Experimental tests of QCD at e^+e^- colliders

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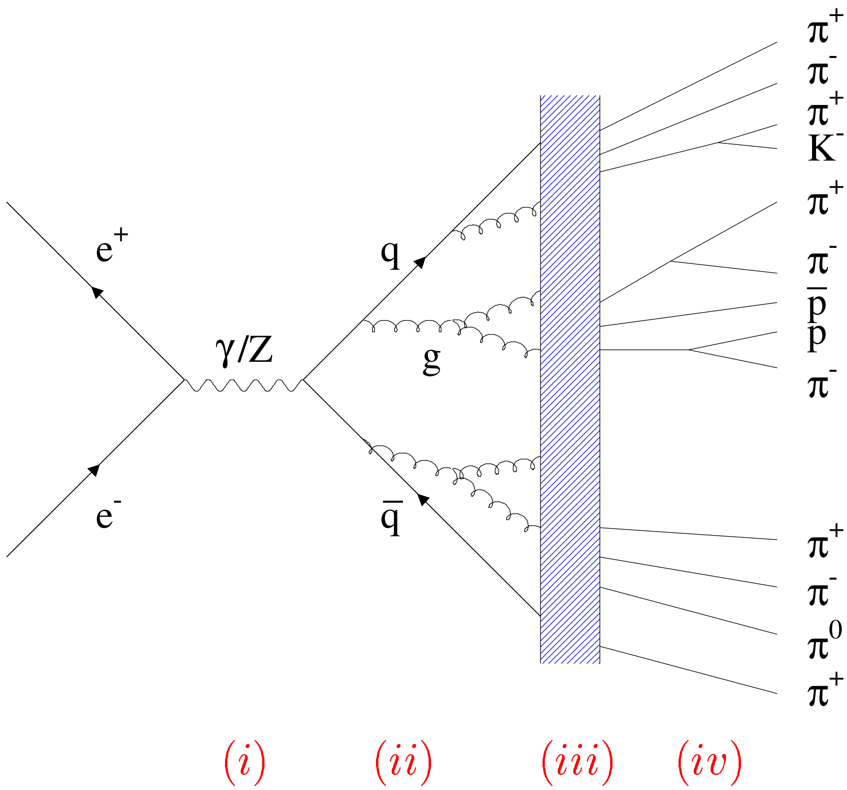
$e^+e^- \to$ hadrons



(*i*) electroweak

(*ii*) perturbative QCD

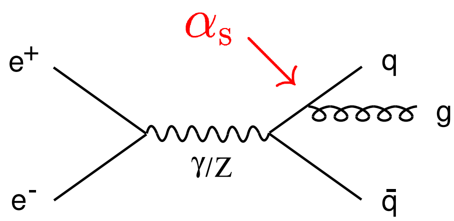
(*iii*) hadronization (non-perturbative QCD)

(*iv*) resonance decays

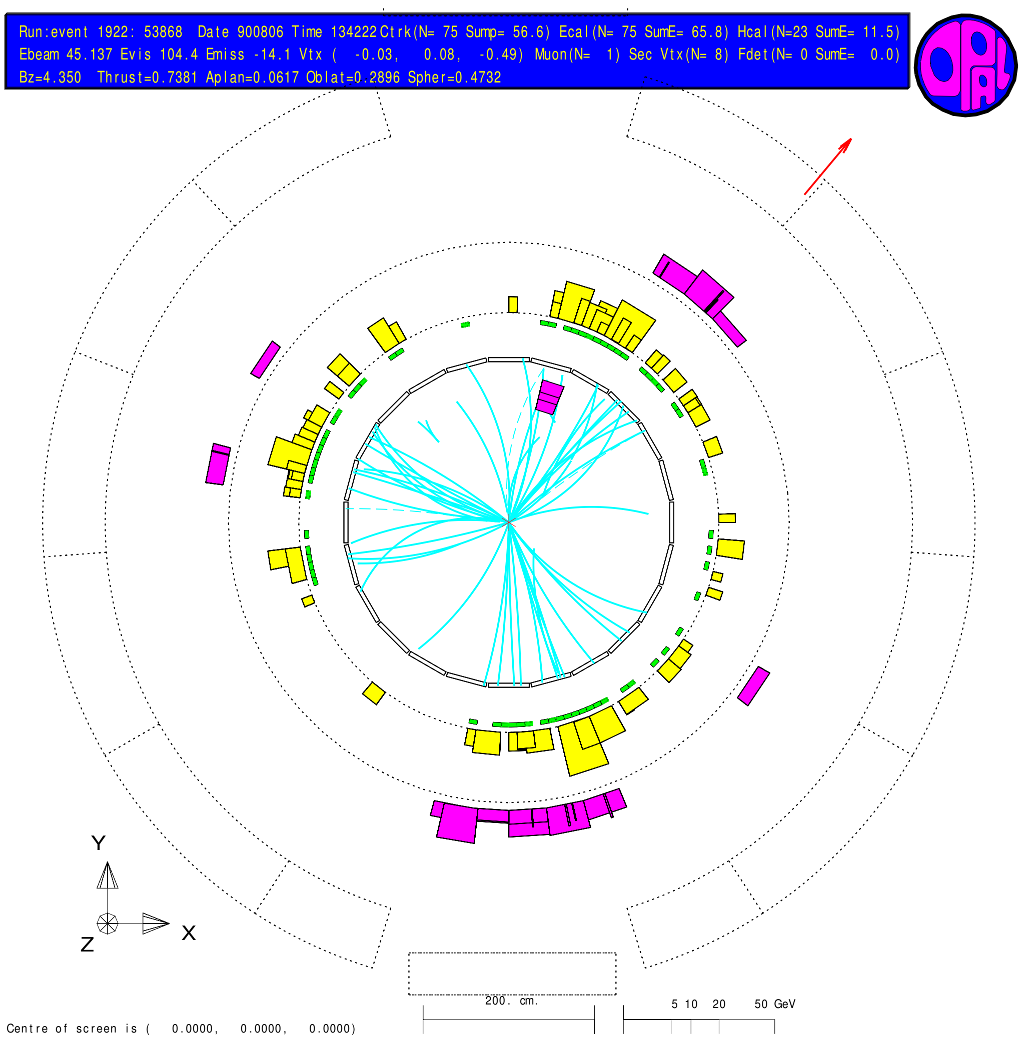
Usually define observable to be sensitive to only one of the above.

α_s from jets and event shapes

Bremsstrahlung-like gluon radiation (cf. $e^+e^- \to \mu^+\mu^-\gamma$)

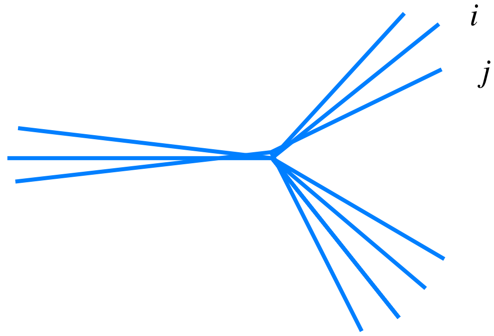


Additional jets $\rightarrow$ rate sensitive to strong coupling α_s



Defining jets

Clustering algorithms: for every pair, compute 'distance' y_{ij}



$\leftarrow$ partons or hadrons

$$\text{e.g.}\quad y_{ij} = \begin{cases} \dfrac{2E_i E_j(1-\cos\theta_{ij})}{s} & \text{(JADE)} \\[2ex] \dfrac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{s} & \text{(Durham)} \end{cases}$$

(*i*) Find pair with smallest y_{ij}

(*ii*) if less than a given y_{cut}, replace i, j with pseudoparticle:

$$p^\mu = p_i^\mu + p_j^\mu \qquad \text{('E' scheme)}$$

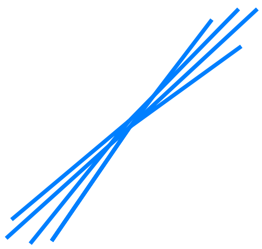
(*iii*) iterate until all $y_{ij} > y_{\mathrm{cut}}$

remaining pseudoparticles $\rightarrow$ jets

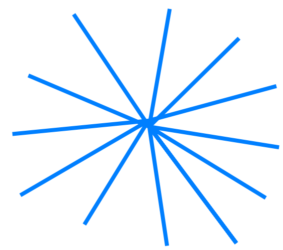
Other jet definitions also used, e.g., cone algorithm.

Event-shape variables

Thrust: $$T = \max \frac{\sum_i |\vec{p}_i \cdot \vec{n}_{\mathrm{T}}|}{\sum_i |\vec{p}_i|}$$



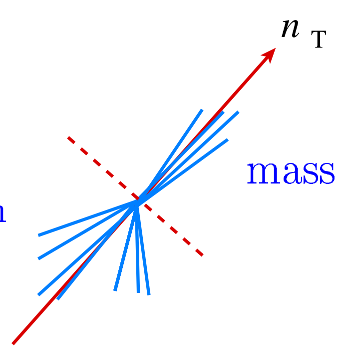
$T \approx 1$



$T \approx 1/2$

Heavy jet mass: divide event into hemispheres with thrust axis

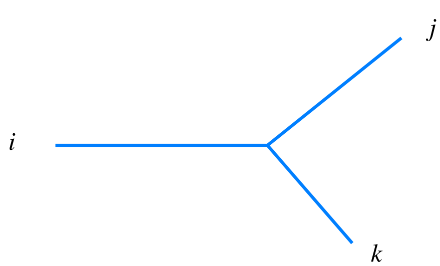
mass M_{h}



mass M_{l}

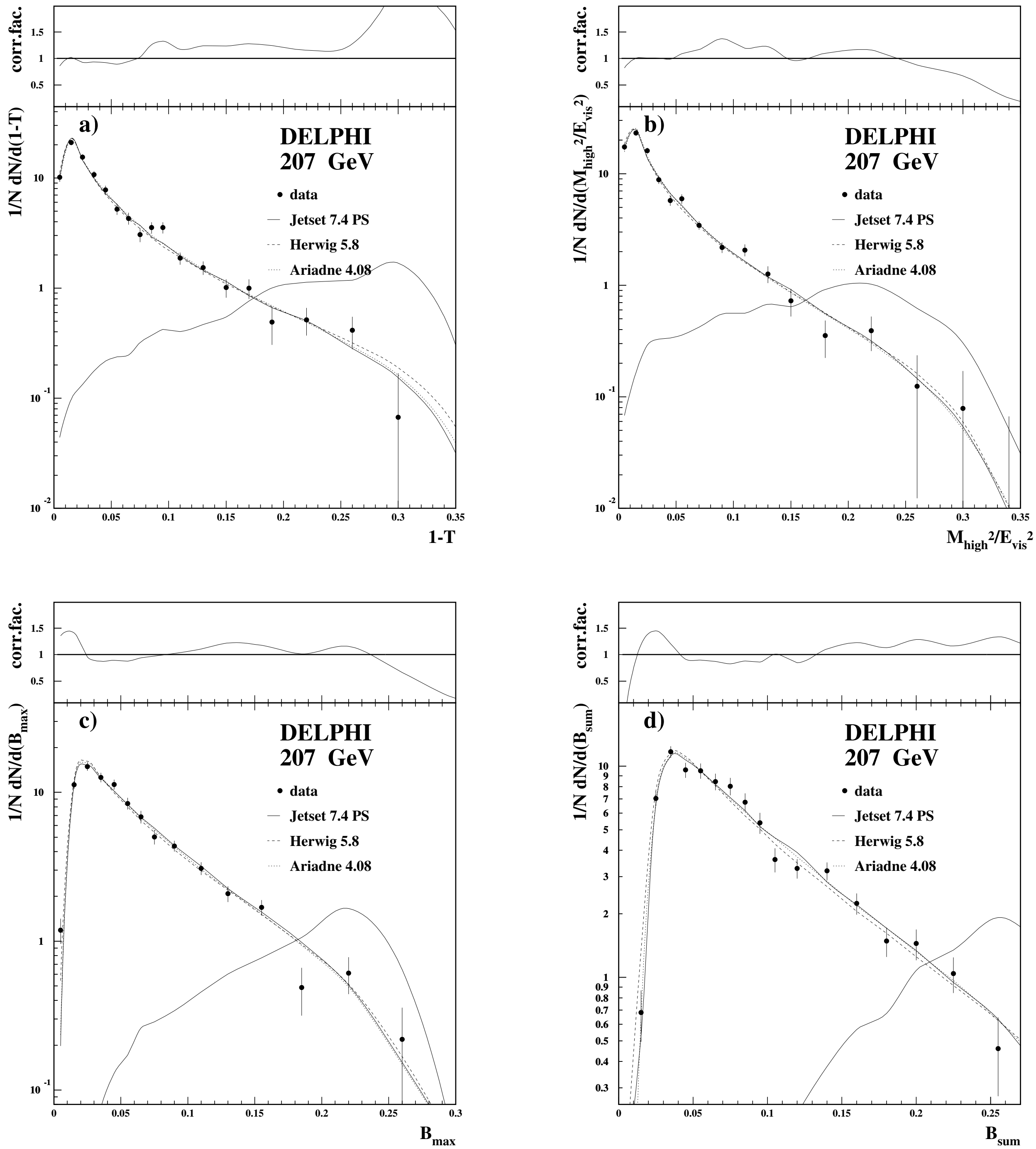
Often use $\rho = M_{\mathrm{h}}^2/s$

y_3: cluster event to three jets



$y_3 = \min(y_{ij})$

DELPHI hep-ex/0406011, accepted by Eur. Phys. J. C



WW and ZZ background subtracted

Currently computable (ERT + **EVENT2**) to next-to-leading order:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dy} = A(y)\frac{\alpha_s(\mu)}{2\pi} + \left[B(y) + 2\pi b_0 A(y)\ln\left(\frac{\mu^2}{s}\right)\right]\left(\frac{\alpha_s(\mu)}{2\pi}\right)^2$$

All amplitudes for NNLO computed; assembling the pieces difficult

N.G.— summer 2005?

For small y , $\ln y$ terms dominate at all orders

→ LL, NLL resummed predictions. Some ambiguities:

Avoiding double counting when combining NLO with LL & NLL

→ 'R, $\ln R$ matching schemes'.

Definition of log to resum

→ $\ln y \rightarrow \ln(x_L y)$, e.g., $2/3 < x_L < 3/2$.

Need modifications to satisfy kinematic limits.

Incomplete cancelation of μ dependence from missing higher orders

Variation of μ $\sim$ measure of uncertainty due to

missing higher order terms, e.g., $\frac{1}{2} \leq \frac{\mu}{\sqrt{s}} \leq 2$

Non-perturbative corrections:

MC hadronization models (JETSET, HERWIG, . . .), or

Power law corrections ($\sim 1/Q$)

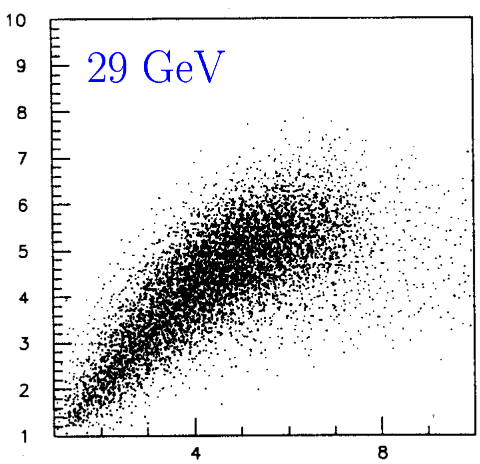
Hadronization corrections

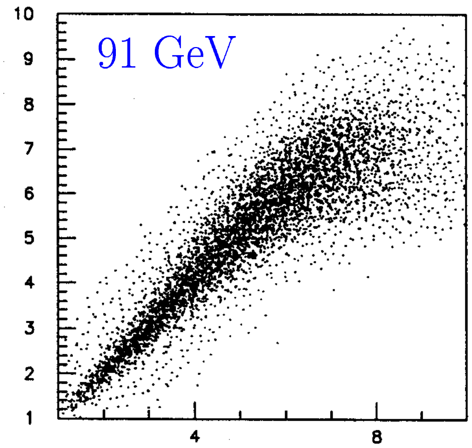
$$\left(\frac{d\sigma}{dy}\right)_{\text{had}} (\text{bin } i; \alpha_{\text{s}}) = \sum_j \left(\frac{d\sigma}{dy}\right)_{\text{QCD}} (\text{bin } j; \alpha_{\text{s}}) \cdot P_{ij}$$

$$P_{ij} = P\left(\begin{array}{c|c} \text{hadron level} & \text{parton level} \\ \text{in bin } i & \text{in bin } j \end{array} \right) \quad \leftarrow \text{from MC model}$$

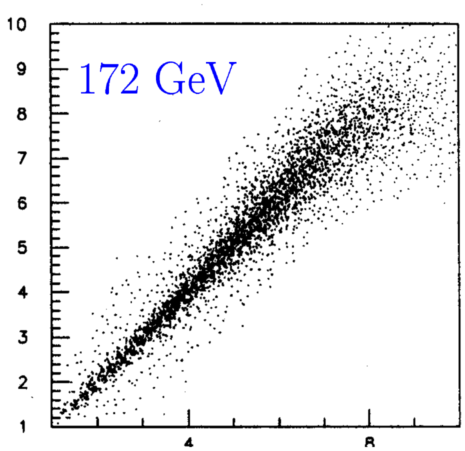
e.g. for $-\ln y_3$ hadron vs. parton level (JETSET):

hadron level





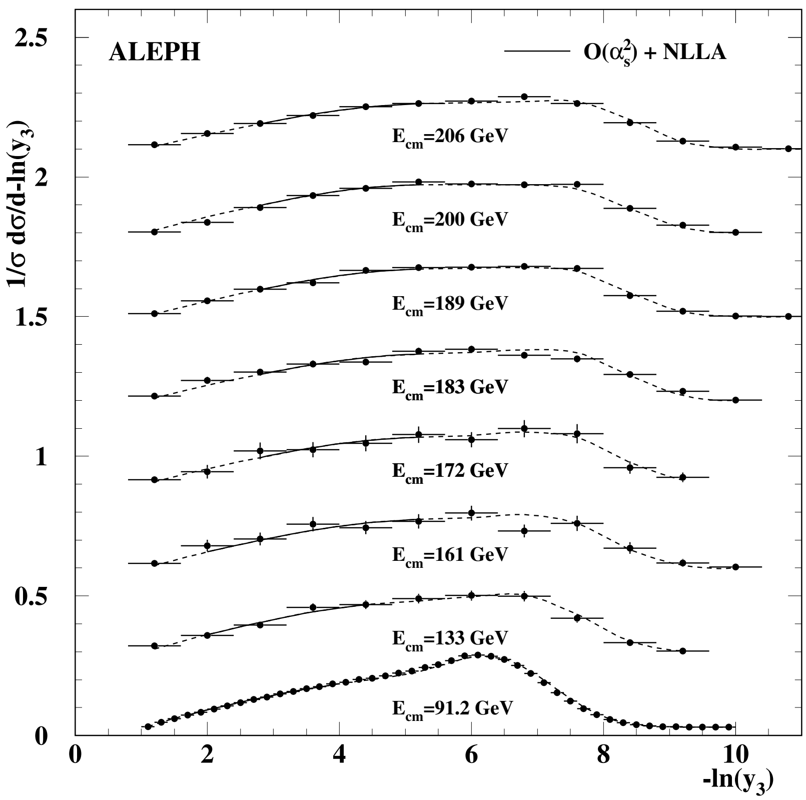
parton level



Estimate uncertainty in α_{s} by variation of model, e.g., JETSET, HERWIG, ARIADNE, . . .

Hadronization error small compared to perturbative uncertainty.

ALEPH, Eur. Phys. J. C35 (2004) 457



E_{cm}	$\alpha_s(E_{cm})$
206	0.1024 ± 0.0039
200	0.1091 ± 0.0039
189	0.1080 ± 0.0039
183	0.1058 ± 0.0053
172	0.1078 ± 0.0098
161	0.1118 ± 0.0089
133	0.1180 ± 0.0064
91.2	0.1180 ± 0.0042

Fit ranges (solid curves) chosen to minimize α_s error.

Compromise between statistics, theoretical uncertainty, . . .

Total error dominated by:

theory at LEP I,

usually theory at LEP II (stat. error big at 161, 172 GeV)

At LEP II, all χ^2 values good;

at LEP I, poor for ρ and B_W (ALEPH).

Estimating α_s uncertainty

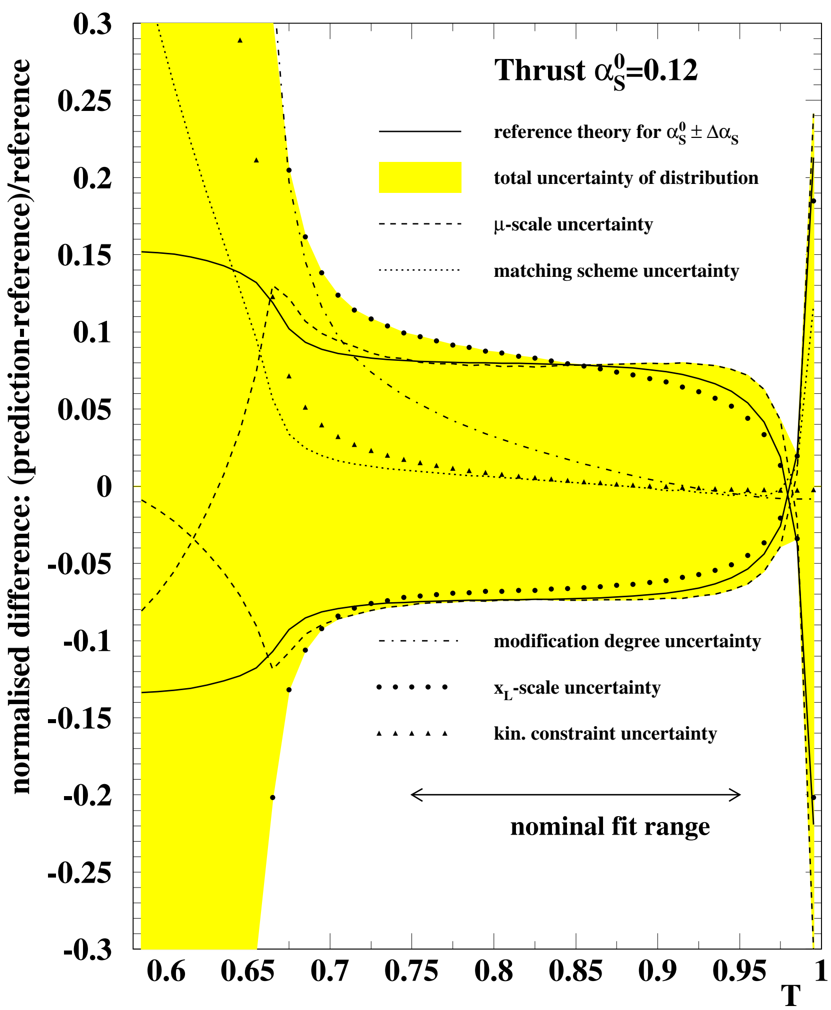
Studied by LEP QCD Working Group

Jones et al., JHEP 12 (2003) 007; hep-ph/0312016

Perturbative theory error dominates (missing higher orders).

Vary theory: μ, x_L, NLO+NLLA matching, kinematic constraints

Relative change in distribution $\rightarrow$ uncertainty band.



Then use nominal theory; vary α_s so that prediction stays in band $\rightarrow$ $\Delta\alpha_s$ (theory) .

Combining α_s measurements from event shapes

LEP QCD Working Group procedure

lepqcd.web.cern.ch/LEPQCD/annihilations

Variables: T, M_h^2/s, C, y_3, B_W, B_T

4 LEP experiments × all LEP I/II E_{cm} → 194 α_s values

First attempt:

Estimate full covariance matrix (stat., sys., theory, hadronization)

→ negative weights, sensitive to poorly known correlations

Second attempt:

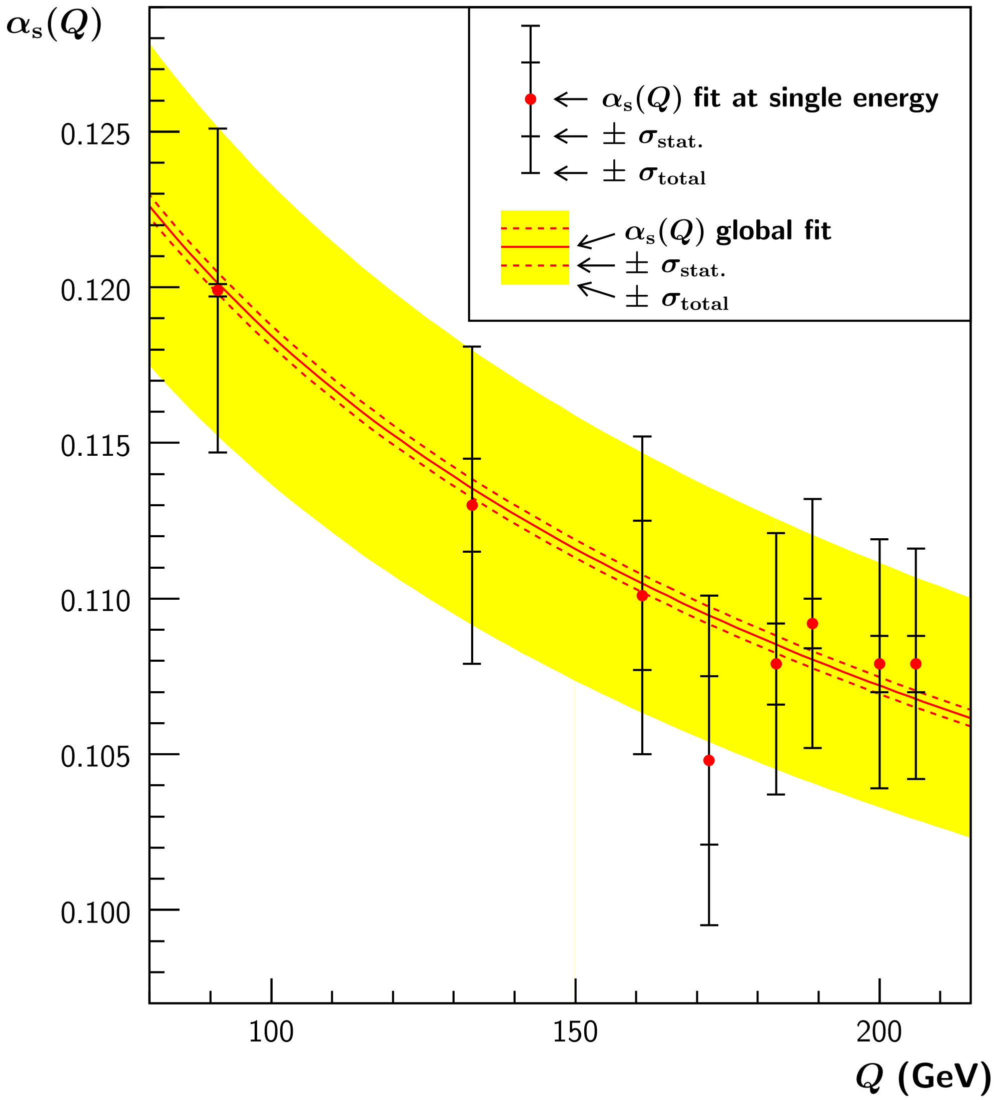
For weights, zero correlations from theory, hadronization;

error of average not smaller than that of some individual

measurements, but result more 'robust'.

LEP QCD Group results preliminary ('almost final')

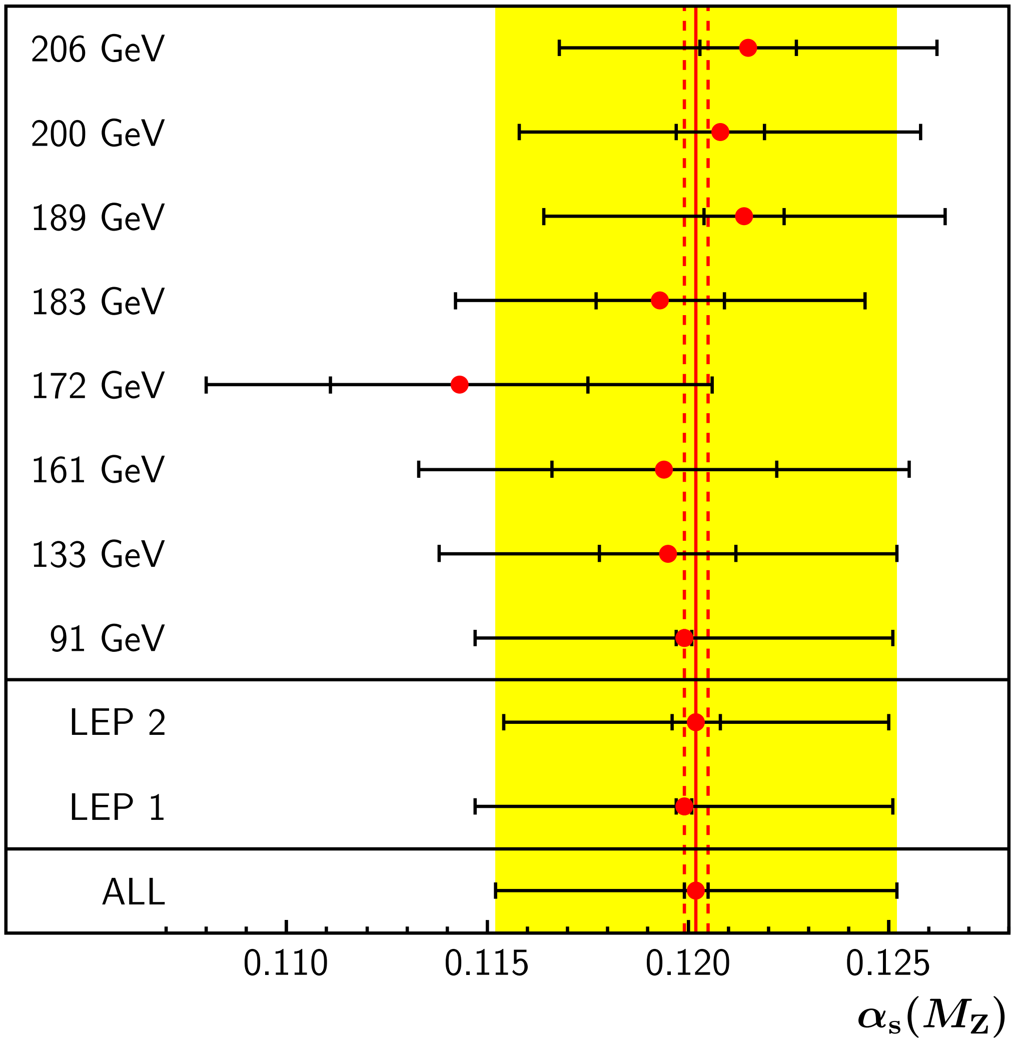
$\alpha_s(E_{cm})$ compared to QCD prediction for running (three-loop RGE)



$$\begin{aligned}\alpha_s(M_Z) = 0.1202 &\pm 0.0003 \text{ (stat.)}\\ &\pm 0.0009 \text{ (exp.)}\\ &\pm 0.0013 \text{ (hadronization)}\\ &\pm 0.0047 \text{ (pert. theory)}\end{aligned}$$

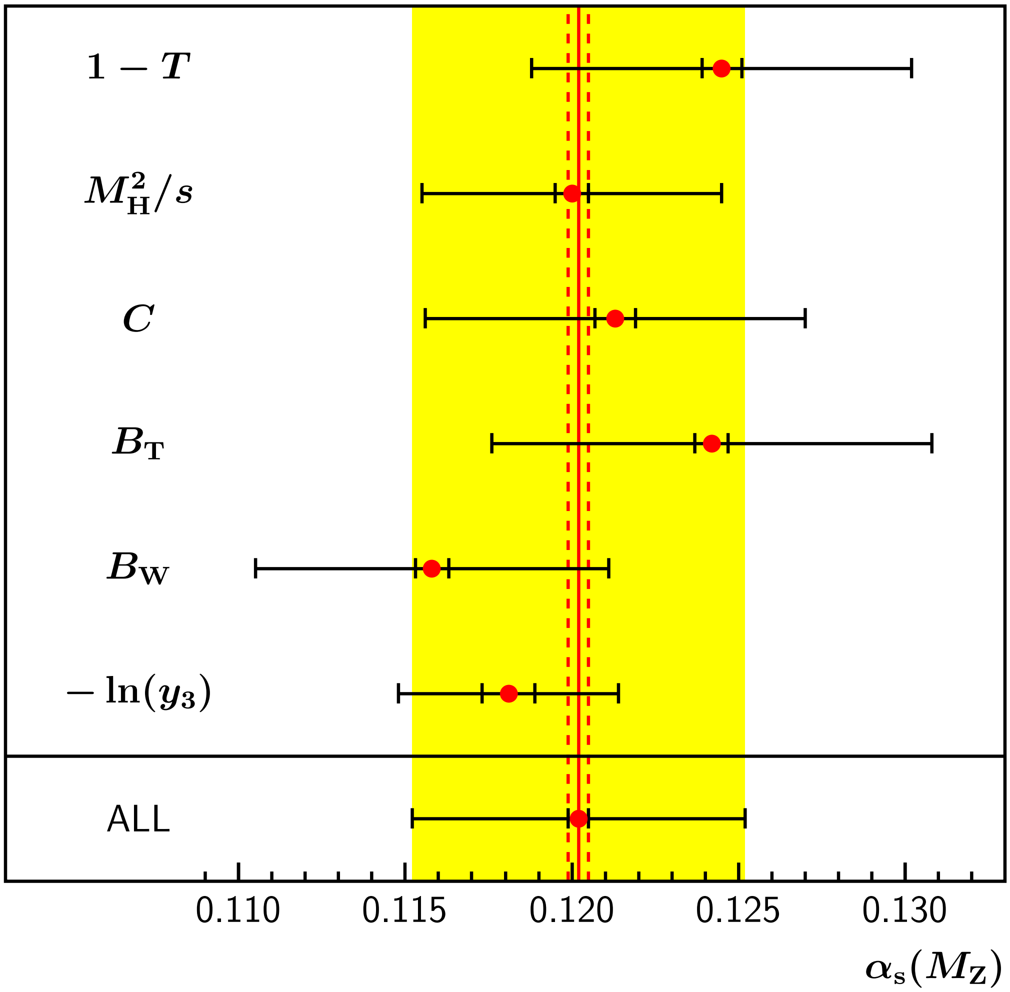
α_s from LEP

Evolve values to $\alpha_s(M_Z)$ from each centre-of-mass energy range

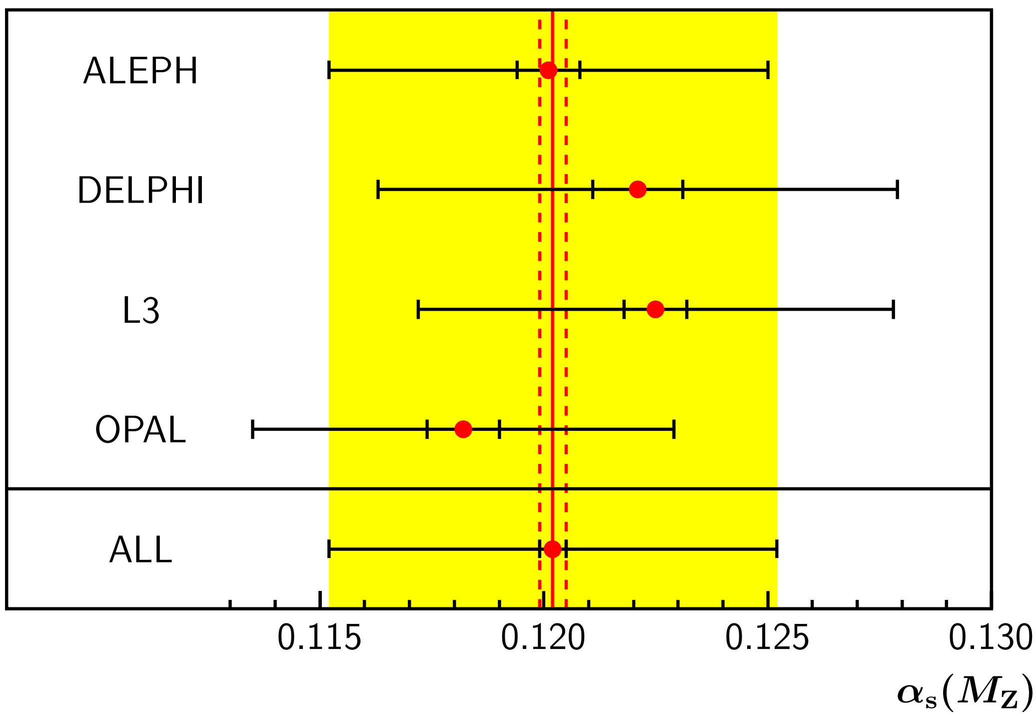


	$\alpha_s(M_Z)$	stat.	exp.	had.	theo.
LEP I	0.1199	$\pm\,0.0002$	$\pm\,0.0008$	$\pm\,0.0017$	$\pm\,0.0048$
LEP II	0.1202	$\pm\,0.0006$	$\pm\,0.0010$	$\pm\,0.0010$	$\pm\,0.0046$
All E_{cm}	0.1202	$\pm\,0.0003$	$\pm\,0.0009$	$\pm\,0.0013$	$\pm\,0.0047$

$\alpha_s(M_Z)$ from individual observables, all E_{cm}

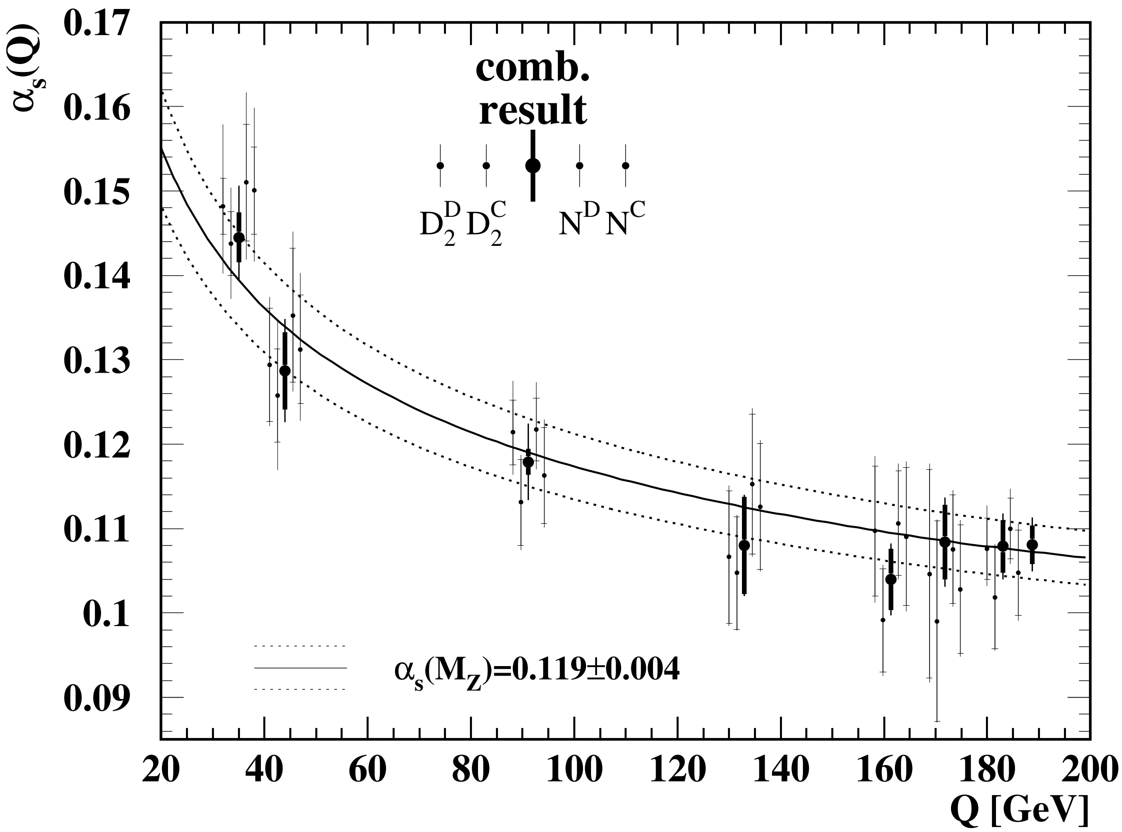


$\alpha_s(M_Z)$ from individual experiments, all observables and E_{cm}



Common α_s measurements by JADE and OPAL experiments

Eur. Phys. J. C17 (2000) 19.



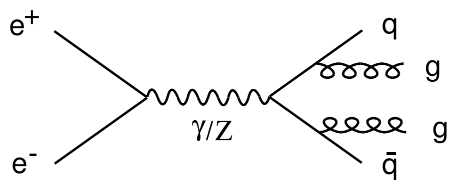
Inner error bars – uncorrelated errors (e.g. stat.)

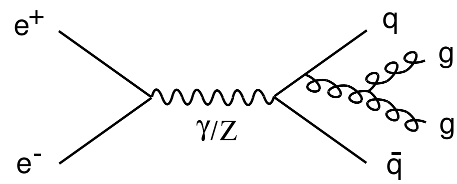
Outer error bars – total uncertainty

→ good agreement with predicted running.

Four-jet events

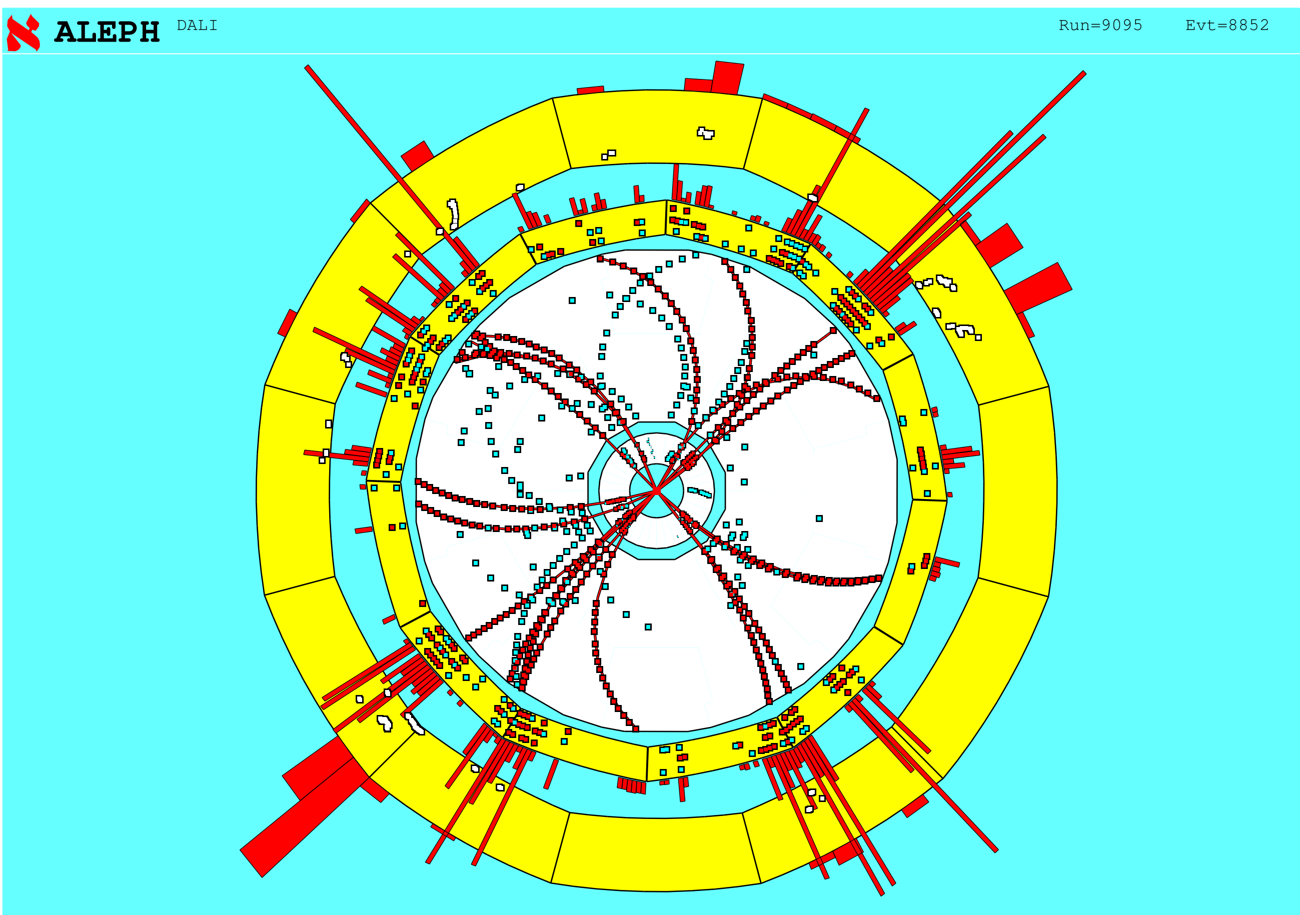
Four-jet properties → triple-gluon vertex, QCD gauge structure





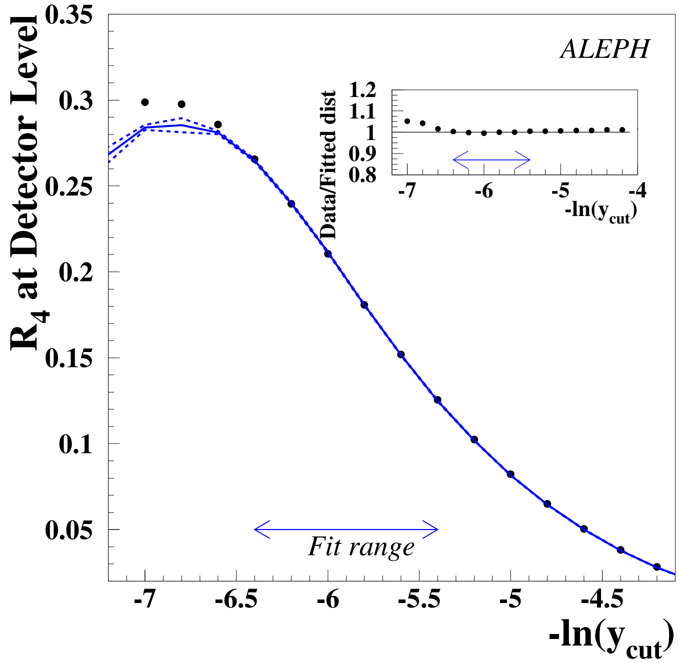
Four-jet matrix element calculated to NLO

Dixon, Signer, Nagy, Trócsányi



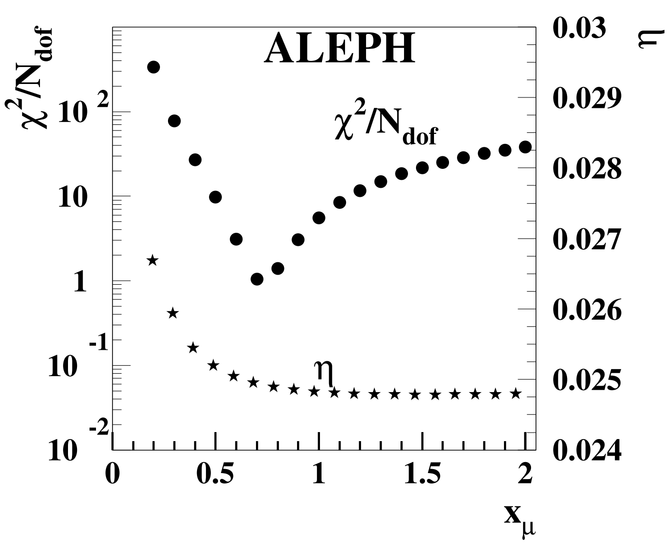
α_s from four-jet rate

ALEPH, Eur. Phys. J. C27 (2003) 1



α_s fitted to four-jet rate using NLO + NLLA QCD

$$\alpha_s(M_Z) = 0.1170 \pm 0.0001\ (\text{stat.})\ \ \pm 0.0013\ (\text{sys.})$$



Error dominated by μ variation; large variation range rejected as χ^2 rapidly deteriorates; not much change in $\eta \propto \alpha_s$

No error contribution estimated from NLO+NLLA matching.

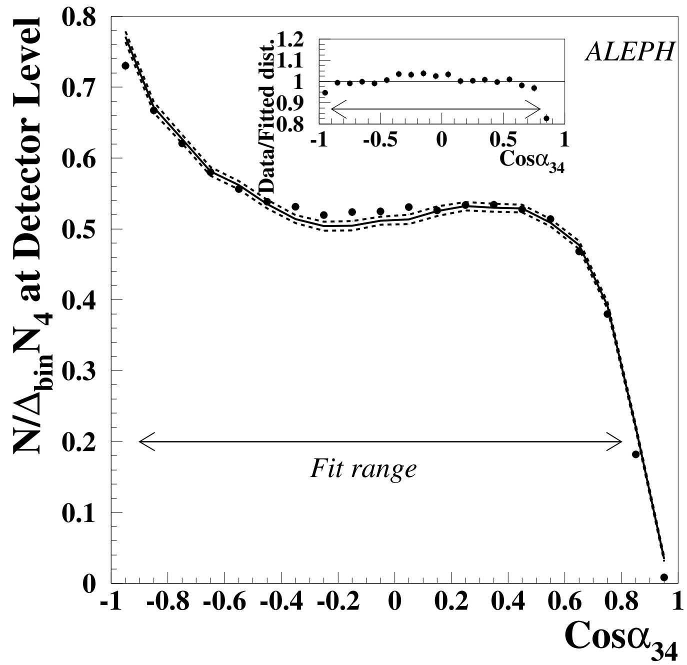
QCD colour factors

Summing over colours, QCD predicts

$$P(q \to qg) \propto C_F = 4/3,$$
$$P(g \to gg) \propto C_A = 3,$$
$$P(g \to q\bar{q}) \propto T_F = 1/2$$

Four-jet angular distributions provide info on colour factors,

e.g., α_{34} = angle between two lowest energy jets.



Recent analyses based on NLO predictions:

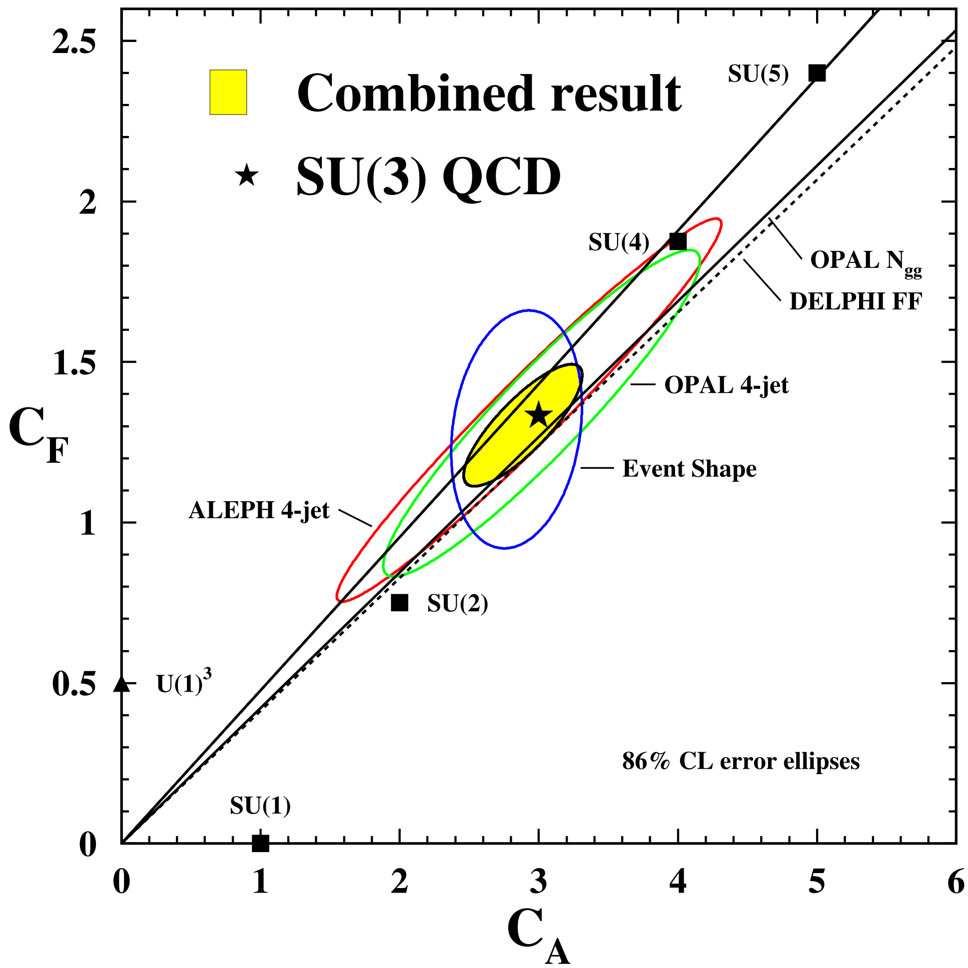
ALEPH, Eur. Phys. J. C27 (2003) 1;

OPAL, Eur. Phys. J. C20 (2001) 601.

QCD colour factors (cont.)

Averages of results on colour factors

S. Kluth, hep-ex/0309070



$$C_A = 2.89 \pm 0.03\ (\text{stat.}) \pm 0.21\ (\text{sys.}),$$

$$C_F = 1.30 \pm 0.01\ (\text{stat.}) \pm 0.09\ (\text{sys.}).$$

Excellent agreement with QCD: $C_A = 3$, $C_F = 4/3$.