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

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

QCD an Hadron-Bechleunigern: –> WS

Geschichte der Starken Wechselwirkung (1)

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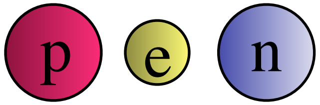
1932: Entdeckung des Neutrons



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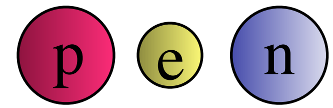

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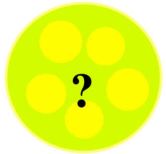

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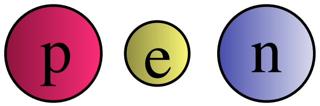

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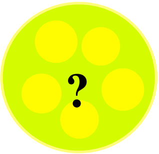

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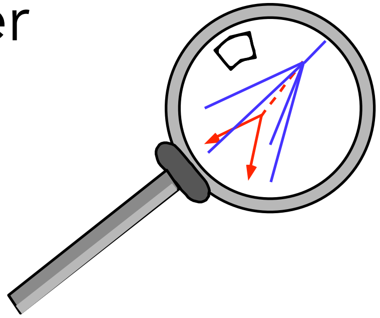

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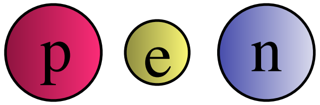

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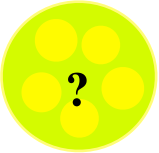

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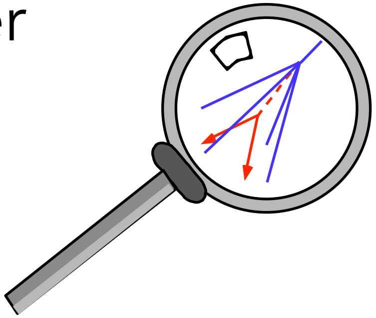

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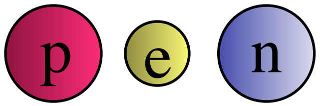

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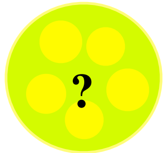

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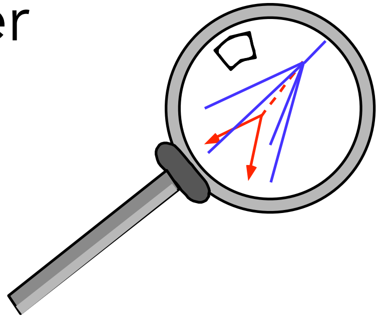

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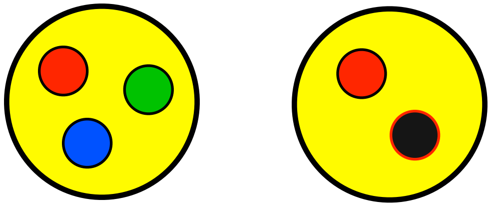

Baryon (p,n, Λ,...)   Meson (π,K,...)

Geschichte der Starken Wechselwirkung (2)

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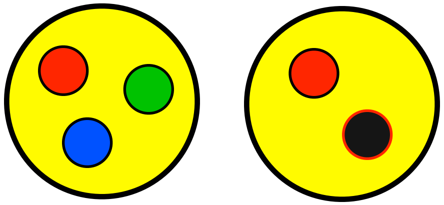

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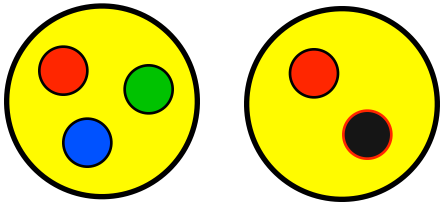

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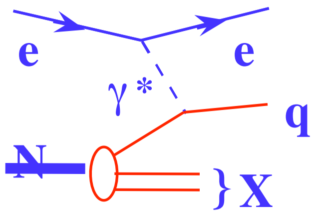

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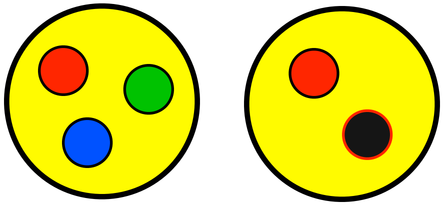

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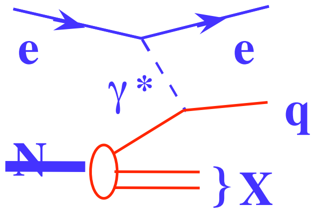

1973: Konzept der Asymptotischen Freiheit ;
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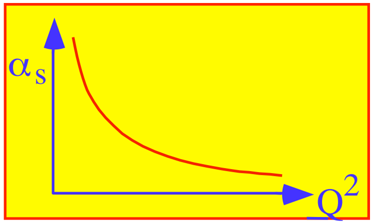

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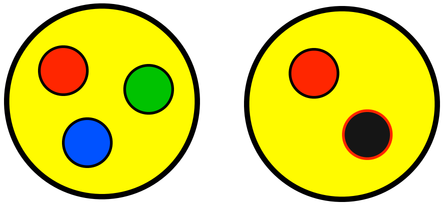

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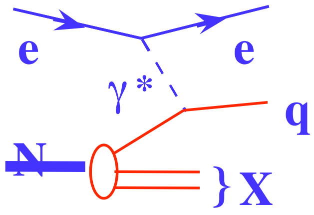

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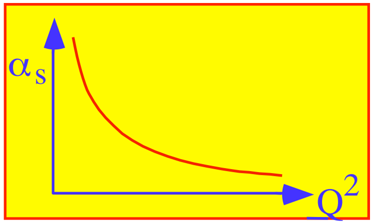
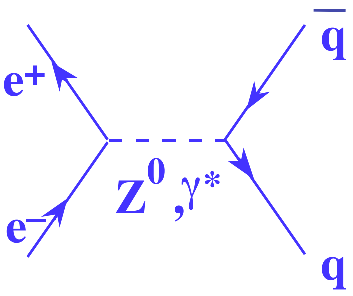


1975: 2-Jet Struktur in $e^+ e^-$-Vernichtung:
Bestätigung Quark-Parton-Modell.



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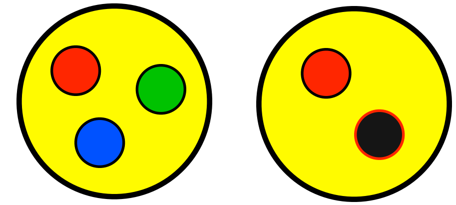

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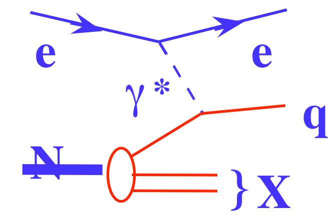

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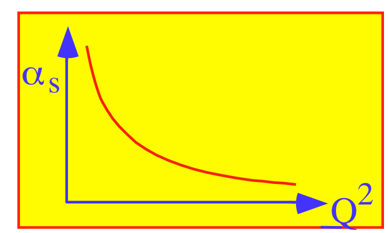

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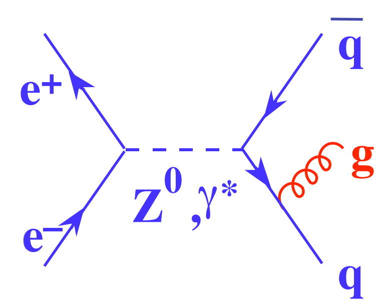
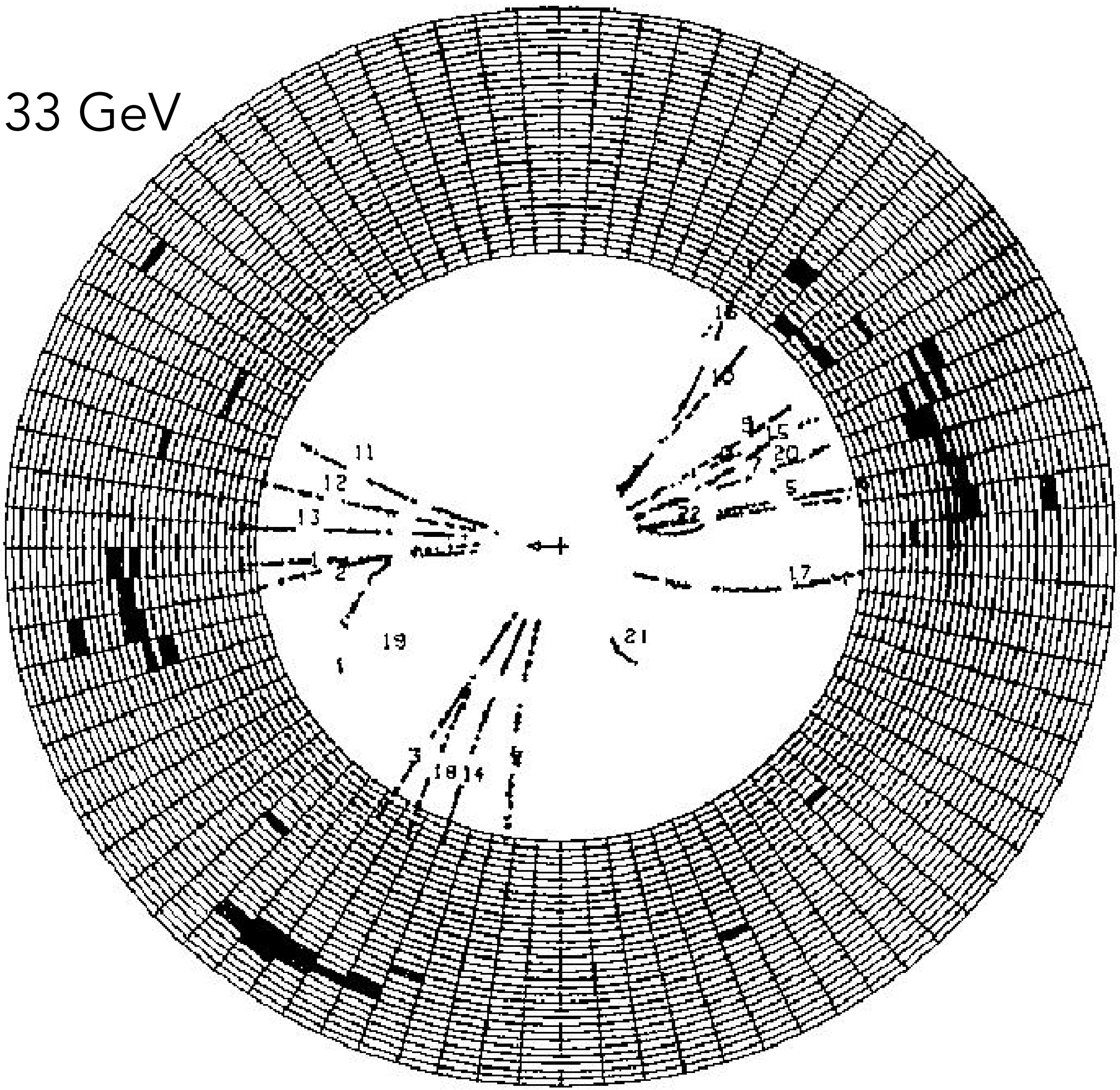


1979: Entdeckung des Gluons in 3-Jet-Ereignissen der $e^+ e^-$-Vernichtung.

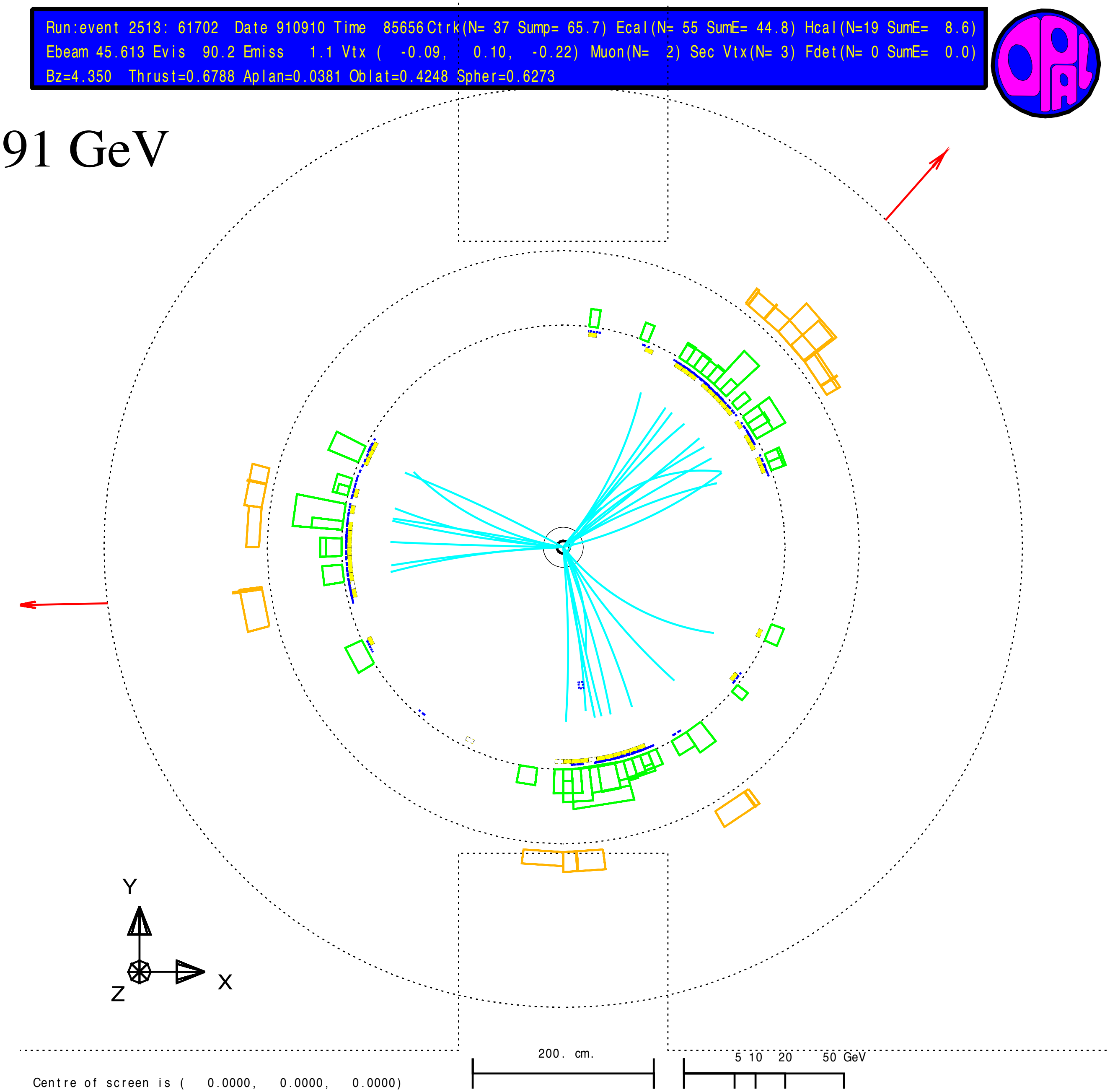
3-Jet Ereignis gemessen mit dem JADE Detektor (1979-1986)

E_{cm} ~33 GeV



3-Jet Ereignis gemessen mit dem OPAL Detektor (1989-2000)

$E_{cm} = 91$ GeV



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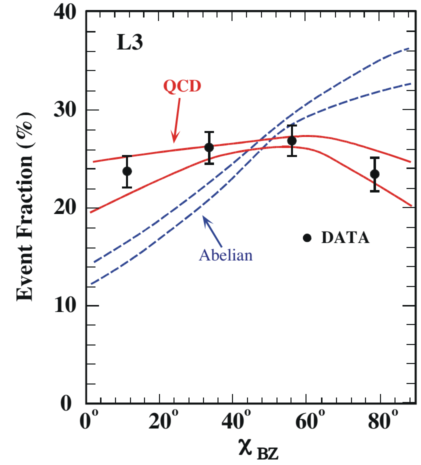

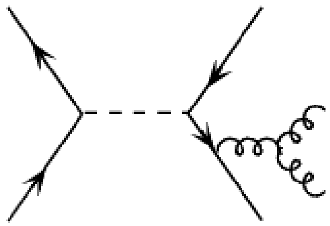

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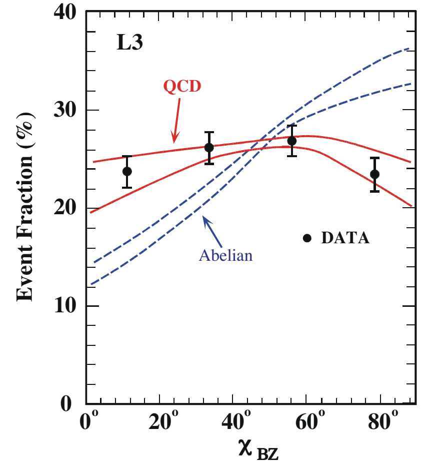
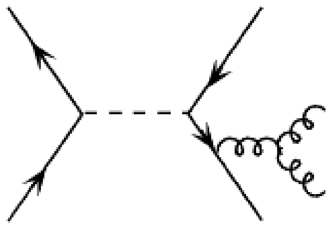
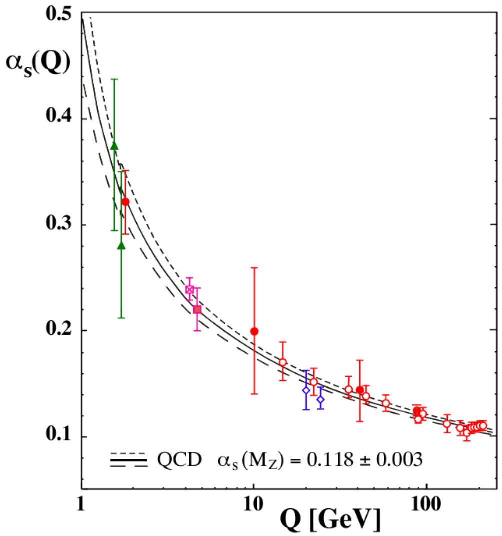




1990-2000: Bestätigung der Asymptotischen Freiheit



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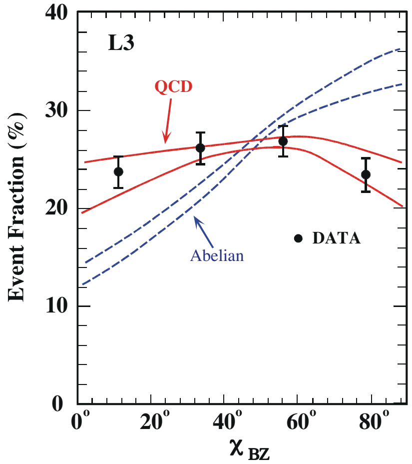

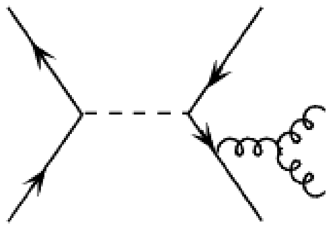

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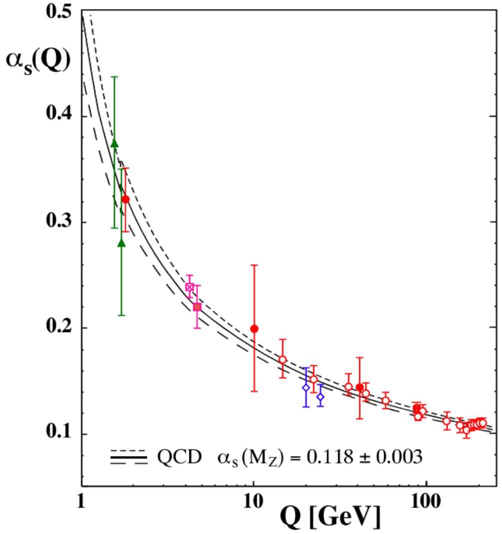
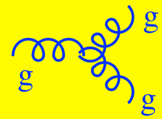
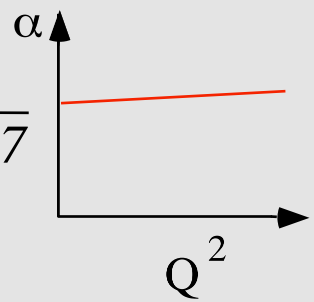
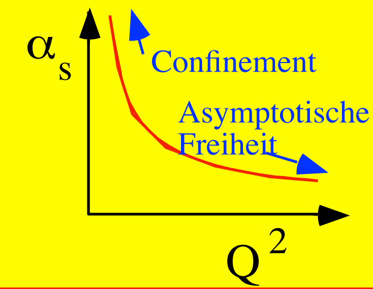


2004: Nobelpreis (Konzept der A.F.) an
D. Gross, H.D. Politzer und F. Wilczek

QCD:

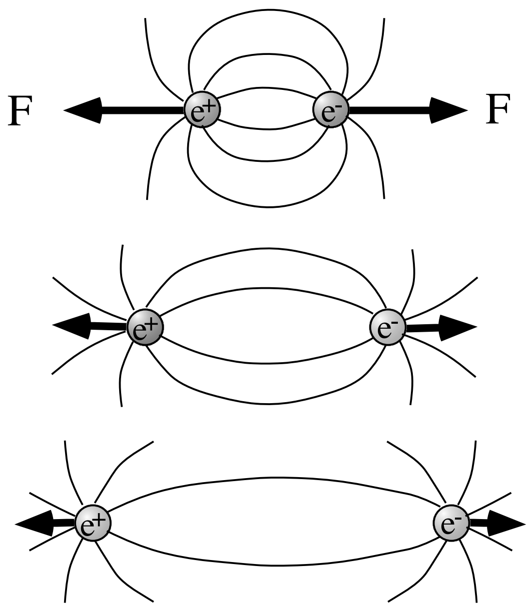
- Eich-Feldtheorie der Starken Wechselwirkung
- zugrunde liegende Eichgruppe: SU(3) ; nicht-abelsch
- „Kraft“- oder Austausch-Teilchen: Gluonen
- Selbstwechselwirkung der Gluonen
- renormierte Kopplungskonstante α_s ist energieabhängig:
- α_s groß bei kleinen Energien (grossen Abständen):
  Confinement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

Eigenschaften der QED und der QCD :

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

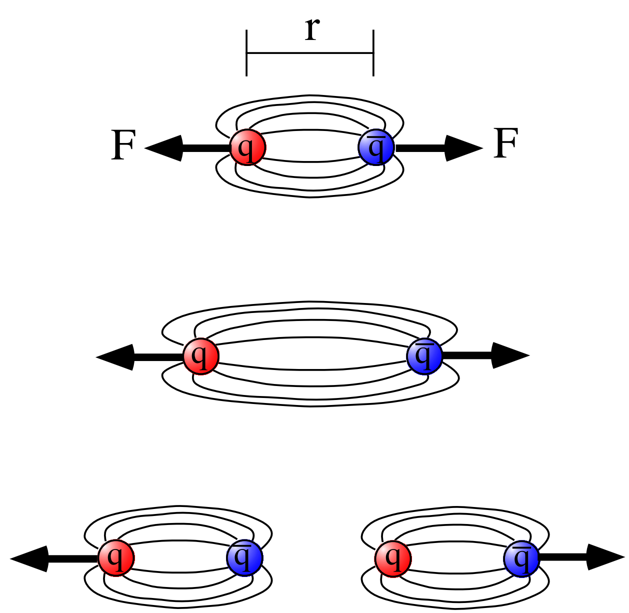
Warum gibt es keine freien Quarks?

QED	QCD
Elektrische Ladungen: Kraft $F \propto 1/r^2$; Energiedichte $\propto 1/r$	Farbladungen: Kraft $F \propto$ const ; Energiedichte $\propto r$



Kraft- und Energiedichte zwischen Ladungsträgern nimmt ab.

⇒ Träger elektrischer Ladung sind freie Teilchen



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:

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} \alpha_i(\mu) = -\beta_0 \, \alpha_i^2$$

mit

$$\beta_0 = \frac{1}{2\pi}\left[\frac{11}{3}\begin{pmatrix} N_c \equiv 0 \\ N_c \equiv 2 \\ N_c \equiv 3 \end{pmatrix} - \frac{4}{3}\begin{pmatrix} N_{fam} \\ N_{fam} \\ N_f/2 \end{pmatrix} - N_{Higgs}\begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}\right] \begin{matrix} \longleftarrow \text{QED} \\ \longleftarrow \text{weak} \\ \longleftarrow \text{QCD} \end{matrix}$$

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- Integration ⇒

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

or

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

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

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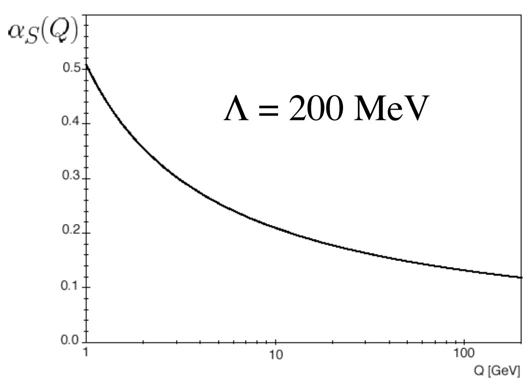
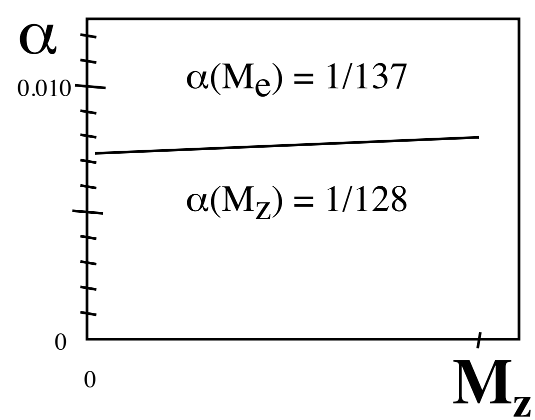
QCD: $N_c = 3$; $\beta_0 = \frac{23}{6\pi}$



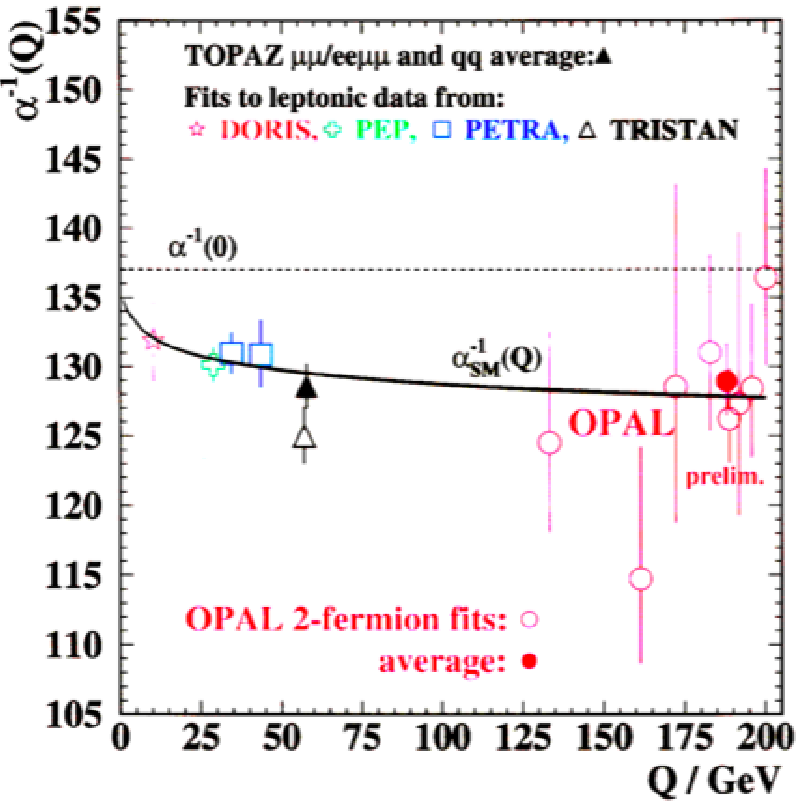
QED: $N_c = 0$; $N_{fam} = 3$ $\beta_0 = -\frac{12}{6\pi}$



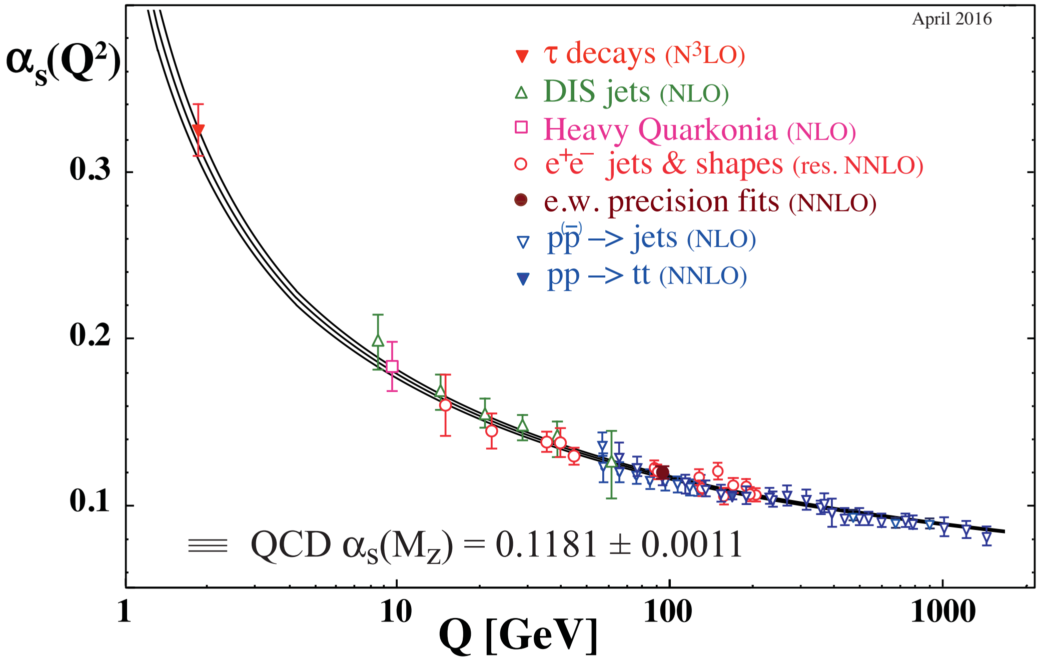
Energieabhängigkeit der Kopplungs"konstanten":

- experimentell mit hoher Genauigkeit verifiziert

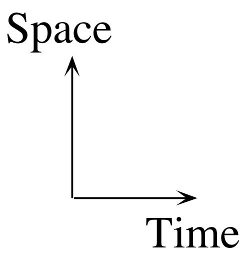
QED



QCD



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



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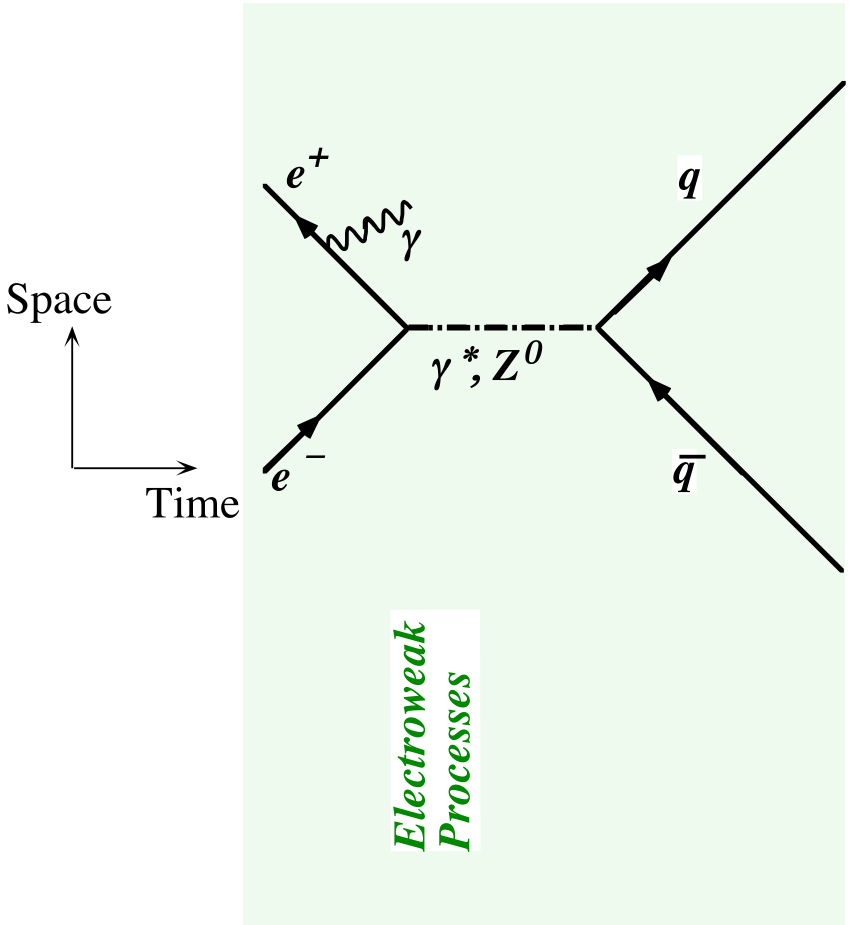

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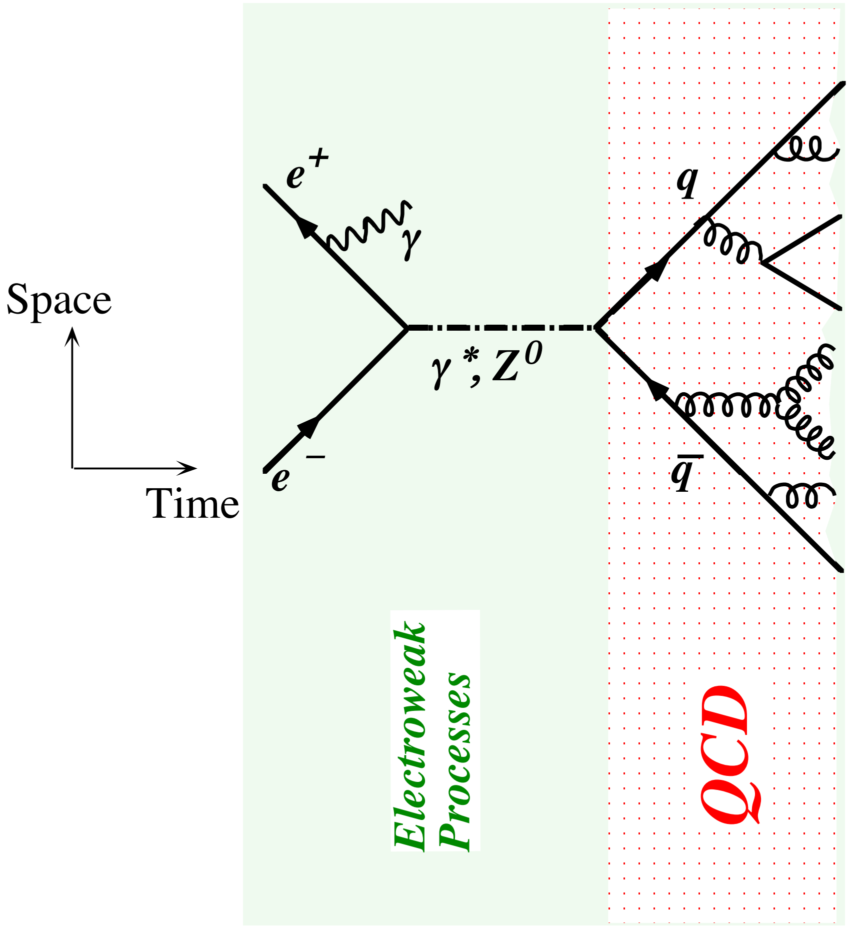

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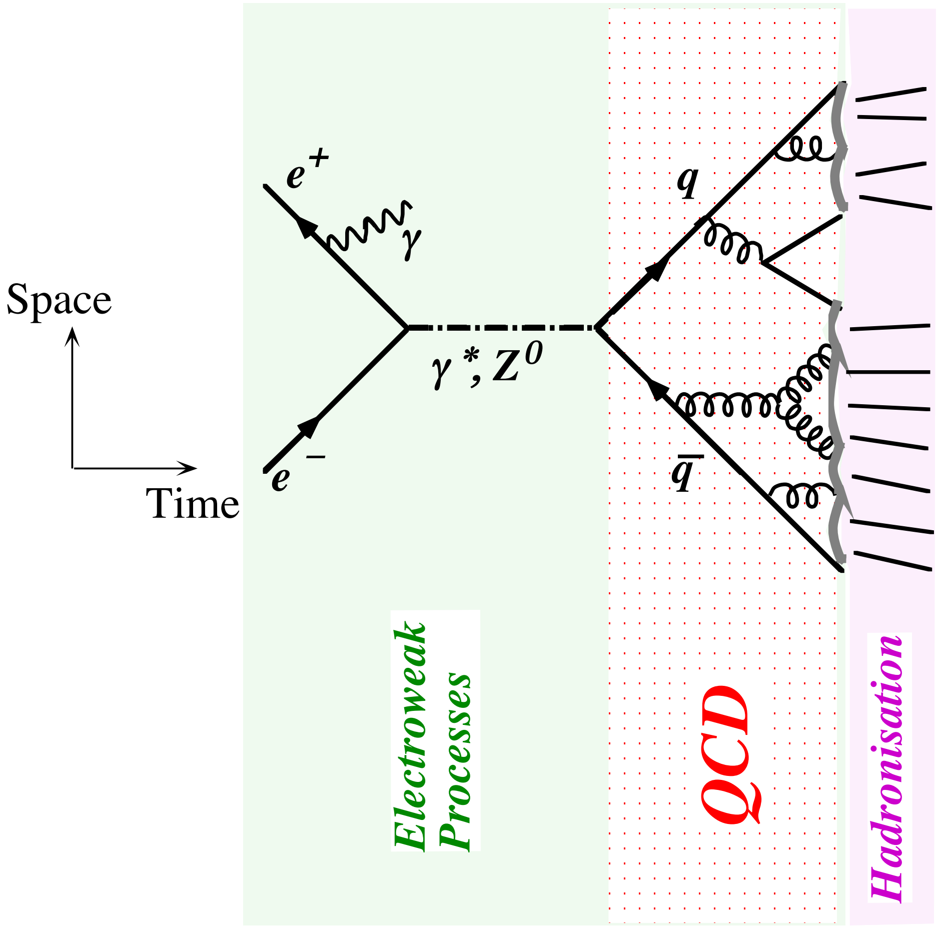

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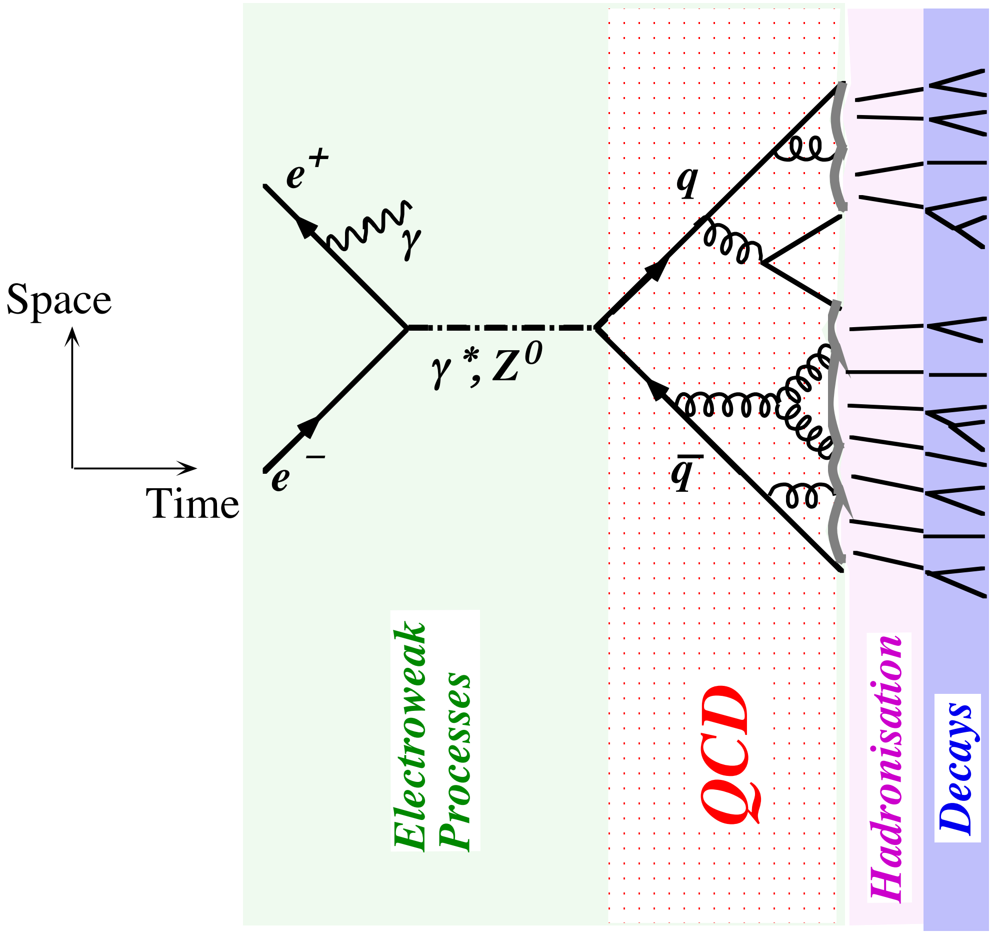

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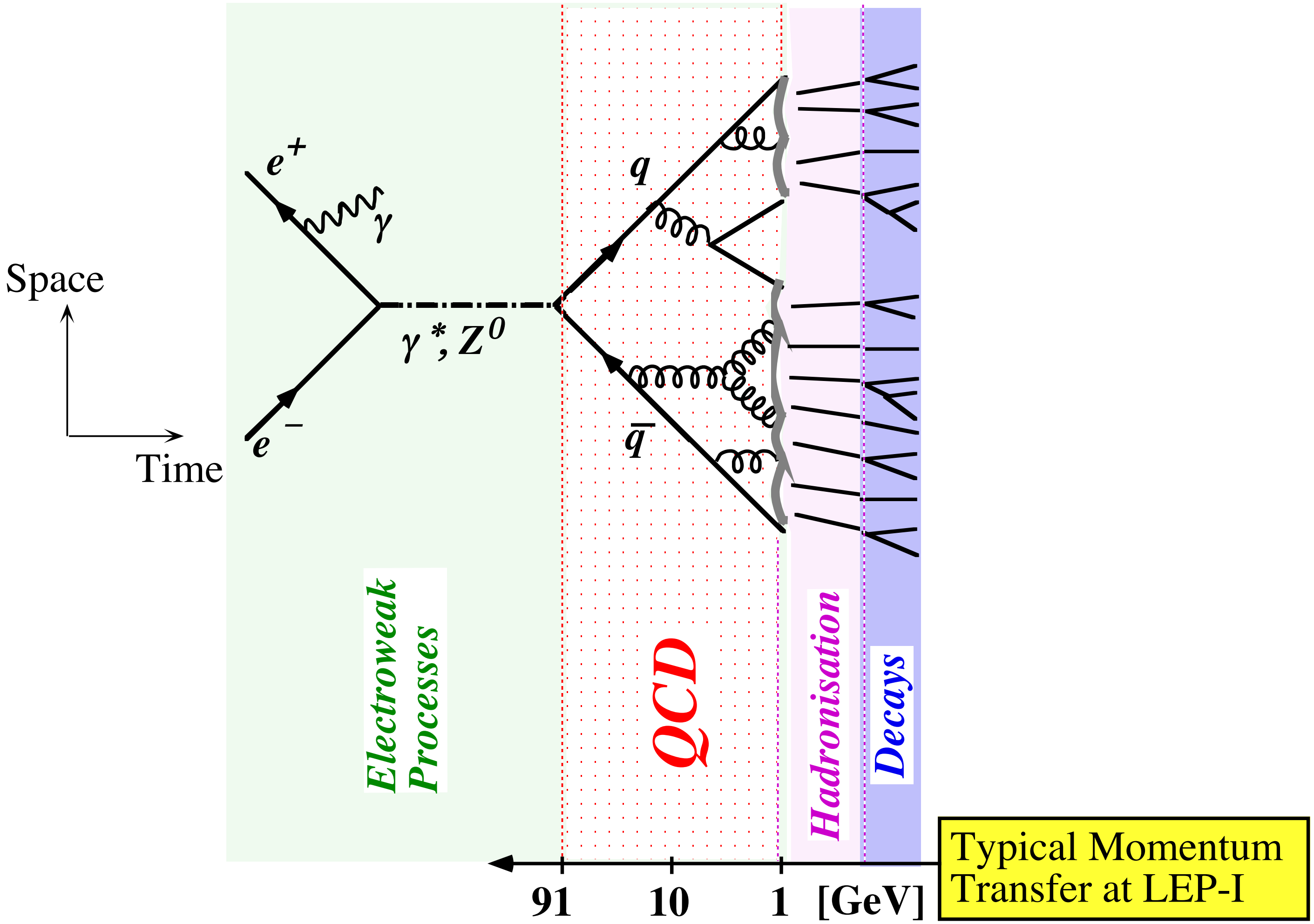

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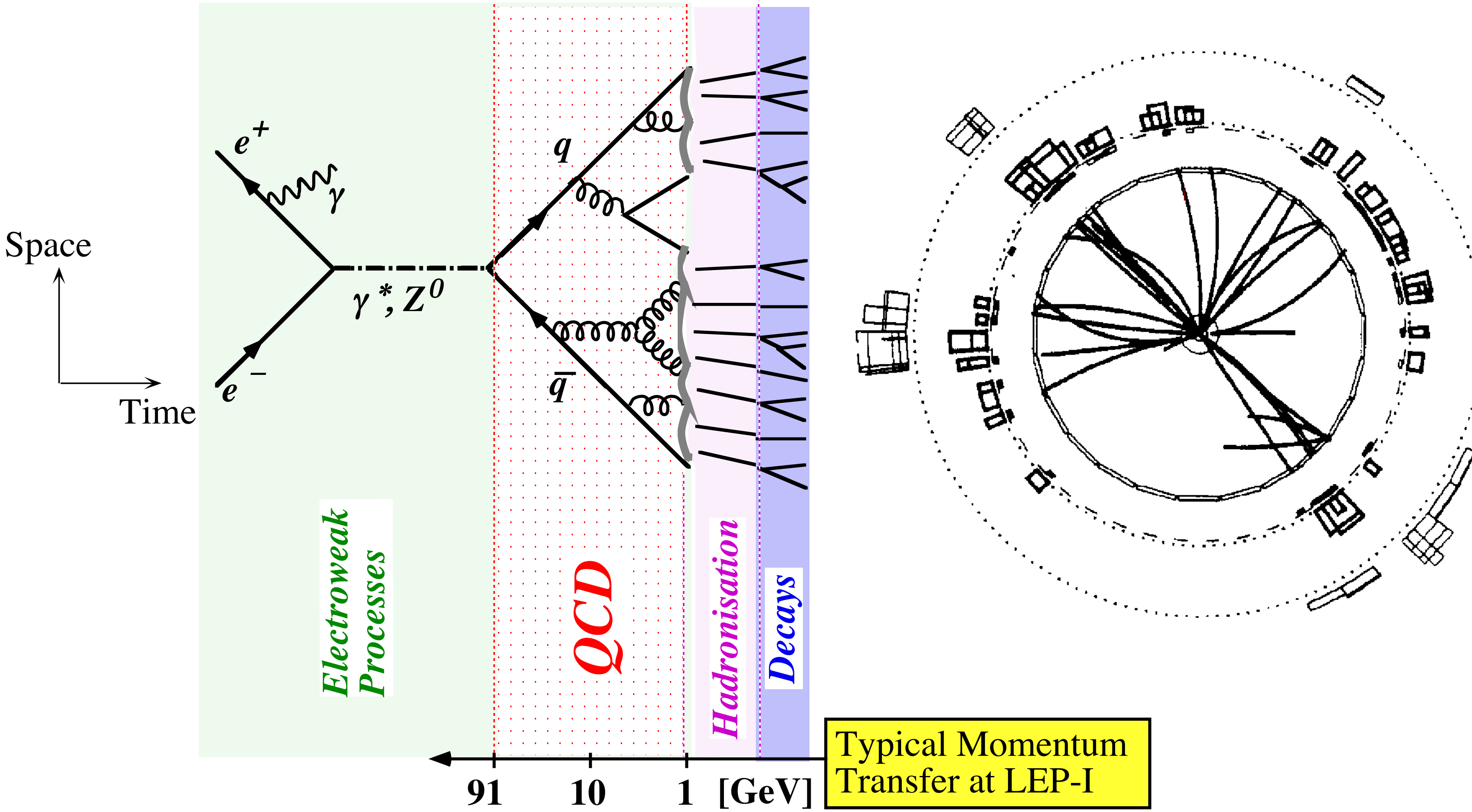

- QCD: shower development calculated in perturbation theory (fixed order; (N)LLA)
- Hadronisation: phenomenological models of string-, cluster- or dipole fragmentation
- Decays: randomized according to experimental decay tables

Physik der Hadronen-Jets

Zum Vergleich von Hadronen-Jets
mit analytischen QCD -Rechnungen
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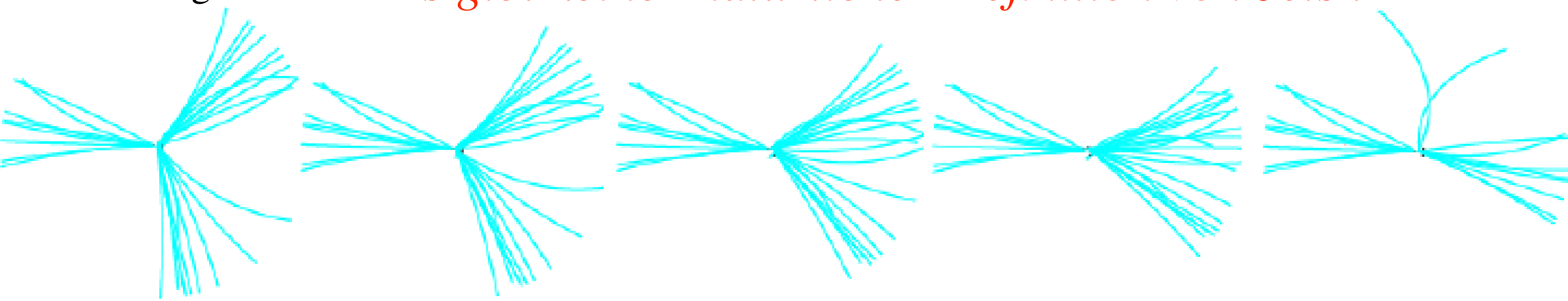

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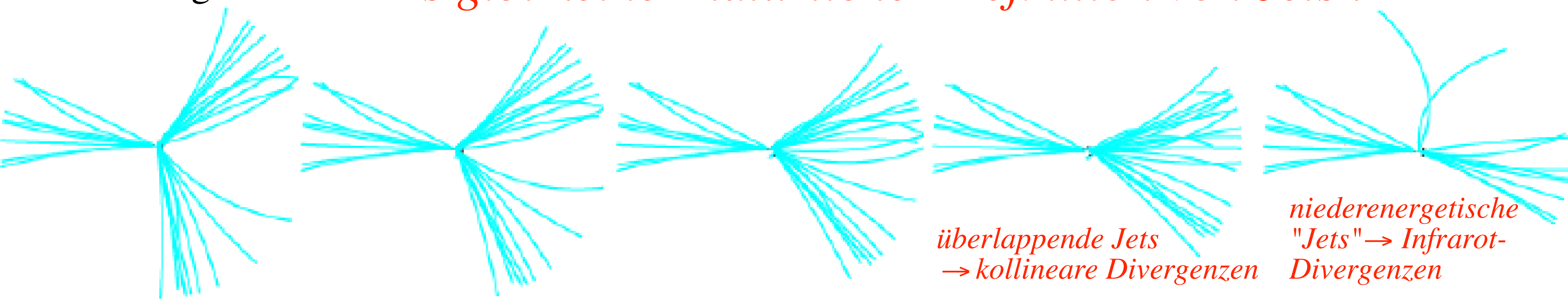

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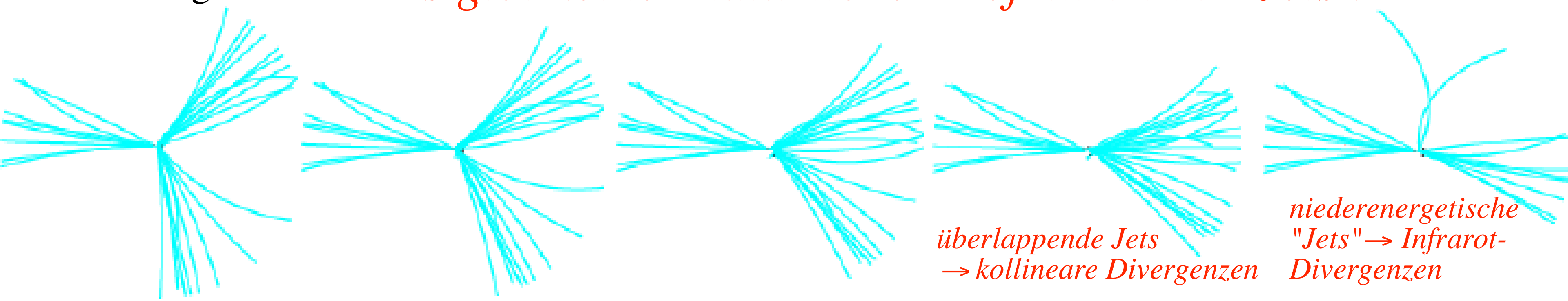

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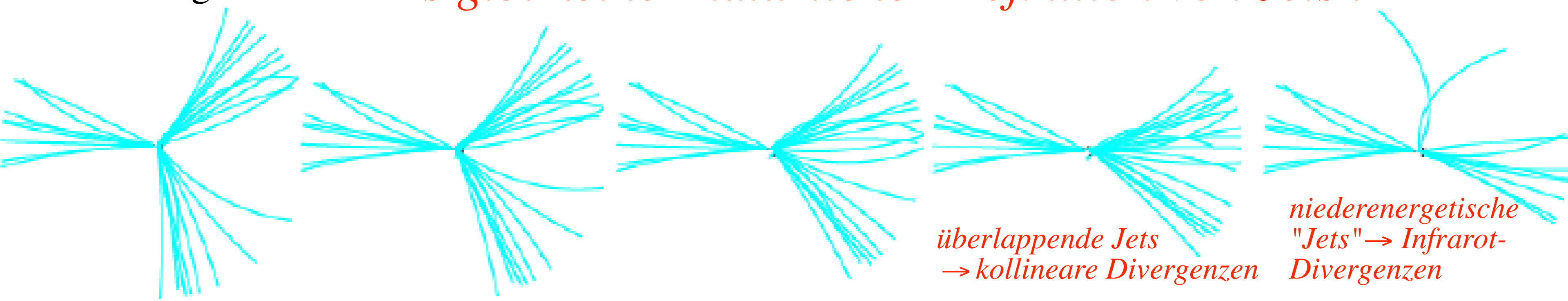

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2 Gruppen von Teilchen, i und j, können aufgelöst werden falls für die minimale transversale Energie der 4er-Vektoren, $y_{ij} = 1/2 \min(E_i^2, E_j^2) \cdot (1 - \cos(\theta_{ij}))$, gilt: $y_{ij} \geq y_{cut}$

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 $y_{ij} \geq y_{cut}$).

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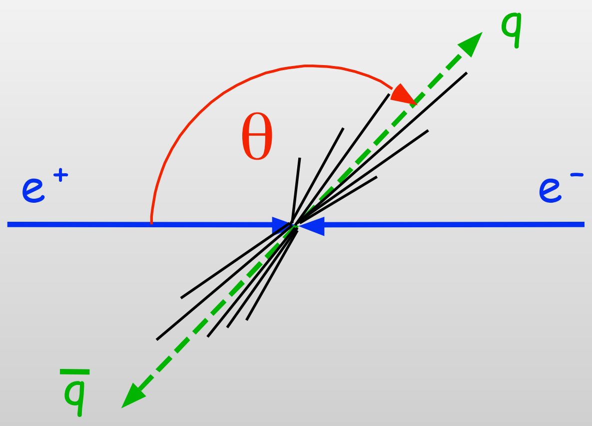
Quark-Spin = 1/2 $\leftrightarrow$ $\frac{d\sigma}{d\theta} \sim (1 + \cos^2\theta)$



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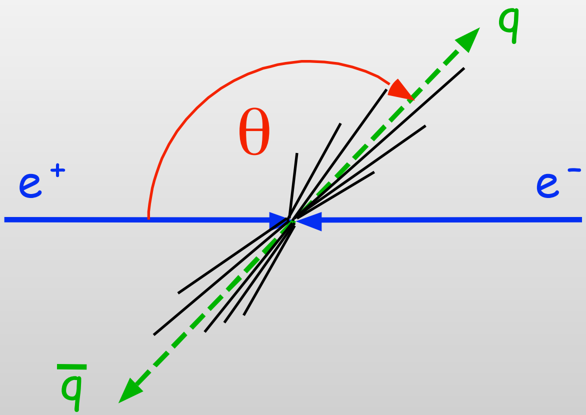

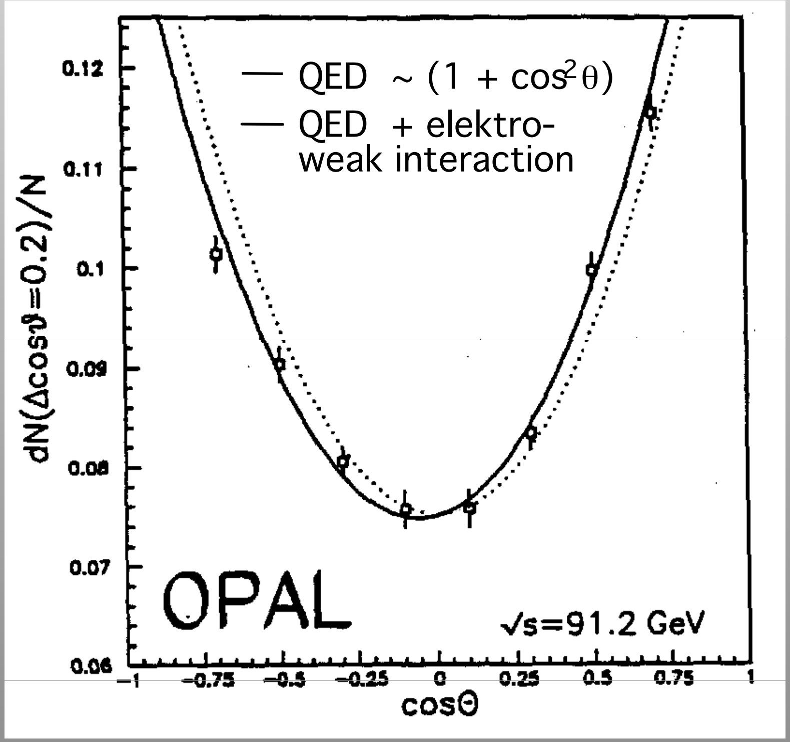

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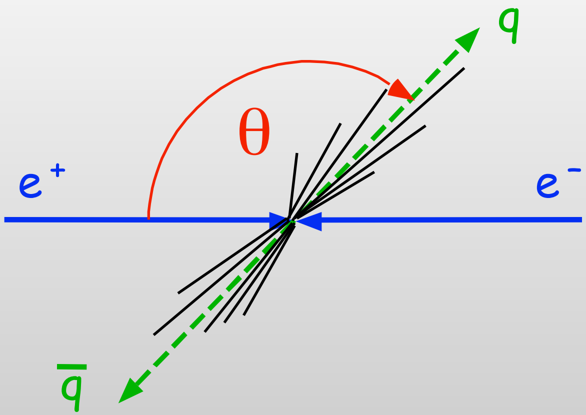

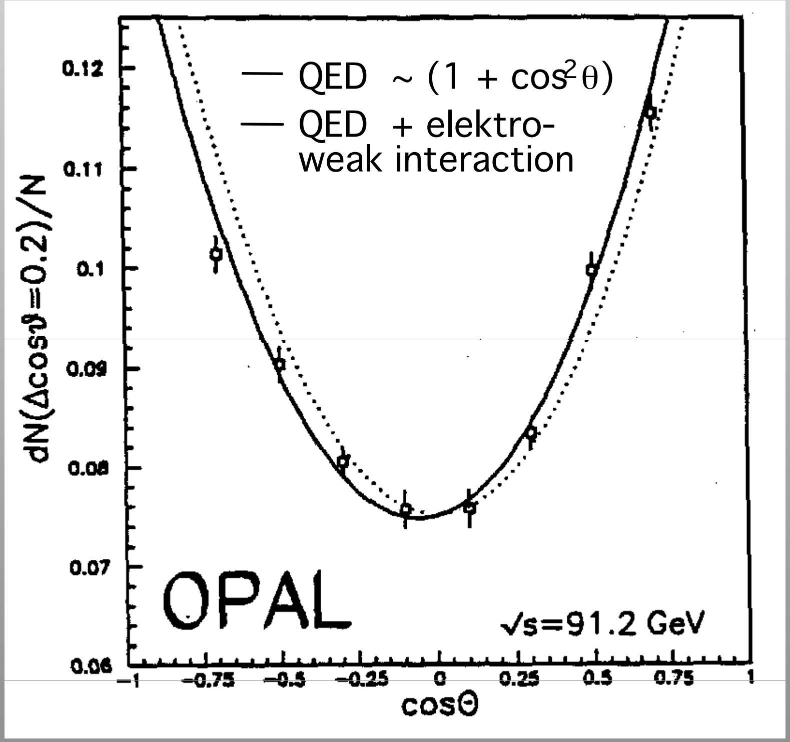

coarse structure: quarks have spin 1/2

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

$\sin^2\theta_W = 0.2255 \pm 0.00212$

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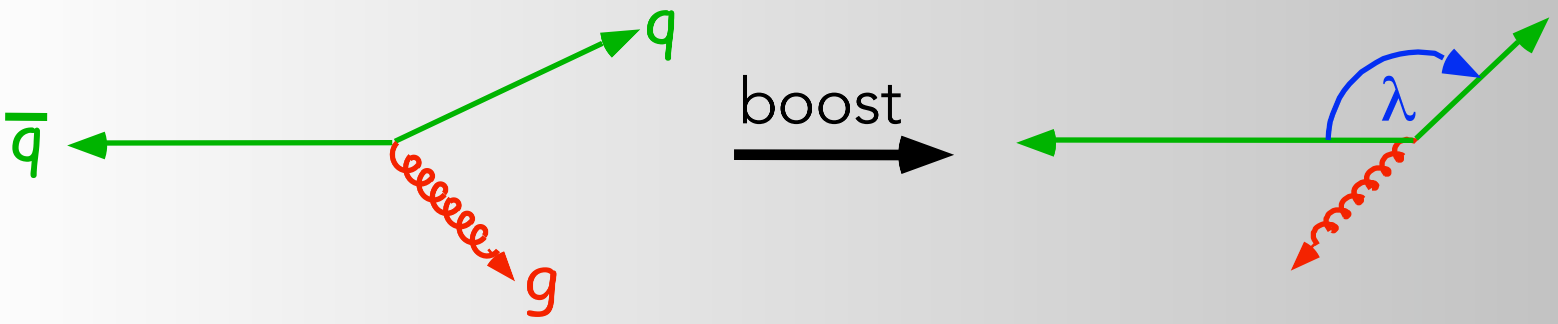

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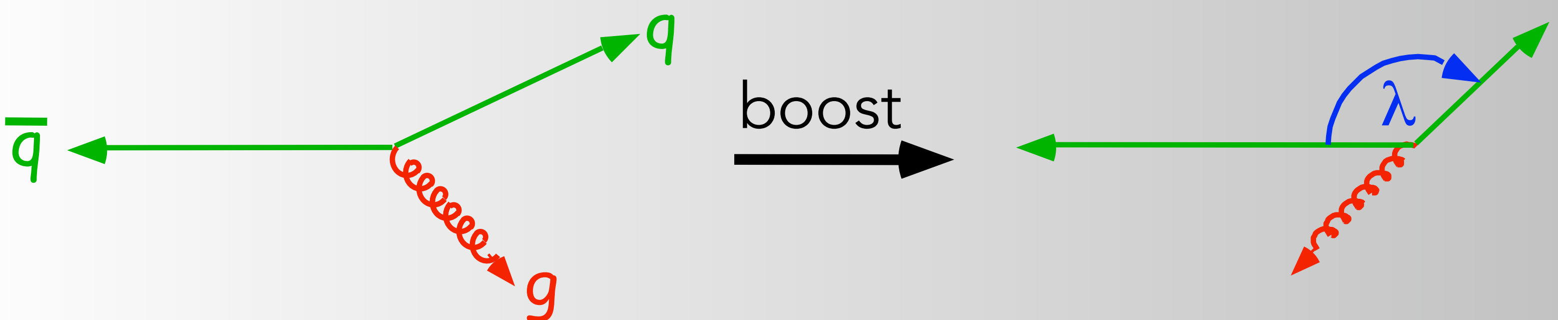

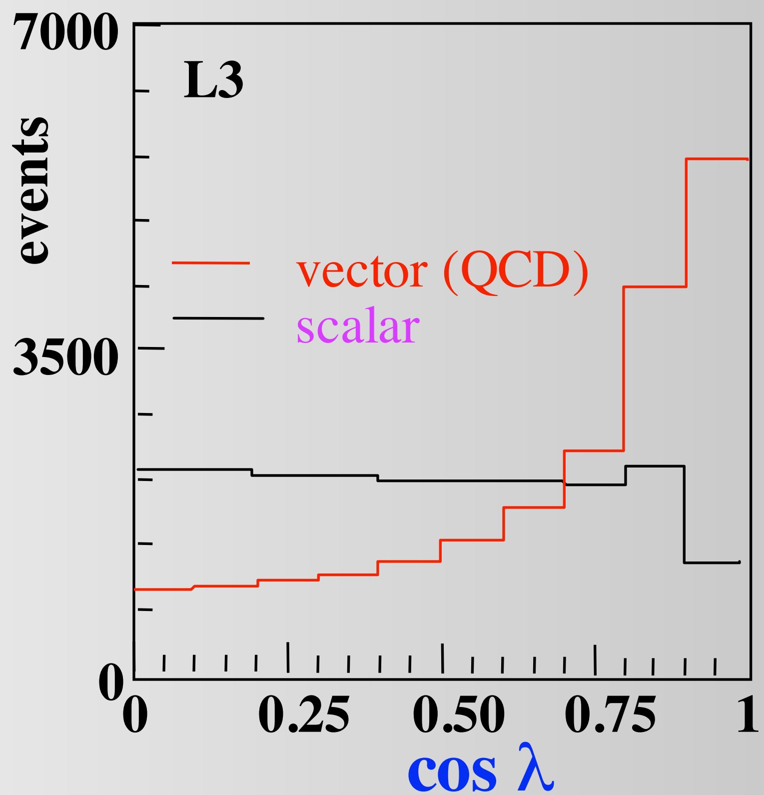

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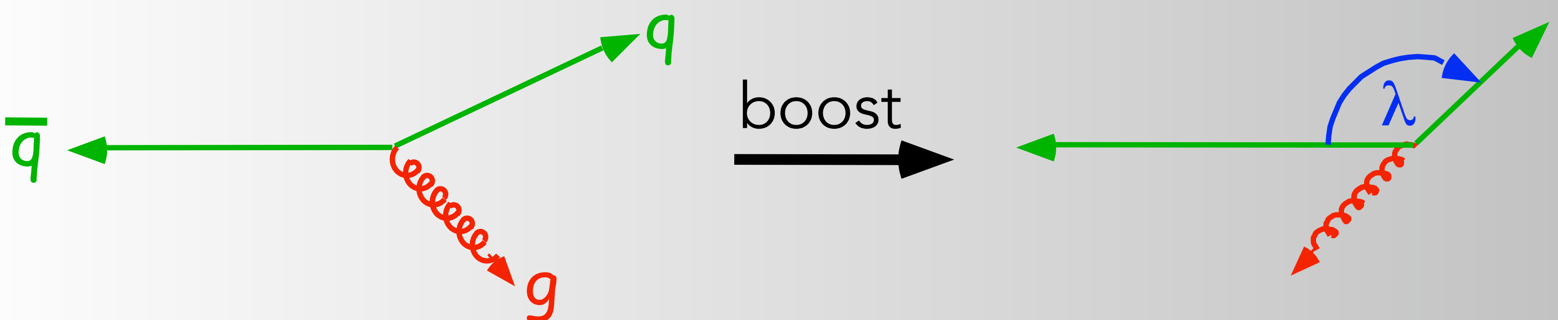
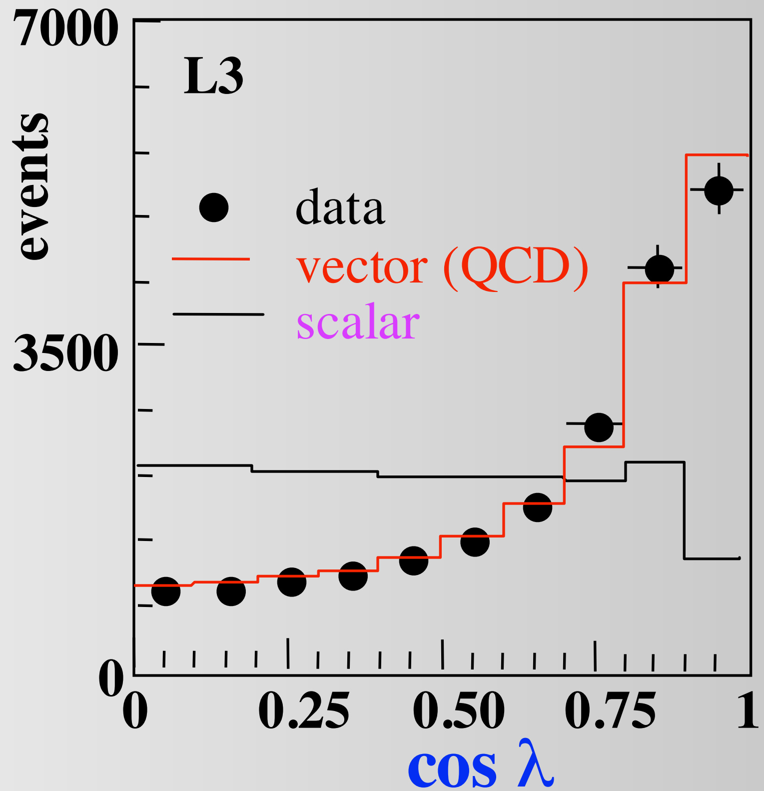
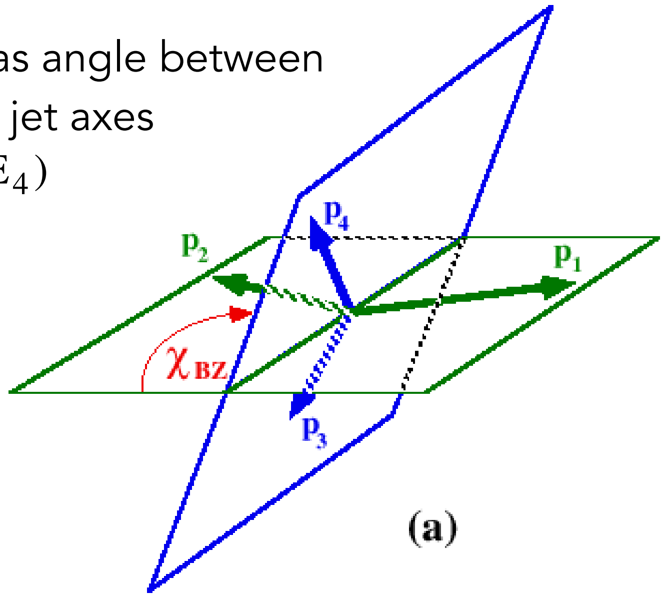




Non-Abelian gauge structure from 4-jet events

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



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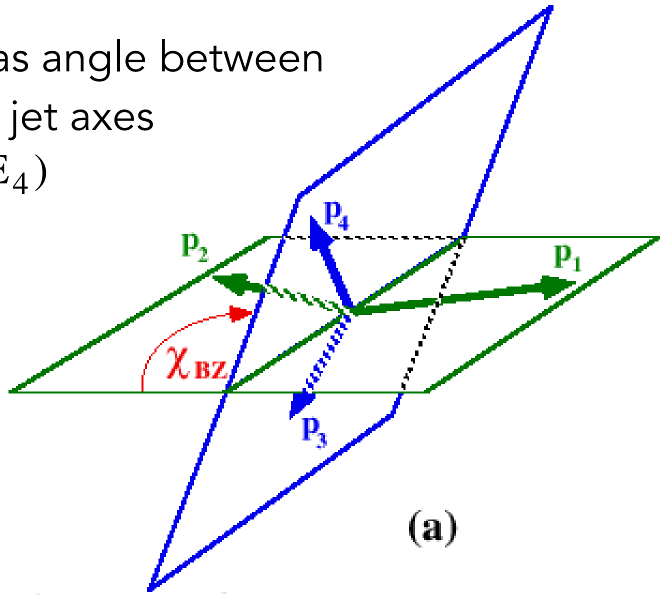

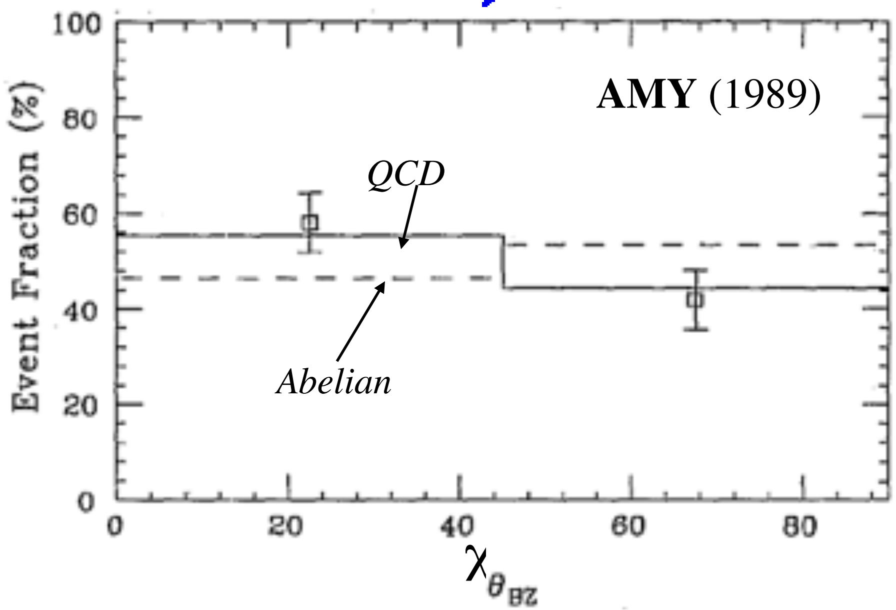

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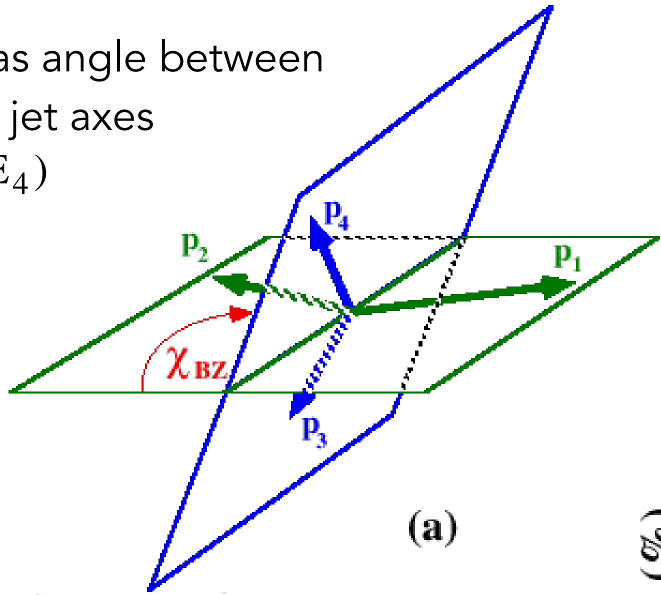

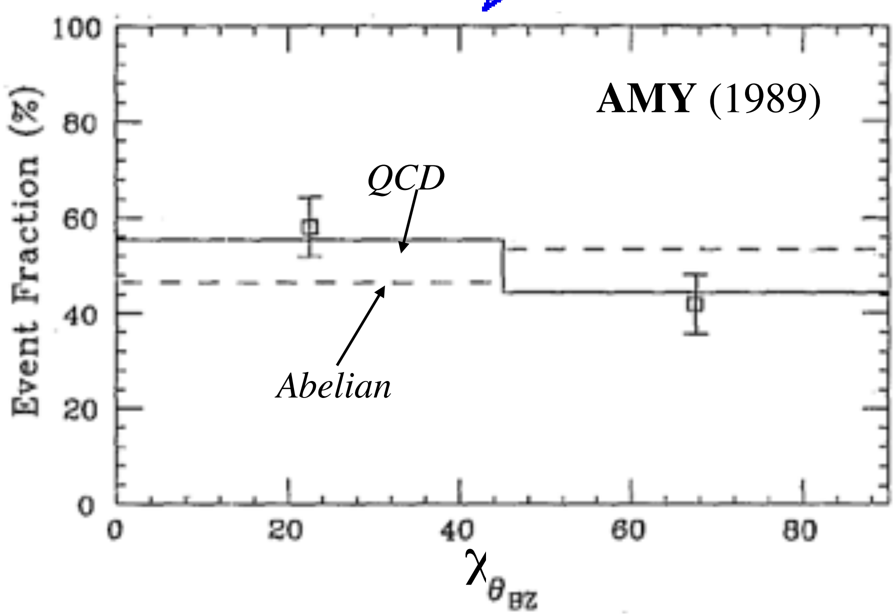

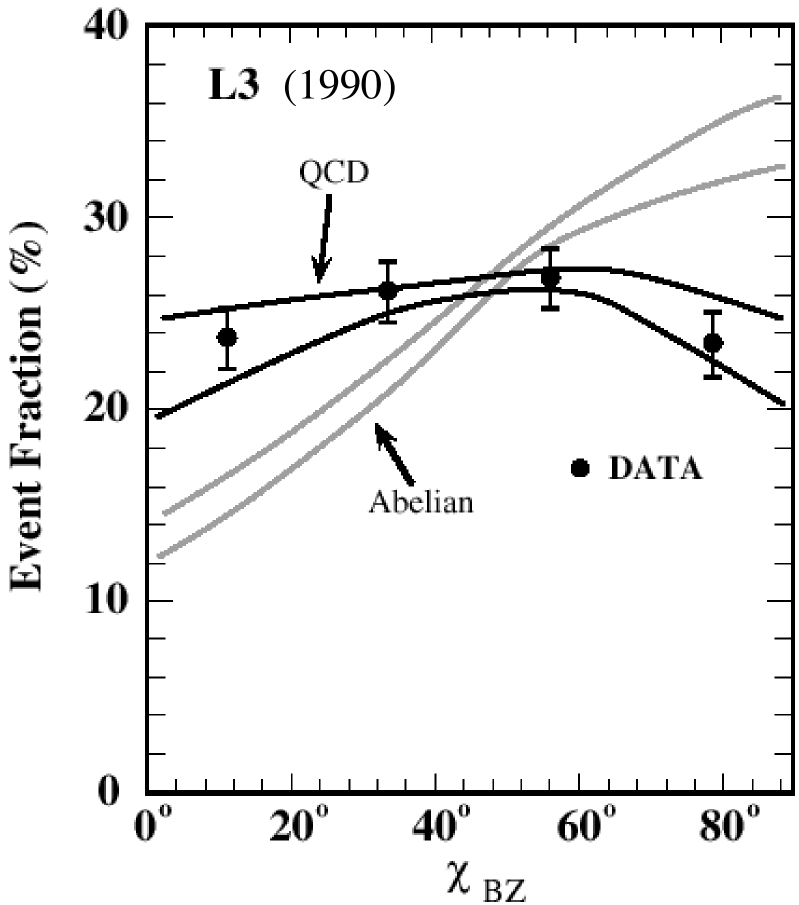

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energy dependence of 3-jet production rates (R_3):

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

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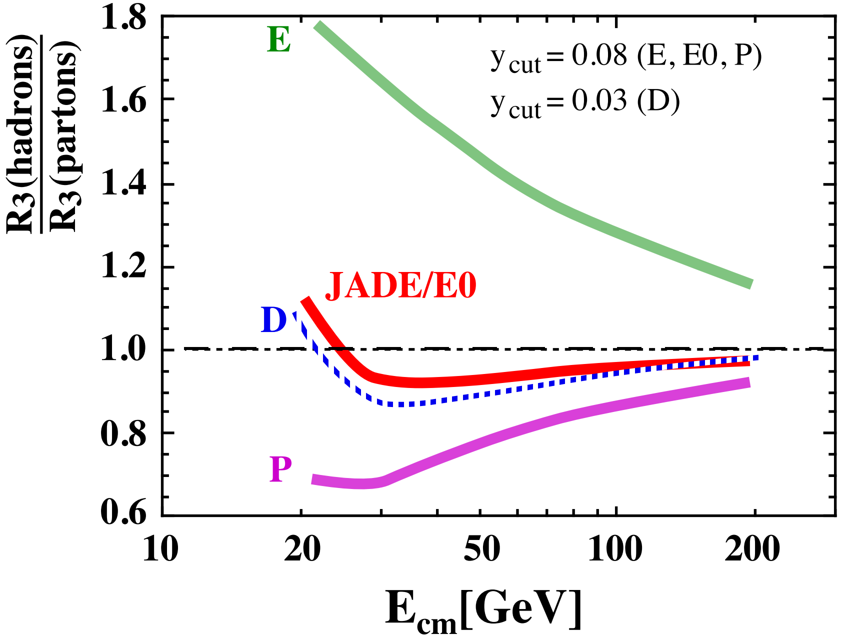

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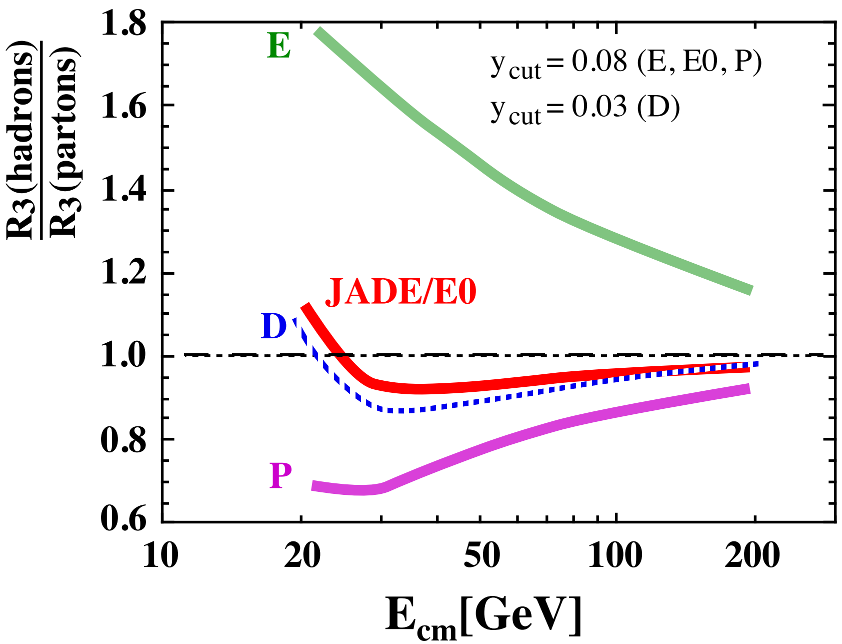

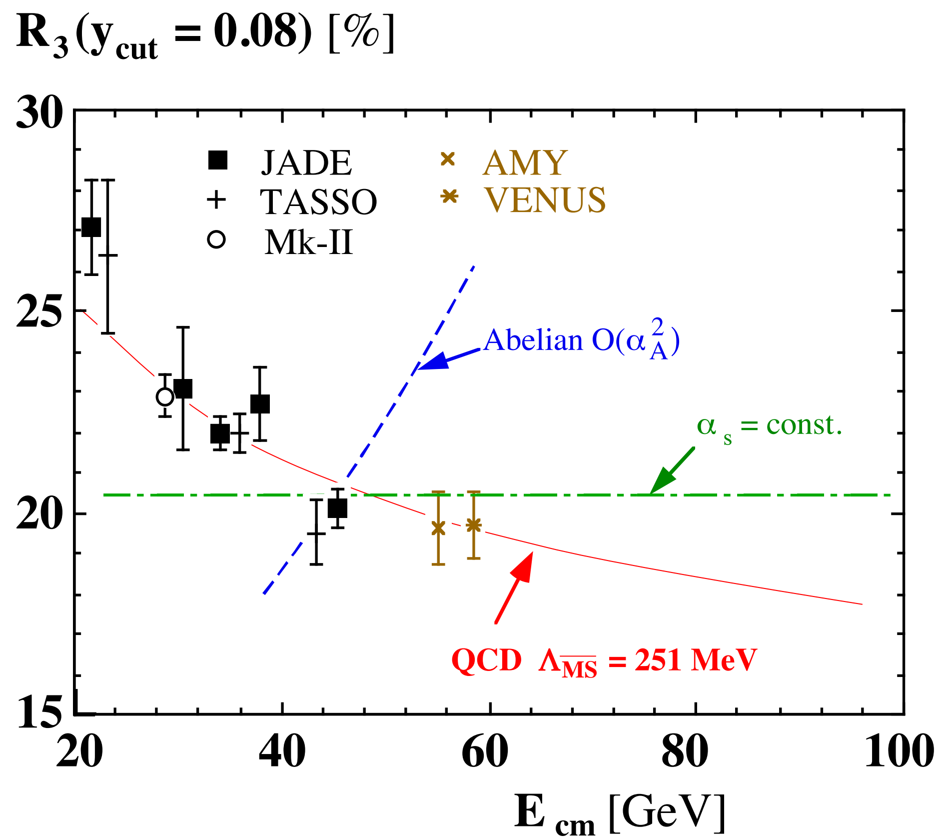

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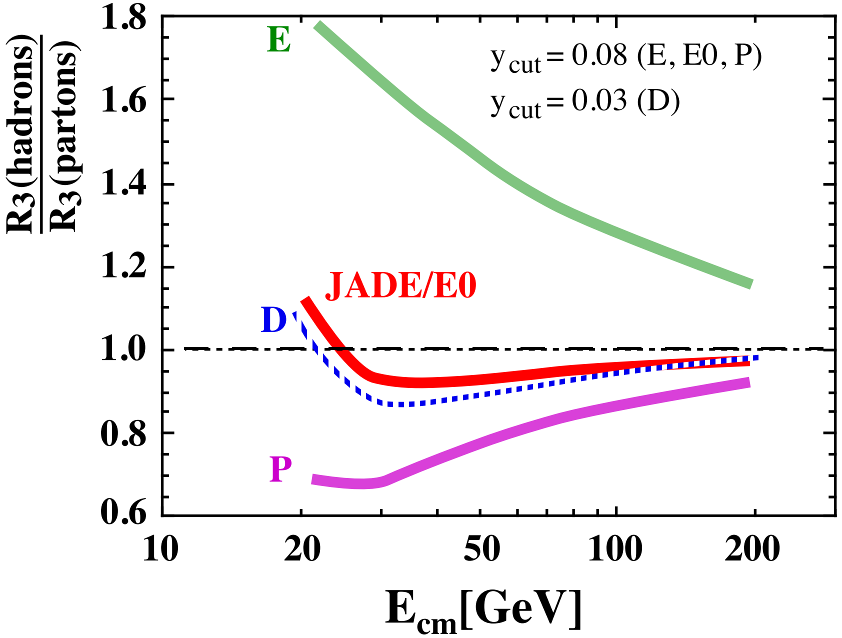
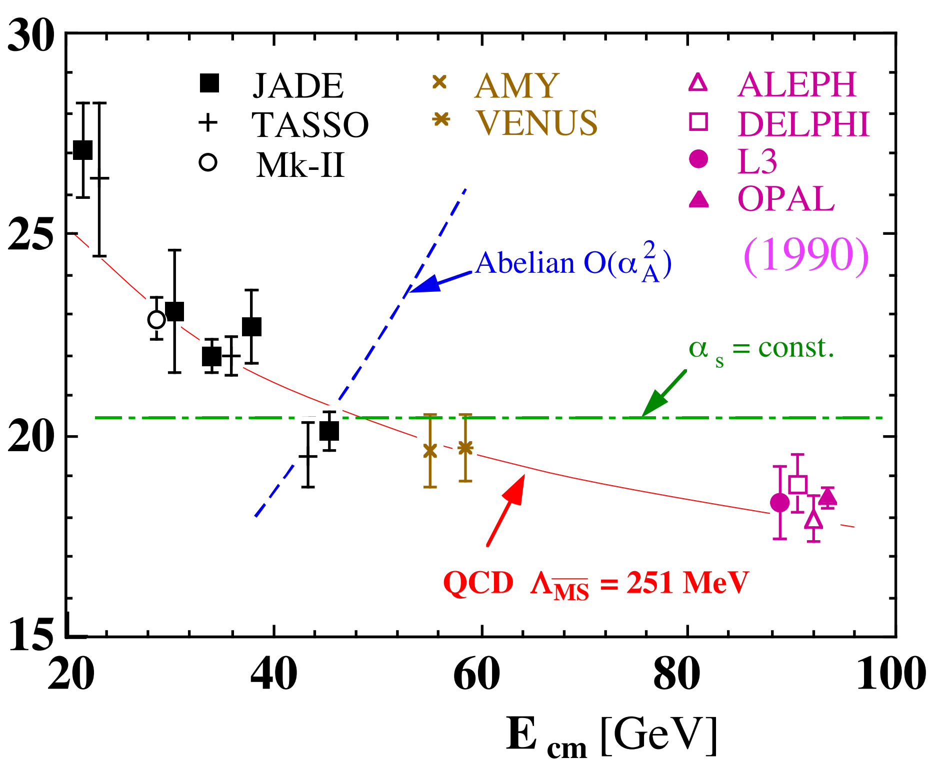
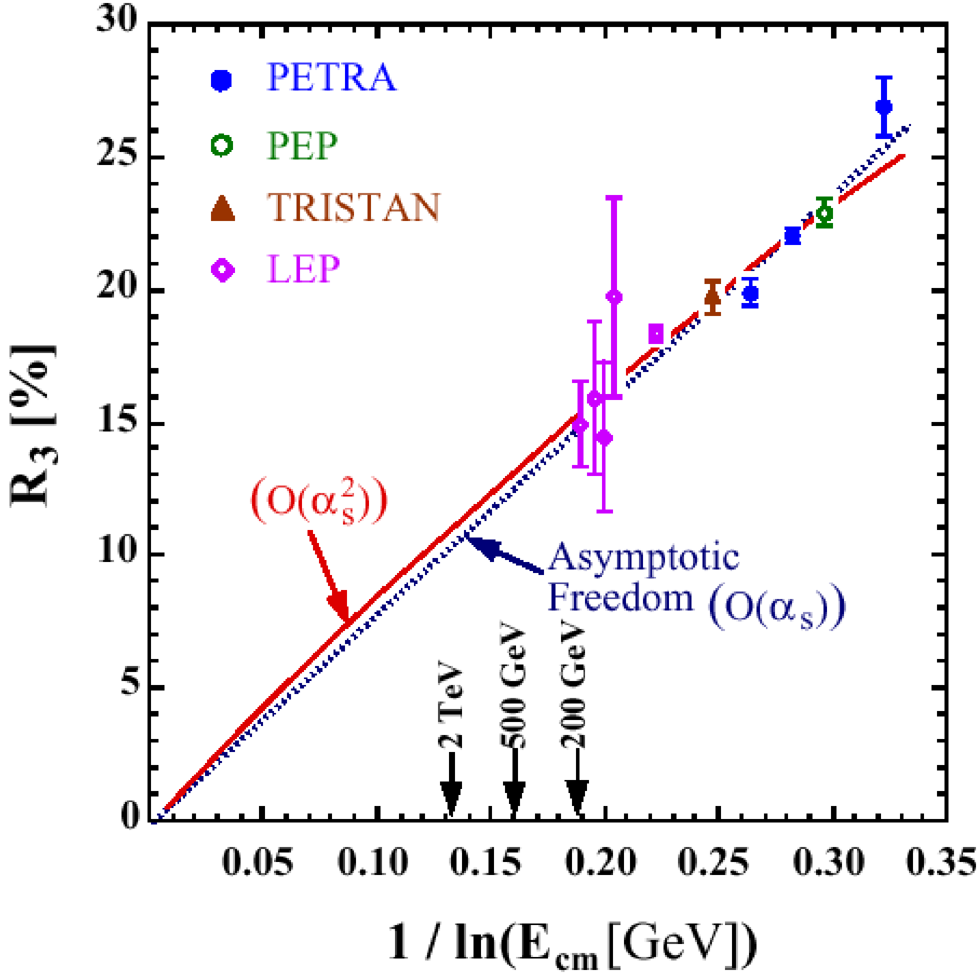




Asymptotic Freedom from jet rates

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



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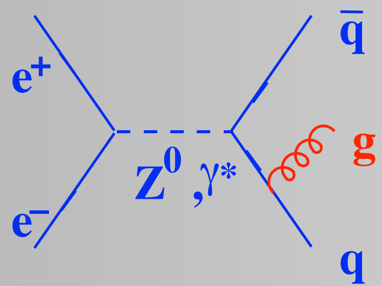

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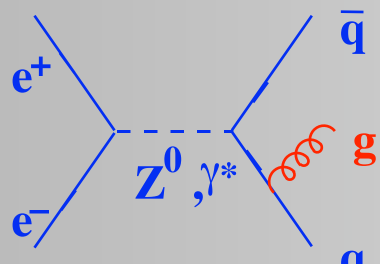

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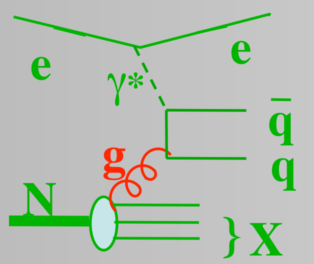

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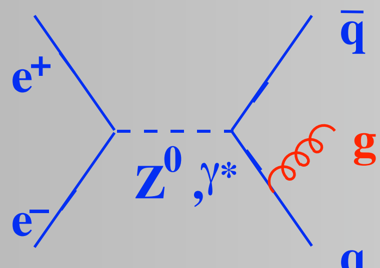

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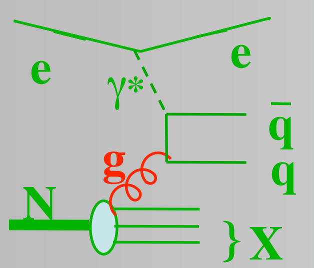

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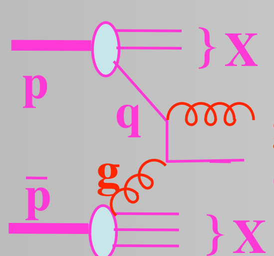


- proton-(anti-)proton collisions
  - jet rates
  - photoproduction
  - t-quark production cross section

running α_s up to 4th order:

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

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

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

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

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

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

$$\begin{aligned}\alpha_s(Q^2) = {} & \frac{1}{\beta_0 L} - \frac{1}{\beta_0^3 L^2}\beta_1 \ln L \\ & + \frac{1}{\beta_0^3 L^3}\left(\frac{\beta_1^2}{\beta_0^2}\left(\ln^2 L - \ln L - 1\right) + \frac{\beta_2}{\beta_0}\right) \\ & + \frac{1}{\beta_0^4 L^4}\left(\frac{\beta_1^3}{\beta_0^3}\left(-\ln^3 L + \frac{5}{2}\ln^2 L + 2\ln L - \frac{1}{2}\right) - 3\frac{\beta_1\beta_2}{\beta_0^2}\ln L + \frac{\beta_3}{2\beta_0}\right)\end{aligned}$$

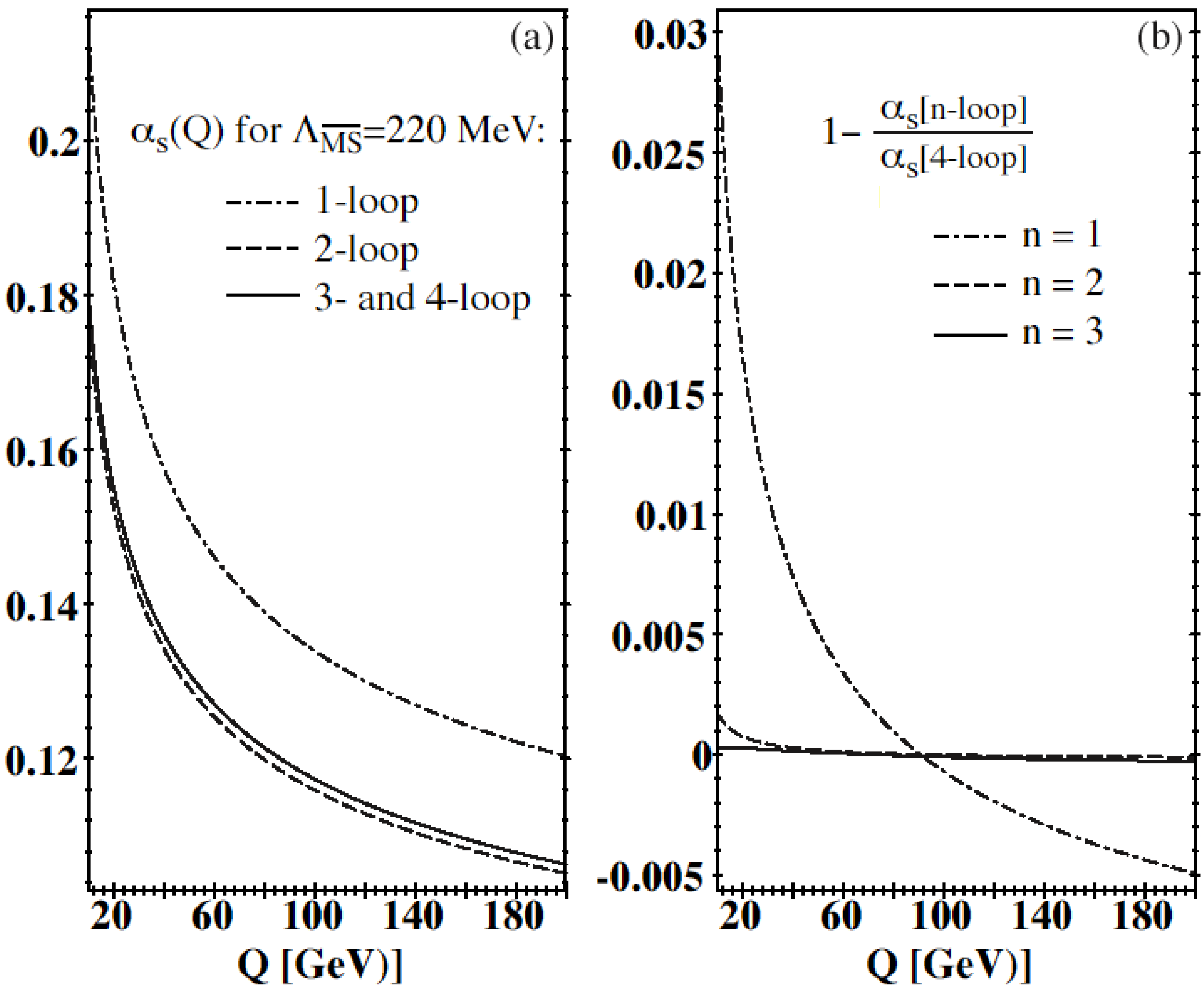
$$L = \ln\frac{Q^2}{\Lambda^2_{\overline{MS}}}$$

Ritbergen, Vermaseren, Larin

β_0 and β_1 do not depend on renormalisation scheme; β_2 and β_3 … do !

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

relative size of higher order corrections



heavy quark threshold matching

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

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

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

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

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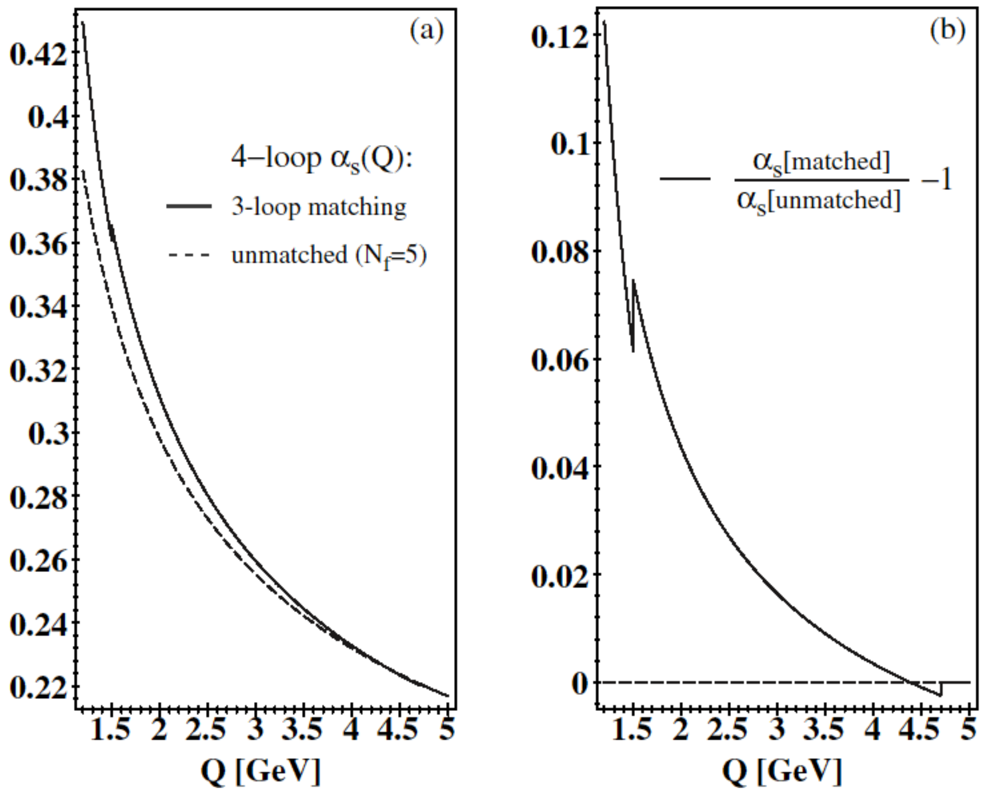

perturbative predictions for physical quantities

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$$\mathcal{R}(Q^2) = P_l \sum_n R_n \alpha_s^n$$
$$= P_l \left(R_0 + R_1 \alpha_s(\mu^2) + R_2 (Q^2/\mu^2) \alpha_s^2(\mu^2) + \ldots \right)$$

in n^{th} order perturbation theory

R_1 : "leading order coefficient" (lo)

R_2 : "next to leading coefficient" (nlo)

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Resummation of logs arising from soft and collinear singularities:

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

$$G(\alpha_s, L) = \sum_{n=1}^{\infty}\sum_{m=1}^{n+1} G_{nm}\hat{\alpha}_s^n L^m$$
$$\equiv L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \alpha_s^2 g_4(\alpha_s L) \cdots$$

	Leading logs	Next-to-Leading logs	Subleading logs	Non-log. terms	
$\ln \Sigma(\mathcal{R}) =$	$G_{12}\hat{\alpha}_s L^2$	$+G_{11}\hat{\alpha}_s L$		$+\alpha_s \mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$
	$+G_{23}\hat{\alpha}_s^2 L^3$	$+G_{22}\hat{\alpha}_s^2 L^2$	$+G_{21}\hat{\alpha}_s^2 L$	$+\alpha_s^2 \mathcal{O}(1)$	$\mathcal{O}(\alpha_s^2)$
	$+G_{34}\hat{\alpha}_s^3 L^4$	$+G_{33}\hat{\alpha}_s^3 L^3$	$+G_{32}\hat{\alpha}_s^3 L^2 + \cdots$	$+\cdots$	$\mathcal{O}(\alpha_s^3)$
	$+\cdots$	$+\cdots$	$+\cdots$	$+\cdots$	$\vdots$
$=$	$L g_1(\alpha_s L)$	$+g_2(\alpha_s L)$	$+\cdots$	$+\cdots$	

renormalisation scale dependence

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

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

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

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$$\begin{aligned} R_0 &= \text{const.} \; , \\ R_1 &= \text{const.} \; , \\ R_2 \left(\frac{Q^2}{\mu^2} \right) &= R_2(1) - \beta_0 R_1 \ln \frac{Q^2}{\mu^2} \; , \\ R_3 \left(\frac{Q^2}{\mu^2} \right) &= R_3(1) - [2 R_2(1) \beta_0 + R_1 \beta_1] \ln \frac{Q^2}{\mu^2} + R_1 \beta_0^2 \ln^2 \frac{Q^2}{\mu^2} \end{aligned}$$

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Perturbative QCD coefficients beyond leading order become renormalisation scale dependend !

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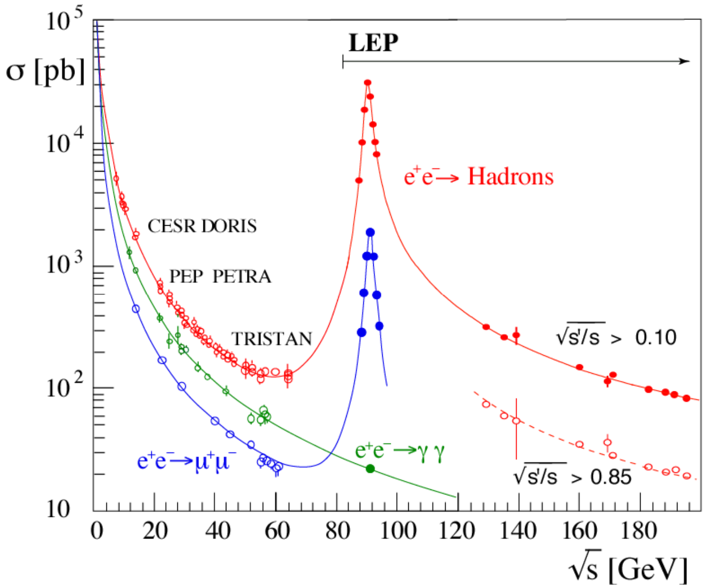
Perturbative QCD coefficients beyond leading order become renormalisation scale dependend !

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

hadronische Breite des Z^0 Boson



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

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

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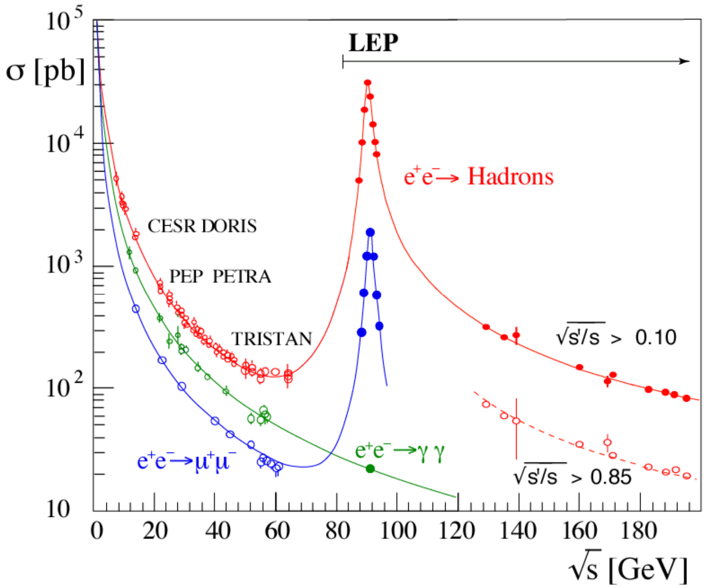

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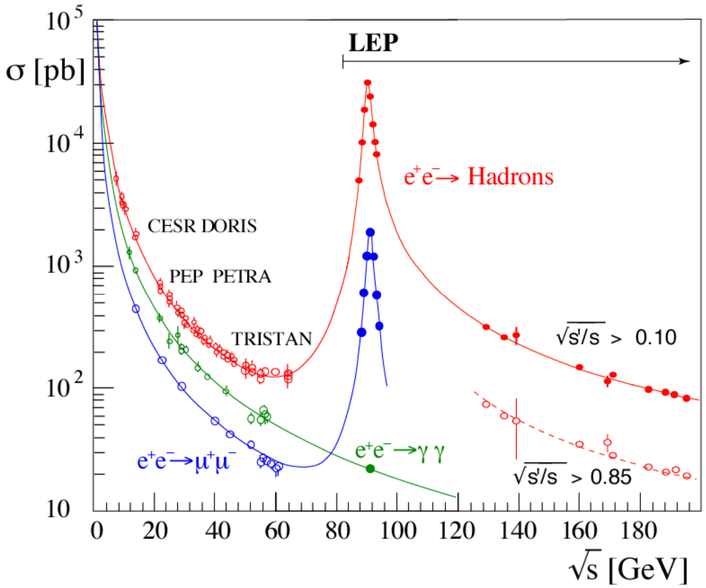

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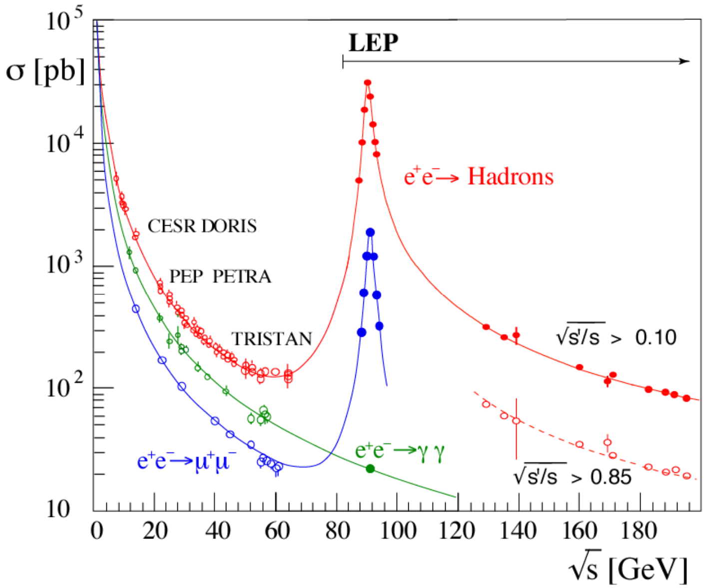

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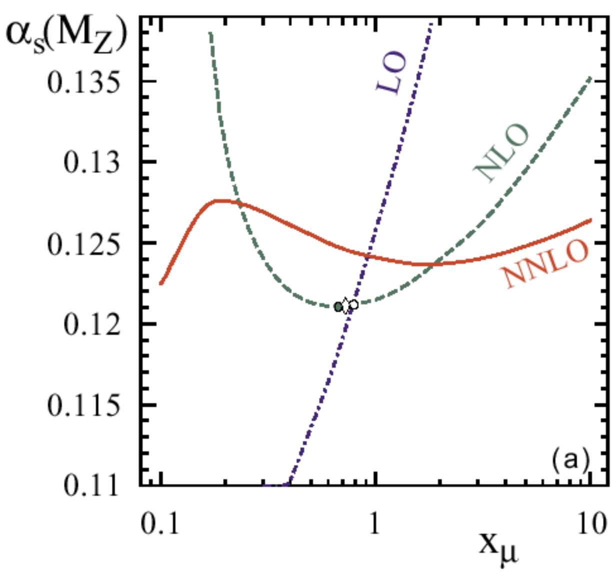
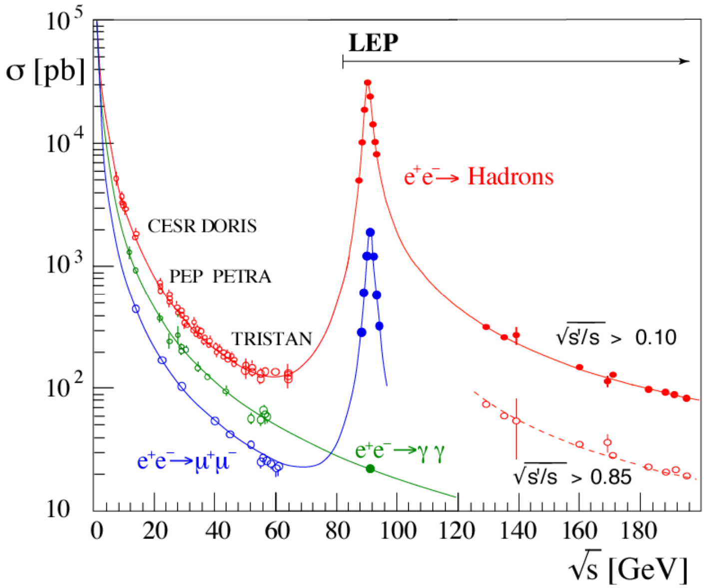


$x_\mu = \mu / E_{cm}$

hadronische Breite des Z^0 Boson



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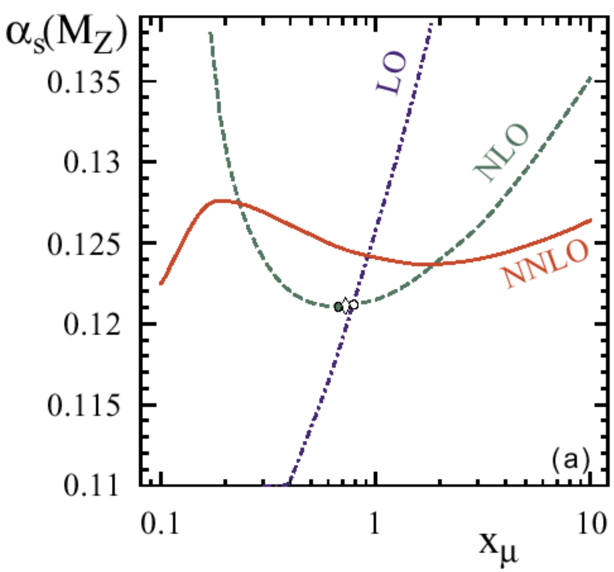

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error source	$\Delta\alpha_s(M_{Z^0})$
$\Delta M_{Z^0} = \pm 0.0021$ GeV	± 0.00003
$\Delta M_t = \pm 5$ GeV	± 0.0002
$M_H = 100 \ldots 1000$ GeV	± 0.0017
$\mu = (\frac{1}{4} \ldots 4)\ M_{Z^0}$	$^{+\,0.0028}_{-\,0.0004}$
renormalization schemes	± 0.0002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

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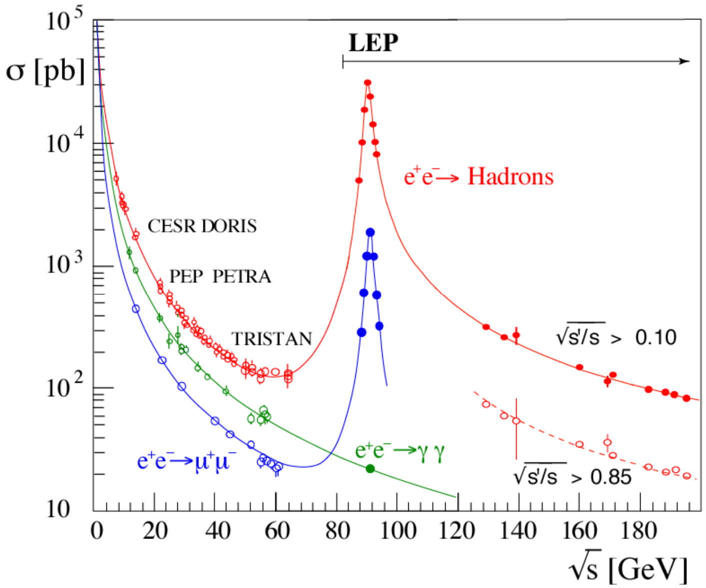

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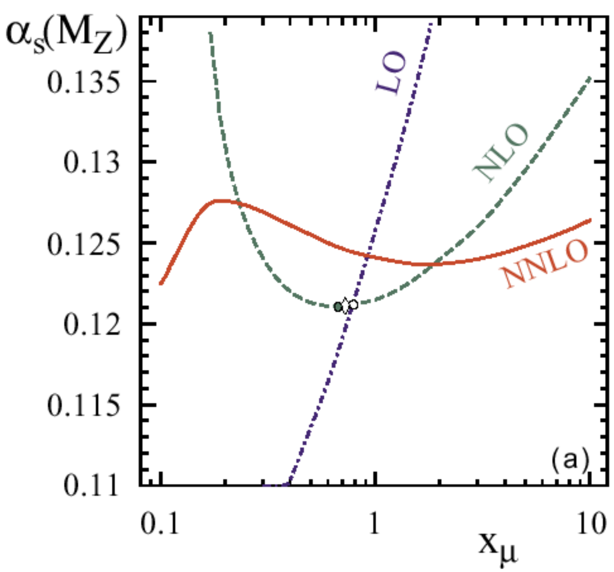

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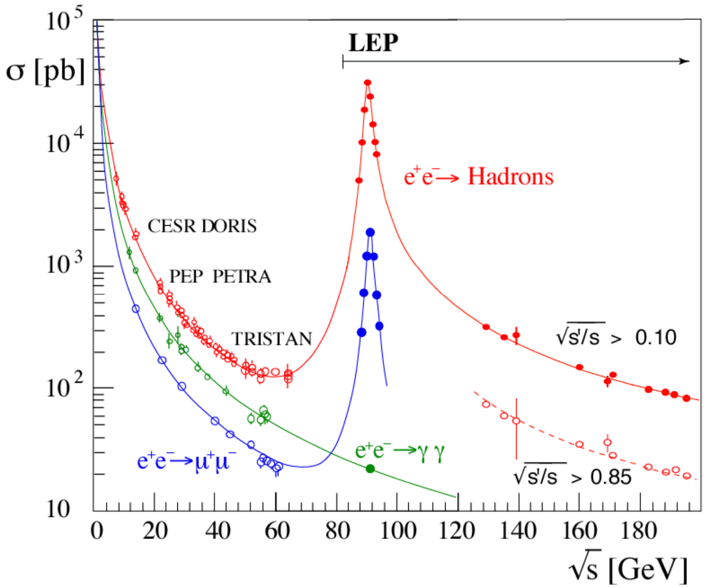

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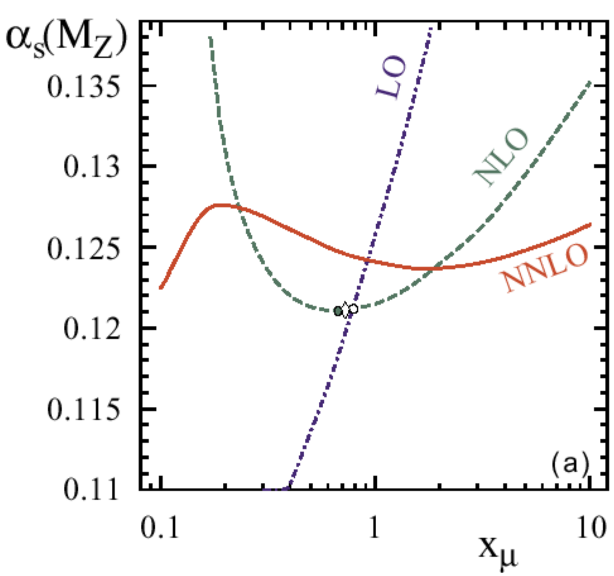

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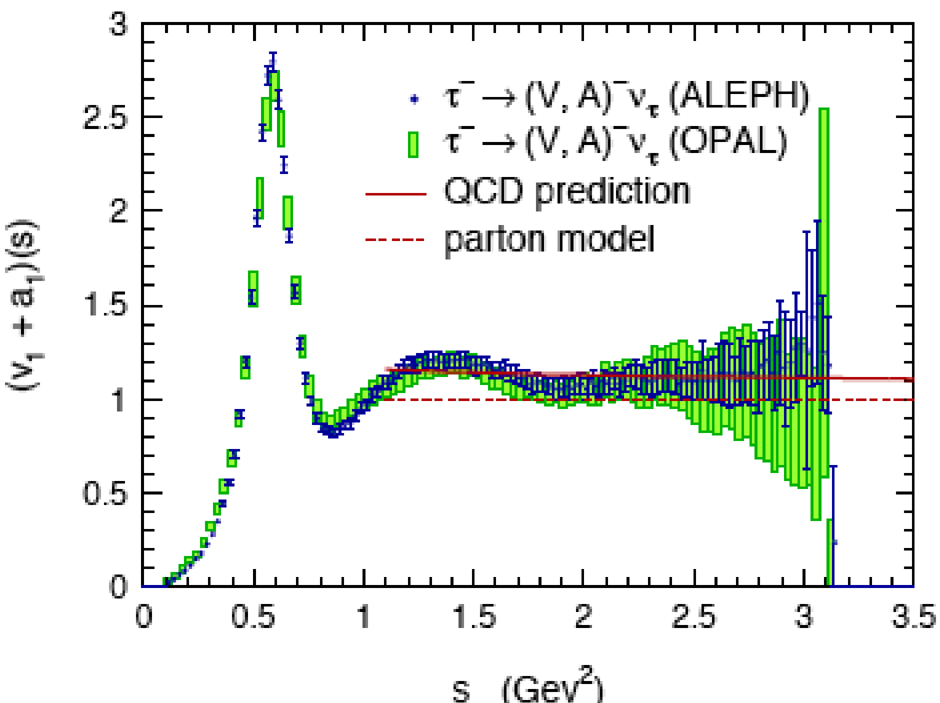
α_s from τ-decays

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

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

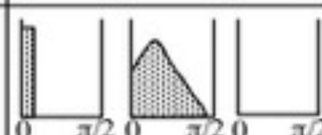
$$\delta_{pert} = \frac{\alpha_s(m_\tau)}{\pi} + 5.20\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^2 + 26.37\left(\frac{\alpha_s(m_\tau)}{\pi}\right)^3$$

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

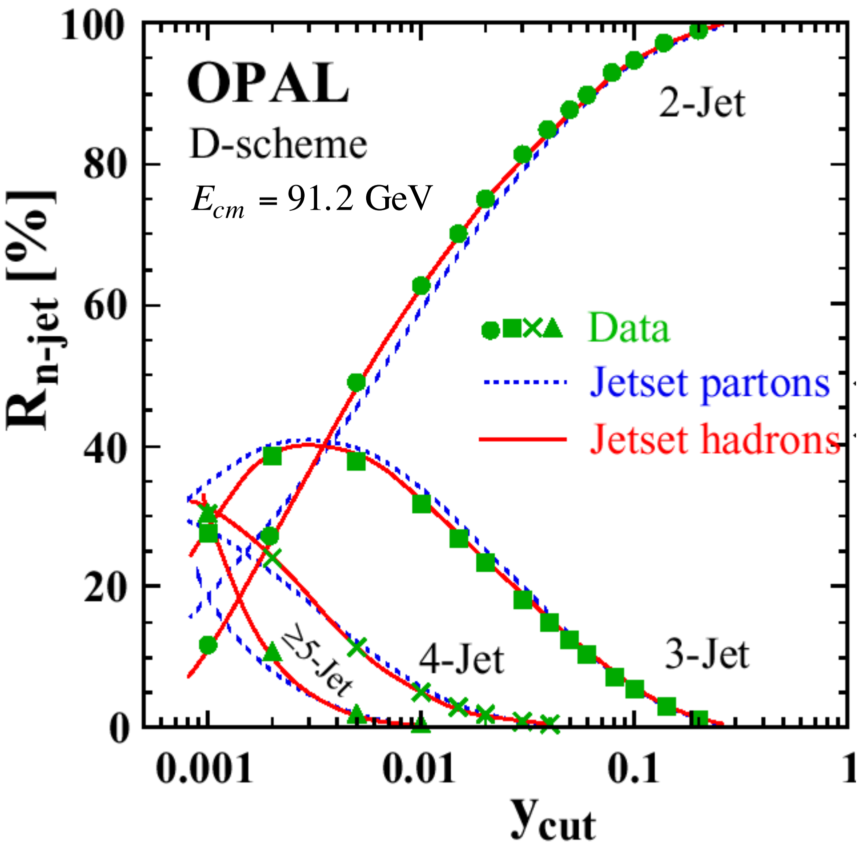


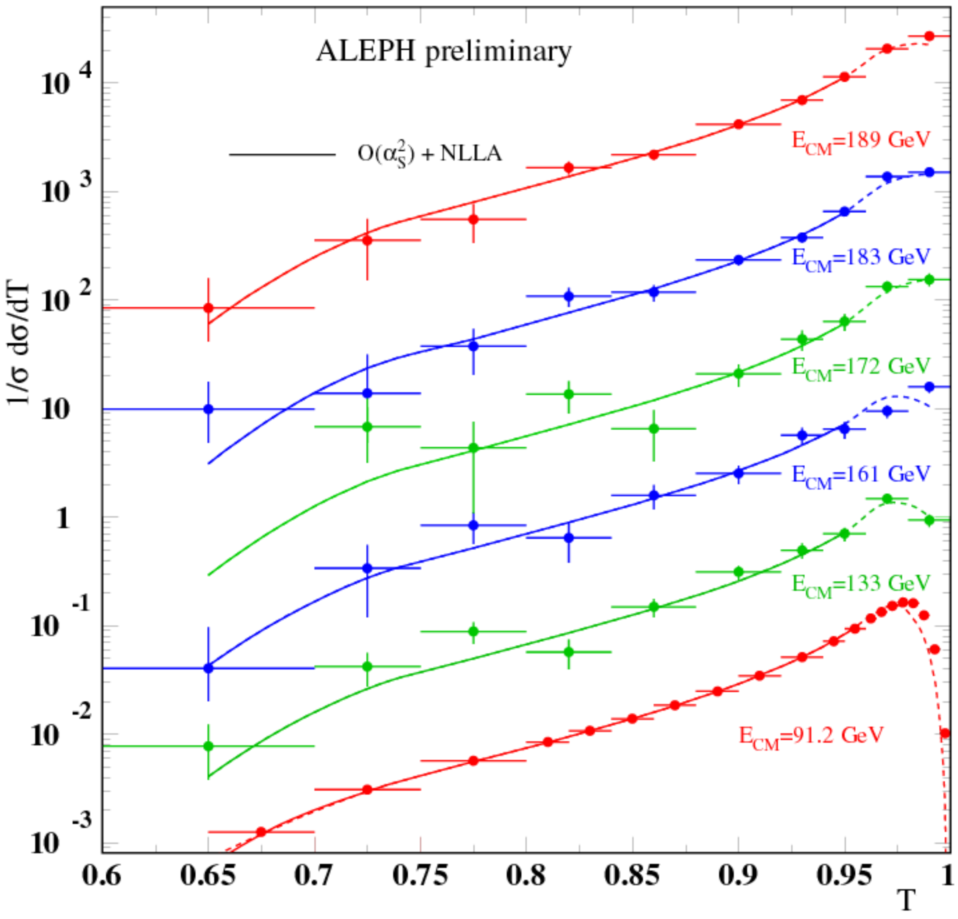
$\alpha_s(M_z) = 0.1213 \pm 0.0006_{\text{exp}} \pm 0.0010_{\text{theo}}$

Event Shape Observables

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





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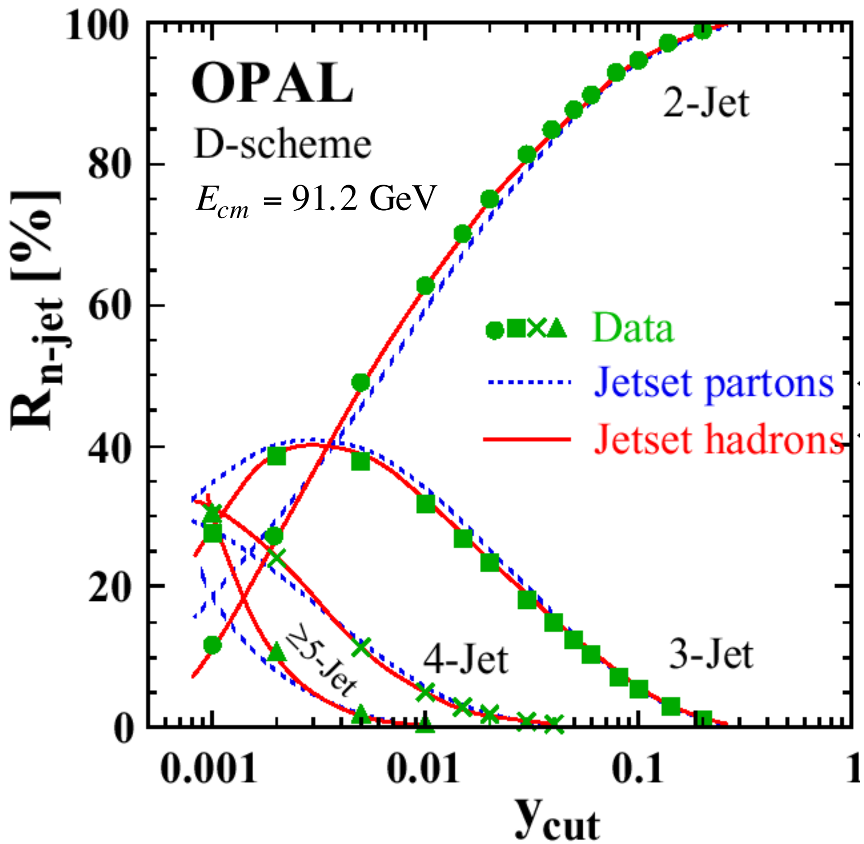

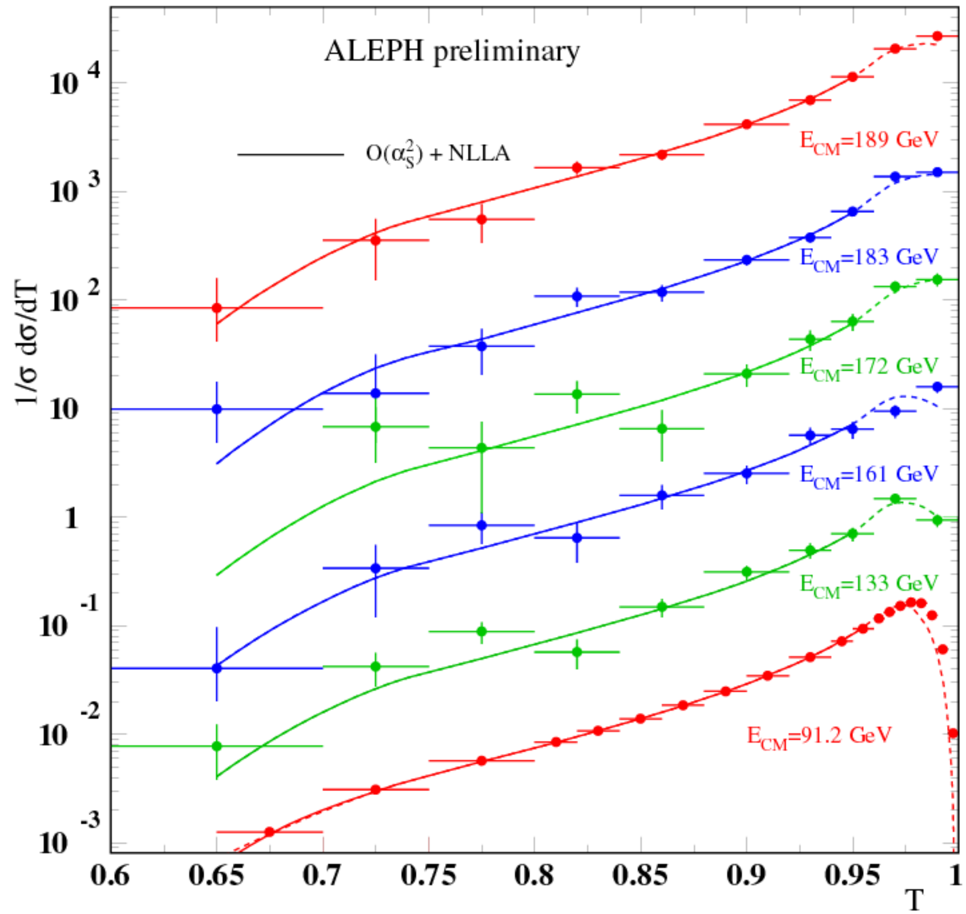

Pert. QCD

- 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
- plus resummation of leading and next-to-leading logarithms (NLLA) –> "matching schemes" Catani, Trentadue, Turnock, Webber

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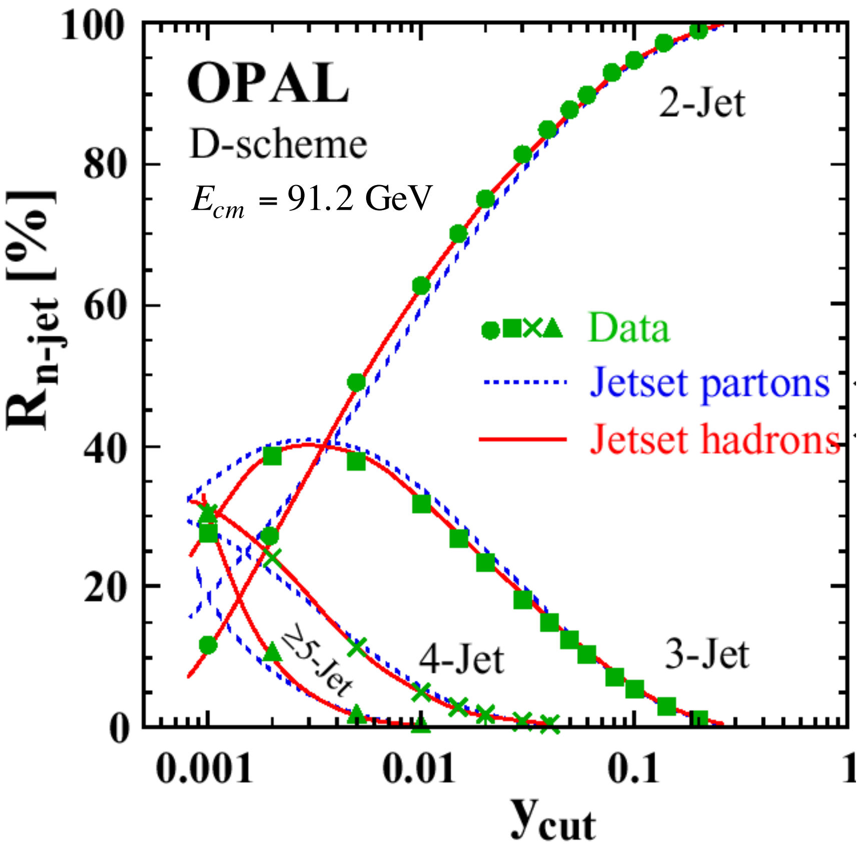

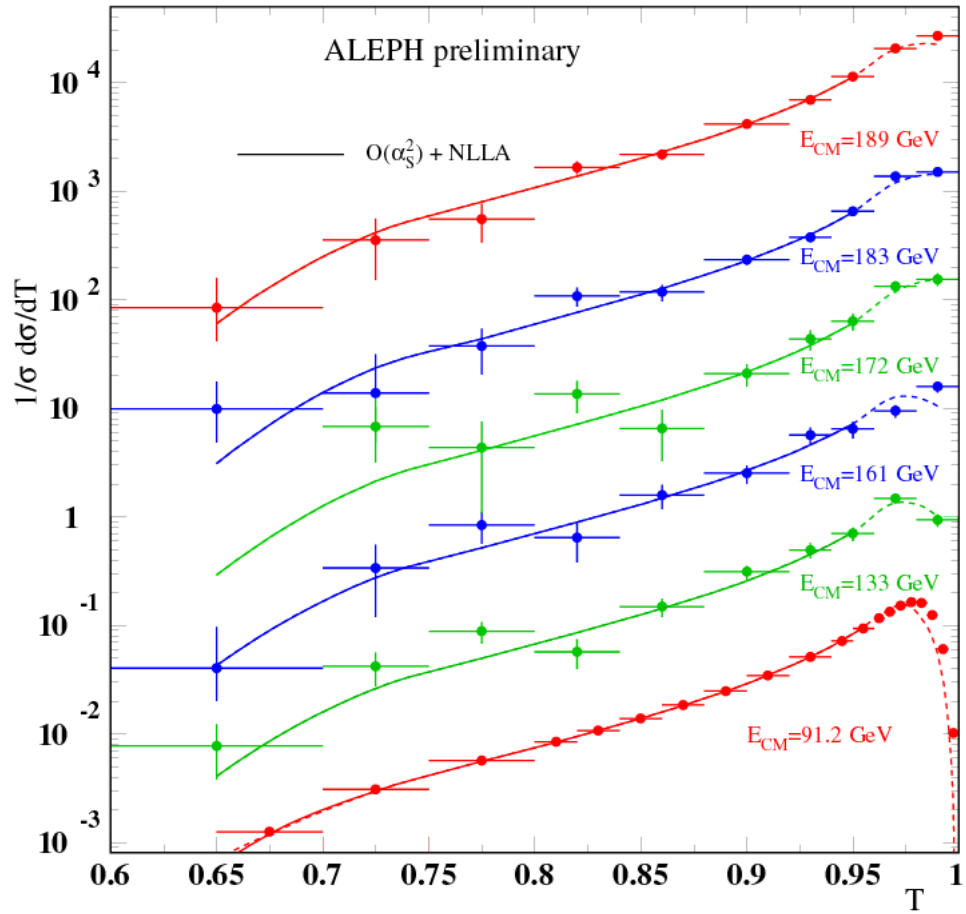

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Ellis, Ross & Terrano (ERT); Kunszt & Nason, Catani & Seymour

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

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α_s aus Jetraten und event shapes in NNLO QCD:

2009

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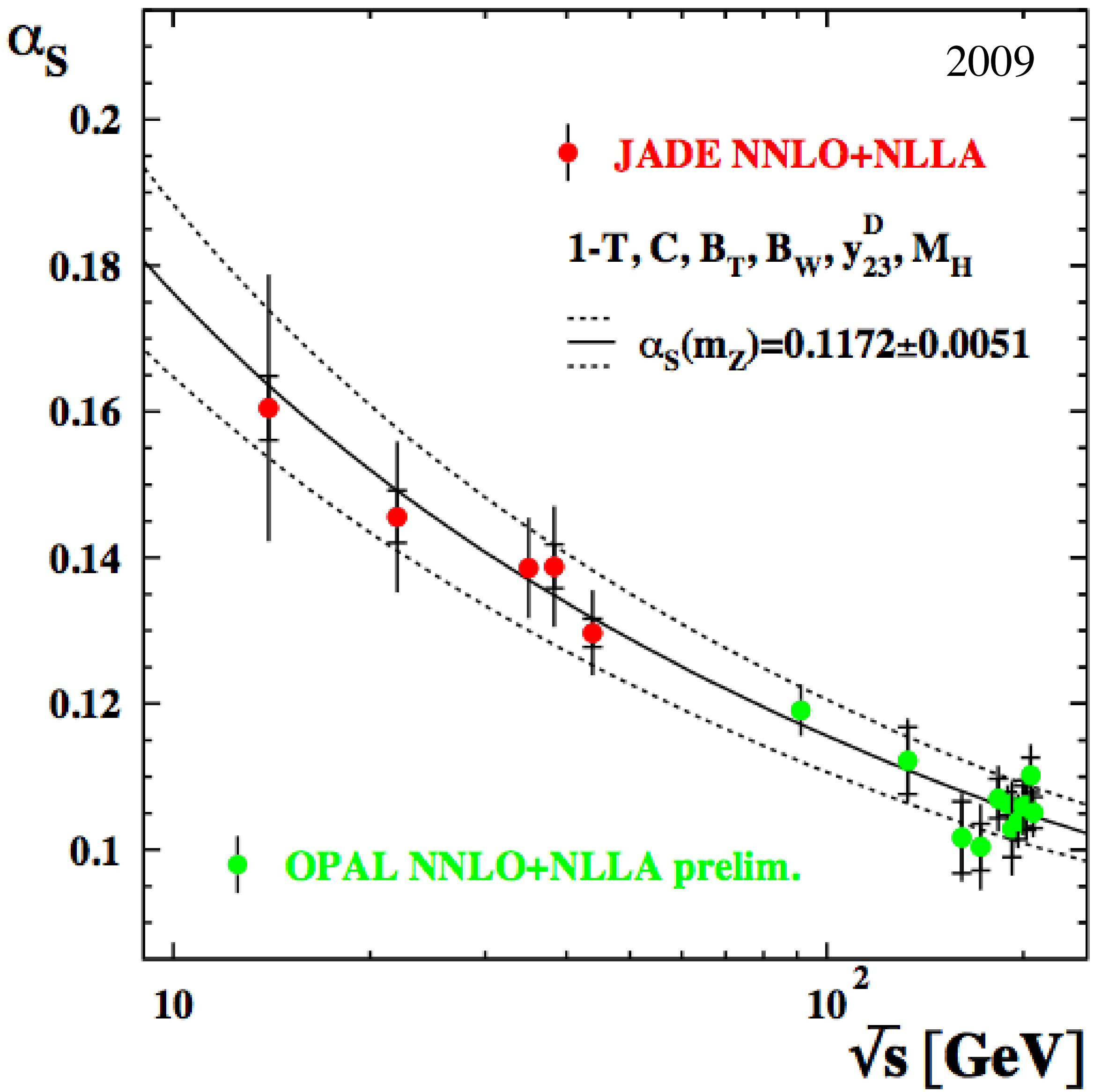
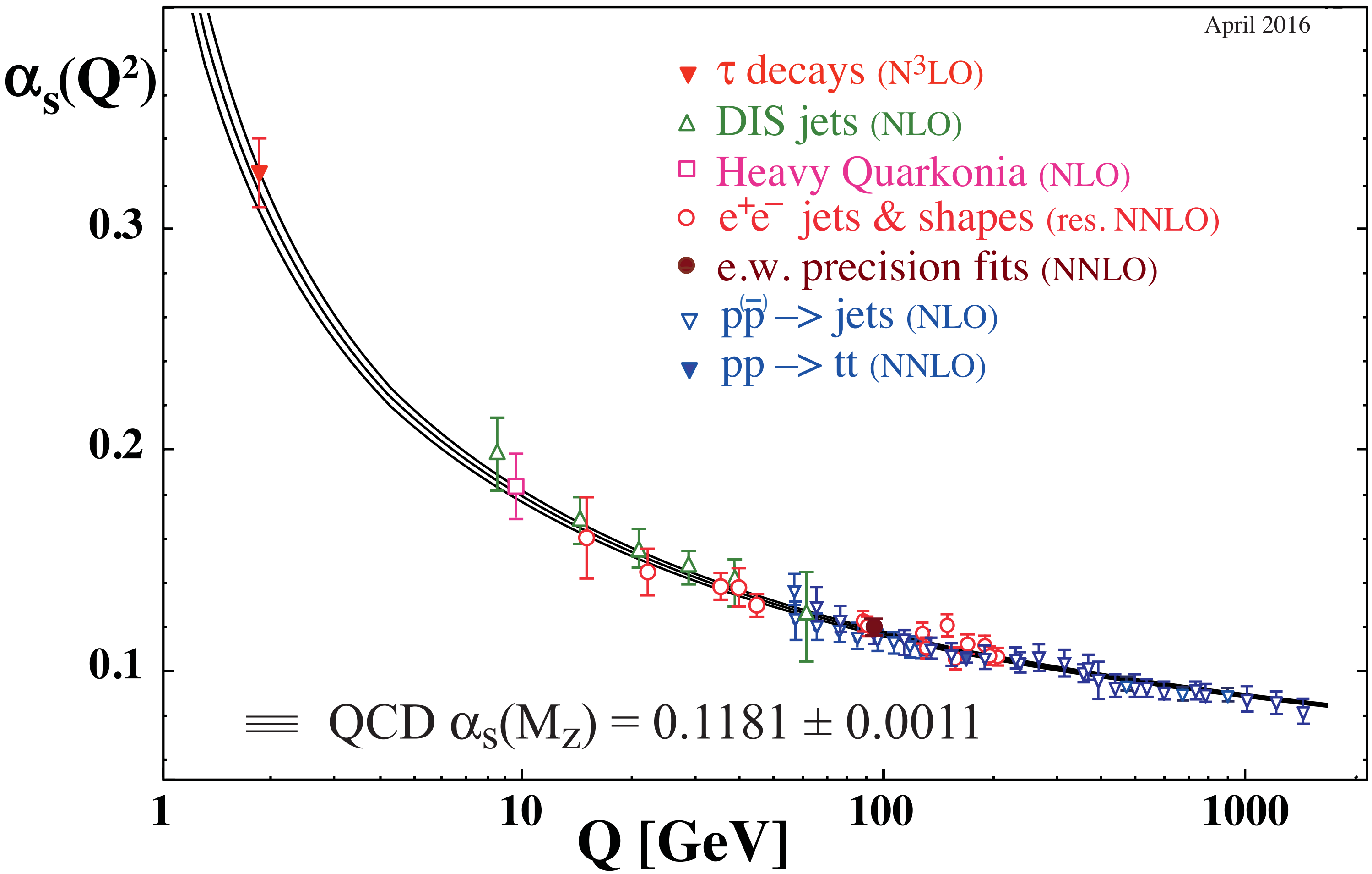
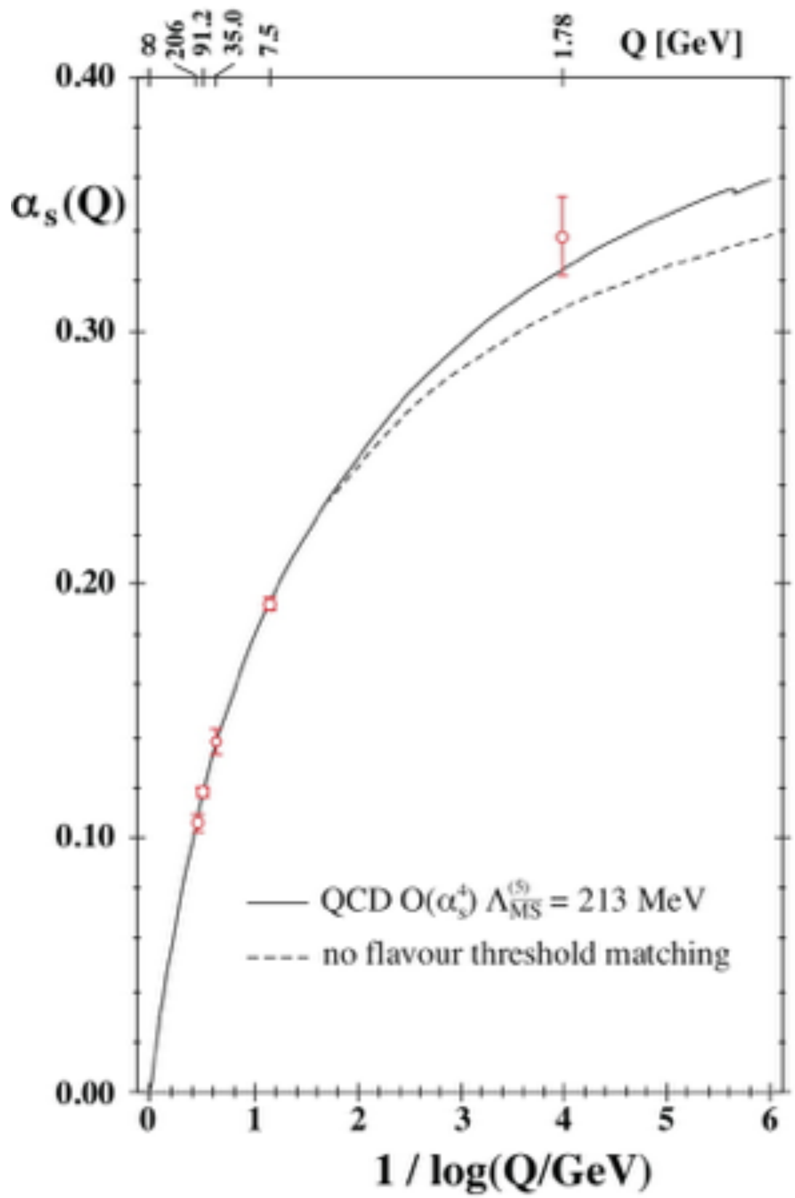


globale Zusammenfassung der Messungen von α_s



Evidence for Asymptotic Freedom:



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- Messung von α_s aus vielen Reaktionen:
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