From LEP-1 to LEP-2:

Energy Upgrades and

First Physics at 130 GeV

IOP New Year Meeting on
LEP-2 Physics,
University College

5 January 1996

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Outline

- LEP Upgrade
  - Energy
  - Luminosity
  - Timescale
  - The test high-energy run in 1995: LEP-1.5

- Physics at LEP-1.5
  - Electroweak and QED tests
  - QCD studies
  - Four-fermion final states
  - Searches

Note:

All results shown are **preliminary** or **very preliminary**

The Primary Issue for LEP-2: Beam Energy

Energy lost from beam by synchrotron radiation:

$$\Delta E \propto \frac{E^4}{R}$$

Beam energy loss per turn:

45.6 GeV : 125 MeV

90 GeV : 1890 MeV

Need $\times$10 increase in RF power going from LEP-1 to LEP-2!

At LEP-1: Cu RF cavities, 1.5 MV/m gradient

At LEP-2: would need 1.5 km if used Cu only, 83 MW power

The solution: superconducting RF

- Much higher gradients possible: 5-6 MV/m
- Lower power consumption: need $\sim$30 MW (into beam)
- Needs large cryogenic plant

The Cavities

Cu cavities already installed:

- 120 in LEP
- 5-cell accelerating cavities + storage cavity —
- total voltage: 300 MV

SC cavities:

- currently 60 working cavities in LEP —
- total of 272 by the end of LEP-2 program
- 4-cell cavities, 4 cavities to a 12m long cryostat
- total voltage: 2700 MV
- technically difficult to make: cleanliness; quality
- very high power throughput: RF couplers, klystrons, safety systems in case of reflection
- difficult to operate: power couplers, HOM couplers, tuning, all need new techniques

Luminosity at LEP-2

Need $>$150 pb^{-1} per year at LEP-2

Cf. best LEP-1 year (1994): 65 pb^{-1} delivered

Pretzel scheme used in 1994 not good for LEP-2 (current limit at injection)

New bunch train scheme is commissioned now for LEP-2
$\Rightarrow$ similar performance to pretzel

Other considerations:

- "year" shorter at LEP-2 (cash)
- $\mathcal{L}$ lifetime shorter (not beam-beam limited)
- efficiency lower? (large SC RF installation)

To get there, need:

- higher bunch currents
- different machine optics (lower emittances)

Progress so far:

- bunch trains
- inject at 22 GeV (10% more current than at 20 GeV)
- "synchro-betatron injection" (faster, lower backgrounds)

The best estimates (S.Myers):

- Maximum current per bunch: $\leq$ 1 mA
- Power available for c. 8 mA total
- $\Rightarrow$ 8 bunches probably optimal for LEP-2

Further Issues

Energy calibration

- Common error on W mass measurement
- With resonant beam depolarisation at LEP-1, have achieved beam energy uncertainties of a few MeV
- No polarisation expected at LEP-2
- Rely on extrapolation using magnetic measurements
- Expect error of approx 15 MeV
- Probably below total precision on M_{W}, but not by much

Backgrounds

At LEP-1, background from:

- off-momentum electrons
- synchrotron radiation hits

Synchrotron radiation photons increase as E^3

- special synchrotron radiation masks installed
- huge reduction in synchrotron radiation background

Off-momentum background

- less clear
- estimate similar rate at LEP-2 as LEP-1 (G.von Holtey)

Timescales

Current planning of energy upgrade

Date	Max. E_{cm} (GeV)	Max. $\mathcal{L}$ (10^{31} cm^{-2}s^{-1})	
Nov 95	136	3	"LEP-1.5"
Jun 96	163	8	$\mathrm{W^+W^-}$ threshold
Oct 96	172	9	short run
Jun 97	187	9	main 1997 run
Jun 98	191	11	"Phase IV"

(adapted from S. Myers, LEPC Nov. 1995)

Max. E_{cm}: one RF unit can trip without losing beam

The LEP-1.5 Run

31 Oct – 22 Nov 1995

Main aim: learn about high-energy operation of superconducting RF

Nearly all fills lost due to RF trips, various reasons:

- one new unit not debugged properly
- faulty klystron (rare!)
- faulty electronics (noise)
- RF feedback debugging (but needed!)

Very valuable learning experience for the RF group

Physics goal: Collect $\geq$5 pb^{-1} at high energy

In practice:

- 3 pb^{-1} at 130 GeV
- 3 pb^{-1} at 136 GeV
- 0.05 pb^{-1} at 140 GeV
- 30% differences in $\mathcal{L}$ between experiments!

Total $\mathcal{L}$ exceeded aim: **LEP-1.5 run a resounding success**

Physics at LEP-1.5

Standard Physics

- Fermion pair $\mathrm{f\overline{f}}$ production dominates cross-section
- QED process: $\gamma\gamma$ final-state
- Properties of $\mathrm{q\overline{q}}$ events: QCD studies
- Four-fermion final states

Backgrounds for LEP-2!

Searches

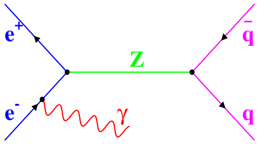
- Grahame Blair will cover rationale and techniques
- Here just brief summary of LEP-1.5 data

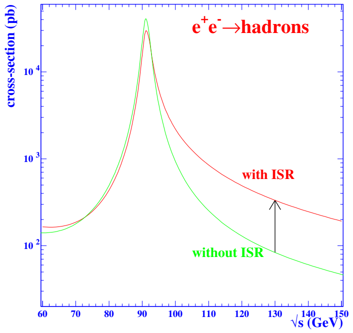
Fermion-pair production above the Z^0

Hadronic cross-section:

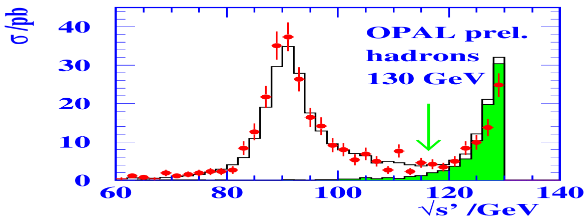
$\sigma_{q\bar{q}}(130\text{GeV}) \simeq 300\,\text{pb}$

factor 100 less than $\sigma_{q\bar{q}}(M_Z)$





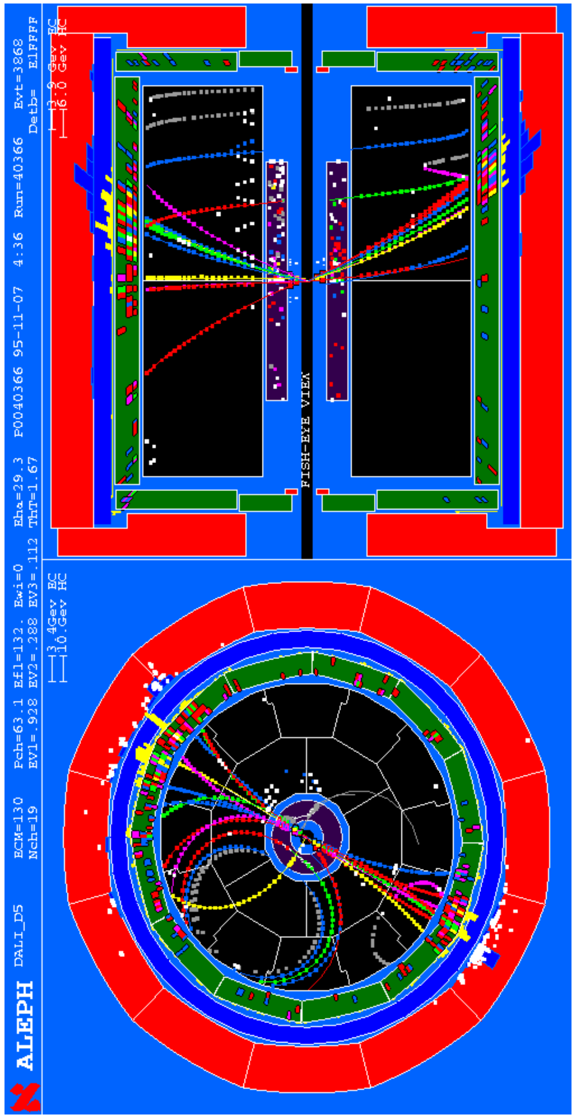
Effective centre-of-mass energy, $\sqrt{s'}$, distribution:

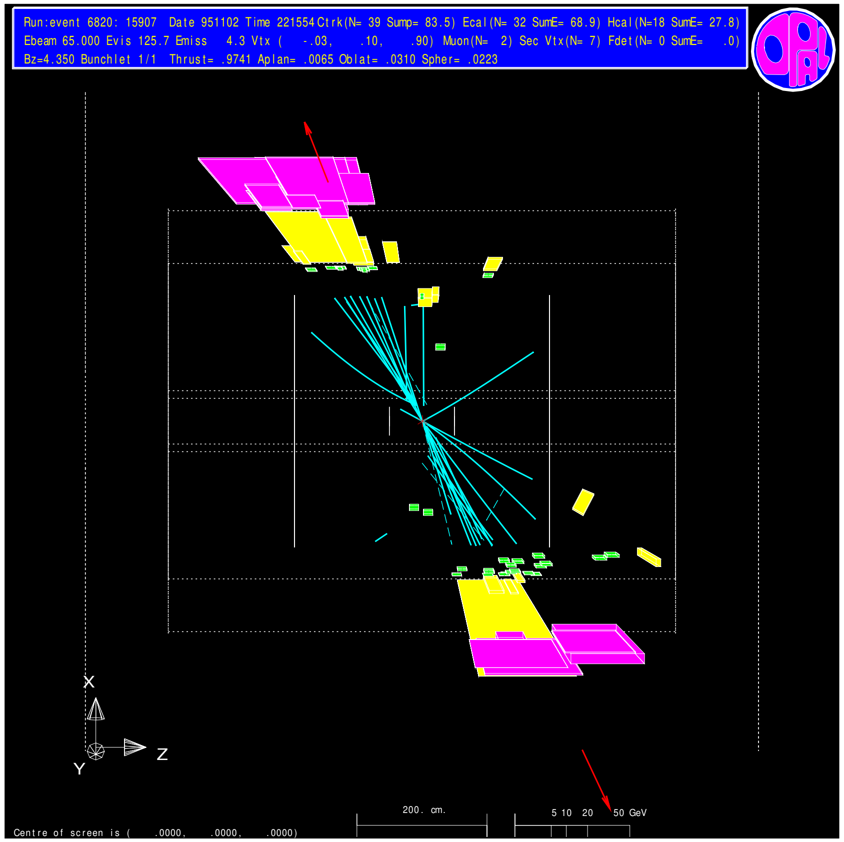


Broadly, two types of events:

- "Radiative return" $\sqrt{s'} \simeq M_Z$
- "Non-radiative" $\sqrt{s'} \simeq \sqrt{s}$

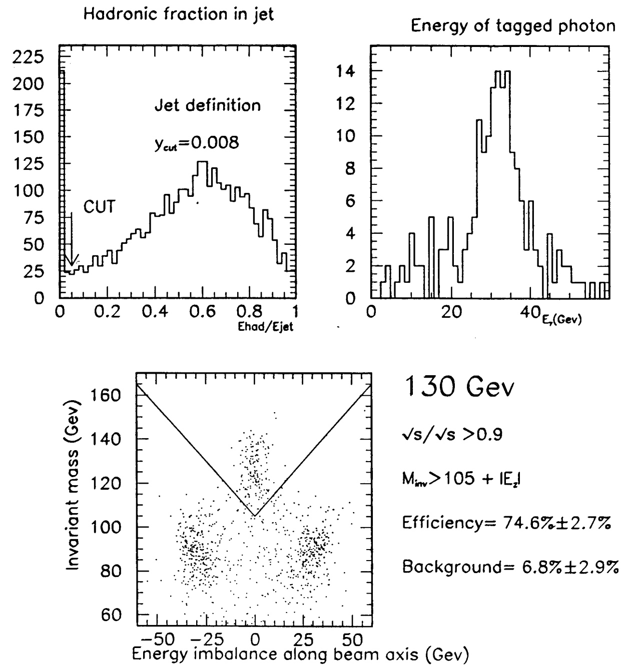
Non-radiative events are more interesting!



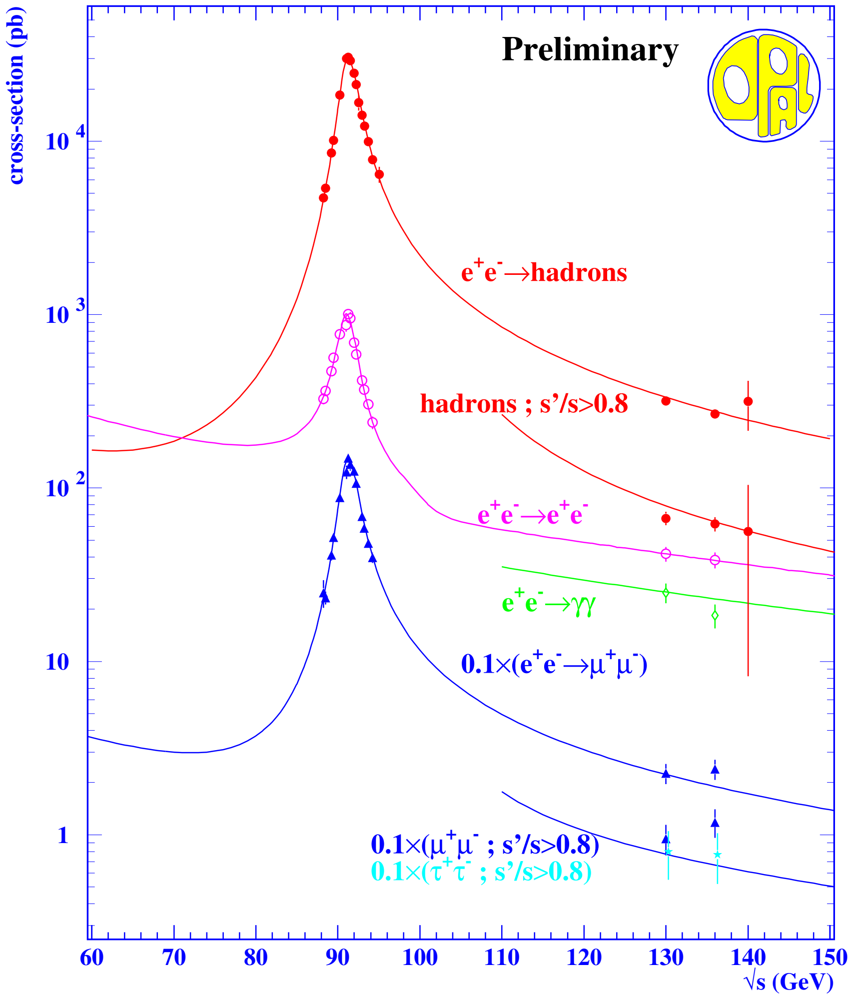


Separation of non-radiative events

ALEPH:



Exact definition ($\sqrt{s'}$ cut) varies slightly between experiments, but all make the separation

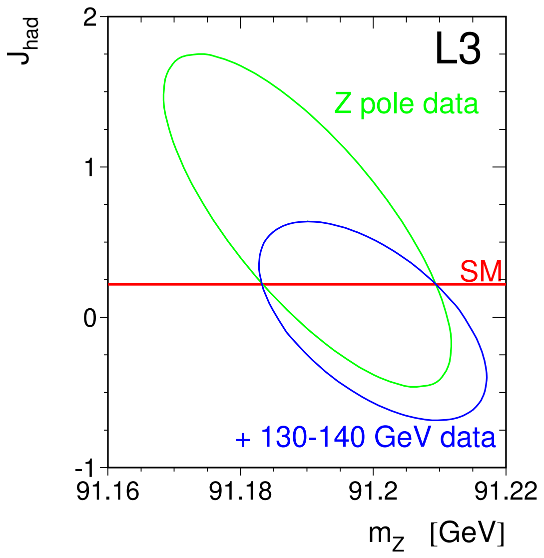


Impact on Z^0 Lineshape Fits

Without radiative corrections:

$$\sigma_{q\bar{q}}(\sqrt{s}) = \frac{A_\gamma}{s} + \frac{A_{\gamma Z}(s - M_Z{}^2) + A_Z s}{(s - M_Z{}^2)^2 + s^2\Gamma_Z{}^2/M_Z{}^2}$$

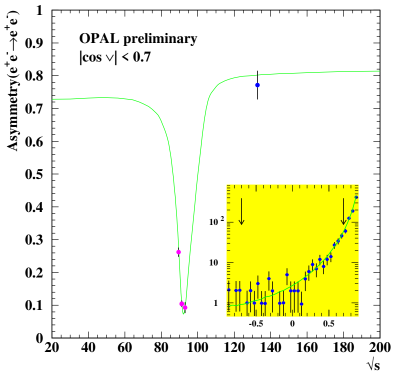
- Standard fit: relative sizes of A_γ, $A_{\gamma Z}$, A_Z fixed by SM $\to M_Z, \Gamma_Z$
- "S-Matrix" fit effectively allows interference term $A_{\gamma Z}$ to float $\to J_{\mathrm{had}}$
- M_Z precision reduced in this case where $A_{\gamma Z}$ floats
- 130 GeV data particularly sensitive to interference term



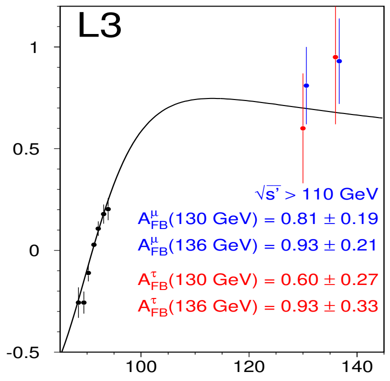
Asymmetries

Leptonic forward-backward asymmetry

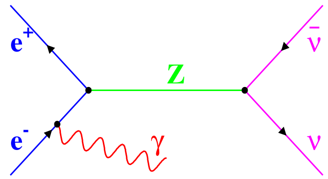
- e^+e^-: t-channel scattering dominates $\longrightarrow A_{\mathbf{FB}}$ large



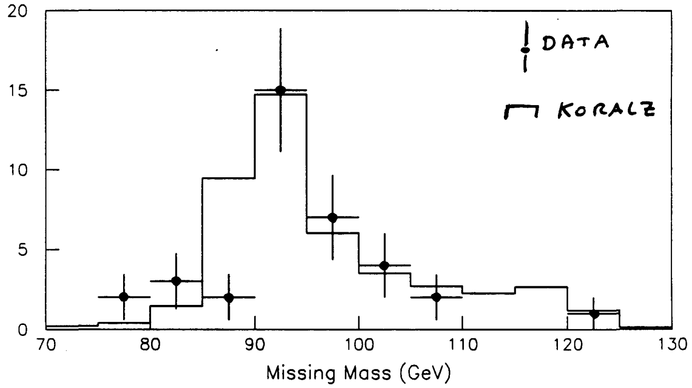
- $\mu^+\mu^-/\tau^+\tau^-$: γZ-interference effect large



Single photon production

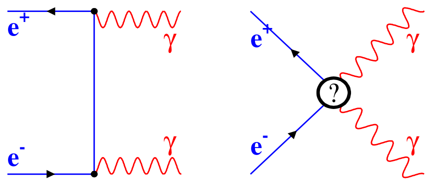


ALEPH:



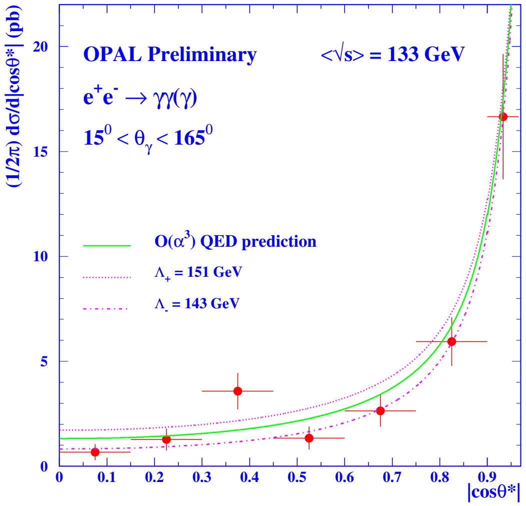
Measured cross-sections agree with SM expectations

$\gamma\gamma(\gamma)$ final state



QED process, sensitive to possible contact interaction

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\mathcal{O}(\alpha^3)} \left(1 \pm \frac{s^2}{2\Lambda_\pm{}^4}(1 - \cos^2\theta)\right)$$

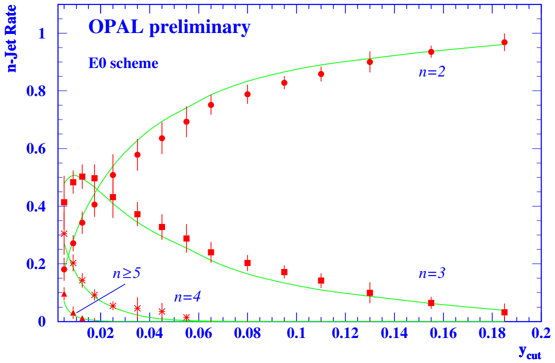


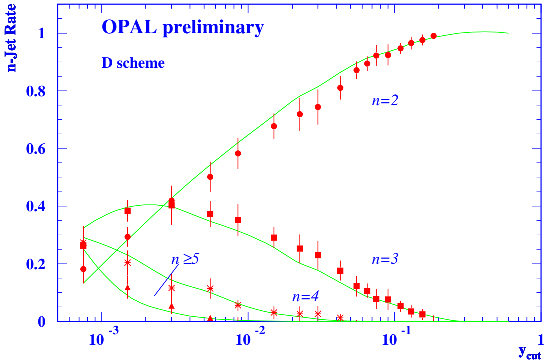
Similar $\Lambda_\pm$ sensitivity as best LEP-1 limit

QCD Tests at LEP-1.5

Study non-radiative events – new energy scale

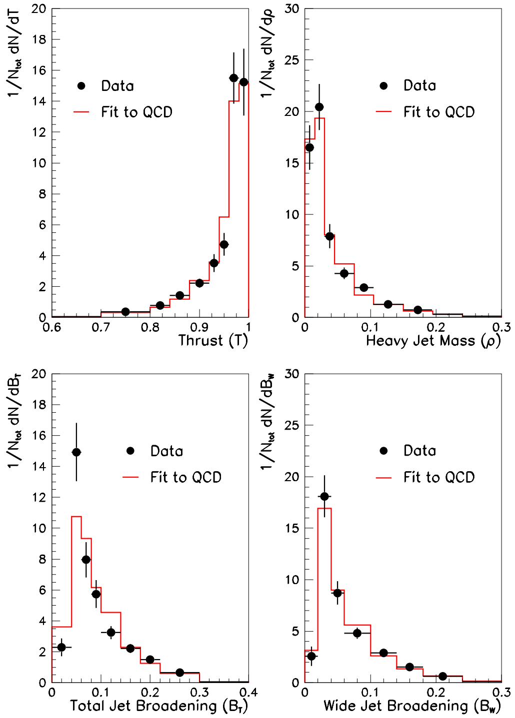
Jet Rates





Hadronic Event Shapes

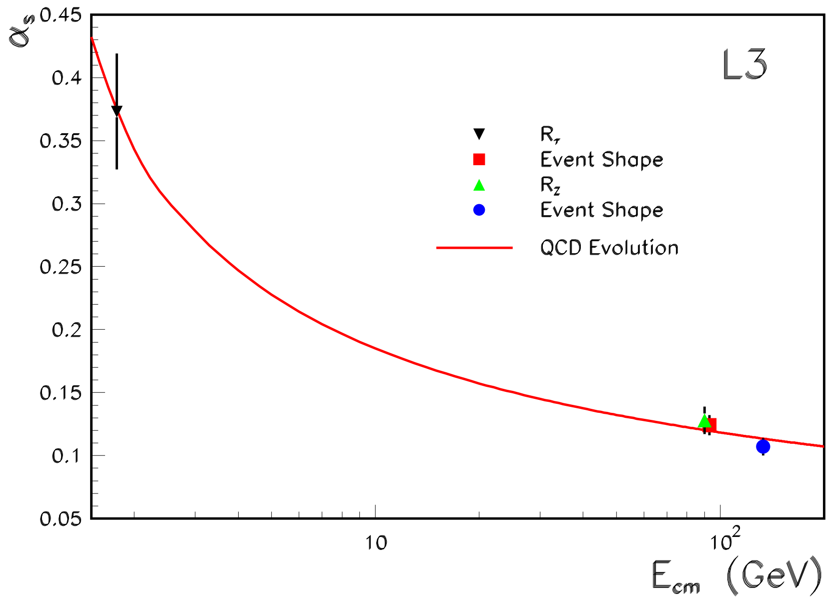
Event shapes agree with expectation, eg from **L3**:



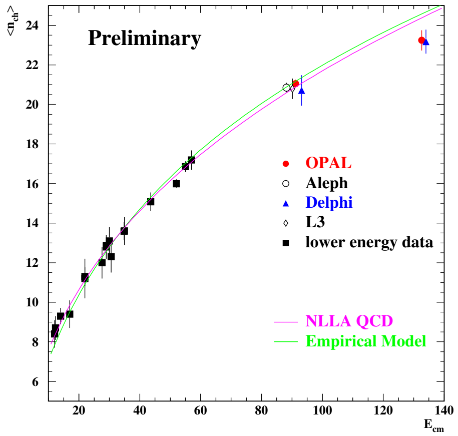
L3 has used them to extract α_s

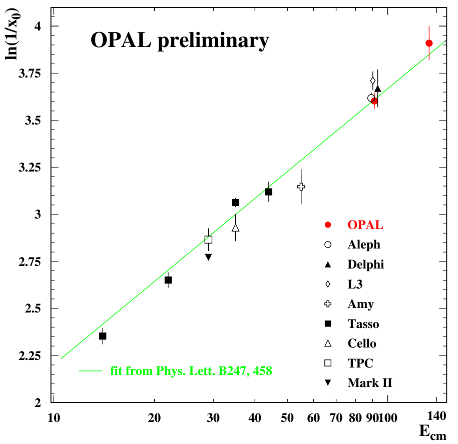
$$\alpha_s(133\mathrm{GeV}) = 0.107 \pm 0.005 \pm 0.006$$

Running of α_s

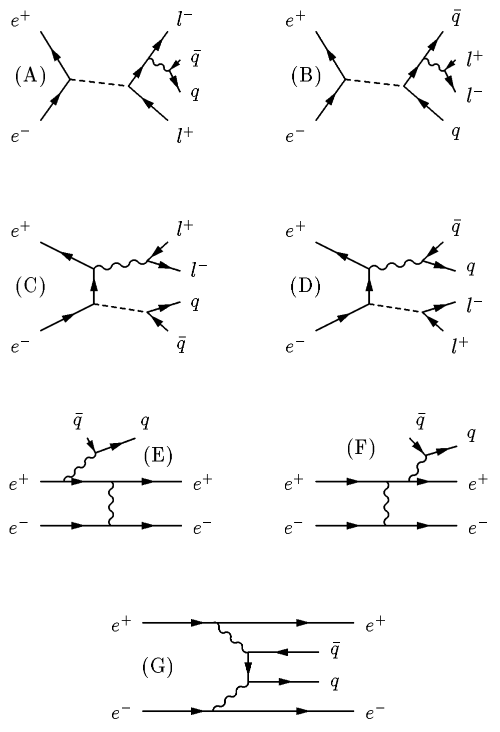


Inclusive charged particle measurements





Four-fermion final states



OPAL have studied $q\bar{q}\ell^+\ell^-$ final states ($\ell = e, \mu$)

Four-fermion events seen by OPAL

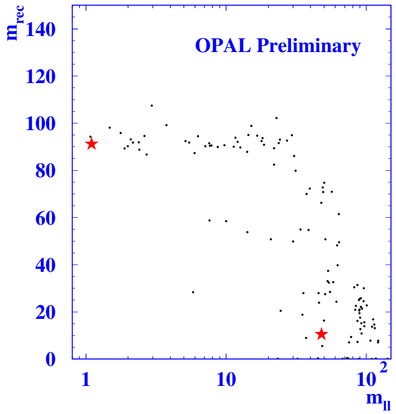
In selected sample, expect:

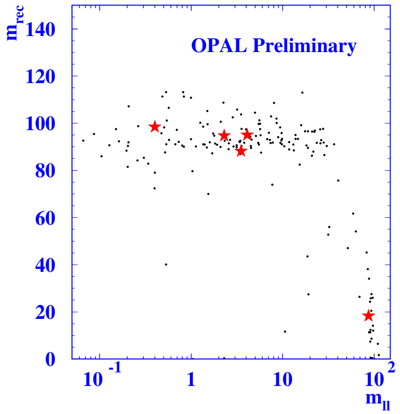
- 1.2 ± 0.1 signal events (FERMISV)
- 0.6 ± 0.2 background events (PYTHIA etc)

OPAL see **7** events in the data, 2 $\mathrm{q\bar{q}e^+e^-}$, 5 $\mathrm{q\bar{q}}\mu^+\mu^-$ $\longrightarrow$

Probability of 7 or more events: 0.26%

Event properties *are* consistent with expectation:

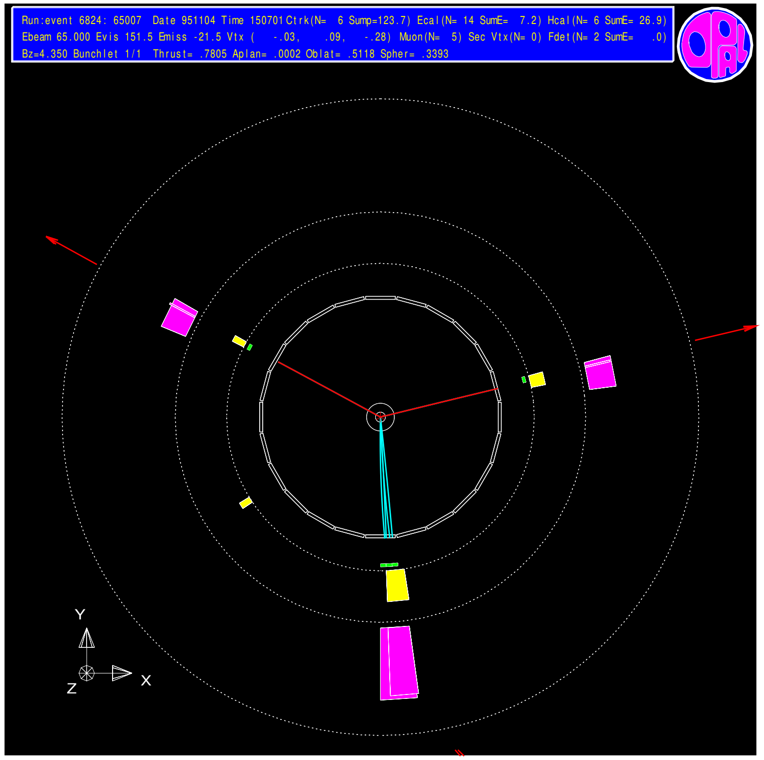




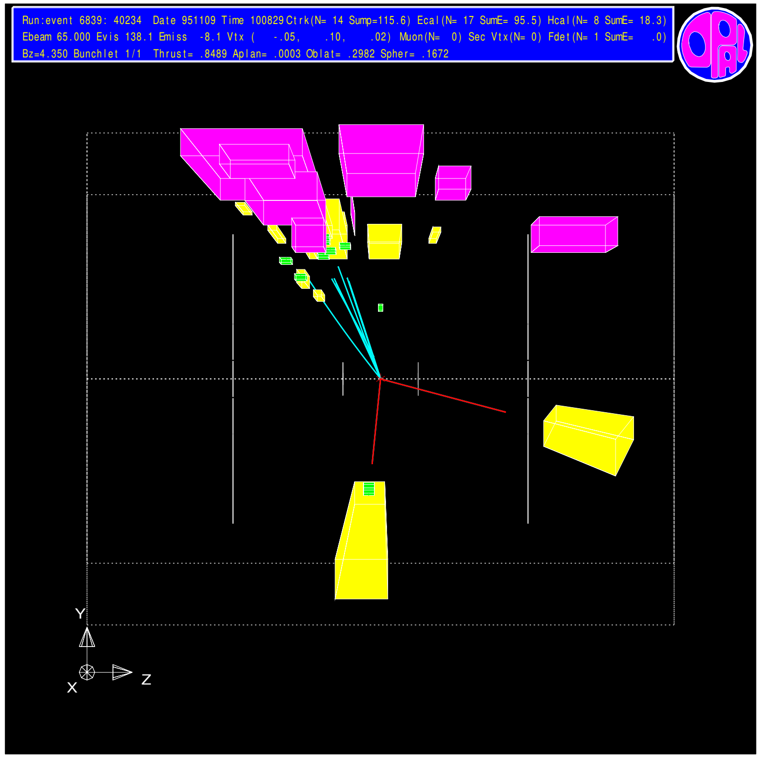
Perhaps 4-fermion rate prediction unreliable?

Important for LEP-2!

$\mathrm{q\bar{q}}\mu^+\mu^-$ Event

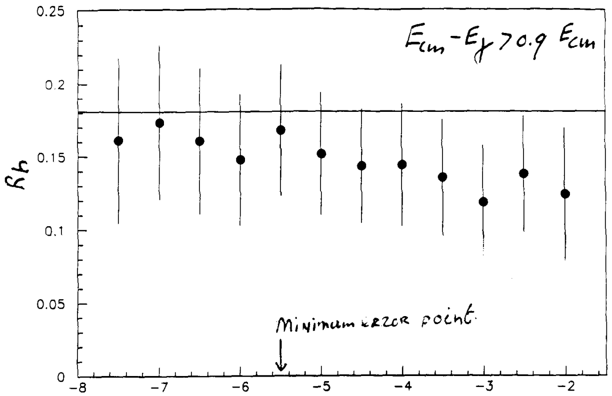


$q\bar{q}e^+e^-$ Event



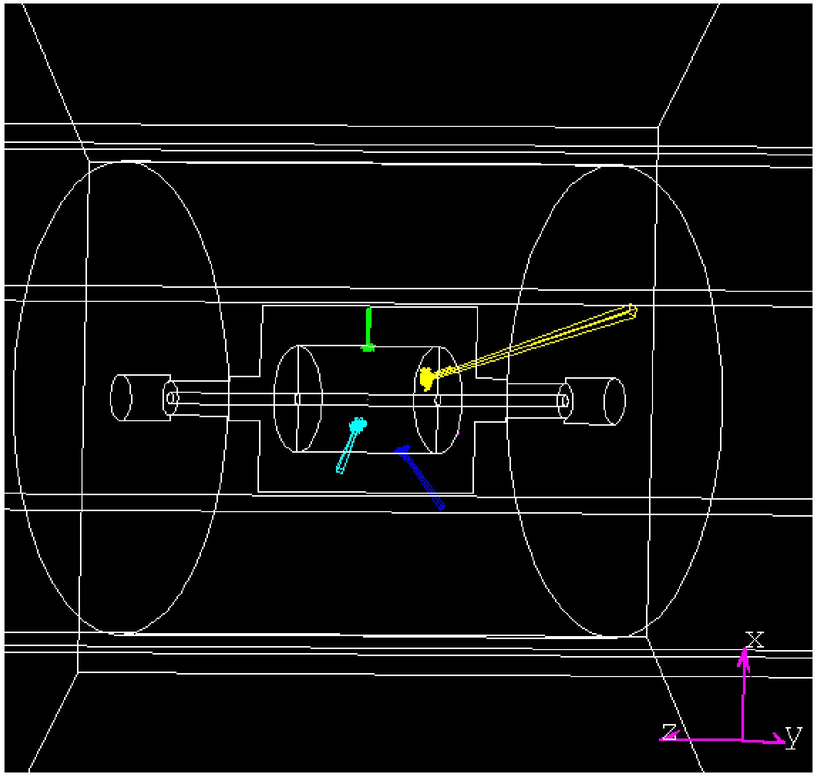
Other studies

- DELPHI have looked at R_b, the b fraction in hadronic events



- DELPHI have looked at two-photon interactions
- DELPHI have looked at Bose-Einstein correlations
- 3γ and 4γ final states consistent with expectations (ALEPH,L3,OPAL), L3 see a nice 4γ event ⟶

4γ event seen by L3



Searches for New Physics

Many searches performed using LEP-1.5 data:

- Supersymmetry searches:
  - chargino
  - neutralino
  - slepton
  - stop
- excited leptons
- charged heavy leptons
- hA (SUSY Higgs) search

Procedures very similar to those that will be used at LEP-2

(⟶ Grahame Blair's talk, later this afternoon)

Many limits improved over LEP-1 data, but not all

All searches negative

(but see ALEPH 4-jet study, next..)

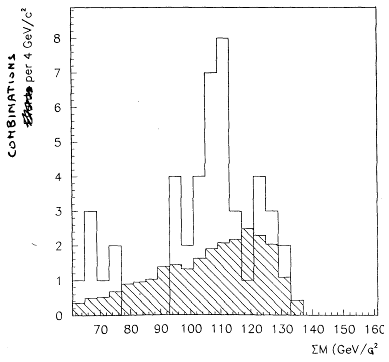
Search in 4-jet channel by ALEPH

ALEPH reported a search in 4-jet channel, originally for hA

- Select hadronic events with high $\sqrt{s'}$
- Require 4 or 5 jets (Durham jet-finder $y = 0.008$)
- Veto photon-like jets
- Rescale jet energies using jet directions and total centre-of-mass energy, reject any event with $E_{jet} < 0$
- require jet-jet masses above 25 GeV, pairwise sums of jet masses above 10 GeV, high charged multiplicity jets

Leaves 15 four-jet events, expect 8.6 from PYTHIA + 4-f MC

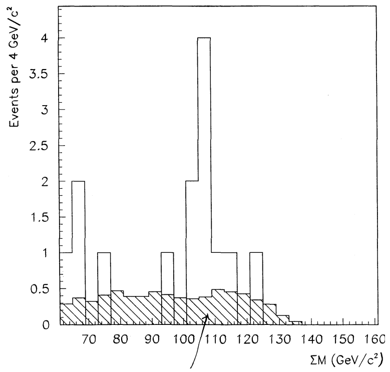
Look at $\Sigma M_{jet-jet}$:



In 102-116 GeV range, 22 combinations, 6.1 expected

- choose combination with smallest mass difference between jet-jet pair masses, require all such differences less than 20 GeV (biasses towards equal masses)

Leaves 14 events, 7.1 expected



In 102-116 GeV range, 8 events, 1.35 expected, prob $\sim 10^{-3}$

Look in more detail at events:

- Try kinematic fit: events get slightly closer together (12 GeV $\longrightarrow$ 9 GeV)
- only one event looks like $\mathrm{b\bar{b}b\bar{b}}$ from lifetime
- no lepton tags

$\Rightarrow$ There is no $\mathrm{b\bar{b}}$ excess, as would expect from hA

Also does not match with H^+H^- (rate too high, no $H^- \longrightarrow \tau\nu$)

If this were a signal, it would correspond to

$$\sigma = 2.5 \pm 1\mathrm{pb}$$

Conclusion

- The LEP energy upgrade has produced its first physics
- Many and varied standard model measurements:
  - cross-sections (total and non-radiative)
  - asymmetries
  - QED tests
  - QCD tests
- $\mathrm{q\overline{q}}\ell^+\ell^-$ rate high? (OPAL)
  event properties look as expected
- clustering of 4-jet masses? (ALEPH)
  doesn't look like any expected new physics...
- Other searches all negative

For both machine and experiments,

LEP-1.5 was a resounding success