α_s determination at LEP

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- L3
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  - Studies of Hadronic Event Structure in e^+e^- Annihilation from 30 GeV to 209 GeV with the L3 Detector, Phys. Rep. 399 (2004) 71.
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  - Measurement of the Strong Coupling α_s from Four-Jet Observables in e^+e^- annihilation, CERN-PH-EP/2005-057, Submitted to Eur. Phys. J.C
  - Determination of α_s Using Jet Rates at LEP with the OPAL Detector, Eur. Phys. J. C45 (2006) 547.
  - Measurement of event shape distributions and moments in e+e -> hadrons at 91-209 GeV and a determination of a_s, Eur. Phys. J. C40 (2005) 287.
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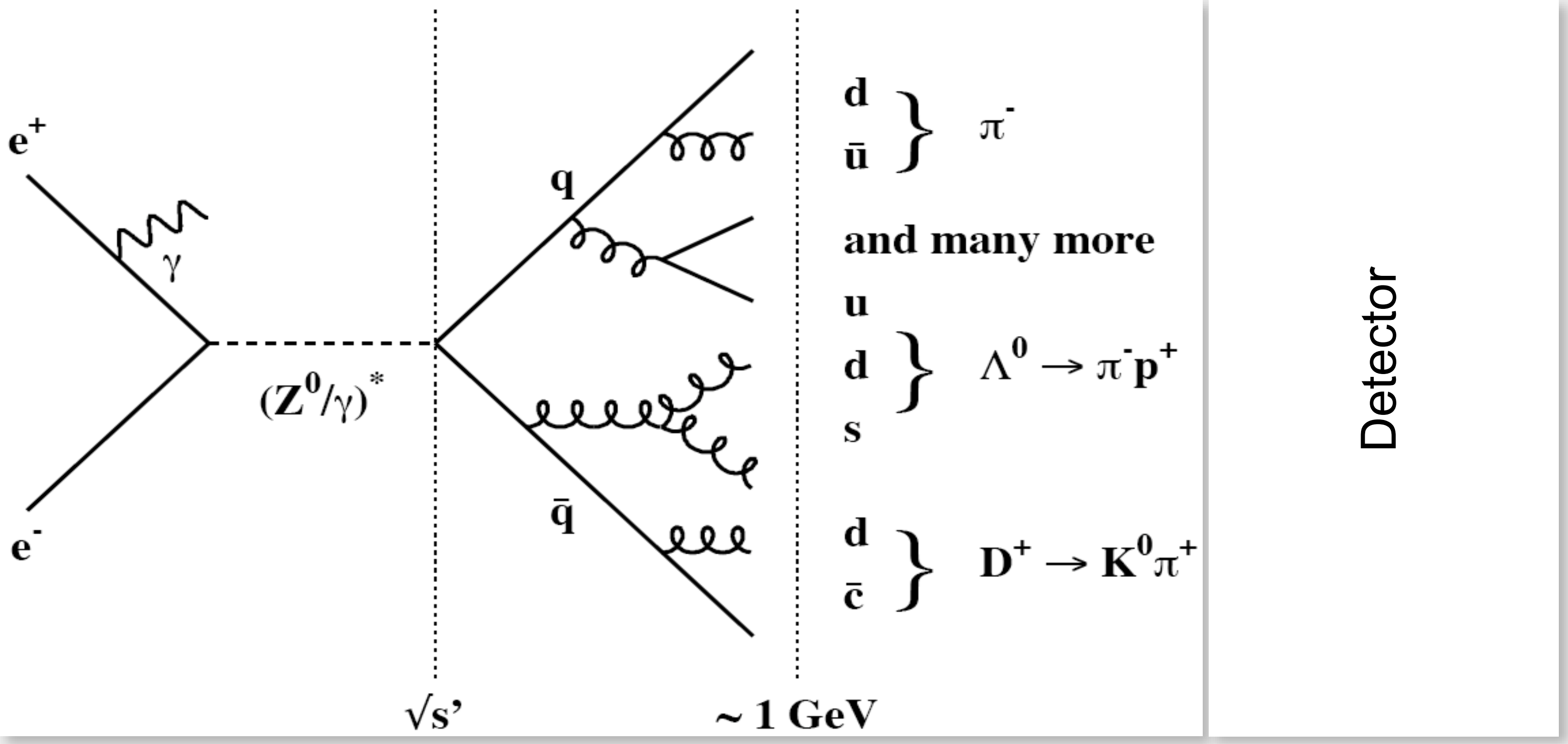
Combined results taken from this review and references therein

QCD studies at LEP: $e^+e^- \rightarrow$ hadrons

EW production Parton shower Hadronisation Detector effects



Parton level Hadron level Detector level

Observables

- Need observables sensitive to hard gluon radiation, but …
- …not sensitive to hadronisation and non-perturbative effects
  - Infrared-safe
  - Collinear-safe

- Concentrate on two types of observables in this talk
  - Event shapes: Global properties of the event calculated from the four momenta of all final state particles
  - Jet rates: Algorithms to define and count the number of jets in and event based on a resolution parameter

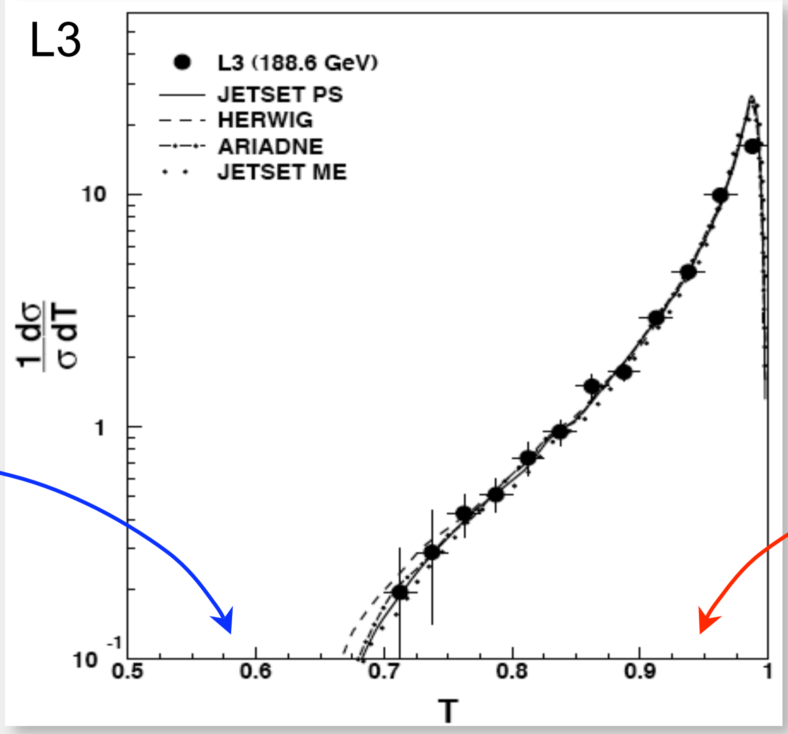
- Other observables include
  - Scaling violations
  - Z-lineshape observables
  - σ_L / σ_{Tot}

Event shape observables

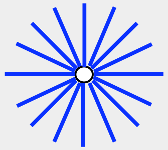
- Example: Thrust

$$T = \max_{\hat{n}} \left(\frac{\sum_i |\vec{p_i} \cdot \hat{n}|}{\sum_i |\vec{p_i}|} \right)$$

Sum of absolute momentum components of all observed particles projected along the axis that maximizes this sum



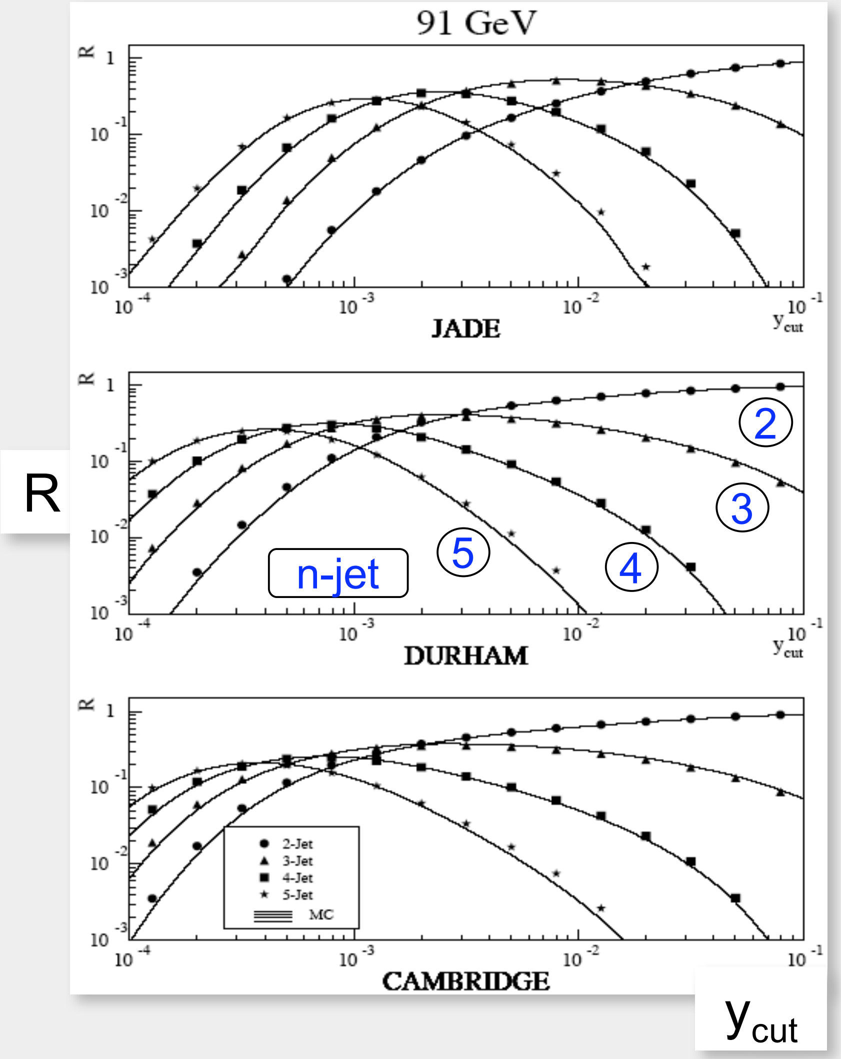
Spherical event
Many branchings



Pencil-like event
Few branchings

Jet rate observables

DELPHI



- Algorithm with resolution parameter to group particles into jets, → i.e. for the Durham algorithm:

$$y_{ij} = \frac{2\min\{E_i^2, E_j^2\}(1-\cos\theta_{ij})}{E_{vis}^2}$$

→ combine particles of smallest y_{ij} until $y_{ij} > y_{cut}$ for all pairs

- Experimental observables
  - Probability of finding n jets, $R_n(y_{cut})$, or its derivative D_n
  - Mean number of jets $\langle N\rangle(y_{cut})$

QCD predictions for three jet observables

- Fixed order ME calculations for the distribution R(y) of any event shape y yield good results if single hard gluon radiation dominates:

$$\mathrm{R(y)} = 1 + \mathcal{A}(\mathrm{y})\alpha_\mathrm{s} + \mathcal{B}(\mathrm{y})\alpha_\mathrm{s}^2$$

- For softer/collinear configurations (2-jet limit) new divergent terms appear and need to be re-summed:

$$\ln \mathrm{R} = \mathrm{L}\, \mathrm{g}_1(\alpha_\mathrm{s}\, \mathrm{L}) + \mathrm{g}_2(\alpha_\mathrm{s}\, \mathrm{L}) + \ldots$$

- Match (“mod. Log R”) to get the best perturbative prediction
  - Available for (1-T), M_H, B_T, B_W, C, y_{23}, jet rates
    → these are the observables of choice
- Parton shower + hadronisation model for non-pert. effects
  - Hadron level predictions

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Experimental procedure

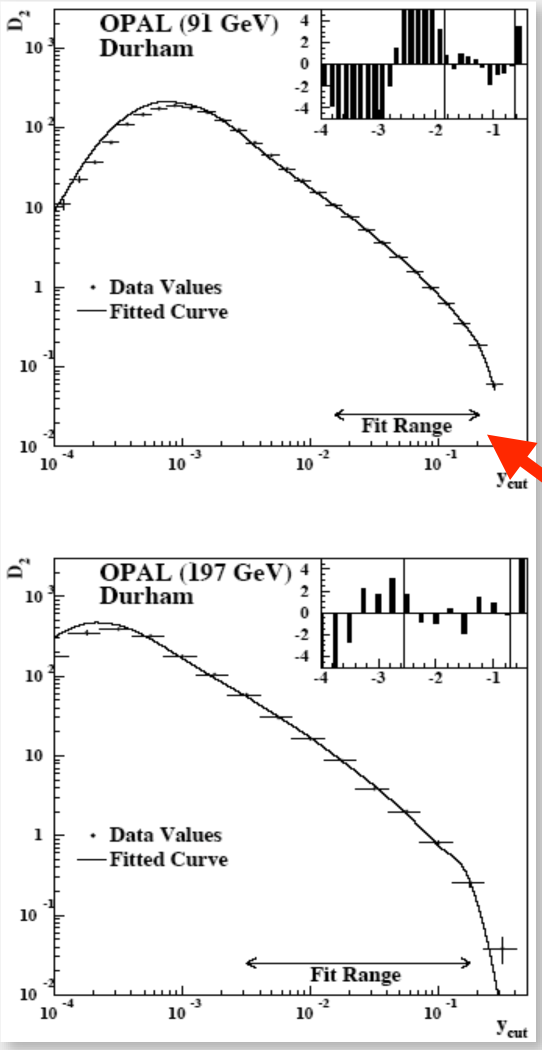
- Need to select $e^+e^- \rightarrow Z/\gamma \rightarrow$ qq, qqg, qqgg,qqq, … events
  - Reject events with radiation from initial state (isolated energetic γ)
  - Reject WW and ZZ events (likelihood variables)

- Determine detector-level event shapes and jet rates, then use MC to correct for background, efficiency,detector effects
  → Hadron level quantities

- Fit hadron level theory prediction to the data to determine α_s

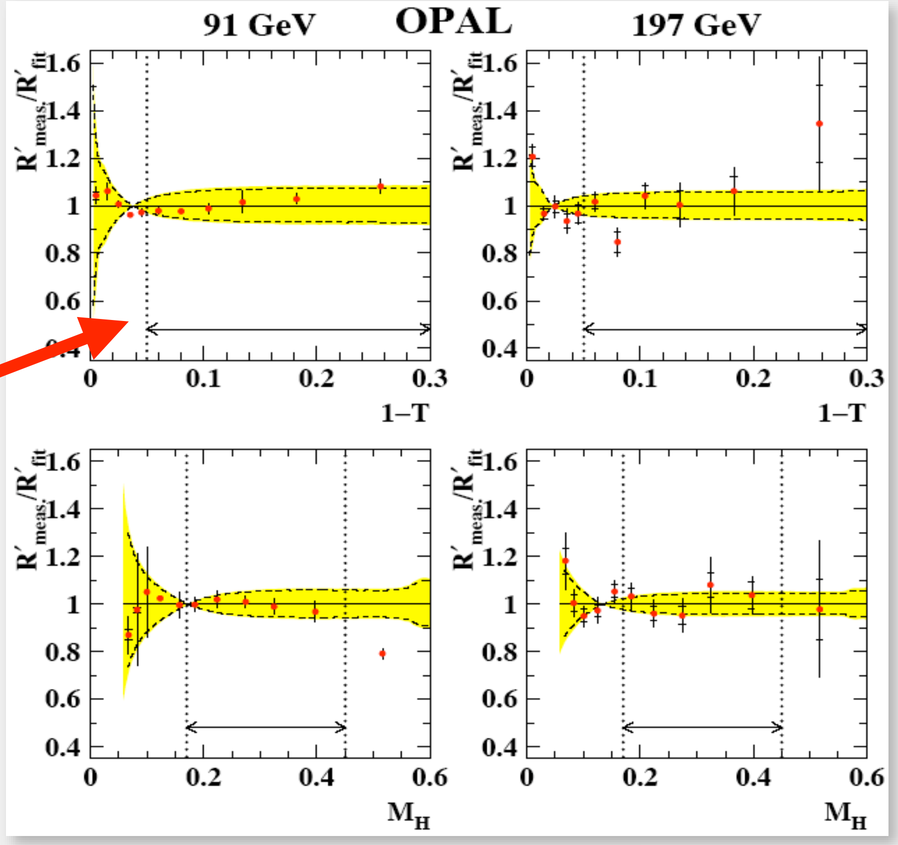
QCD fits to event shapes and jet rates

Multitude of fits to event shape and jet rate observables at several $\sqrt{s_{ee}}$ yielding α_s values to be combined



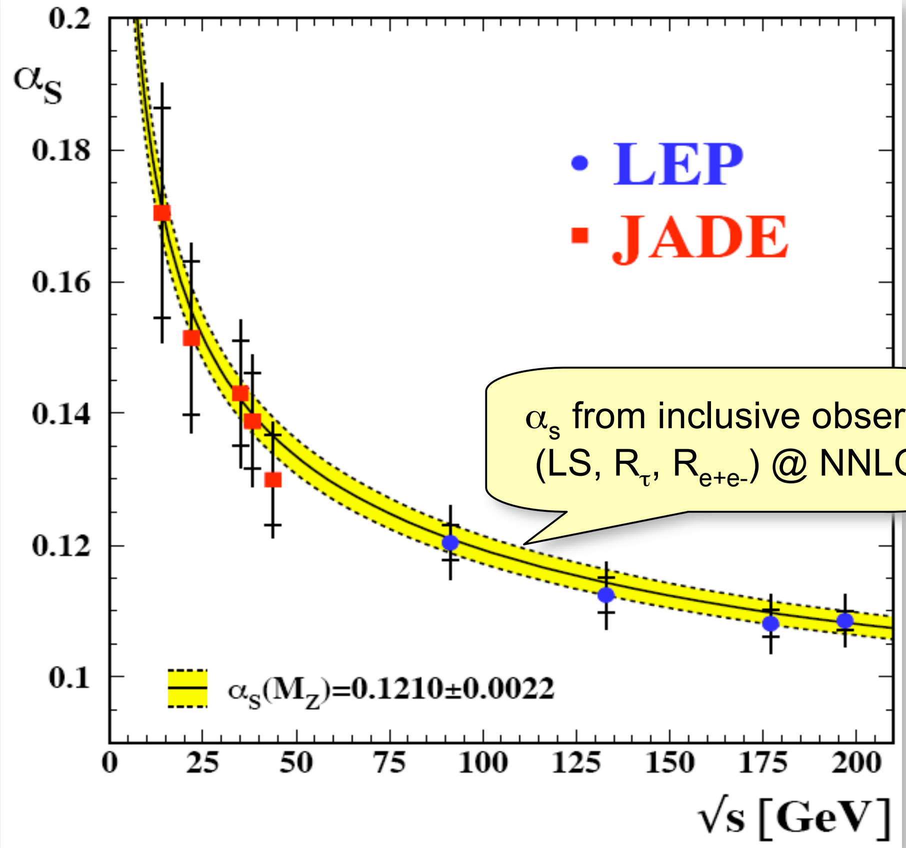
Durham D_2 (y_{23})

Fit Range

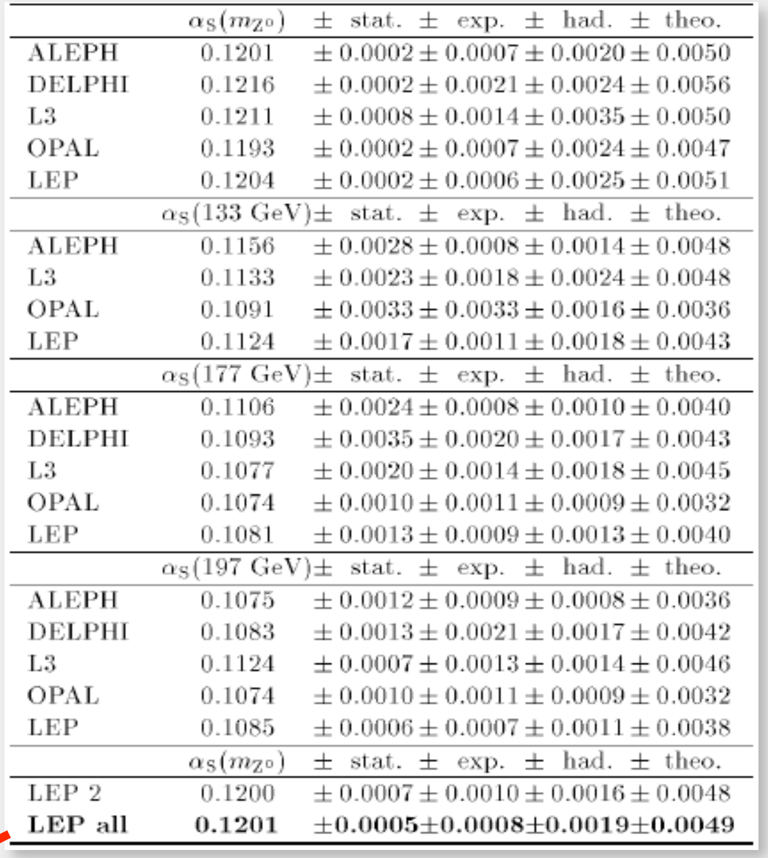


Thrust and heavy jet mass

α_s from event shapes and jet rates (3-jet)



α_s from inclusive observ. (LS, R_τ, R_{e+e-}) @ NNLO



	$\alpha_S(m_{Z^0})$	± stat.	± exp.	± had.	± theo.
ALEPH	0.1201	± 0.0002	± 0.0007	± 0.0020	± 0.0050
DELPHI	0.1216	± 0.0002	± 0.0021	± 0.0024	± 0.0056
L3	0.1211	± 0.0008	± 0.0014	± 0.0035	± 0.0050
OPAL	0.1193	± 0.0002	± 0.0007	± 0.0024	± 0.0047
LEP	0.1204	± 0.0002	± 0.0006	± 0.0025	± 0.0051
	α_S(133 GeV)	± stat.	± exp.	± had.	± theo.
ALEPH	0.1156	± 0.0028	± 0.0008	± 0.0014	± 0.0048
L3	0.1133	± 0.0023	± 0.0018	± 0.0024	± 0.0048
OPAL	0.1091	± 0.0033	± 0.0033	± 0.0016	± 0.0036
LEP	0.1124	± 0.0017	± 0.0011	± 0.0018	± 0.0043
	α_S(177 GeV)	± stat.	± exp.	± had.	± theo.
ALEPH	0.1106	± 0.0024	± 0.0008	± 0.0010	± 0.0040
DELPHI	0.1093	± 0.0035	± 0.0020	± 0.0017	± 0.0043
L3	0.1077	± 0.0020	± 0.0014	± 0.0018	± 0.0045
OPAL	0.1074	± 0.0010	± 0.0011	± 0.0009	± 0.0032
LEP	0.1081	± 0.0013	± 0.0009	± 0.0013	± 0.0040
	α_S(197 GeV)	± stat.	± exp.	± had.	± theo.
ALEPH	0.1075	± 0.0012	± 0.0009	± 0.0008	± 0.0036
DELPHI	0.1083	± 0.0013	± 0.0021	± 0.0017	± 0.0042
L3	0.1124	± 0.0007	± 0.0013	± 0.0014	± 0.0046
OPAL	0.1074	± 0.0010	± 0.0011	± 0.0009	± 0.0032
LEP	0.1085	± 0.0006	± 0.0007	± 0.0011	± 0.0038
	$\alpha_S(m_{Z^0})$	± stat.	± exp.	± had.	± theo.
LEP 2	0.1200	± 0.0007	± 0.0010	± 0.0016	± 0.0048
LEP all	**0.1201**	**±0.0005**	**±0.0008**	**±0.0019**	**±0.0049**

LEP combined $\alpha_s(m_Z)$: 0.1201±0.0053 (uncertainty dominated by theory)

α_s from 4-jet rates

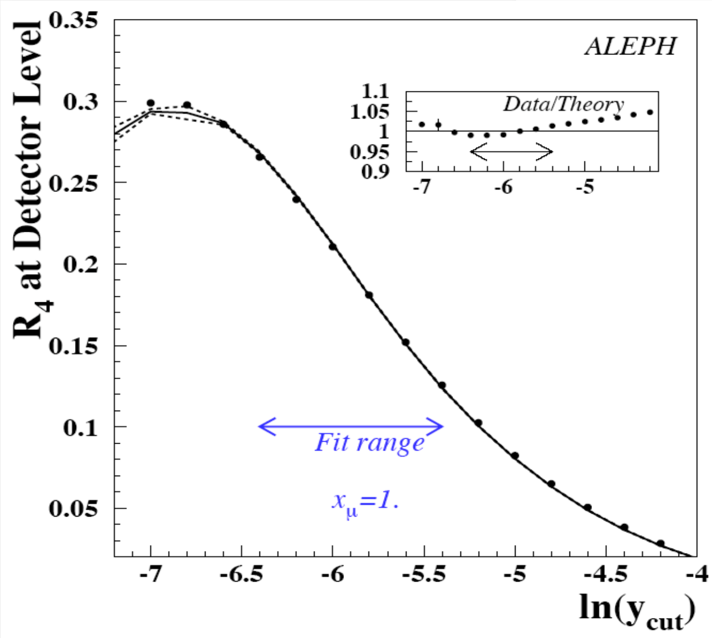
- Promising observable:
  - Higher sensitivity of 4-jet observables (~ α_s^2) then for 3-jet observables (~ α_s)

- QCD predictions available at NLO
  - For R_4 LO is $O(\alpha_s^2)$, radiative corrections are $O(\alpha_s^3)$
  - Calculations matched with existing NLLA calculations

- Measurements performed by ALEPH, DELPHI, OPAL
  - ALEPH: Fit $O(\alpha_s^3)$+NLLA corrected for hadronisation and detector effects to detector level data at the Z-peak
  - DELPHI: Fit $O(\alpha_s^3)$ corrected for hadronisation with experimentally optimised scale x_μ to hadron level corrected data at the Z-peak
  - OPAL: Fit $O(\alpha_s^3)$+NLLA corrected for hadronisation to data from 91 GeV to 209 GeV CME, α_s presented at four CME points

QCD fits to four-jet rate: ALEPH / DELPHI

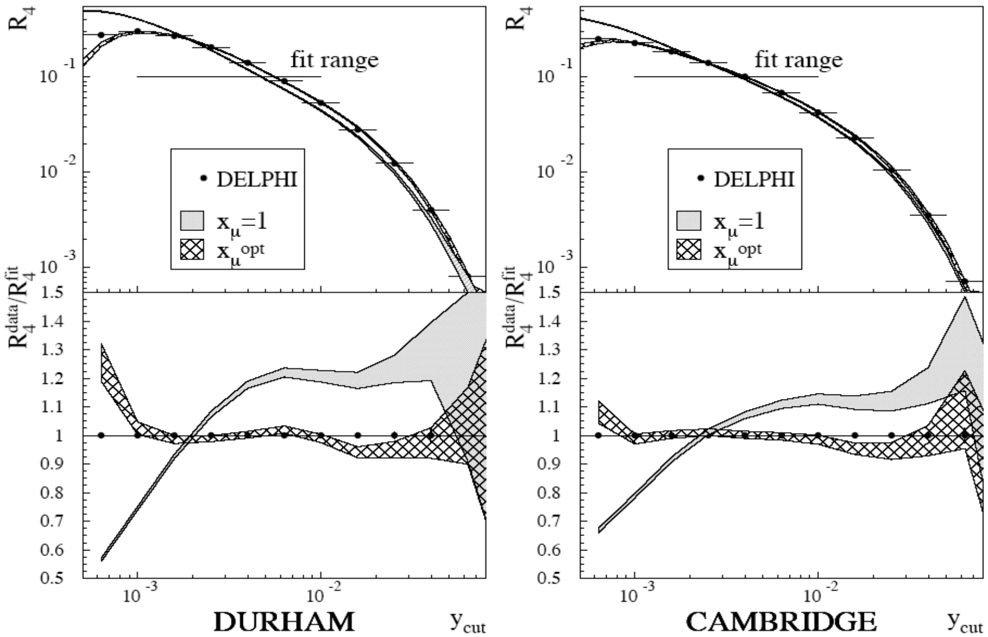
ALEPH



$\alpha_s(m_Z) = 0.1170 \pm 0.0022$

± 0.0001 (stat.)
± 0.0009 (exp.)
± 0.0010 (hadr.)
± 0.0017 (theory)

DELPHI



$\alpha_s(m_Z) = 0.1175 \pm 0.003$

± 0.0005 (stat.)
± 0.0010 (exp.)
± 0.0027 (hadr.)
± 0.0007 (theory)

Very sensitive to increased μ_r variation

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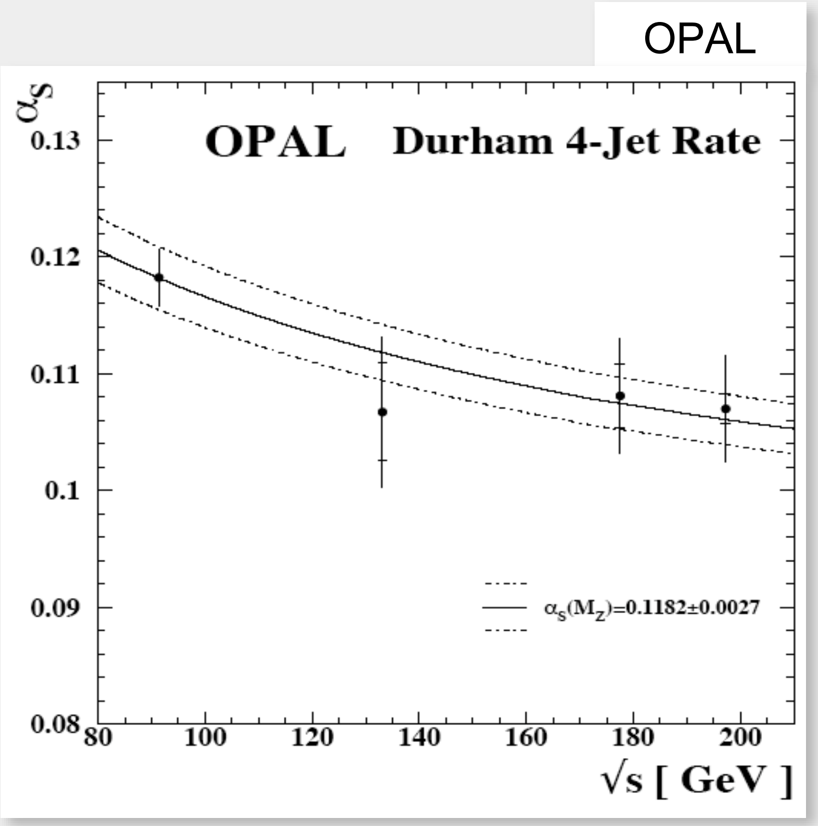
α_s from four- jet rates



$\alpha_s(m_Z) = 0.1182 \pm 0.0026$

± 0.0003 (stat.)
± 0.0015 (exp.)
± 0.0011 (hadr.)
± 0.0018 (theory)

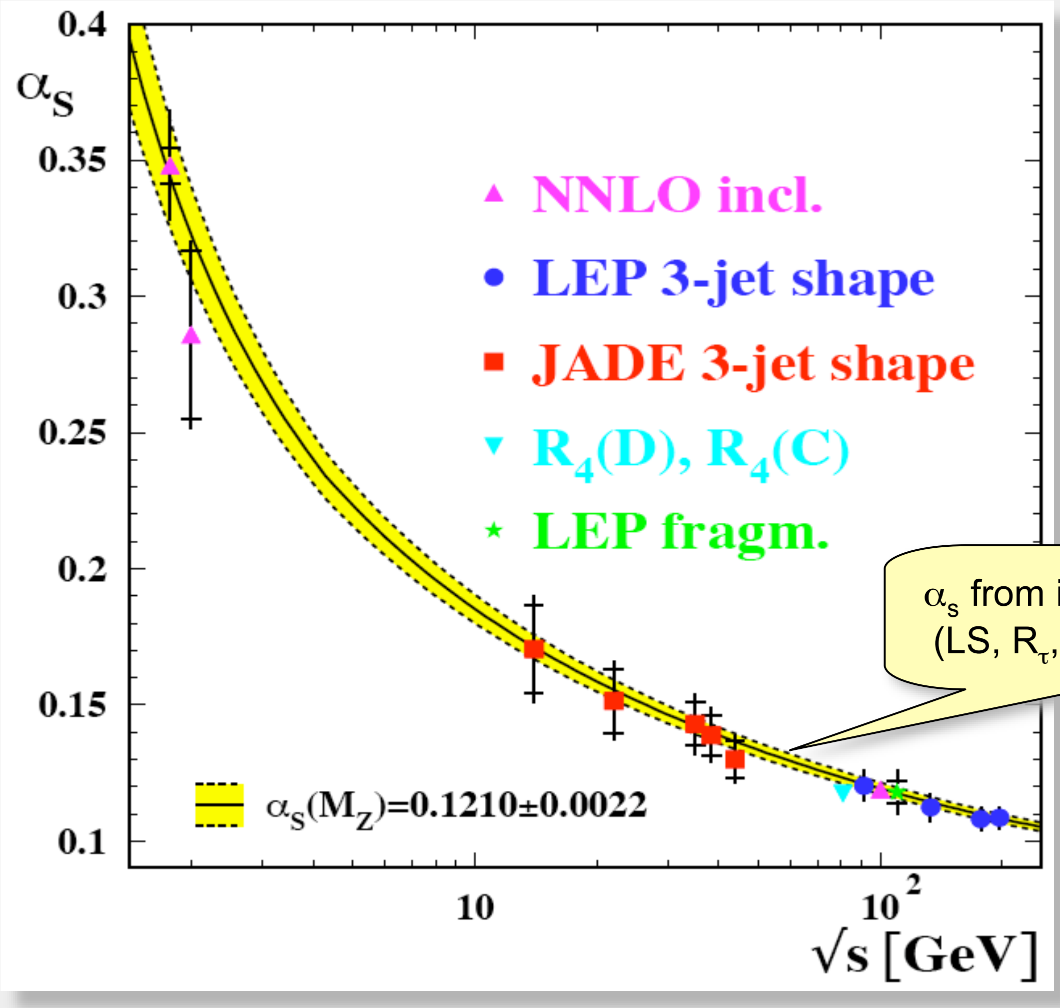
Combining all three R_4 results yields

$\alpha_s(m_Z) = 0.1175 \pm 0.0029$

± 0.0002 (stat.)
± 0.0010 (exp.)
± 0.0014 (hadr.)
± 0.0015 (theory)

Uncertainties of similar size as for inclusive line shape (LS) variables at NNLO

Overview of α_s determinations in e^+e^-



α_s from inclusive observ. (LS, R_τ, R_{e+e-}) @ NNLO

- Very consistent picture
- Clear demonstration of asymptotic freedom

Summary

- Theoretically + experimentally well behaved observables of event shapes and jet rates
  - Direct tests of advanced perturbative QCD predictions
  - Clear demonstration of asymptotic freedom
  - Precise determination of the value of α_s

α_s from 3-jets observables

- Reliable and precise results based on NLO+NLLA
- Consistent with world average(s)
- May be able to reduce total uncertainty to ~ 2 % using NNLO (from 5% now)

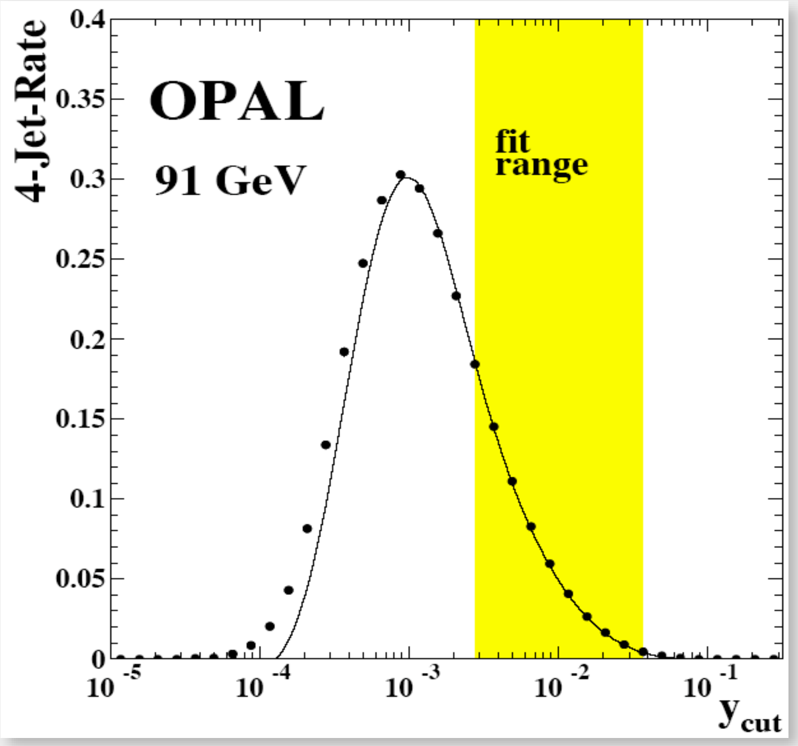
α_s from 4-jets rate

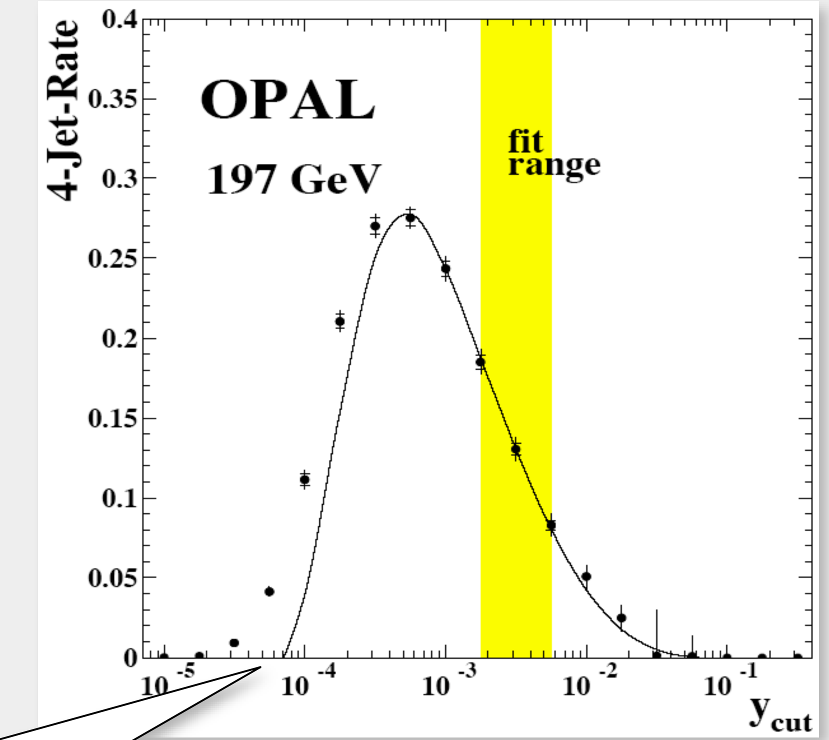
- Results available based on NLO+NLLA
- Precision reached is comparable to most precise determinations available today

World averages

Bethke '04:	0.1184 ± 0.0027
PDG '04:	0.1187 ± 0.0020

QCD fits to four-jet rate: OPAL





At low y_{cut}

- Large hadronisation corrections (100 %)
- Significant deviations between different hadronisation models