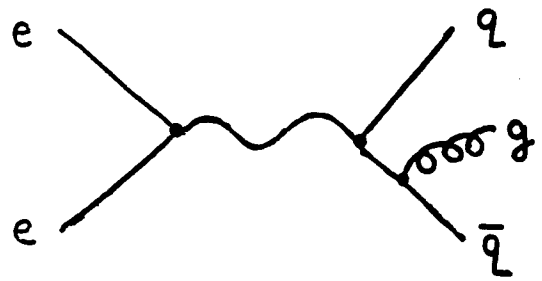
Jets from e^+e^- annihilations:



What's understood and What's not ?

J. William GARY

U. California, Riverside

Principal Topics in e^+e^- Jet Physics

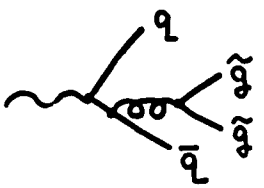
→ Are there controversial or unresolved issues?

→ Is there a failure of pQCD ?

1) jet rates

2) jet energy and angular distributions
   → 3-, 4- and 5-jet matrix elements

3) 4- and 5-jet angular correlations
   → Casimir factors C_A, C_F, T_F
   → sensitivity to gluino $\tilde{g}$

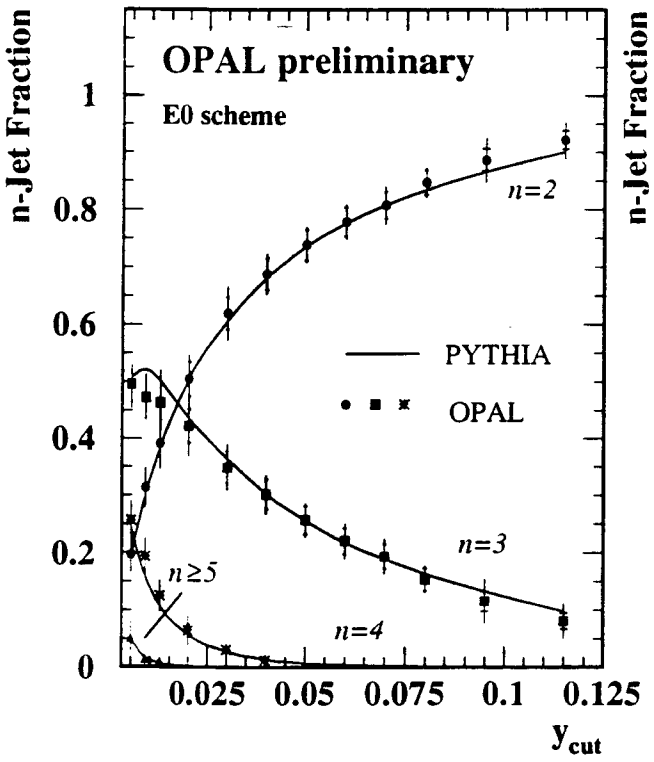


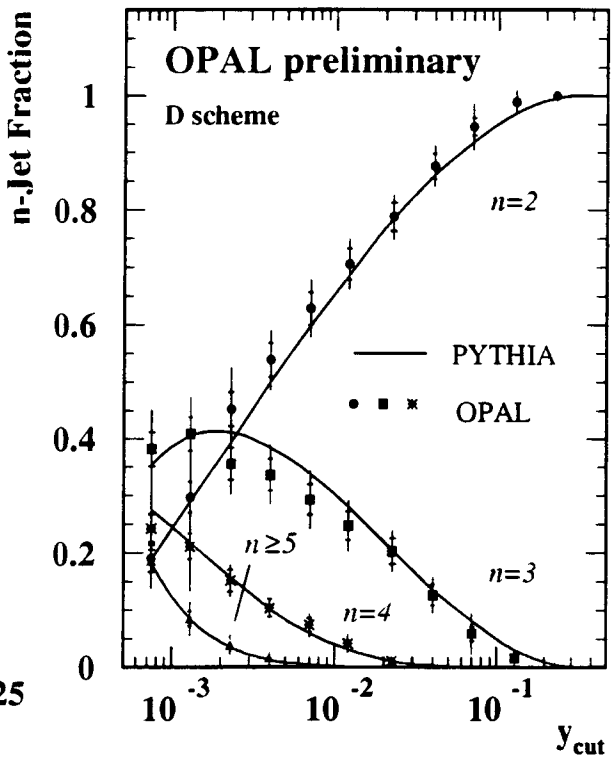
4) Coherence and LPHD
   → distribution of soft particles in jets

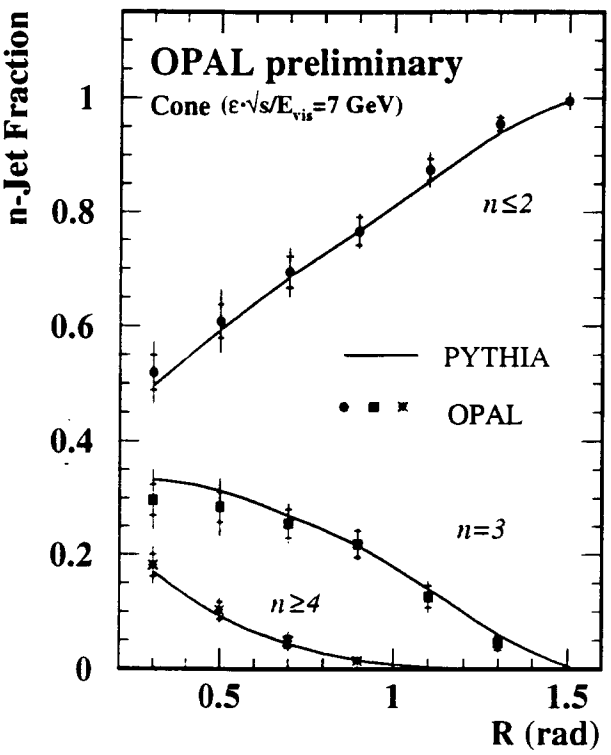
5) Separated gluon and quark jets
   → test of analytic prediction
   $\langle n \rangle_{gluon} / \langle n \rangle_{quark} = C_A/C_F = 9/4$ l.o.

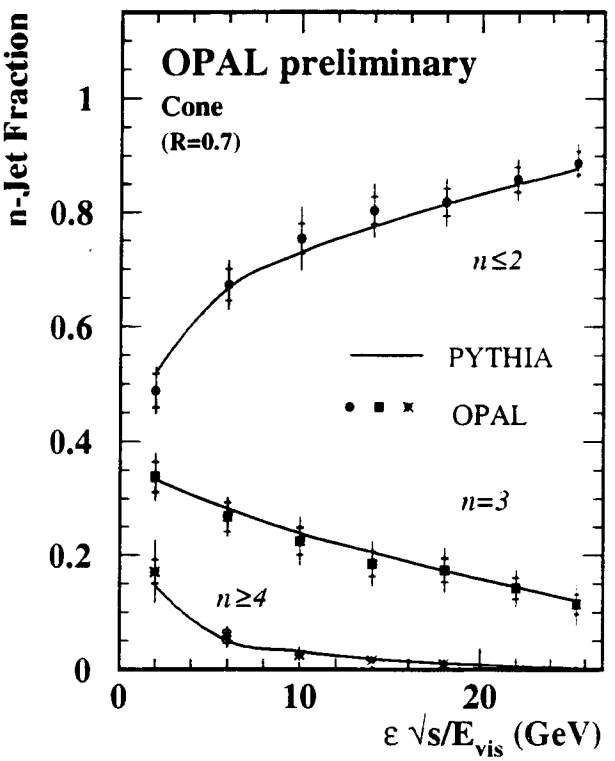
6) Tests of jet universality
   → connection with $p\bar{p}$, splashout

e^+e^- jet rates at $\sqrt{s}$ = 161 GeV



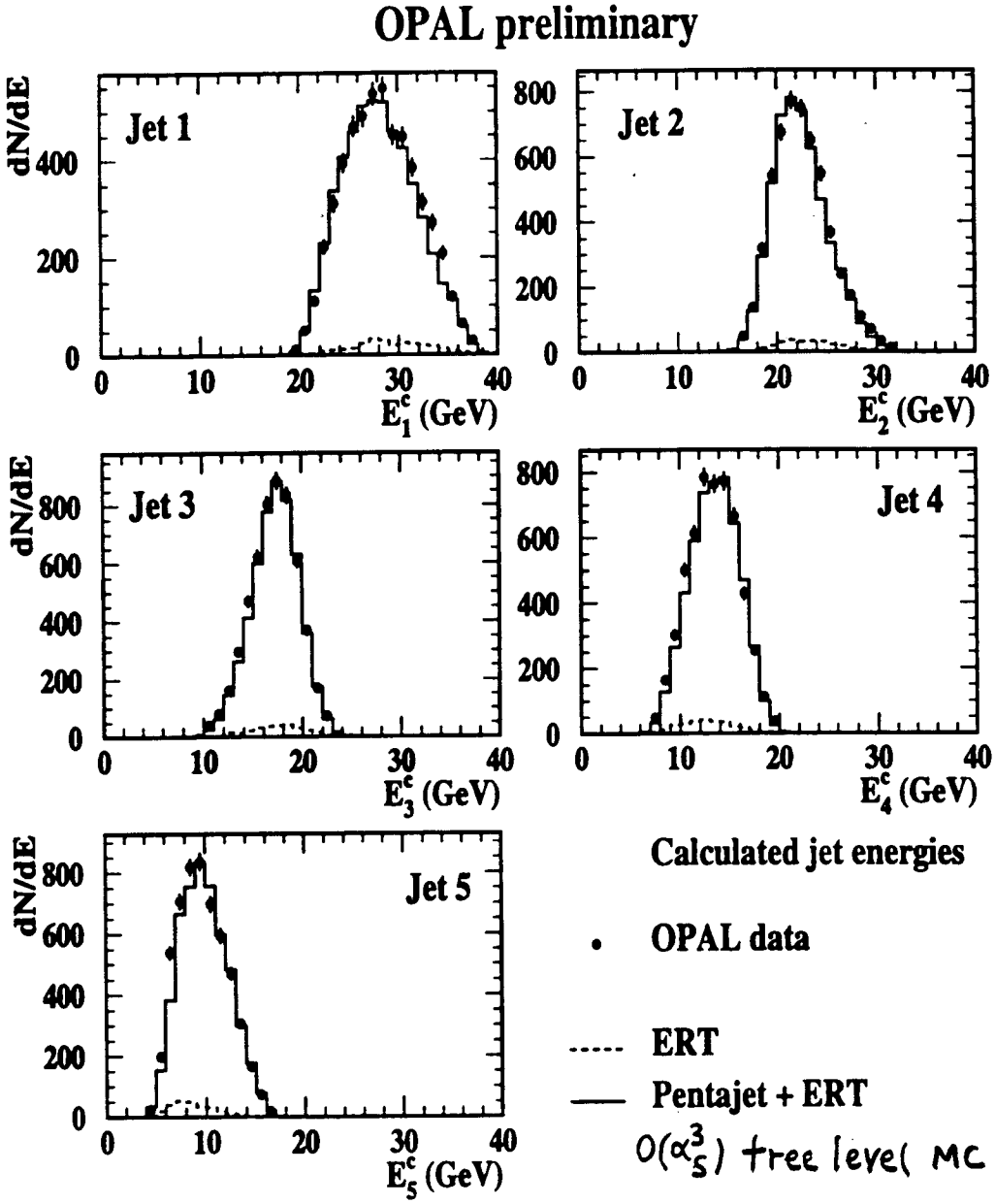






Test of the 5-jet matrix element

$\sqrt{s}$ = 91 GeV



gluon jet content ~ 35, 50, 60, 70, 80 %
for the five jets $E_1 > E_2 > E_3 > E_4 > E_5$

$\tilde{g}$ with $m_{\tilde{g}} \lesssim 1.5$ GeV not excluded

From B. Kileng, P. Osland, 9th Int. Workshop on HEP and QFT (Moscow 1994)

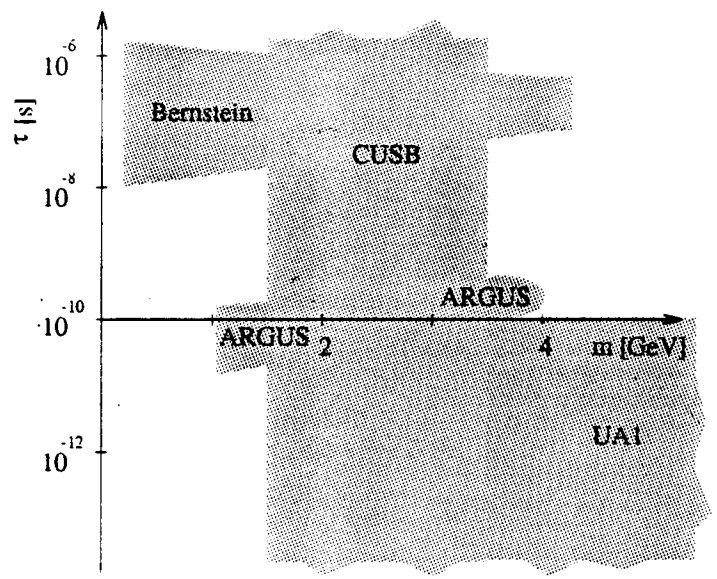
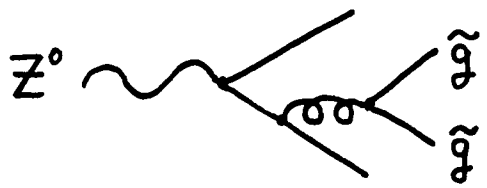


Fig. 1

Reproduced in S. Moretti, R. Muñoz-Tapia, K. Odagiri, hep-ph/9609295 (Sept. '96)
UG-FT-68, DFTT 25/96, Cavendish-HEP-96/6

Light gluinos $\tilde{g}$ in e^+e^- 4-jet events

→ mimic the angular structure of the 4-quark final-state



"light gluino": $m_{\tilde{g}} \lesssim 1.5$ GeV

→ effective nr. of flavors increases from $n_f \simeq 5$ to $n_f \simeq 8$ in the Limit that $m_{\tilde{g}} \simeq 0$

→ appears as an increase in $\frac{T_F}{C_F}$:

$$\text{"}\frac{T_F}{C_F}\text{"} = \frac{1}{n_f}\underbrace{\left(\frac{T_F}{C_F}\text{"}n_f\text{"}\right)}_{\text{measured quantity}} = \frac{1}{5}\left(\frac{3}{8}\cdot 5\right) = \frac{3}{8} \quad \underline{\text{QCD}}$$

$$\frac{1}{5}\left(\frac{3}{8}\cdot 8\right) = \frac{3}{5} \quad \underline{\text{QCD} + \tilde{g}}$$

$\underline{n_f = 5}$: b quark treated as fully active in the perturbative development of a jet

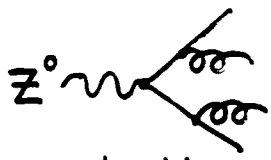
Color factors from 4-jet events

(ALEPH/DELPHI/L3/OPAL)

2nd order (tree level) expression for $e^+e^- \to$ 4 jets

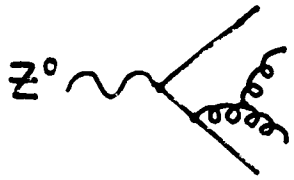
$$\frac{1}{\sigma_0} d\sigma(e^+e^- \to 4\,\text{jets}) = \left(\frac{\alpha_s C_F}{\pi}\right)^2 \times$$

$$\Big[\sigma_A(y) + \left(1 - \frac{C_A}{2C_F}\right)\sigma_B(y)$$



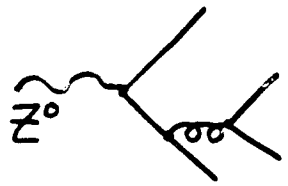
double bremsstrahlung

$$+ \frac{C_A}{C_F}\sigma_C(y)$$



triple gluon vertex

$$+ \frac{T_F}{C_F} n_f \sigma_D(y) + \left(1 - \frac{C_A}{2C_F}\right)\sigma_E(y)$$



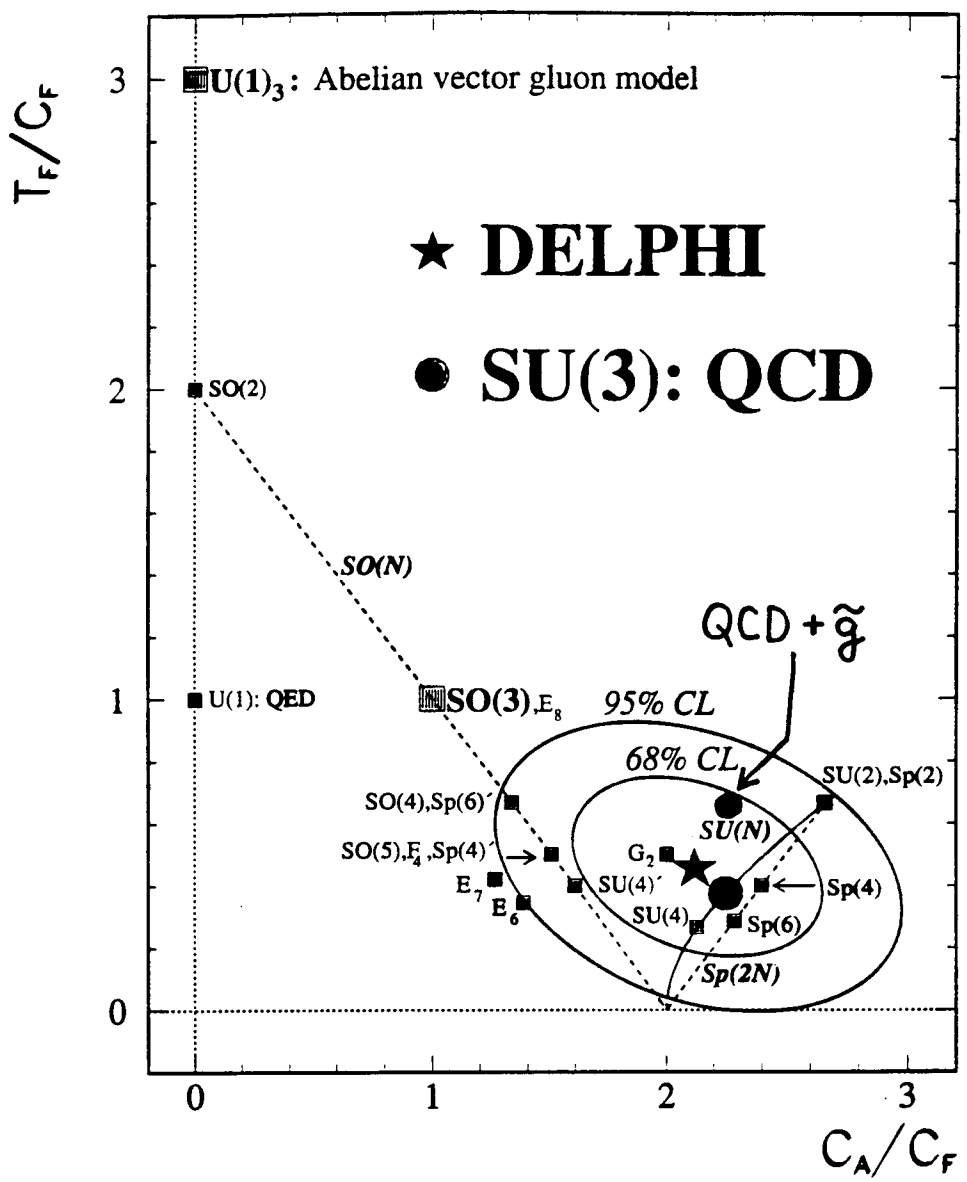
4-quark final-state

$$\Big] dy$$

$\sigma_A \cdots \sigma_E$: group independent factors

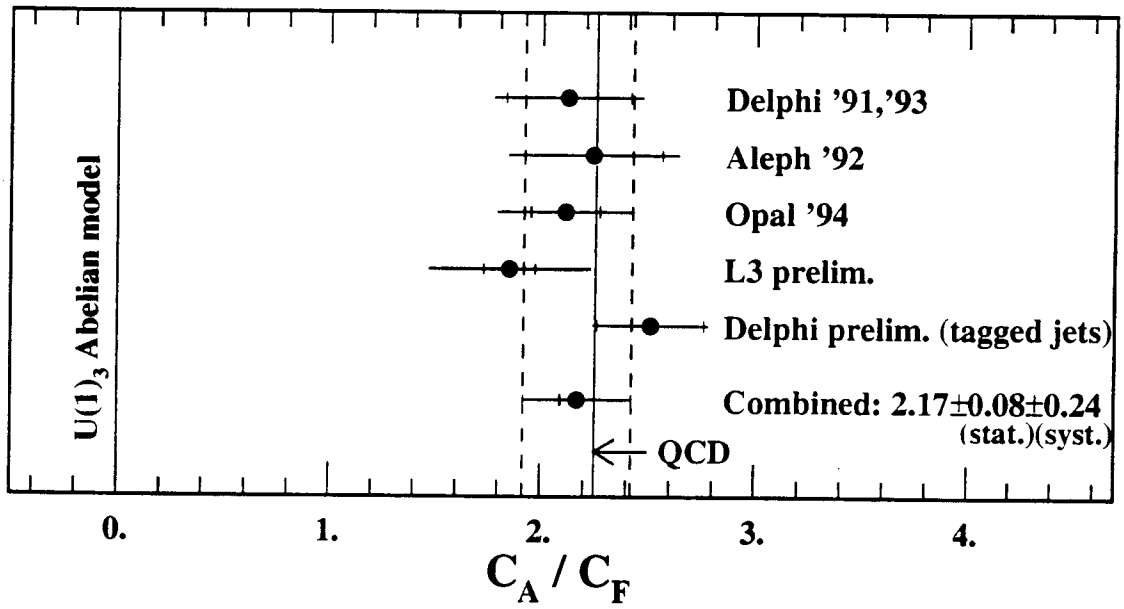
y : 2-jet invariant masses (angular correlations)

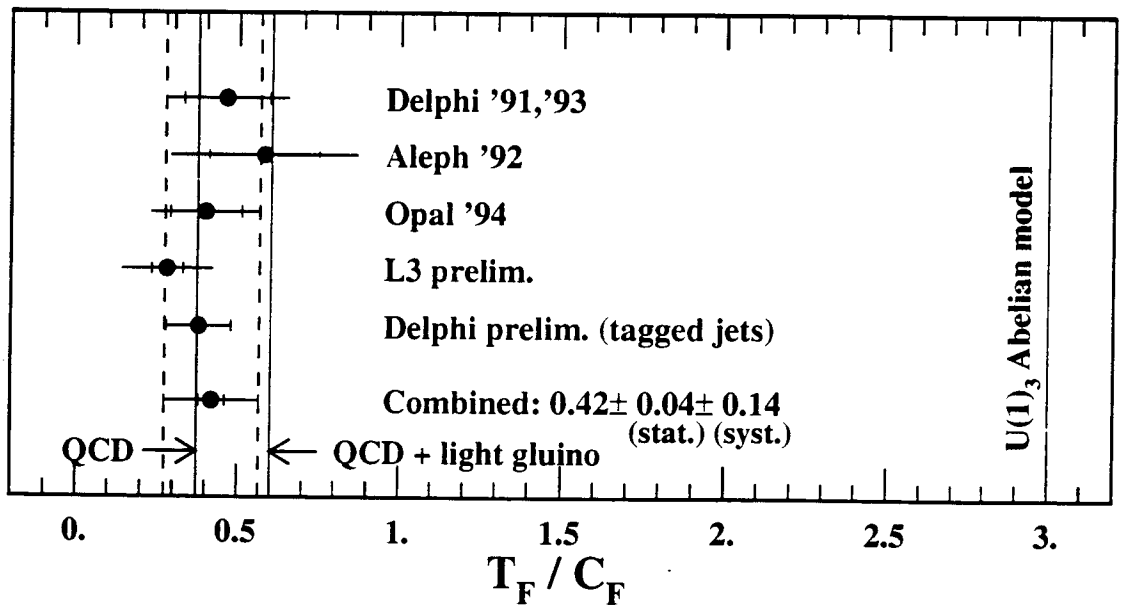
Results for color factor ratios $\frac{C_A}{C_F}$ and $\frac{T_F}{C_F}$



→ Some correlation between the C_A/C_F and T_F/C_F results

Color factor ratios from 4-jet events



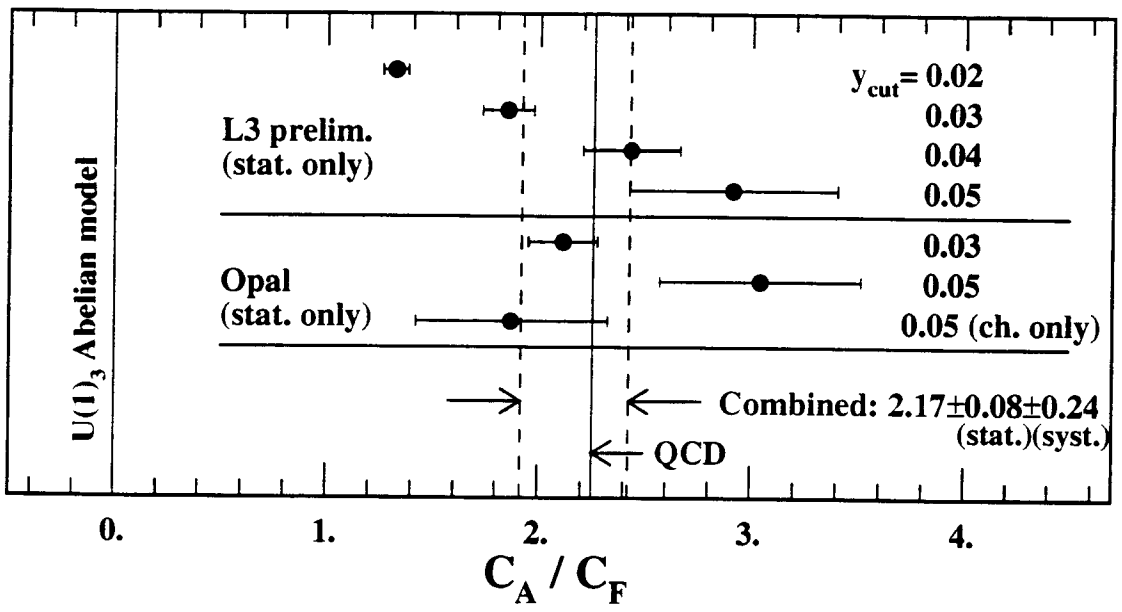


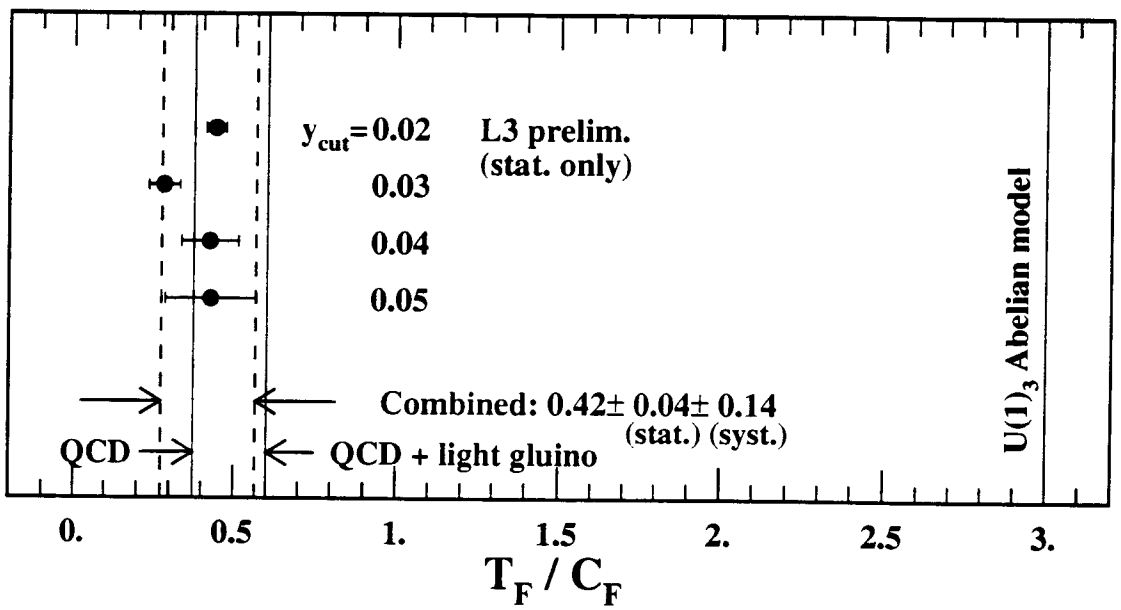
massive b quark → reduces effective n_f

gluino $\tilde{g}$ → increases " "

The two could (partially) compensate each other

y_{cut} dependence of color factor ratios





OPAL: no y_{cut} dependence observed for $\frac{T_F}{C_F}$
(i.e. the same as the L3 observation)

y_{23} dependence of C_A/C_F →

- doesn't much affect the overall result (gauge group structure underlying the strong interaction)
- no y_{23} dependence observed for T_F/C_F

but it does represent an important systematic effect which is not understood

Possible origin:

(1) Deficiencies in the QCD simulation?
- tree level 4-jet M.E.
- 2-, 3-, 5-jet background

(2) Deficiencies in the detector (calorimeter) simulation? (→ OPAL interpretation)

(3) New physical phenomena?

→ Needs a careful investigation

A. de Gouvêa, H. Murayama

LBL-39030 (hep-ph/9606449, June 1996)

→ overwhelming experimental support for QCD suggests that $C_A/C_F = 9/4$ is not in doubt

1) Fix $\frac{C_A}{C_F}$ to $\frac{9}{4}$

2) Perform a 1-D χ^2 fit to the LEP 4-jet data to determine T_F/C_F

→ $\frac{T_F}{C_F} = 0.36 \pm 0.15$ (OPAL data only)

[uncertainty ~ 50% stat., ~ 50% syst.]

versus $\frac{T_F}{C_F} = 0.42 \pm 0.15$ (LEP combined result)

[uncertainty ~ 100% syst.]

de Gouvêa, Murayama → gluino with $m_{\tilde{g}} \lesssim 1.5\,\text{GeV}$ excluded at 90% c.l.

Conclusion

→ the data marginally prefer QCD over QCD + $\tilde{g}$ (assuming $n_f = 5$ for QCD, i.e. five fully active flavors)

→ the issue of a light $\tilde{g}$ remains unresolved.

Potential improvements to the data analysis which could help resolve the issue:

- full 1-loop M.E. calculation of $e^+e^- \rightarrow 4$ jets
- tagged quark jets (DELPHI, prelim.)
  - → better identification of G, Q jets than energy ordering
  - → better sensitivity to the color factors

→ systematic effects (your dependence of $\frac{C_A}{C_F}$) not fully understood

Coherence and LPHD

- Coherence: QCD interference affecting the multiplicity and radiation pattern of soft gluons

- LPHD (Local hadron-parton duality): the distribution of soft hadrons can be directly compared to that of soft gluons;

Investigations of Coherence/LPHD at LEP

1) Fragmentation function $x_p = 2p/E_{c.m.}$

→ logarithmic distribution $\xi_p \equiv \ln(1/x_p)$ ★

2) $\langle n_{ch.} \rangle$ versus $E_{c.m.}$ ★

3) Two-particle correlations

i) momentum (ξ_1, ξ_2) ★

ii) azimuthal

iii) PPC (particle-particle correlation)

4) Interjet multiplicity → "String effect" ★

5) Subjet multiplicity ★

★ : comparison of data to analytic formulae

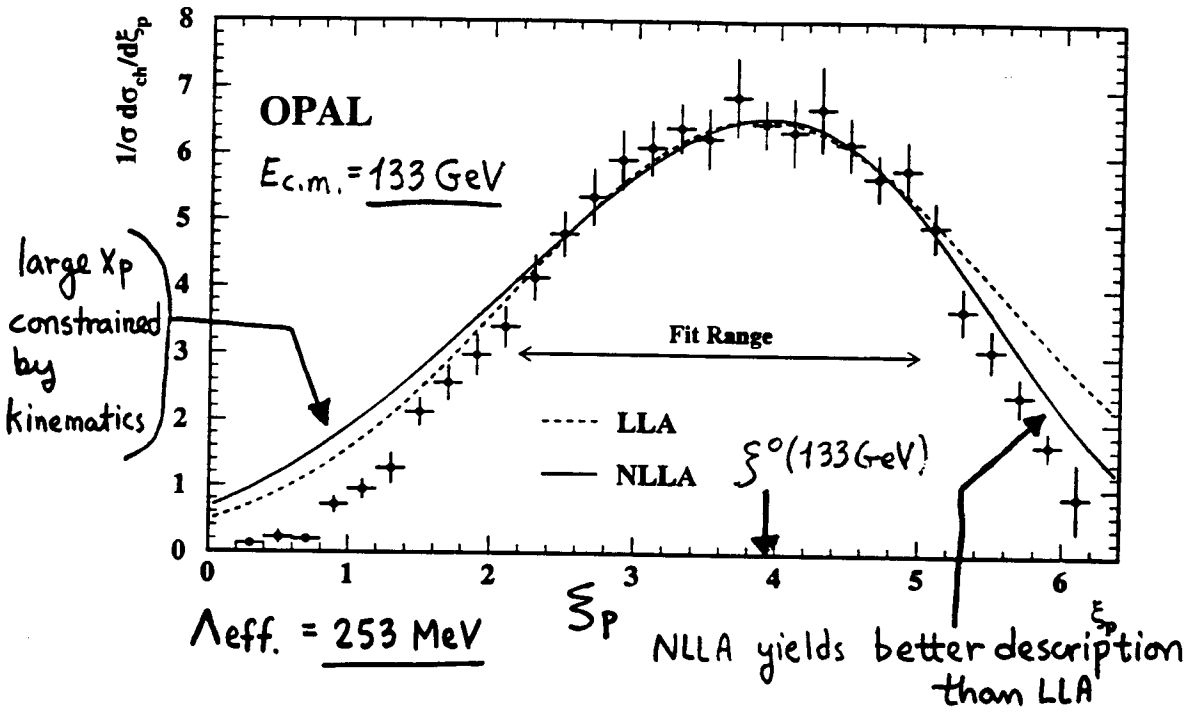
MLLA, NLLA } all leading and next-to-leading logarithmic terms

(Differ in the integration methods to obtain H.O.T.)

MLLA: energy conservation sometimes included, not $\vec{p}$ cons.

Single Particle Momentum Distribution

$$\xi = \ln(1/x_p)$$

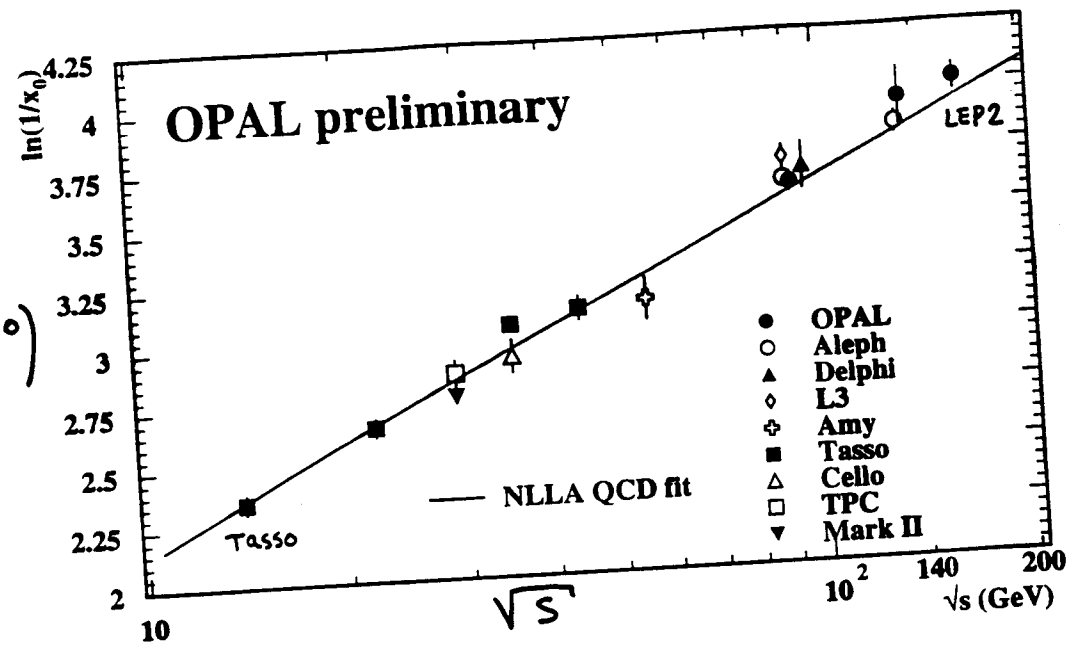


Free parameters for fit of NLLA formula:

(1) $\Lambda_{eff.}$: effective QCD scale
(energy independent)

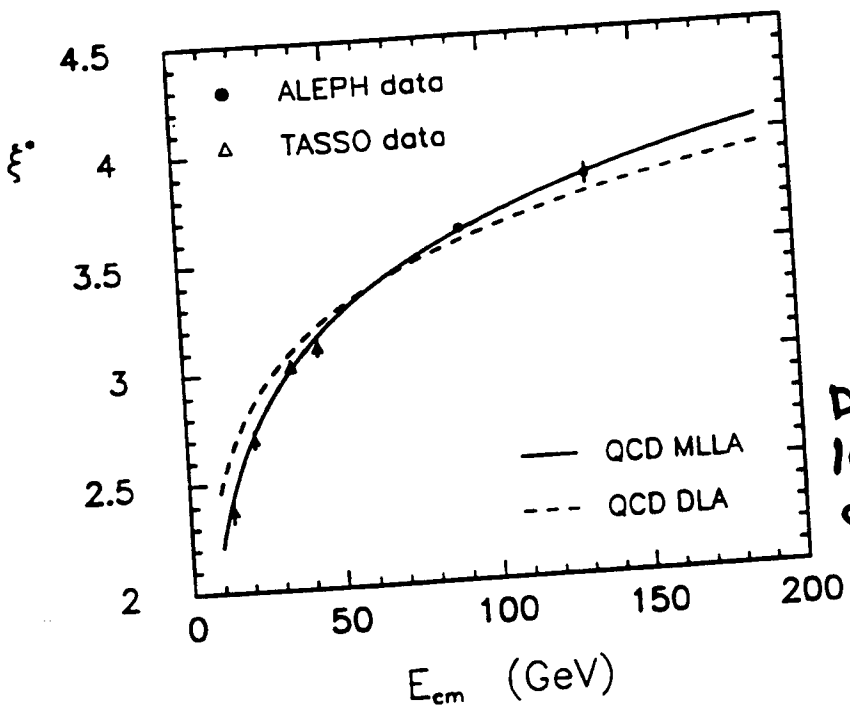
(2) Overall normalization
(c.m. energy dependent)
→ not relevant for the peak position ξ^*

Peak Position ξ^* versus $E_{c.m.}$



$\ln(\xi^*)$

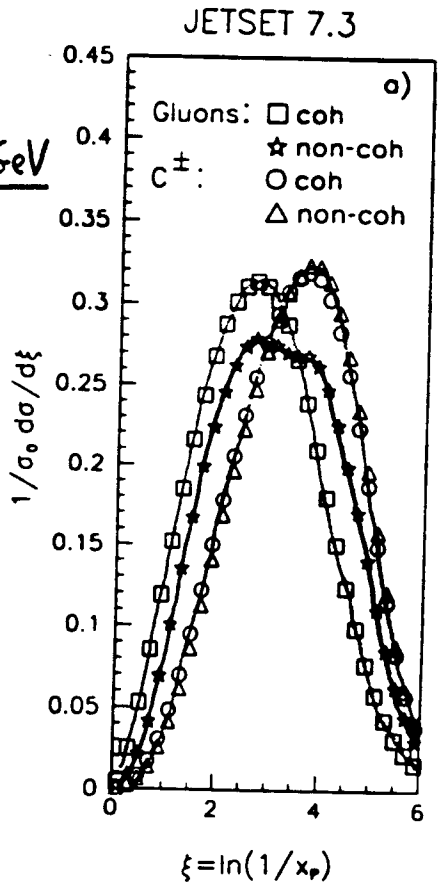
fit → $\Lambda_{eff} = 263 \pm 4$ MeV
(the single free parameter)



DLA = leading order

E.R. Boudinov, P.V. Chliapnikov, V.A. Uvarov
Phys. Lett. B309 (1993) 210.

$E_{c.m.} = 91\,GeV$



parton level:
— □ — with coherence
— ☆ — no coherence

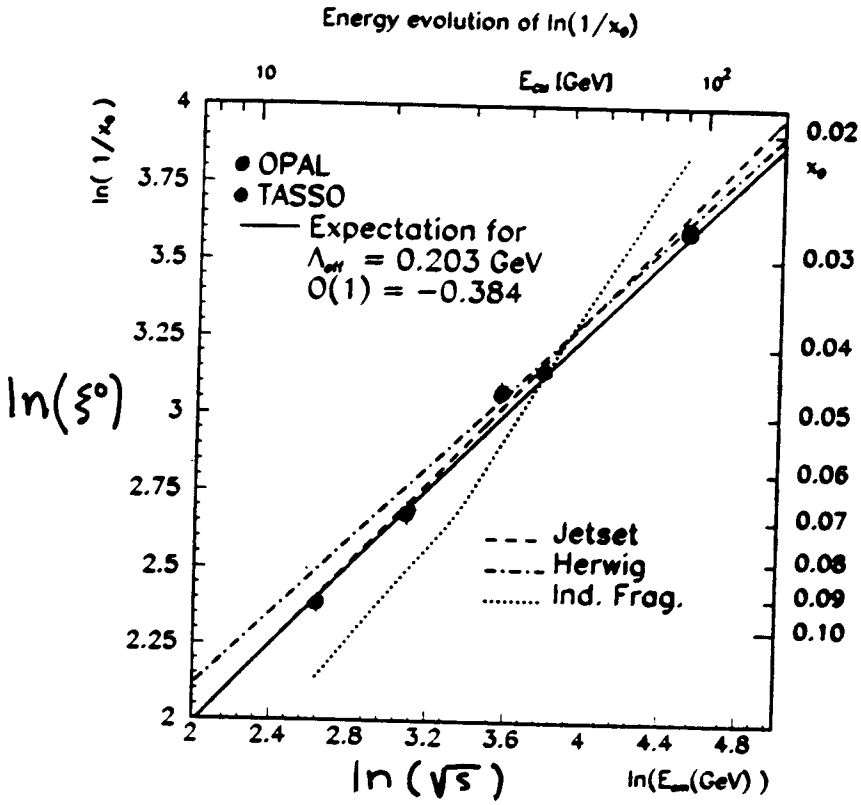
hadron level:
— ○ — with or
— △ — without coherence
coherence

→ MC distributions with and without coherence yield different parton distributions, the same hadron distributions

→ Question the sensitivity to coherence, the validity of LPHD for this distribution.

(W. Ochs : MCs should be used with $\Lambda_{eff.} \simeq 250$ MeV, not $\simeq$ 1GeV to make this test)

Chliapnikov et al. : it is possible that the energy evolution of ξ^0 can be explained by phase space



1990 LEP analysis

MC curves suggest that phase space alone is not enough to describe the energy evolution of the data

→ needs to be revisited by the LEP experiments

Two Particle Momentum Correlations

$\xi = \ln(1/x_p)$

$$R(\xi_1, \xi_2) = \frac{D^{(2)}(\xi_1, \xi_2)}{D^{(1)}(\xi_1)\, D^{(1)}(\xi_2)}$$

$$D^{(1)}(\xi) = \frac{1}{N}\frac{dn}{d\xi} \quad ; \quad D^{(2)}(\xi_1, \xi_2) = \frac{1}{N}\frac{d^2 n}{d\xi_1 d\xi_2}$$

(doubly differential distribution)

- Normalization factor associated with LPHD cancels
- Λ_{eff} is the only free parameter

NLLA Calculation → (Webber, Fong)

$$R(\xi_1, \xi_2) = C_1 + C_2(\xi_1 + \xi_2) + C_3(\xi_1 - \xi_2)^2$$

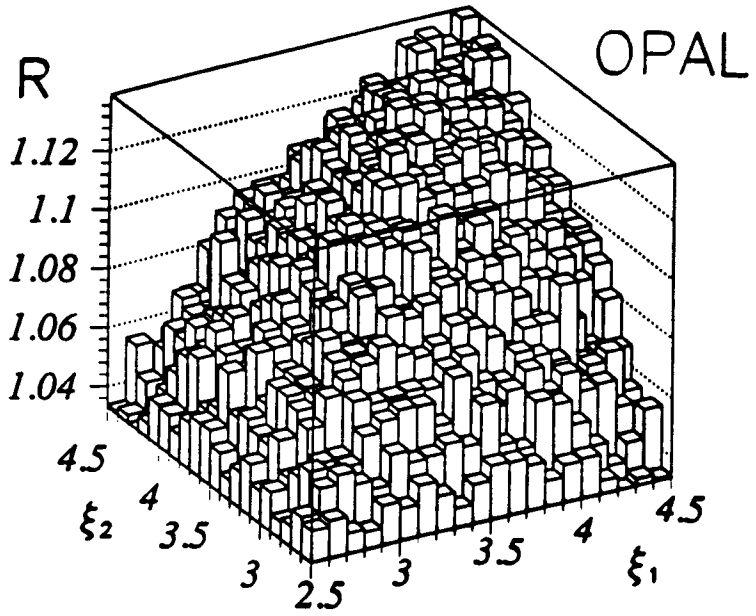
$$C_1 = 1.375 - \frac{1.262}{\sqrt{\ln(Q/\Lambda)}} \qquad C_2 = \frac{0.877}{(\sqrt{\ln(Q/\Lambda)})^3}$$

$$C_3 = -\frac{1.125}{(\ln(Q/\Lambda))^2}$$

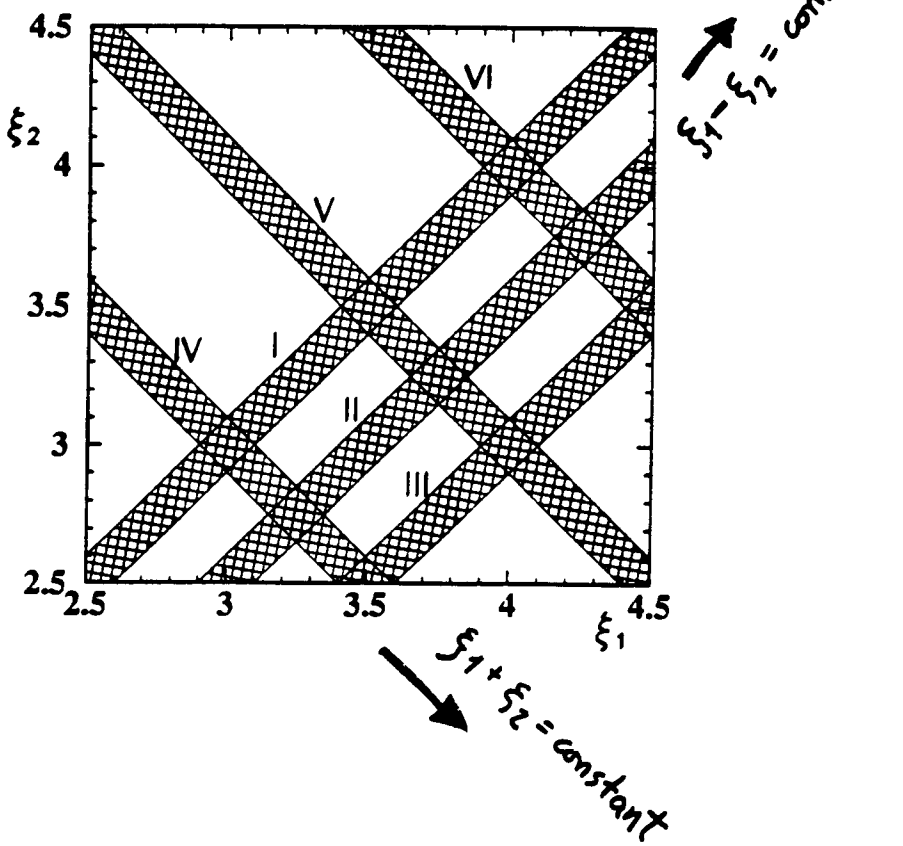
maximum correlation for $\xi_1 \simeq \xi_2$ (since $C_3 < 0$)

Correlation R a maximum for $\xi_1 \approx \xi_2$

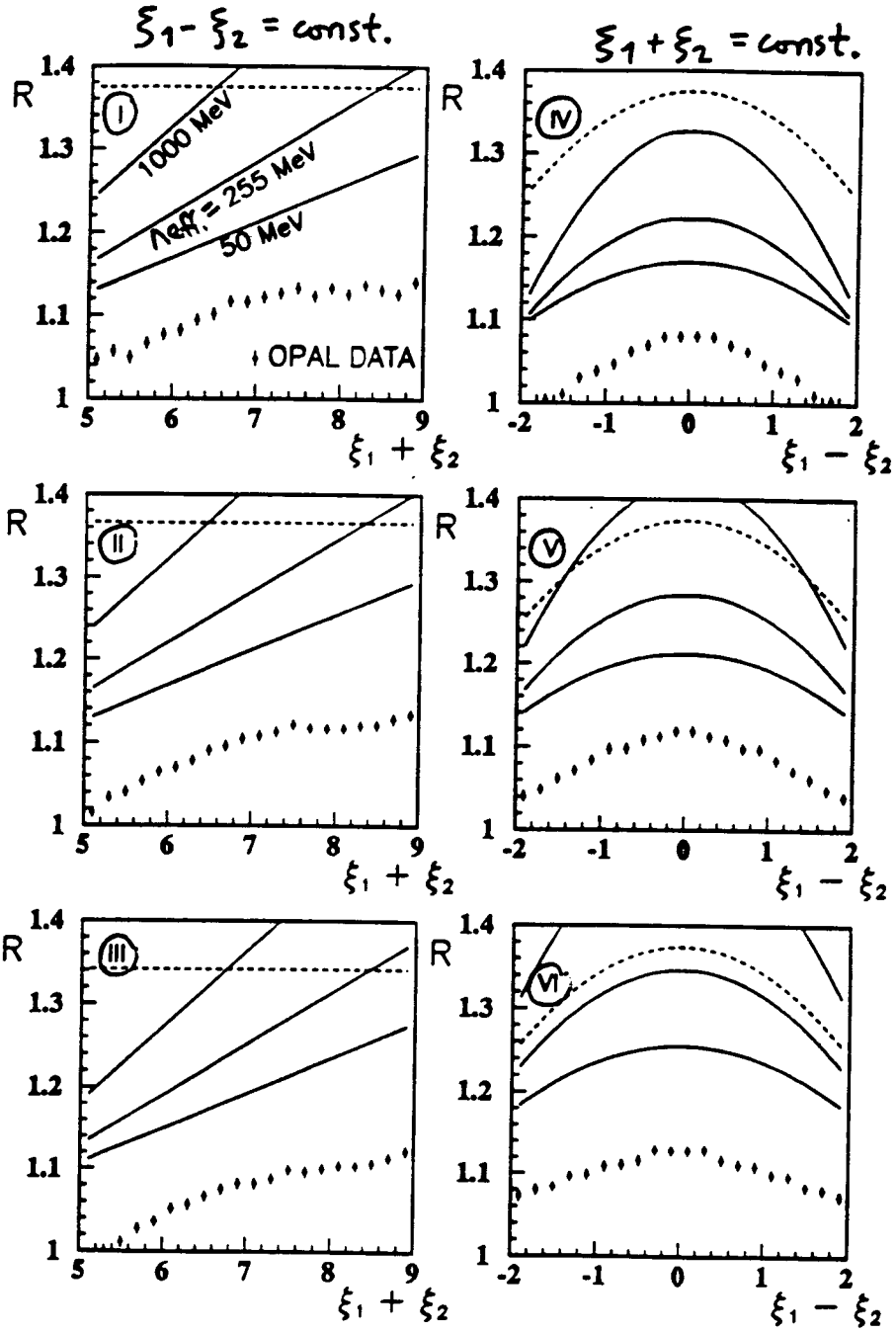
→ qualitative agreement with NLLA calculation



$$R(\xi_1,\xi_2) = c_1 + c_2(\xi_1+\xi_2) + c_3(\xi_1-\xi_2)^2$$



$$R(\xi_1,\xi_2) = C_1 + C_2(\xi_1+\xi_2) + C_3(\xi_1-\xi_2)^2$$



Shape of the correlation is generally <u>the same</u> between data and calculation:

→ linear along lines of constant $\xi_1 - \xi_2$ (bands I, II, III)

→ quadratic along lines of constant $\xi_1 + \xi_2$ (bands IV, V, VI)

but the NLLA theory fails to describe the <u>strength</u> of the correlations.

Fit to full $R(\xi_1, \xi_2)$ distribution:

		$\Lambda_{eff.}$	
C_1	→	32 ± 2	MeV
C_2	→	2^{+5}_{-1}	MeV
C_3	→	60^{+38}_{-27}	MeV

} not consistent and not "reasonable", i.e. not ~ 0 (250 MeV)

χ^2/d.o.f. = 1800/207

with C_1, C_2, C_3 treated as independent parameters

- inconsistency of $\Lambda_{eff.}$ values
- the large χ^2/d.o.f.

→ the data cannot be fitted by the present QCD calculations

(This in contrast to the <u>single particle</u> momentum distribution)

→ Need for higher orders ?

→ Invalidity (misapplication) of <u>LPHD</u> ??

→ need for higher (asymptotic) energies ?

Conclusion

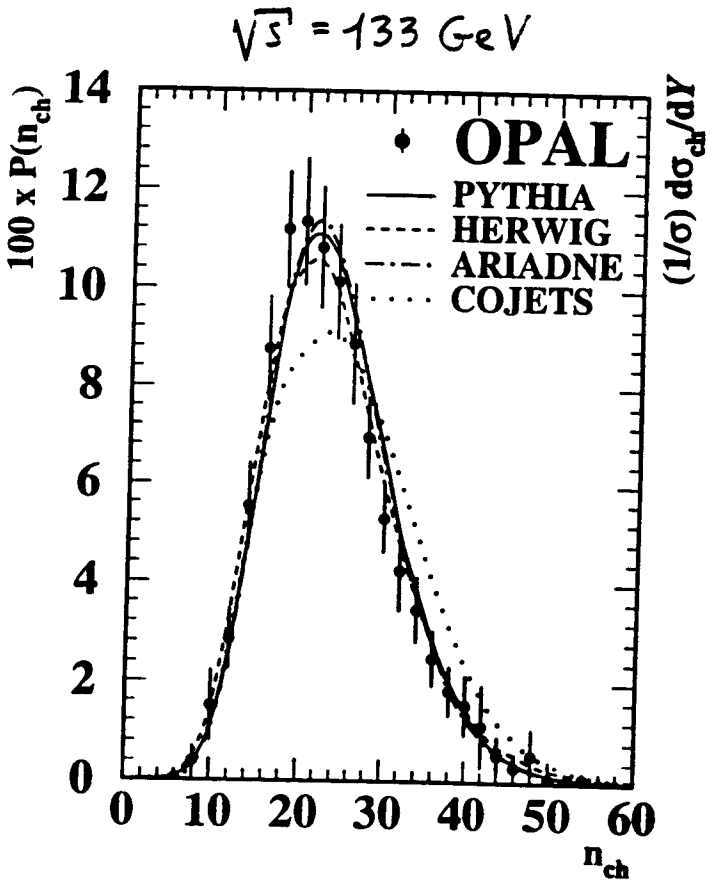
Some controversy regarding the sensitivity of the data to coherence and the validity of LPHD (also for string effect → not discussed here)

The totality of the data yields fairly consistent conclusion that the data are sensitive to coherence phenomena, especially through the study of c.m. energy dependence.

This is perhaps the most challenging area in "confronting QCD with experiment" for e^+e^- jet physics

Cojets Monte Carlo - R. Odorico

→ no coherence in the parton shower



Cojets tuned to the 91 GeV data

→ description at 91 GeV of equal quality to Pythia or Herwig

Energy scaling behavior wrong

→ does not describe the 133 GeV data

Separated Gluon and Quark jets

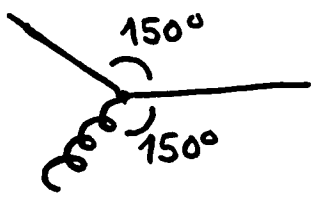
→ mean multiplicity ratio

$$r \equiv \frac{\langle n \rangle_{gluon}}{\langle n \rangle_{quark}}$$

and analytic calculations

Test of QCD analytic predictions for G-Q jet differences

Q-G jet difference studies at LEP have so far been (mostly) based on



⇒ use jet finder

"Y" three jet events (OPAL 1991)

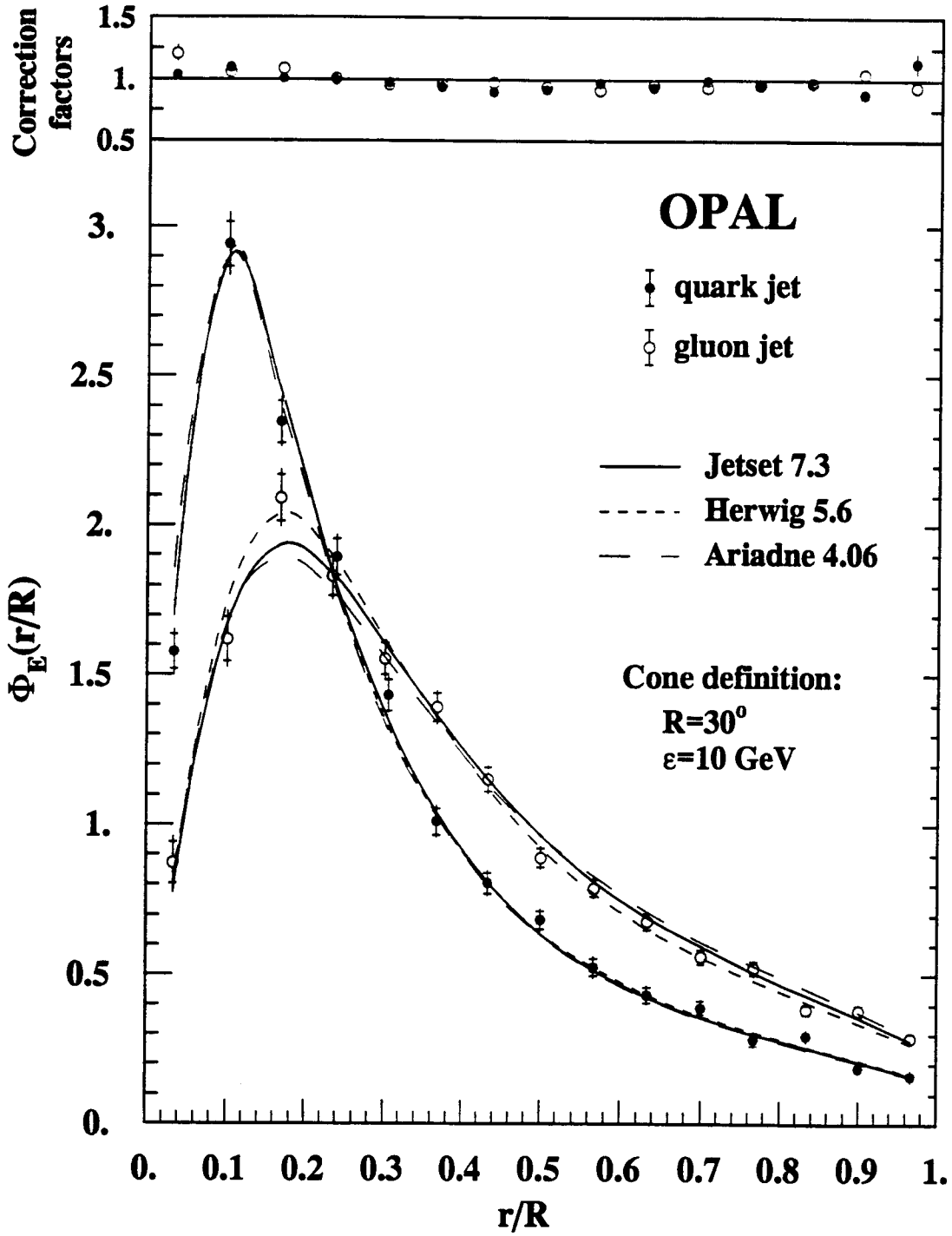
- OPAL 1991, 1993, 1995
- ALEPH 1995
- DELPHI 1995

→ $r_{ch.} \equiv \frac{\langle n_{ch.} \rangle_{gluon}}{\langle n_{ch.} \rangle_{quark}} \simeq (1.20\text{-}1.25) \pm 0.03$

using the $k_\perp$ jet finder

Differential jet energy profile (cone analysis)

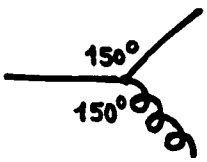
Gluon jets are broader than Quark jets



Ratio Full width at half maximum: G/Q = 1.6

$r_{ch.}$ for Y events

$$r_{ch.} = \frac{\langle n_{ch.} \rangle_{gluon}}{\langle n_{ch.} \rangle_{quark}}$$



d, u, s, c, b
$\approx$ 0.22, 0.17, 0.22, 0.17, 0.21
$\langle E \rangle_{jet} \simeq 24$ GeV

	$K_\perp$	cone	JADE
ALEPH	1.19 ± 0.04		
DELPHI*	1.24 ± 0.03		1.37 ± 0.04
OPAL	1.25 ± 0.04	1.10 ± 0.03	
SLD	1.36 ± 0.24		

* DELPHI quark jet composition ~11% b, ~33% c

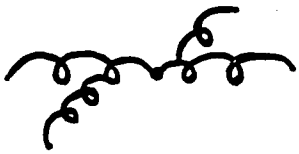
So far: require a jet algorithm to separate particles in a three jet event into a gluon jet part and a quark jet part

→ the results depend on the jet algorithm

$r_{ch.} \simeq 1.10$ cone (OPAL)
$\simeq 1.35$ JADE-Eϕ (DELPHI)

→ the results cannot be directly compared to the QCD analytic prediction

analytic results:

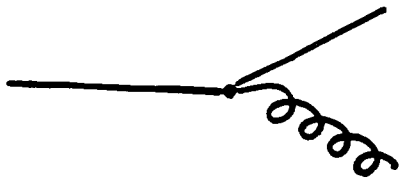


$\langle n \rangle_{gg\,\text{events}}$ → inclusive multiplicity from gg events

$\langle n \rangle_{q\bar{q}\,\text{events}}$ → inclusive multiplicity from $q\bar{q}$ events

$$r_{analytic} = \frac{\langle n \rangle_{gg\,\text{events}}}{\langle n \rangle_{q\bar{q}\,\text{events}}} = \frac{9}{4}$$ leading order

NOT the same as a 3-jet event



(requires a jet finding algorithm, is restricted to 3-jet events, and uses the jet finder to assign particles to the quark and gluon jets)

$q\bar{q}$ events → natural e^+e^- annihilation sample

gg events → not a naturally occuring process in e^+e^- annihilations

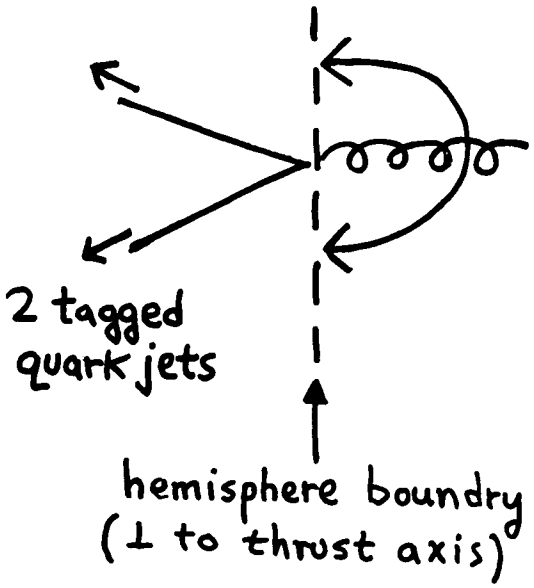
but

has the same color structure as

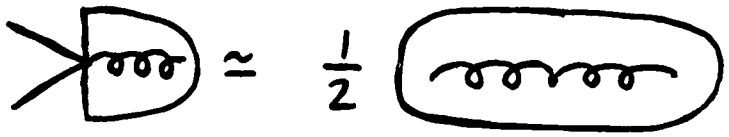
(in the limit that q and $\bar{q}$ are colinear)

and it IS an event class in Z^0 decays

Analysis method : JWG, PRD49 (1994) 4503



gluon jet $g_{incl.}$ defined by all particles in the hemisphere opposite to that containing 2 tagged quark jets



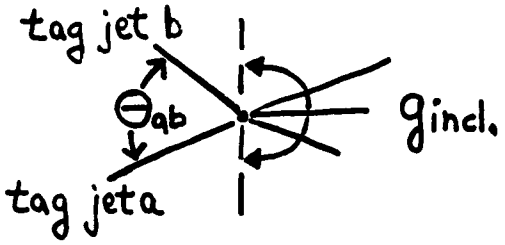
$$\langle n_{ch.} \rangle_{g_{incl.}} \simeq \frac{\langle n_{ch.} \rangle_{gg\,events}}{2}$$

Tested using Herwig and Jetset/Pythia for which gg production from a point source is possible

gluon jet sample $g_{incl.}$

① Divide event into hemispheres using the plane $\perp$ to the thrust axis

② Reconstruct two tagged b jets in one of the two hemispheres :



$\underline{\Theta_{ab} > 50°}$

Note: i) A jet with a B hadron is almost always a quark jet in e^+e^-

ii) The properties of a gluon jet are independent of event flavor

3 712 000 Z^0 events $\longrightarrow$ 278 $g_{incl.}$ jets

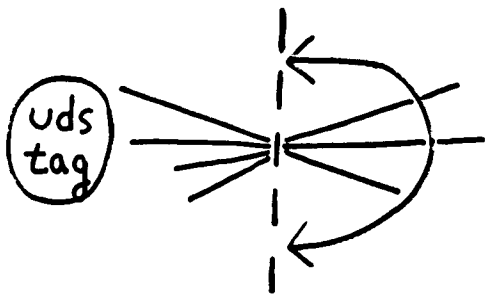
estimated purity = 83%

$\langle E \rangle_{g_{incl.}} = 39.2 \pm 1.8 GeV$

quark jet sample → uds event hemispheres

(inclusive definition of light quark jets)

light quarks uds → correspond to the massless quark assumption of the analytical calculations



uds quark jet defined by all particles in the hemisphere opposite to that containing a tagged uds jet

uds tag: all tracks consistent with the primary origin and at least one high x track ($x > 0.50$)

840 000 Z^0 events → 28 000 uds jets

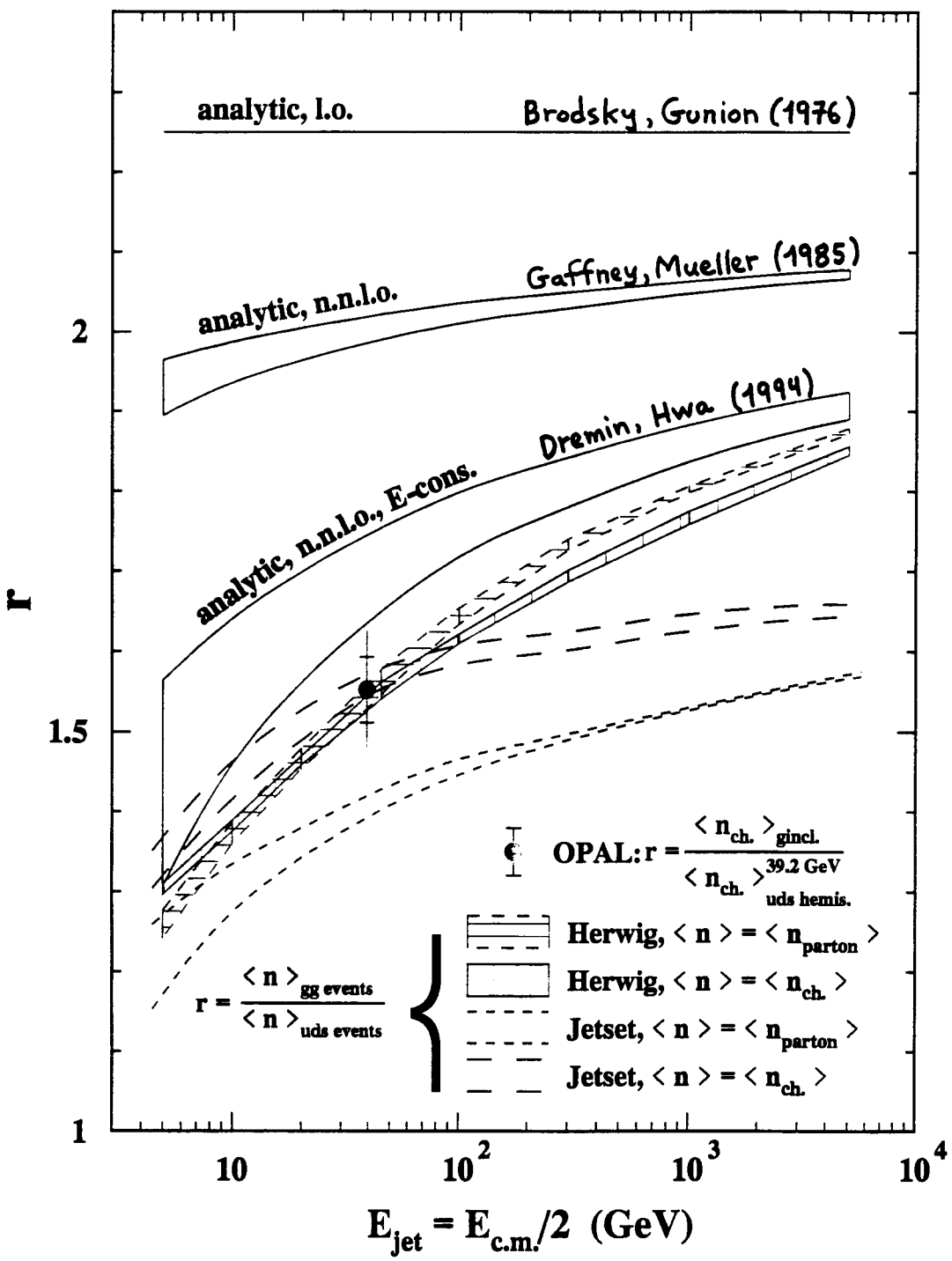
estimated purity = 93%

$\langle E \rangle_{\substack{uds \\ hemis.}} = 45.6$ GeV

$$r_{ch.} \equiv \frac{\langle n_{ch.} \rangle_{gluon}}{\langle n_{ch.} \rangle_{quark}} = 1.552 \pm 0.041 \pm 0.060$$

(stat.) (syst.)

(CERN-PPE/96-116) August 1996 39 GeV jets



Conclusion

The analytic prediction is in overall agreement with the measurement, given the uncertainties due to

(1) the approximate nature of energy-momentum conservation in the calculation

(2) missing higher order terms

(3) the energy scale at which to evaluate α_s

(4) the nr. of flavors to use for the calculation

(5) hadronization

Tests of jet universality

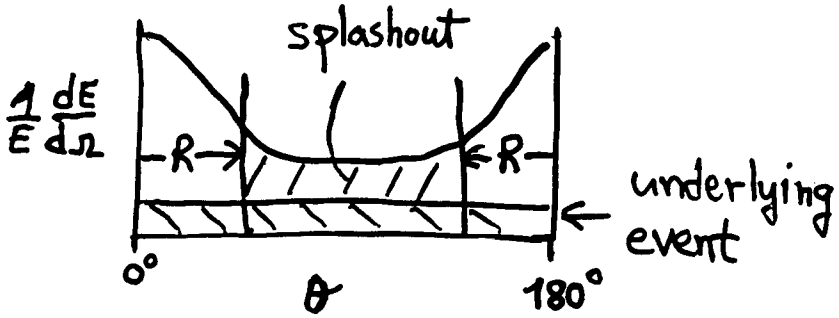
→ e^+e^- versus $p\bar{p}$ jets,

splashout

jet "splashout"

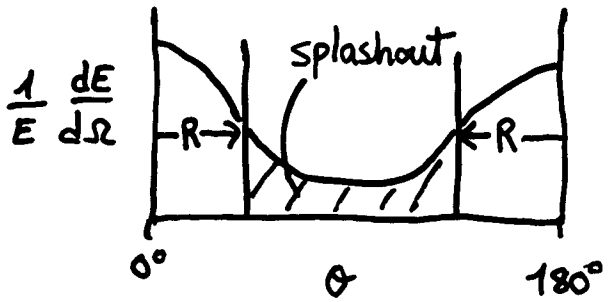
Event energy associated with the hard scattering process, but which falls outside a cone used to define a jet:

$p\bar{p}$ two jet event

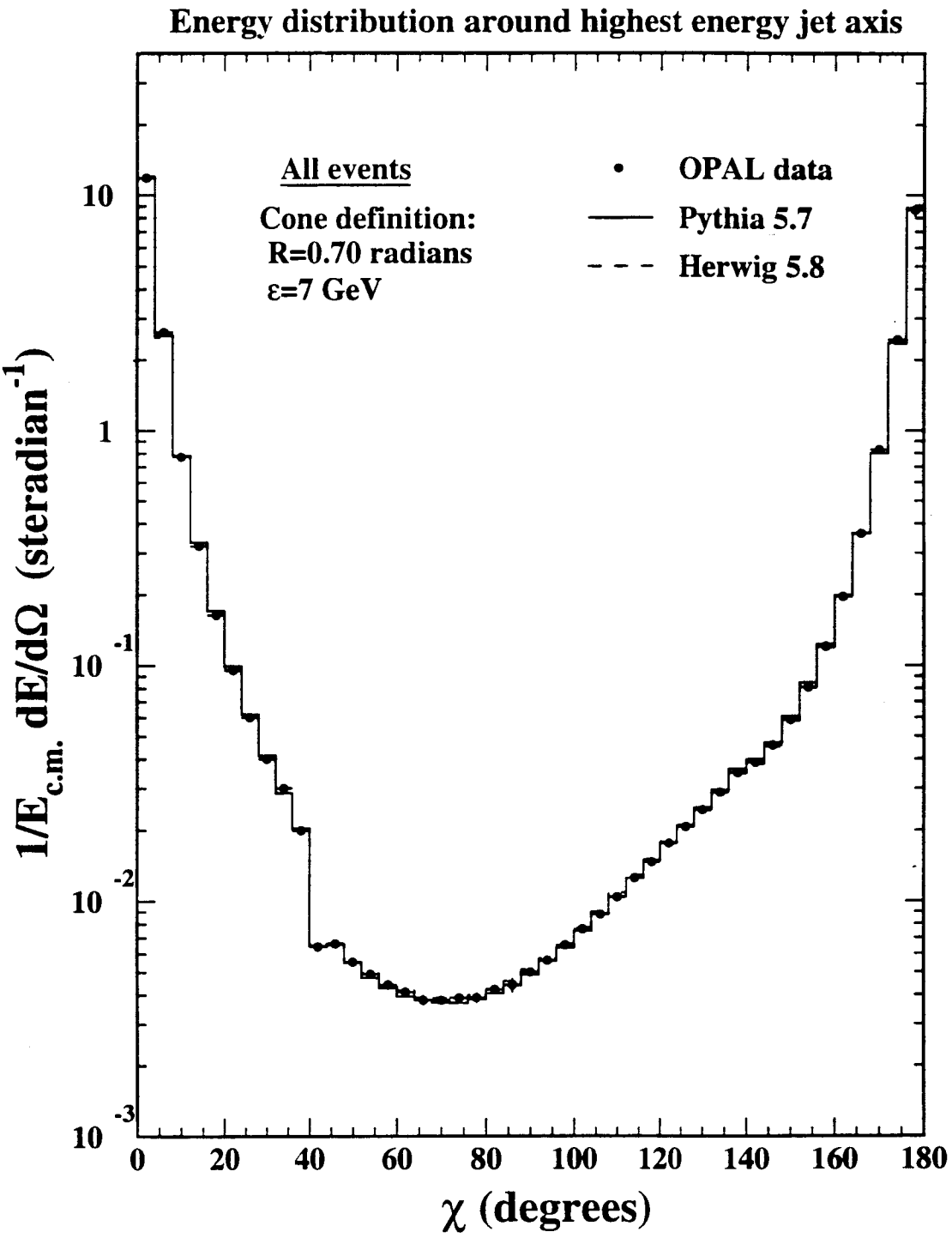


→ need to know splashout in order to properly correct for the underlying event

e^+e^- two jet event → no underlying event
(using the cone algorithm)



→ the e^+e^- data can be used to measure the splashout, test the accuracy of the QCD MC common to $p\bar{p}$ and e^+e^-


Energy distribution around highest energy jet axis
All events
Cone definition:
R=0.70 radians
ε=7 GeV
OPAL data
Pythia 5.7
Herwig 5.8
1/E_c.m. dE/dΩ (steradian^-1)
10
1
10^-1
10^-2
10^-3
0
20
40
60
80
100
120
140
160
180
χ (degrees)

Conclusion: e^+e^- jets

Here, have discussed

- 4-jet angular correlations (gluino $\tilde{g}$)
- coherence and LPHD
- gluon to quark jet *multiplicity* ratio
- jet profiles, splashout

→ not too many problems or controversy, but a number of quantitative tests of QCD analytic predictions, many of them unique to e^+e^-

→ messaage to theorists:
need higher orders <u>and</u> energy conservation

Many comparisons of data to MC:
flavor tagged multiplicities, fragmentation functions, photon spectra → no fundamental problems