Latest QCD results from LEP

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Latest QCD results from LEP

1 Quark and gluon jet fragmentation functions
(OPAL)

2 Unbiased gluon jets, with the "jet boost" algorithm
(OPAL)

3 Coherence soft particle production in three-jet events
(DELPHI)

4 α_{s} from event shapes
(LEP combined, with new published input from ALEPH and L3)

Scaling violations of quark and gluon jet fragmentation functions

Define the fragmentation function

$$D_a = \frac{1}{N_{\text{jet}}(Q)} \frac{\mathrm{d}N_{\text{p}}(x_E, Q)}{\mathrm{d}x_E}$$

for a parton a fragmenting into hadrons with the momentum fractions $x_E = E_{\text{hadron}}/E_{\text{jet}}$.

Several ways to identify jets in $e^+e^- \to q\bar{q}(g)$ events:

- Biased jets (using Durham jet-finder to select 3-jet events):
  - b-tagging (neural network) ⇒ samples enriched in udsc, b and gluon jets.
  - Energy-ordering ⇒ samples enriched in quark and gluon jets.
- Unbiased quark jets, defined by hemispheres of inclusive hadronic events:
  - b-tagging ⇒ unbiased udsc and b jets
- Unbiased gluon jets, using the "jet boost" algorithm
  (NB previous measurements have been published using other algorithms)

Can measure fragmentation functions in all cases.

Fragmentation functions (contd.)

- NLO predictions exist for Q-dependence of quark and gluon fragmentation functions, but not explicitly for x_E-dependence (predictions are based on fits to data).

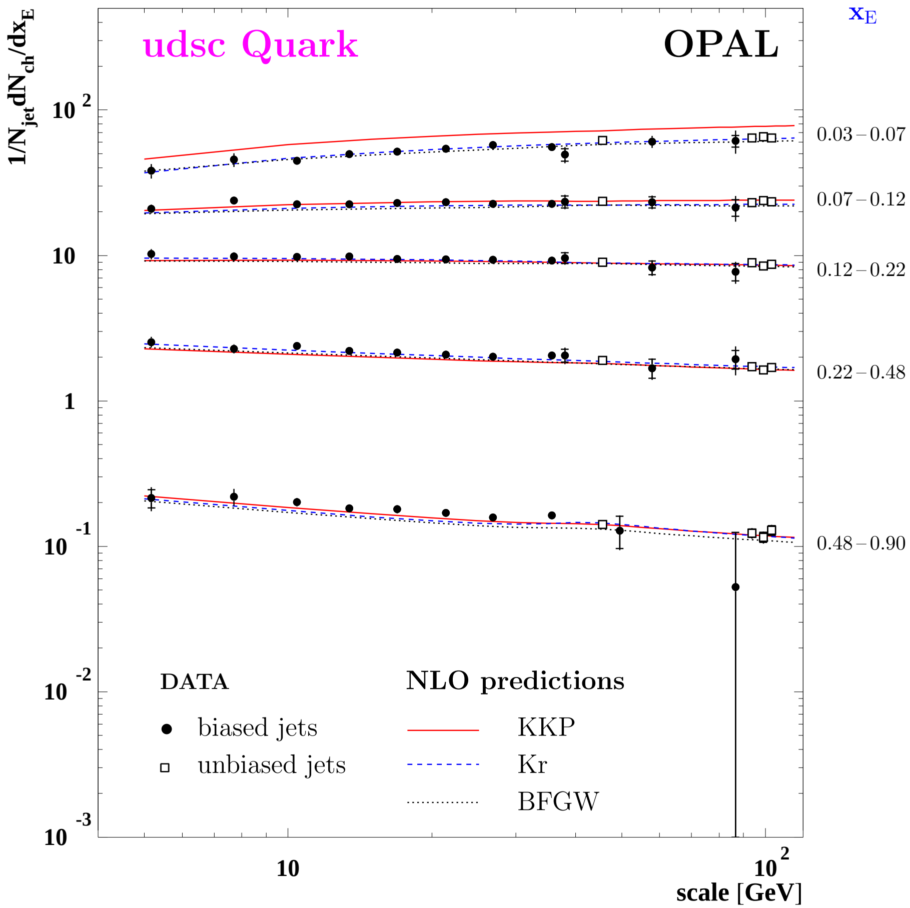
- All theory predictions are based on unbiased jets (not dependent on choice of jet-finder).

- Must choose appropriate energy scale for each jet when comparing with theory:
  - $Q = \sqrt{s}/2$ for unbiased quark jets
  - $Q_{\text{jet}} = E_{\text{jet}} \sin(\theta/2)$ for biased jets, where θ is the angle to the nearest jet.

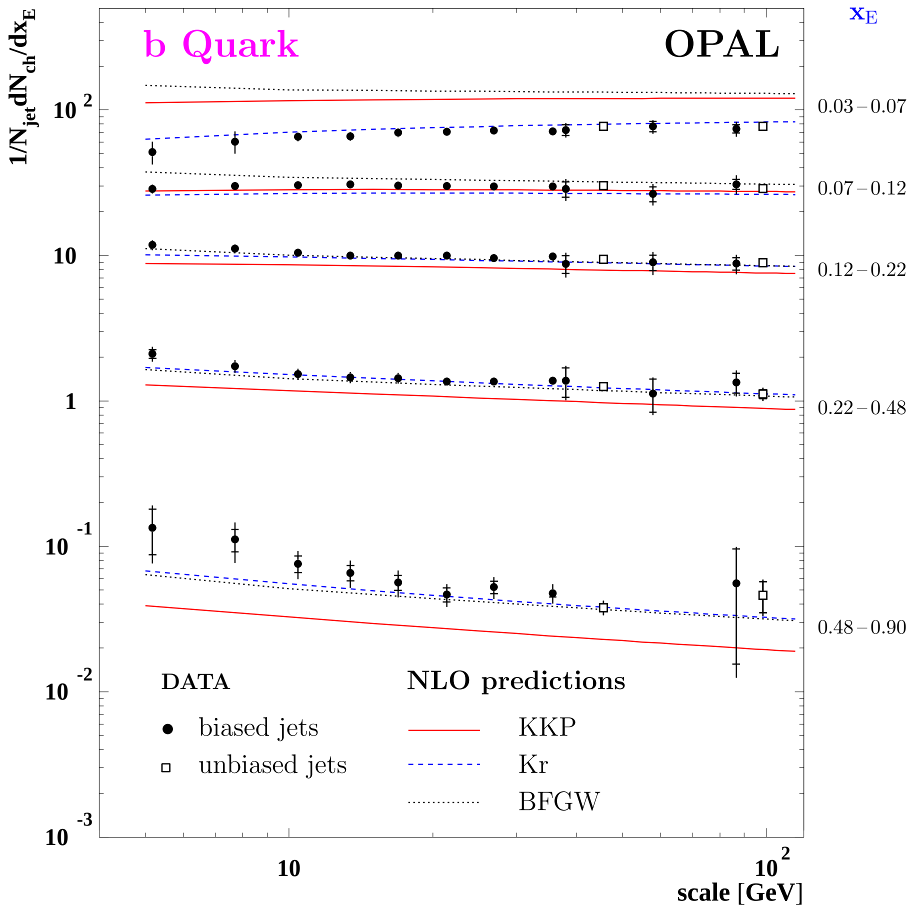
- Measurements allow comparisons between:
  - Data and theory
  - Data and MC
  - Biased and unbiased jets

Scale dependence of quark jet fragmentation functions

udsc quark jets

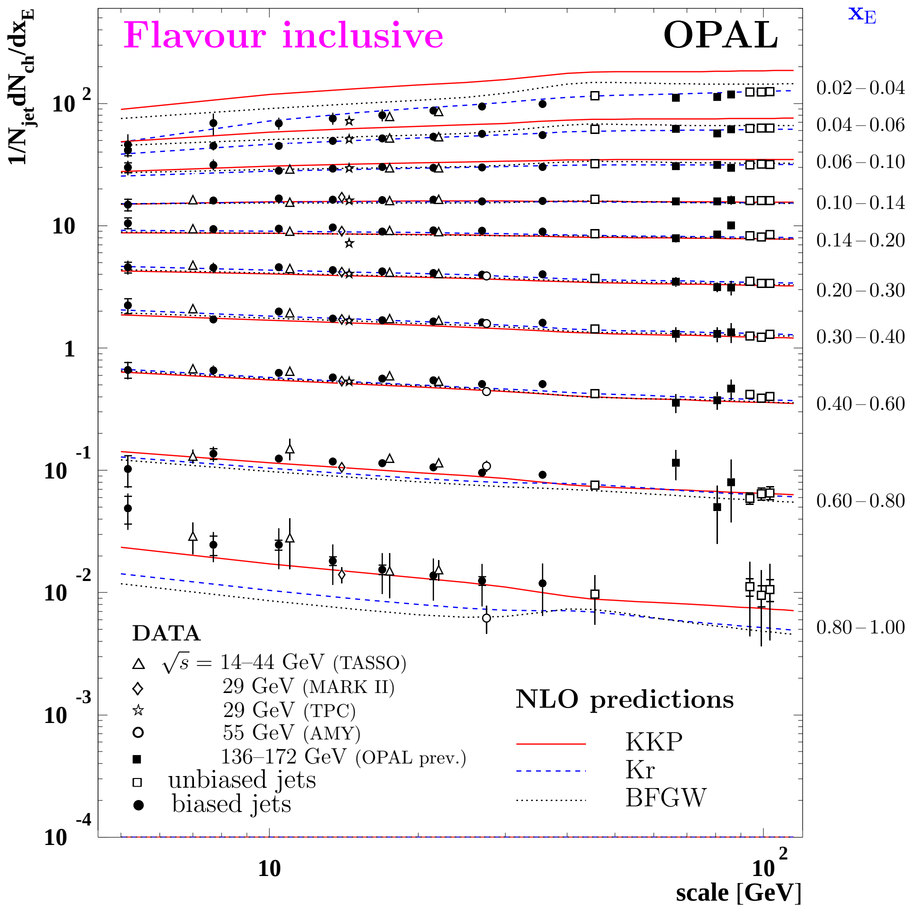


b quark jets

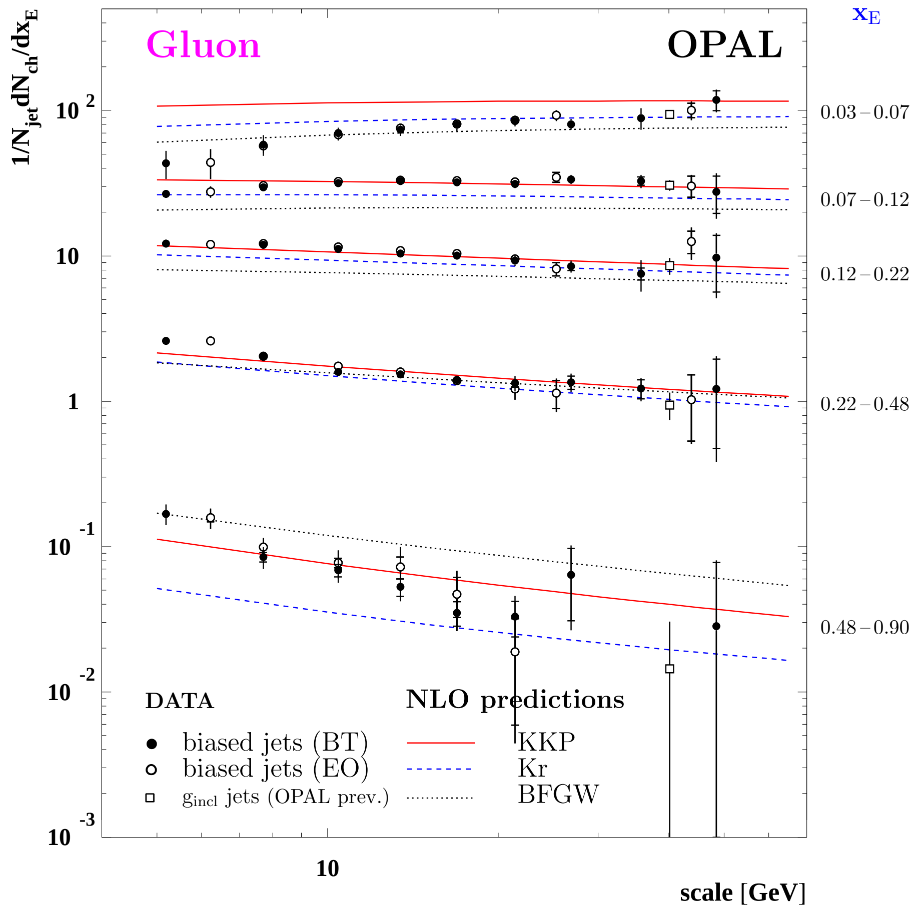


Scale dependence of quark/gluon jet fragmentation functions

Flavour-inclusive quark jets



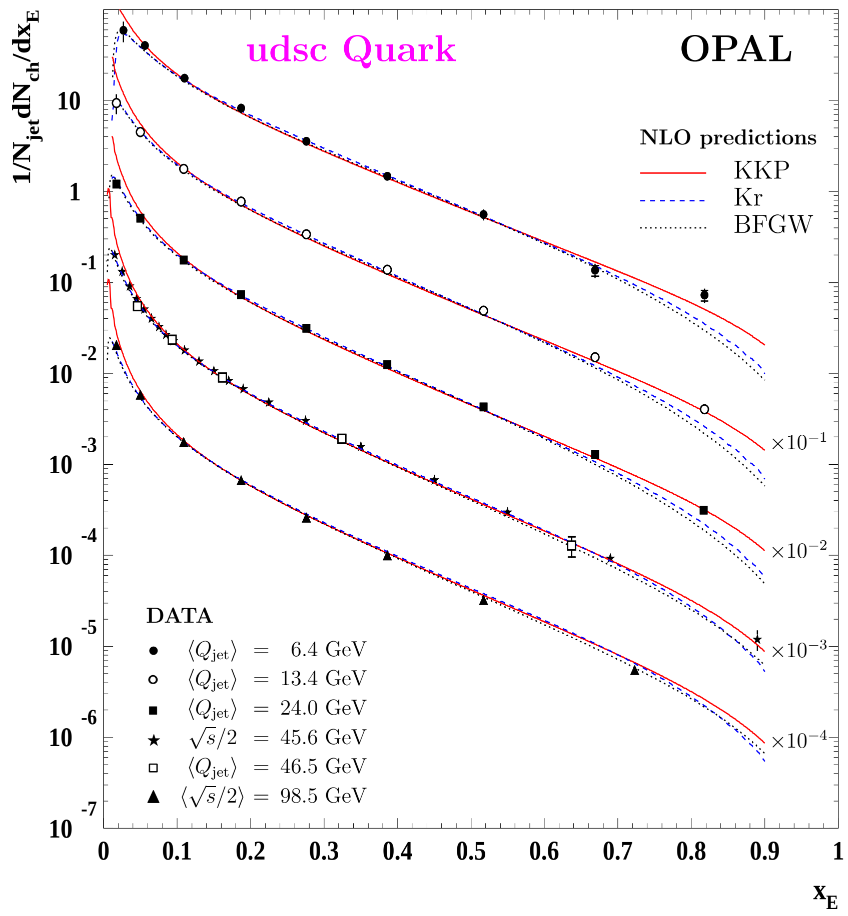
Gluon jets

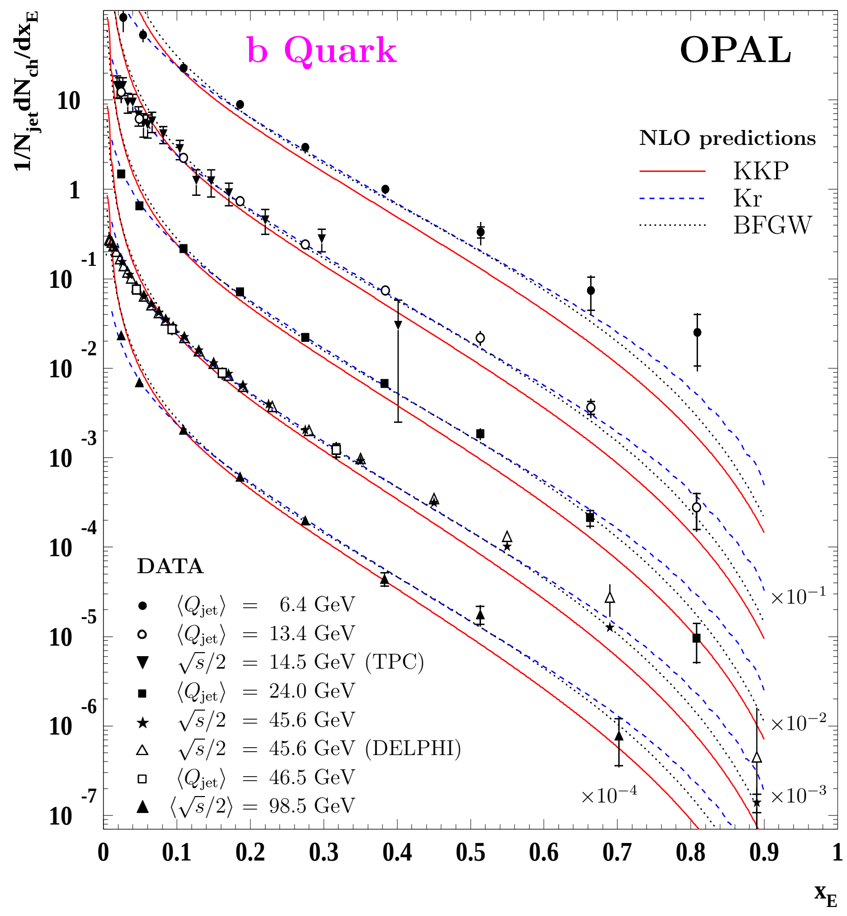


x_E dependence of quark jet fragmentation functions

udsc quark jets

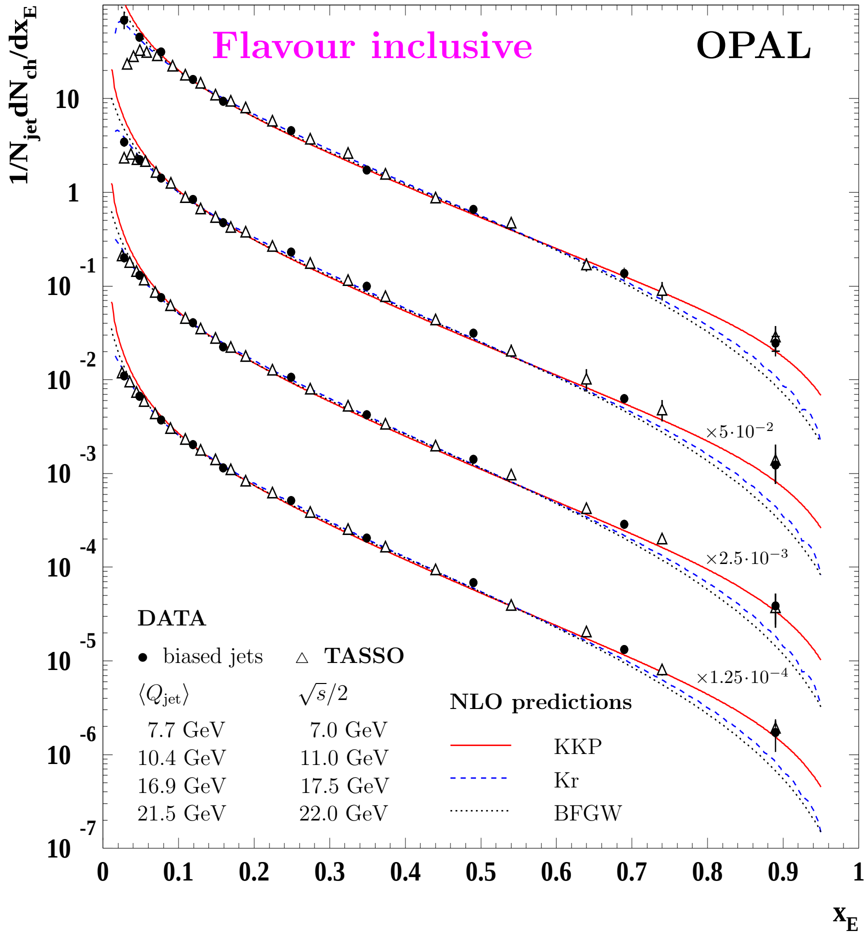
b quark jets



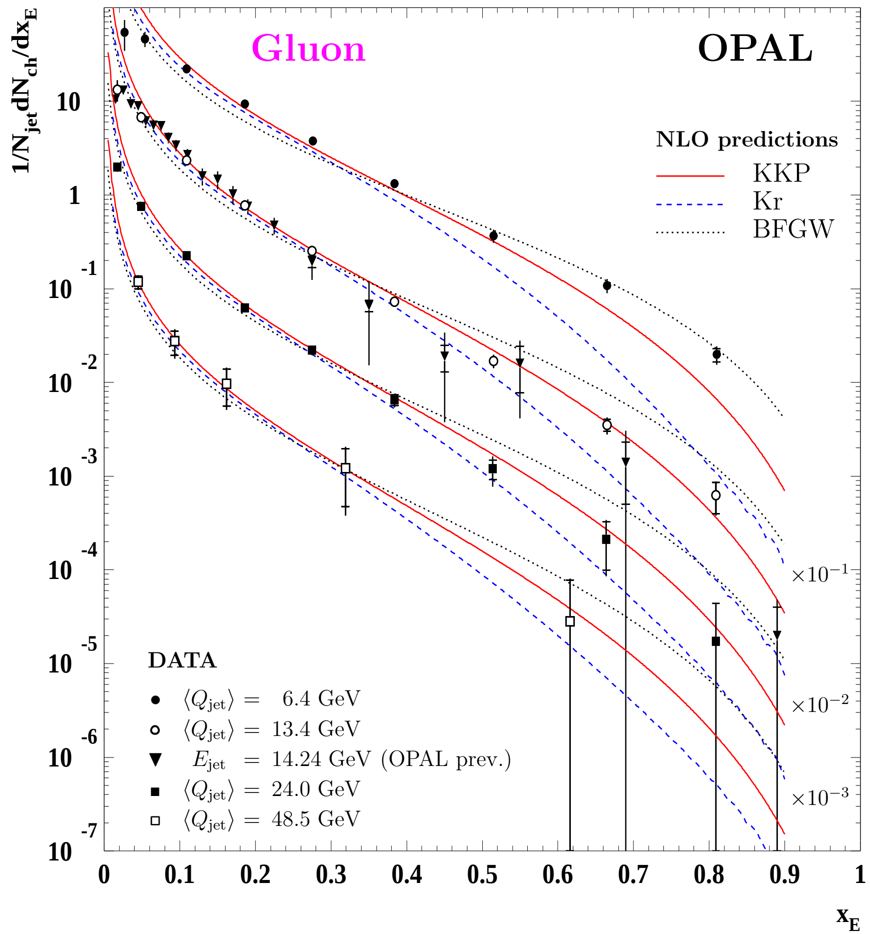


x_E dependence of quark/gluon jet fragmentation functions

Flavour-inclusive quark jets



Gluon jets



Fragmentation functions (contd.)

Conclusions from latest OPAL results:

- Good agreement between biased and unbiased jet measurements, suggesting $Q_{\text{jet}} = E_{\text{jet}} \sin(\theta/2)$ is a suitable scale for biased measurements.

- Good agreement with previous OPAL and DELPHI measurements, where available.

- Scaling violation (Q-dependence) is positive at low x_E and negative at high x_E for all fragmentation functions.

- All theory predictions in good agreement with data for the light quark jets. Poorer agreement for gluon and b-quark jets, especially at low and high x_E.

- Good agreement between data and MC, except at high x_E and small Q.

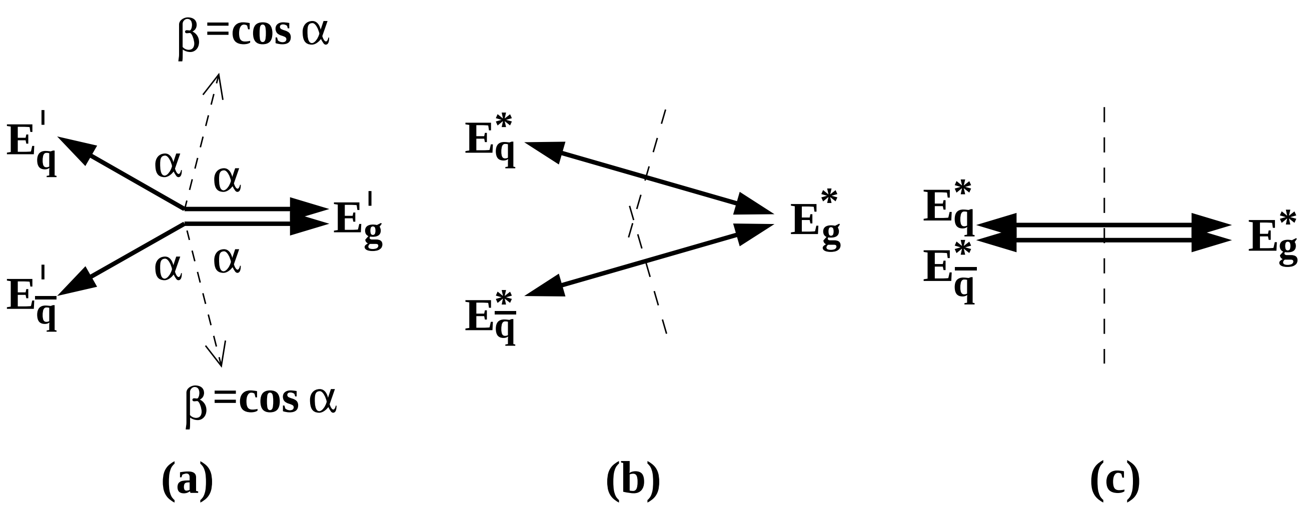
Unbiased gluon jets with the jet boost algorithm

- The jet boost algorithm (*Edén & Gustafson, 1998*) proposes a way to relate gluon jets in $q\bar{q}g$ events to the hemispheres of a gg system.
  ⇒ unbiased gluon jets

(a) decompose the $q\bar{q}g$ system into two colour dipoles:
qg and $\bar{q}g$

(b) boost each dipole into a back-to-back frame

(c) re-combine the two components of the gluon



- Use HERWIG to compare boost algorithm with ‘real’ gg hemispheres: good agreement found for jet multiplicities and fragmentation functions.

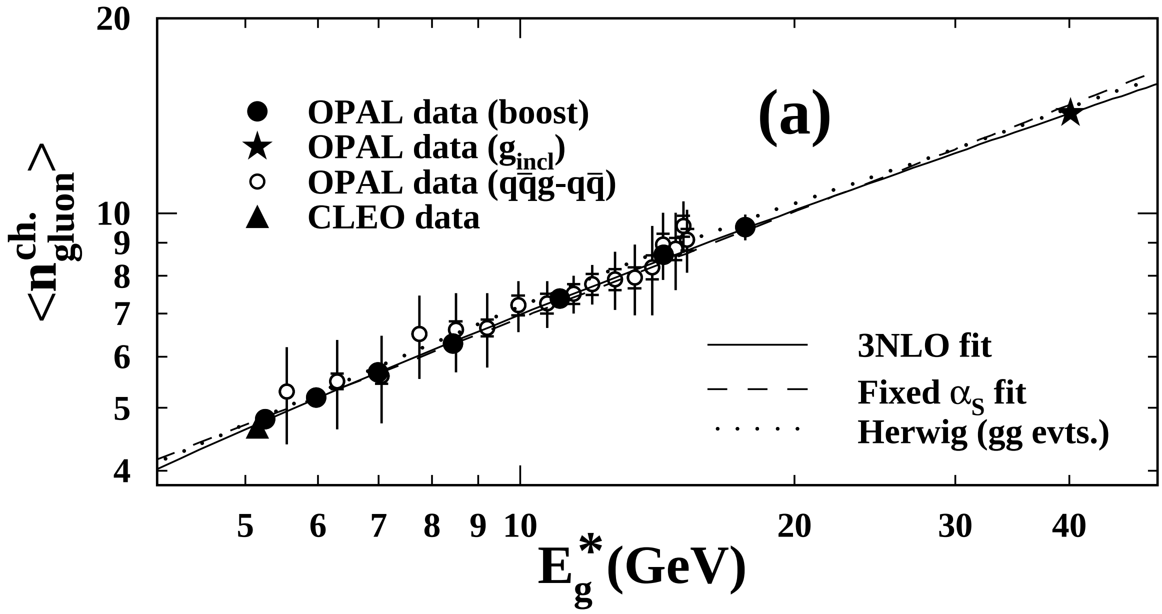
  ⇒ can compare experimental measurements with pQCD predictions.

Unbiased gluon jets (contd.)

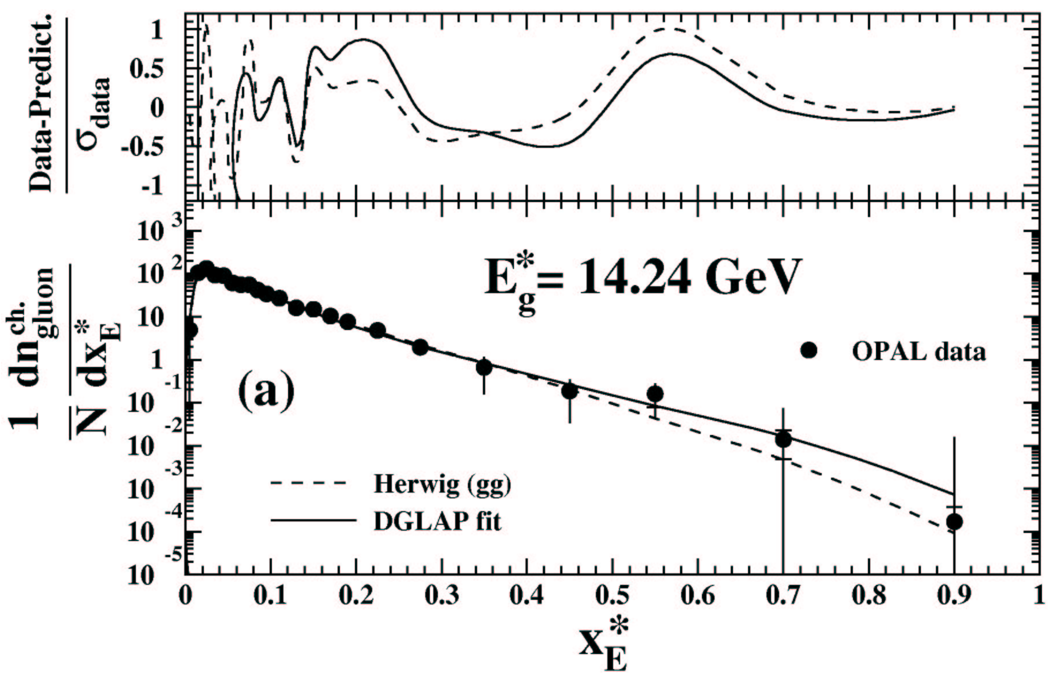
OPAL have measured properties of unbiased gluon jets using the jet boost algorithm, with LEP1 data.

For example:

- Scale-dependence of mean charged particle multiplicity:



- Fragmentation functions (at $E^*_{\text{jet}} = 14.24,\ 17.72$ GeV):



Coherent soft particle production in $e^+e^- \to Z^0 \to q\bar{q}g$ events

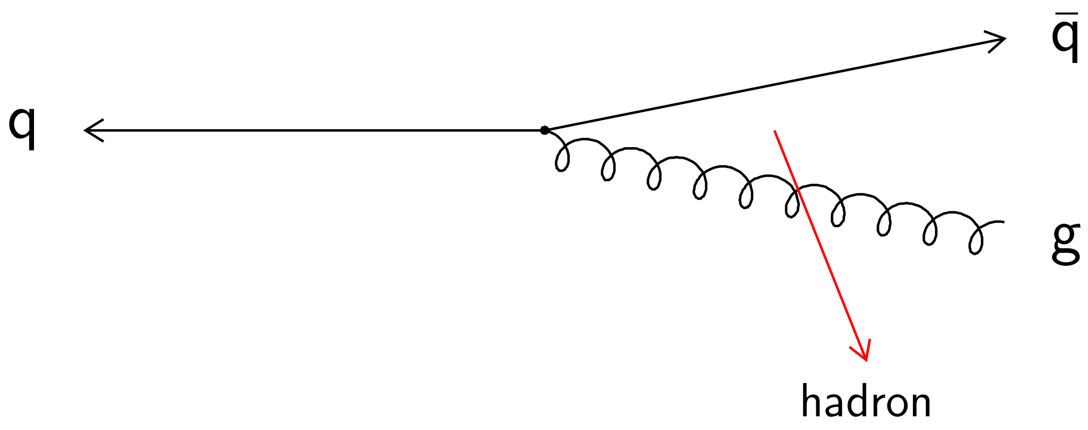
- Interference is fundamental to all quantum-mechanical gauge theories, including QCD.

- Interference is built into the standard shower evolution/fragmentation models...

  However, incoherent models with many tunable parameters can also describe the data.

  $\Rightarrow$ need a direct test for the coherence effects.

- Consider low-energy hadrons emitted at large angle. They cannot be assigned to a specific jet, so must treat them as coherent emissions from multiple jets.



Coherent soft particle production (contd.)

- QCD theory prediction at leading order:

$$d\sigma_3 = \frac{1}{4}\frac{C_A}{C_F}\left[\widehat{\mathrm{qg}} + \widehat{\bar{\mathrm{q}}\mathrm{g}} - \frac{1}{N_c^2}\widehat{\mathrm{q}\bar{\mathrm{q}}}\right] d\sigma_2$$

  where

  $d\sigma_2$ = cross section for soft gluon emission perpendicular to axis of $\mathrm{q}\bar{\mathrm{q}}$ event

  $d\sigma_3$ = cross section for soft gluon emission perpendicular to plane of $\mathrm{q}\bar{\mathrm{q}}\mathrm{g}$ event

  $\widehat{ij} = 2\sin^2(\theta_{ij}/2)$, where θ_{ij} is the opening angle between two jets (*antenna function*)

- The $\frac{1}{N_c^2}\widehat{\mathrm{q}\bar{\mathrm{q}}}$ term is responsible for destructive interference effects.

- Experimental measurements $\Rightarrow$
  - Test theory prediction
  - Verify coherence effect
  - Measure the slope, corresponding to C_A/C_F at leading order.

Coherent soft particle production (contd.)

DELPHI results use the *angular ordered Durham jet algorithm*, with $y_{\rm cut} = 0.015$ applied to hadronic events at $\sqrt{s} = 91$ GeV.

- Compare multiplicities in cones of angle 30° perpendicular to (i) q$\bar{\rm q}$g plane in 3-jet events, and (ii) q$\bar{\rm q}$ axis in 2-jet events.

- Fit multiplicity ratios to the destructive interference term $k\,\frac{1}{N_c^2}\,\widehat{\rm q\bar{q}}$, where $k = 1$ is the fully coherent LO prediction, and $k = 0$ corresponds to no destructive interference:

$$k = 1.37 \pm 0.05\ \text{(stat.)} \pm 0.33\ \text{(syst.)}$$

$$[\chi^2/\text{dof} = 1.2]$$

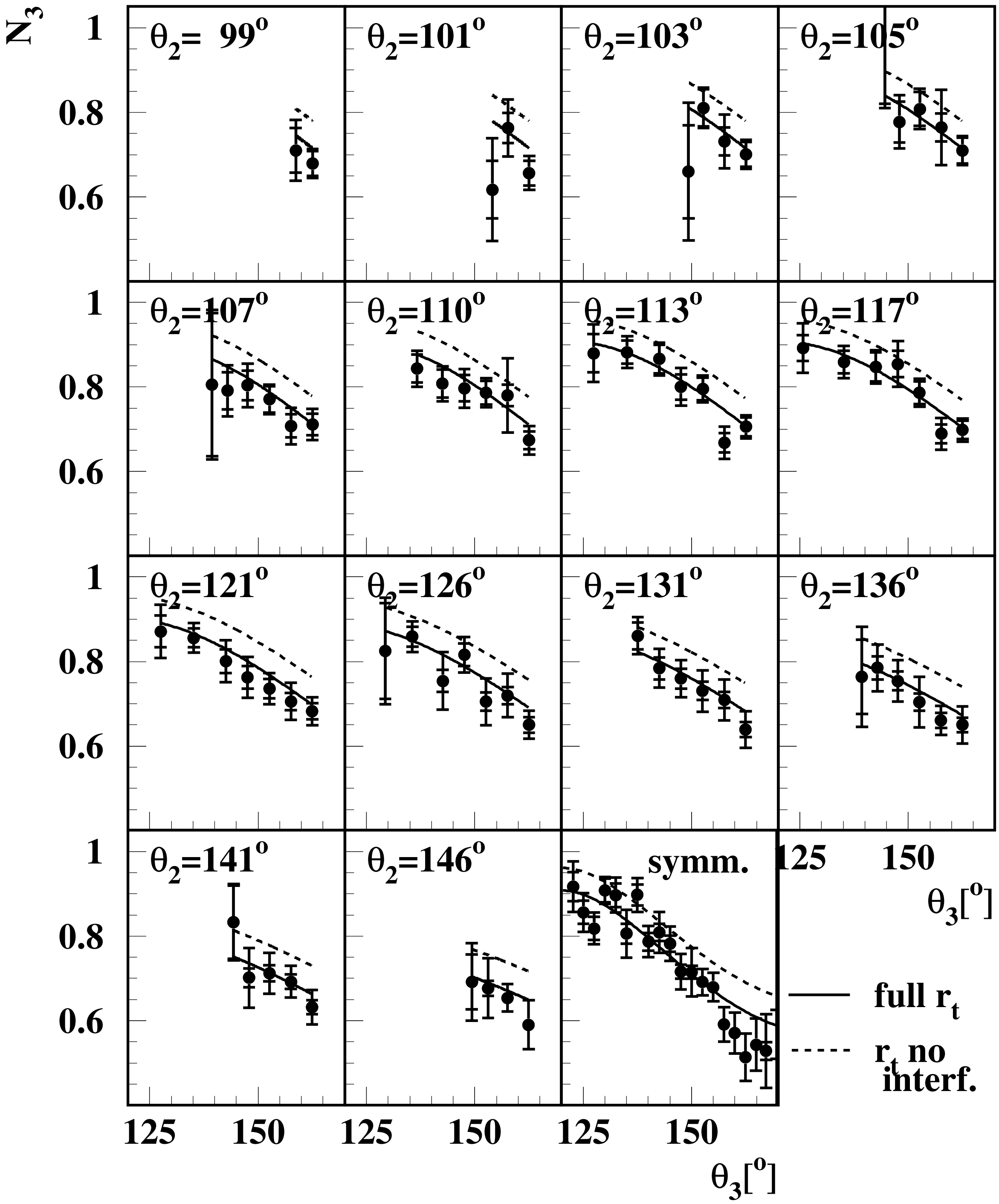
- Measure slope, corresponding to C_A/C_F at LO (c.f. QCD value $C_A/C_F = 2.25$):

$$\frac{C_A}{C_F} = 2.211 \pm 0.014\ \text{(stat.)} \pm 0.053\ \text{(syst.)}$$

$$[\chi^2/\text{dof} = 1.3]$$

Coherent soft particle production (contd.)

DELPHI results strongly favour the theory prediction with full coherence included:



Combined LEP measurement of $\alpha_s(M_Z)$ from event shape observables

- Define 6 standard event shape observables, in events of the type $e^+e^- \to Z/\gamma \to$ hadrons:

T – Thrust	B_W – Wide jet broadening
M_H – Heavy jet mass	C – C-parameter
B_T – Total jet broadening	y_{23} – Durham 2–3 jet transition

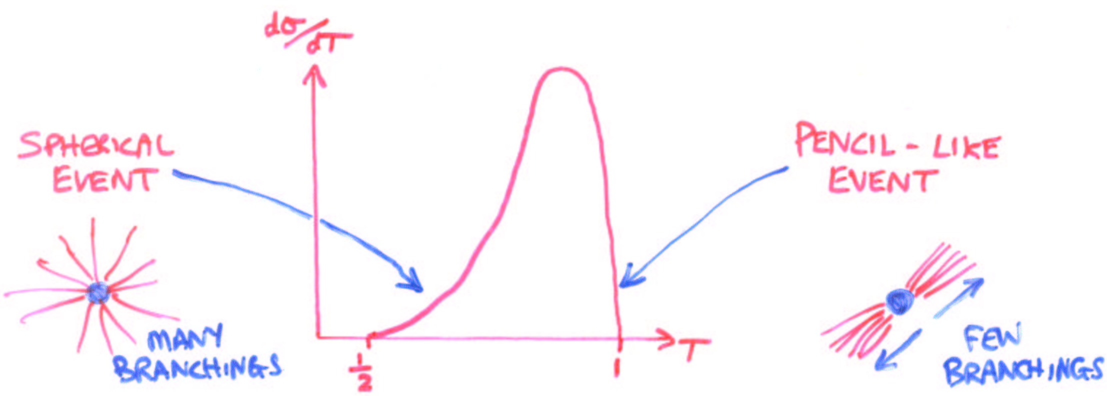
- Observables describe the inclusive geometry of the hadronic final state. No need for explicit jet-finding or particle identification.

- All 6 observables are *infrared-safe*, i.e. invariant under soft or collinear gluon emission, and relatively insensitive to non-perturbative physics

  $\Rightarrow$ ideal test for hard interactions in pQCD.

- Example: Thrust (T):
  Thrust axis, $\hat{\boldsymbol{n}}_T$, is chosen to maximize the sum of absolute momentum components for *all observed particles* projected along that axis.

$$T = \max_{\hat{\boldsymbol{n}}} \left(\frac{\sum_i |\boldsymbol{p}_i \cdot \hat{\boldsymbol{n}}|}{\sum_i |\boldsymbol{p}_i|} \right)$$



$\alpha_s(M_Z)$ from event shapes (contd.)

- 2 perturbative theory predictions for each event shape distribution, parameterised in terms of α_s:
  - $\mathcal{O}(\alpha_s^2)$ calculation using matrix elements: *best available prediction for multi-jet events*
  - NLLA calculation, resumming logarithmically enhanced terms to all orders in α_s: *best available prediction for 2-jet region*

  Combine calculations using $\log(R)$ matching scheme

  $\Rightarrow$ prediction for wide range of each observable.

- Use MC models to correct perturbative theory to hadron level

  NB some analyses use power correction models instead. Use only MC here, in the interests of consistency between experiments

- Fit theory to experimental distributions

  $\Rightarrow$ measure α_s

- Final measurements now available at all energies from ALEPH, DELPHI and L3, including re-analysis of older data with improved theory and MC.

  Final OPAL measurements expected summer 2004.

$\alpha_s(M_Z)$ from event shapes (contd.)

- Combine all available LEP α_s measurements, using consistent theory predictions:

$\sqrt{s}$	T	M_H	B_W	B_T	C	y_{23}
91.2	ADLO	ADLO	ADLO	ADLO	ADL	A O
133.0	ADLO	ADLO	A LO	A LO	A L	A O
161.0	ADLO	ADLO	A LO	A LO	A L	A O
172.0	ADLO	ADLO	A LO	A LO	A LO	A O
183.0	ADLO	ADLO	ADLO	ADLO	ADLO	A O
189.0	ADLO	ADLO	ADLO	ADLO	ADLO	A O
200.0	ADLO	ADLO	ADLO	ADLO	ADLO	A O
206.0	ADLO	ADLO	ADLO	ADLO	ADLO	A O

(A=ALEPH, D=DELPHI, L=L3, O=OPAL)

- Form covariance matrix between measurements from all variables, experiments and energies:

$$V_{ij} = V_{ij}^{\text{stat.}} + V_{ij}^{\text{exp.}} + V_{ij}^{\text{had.}} + V_{ij}^{\text{theo.}}$$

  Four uncertainty contributions (statistical, experimental, hadronisation and theory) have different correlations between measurements.

- After running all input measurements to the Z^0 scale, the least-squares fit for α_s is a linear combination of the inputs:

$$\hat{\alpha}_s = \sum_i w_i \, (\alpha_s)_i \ , \quad \text{with weights} \quad w_i = \frac{\sum_j V_{ij}^{-1}}{\sum_{jk} V_{jk}^{-1}}$$

$\alpha_s(M_Z)$ from event shapes (contd.)

- Harmonize uncertainties where possible:

$\sigma_{\text{stat.}}$: Use values quoted by experiments

$\sigma_{\text{exp.}}$: Average the values quoted by different experiments

$\sigma_{\text{hadr.}}$: Take standard deviation of results quoted for PYTHIA, HERWIG and ARIADNE for each input.

$\Rightarrow$ then fit the form $\sigma_{\text{hadr.}} = A_y/Q + B_y$ for each observable y.

$\sigma_{\text{theo.}}$: Re-evaluate independently, using "uncertainty band" method. Vary several arbitrary parameters of the theory (not only the renormalisation scale μ).

More details in hep-ph/0312016

- Treat hadronisation and theory uncertainties as uncorrelated when calculating the weights w_i (otherwise we have large *negative* weights $\Rightarrow$ unstable combination).

  BUT include 100% correlation when calculating the hadronisation and theory uncertainties of our combined $\alpha_s(M_Z)$.

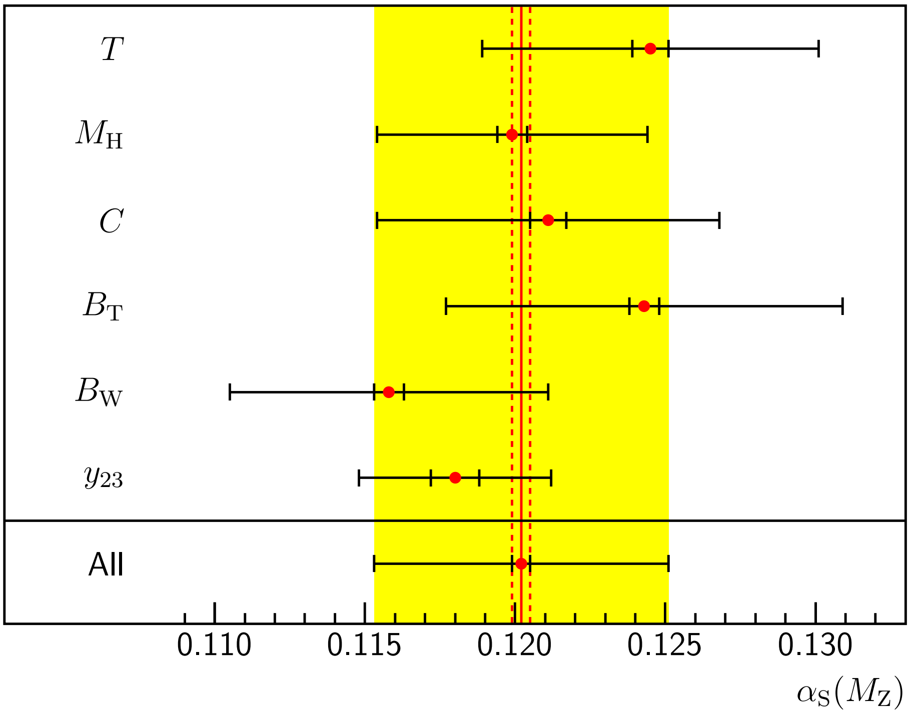
  This approach gives a stable fit... but does not always minimise the total uncertainty of the combined measurement.

$\alpha_s(M_Z)$ from event shapes (contd.)

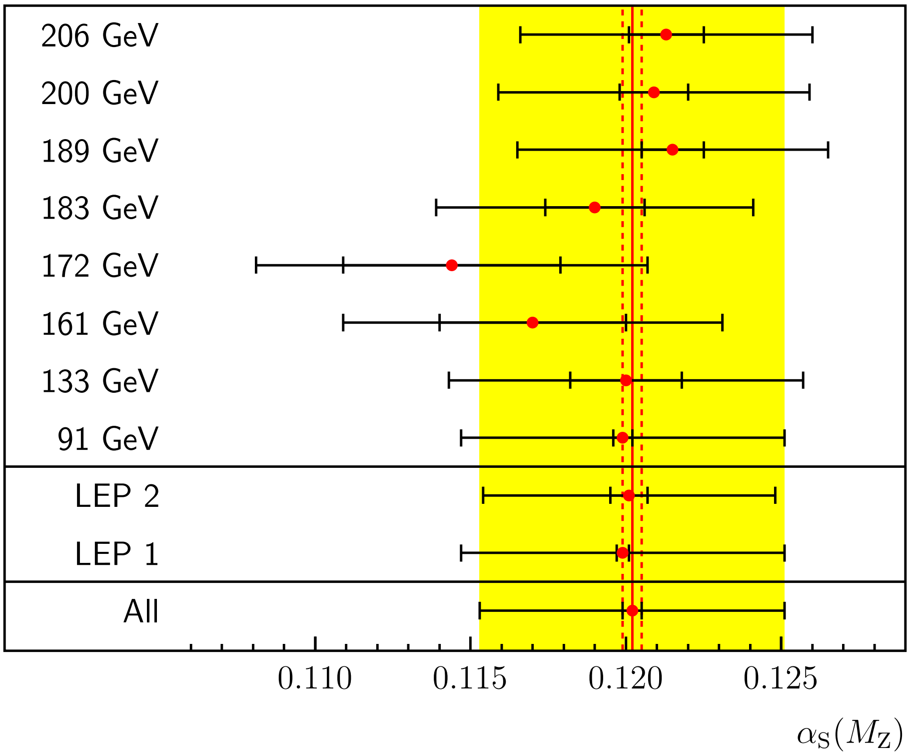
- Complete $\alpha_s(M_Z)$ combination:

$$\alpha_s(M_Z) = 0.1202 \pm 0.0003\ \text{(stat.)} \pm 0.0009\ \text{(exp.)} \\ \pm 0.0013\ \text{(hadr.)} \pm 0.0047\ \text{(theo.)}$$

- $\alpha_s(M_Z)$ combinations for single observables:

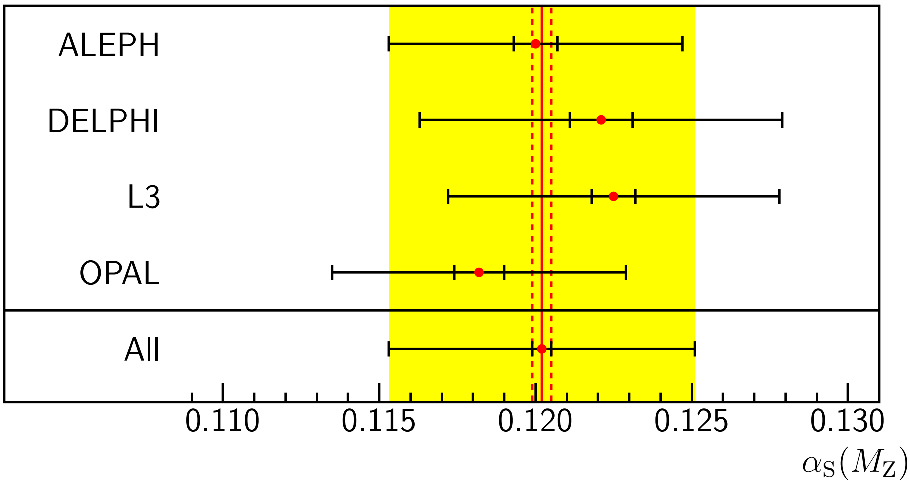


- $\alpha_s(M_Z)$ combinations for single energies:

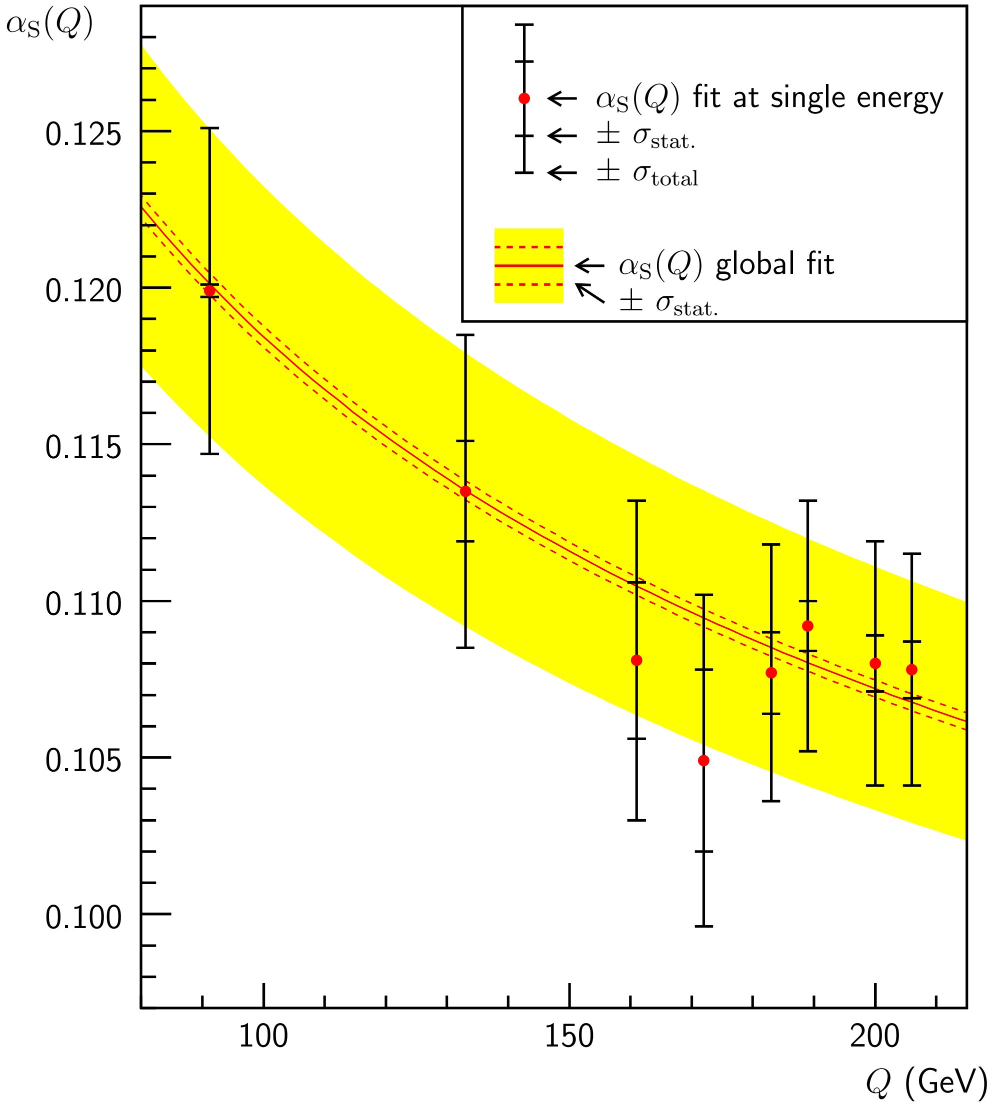


$\alpha_s(M_Z)$ from event shapes (contd.)

- LEP combination method applied to single experiments:



- Combinations at single energies, compared with QCD running prediction:



Conclusions

- Original tests of QCD are still being performed with LEP data, more than 3 years after shutdown:
  - Unbiased gluon jets (OPAL)
  - Coherent soft particle production (DELPHI)

- Combined measurements of α_{s} from event shapes are converging towards a final publication. Results from all individual experiments will be finalised by summer 2004.

- Improved α_{s} measurements will be possible when NNLO/NNLLA QCD predictions become available. Validity of future improvements to the event-shape distributions can be tested using LEP1 data.

- Other LEP QCD results have not been mentioned, due to lack of time! (power corrections, colour reconnection, glueball searches, pentaquark searches. . .)