Tests of the Standard Model and constraints on new physics from

Fermion-pair production at LEP2

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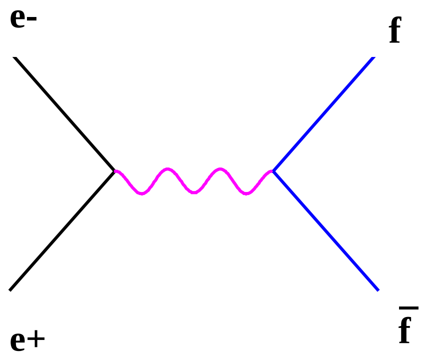
Outline

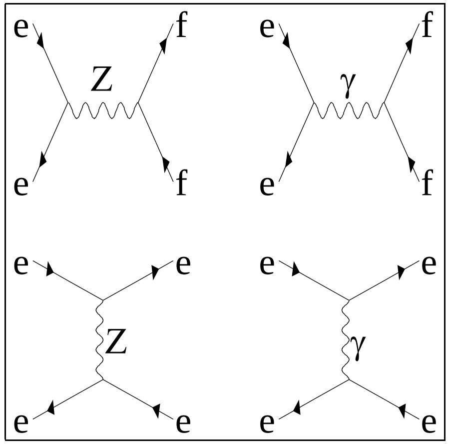


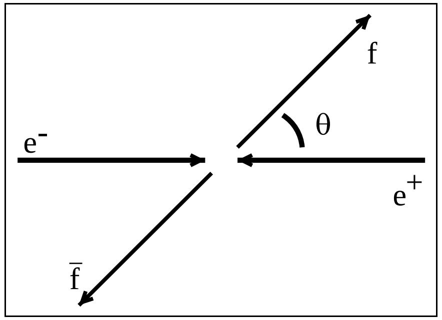
$f = e, \mu, \tau, q$ (inclusive / b / c)

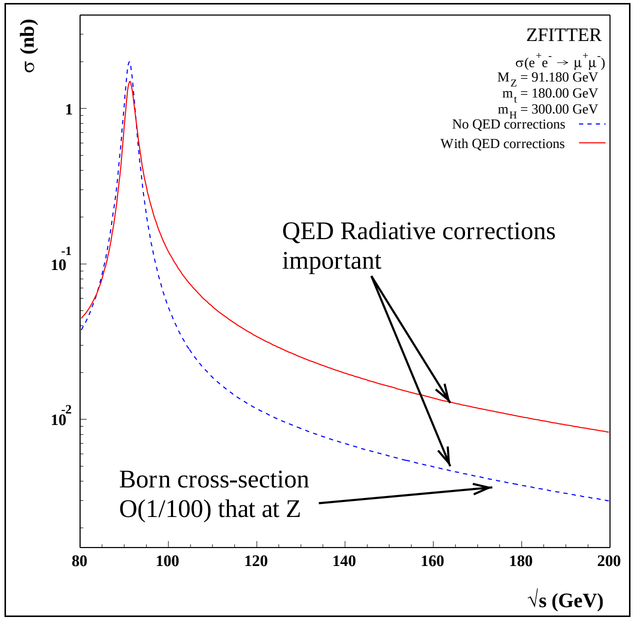
$\sqrt{s} = 130 - 209$ GeV

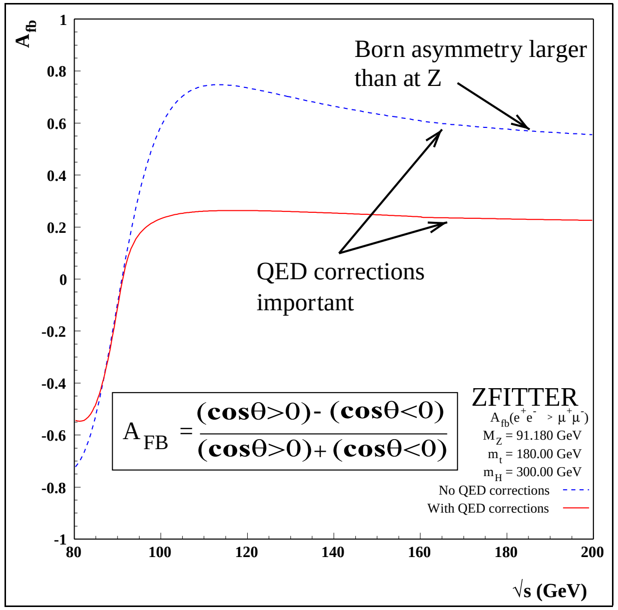
- Features of fermion-pair production above the Z peak
- Measurements of σ, A_{FB}, R_q, $d\sigma/d\cos\theta$
- Tests of the Standard Model (SM)
- Indirect searches for physics beyond SM
  - – virtual contributions interfering with SM diagrams
  - – sensitive to energies higher than $\sqrt{s}$

Fermion pair production in SM

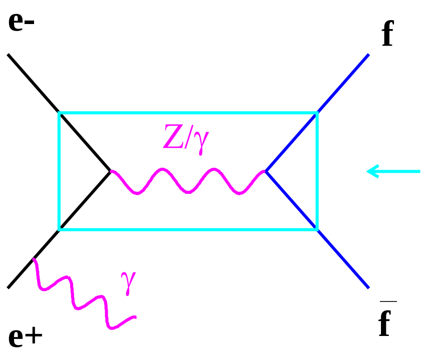








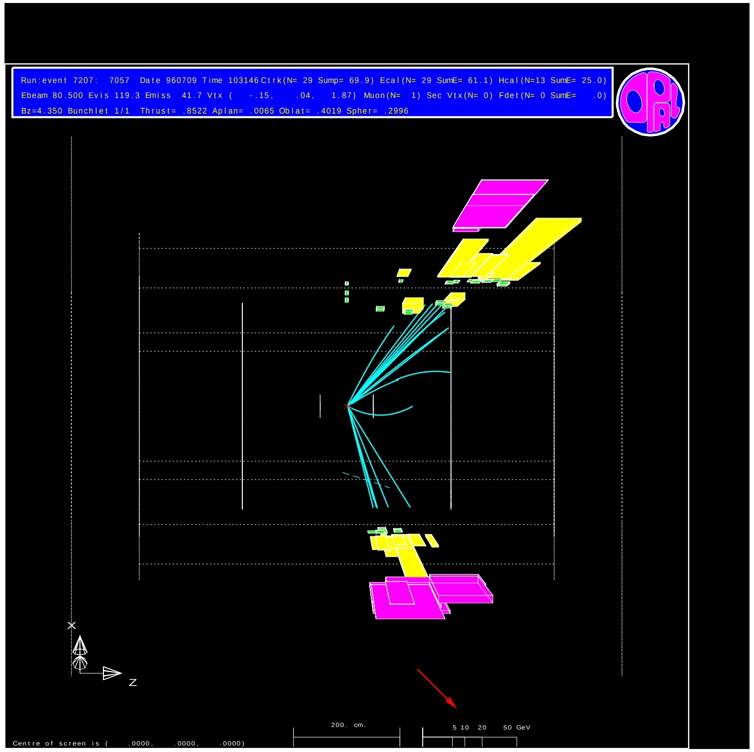
Z radiative return



← Effective center of mass energy $\sqrt{s'}$

Photon radiation very important at LEP2

Radiative return peaks at $\sqrt{s'} \sim m_Z$



Radiative events have usually acollinear fermion pairs and large missing momentum along the beam pipe

(Non-radiative events have back-to-back fermion pairs)

s’ measured in different ways by experiments

Signal Definition

Inclusive sample $\sqrt{s'/s} \geq 0.1$

Non-radiative sample $\sqrt{s'/s} \geq 0.85$

More relevant to look for new physics

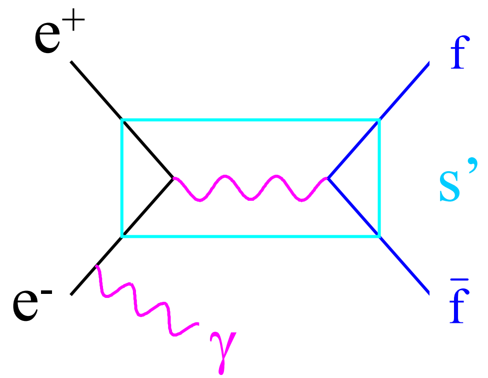
Two preferred definitions of **s'** :

- s-channel propagator mass (with IFSR subtracted) L3, OPAL
- bare invariant mass $f\bar{f}$ (with IFSR included) ALEPH, DELPHI

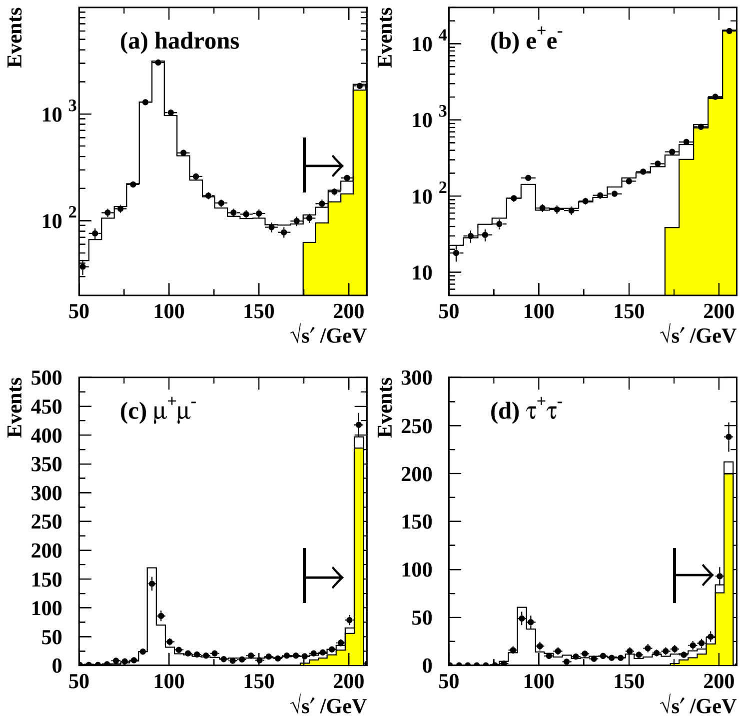
Complications :

Initial-Final-State Interference

Extra Pairs from 4-fermion procs



OPAL 206 GeV preliminary



Data Samples / current precision

Year	Nominal Energy GeV	Actual Energy GeV	Luminosity pb^{-1}/expt
1995	130	130.2	~ 3
	136	136.2	~ 3
	133*	133.2	~ 6
1996	161	161.3	~ 10
	172	172.1	~ 10
	167*	166.6	~ 20
1997	130	130.2	~ 2
	136	136.2	~ 2
	183	182.7	~ 50
1998	189	188.6	~ 170
1999	192	191.6	~ 30
	196	195.5	~ 80
	200	199.5	~ 80
	202	201.6	~ 40
2000	205	204.9	~ 80
	207	206.7	~ 140

Experimental errors

(Non-radiative data at 189 GeV)

	(stat)	(syst)
qq	2 %	1-2 %
μμ	5 %	2 %
ττ	5-7 %	2-3 %
ee	1.5-2 %	0.5-1 %

Combining LEP2 data:
Statistics increase ≈ 4×3 times
→ errors / $\sqrt{12}$
Systematics mostly uncorrelated between exps → errors / 2

Total Experimental precision on deviations from SM averaged over all energies:
qq ≈ 1 %   μμ, ττ ≈ 2 %   ee ≈ 0.5 %

Theoretical Uncertainties
(from *LEP2 MC Workshop*)
qq : 0.26 %   μμ, ττ : 0.4 %
ee : 2.0 % (barrel), 0.5 % (endcap)

→ Adequate except for electron pairs

LEP combinations - (all preliminary) -

- Non-radiative data $\sqrt{s'/s} \geq 0.85$ (e^+e^- not yet combined)
- Cross sections: hadronic, $\mu^+\mu^-$, $\tau^+\tau^-$
- Forward-Backward asymmetries: $\mu^+\mu^-$, $\tau^+\tau^-$
- Differential cross sections $\frac{d\sigma}{d\cos\theta}$ for $\mu^+\mu^-$, $\tau^+\tau^-$
- Heavy Flavours: $R_b, A_{FB}^b, R_c, A_{FB}^c$

→ Covariance matrix built from errors split in 5 classes to account for different correlations (within/between exps)

→ Corrections of each exp's data to a common signal definition

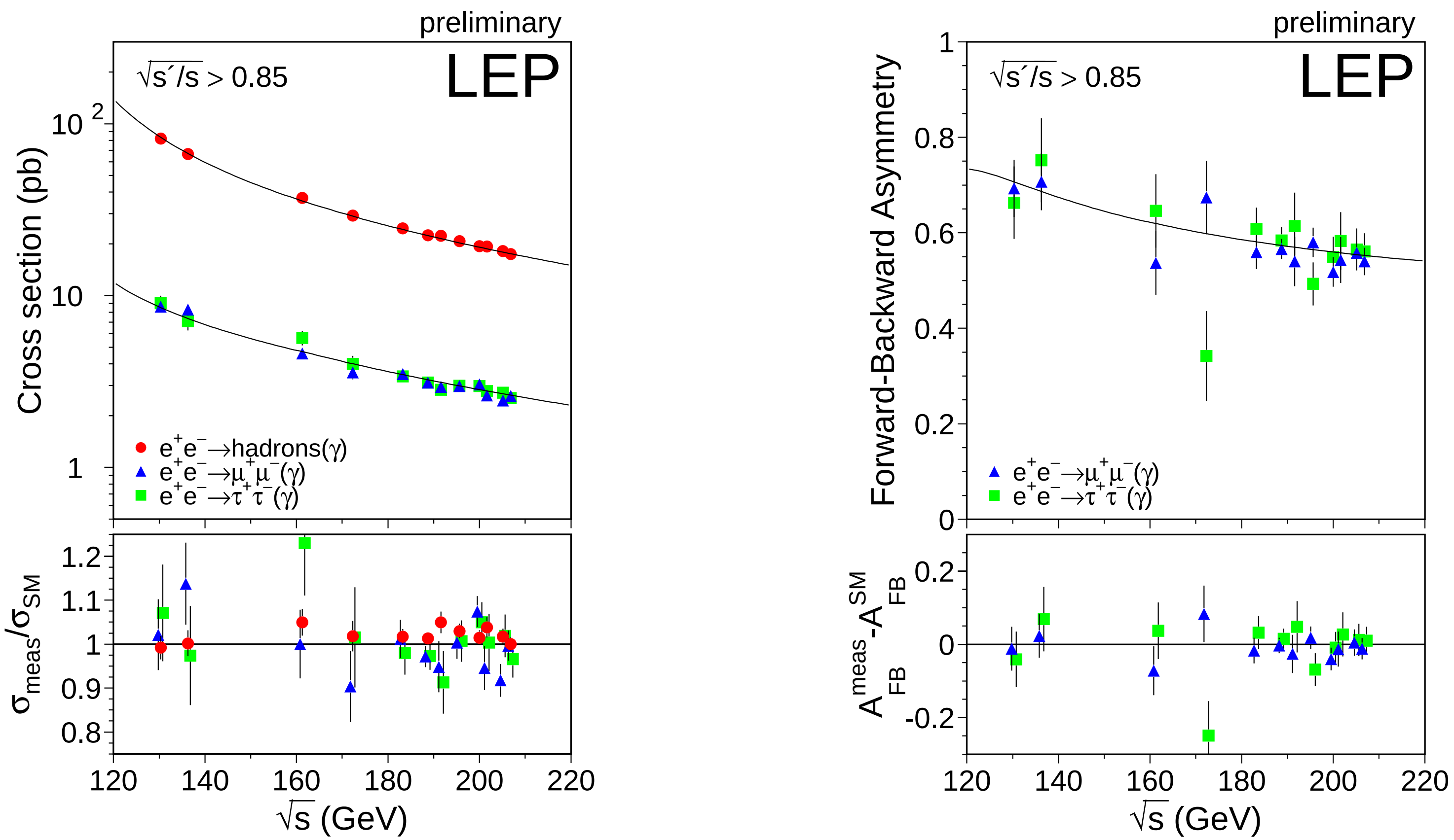
→ χ^2 minimisation procedure

Combined errors dominated by statistics and uncorrelated systematics

Good Agreement between DATA and Standard Model

⇨ **Set limits on NEW Physics !**

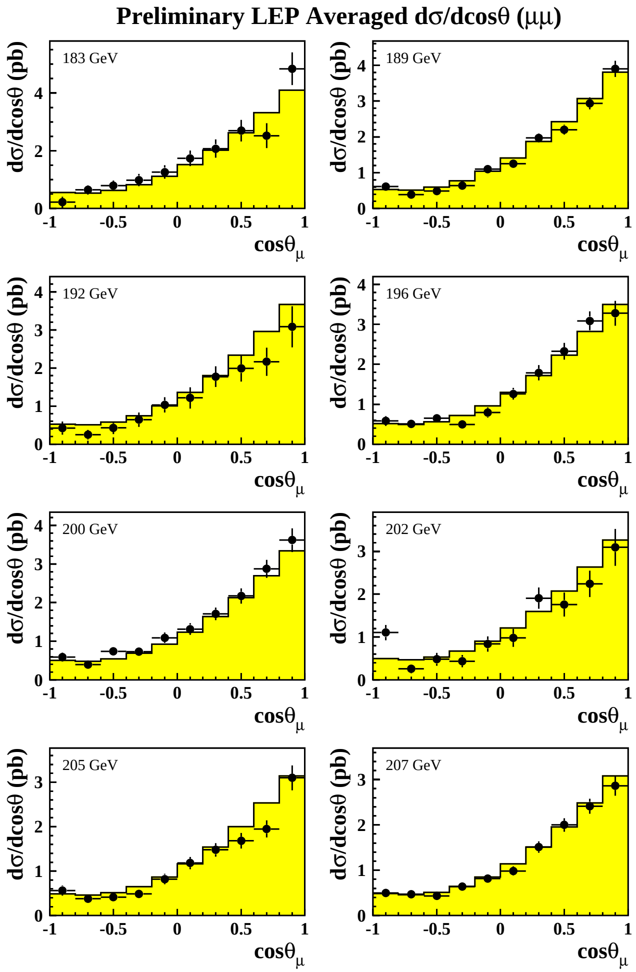
Cross-sections and Forward-Backward asymmetries

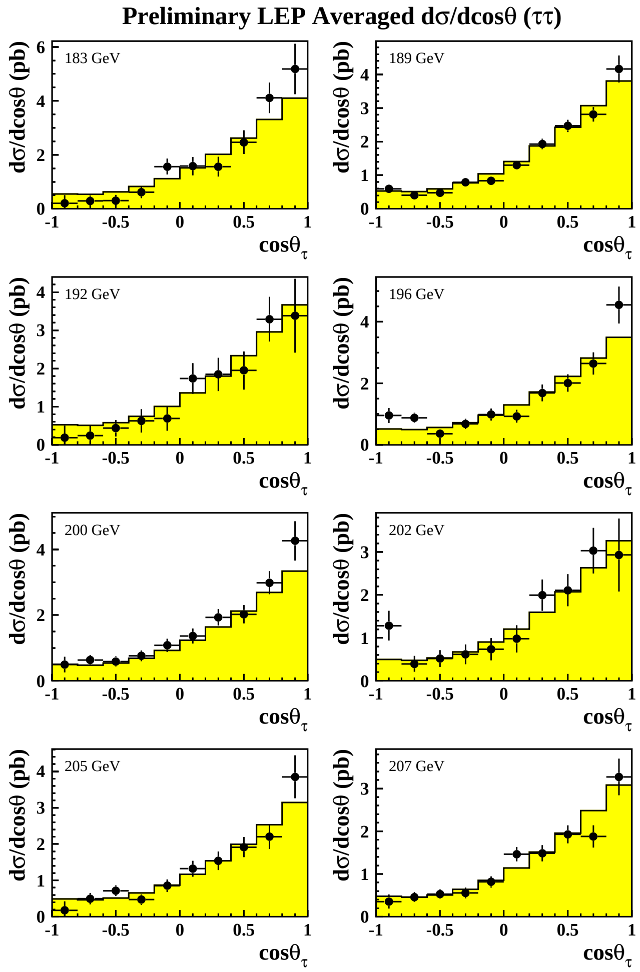


Good agreement with SM

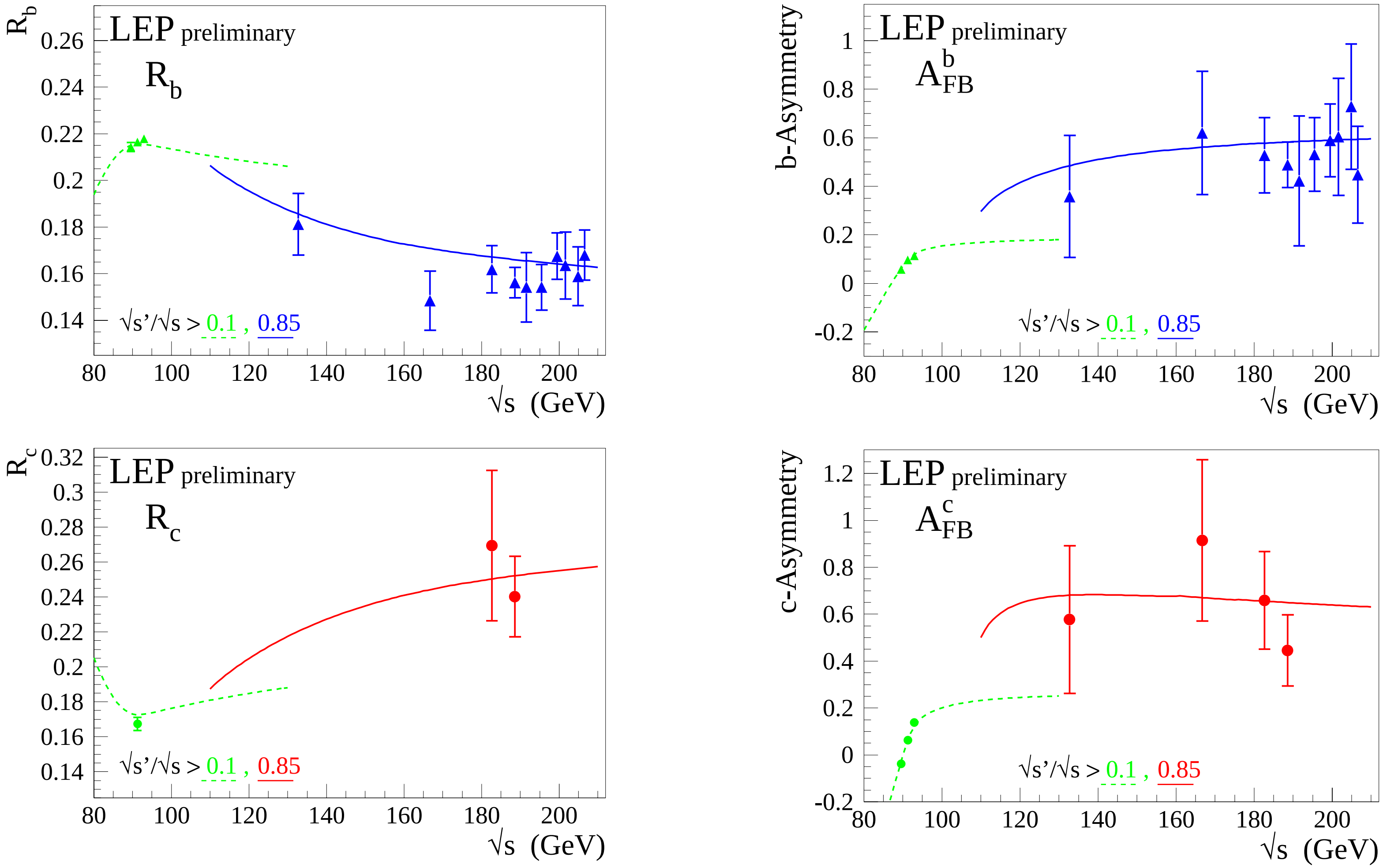
(hadronic σ 1.8 s.d. excess averaged over all energies)

Differential cross-sections $\frac{d\sigma}{d\cos\theta}$

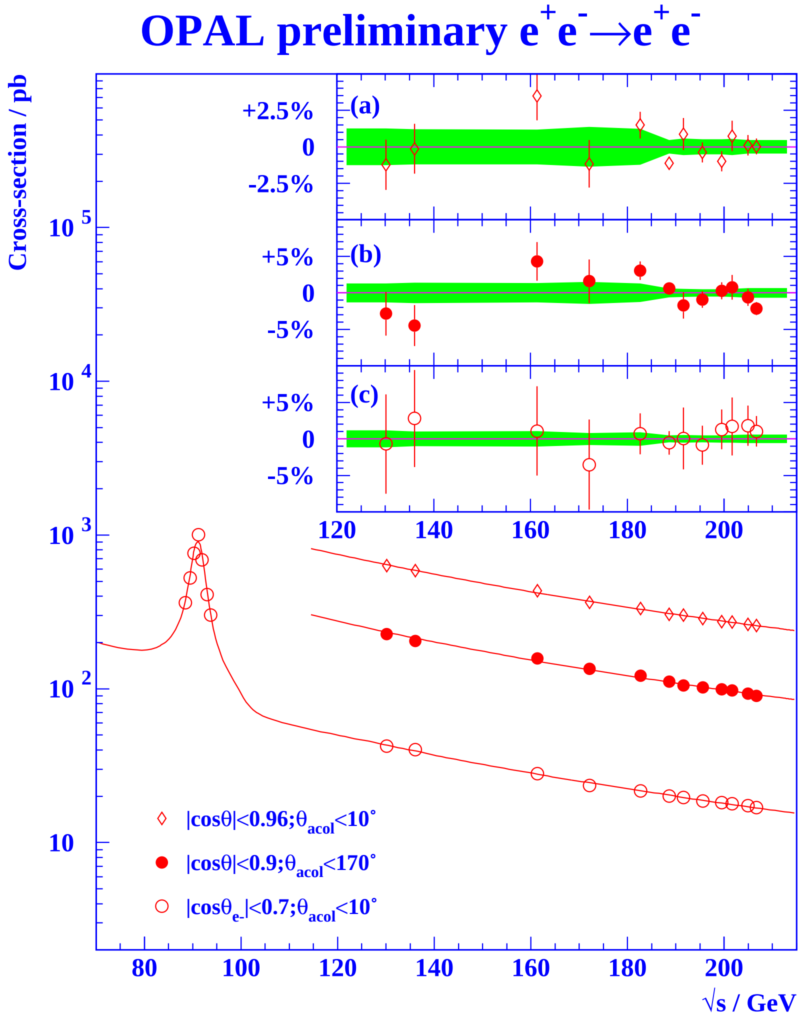




Heavy Flavours



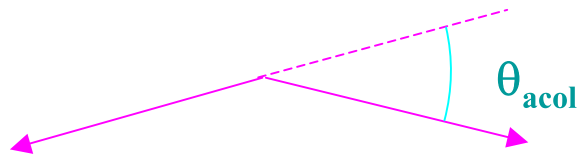
Bhabha scattering

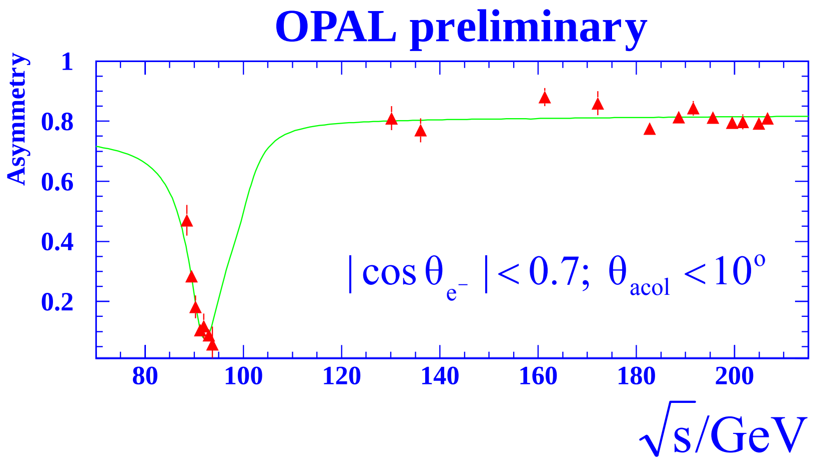


Dominated by t-channel exchange

s' not natural

→ cut on acollinearity
(OPAL: $\theta_{acol} < 10°$)





S-matrix fit

Minimal theoretical assumptions: free parameters $\overline{m}_Z, \overline{\Gamma}_Z, g_f^a, j_f^a, r_f^a$

$$\sigma_a^0(s) = \frac{4}{3}\pi\alpha^2 \left[\frac{g_f^a}{s} + \frac{j_f^a(s-\overline{m}_Z^2) + r_f^a\, s}{(s-\overline{m}_Z^2)^2 + \overline{m}_Z^2\overline{\Gamma}_Z^2} \right]$$

$$A_{fb}^0(s) = \frac{3}{4}\frac{\sigma_{fb}^0(s)}{\sigma_{tot}^0(s)}$$

a = tot, fb

f = had, e, μ, τ

g_f^a → γ exchange assumed to be known

j_f^a → γ -Z interference

r_f^a → Z-exchange

$$m_Z = \overline{m}_Z\sqrt{1+\overline{\Gamma}_Z^2/\overline{m}_Z^2} \approx \overline{m}_Z + 34\text{ MeV}$$

$$\Gamma_Z = \overline{\Gamma}_Z\sqrt{1+\overline{\Gamma}_Z^2/\overline{m}_Z^2} \approx \overline{\Gamma}_Z + 1\text{ MeV}$$

To compare with usual definitions where

$\overline{\Gamma}_Z \rightarrow \Gamma_Z = s\,\overline{\Gamma}_Z/\overline{m}_Z^2$

⇒ hadronic γ – Z interference left free

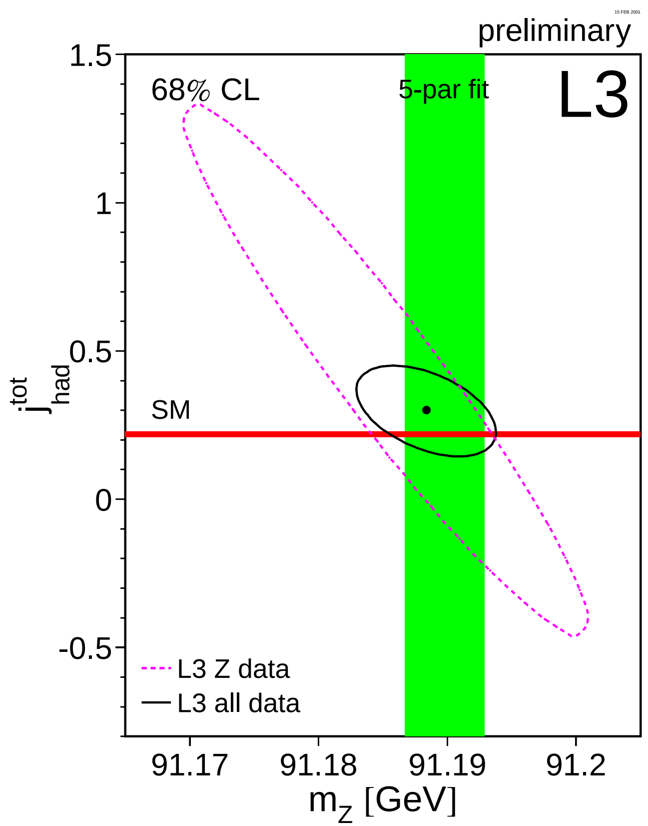
(usually S.M. prediction is used for lineshape fits)

S-matrix fit

m_Z - j^{tot}_{had} strongly correlated

LEP1 only (L3): δm_Z $(j^{tot}_{had}) = \pm$ 9.8 MeV

LEP1+LEP2 (L3):
$\pm$ 1.8 MeV



Fit with/without lepton universality

All LEP1 + LEP2 data included

Parameter	Treatment of Charged Leptons non–universality	universality	Standard Model
m_Z [MeV]	91 188.8±3.6	91 188.4±3.6	—
Γ_Z [MeV]	2 502.7±4.1	2 502.5±4.1	2 492.8
r^{tot}_{had}	2.9854±0.0092	2.9849±0.0092	2.960
r^{tot}_{e}	0.14315±0.00075	—	
r^{tot}_{μ}	0.14281±0.00079	—	
r^{tot}_{τ}	0.14367±0.00102	—	
r^{tot}_{ℓ}	—	0.14318±0.00059	0.14245
j^{tot}_{had}	0.29±0.10	0.30±0.10	0.21
j^{tot}_{e}	-0.034±0.043	—	
j^{tot}_{μ}	-0.012±0.025	—	
j^{tot}_{τ}	0.043±0.029	—	
j^{tot}_{ℓ}	—	0.005±0.018	0.004
r^{fb}_{e}	0.00176±0.00111	—	
r^{fb}_{μ}	0.00329±0.00064	—	
r^{fb}_{τ}	0.00448±0.00092	—	
r^{fb}_{ℓ}	—	0.00330±0.00047	0.00263
j^{fb}_{e}	0.685±0.073	—	
j^{fb}_{μ}	0.795±0.033	—	
j^{fb}_{τ}	0.745±0.041	—	
j^{fb}_{ℓ}	—	0.760±0.024	0.799
χ^2/dof	60/66	62/74	—

Consistent with LEP1 SM fit (L3): m_Z= 91189.8 ± 3.1 MeV

Energy Dependence of α_{em}

μ/τ pairs (non-radiative)
dominated by s-channel γ-exchange

$\sigma \rightarrow \alpha^2_{em}$ $A_{FB} \rightarrow \alpha_{em}$

OPAL (prel., all LEP2 data)

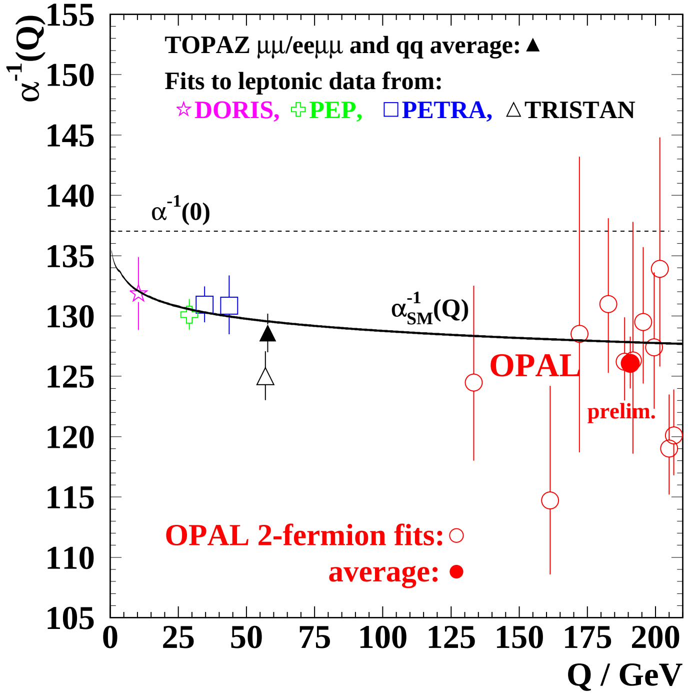
$\alpha_{em}^{-1}(190.7\,\mathrm{GeV}) = 126.1^{+2.2}_{-2.1}$ (SM : 127.9)

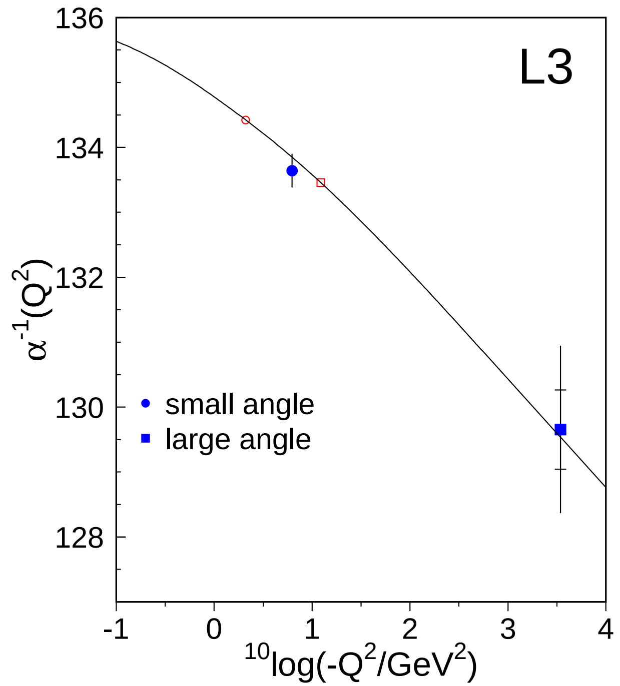
→ see running from the scale of *Luminosity* meas. where $\alpha_{em} \geq 133$

Bhabha scattering at small and intermediate angles dominated by t-channel γ –exchange.
L3 results from LEP1 and LEP2 data

$\alpha^{-1}_{em}(-2.1\,\mathrm{GeV}^2) - \alpha^{-1}_{em}(-6.25\,\mathrm{GeV}^2) = 0.78 \pm 0.26$

$\alpha^{-1}_{em}(-12.25\,\mathrm{GeV}^2) - \alpha^{-1}_{em}(-3434\,\mathrm{GeV}^2) = 3.80 \pm 1.29$



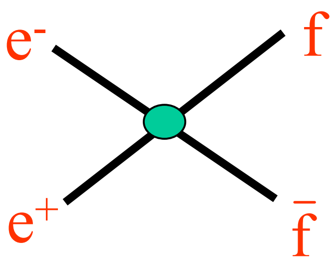


Four-Fermion Contact Interactions

Convenient way to describe any sign of new physics in $ee \to f\bar{f}$ at scale $\Lambda >> \sqrt{s}$

Effective Lagrangian

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



$$\delta = \begin{cases} 1 & f = e \\ 0 & f \neq e \end{cases} .$$

Chiral structure

Model	LL	RR	LR	RL	VV	AA	V0	A0
η_{LL}	±1	0	0	0	±1	±1	±1	0
η_{RR}	0	±1	0	0	±1	±1	±1	0
η_{LR}	0	0	±1	0	±1	∓1	0	±1
η_{RL}	0	0	0	±1	±1	∓1	0	±1

Four-Fermion Contact Interactions

$$\frac{d\sigma}{d\cos\theta} = A(s,t) + B(s,t)\,\varepsilon + C(s,t)\,\varepsilon^2$$

Fit $\varepsilon = 1/\Lambda^2$ (set $g^2=4\pi$)

ε compatible with S.M.

↓

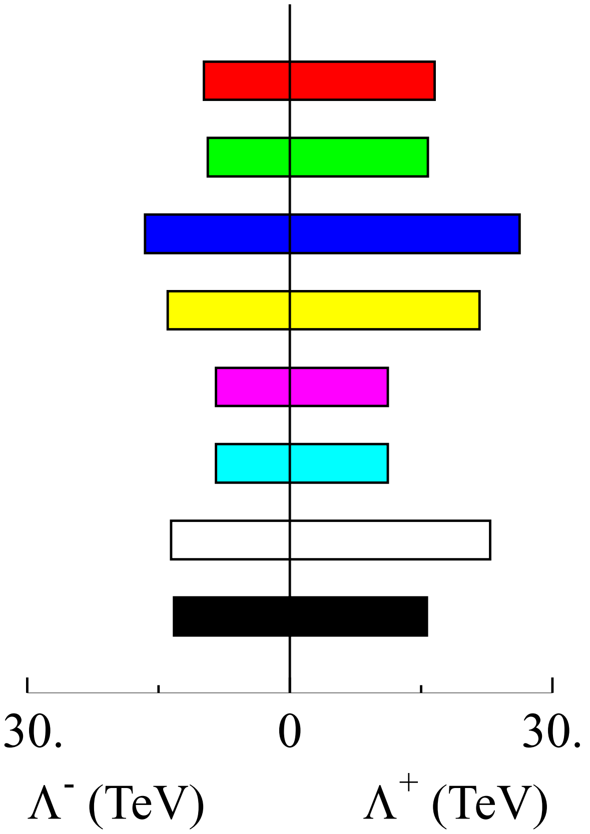
95% C.L. limits for both signs

$\Lambda > 8.5 - 26.2$ TeV

LEP Preliminary comb. ($\mu\mu$ & $\tau\tau$)

	Λ^-	Λ^+
LL	9.8	16.5
RR	9.4	15.8
VV	16.5	26.2
AA	14.0	21.7
RL	8.5	11.2
LR	8.5	11.2
V0	13.5	22.9
A0	13.2	15.6

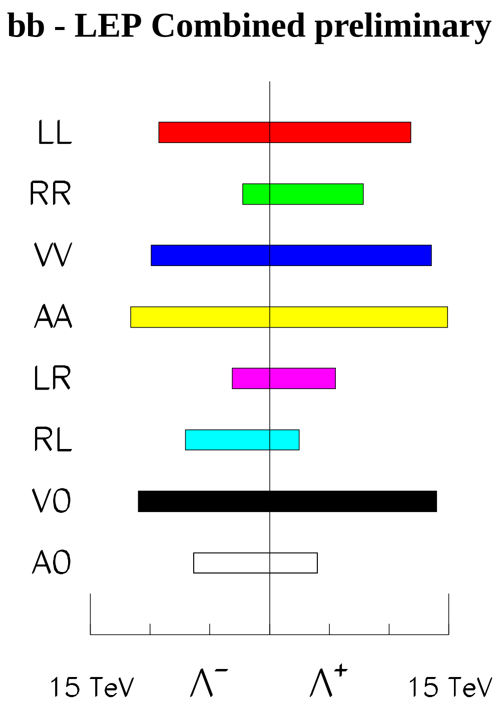
l^+l^-

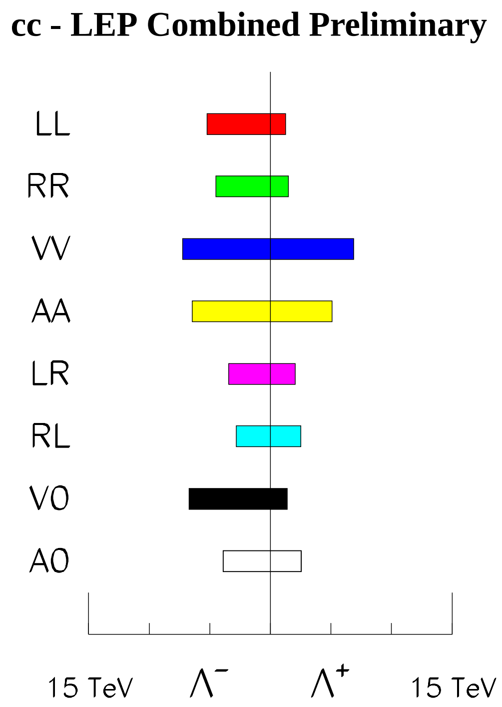


Contact Interactions for quarks

Heavy flavour measurements give limits on eebb, eecc C.I.

These limits and those on eell only accessible to LEP data

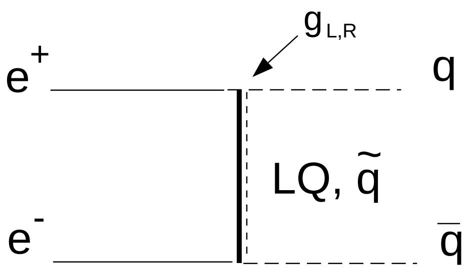




bb **$\Lambda > 2.2 - 14.6$ TeV** (95% C.L.)

cc **$\Lambda > 1.4 - 7.4$ TeV** (95% C.L.)

Leptoquarks / RPV squarks



$S_0(L) \Leftrightarrow \tilde{d}$

$\tilde{S}_{1/2}(L) \Leftrightarrow \tilde{\bar{u}}$

From all $q\bar{q}$ cross sections and asymmetries

	Limit on scalar LQ mass (GeV/c^2)						
	$S_0(L)$	$S_0(R)$	$\tilde{S}_0(R)$	$S_{\frac{1}{2}}(L)$	$S_{\frac{1}{2}}(R)$	$\tilde{S}_{\frac{1}{2}}(L)$	$S_1(L)$
LQ_{1st}	632	103	170	179	158	-	387
LQ_{2nd}	593	-	174	180	167	-	405
LQ_{3rd}	NA	NA	358	NA	-	136	747
	Limit on vector LQ mass (GeV/c^2)						
	$V_0(L)$	$V_0(R)$	$\tilde{V}_0(R)$	$V_{\frac{1}{2}}(L)$	$V_{\frac{1}{2}}(R)$	$\tilde{V}_{\frac{1}{2}}(L)$	$V_1(L)$
LQ_{1st}	829	147	409	167	340	120	620
LQ_{2nd}	846	148	408	168	314	120	633
LQ_{3rd}	448	183	NA	196	353	NA	448

LQ: $g_L.g_R$ strongly constrained by low energy data

Assume only one non-vanishing coupling at a time

ALEPH preliminary ($g^2 = 4\pi\alpha$)

(data with $s^{1/2} \leq 202$ GeV)

Limits much higher than the beam energy

For comparison, Direct Limits for 1st generation LQ:

from Tevatron ~ 225 GeV (indip. of g) if LQ decays 100% to charged lepton

from Hera ~ 275-290 GeV ($g^2 = 4\pi\alpha$)

Indirect limits from Low energy data (atomic parity violation, rare decays)

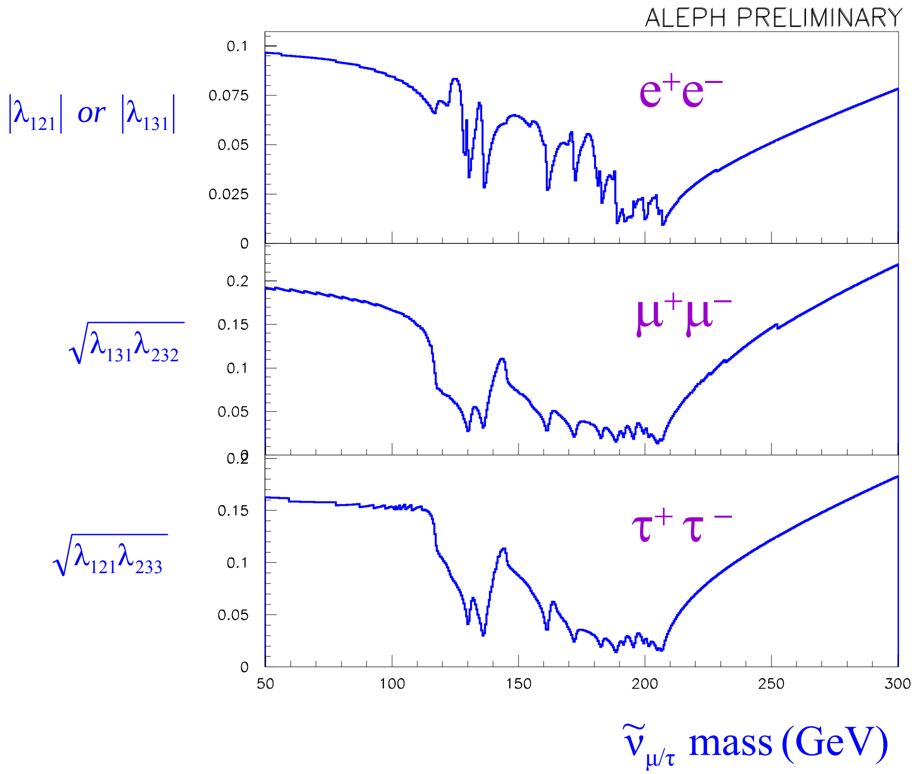
~ 430-1500 GeV ($g^2 = 4\pi\alpha$)

RPV Sneutrinos

Superpotential term $\lambda_{ijk} L^i_L L^j_L \overline{E}^k_R \quad (i < j)$

would contribute to dilepton production via both s- and t-channel diagrams

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



Fit to differential cross sections assuming $\Gamma_{\tilde{\nu}} \leq 1$GeV

If only one non-zero coupling is assumed only t-channel exchange is possible for μμ and ττ final states
⇒ weaker limits

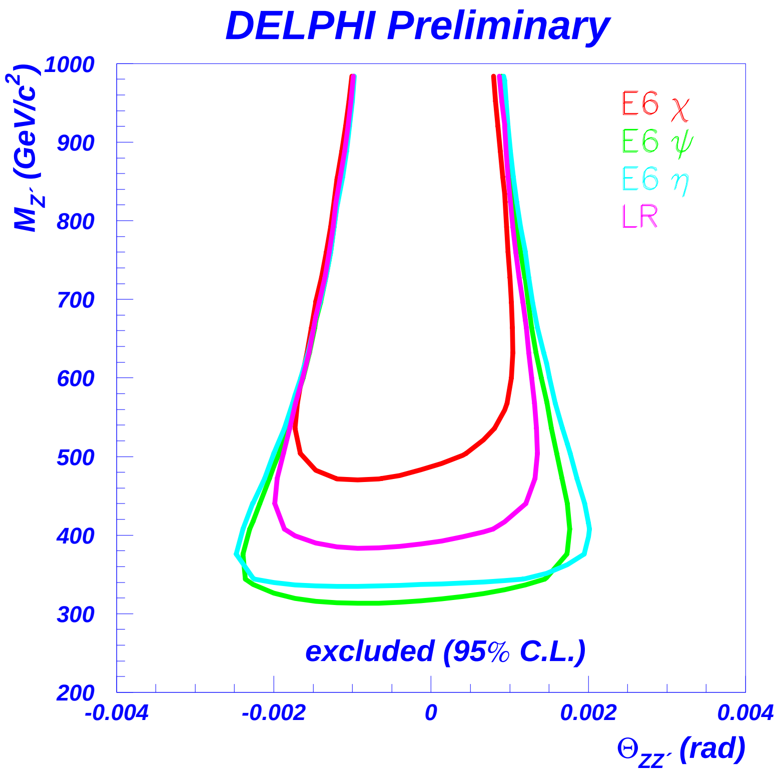
$m_{\tilde{\nu}}$	100 GeV	200 GeV	
$\lvert\lambda_{121}\rvert$	< 0.21	< 0.28	@ 95% C.L.
$\lvert\lambda_{131}\rvert$	< 0.48	< 0.66	(DELPHI)

Extra Z Bosons

Model dependent fits of both LEP1 and LEP2 data

$\theta_{ZZ'}$ ← → $M_{Z'}$

($qq/\mu\mu/\tau\tau$ cross sections + μ/τ asymmetries)



Predicted in **GUT** theories

E(6) $\Rightarrow$ χ, ψ, η models

Left-Right simmetric (LR)

Sequential Standard Model (SSM)

Prel. LEP combination (all LEP2 data)

assuming $\theta_{ZZ'} = 0$ **Lower limits @ 95% C.L.**

Model	χ	ψ	η	L-R	SSM
$M_{Z'}^{limit}$ (GeV/c^2)	678	463	436	800	1890

Model independent fits to *ll* channels assuming universality (DELPHI), $\theta_{ZZ'} = 0$

Limits on normalized couplings (for a given $M_{Z'}$ and $g'^2 = 4\pi$)

$$|a_l^N| = a_l \sqrt{\frac{s}{m_{Z'}^2 - s}} < 0.19 \qquad |v_l^N| < 0.21$$

Low Scale Gravity

Extreme weakness of gravity
→ Hierarchy problem

$$M_{Pl} = G_N^{-1/2} \cong 10^{19} \text{ GeV} >> M_{EW} \cong 10^3 \text{ GeV}$$

Possible solution by *Arkani-Hamed, Dimopoulos, Dvali* : quantum gravity scale could be ≈ 1 TeV if gravitons propagate in large **extra-dimensions** while other particles are confined to **3+1** dimensions

$$M_{Pl}^2 \approx R^n M_D^{n+2}$$

n: number of extra-dimensions

$$M_D \approx M_{EW}$$

R: compactification radius

For $n = 1$ this happens at $R \cong 10^{13}$ cm → **excluded !**

$n = 2$: $R \cong 0.1–1$ mm → (stringent bounds from SN1987A)

$n = 3\text{-}7$: $R \cong 1$ nm – 1 fm

→ **Not excluded by current gravity meas.**

The size of extra dimensions could be within reach of present and future colliders

In our 4D-world gravitons would appear as massive due to momentum escaped into the extra dimensions

Low Scale Gravity

Virtual graviton exchange would modify fermion pair cross sections

$$\frac{d\sigma}{d\cos\theta} = A(s,t) + \frac{\lambda}{M_s^4} B(s,t) + \frac{\lambda^2}{M_s^8} C(s,t)$$

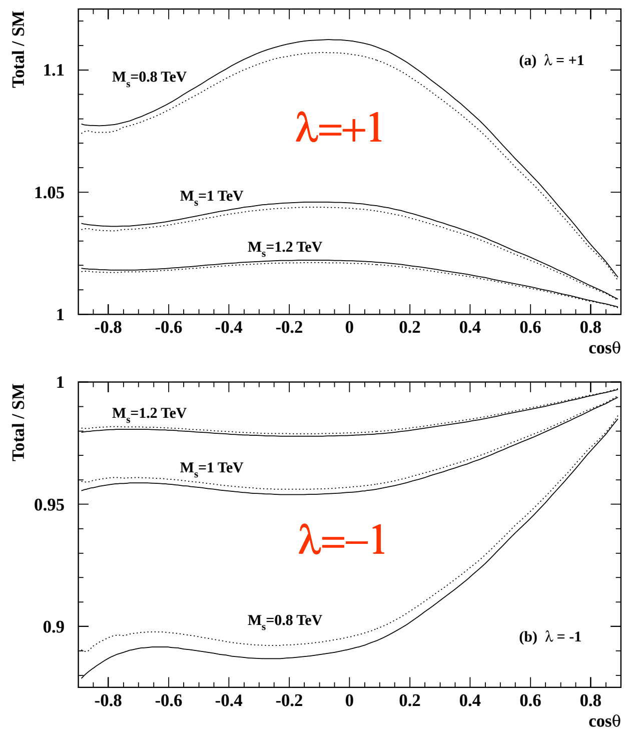
$M_s \approx M_D$ *(Hewett, Rizzo)*

$\lambda \approx O(1)$ depending on the full theory (weakly on n)

Similar to Contact Interaction but:

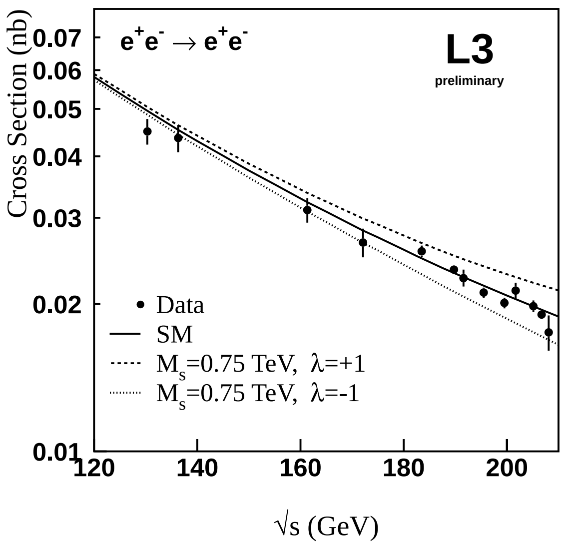
- scale dependence $\approx 1/M^4$,
- angular distribution has terms with $\cos^3\theta$, $\cos^4\theta$

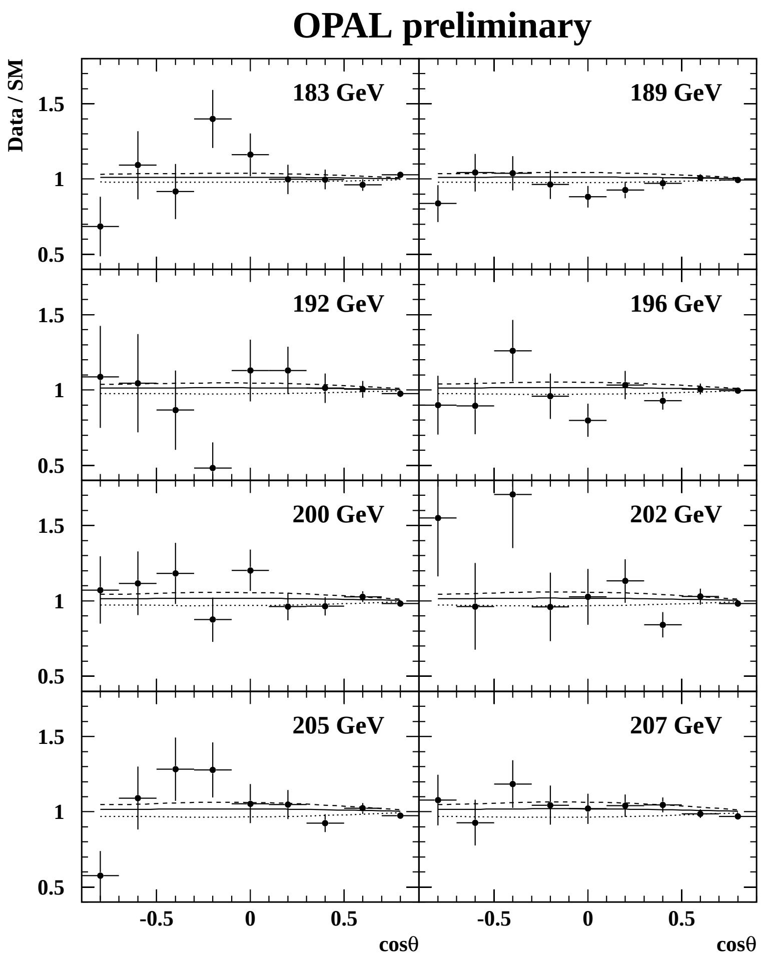
Maximum sensitivity in **Bhabha** scattering due to interference with t-channel γ –exchange



Fractional deviation from SM decreases at large cosθ
⇒ effect on the *Luminosity* meas. $< 10^{-4}$ for M_s =1 TeV

Extra Dimensions - results from Bhabha





Ms lower limits (TeV) @ 95% C.L.

	λ = +1	λ = -1
ALEPH	> 1.18	> 0.80
L3	> 1.06	> 0.98
OPAL	> 1.00	> 1.15

TeV Strings – results from Bhabha

String theory of quantum gravity could lead to contact interactions, with stronger effects than virtual graviton exchange.

(Accomando, Antoniadis, Benakli

Cullen, Perelstein, Peskin)

Bhabha cross section modified to:

$$\frac{d\sigma}{d\cos\theta} = \left(\frac{d\sigma}{d\cos\theta}\right)_{SM} \left| \frac{\Gamma(1-\frac{s}{M_S^2})\Gamma(1-\frac{t}{M_S^2})}{\Gamma(1-\frac{s}{M_S^2}-\frac{t}{M_S^2})} \right|^2$$

M_s string scale

L3 preliminary result:
$M_s > 0.57$ TeV @ 95% C.L.

Conclusions / Prospects

- Results (final / preliminary) from each experiment consistent with SM.

- Preliminary LEP combinations with the full statistics consistent with SM. *(Experimental Systematics under control and not dominant.)*

- No evidence for new physics, tight constraints set, some limits only accessible to LEP data.

- Each experiment should finalize data analyses soon.

- LEP data will be combined: final agreement on what to do within LEP Working Group (definitions, method, common uncertainties, ...)

- Combine measurements of electron pairs, most sensitive channel for many indirect searches. *(Theoretical uncertainties could be the dominant ones)*

- Cover as many interpretations as possible.