

**QCD coherence studies
using correlations of particles
at restricted momenta**

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OUTLINE

- Motivation and definitions
- Theoretical predictions
- Recent relevant measurements
- OPAL preliminary results
- Conclusions

Motivation

- The conventional global observables:
averaged single-particle distributions and
averages, e.g. $\rho(n)$, $\langle n \rangle$, $\langle \mathbf{p}_T \rangle$, $\rho(y)$, etc.
- **Multiplicity** $\rho(n)$ distributions: essentially
non- (wider than) **Poissonian** distributions
- A step beyond: to study **local** fluctuations
and **short-range** correlations
⇒ **bin-averaged** moments
- Analytical perturbative QCD description:
scales and **parameters** at (transition to)
non-perturbative level
- Local Parton-Hadron Duality (LPHD):
does it hold?

pQCD + LPHD/Monte Carlo ⇒ Measurements

- e^+e^- at LEP – an **exceptional** opportunity
for **novel detailed** tests

Factorial moments:

a well established technique

- Normalized factorial moments of order q :

$$F_q(\Gamma_k) = \frac{\rho_q(k_1, \dots, k_q)}{[\int_{\Gamma_k} dk \rho_1(k)]^q}$$

in the phase space bin Γ_k

- In terms of **multiplicities** $n(\Gamma_k)$:

$$F_q = \frac{\langle n(n-1)\cdots(n-q+1) \rangle}{\langle n \rangle^q}$$

$\langle \cdots \rangle$ = averaging over events

- Dynamical, non-Poissonian, fluctuations are extracted; $F_q = 1$ in the Poissonian case

A. Białas, R. Peschanski (1986)

E.A. De Wolf, I.M. Dremin, W. Kittel, *Phys. Reports* 270 ('96) 1
I.M. Dremin, J.W. Gary, *Phys. Reports* 349 (2001) 301

OPAL Collab., *Phys. Lett. B* 262 (1991) 351 (PR031)

OPAL Collab., *Europ. Phys. J. C* 11 (1999) 239 (PR270)

OPAL Collab., *Phys. Lett. B* 523 (2001) 35 (PR346)

The momentum-cut factorial moments

- Normalized momentum-cut factorial moments of order q :

$$F_q(k_i < k^{\text{cut}}) = \frac{\rho_q(k_1, \dots, k_i, \dots, k_q)}{[\int_{k_i < k^{\text{cut}}} dk \rho_1(k)]^q}$$

- In terms of **multiplicities** $n(k_i < k^{\text{cut}})$:

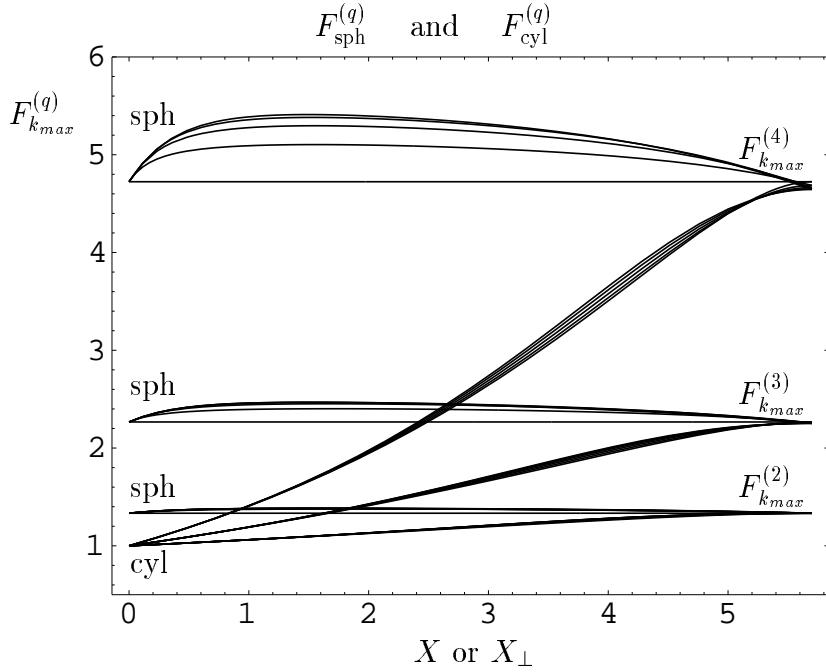
$$F_q = \frac{\langle n(n-1)\cdots(n-q+1) \rangle}{\langle n \rangle^q}$$

$\langle \cdots \rangle$ = averaging over events

- **QCD coherence effects**
are expected at hadron level due to the
LPHD hypothesis

S.Lupia, W.Ochs, J.Wosiek (1999)

S.Lupia, W.Ochs, J.Wosiek, Nucl.Phys. B540 (1999) 405



Cylindrically cut moments

$$F^{(q)}(X_\perp, Y) \cong 1 + \frac{q(q-1)}{6} \frac{X_\perp}{Y}$$

[up to $\mathcal{O}(K^{(3)})$ ($X_\perp = \ln \frac{k_\perp^{\text{cut}}}{Q_0}$, $Y = \ln \frac{P\Theta}{Q_0}$)]

\Rightarrow Poissonian limit (QCD coherence):

$$F_q \rightarrow 1 @ X_\perp \rightarrow 0 (k_\perp^{\text{cut}} \rightarrow Q_0)$$

Spherically cut moments

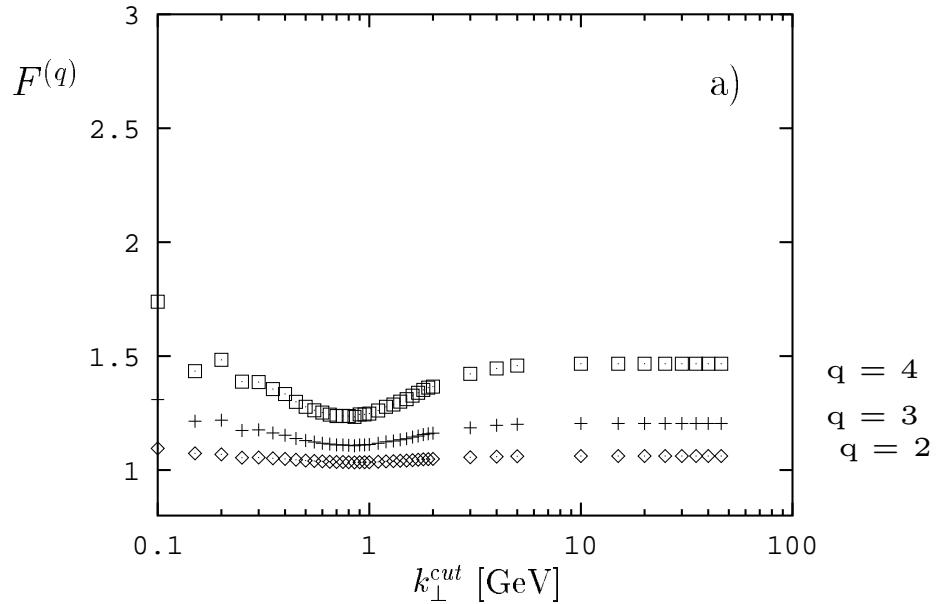
$$F^{(q)}(X, Y) = \text{const}(X)$$

\Rightarrow Non-Poissonian multiplicity distrib.:

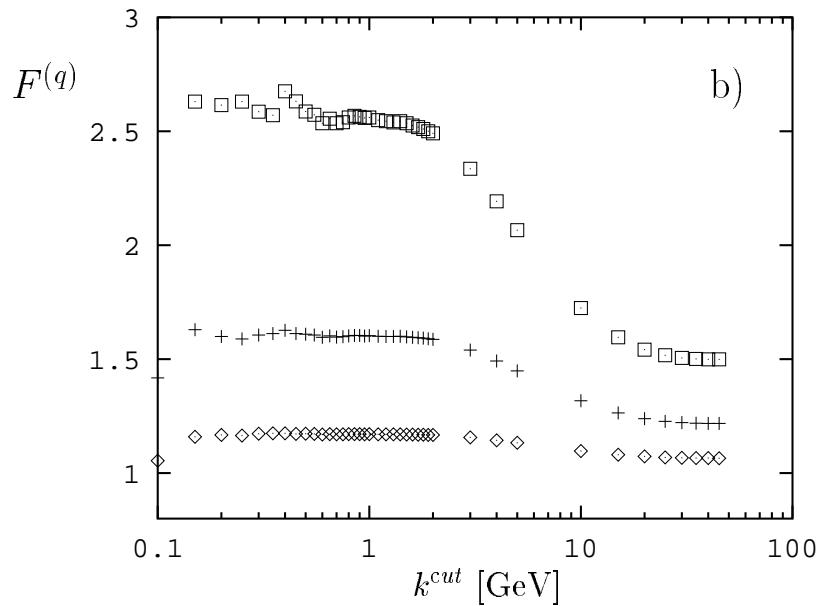
$$F_q = f(q) > 1 @ X \rightarrow 0 (k^{\text{cut}} \sim k_T^{\text{cut}})$$

- no $E-p$ conservation, asymptotic behaviour

Monte Carlo predictions Hadron level



ARIADNE ($Q_0 = 0.2$ GeV): $F_q \rightarrow 1$ @ $k_T^{\text{cut}} < 1$ GeV
(Poissonian limit) + Hadronisation @ $k_T^{\text{cut}} < Q_0$

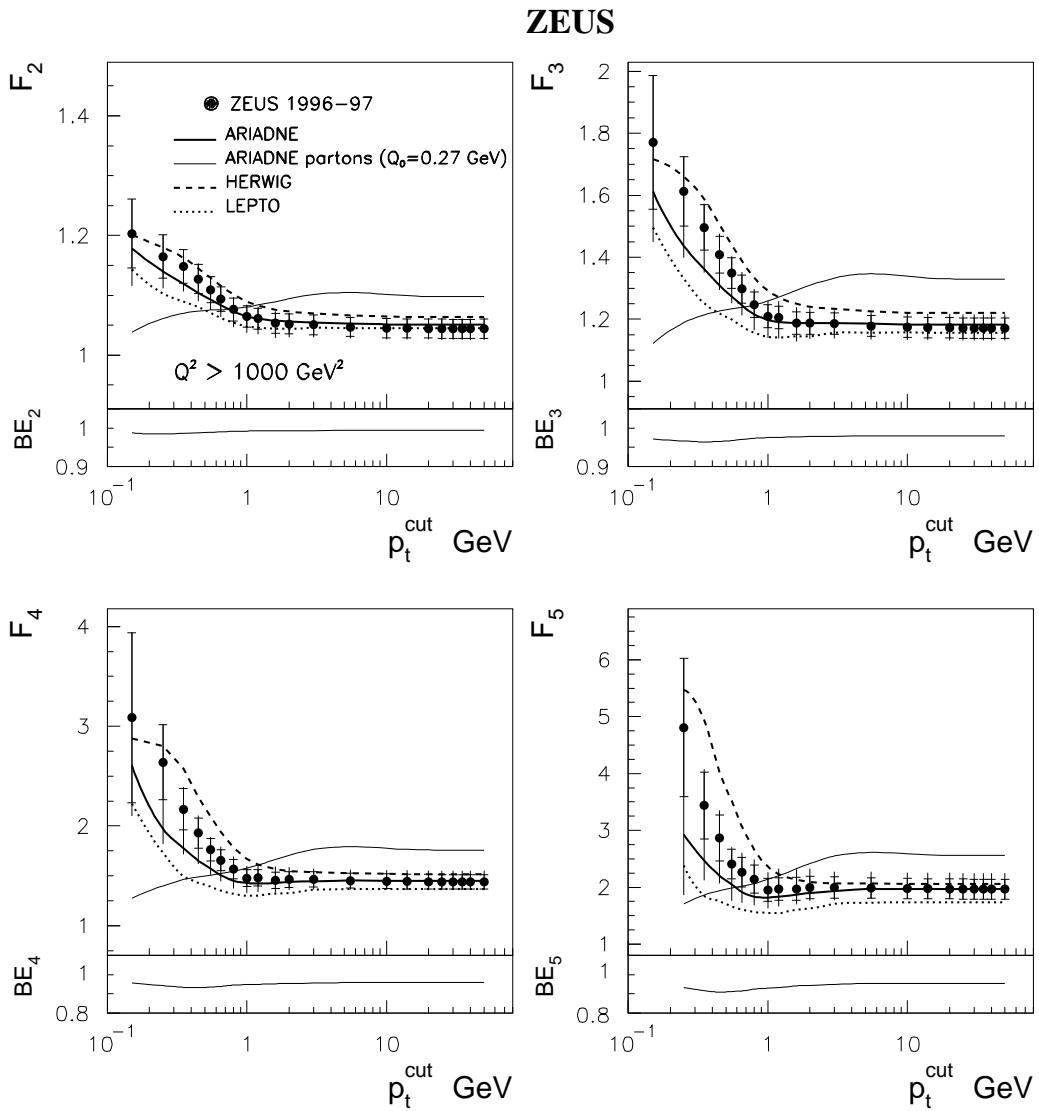


ARIADNE ($Q_0 = 0.2$ GeV): $F_q = C(q) > 1$ @ $k^{\text{cut}} \sim 1$ GeV
(non-Poissonian limit) + Hadronisation

S.Lupia, W.Ochs, J.Wosiek, Nucl.Phys. B540 (1999) 405

Cylindrically cut moments (p_T -cut)

ZEUS data



- No Poissonian limit expected from DLA:

$$F_q(p_T^{\text{cut}}) \simeq 1 + \frac{q(q-1)}{6} \frac{\ln(p_T^{\text{cut}}/Q_0)}{\ln P/Q_0} \neq 1 @ p_T^{\text{cut}} \sim Q_0$$

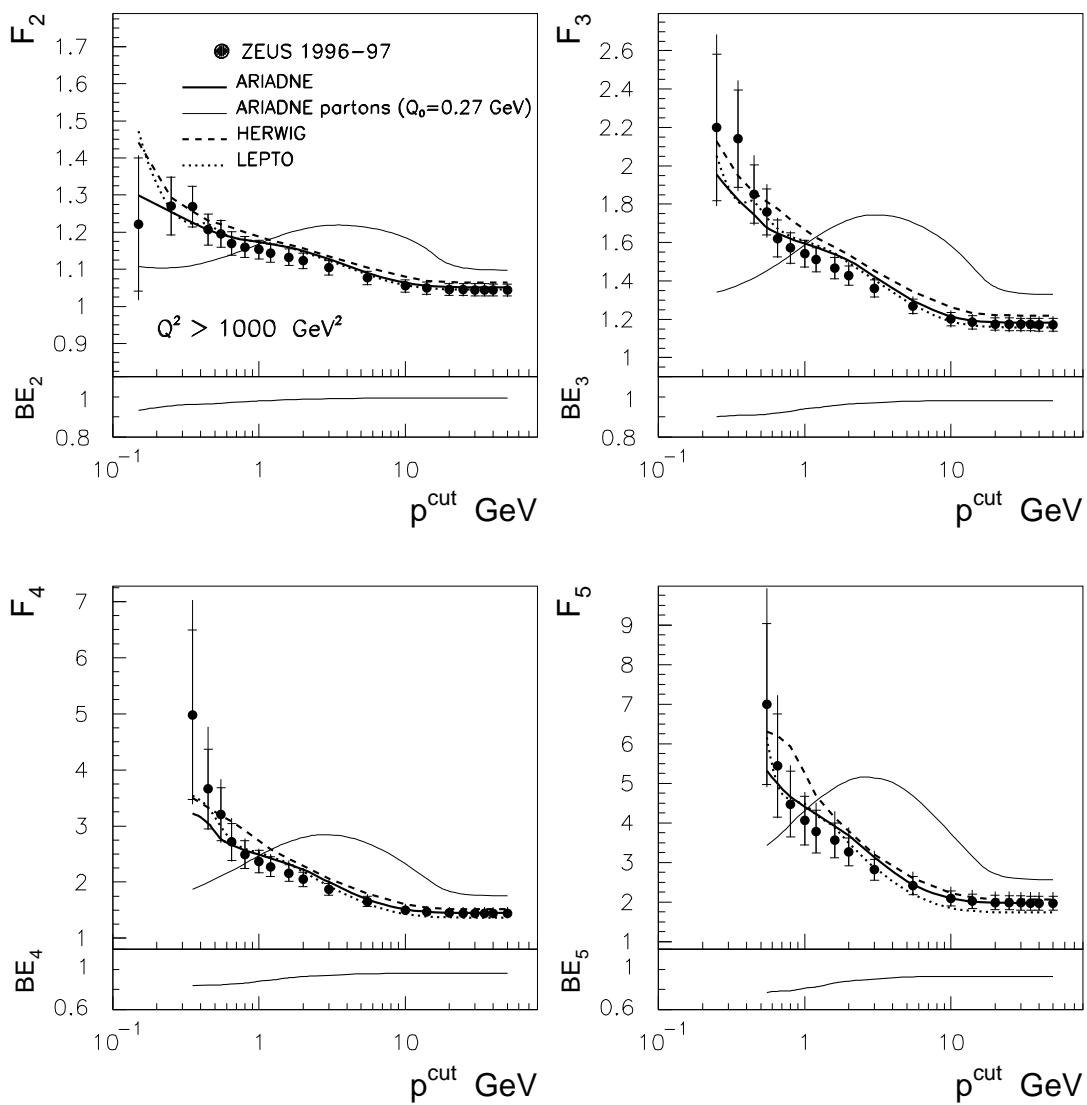
- No dip in perturbative \rightarrow non-perturbative transition region ($p_T = 1 - 2 \text{ GeV}$)

ZEUS Collab., S.Chekanov et al., Phys. Lett. B 510 (2001) 36

Spherically cut moments (p -cut)

ZEUS data

ZEUS



Not a constant value as expected from DLA:

$$F_q(p^{\text{cut}}) \neq \text{const} > 1$$

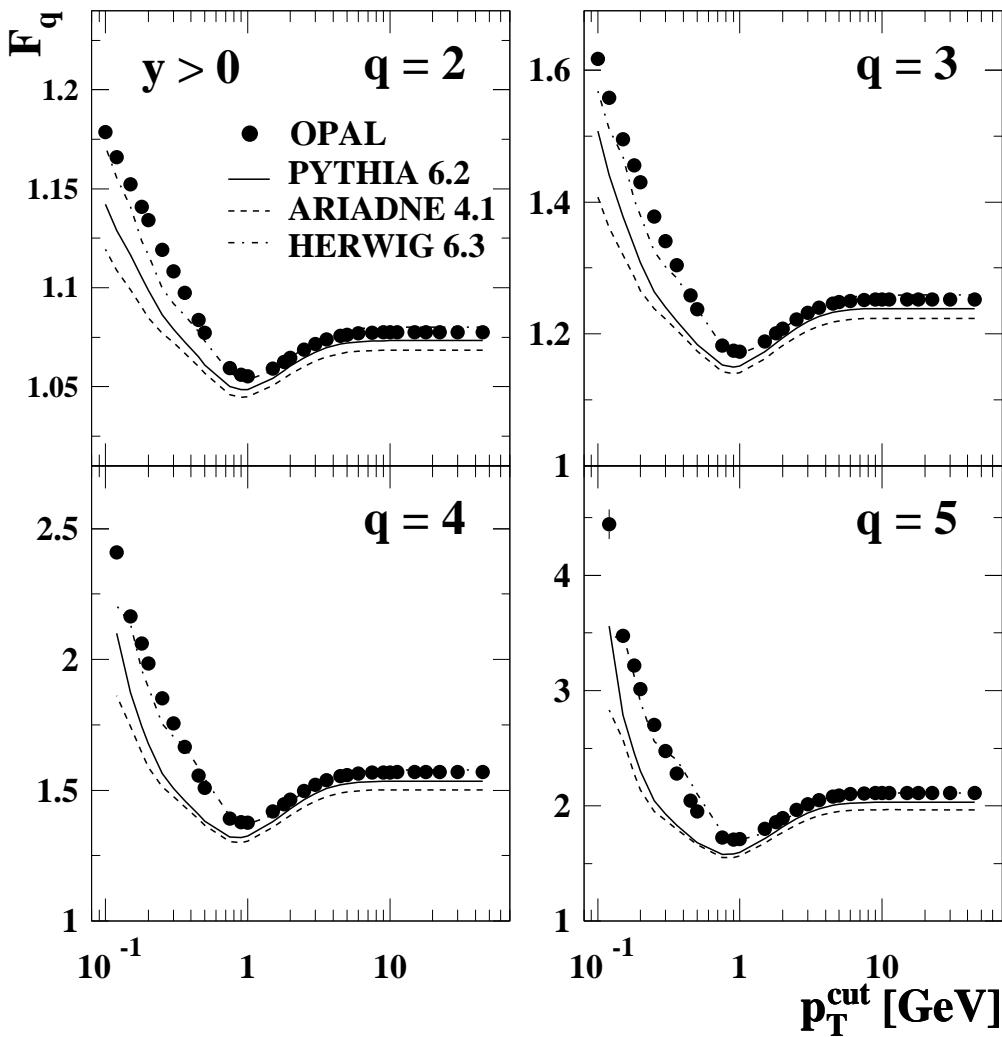
Conclusion: pQCD fails to describe, LPHD is inconsistent with many-hadron densities

ZEUS Collab., S.Chekanov et al., Phys. Lett. B 510 (2001) 36

Data and MC events

- The **multihadron** sample: about 4M events
- **After the cuts:** about 2.9M events
- One hemisphere, $y > 0$, w.r.t. the **thrust axis**
$$\left(y = \ln \frac{E+p_{\parallel}}{E-p_{\parallel}} \right)$$
- Data **corrected** for the detector level
(JETSET/PYTHIA)
- **Monte Carlo** 3M events used (each sample of JETSET/PYTHIA, ARIADNE, HERWIG)

Cylindrically cut moments (p_T -cut)

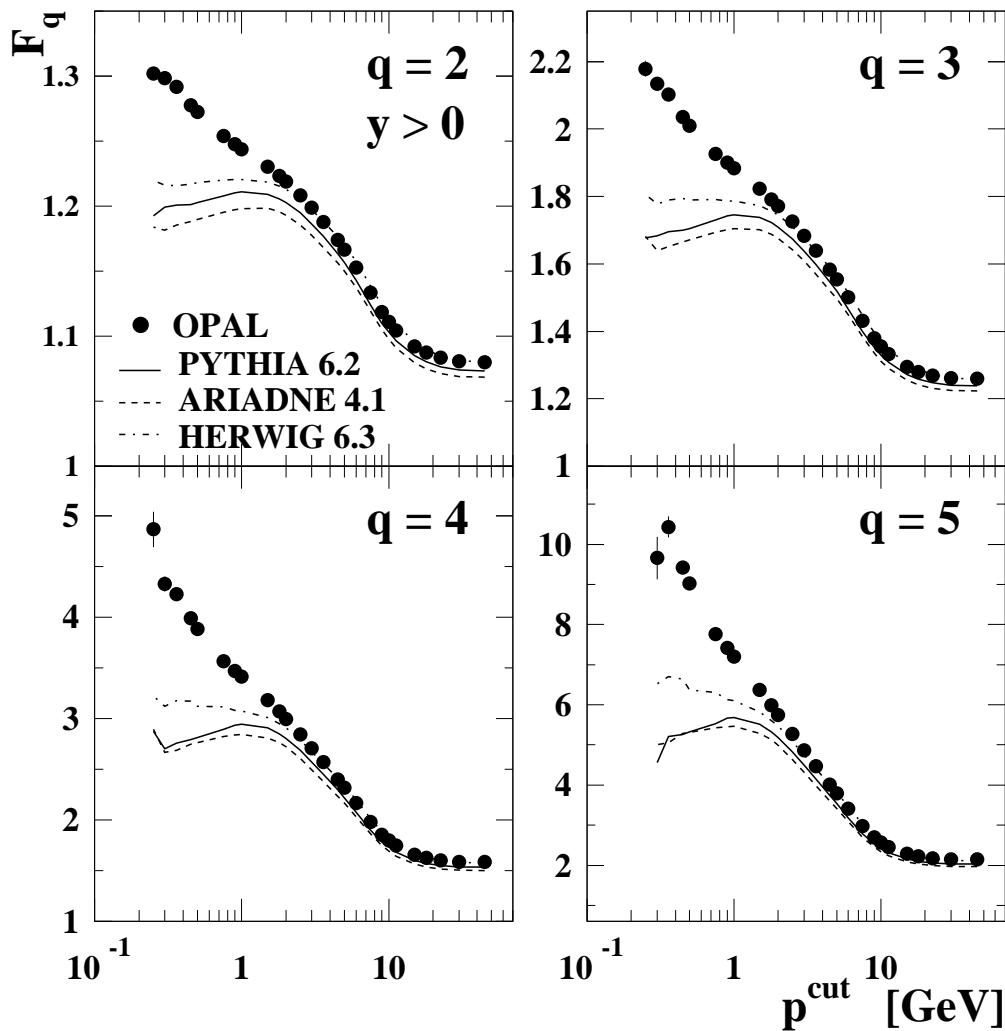


- DATA: No Poissonian limit predicted in DLA:

$$F_q(p_T^{\text{cut}}) \simeq 1 + \frac{q(q-1)}{6} \frac{\ln(p_T^{\text{cut}}/Q_0)}{\ln P/Q_0} \neq 1 @ p_T^{\text{cut}} \sim Q_0$$

- Visible perturb. \rightarrow non-perturb. dip ($p_T^{\text{cut}} \sim 1$ GeV)
- MCs follow data trend [HERWIG ?]; similar to the ZEUS case

Spherically cut moments (p -cut)



- DATA: No constant value expected from DLA:

$$F_q(p^{\text{cut}}) \neq \text{const} > 1$$

- MCs follow DLA+LPHD (expected) [except HERWIG], not the data; not the ZEUS case

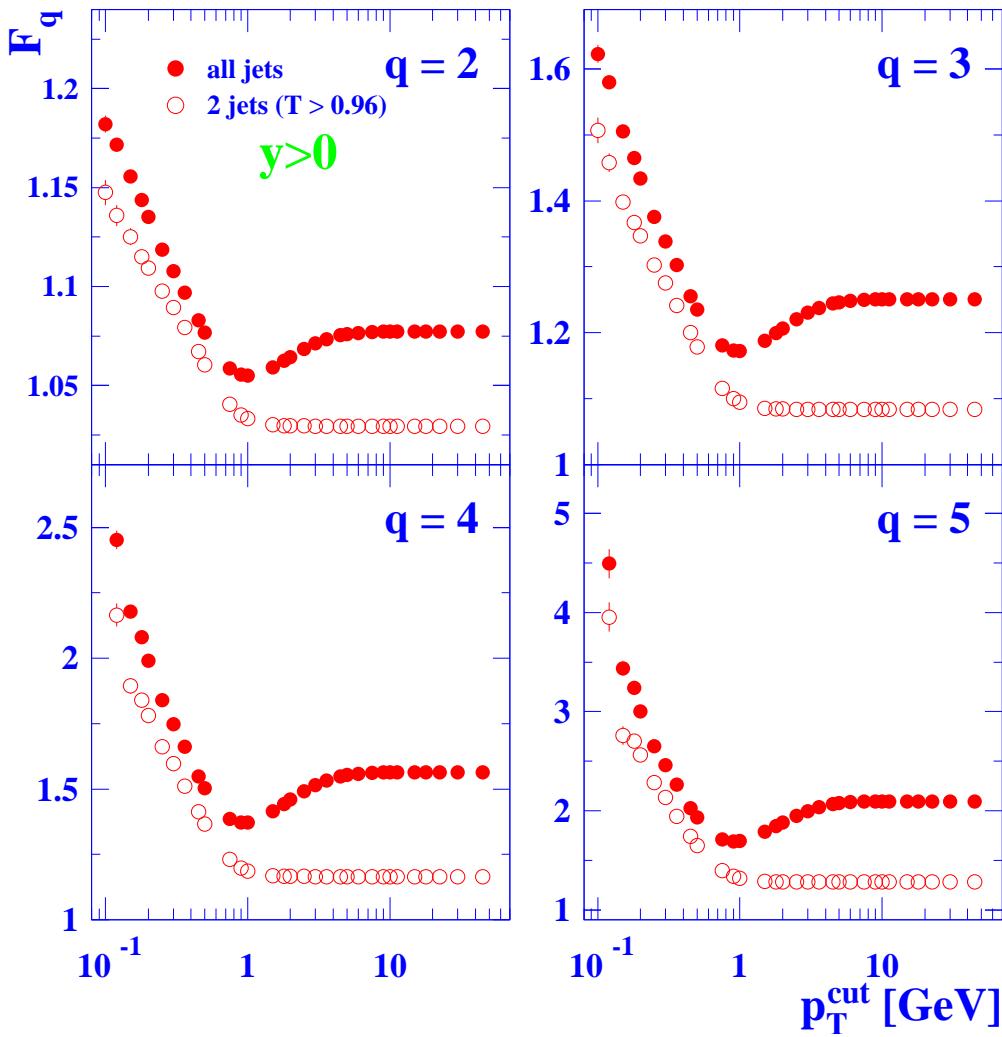
Futher investigations

- To check other possible **contributions**:
 - electron pairs
 - $\rho_0, \eta, \eta', \omega$ decays
 - invariant mass vs. momenta cuts
 - Bose-Einstein correlationsNo influence obtained
- To proceed with **2-jet events**:
T(hrust)-cut vs. jet-finder (Durham) alg.
No differences observed
- To take into account **DIS kinematics**: to cut in rapidity, $y > y_0$
Done, see later
- To study genuine correlations in terms of **cumulants** + QCD predictions exist
Done, see later
- To investigate **HERWIG** behaviour
Done, see later

2-jet vs. all-jet samples

Cylindrically cut moments (p_T -cut)

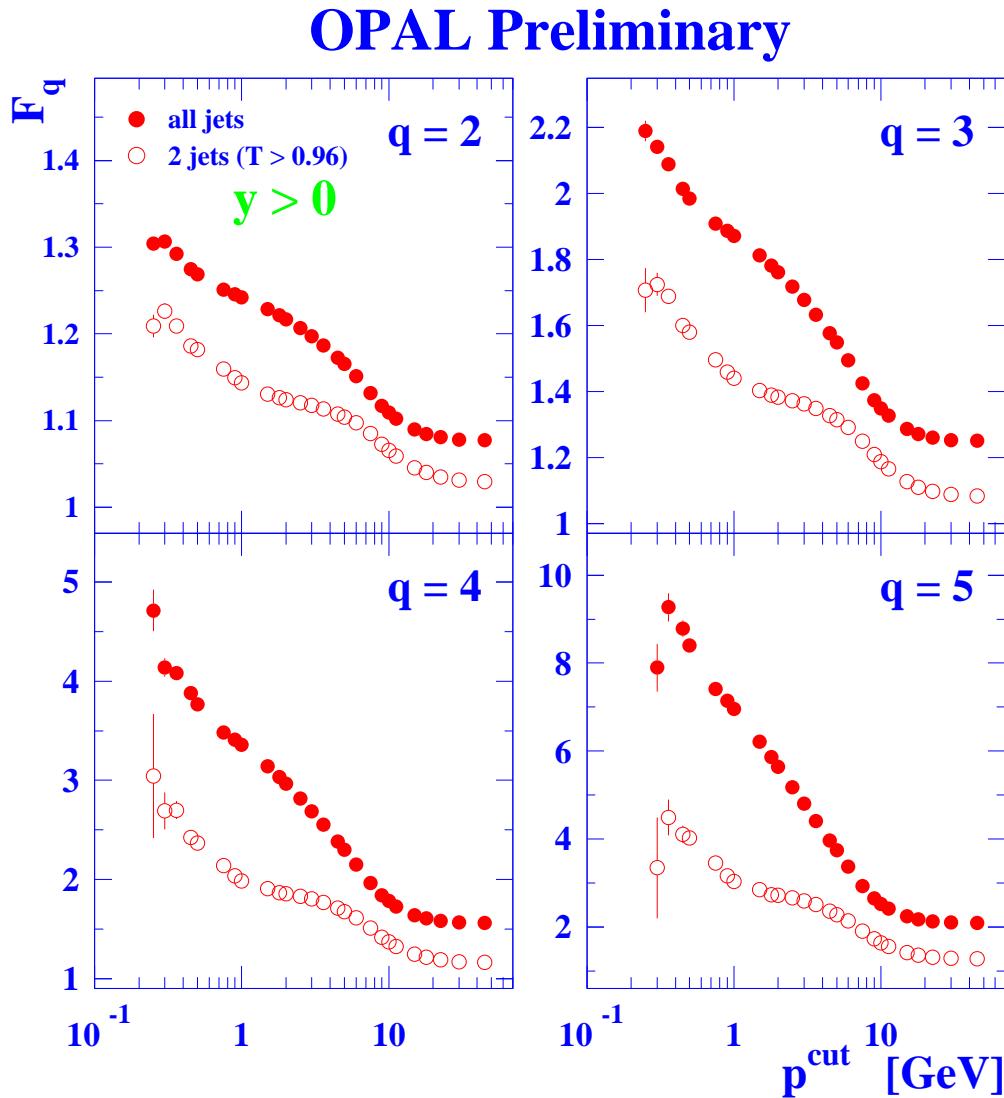
OPAL Preliminary



- DATA: No Poissonian limit predicted by DLA, $F_q(p_T^{\text{cut}}) \neq 1$ @ $p_T^{\text{cut}} \sim Q_0$; 2 jets: all-jet-like rise
- 2 jets: No dip at $p_T^{\text{cut}} \sim 1$ GeV
- 2-jet MCs follow data, similar to all-jet case
- 2 jets with Durham algorithm: the same results

2-jet vs. all-jet samples

Spherically cut moments (p -cut)

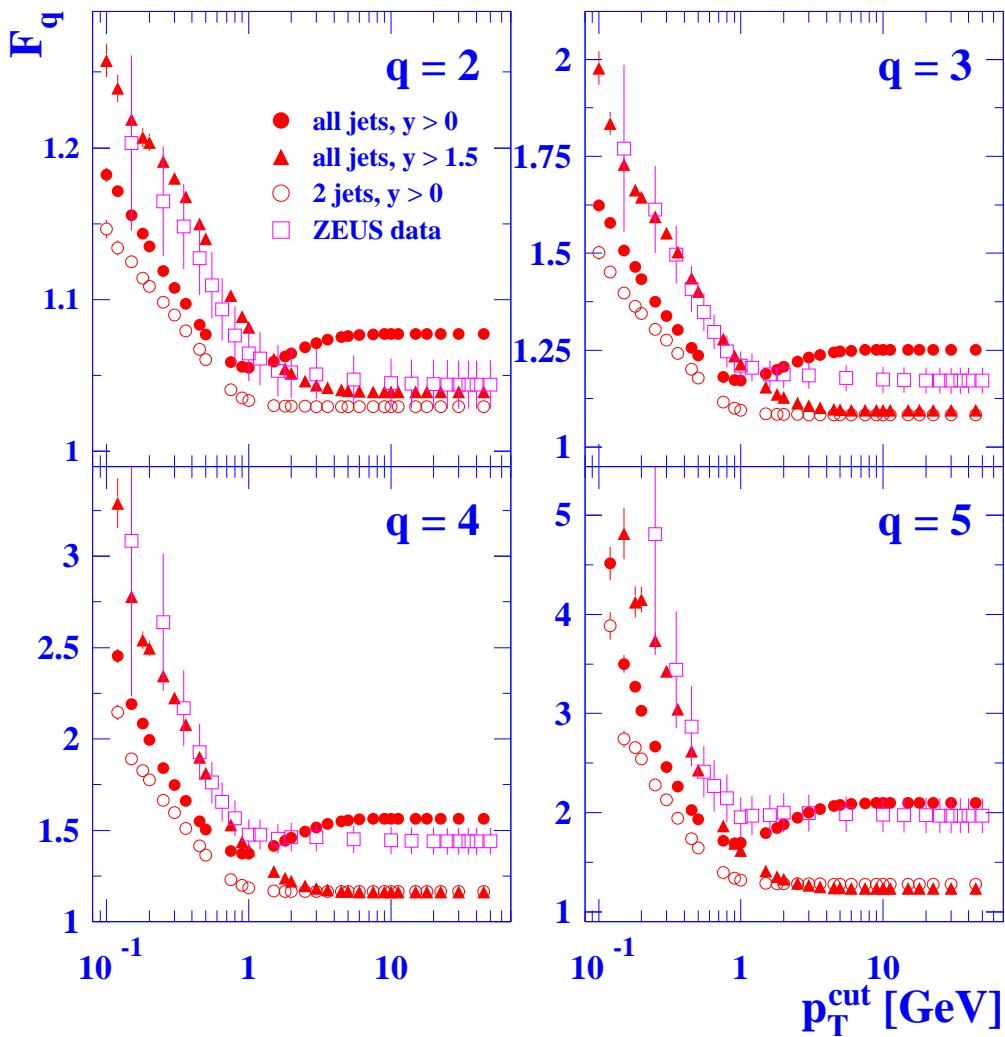


- DATA: No constant value expected from DLA, $F_q(p^{\text{cut}}) \neq \text{const} > 1$; 2 jets: slower rise
- 2-jet MCs follow DLA+LPHD in a way similar to all-jet case
- 2 jets with Durham algorithm: the same results

Comparison

Cylindrically cut moments (p_T -cut)

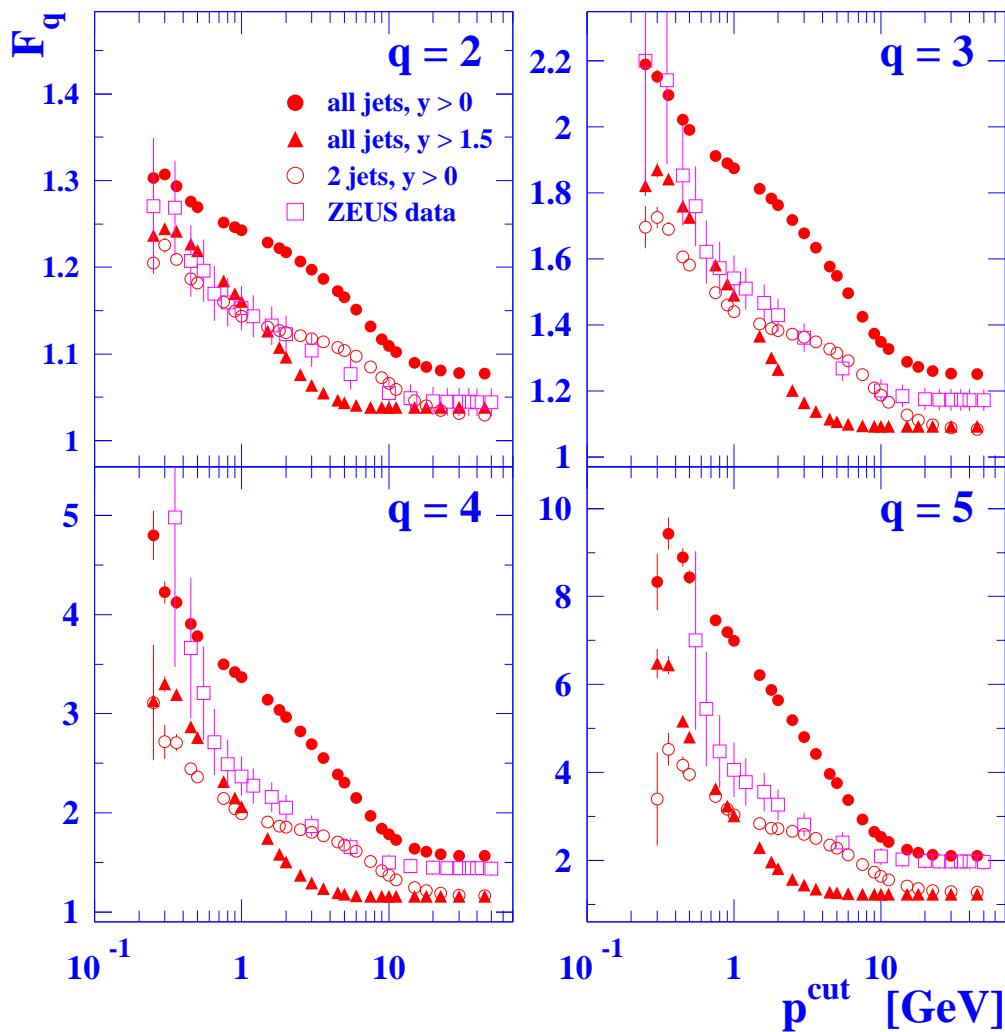
OPAL Preliminary



- At $p_T^{\text{cut}} \sim 1$ GeV: y -cut and 2-jet data behave like ZEUS data: no dip
- all-jet $y > 1.5$ data well reproduces ZEUS data at $p_T^{\text{cut}} < 1$ GeV for all q , at $p_T^{\text{cut}} > 1$ GeV for $q = 2$
- all-jet no y -cut data reproduces ZEUS data at $p_T^{\text{cut}} > 1$ GeV for $q > 2$
- 2-jets: not relevant

Comparison Sperically cut moments (p -cut)

OPAL Preliminary



- **all-jet $y > 1.5$** data well reproduces ZEUS data at $p_{\text{cut}}^q < 1$ GeV for all q , at $p_{\text{cut}}^q > 1$ GeV for $q = 2$
- **all-jet no y -cut** data reproduces ZEUS data at $p_{\text{cut}}^q > 1$ GeV for $q > 2$
- **2-jets:** relevant in the **intermediate** region, $1 < p_{\text{cut}}^q < 10$ GeV

Cumulants and correlations

- q -particle genuine correlations \Rightarrow cumulants
- **Normalised momentum-cut cumulants**
(cumulant moments) of order q :

$$K_q(k_i < k^{\text{cut}}) = \frac{C_q(k_1, \dots, k_q)}{\left[\int_{k_i < k^{\text{cut}}} dk \rho_1(k) \right]^q}$$

- $C_q(k_1, \dots, k_q)$ – q th order correlation function
For example,

$$C_2(k_1, k_2) = \rho_2(k_1, k_2) - \rho_1(k_1)\rho_1(k_2)$$

$$C_3(k_1, k_2, k_3) = \rho_3(k_1, k_2, k_3) - \sum_{(3)} \rho_1(k_1)\rho_2(k_2, k_3) + 2\rho_1(k_1)\rho_1(k_2)\rho_1(k_3)$$

- Cumulants **calculated** according to:

$$K_2 = F_2 - 1, \quad K_3 = F_3 - 3F_2 + 2,$$

$$K_4 = F_4 - 4F_3 - 3F_2^2 + 12F_2 - 6, \quad \text{etc.},$$

via normalized momentum-cut factorial moments, F_q

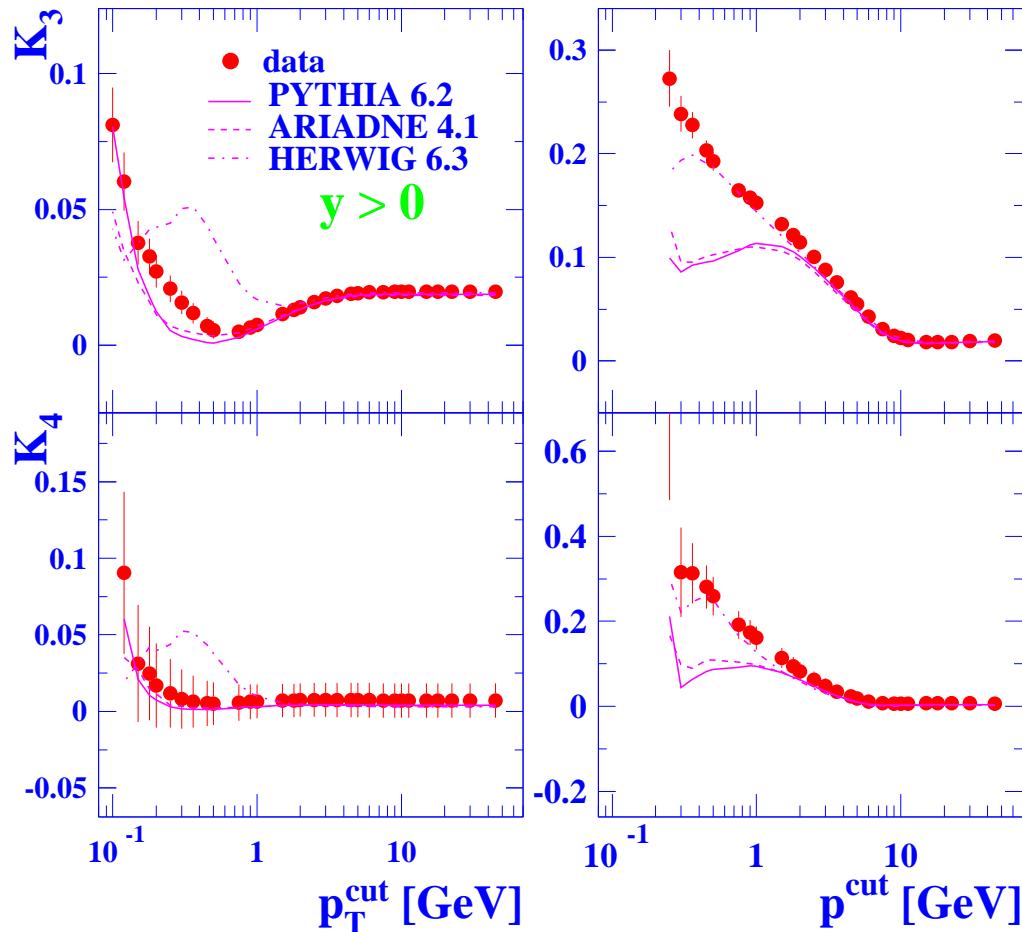
E.A. De Wolf, I.M. Dremin, W. Kittel, Phys. Reports 270 (1996) 1

OPAL Collab., Europ. Phys. C 11 (1999) 239 (PR270)

OPAL Collab., Phys. Lett. B 523 (2001) 35 (PR346)

Momentum-cut cumulants ($q > 3$)

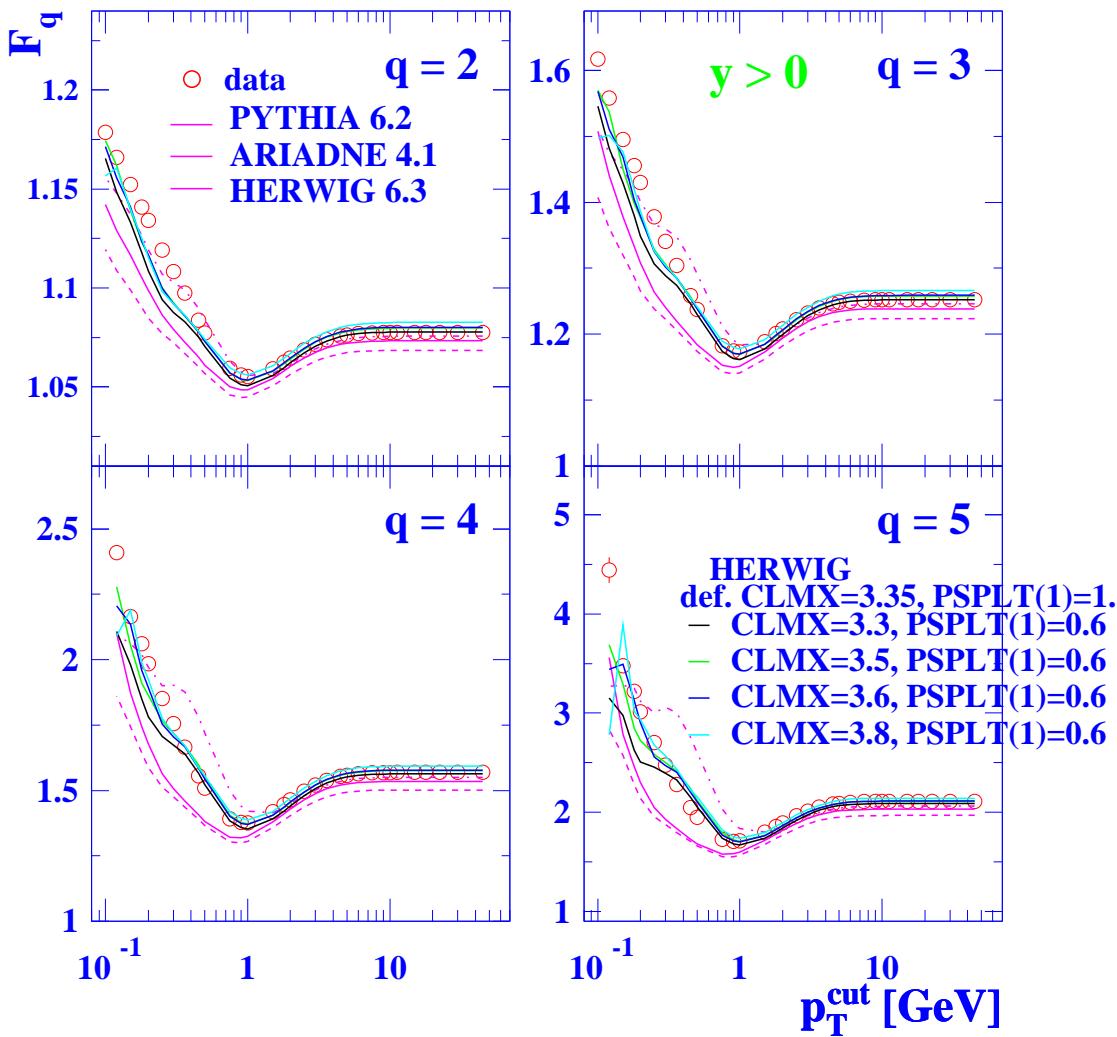
OPAL Preliminary



- K_s : more characteristic & interesting than F_s : genuine correlations + no calcul. approximations
- $K_q \neq 0 @ p_T^{\text{cut}} \sim Q_0$: no Poissonian limit of QCD
- $K_q \neq \text{const}$ as $p_T^{\text{cut}} \rightarrow 0$: disagree with QCD calcul.
- $\underline{p_T^{\text{cut}}} \text{ MCs follow data (HERWIG ?)}$
 $\underline{p_T^{\text{cut}}} \text{ MCs agree with pQCD+LPHD except HERWIG}$

Comparison HERWIG study (p_T -cut)

OPAL Preliminary



- **Change of parameters:**

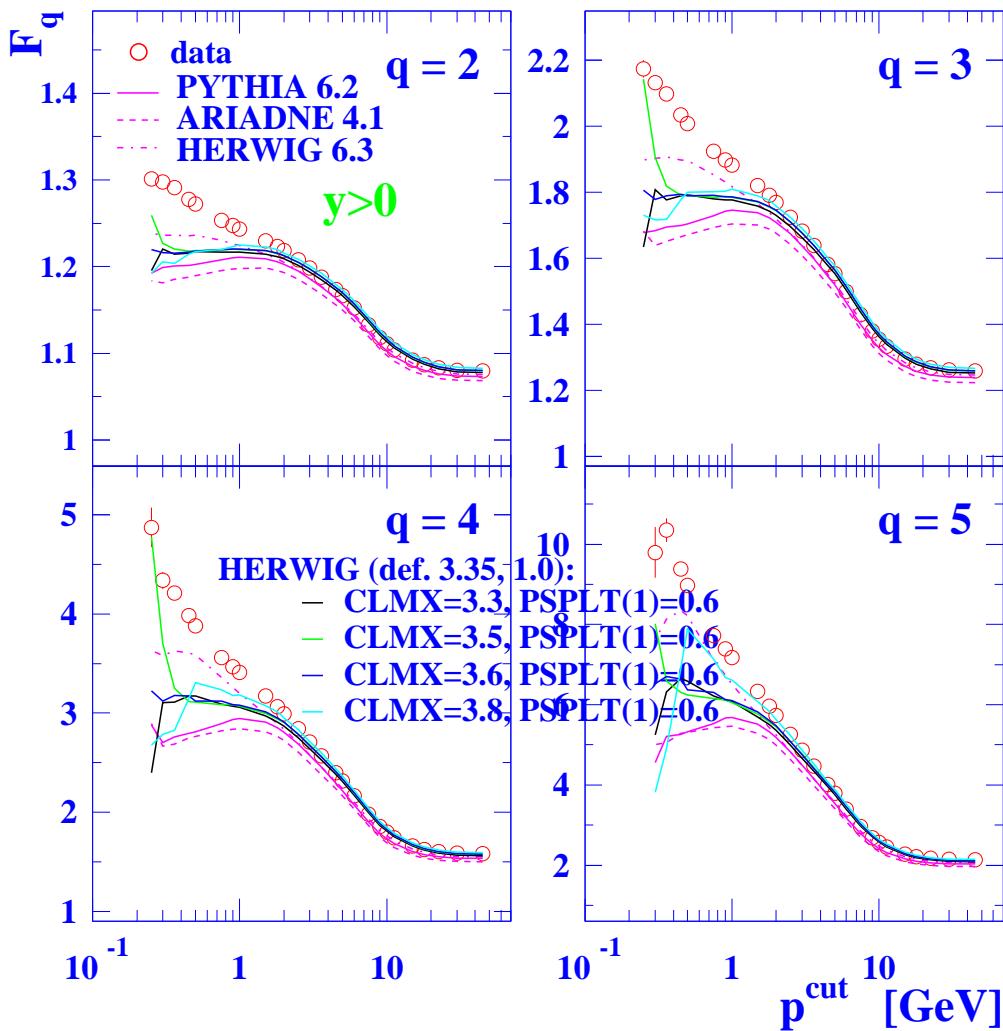
CLMX - allowed maximum cluster mass parameter

PSPLT(1) - u/d/s quark mass distrib. cluster splitting

- Best parameters: CLMX = 3.6 , PSPLT(1) = 0.6 with good χ^2 s of OPAL tune, accord. to TN652.

Comparison HERWIG study (p -cut)

OPAL Preliminary



- **Change of parameters:**

CLMX - allowed maximum cluster mass parameter

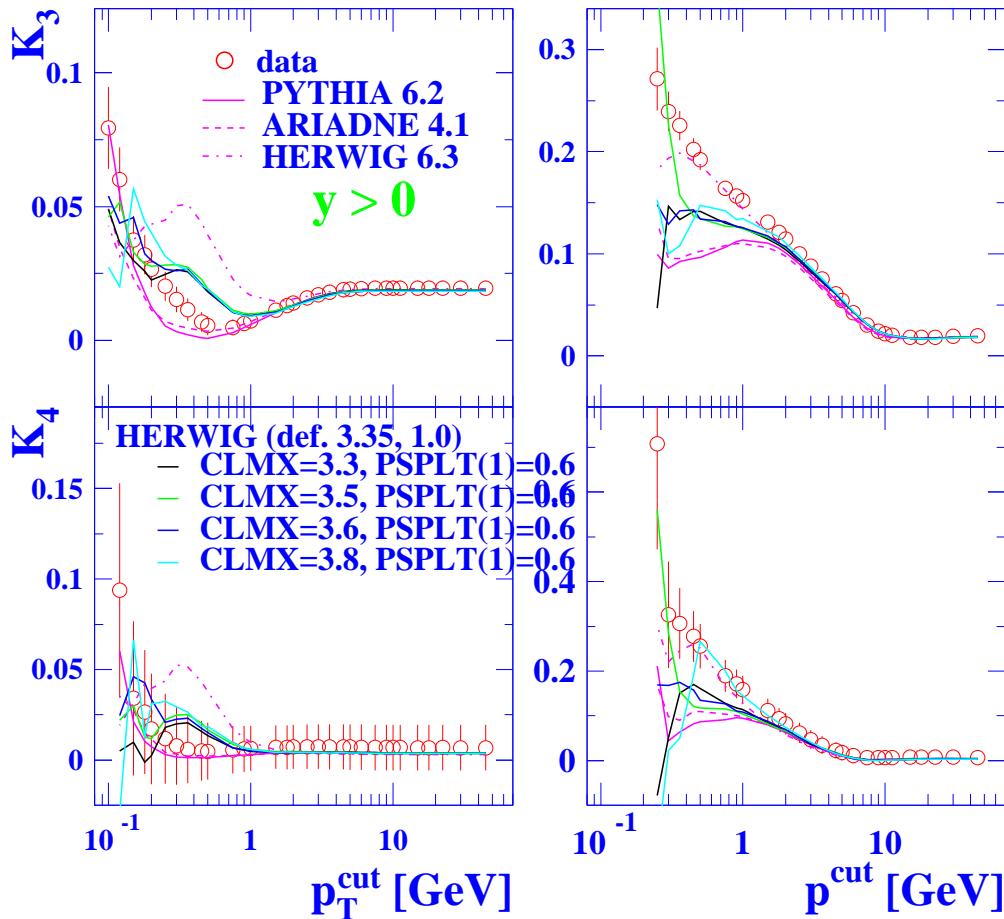
PSPLT(1) - u/d/s quark mass distrib. cluster splitting

- Best parameters: CLMX = 3.6 , PSPLT(1) = 0.6 with good χ^2 s of OPAL tune, accord. to TN652.

Comparison

HERWIG study of cumulants

OPAL Preliminary



- **Change of parameters:**

CLMX - allowed maximum cluster mass parameter

PSPLT(1) - u/d/s quark mass distrib. cluster splitting

- Best parameters: CLMX = 3.6, PSPLT(1) = 0.6 with good χ^2 s of OPAL tune, accord. to TN652.
- **Bump suppressed at small p_T^{cut}**

Summary and conclusions

- A study of QCD coherence is presented in terms of **local** momentum fluctuations and correlations
- **Factorial moments** and **cumulants** measured in $Z^0 \rightarrow$ hadrons with restricted p and p_T
- The QCD **predicted transition point** from perturbative to non-perturbative regimes is observed at $p_T \sim 1$ GeV
- **pQCD** fails to reproduce the measurements quantitatively at $p_T^{\text{cut}}, p^{\text{cut}} < 1$ GeV
(asymptotic character, no E - p conservation?)
- **Monte Carlo** models (JETSET/PYTHIA, ARIADNE) disagree with data at $p^{\text{cut}} < 1$ GeV
- The **LPHD hypothesis** faces difficulties (violation?)
- Earlier ZEUS (ep data) findings of **momentum-cut factorial moments** explained
- “**HERWIG** bump” seems to be understood
- **EB750** set up