Standard Model Results from LEP

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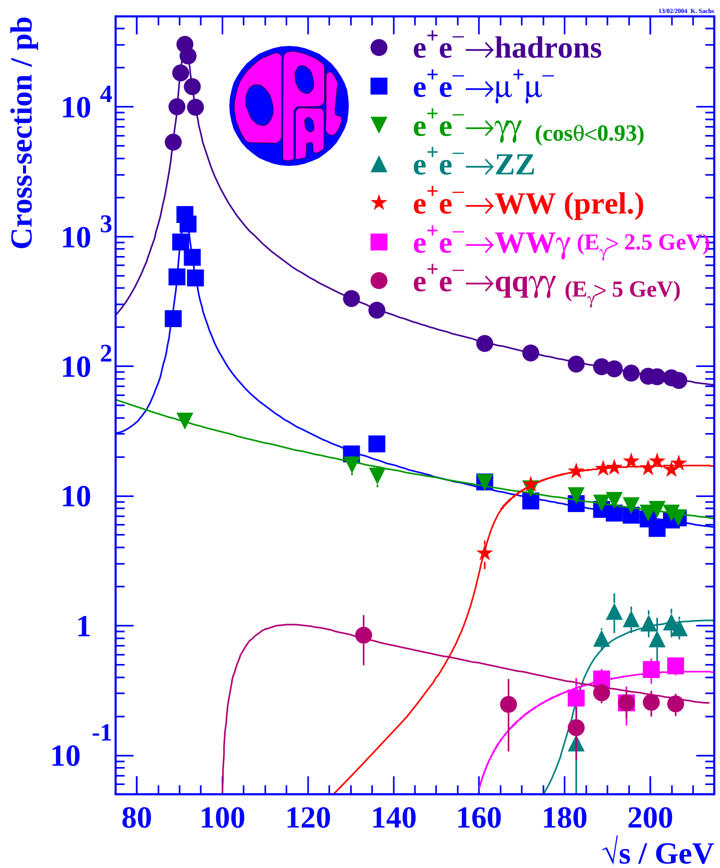
- Introduction
- Electroweak Physics
- QCD and Two-photon Results



Introduction

LEP1 1989–1995 $\sqrt{s} \sim m_Z$ 4.5M Z events / expt

LEP2 1996–2000 $161 < \sqrt{s} < 209$ GeV 10k WW events/expt

- LEP was shut down at the end of 2000, so why are we still giving LEP talks?
- Many physics results still being produced
- In the last 2 years, the 4 LEP experiments (ALEPH, DELPHI, L3 and OPAL) have submitted for publication $>$100 papers

  About 25% of these were on LEP1 physics
- The 4 expts have submitted $>$ 120 papers to ICHEP04

  Majority on Standard Model physics

  Mostly final results, but some new preliminary results too
- This talk will concentrate on results which have been finalized, or are new, in the last year (but include some older important results too)

Introduction

LEP Standard Model physics covers a wide range of topics; no time in this talk for, e.g.,

- Precise measurement of the τ lifetime (DELPHI)
  τ_τ = 290.9±1.4±1.0 fs (c.f. PDG2004: 290.6±1.1 fs)
- τ branching ratios and strange spectral functions (DELPHI, OPAL)
- $\mu^+\mu^-$, $\tau^+\tau^-$ and hard-photon production in two-photon collisions (DELPHI, L3, OPAL)
- Excited b-hadrons, $\mathrm{B_s^0} - \overline{\mathrm{B_s^0}}$ oscillations, B spectral moments (DELPHI)

Will give a brief overview of current results; for more details consult the experiments' web pages: http://aleph.web.cern.ch/aleph/
http://delphiwww.cern.ch/
http://l3.web.cern.ch/l3/
http://opal.web.cern.ch/Opal/PPwelcome.html

LEP1 Electroweak Physics

- Z lineshape measurements final since summer 2000

m_Z = 91.1875±0.0021 GeV

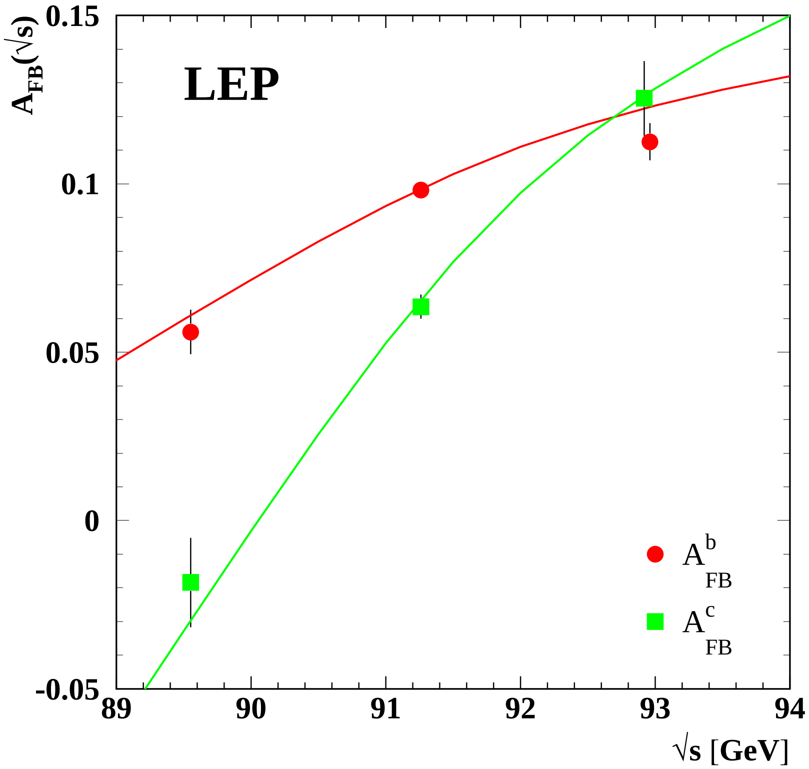
Γ_Z = 2.4952±0.0023 GeV

σ^0_h = 41.540±0.037 nb

R_ℓ = 20.767±0.025

$A^{0,\ell}_{FB}$ = 0.01714±0.00095

- New measurement of A^b_{FB} (DELPHI)
- $\Rightarrow$ new LEP heavy-flavour combination



$A^{0,b}_{FB}$=0.0998±0.0017

LEP1 Electroweak Physics

- OPAL have published new measurements of $\Gamma_{\rm u}, \Gamma_{\rm d}$
- Use hadronic events with FSR $(\rm Z \to q\overline{q}\gamma)$

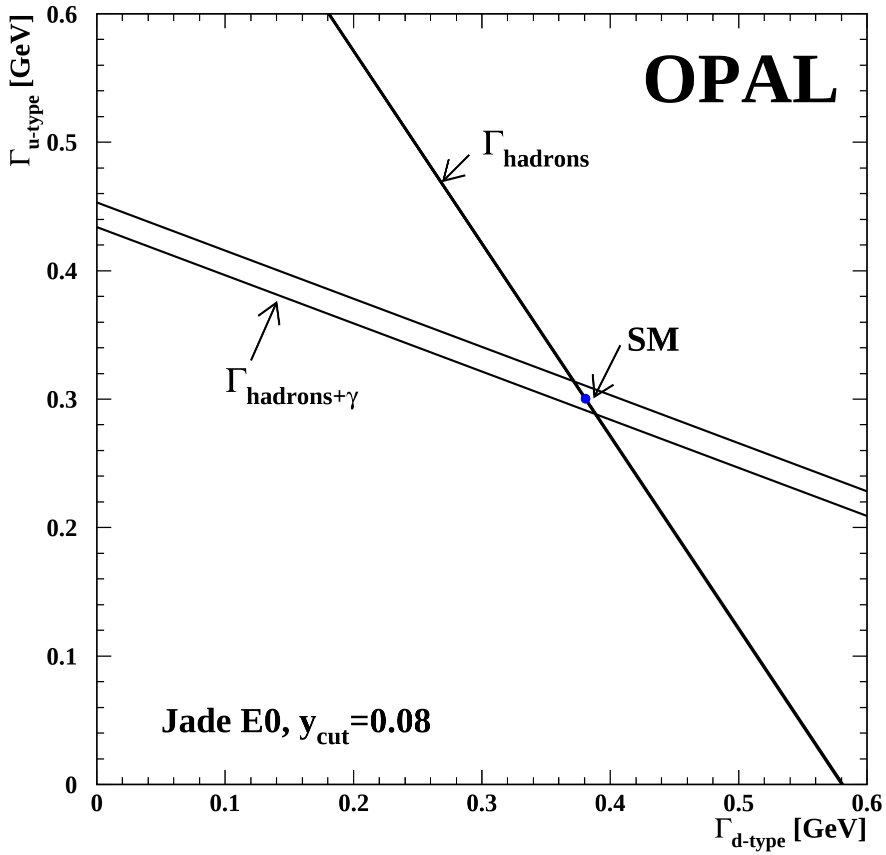
  Enriched in up-type quarks

$$\Gamma_{\rm had} = 2\Gamma_{\rm u} + 3\Gamma_{\rm d}$$
$$\Gamma_{\rm had+\gamma} \sim 8\Gamma_{\rm u} + 3\Gamma_{\rm d}$$

- Results:

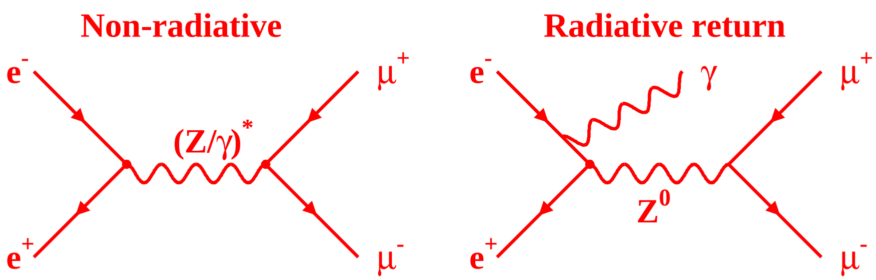
$$\Gamma_{\rm u} = 300^{+19}_{-18}\,\text{MeV}$$
$$\Gamma_{\rm d} = 381^{+12}_{-12}\,\text{MeV}$$

- Good agreement with SM



- More precise than earlier measurements (DELPHI, L3, OPAL)

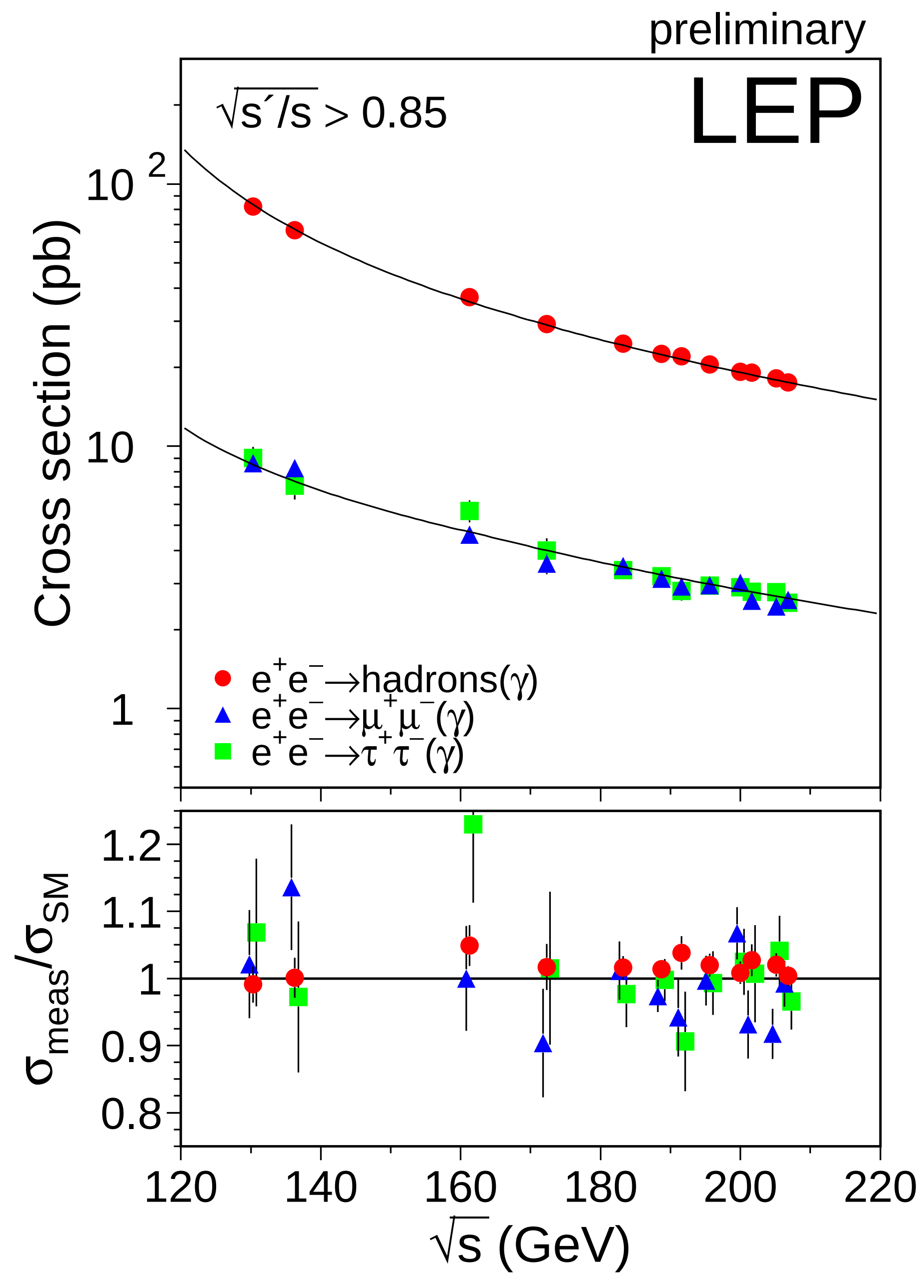
Two-fermion Production at LEP2



- Measure cross-sections and asymmetries for inclusive and 'non-radiative' events
- LEP combination of preliminary measurements

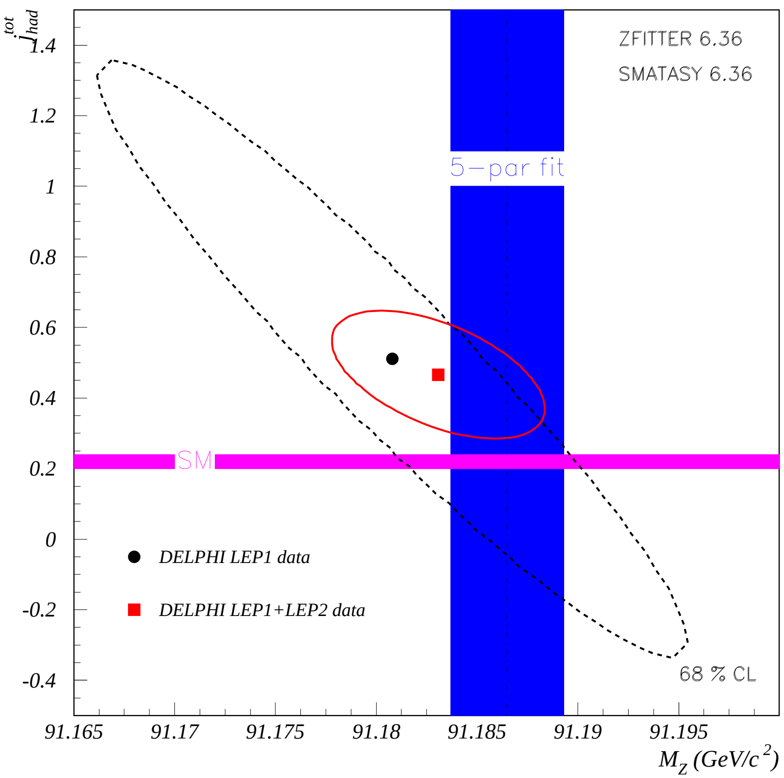
  Good agreement with SM

  $\Rightarrow$ limits on new physics, e.g. Z', leptoquarks, RPV squarks, contact interactions, extra dimensions



Two-fermion Production at LEP2

- At LEP2 energies, γ-exchange becomes important $\Rightarrow$ can measure γ-Z interference $\Rightarrow$ almost model-independent determination of m_Z in S-matrix fit



- e.g.DELPHI results

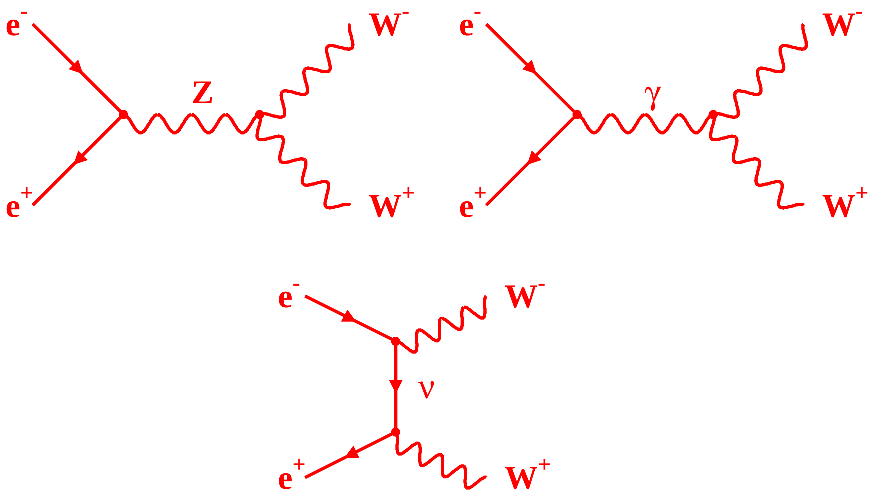
  m_Z = 91.1831$\pm$0.0034 GeV

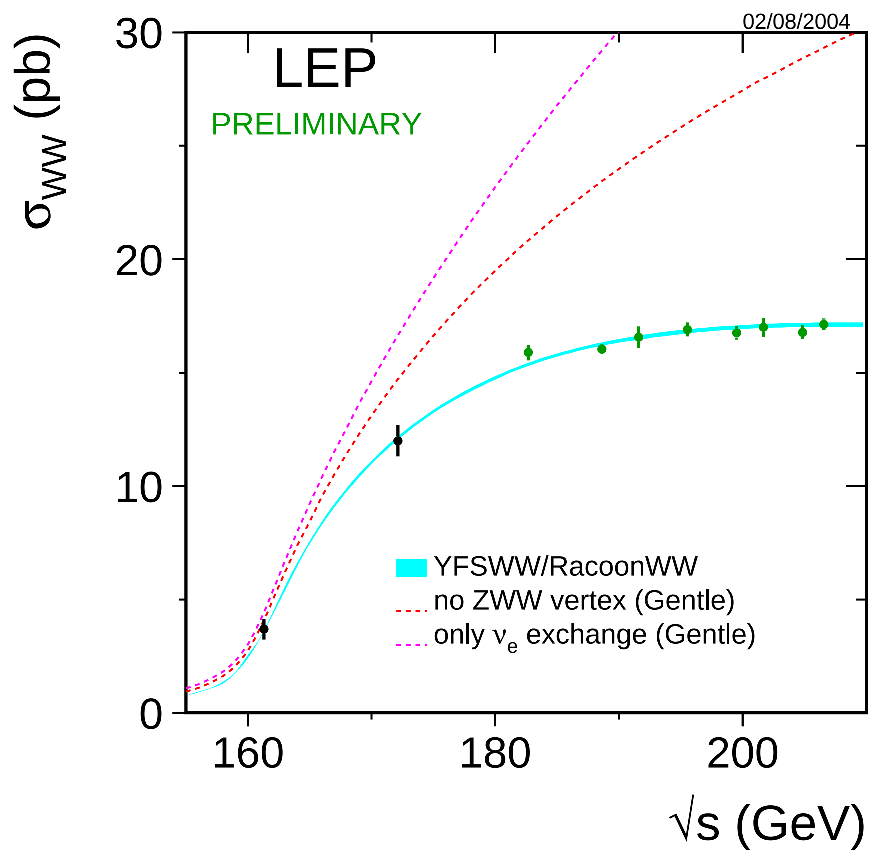
  c.f. m_Z= 91.1863$\pm$0.0028 GeV from standard LEP1 fit assuming SM interference

- OPAL, DELPHI have finalized two-fermion measurements; new combination when all experiments have final results

- Expect small improvements to $\sigma(\mathrm{q\bar{q}})$, but leptons dominated by statistics

WW Cross-sections



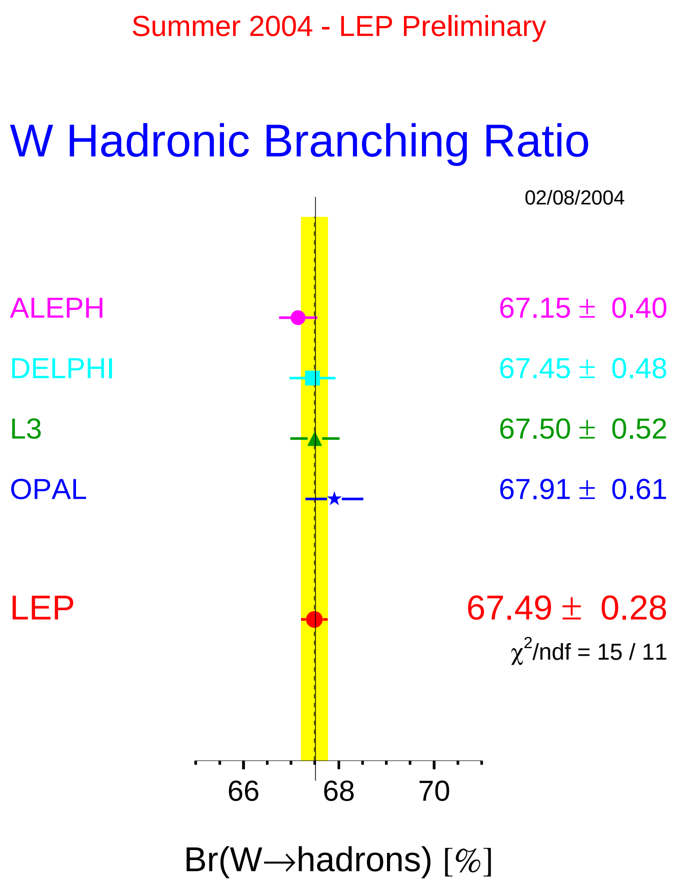


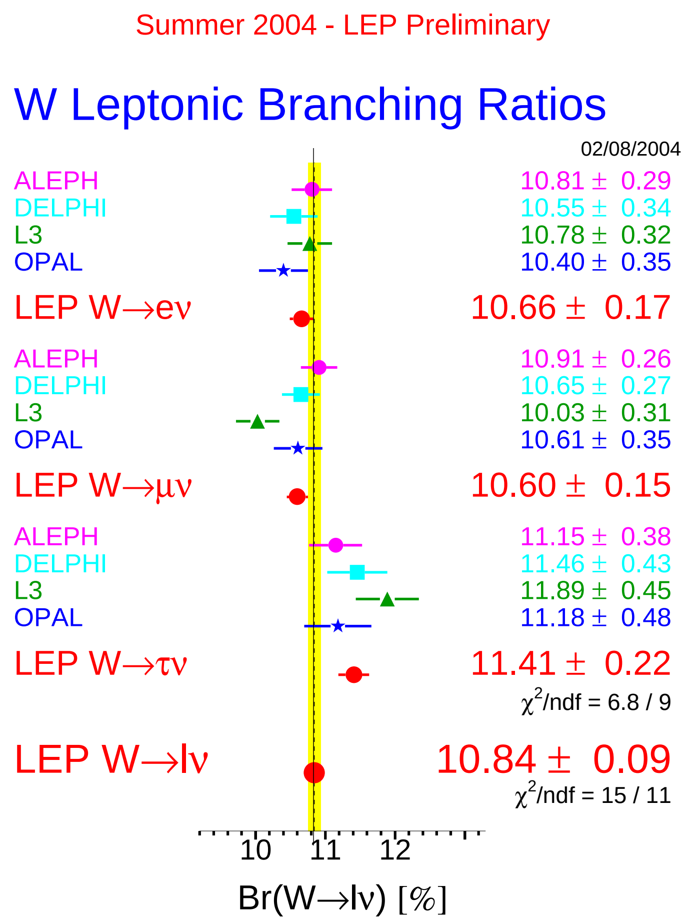
- 3 channels: $W^+W^- \to q\bar{q}q\bar{q}$
  $W^+W^- \to q\bar{q}\ell\overline{\nu}_\ell$
  $W^+W^- \to \ell\overline{\nu}_\ell\ell\overline{\nu}_\ell$
- LEP combination updated with final values from ALEPH, L3
  Final combination awaiting OPAL final results

Good agreement with theoretical expectations

W Branching Ratios

- LEP combination updated with final values from ALEPH, L3

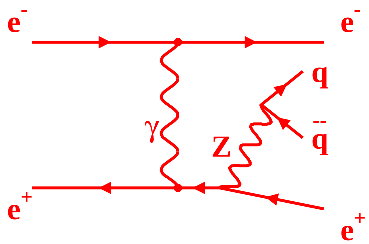




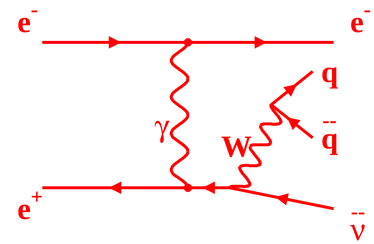
- B(W$\rightarrow \tau\nu$) higher than average of B(W$\rightarrow \mu\nu$) and B(W$\rightarrow e\nu$) by 3σ

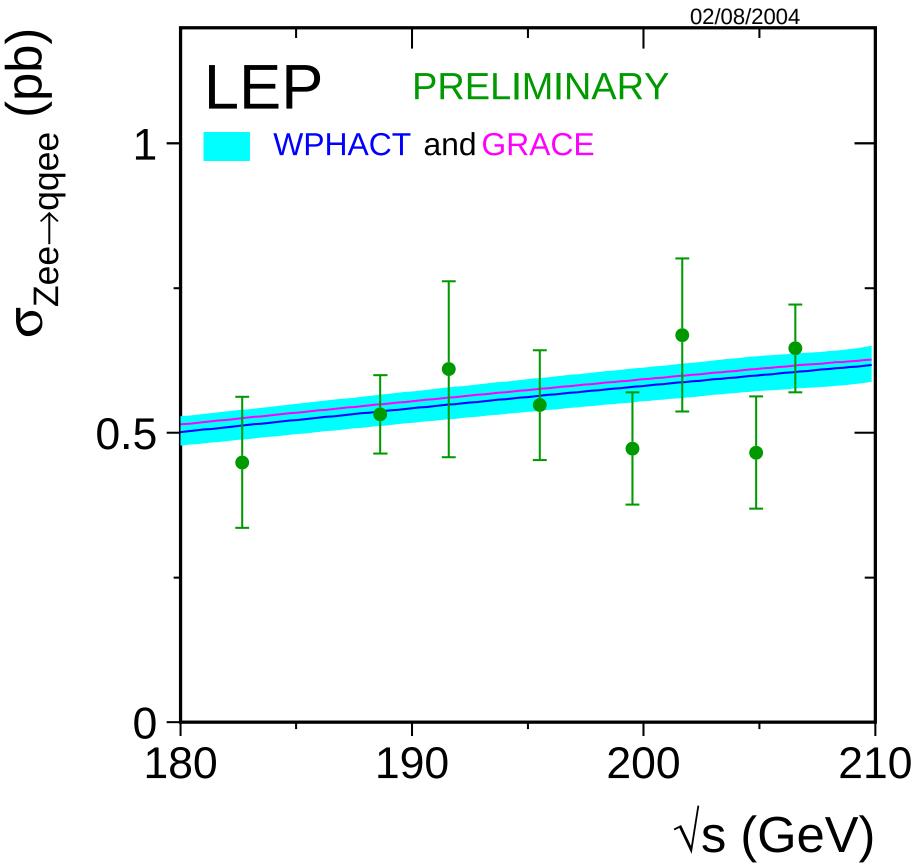
Single Vector Boson Production

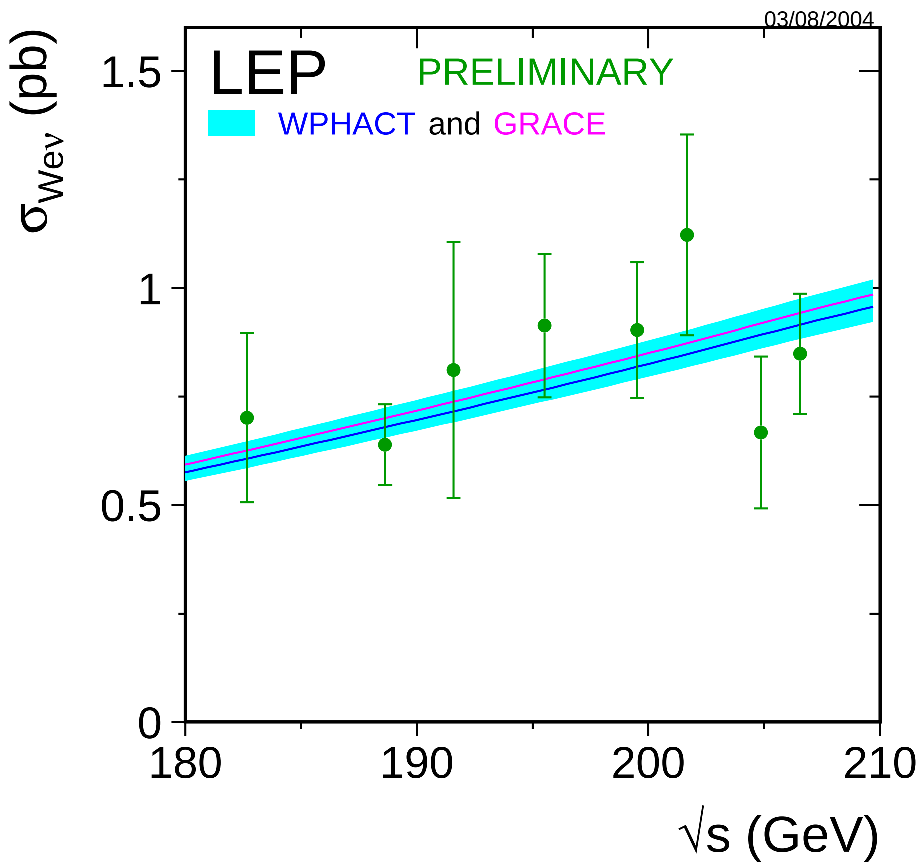
- Zee



- Weν

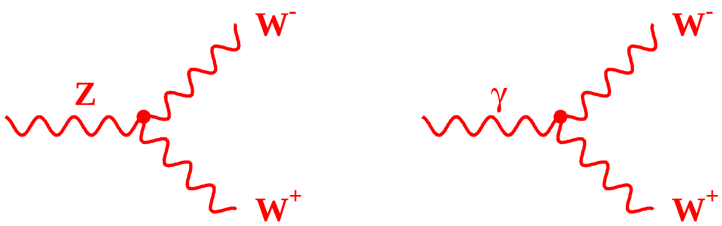


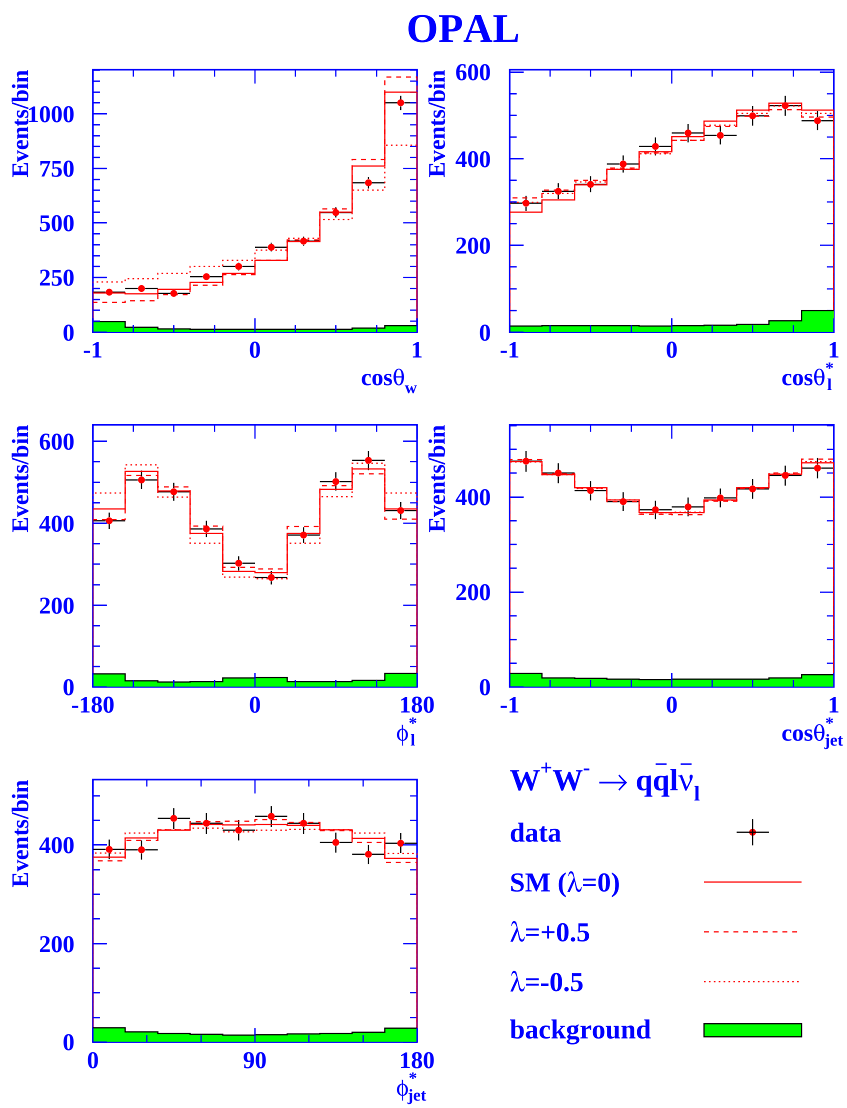




LEP combination updated with final measurements from ALEPH, L3

Charged Triple Gauge Boson Couplings





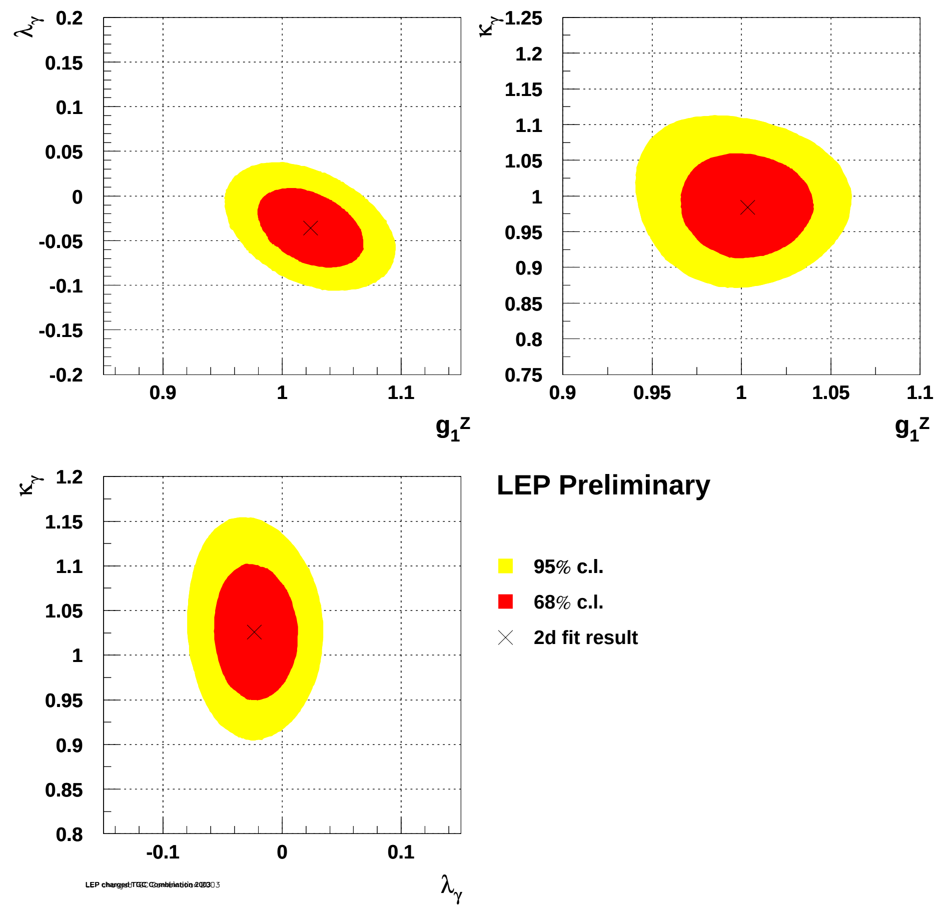
- Measured using WW events:
  σ(WW), $\cos\theta_{\mathrm{W}}$, W decay angles
- Also Weν and $\nu\overline{\nu}\gamma$ channels
- Assuming C, P conservation and gauge constraints: 14 $\longrightarrow$ 3 couplings: $g_1^Z, \lambda_\gamma, \kappa_\gamma$
- LEP combination: combine $\log\mathcal{L}$ curves including correlated systematics

Charged Triple Gauge Boson Couplings

- L3, OPAL values final, ALEPH, DELPHI values preliminary
- LEP combined results allowing one free parameter:

$$g_1^Z = 0.991^{+0.022}_{-0.021}$$
$$\kappa_\gamma = 0.984^{+0.042}_{-0.047}$$
$$\lambda_\gamma = -0.016^{+0.021}_{-0.023}$$

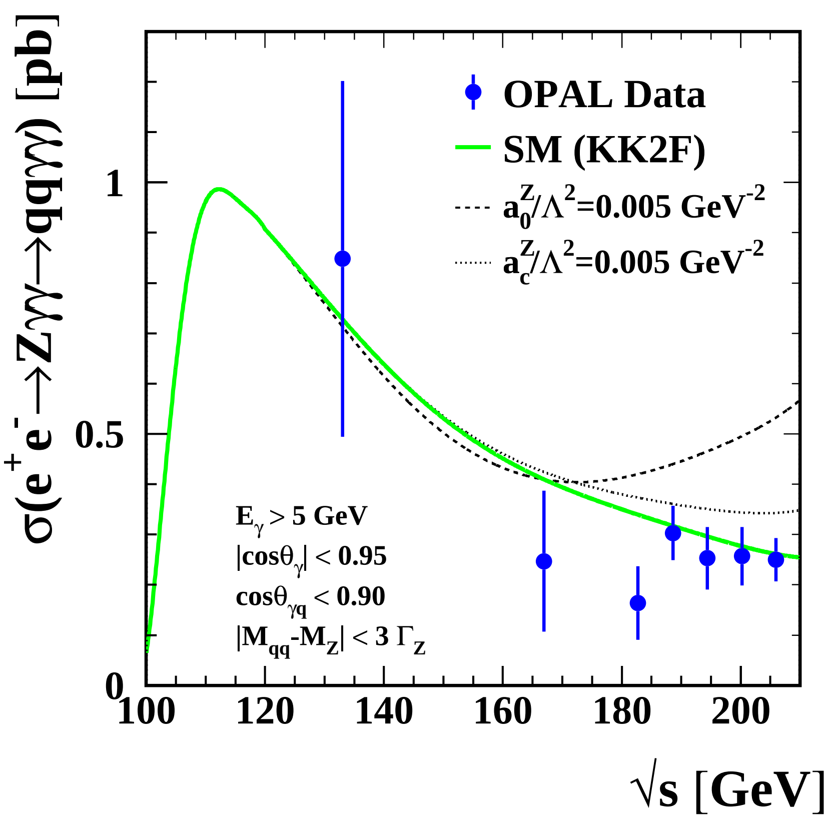
- Good agreement with Standard Model
- Couplings measured with precision of 2–4%

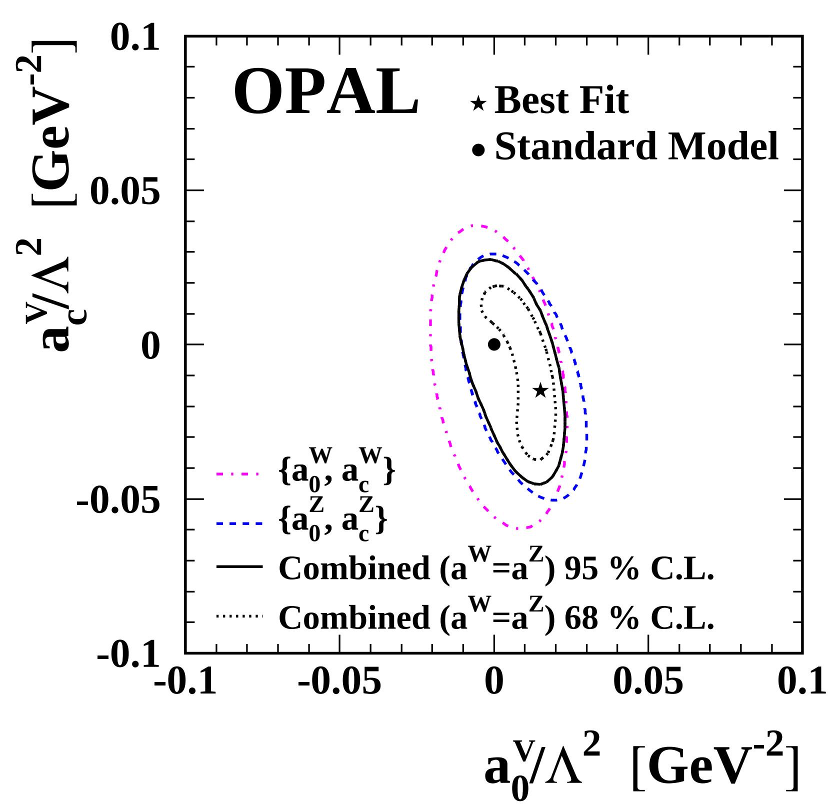


- LEP combined confidence levels allowing 2 free parameters

Other Gauge Boson Couplings

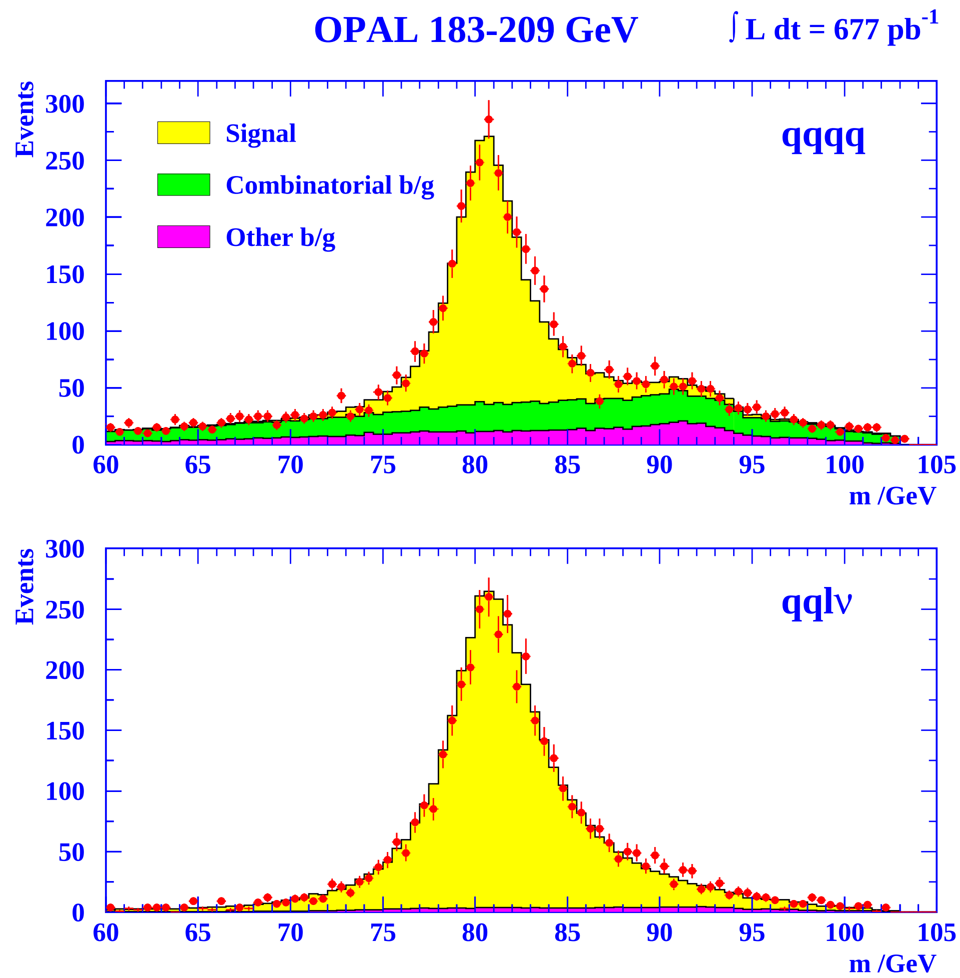
- Neutral Triple Gauge Boson couplings ($ZZ\gamma$, $Z\gamma\gamma$) are zero in SM
- Limits set from ZZ and $Z\gamma$ channels
- SM Quartic Gauge Couplings either zero or too small to be observed at LEP
- Limits set from $WW\gamma$, $Z\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$ channels





W Mass Measurement

- A principal aim of LEP2
- Comparison of direct measurement with indirect determination from EW fits is test of SM
- Measure by direct reconstruction of $q\overline{q}$ or $\ell\overline{\nu}_\ell$ mass in $W^+W^- \to q\overline{q}\ell\overline{\nu}_\ell$ and $W^+W^- \to q\overline{q}q\overline{q}$ channels
- Reconstruct event-by-event mass using beam energy constraint (kinematic fit) to improve resolution



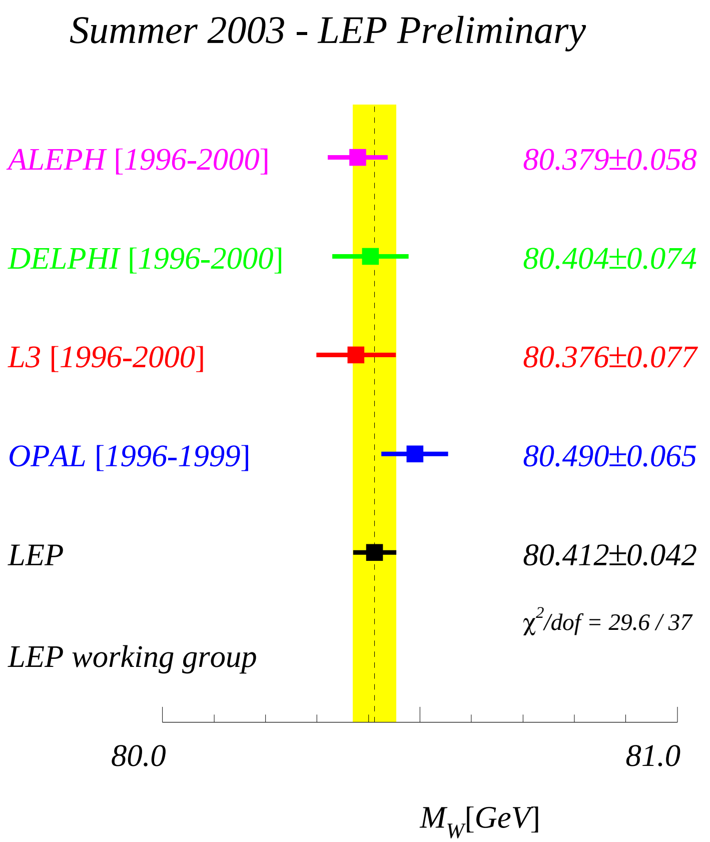
- Fit mass distribution $\Rightarrow m_W$, using MC to correct for bias

W Mass Measurement

- LEP preliminary values:

$m_W(q\bar{q}\ell\bar{\nu}_\ell)$ = 80.411±0.032(stat)±0.030(sys) GeV

$m_W(q\bar{q}q\bar{q})$ = 80.420±0.035(stat)±0.101(sys) GeV



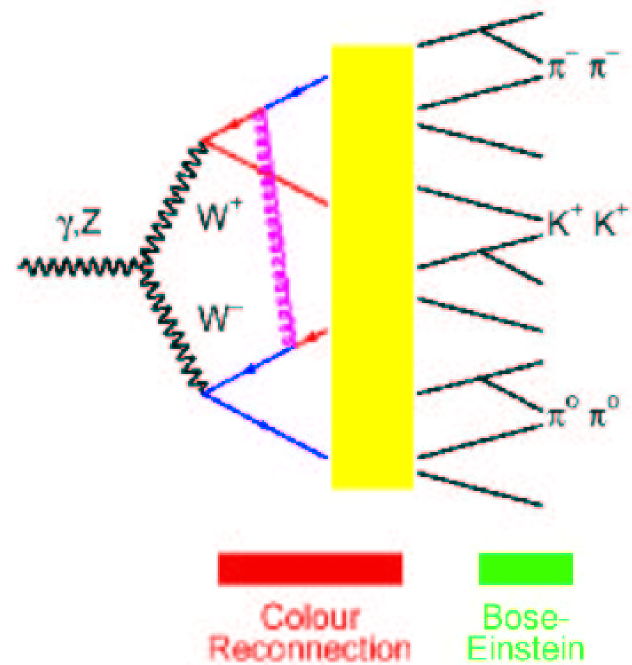
- Systematics completely dominate $q\bar{q}q\bar{q}$ channel (and important in $q\bar{q}\ell\bar{\nu}_\ell$ channel)
- Combined value:

m_W = 80.412±0.042 GeV

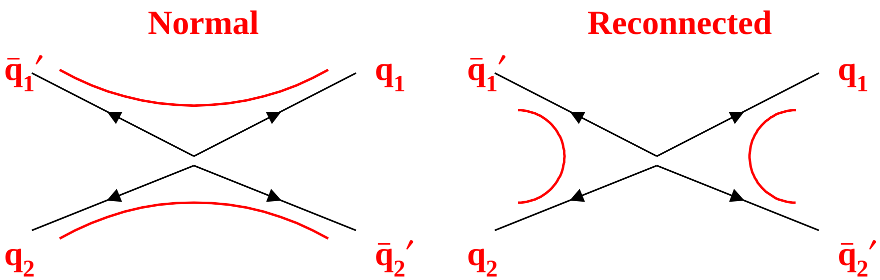
- What has been happening in last year to improve and finalize measurements?

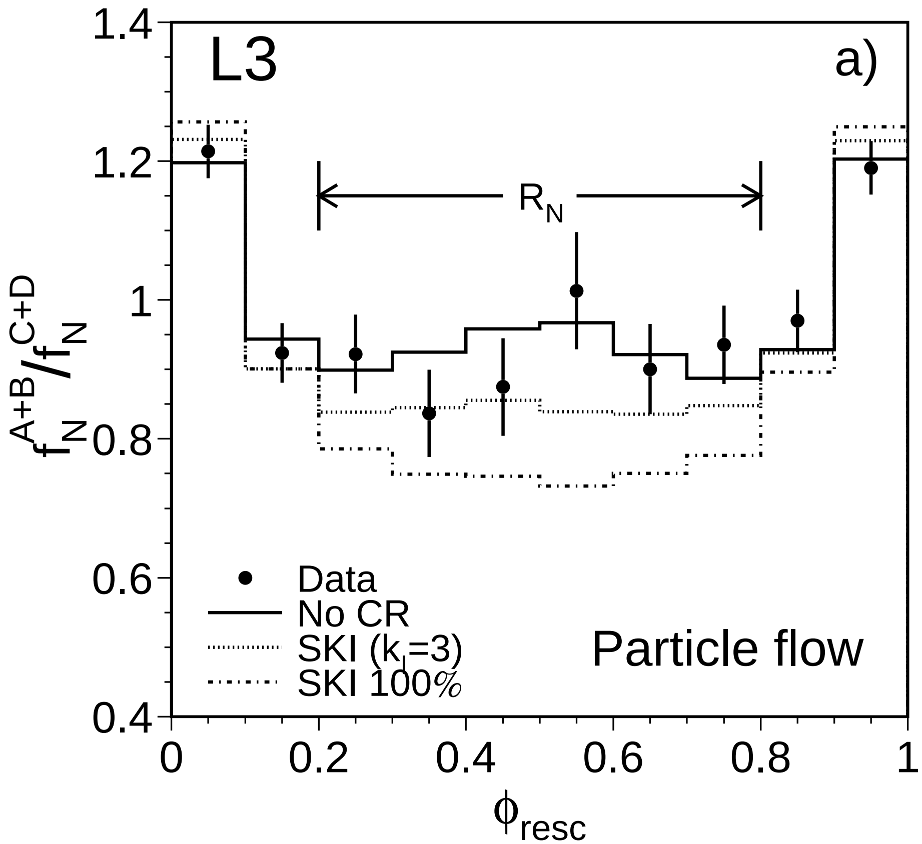
W Mass Measurement

- Main systematics in $\mathrm{q\bar{q}q\bar{q}}$ channel arise from final state interactions
- Separation of W decay vertices $\sim$ 0.1 fm $<$ hadronic scale $\sim$ 1 fm
  $\Rightarrow$ W decays have space-time overlap and can exchange colour:
  Colour Reconnection
- May also be Bose-Einstein Correlations between like-sign particles from different W's
- Both effects may shift measured m_{W} by large amount ($\sim$ 100 MeV)
  Not included in standard MC used to calibrate m_{W} measurement
- Much effort to measure CR and BEC effects to estimate realistic errors



Colour Reconnection





- Effects estimated using phenomenological models
- Look at particle flow between jets in $W^+W^- \to q\bar{q}q\bar{q}$ events
- Compare particle flow in inter-W region with intra-W region
- L3 results final, ADO preliminary
- Use largest reconnection probability compatible with data to set $\Delta(m_W)$

  Current LEP combination uses κ = 2.1 in SK1 model (∼55% reconnected)

  $\Rightarrow \Delta m_W(q\bar{q}q\bar{q})$ = 90 MeV

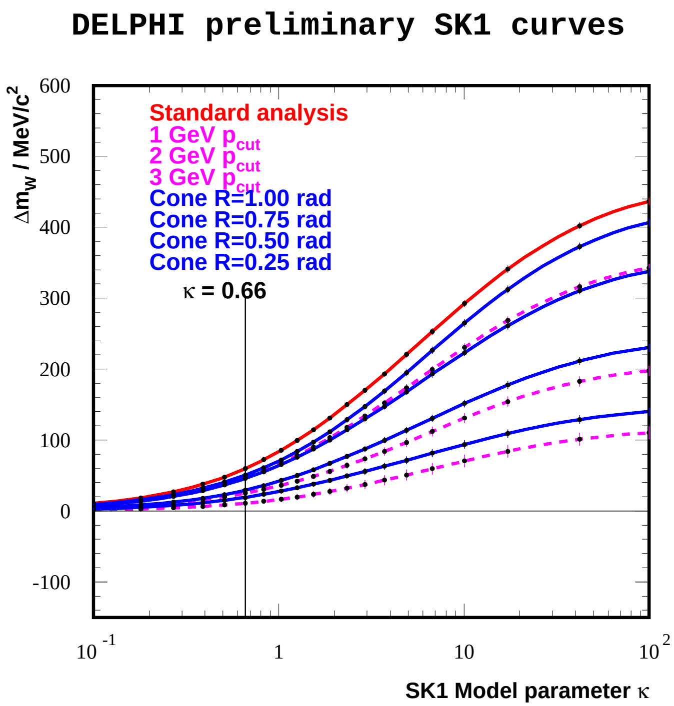
Colour Reconnection

- Soft particles most affected by FSI

  $\Rightarrow$ reduce effects with momentum cuts or jet cone cuts

  Reduces FSI error at expense of statistical error, as jet directions less precisely determined

- Final $m_{\rm W}$ analyses will optimize jet reconstruction



Bose-Einstein Correlations

- BEC between like-sign pions well-established in Z decays

  Do they occur between particles from different W's?

- Currently contributes 35 MeV to $\Delta m_{\rm W}({\rm q\bar{q}q\bar{q}})$ (LUBOEI model)

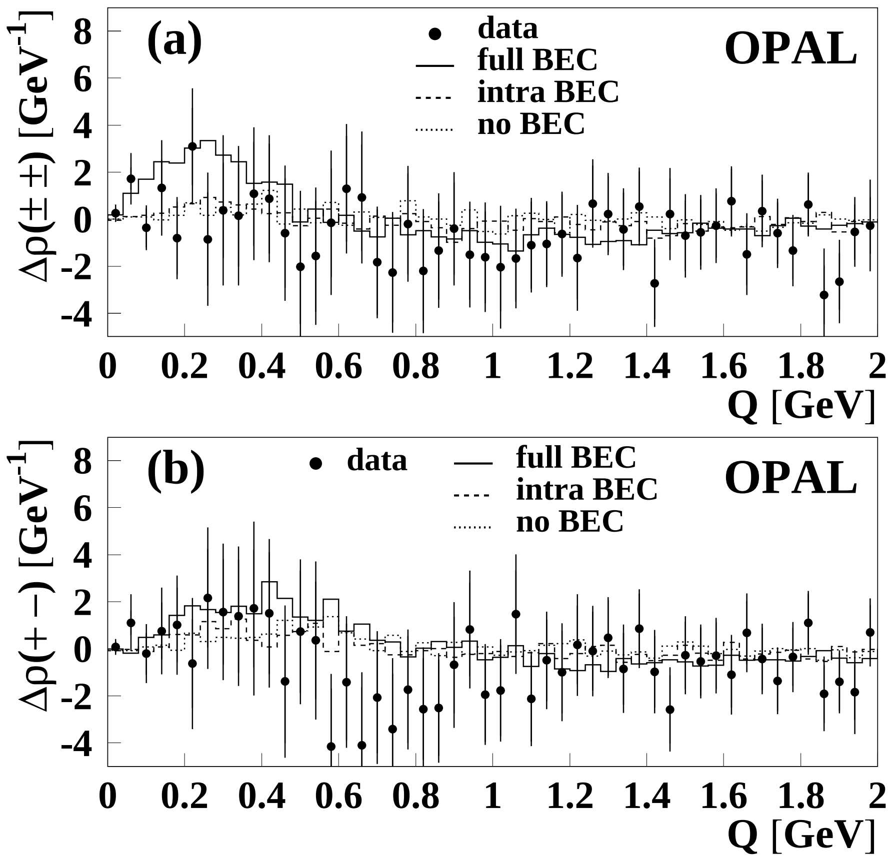
Bose-Einstein Correlations

- Study using two-particle correlations, normalized to 'no BEC'
- Use $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ events to estimate intra-W correlations, mixed events (or MC) for kinematic correlations

$$\Delta\rho(Q) = \rho_2^{\mathrm{WW}}(Q) - 2\,\rho_2^{\mathrm{W}}(Q) - 2\,\rho_{\mathrm{mix}}^{\mathrm{WW}}(Q)$$

- LEP combined data:

$$\frac{\mathrm{data-noBE}}{\mathrm{fullBE-noBE}} = 0.23 \pm 0.13$$



- DELPHI, L3, OPAL results now final
- L3, OPAL compatible with no inter-W BEC, DELPHI sees significant effect

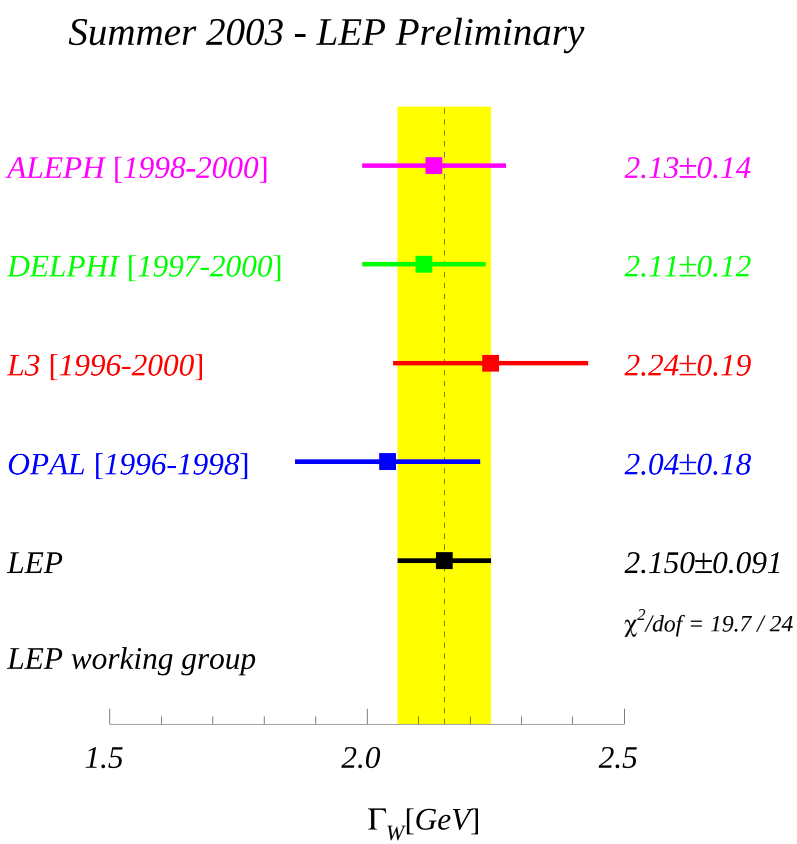
Prospects for Final m_{W} Measurement

- LEP measurements of m_{W} should be finalized soon
- Expect improvements over preliminary measurement
- LEP beam energy uncertainty will decrease from 21 MeV to $\sim$10 MeV
  Final LEP beam energy paper recently submitted for publication
- Analyses in $\mathrm{q\bar{q}q\bar{q}}$ channel will be optimized to reduce total error
- Hadronization and detector effects will be better understood
- In absence of systematics, LEP statistical precision $\sim$21 MeV
  With reduced weight for $\mathrm{q\bar{q}q\bar{q}}$ channel, probably $\sim$25 MeV
- Final total error will probably be in range 32–40 MeV, depending on FSI results

W Width Measurement

- Fits to W mass distributions also determine Γ_W
- Preliminary LEP average:

Γ_W = 2.150$\pm$0.091 GeV



Standard Model Fit

- Standard Model fit by LEPEWWG uses 17 inputs from LEP, SLD, Tevatron:

  Z lineshape: m_Z, Γ_Z, $\sigma^0_{\rm had}$, R_ℓ, $A^{0,\ell}_{\rm fb}$

  τ polarisation: P_τ

  Polarised lepton asymmetry: $\mathcal{A}_\ell$(SLD)

  Heavy flavour: $R_{\rm b}$, $R_{\rm c}$, $A^{0,\rm b}_{\rm FB}$, $A^{0,\rm c}_{\rm FB}$, $\mathcal{A}_{\rm b}$, $\mathcal{A}_{\rm c}$

  Inclusive hadronic charge asymmetry

  $m_{\rm t}$, $m_{\rm W}$, $\Gamma_{\rm W}$

- Updates since summer 2003:
  - Tevatron m_t: 178.0$\pm$2.7$\pm$3.3 GeV
  - LEP1 heavy flavours
  - Theory calculations including full two-loop corrections for $m_{\rm W}$ and $\sin^2\theta^{\rm lept}_{\rm eff}$ (Awramik, Czakon, Freitas, Weiglein)

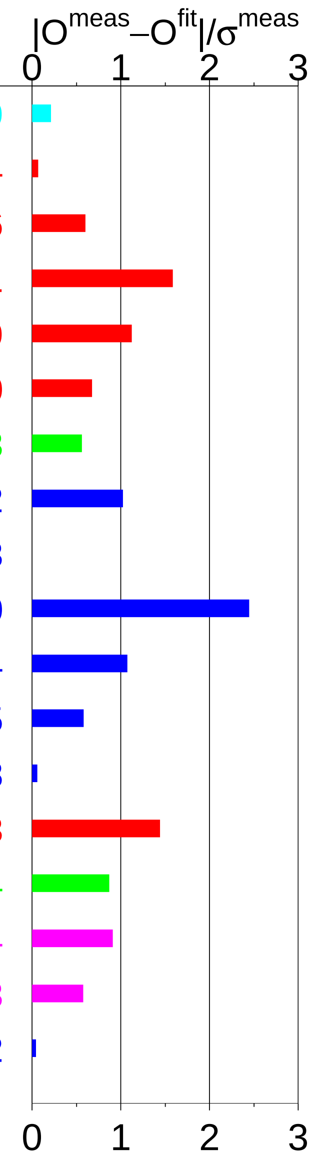
    Shifts predicted value of $m_{\rm H}$ from $\sin^2\theta^{\rm lept}_{\rm eff}$ alone by $\sim$19 GeV

Standard Model Fit

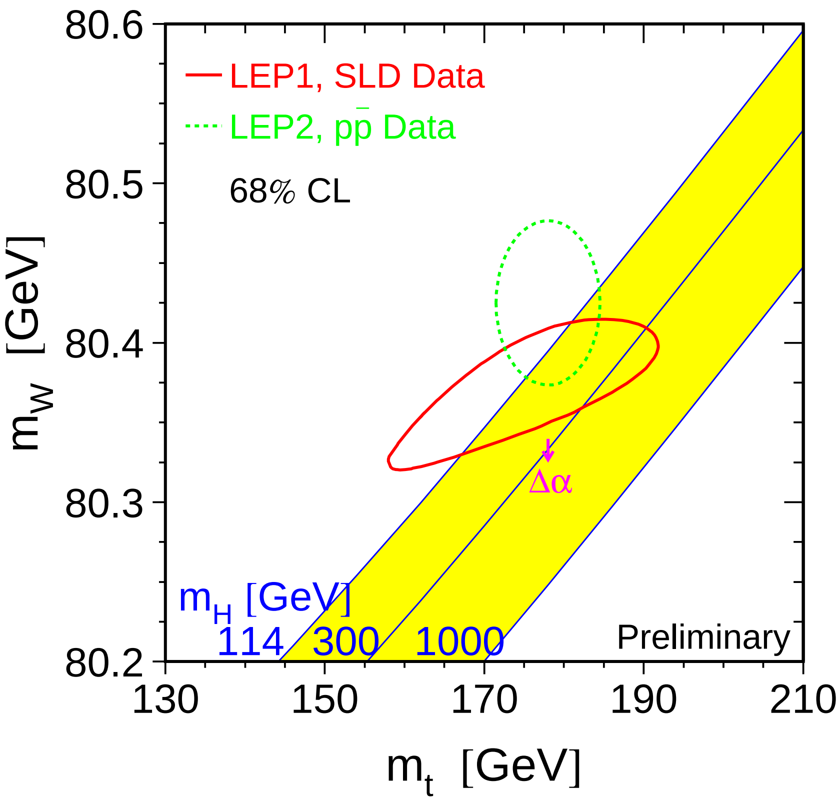
- Fit χ^2/dof = 15.8/13
- 67% correlation between m_t and $\log m_H$
- Largest contribution to χ^2 from $A_{FB}^{0,b}$ (2.4σ)
- $A_{FB}^{0,b}$ prefers large m_H, whereas R_ℓ, m_W and lepton asymmetries prefer small m_H

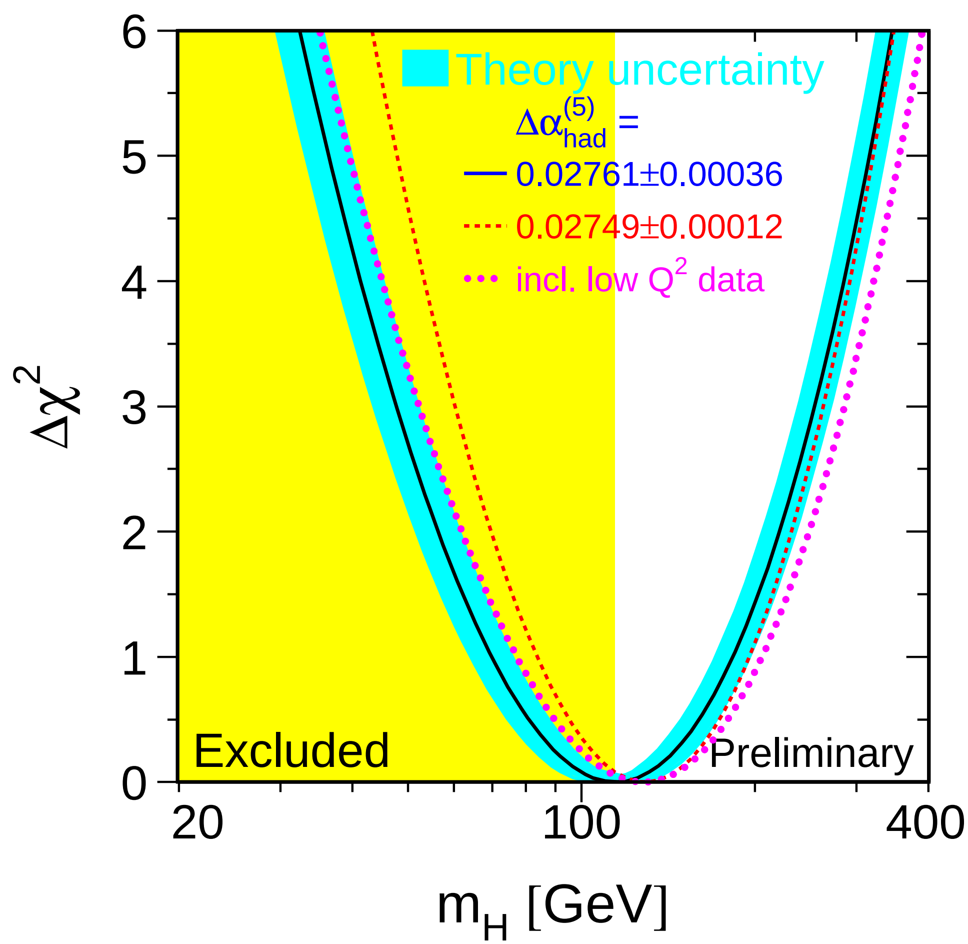
Summer 2004

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A_{fb}^{0,b}$	0.0998 ± 0.0017	0.1040
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2



Standard Model Fit





Good agreement between measured m_{W}, m_{t} and values predicted by fit excluding direct measurements

$m_{\mathrm{H}} < 260$ GeV 95% c.l.

QCD and Two-photon Physics

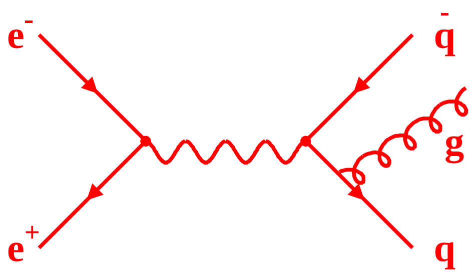
Will discuss:

- α_s from event shapes
- α_s from 4-jet rate
- Unbiased gluon jets
- Coherence effects in Z$\rightarrow$3 jets
- Dead cone effect
- Inclusive jet/hadron production in two-photon events

No time to cover

- Fragmentation functions and scaling violation
- Fermi-Dirac and Bose-Einstein correlations in Z decays
- b-quark mass effects
- Production of Ξ_c^0, Ξ_b in Z decays
- Pentaquark searches

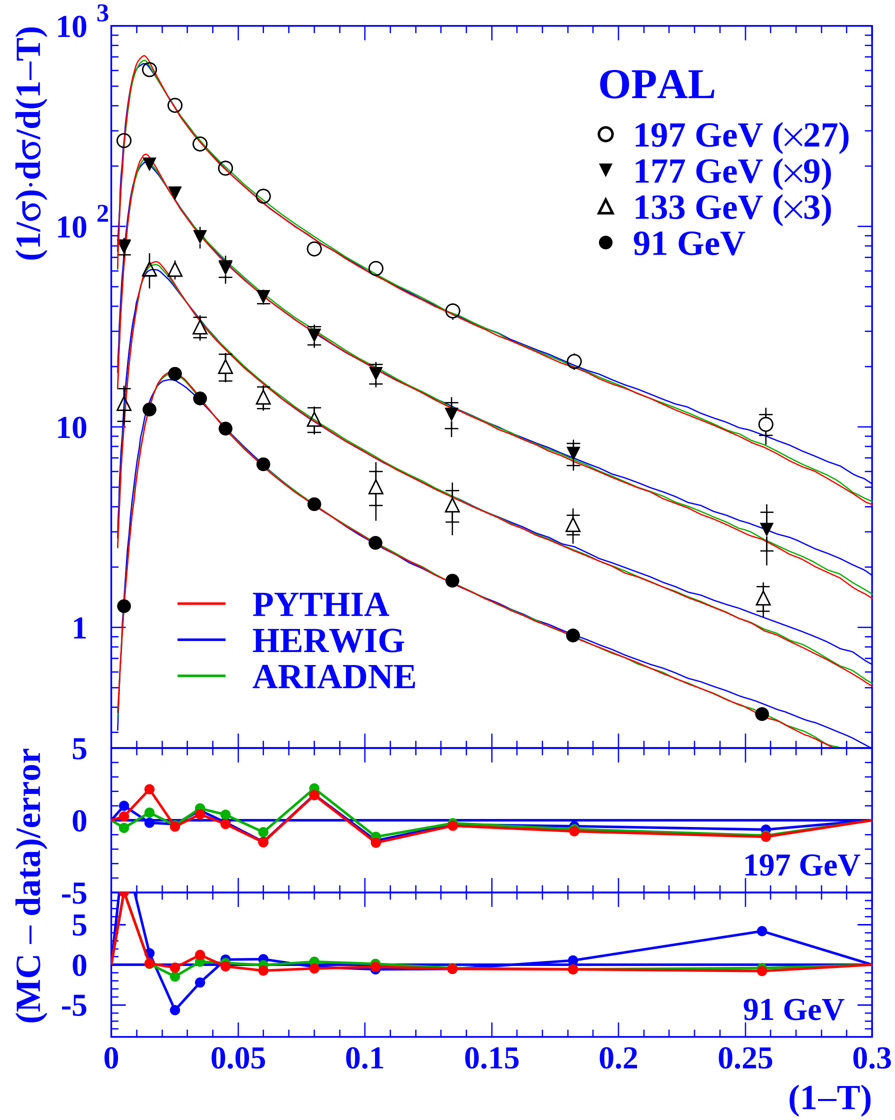
α_s from Event Shapes



- Event shapes sensitive to gluon emission, e.g. thrust:

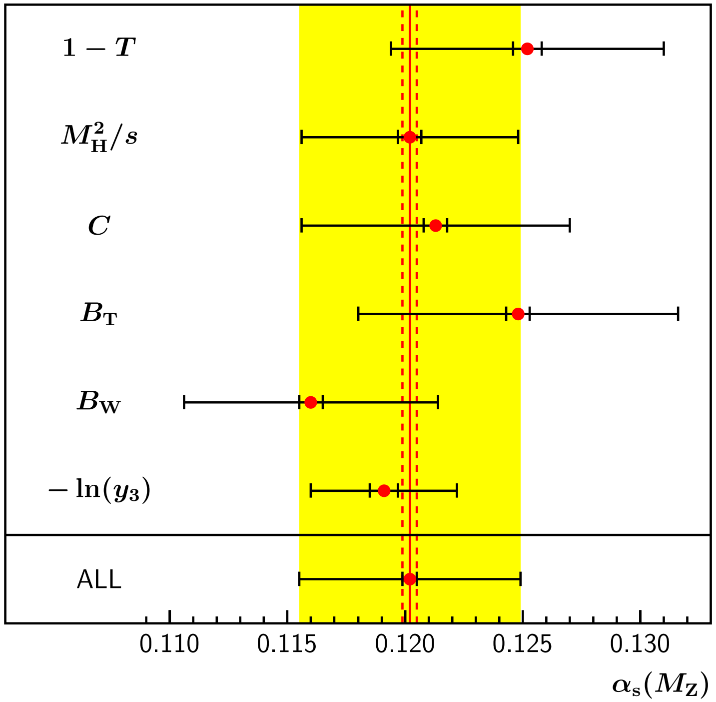
$$T = \max_{\vec{n}} \left(\frac{\sum_i |p_i \cdot \vec{n}|}{\sum_i |p_i|} \right)$$

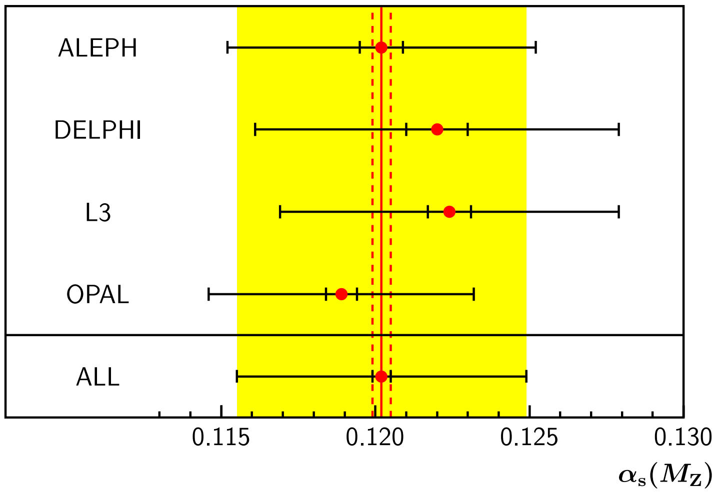
- Fit event shape distributions with $\mathcal{O}(\alpha_s^2)$ + NLLA ($\log R$ matching) QCD predictions $\Rightarrow \alpha_s$
- Final measurements from all experiments



α_s from Event Shapes

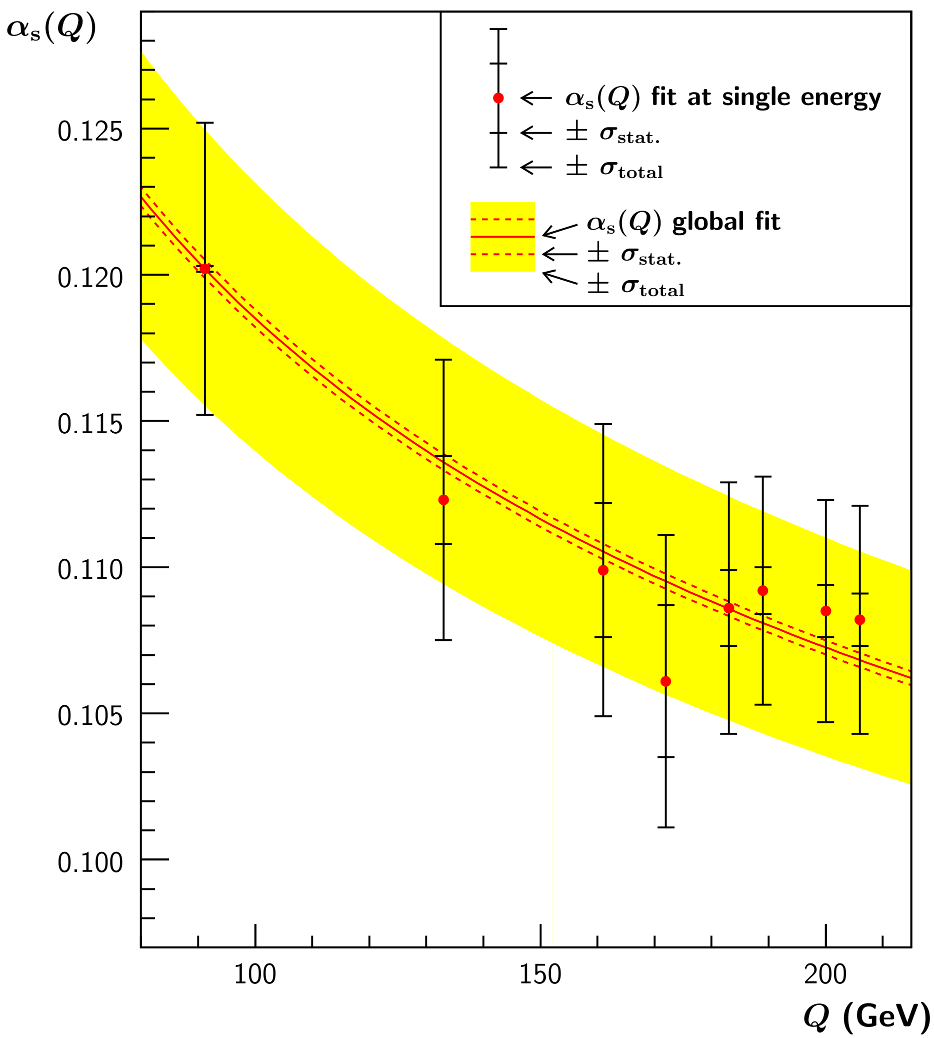
- Combinations by LEPQCD group
- Use variables which are infra-red safe (soft gluon emission) and collinear stable (collinear parton branchings)
- Combination requires care because of large correlated errors
- Treat hadronization and theory errors as uncorrelated when calculating weights, but include 100% correlation when calculating hadronisation and theory uncertainties on combined α_s





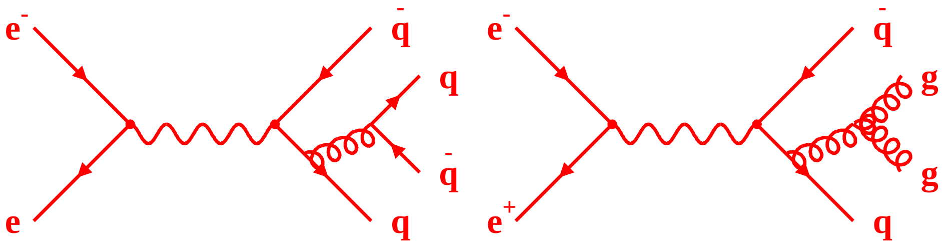
α_s from Event Shapes

- Preliminary combiation of final results from all experiments
- Relative weights in global fit:
  LEP1 46%
  LEP2 54%
- α_s runs as expected from QCD
- Theory error includes variation of renorm. scale: $0.5 < x_\mu < 2$, log rescaling fact.: $2/3 < x_L < 3/2$, matching scheme and kinematic cutoffs

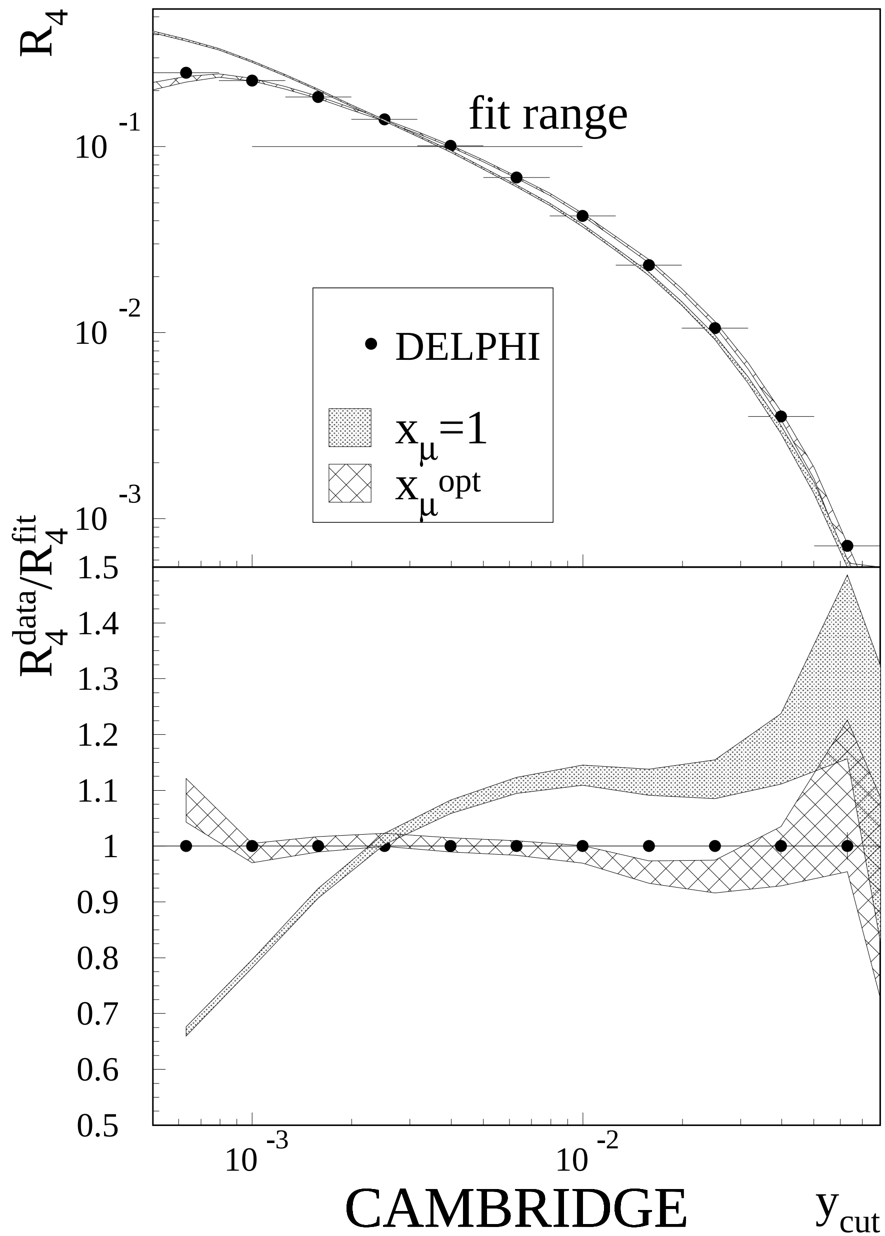


$\alpha_s(m_Z)$ = 0.1202 $\pm$ 0.0003(stat) $\pm$ 0.0007(exp) $\pm$ 0.0015(hadr) $\pm$ 0.0044(theo)

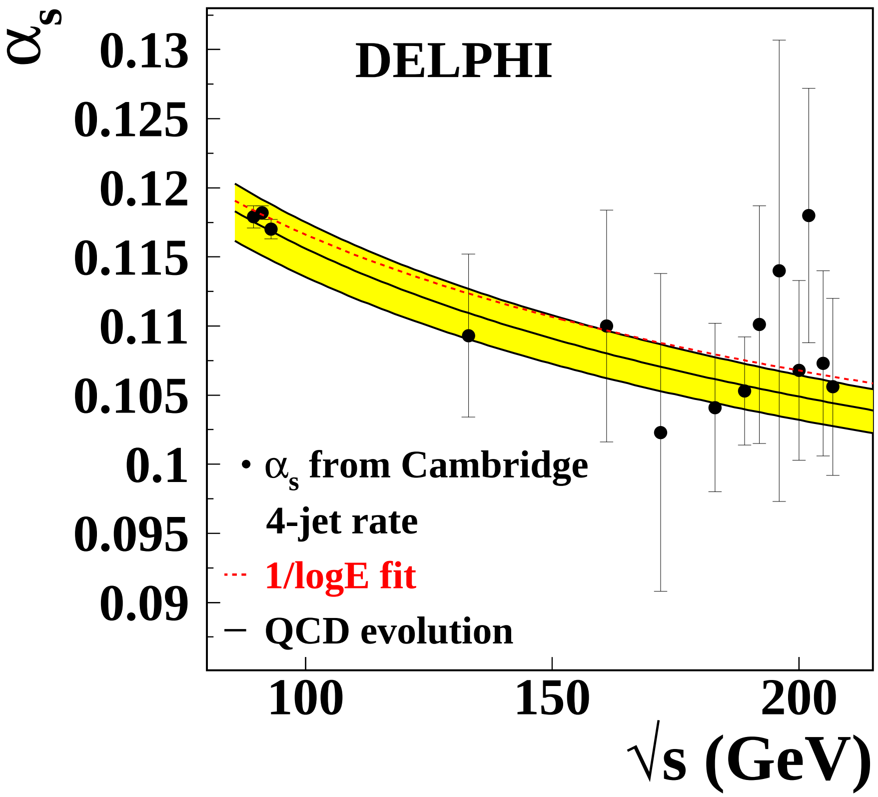
α_s from 4-jet Rate

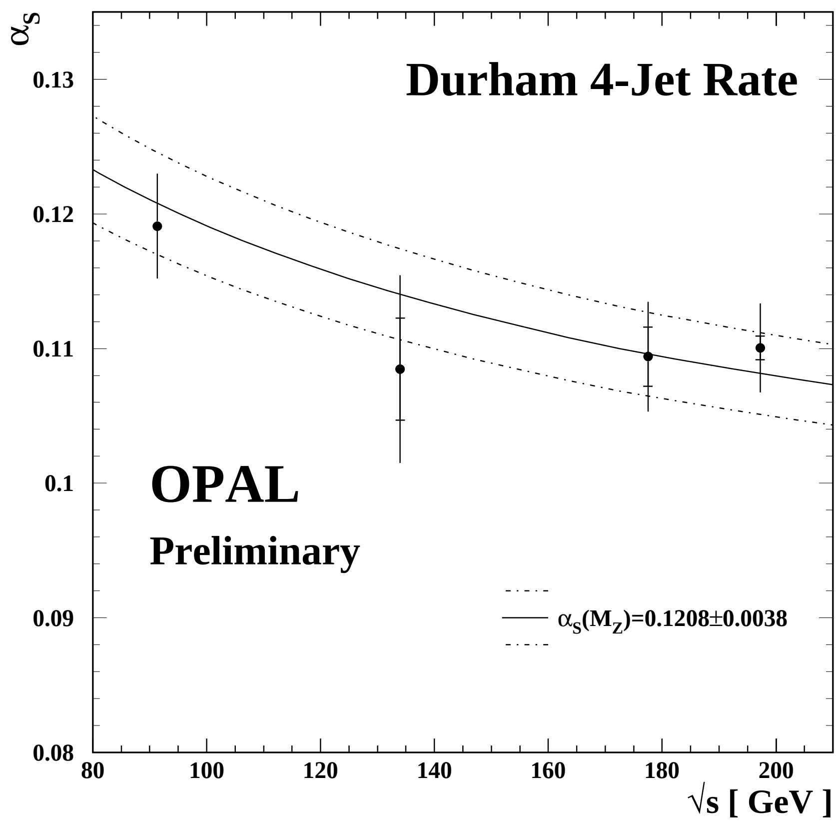


- New meas. of α_s from 4-jet rate
- DELPHI: Cambridge jet algorithm
- Fit to $\mathcal{O}(\alpha_s^3)$ QCD prediction of DEBRECEN (Nagy, Trocsanyi) using experimentally optimized renormalization scale
- OPAL: Durham jet finder
- Fit to $\mathcal{O}(\alpha_s^3)$ + NLLA QCD prediction with x_μ=1



α_s from 4-jet Rate





- DELPHI

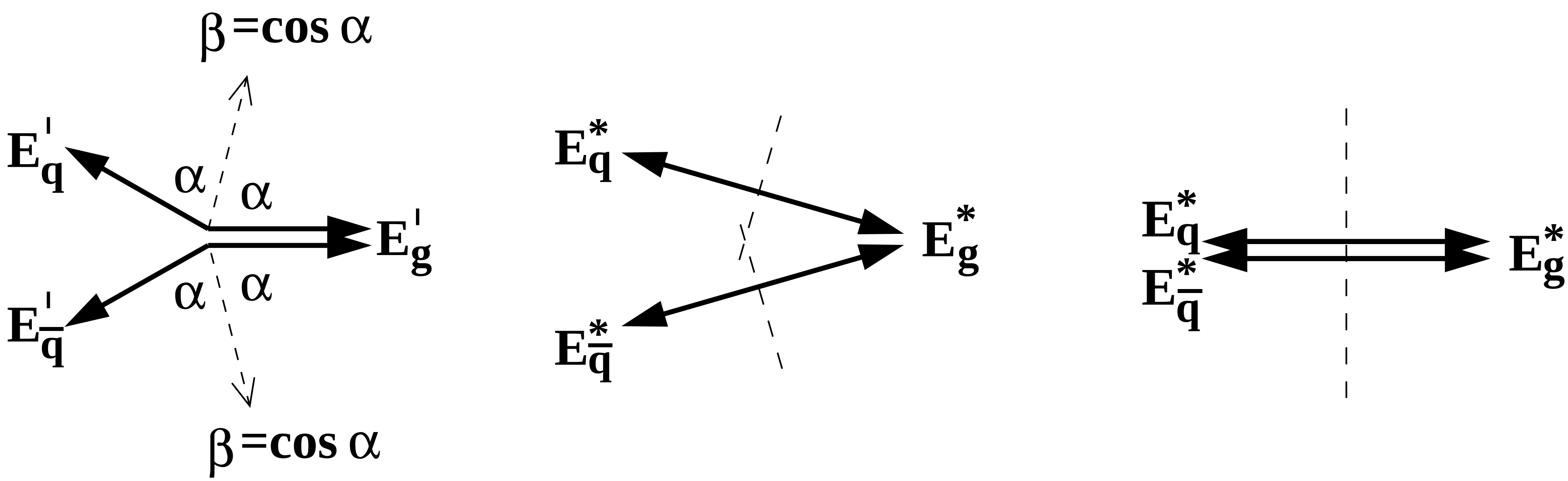
$\alpha_s(m_Z)$= 0.1175±0.0030

- OPAL

$\alpha_s(m_Z)$= 0.1208±0.0038

Unbiased Gluon Jets with Jet Boost Algorithm

- Jet boost algorithm (Eden, Gustafson) relates gluon jets in $q\bar{q}g$ events to gg system $\Rightarrow$ unbiased gluon jets

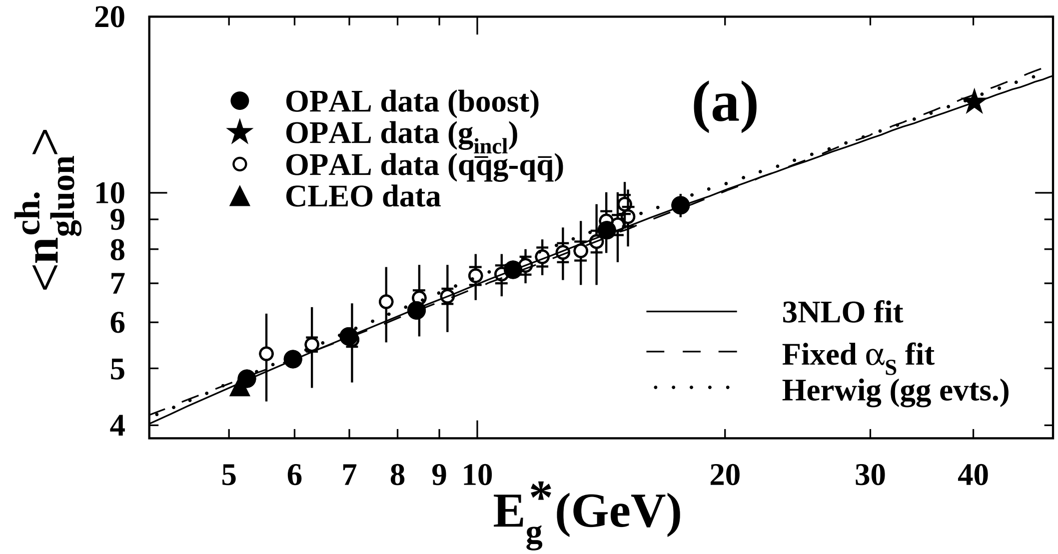


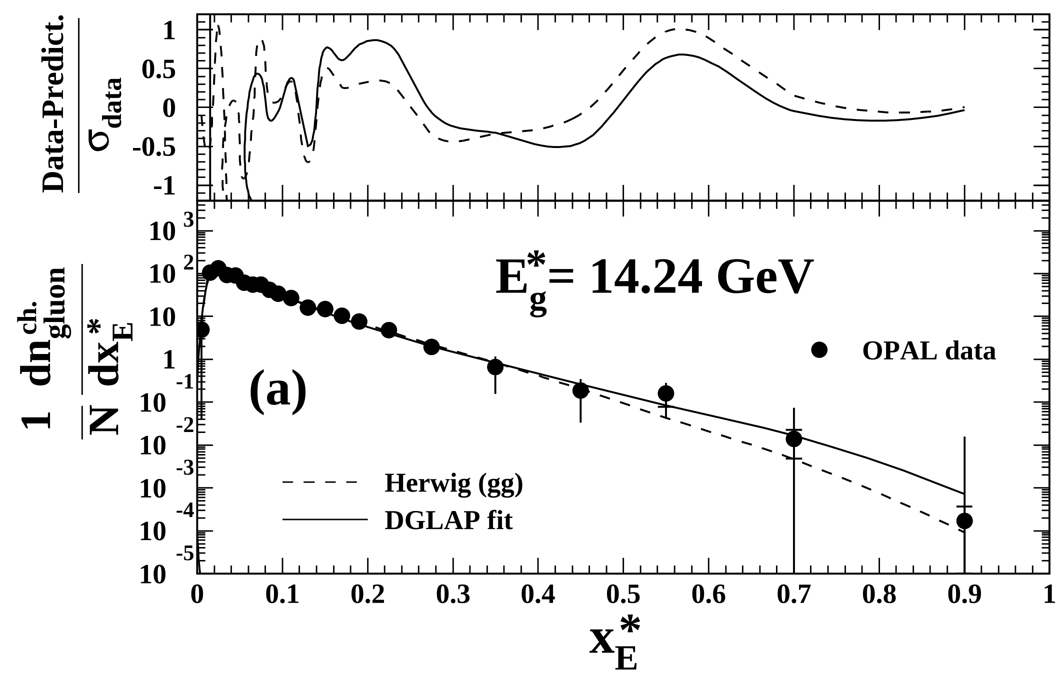
(a) (b) (c)

- Decompose into 2 colour dipoles
- Boost each dipole into back-to-back frame
- Recombine to give event with gg structure

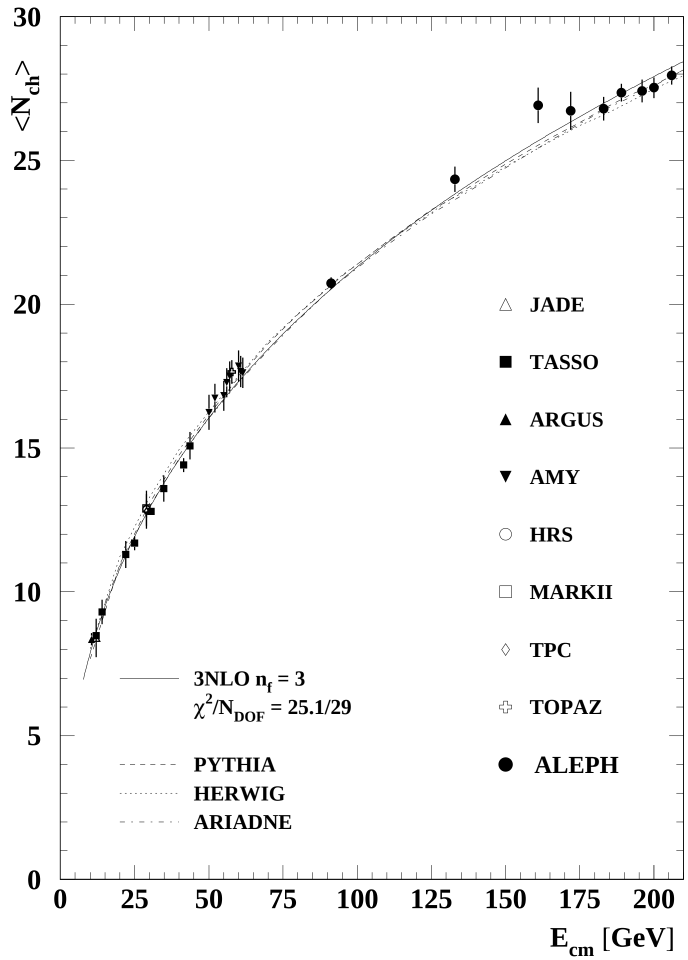
Unbiased Gluon Jets with Jet Boost Algorithm

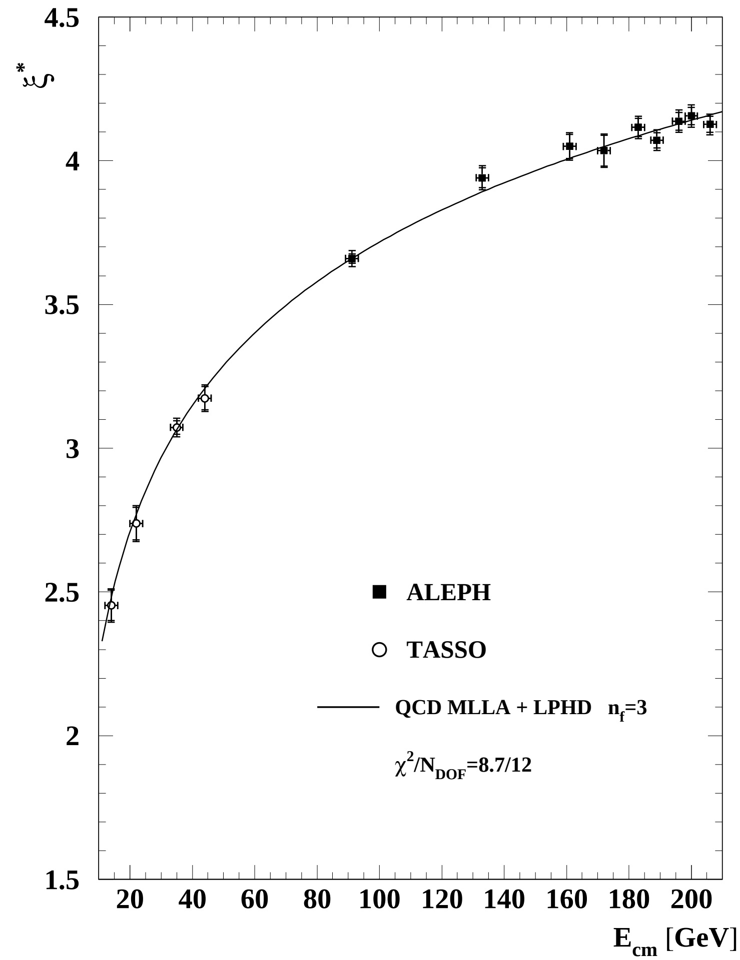
- Method used by OPAL to measure gluon charged multiplicity for 5$< E_{\rm g} <$20 GeV
- Results consistent with other measurements, and most precise for this energy range
- Theoretical fits OK
- Also measure gluon fragmentation function





Inclusive Charged Particle Distributions





- Mean charged multiplicity

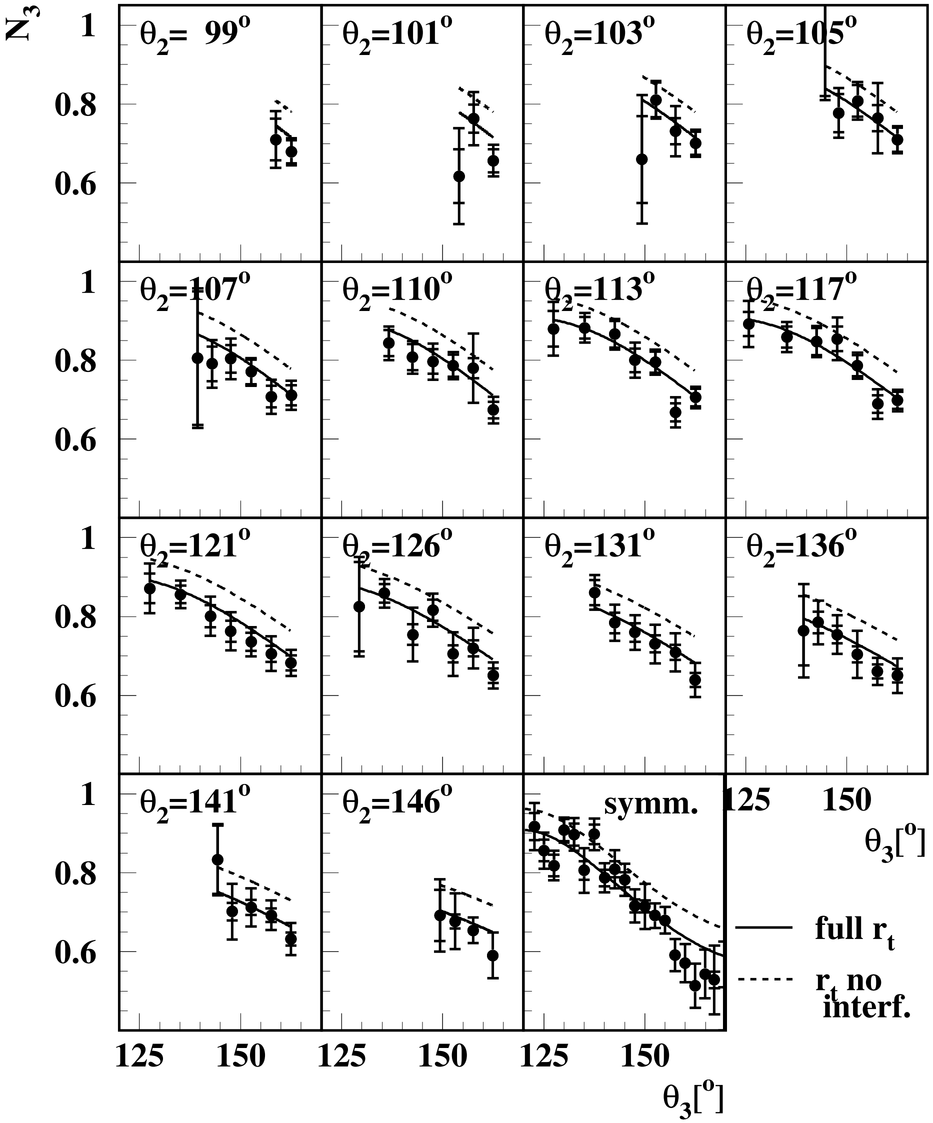
  Well-described by theory or MC

- Peak of $\xi = -\ln x_p$ distribution

  Sensitive to coherence effects

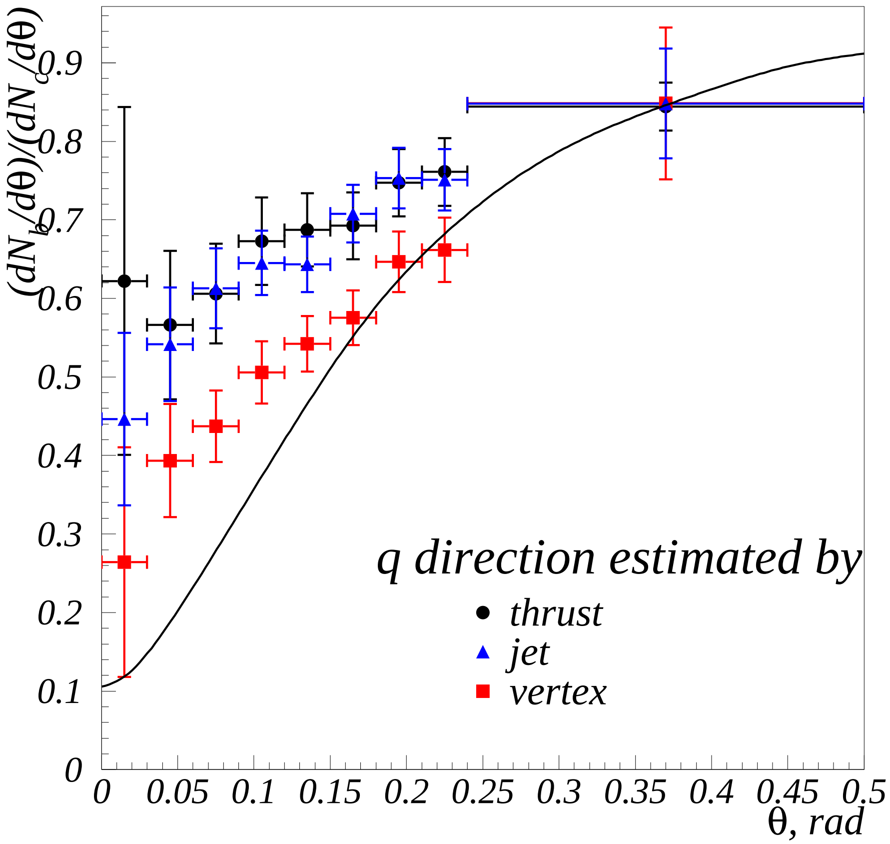
Coherence Effects in 3-jet Events

- New results from DELPHI
- Measure multiplicity in 30° cone perpendicular to event plane in 3-jet events
- Compare with corresponding quantity in 2-jet events
- Direct evidence for coherence effects in soft particle production



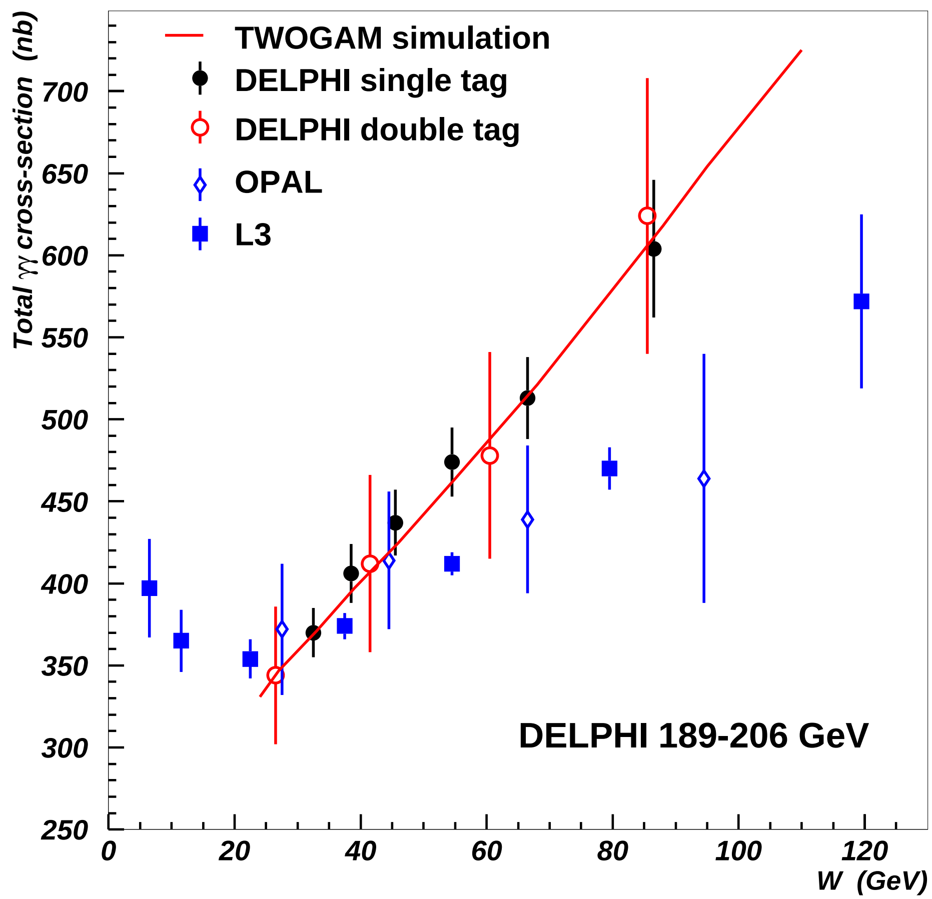
Dead Cone Effect

- QCD predicts gluon radiation off heavy quark suppressed at small angles
- DELPHI study using 2-jet $Z \to b\bar{b}$ and $Z \to c\bar{c}$ events
- Remove particles associated with b- or c-quark
- Compare angular distribution of fragmentation particles in b- and c-jets
- First DIRECT observation of 'dead cone' effect



Two-photon Physics

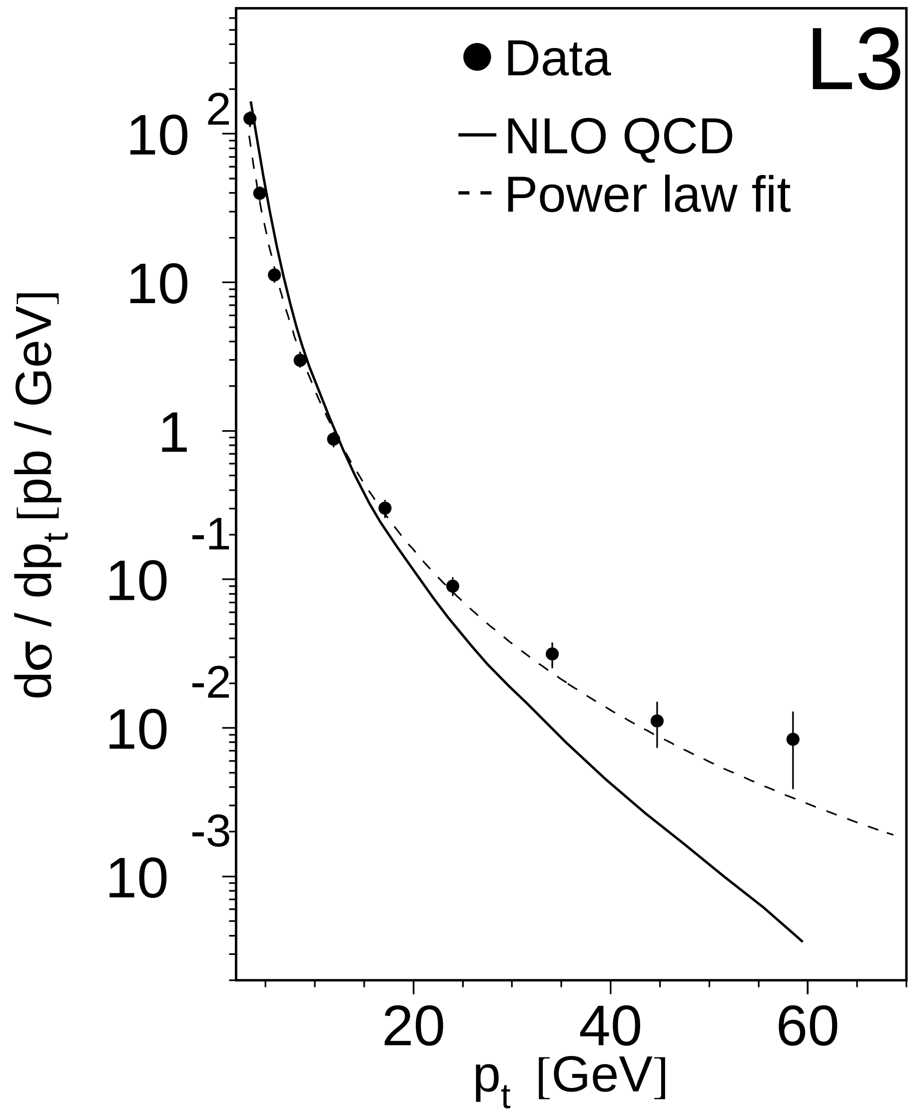
- Active area with many new measurements $\Rightarrow$ test QCD
- e.g. new DELPHI measurement of total hadronic cross-section at low Q^2 uses Very Small Angle Tagger at θ ~3-15 mrad
- Direct event-by-event reconstruction of $\mathrm{W}_{\gamma\gamma}$ for double-tagged events without unfolding $\Rightarrow$ small systematic errors



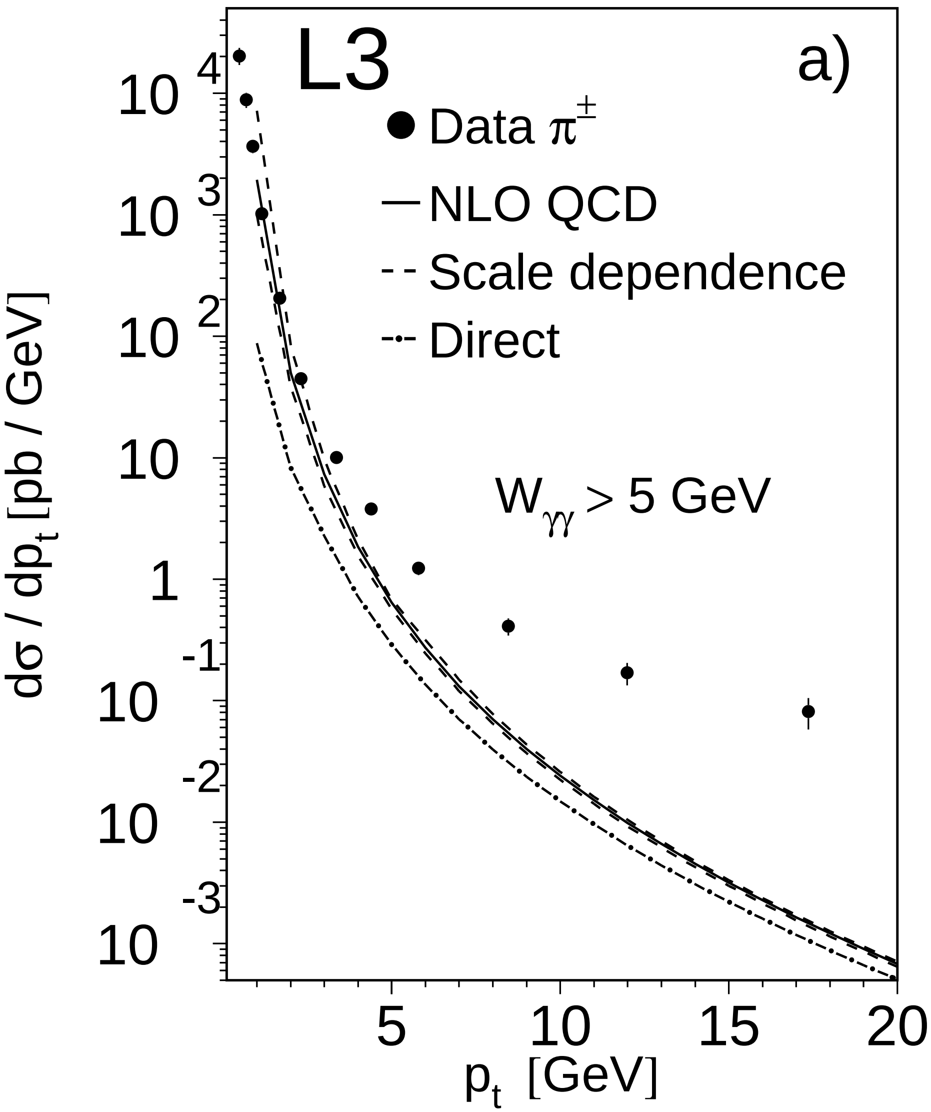
- DELPHI measurements somewhat higher than L3 and OPAL

Inclusive jet production

- L3 measurements of inclusive jet production in two-photon collisions for
  $|\eta| < 1$
  $<\mathrm{W}_{\gamma\gamma}> \sim 30$ GeV
  $<Q^2> \sim 0.2$ GeV^2
- p_t spectrum well-represented by power law
- Data higher than NLO QCD prediction (Frixione, Bertora)



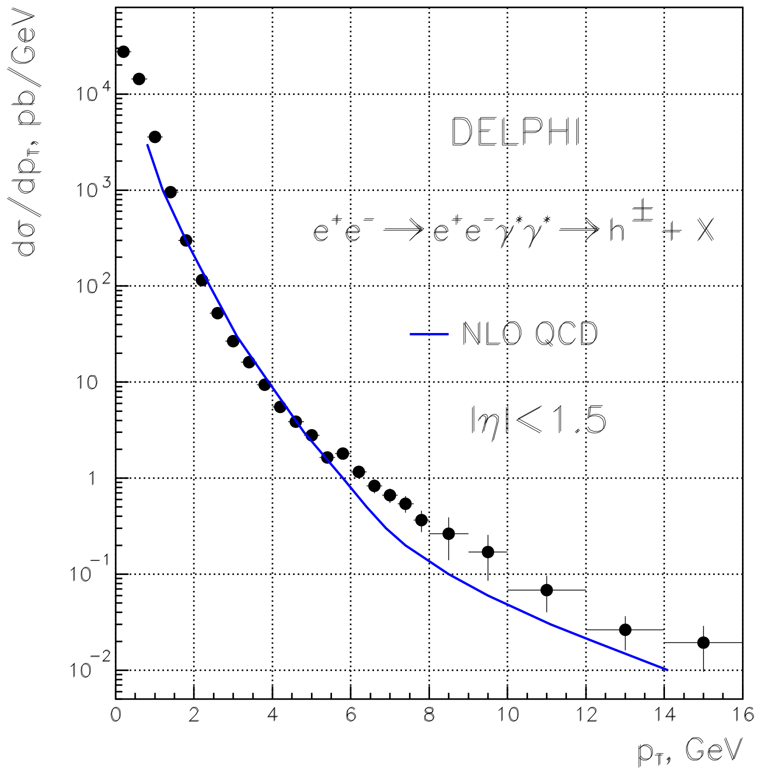
Inclusive hadron production



- L3 measurements of inclusive $\pi^{\pm}$ production in two-photon collisions for
  $|\eta| < 1$
  $<W_{\gamma\gamma}>$ >5 GeV
- Also see excess at high p_t compared with NLO QCD calculations (Binnewies, Kniehl, Kramer)
- Similar disagreement seen in π^0

Inclusive hadron production

- New DELPHI measurement of inclusive hadron production
  $|\eta| < 1.5$
  $5 < \mathrm{W}_{\gamma\gamma} < 203$ GeV
- Good agreement with NLO QCD for $p_t < 6$ GeV
- Some excess of data over NLO QCD at high p_t, but not at L3 level

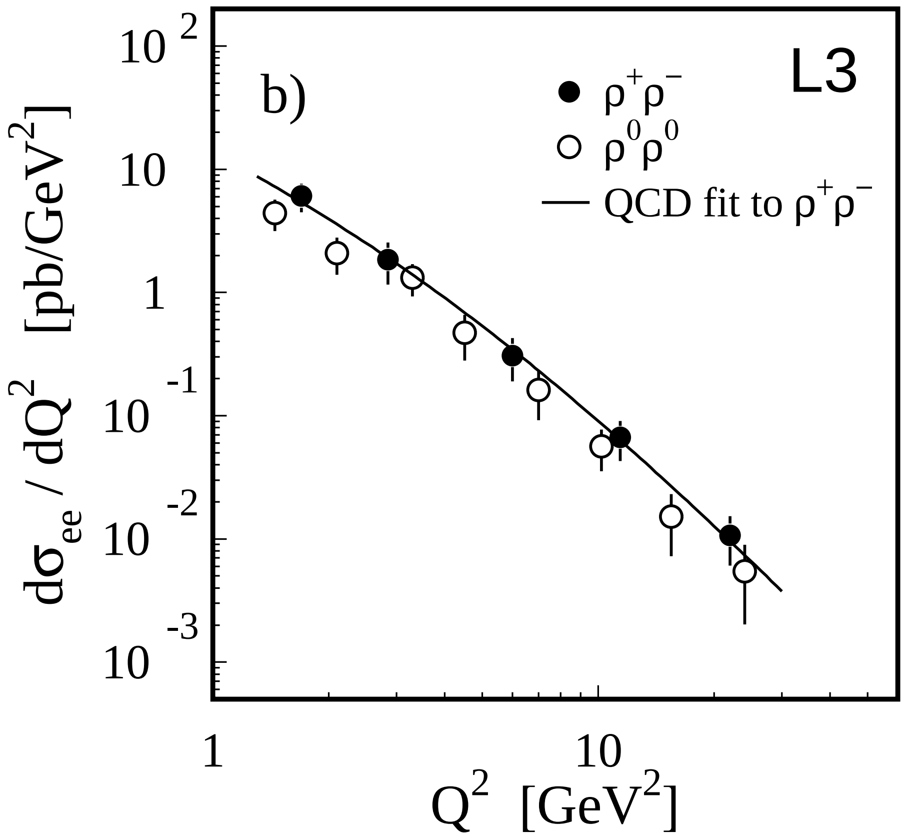


Exclusive Particle Production

- Several measurements of exclusive particle production
- e.g. L3 have measured $\rho^0\rho^0$ and $\rho^+\rho^-$
- In range 1.1$<$ $\mathrm{W}_{\gamma\gamma}$ $<$2.1 GeV, 1.2$< Q^2 <$ 8.5 GeV^2

  $\frac{\sigma(\rho^+\rho^-)}{\sigma(\rho^0\rho^0)}$ = 1.81$\pm$0.47$\pm$0.22

  expect 2 from isospin



- Fit to QCD expectation $\frac{\mathrm{d}\sigma_{\mathrm{ee}}}{\mathrm{d}Q^2} \sim \frac{1}{Q^n(Q^2+<\mathrm{W}_{\gamma\gamma}>^2)^2}$

  gives n = 2.4$\pm$0.3 (2.5$\pm$0.4) for $\rho^0\rho^0(\rho^+\rho^-)$ (expect n = 2)

Summary

- Since LEP finished running in 2000, the experiments have continued to produce lots of new physics results covering a wide range of topics: Fermion- and boson-pair cross-sections, gauge boson couplings, QCD, two-photon physics....
- Some important LEP2 measurements still to be finalized, especially m_{W}
- Important to utilize fully the plentiful, high-quality data produced at LEP