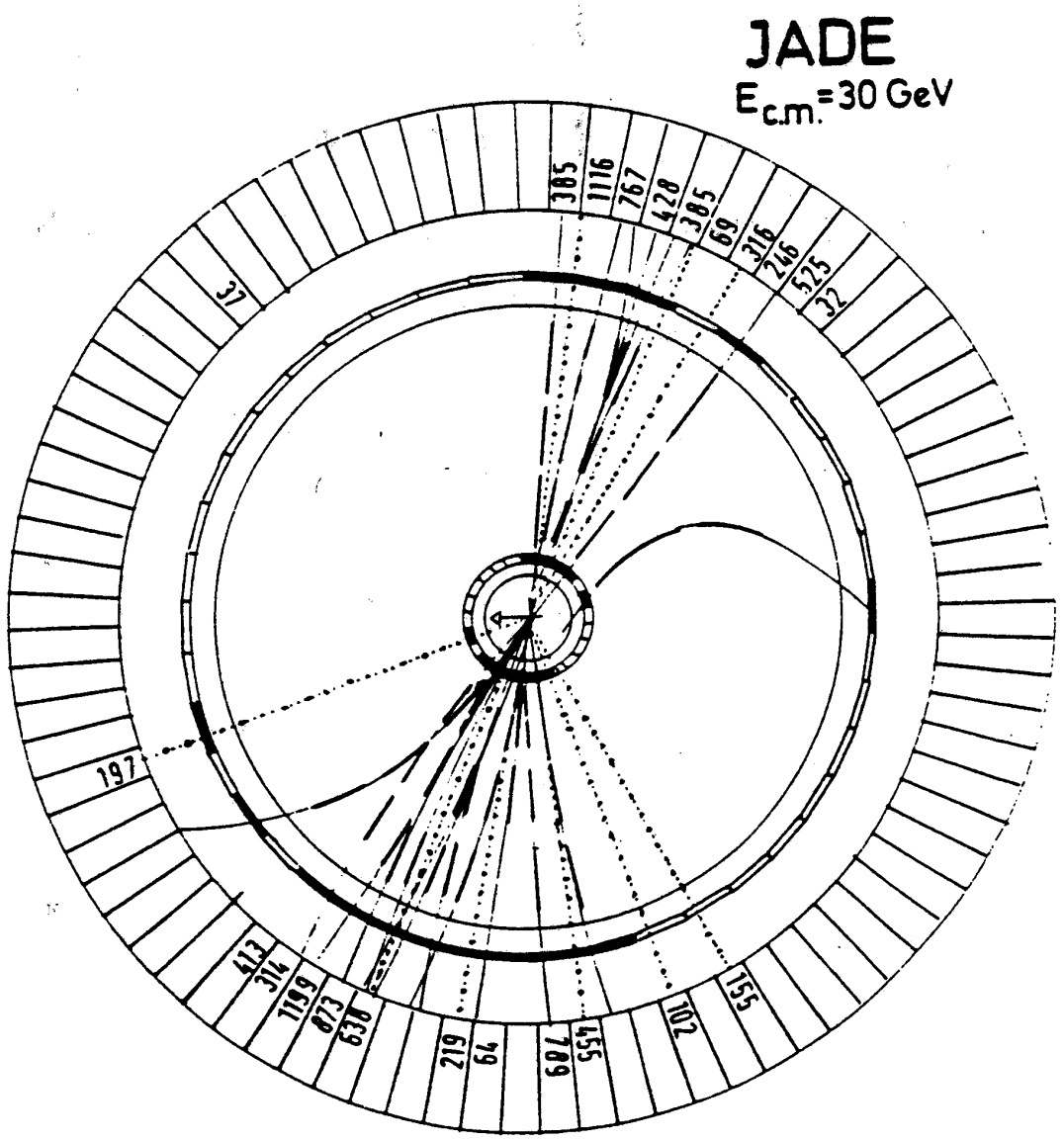
— $e^+e^- \to \pi^+\pi^-$

number of charged particles produced -> jets



data compilation of
R. Schwitters + K. Strauch
Ann. Rev Nucl. Sci. 26, 89 (1976)

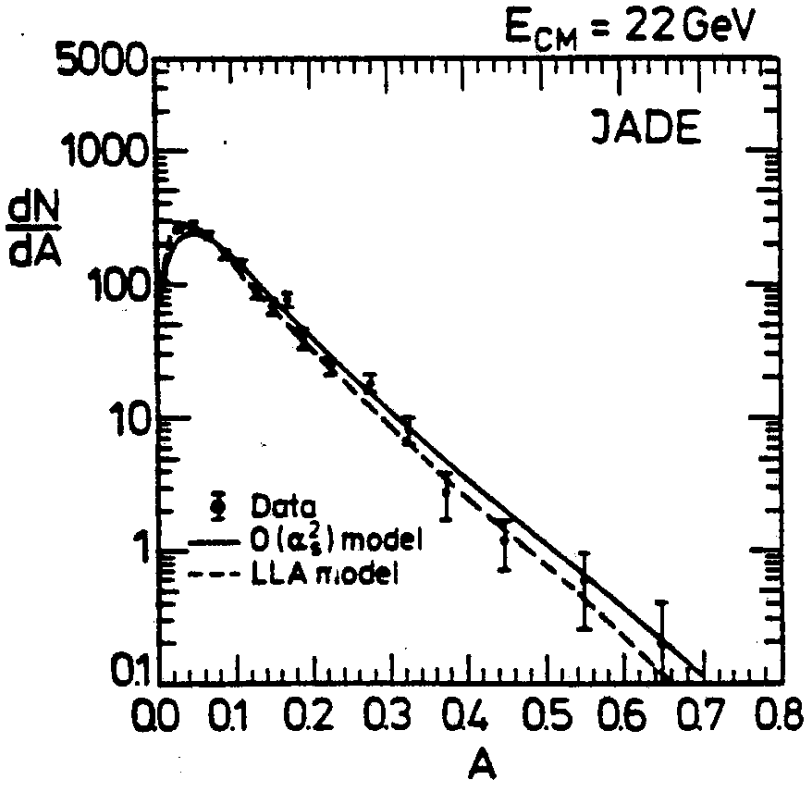
Jets
Thrust axis

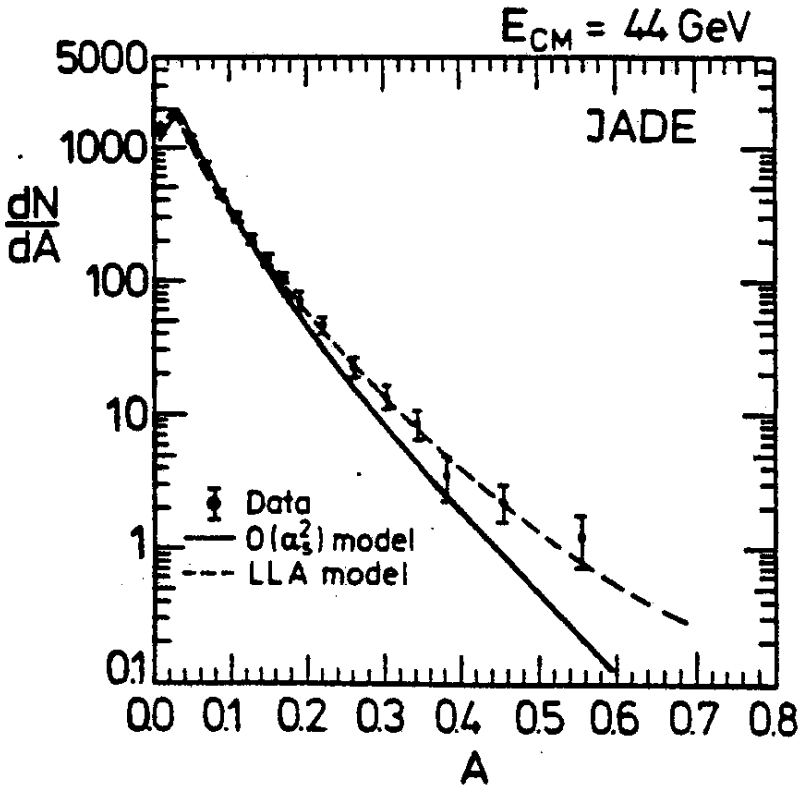


S. Orito

Proceedings of the 1979
Lepton Photon Conference

Acoplanarity





W. Bartel
et al.
(JADE)
Z Phys. C 33,
23 (1986)

Thrust axis direction distribution?

PLOT Fig 9+10

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta)$$

Lesson 3

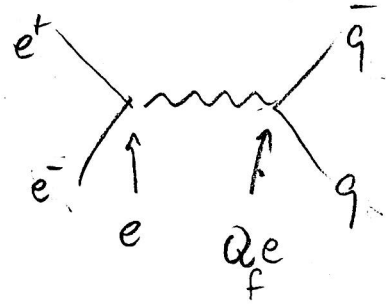
Lessons 1+2: pair production of energetic particles which "hadronize" into many hadrons

3: massless, spin ½ fermions

i.e. quarks!

we can compute this:

same as $e^+e^- \to \mu^+\mu^-$



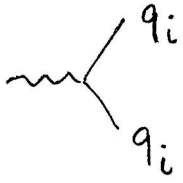
$$R_h = \sum_{\substack{f \\ 2m_f < E_{CM}}} Q_f^2 = \underbrace{(2/3)^2}_{u} + \underbrace{(-1/3)^2}_{d} + \underbrace{(-1/3)^2}_{s} = 2/3$$

too small!

$R_h \sim 2$

PLOT Pg 7

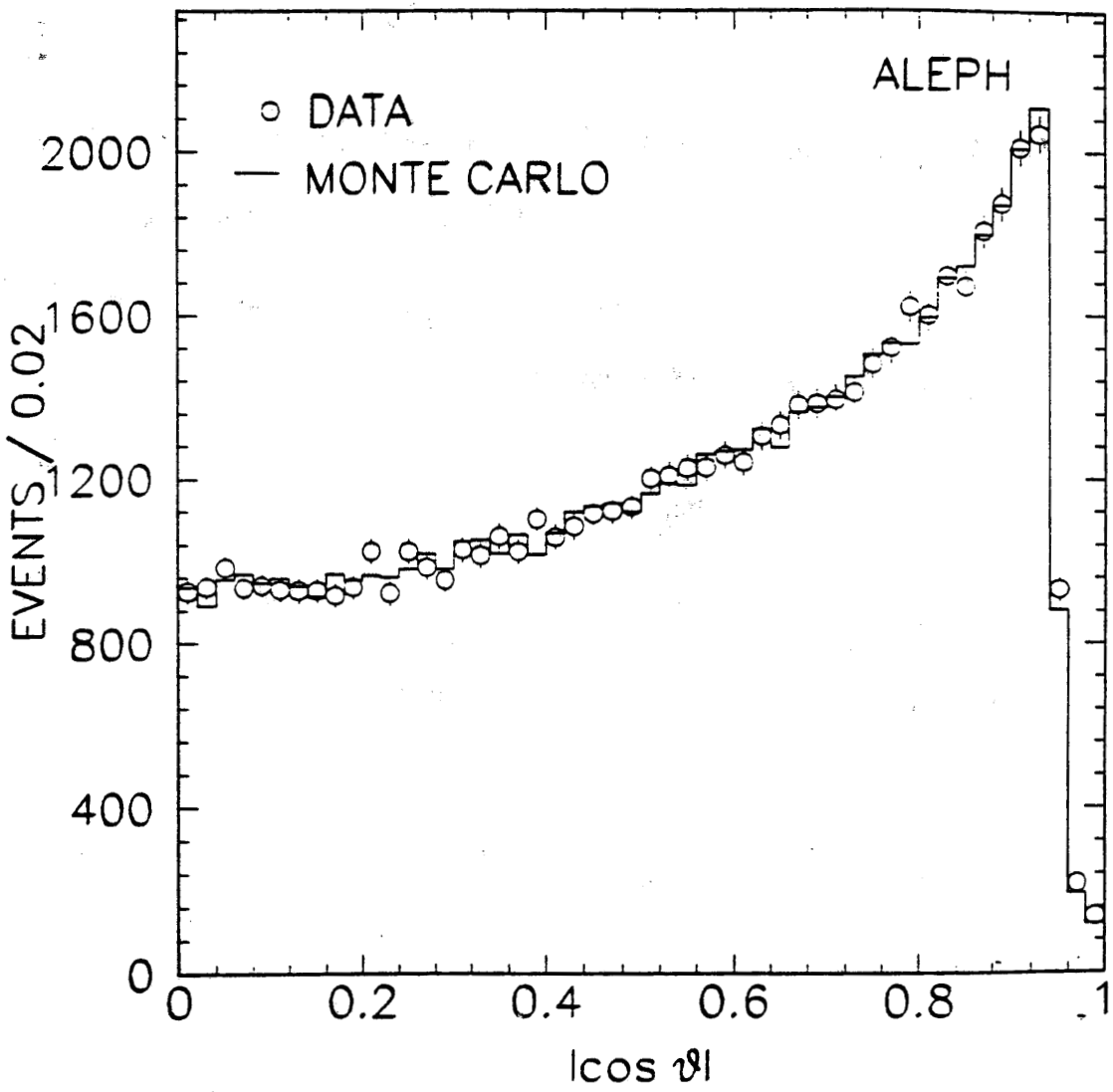
3 colors i



$$\Rightarrow R_h = \sum_f 3Q_f^2 = \begin{cases} 2 & uds \\ 3\,1/3 & +c \\ 3\,2/3 & +b \end{cases}$$

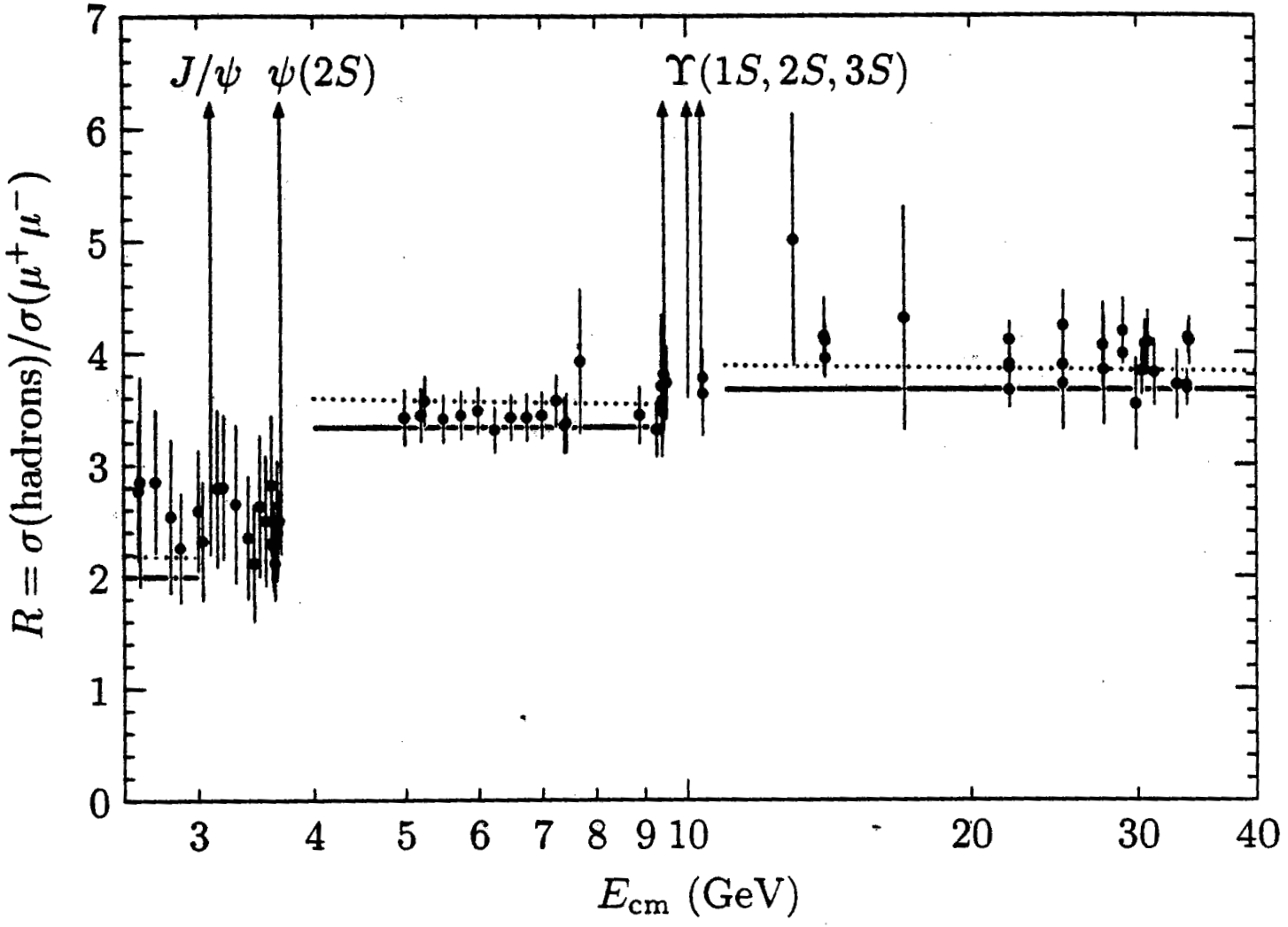
(approx. massless quarks)

Thrust axis angle



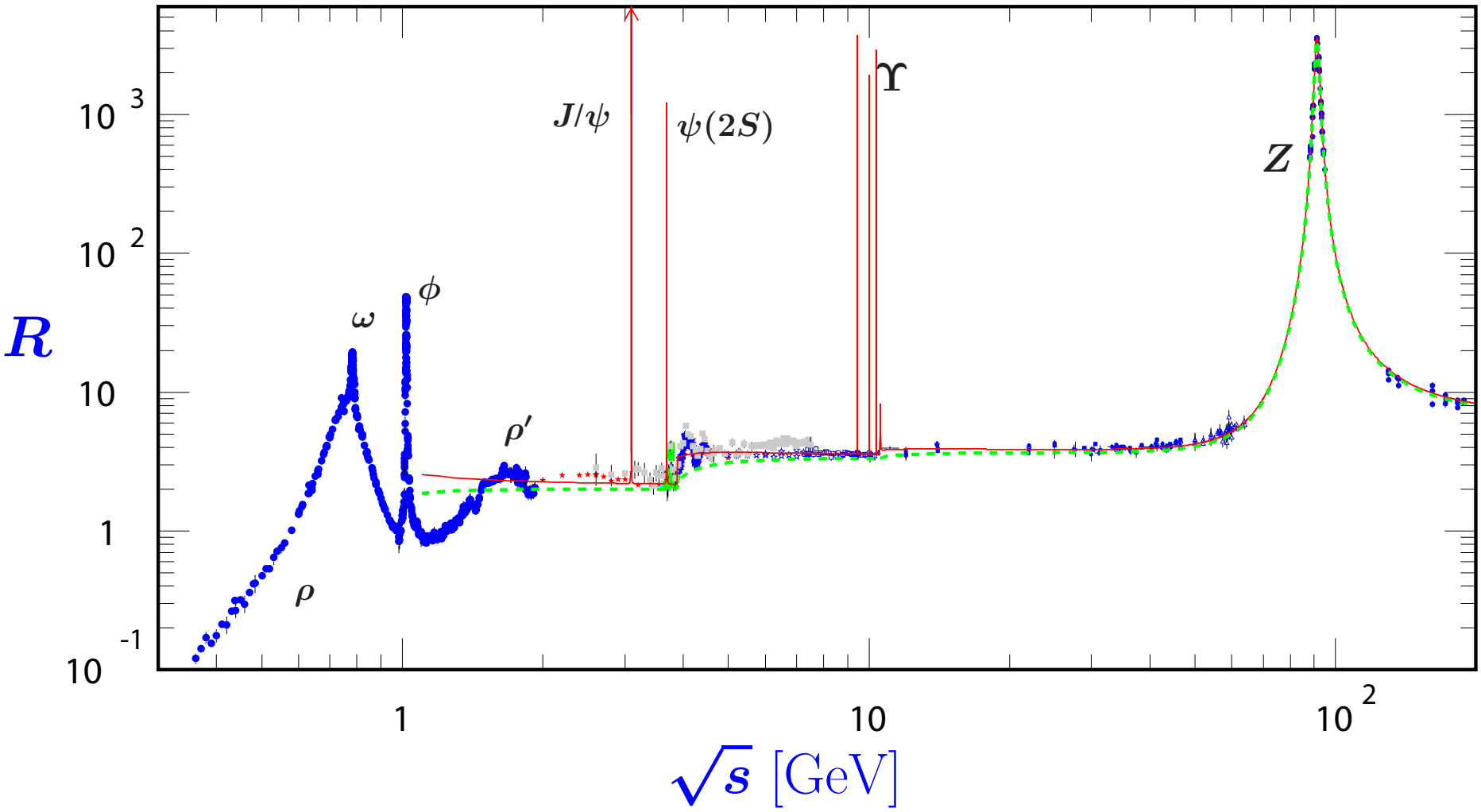
D. Decamp (ALEPH)
Z. Phys. C48, 365 (1990)

R in e^+e^- Collisions



data compiled by M. Swartz.

R in e^+e^- Collisions



Particle Data Group compilation (2018)

PLOT Fig 11

dotted line is radiative corrections

nice fit to theory, resonances near threshold

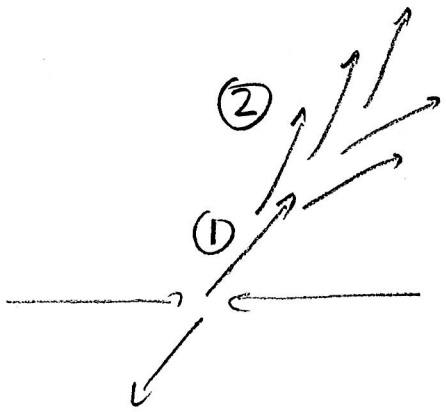
J/ψ ↑ discovery of charm

Υ ↑ discovery of bottom

scattering "factorizes" into

1. hard process (large momentum transfer) $e^+e^- \to q\bar{q}$

2. soft process (small " ") hadronization "fragmentation"



e.g. string model of hadronization