Jet Fragmentation

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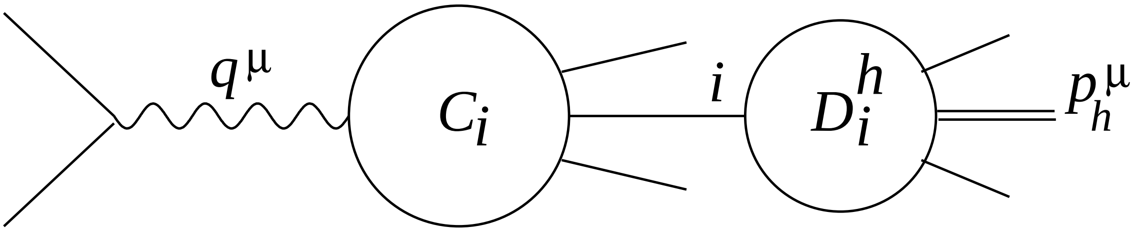
See the fragmentation web pages of the European network "Hadronic Physics with High Energy Electromagnetic Probes" (HaPHEEP) for much useful information:
`http://www.pv.infn.it/ jakob/fragmentation.html`

Jet fragmentation – theory

- Recall the basic factorization structure of the single-particle inclusive distribution, e.g. in $e^+e^- \to hX$:



$$F^h(x,s) = \sum_i \int_x^1 \frac{dz}{z} C_i(z, \alpha_S(s)) D_i^h(x/z, s)$$

$$s = q^2 \,, \qquad\qquad x = 2p_h \cdot q/q^2 = 2E_h/E_{cm}$$

C_i are the coefficient functions for this particular process (including all selection cuts etc.) and D_i^h is the universal fragmentation function for parton $i \to$ hadron h.

- The fragmentation functions are not perturbatively calculable but their s-dependence (scaling violation) is given by the DGLAP equation:

$$s\frac{\partial}{\partial s} D_i^h(x,s) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_S(s)) D_j^h(x/z, s)$$

Thus they can be parametrized at some fixed scale s_0 and then predicted at other energies.

In certain kinematic regions, higher-order corrections are enhanced by large logarithms, which need to be resummed.

- At small x, leading $\log x$ enhanced terms can be resummed by changing the DGLAP equation to

$$s\frac{\partial}{\partial s}D_i^h(x,s) = \sum_j \int_x^1 \frac{dz}{z} P_{ji}(z, \alpha_S(s)) D_j^h(x/z, z^2 s)$$

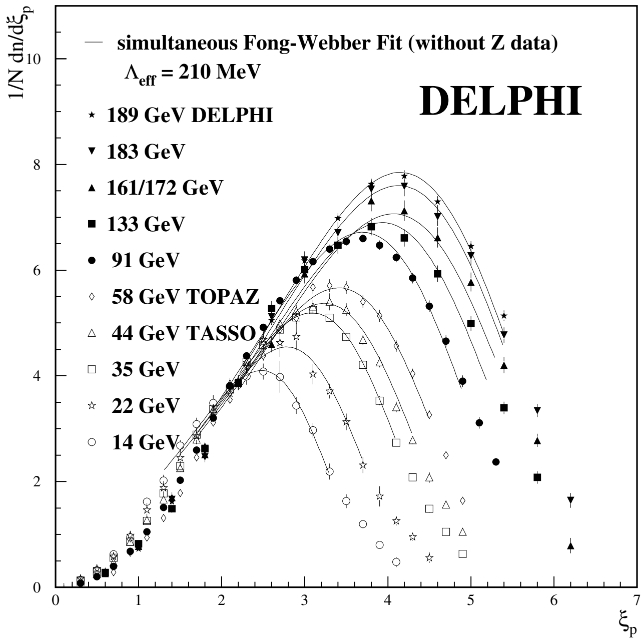
  The effect of this is to generate a characteristic hump-backed shape in the variable $\xi = \ln(1/x)$, with a peak at $\xi_p \sim \frac{1}{4}\ln s$.

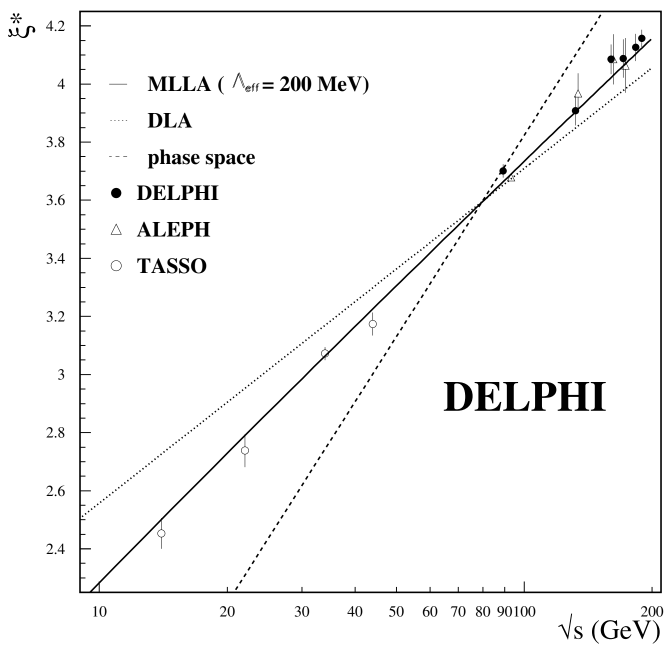
- Large logarithms of ratios of invariants may also appear inside the coefficient functions C_i, for example in three-jet events when the angles between jets become small. In some cases these can be absorbed into a change of scale in the fragmentation functions.

Although universal, fragmentation functions are factorization scheme dependent. The splitting functions P_{ji} are also scheme dependent. To specify the scheme requires calculation of the coefficient functions to (at least) next-to-leading order. This has only been done in a few cases. Thus there is need for theoretical work to make full use of the data on fragmentation functions.

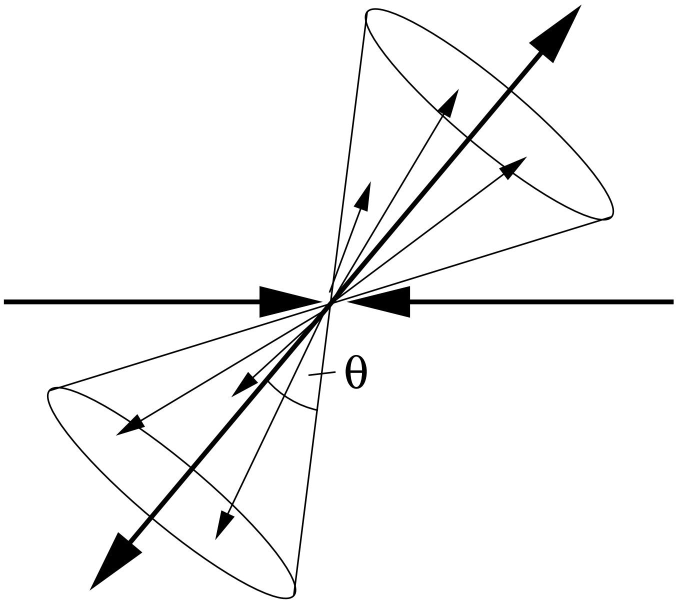
Fragmentation at small x

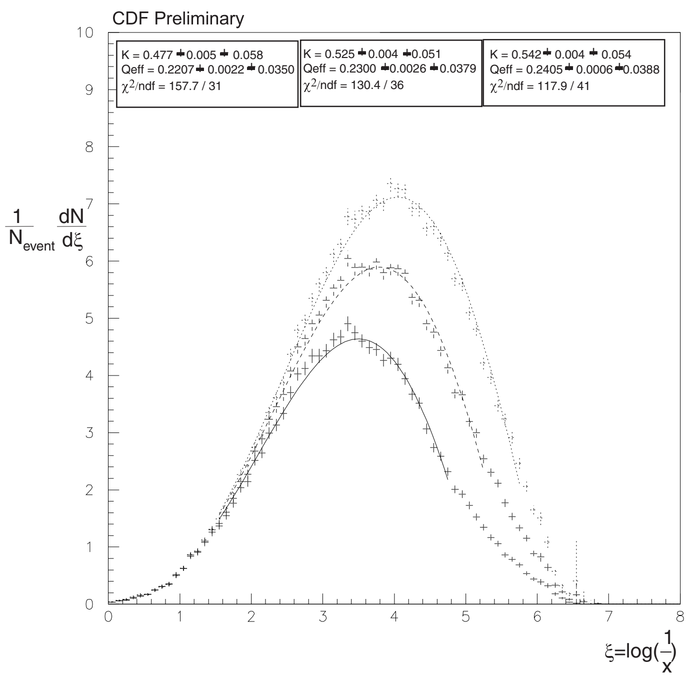
- In e^+e^- annihilation, low-x fragmentation functions agree remarkably well with the resummed (NLLA or MLLA) predictions over a wide energy range.

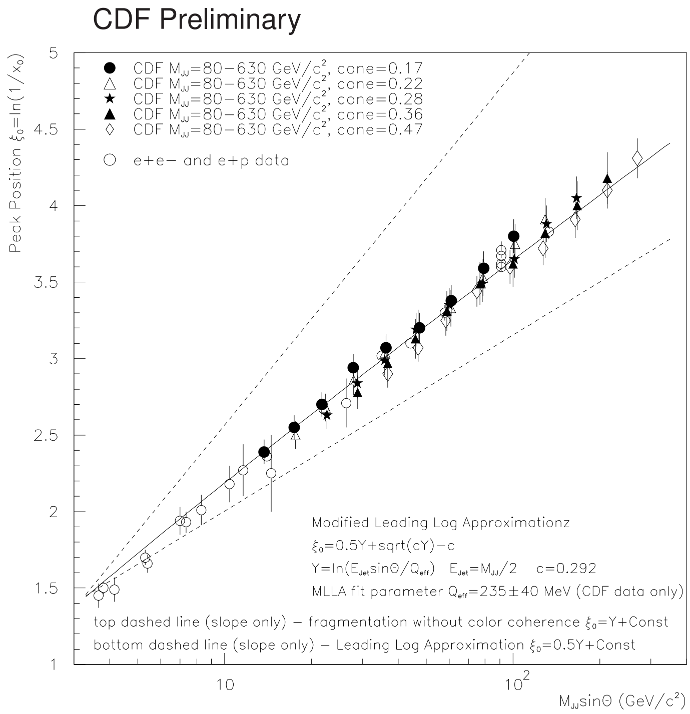




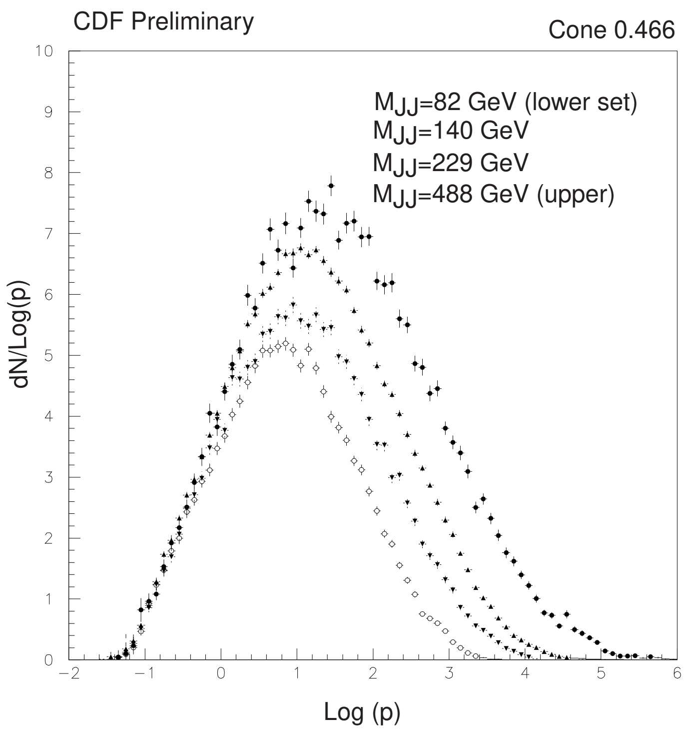
- In $p\bar{p} \longrightarrow$ dijets the relevant scale is taken to be $M_{JJ} \sin\theta$ where M_{JJ} is the dijet mass and θ is the jet cone angle.





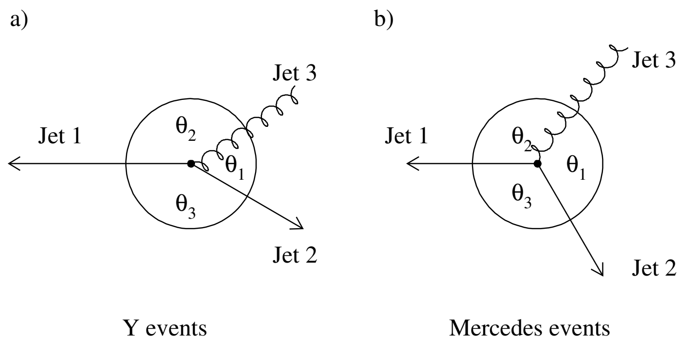


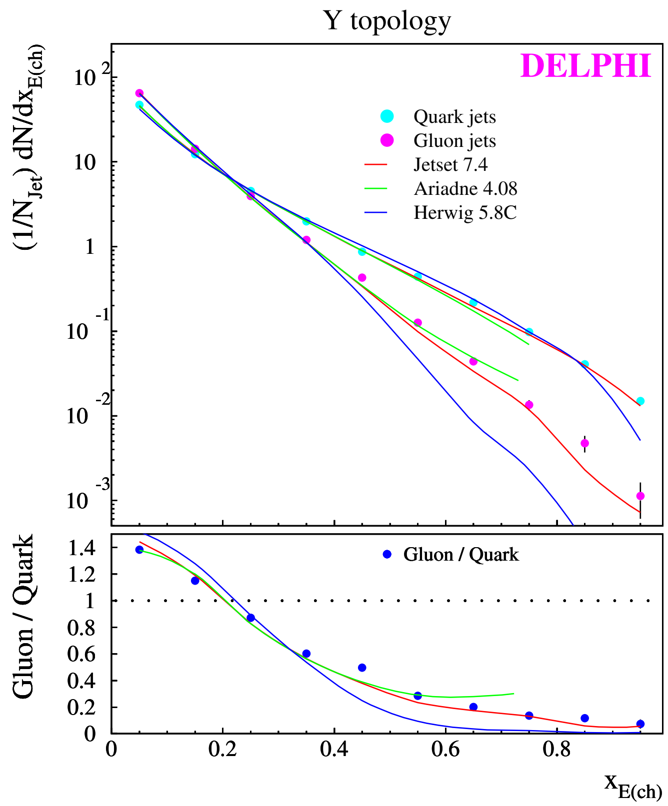
- When plotted against $\ln p$ instead of $\ln(1/x)$, the CDF data show clearly the scale-independence of the soft particle distribution (a test of colour coherence).

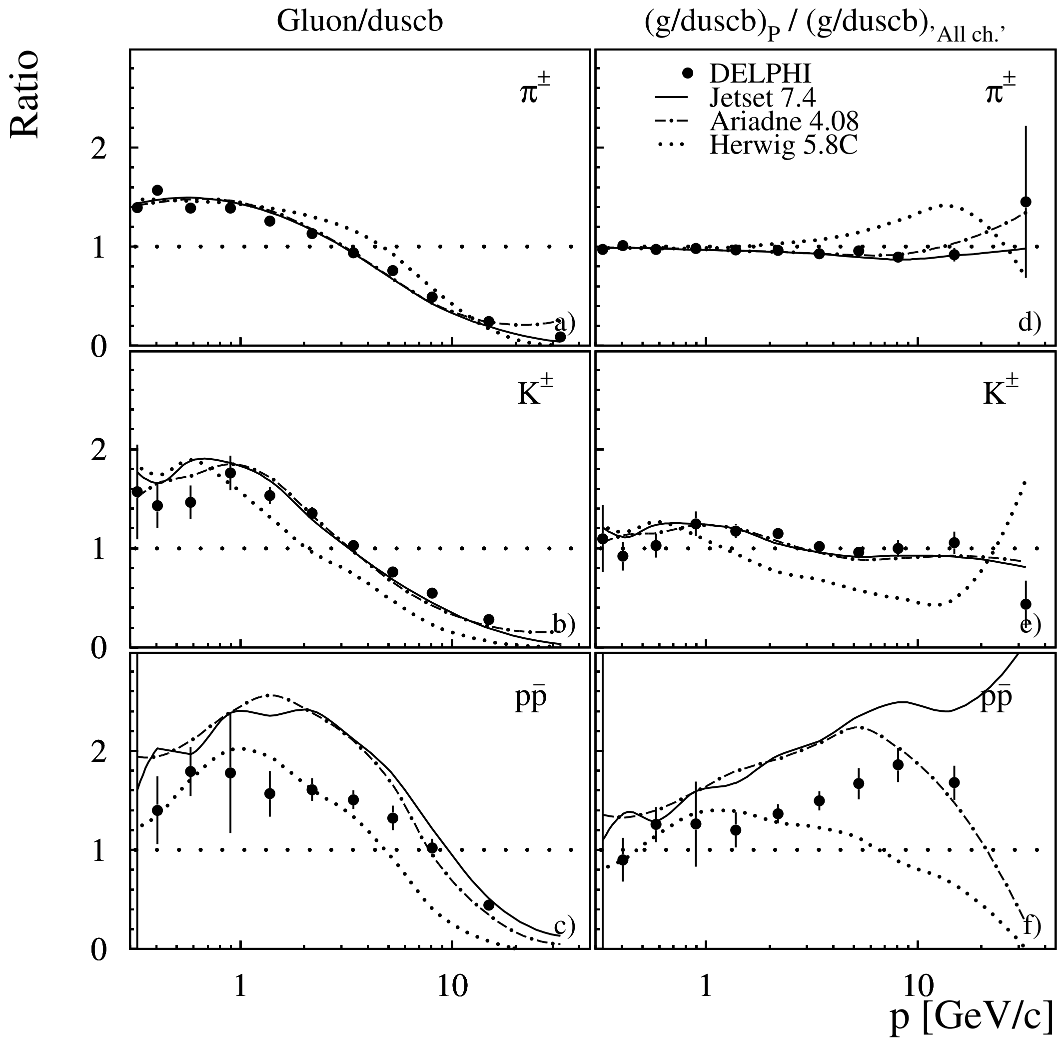


Quark and gluon jets

- DELPHI select gluon jets by anti-tagging heavy quark jets in Y and Mercedes three-jet events





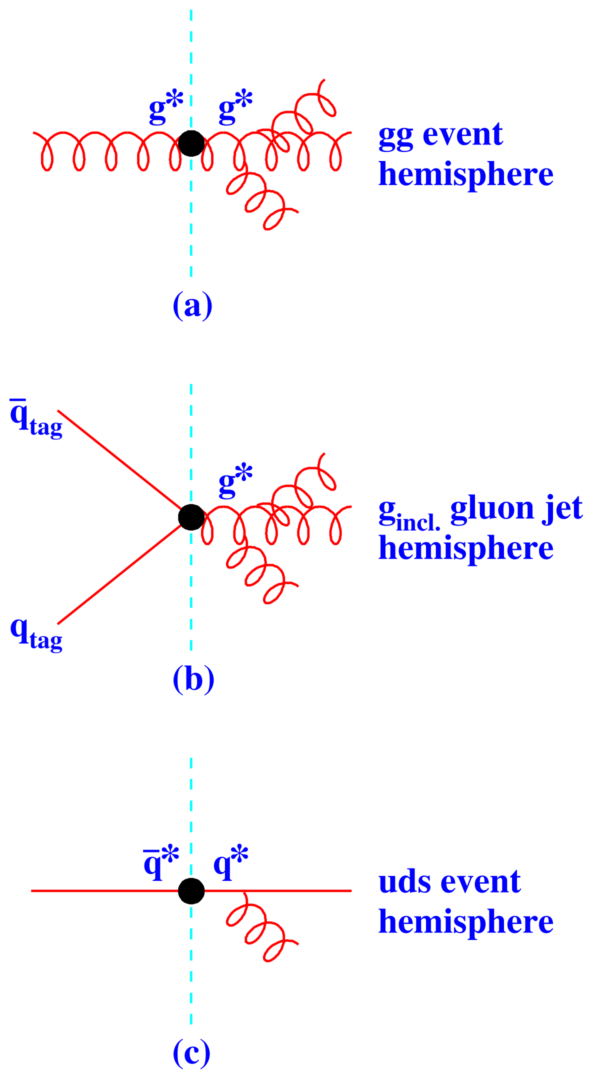


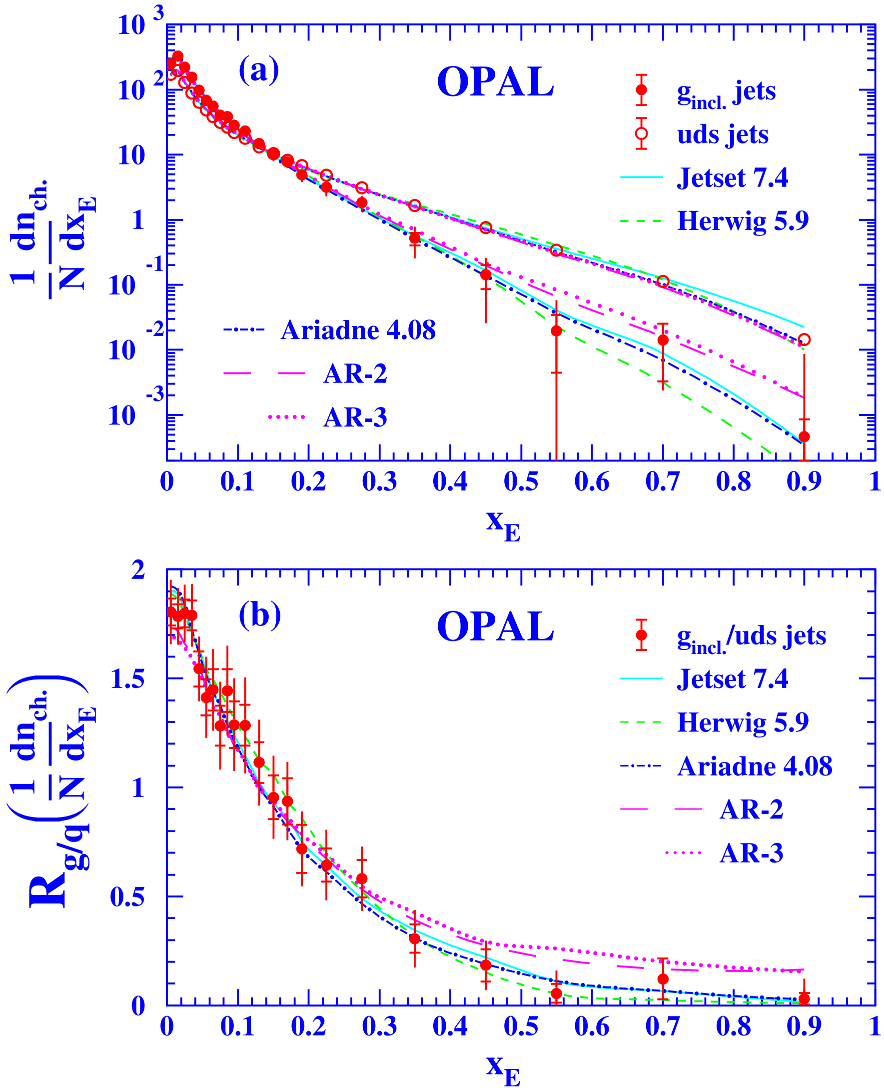
- In general the relative multiplicities of identified particles are consistent with those of all charged, with no clear excess of certain species in gluon jets (ALEPH, DELPHI, SLD)

  In particular there is no enhanced η or $\phi(1020)$ production:

  OPAL: $N_g(\eta)/N_q(\eta) = 1.29 \pm 0.11$
  DELPHI: $N_g(\phi)/N_q(\phi) = 0.7 \pm 0.3$

- OPAL select gluon jets recoiling against tagged b-jets in the same hemisphere. Monte Carlo studies indicate that such jets should be similar to those emitted by a point source of gluon pairs (e.g. a $^1\mathrm{S}_0\ Q\bar{Q}$ state).

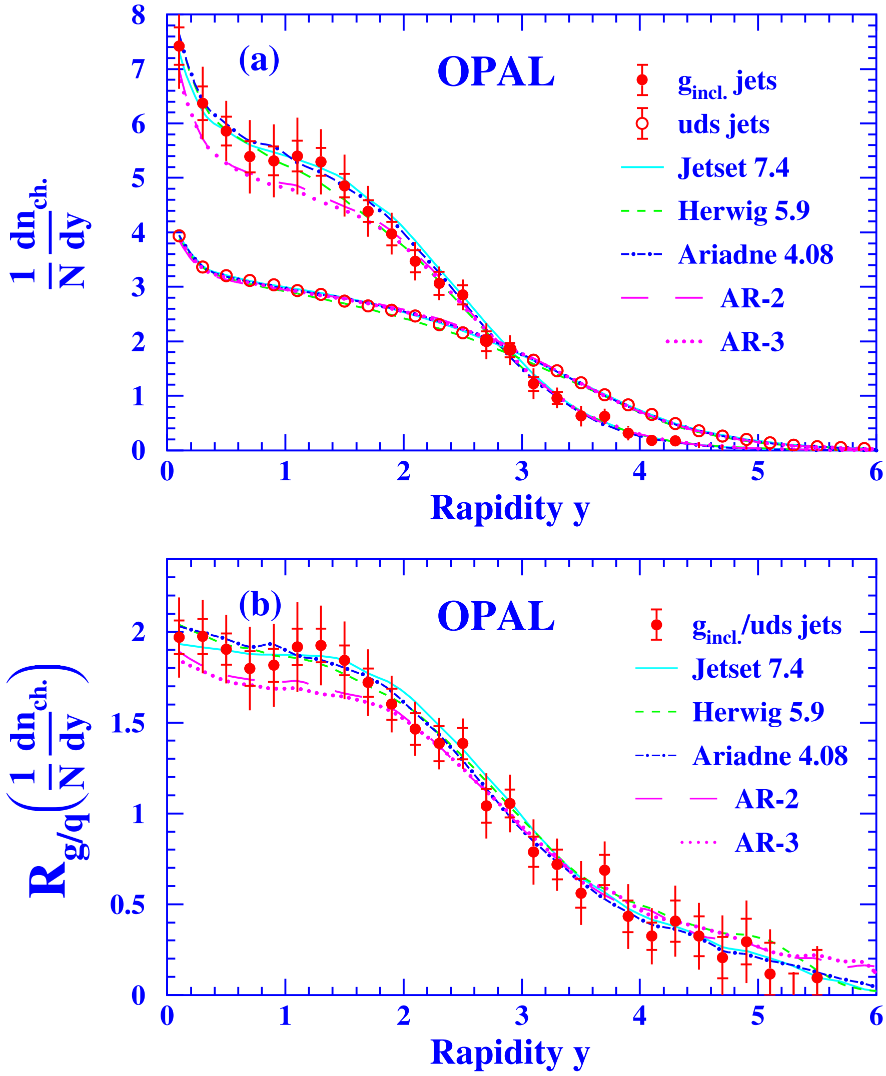




- Next-to-leading order calculations of the relevant coefficient functions are needed to check universality. However the qualitative message is clear:

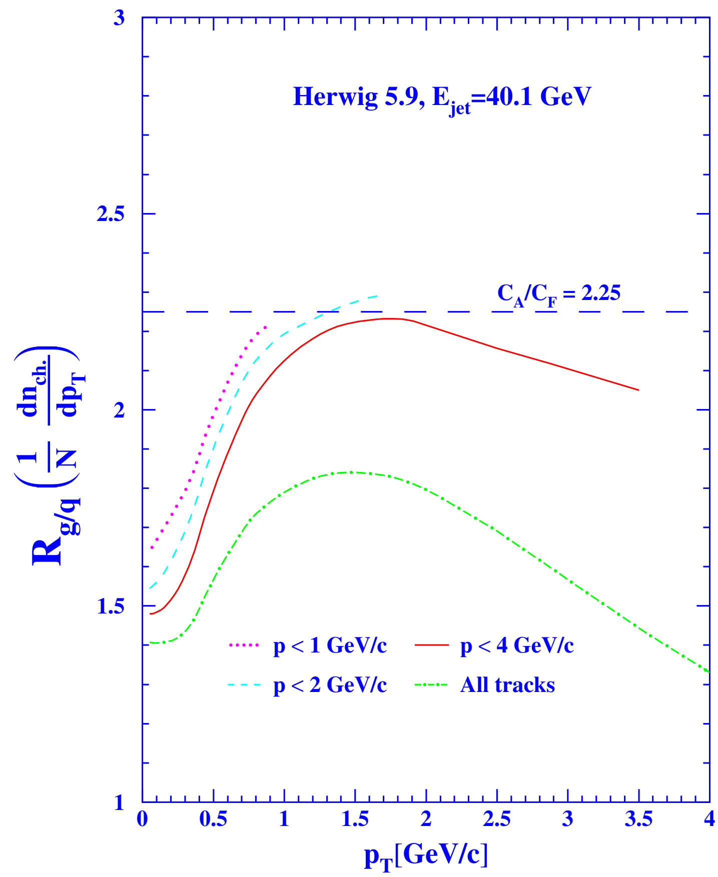
  Gluon jets have softer fragmentation functions than light quark jets, and higher charged multiplicity.

- The ratio of charged multiplicities at low rapidity (large angle) is close to the ratio of colour factors $r \equiv C_A/C_F = 2.25$, in agreement with Local Parton-Hadron Duality (LPHD).



OPAL: $r_{ch}(|y| < 1) = 1.919 \pm 0.047 \pm 0.095$

- Monte Carlo studies suggest that a better measure of C_A/C_F is obtained by selecting low-momentum hadrons with relatively large p_T (i.e. low rapidity)

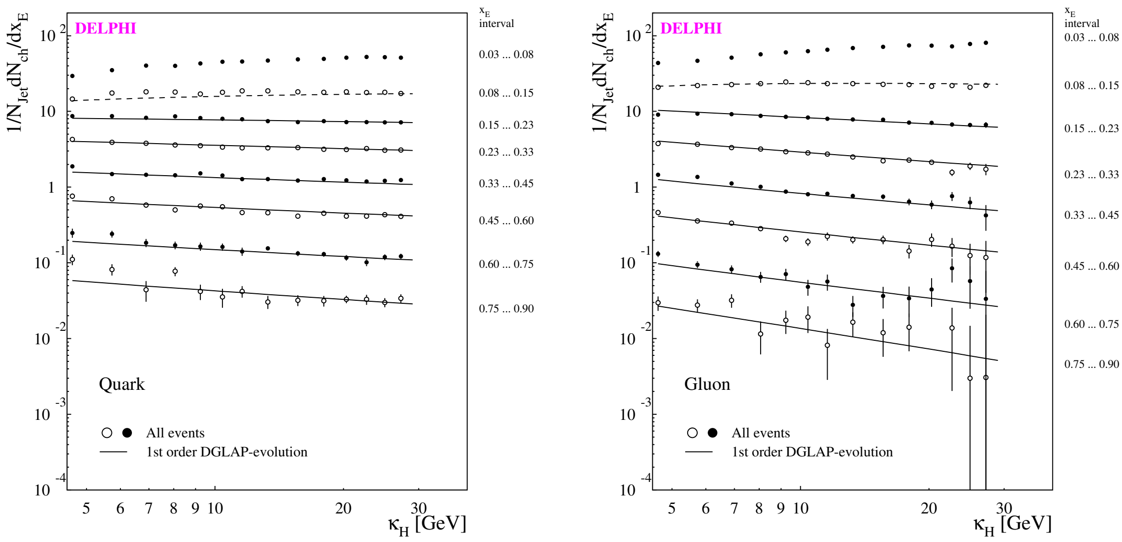


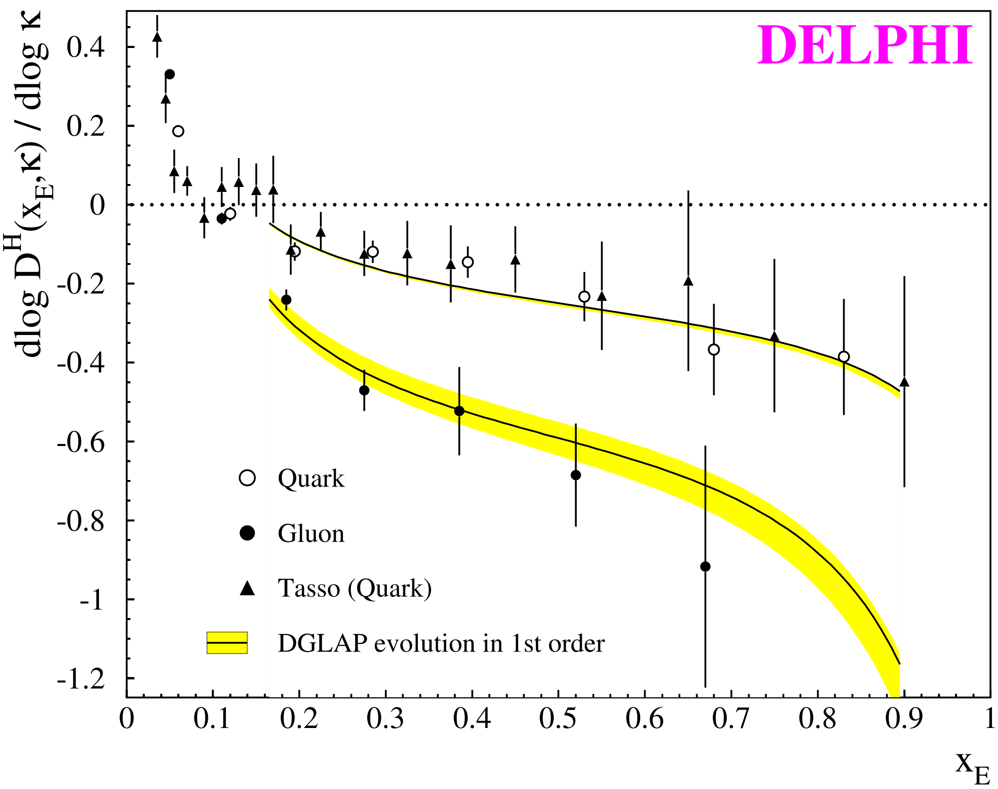
OPAL: $r_{ch}(p < 4,\ 0.8 < p_T < 3\text{GeV}) = 2.29 \pm 0.09 \pm 0.015$

- DELPHI have also observed scaling violation in gluon jet fragmentation by studying the dependence on

$$\kappa_H = E_{jet}\,\sin(\theta/2)\ \ (\simeq \tfrac{1}{2}\sqrt{s y_3})$$

where θ is the angle to the closest jet. This is expected to be the relevant scale, at least when θ gets small.



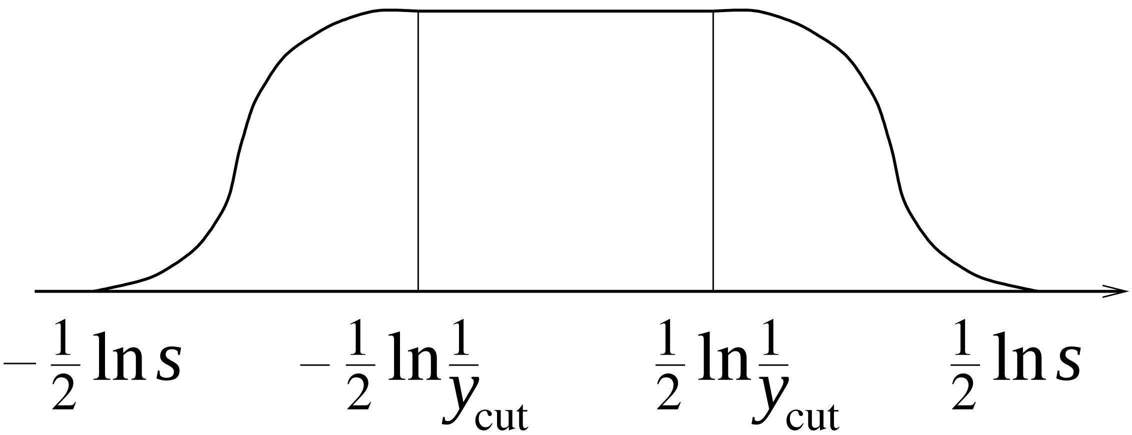


The ratio of scaling violations in quark and gluon jets provides another measure of C_A/C_F:

DELPHI: $r_{\text{sc.viol.}} = 2.23 \pm 0.09 \pm 0.06$

- A crucial point in the above study is that 3-jet events were not selected using a fixed jet resolution $y_{\rm cut}$, but rather each event was clustered to precisely 3 jets. This avoids 'biasing' the gluon jet sample (by preventing further jet emission above $y_{\rm cut}$).

- The same point is well illustrated by the analysis of average multiplicities in 2- and 3-jet events. If $N_{q\bar{q}}(s)$ is the 'unbiased' $q\bar{q}$ multiplicity, then in events with precisely 2 jets at resolution $y_{\rm cut}$ we get a 'rapidity plateau':

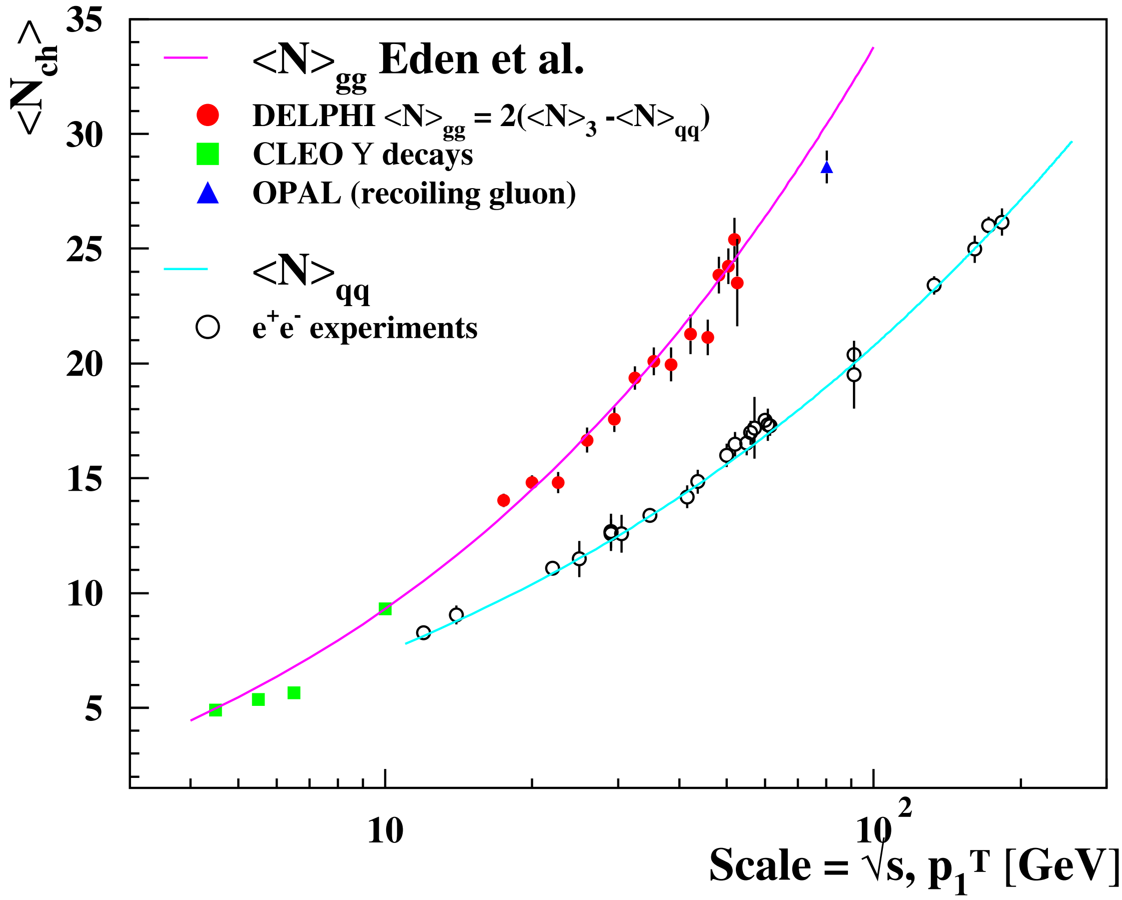


$$N_2(s, y_{\rm cut}) \simeq N_{q\bar{q}}(s y_{\rm cut}) + \ln(1/y_{\rm cut}) N'_{q\bar{q}}(s y_{\rm cut})$$

where $N'(s) \equiv s dN/ds$. Clustering each event to 3 jets we get this with y_3 in place of $y_{\rm cut}$, plus an unbiased gluon jet:

$$N_3(s) \simeq N_2(s, y_3) + \tfrac{1}{2} N_{gg}(s y_3)$$

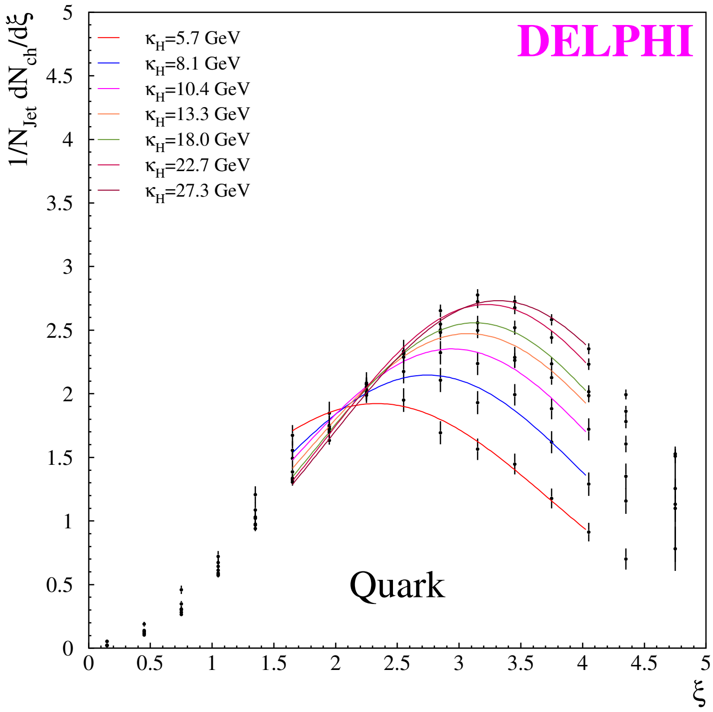
Thus one can obtain the unbiased gg multiplicity (plotted here vs. $p_1^T \sim \sqrt{sy_3}$).

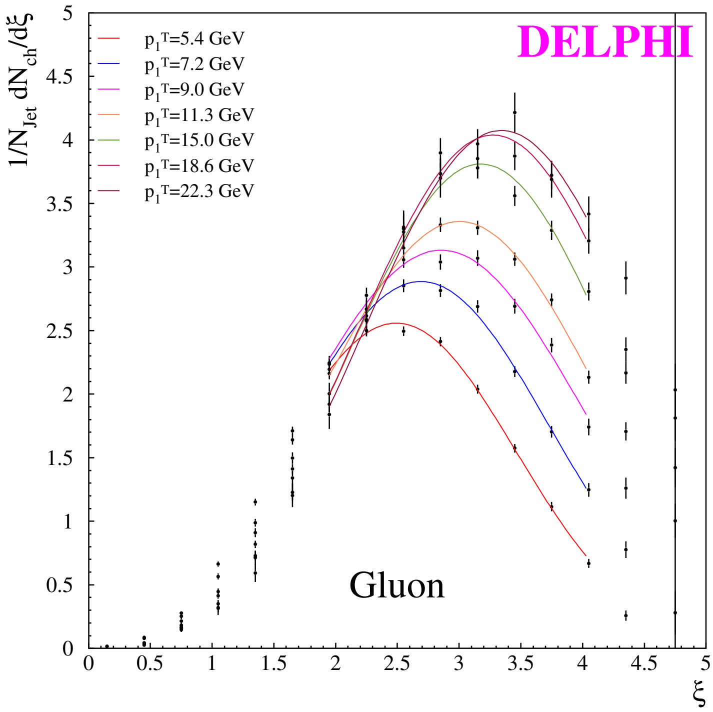


The ratio of slopes gives yet another measure of C_A/C_F:

$r_{\text{mult}} = 2.246 \pm 0.062(\text{stat.}) \pm 0.080(\text{sys.}) \pm 0.095(\text{theo.})$

● The low-x fragmentation functions of quark and gluon jets also agree well with resummed predictions in the "hump" region:



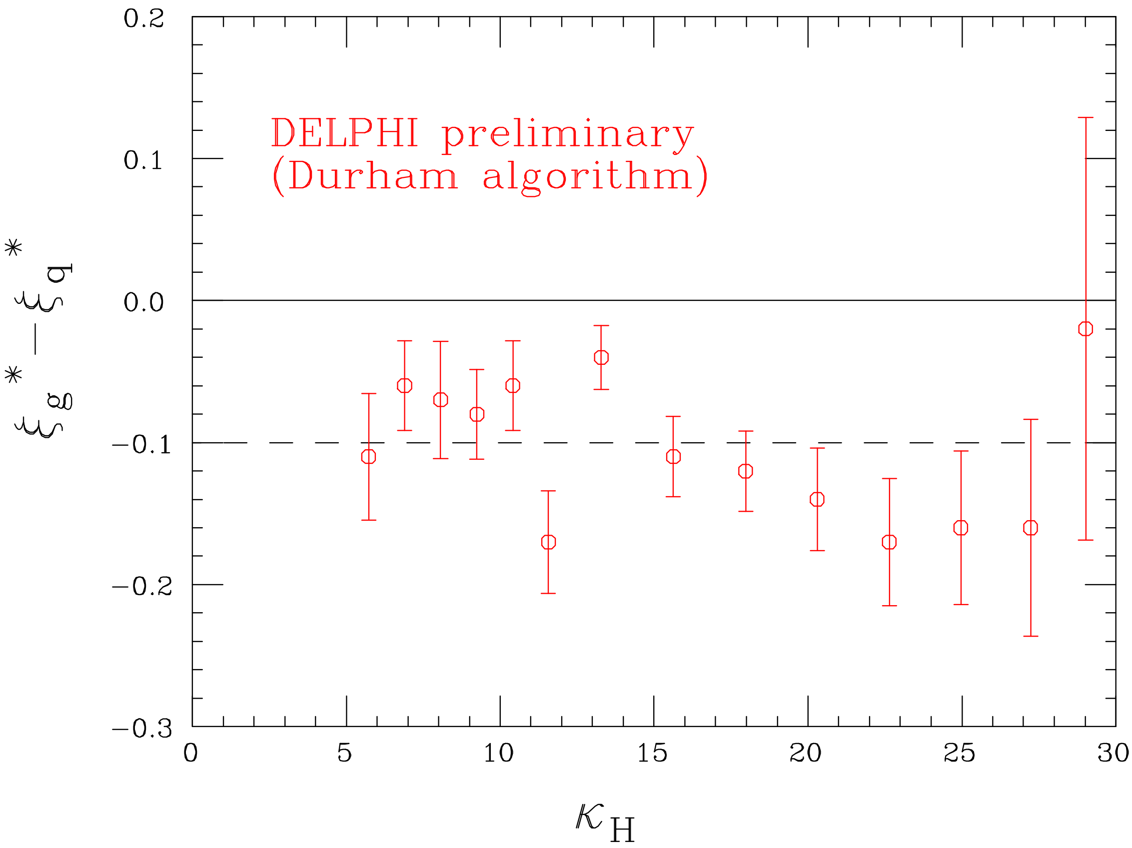


- Predicted asymptotic quark–gluon peak difference is (Fong & W, 1989)

$$\xi_q^* - \xi_g^* = -\frac{1}{12}\left(1+\frac{N_f}{N_c^3}\right) + \mathcal{O}(\sqrt{\alpha_S}) \sim -0.1$$

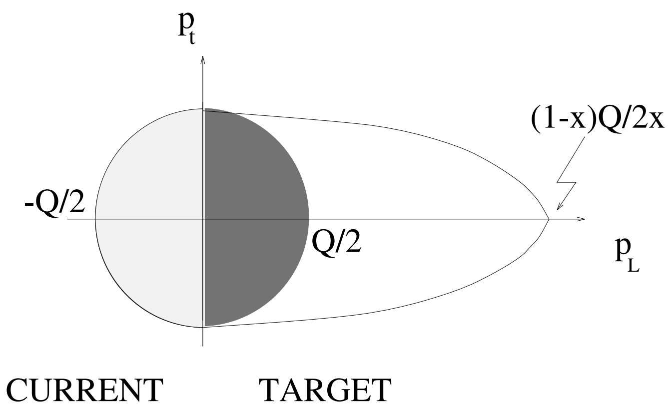
- DELPHI value, averaged over $\kappa_H = 5 - 30$ GeV:

$$\langle \xi_q^* - \xi_g^* \rangle = -0.096 \pm 0.009$$

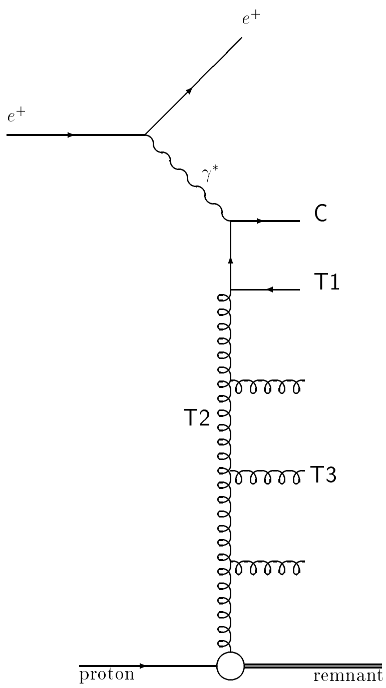


Current and target fragmentation

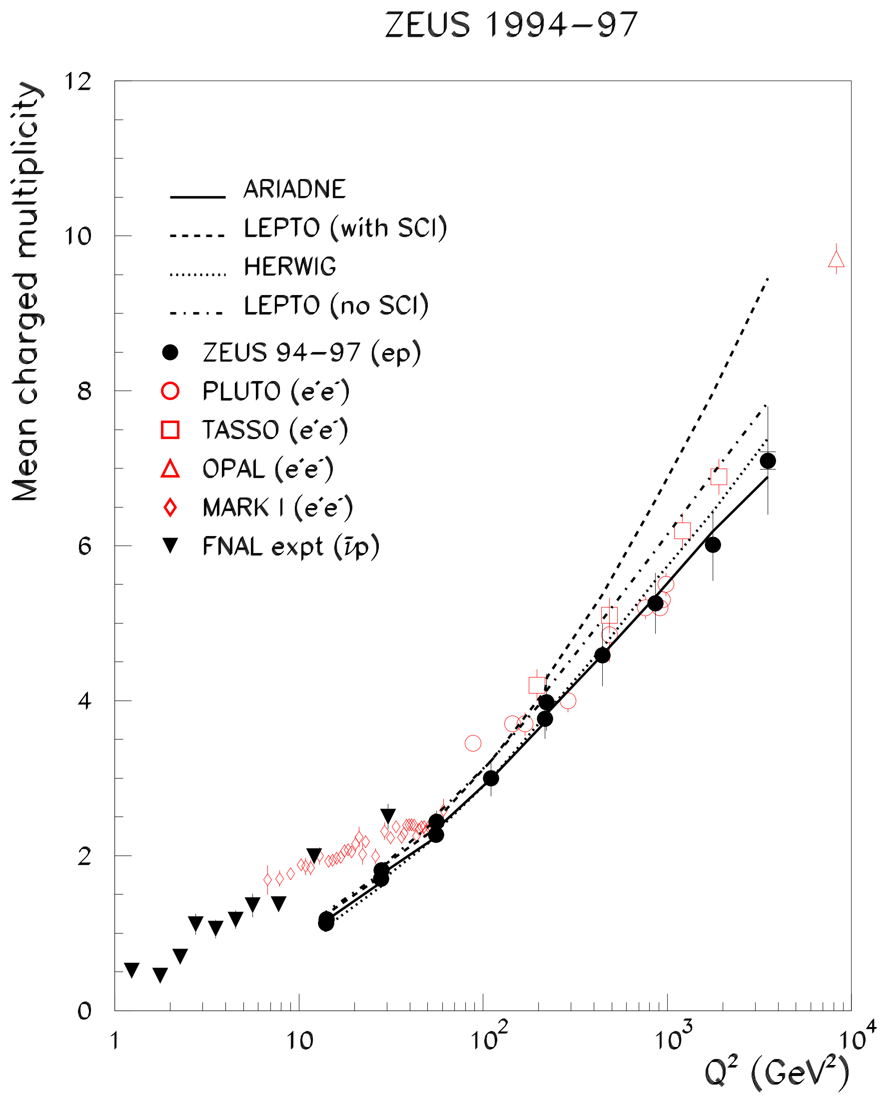
H1 and ZEUS study distributions of $x_p = 2|\boldsymbol{p}|/Q$ in the current and target hemispheres in the Breit frame.



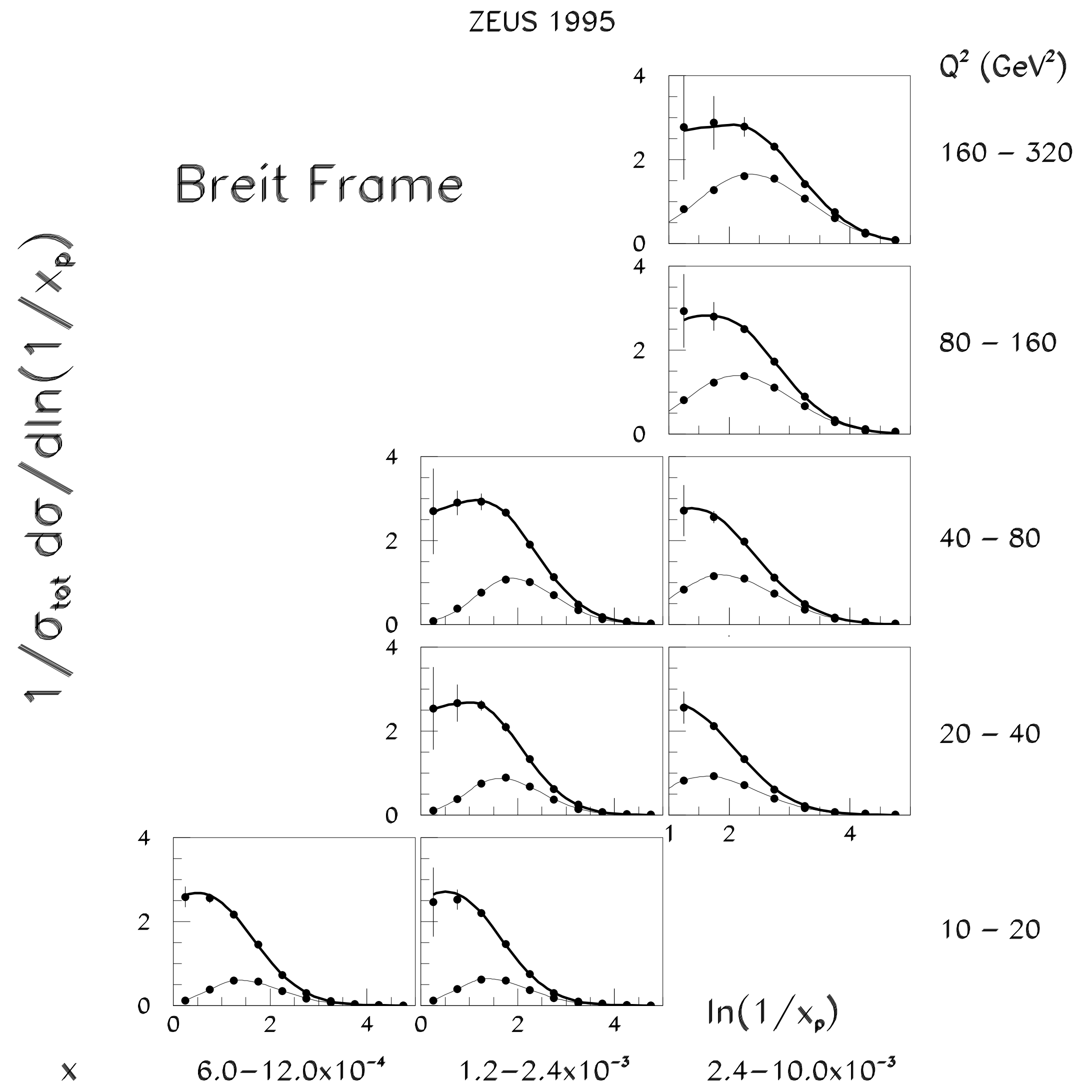
- In the current hemisphere one expects fragmentation of the current jet (C), similar to e^+e^-. In the target hemisphere, contribution T1 is similar to C, T2 gives extra particles with $x_p < 1$, while T3 gives $x_p \gtrsim 1$, generally outside acceptance.



- The charged multiplicity in the current hemisphere is indeed similar to e^+e^-. Differences at low Q^2 are consistent with the boson-gluon fusion contribution at low Q^2.

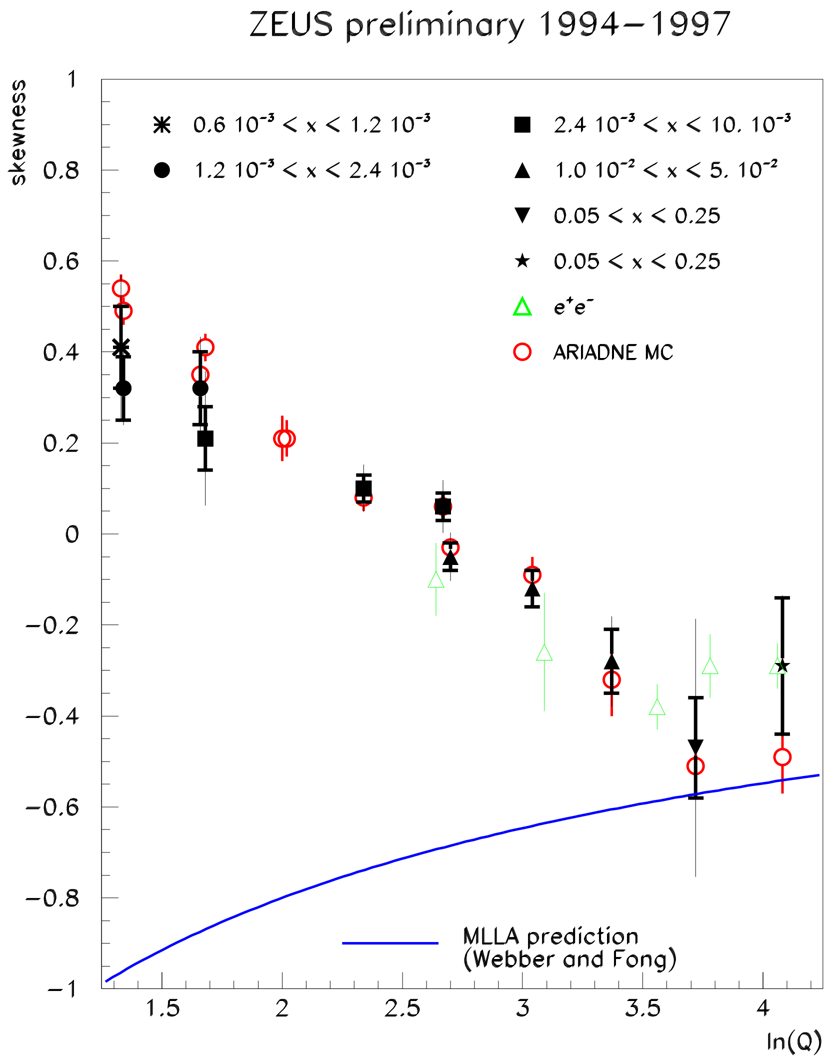


❖ The current-hemisphere distribution of $\xi = \ln(1/x_p)$ is also similar to e^+e^-, i.e. close to gaussian with little Bjorken x dependence.

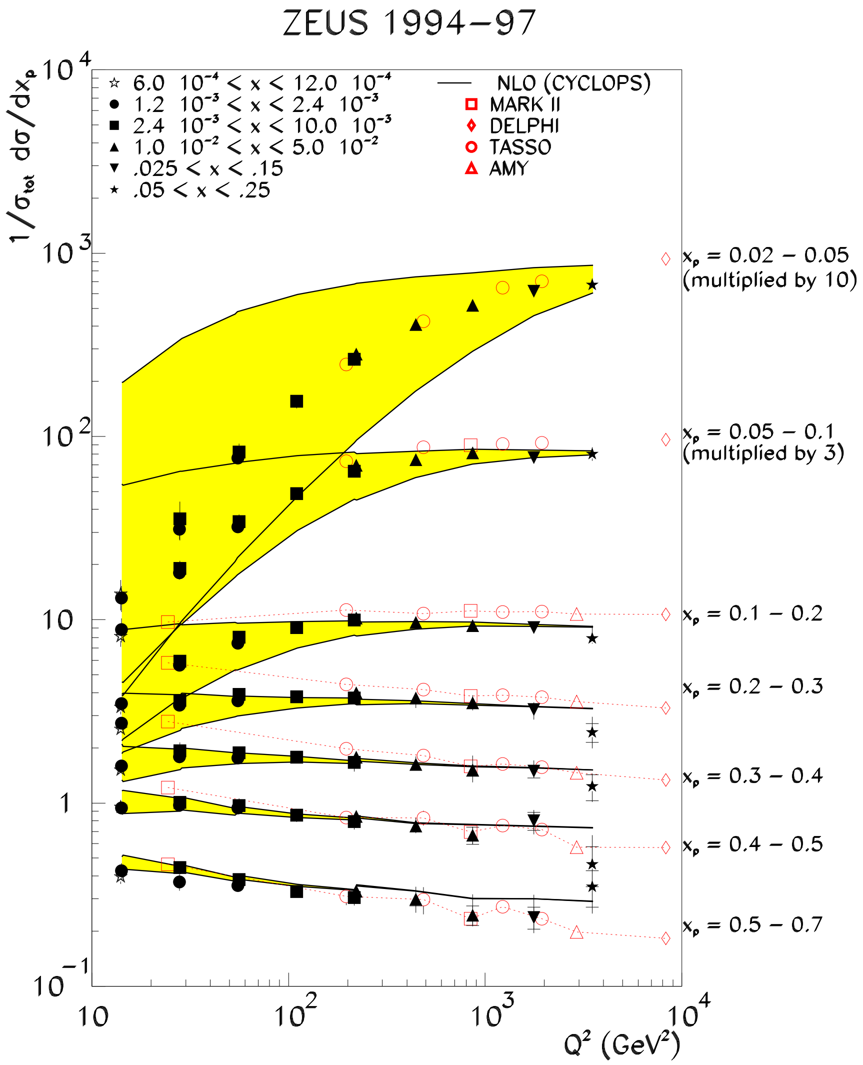


❖ At low Q^2 there is evidence of strong subleading corrections. The distribution is skewed towards higher values of ξ (smaller x_p), contrary to NLLA predictions.

$$\text{Skewness} \equiv \langle(\xi - \bar{\xi})^3\rangle \,/\, \langle(\xi - \bar{\xi})^2\rangle^{\frac{3}{2}}$$



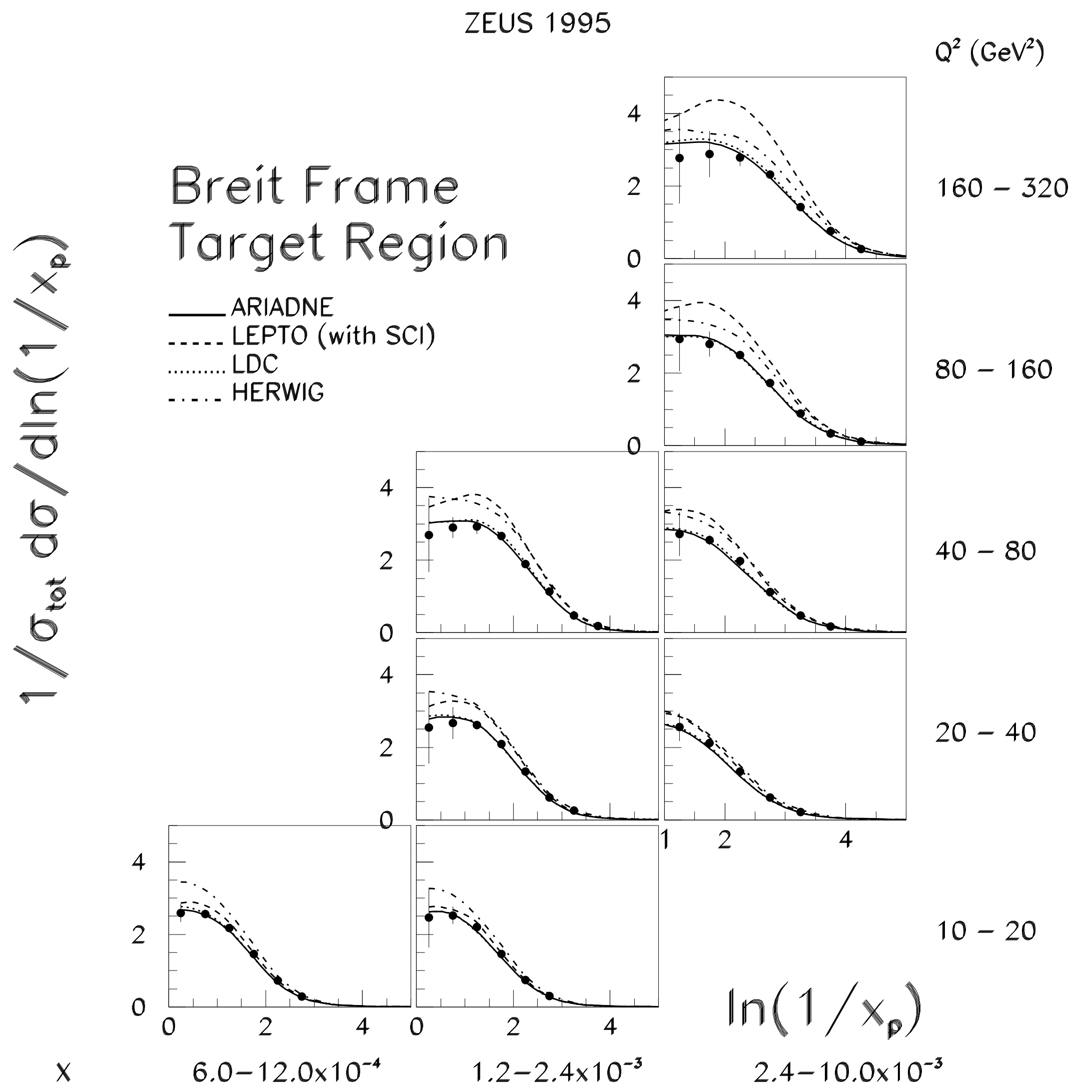
❖ On the other hand, the data lie well below the fixed-order perturbative prediction (CYCLOPS) at low x_p and Q^2.



Discrepancies could be due to power-suppressed $(1/Q^2)$ corrections, of dynamical and/or kinematic origin. The bands correspond to a correction factor

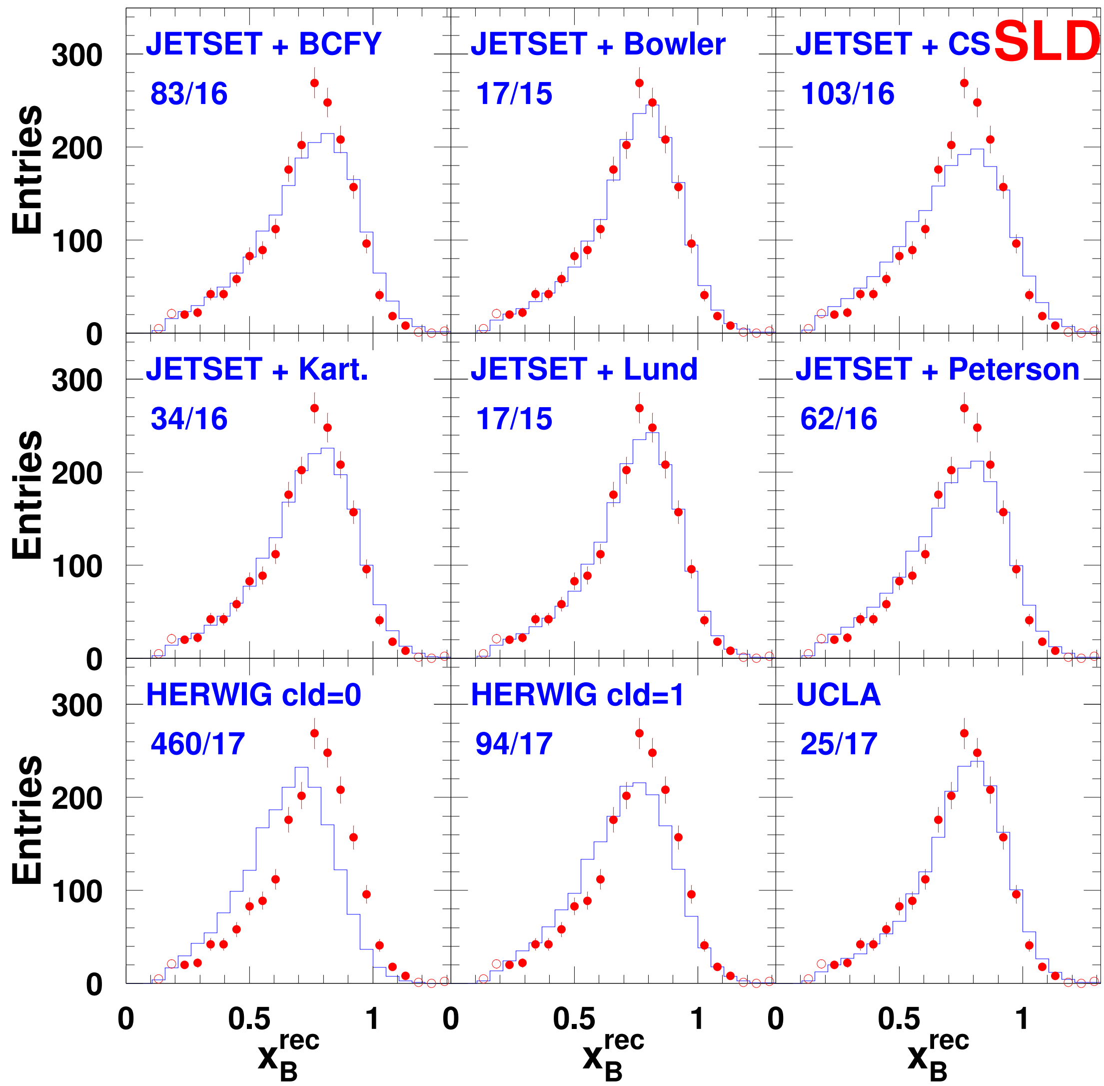
$$\left[1+\left(\frac{m_{\rm eff}}{Qx_p}\right)^2\right]^{-1} \qquad (0.1 < m_{\rm eff} < 1\ \text{GeV})$$

- In the target hemisphere there is also disagreement with MLLA, possibly due to the T3 contribution "leaking" into the region $x_p < 1$. If anything, models predict too much leakage. Little Q^2 dependence is observed.



Heavy quark fragmentation

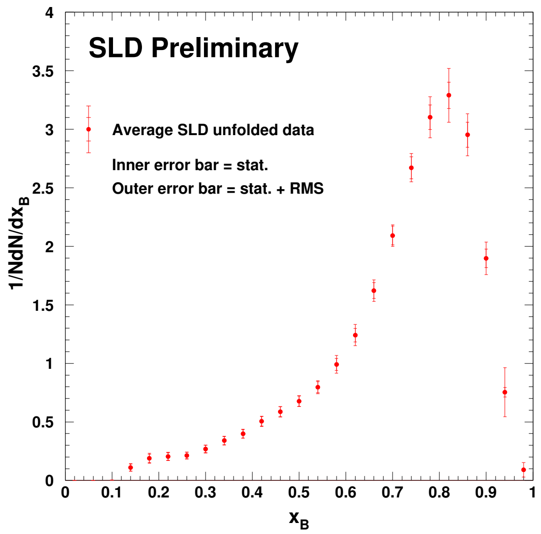
- New data on $b \to$ B fragmentation from SLD, using high-precision vertexing, discriminate between parton-shower plus hadronization models. [N.B. Uncorrected data.]

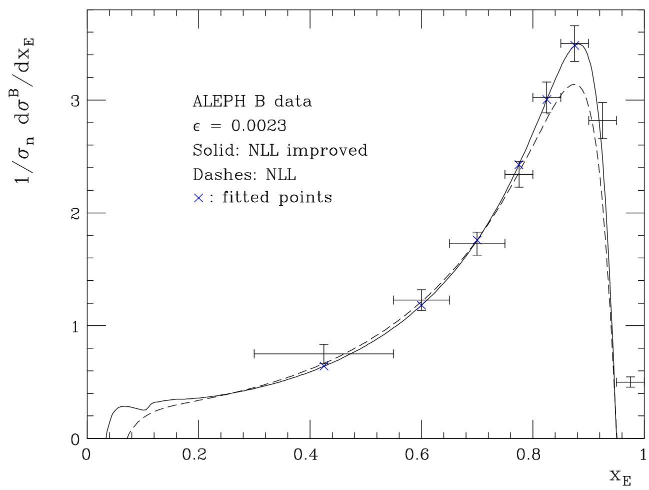


- Including more perturbative QCD leads to a reduction in the amount of non-perturbative smearing required.

Peterson function: $$\frac{1}{z}\left(1-\frac{1}{z}-\frac{\epsilon_b}{1-z}\right)^{-2}$$

- Pure Peterson: $\epsilon_b = 0.036$
  JETSET ($\simeq$ LLA QCD) + Peterson : $\epsilon_b = 0.006$
  NLLA QCD + Peterson (Nason & Oleari): $\epsilon_b = 0.002$

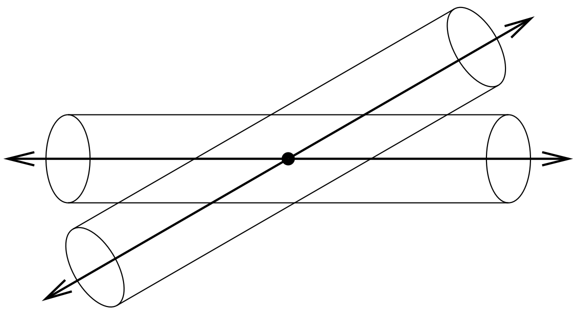




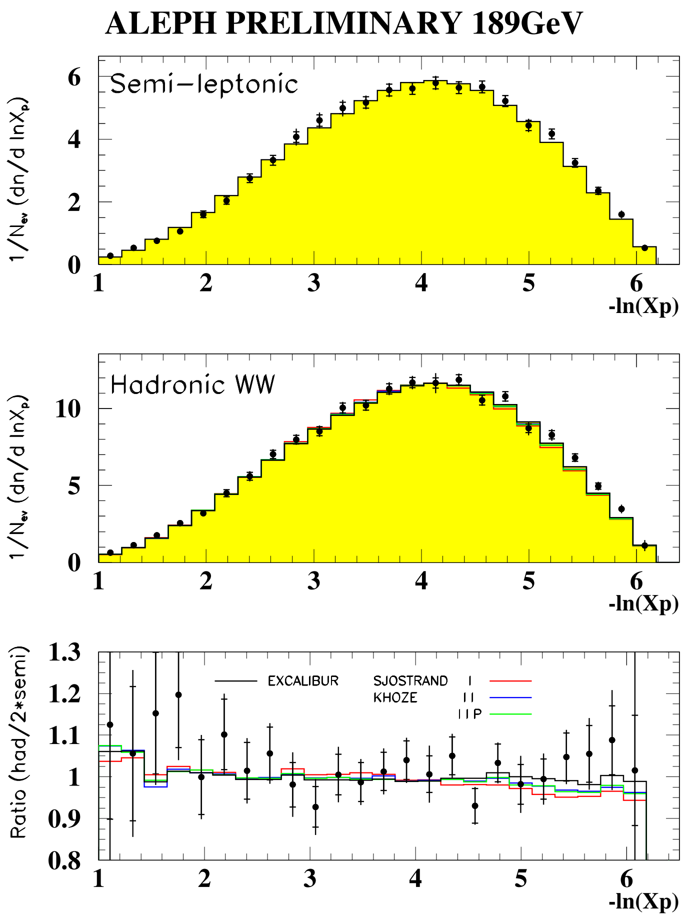
- In the universal low-scale α_S model, the perturbative prediction is extrapolated smoothly to the non-perturbative region, with no Peterson function (Dokshitzer, Khoze & Troyan)

WW fragmentation

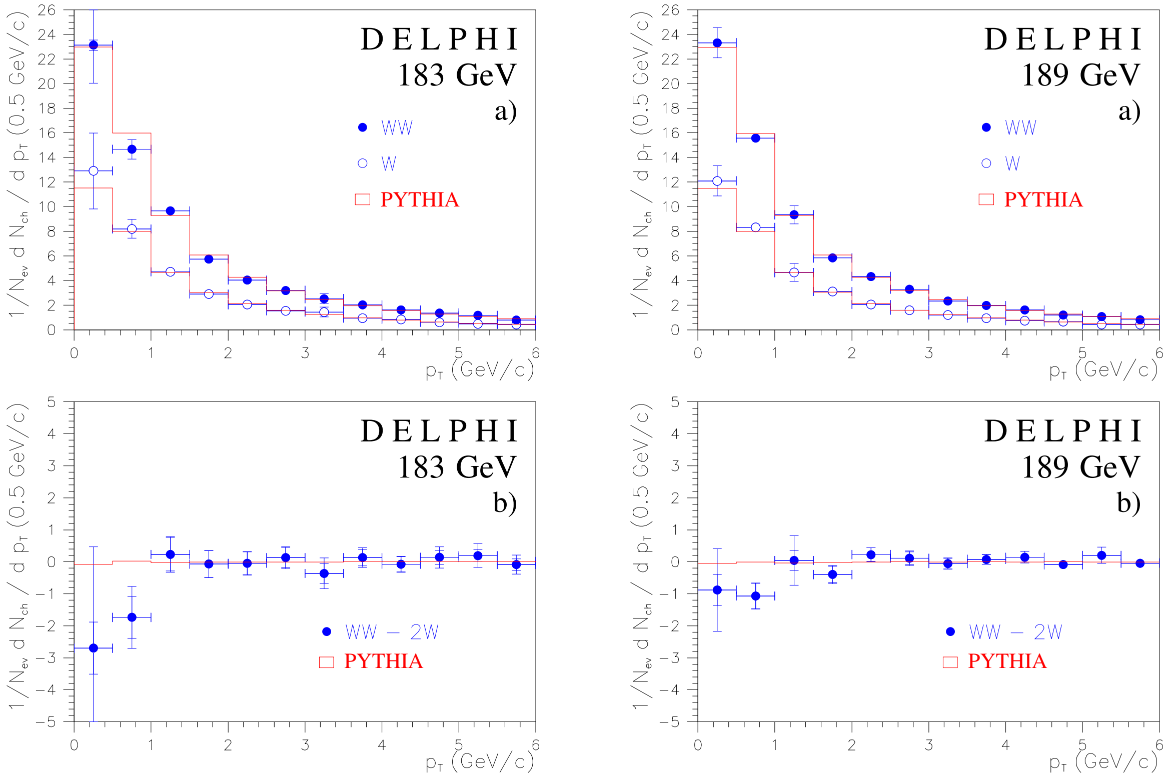
In general we expect colour reconnection: correlation between W hadronic decays due to overlap of hadronization volumes. This occurs mainly in the central region, and is orientation-dependent.



- No effects seen yet in charged particle energy spectra



- DELPHI report a possible small ($\sim 2\sigma$?) effect in the distribution of p_T (relative to the thrust axis):

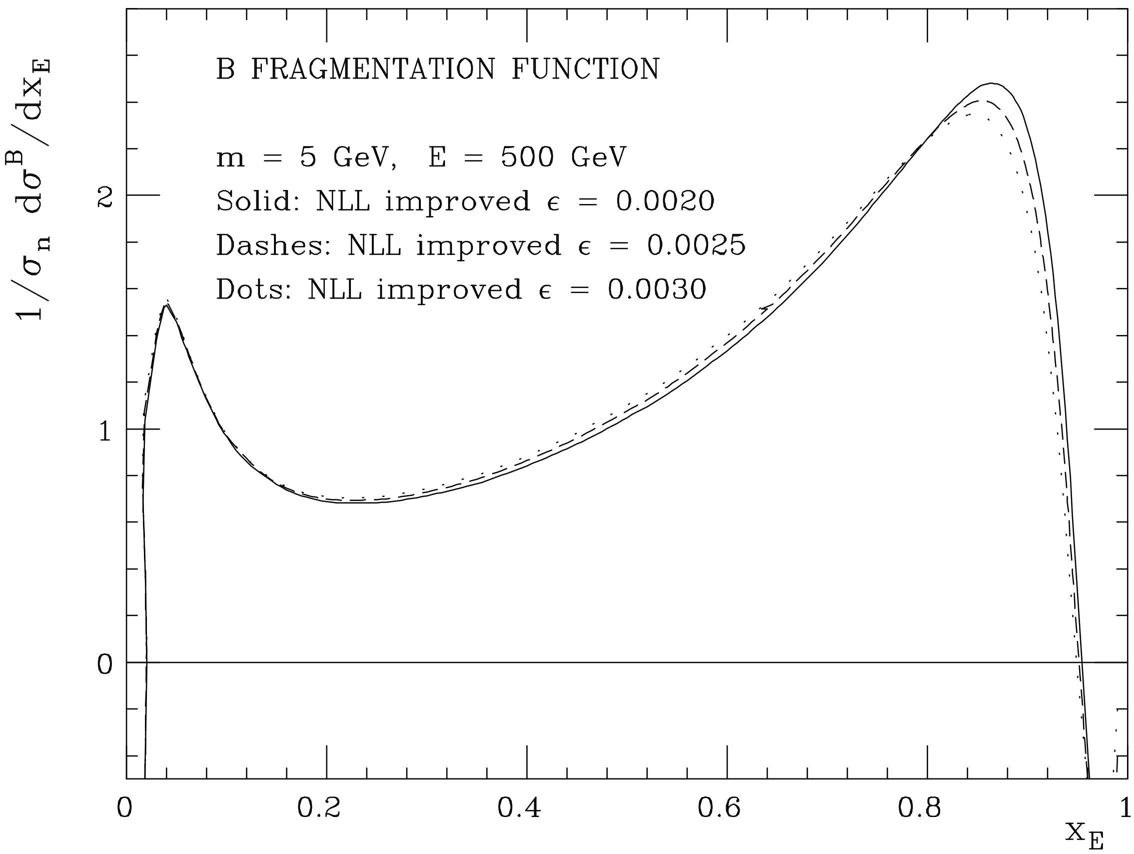


Conclusions

- Detailed fragmentation studies need more theoretical input (coefficient functions).
- Experimenters finally understand how to disentangle the properties of quark and gluon jets.
- Gluon jets have the expected properties and can be used to measure ratio of colour factors C_A/C_F. There is no strong evidence (yet) of different particle content.
- Fragmentation in DIS shows disagreements with perturbative predictions: higher-order and/or non-perturbative?
- New b quark fragmentation data test models and suggest perturbative effects dominate.
- WW fragmentation still shows no firm evidence for correlation between the decay products of the two W's.

(Evolution of b fragmentation to NLC)

Fragmentation function for $b \to B$ evolved from $\sqrt{s} = M_Z$ to 500 GeV (Nason & Oleari)



(Evolution of proton spectrum to UHE)

Decay of superheavy ($M \sim 10^{21}$ eV) metastable relic particles in the galactic halo has been suggested as a possible source of ultra-high energy cosmic rays.

Assuming no new physics, evolution of the proton spectrum from $\sqrt{s} = M_Z$ could give a sufficiently hard spectrum (Rubin)