Fermion Pair Cross-Sections and Asymmetries and Limits on New Physics

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Aleph, Delphi, L3, Opal collaborations

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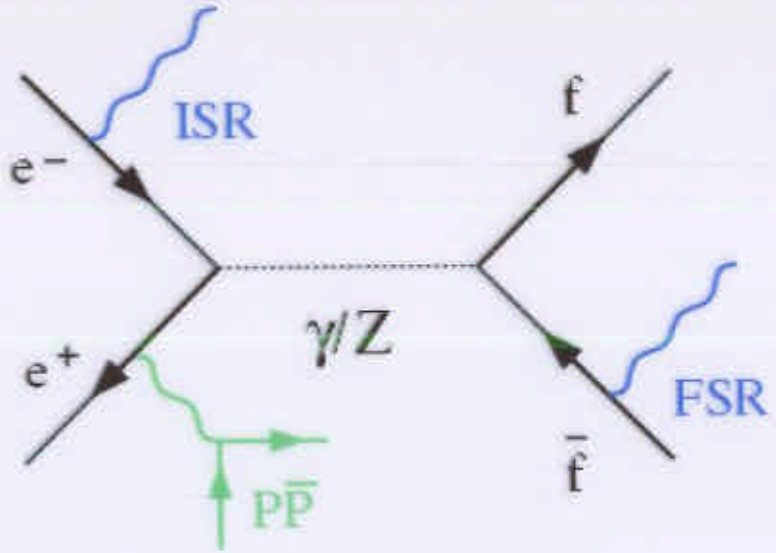
Outline

- Features of fermion-pair production above the Z pole
- Experimental aspects and measurements of cross - sections and asymmetries for the process:



Initial State Radiation

Final State Radiation

IF State Radiation interference

initial state Pair Production

(gluon radiation)

$f\bar{f} = e^+e^-, \mu^+\mu^-, \tau^+\tau^-, q\bar{q}$

(e^+e^- : also t-channel)

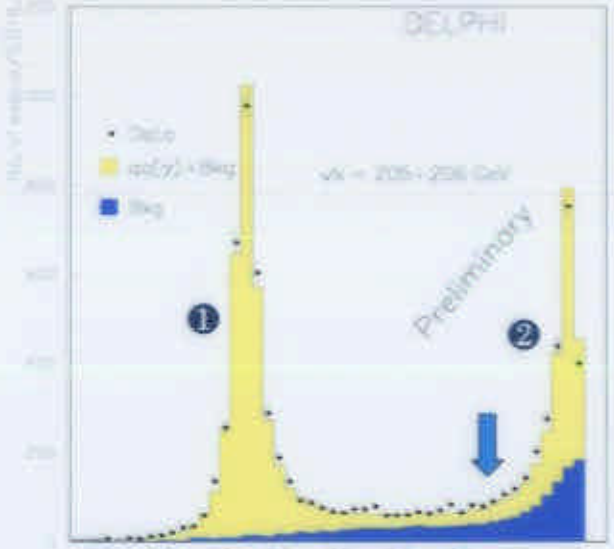
- Interpretations of the results
- Conclusions

Effective Center of Mass Energy

fermion pair production at LEP2 :

1) radiative return events $\left(\sqrt{s'} \approx M_Z\right)$

2) full energy events $\left(\sqrt{s'} \approx \sqrt{s}\right)$

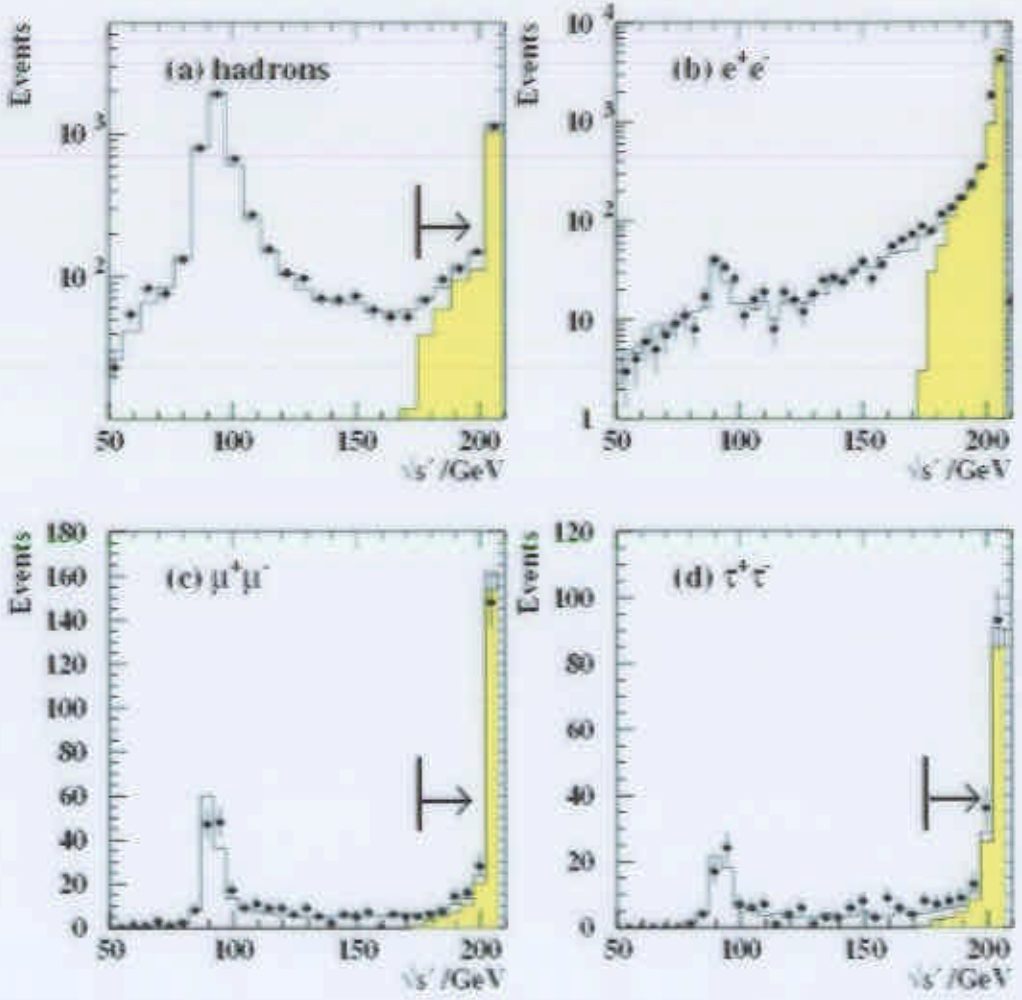


$\sqrt{s'}$ measured from detected γ

jet/lepton angles

visible energy

kinematic fit



SM Processes above the Z Peak

Two classes of events:

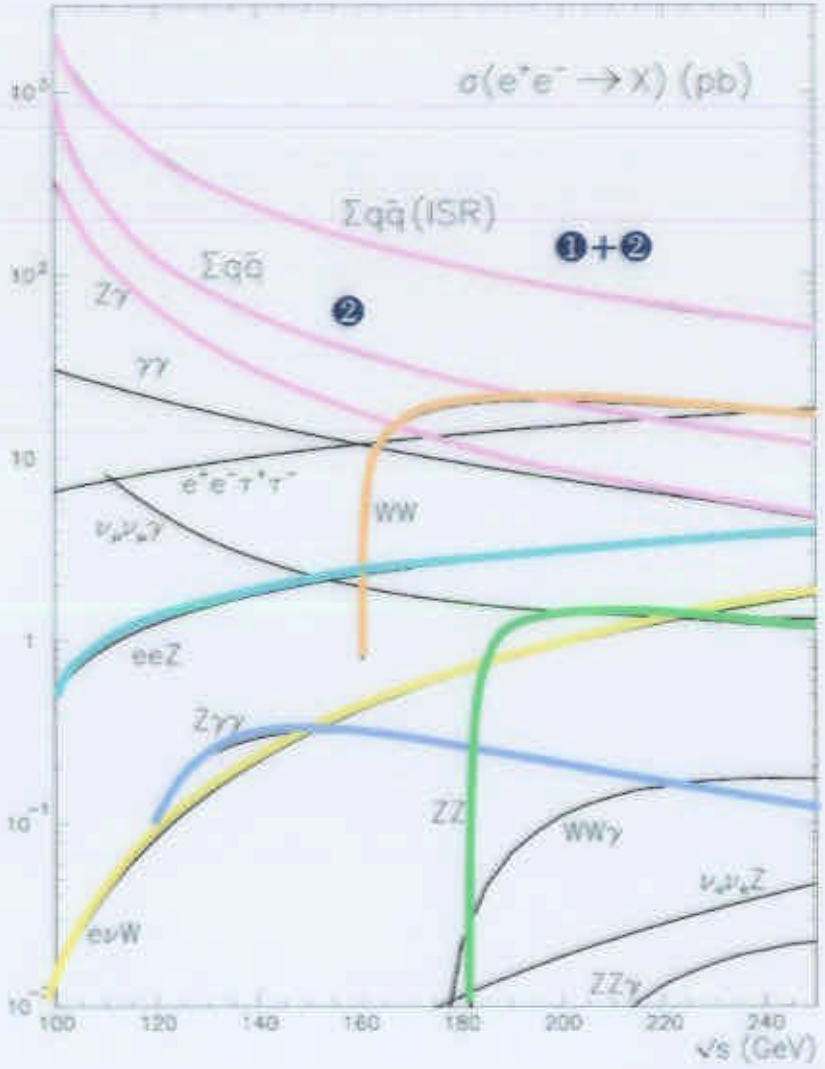
❶+❷ (inclusive sample): $\begin{cases} \sqrt{s'}/\sqrt{s} > 0.10\ (q\bar{q}) \\ \sqrt{s'} > 75\ \text{GeV}\ (\mu, \tau) \end{cases}$

❷ (non-radiative sample): $\sqrt{s'}/\sqrt{s} > 0.85, 0.90$

❷/(❶+❷) ≅ 22 % for hadrons
42 % for μ, τ

❶+❷ same physics as measured at LEP1 (with higher accuracy)

❷ sensitive to new physics



Definition of the Signal

1) $\sqrt{s'}$ - mass of the s-channel propagator
IFSR interference subtracted (L3, OPAL)

2) $\sqrt{s'}$ - $q\bar{q}$: mass of the s-channel propagator
l^+l^- : bare invariant mass of lepton pair
IFSR interference included (ALEPH, DELPHI)

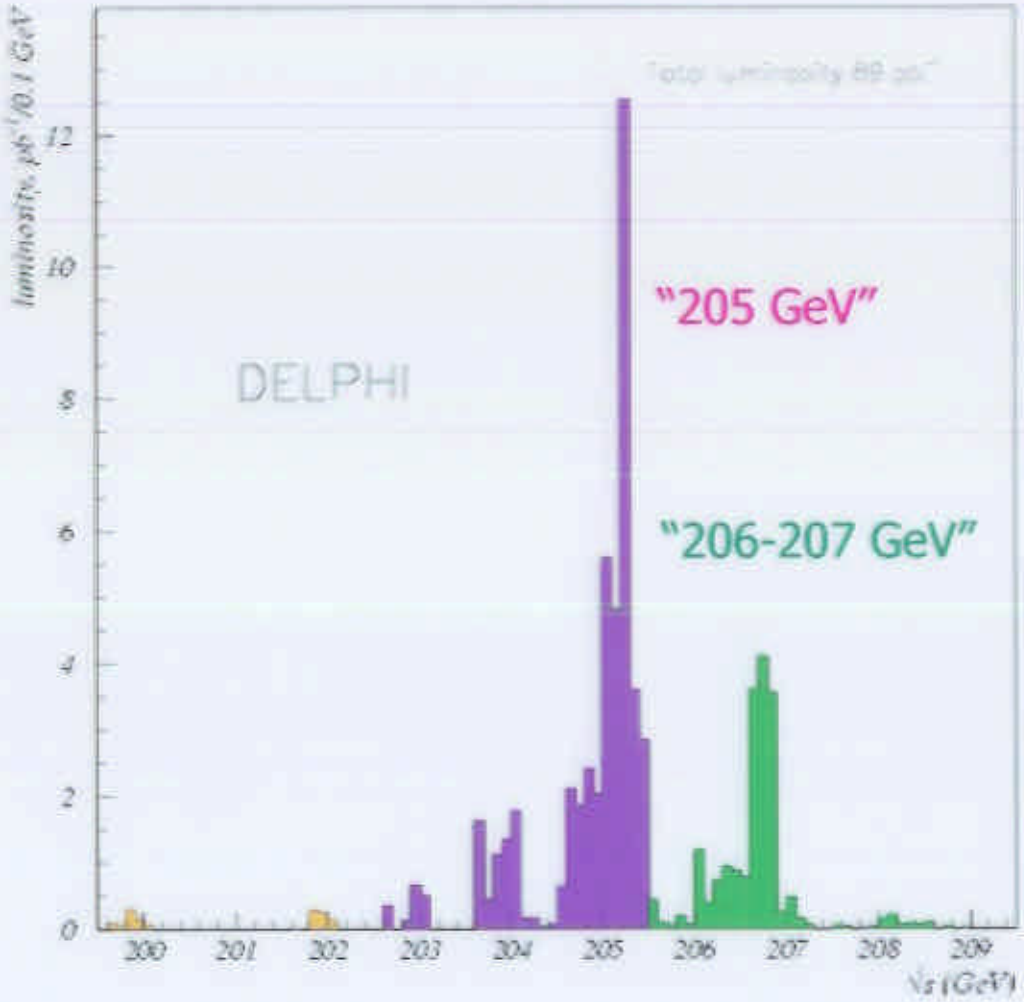
(IFSR interference for $\sqrt{s'}/\sqrt{s} > 0.85$ is about 1-2 %
predominantly for large $|\cos\theta|$)

Data Samples

in 1999 : $\sim 228\ pb^{-1}$/exp.
at E ÷ 192 - 202 GeV

in 2000 : $\sim 58\ pb^{-1}$/exp.
at ⟨E⟩ ~ 205 GeV
$\sim 29\ pb^{-1}$/exp.
at ⟨E⟩ ~ 207 GeV

$\left(\mathcal{L}_{LEP2} \cong 580\ pb^{-1}/\text{exp.}\ !!!\right)$

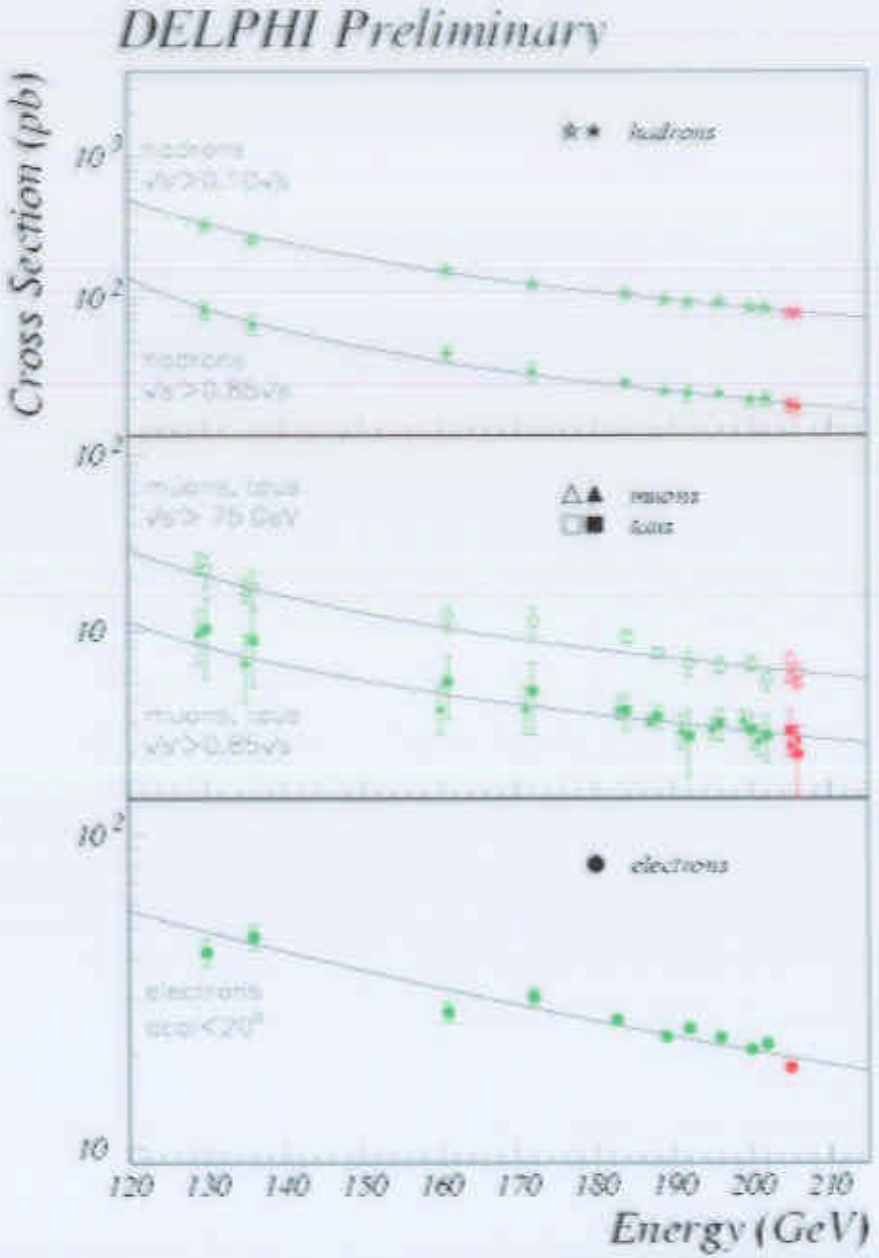


Cross-Sections

Typical Systematic Errors:

$\sqrt{s'}/\sqrt{s}$	>0.10	>0.85
$q\bar{q}$	0.5-1%	1-2%
e^+e^-	0.5-1%	0.5-1%
$\mu^+\mu^-$	1-2%	1-2%
$\tau^+\tau^-$	3-4%	3%

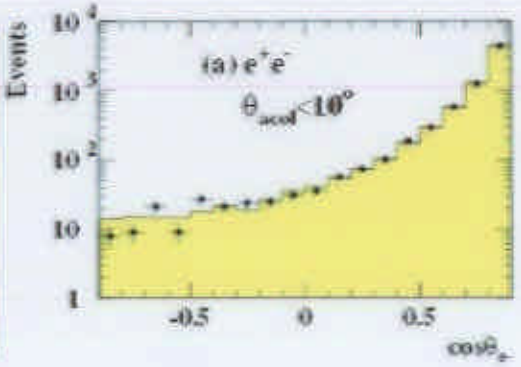
theoretical error on σ_{had}: ~0.5 %



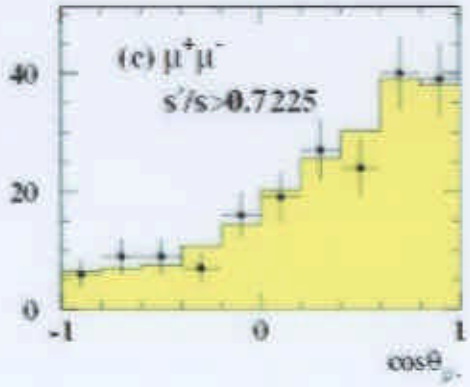
Angular Distributions and Asymmetries

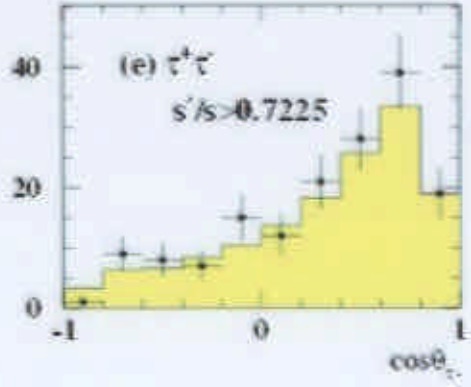
Typical Systematic Errors:

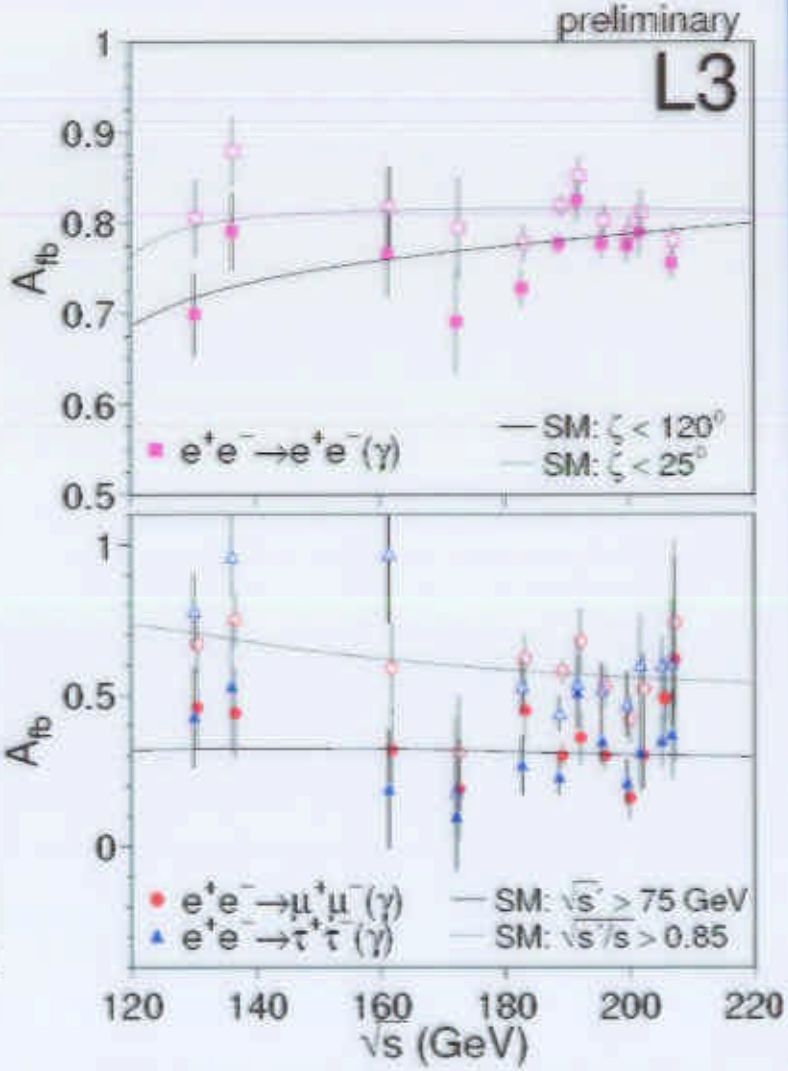
$\sqrt{s'}/\sqrt{s}$	>0.10	>0.85
e^+e^-	-	5×10^{-3}
$\mu^+\mu^-$	1×10^{-2}	1×10^{-2}
$\tau^+\tau^-$	1×10^{-2}	1×10^{-2}



OPAL 205.4 GeV preliminary

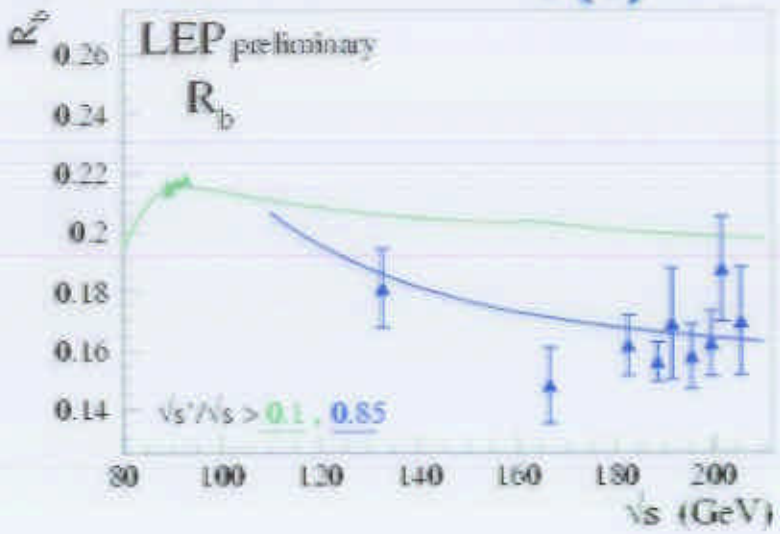


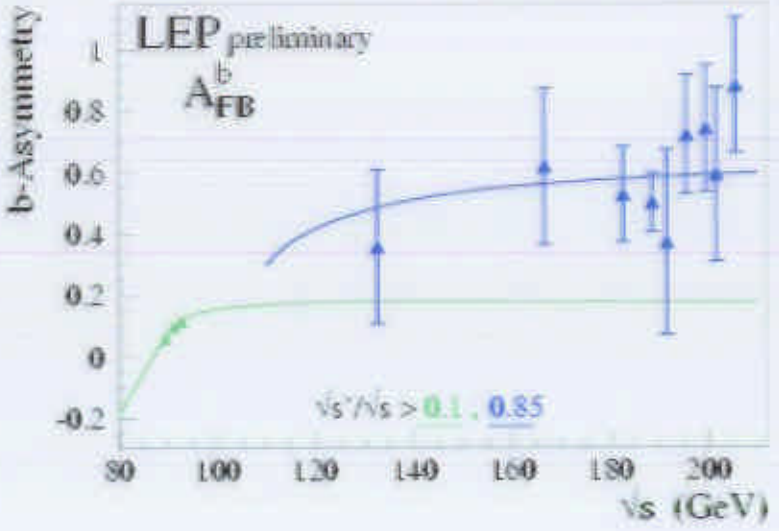


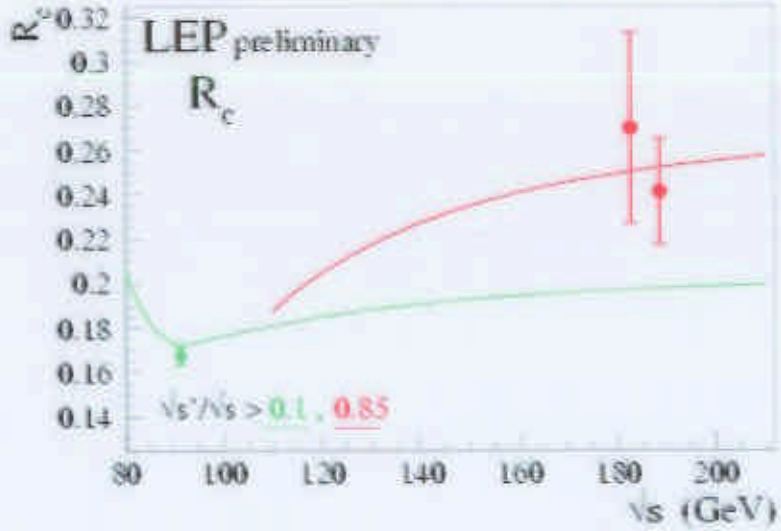


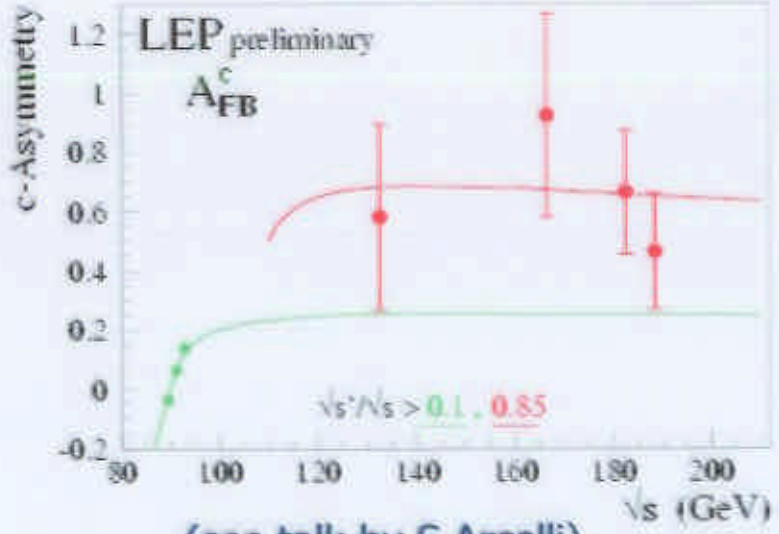
Heavy Flavors: $R_{b(c)}$ and $A^{b(c)}_{FB}$

LEP averages of published and preliminary data









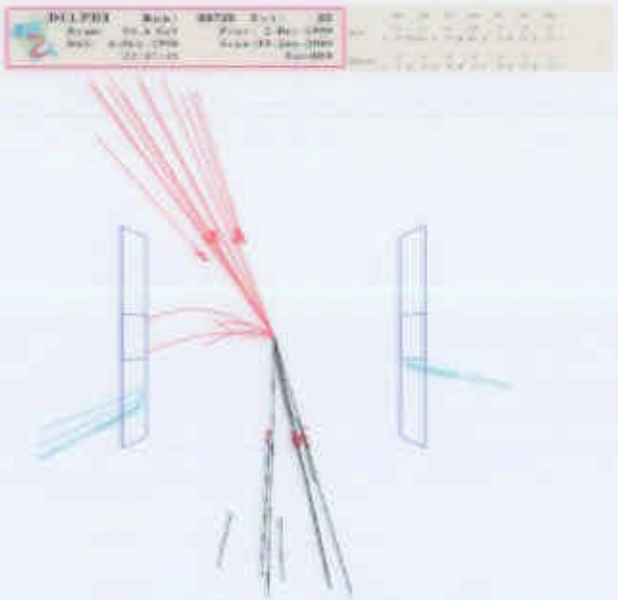
(see talk by S.Arcelli)

Symmetric Double Radiative Return

Two back-to-back photons, Z^0 almost at rest, $Z^0 \to q\bar{q}$ final state $\Rightarrow E(\gamma\gamma) = E_{CM} - M_Z$

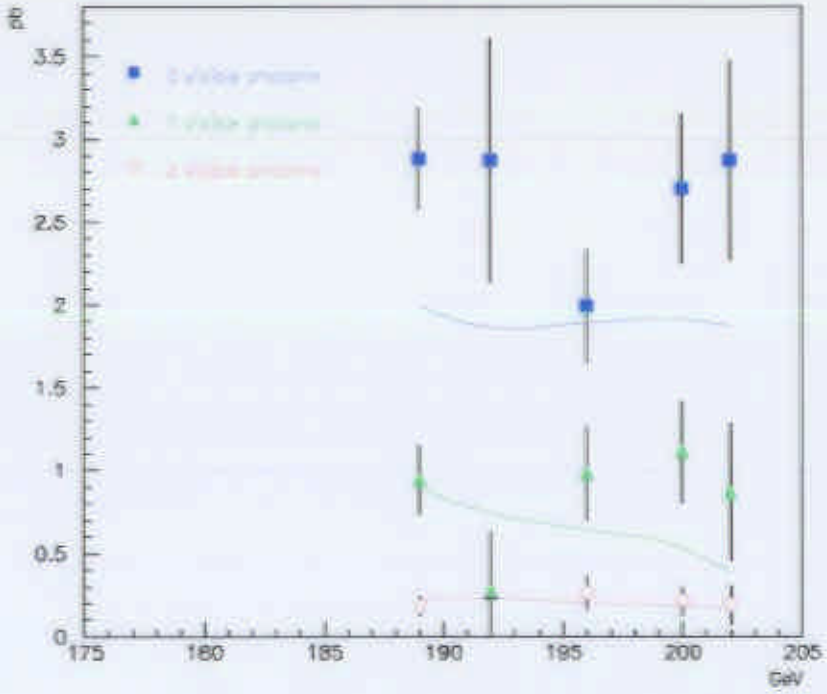
- first measurement of $\sigma_{e^+e^- \to Z\gamma\gamma}$
- cross-check on MC generators
- important background for $H\nu\nu$ searches

(0, 1, 2 photons seen in the detector)



$E_{CM} = 189$ GeV $M(jj) = M_Z$

$E(\gamma_1) = 53$ GeV $E(\gamma_2) = 37$ GeV



(LEP2 : 189 to 202 GeV data, DELPHI)

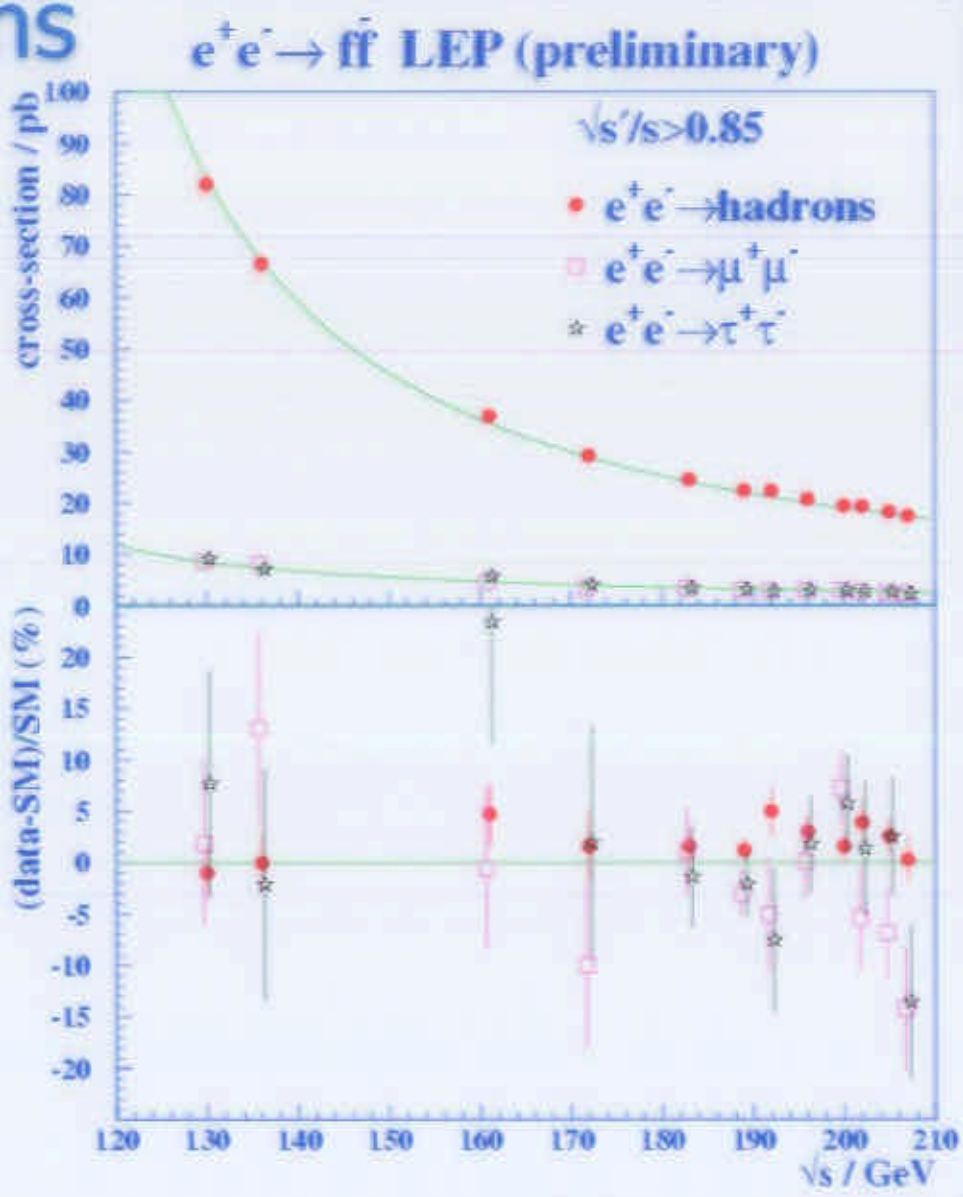
Interpretations of the Results

- comparisons with Standard Model predictions:
  - energy dependence of α_{QED}
  - S-Matrix framework
- constraints on new physics:
  - additional Z' bosons
  - four-fermion contact interactions
  - R-parity violating sneutrino exchange
  - lepto-quark exchange
  - gravity in extra dimensions

Fermion Cross-Sections

LEP averages of published and preliminary results:

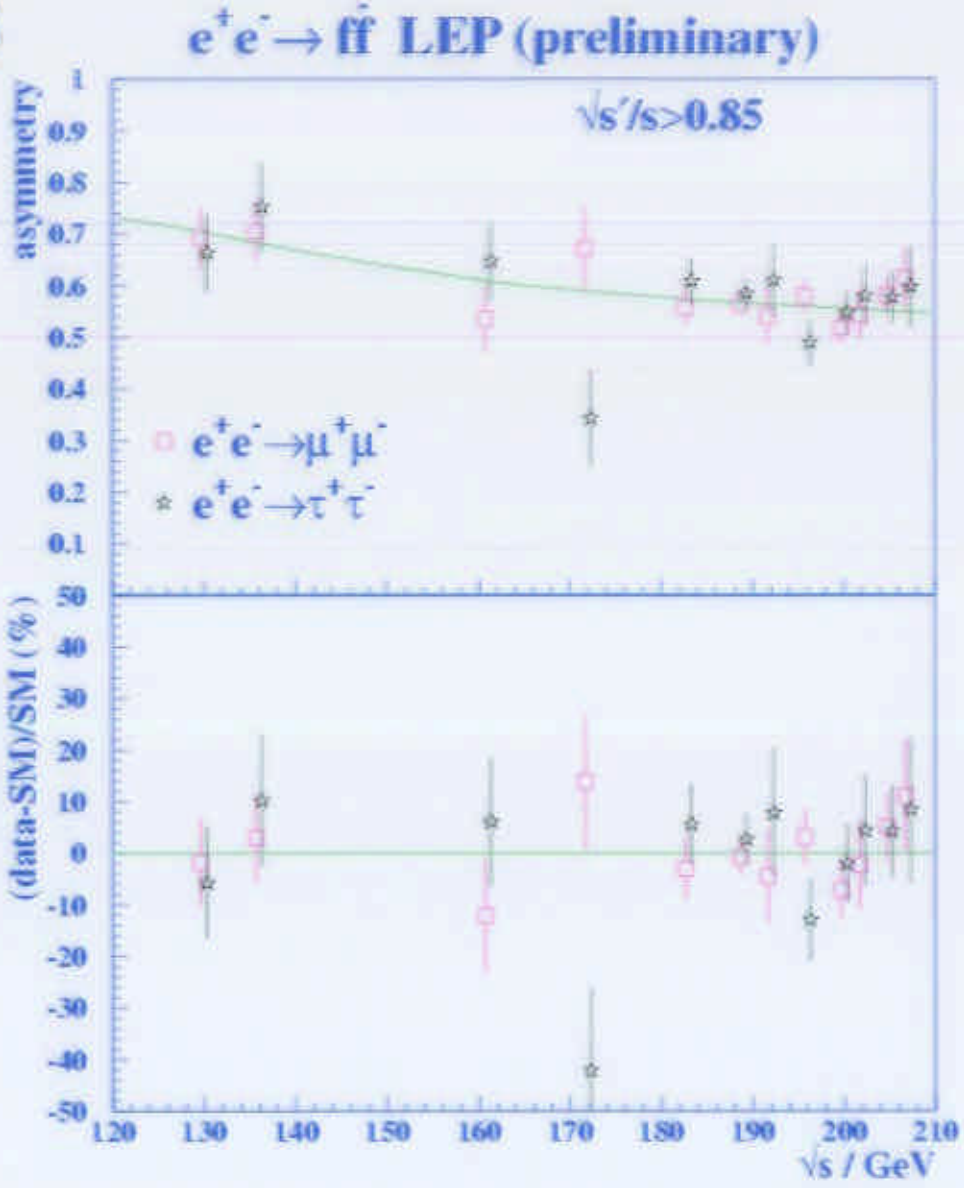
- fair agreement with Standard Model predictions (hadronic cross section is high)
- correlated errors are taken into account in the combinations



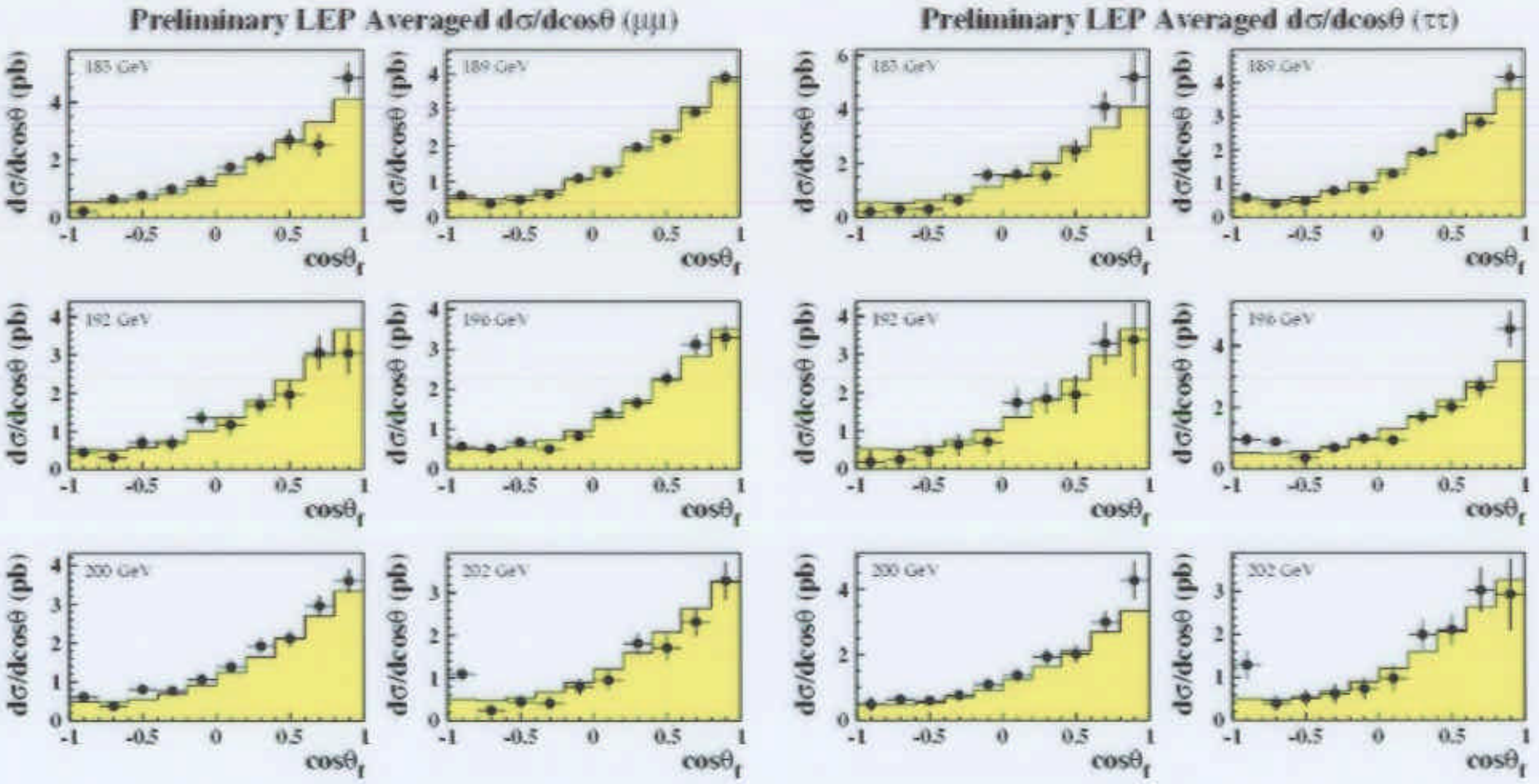
Lepton Asymmetries

LEP averages of published and preliminary results:

- good agreement with Standard Model predictions
- errors are mainly statistical



Lepton Differential Cross-Sections



LEP averages of published and preliminary results:
good agreement with SM predictions

Energy Dependence of α_{QED}

Fit to $\mu^+\mu^-$ and $\tau^+\tau^-$ non-radiative cross-sections and asymmetries:

$\alpha_{QED}^{-1}(187) = 128.4^{+2.5}_{-2.3}$ (SM: 127.9)

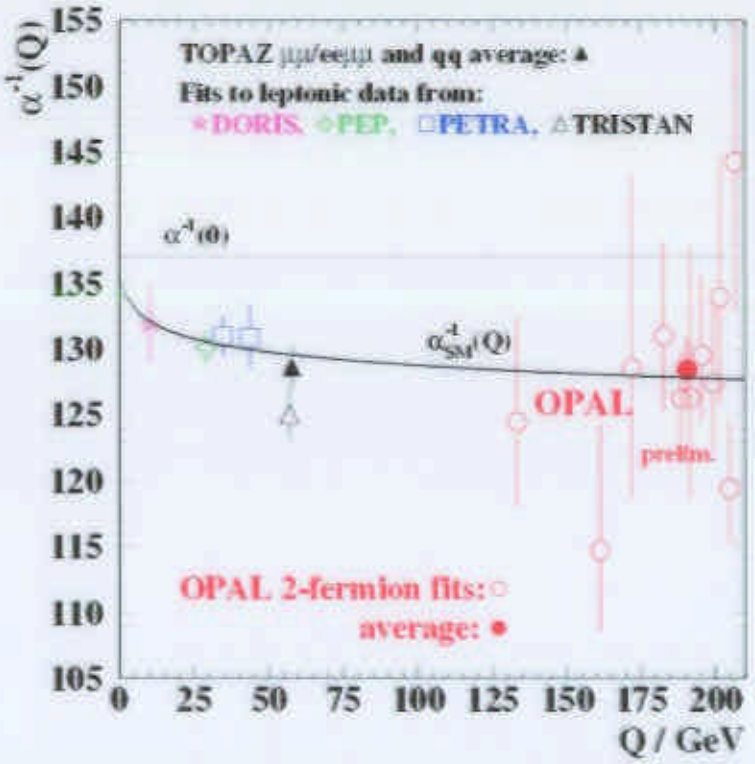
assuming SM up to $\alpha_{QED}^{-1}(Q_{lumi})$

Small angle Bhabha scattering at LEP1:

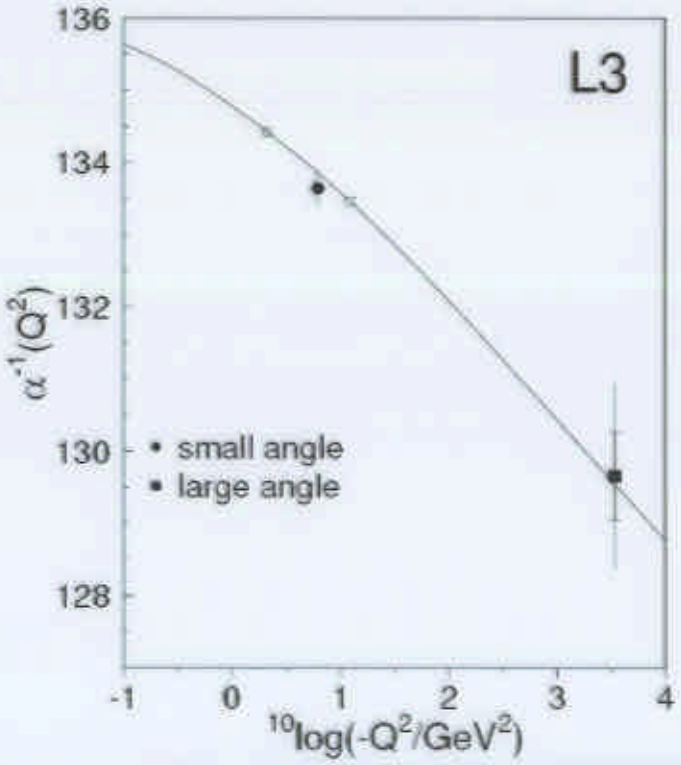
$\alpha_{QED}^{-1}(-2.1\ \mathrm{GeV}^2) - \alpha_{QED}^{-1}(-6.25\ \mathrm{GeV}^2) = 0.78 \pm 0.26$

Large angle Bhabha scattering at LEP2:

$\alpha_{QED}^{-1}(-12.25\ \mathrm{GeV}^2) - \alpha_{QED}^{-1}(-3434\ \mathrm{GeV}^2) = 3.80 \pm 1.29$



(LEP2: 130 to 206 GeV data, OPAL)

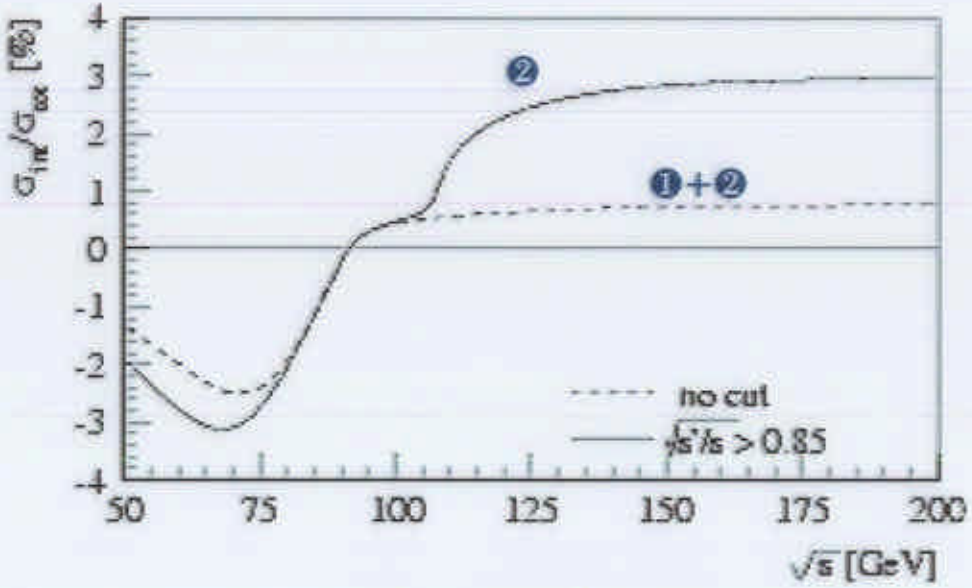


(LEP1+LEP2: 189 GeV data, L3)

S-Matrix Framework - I

Z lineshape fit, LEP1 data only,
to $M_Z, \Gamma_Z, \sigma^0_h, \Gamma_h/\Gamma_Z, A^{0,l}_{FB}$
(L3, γZ interference fixed to SM):

$M_Z = 91189.5 \pm 3.1$ MeV
$\Gamma_Z = 2502.5 \pm 4.2$ MeV



$$\sigma^0_a(s) = \frac{4}{3}\pi\alpha^2\left[\frac{g^a_f}{s} + \frac{j^a_f\left(s-\overline{M}^2_Z\right)+r^a_f s}{\left(s-\overline{M}^2_Z\right)^2+\overline{M}^2_Z\overline{\Gamma}^2_Z}\right]$$

$$A^0_{FB}(s) = \frac{3}{4}\frac{\sigma^0_{fb}(s)}{\sigma^0_{tot}(s)} \qquad a = tot, fb$$

g^a_f - γ exchange
r^a_f - Z exchange
j^a_f - γZ interference

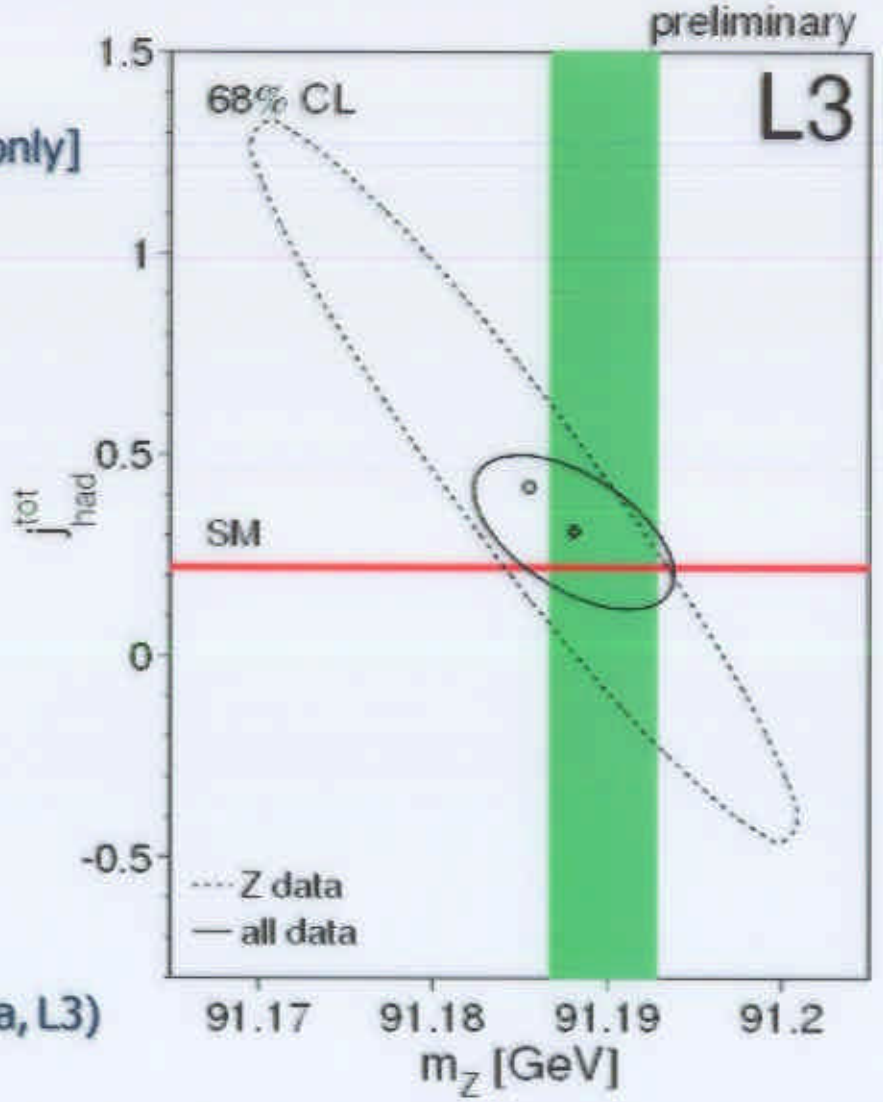
At LEP2, for μ, τ and for $\sqrt{s'} \approx \sqrt{s}$
γ-exchange is 2-4 $\times$ Z-exchange

S-Matrix Framework - II

S-matrix fit, LEP1+LEP2 data [LEP1 data only]
(assuming lepton universality)

$$M_Z = 91188 \pm 4[10]\,\text{MeV}$$
$$\Gamma_Z = 2503 \pm 4[5]\,\text{MeV}$$
$$r^{tot}_{had} = 2.9850 \pm 0.0092[0.010]$$
$$r^{tot}_{lept} = 0.1432 \pm 0.0006[0.0007]$$
$$j^{tot}_{had} = 0.31 \pm 0.13[0.59]$$
$$j^{tot}_{lept} = 0.010 \pm 0.018[0.035]$$
$$r^{FB}_{lept} = 0.0033 \pm 0.0005[0.0005]$$
$$j^{FB}_{lept} = 0.761 \pm 0.024[0.033]$$

(LEP2: 130 to 202 GeV data, L3)



Additional Z′ Bosons

GUT theories ⇒ new gauge bosons, i.e. Z′ (χ,ψ,η models)
also left-right symmetric (LR) and sequential SM (SSM) models

LEP1: sensitive to mixing

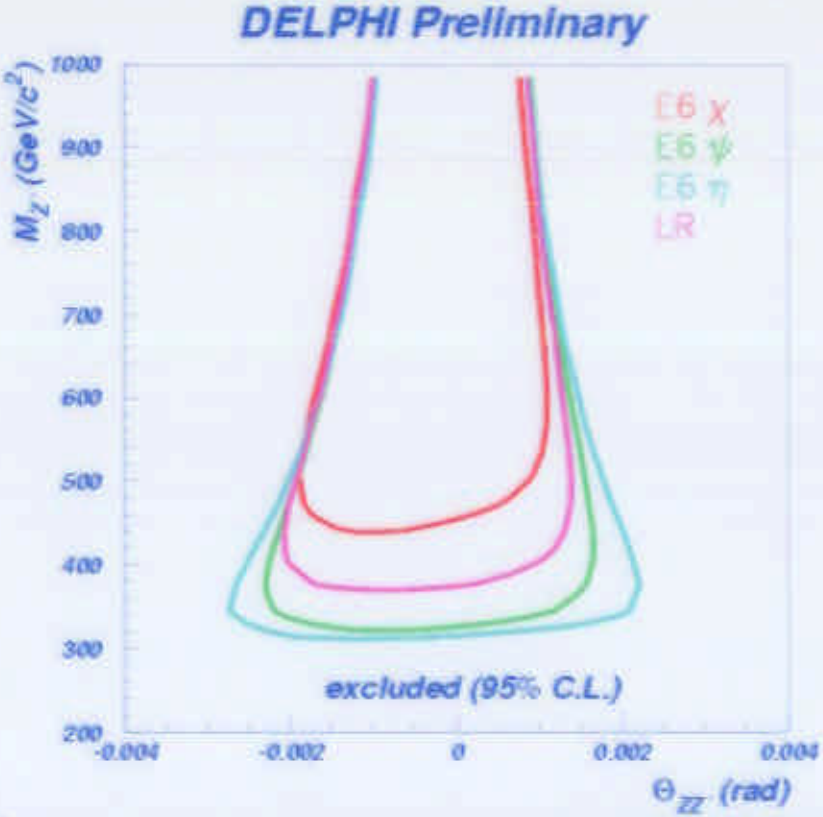
$Z = Z^0 \cos\theta_M + Z' \sin\theta_M$

$$\mathcal{L} = eA_\beta J^\beta_\gamma + gZ^0_\beta J^\beta_{Z^0} + g' Z'_\beta J^\beta_{Z'}$$

LEP2: sensitive to mass

$e^+e^- \rightarrow \gamma/Z/Z' \rightarrow f^+f^-$

Z′ model	$m_{Z'}$(GeV)
$E_6(\chi)$	753 (O)
$E_6(\psi)$	410 (A)
$E_6(\eta)$	486 (O)
$E_6(I)$	510 (A)
LR	635 (O)
SSM	1000 (L)



(LEP2: 130 to 206 GeV data, 95 % CL limits, DELPHI)

Four-Fermion Contact Interactions

Any kind of new physics at TeV scale

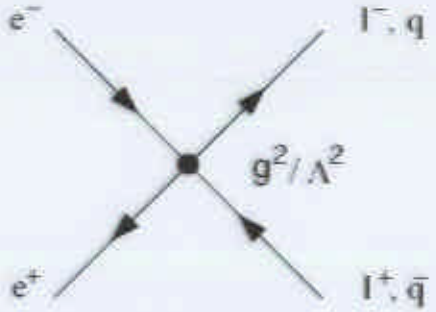
$$\mathcal{L} = \frac{g^2}{(1+\delta)\Lambda_{\pm}^2} \sum_{i,j=L,R} \eta_{ij} [\bar{e}_i \gamma^\mu e_i][\bar{f}_i \gamma_\mu f_i]$$

$g = 4\pi$

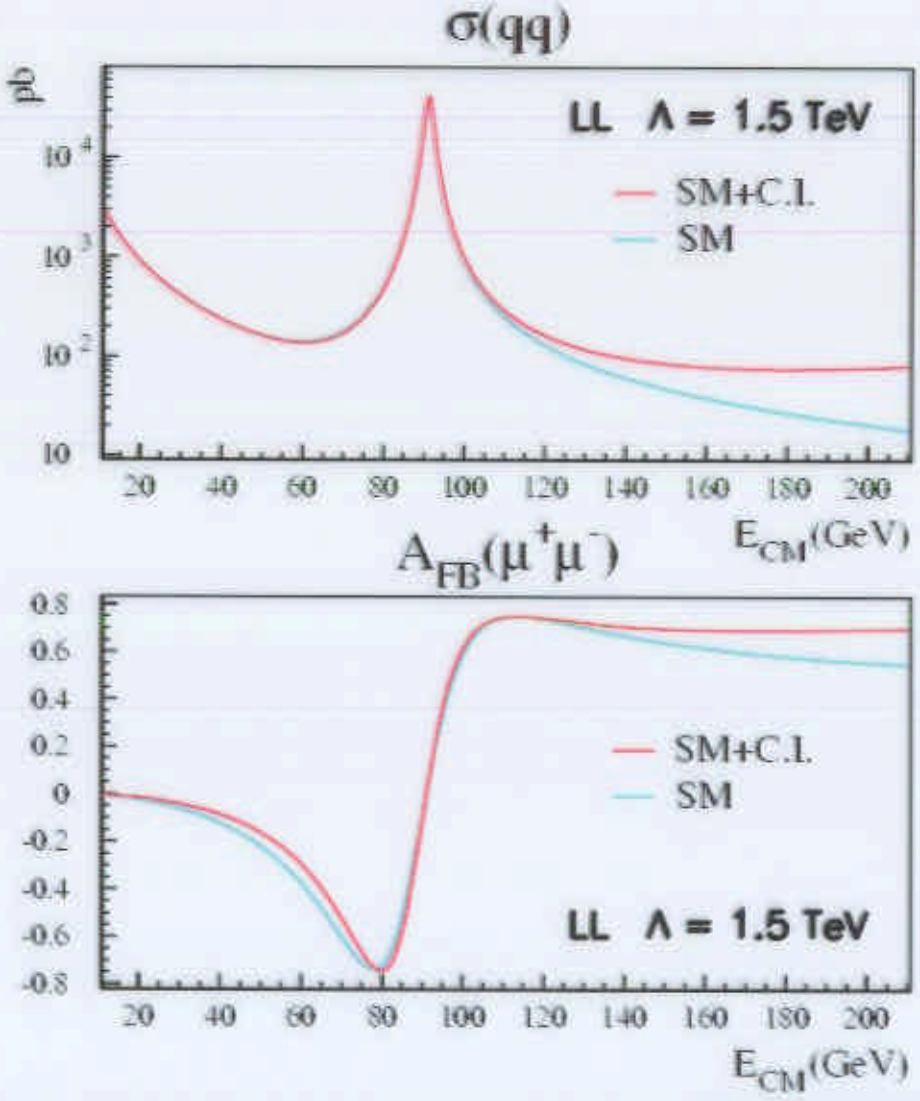
Λ=energy scale

δ=0 (1 for e^+e^-)

η_{ij}=elicity amplitude



$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{SM}}{d\cos\theta} + c_{int}(s,\cos\theta)\frac{1}{\Lambda^2} + c_{ci}(s,\cos\theta)\frac{1}{\Lambda^4}$$

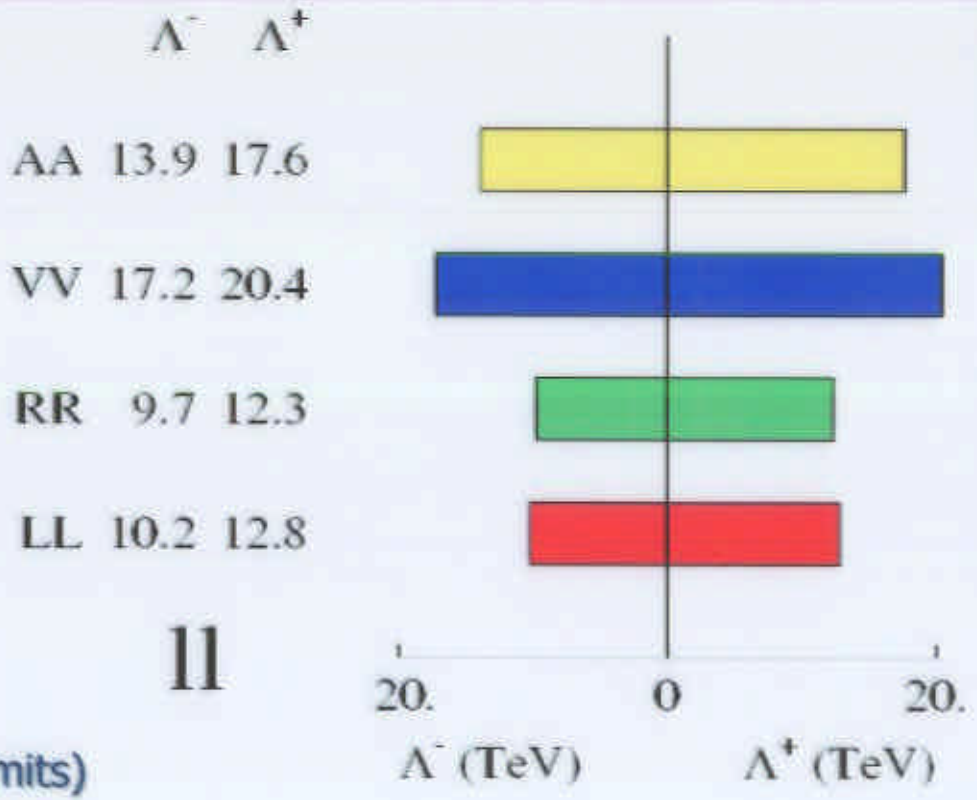


Limits on Contact Interactions-I

LEP combined fits on μ and τ differential cross-sections assuming lepton universality

classified according to chirality of initial and final state fermions:

	η_{RR}	η_{LL}	η_{LR}	η_{RL}
AA	± 1	± 1	∓ 1	∓ 1
VV	± 1	± 1	± 1	± 1
LL	± 1	0	0	0
RR	0	± 1	0	0



(LEP2 : 130 to 202 GeV data, 95 % CL limits)

Limits on Contact Interactions-II

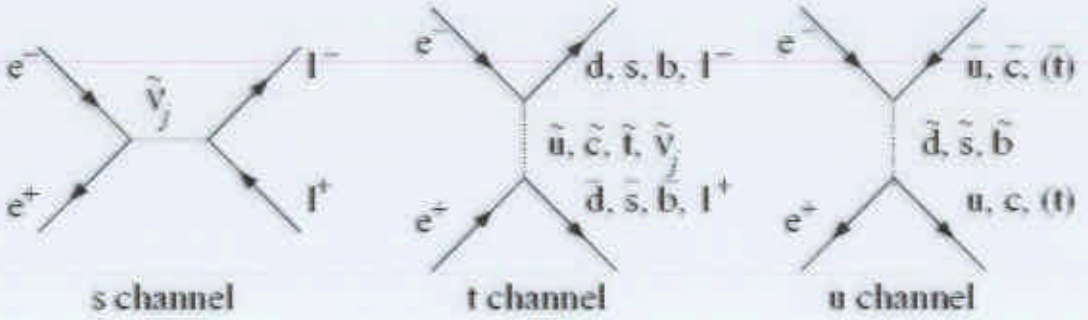
LEP combined fits of $\sigma_{bb(cc)}$ (from $R_{b(c)}$ and σ_{qq}), $A^{b(c)}_{FB}$

(LEP2 : 130 to 202 GeV data, 95 % CL limits)

R-Parity Violating SUSY

R-parity violating term:

$$\mathcal{L} = \lambda_{ijk} L^i_L L^j_L \overline{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \overline{D}^k_R + \lambda''_{ijk} Q^i_L Q^j_L \overline{D}^k_R$$



Sneutrino exchange leading to lepton pairs:

$$\mathcal{L}^{\overline{\nu}}_{\not R} = \lambda_{ijk}\left[\tilde{\overline{\nu}}^j_L \overline{e}^k_R e^i_L - \tilde{\overline{\nu}}^i_L \overline{e}^k_R e^j_L\right]$$

λ : Yukawa coupling

ν : lepton singlet superfield

e : lepton doublet superfield

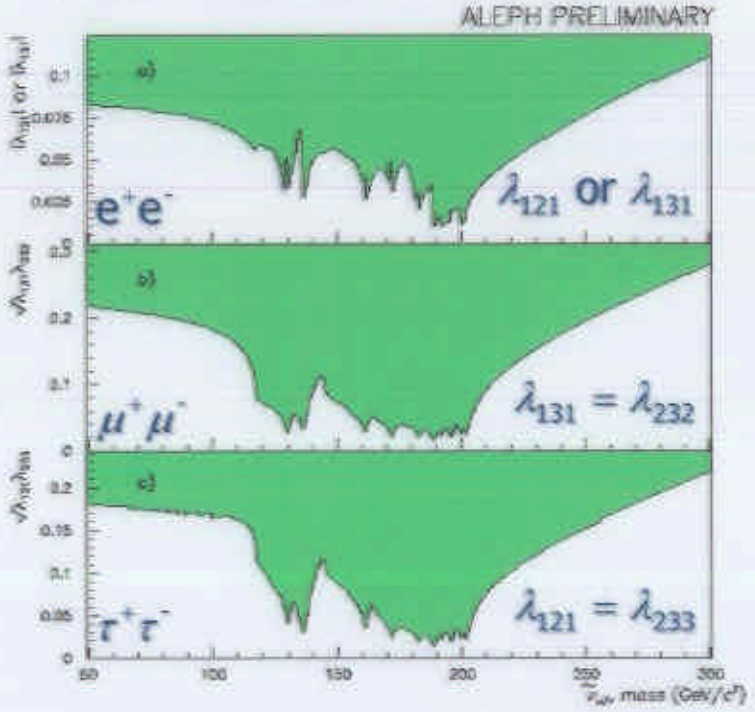
(only accessible at e^+e^- colliders)

	e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$
λ^2_{121}	$\tilde{\nu}_\mu$(t,s)	$\tilde{\nu}_e$(t,s)	
λ^2_{131}	$\tilde{\nu}_\tau$(t,s)		$\tilde{\nu}_e$(t)
$\lambda_{121}\lambda_{233}$			$\tilde{\nu}_\mu$(s)
$\lambda_{131}\lambda_{232}$		$\tilde{\nu}_\tau$(s)	

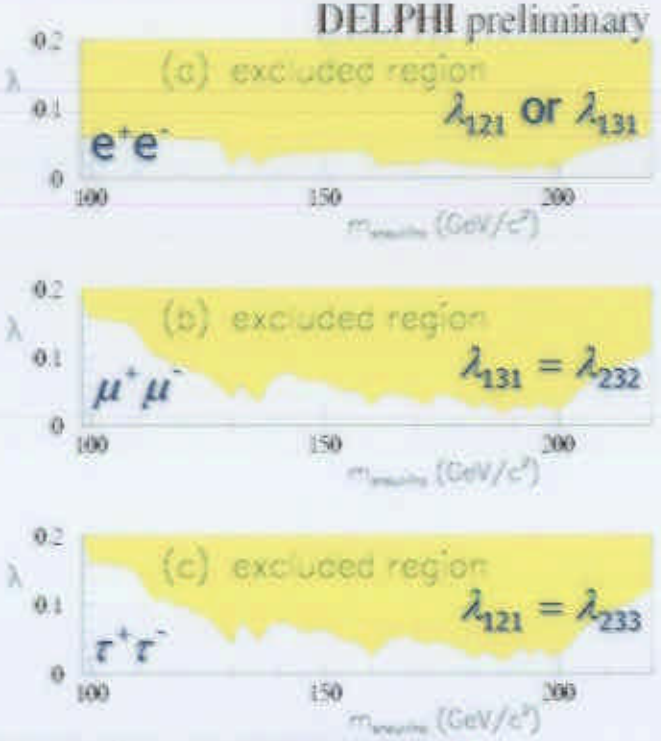
(see talks by T.Takeuchi and I.Fleck)

Limits on Sneutrino Exchange

From l^+l^- differential cross - sections :



(LEP2: 130 to 202 GeV data, ALEPH)



(LEP2: 130 to 202 GeV data, DELPHI)

	$m_{\tilde{\nu}} = 100$ GeV/c^2	$m_{\tilde{\nu}} = 200$ GeV/c^2
$\lambda(t, \tilde{\nu}_i$ in $\mu^+\mu^-)$	0.21	0.28
$\lambda(t, \tilde{\nu}_i$ in $\tau^+\tau^-)$	0.48	0.66

(LEP2 : 130 to 202 GeV data, 95 % CL limits, DELPHI)

Limits on Lepto-Quark Exchange

t-channel exchange of LQ
can modify $\sigma_{q\bar{q}}$ and Q_{FB}

Limit on scalar LQ mass (GeV/c^2)						
$S_0(L)$	$S_0(R)$	$\tilde{S}_0(R)$	$S_{1/2}(L)$	$S_{1/2}(R)$	$\tilde{S}_{1/2}(L)$	$S_1(L)$
380	56	128	120	120	-	319

$\tilde{S}_{1/2}$ leptoquark $\Leftrightarrow$ u-type squark
S_0 leptoquark $\Leftrightarrow$ d-type squark
(limits on λ'_{jk})

Limit on vector LQ mass (GeV/c^2)						
$V_0(L)$	$V_0(R)$	$\tilde{V}_0(R)$	$V_{1/2}(L)$	$V_{1/2}(R)$	$\tilde{V}_{1/2}(L)$	$V_1(L)$
618	137	331	144	169	105	515

(LEP2 : 130 to 202 GeV data, 95 % CL limits, $g = e$, ALEPH)

Tevatron limit: 225 GeV/c^2 (any LQ coupling)
Hera limit: 275 GeV/c^2 (1st generation LQ)
atomic parity violating exp. limits: 430-1500 GeV/c^2

(see talks by M.Falagan and A.F.Zarnecki)

Gravity in Extra Dimensions

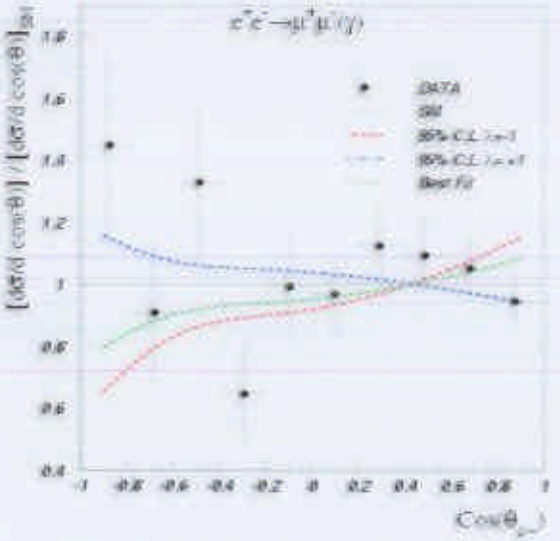
Fits to μ and τ differential cross-sections for fermion-pair production, including virtual graviton exchange:

$$\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{SM}}{d\cos\theta} + B(\cos\theta)\left[\frac{\lambda}{M_s^4}\right] + C(\cos\theta)\left[\frac{\lambda}{M_s^4}\right]^2$$

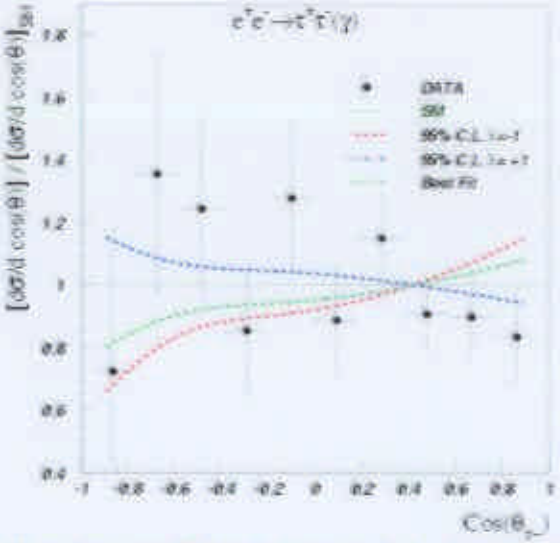
M_s = energy scale, λ = interference with SM

λ	M_s (TeV)
+1	0.76
-1	0.60

(LEP2 : 130 to 202 GeV data, 95 % CL limits, DELPHI)



DELPHI PRELIMINARY



(see talks by H.Terao and J.L.Hewett)

Summary and Outlook - I

- cross-section and asymmetry measurements at 130-202 GeV are in good agreement with SM predictions
- preliminary results at 205-206 GeV are also consistent with SM
- running of α_{QED} is confirmed
- mass of Z' must be higher than 400 GeV (SSM: 1 TeV)
- further improvements on m_Z, j_{had} within S-matrix framework

Summary and Outlook - II

- energy scale for new (contact) interactions constrain to values above 10-20 TeV
- R-parity violating SUSY: $\lambda<0.1$ for sneutrino masses in the range 130-210 GeV/c^2
- lepto-quarks: excluded mass below 60-620 GeV
- energy scale for gravity in extra dimensions constrain to values above 600 GeV