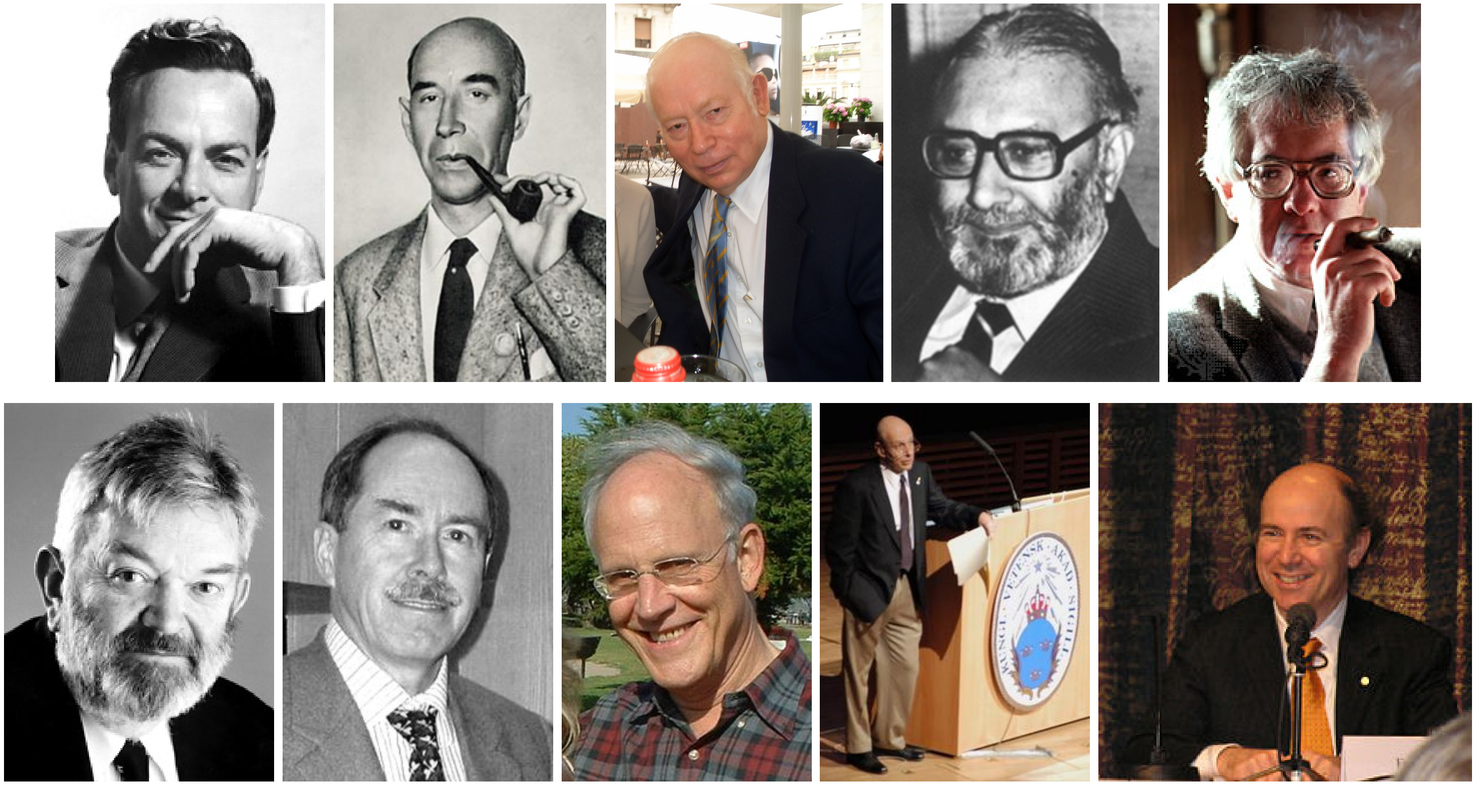
Experimental Foundations of the Standard Model IV



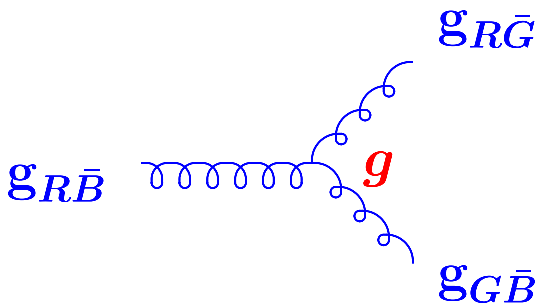
Postgraduate Course, UC Louvain, 2009

UNIVERSITÉ DE GENÈVE

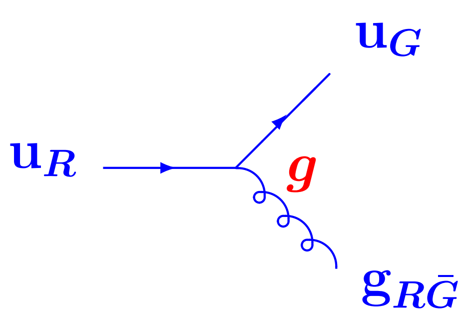
Martin Pohl

Strong Interactions

QCD is a gauge theory of strong interactions, based on an unbroken, non-abelian gauge symmetry of the group SU(3). The vertex defining the interaction strength is again an interaction among gauge bosons:



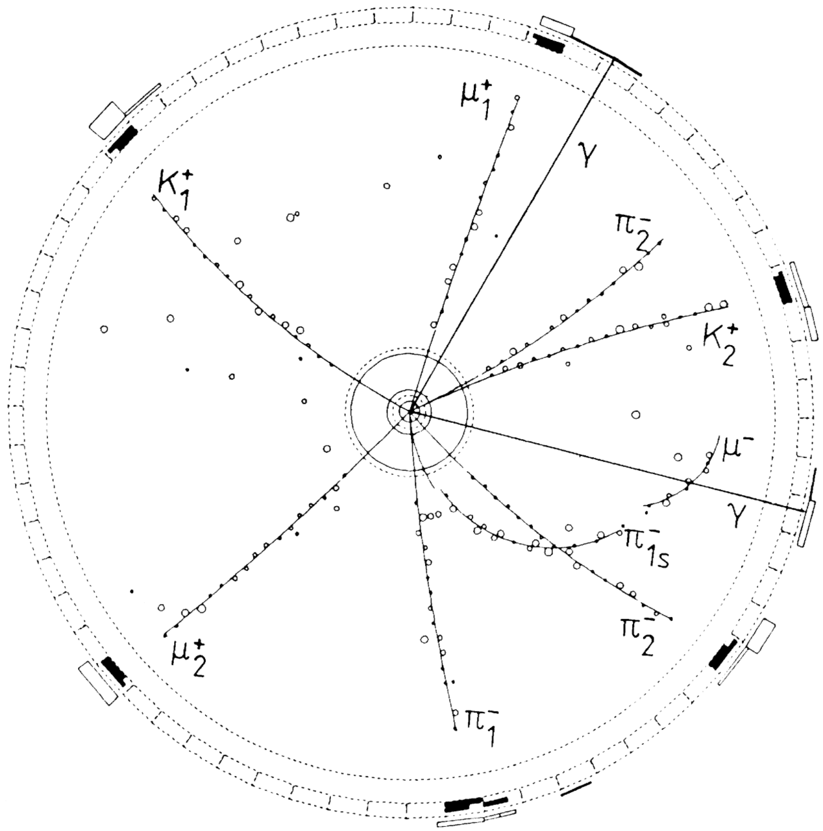
The couplings constant g also fixes the universal coupling of gluons to all quarks:



Hadron Production at Electron-Positron Colliders

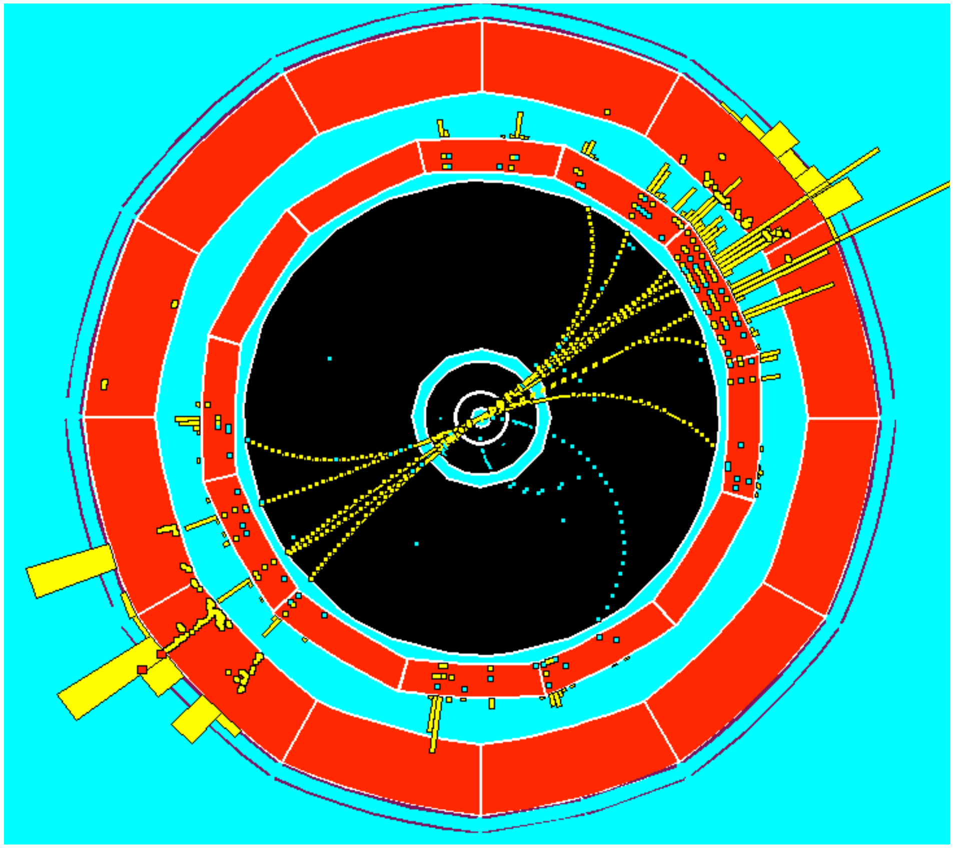
At electron-positron colliders, the lowest order production process for hadron is $\mathrm{e}^+\mathrm{e}^- \longrightarrow q\bar{q}$:

$\sqrt{s} = 10$ GeV



ARGUS, PEP-II, DESY

$\sqrt{s} = 91$ GeV

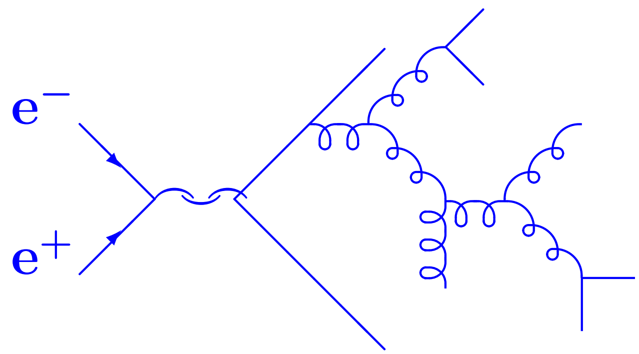


ALEPH, LEP, CERN

Jets and partons

Jets are the footprints of quarks and gluons:

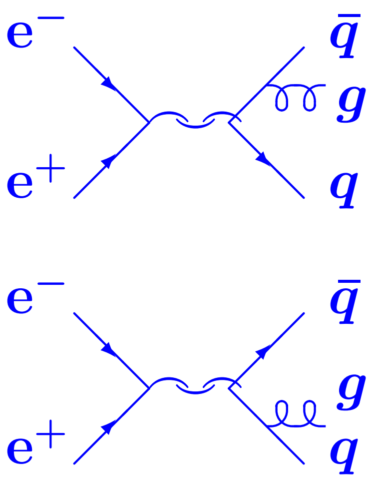
- Jets are NOT hadronic or electromagnetic showers in the calorimeters
- Jets are NOT fundamental particles of the Standard Model
- Jets are the consequence of the infrared slavery in QCD, which does not allow open color of quarks and gluons to persist. It requires that quarks and gluons form colorless hadrons with unit probability:

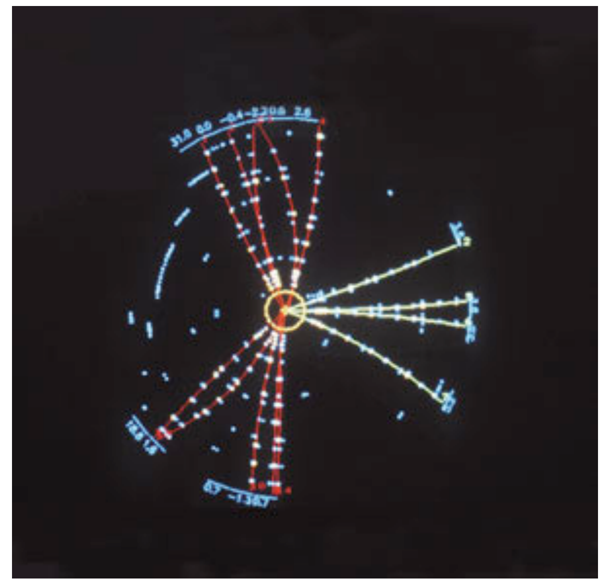


- Experimentally, jets are the results of algorithms which aggregate information from visible tracks and energy deposits to extract information about partons.

Gluon Bremsstrahlung

The earliest observed manifestation of QCD was gluon bremsstrahlung in the process $\mathrm{e}^+\mathrm{e}^- \to q\bar{q}g$:



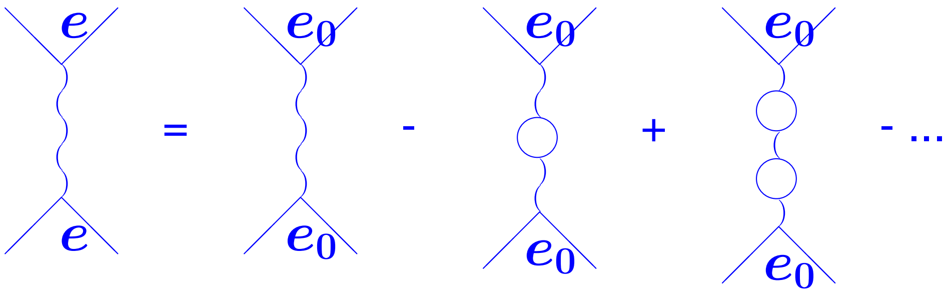


27GeV $\mathrm{e}^+\mathrm{e}^-$ collisions PETRA,DESY,1979

$$R = \frac{\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\bar{\mathrm{q}}(\mathrm{g}))}{\sigma(\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-)} = 3\sum_{q_i} Q_i^2 \left(1 + \frac{\alpha_s}{\pi}\right)$$

JADE Collab. *Phys. Lett.*B91 (1980) 142
MARK J Collab. *Phys. Rev. Lett.*43 (1979) 830
PLUTO Collab. *Phys. Lett.*B86 (1979) 418
TASSO Collab. *Phys. Lett.*B86 (1979) 243

Vacuum Polarization in QED and QCD



Walking coupling constant:

$$\alpha(Q^2) = \frac{\alpha_0}{1 - \frac{\alpha_0}{3\pi}\log\frac{Q^2}{M^2}}$$

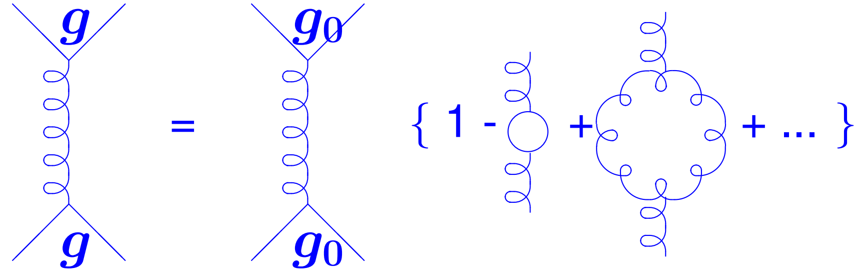
Increasing with Q^2.

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi}(33 - 2n_f)\log\frac{Q^2}{\mu^2}}$$

With scale parameter Λ:

$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\log\frac{Q^2}{\Lambda^2}}$$

$$\Lambda^2 = \mu^2 e^{\frac{-12\pi}{(33-2n_f)\alpha_s(\mu^2)}}$$



Running coupling constant. Decreasing with Q^2: infrared slavery, asymptotic freedom.

Total Hadronic Cross Section

The hadronic width of the Z receives important radiative corrections from strong interactions:

$$\Gamma_{had} = \Gamma_{had}^{EW}\left(1 + \sum_n C_n \alpha_s^n\right)$$

known to NNLO, $\mathcal{O}(\alpha_s^3)$. Result :

$$\alpha_s(M_Z^2) = 0.1226 \pm 0.0038 \text{ (exp.) } {}^{+0.0033}_{-0.0000} \, (M_H) \, {}^{+0.0028}_{-0.0005} \text{ (QCD)}$$

From the total leptonic pole cross section at the Z pole:

$$\sigma_l^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_l^2}{\Gamma_Z^2}$$

one also gets a result, since Γ_Z contains Γ_{had}:

$$\alpha_s(M_Z^2) = 0.1183 \pm 0.0030 \text{ (exp.) } {}^{+0.0026}_{-0.0000} \, (M_H) \, {}^{+0.0050}_{-0.0010} \text{ (QCD est.)}$$

From a combined fit of all Z pole data one obtains:

$$\alpha_s(M_Z^2) = 0.1190 \pm 0.0027 \text{ (exp.)}$$

Tau Lepton Hadronic Width

Tau is the only lepton that can decay hadronically. The hadronic widths receives important radiative corrections from strong interactions:

$$R_\tau = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(\tau \to \mathrm{e}\bar{\nu}_\mathrm{e}\nu_\tau)} = \frac{1 - \mathcal{B}(\tau \to \mathrm{e}\bar{\nu}_\mathrm{e}\nu_\tau) - \mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau \to \mathrm{e}\bar{\nu}_\mathrm{e}\nu_\tau)}$$
$$= 3\left(|V_\mathrm{ud}|^2 + |V_\mathrm{us}|^2\right) S_{EW}$$
$$\times \left(1 + \frac{\alpha_s}{\pi} + 5.2023\left(\frac{\alpha_s}{\pi}\right)^2 + 26.366\left(\frac{\alpha_s}{\pi}\right)^3 + (78 + d_3)\left(\frac{\alpha_s}{\pi}\right)^4 + \delta_{NP}\right)$$

Result:

$$\alpha_s(M_\tau^2) = \mathbf{0.322} \pm \mathbf{0.005}\ \text{(exp.)} \pm \mathbf{0.030}\ \text{(theo.)}$$

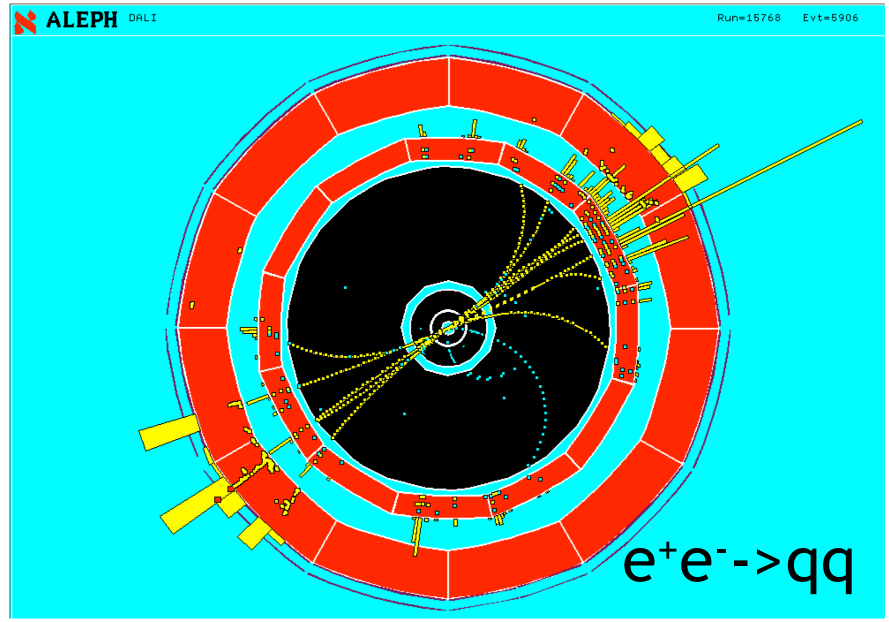
The strong coupling runs very fast!

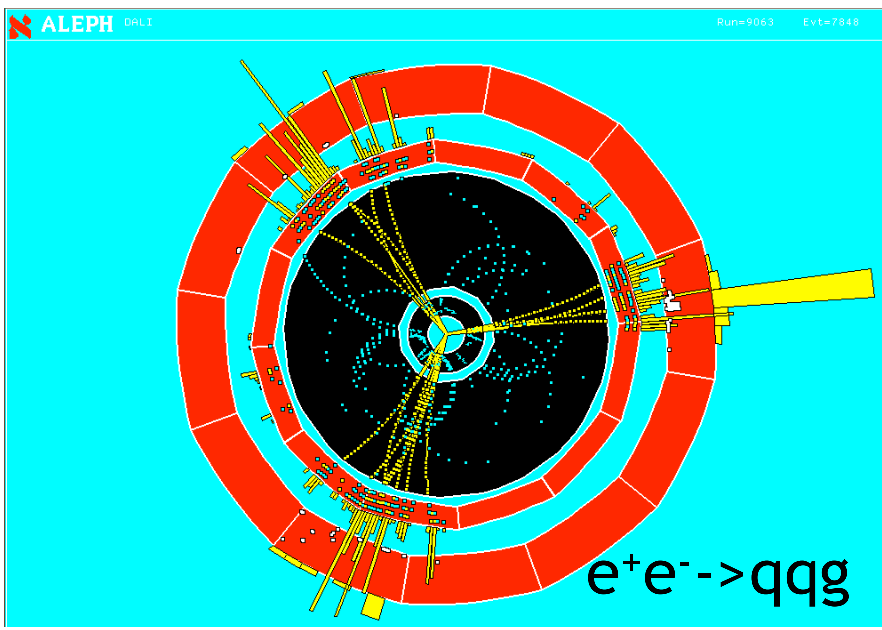
Multijet Events at LEP

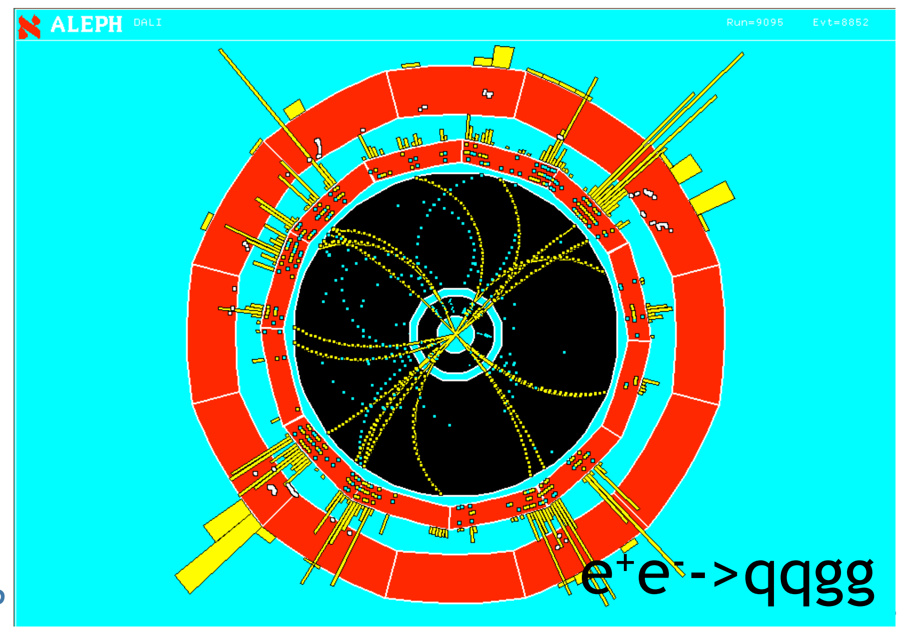
- Without gluon emission: 2 jets
- With emission of a gluon 3 jets
- With emission of two gluons 4 jets

- The counting of such events allows to measure the strong coupling constant

$\alpha_S = kN_{3jet}/N_{2jet}$ (k~0.2)







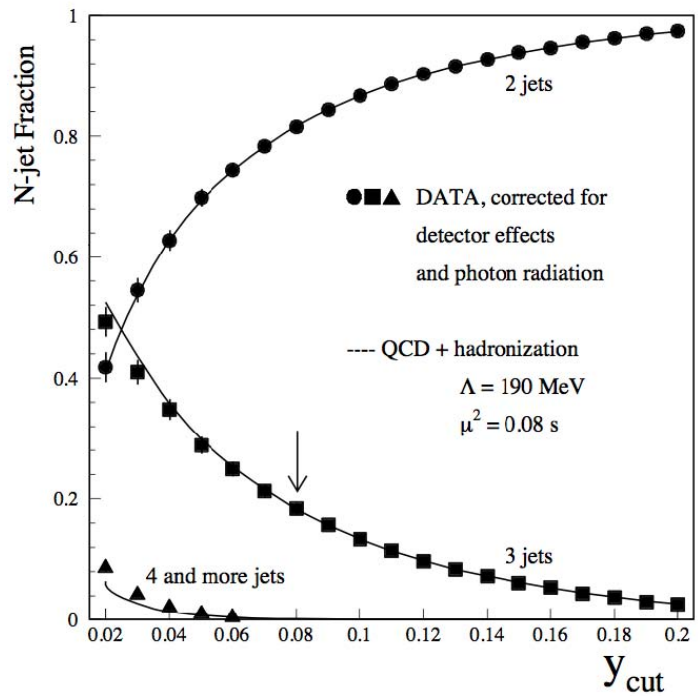
Fraction of Multijet Events at LEP

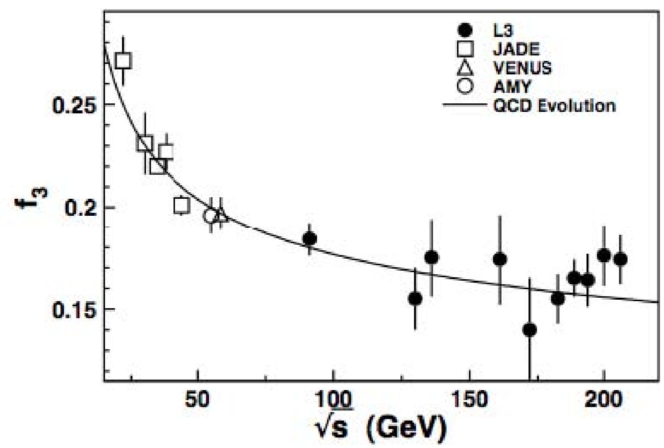
Jet algorithm: (e.g. Jade Coll, Z. Phys. C33 (1986) 23)

- The distance between two particles i and j is defined as:

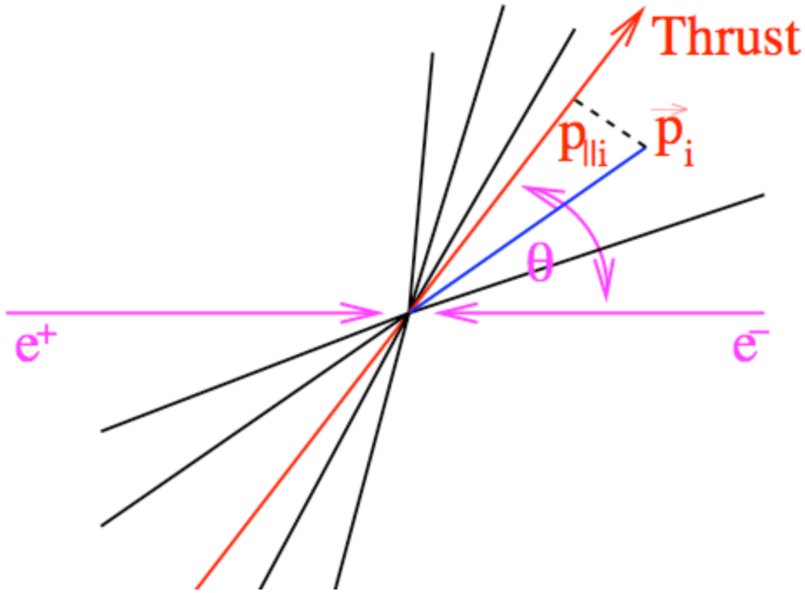
$$y_{ij} = 2E_iE_j(1-\cos\theta_{ij})/E^2_{vis}$$

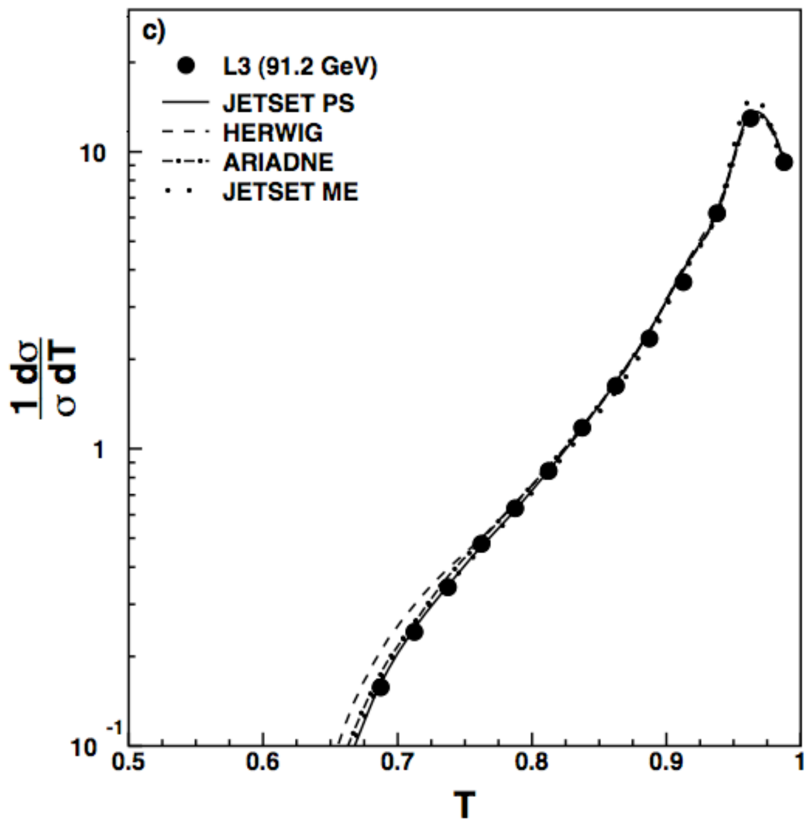
- A threshold y_{cut} is chosen a priori
- The distance is calculated for each particle pair
- The pair (h,k) with minimal distance y_{hk} is chosen
- If $y_{hk} < y_{cut}$ the four-vectors of h and k are summed into a new object, a "jetlet" l.
- Iterate until $y_{ij} > y_{cut}$ for all possible pairs objects (particles, jetlets, mixed)
- The remaining objects are the jets.





Event Shape Variables: Thrust

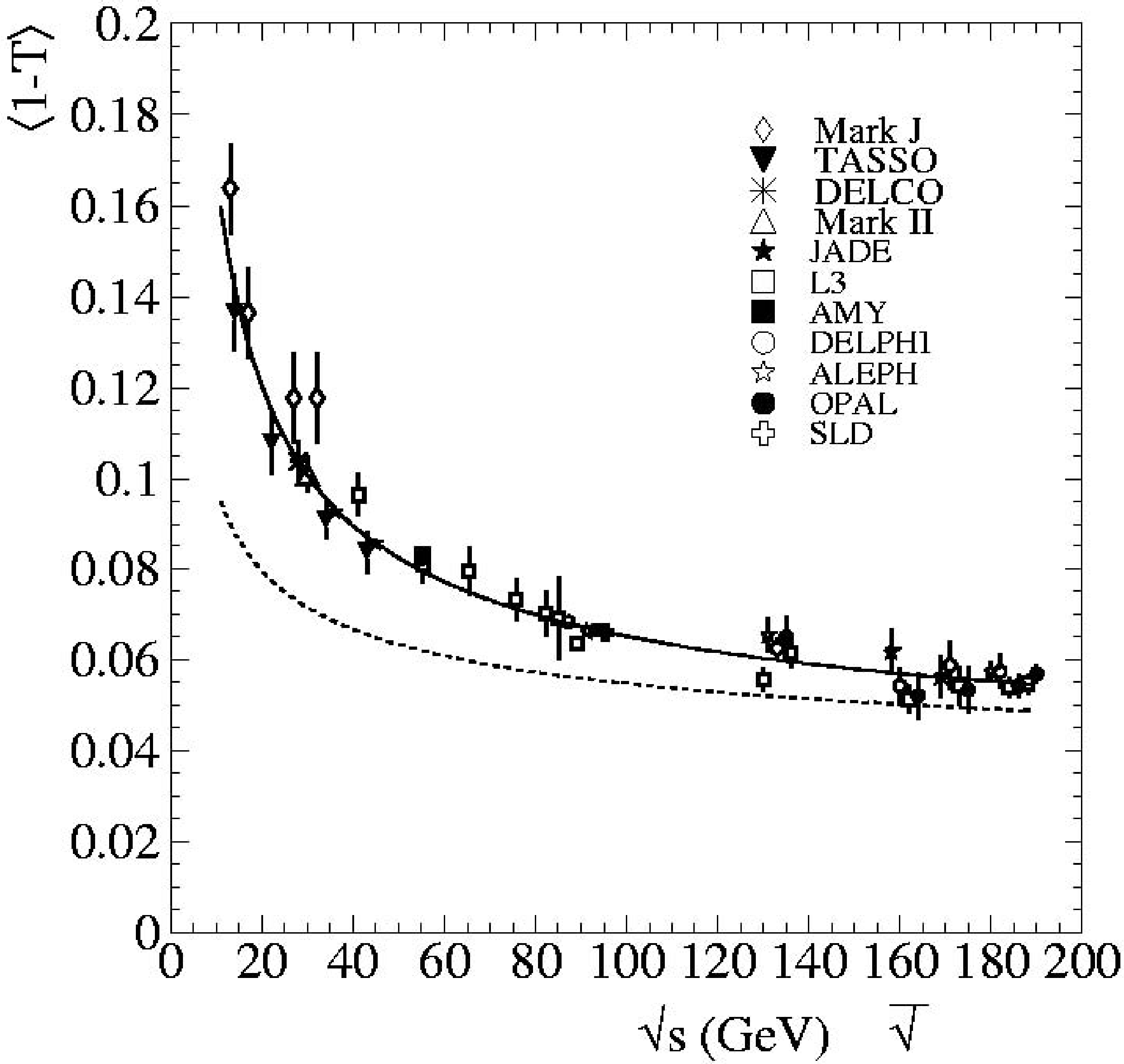




The Thrust vector is the one which maximizes:

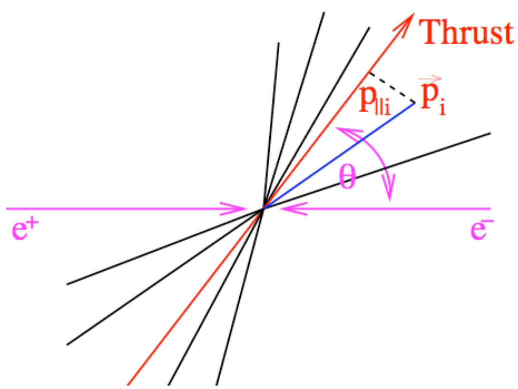
$$T = \frac{\sum |\vec{p}_i \cdot \vec{n}_\mathrm{T}|}{\sum |\vec{p}_i|}$$

Mean Thrust as a Function of Energy

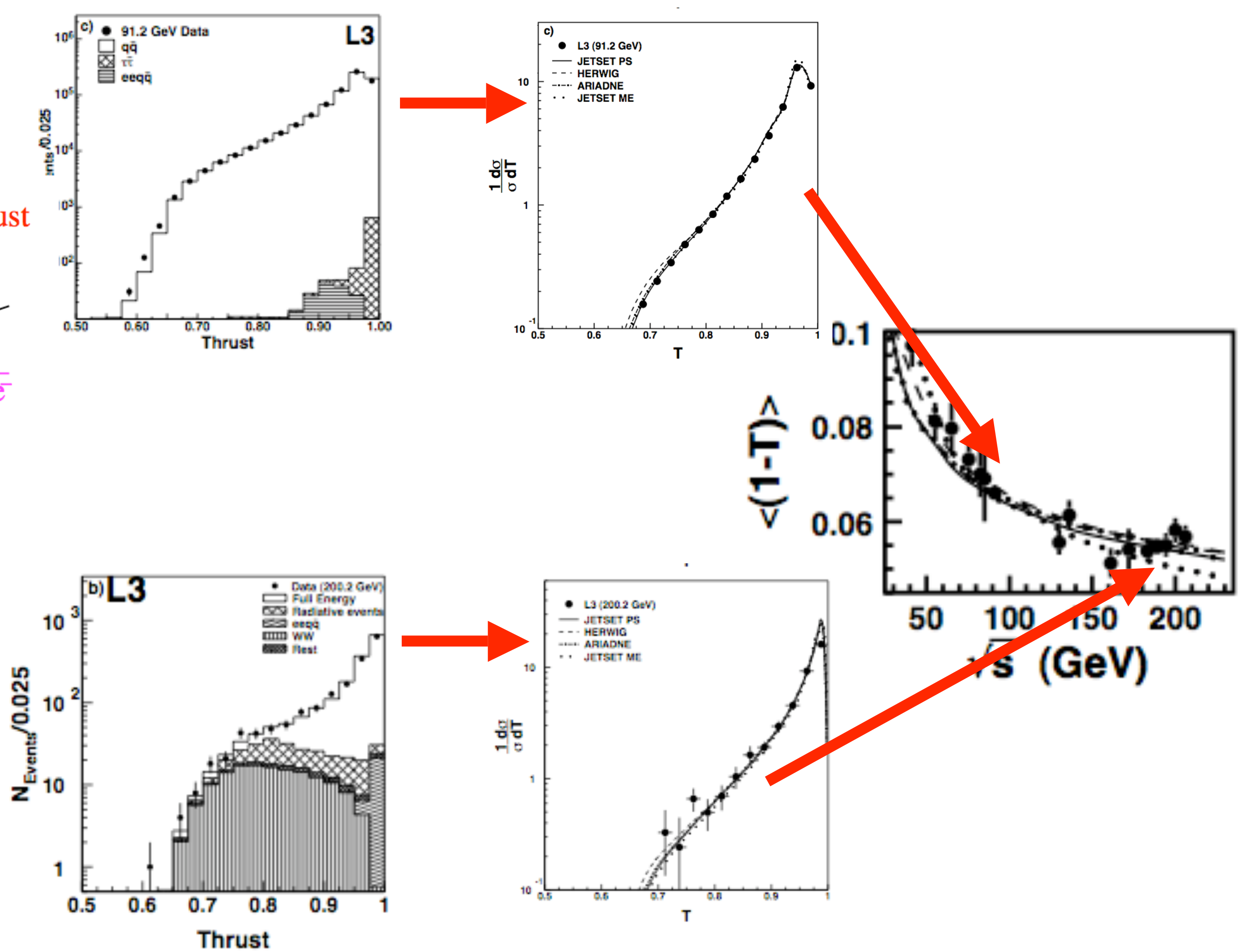


Strong Coupling from Event Shape Variables

Sensitive to the number and kinematics of jets, and therefore to α_s. Example: Thrust. Fit 5 different variables at 9 energy points

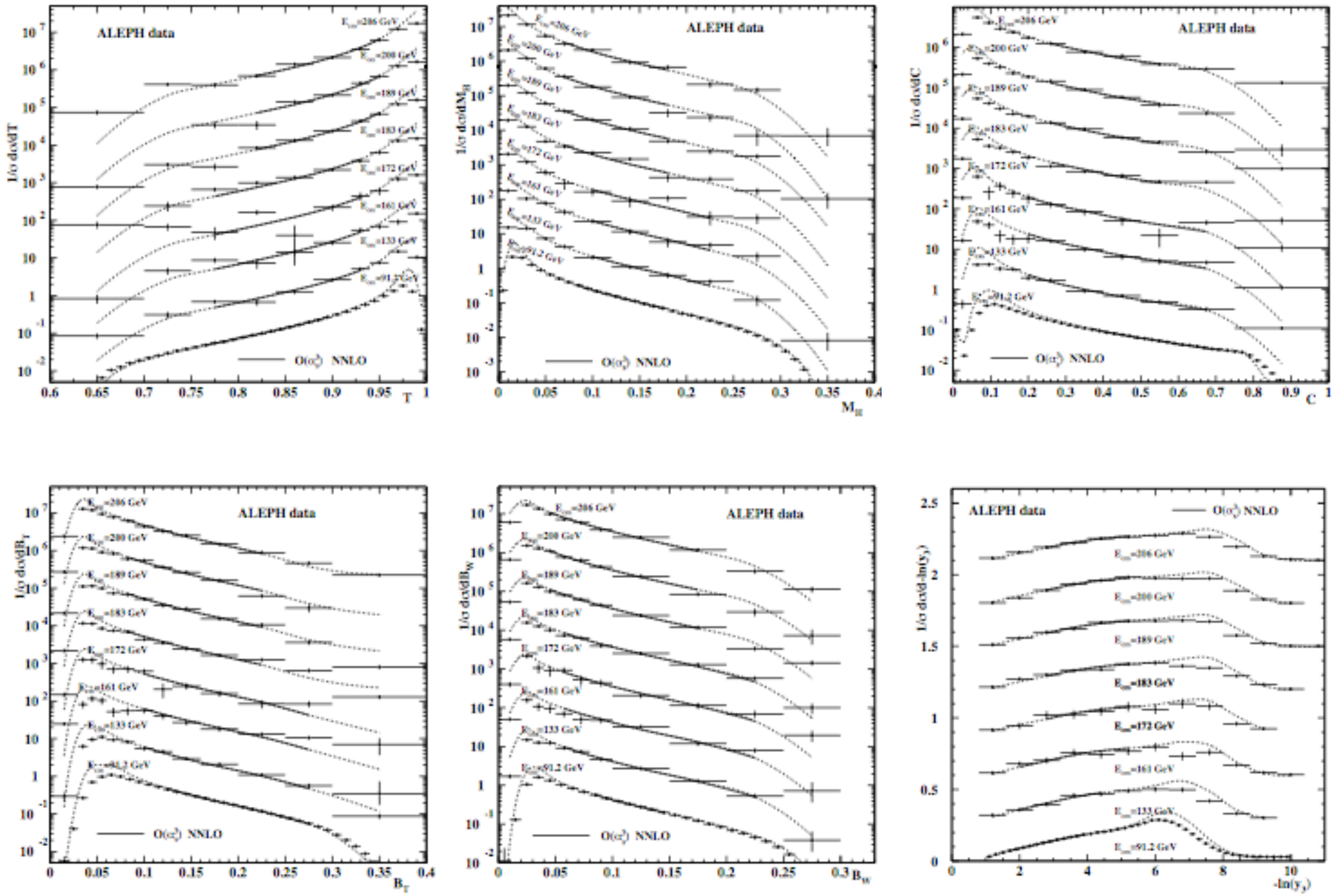


$$T = \frac{\sum |\vec{p}_i \cdot \vec{n}_{\mathrm{T}}|}{\sum |\vec{p}_i|}$$



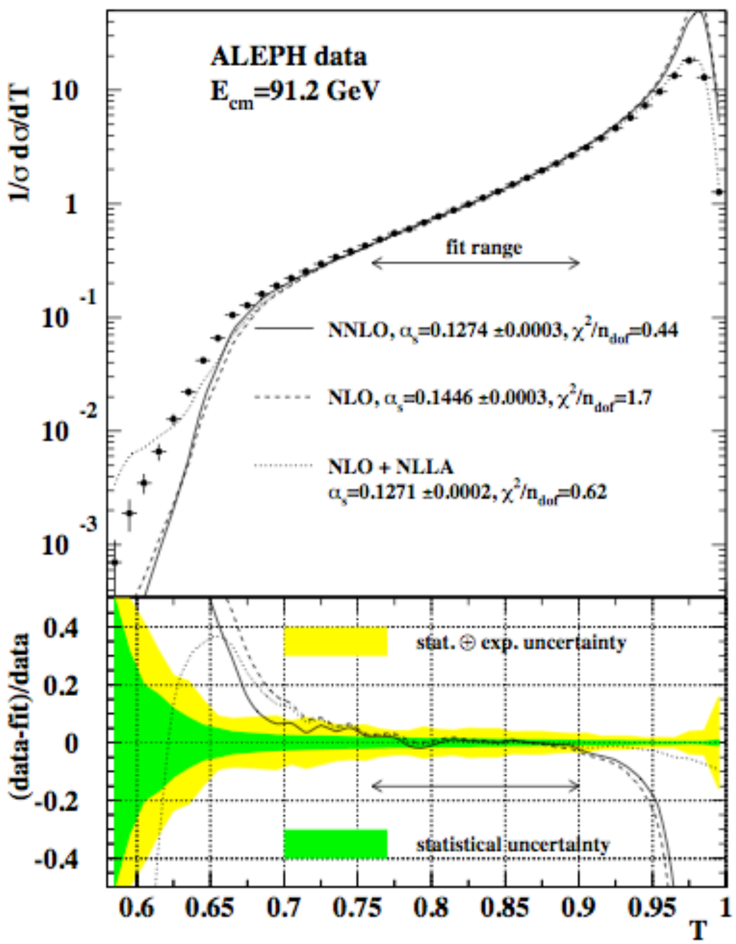
Strong Coupling from Event Shape Variables

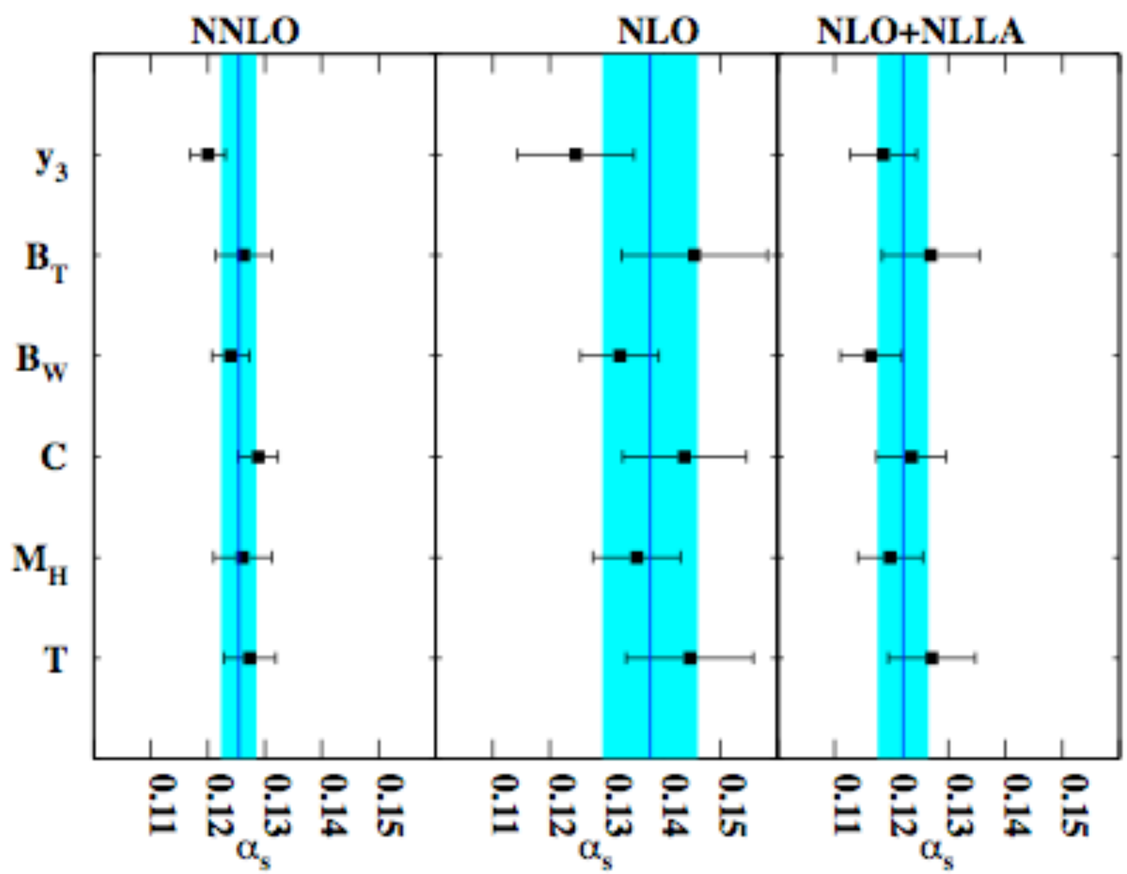
G. Dissertori et al., JHEP 0802:040,2008



Event Shape Variables from NNLO Calculation

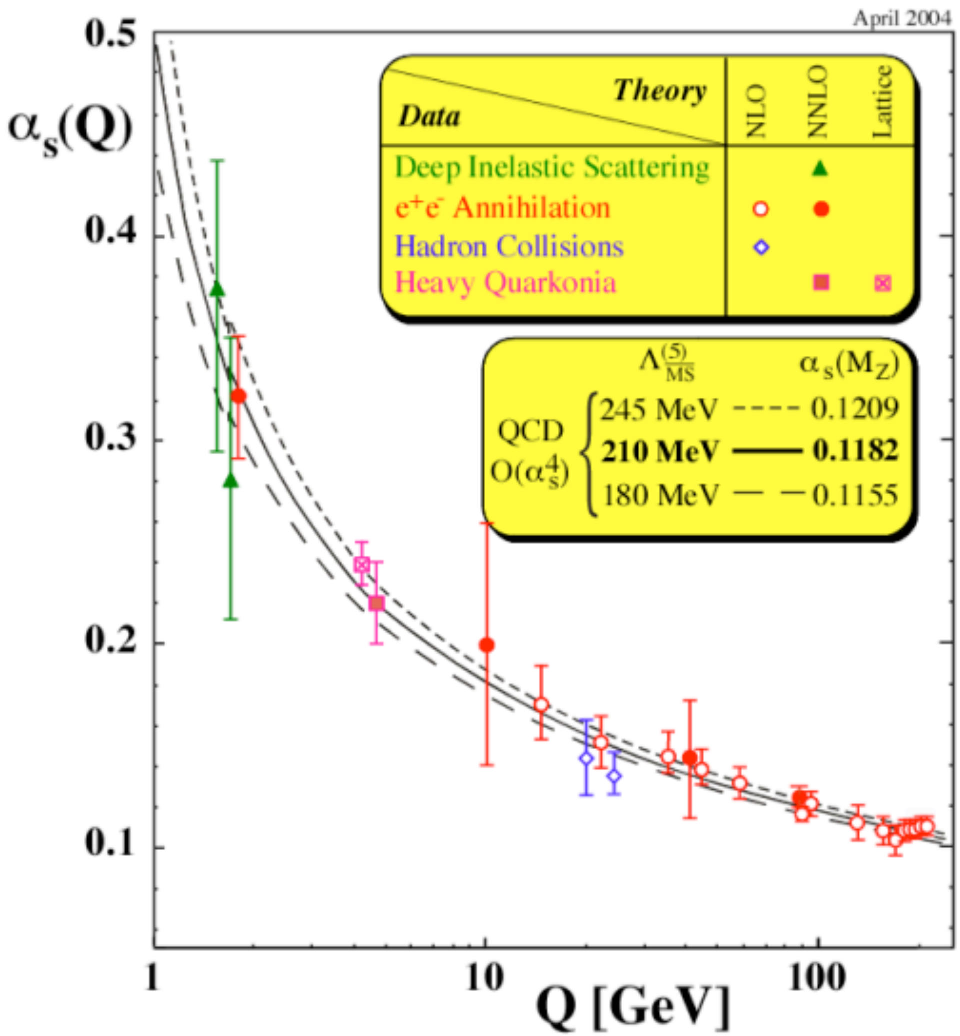
G. Dissertori et al., JHEP 0802:040,2008

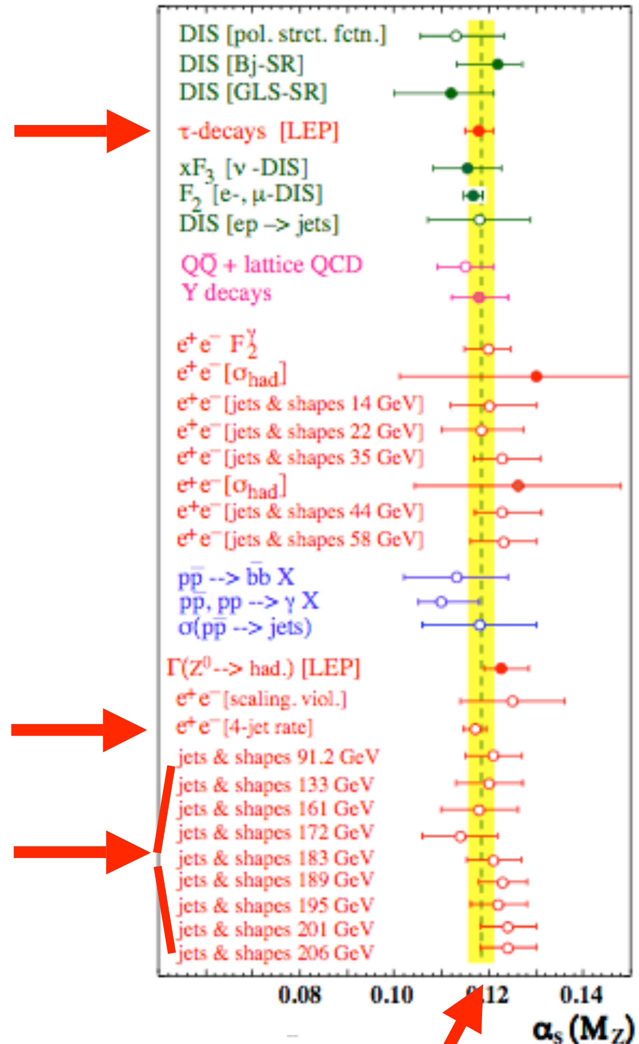




Strong Coupling from Everything

S. Bethke, Phys.Rept. 403:203,2004.





$$\alpha_S(m_Z^2) = 0.118 \pm 0.003$$