QCD Results from the LEP Experiments

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☛ $e^+e^- \to$ *hadrons*

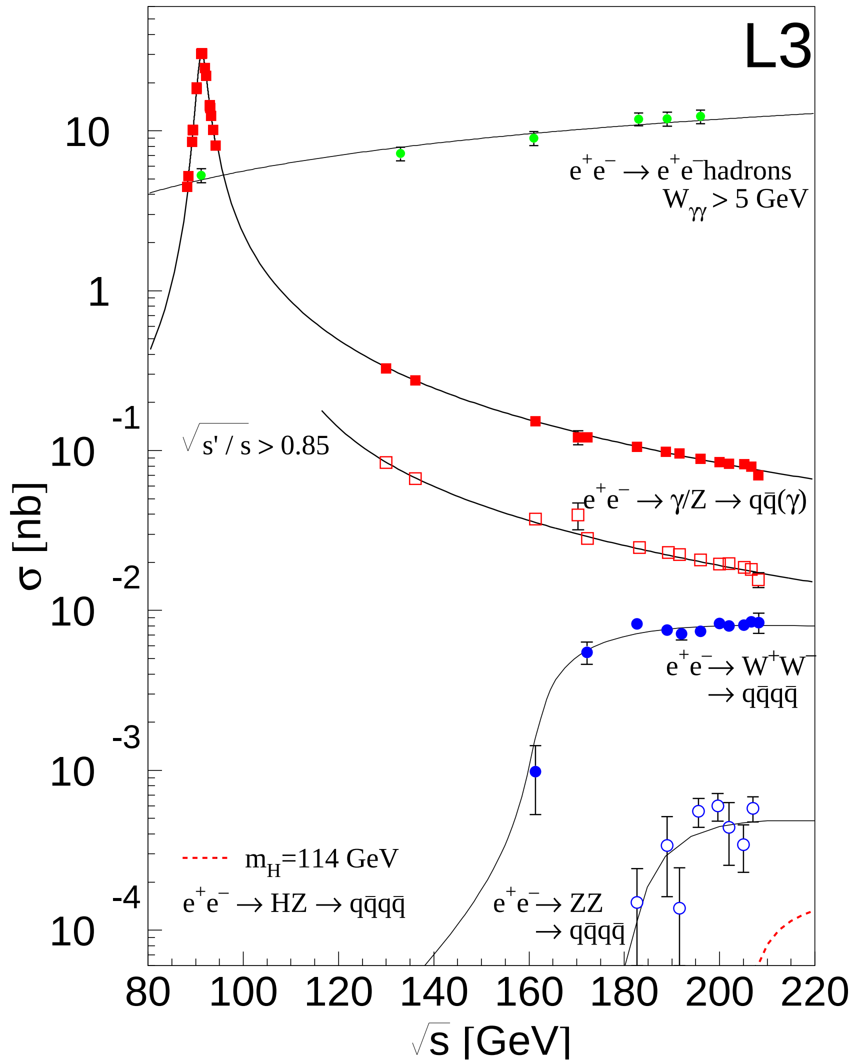
- Inclusive charged particle distributions
- Measurement of α_s

☛ $e^+e^- \to e^+e^-$ *hadrons*

- The photon structure function
- Double tag and BFKL tests
- Inclusive particle production
- Heavy flavour production
- Exclusive channels

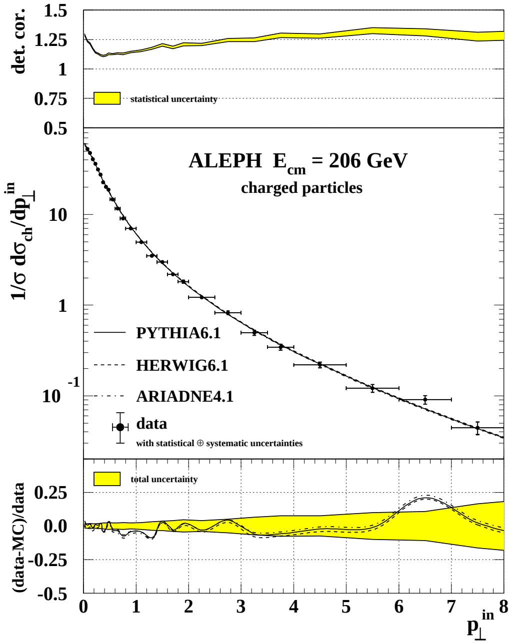
☛ Conclusions

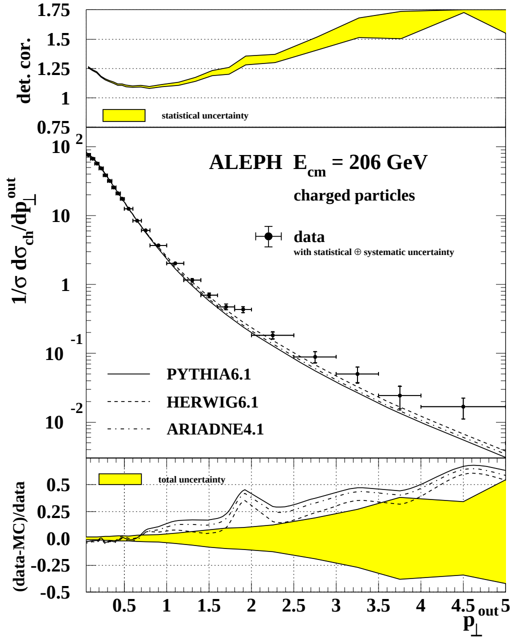
Hadron production at LEP



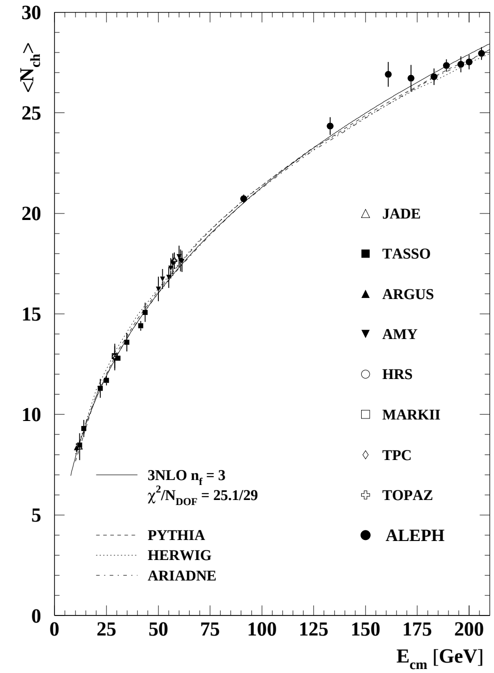
- Many processes for hadron production have been investigated
- Annihilation processes:
  ALEPH CERN-EP/2003-084
  DELPHI Eur. Phys.J.C 29 (2003) 285
  L3 Phys.Lett.B 536 (2002) 217
  OPAL Eur. Phys.J.C 27 (2003) 467
- Two-photon cross-section increases as $\ln^2 s$
  ⇨ dominant at LEP

Inclusive charged particle distributions





Mean charged particle multiplicity



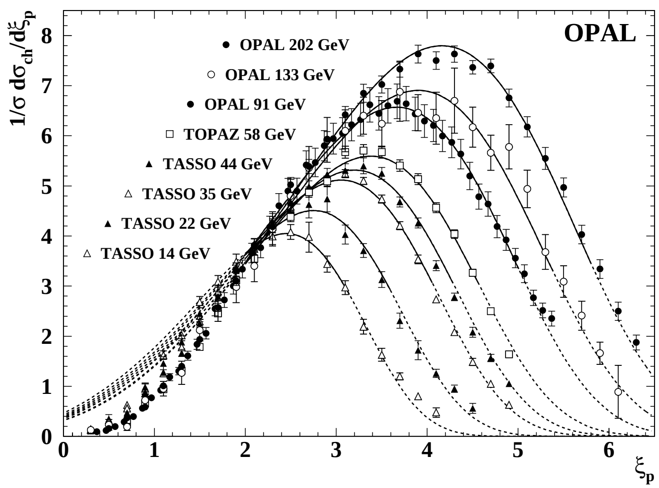
$p_\perp^{in}$ momentum projection in the event plane transverse to the sphericity axis.

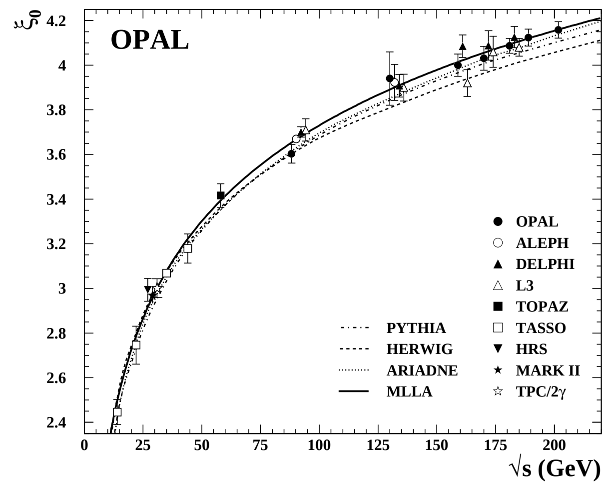
$p_\perp^{out}$ momentum transverse to the event plane.

Data corrected for detector effects and background, MC tuned to LEP1 data.

- ➩ All variables are well described by MC, but $p_\perp^{out}$ harder than MC at all energies
- ➩ Fit next-to-next-to-next-to-leading order (3NLO): $N_f = 5 \quad \Lambda = 202 \pm 31$ MeV
  I.M.Dremlin and J.W.Gary Physics Reports 349 (2001) 301.

Distribution and Peak Position of ξ





$x_p = 2p/\sqrt{s}$ scaled particle momentum.

$\xi_p = -\ln x_p$ sensitive to coherence phenomena in multiple gluon radiation

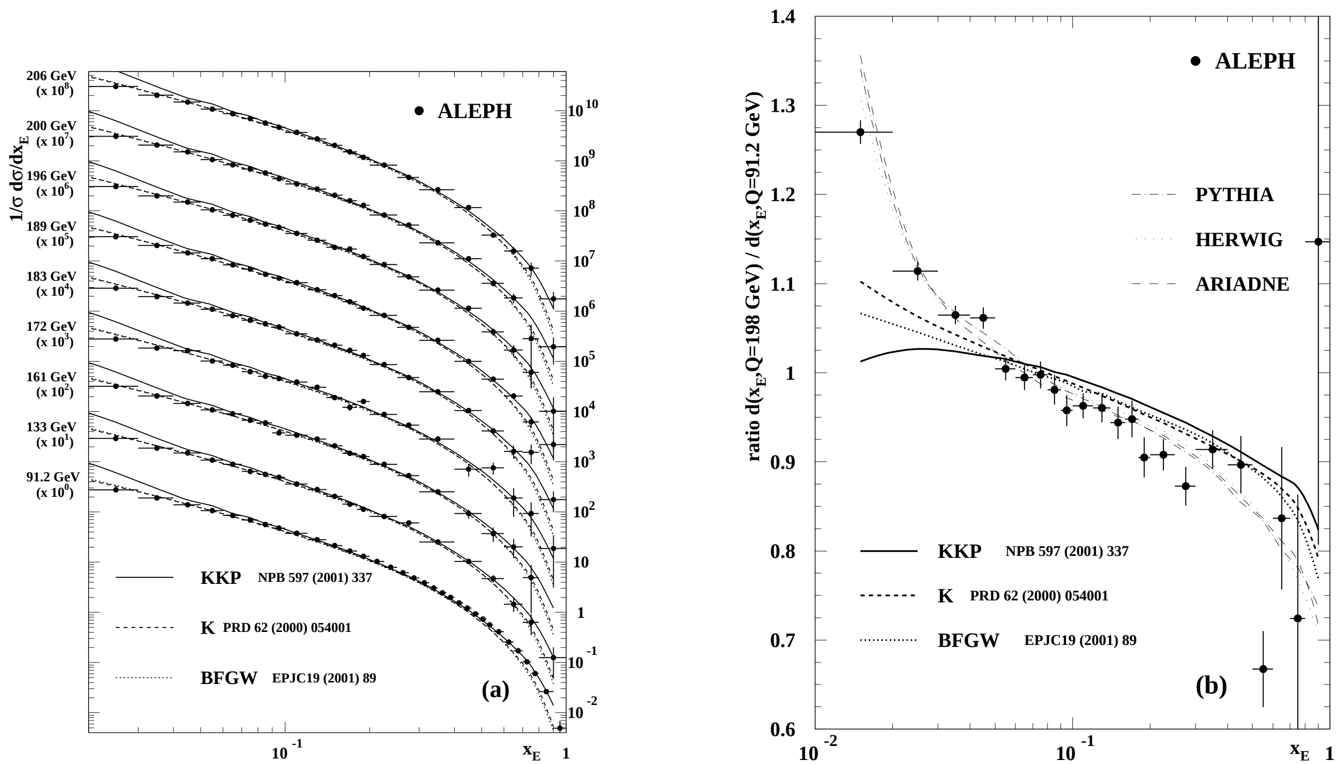
ξ_0 peak position (skewed gaussian C.P.Fong and B.R. Webber Nucl. Phys. B 355(1991)54)

⇨ QCD fit MLLA :

(V.A. Khoze and W. Ochs, Int. J. Mod Phys. A 12 (1997) 2949.)

$N_f = 3 \;\; \Lambda = 203 \pm 2$ MeV (done by OPAL with all available data)

Scaling violation in the fragmentation

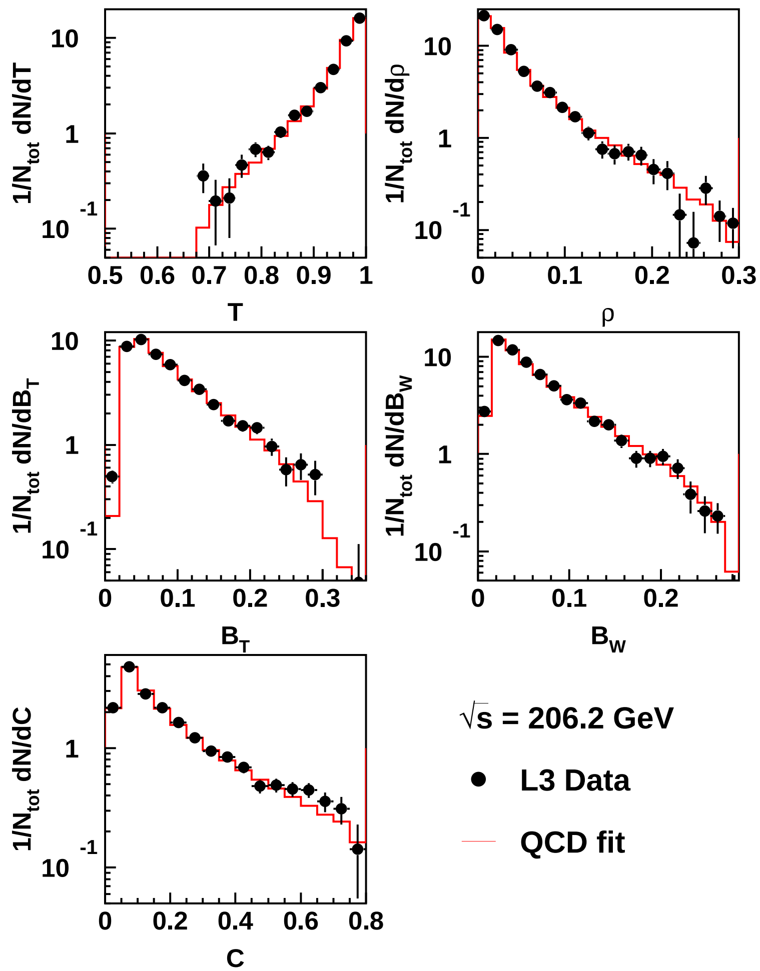


$x_E = 2E/\sqrt{s}$ scaled particle momentum.

- ⇨ Test various parametrisations of the fragmentation function $D(x, Q_0^2) = Nx^a(1-x)^b$, fitted to the data at the Z peak.
- ⇨ Test DGLAP evolution

Clear evidence of scaling violation well reproduced by MC.
DGLAP does not apply for small x_E where MLLA gives a better description

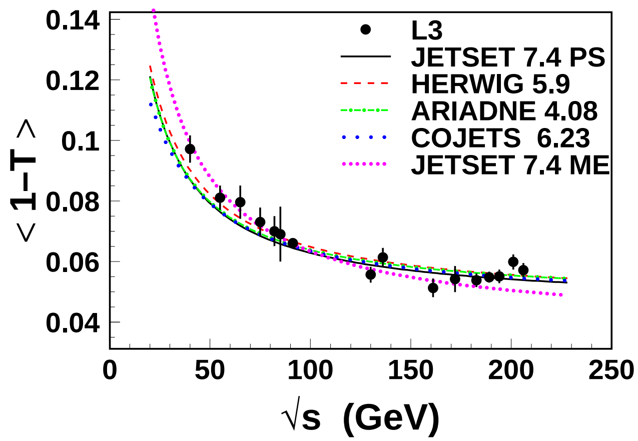
Event shapes used to measure α_s

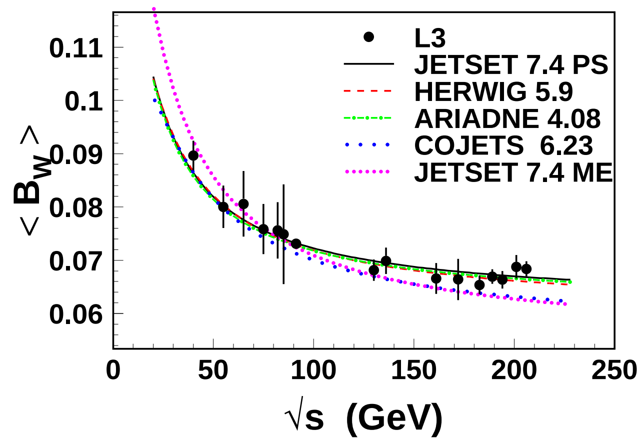


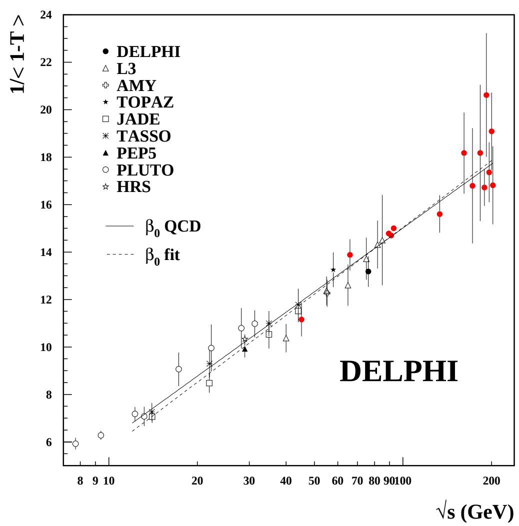
- Infrared and collinear safe observables,(f) : Thrust (1-T), Heavy Jet Mass (ρ), Total Jet Broadening (B_T), Wide Jet Broadening (B_W), C-parameter (C), three-jet resolution $(-\ln y_{23})$
- Fit with theory : $O(\alpha_s{}^2)$
- For $f << 1$ resum entire set of logarithmic terms at all order in α_s
- Matching scheme
- Correct for hadronisation with MC
- Refined treatement of the errors : R. Jones et al. hep-ph/0312016 (2003)

Energy scale dependence of $\alpha_s(s)$

Radiative events are used to go below 91 GeV.







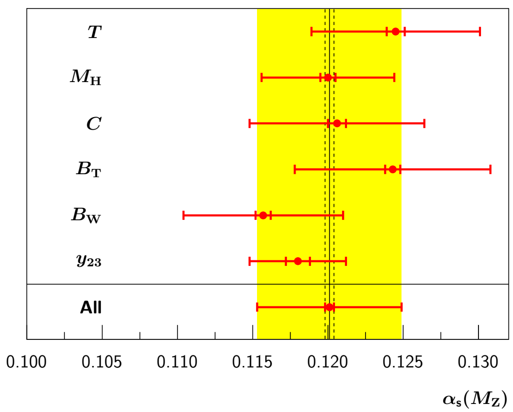
Renormalisation Group Invariant approach

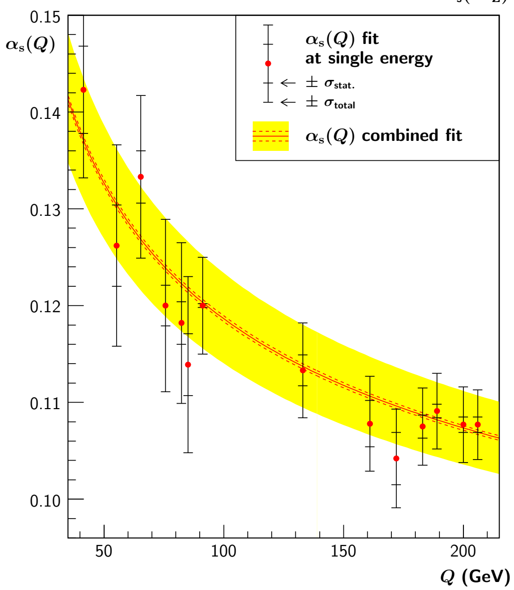
A. Dhar and V. Gupta Phys. Rev. D 29(1984)2822

J.G. Korner et al. Phys. Rev. D 63(2001)036001.

$$\beta_0 = 7.86 \pm 0.32 \; n_f = 4.75 \pm 0.44$$

Precision of α_s measurements



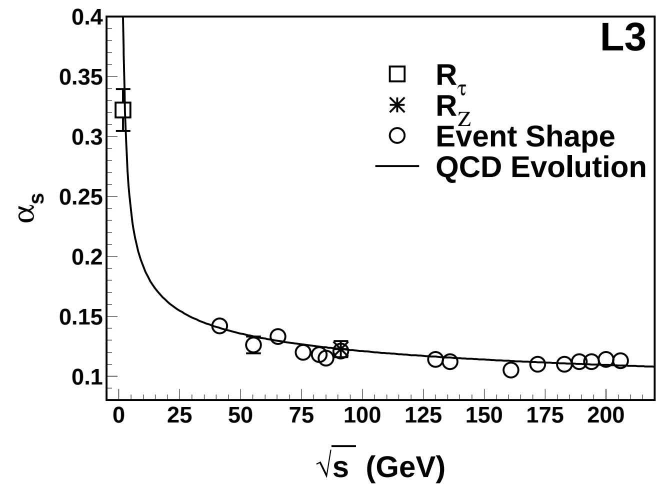


- From event shape preliminary LEP average :

$$\alpha_s(M_Z) = 0.1201 \pm 0.0003(stat.) \pm 0.0009(exp.) \pm 0.0009(had.) \pm 0.0047(theo.)$$

- from $R_Z = 20.767 \pm 0.025$

$$\alpha_s(M_Z) = 0.1240 \pm 0.0037(exp.) \pm 0.0026(theo.)$$



Power Corrections

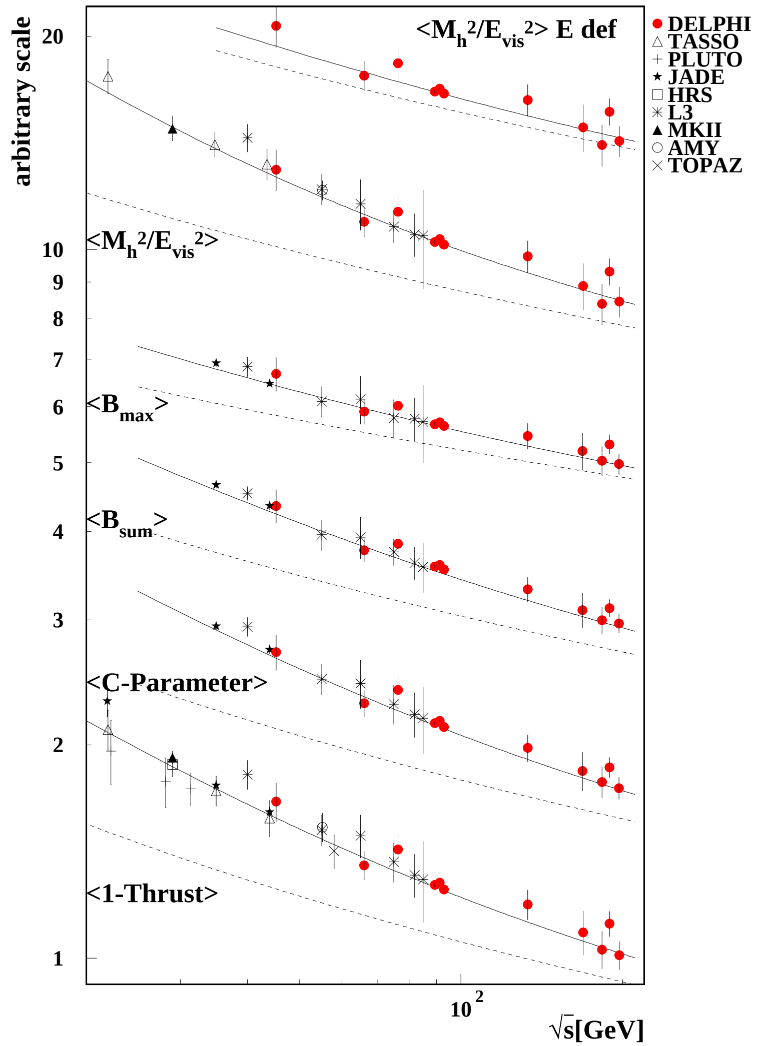
The energy dependence of the event shape variables is described as

(Yu.L.Dokshitzer, B.R.Webber, Phys.Lett.B 352(1995)451)

$< f > = < f_{\text{pert}} > + < f_{\text{pow}} >$

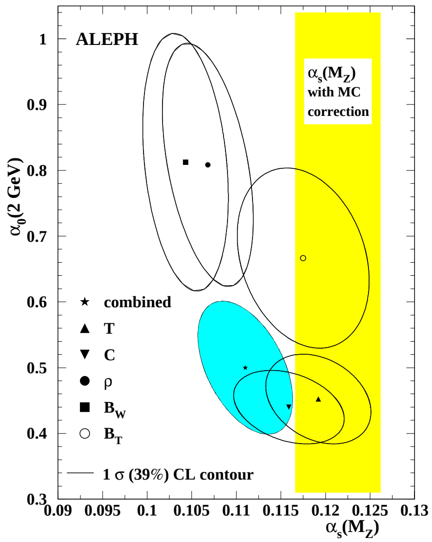
sum of the perturbative contribution and a power law in $1/Q$ expressing higher twist effects.

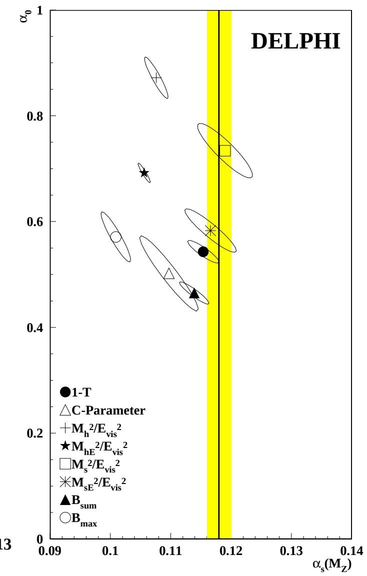
A parameter α_0 measures the effective strenght of the coupling below an infrared matching scale $\mu_I \simeq 2$ GeV



dashed line : perturbative contribution

Power Corrections: fit to the shapes





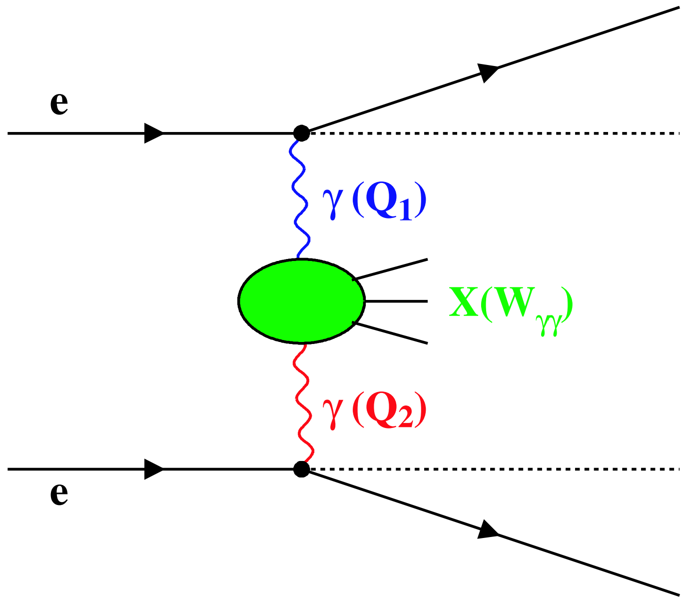
- α_s lower than with MC corrections
- large spread between the results of different variables
- α_0 universality ?

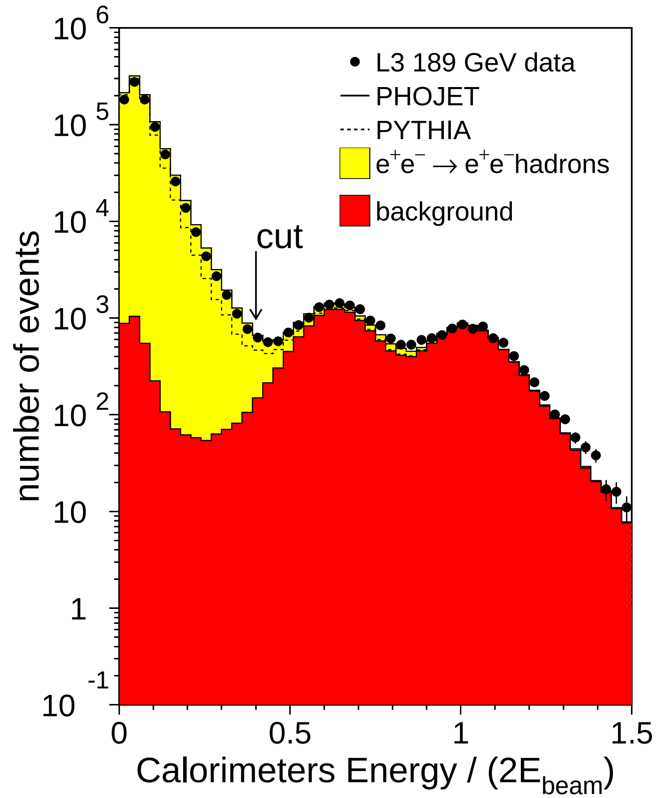
Combined results :

	$\alpha_s(M_Z)$	$\alpha_0(\mu_I = 2\ \mathrm{GeV})$	correlation
ALEPH	$0.1112 \pm 0.0006 \pm 0.0053$	$0.496 \pm 0.006 \pm 0.101$	-0.48
DELPHI	$0.1110 \pm 0.0005 \pm 0.0018$	$0.546 \pm 0.005 \pm 0.025$	

⇨ Need futher investigations

Two-photon events : $e^+e^- \to e^+e^-$ *hadrons*



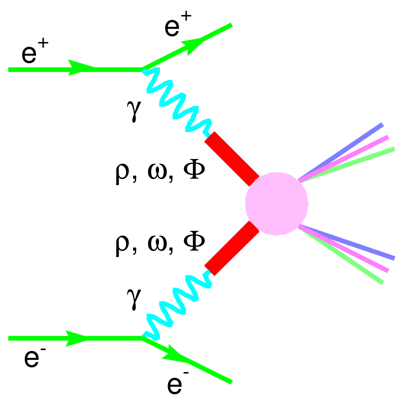


- $Q_1^2 \simeq Q_2^2 \simeq 0$ Untagged
- $Q_1^2 > Q_2^2 \simeq 0$ Single-tag
- $Q_1^2 \simeq Q_2^2 > 0$ Double-tag

- Low energy hadrons (trigger!)
- Clean sample with low background

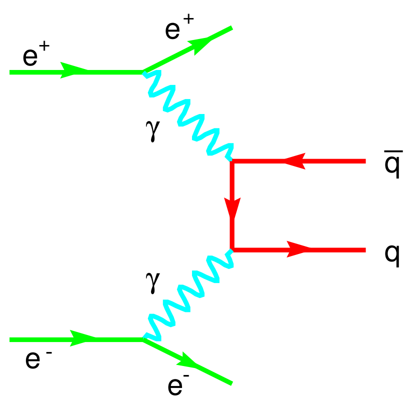
Diagrams contributing to $\gamma\gamma$ interactions

SOFT:

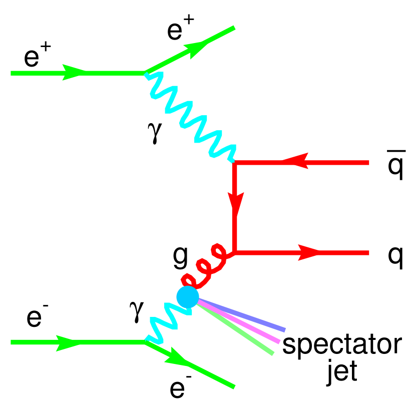


VDM

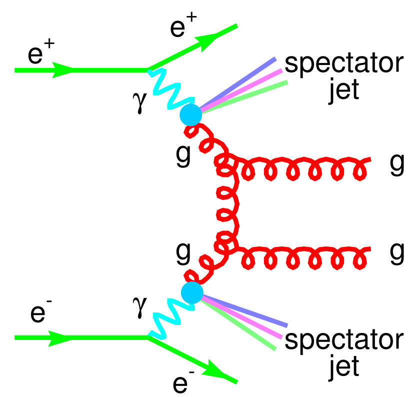
HARD:



Direct



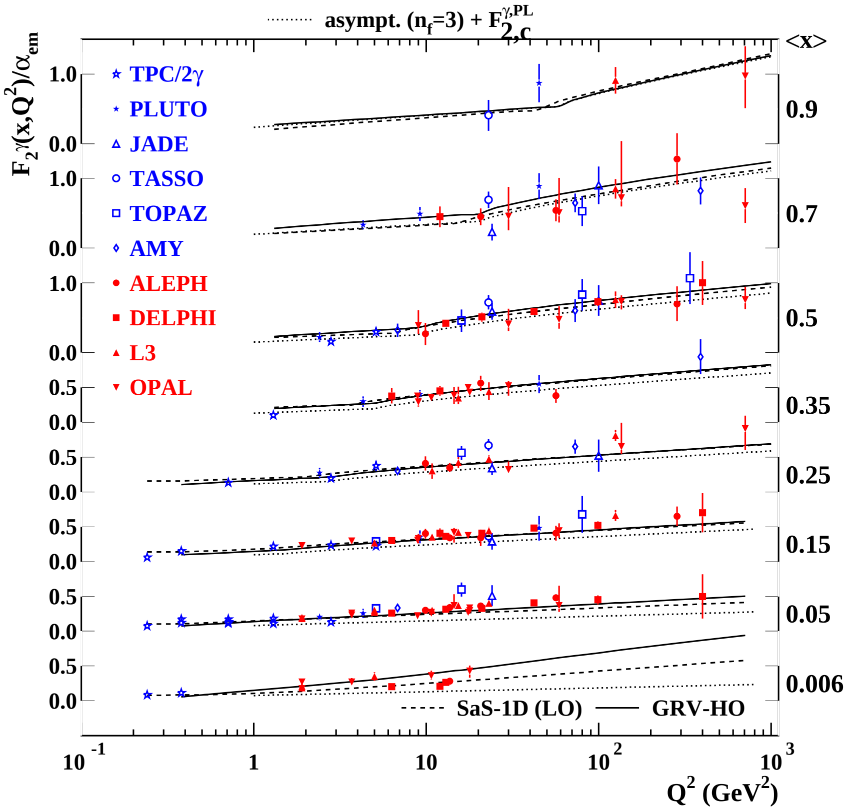
Single Resolved



Double Resolved

Ingredients for MC models : VDM, LO QCD and pdf in the photon

Single-tag cross-sections : F_2^γ



R. Nisius, Phys. Rep. 332 (2000) 165

ALEPH Eur. Phys.J.C 30 (2003) 145

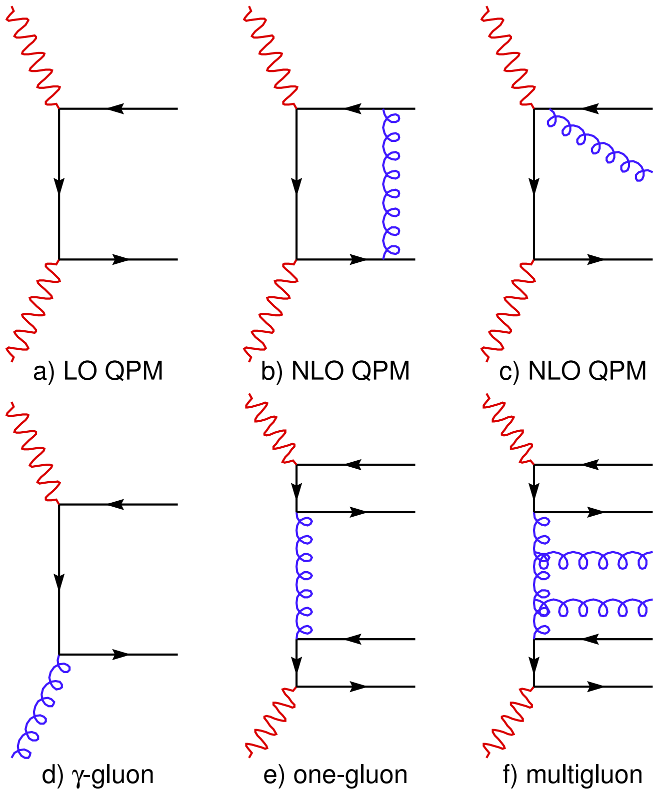
OPAL Eur. Phys.J.C 16 (2000) 579

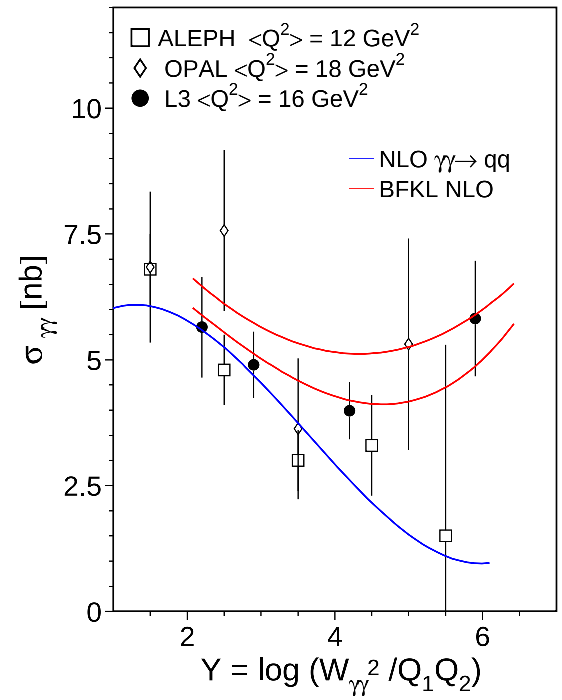
An hard photon ($Q_1 >> 0$) explores the parton content of the other ($Q_2 \simeq 0$)

- Large range of Q^2 and $x = \frac{Q^2}{Q^2 + W^2_{\gamma\gamma}}$
- Positive scaling violation for all x
  ⇨ $\gamma \to q\bar{q}$ (QED).
- Parametrisations before LEP (82 points)
- At present 220 points, not yet all data !

BFKL dynamics

Double-tag: $Q_1^2 \simeq Q_2^2 >> 0$





- For Y$\leq$ 4 NLO QPM is sufficient
- Excess for Y$>$ 4 :
  Resolved photon or BFKL dynamics.

QPM M. Cacciari et al. JHEP 102 (2001) 29

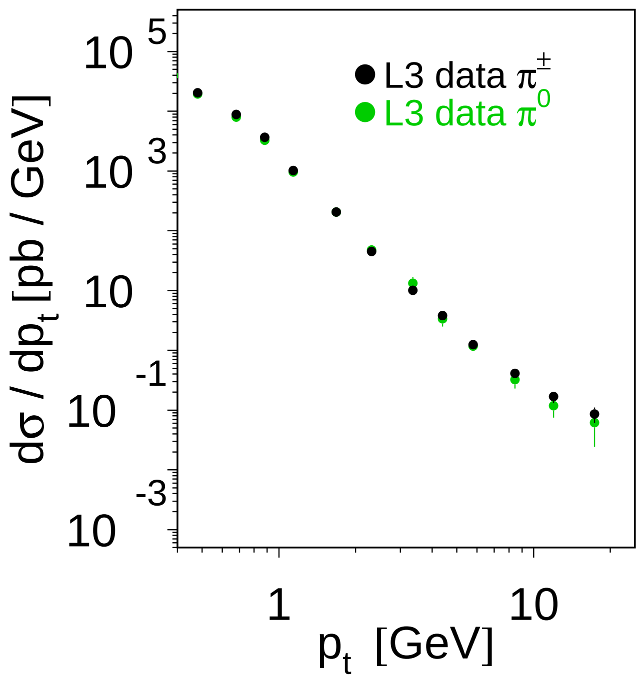
BFKL S.J. Brodsky et al. JETP Lett.76(2002)249

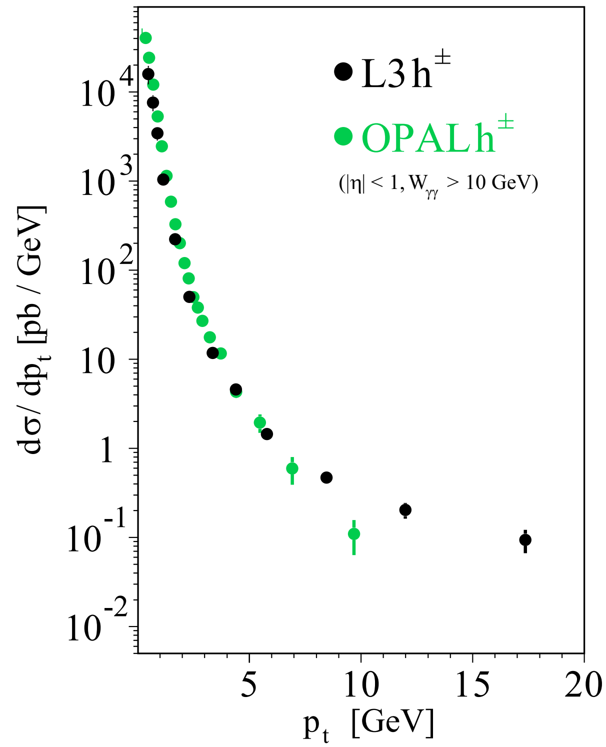
ALEPH hep-ex/0305107

OPAL Eur. Phys.J.C 24 (2002) 17

L3 Phys.Lett.B 531 (2002) 39

Inclusive single hadron production





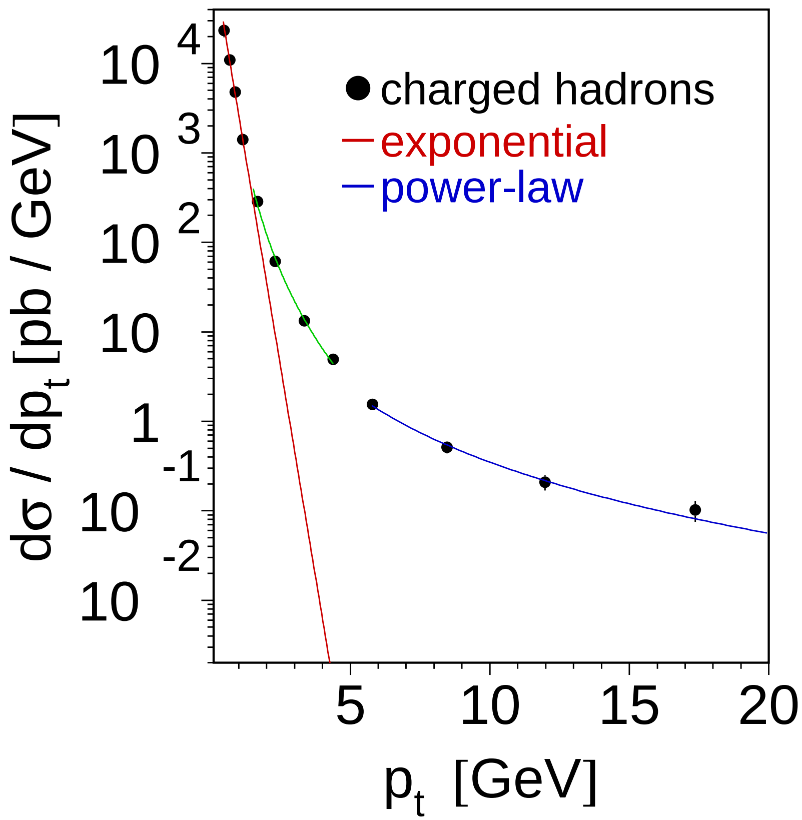
- $\pi^{\pm}$ in h$^{\pm}$ sample separated by MC (JETSET 7.409)
- Good agreement of $\pi^{\pm}$ and π^{0} data
- Agreement between experiments

$h^{\pm}$, $<\sqrt{s}>= 165$ GeV K. Ackerstaff et al. Eur.Phys.J. C 6(1999)253.

π^{0} and K^0_S ,$<\sqrt{s}>= 194$ GeV P. Achard et al. PLB 524(2001)44.

$\pi^{\pm}$ and $K^{\pm}$, $<\sqrt{s}>= 194$ GeV P. Achard et al. PLB554 (2003)105.

Fits to the data



- For $p_t < 1.5$ GeV

  Exponential $Ae^{-p_t/<p_t>}$

  $< p_t > \simeq 230$ MeV for $\pi^\pm, \pi^0$
  $\simeq 290$ MeV for $K^\pm, K_S^0$
  $\simeq 350$ MeV for Λ

  $\Rightarrow$ Soft interactions

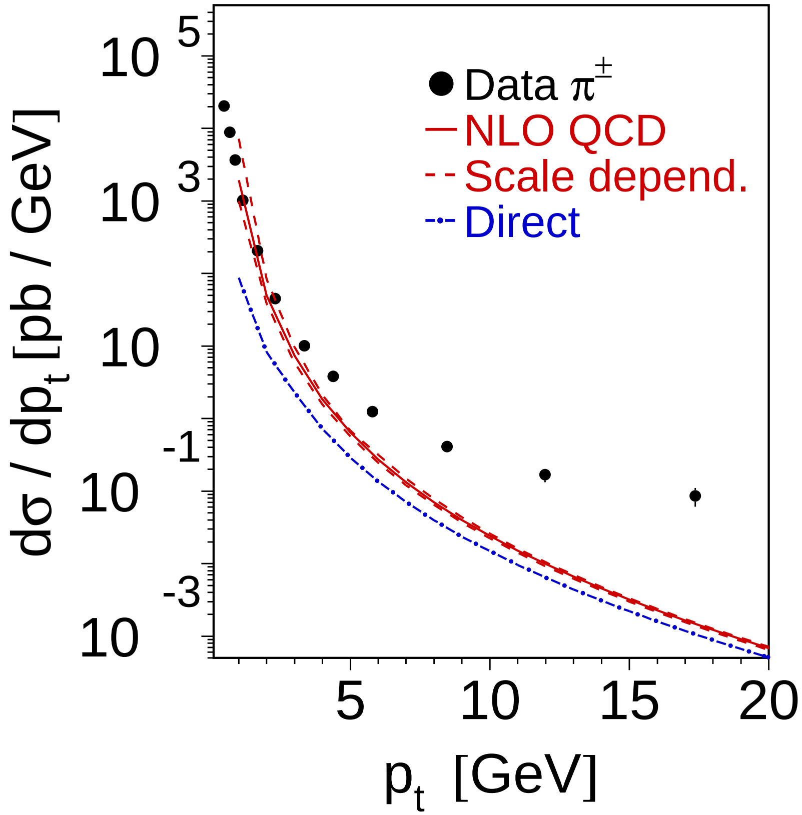
- For $p_t > 1.5$ GeV

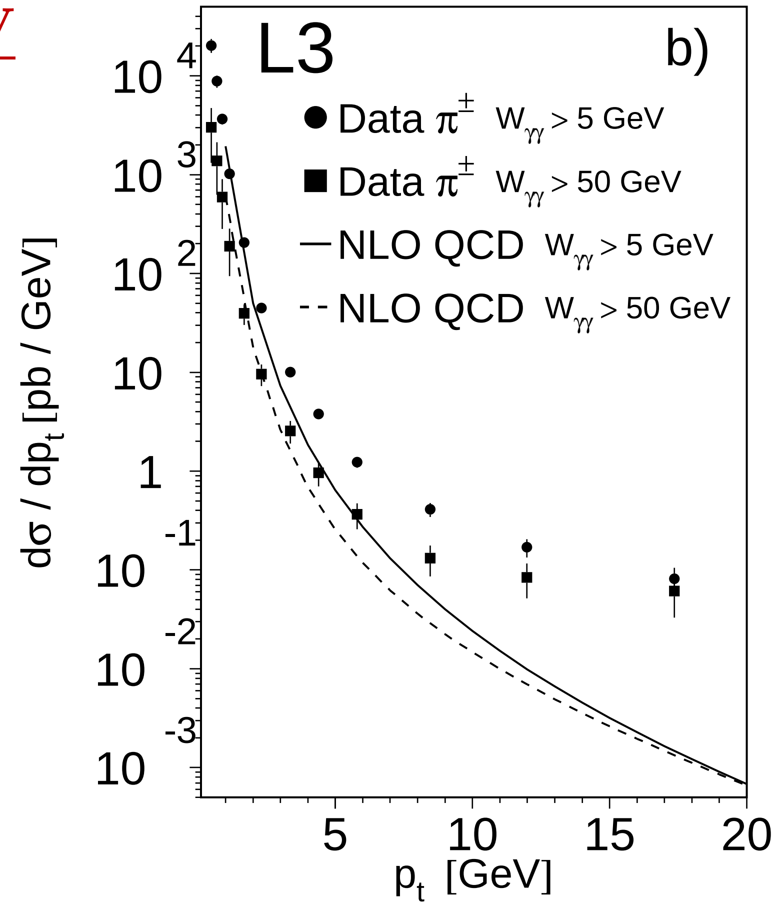
  power law Ap_t^{-B}
  $1.5 \leq p_t < 5.$ GeV B $= 4.2 \pm 0.2$
  $\chi^2/d.o.f. = 4.7/2$

  $5.0 \leq p_t < 20.$ GeV B $= 2.6 \pm 0.3$
  $\chi^2/d.o.f. = 0.7/2$

  $\Rightarrow$ Direct and resolved (QCD)

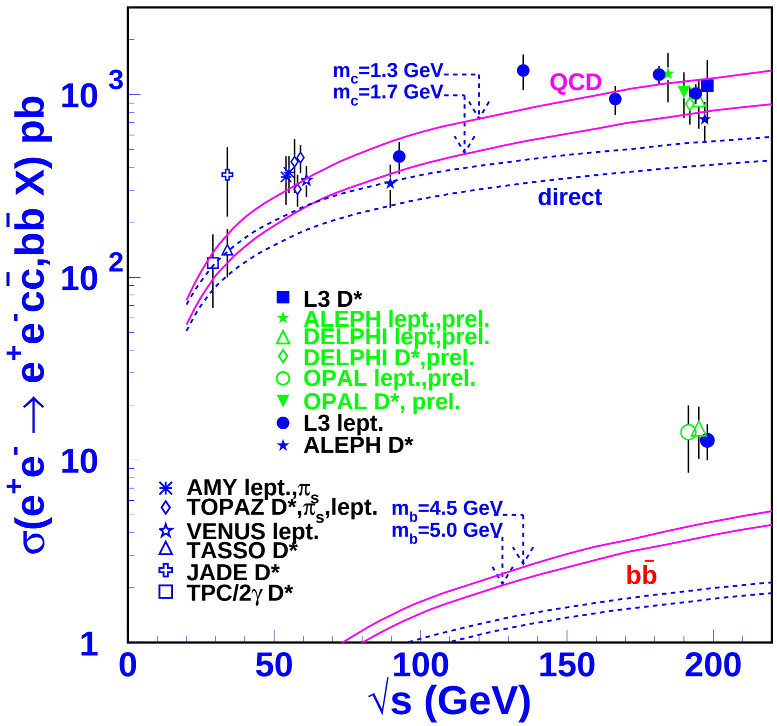
Comparison with Theory





- Measurements exceed QCD predictions at high p_t (J.Binnewies, B.A.Kniehl and G. Kramer Phys.Rev.D 53(1996)6110) for all two-photon mass intervals.
- The data are largely beyond the direct contribution

$c\bar{c}$ and $b\bar{b}$ production



- Cross-section rises from $c\bar{c}$ threshold.
- Direct ($\gamma\gamma \to c\bar{c}$) is not sufficient.
- ⇨ Need $\gamma g \to c\bar{c}$
- $b\bar{b}$ 7 st.dev higher than predictions
- ⇨ a challenge for the theory

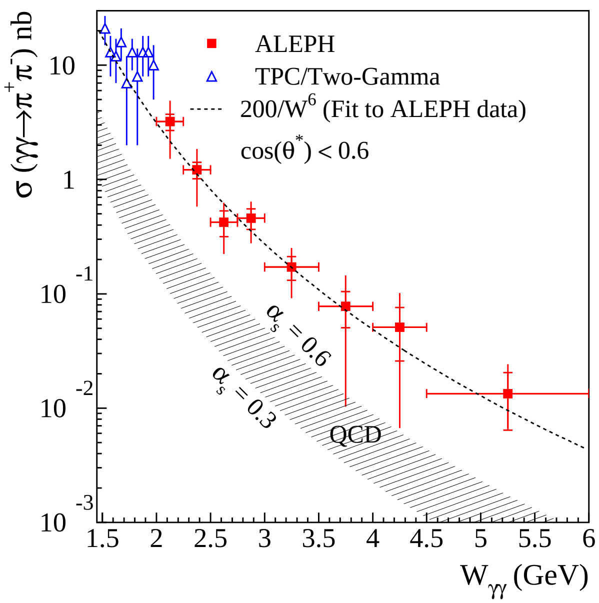
ALEPH Eur. Phys.J.C 28 (2003) 437

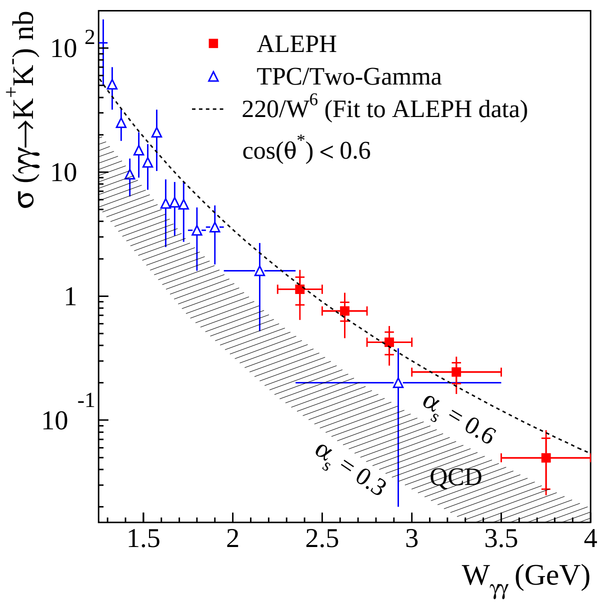
DELPHI W. Da Silva Nucl.Phys.B 126 (2004) 185

OPAL A.Csilling hep-ex/0010060

L3 Phys.Lett.B 503(2001)10

Exclusive $\pi^+\pi^-$ and K^+K^- production





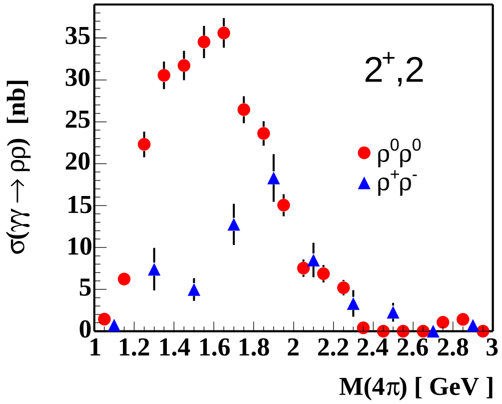
ALEPH Phys. Lett. B 569 (2003) 140

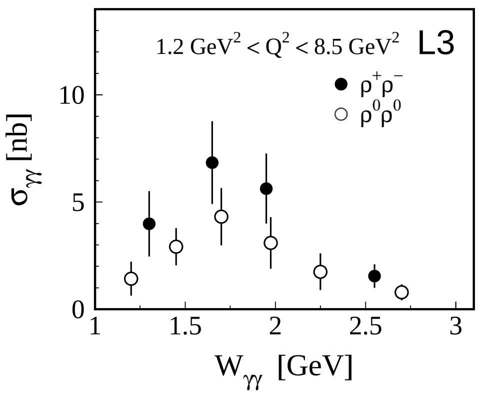
Factorisation of a hard scattering aplitude ($\gamma\gamma \to q\bar{q}$) and a hadron distribution amplitute $\Phi_M(x,Q)$ S.J.Brodsky and G.P.Lepage Phys. Rev. D24 (1981) 1808

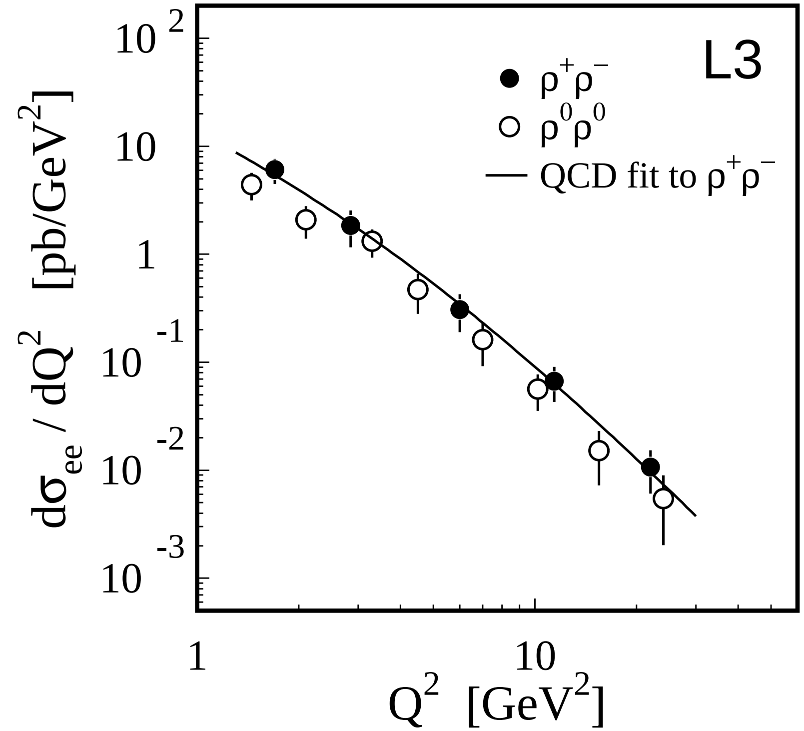
M. Diehl, P. Kroll and C. Vogt : $\Phi_M(x,Q) = \sqrt{3}x(1-x)$

- Shapes are well described by the theory,
- but K^+K^- and $\pi^+\pi^-$ production are equal while theory expects a ratio of 2.23!

Exclusive $\rho^+\rho^-$ and $\rho^0\rho^0$ production







The large difference of $\rho^+\rho^-$ and $\rho^0\rho^0$ for $W_{\gamma\gamma} < 2$ GeV at $Q^2 \simeq 0$ is not present at high Q^2

L3 Phys. Lett. B 568 (2003) 11

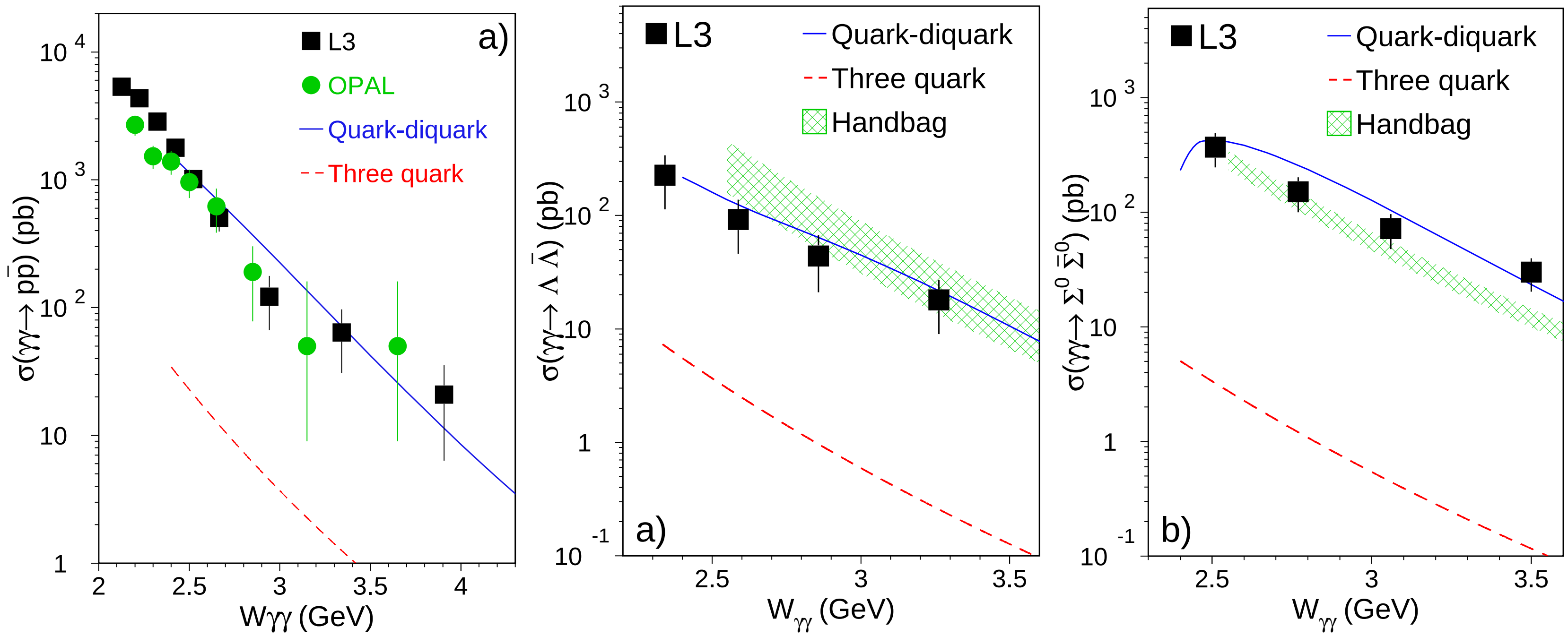
⇨ Well fitted by GVDM form factor or by QCD calculations:

M. Diehl, T. Gousset and B. Pire

Phys.Rev.D 62(2000) 073014.

I.V.Anikin et al. Phys.Rev.D 69(2004) 014018.

Exclusive $p\bar{p}$, $\Lambda\bar{\Lambda}$ and $\Sigma^0\bar{\Sigma}^0$ production



Baryon distribution amplitudes :

- Three quarks G.Farrar et al. Nucl.Phys.B259(1985)702 Too low !
- Quark-diquark M. Anselmino et al Jour.Mod.Phys.A 4(1989) 5213 Fair agreement
- Handbag M.Diehl,P.Kroll,C.Vogt, Eur.Phys.J C26(2003)567 Predicts the other baryons from $p\bar{p}$

L3 Phys. Lett. B 536(2002)24 ; Phys. Lett. B 571(2003)11
OPAL Eur.Phys.J C 28(2003)45

Conclusions

- Diverse and accurate measurements are performed at LEP. They are the basis for understanding QCD not only in the perturbative sector, but also in the field of non-perturbative phenomena.
- At present is the experiment that pushes the theory towards more precise calculations (α_s) and new interpretations for the unexplained discrepancies in two-photon physics.

APOLOGIES !!!! for the many subjets I could not discuss : jets, colour-field effects, etc.