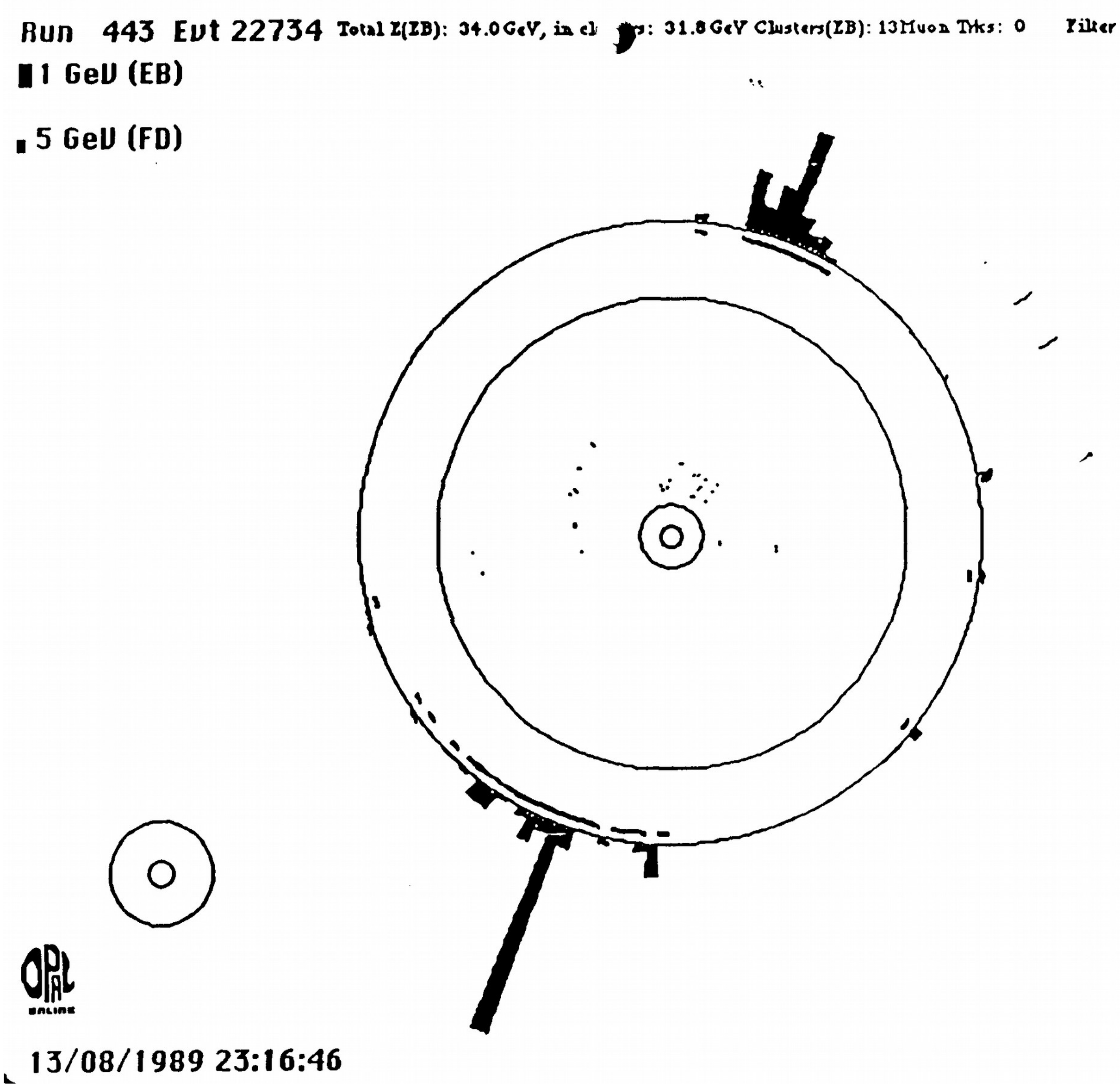


30 years after LEP first data: QCD and heavy flavours

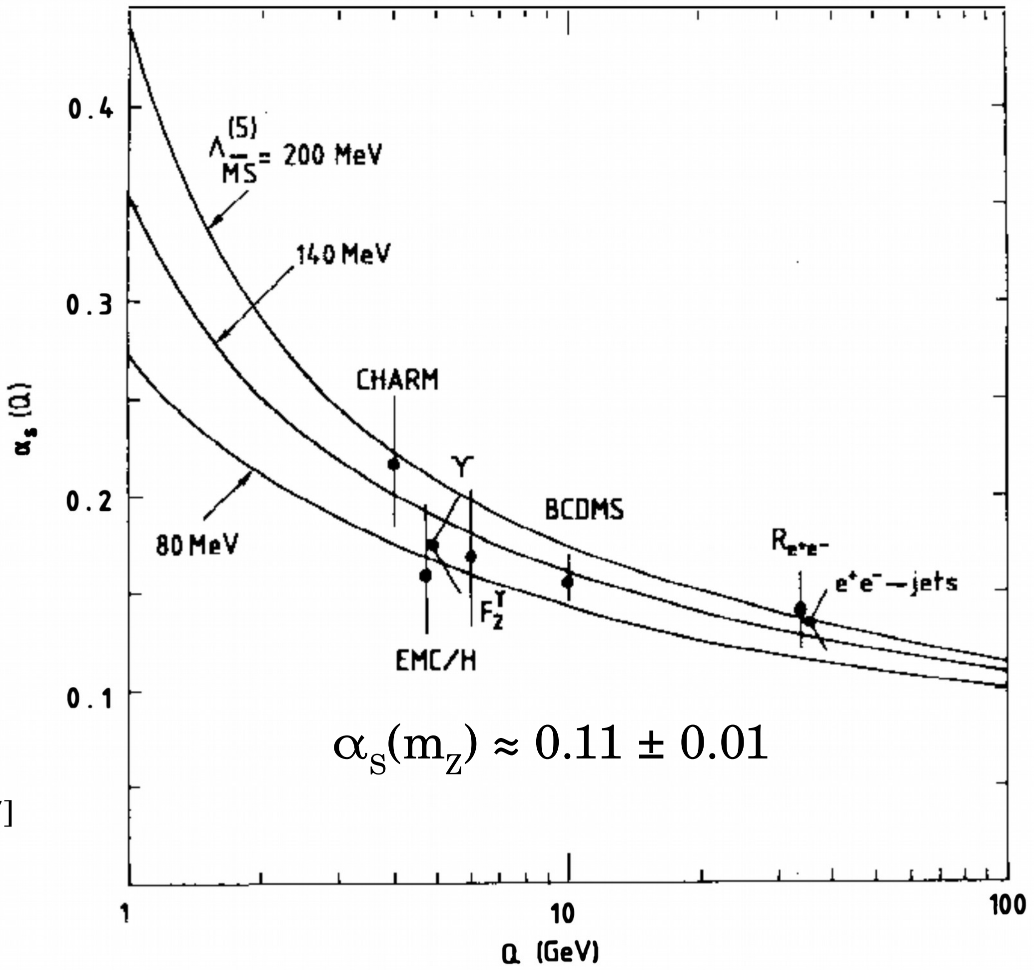
Stefan Kluth
MPI für Physik
28.11.2019

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."

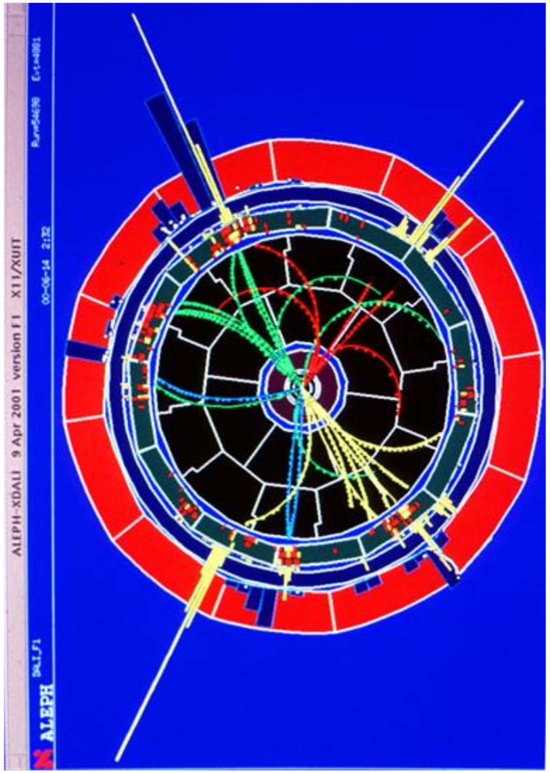
[Ann. Rev. Nucl. Part. Sci. 39 (1989) 357]

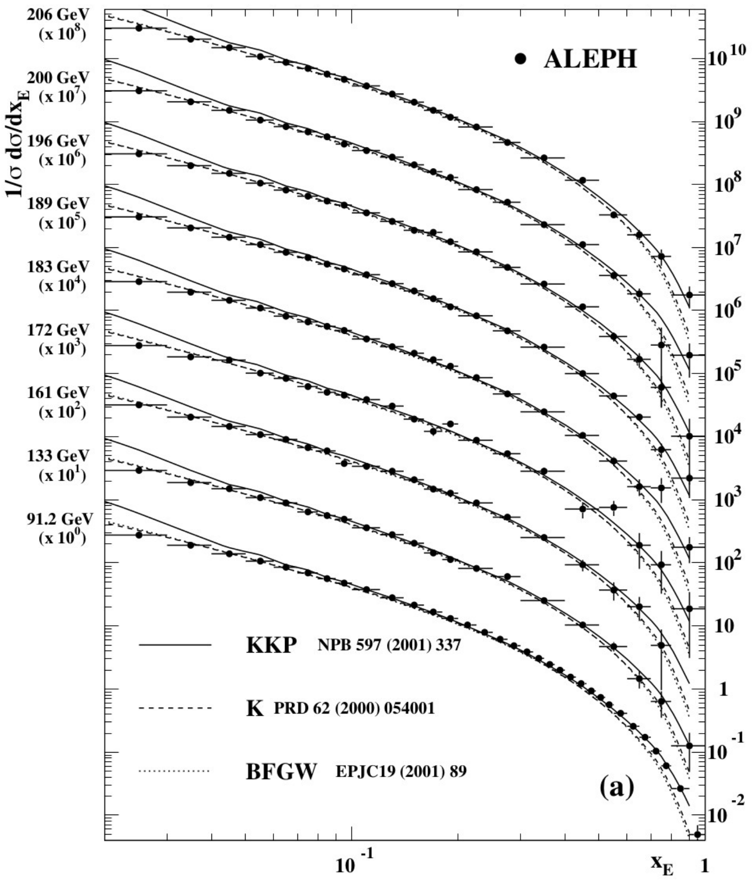


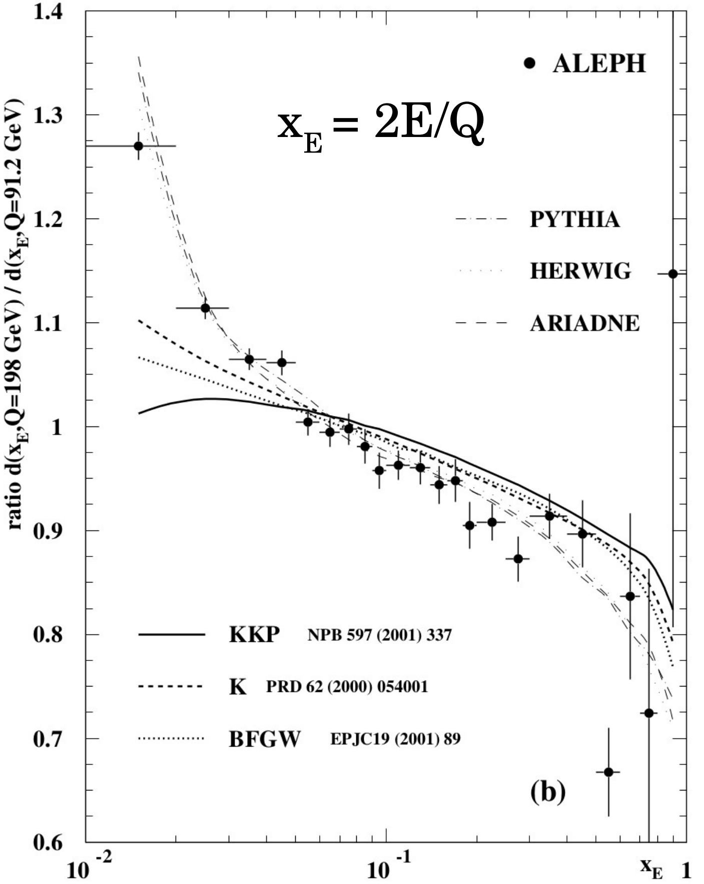
$\alpha_S(m_Z) \approx 0.11 \pm 0.01$

Particle spectra

[Eur. Phys. J. C35 (2004) 457]



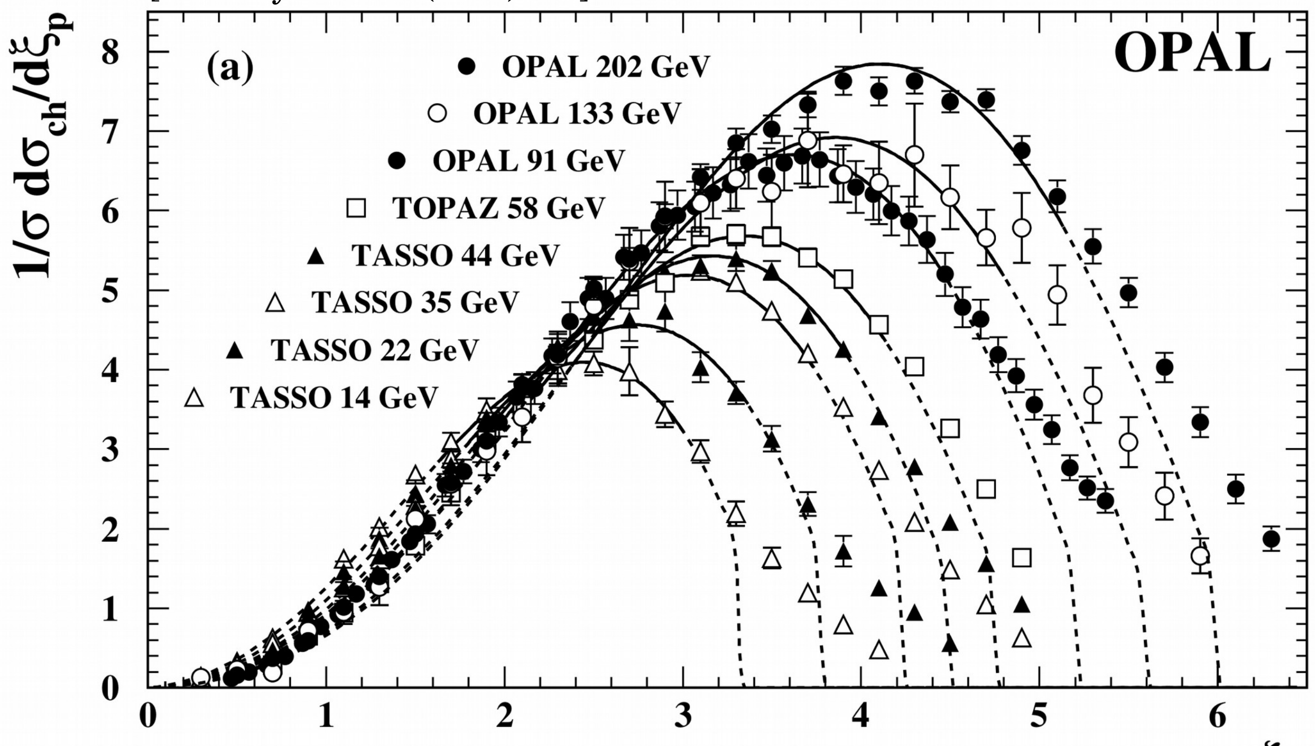




Local Parton Hadron Duality

Or why we can measure jets and talk about partons

[Eur. Phys. J. C27 (2003) 467]



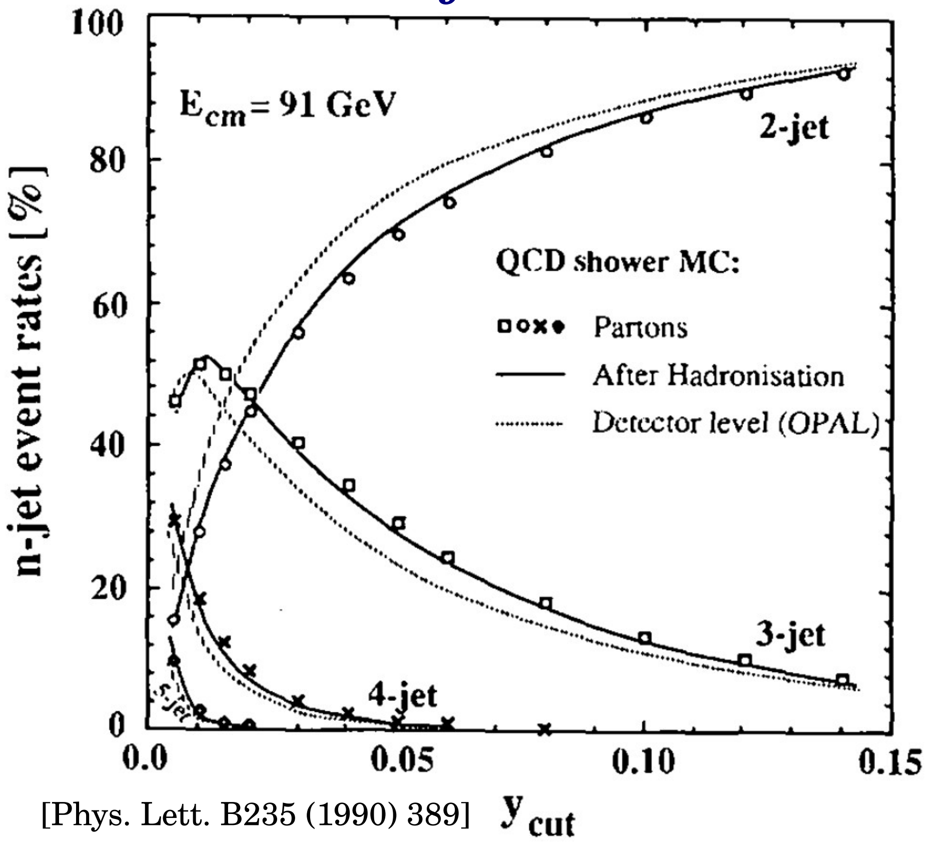
Solid lines: QCD MLLA

Destructive soft gluon interference in $q\bar{q}$ system reflected in hadron x_p spectrum

$\xi_p = \log(1/x_p)$, $x_p = 2p/Q$

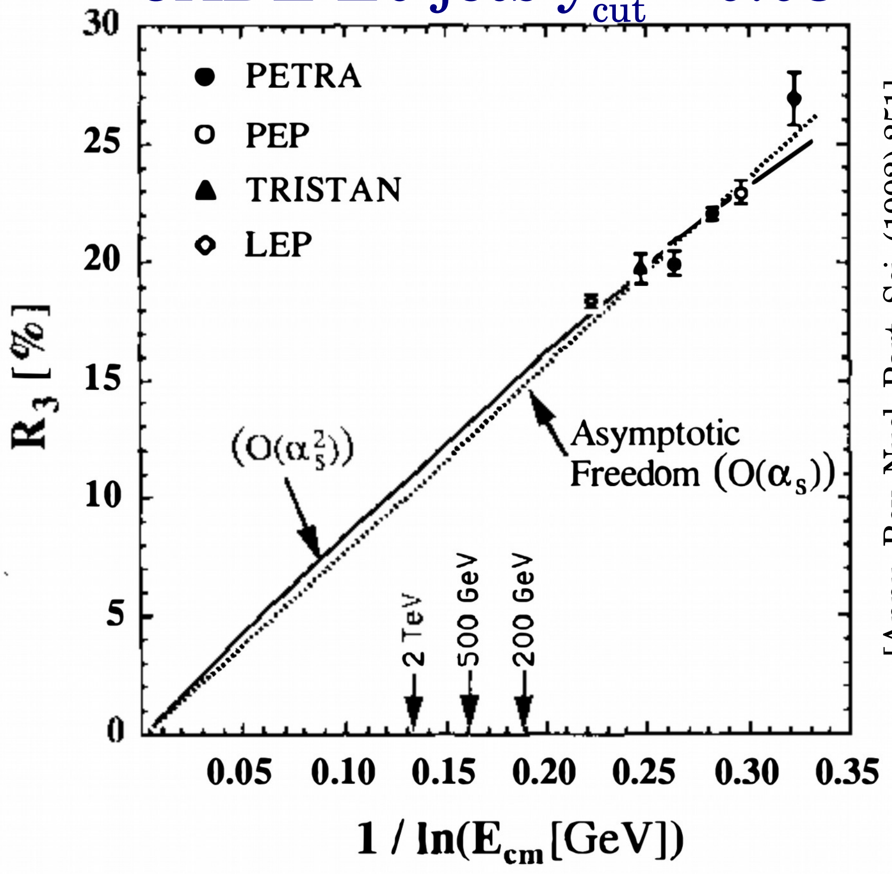
Jets and asymptotic freedom

JADE E0 jets



[Phys. Lett. B235 (1990) 389]

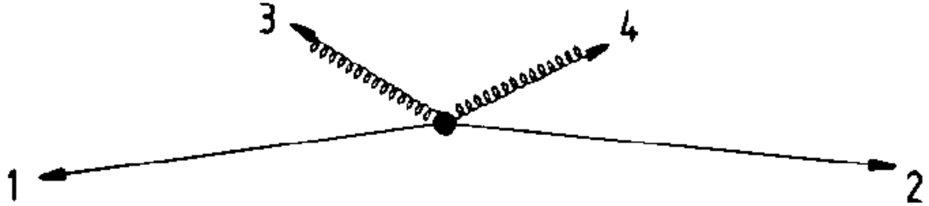
JADE E0 jets $y_{cut} = 0.08$



[Annu. Rev. Nucl. Part. Sci. (1992) 251]

Durham (k_t) jet algorithm

[Phys. Lett. B269 (1991) 432, Z. Phys. C53 (1992) 629]



Iterative jet clustering metrics

JADE: $y_{ij} = 2E_iE_i(1\text{-}\cos\theta_{ij})/s$

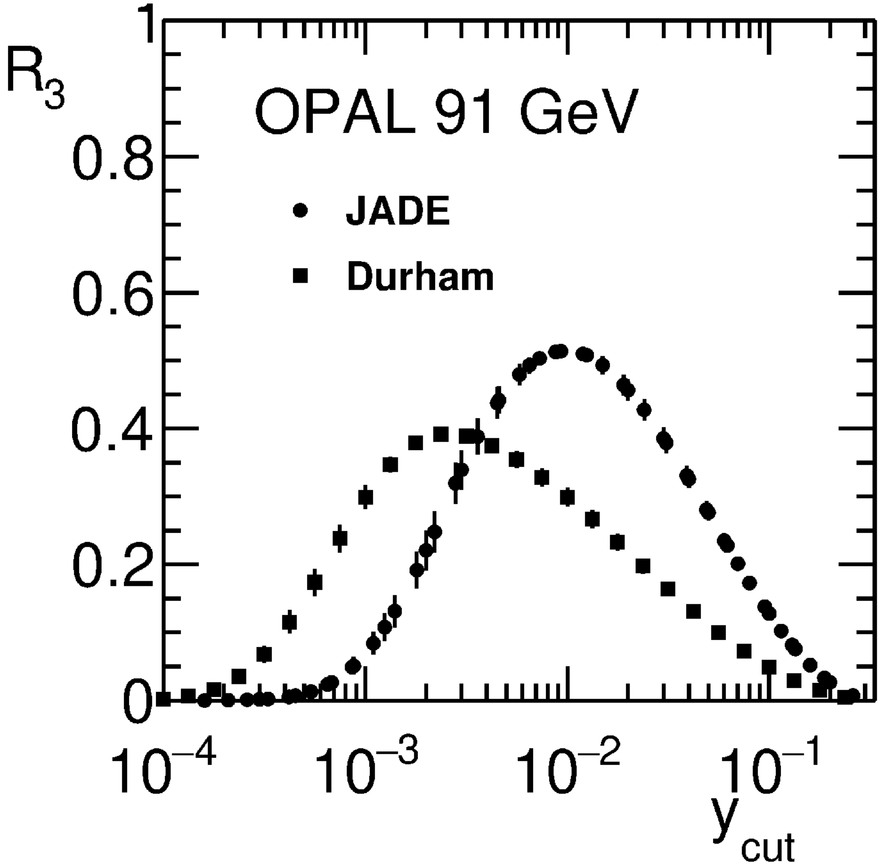
$y_{13} \sim y_{24} \sim y_{34}$

Durham: $d_{ij} = 2\min(E_i,E_i)^2(1\text{-}\cos\theta_{ij})/s$

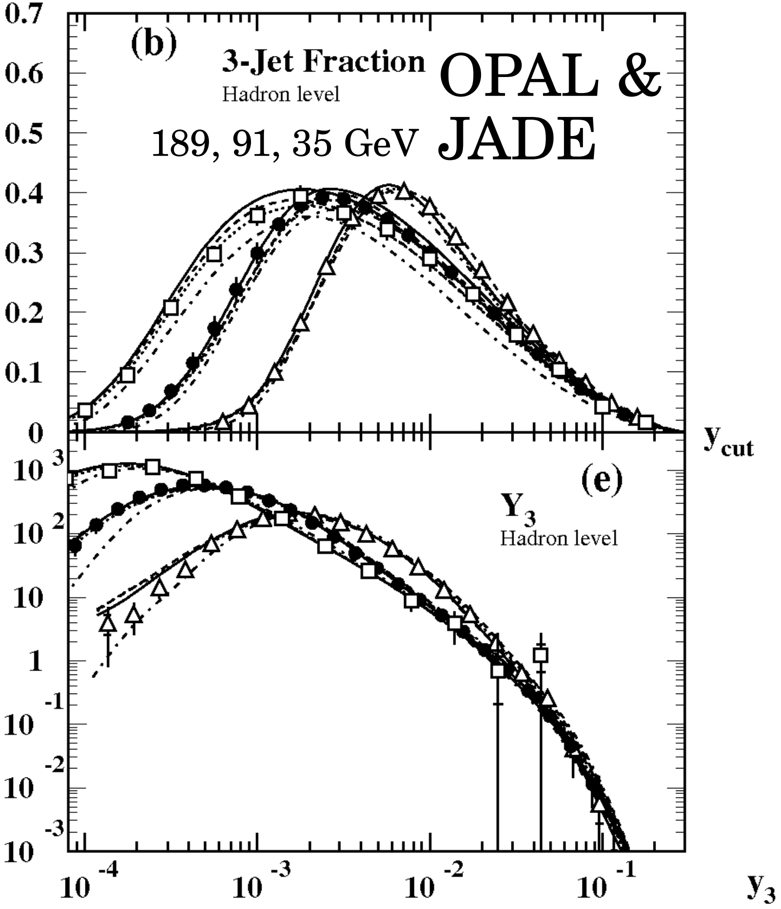
$d_{13} \sim d_{24} < d_{34}$

Durham allows QCD resummation, smaller non-pert. corrections

Data from [Eur. Phys. J. C17 (2000) 19]

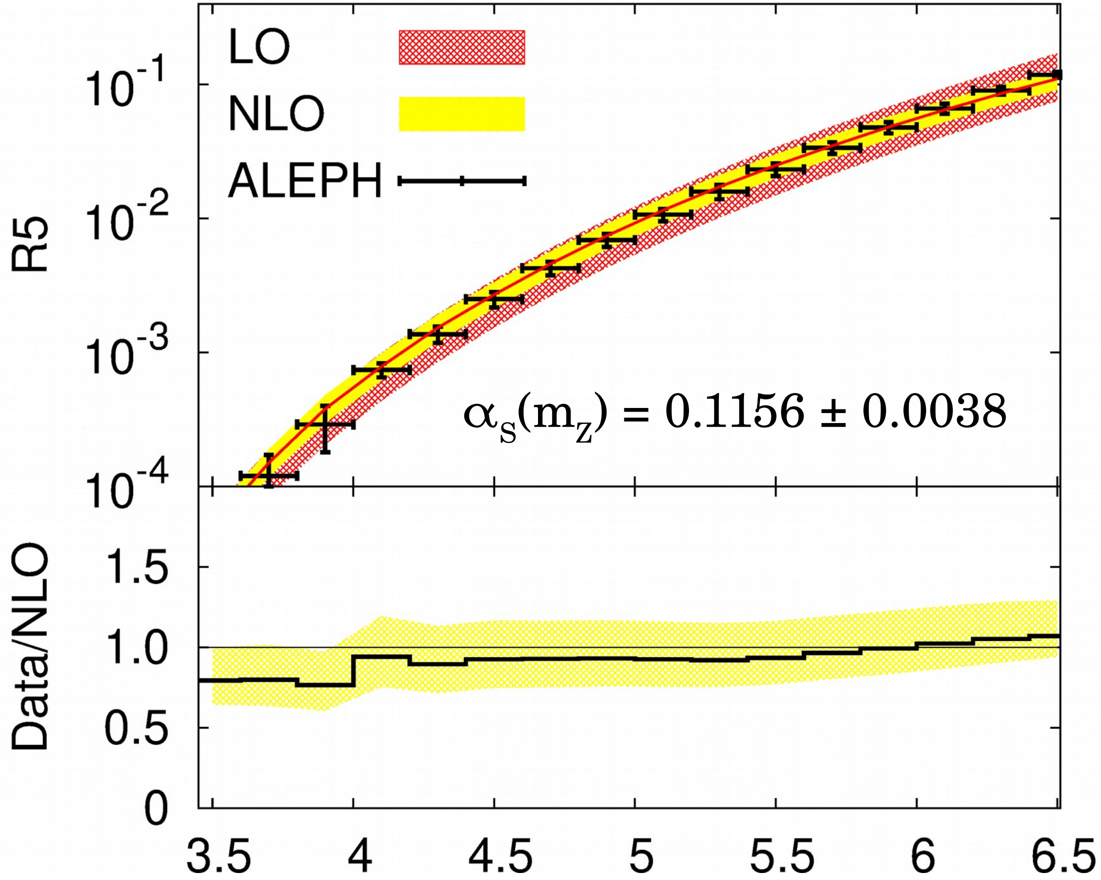


Durham jet production



[Eur. Phys. J. C17 (2000) 19]

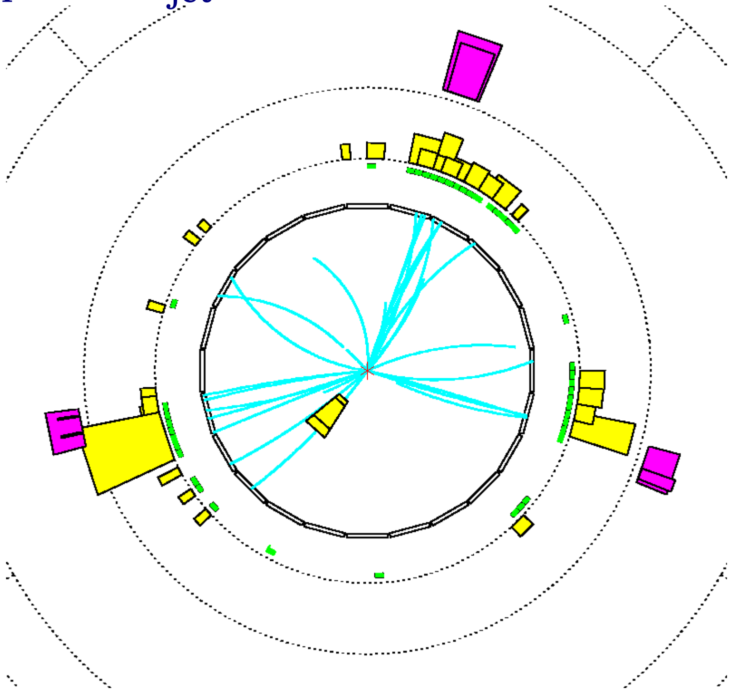
[JHEP 1011 (2010) 050]



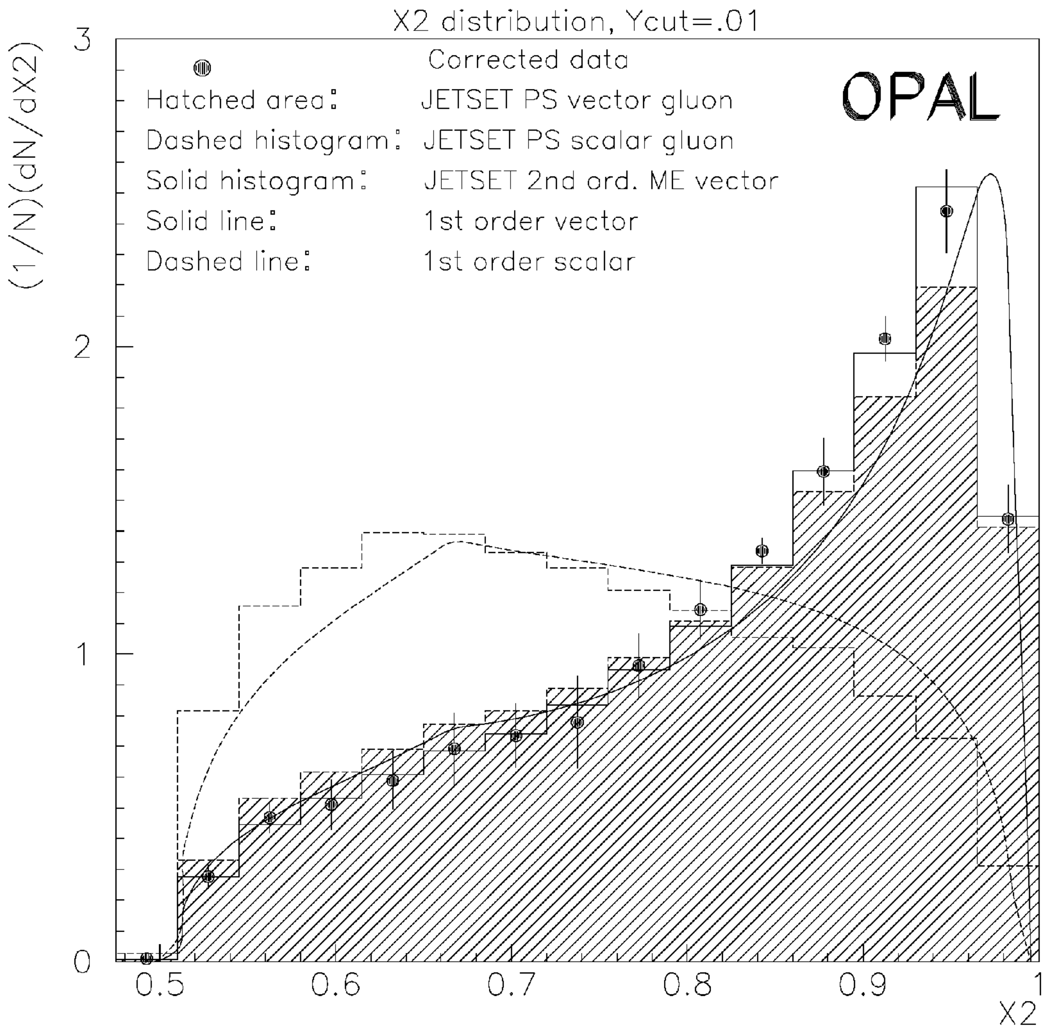
Gluon Spin

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

$x_i = 2E_{jet}/Q$



[Z. Phys. C52 (1991) 543]

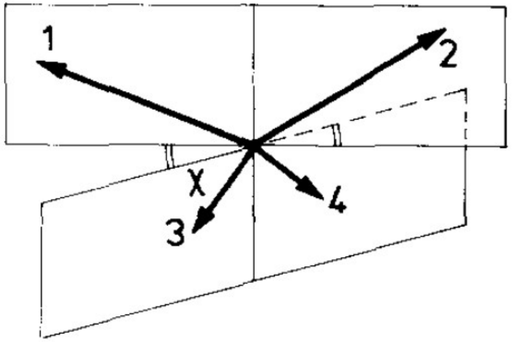


Three Gluon Vertex (TGV)

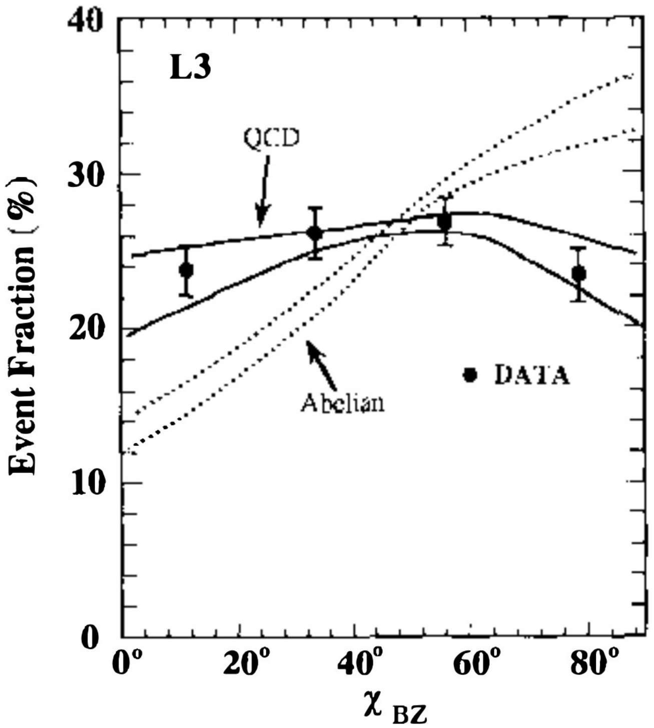
Four-jet events with
$x_1 > x_2 > x_3 > x_4$

Expect TGV

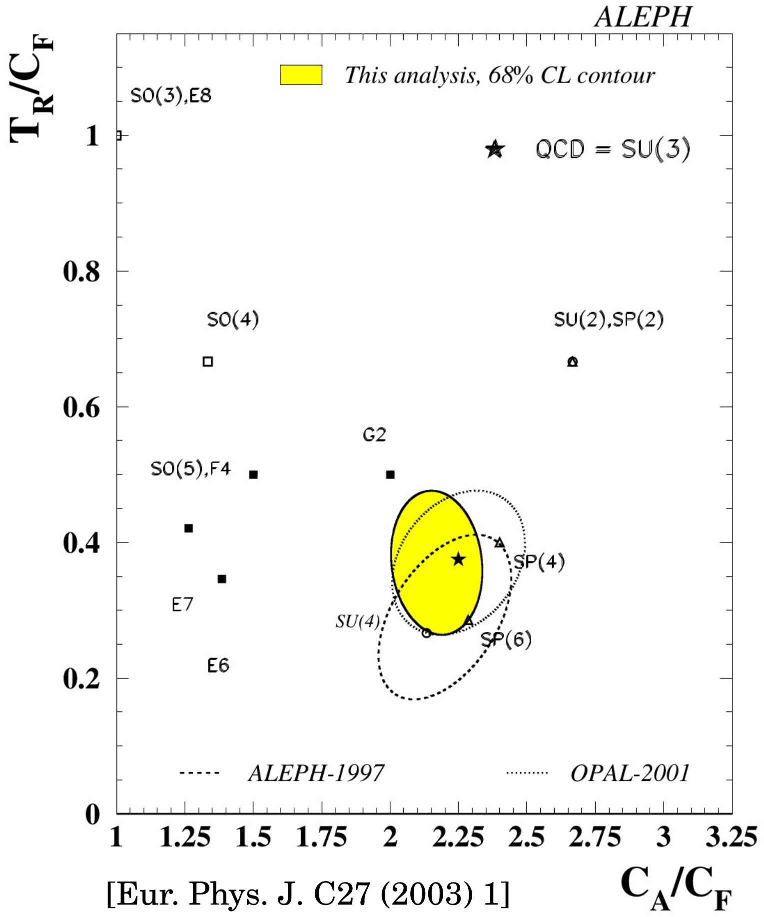
Analyse jet angles



[Phys. Lett. B208 (1988) 306]



[Annu. Rev. Nucl. Part. Sci. (1992) 251]

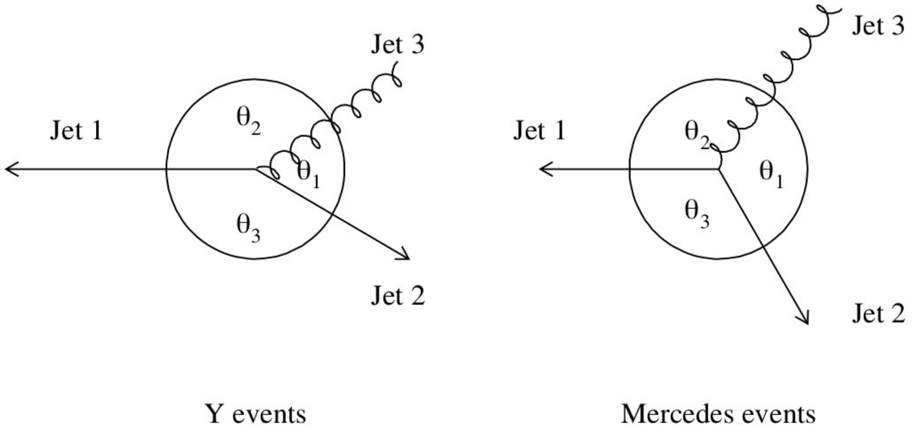


[Eur. Phys. J. C27 (2003) 1]

Gluon FF

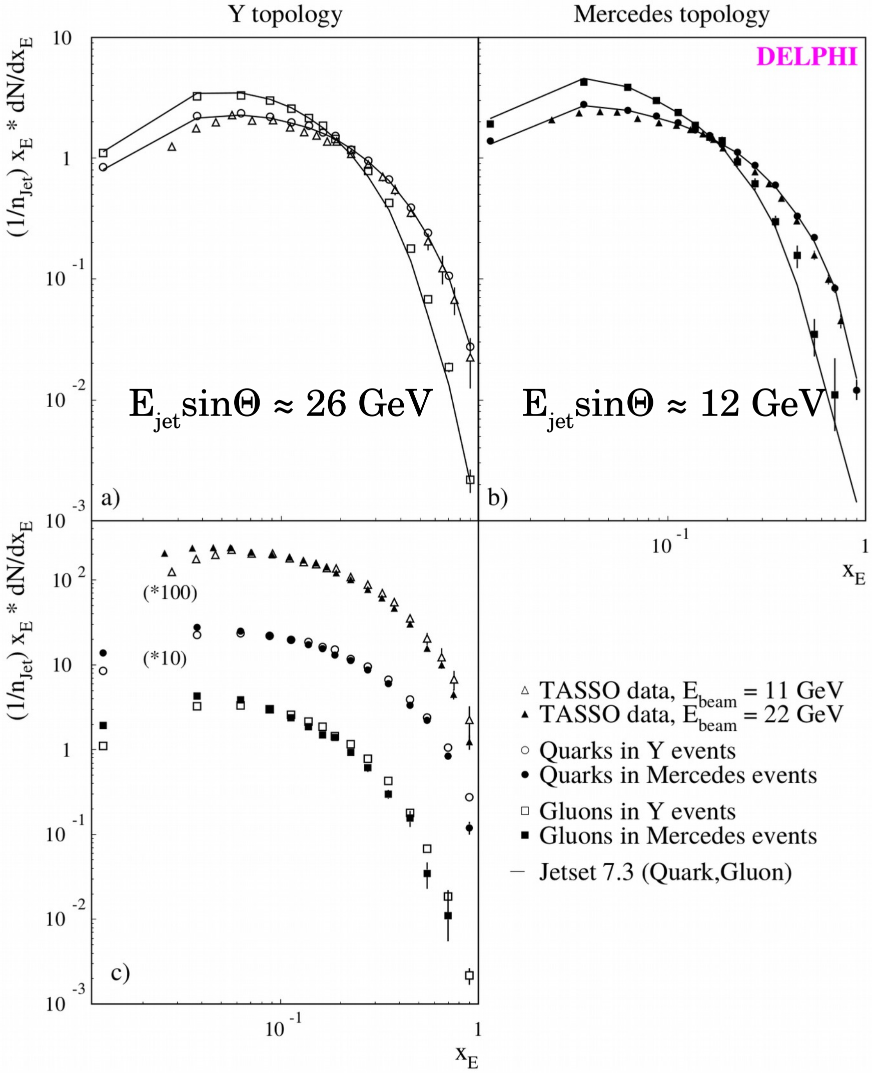
3-jet events (Durham) $y_{cut} = 0.015$

Select "Y" and "Mercedes" topologies



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

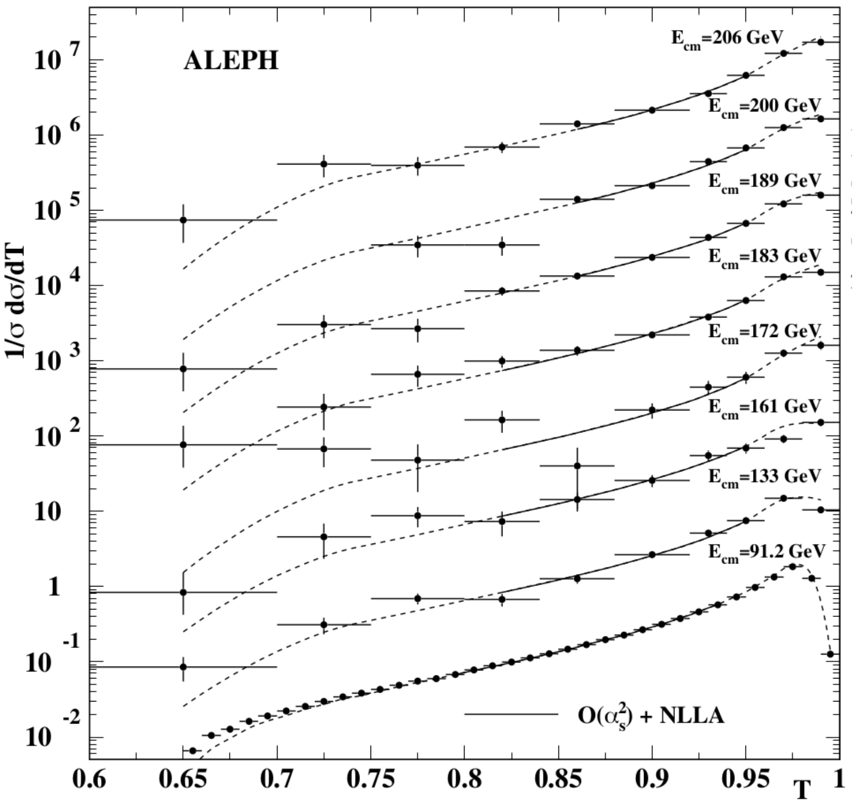
[Eur. Phys. J. C4 (1998) 1]

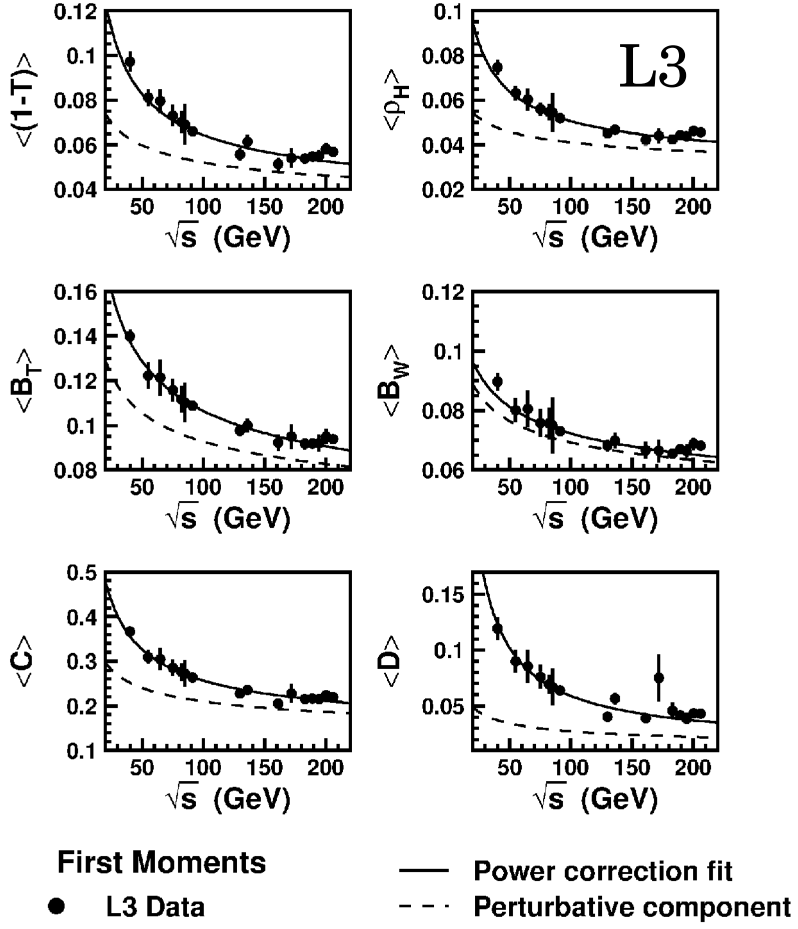


Event shape observables

[Eur. Phys. J. C35 (2004) 457-486]

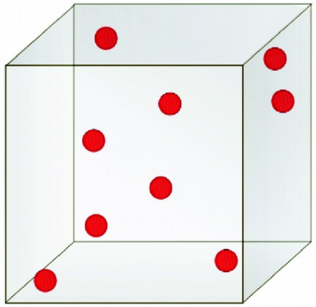
$T = \max_{\mathbf{n}}(\Sigma_i p_i \cdot \mathbf{n})/(\Sigma_i |p_i|))$



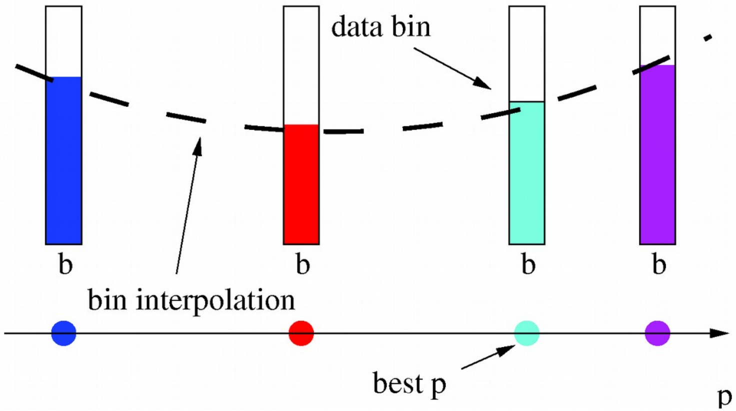


[Phys.Rept. 399 (2004) 71]

Monte Carlo Generators

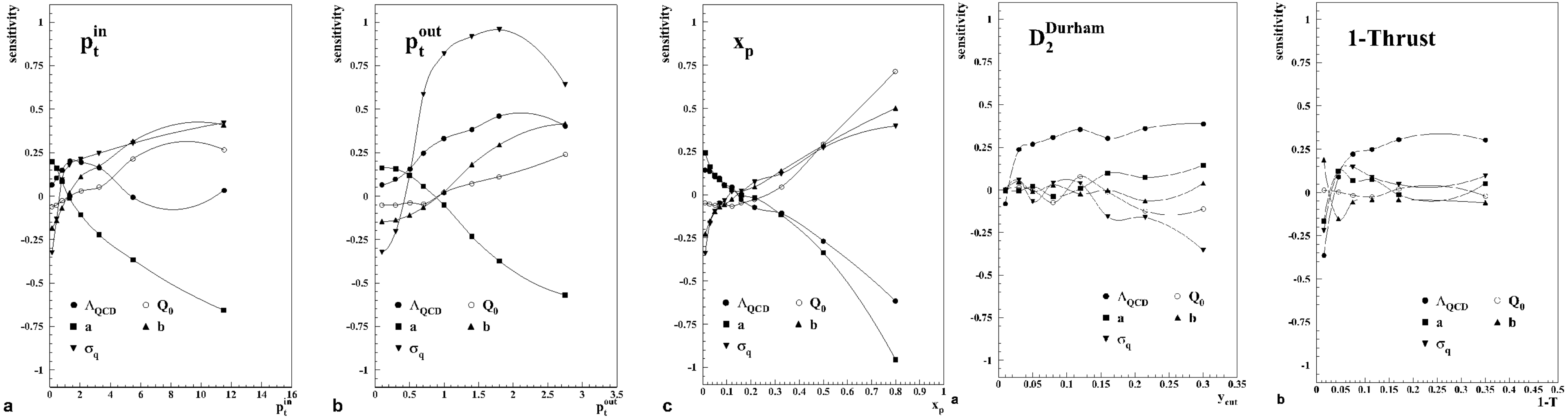


[Eur. Phys. J. C65 (2010) 331]



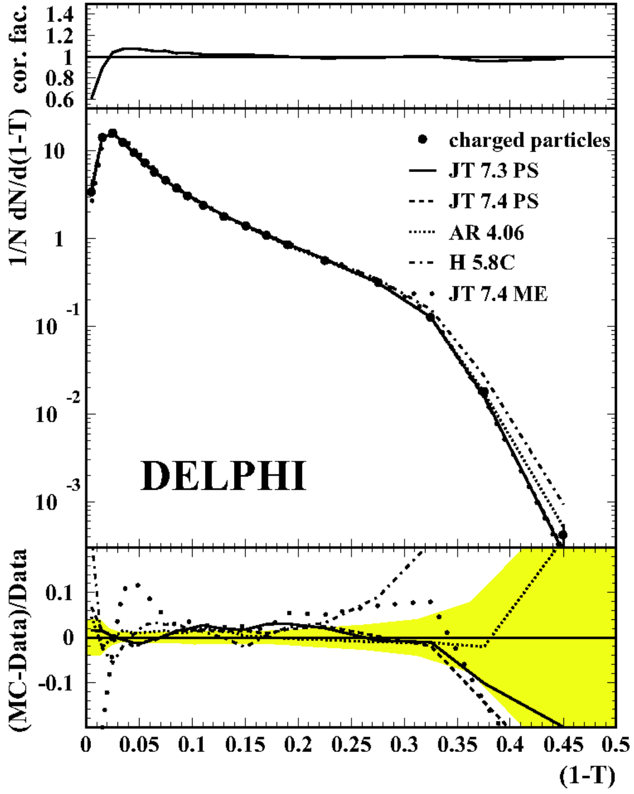
DELPHI

[Z. Phys. C73 (1996) 11]

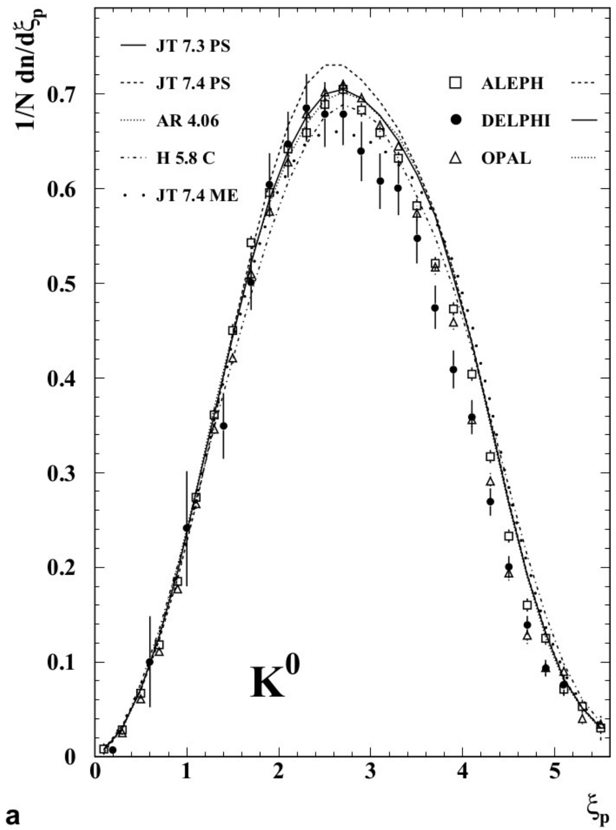


Monte Carlo Generators

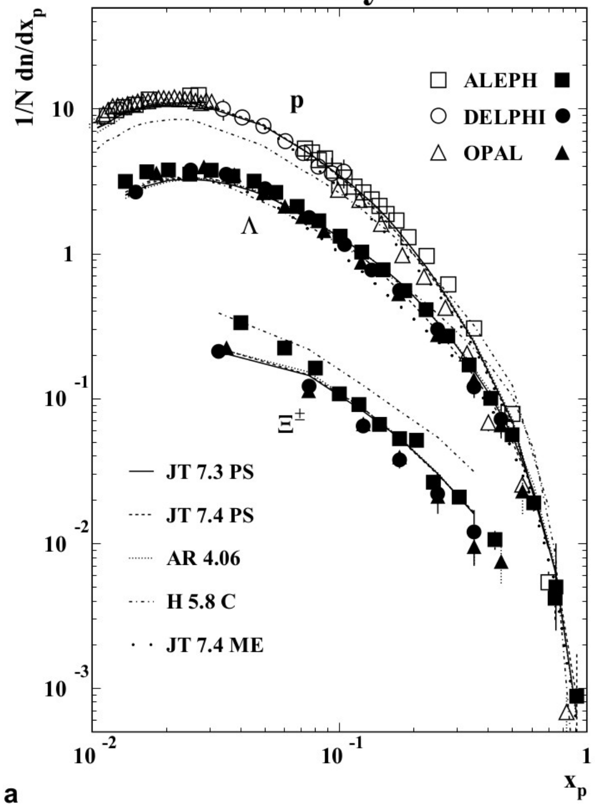
1-Thrust



[Z. Phys. C73 (1996) 11]



Octet-Baryons

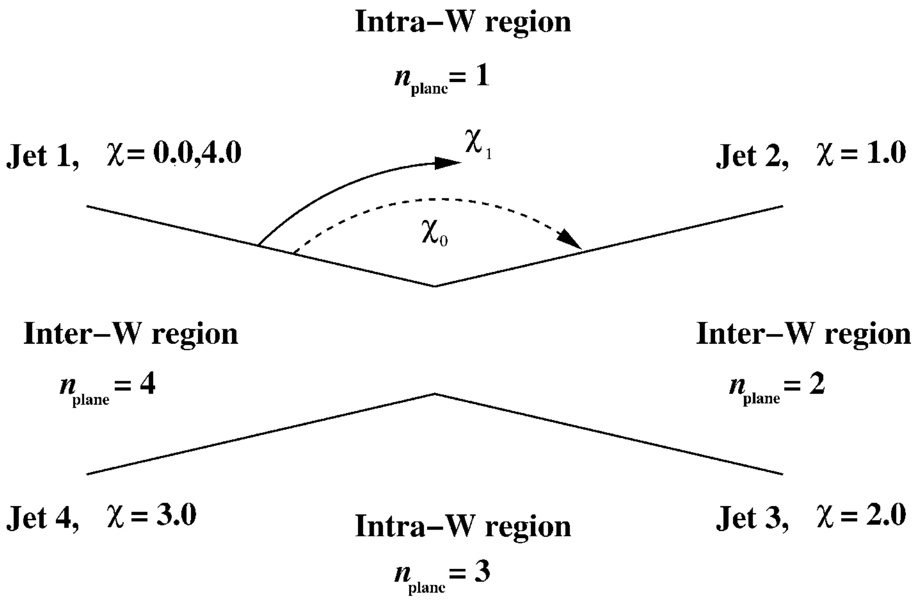


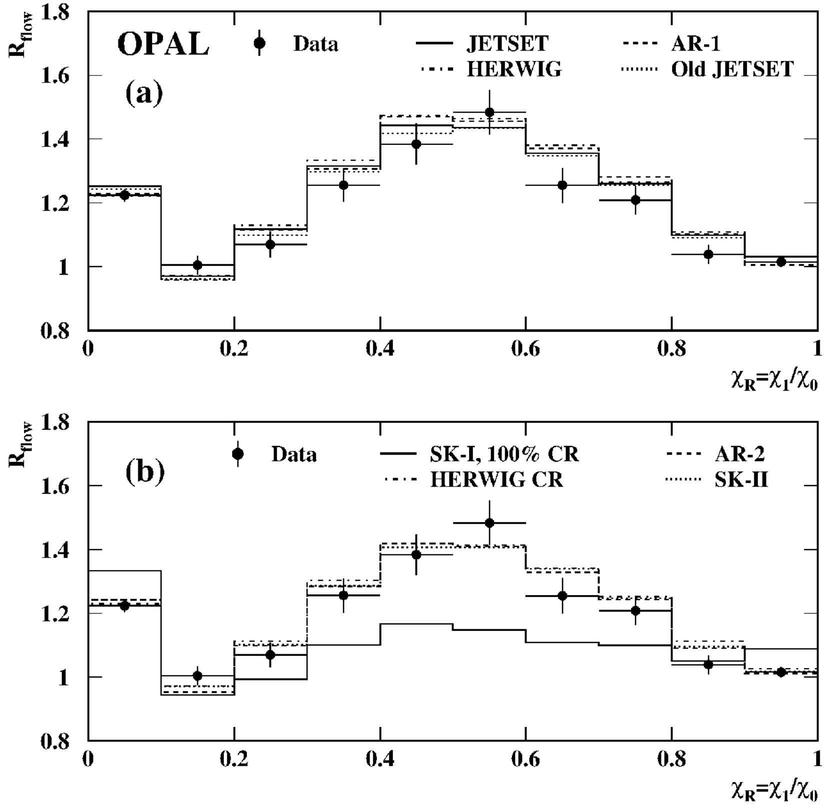
Colour Reconnection

$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$

[Eur. Phys. J. C45 (2006) 291]

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

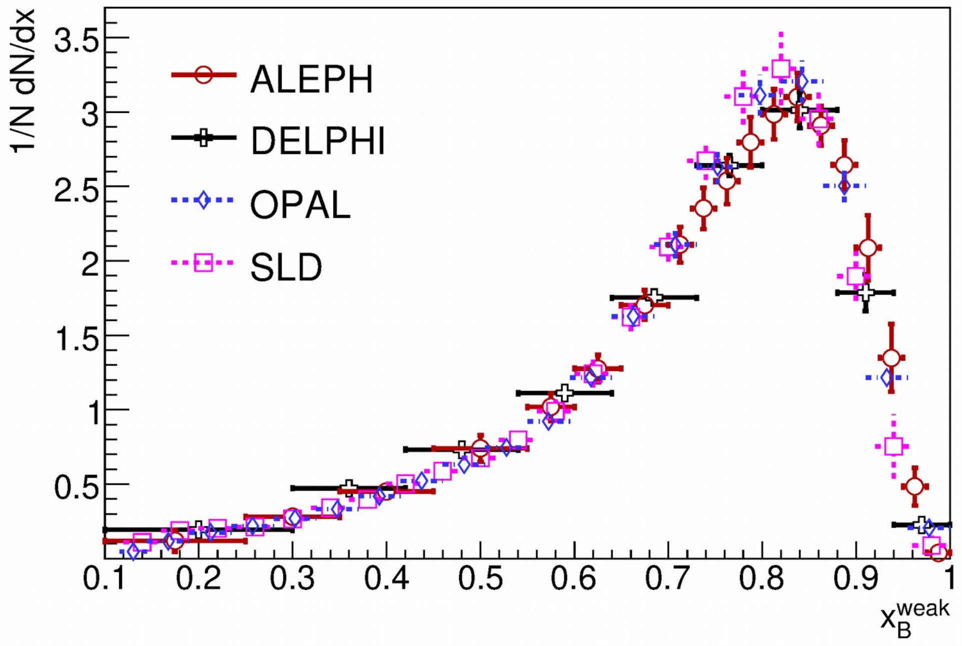




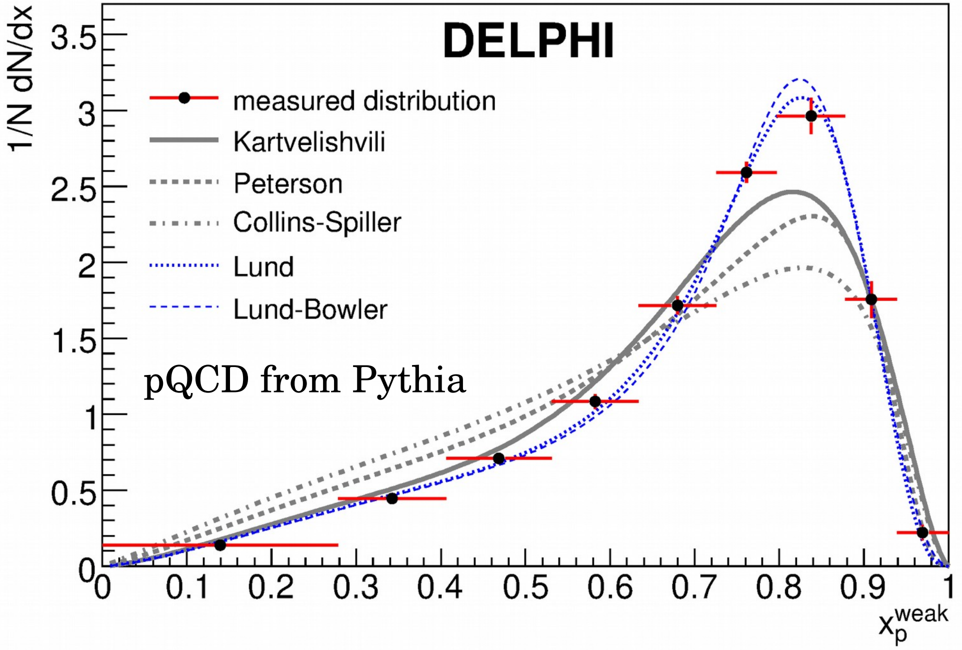
b-quark Fragmentation

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

Best description by Lund model $f(x) = 1/x(1-x)^a \exp(-bm_{b,t}^2/x)$



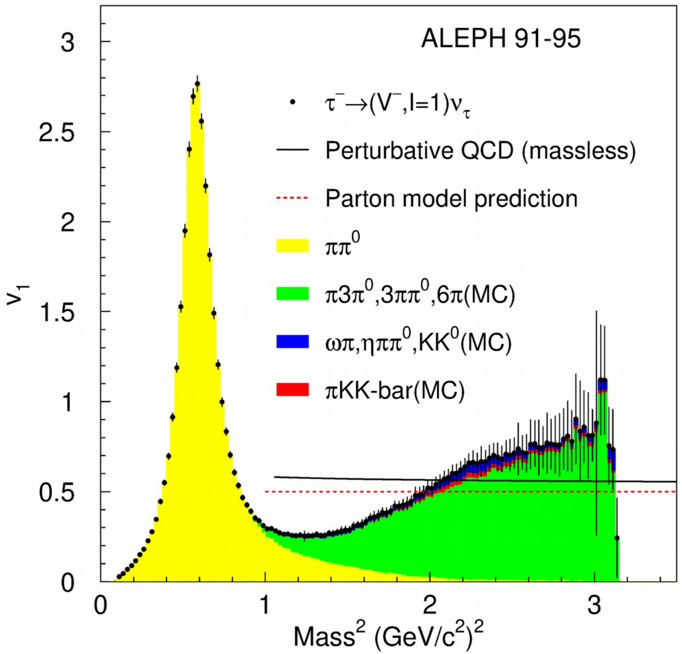
[Eur. Phys. J. C71 (2011) 1557]

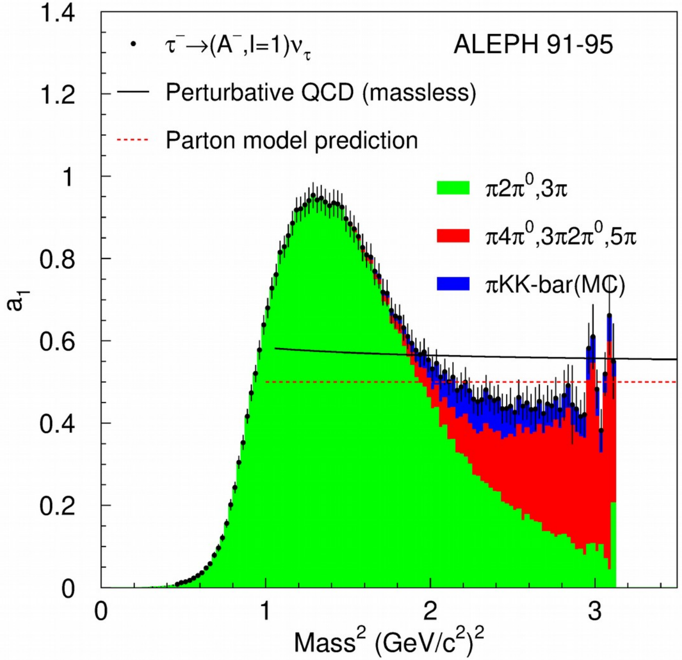


τ Physics: Spectral Function

Spectral function:

m_h^2 of non-strange hadronic τ decays (after kinematic factor)





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

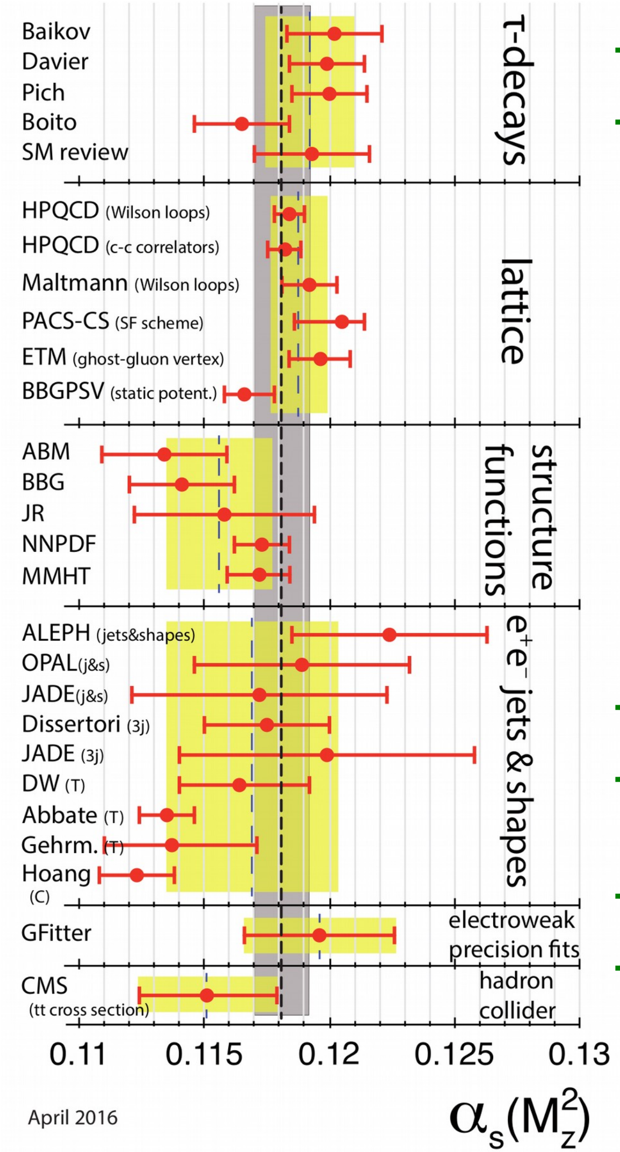
$$R^{k,l}_{\tau,v/a}(s_0) = 3/2 \, S_{EW} |V_{ud}|^2 (1 + \delta^{kl}_{EW} + \delta^{kl}_{pert} + \delta^{kl}_{NP,v/a})$$

[Phys. Rept. 421 (2005) 191]

$\alpha_S(m_\tau) = 0.340 \pm 0.005_{exp} \pm 0.0014_{th}$

$\alpha_S(m_Z) = 0.1209 \pm 0.0018$

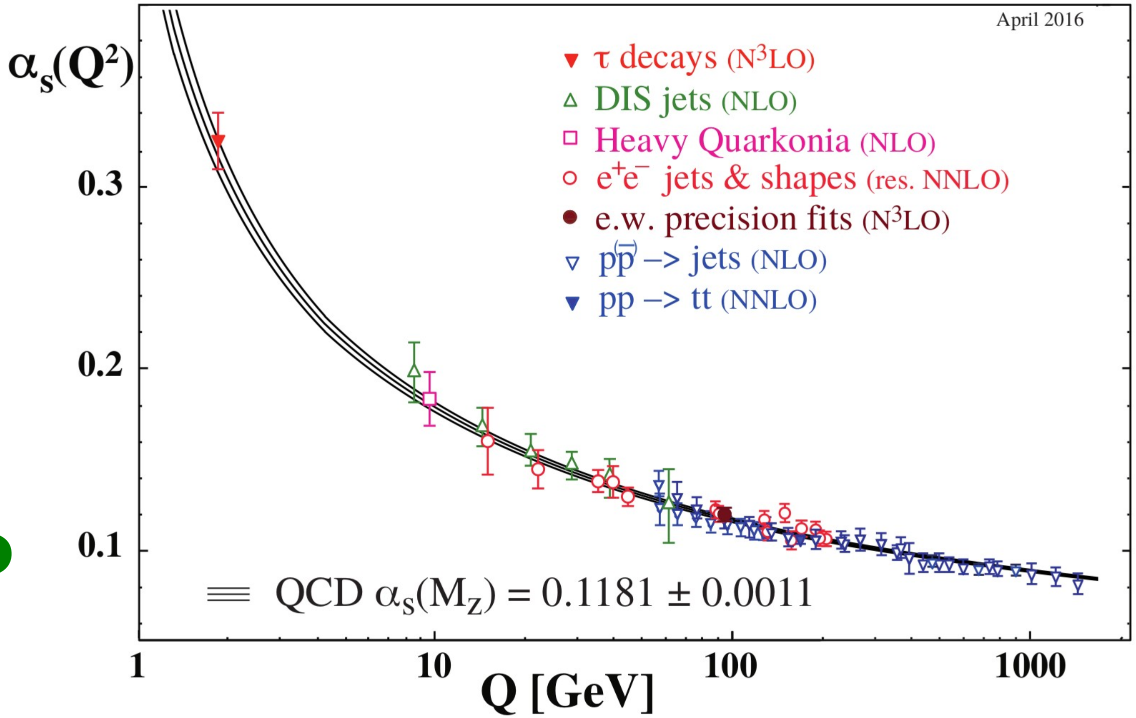
$\alpha_s(m_Z)$ and LEP



LEP

LEP

LEP



The best is yet to come … and even better with ILC, CLIC, FCC-ee, CepC!

[Chin. Phys. C40 (2016) 100001]

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 $\Delta\alpha_S(m_Z)$ ~9% to ~1%!

τ Physics: Polarisation

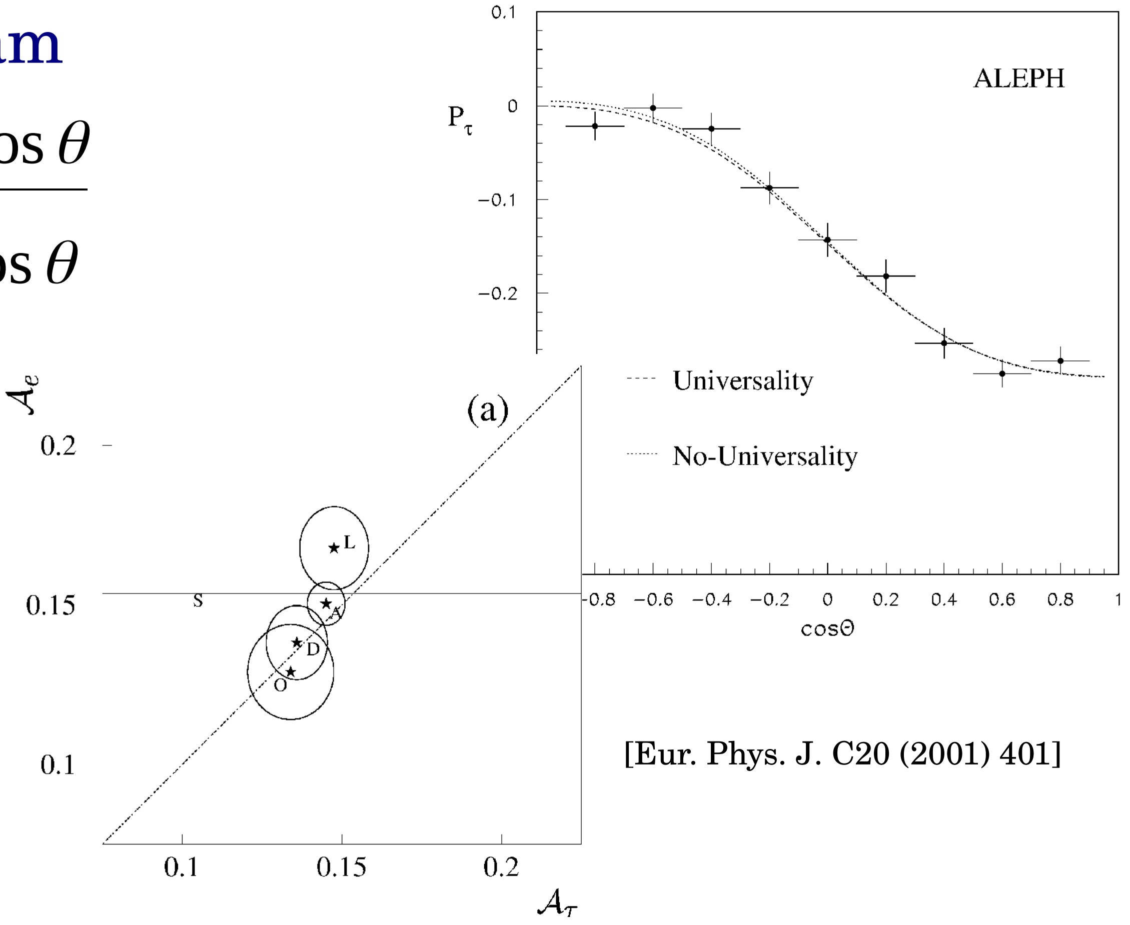
θ: angle between τ^- and e^- beam

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

$$A_l = \frac{2 g_V^l g_A^l}{\left((g_V^l)^2 + (g_A^l)^2\right)}$$

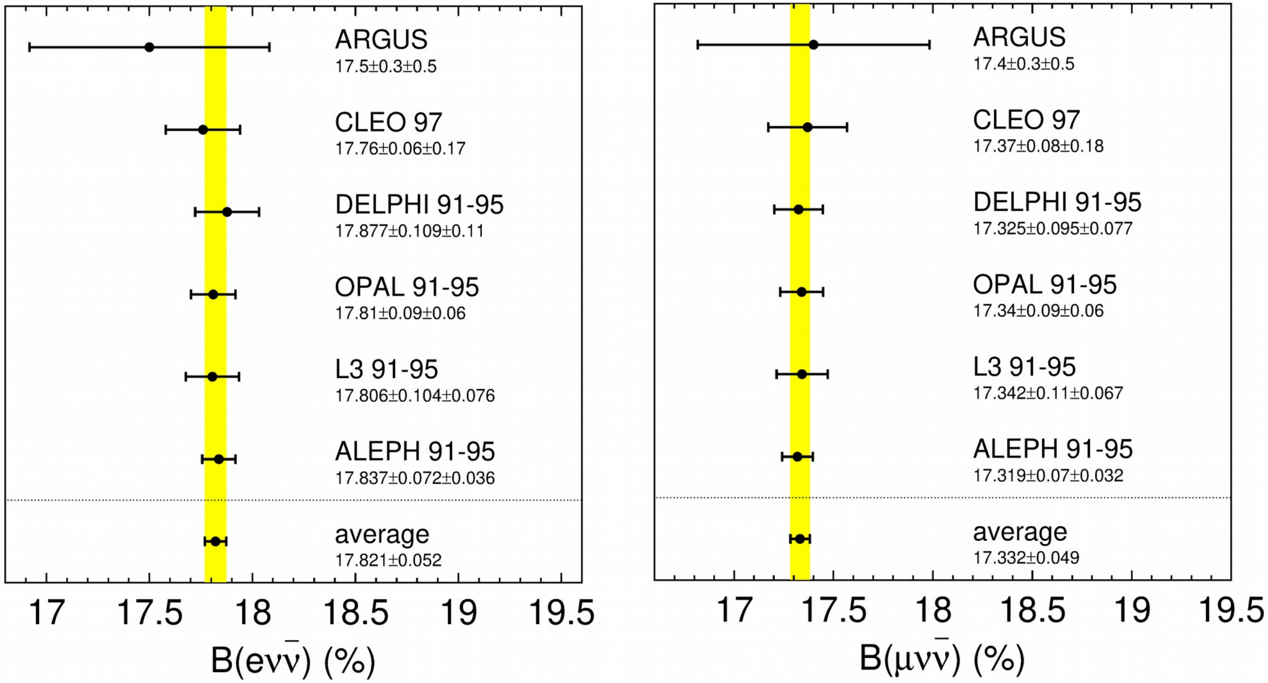
$$\frac{g_V^l}{g_A^l} = 1 - 4\sin^2\theta_W^{eff}$$

$\sin^2\theta_W^{eff} = 0.2315 \pm 0.0006$



[Eur. Phys. J. C20 (2001) 401]

τ Physics: Lepton Universality



Coupling ratios:

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

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

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

[Phys. Rept. 421 (2005) 191]