

# QCD und Jet Physik an $e^+e^-$ Beschleunigern

- Geschichte der Starke Wechselwirkung
- QCD; confinement; asymptotic freedom
- Hadronisierung und Hadron-Jets
- Quark-Spin
- Gluon-Spin
- Selbstkopplung des Gluons
- Asymptotische Freiheit aus Jetraten
- Messungen von  $\alpha_s$

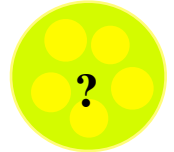
QCD an Hadron-Beschleunigern:  $\rightarrow$  WS

# Geschichte der Starken Wechselwirkung (1)

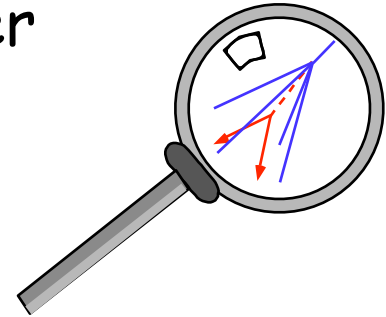
1932: Entdeckung des **Neutrons**



1933:  $\vec{\mu} \cong 2.5 \frac{e}{2 m_p} \vec{\sigma} \Rightarrow$  **Substruktur** des Protons

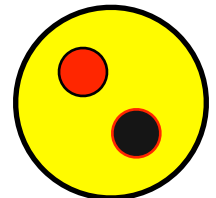
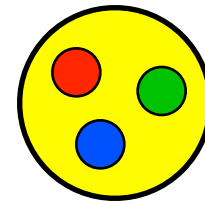


1947: Entdeckung der  $\pi$ -Mesonen und langlebiger V-Teilchen ( $K^0$ ,  $\Lambda$ ) in **Höhenstrahlung**



1953: V-Teilchen an **Beschleunigern** produziert; neue innere Quantenzahl ("**strangeness**").

1964: Statisches **Quark-Modell**; neue innere Quantenzahl: **Farbe**.

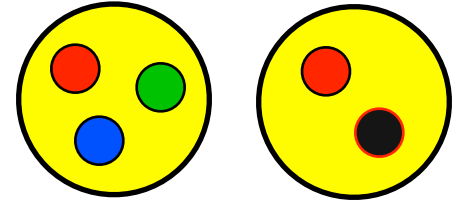


Baryon  
(p, n,  $\Lambda$ , ...)

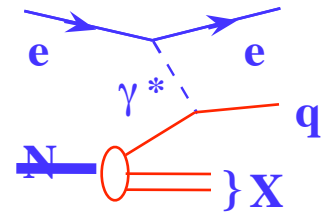
Meson  
( $\pi$ , K, ...)

# Geschichte der Starken Wechselwirkung (2)

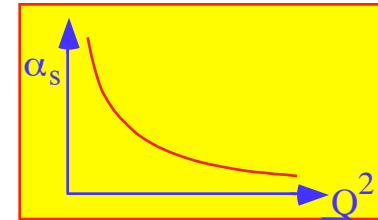
1964: Statisches **Quark-Modell**;  
neue innere Quantenzahl: **Farbe**.



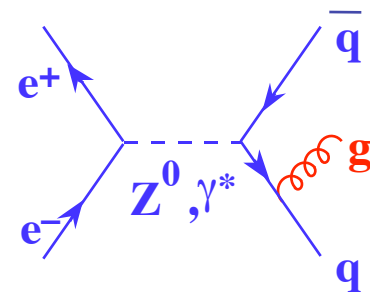
1969: Dynamisches **Partonenmodell**:



1973: Konzept der **Asymptotischen Freiheit**;  
**Quanten Chromo Dynamik**.



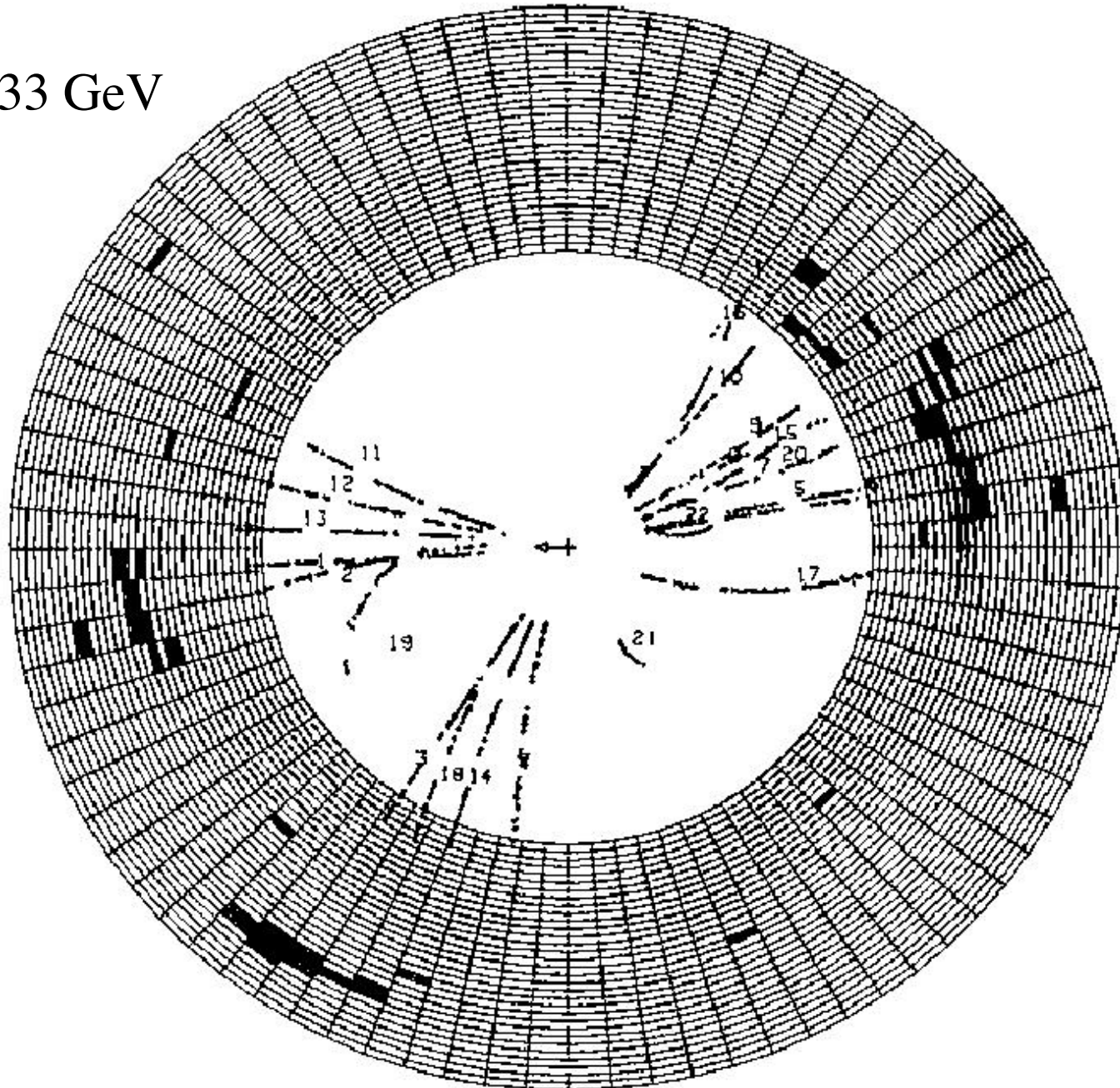
1975: **2-Jet Struktur** in  $e^+e^-$ -Vernichtung:  
Bestätigung **Quark-Parton-Modell**.



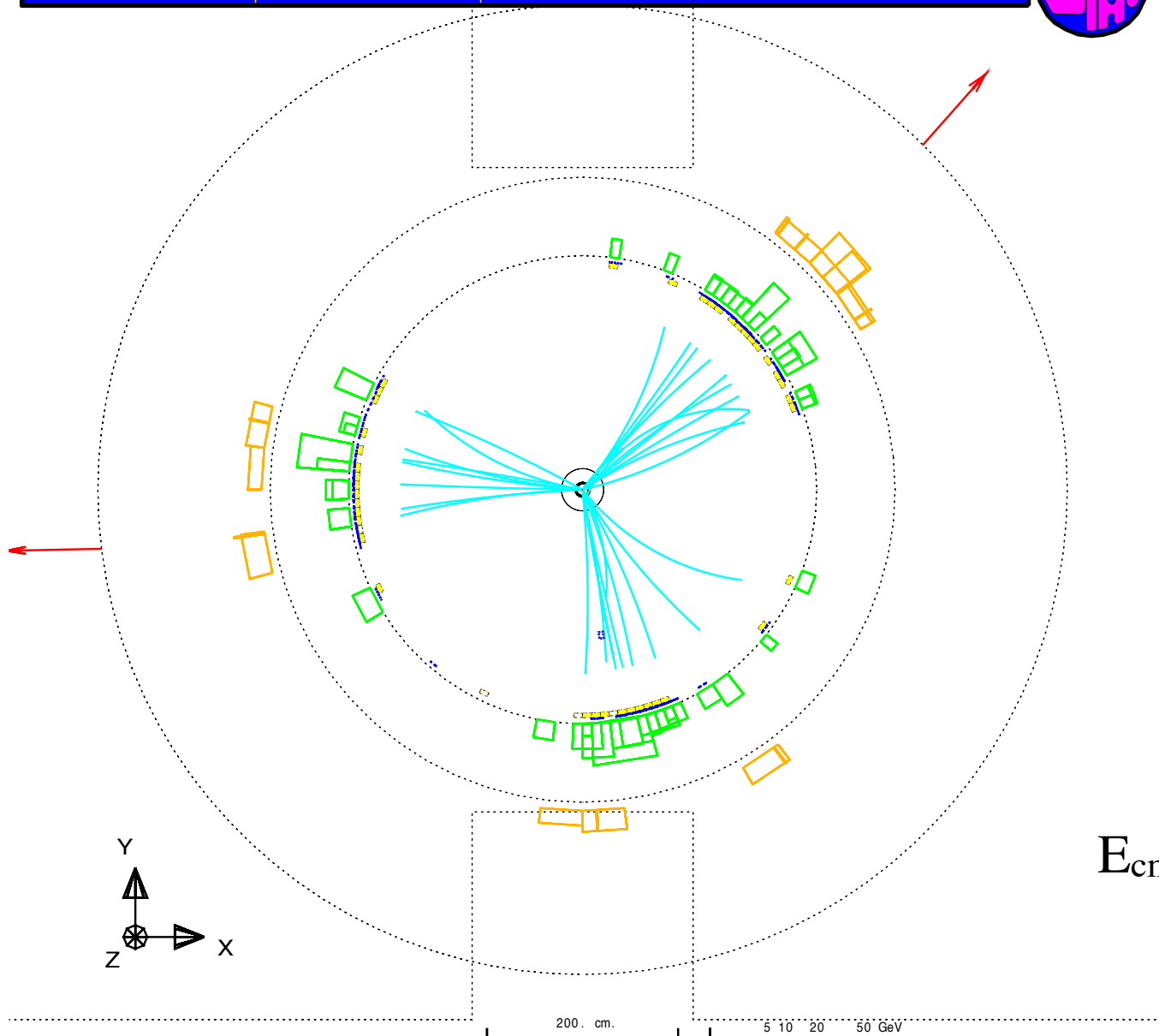
1979: Entdeckung des **Gluons** in **3-Jet-**  
Ereignissen der  $e^+e^-$ -Vernichtung.

# 3-Jet Ereignis gemessen mit dem JADE Detektor (1979-1986)

$E_{cm} \sim 33 \text{ GeV}$



Run:event 2513: 61702 Date 910910 Time 85656 Ctrk(N= 37 Sump= 65.7) Ecal(N= 55 SumE= 44.8) Hcal(N=19 SumE= 8.6)  
 Ebeam 45.613 Evis 90.2 Emiss 1.1 Vtx ( -0.09, 0.10, -0.22) Muon(N= 2) Sec Vtx(N= 3) Fdet(N= 0 SumE= 0.0)  
 Bz=4.350 Thrust=0.6788 Aplan=0.0381 Oblat=0.4248 Spher=0.6273

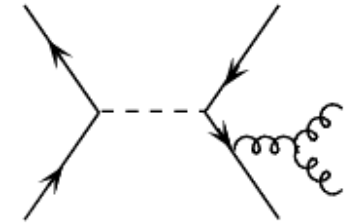
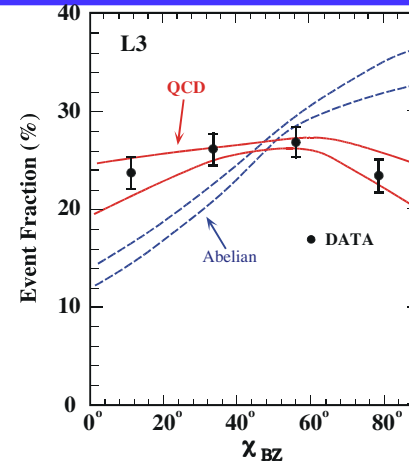


$E_{cm} = 91 \text{ GeV}$

Centre of screen is ( 0.0000, 0.0000, 0.0000)

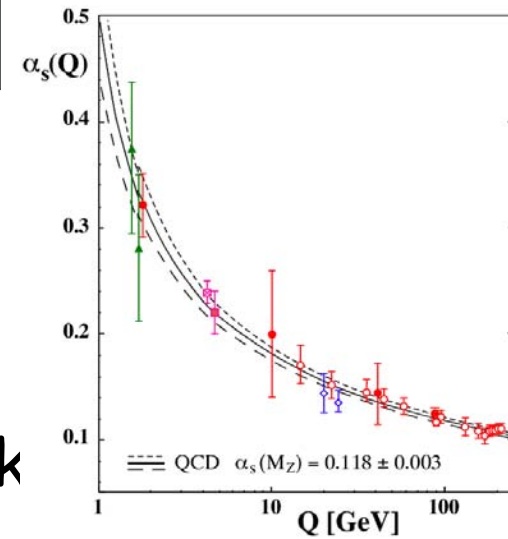
# Geschichte der Starken Wechselwirkung (3)

1991: exp. Signatur der  
Gluon-Selbstkopplung



1990-2000: Bestätigung der  
Asymptotischen Freiheit


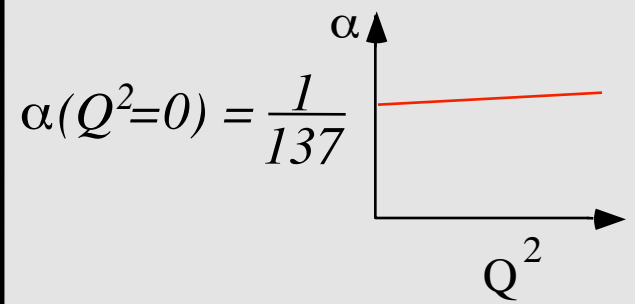
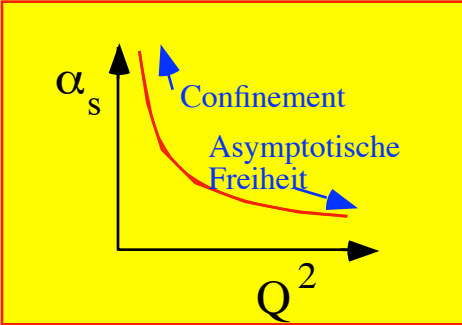
2004: Nobelpreis (Konzept der A.F.) an  
D. Gross, H.D. Politzer und F. Wilczek



# QCD:

- Eich-Feldtheorie der Starke Wechselwirkung
- zugrunde liegende Eichgruppe:  $SU(3)$  ; nicht-abelsch
- „Kraft“- oder Austausch-Teilchen: Gluonen
- Selbstwechselwirkung der Gluonen
- renormierte Kopplungskonstante  $\alpha_s$  ist energieabhängig:
- $\alpha_s$  groß bei kleinen Energien (grossen Abständen):  
Confinement der Quarks
- $\alpha_s$  klein bei grossen Energien (kleinen Abständen)  
Asymptotische Freiheit der Quarks

# Eigenschaften der QED und der QCD:

	QED	QCD
<i>Fermionen</i>	<i>Leptonen (e, μ, τ)</i>	<i>Quarks (u, d, s, c, b, t)</i>
<i>Kraft koppelt an:</i>	<i>elektrische Ladung</i>	<b>3 Farb-Ladungen</b>
<i>Austausch-quantum</i>	<i>Photon (γ) (trägt keine Ladung)</i>	<i>Gluonen (g) (tragen 2 Farbladungen)</i> ⇒  ist möglich
<i>Kopplungs- "Konstante"</i>	$\alpha(Q^2=0) = \frac{1}{137}$ 	$\alpha_s(Q^2 = M_Z^2) \approx 0.12$ 
<i>Freie Teilchen</i>	<i>Leptonen (e, μ, τ)</i>	(Farbneutrale, gebundene Zustände von $\bar{q}$ and $q$ ) <b>Hadronen</b>
<i>Theorie</i>	<i>Störungstheorie bis zur <math>O(\alpha^5)</math></i>	<i>Störungstheorie bis <math>O(\alpha_s^4)</math></i>
<i>Erreichte Präzision</i>	$10^{-6} \dots 10^{-7}$	1% ... 20%

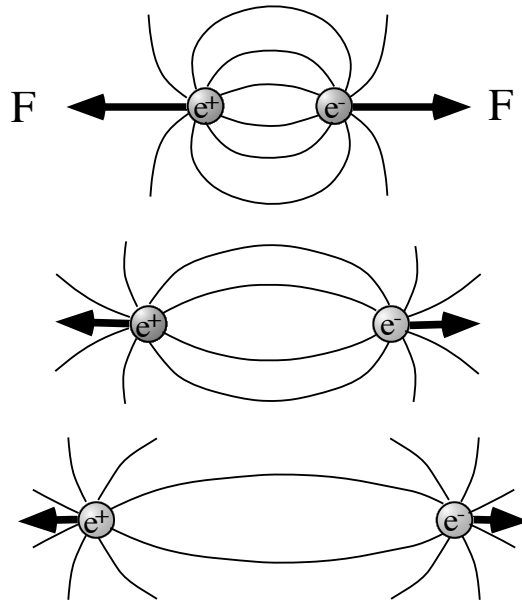


# Warum gibt es keine freien Quarks?

**QED**

Elektrische Ladungen:

Kraft  $F \propto 1/r^2$ ; Energiedichte  $\propto 1/r$



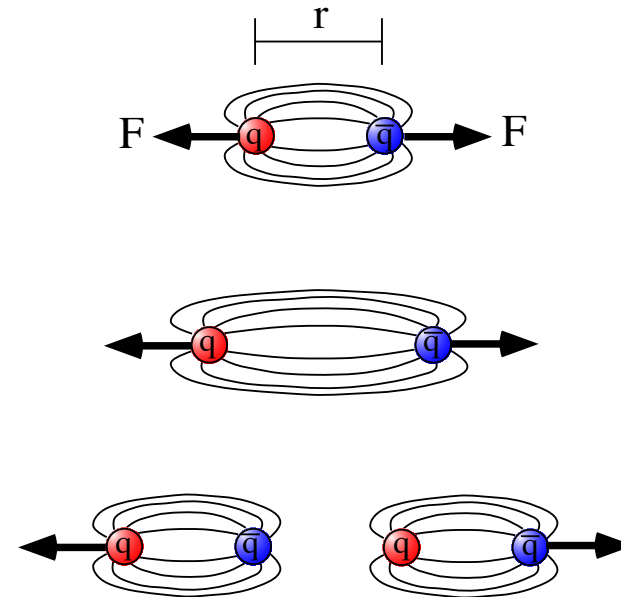
Kraft- und Energiedichte zwischen Ladungsträgern nimmt ab.

⇒ Träger elektrischer Ladung sind freie Teilchen

**QCD**

Farbladungen:

Kraft  $F \propto \text{const}$ ; Energiedichte  $\propto r$



Kraft- und Energiedichte steigen an, bis ein neues Quark- Antiquark-Paar aus dem Vakuum erzeugt wird.

⇒ Träger von Farbladung kommen nur in gebundenen, 'farbneutralen' Zuständen vor.

**"Confinement"**

# Energieabhängigkeit der Kopplungs-“Konstanten“:

## Renormalisation Group Equation (“β-function”)

- in führender Ordnung Störungstheorie:

$$\mu \frac{d}{d\mu} \alpha_i(\mu) = -\beta_0 \alpha_i^2 \quad \text{mit} \quad \beta_0 = \frac{1}{2\pi} \left[ \frac{11}{3} \begin{pmatrix} N_c \equiv 0 \\ N_c \equiv 2 \\ N_c \equiv 3 \end{pmatrix} - \frac{4}{3} \begin{pmatrix} N_{fam} \\ N_{fam} \\ N_f/2 \end{pmatrix} - N_{Higgs} \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix} \right] \begin{matrix} \leftarrow \text{QED} \\ \leftarrow \text{weak} \\ \leftarrow \text{QCD} \end{matrix}$$

- Integration  $\Rightarrow$

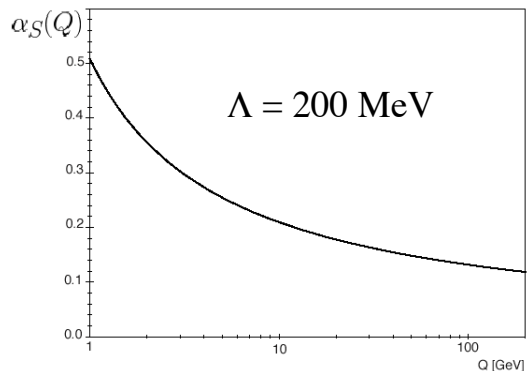
$$\alpha_i(q^2) = \frac{\alpha_i(\mu^2)}{1 + \frac{\beta_0}{2} \alpha_i(\mu^2) \ln \frac{q^2}{\mu^2}}$$

or

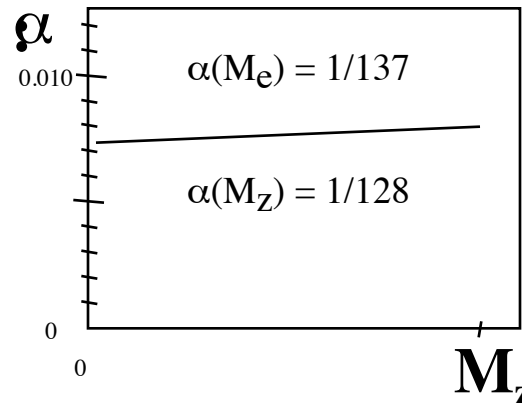
$$\alpha_i(q^2) = \frac{2}{\beta_0 \ln \frac{q^2}{\Lambda^2}}$$

$$\text{with } \Lambda^2 = \frac{\mu^2}{e^{2/\beta_0 \alpha_s(\mu^2)}}$$

**QCD:**  $N_c = 3$  ;  $\beta_0 = \frac{23}{6\pi}$

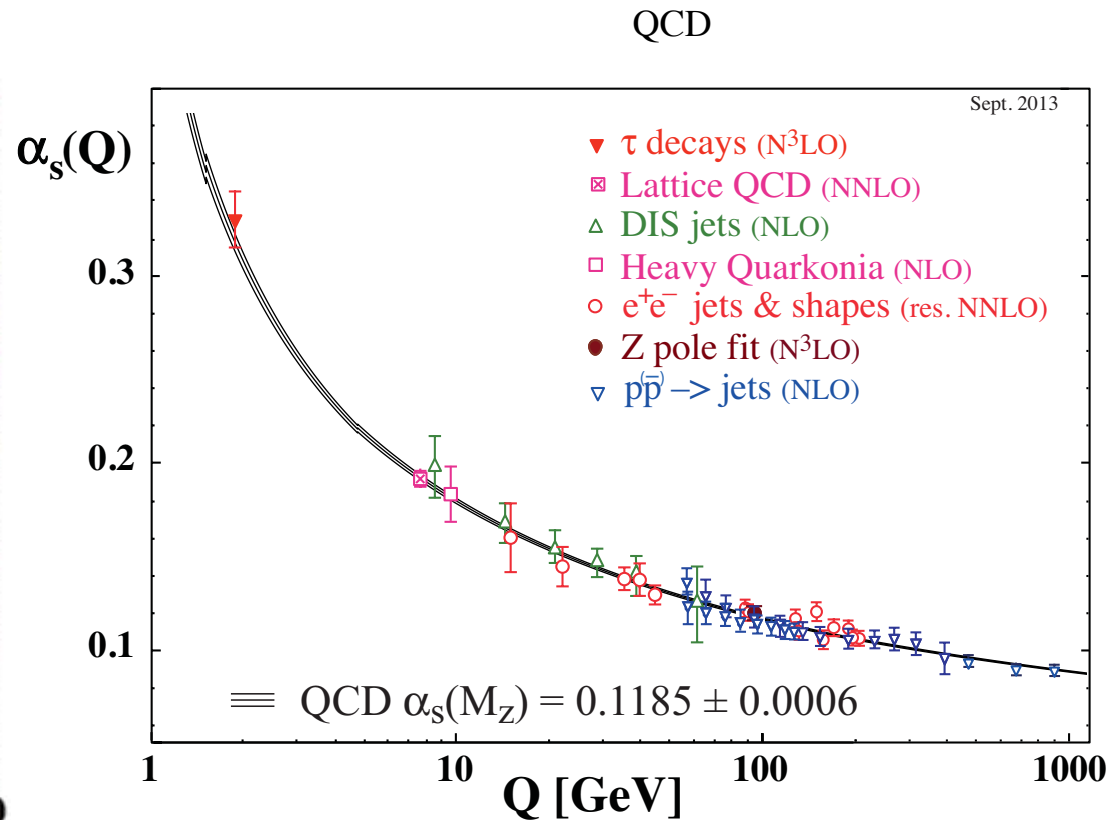
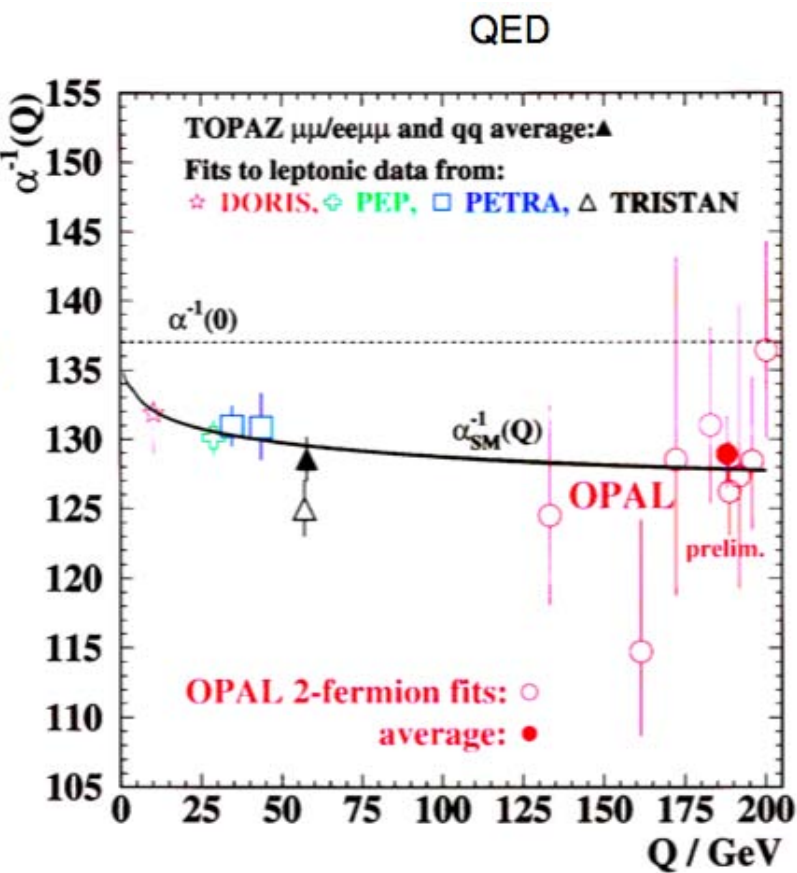


**QED**  $N_c = 0$  ;  $N_{fam} = 3$   $\beta_0 = -\frac{12}{6\pi}$

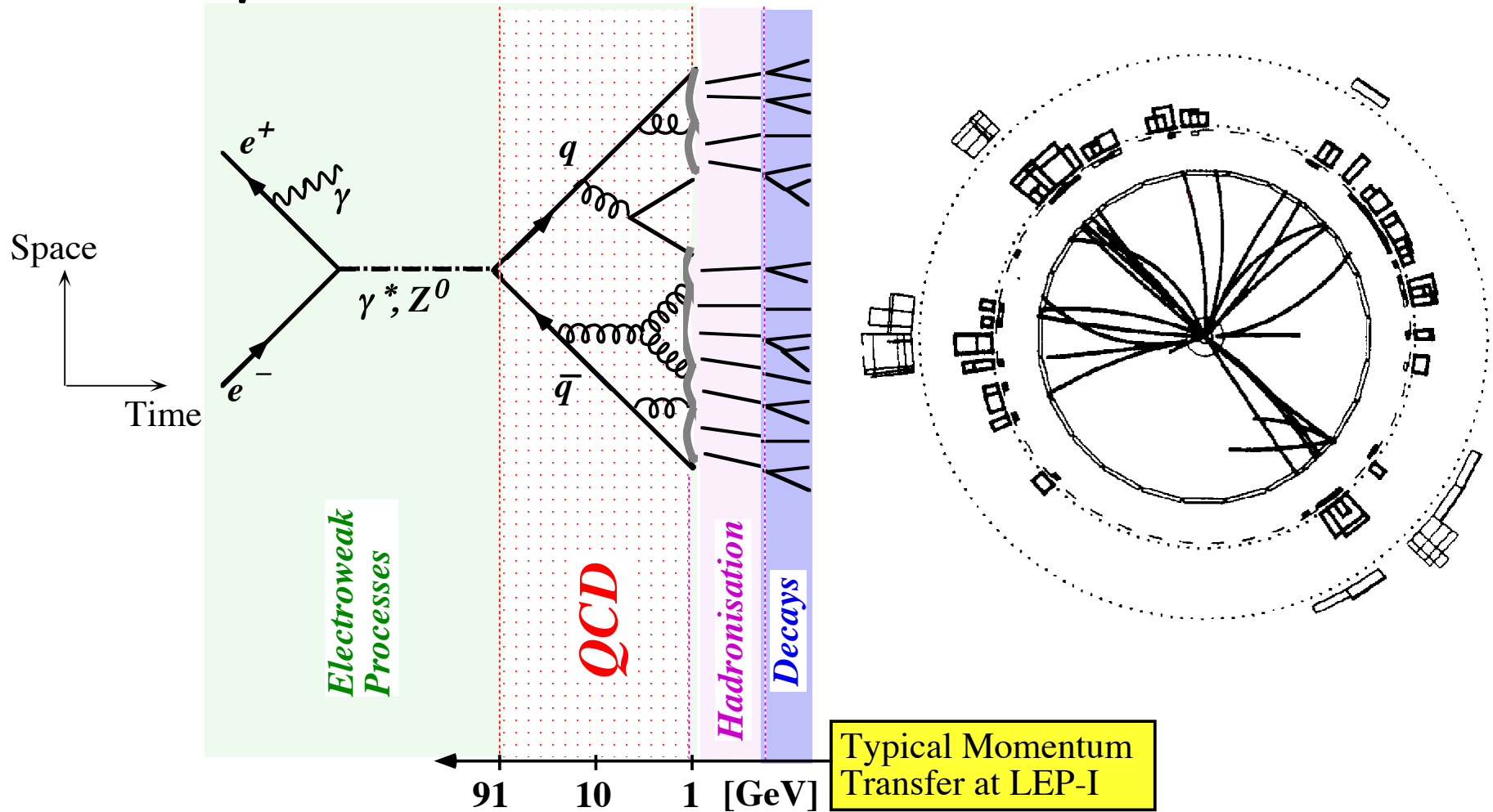


# Energieabhängigkeit der Kopplungs"konstanten":

- experimentell mit hoher Genauigkeit verifiziert



# 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

# Physik der Hadronen-Jets

Zum Vergleich von Hadronen-Jets mit analytischen QCD -Rechnungen (Quark- und Gluondynamik)

muß man

auflösbare Teilchenjets

Theorie und Praxis definieren.

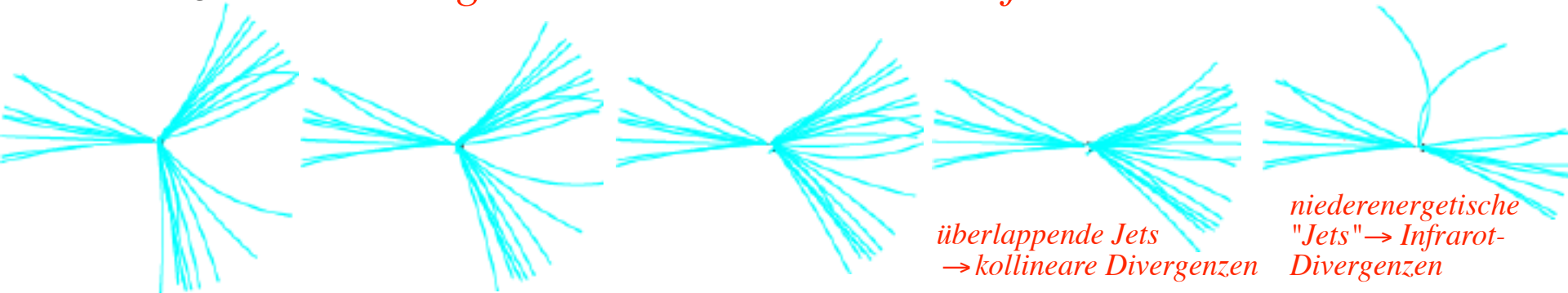


Dazu benötigt man:

- Definition eines **Auflösungskriteriums** (z.B. minimale invariante Paarmasse, minimale Winkel, minimale Energien ..)
- Vorschrift, wie man nichtauflösbare Jets **rekombiniert**.

allerdings:

*Es gibt keine "natürliche" Definition von Jets !*



*überlappende Jets*

*-> kollineare Divergenzen*

*niederenergetische "Jets" -> Infrarot-Divergenzen*

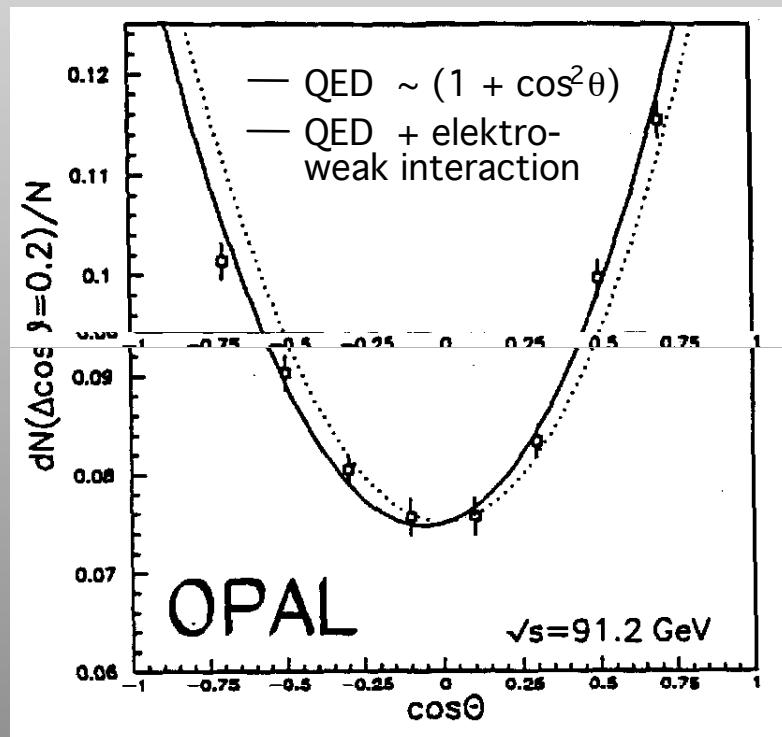
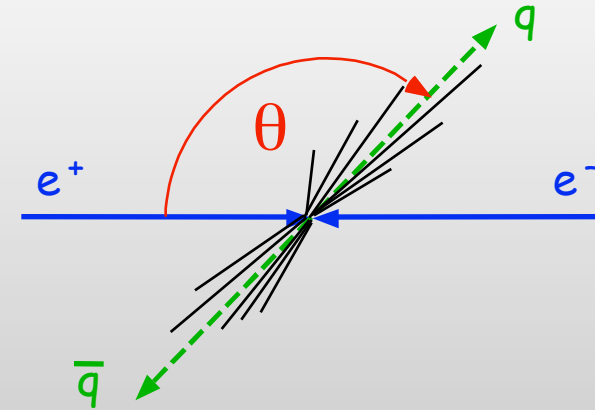
Durham - Jetdefinition: (meistbenutzt in  $e^+ e^-$  -Vernichtung)

2 Gruppen von Teilchen,  $i$  und  $j$ , können aufgelöst werden falls für die minimale transversale Energie der 4er-Vektoren,  $y_{ij} = 1/2 \min(E_i^2, E_j^2) \cdot (1 - \cos(\theta_{ij}))$ , gilt:  $y_{ij} \geq y_{cut}$

Falls  $y_{ij} < y_{cut}$ , werden die 'Proto-jets'  $i$  und  $j$  von einem neuen, einzelnen (Proto-) Jet  $k$  ersetzt (Rekombination):  $p_k = p_i + p_j$  (rekursives Verfahren, bis alle  $y_{ij} \geq y_{cut}$ ).

# Test of basic quantum numbers (q-, g-spin):

$$\text{Quark-Spin} = 1/2 \Leftrightarrow \frac{d\sigma}{d\theta} \sim (1 + \cos^2\theta)$$

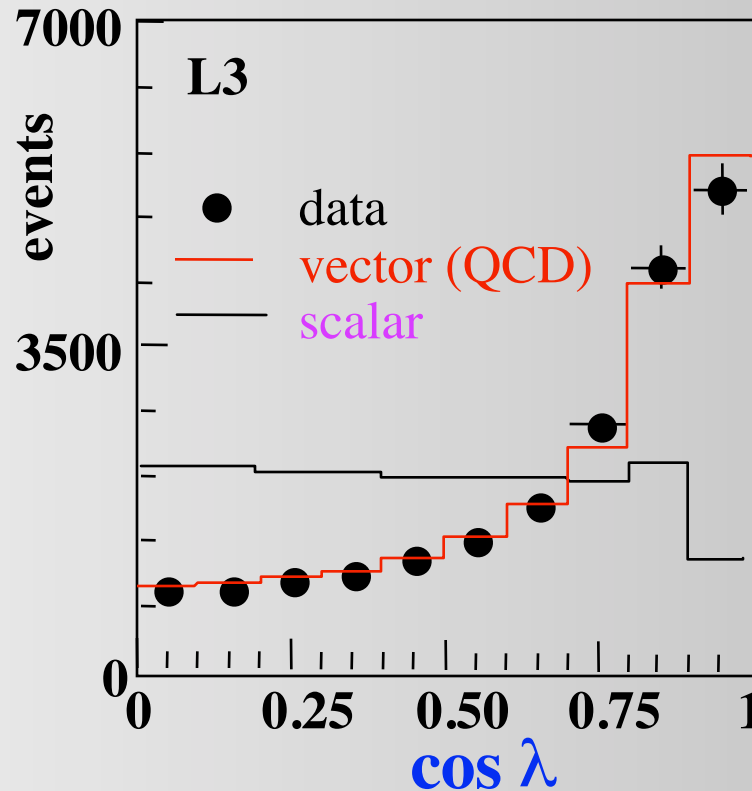
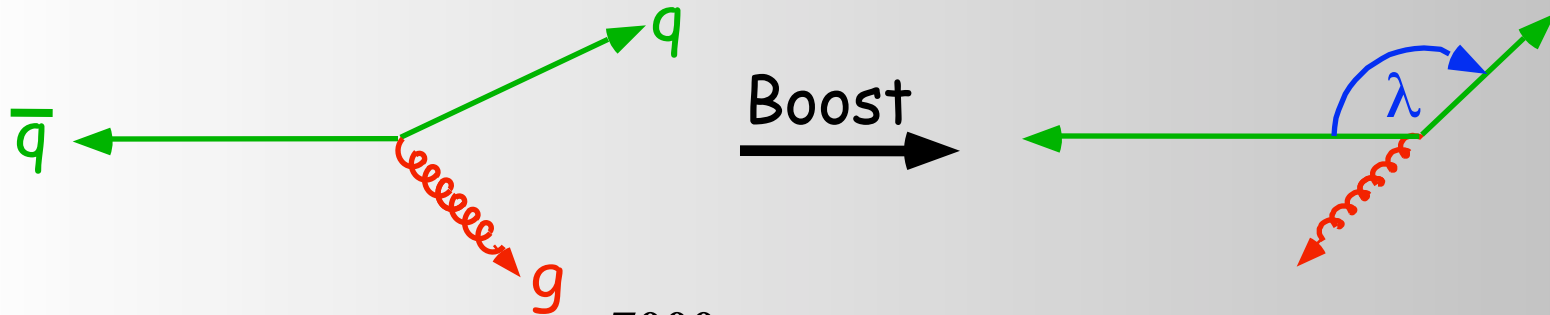


coarse structure: quarks have spin 1/2

fine structure: deviation from  $1 + \cos^2\theta$  is due to electro-weak interference contributions of 4.5%;  
 $\sin^2\theta_w = 0.2255 \pm 0.00212$

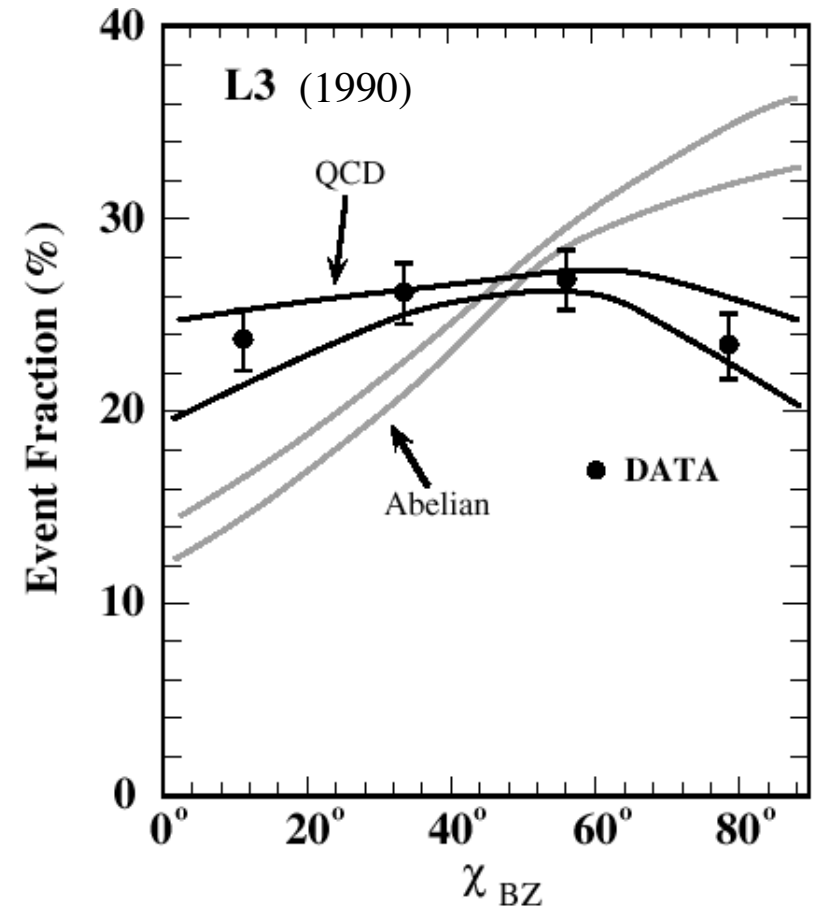
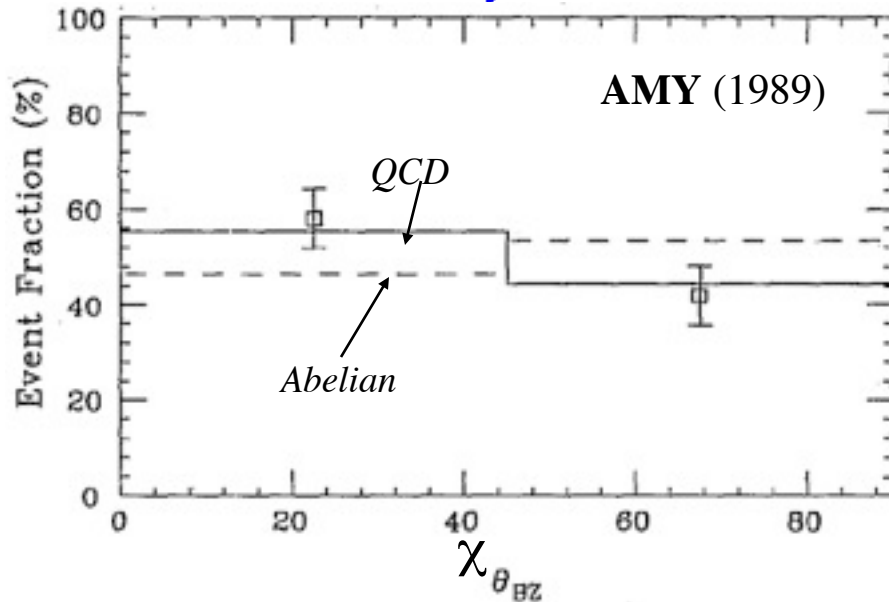
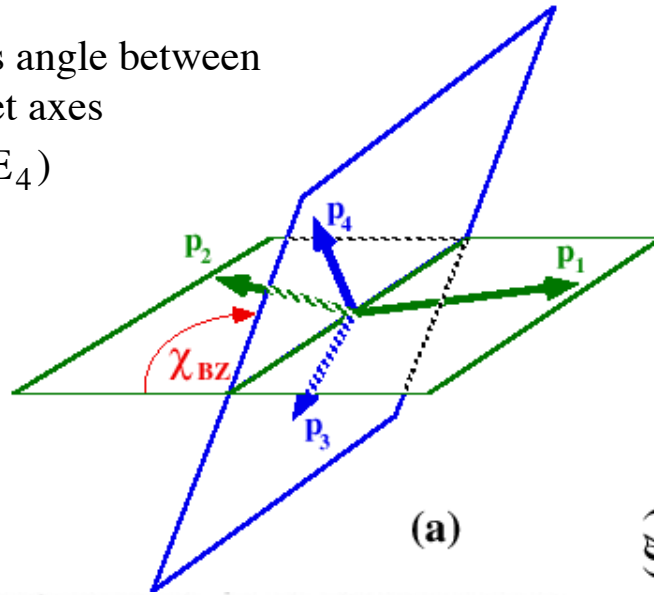
# Orientation of Gluon-Jets in 3-Jet-Events:

Test of the Gluon-Spin (QCD:  $g$ -spin = 1)



# Non-Abelian gauge structure from 4-jet events

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





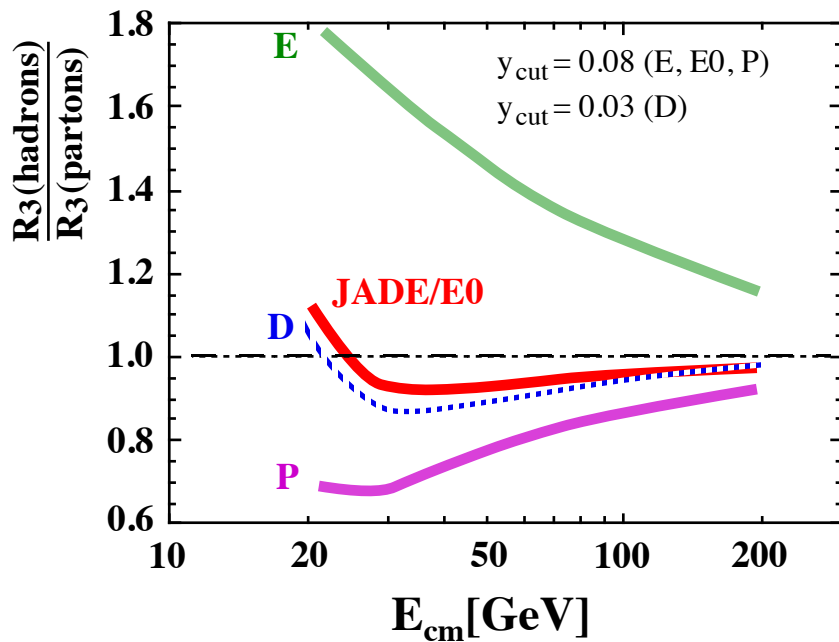
# Asymptotic Freedom (running $\alpha_s$ )

Historically (1987):

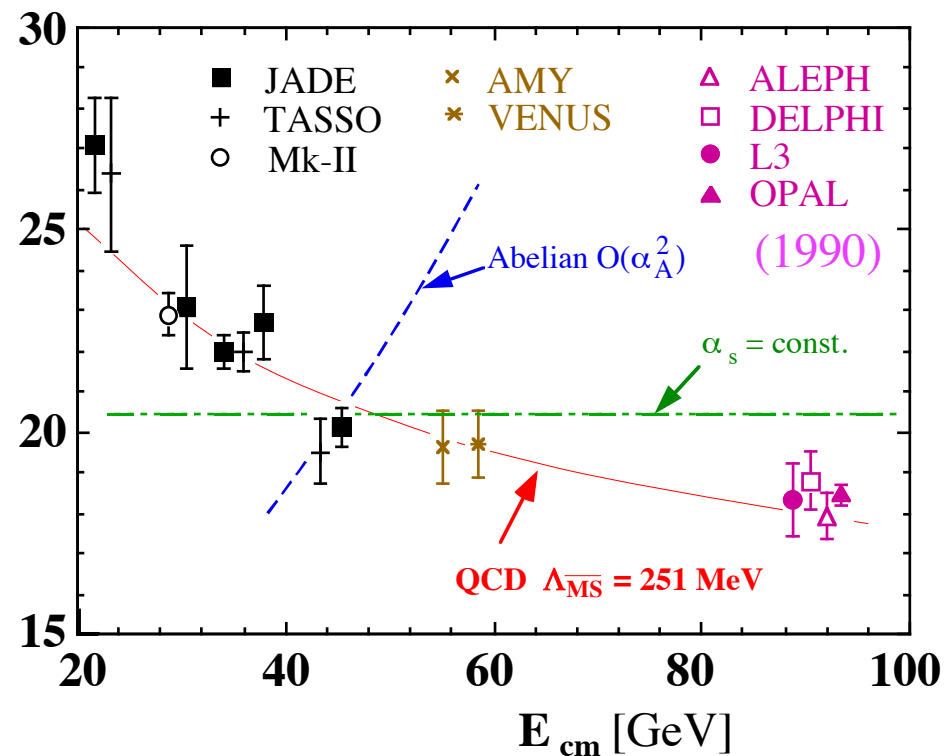
energy dependence of 3-jet production rates ( $R_3$ ):

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

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

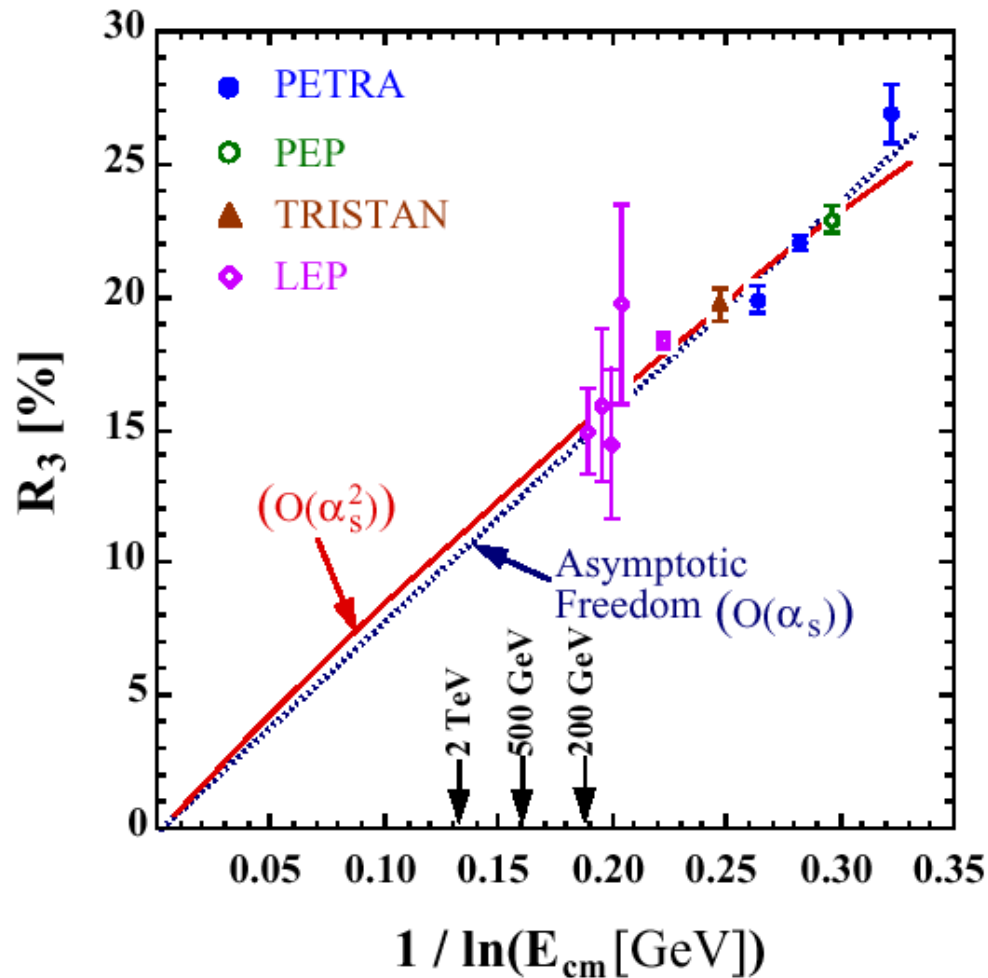


$R_3(y_{\text{cut}} = 0.08)$  [%]



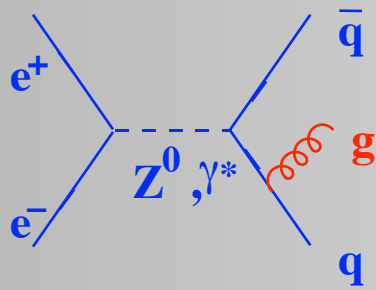
# Asymptotic Freedom from jet rates

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

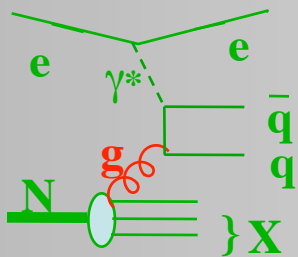


# Experimental Determination of $\alpha_s$

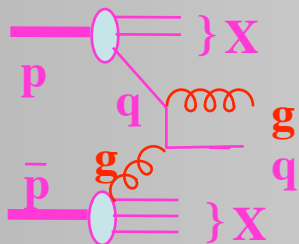
in all processes in which gluons occur:



- $e^+e^-$  annihilations
  - total hadronic production cross section
  - hadronic decay widths of the  $Z^0$  and of the  $\tau$
  - jet rates and shape variables



- deep inelastic lepton-nucleon-scattering
  - scaling violations of structure functions
  - sum rules of structure functions
  - jet rates and shape variables



- proton-(anti-)proton collisions
  - jet rates
  - photoproduction
  - inclusive b-quark production

# running $\alpha_s$ up to 4<sup>th</sup> order:

$$Q^2 \frac{\partial \alpha_s(Q^2)}{\partial Q^2} = \beta(\alpha_s(Q^2))$$

$$\beta(\alpha_s(Q^2)) = -\beta_0 \alpha_s^2(Q^2) - \beta_1 \alpha_s^3(Q^2) - \beta_2 \alpha_s^4(Q^2) - \beta_3 \alpha_s^5(Q^2) + \mathcal{O}(\alpha_s^6)$$

$$\beta_0 = \frac{33 - 2N_f}{12\pi},$$

$$\beta_1 = \frac{153 - 19N_f}{24\pi^2},$$

$$\beta_2 = \frac{77139 - 15099N_f + 325N_f^2}{3456\pi^3},$$

$$\beta_3 \approx \frac{29243 - 6946.3N_f + 405.089N_f^2 + 1.49931N_f^3}{256\pi^4}$$

$$\alpha_s(Q^2) = \frac{1}{\beta_0 L} - \frac{1}{\beta_0^3 L^2} \beta_1 \ln L$$

$$+ \frac{1}{\beta_0^3 L^3} \left( \frac{\beta_1^2}{\beta_0^2} (\ln^2 L - \ln L - 1) + \frac{\beta_2}{\beta_0} \right)$$

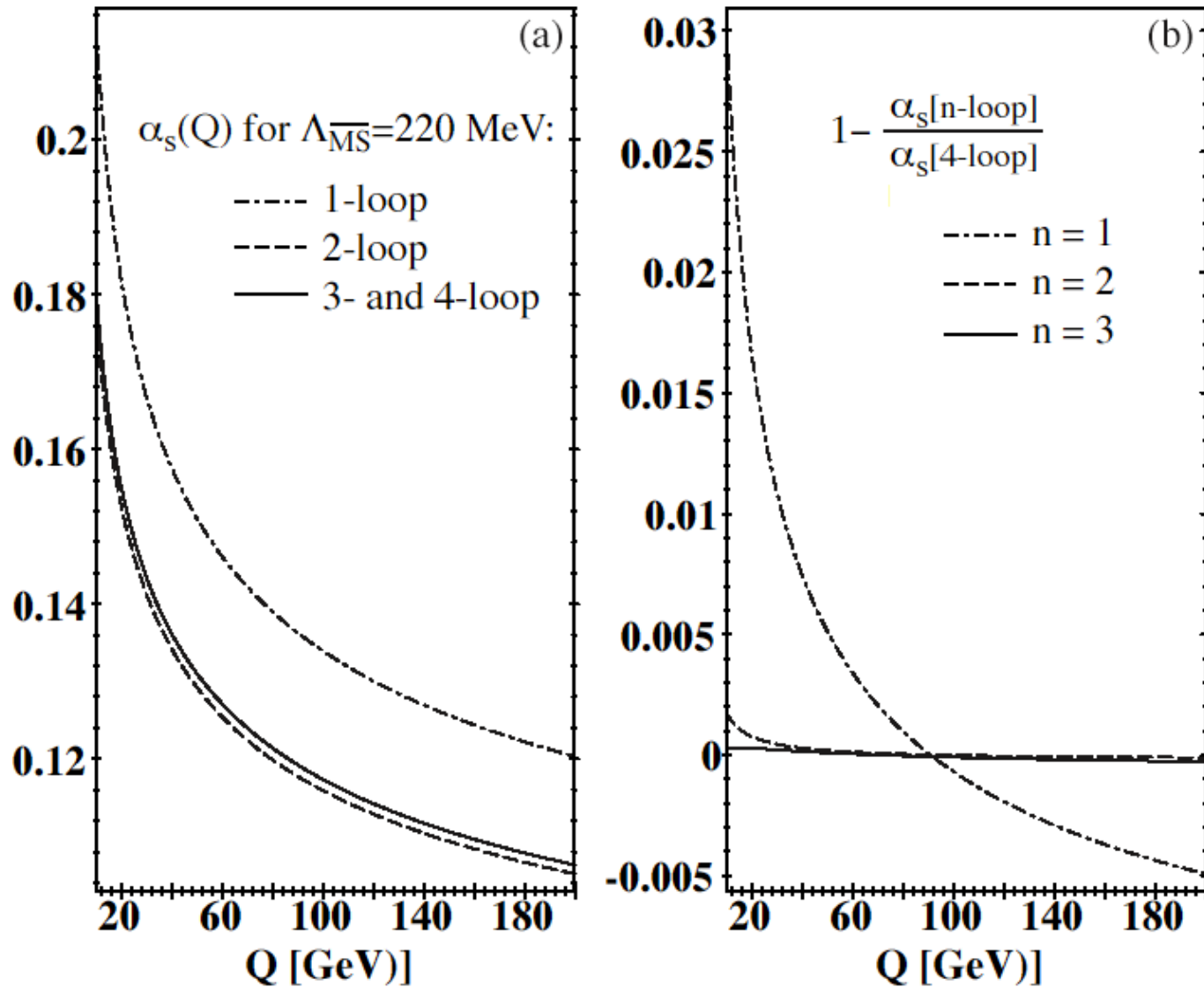
$$+ \frac{1}{\beta_0^4 L^4} \left( \frac{\beta_1^3}{\beta_0^3} \left( -\ln^3 L + \frac{5}{2} \ln^2 L + 2 \ln L - \frac{1}{2} \right) - 3 \frac{\beta_1 \beta_2}{\beta_0^2} \ln L + \frac{\beta_3}{2\beta_0} \right) \quad L = \ln \frac{Q^2}{\Lambda_{\overline{MS}}^2}$$

Ritbergen,  
Vermaseren,  
Larin

$\beta_0$  and  $\beta_1$  **do not** depend on renormalisation scheme;  $\beta_2$  and  $\beta_3 \dots$  **do** !

choose  $\overline{MS}$  scheme for all of the following discussion.

# relative size of higher order corrections



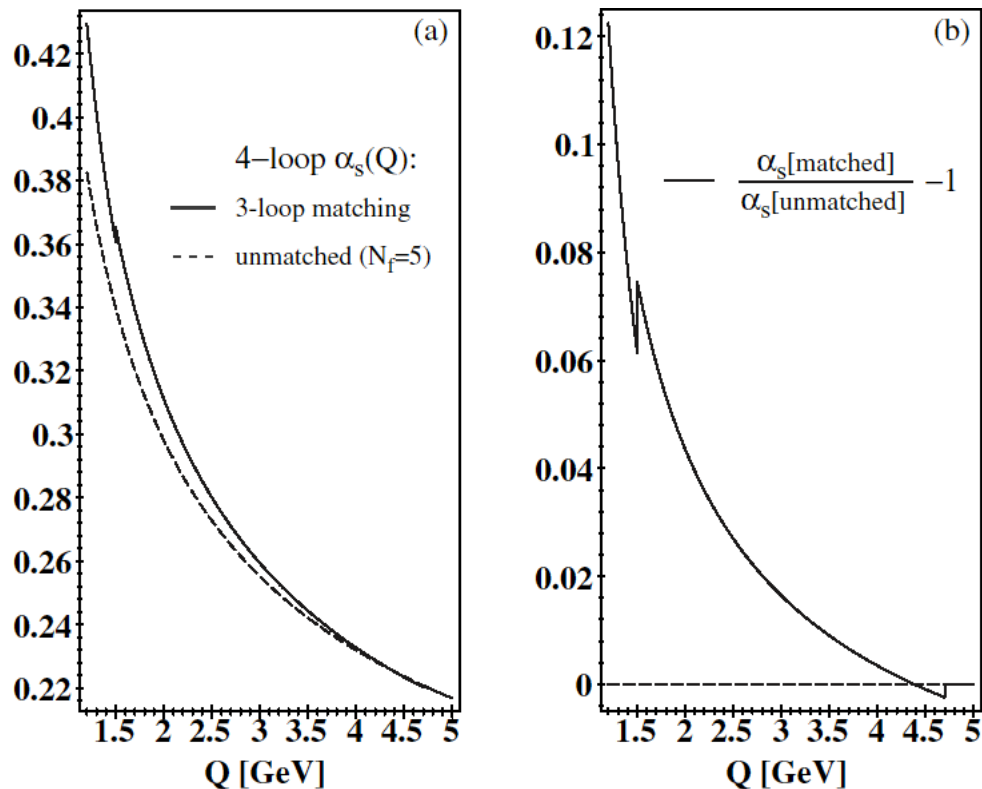
# heavy quark threshold matching

Matching conditions for the choice  $\mu^{(N_f)} = M_Q$  (pole mass definition):

$$\frac{a'}{a} = 1 + C_2 a^2 + C_3 a^3 \quad (\text{with } a' = \alpha_s^{(N_f-1)}/\pi; \quad a = \alpha_s^{(N_f)}/\pi)$$

$$C_2 = -0.291667 \text{ and } C_3 = -5.32389 + (N_f - 1) \cdot 0.26247$$

(3-loop condition; Chetyrkin, Kniehl, Steinhauser)



# perturbative predictions for physical quantities

$$\begin{aligned} \mathcal{R}(Q^2) &= P_l \sum_n R_n \alpha_s^n \\ &= P_l (R_0 + R_1 \alpha_s(\mu^2) + R_2(Q^2/\mu^2) \alpha_s^2(\mu^2) + \dots) \end{aligned}$$

in  $n^{\text{th}}$  order perturbation theory

$R_1$  : “leading order coefficient” (lo)  
 $R_2$  : “next to leading coefficient” (nlo)  
 $R_3$  : “next-next-to leading” (nnlo)

Resummation of logs arising from soft and collinear singularities:

$$\Sigma(\mathcal{R}) \equiv \int_0^{\mathcal{R}} \frac{1}{\sigma} \frac{d\sigma}{d\mathcal{R}} d\mathcal{R} = C(\alpha_s) \exp[G(\alpha_s, L)] + D(\alpha_s, \mathcal{R}) \quad L = \ln(1/\mathcal{R}) \quad C(\alpha_s) = 1 + \sum_{n=1}^{\infty} C_n \hat{\alpha}_s^n$$

$$\begin{aligned} G(\alpha_s, L) &= \sum_{n=1}^{\infty} \sum_{m=1}^{n+1} G_{nm} \hat{\alpha}_s^n L^m \\ &\equiv Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \alpha_s^2 g_4(\alpha_s L) \dots \end{aligned}$$

	Leading logs	Next-to-Leading logs	Subleading logs	Non-log. terms	
$\ln \Sigma(\mathcal{R}) =$	$G_{12} \hat{\alpha}_s L^2$	$+ G_{11} \hat{\alpha}_s L$		$+ \alpha_s \mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$
	$+ G_{23} \hat{\alpha}_s^2 L^3$	$+ G_{22} \hat{\alpha}_s^2 L^2$	$+ G_{21} \hat{\alpha}_s^2 L$	$+ \alpha_s^2 \mathcal{O}(1)$	$\mathcal{O}(\alpha_s^2)$
	$+ G_{34} \hat{\alpha}_s^3 L^4$	$+ G_{33} \hat{\alpha}_s^3 L^3$	$+ G_{32} \hat{\alpha}_s^3 L^2 + \dots$	$+ \dots$	$\mathcal{O}(\alpha_s^3)$
	$+ \dots$	$+ \dots$	$+ \dots$	$+ \dots$	$\vdots$
$=$	$Lg_1(\alpha_s L)$	$+ g_2(\alpha_s L)$	$+ \dots$	$+ \dots$	

# renormalisation scale dependence

$$\mathcal{R} \equiv \mathcal{R}(Q^2/\mu^2, \alpha_s); \quad \alpha_s \equiv \alpha_s(\mu^2)$$

since choice of  $\mu$  is arbitrary, physical observables  $\mathcal{R}$  should not depend on  $\mu$

$$\mu^2 \frac{d}{d\mu^2} \mathcal{R}(Q^2/\mu^2, \alpha_s) = \left( \mu^2 \frac{\partial}{\partial \mu^2} + \mu^2 \frac{\partial \alpha_s}{\partial \mu^2} \frac{\partial}{\partial \alpha_s} \right) \mathcal{R} \stackrel{!}{=} 0$$

$$\begin{aligned} 0 = & \mu^2 \frac{\partial R_0}{\partial \mu^2} + \alpha_s(\mu^2) \mu^2 \frac{\partial R_1}{\partial \mu^2} + \alpha_s^2(\mu^2) \left[ \mu^2 \frac{\partial R_2}{\partial \mu^2} - R_1 \beta_0 \right] \\ & + \alpha_s^3(\mu^2) \left[ \mu^2 \frac{\partial R_3}{\partial \mu^2} - [R_1 \beta_1 + 2R_2 \beta_0] \right] \\ & + \mathcal{O}(\alpha_s^4) . \end{aligned}$$

→

$$R_0 = \text{const.} ,$$

$$R_1 = \text{const.} ,$$

$$R_2 \left( \frac{Q^2}{\mu^2} \right) = R_2(1) - \beta_0 R_1 \ln \frac{Q^2}{\mu^2} ,$$

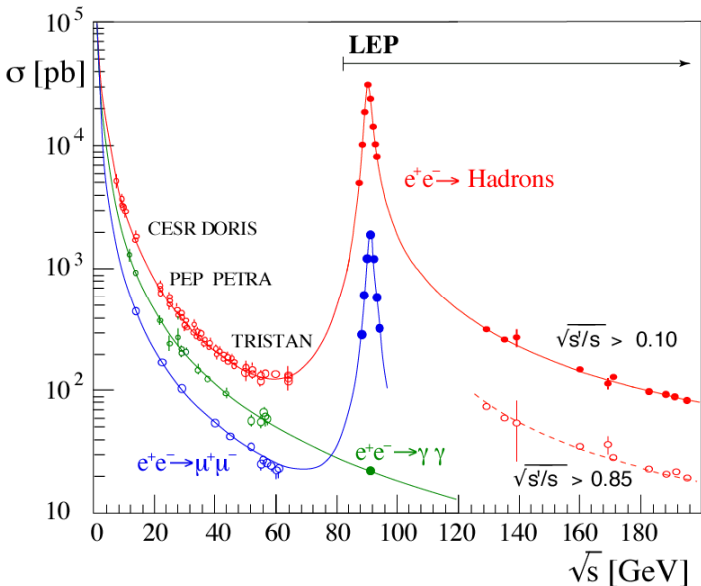
$$R_3 \left( \frac{Q^2}{\mu^2} \right) = R_3(1) - [2R_2(1)\beta_0 + R_1\beta_1] \ln \frac{Q^2}{\mu^2} + R_1\beta_0^2 \ln^2 \frac{Q^2}{\mu^2}$$

Perturbative QCD coefficients beyond leading order become renormalisation scale dependent !

This dependence is used to quantify theoretical uncertainties due to unknown higher orders.



# hadronische Breite des $Z^0$ Boson



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

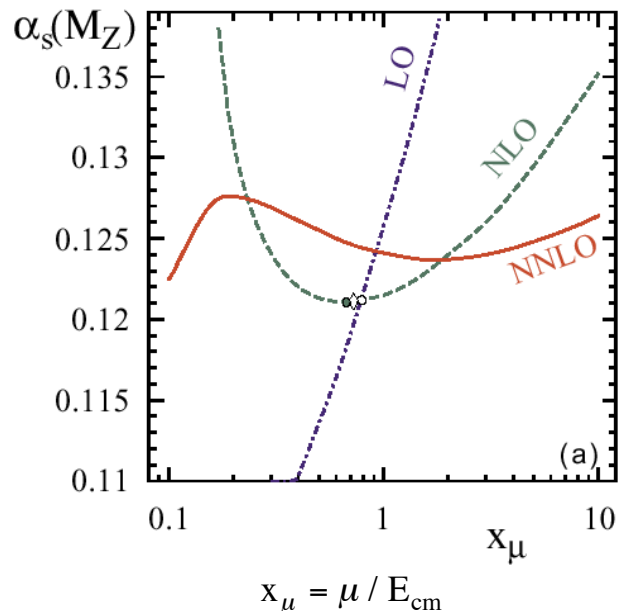
$$R_Z = 19.934 \left[ 1 + 1.045 \frac{\alpha_s(\mu)}{\pi} + 0.94 \left[ \frac{\alpha_s(\mu)}{\pi} \right]^2 - 15 \left[ \frac{\alpha_s(\mu)}{\pi} \right]^3 \right]$$

$$\Rightarrow \alpha_s(M_Z) = 0.124 \pm 0.004 \quad (\text{exp.})$$

$$\pm 0.002 \quad (M_H, M_{\text{top}})$$

$$+ 0.003 \quad (\text{QCD})$$

$$- 0.001$$



error source	$\Delta\alpha_s(M_{Z^0})$
$\Delta M_{Z^0} = \pm 0.0021 \text{ GeV}$	$\pm 0.00003$
$\Delta M_t = \pm 5 \text{ GeV}$	$\pm 0.0002$
$M_H = 100 \dots 1000 \text{ GeV}$	$\pm 0.0017$
$\mu = \left(\frac{1}{4} \dots 4\right) M_{Z^0}$	$+ 0.0028$ $- 0.0004$
renormalization schemes	$\pm 0.0002$
total	$+ 0.003$ $- 0.002$

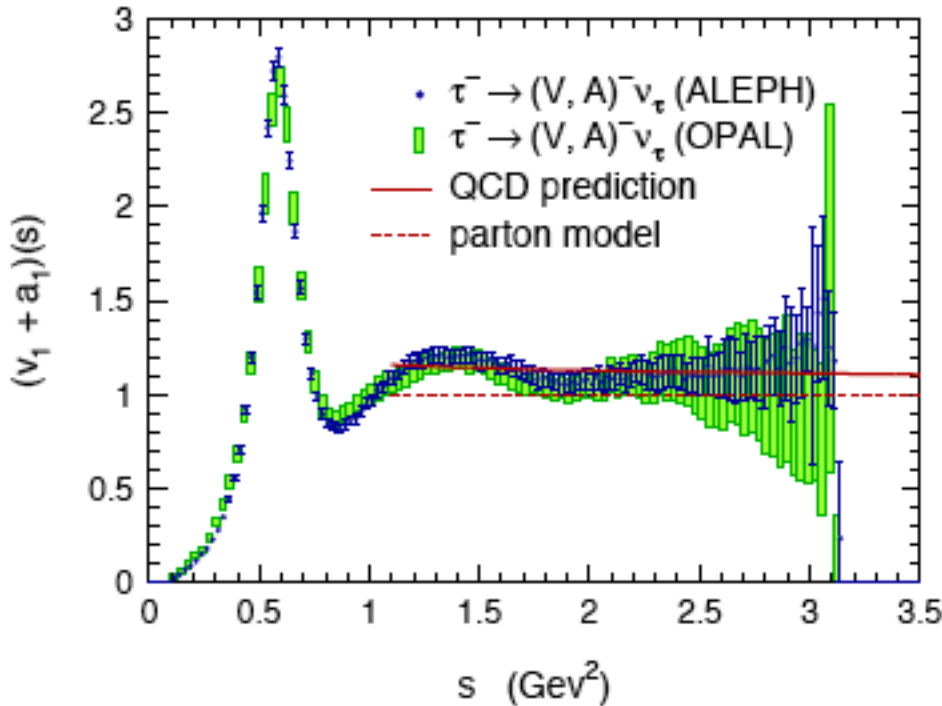
# $\alpha_s$ from $\tau$ -decays

$$R_\tau = \frac{\Gamma(\tau \rightarrow \text{hadrons } \nu_\tau)}{\Gamma(\tau \rightarrow e \nu_e \nu_\tau)}$$

$$QCD: R_\tau = 3.058(1.001 + \delta_{pert} + \delta_{nonpert})$$

$$\delta_{pert} = \frac{\alpha_s(m_\tau)}{\pi} + 5.20 \left( \frac{\alpha_s(m_\tau)}{\pi} \right)^2 + 26.37 \left( \frac{\alpha_s(m_\tau)}{\pi} \right)^3$$

measurements of R as well as the mass spectra of hadronic  $\tau$ -decays and comparison with  $O(\alpha_s^3)$  perturbative QCD results in  $\alpha_s(M_\tau)$  and also provides an independent determination of the leading nonperturbative contributions  $\delta_{nonpert}$

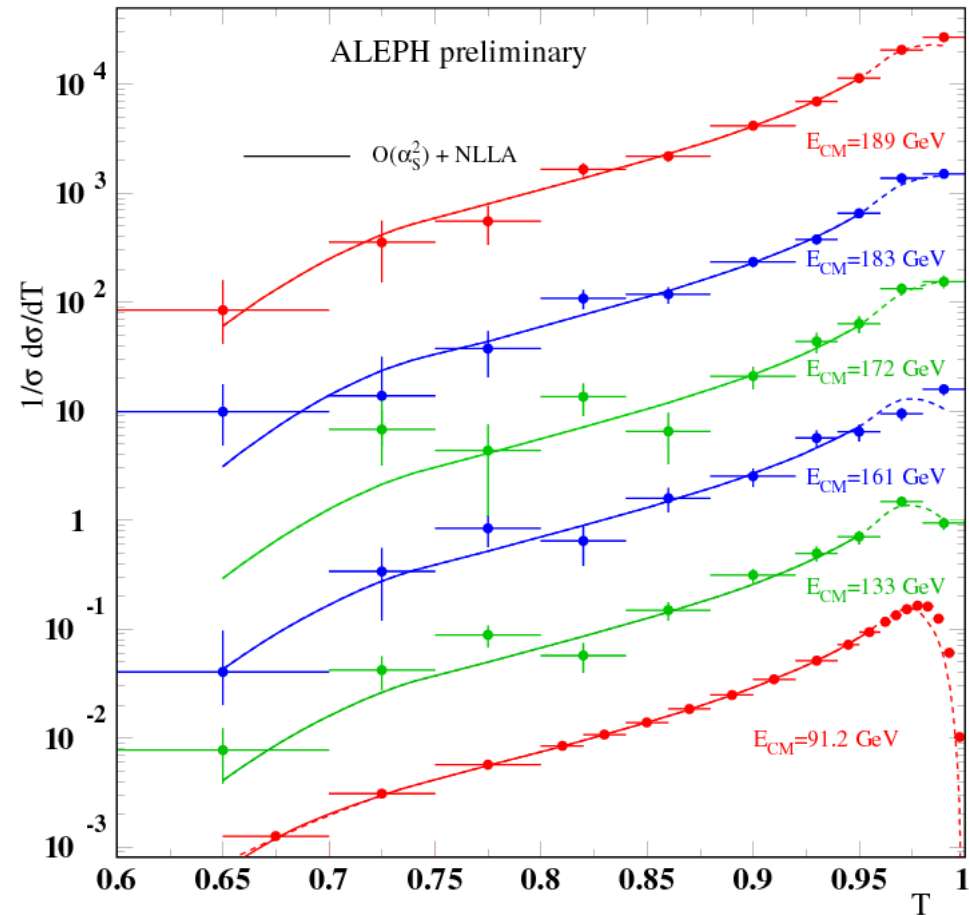
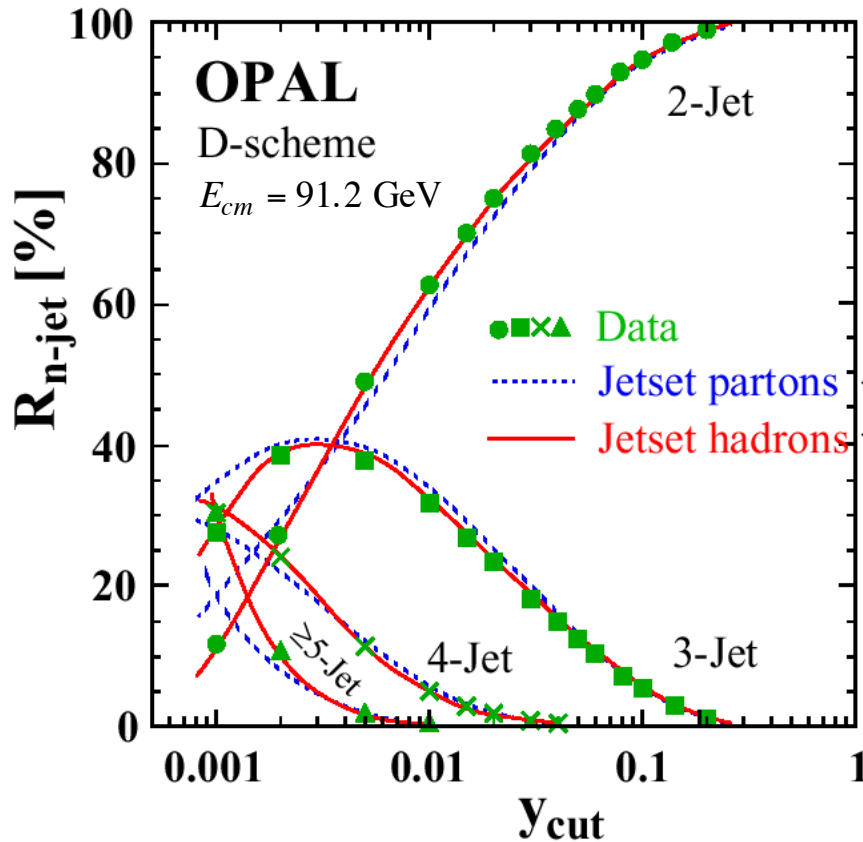


$$\alpha_s(M_Z) = 0.1213 \pm 0.0006_{\text{exp}} \pm 0.0010_{\text{theo}}$$

# Event Shape Observables

Name of Observable	Definition	Typical Value for:			QCD calculation
Thrust	$T = \max_{\vec{n}} \left( \frac{\sum_i  \vec{p}_i \vec{n} }{\sum_i  \vec{p}_i } \right)$	1	$\geq 2/3$	$\geq 1/2$	(resummed) $O(\alpha_s^2)$
Thrust major	Like T, however $T_{maj}$ and $\vec{n}_{maj}$ in plane $\perp \vec{n}_T$	0	$\leq 1/3$	$\leq 1/\sqrt{2}$	$O(\alpha_s^2)$
Thrust minor	Like T, however $T_{min}$ and $\vec{n}_{min}$ in direction $\perp$ to $\vec{n}_T$ and $\vec{n}_{maj}$	0	0	$\leq 1/2$	$O(\alpha_s^2)$
Oblateness	$O = T_{maj} - T_{min}$	0	$\leq 1/3$	0	$O(\alpha_s^2)$
Sphericity	$S = 1.5 (Q_1 + Q_2)$ ; $Q_1 \leq \dots \leq Q_3$ are Eigenvalues of $S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i p_i^2}$	0	$\leq 3/4$	$\leq 1$	none (not infrared safe)
Aplanarity	$A = 1.5 Q_1$	0	0	$\leq 1/2$	none (not infrared safe)
Jet (Hemisphere) masses	$M_{\pm}^2 = (\sum_i E_i^2 - \sum_i \vec{p}_i^2)_{i \in S_{\pm}}$ ( $S_{\pm}$ : Hemispheres $\perp$ to $\vec{n}_T$ ) $M_H^2 = \max(M_+^2, M_-^2)$ $M_D^2 =  M_+^2 - M_-^2 $	0	$\leq 1/3$	$\leq 1/2$	(resummed) $O(\alpha_s^2)$
Jet broadening	$B_{\pm} = \frac{\sum_{i \in S_{\pm}}  \vec{p}_i \times \vec{n}_T }{2 \sum_i  \vec{p}_i }$ ; $B_T = B_+ + B_-$ $B_w = \max(B_+, B_-)$	0	$\leq 1/(2\sqrt{3})$	$\leq 1/(2\sqrt{2})$	(resummed) $O(\alpha_s^2)$
Energy-Energy Correlations	$EEC(\chi) = \sum_{\alpha \neq \beta} \int_{\chi - \frac{\pi}{2}}^{\chi + \frac{\pi}{2}} \sum_{i,j} \frac{E_i E_j}{E_{vis}^2} \delta(\chi - \chi_{ij}) d\chi$				(resummed) $O(\alpha_s^2)$
Asymmetry of EEC	$\Delta EEC(\chi) = EEC(\pi - \chi) - EEC(\chi)$				$O(\alpha_s^2)$
Differential 2-jet rate	$D_2(y) = \frac{R_2(y - \Delta y) - R_2(y)}{\Delta y}$				(resummed) $O(\alpha_s^2)$

# Jet production and hadronic event shapes



## Pert. QCD

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

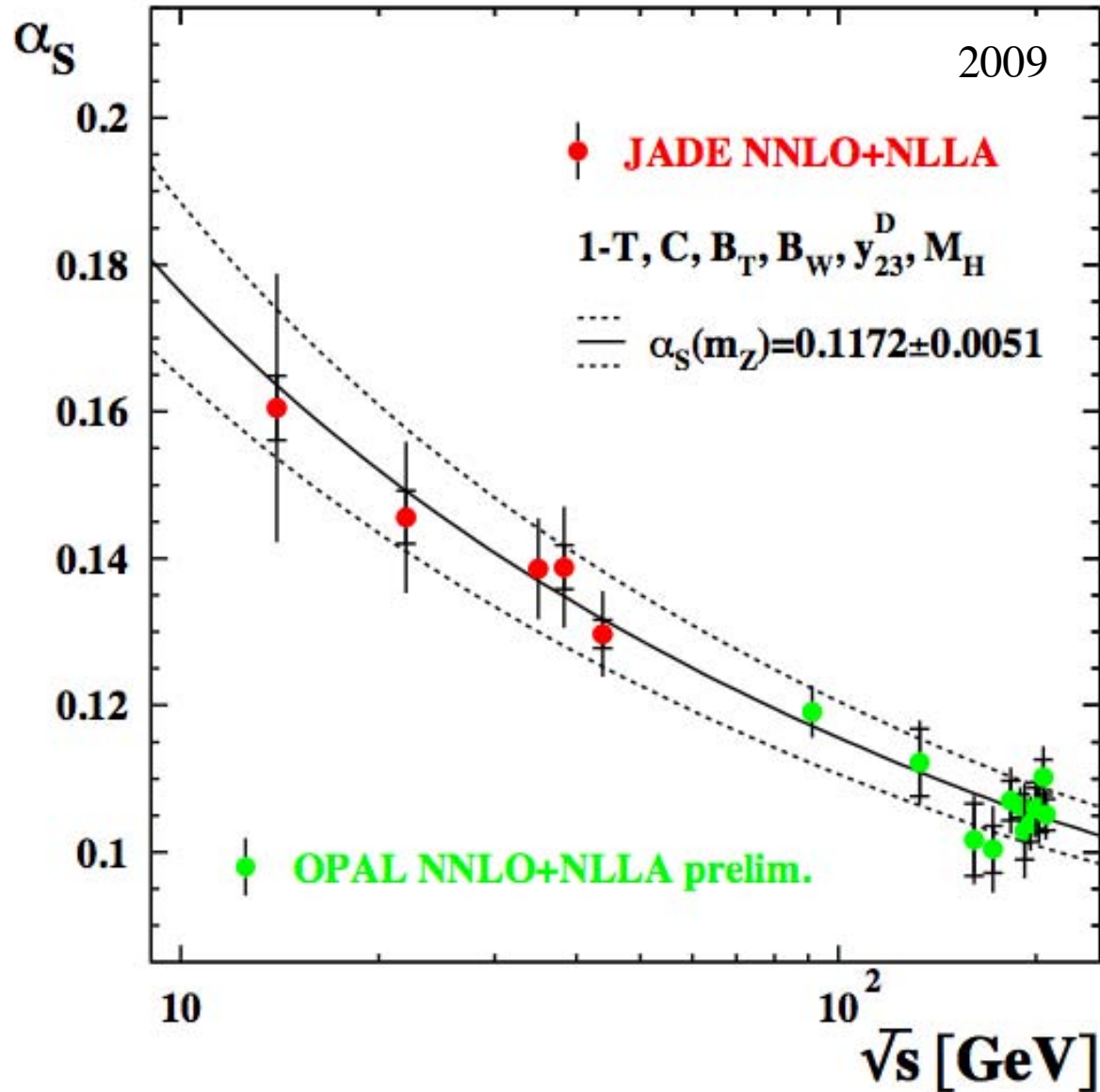
Ellis, Ross & Terrano (ERT);  
Kunszt & Nason, Catani & Seymour

in NNLO: A. Gehrmann-de Ridder et al., 2007

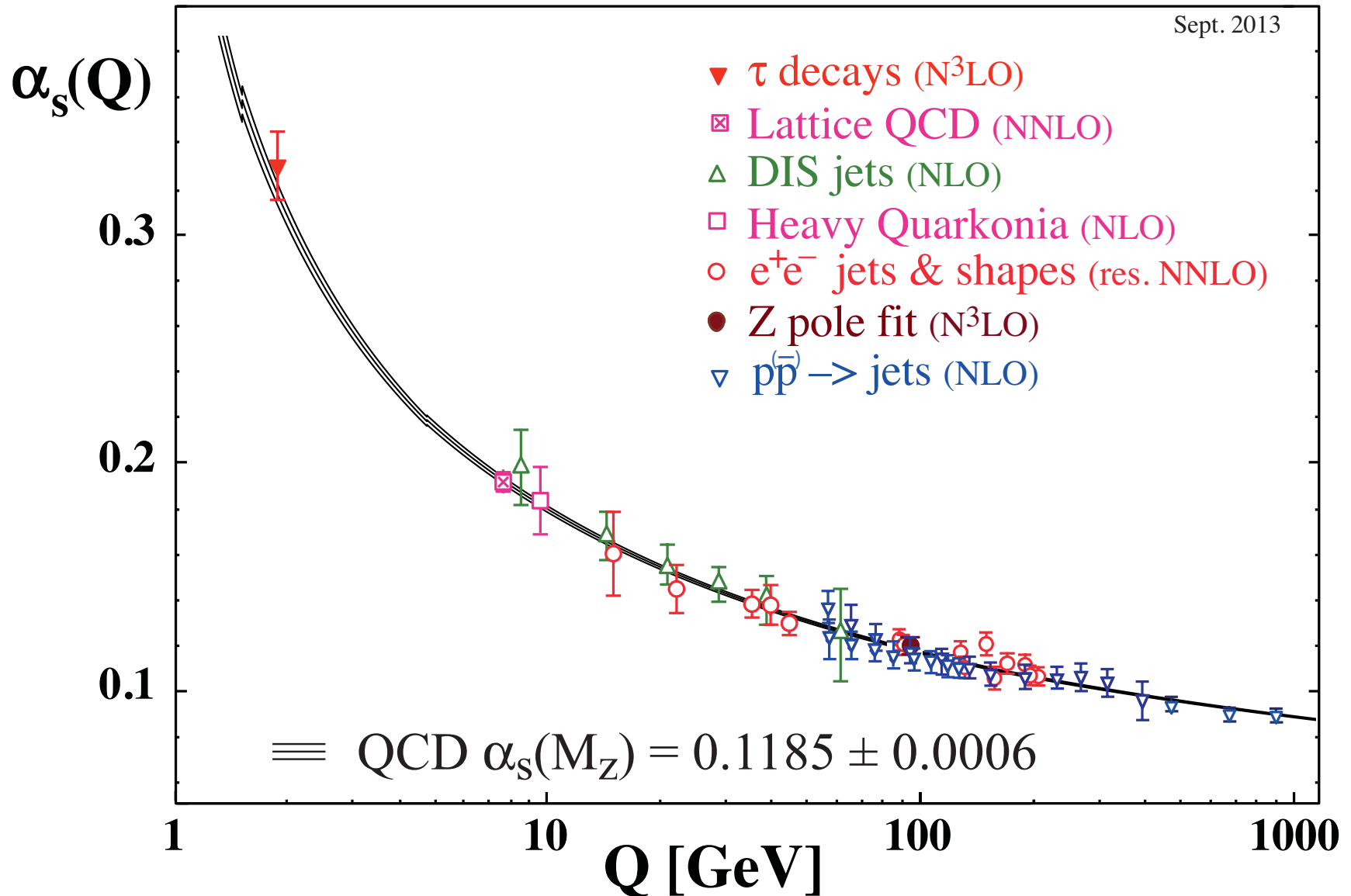
- plus resummation of leading and next-to-leading logarithms (NLLA) → "matching schemes"

Catani, Trentadue, Turnock, Webber

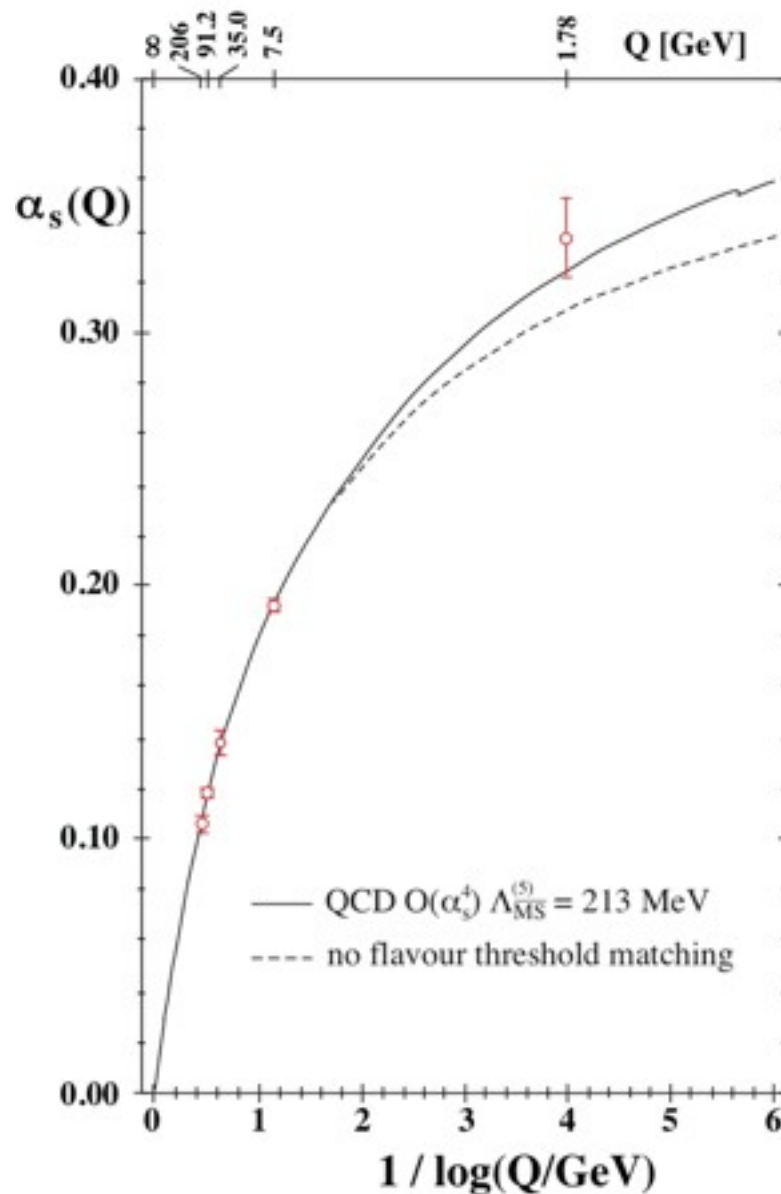
# $\alpha_s$ aus Jetraten und event shapes in NNLO QCD:



# globale Zusammenfassung der Messungen von $\alpha_s$



# Evidence for Asymptotic Freedom:



# Zusammenfassung:

- QCD als Eich-Feldtheorie der Starken Wechselwirkung etabliert:
  - asymptotische Freiheit aus Energieabhängigkeit der Jetraten und von  $\alpha_s$  experimentell verifiziert
  - Farbladung der Gluonen etabliert
  - Spins der Quarks (1/2) und der Gluonen (1) gemessen
- Quarks und Gluonen existieren nicht als freie Teilchen, sondern nur in gebundenen, „farblosen“ Zuständen (Hadronen)
- bei hohen Reaktionsenergien folgen Hadronen den Richtungen der erzeugten primären Quarks und Gluonen („Jets“)
- präzise Messungen der Eigenschaften der Jets ermöglichen quantitative Tests der QCD
- Messung von  $\alpha_s$  aus vielen Reaktionen:  
 $\alpha_s(M_Z) \sim 0.12 \quad (0.1185 \pm 0.0006)$



# Literaturempfehlungen

- Ellis, Stirling, Webber: “QCD and Collider Physics”, Cambridge Monographs,
- A QCD primer, G. Altarelli, CERN School 2001,  
<http://preprints.cern.ch/cernrep/2002/2002-002/2002-002.html>
- Quantum Chromodynamics, M.H.Seymour, 2004 European School of High-Energy Physics, hep-ph/0505192
- *QCD Studies at LEP*, S. Bethke, Phys. Rept. 403-404 (2004) 203-220,  
hep-ex/0406058
- *The 2009 World Average of  $\alpha(s)$* , S. Bethke, Eur.Phys.J. C64:689-703, 2009.  
arXiv:0908.1135 [hep-ph]