LEP Fest, Oct. 11, 2000
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An attempt to summarize 11 years of
QCD at LEP

> 200 journal pub.'s on hadronic physics
> 30 journal publications on 2γ physics

sorry: today, no...
- BE correlations
- Intermittency
- inclus. particle ID
- ... and lots of other interesting studies

Many thanks to:
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H. Stenzel
The LEP QCD WG
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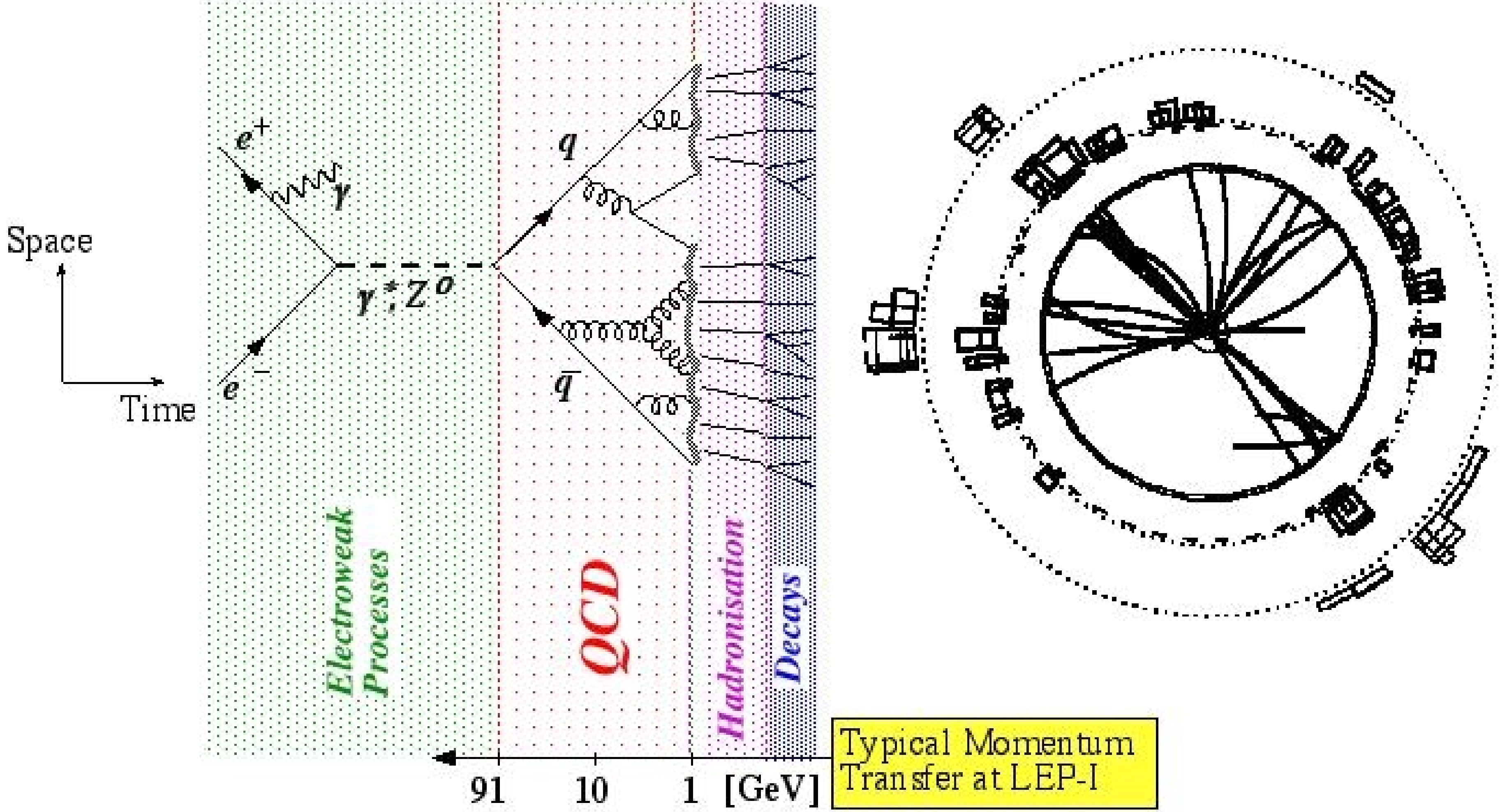
CERN
SL-Division
all who helped to make LEP a success

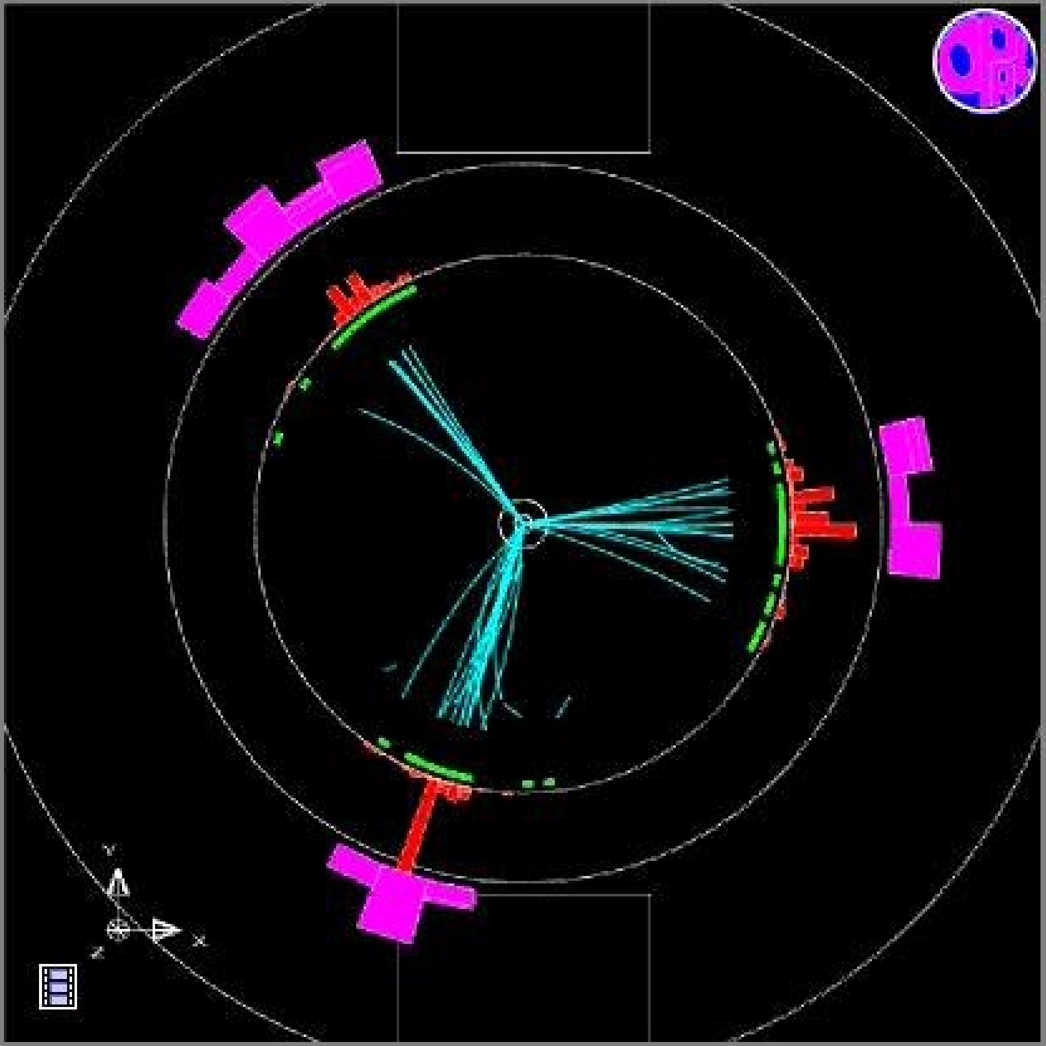
- status of QCD before and at the end of LEP
- hadronic events, event shapes, hadronisation
- measurements of α_s
- tests of asymptotic freedom
- non-Abelian gauge structure of QCD
- differences between quark- and gluon-jets
- gluon coherence; local parton-hadron duality
- power corrections
- scaling violations
- 2-photon physics

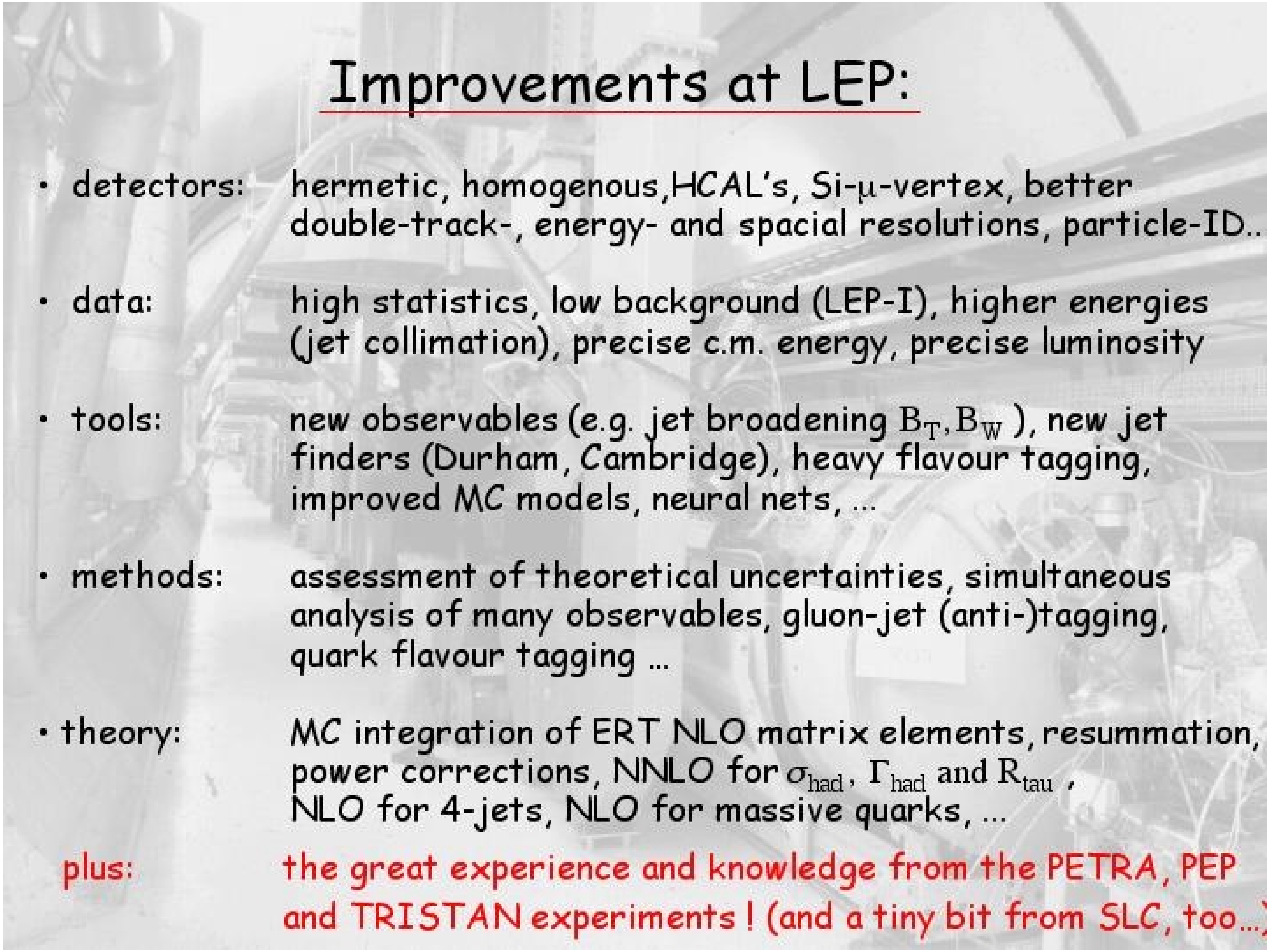
Anatomy of hadronic events in e^+e^- annihilation



- QCD: shower development calculated in perturbation theory (fixed order; (N)LLA)
- Hadronisation: phenomenological models of string-, cluster- or dipole fragmentation
- Decays: randomized according to experimental decay tables

Hadronic event recorded at 205.4 GeV c.m.



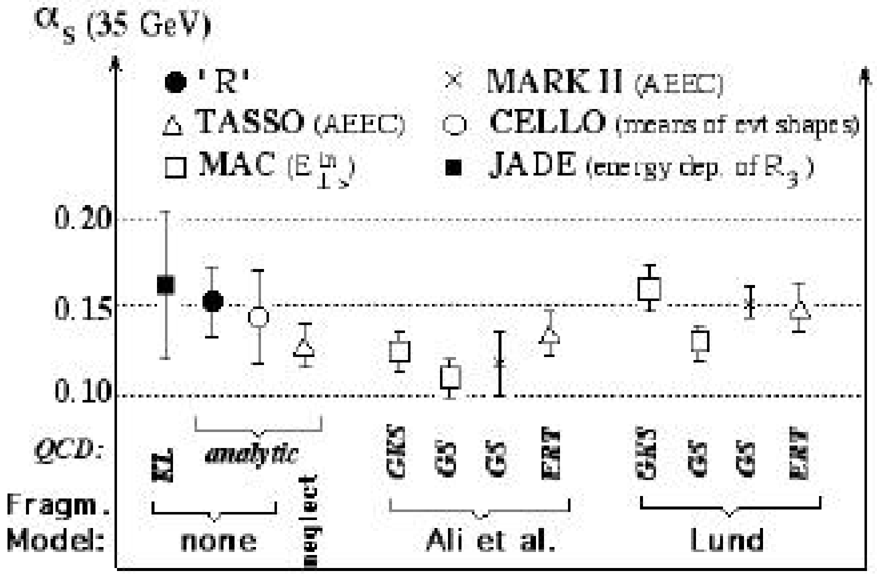


Improvements at LEP:

• detectors:	hermetic, homogenous,HCAL's, Si-μ-vertex, better double-track-, energy- and spacial resolutions, particle-ID..
• data:	high statistics, low background (LEP-I), higher energies (jet collimation), precise c.m. energy, precise luminosity
• tools:	new observables (e.g. jet broadening $\mathrm{B_T}, \mathrm{B_W}$), new jet finders (Durham, Cambridge), heavy flavour tagging, improved MC models, neural nets, ...
• methods:	assessment of theoretical uncertainties, simultaneous analysis of many observables, gluon-jet (anti-)tagging, quark flavour tagging ...
• theory:	MC integration of ERT NLO matrix elements, resummation, power corrections, NNLO for σ_{had}, Γ_{had} and $\mathrm{R_{tau}}$, NLO for 4-jets, NLO for massive quarks, ...
plus:	the great experience and knowledge from the PETRA, PEP and TRISTAN experiments ! (and a tiny bit from SLC, too...)

α_s in e^+e^- annihilations

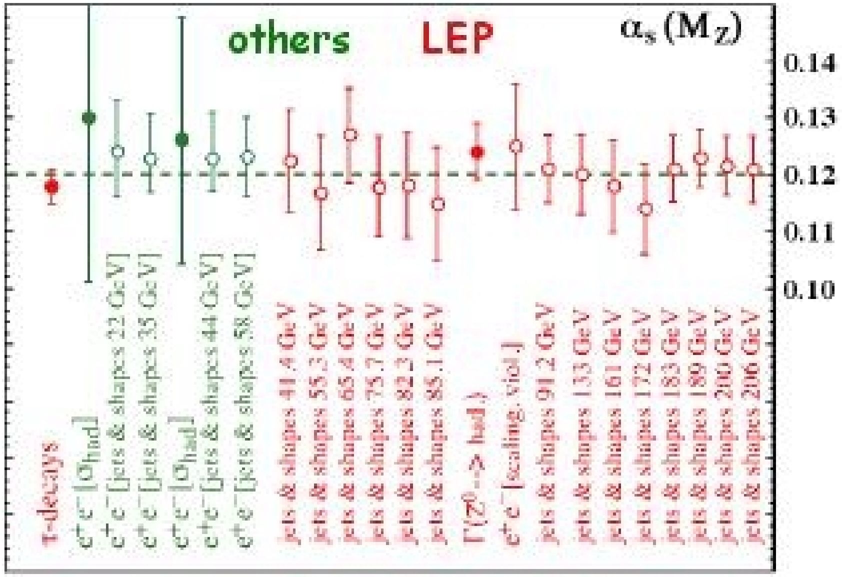
1989



$$\alpha_s(35\ \text{GeV}) = 0.14 \pm 0.02\ (\text{NLO})$$

$$\Rightarrow\ \alpha_s(M_Z) = 0.119 \pm 0.016\ (\text{NLO})$$

2000

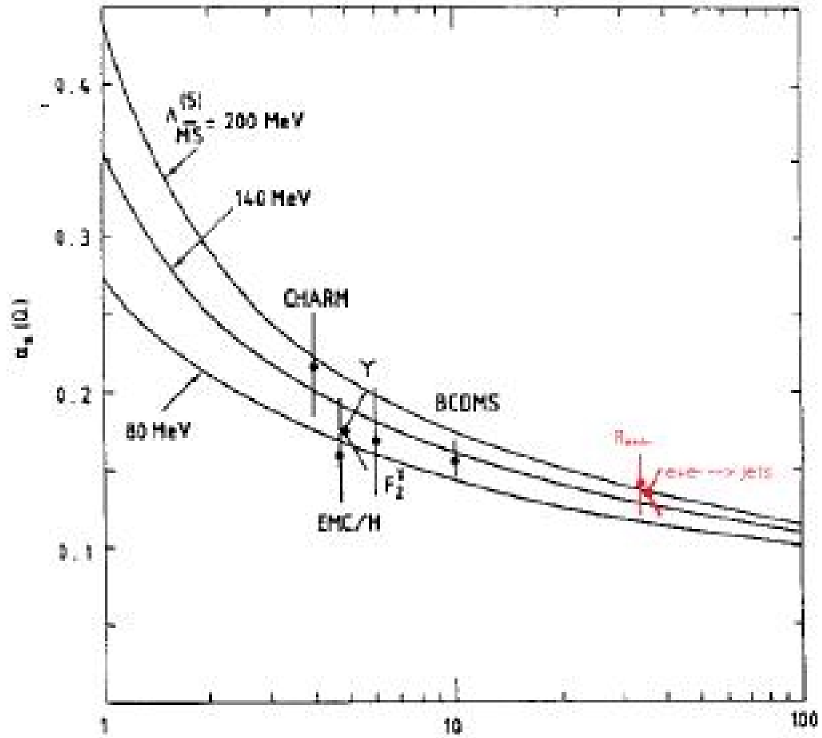


$$\alpha_s(M_Z) = 0.121 \pm 0.005\ (\text{res. NLO})$$

$$\alpha_s(M_Z) = 0.120 \pm 0.003\ (\text{NNLO})$$

World summary of α_s

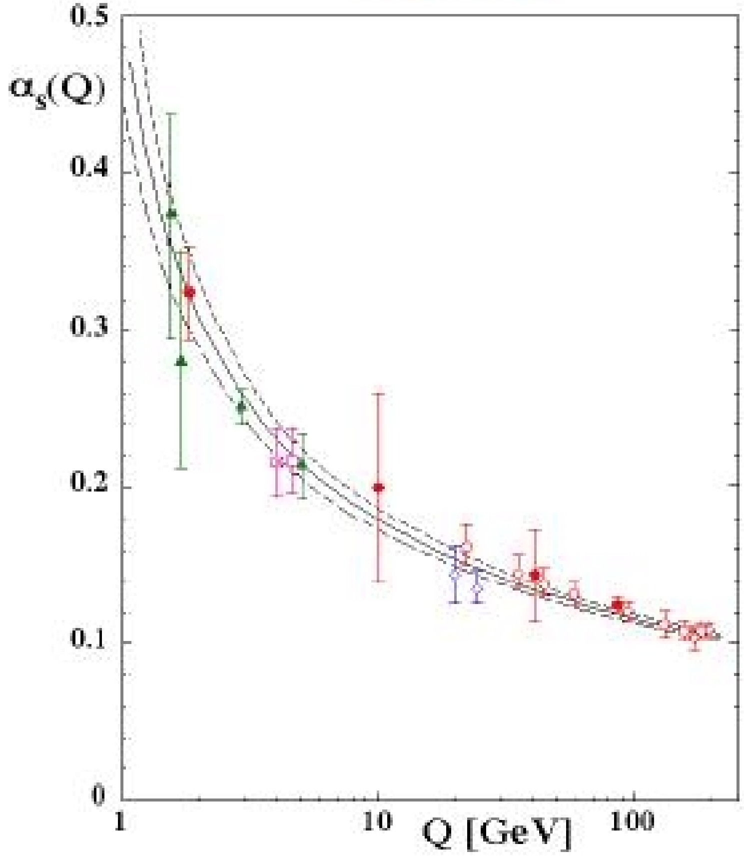
1989



$$\alpha_s(M_Z) = 0.110^{+0.006}_{-0.008} \text{ (NLO)}$$

G. Altarelli , Ann. Rev. Nucl. Part. Sci. 39, 1989

2000



$$\alpha_s(M_Z) = 0.1184 \pm 0.0031 \text{ (NNLO)}$$

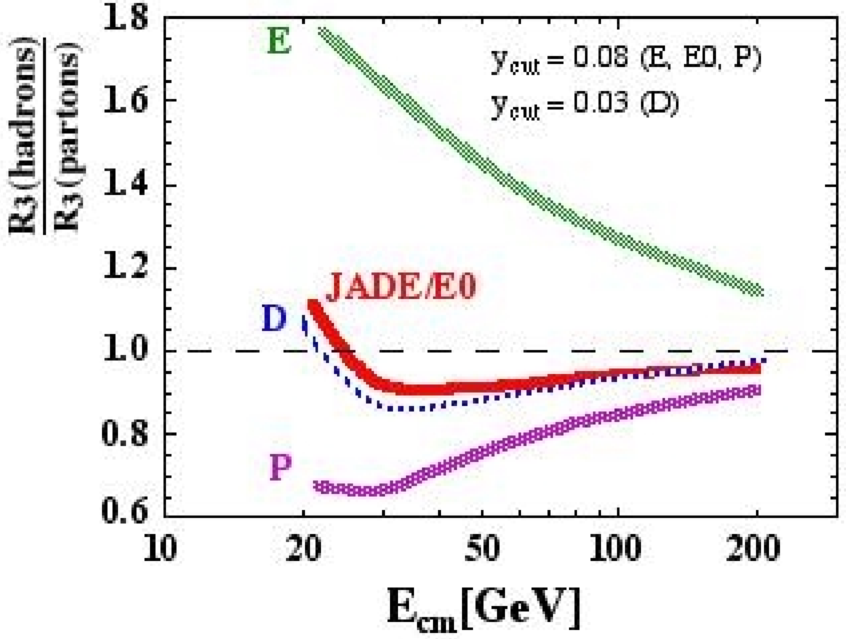
S. B. , J. Phys. G 26, 2000

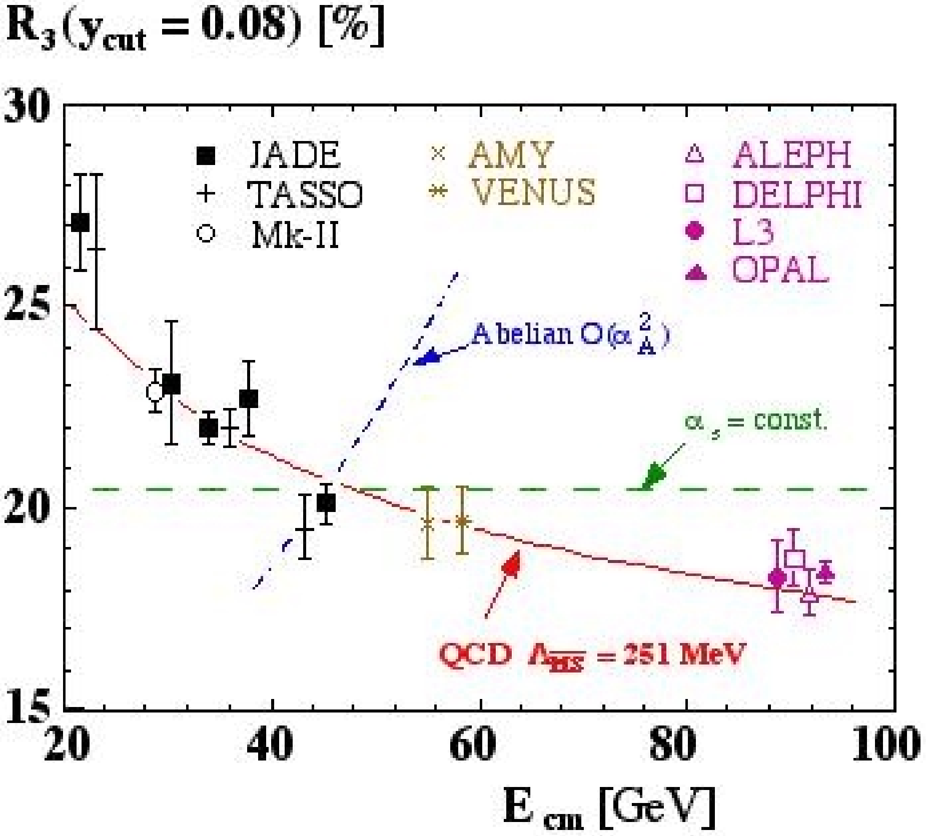
Asymptotic Freedom (running α_s)

energy dependence of 3-jet production rates (R_3):

$$R_3 = C_1(y_{cut}) \cdot \alpha_s(\mu) + C_2(y_{cut}) \cdot \alpha_s^2(\mu)$$

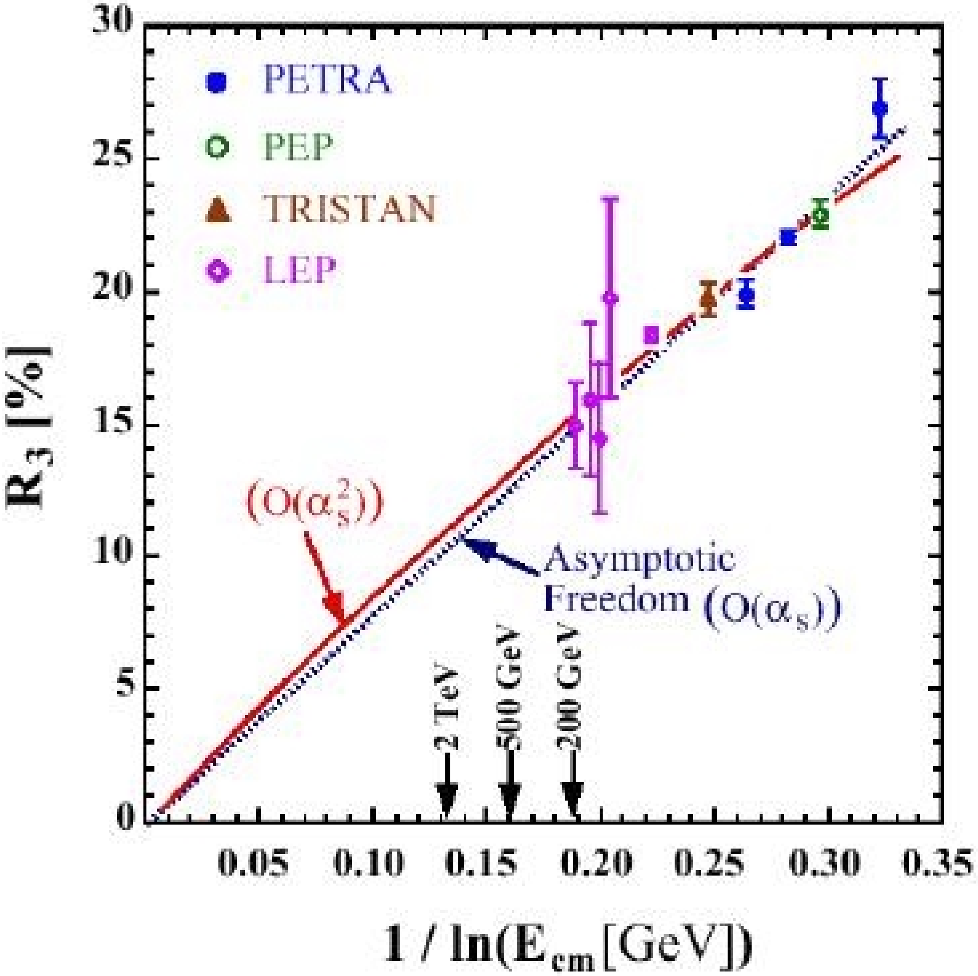
JADE Jet finder:
small and (almost) energy independent
hadronisation corrections:





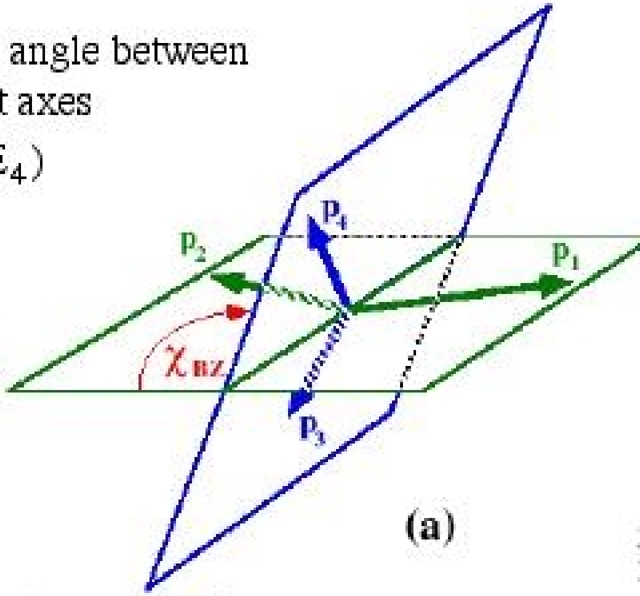
Asymptotic Freedom from jet rates

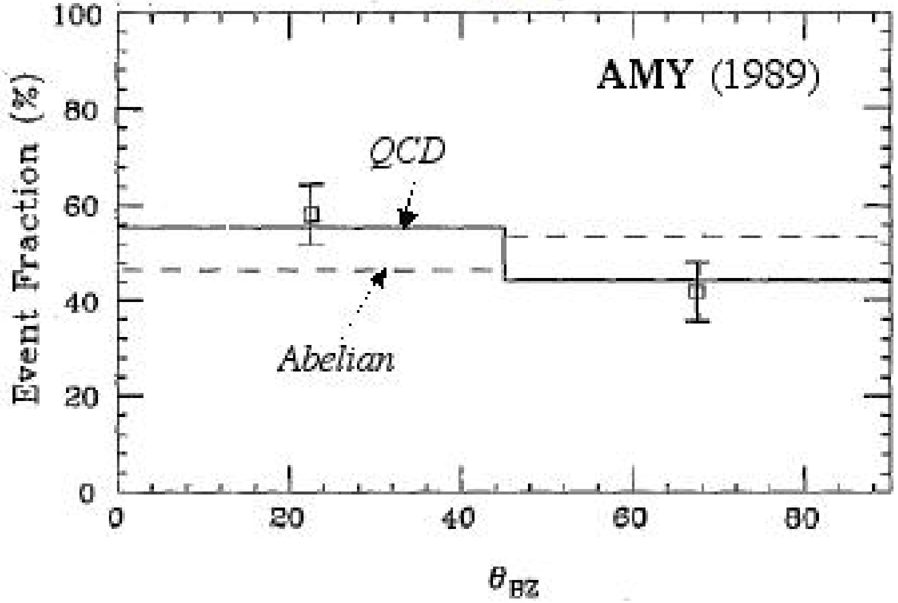
$$R_3 \equiv \frac{\sigma_{3-\mathrm{jet}}}{\sigma_{\mathrm{tot}}} \propto \alpha_s(E_{\mathrm{cm}}) \propto \frac{1}{\ln E_{\mathrm{cm}}}$$

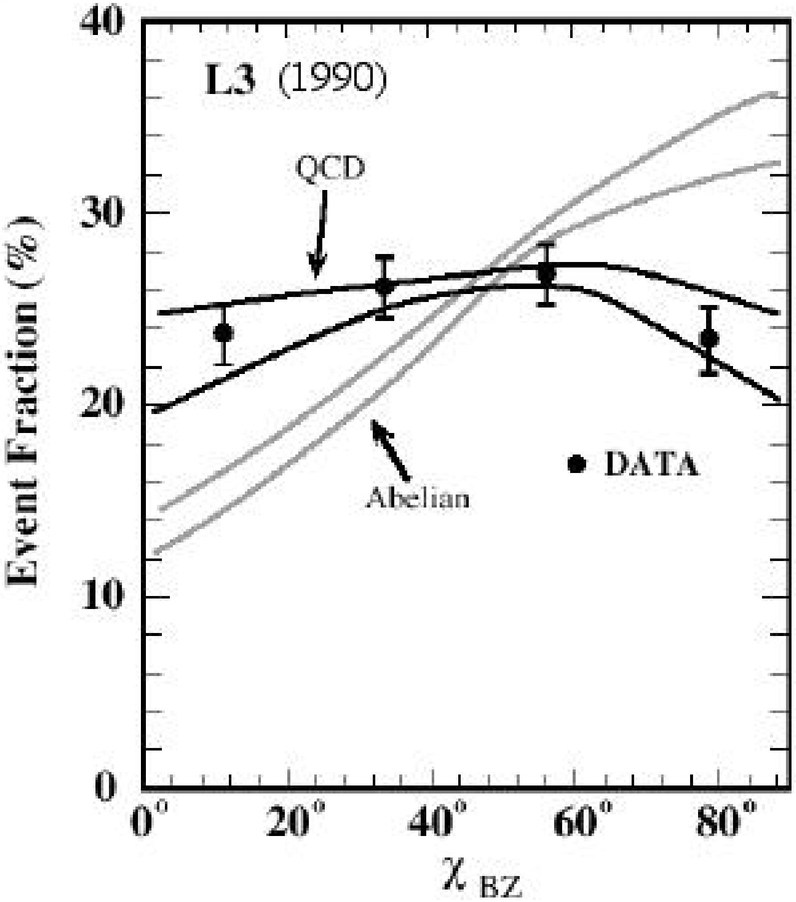


Non-Abelian gauge structure from 4-jet events

Bengtson-Zerwas angle between energy-ordered jet axes
($E_1 \geq E_2 \geq E_3 \geq E_4$)



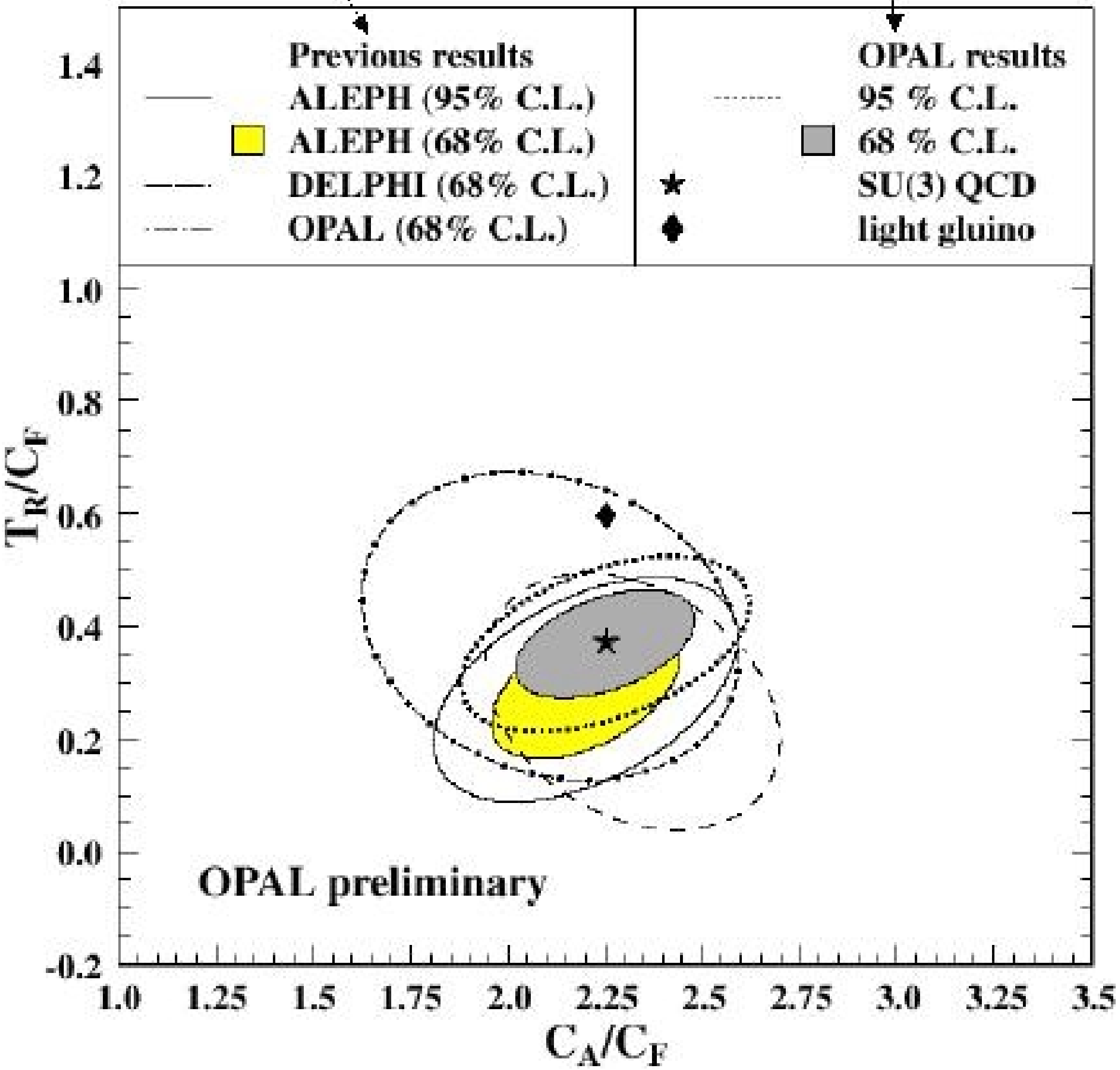




Non-Abelian gauge structure from 4-jet events

4-jets in LO QCD

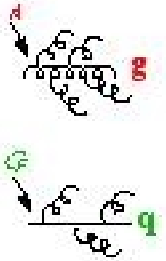
4-jets in NLO QCD



Differences between q- and g-jets

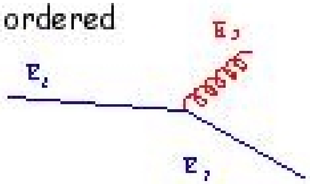
"naive" QCD-expectation:

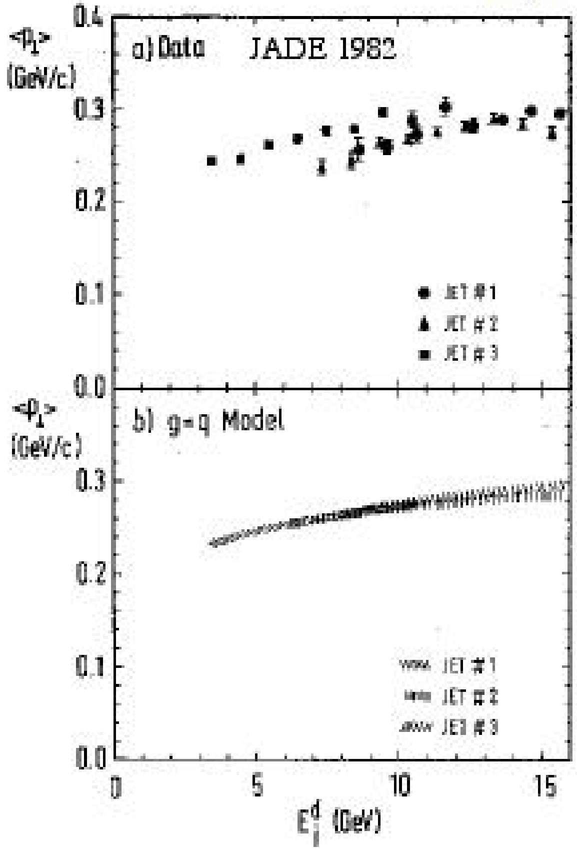
(i.e. at ∞ energies, in leading order perturbation theory)



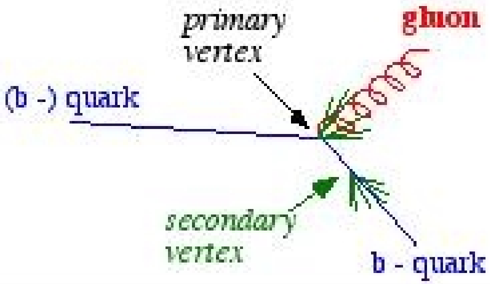
- Gluonjets are 'broader' than Quarkjets
- particles in Gluonjets are 'softer'
  (i.e. they are less energetic)
- $\frac{N_{had}\,(g\text{-jet})}{N_{had}\,(q\text{-jet})} \approx \frac{C_A}{C_F} = \frac{3}{4/3} = \frac{9}{4}$

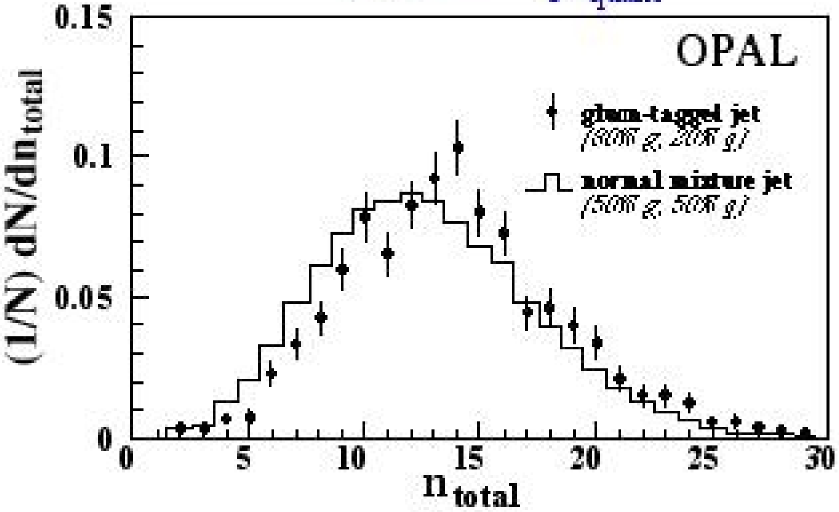
JADE 1982: Energy ordered 3-jet events ($E_1 \geq E_2 \geq E_3$)





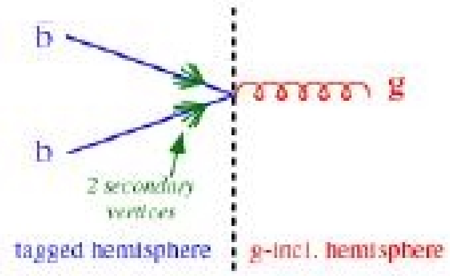
OPAL 1991: antitagging of g-jets in symmetric 3-jet events



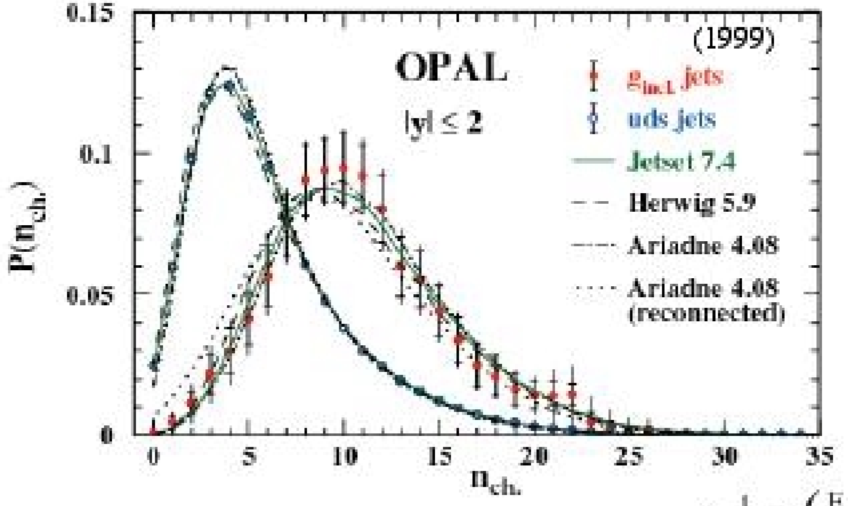


Differences between q- and g-jets

g recoiling vs. $q\bar{q}$: direct comparison with QCD prediction



- compare g-tagged to uds event hemispheres
- $\langle E_g \rangle \approx 42$ GeV



$y = \frac{1}{2}\ \ln\left(\frac{E + p_{\parallel}}{E - p_{\parallel}}\right)$

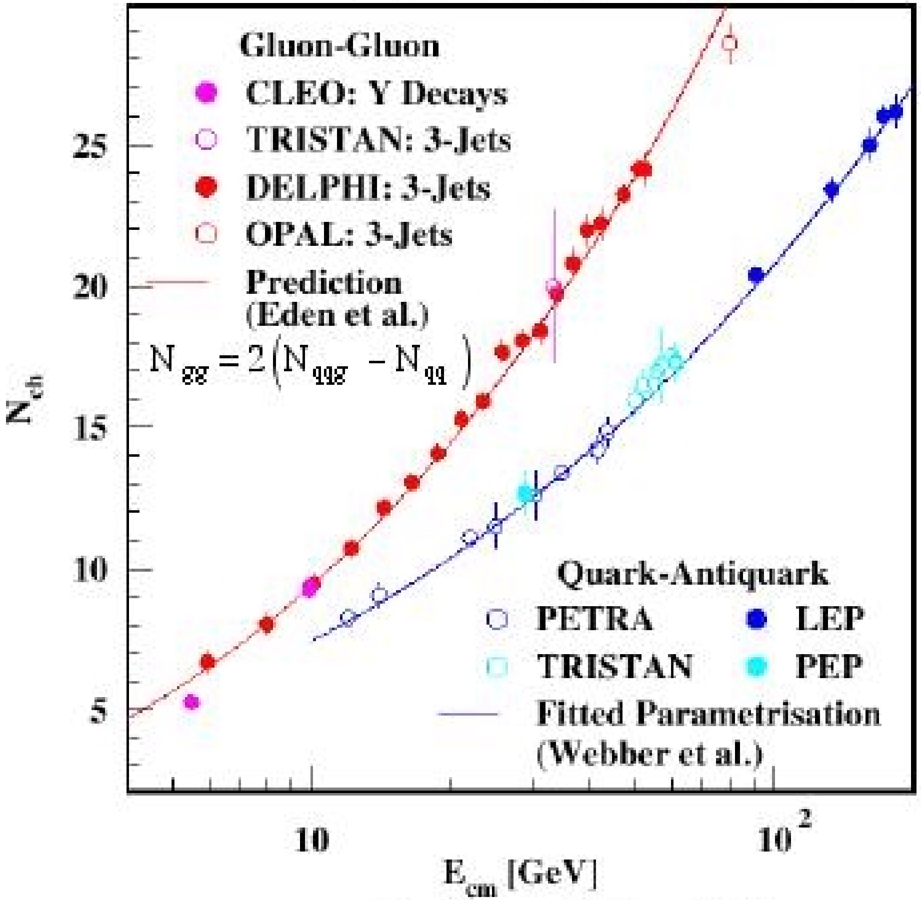
$$r_{ch} = \frac{n_{ch}(g_{incl.})}{n_{ch}(uds)} = 1.509 \pm 0.022\ (\text{stat.}) \pm 0.046\ (\text{sys.}) \quad (\text{all } y)$$

$$= 1.815 \pm 0.038\ (\text{stat.}) \pm 0.062\ (\text{sys.}) \quad (|y|<2)$$

$$= 1.87 \pm 0.05\ (\text{stat.}) \pm 0.12\ (\text{sys.}) \quad (|y|<1)$$

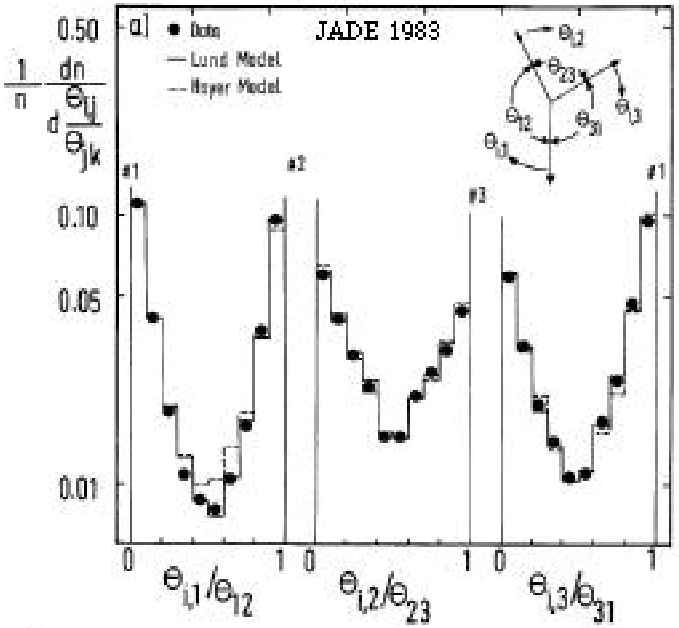
Remaining difference to r = 2.25 (asymptotic QCD prediction) due to finite energy effects

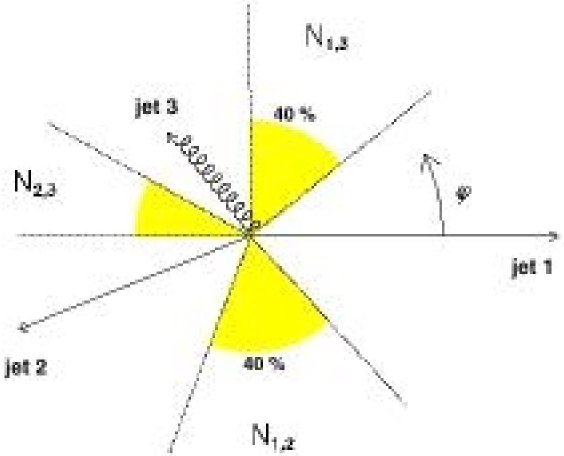
Delphi (2000): determination of N_{ch} for gg-events from symmetric 3-jet events and from multiplicities of average hadronic $(q\bar{q})$ events, based on theoretical predictions of Eden et al.



$$\Rightarrow C_A / C_F = 2.22 \pm 0.11$$

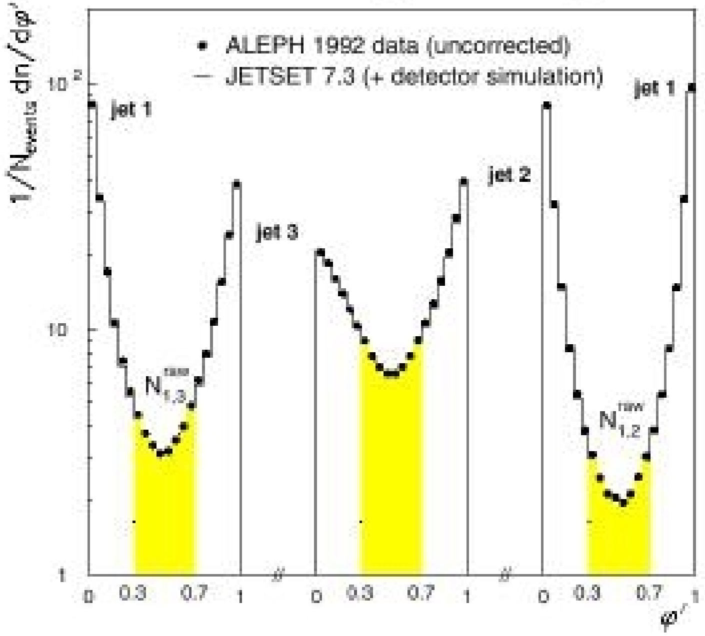
String-effect and hadronisation models

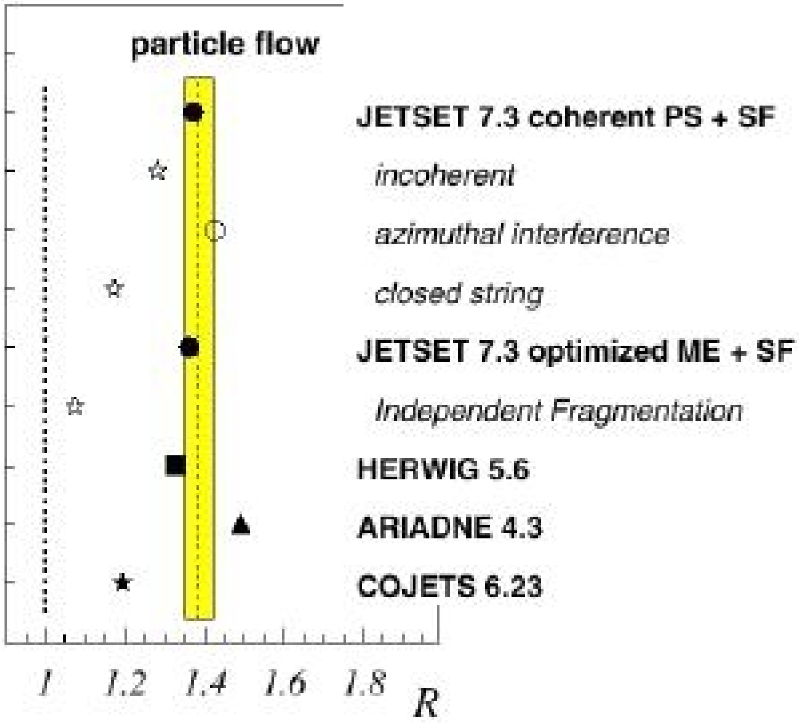




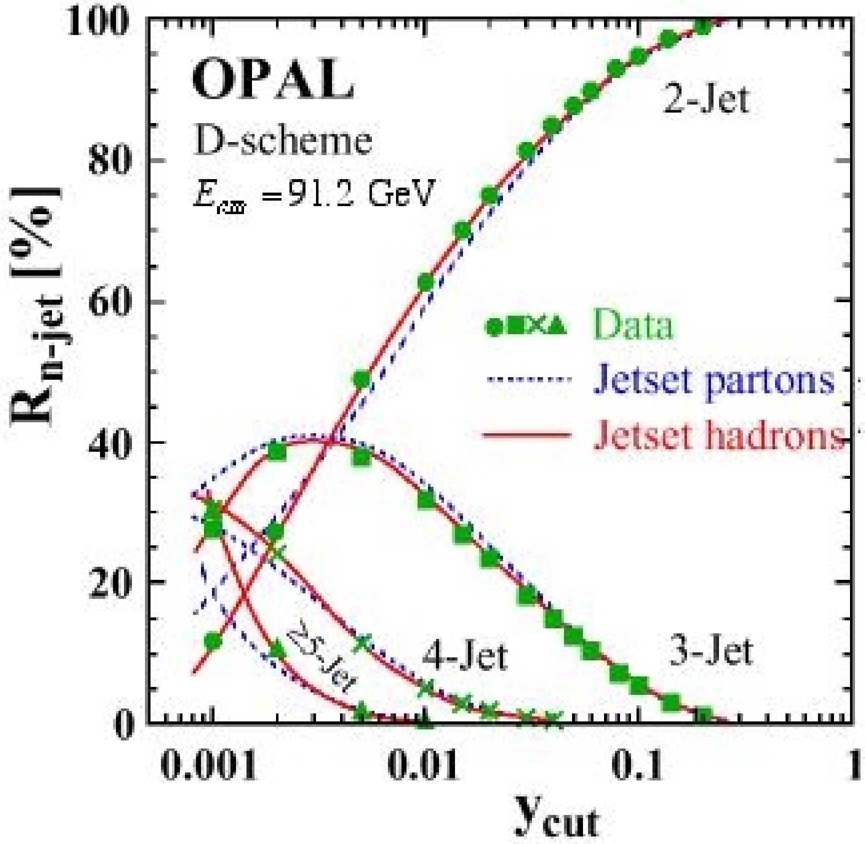
$R := N_{1,3} / N_{1,2}$ $(E_1 > E_2 > E_3)$

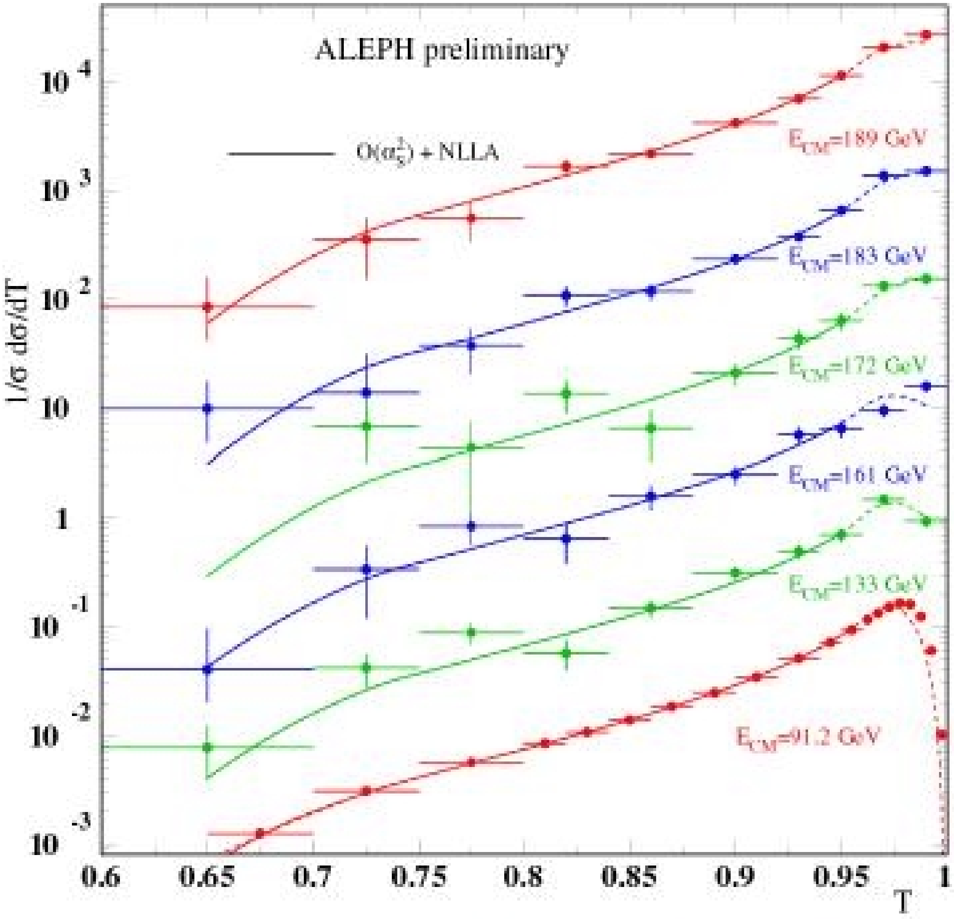
ALEPH





Jet production and hadronic event shapes





Pert. QCD

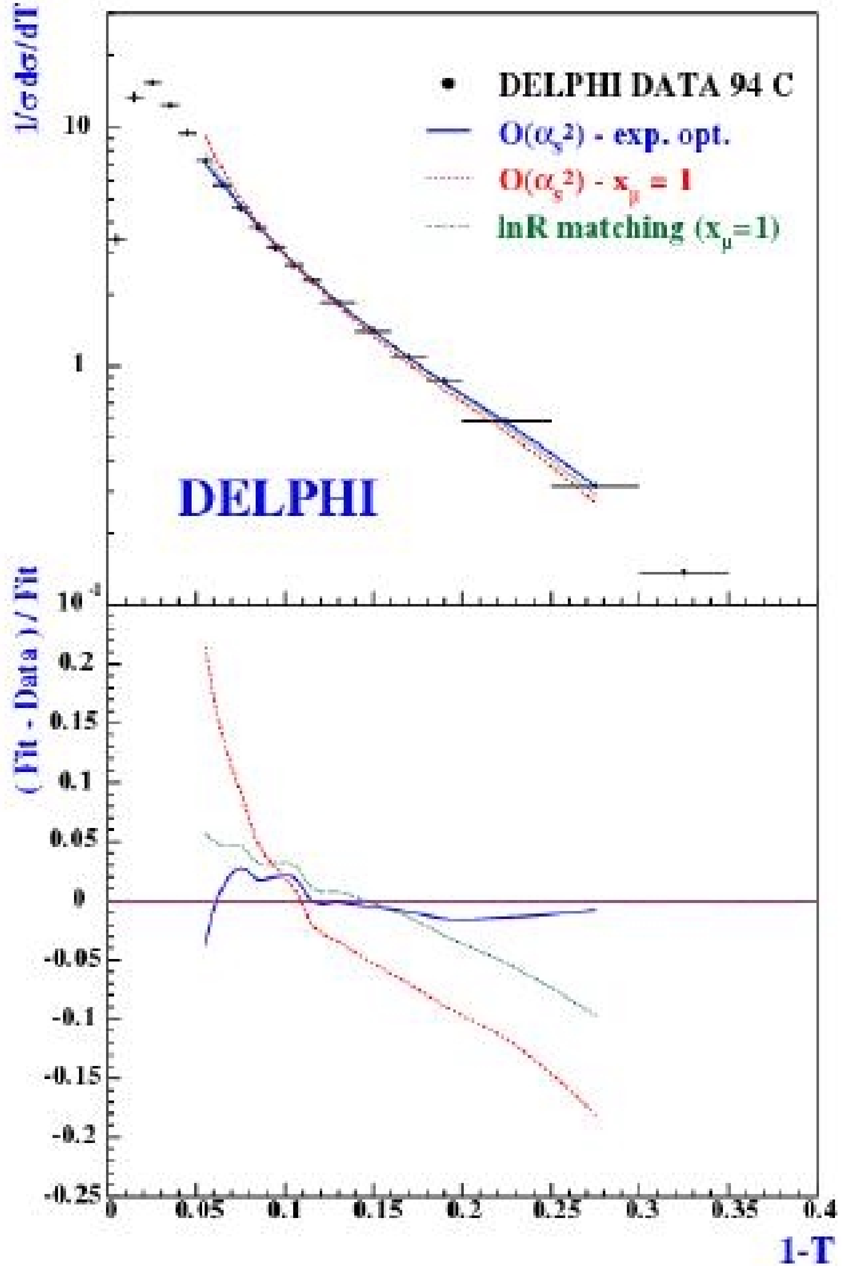
- in NLO: $\frac{1}{\sigma_0}\frac{d\sigma}{dy} = R_1(y)\,\alpha_s\left(\mu^2\right) + R_2\left(y,\frac{\mu^2}{Q^2}\right)\alpha_s^2\left(\mu^2\right)$

Ellis, Ross & Terrano (ERT);
Kunszt & Nason, Catani & Seymour

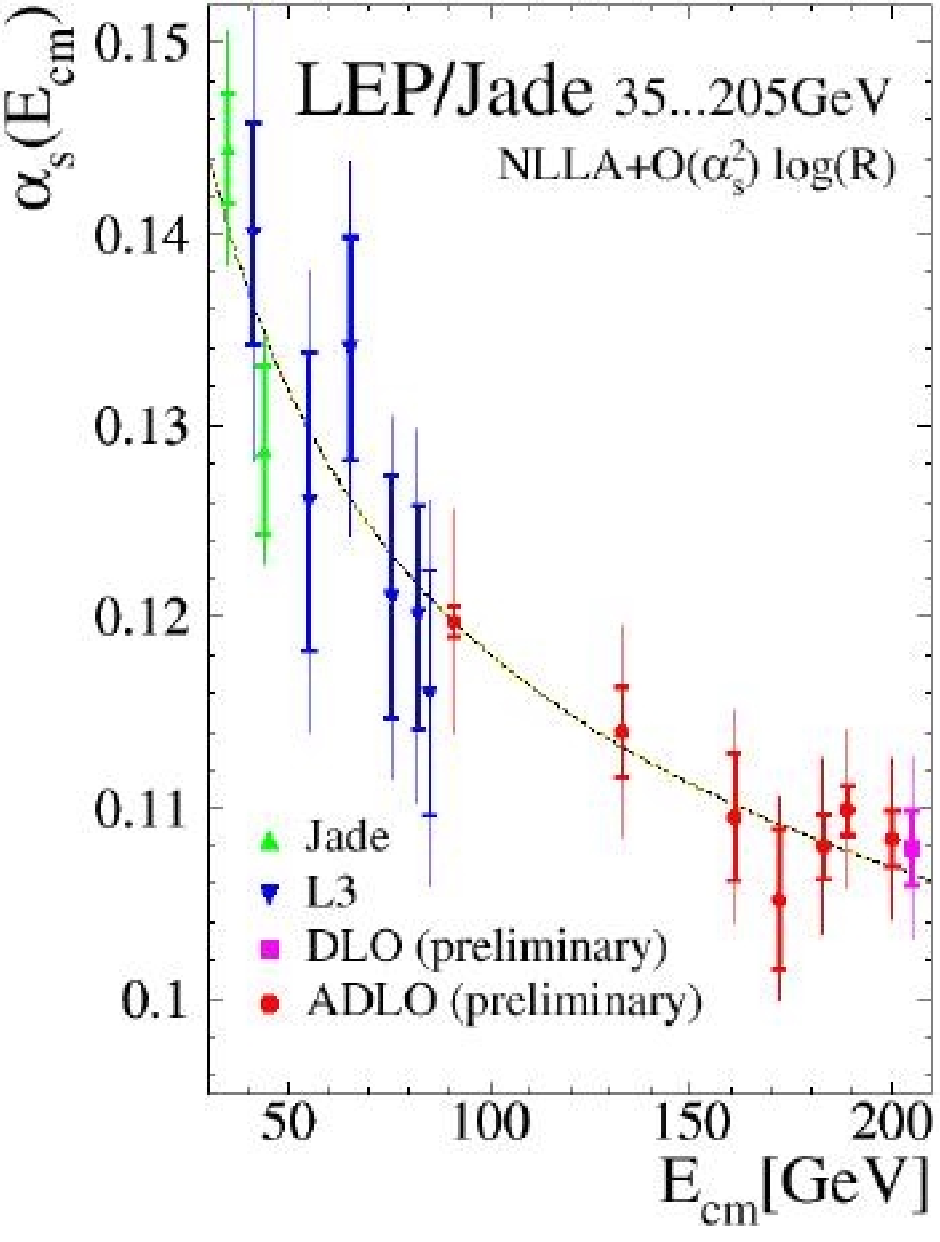
- plus resummation of leading and next-to-leading logarithms (NLLA) -> "matching schemes"

Catani, Trentadue, Turnock, Webber

Precision event shapes and pert. QCD



α_s from event shapes and jet rates



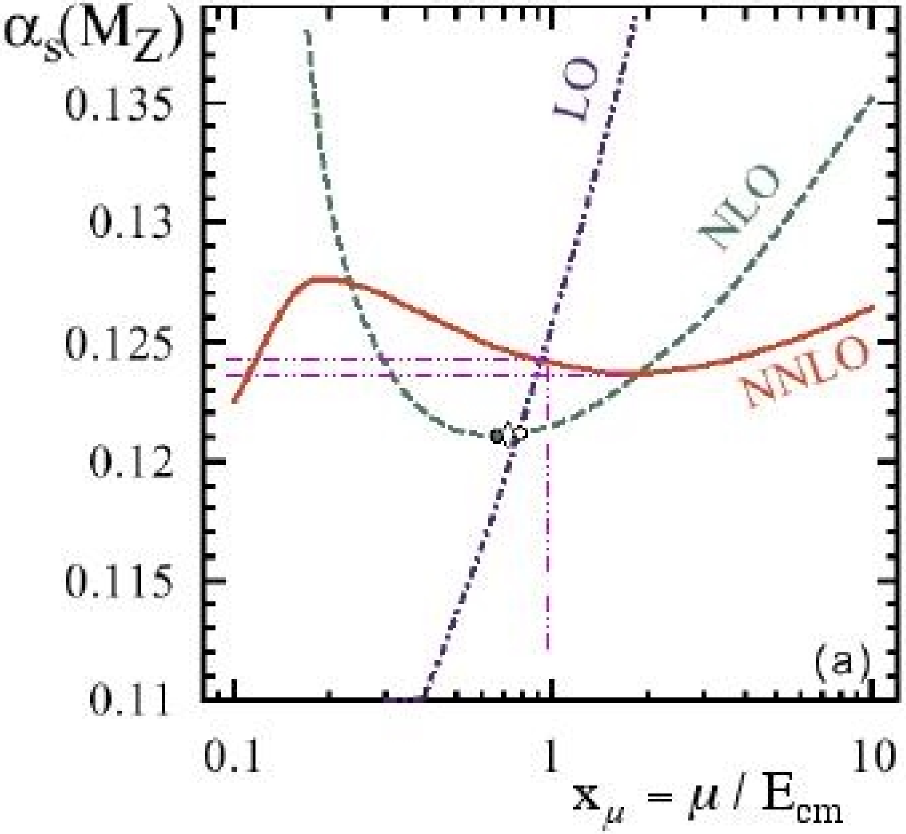
LEP QCD Working Group

Renormalisation scale dependence

$$R_Z = \frac{\Gamma(Z^0 \to \text{hadrons})}{\Gamma(Z^0 \to \text{leptons})} = 20.768 \pm 0.0024$$

$$R_Z = 19.934\left[1 + 1.045\frac{\alpha_s(\mu)}{\pi} + 0.94\left[\frac{\alpha_s(\mu)}{\pi}\right]^2 - 15\left[\frac{\alpha_s(\mu)}{\pi}\right]^3\right]$$

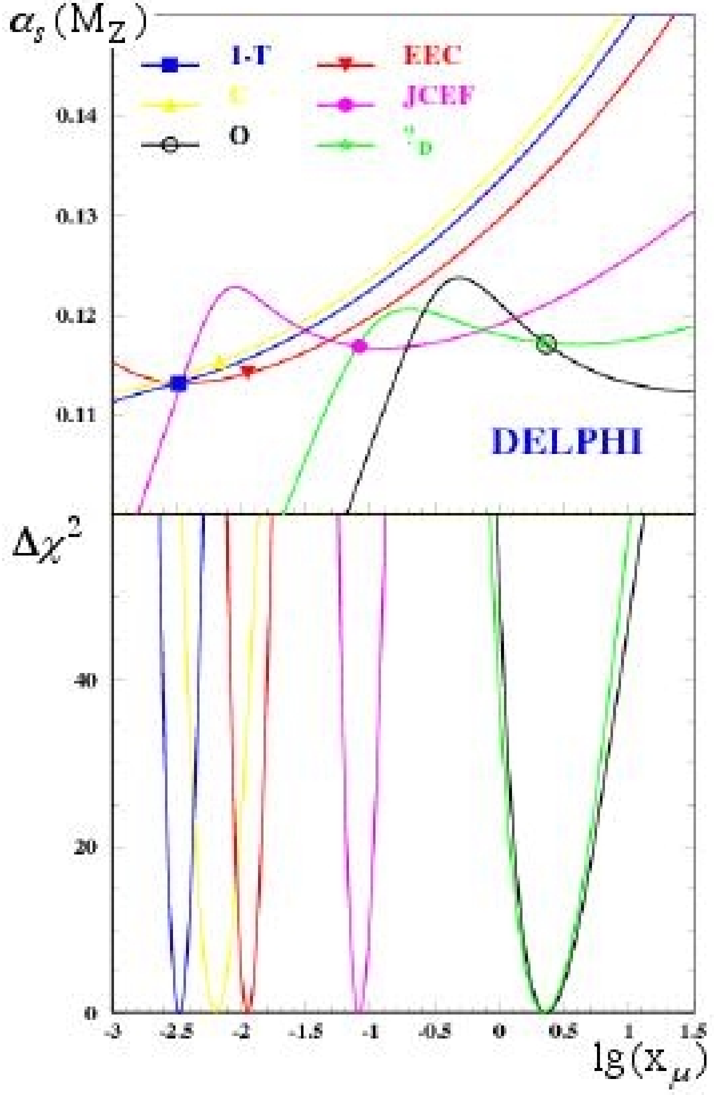
Larin, van Ritbergen,, Vermaseren, Chetyrkin, Tarasov, Kühn, Steinhauser, Hoang,……

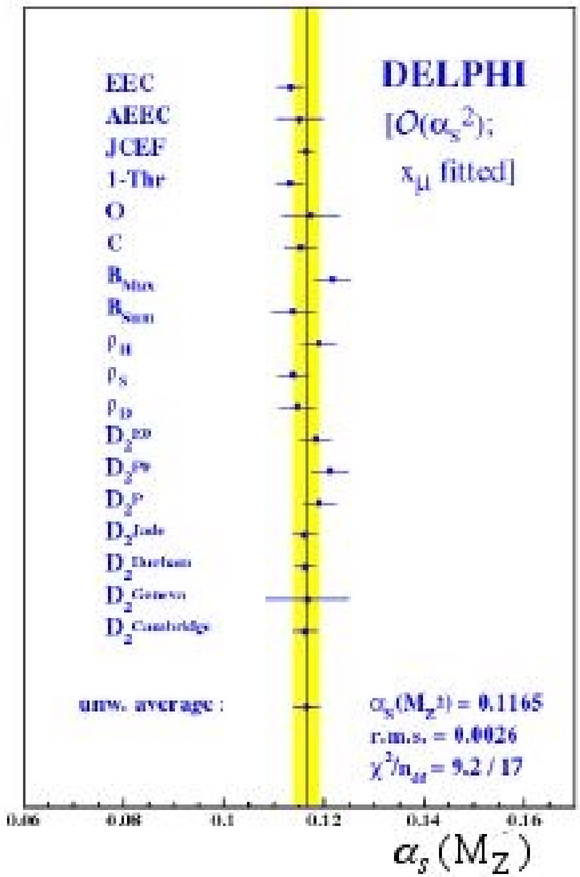


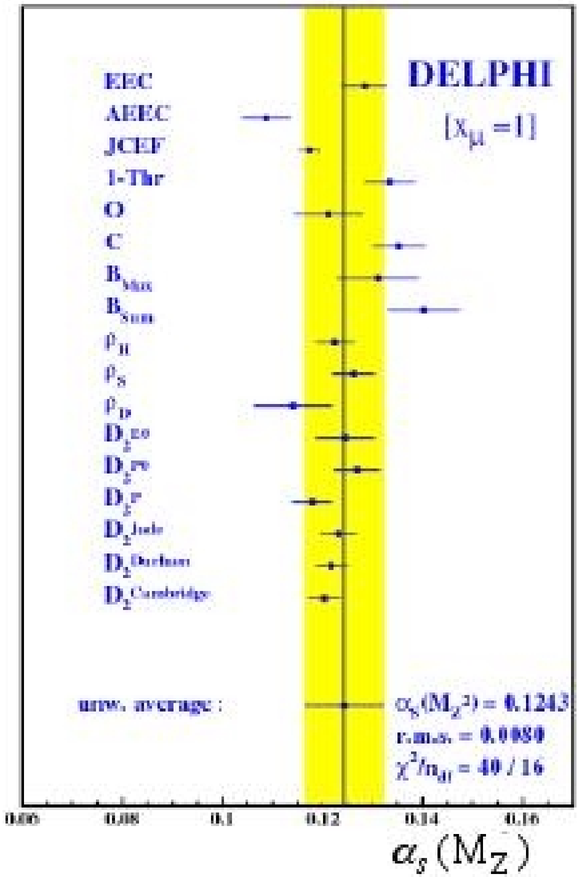
$$\Rightarrow \quad \alpha_s(M_Z) = 0.124 \pm 0.004 \ (\text{exp.}) \\ \pm 0.002 \ (M_H, M_{top}) \\ {}^{+0.003}_{-0.001} \ (\text{QCD})$$

Renormalisation scale dependence in NLO

(event shapes and jet rates)







- exp. scale otpimisation gives consistent results in NLO
- how to define the corresponding scale uncertainty?

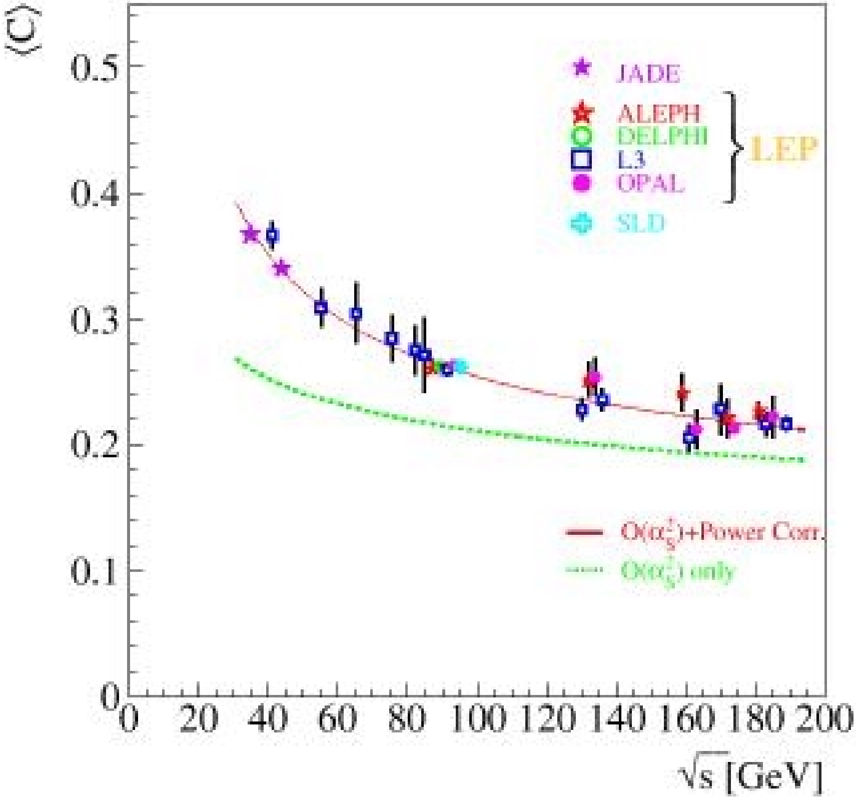
Power corrections

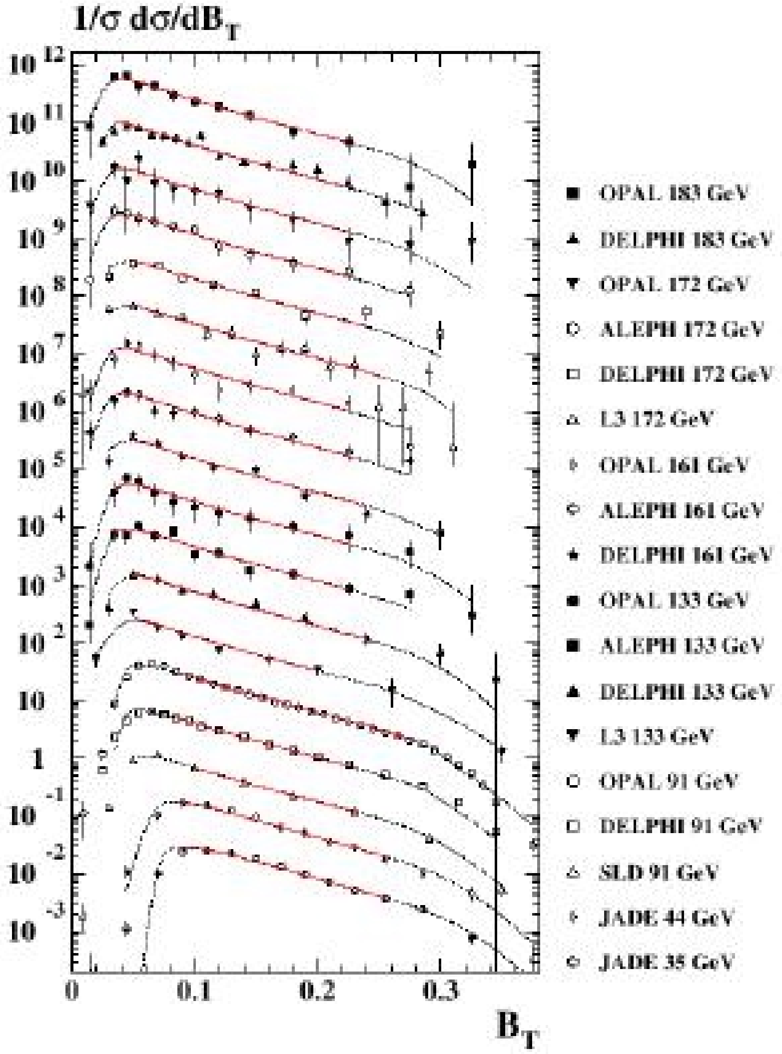
Analytical approach to approximate nonperturbative hadronisation effects , introducing a universal parameter

$$\alpha_0(\mu_i) = \frac{1}{\mu_i}\int_0^{\mu_I} \mathrm{d}k\ \alpha_s(k)$$

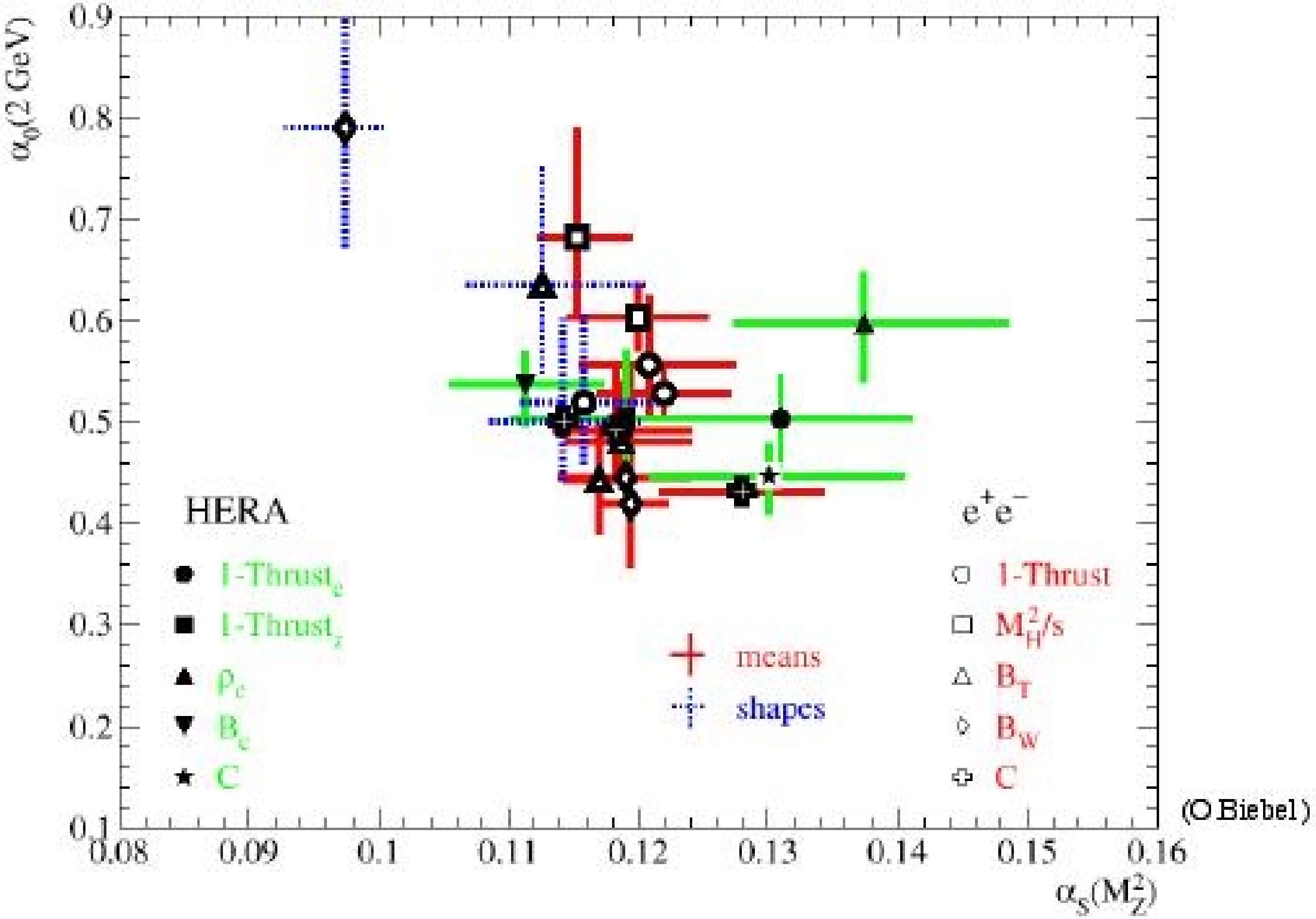
→ corrections ∝ $1/Q$, as alternative to hadronisation Models.

(Dokshitzer , Webber, Marchesini , Catani,...)



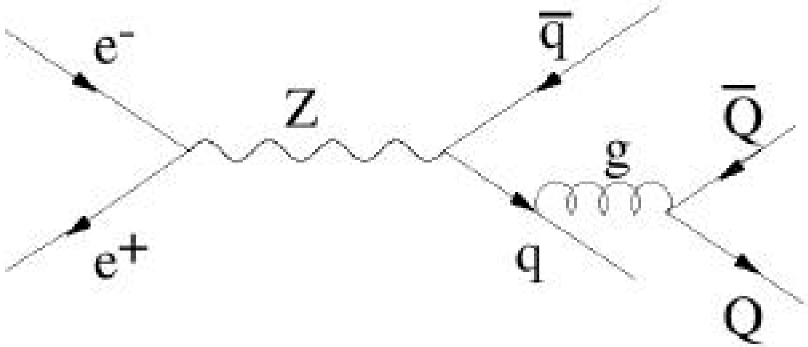


Power corrections



- $\alpha_s(M_z)$ from mean values ~ 0.120 (similar to analyses using hadronisation models)
- $\alpha_s(M_z)$ from differ. shapes ~ 0.112 (smaller than analyses using hadr. Models)
- α_0 ~ 0.5, appears to be "universal" within about 20%
- still a problem with calculation of B_W
- reasonable agreement with results from deep inelastic scattering (HERA)

Gluon splittings $\mathrm{g} \rightarrow \mathrm{b\bar{b}}$ and $\mathrm{g} \rightarrow \mathrm{c\bar{c}}$



$$g_{b\bar{b}} = \frac{\mathrm{BR(Z \rightarrow q\bar{q}b\bar{b})}}{\mathrm{BR(Z \rightarrow hadrons)}}$$

$$g_{4b} = \frac{\mathrm{BR(Z \rightarrow b\bar{b}b\bar{b})}}{\mathrm{BR(Z \rightarrow hadrons)}}$$

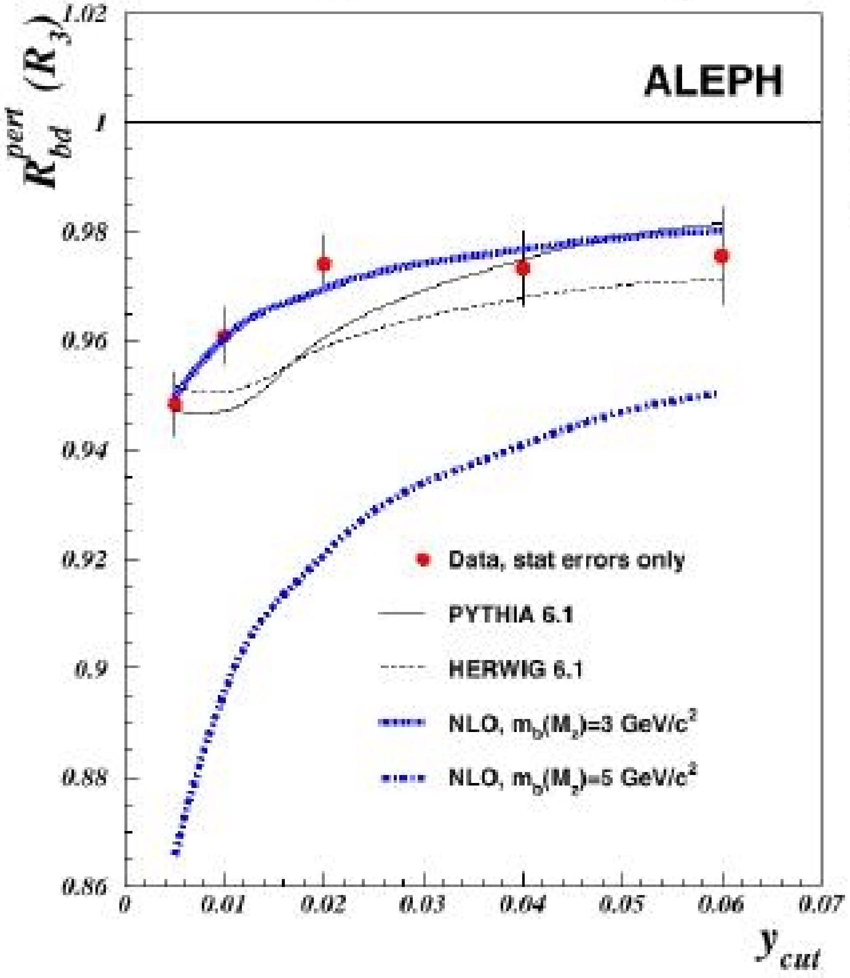
$$g_{c\bar{c}} = \frac{\mathrm{BR(Z \rightarrow q\bar{q}c\bar{c})}}{\mathrm{BR(Z \rightarrow hadrons)}}$$

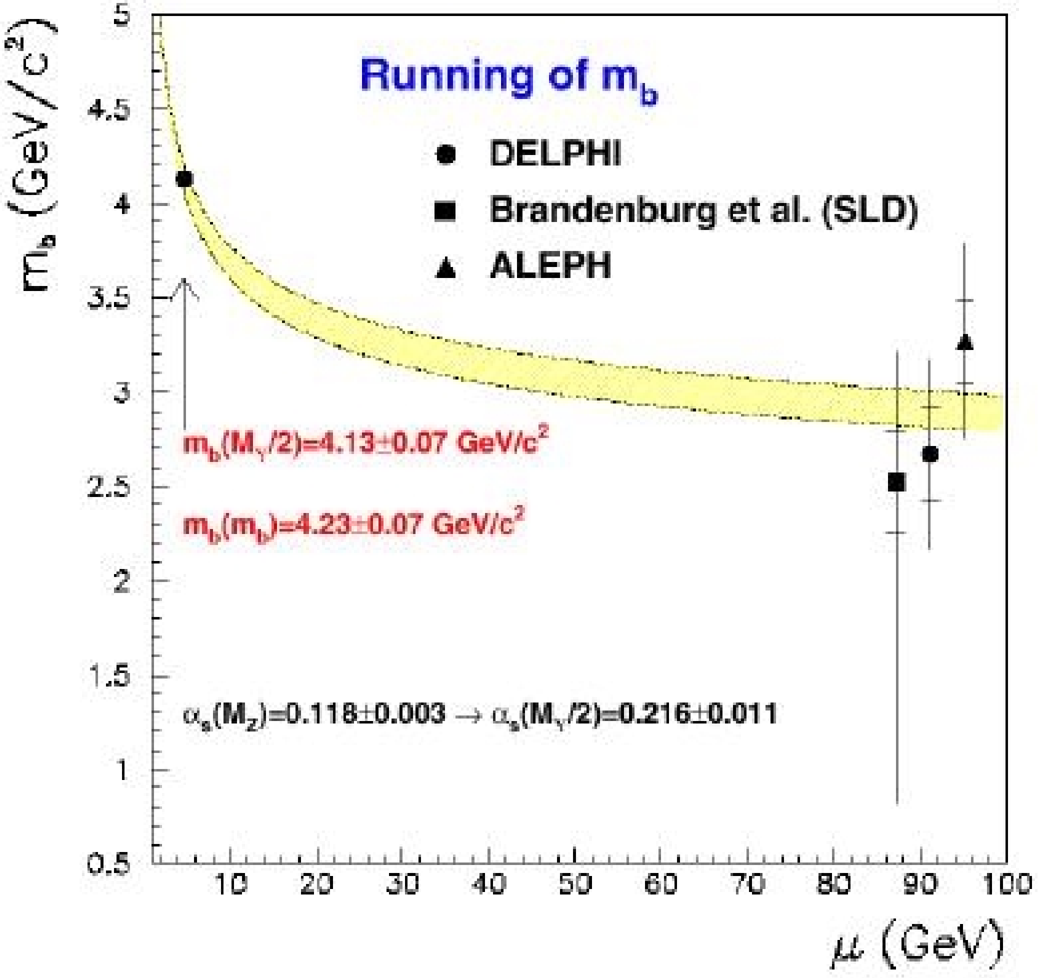
	$g_{b\bar{b}} \times 10^3$	$g_{4b} \times 10^4$	$g_{c\bar{c}} \times 10^2$
ALEPH	$\mathbf{2.77 \pm 0.42 \pm 0.57}$		$\mathbf{3.23 \pm 0.48 \pm 0.53}$
DELPHI	$\mathbf{3.3 \pm 1.0 \pm 0.8}$	$\mathbf{6.0 \pm 1.9 \pm 1.4}$	
L3			$\mathbf{2.45 \pm 0.29 \pm 0.53}$
OPAL	$\mathbf{3.07 \pm 0.53 \pm 0.97}$	$\mathbf{3.6 \pm 1.7 \pm 2.7}$	$\mathbf{3.20 \pm 0.21 \pm 0.38}$
SLD	$\mathbf{2.84 \pm 0.61 \pm 0.59}$		
Theory	**1.8-2.9**	**3.2-5.2**	**1.3-2.0**

(H. Stenzel)

Running b-quark mass: $m_b(M_Z)$

R_b: ratio of 3 - jet rates of b - and light quark events

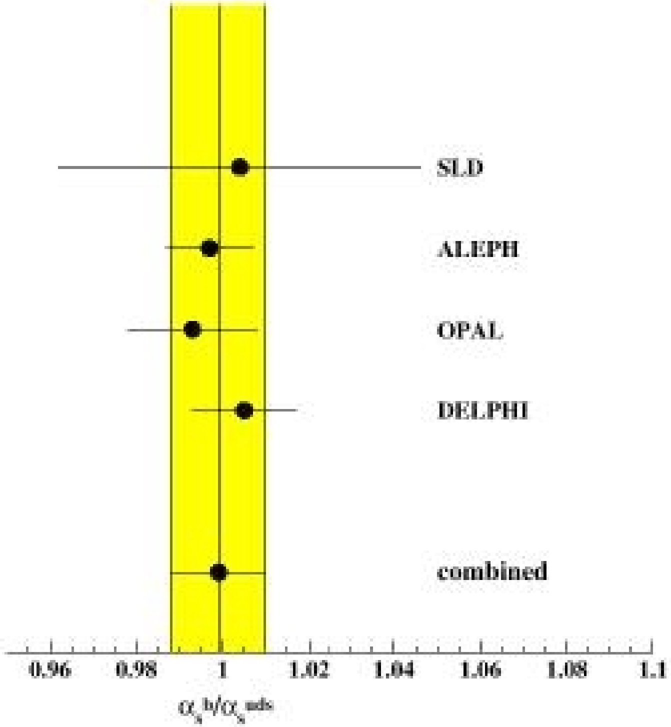




ALEPH: $m_b(M_Z) = 3.27 \pm 0.52$ GeV

DELPHI: $m_b(M_Z) = 2.61 \pm 0.54$ GeV

Flavour independence of α_s



(H. Stenzel)

$$\alpha_s^b / \alpha_s^{uds} = 0.999 \pm 0.011 \quad \text{(combined SADO)}$$

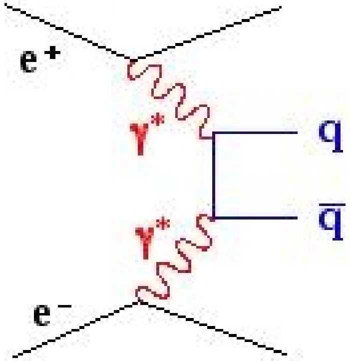
$$\alpha_s^c / \alpha_s^{uds} = 1.012 \pm 0.040 \quad \text{(combined SO)}$$

$$\alpha_s^s / \alpha_s^d = 0.956 \pm 0.053 \quad (\text{OPAL } \langle \mathrm{n}_{ch} \rangle)$$

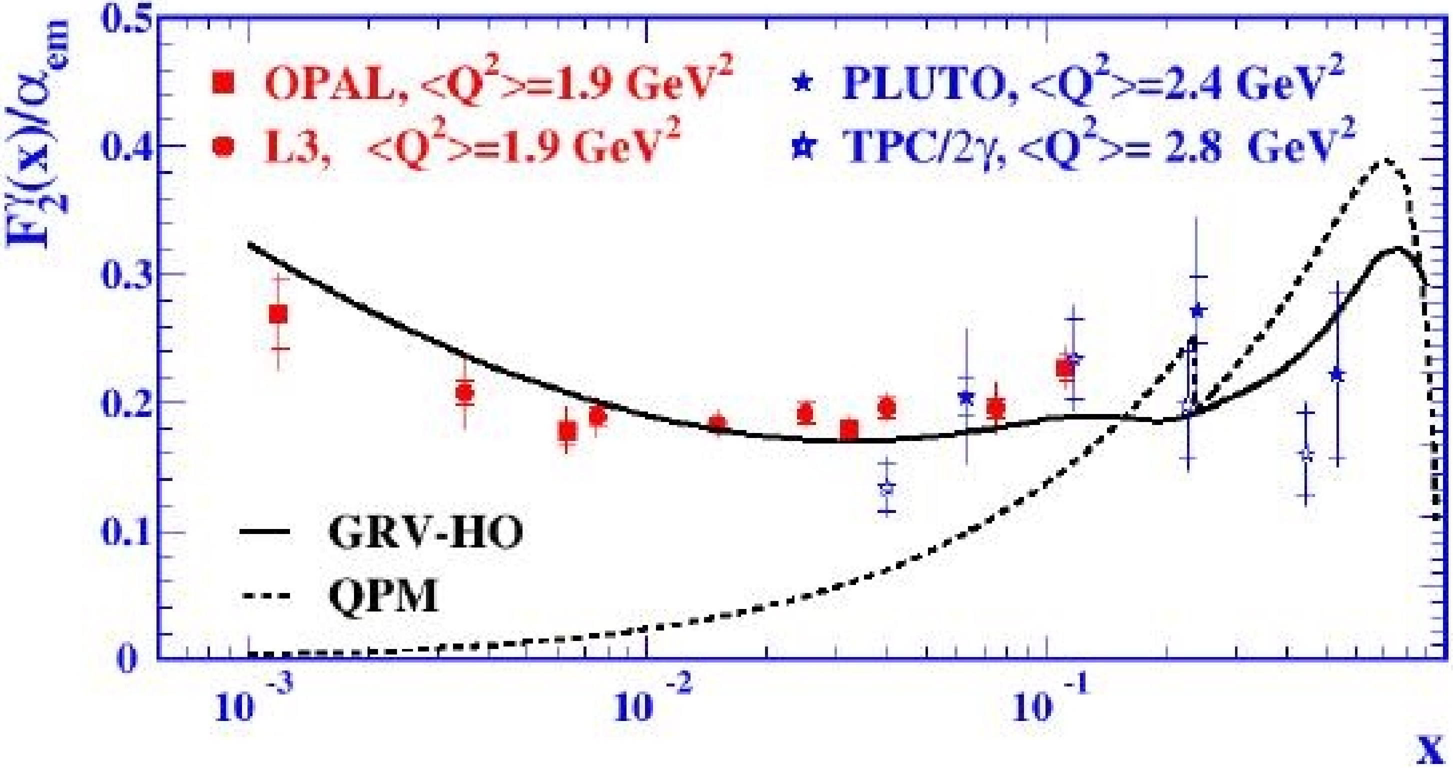
$$\alpha_s^s / \alpha_s^u = 1.090 \pm 0.056 \quad (\text{OPAL } \langle \mathrm{n}_{ch} \rangle)$$

$$\alpha_s^u / \alpha_s^d = 0.877 \pm 0.081 \quad (\text{OPAL } \langle \mathrm{n}_{ch} \rangle)$$

2-photon physics: $F_2^\gamma\left(x,Q^2\right)$

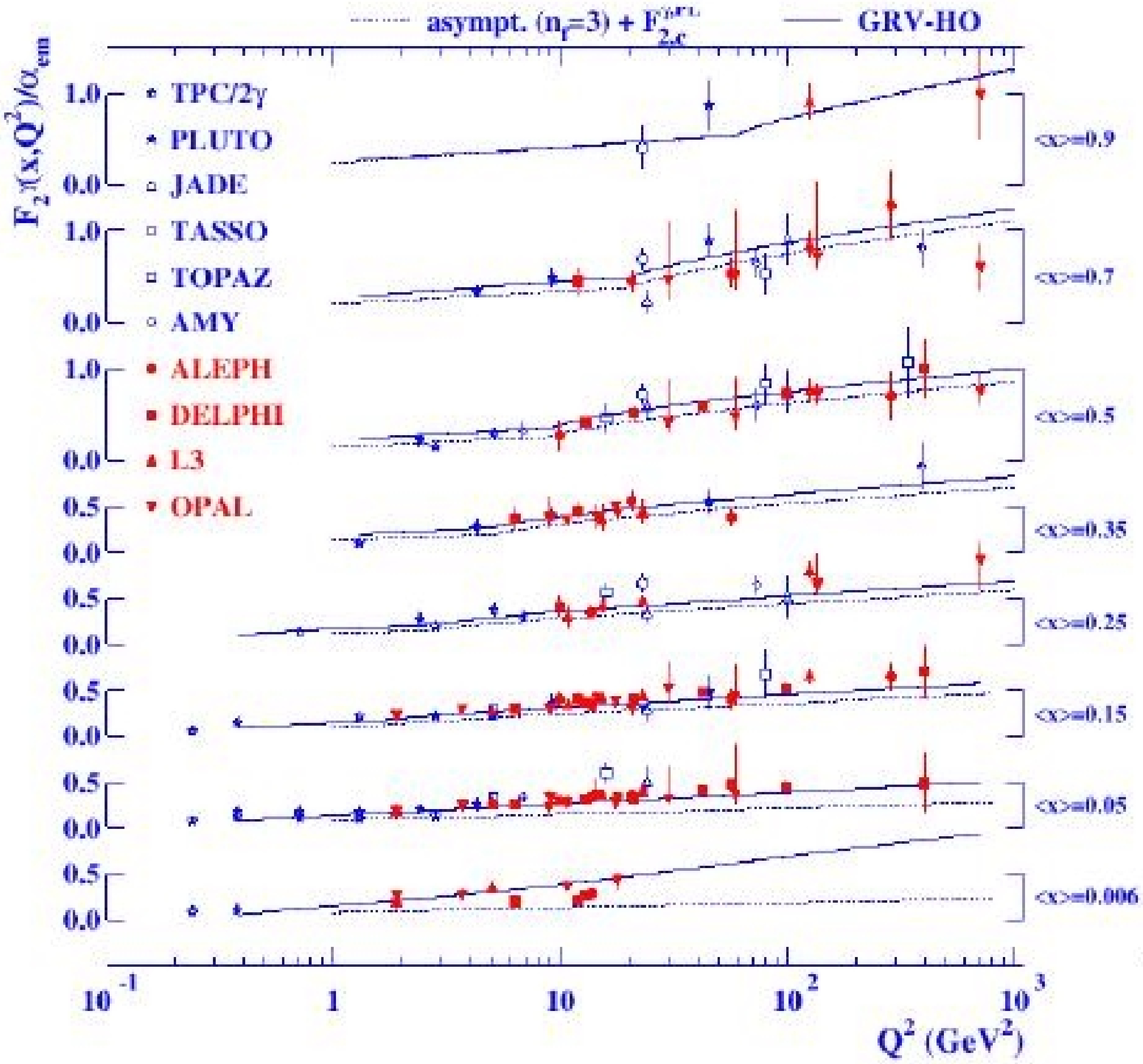


- $\dfrac{d^2\sigma_{e\gamma\to eX}}{dx\,dQ^2} = \dfrac{2\pi}{xQ^2}\left[\left(1+(1-y)^2\right)F_2^\gamma(x,Q^2) - y^2 F_L^\gamma(x,Q^2)\right]$
- determined from single tag events
- Q^2 from scattered electron; x from hadronic final state
- evidence for rise at low x ?



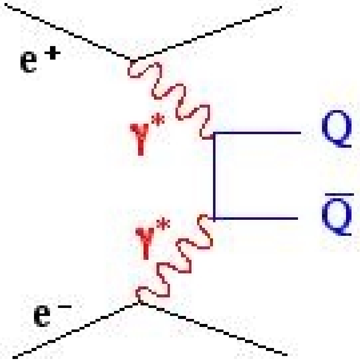
(S. Söldner-Rembold)

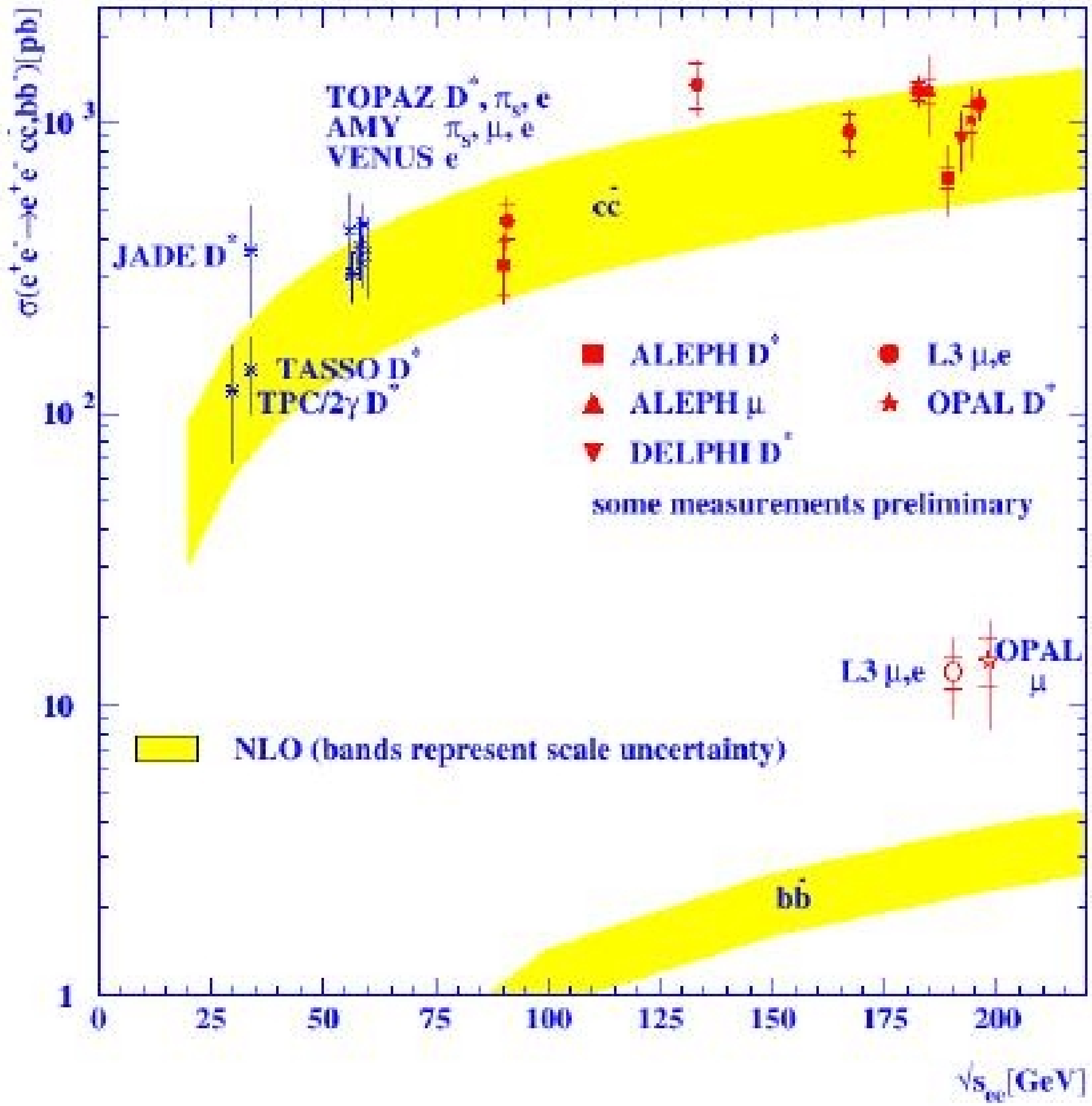
2-photon physics: scaling violations of $F_2^\gamma(x,Q^2)$



(S.Söldner-Rembold)

2-photon physics: heavy quark production





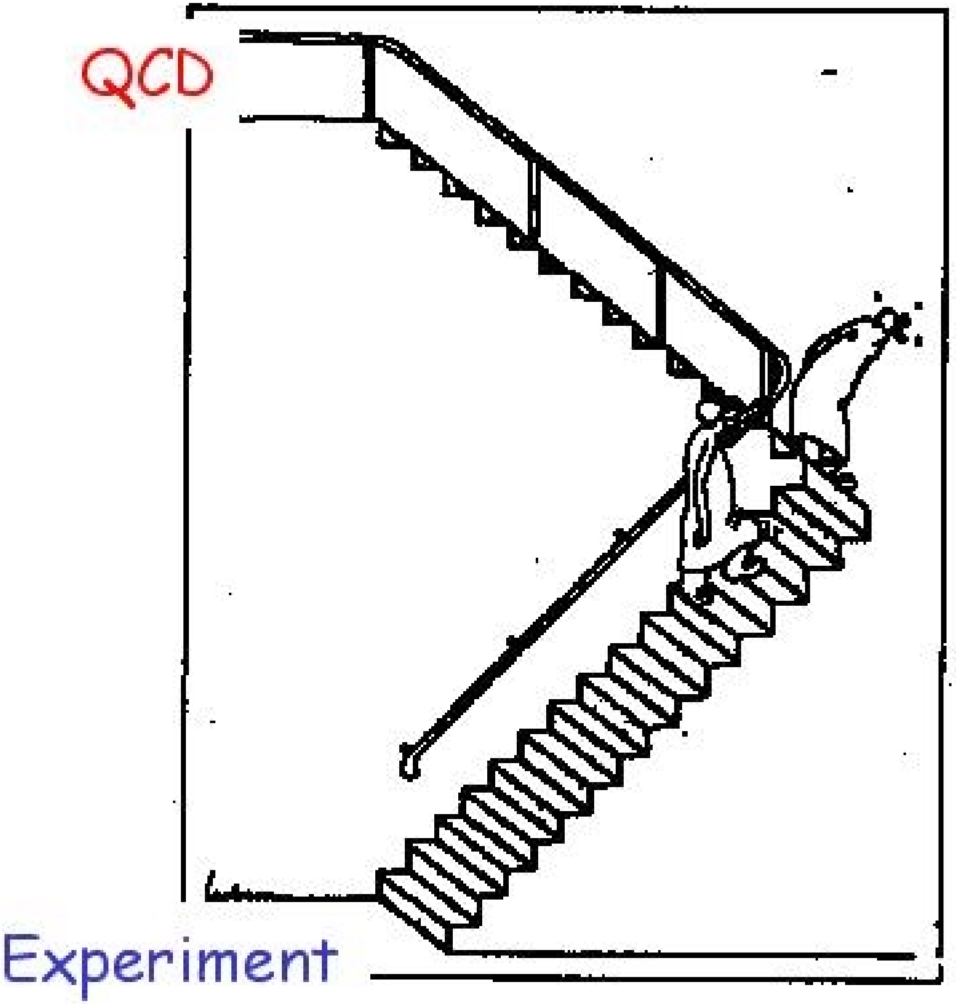
(S.Söldner-Rembold)

Summary: QCD at LEP

- $\alpha_s(M_Z) = 0.121 \pm 0.005$ (res. NLO; jets & shapes)
- $\alpha_s(M_Z) = 0.120 \pm 0.003$ (NNLO; R_Z, R_τ) (World average 0.1184 ± 0.0031
- running of α_s , asymptotic freedom confirmed
- non-Abelian structure (gluon self-coupling) confirmed
- quark / gluon differences studied in detail
- effects of gluon coherence confirmed
- deeper understanding of hadronisation, in terms of power corrections, local parton-hadron duality, hadronisation models, ...

- running b-quark mass, flavour independence of α_s determined
- gluon splitting into heavy quarks
- 2-photon physics: F_2^γ at small x, scaling violation, cross sections...

To do:
- NNLO for more observables (shapes; jets) !
- deeper understanding of theoretical uncertainties
- further assessment of nonperturbative effects



Not yet the end of (QCD at) LEP