30 years after LEP first data: QCD and heavy flavours

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Before LEP

G. Altarelli 1989

“At present, it is fair to say that the experimental support of QCD is quite solid and quantitative. The forthcoming experiments at pp colliders, at LEP, SLC, and HERA will certainly be very important with their great potential for extending the experimental investigation of the validity of QCD.”

\[
\alpha_s(m_Z) \approx 0.11 \pm 0.01
\]

Particle spectra

$\frac{d\alpha}{dx} = \frac{2E}{Q}$


QCD and heavy flavour
Local Parton Hadron Duality
Or why we can measure jets and talk about partons

Solid lines: QCD MLLA

Destructive soft gluon interference in \( qq \) system reflected in hadron \( x_p \) spectrum

\[ \xi_p = \log(1/x_p), \quad x_p = 2p/Q \]
Jets and asymptotic freedom

JADE E0 jets

\[ y_{\text{cut}} = 0.08 \]

\[ E_{\text{cm}} = 91 \text{ GeV} \]


QCD and heavy flavour
Durham ($k_t$) jet algorithm

Iterative jet clustering metrics

**JADE:** \[ y_{ij} = 2E_i E_j (1 - \cos \theta_{ij}) / s \]
\[ y_{13} \sim y_{24} \sim y_{34} \]

**Durham:** \[ d_{ij} = 2 \text{min}(E_i, E_j)^2 (1 - \cos \theta_{ij}) / s \]
\[ d_{13} \sim d_{24} < d_{34} \]

Durham allows QCD resummation, smaller non-pert. corrections


Durham jet production

$\alpha_s(m_Z) = 0.1156 \pm 0.0038$

QCD and heavy flavour
Gluon Spin

3-jet events with $x_1 > x_2 > x_3$

$x_i = \frac{2E_{\text{jet}}}{Q}$

Three Gluon Vertex (TGV)

Four-jet events with $x_1 > x_2 > x_3 > x_4$

Expect TGV

Analyse jet angles

QCD and heavy flavour
Gluon FF
3-jet events (Durham) $y_{\text{cut}} = 0.015$

Select “Y” and “Mercedes” topologies

Double b-tag to define gluon jets, correct for pure light quark and gluon jets

$E_{\text{jet}} \sin \Theta \approx 26 \text{ GeV}$  
$E_{\text{jet}} \sin \Theta \approx 12 \text{ GeV}$

Event shape observables

\[ T = \max_n \left( \frac{\Sigma_i p_i \cdot n}{\Sigma |p_i|} \right) \]
Monte Carlo Generators

QCD and heavy flavour
Monte Carlo Generators

1-Thrust

\[ \frac{1}{N} \frac{dN}{d(1-T)} \text{ corr. enc.} \]

- charged particles
- JT 7.3 PS
- JT 7.4 PS
- AR 4.06
- H 5.8C
- JT 7.4 ME

DELPHI

\[ \frac{1}{N} \frac{dN}{d\xi_p} \]

K^0

Octet-Baryons

\[ \frac{1}{N} \frac{dN}{d\xi_p} \]

QCD and heavy flavour
Colour Reconnection

\[ e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q} \]

Ratio of charged particle flow in planes within (intra) or between (inter) Ws

\[ \text{Intra–W region} \]
\[ n_{\text{plane}} = 1 \]

\[ \text{Jet 1, } \chi = 0.0, 4.0 \]

\[ \text{Jet 2, } \chi = 1.0 \]

\[ \text{Inter–W region} \]
\[ n_{\text{plane}} = 4 \]

\[ \text{Jet 4, } \chi = 3.0 \]

\[ \text{Intra–W region} \]
\[ n_{\text{plane}} = 3 \]

b-quark Fragmentation

$2E_B/Q = x_b^{\text{weak}}$ for weak B decays inclusively from vertex tagged jets

Best description by Lund model

$$f(x) = \frac{1}{x(1-x)^a}\exp(-b m_h^2/x)$$

**Graphs:**
- ALEPH
- DELPHI
- OPAL
- SLD
- Measured distribution
- Kartvelishvili
- Peterson
- Collins-Spiller
- Lund
- Lund-Bowler

**τ Physics: Spectral Function**

Spectral function:

\[ m_h^2 \text{ of non-strange hadronic } \tau \text{ decays (after kinematic factor)} \]

\[
R^{k,l}_{\tau,v/a}(s_0) = \frac{s_0}{\int_0^s (1 - s/s_0)^{k} (s/m_{\tau}^2)^l \, dR_{\tau,v/a} \, ds}
\]

\[
R^{k,l}_{\tau,v/a}(s_0) = \frac{3}{2} S_{EW} \left| V_{ud} \right|^2 \left( 1 + \delta_{EW}^{kl} + \delta_{pert}^{kl} + \delta_{NP}^{kl} \right)_{v/a}
\]


\[ \alpha_S(m_\tau) = 0.340 \pm 0.005^{\text{exp}} \pm 0.0014^{\text{th}} \]

\[ \alpha_S(m_Z) = 0.1209 \pm 0.0018 \]
The best is yet to come … and even better with ILC, CLIC, FCC-ee, CepC!

QCD and heavy flavour

$$\alpha_s(m_Z)$$ and LEP

$$\alpha_s(Q^2)$$

$$\tau$$ decays (N$^3$LO)

$\Delta$ DIS jets (NLO)

$\square$ Heavy Quarkonia (NLO)

$\bullet$ e$^+e^-$ jets & shapes (res. NNLO)

$\nabla$ e.w. precision fits (N$^3$LO)

$\triangleright$ $pp \rightarrow$ jets (NLO)

$\bigtriangledown$ $pp \rightarrow$ tt (NNLO)

QCD $$\alpha_s(M^2_Z) = 0.1181 \pm 0.0011$$
Summary

● LEP was a QCD precision machine
  – Excellent detectors, clean events, high statistics
  – Strong Theory-Experiment interactions
● Establish gluons as particles
  – Spin, TGV, colour interference, CR limits, ...
● The mechanics of event evolution: LPHD
  – Hard scatter, parton shower, hadronisation
● Strong coupling from $\Delta \alpha_s(m_Z) \sim 9\%$ to $\sim 1\%$!
τ Physics: Polarisation

\( \theta \): angle between \( \tau^- \) and \( e^- \) beam

\[
P_\tau(\cos \theta) = -\frac{A_\tau (1 - \cos^2 \theta) + A_e 2 \cos \theta}{(1 + \cos^2 \theta) + \frac{4}{3} A_{fb} 2 \cos \theta}
\]

\[
A_l = \frac{2 g_V^l g_A^l}{(g_V^l)^2 + (g_A^l)^2}
\]

\[
g_V^l = 1 - 4 \sin^2 \theta_W^{\text{eff}}
\]

\[
g_A^l = 1 - 4 \sin^2 \theta_W^{\text{eff}}
\]

\[
\sin^2 \theta_W^{\text{eff}} = 0.2315 \pm 0.0006
\]

[Note: Image references to charts and graphs, possibly showing data or plots related to the equations provided.]
$\tau$ Physics: Lepton Universality

Coupling ratios:

$g_\mu / g_e = 0.999 \pm 0.003$

$g_\tau / g_e = 1.000 \pm 0.003$

$g_\tau / g_\mu = 1.000 \pm 0.003$