Single and Pair Production of Neutral Electroweak Gauge Bosons at LEP

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representing the LEP collaborations

Thanks to experiments' representatives,
special thanks to David Strom

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- First Observation of Z Pair Production (DELPHI,L3,OPAL)
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  - High stat. Mass Distributions
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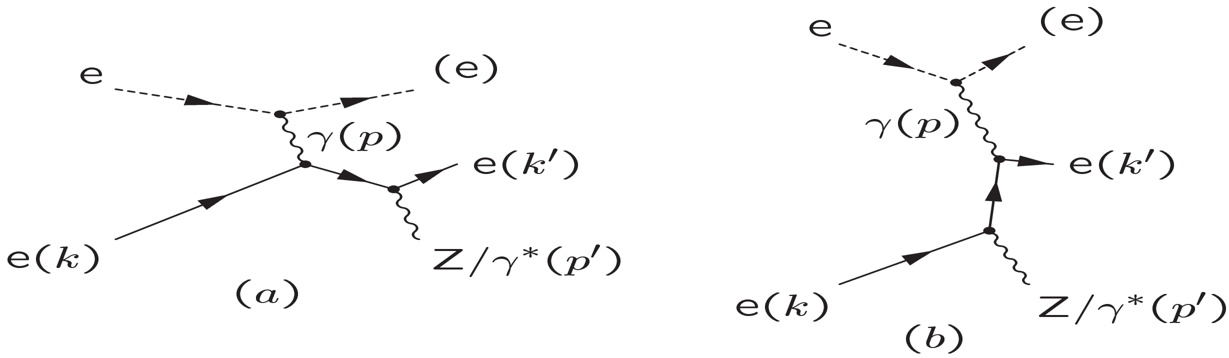
Electroweak Compton Scattering

Single neutral Boson Production (e)eV
Alias: (e)eγ, (e)eγ^*, (e)eZ



Mandelstam variables

$\hat{s} = (k' + p')^2$, $\hat{t} = (k' - k)^2$, $\hat{u} = (p' - k)^2$

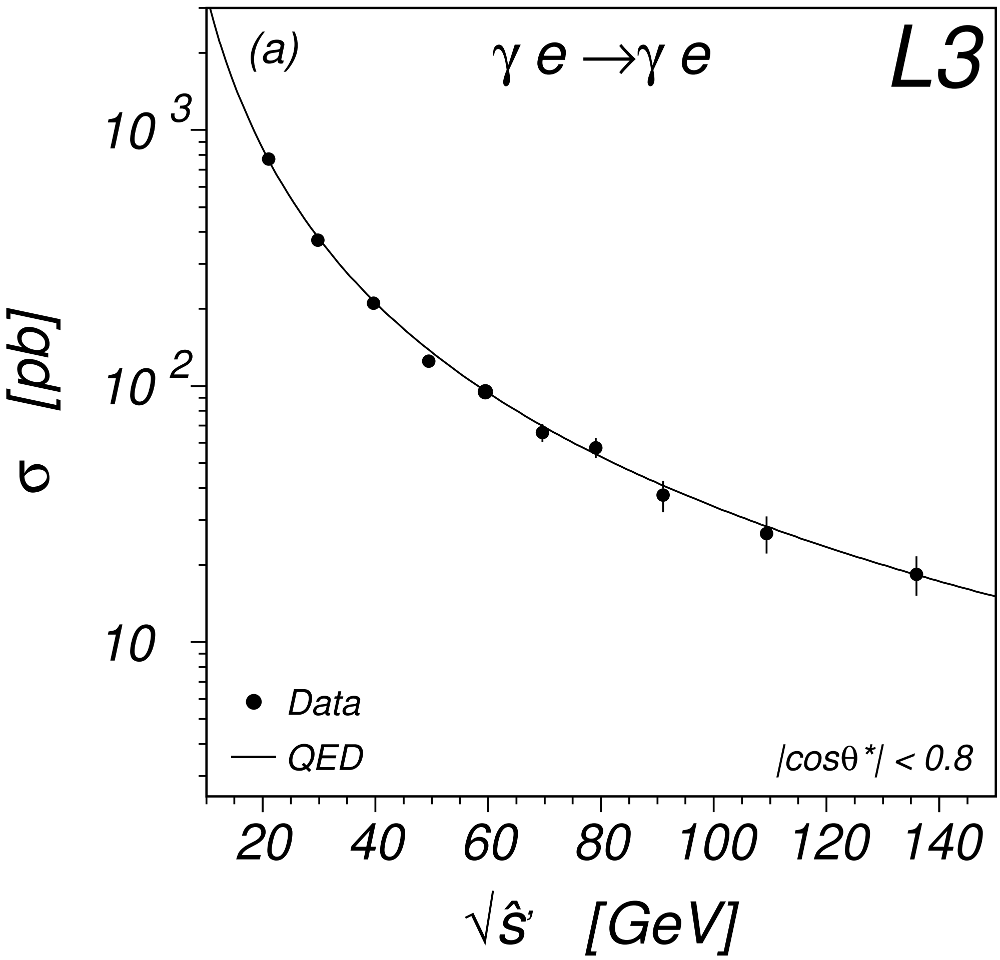
$$\frac{d\sigma}{d\hat{t}} \propto \frac{1}{\hat{s}^2}\left(\frac{\hat{u}}{\hat{s}} + \frac{2M_V^2\hat{t}}{\hat{u}\hat{s}} + \frac{\hat{s}}{\hat{u}}\right)$$

- **s-channel**
  - **suppressed due to large $\hat{s}$ (large $|\vec{p}|$)**
  - **could be enhanced by s-channel resonance (e*)**
- **u-channel**
  - **dominant, since $\hat{u} \to 0$**
  - **hard spectrum of V, prefers $\cos\theta^* \sim -1$**
  - **soft spectrum of electron**

L3: eγ $\rightarrow$eγ

Data: 230 pb^{-1} from $\sqrt{s}$=91–183 GeV
(CERN-EP/98-109 June 29, 1998)

- **Quasi-real incoming photons ($p_t^{e\gamma}$)**
- $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma\gamma, \mathrm{e}^+\mathrm{e}^-$ **rejection (E_2)**
- **calculate $\sqrt{\hat{s}}$ via angles**



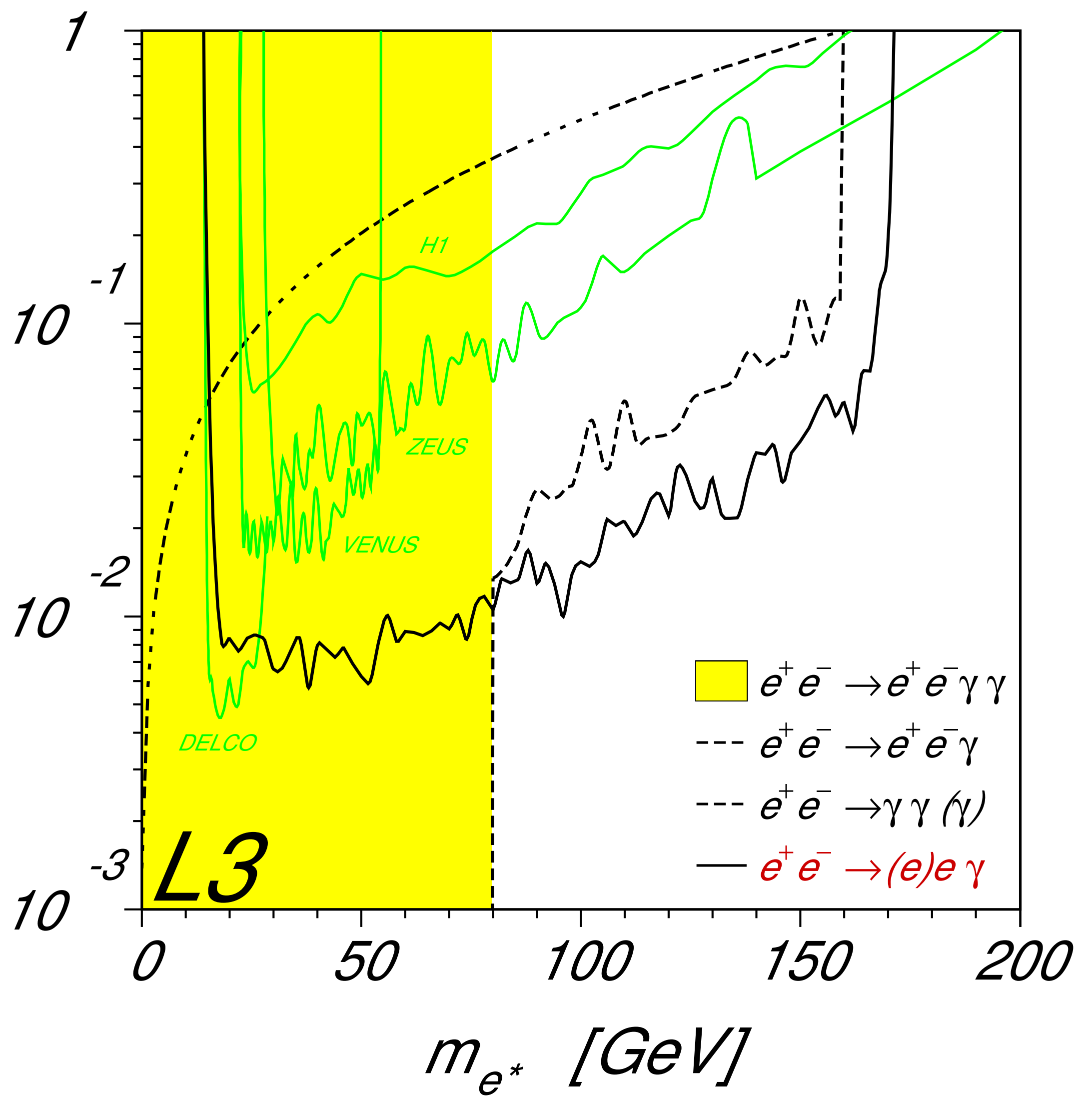
- **4641 events w/ 0.5% backg ($\gamma\gamma$,e$^+$e$^-$)**
- **no structure in $\hat{s}$**
- **Highest $\hat{s}$ $\approx$140 GeV measured so far**

L3: Limits on e*

$$\sigma(e\gamma \to e^* \to e\gamma) = \frac{8\pi^2}{m_{e^*}^2}\frac{\Gamma_{e\gamma}^2}{\Gamma m_{e^*}}$$

with free coupling parameter λ

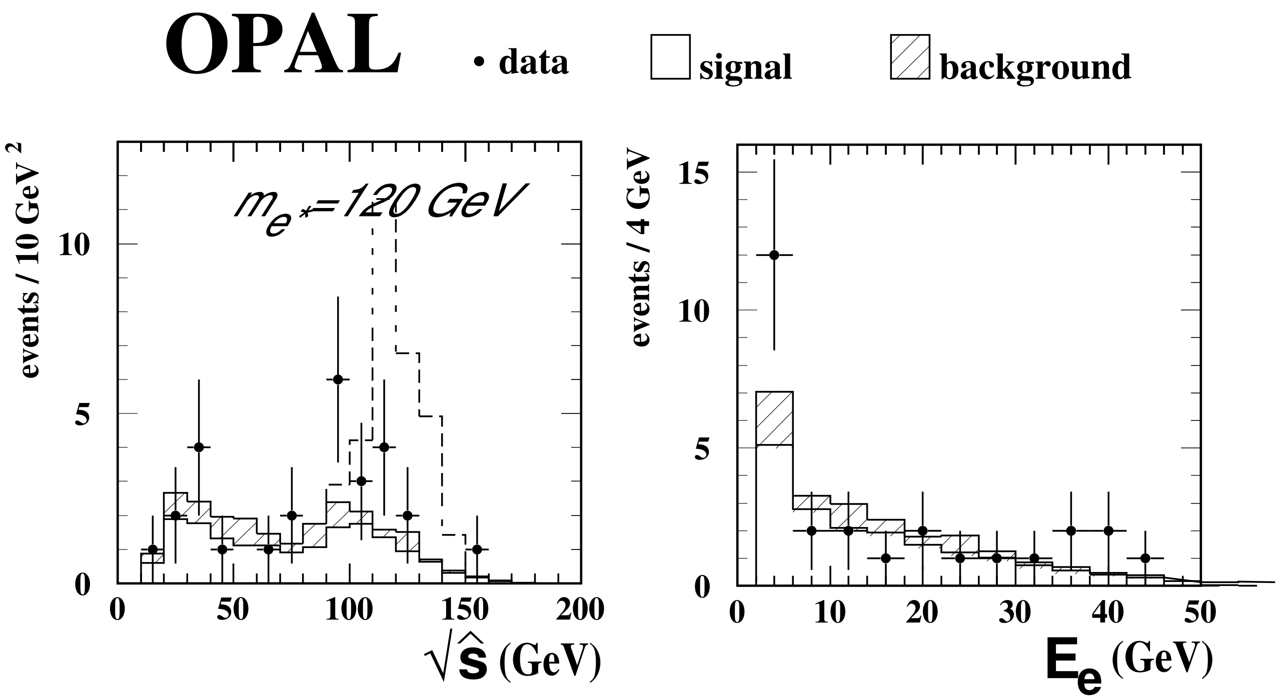
$$\Gamma_{e\gamma} = \frac{1}{2}\lambda^2\alpha m_{e^*}$$



OPAL: e$\gamma \rightarrow$eγ^*/Z

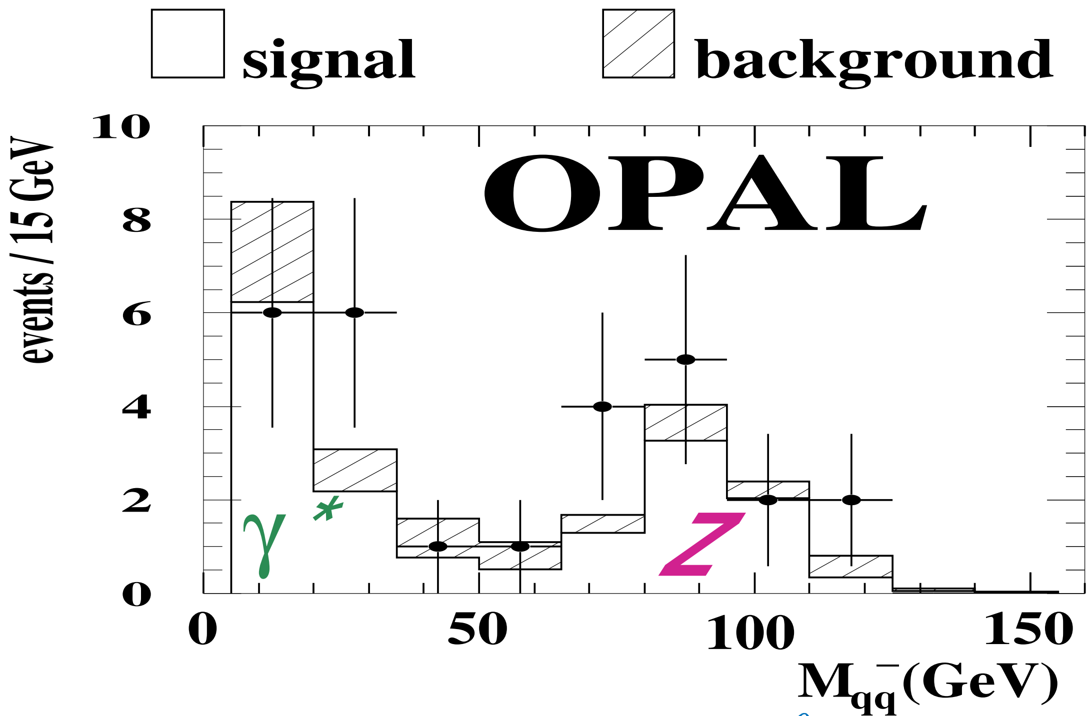
Data: 55 pb^{-1} at $\sqrt{s}$=183 GeV
(CERN-EP/98-1xx July 17, 1998)
Detect γ^*/Z in decay to hadrons

- Preselection: Multihadronic and isolated e
  - expect 38 signal and 1600 background
- angular cuts (kinematic)
- missing momentum cuts (other electron)
- fake electron rejection
  - expect 17 signal and 6.5 background
  - Observe 27 events



Limits on e$^* \rightarrow$eZ, νW, eγ see R.Teuscher, Session PA10

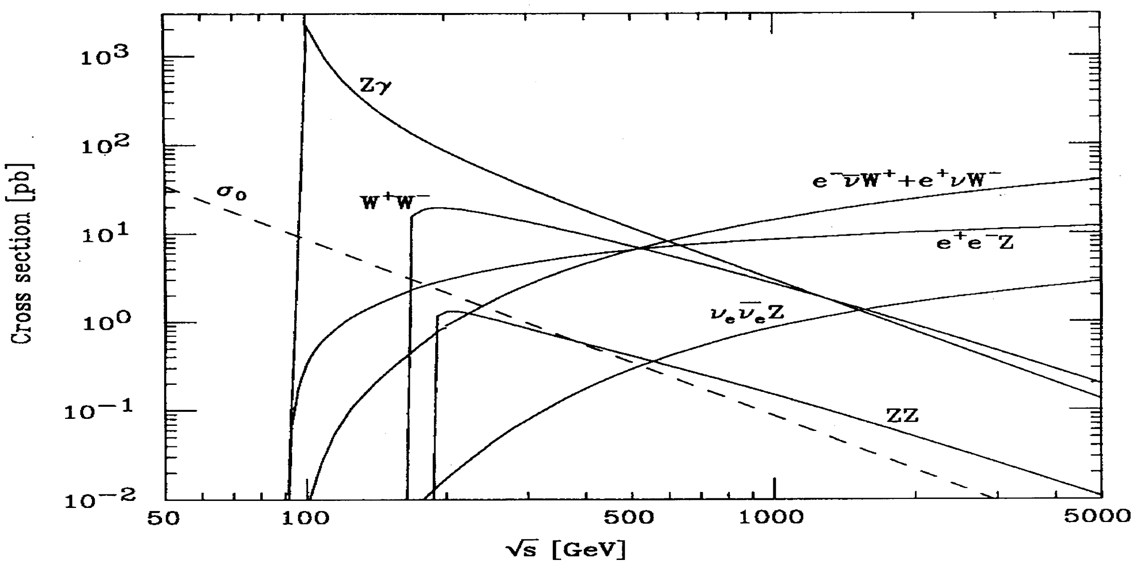
Cross-section for Electroweak Compton



Observe within kinematic bounds on $\cos\theta_f$

	5 GeV $< M_{q\bar{q}} < 60$ GeV	60 GeV $< M_{q\bar{q}}$
events	14	13
efficiency	$(4.1 \pm 0.1 \pm 0.5)\%$	$(22.3 \pm 0.6 \pm 2.4)\%$
σ_{meas}	$(4.1 \pm 1.6 \pm 0.6)$ pb	$(0.9 \pm 0.3 \pm 0.1)$ pb
grc4f pred.	4.21 pb	0.59 pb
PYTHIA pred.	4.02 pb	0.72 pb

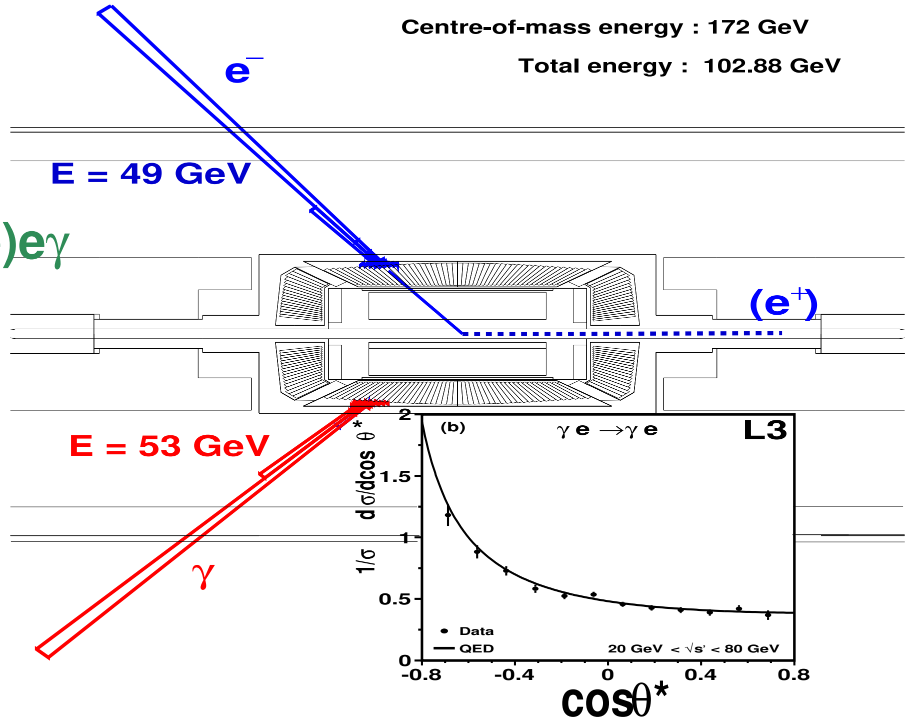
Pred. sensitive to modelling of incoming (small) photon virtuality
(e)eZ will be the dominant Z production at future e^+e^- colliders!



Single Neutral EW Boson Production

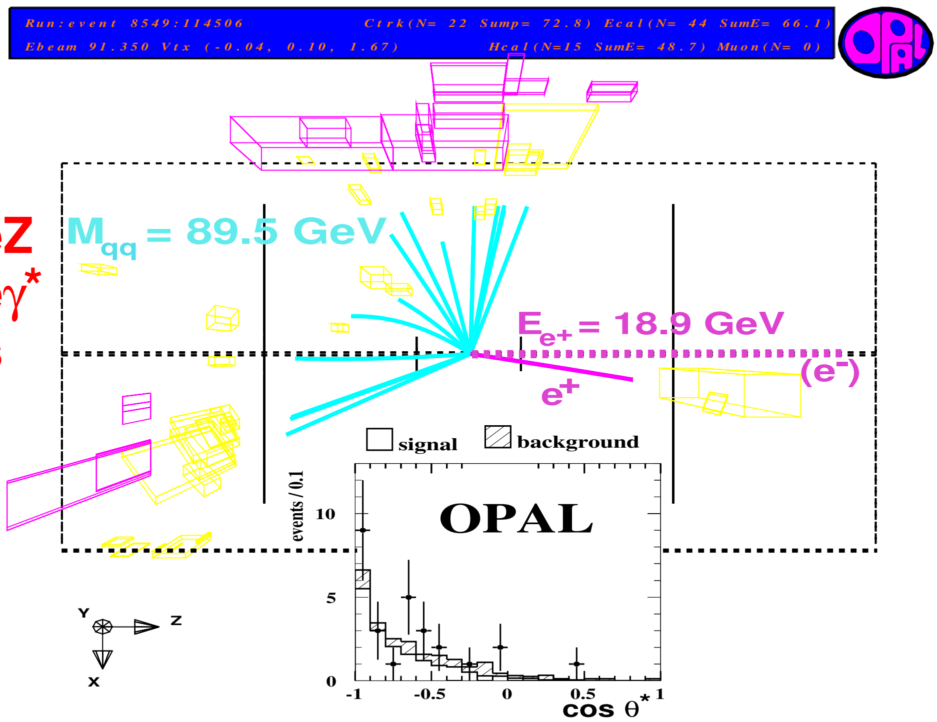
L3 : Highest Energy Compton Scattering

4641 (e)eγ
events



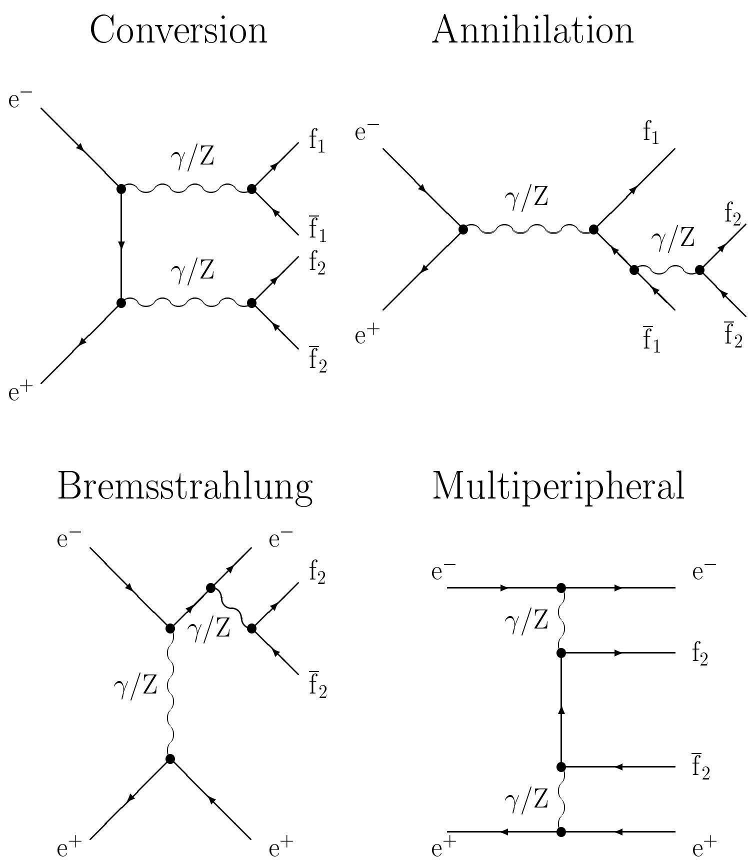
OPAL: First Observation of Z/γ^* in Compton Sc.

13 (e)eZ
14 (e)eγ^*
events



Typical $\hat{u}$-channel angular distributions
No excited electrons seen

Neutral Current 4-Fermions



DELPHI 183 GeV prelim.

also results from lower $\sqrt{s}$ in note

channel	N_{obs}	signal	backg.
$\mathrm{e^+e^-q\bar{q}}$	3	2.9 ± 0.2	0.6 ± 0.2
$\mu^+\mu^-\mathrm{q\bar{q}}$	8	2.9 ± 0.2	0.4 ± 0.2
$\ell^+\ell^-\ell^+\ell^-$	3	3.7 ± 0.2	0.1 ± 0.2

L3 183 GeV prelim.

$\ell^+\ell^-\mathrm{q\bar{q}}$	13	7.4 ± 0.4	2.0 ± 0.1
$\ell^+\ell^-\ell^+\ell^-$	11	4.4 ± 0.1	4.2 ± 0.9

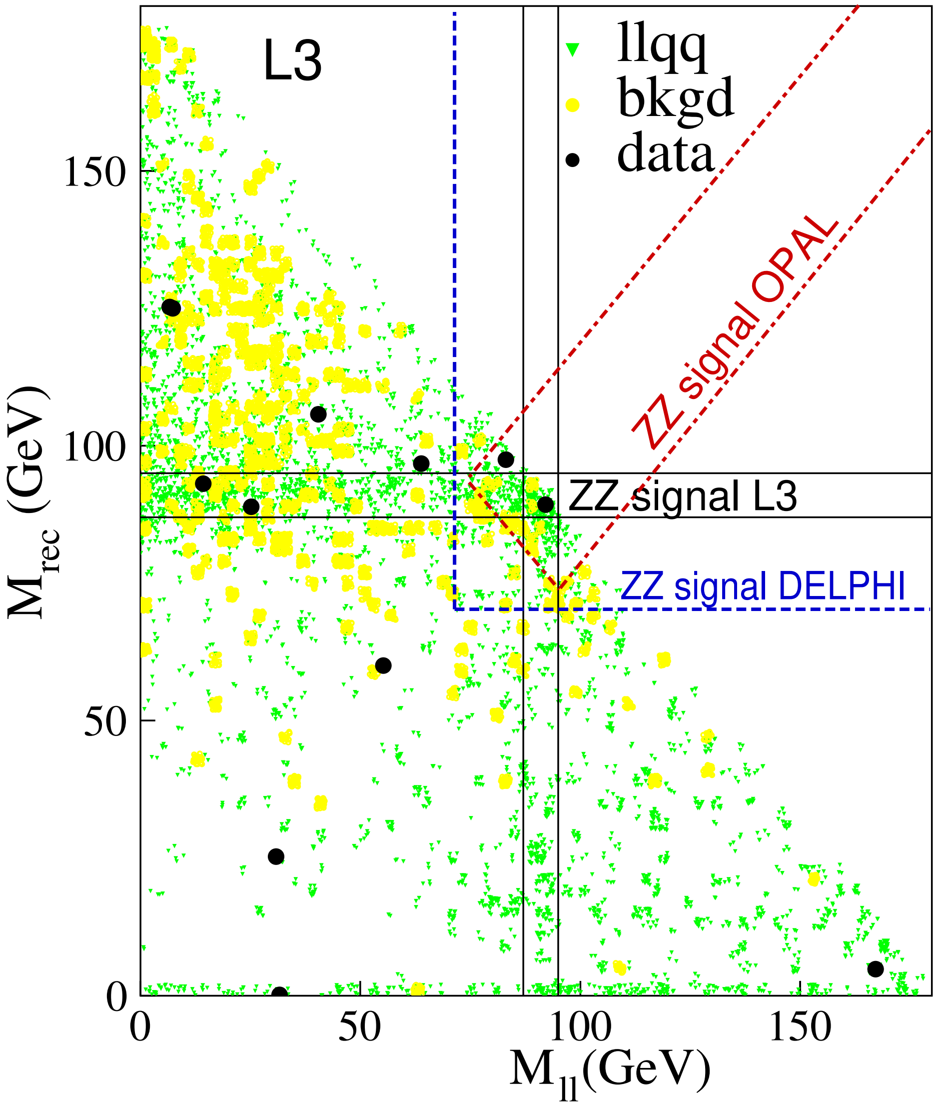
Rather more $\ell^+\ell^-\mathrm{q\bar{q}}$ observed than predicted

Z Pair production

- Many final states
  - $\mathrm{q\bar{q}q\bar{q}}$: **49%**
  - $\mathrm{q\bar{q}b\bar{b}}$: **19% (subsample)**
  - $\mathrm{q\bar{q}}\nu\nu$: **28%**
  - $\mathrm{q\bar{q}}\mathbf{e}^+\mathbf{e}^-$: **5%**
  - $\mathrm{q\bar{q}}\mu^+\mu^-$: **5%**
  - $\mathrm{q\bar{q}}\tau^+\tau^-$: **5%**
  - $\ell^+\ell^-\nu\nu$: **4%**
  - $\nu\nu\nu\nu$: **4%**
  - $\ell^+\ell^-\ell^+\ell^-$: **1%**
- "easy channels" have small BR (and vice versa)
- Ratio $(\mathrm{b\bar{b}f\bar{f}})/(\mathrm{f\bar{f}f\bar{f}})$ **only way** to separate
  - **anomalous ZZ production**
  - **ZH with** $m_H \sim m_Z$

$\longrightarrow$ all channels should be measured with and without b-tag

Z Pair signal definition



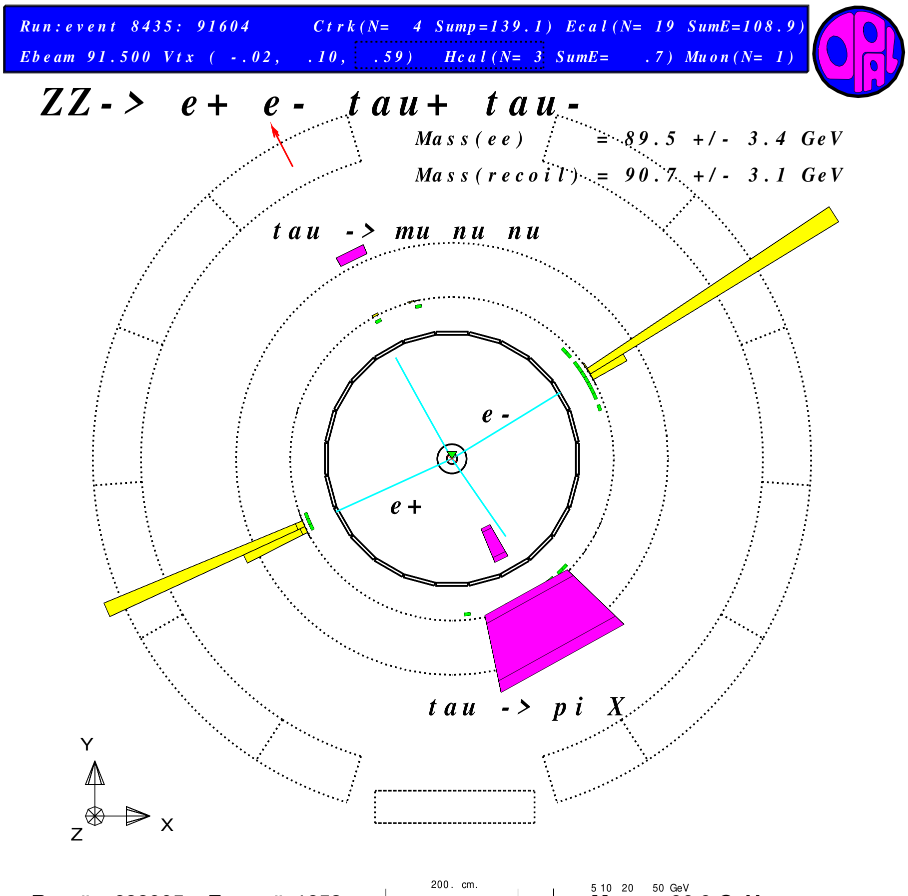
Very different ZZ signal definitions
Correct each channel to pure ZZ diagram by

$$f_i = \frac{\sigma_i(ZZ + Z\gamma^* + \gamma^* Z + eeZ)_{\text{signal}}}{\sigma_i(ZZ)_{\text{total}}}$$

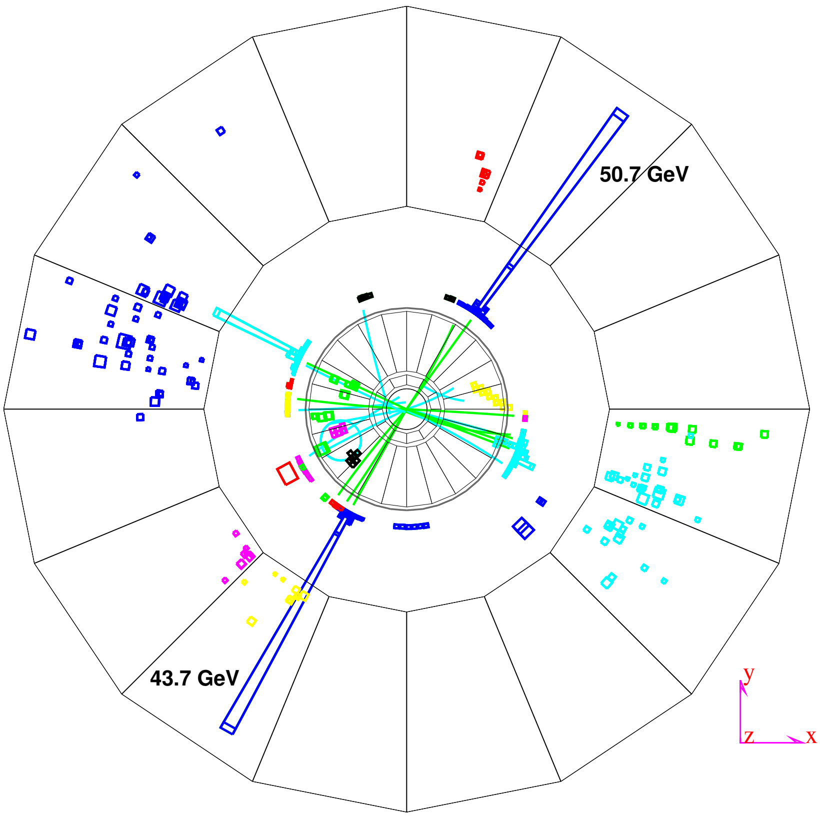
We arrive using YFSZZ (for ZZ) and grc4f and FERMISV at

channel	DELPHI	L3	OPAL
$\ell^+\ell^-\ell^+\ell^-$	1.40	0.55	0.98
$e^+e^- q\bar{q}$	1.42	0.54	1.01
$\mu^+\mu^- q\bar{q}$	1.05	0.52	0.89
$q\bar{q}q\bar{q}$	0.95	0.51	0.86

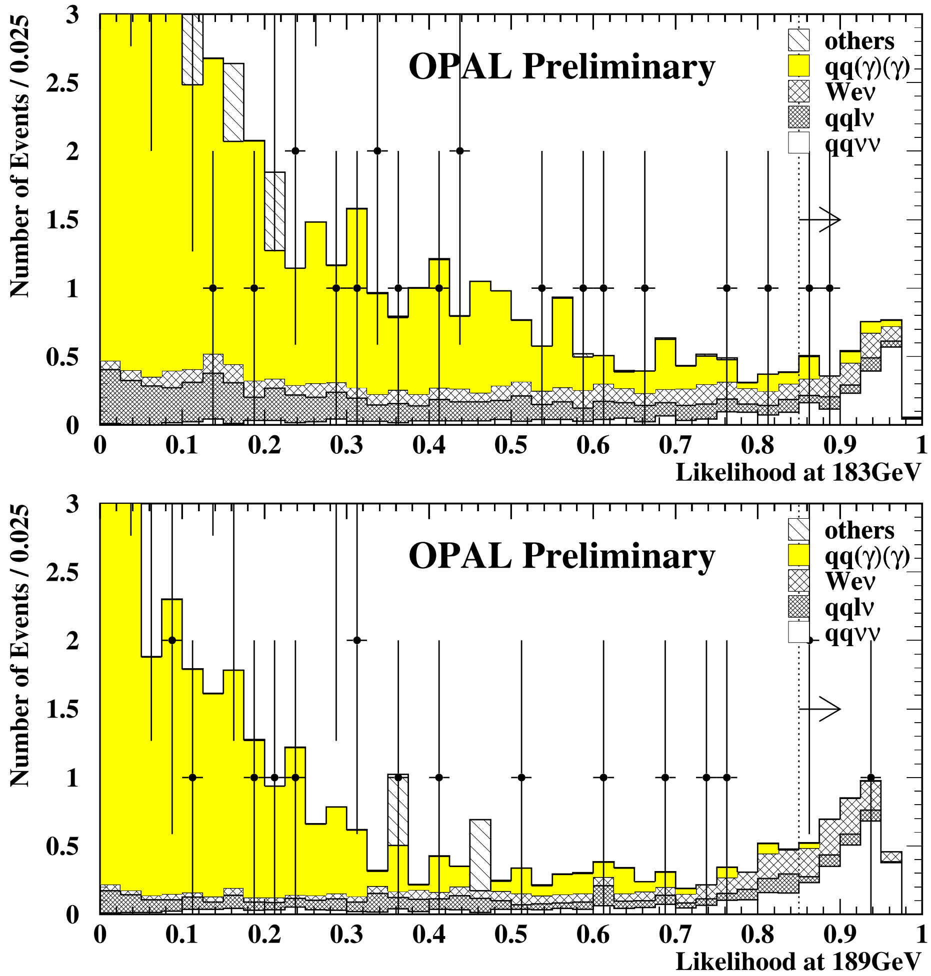
Clear Candidates



Run # 688905 Event # 1652 Mequ = 90.9 GeV

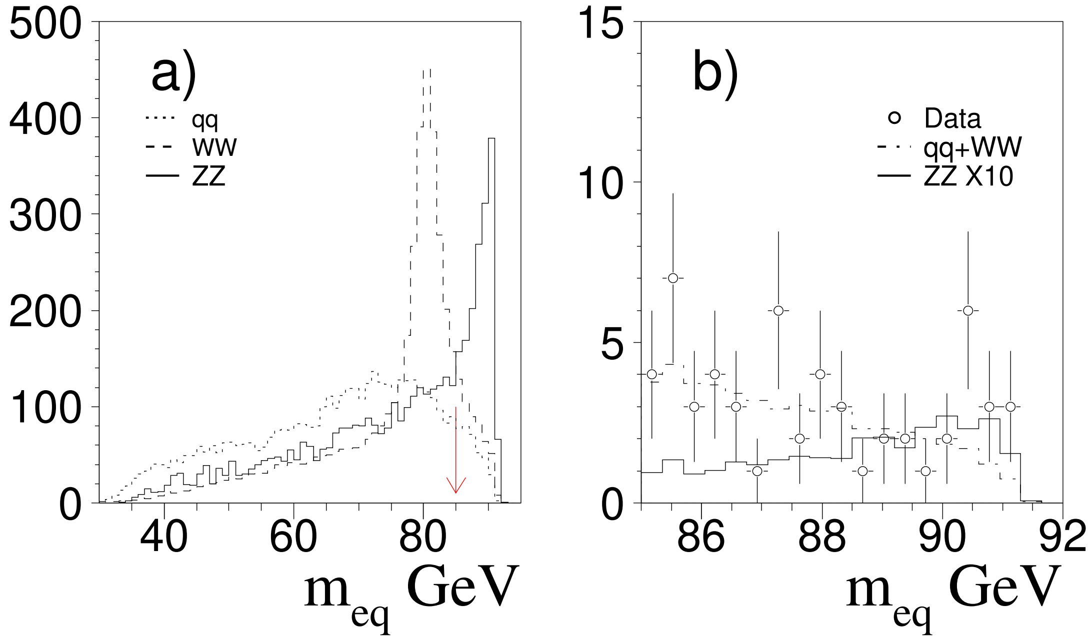


The $\nu\nu q\bar{q}$ Channel



- large background from Weν, WW$\rightarrow$qq$\tau\nu$, $(\gamma\gamma)q\bar{q}$
- OPAL: WW veto, and likelihood selection based on
  - visible $\pm$ recoil mass
  - hemisphere masses
  - p_t significance perp. to jets
- efficiency 31%

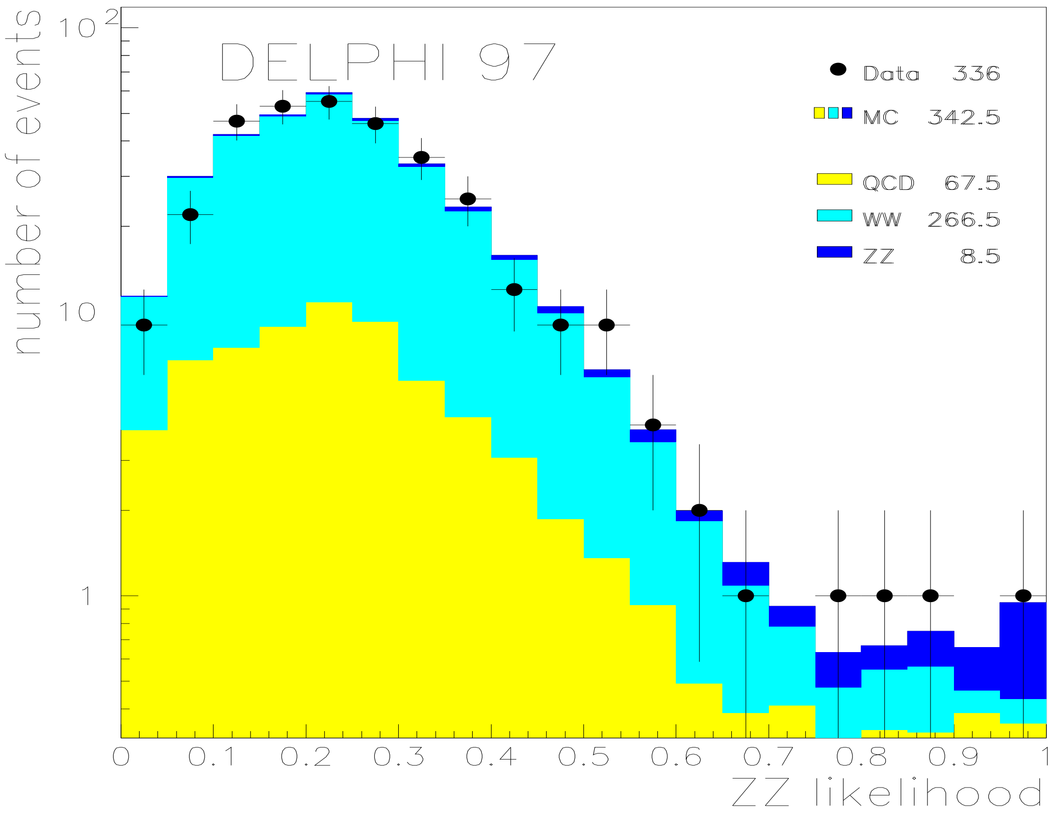
Four Jets without b-Tagging



- huge background from WW
- L3: 5C-Fit to equal di-jet masses (Fig.) and NN with 15 event variables
  - multiplicities
  - topological variables
  - kinematic variables
  - mass pairings

  $\rightarrow$ LogL fit to NN output distribution
- OPAL: combination of cuts and Likelihood

Four Jets with b-Tagging



- background from WW and qqgg (QCD)
- DELPHI and OPAL: Likelihood based on
  - event shapes
  - kinematic variables
  - b-tag and mass pairings
- DELPHI: global discriminating variable from
  2-dimensional likelihood.vs.sum(masses)

The 183 GeV LEP average

- DELPHI
  - 7 events observed in 4 channels: $\ell^+\ell^-\ell^+\ell^-$, $\mathrm{q\bar{q}}$e$^+$e$^-$, $\mathrm{q\bar{q}}\mu^+\mu^-$, $\mathrm{q\bar{q}b\bar{b}}$
  - expected background 1.3 ± 0.2 events (stat. errors only)
  - efficiencies not given (estimated from N_{expected})
- L3
  - 1 event observed in 2(3) channels: $\ell^+\ell^-\ell^+\ell^-$, $\mathrm{q\bar{q}}$(e$^+$e$^-$+$\mu^+\mu^-$) ($\mathrm{q\bar{q}}\nu\nu$ and $\mathrm{q\bar{q}q\bar{q}}$ not useable here)
  - expected background 0.20 ± 0.04 events (stat. errors only)
  - efficiencies not given (estimated from N_{expected})
- OPAL
  - 8 (5 w/o qqqq) events observed in 8 channels: $\ell^+\ell^-\ell^+\ell^-$, $\mathrm{q\bar{q}}$e$^+$e$^-$, $\mathrm{q\bar{q}}\mu^+\mu^-$, $\mathrm{q\bar{q}}\tau^+\tau^-$, $\mathrm{q\bar{q}}\nu\nu$, $\mathrm{q\bar{q}b\bar{b}}$, $\mathrm{q\bar{q}q\bar{q}}$, overlap
  - expected background 7.6 ± 1.1 (2.5 ± 0.2 w/o qqqq) (stat. plus syst. errors)
  - efficiencies and errors as given in note

$\rightarrow$ each channel used separately in max. Likelihood fit (courtesy D.S.)

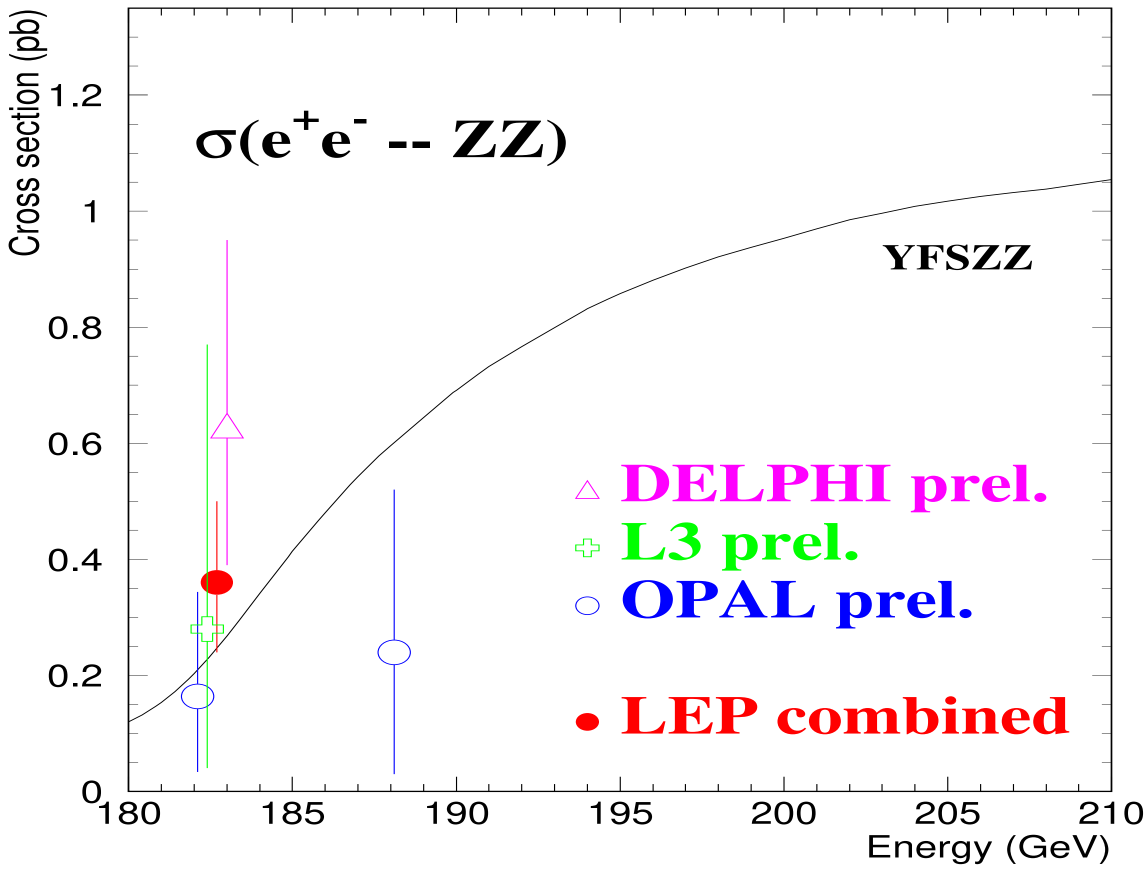
The ZZ cross-sections (prel.)

183 GeV ($\sim$ 55 pb^{-1}):

DELPHI	4 chan	$(0.63^{+0.31+0.06}_{-0.24-0.02})$	pb
L3	2(3) chan	$(0.28^{+0.48+0.10}_{-0.24-0.02})$	pb
OPAL	8(7) chan	$(0.16^{+0.17+0.04}_{-0.12-0.02})$	pb
LEP	14 chan	$(0.36^{+0.14+0.03}_{-0.12-0.02})$	pb

189 GeV ($\sim$ 40 pb^{-1}):

OPAL 8(7) chan $(0.24^{+0.28+0.05}_{-0.21-0.02})$ pb



LEP combined at 183 GeV:
First observation of Z-Pair production

Prospects

Higher Stat. Mass Distributions

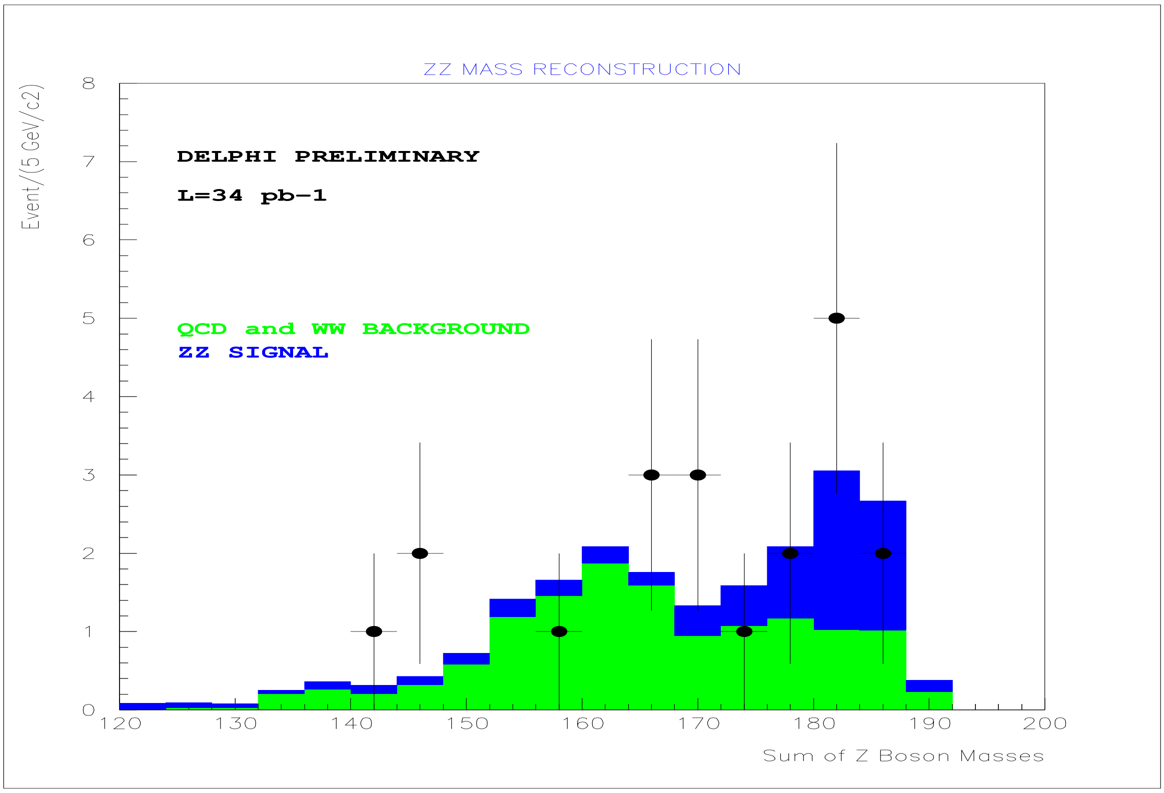
DELPHI update: 34 pb^{-1} at $\sqrt{s}$=189 GeV

(ICHEP-98#286 July 21, 1998)

one more channel compared to 183 GeV

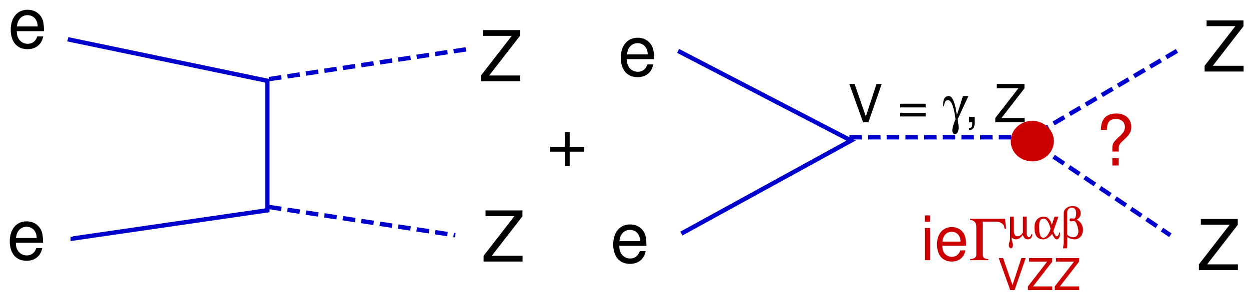
$\ell^+\ell^-\ell^+\ell^-$, $e^+e^-\mathrm{q\bar{q}}$, $\mu^+\mu^-\mathrm{q\bar{q}}$, $\mathrm{q\bar{q}b\bar{b}}$, plus $\nu\nu\mathrm{q\bar{q}}$

Combined mass sum for all channels:



- **observed within ZZ signal definition: 11 events**
  - expected signal: 5.7±0.2 events
  - expected backg: 4.5±0.3 events
  - (statistical errors, only)

Anomalous couplings



for V(P), Z(q), Z(q´):

$$\Gamma^{\mu\alpha\beta}_{VZZ} = \frac{s - m_V^2}{m_Z^2} \times \begin{cases} i\, f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) & \text{CP-odd} \\ i\, f_5^V\, \varepsilon^{\mu\alpha\beta\rho} (q - q')_\rho & \text{CP-even} \end{cases}$$

- for <u>on-shell</u> ZZ
  - 2 anomalous couplings for γZZ and ZZZ vertex, each
  - **independent** of $h^V_{1,2,3,4}$ for γZZ*

$\longrightarrow$ 6 of 7 possible couplings covered

- possible models
  - 2 Higgs doublets (Chang, Keung, Pal)
  - Compositeness
- Standard Model in lowest order: $f_4 = f_5 = 0$

Possible limits on $f^V_{4,5}$ Couplings