Determination of α_s in e^+e^- collisions up to 183 GeV with the L3 detector

- Introduction & Overview of α_s determinations
- Event Shape method, from 30 to 183 GeV
- Lineshape & R_τ methods
- Results from all 3 methods compared
- Conclusions & Prospects

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LLWI, QCD
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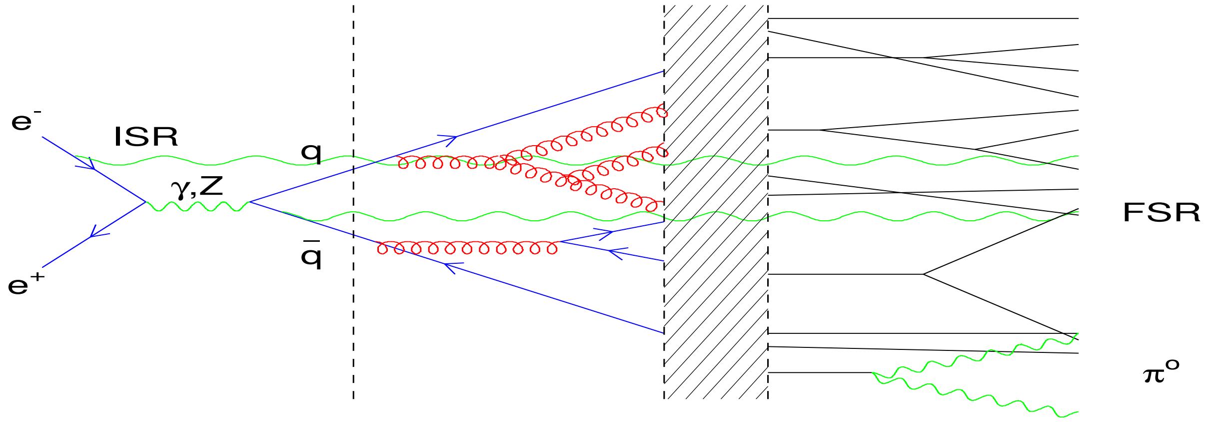
QCD is rich in predictions, however 2 problems:

- We don't directly see partons:



- Calculations are difficult:

$$\langle \text{observable} \rangle = \Sigma_i \left(a_i \left(\frac{\alpha_s}{\pi} \right)^i \right) + \Sigma_j \frac{b_j}{Q_j}$$

perturbative — non-perturbative

$\mathcal{O}(\alpha_s{}^2 \text{or } \alpha_s{}^3)$

$\rightarrow$ 'un-physical' RS,Λ dependance

As a result theoretical uncertainties are often dominant in α_s determinations.

Within perturbative QCD, $\alpha_s \rightarrow 0$ as $Q^2 \rightarrow \infty$ (asymptotic freedom); evolving with Q^2 as:

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2)} \left\{ 1 - \frac{2\beta_1}{\beta_0^2} \frac{\ln(\ln(Q^2/\Lambda^2))}{\ln(Q^2/\Lambda^2)} + \ldots \right\}$$

$$\beta_0 = 11 - \frac{2}{3} n_f \qquad \beta_1 = 102 - \frac{38}{3} n_f$$

where n_f is the number of flavours

Overview of α_s determinations in e^+e^- collisions

Three techniques are used to determine α_s with L3:

- R_Z
  Electroweak SM fits to Z lineshape data (in particular Γ_Z, $\sigma^0_{\rm had}$) are sensitive to α_s and benefit from $\mathcal{O}({\alpha_s}^3)$ calculations of R_Z.
  Applicable only at one scale: m_Z

- R_τ
  Analogous method to R_Z in τ decays, again benefiting from $\mathcal{O}({\alpha_s}^3)$ calculations.
  BUT: strong assumption of "parton hadron duality"
  Applicable only at one scale: m_τ

- Event Shape Variables characterise hadronic events.
  Observed distributions (e.g. Thrust) are corrected for:
  - Backgrounds remaining after hadron selection
  - Resolution & Acceptance
  - Initial and Final state radiation
  - Hadronisation effects

  yielding distributions to compare(and fit) with analytical predictions for the variables. For some variables resummed $\mathcal{O}({\alpha_s}^2)$ calculations are available.
  Technique applicable to many energy scales → ideal method to test the α_s evolution prediction of QCD.

Hadronic final states are characterised by:

- Thrust

$$T = \max \frac{\sum_a |\vec{p_a} \cdot \vec{n_T}|}{\sum_a |\vec{p_a}|}$$

- Scaled Heavy Jet Mass

$$\begin{aligned} M_\pm^2 &= \left(\sum_{a \in S_\pm} p_a\right)^2 \\ M_H &= \max[M_+(\vec{n_T}), M_-(\vec{n_T})] \\ \rho &= M_H^2/s \end{aligned}$$

- Jet Broadening Variables

$$B_\pm = \frac{\sum_{a \in S_\pm} |\vec{p_a} \times \vec{n_T}|}{2\sum_a |\vec{p_a}|}$$

  - Total Jet Broadening $B_T = B_+ + B_-$
  - Wide Jet Broadening $B_W = \max(B_+, B_-)$

Hadronisation effects are studied and corrected for using models with different approaches to the QCD evolution:

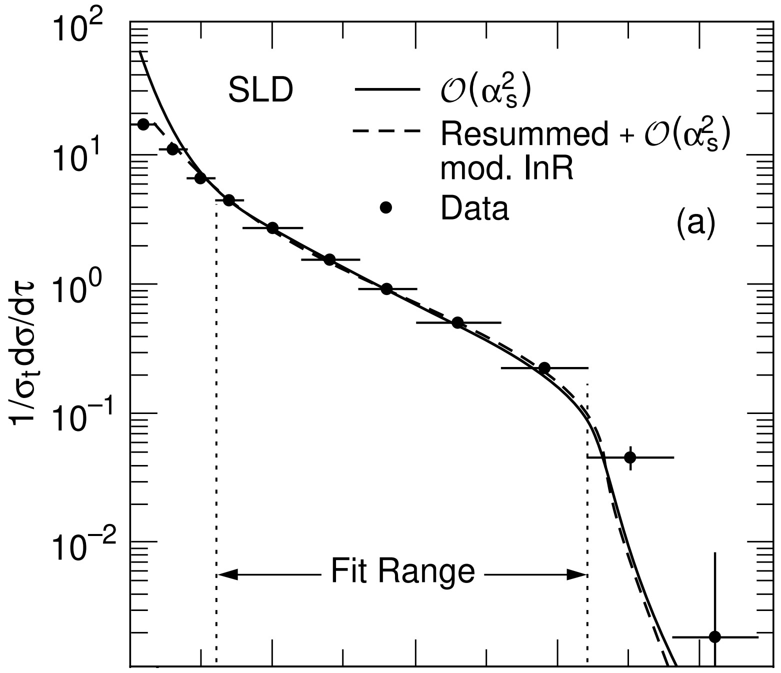
QCD Model	Shower Development	Fragmentation
JETSET	Parton Shower	String
HERWIG	Parton Shower	Cluster
ARIADNE	Colour Dipole	String
COJETS	Incoherent Parton Shower	Independent

The "default" parameters of the models are chosen by tuning on LEP I data.

"y" (T,ρ,B_T,B_W) are proportional to α_s at leading order.
$\mathcal{O}(\alpha_s{}^2)$ QCD predictions have been calculated:

$$R(\alpha_s, y) \equiv \frac{1}{\sigma}\frac{d\sigma}{dy} = \left(\frac{\alpha_s}{2\pi}\right) A(y) + \left(\frac{\alpha_s}{2\pi}\right)^2 \left[B(y) + 2\pi\beta_0\, ln\frac{\mu^2}{s} A(y)\right]$$

BUT truncation → renormalisation scale (μ) and scheme dependance and the predictions fail in the 2-jet region (small "y") as fixed order calculations cannot describe multi-gluon emission.



$\tau = 1 - T$

For "y" (and a few others) the singular terms of the full perturbation series have been summed in the form of an exponential.

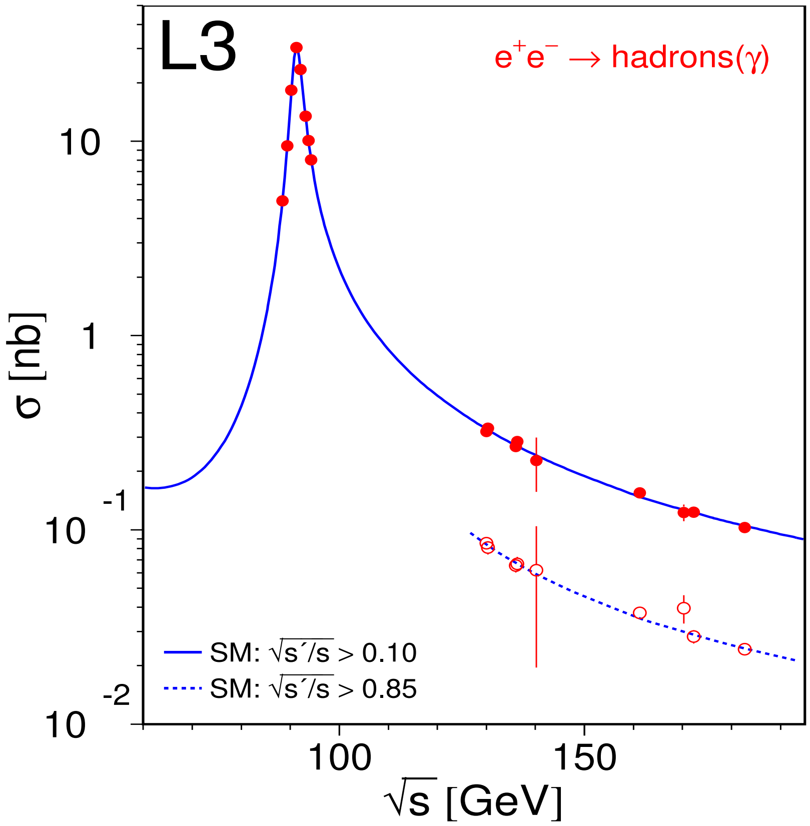
Such calculations are combined with the $\mathcal{O}(\alpha_s{}^2)$ results by a matching scheme, ensuring no double counting.

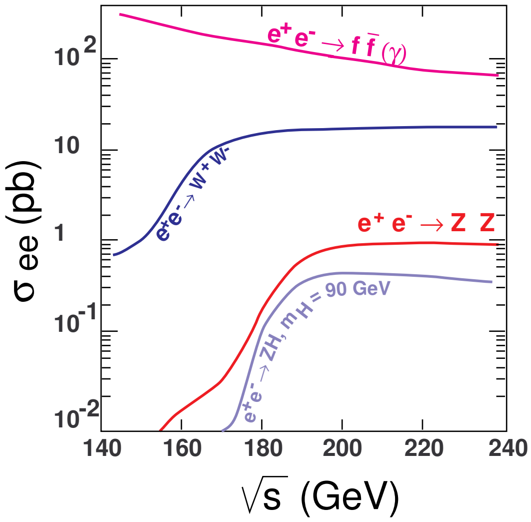
Resummation:

- extends the range of validity of predictions.
- reduces higher-order term uncertainties in α_s determinations.

$\sqrt{s}$: 30 → 183 GeV Hadronic dataset, $e^+e^- \to q\bar{q}$

Selected by large visible energy and high multiplicity.





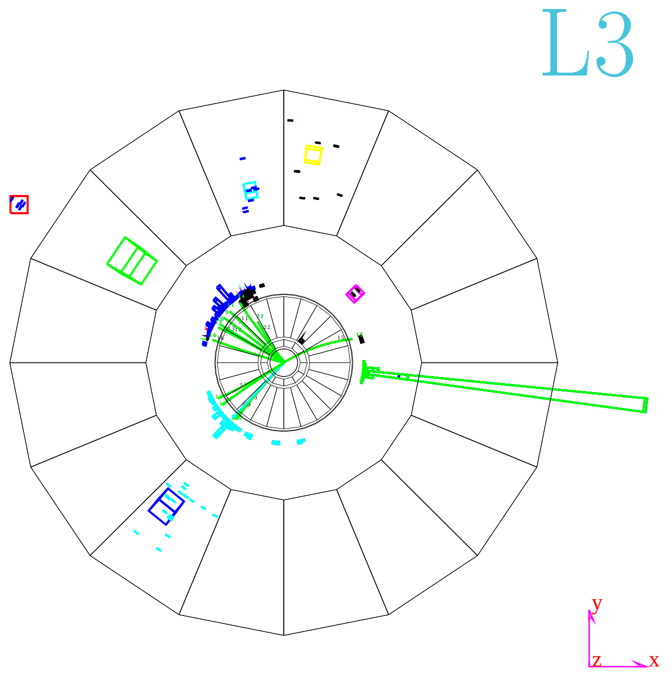
	LEP1.0		LEP1.5-2.0 after '95			
$\sqrt{s}$ (GeV):	30 – 86	≈ 91.2	130 – 140	161	172	183
$\int \mathcal{L}(\mathrm{pb}^{-1})$:	142.4	8.0	5.0	11.1	10.2	52.2
# $q\bar{q}$ events:	3.578M	248k	402	443	341	1516
W^+W^- bgd. (%)	-	-	-	4	9(17)	11.9
2γ & $\tau^+\tau^-$ bgd. (%)	0.2	< 0.2	< 2	3	3	3.2
ϵ ($E_\gamma^{ISR} < 30$ GeV) (%)	-	-	96	90	85	90

Backgrounds depend on $\sqrt{s}$:

- Radiative return to Z (hard ISR events), $\sqrt{s} > m_Z$
- Hadronic W decays, $\sqrt{s} > 161$ GeV
- Non-resonant 2γ collisions ($e^+e^- \to e^+e^- +$ hadrons), all $\sqrt{s}$

$\boxed{\sqrt{s} < m_Z}$ Analysis of $e^+e^- \to \text{hadrons} + \gamma$

γ from ISR/quark bremsstrahlung - long before hadronisation.
$\to$ system recoiling against γ is at reduced energy $\sqrt{s'}$.
Checked by comparison with JETSET generator at reduced $\sqrt{s}$.



$$\sqrt{s'} = \sqrt{s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)}$$

Isolated photon candidates are selected:

- neutral electromagnetic shower with $E > 5$ GeV
- isolated: no other cluster $< 15°$ & $> 20°$ from nearest jet
- neural network π^0/γ (multi-γ/single-γ) discriminator

$\sqrt{s'}$ (GeV):	30-50	50-60	60-70	70-80	80-84	84-86
# $q\bar{q}\gamma$ events:	1247	1047	1575	2938	2091	1607
hadronic bgd. (%):	29.3	19.2	11.6	9.2	7.7	11.6
purity (%):	68.4	78.0	86.0	89.0	90.5	87.0

Remove γ & boost event into recoiling system, then compute event shape variables for QCD fits.

$\to$ Measurements of α_s for each energy bin.

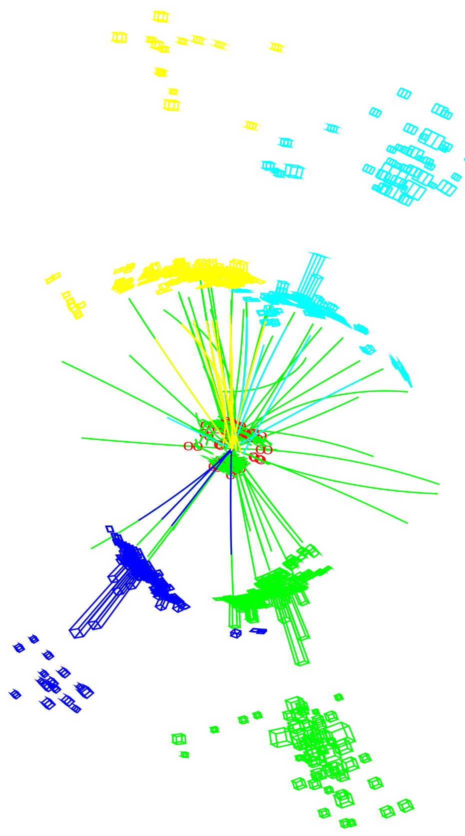
$\boxed{\sqrt{s} > 161 \text{ GeV}}$ Rejection of W^+W^- Events

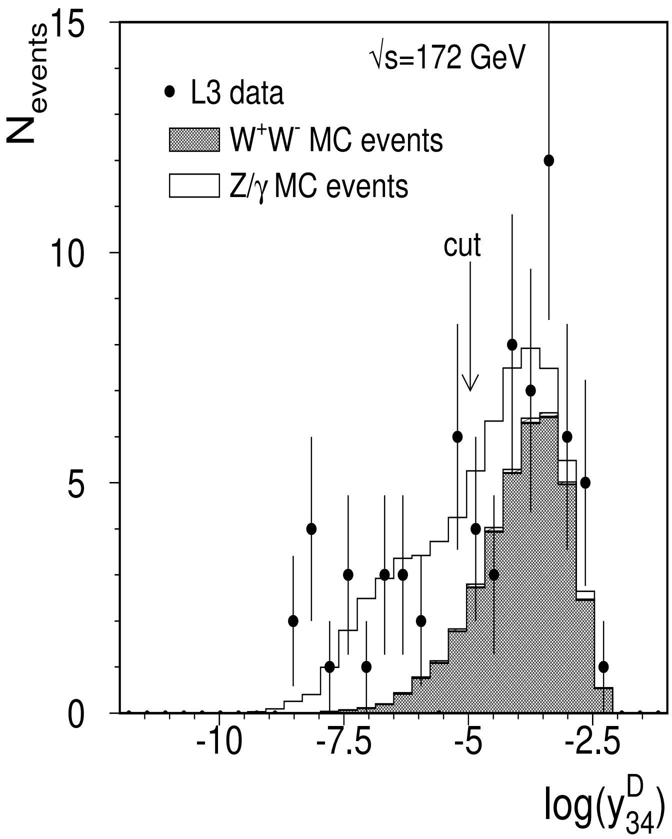
Above W^+W^- threshold , large background from:

$$e^+e^- \to W^+W^- \to q\bar{q}q\bar{q}$$

Select (then reject) these events by:

- Requiring high multiplicity
- Force them into four jets with Durham algorithm
- Improve jet energies using jet directions, and energy order
- Impose "good" 4-jet cuts: $E_{jet1} < 0.4\sqrt{s}$, $E_{jet4} > 0.1\sqrt{s}$
- Jet resolution requirement $y^D_{3\to4} \geq 0.007$



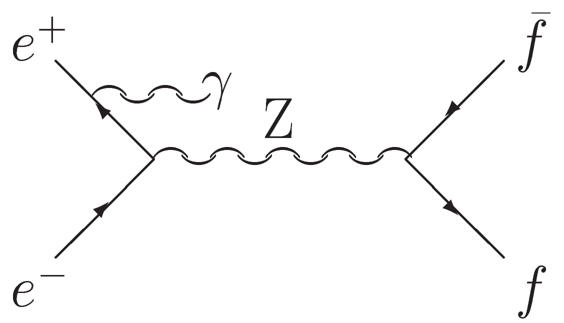


$\sqrt{s}$ (GeV):	130 – 140	161	172	183
W^+W^- bgd. (%)	-	4	9(*)	12

(*): before this rejection, the bgd. at 172 GeV was 17%

Rejection of Radiative Return Events

Above the Z, many hard ISR γ "return" $\sqrt{s} \to m_Z$



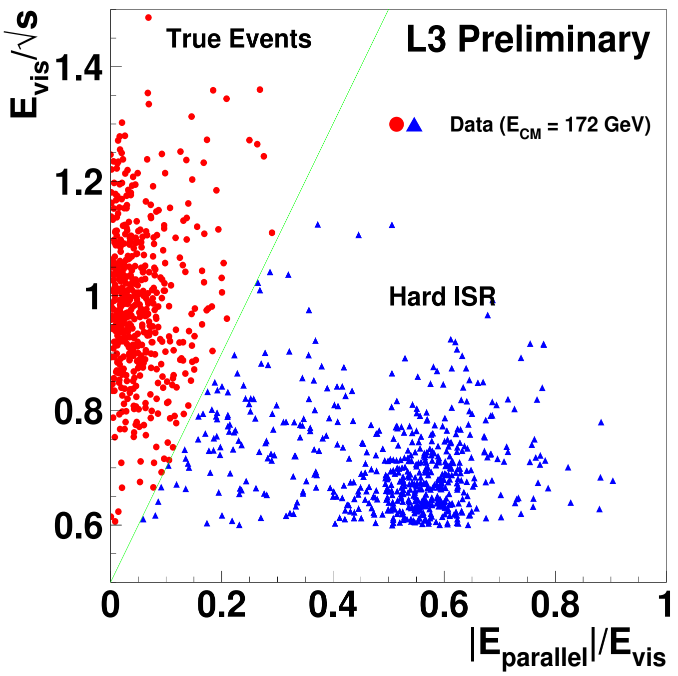
ISR photons are collimated to the $e^{\pm}$ direction, and are lost in beampipe.

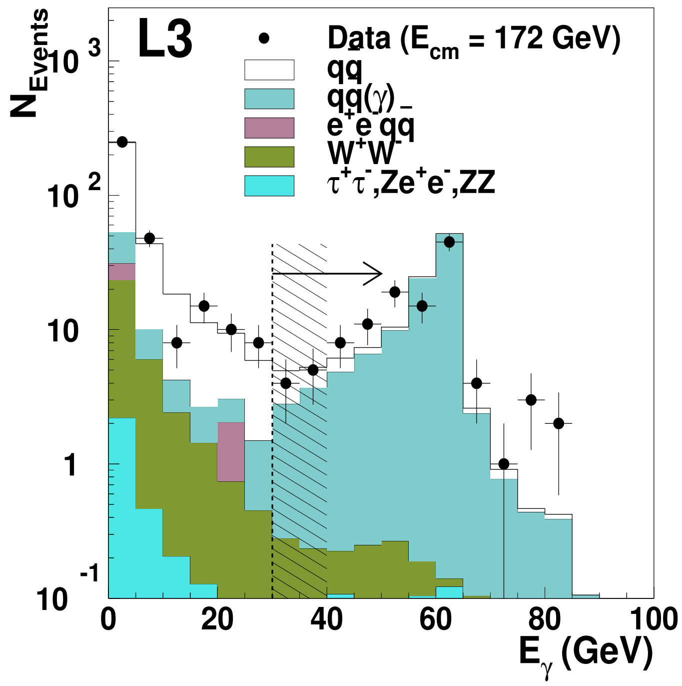
$\rightarrow$ Z's are produced recoiling against γ

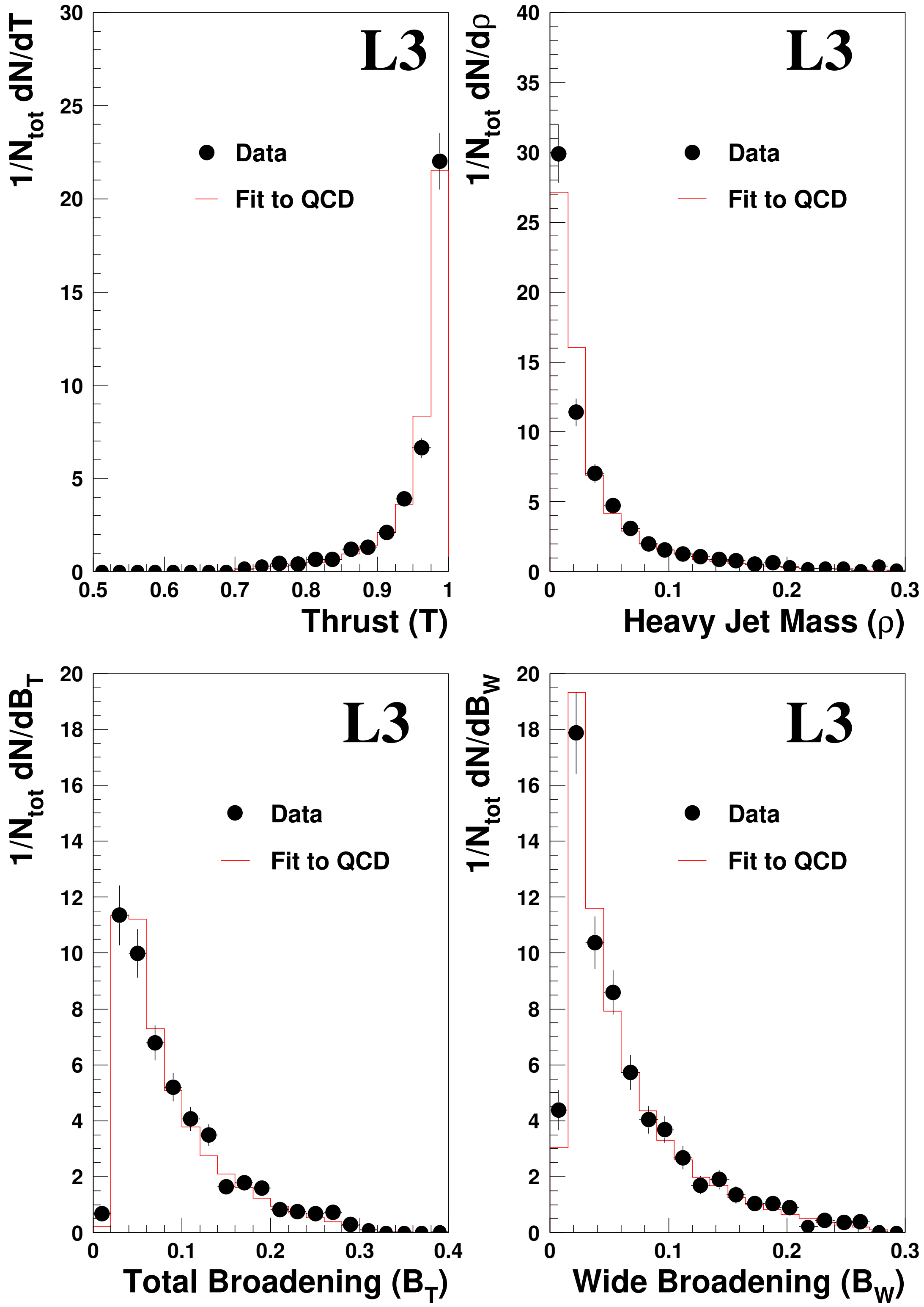
$\rightarrow$ events have large longitudinal imbalance

So reject these unbalanced events by:

- $(\mathrm{E_{vis}}/\sqrt{s}) > a(\sqrt{s}) \cdot (\mid \mathrm{E}_{\parallel} \mid /\mathrm{E_{vis}}) + 0.5$; $a(172\,\mathrm{GeV}) = 2.0$
- $\mathrm{E}_\gamma < 30$ GeV no energetic photon in detector



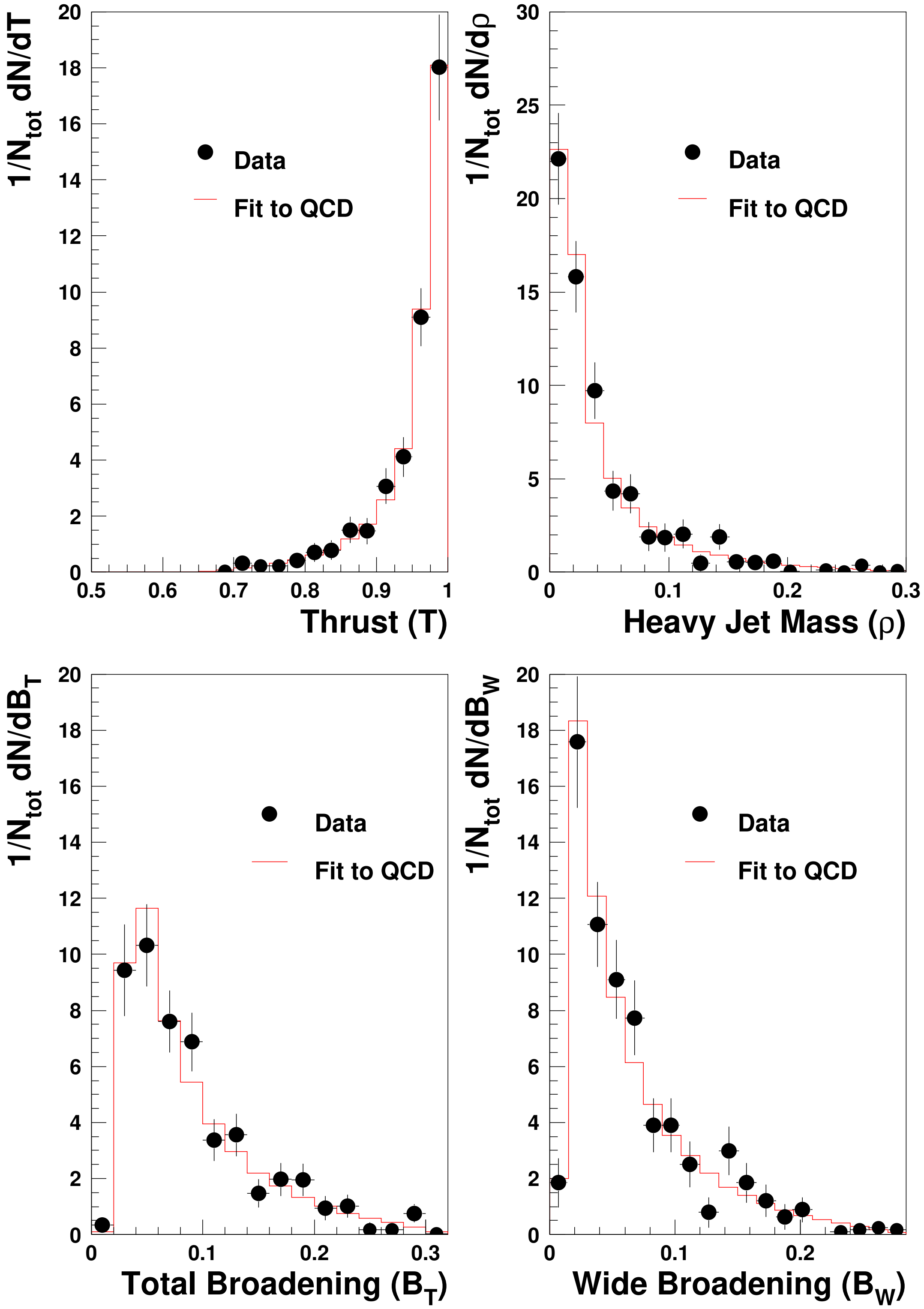




Good fits to QCD distributions with one free parameter α_s

	$(1-T)$	ρ	B_T	B_W
$\alpha_s(183\,\mathrm{GeV})$	0.093	0.091	0.103	0.095

$\rightarrow$ $\boxed{\alpha_s(183\,\mathrm{GeV}) = 0.095 \pm 0.005 \pm 0.005}$ (Prelim.)



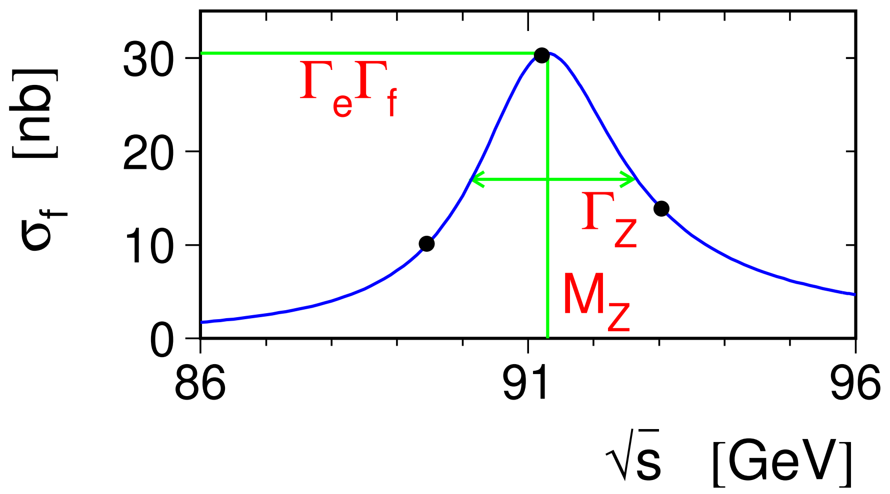
	$(1-T)$	ρ	B_T	B_W
$\alpha_s(172\,\mathrm{GeV})$	0.108	0.104	0.106	0.099
χ^2/d.o.f.	0.28	0.89	1.12	1.08

Event shape uncertainties

	$(1-T)$	ρ	B_{T}	B_{W}
Fit range	0.00-0.30	0.00-0.20	0.00-0.25	0.00-0.20
$\alpha_{\mathrm{s}}(172\,\mathrm{GeV})$	0.108	0.104	0.106	0.099
$\chi^2/\mathrm{d.o.f.}$	0.28	0.89	1.12	1.08
Statistical	± 0.005	± 0.005	± 0.004	± 0.004
Systematic	± 0.003	± 0.003	± 0.003	± 0.003
Overall experimental	± 0.006	± 0.006	± 0.005	± 0.005
Fragmentation model	± 0.003	± 0.002	± 0.003	± 0.001
Model parameters	± 0.002	± 0.002	± 0.001	± 0.001
Hadronisation total	± 0.003	± 0.002	± 0.003	± 0.001
QCD scale uncertainty	± 0.004	± 0.003	± 0.005	± 0.005
Matching scheme	± 0.002	± 0.003	± 0.005	± 0.005
Error due to higher orders	± 0.004	± 0.003	± 0.005	± 0.005
Overall theoretical	± 0.005	± 0.004	± 0.006	± 0.005

- Fit range choosen for: reliable calculation, small corrections, sufficient statistics.
- Systematic: variations in energy calib. and bkg. content
- Fragmentation model: changing the model and changing the parameters by 1σ
- QCD scale uncertainty: using different renormalisation scales $0.5\sqrt{s} \leq \mu \leq 2.0\sqrt{s}$

$$\boxed{\alpha_{\mathrm{s}}(172\,\mathrm{GeV}) = 0.104 \pm 0.006 \pm 0.005}$$



- Perturbative coefficients for $\Gamma_{\rm had}$ & R_Z known to $\mathcal{O}(\alpha_s{}^3)$:

$$R_Z = \frac{\Gamma_{\rm had}}{\Gamma_{\rm lep}} \approx R_0 \left[1 + 1.06\left(\frac{\alpha_s}{\pi}\right) + 0.9\left(\frac{\alpha_s}{\pi}\right)^2 - 15\left(\frac{\alpha_s}{\pi}\right)^3 + \ldots\right]$$

(R_0 includes m_t,m_h dependant radiative corrections.)

- BUT, QCD effect is small $\rightarrow$ limited sensitivity to α_s.

SM fits (m_Z,m_t,m_h,α_s) to Preliminary L3 '90-'95 data:

$$\boxed{m_Z \quad \Gamma_Z \quad \sigma^0_{had} \quad R_l \quad A^{0,l}_{FB} \quad P_\tau \quad A^{0,b}_{FB} \quad R_b}$$

using a fixed $m_h = 300$ GeV, yields:

$$m_t = 189^{+14}_{-15} \pm 16 \text{ GeV}$$

$$\alpha_s = 0.126 \pm 0.007 \pm 0.002$$

The 2nd error refers to a variation of m_h from 60 $\rightarrow$ 1000 GeV.

Analogously to R_Z, the ratio of the hadronic and leptonic decay widths of the τ:

$$R_\tau \equiv \frac{\Gamma^\tau_{had}}{\Gamma^\tau_l} = \frac{B^\tau_{had}}{B^\tau_l} = R^0_\tau \left[1 + \delta^\tau_{QCD}\right]$$

$R^0_\tau = 3.03 \pm 0.01$ including:

- Assumption of parton hadron duality - controversial ?
- non-perturbative QCD corrections.
- m_t,m_h dependant electroweak radiative corrections.
- colour factor, $N_c = 3$
- small corrections from CKM matrix elements

δ^τ_{QCD} follows the same form as R_Z perturbative expansion.

Branching Ratios	Lifetimes
$R_\tau = \frac{1-B_e-B_\mu}{B_e}$	$\tau_\tau = \tau_\mu \cdot \left(\frac{m_\mu}{m_\tau}\right)^5 \cdot B_e$ $B_\mu = 0.973 \cdot B_e$
$R^{\mathrm{BR}}_\tau = 3.61 \pm 0.15$	$R^{\mathrm{lifetime}}_\tau = 3.60 \pm 0.29$
$R^{\mathrm{avg}}_\tau = 3.61 \pm 0.13$	

Yielding α_s at the τ mass m_τ, and extrapolating to m_Z:

$\alpha_s(m_\tau) = 0.35 \pm 0.06(expt.) \pm 0.03(th.)$
$\alpha_s(m_Z) = 0.121 \pm 0.006(expt.) \pm 0.003(th.)$

Note the incredible shrinking error.

L3 α_s results from event shape, R_τ, R_Z

Event shape fits – primarily theory limited

$\sqrt{s}$ (GeV)	α_s ($\sqrt{s}$)	Evolved α_s (m_Z)
41.2	$0.140 \pm 0.006 \pm 0.011$	0.122 ± 0.005
55.3	$0.126 \pm 0.007 \pm 0.010$	0.117 ± 0.006
65.4	$0.134 \pm 0.006 \pm 0.009$	0.127 ± 0.005
75.7	$0.121 \pm 0.006 \pm 0.009$	0.118 ± 0.006
82.3	$0.120 \pm 0.006 \pm 0.009$	0.118 ± 0.006
85.1	$0.116 \pm 0.007 \pm 0.008$	0.115 ± 0.007
91.2	$0.122 \pm 0.002 \pm 0.007$	0.122 ± 0.002
133.0	$0.107 \pm 0.005 \pm 0.006$	0.113 ± 0.006
161.0	$0.103 \pm 0.005 \pm 0.005$	0.111 ± 0.006
172.0	$0.104 \pm 0.006 \pm 0.005$	0.114 ± 0.007
183.0	$0.095 \pm 0.005 \pm 0.005$	0.104 ± 0.006

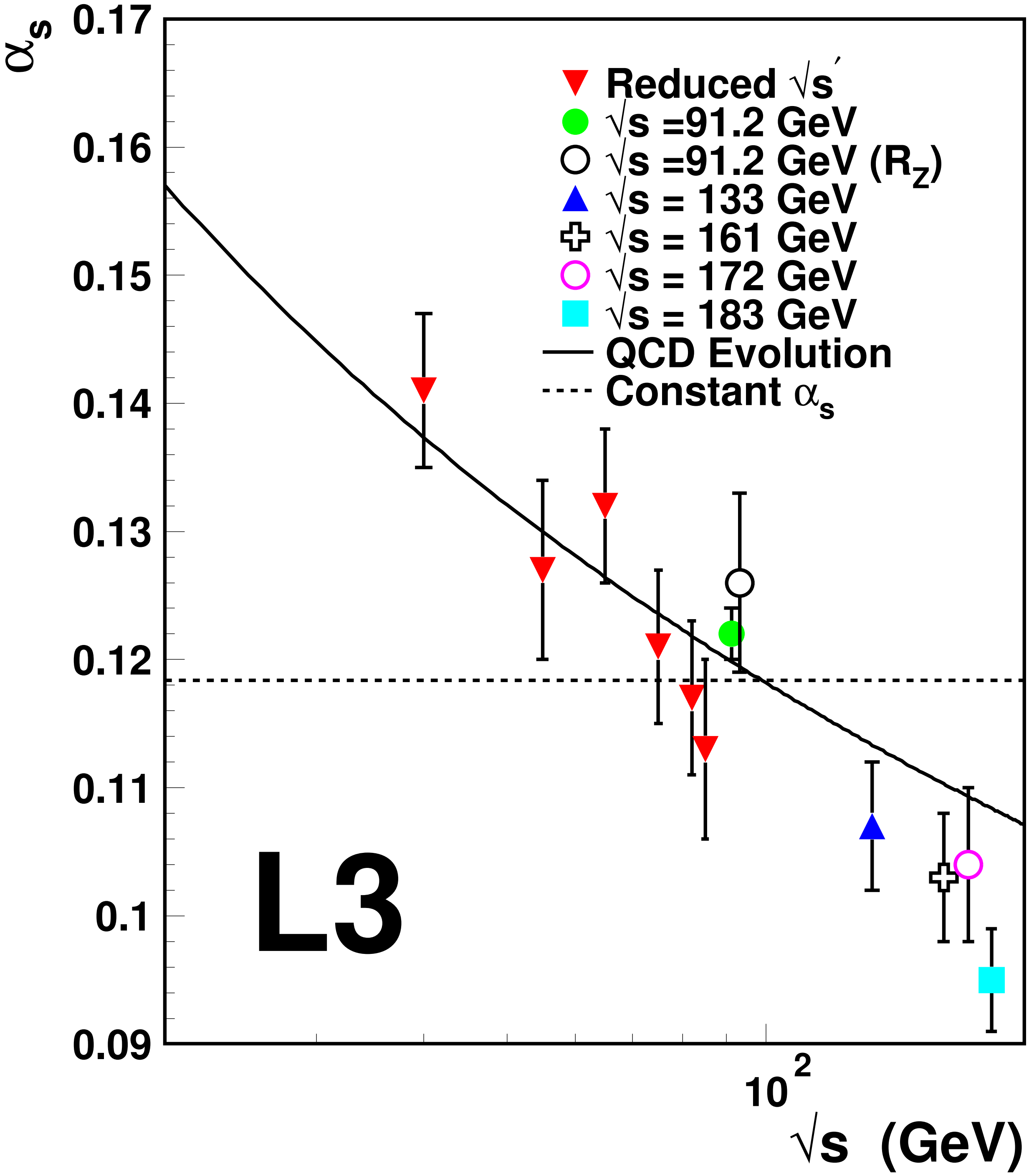
R_τ – Statistics limited

1.7769	$0.35 \pm 0.06 \pm 0.03$	$0.121 \pm 0.006 \pm 0.003$

R_Z – Statistics limited

91.2	$0.126 \pm 0.007 \pm 0.002$	-

Experimental and theoretical errors listed.



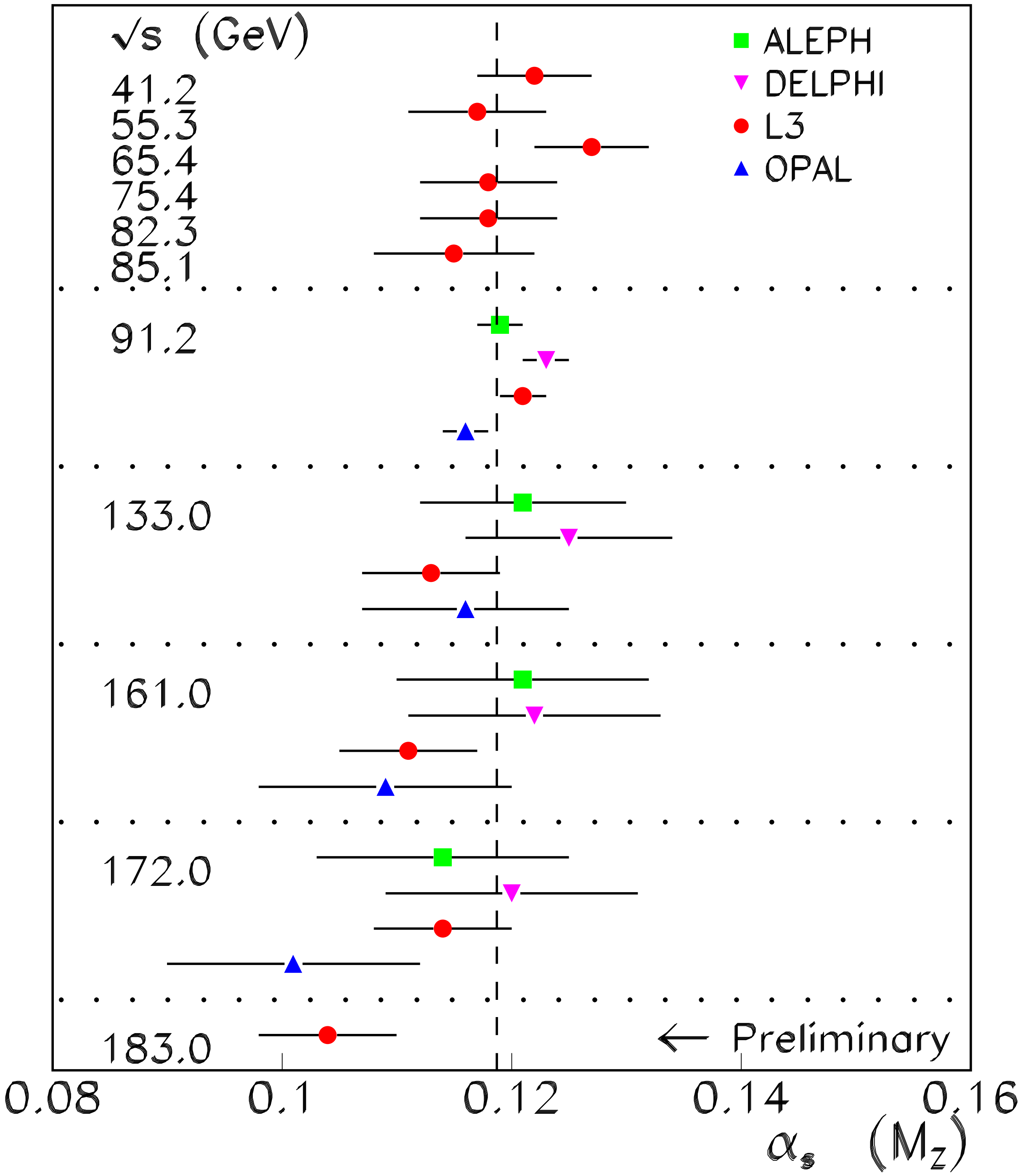
- Fit to the 3-loop QCD evolution equation using event shape results (experimental errors only) gives:

$$\alpha_s(m_Z) = 0.1205 \pm 0.0016 \text{ (expt)} \pm 0.0066 \text{ (theory)}$$
$$\chi^2 = 12.6 \text{ for } 10 \text{ DF}, \text{ CL } = 0.25$$

- Fit to constant α_s gives:

$$\chi^2 = 47.5 \text{ for } 10 \text{ DF}, \text{ CL } = 8 \times 10^{-7}$$

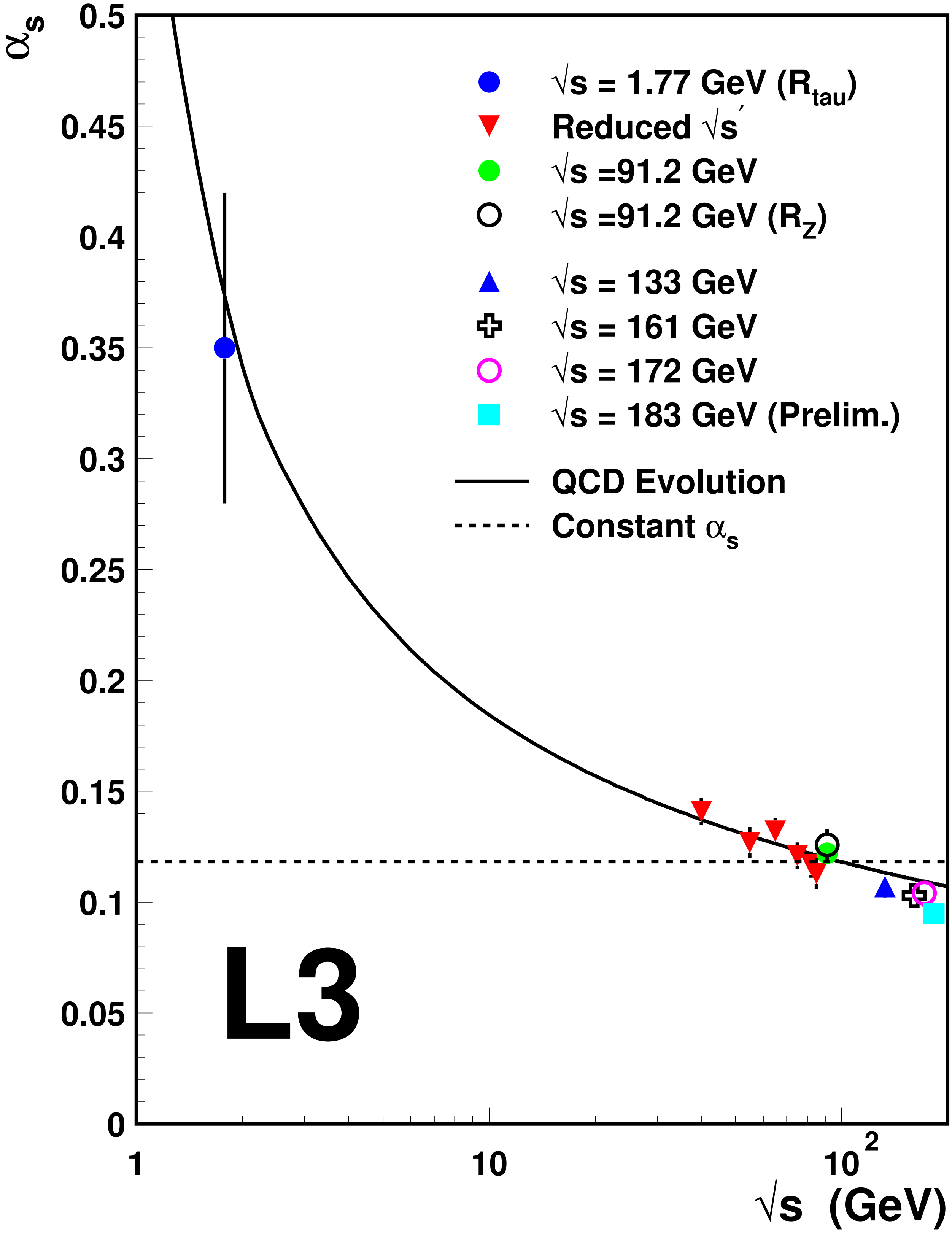
- DELPHI and OPAL have performed similar analyses for Z-peak and LEP 2 data
- ALEPH measured α_s from differential two jet rate



A combined fit to LEP measurements yields:

$$\boxed{\alpha_s(m_Z) \;=\; 0.1188 \;\pm\; 0.0009\;(\text{exp})}$$

α_s from the 3 methods: event shape, R_Z, R_τ.



Convincing demonstration of QCD prediction of α_s evolution.

- α_s measurements by L3: $m_\tau \leq \sqrt{s} \leq 183$ GeV
- QCD energy evolution of α_s demonstrated convincingly

- R_τ, R_Z statistics limited (low sensitivity)
- $\sqrt{s} < m_Z$ event shape – "just" theory limited
- $\sqrt{s} = m_Z$ event shape – theory limited
- $\sqrt{s} > m_Z$ event shape –
  experimental uncertainties comparable to theory

L3 measures (from event shape only):

$$\boxed{\alpha_s(m_Z) = 0.1205 \pm 0.0016\ (\mathrm{exp.})\ \pm 0.0066\ (\mathrm{th.})}$$

Future prospects:

- Event shapes – "fully" combine LEP results (Summer '98)
- Clarify the $\approx 2\sigma$ low α_s for $\sqrt{s} > 172$ GeV
- R_Z – "finalisation" of LEP1 Electroweak results (during '98)