Fermion-pair Production above the Z and Search for New Phenomena

D.Bourilkov

ETH - Zürich

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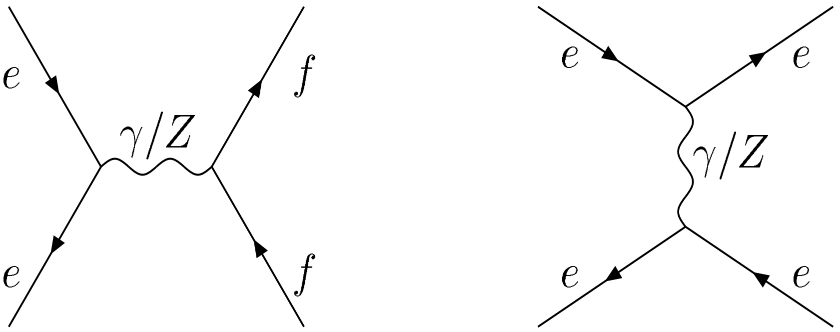
- **Fermion-pair production above the Z**
- **Measurements of cross sections and asymmetries at LEP2**
  Leptons: $e^+e^- \longrightarrow l^+l^-(\gamma)$
  Hadrons: $e^+e^- \longrightarrow q\bar{q}(\gamma)$
  Flavour-tagged: b, c, uds
- **Searches for new phenomena**
  Contact interactions & Compositeness
  R-parity breaking: sneutrino/squark exchange
  Leptoquarks
  Z'



$$|\sum_{i=1}^{n} A_i|^2 = \sum_{i=1}^{n} |A_i|^2 + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} \mathrm{Re} A_i A_j^*$$

$$\frac{d\sigma}{d\Omega} = |\gamma_s + Z_s + \mathrm{elec} * (\gamma_t + Z_t) + \text{New Physics ?!}|^2$$

Helicity amplitudes

$$\mathcal{A}^{ef}_{LR(RL)}(s) = (Q_e Q_f + C^e_{L(R)} C^f_{R(L)} \chi(s)) \frac{t}{s}$$

$$\mathcal{A}^{ef}_{LL(RR)}(s) = (Q_e Q_f + C^e_{L(R)} C^f_{L(R)} \chi(s)) \frac{u}{s}$$

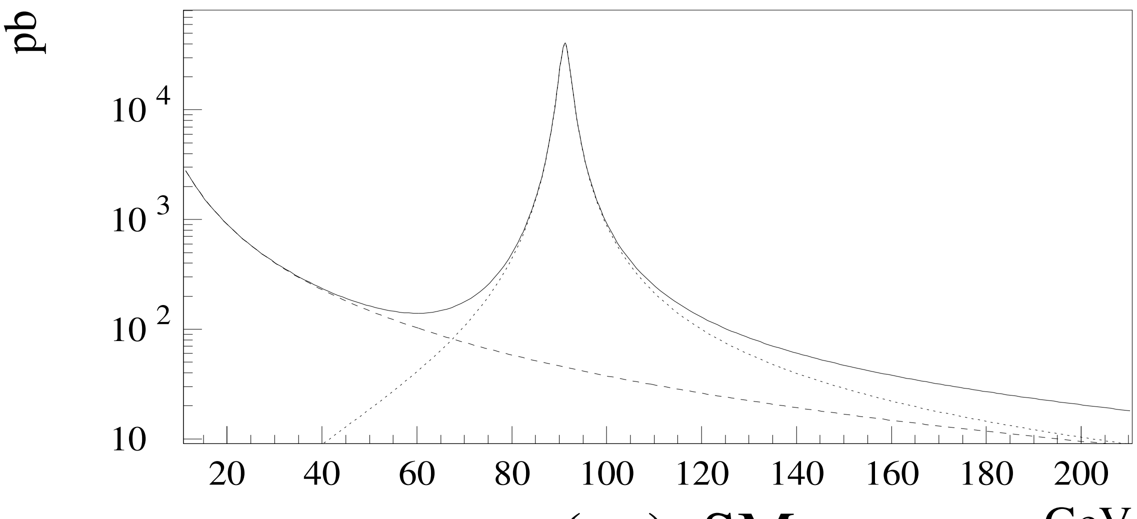
$$\chi(s) = \frac{s}{(s - M_Z^2) + \imath s \frac{\Gamma_Z}{M_Z}} \quad \chi(t) = \frac{t}{(t - M_Z^2)}$$

$$C_R = v - a \qquad v_f = \frac{1}{2 s_W c_W}(T_f^3 - 2 s_W^2 Q_f)$$
$$C_L = v + a \qquad a_f = \frac{1}{2 s_W c_W} T_f^3$$

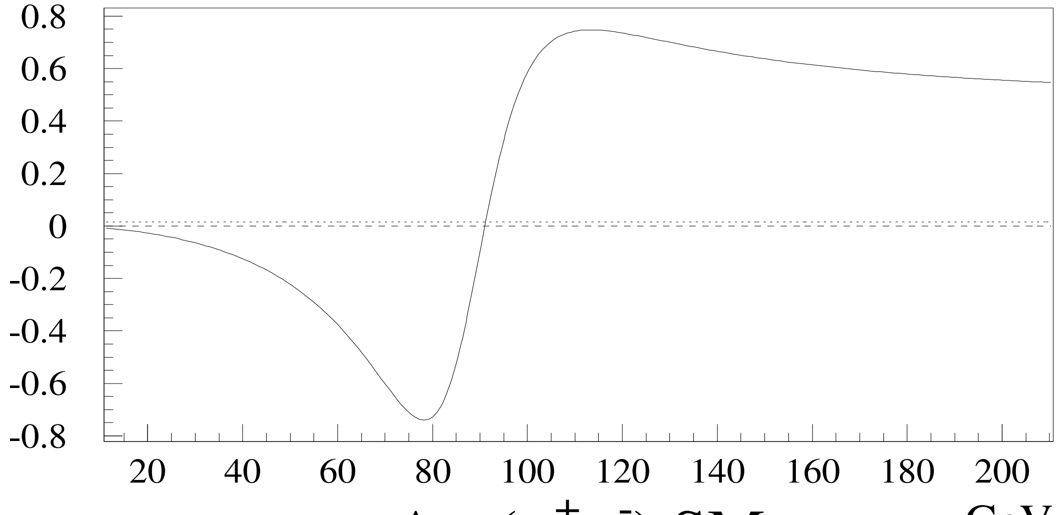
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}[A_0(1+\cos^2\theta) + A_1\cos\theta]$$

$$A_0 = Q_e^2 Q_f^2 + 2Q_eQ_fv_ev_f\Re\chi(s) + (v_e^2 + a_e^2)(v_f^2 + a_f^2)|\chi(s)|^2$$

$$A_1 = 4Q_eQ_fa_ea_f\Re\chi(s) + 8v_ea_ev_fa_f|\chi(s)|^2$$



σ(qq) SM



$A_{FB}(\mu^+\mu^-)$ SM

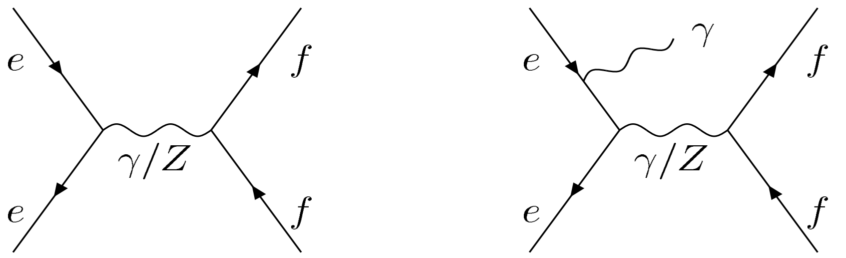
- Data from all four LEP experiments: 130-172 GeV some final, some preliminary, 183 GeV preliminary
- Up to 172 GeV statistical errors dominant
- At 183 GeV & 55 pb^{-1} systematic effects gain in importance

Year	$\sqrt{s}$ [GeV]	$\mathcal{L}$/expt [pb^{-1}]
1995 & 1997	130	~ 6
1995 & 1997	136	~ 6
1996	161	~ 10
1996	172	~ 10
1997	183	~ 55

Extension of selections on the Z peak , but

- ISR radiation (‘return to the Z’)
  $\Rightarrow$ acollinear events

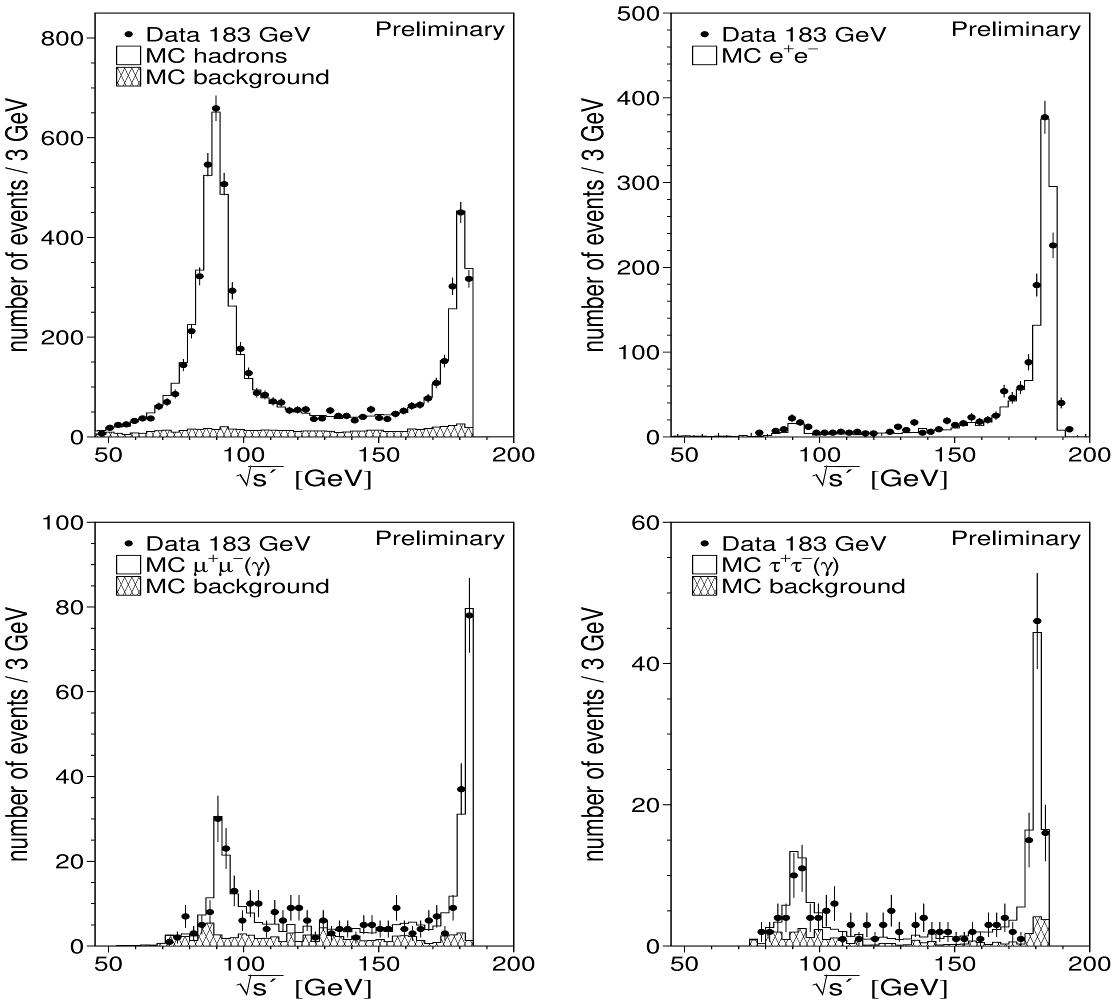
Non-radiative Radiative Return



- Cross section $\sim 10^{-2}$ of Z peak values
  - higher non-annihilation background (beam-wall/gas, cosmic muons)
  - higher 2-γ background ($\mathrm{e^+e^-} \longrightarrow \mathrm{e^+e^-}\ \mathrm{f\bar{f}}$)
- 4-fermion ‘background’ (W^+W^-, ZZ, Z $\mathrm{e^+e^-}$, $We\nu$, ...)

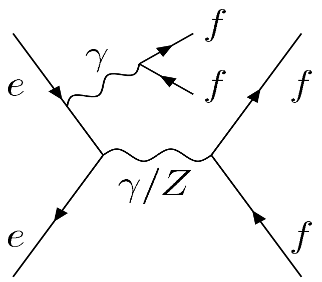
Effective CMS Energy $\sqrt{s'}$

- Cross sections and asymmetries measured for:
  inclusive events - $\sqrt{s'}/\sqrt{s} > 0.1$
  non-radiative events - $\sqrt{s'}/\sqrt{s} > 0.85 - 0.90$
- The non-radiative sample is the main search field for new physics
- s' is calculated from ISR photon seen in the detector or from the angles of outgoing fermions / kinematic fit



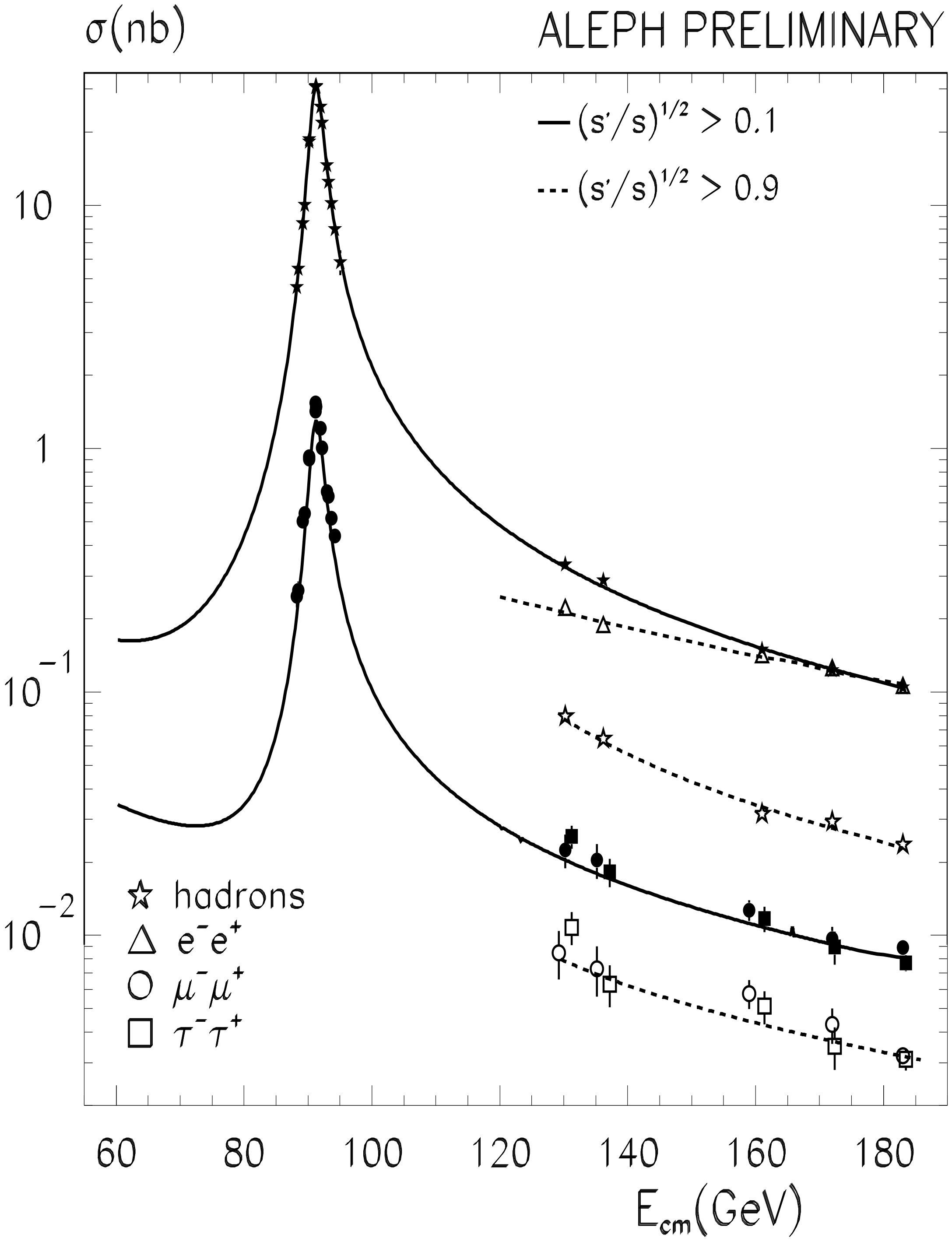
Problems

- Definition of s′ is not unique due to interference between initial- and final-state radiation
  OPAL corrects cross-sections to ‘no interference’ (corrections are $\sim$ 1-2 % for $\sqrt{s'}/\sqrt{s} > 0.85$ and rely on the theoretical estimate calculated only to $\mathcal{O}(\alpha)$)
  ALEPH prefers an inclusive approach and defines $\sqrt{s'}$ as the effective mass of the outgoing fermion pair
- Treatment of 4-fermion events



low mass fermion pairs are signal, like photons
the corrections are negligible for the non-radiative sample

Update for 183 GeV by
ALEPH, DELPHI, L3, OPAL
Good agreement with SM predictions



Update for 183 GeV by
ALEPH, DELPHI, L3, OPAL
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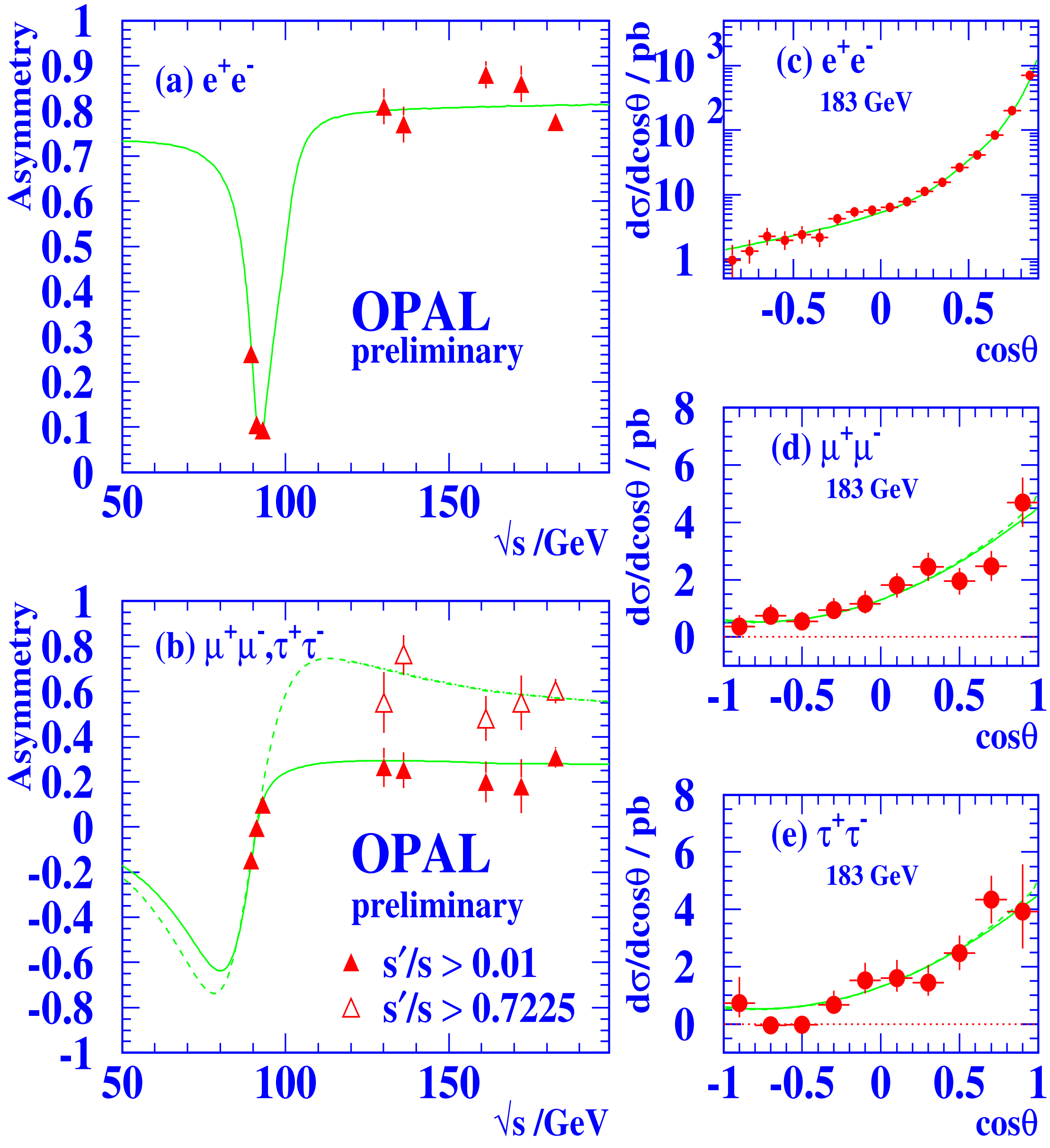
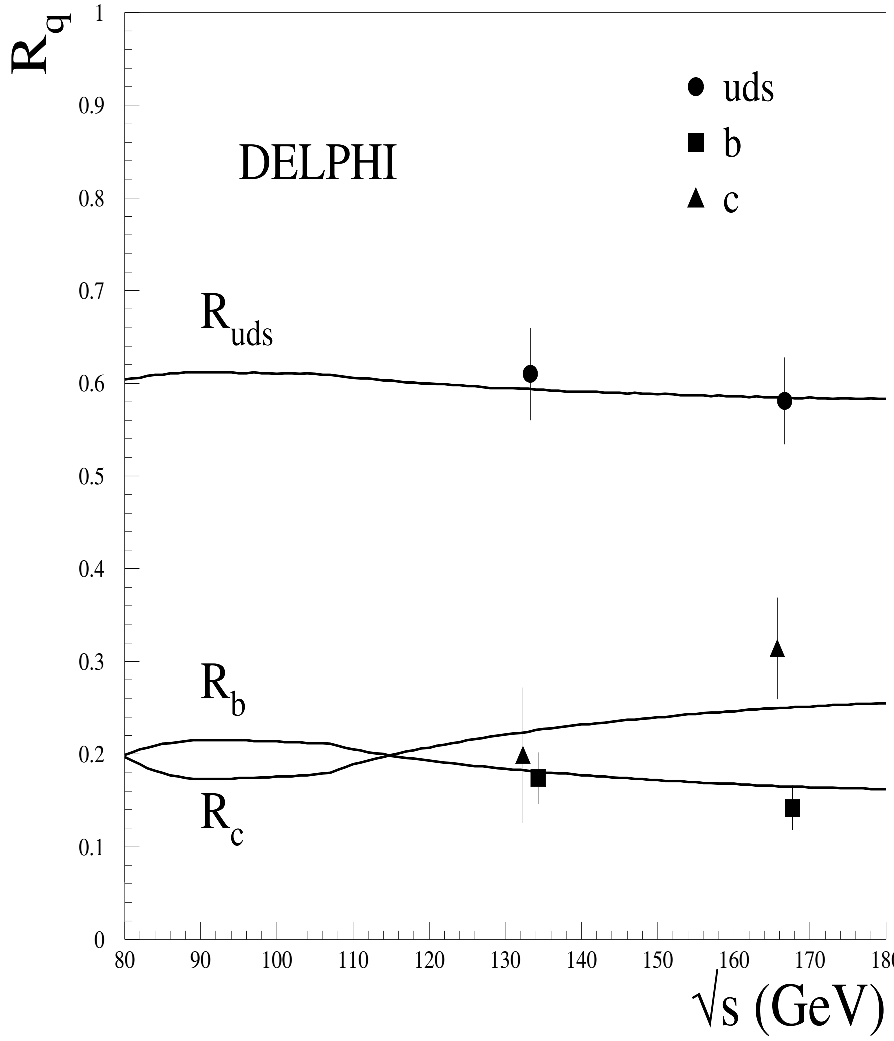


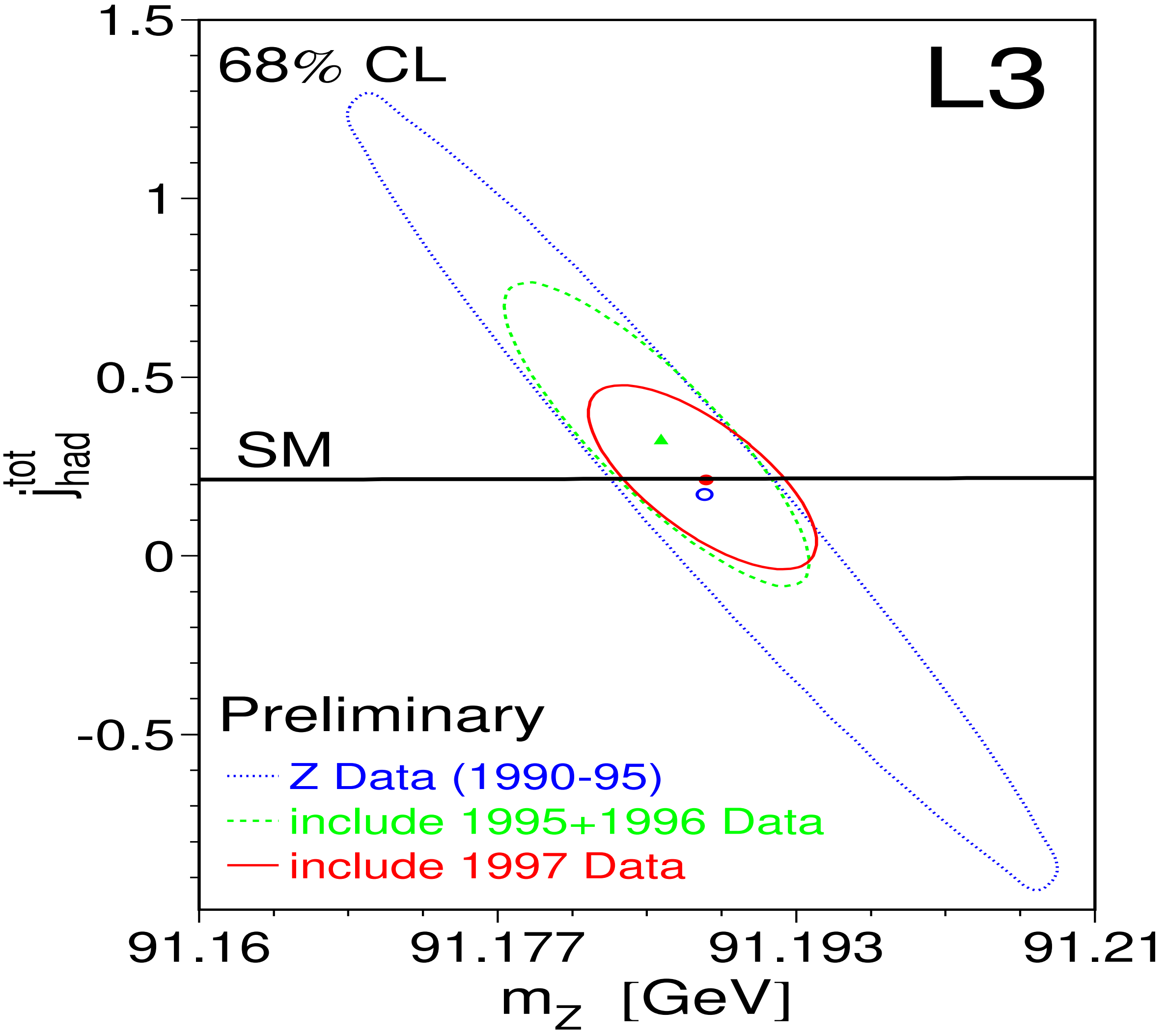
R_b by ALEPH, DELPHI, OPAL
R_c, R_{uds} & A_{FB} by DELPHI
Good agreement with SM predictions

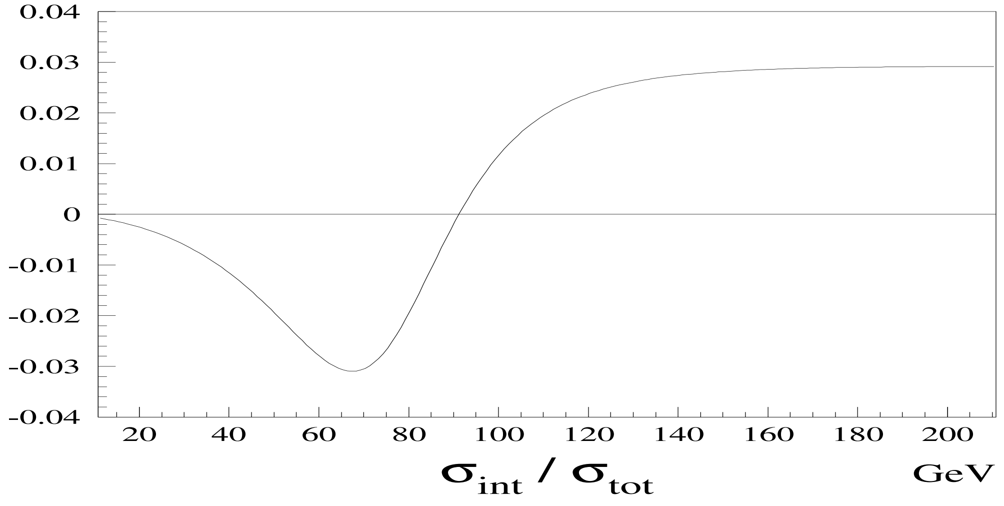
Experiment	R_b at 183 GeV	SM Prediction
ALEPH	0.186 ± 0.018	0.165
OPAL	0.190 ± 0.023	0.163

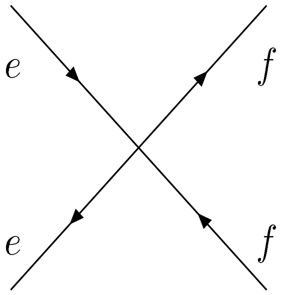


Update for 183 GeV by L3

Reduced correlation and errors on m_Z, j^{tot}_{had}







general framework for a new interaction with coupling g and typical energy scale $\Lambda \gg \sqrt{\mathrm{s}}$

$$\mathcal{L}^{\mathrm{ef}}_{\mathrm{contact}} = \frac{1}{(1+\delta_{\mathrm{ef}})} \frac{\mathrm{g}^2}{\Lambda^2} \sum_{\mathrm{i,j=L,R}} \eta_{\mathrm{ij}} [\bar{\mathrm{e}}_{\mathrm{i}} \gamma^{\mu} \mathrm{e}_{\mathrm{i}}][\bar{\mathrm{f}}_{\mathrm{j}} \gamma_{\mu} \mathrm{f}_{\mathrm{j}}]$$

by convention $\frac{g^2}{4\pi} = 1$ and $|\eta_{ij}| \leq 1$; $\varepsilon = \frac{\mathrm{g}^2}{4\pi} \frac{\mathrm{sign}(\eta)}{\Lambda^2}$

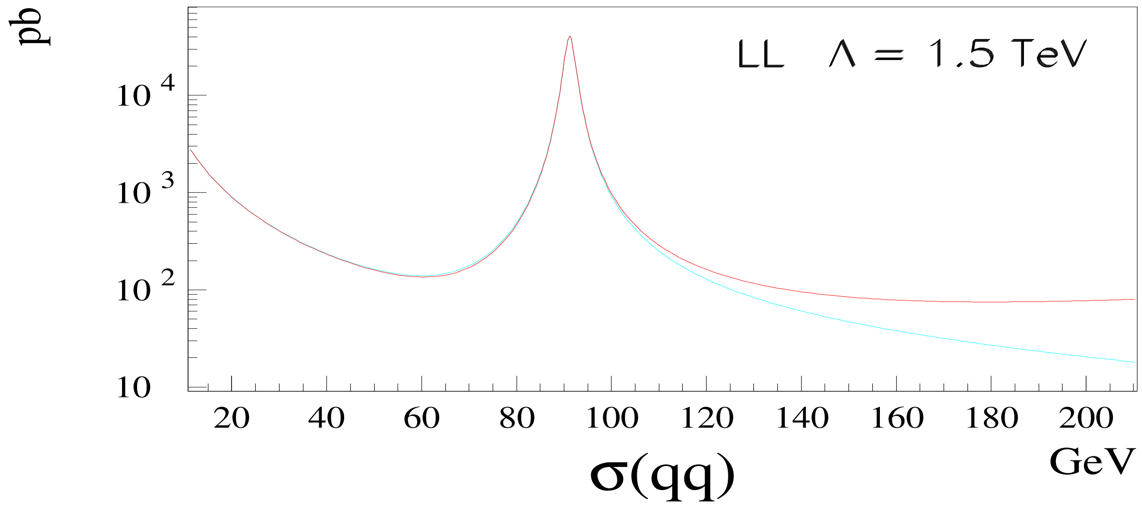
$$\mathcal{A}^{\mathrm{ef}}_{\mathrm{LR(RL)}}(\mathrm{s}) = (\mathcal{A}^{\mathrm{SM}}_{\mathrm{LR(RL)}} + \eta_{\mathrm{LR(RL)}} \frac{\mathrm{s}}{\alpha} \frac{1}{\Lambda^2}) \frac{\mathrm{t}}{\mathrm{s}}$$

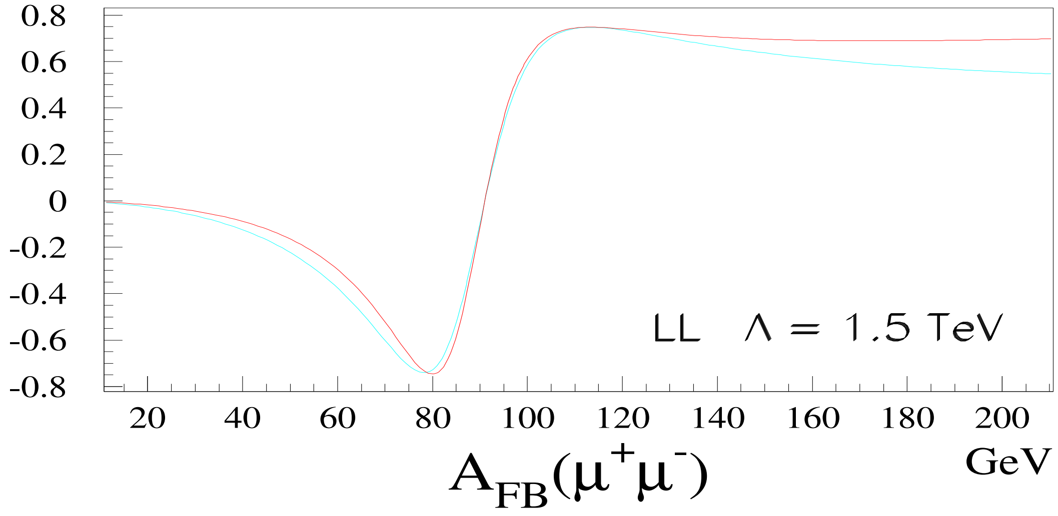
$$\mathcal{A}^{\mathrm{ef}}_{\mathrm{LL(RR)}}(\mathrm{s}) = (\mathcal{A}^{\mathrm{SM}}_{\mathrm{LL(RR)}} + \eta_{\mathrm{LL(RR)}} \frac{\mathrm{s}}{\alpha} \frac{1}{\Lambda^2}) \frac{\mathrm{u}}{\mathrm{s}}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \mathrm{SM}(\mathrm{s},\mathrm{t}) + \frac{\mathrm{g}^2}{\Lambda^2} \mathrm{C}_{\mathrm{Int}}(\mathrm{s},\mathrm{t}) + \frac{\mathrm{g}^4}{\Lambda^4} \mathrm{C}_{\mathrm{NewPh}}(\mathrm{s},\mathrm{t})$$

Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}	$\tilde{\nu}$	$\tilde{q}$	Lepto-q
LL**	±1	0	0	0		$\tilde{d}$-type	$S_0(g_L)$
RR*	0	±1	0	0			
LR	0	0	±1	0	$\star$	$\tilde{u}$-type	$\tilde{S}_{1/2}$
RL	0	0	0	±1	$\star$		
VV	±1	±1	±1	±1			
AA	±1	±1	∓1	∓1			
LL+RR	±1	±1	0	0			
LR+RL	0	0	±1	±1			

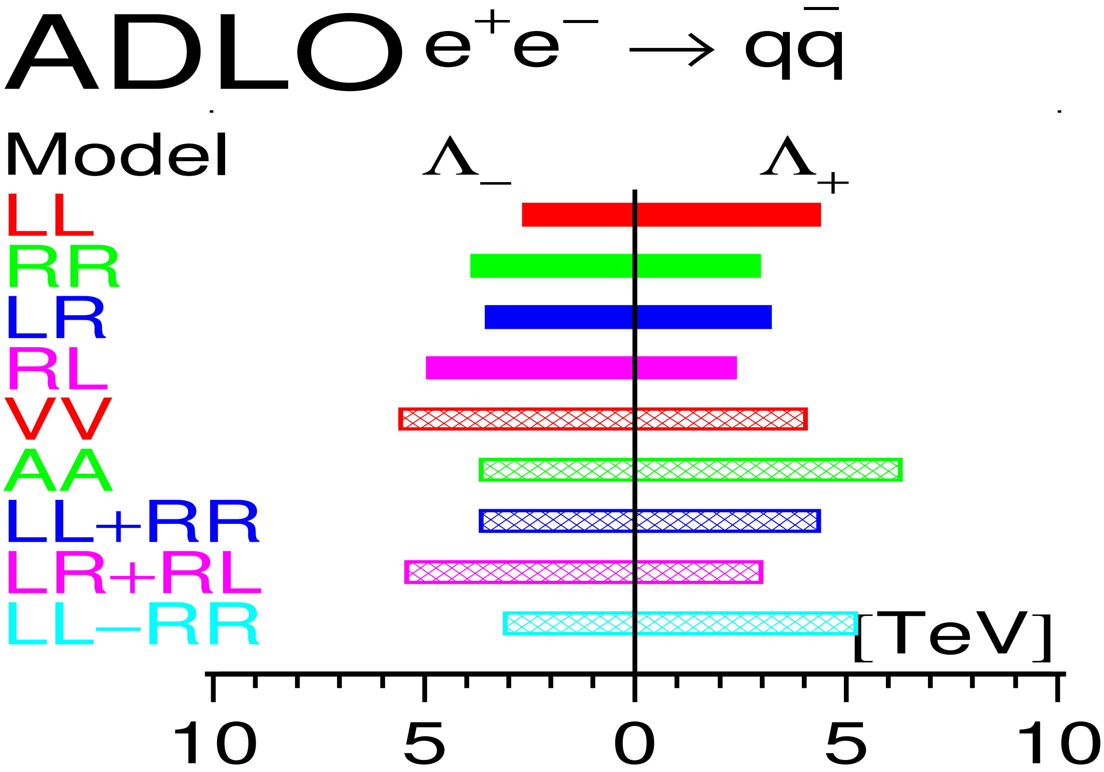
* - strongest amplitudes in the LEP2 energy range





l^+l^-	ALEPH		DELPHI		L3		OPAL	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	5.4	6.1	4.4	3.8	4.1	5.8	5.3	5.2
RR	5.2	5.9	4.2	3.7	4.0	5.6	5.1	5.0
LR	5.2	6.5	4.7	4.1	5.4	3.9	5.2	5.6
VV	9.4	11.8	8.2	7.1	8.5	8.5	9.3	9.6
AA	9.0	8.2	6.1	6.2	5.3	9.3	8.3	7.7
$q\bar{q}$	ALEPH		DELPHI		L3		OPAL	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	2.7	3.9	tag		2.5	3.8	2.8	4.4
RR	3.6	2.9			3.5	2.8	3.9	3.0
LR	3.4	3.1			3.2	3.0	3.6	3.3
VV	5.2	4.0			5.0	3.8	5.7	4.1
AA	3.7	5.6			3.5	5.6	3.8	6.3

Limits for e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, l^+l^-, $q\bar{q}$, $u\bar{u}$, $d\bar{d}$, flavour-tagged, $f\bar{f}$



the most general superpotential even for a minimal supersymmetric model contains interactions violating L (and B)

$$W_{\not{R}} = \lambda_{ijk} L_L^i L_L^j \bar{E}_R^k + \lambda'_{ijk} L_L^i Q_L^j \bar{D}_R^k + ...$$

L,Q - left-handed doublets of leptons, quarks

E,D - right-handed singlets of charged leptons, down-type quarks

ijk - generation indices

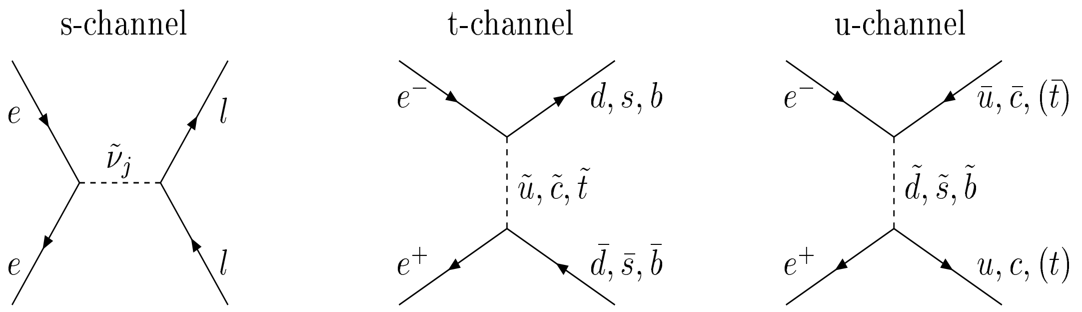
(9 λ + 27 $\lambda^{'}$ + ...) independent Yukawa couplings

$\lambda_{ijk} \neq 0$ only for $i \neq j$

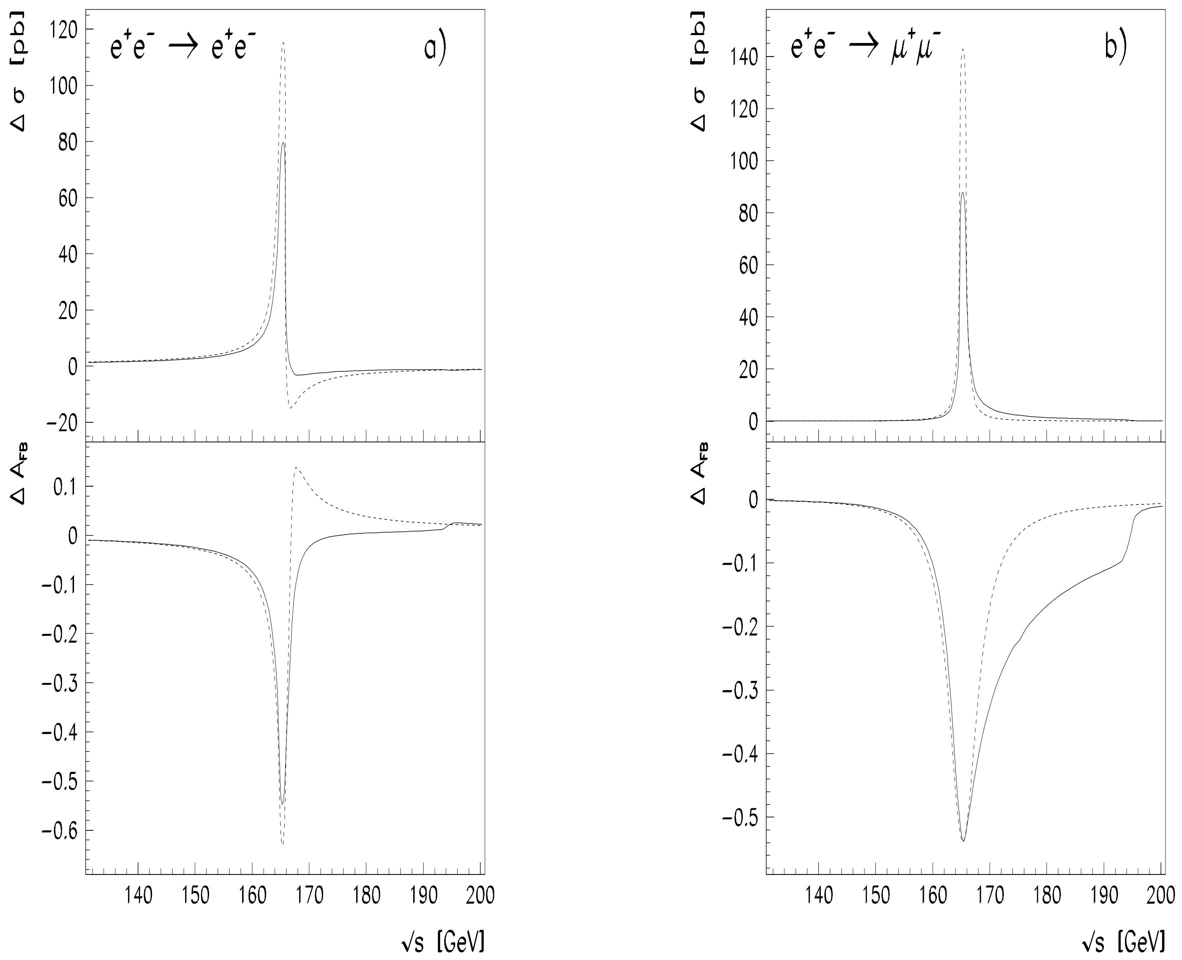
ijk	$\lambda_{\rm ijk}$	Source	*ijk*	$\lambda^{'}_{\rm ijk}$	Source
121	0.05*	CC univ.	111	0.00035	$(\beta\beta)0\nu$
122	0.05*	CC univ.	112	0.02*	CC univ.
123	0.05*	CC univ.	113	0.02*	CC univ.
131	0.06	$\Gamma(\tau \longrightarrow e\nu\bar{\nu})/\Gamma(\tau \longrightarrow \mu\nu\bar{\nu})$	121	0.035*	Atomic PV
132	0.06	$\Gamma(\tau \longrightarrow e\nu\bar{\nu})/\Gamma(\tau \longrightarrow \mu\nu\bar{\nu})$	122	0.02	ν_e mass
133	0.003	ν_e mass	123	0.20	$D^0 - \bar{D}^0$ mix.
231	0.06	$\Gamma(\tau \longrightarrow e\nu\bar{\nu})/\Gamma(\mu \longrightarrow e\nu\bar{\nu})$	131	0.035*	Atomic PV
232	0.06	$\Gamma(\tau \longrightarrow e\nu\bar{\nu})/\Gamma(\mu \longrightarrow e\nu\bar{\nu})$	132	0.34	R_e (LEP)
233	0.06	$\Gamma(\tau \longrightarrow e\nu\bar{\nu})/\Gamma(\mu \longrightarrow e\nu\bar{\nu})$	133	0.0007	ν_e mass

Limits for sparticle mass of 100 GeV (* - 2 σ limits)

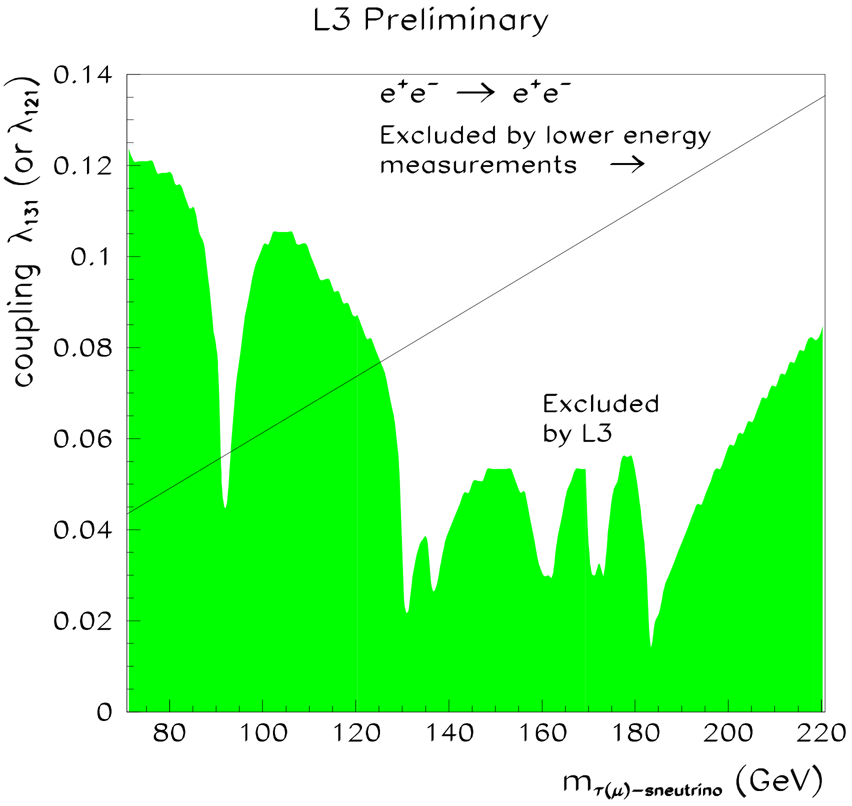
Resonance formation & t-channnel exchange of single $\tilde{\nu}$ / $\tilde{\mathrm{q}}$ in $\not{R}_P$ theories

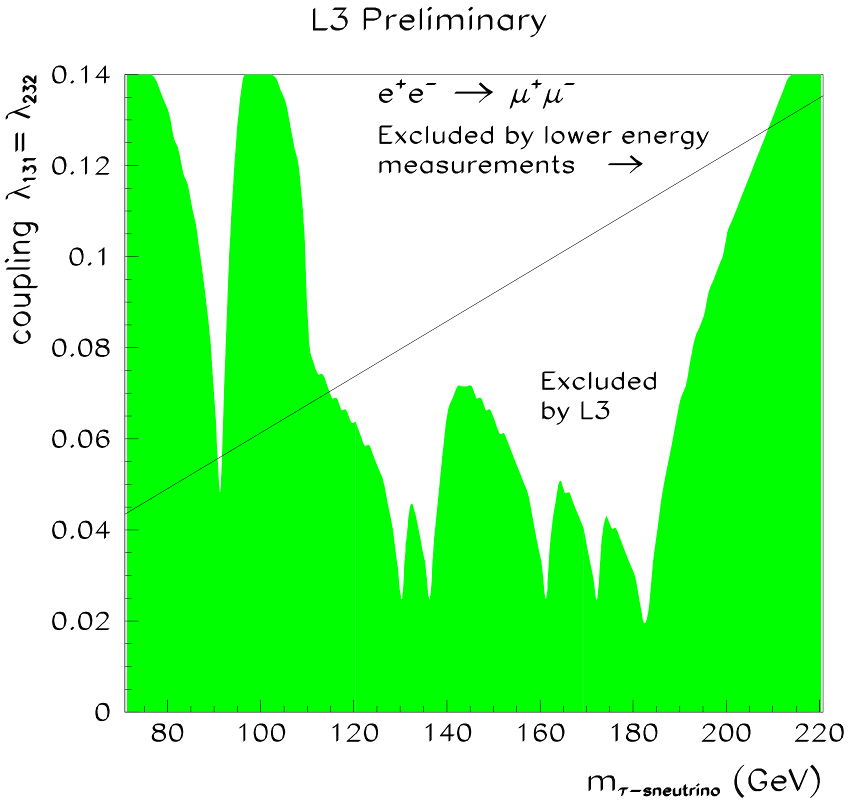


	s-channel	t/u-channel	Coupling
Amplitude	$\frac{1}{2} \cdot \frac{(\lambda_{1\mathrm{jk}}/\mathrm{e})^2 \cdot \mathrm{s}}{s - m_j^2 + i\Gamma_j m_j}$	$\frac{1}{2} \cdot \frac{(\lambda_{1\mathrm{jk}}/\mathrm{e})^2 \cdot \mathrm{s}}{t - m_j^2}$	$\frac{\lambda}{\mathrm{m_X}} \simeq \frac{\sqrt{8\pi}}{\Lambda} \Rightarrow \lambda \simeq 5.01 \frac{\mathrm{m_X}}{\Lambda}$



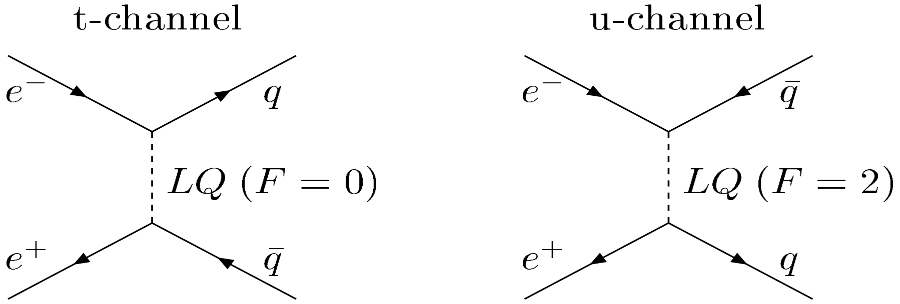
Results from L3, DELPHI, OPAL (s′-scan)





Leptoquarks appear in many unification theories

- carry fermion number, F = L + 3B
- have fractional charge
- conserve B and L, couple family diagonal
- have spin 0 (scalar LQ S_I) or 1 (vector LQ V_I)
- couple either to left- or right-handed quarks

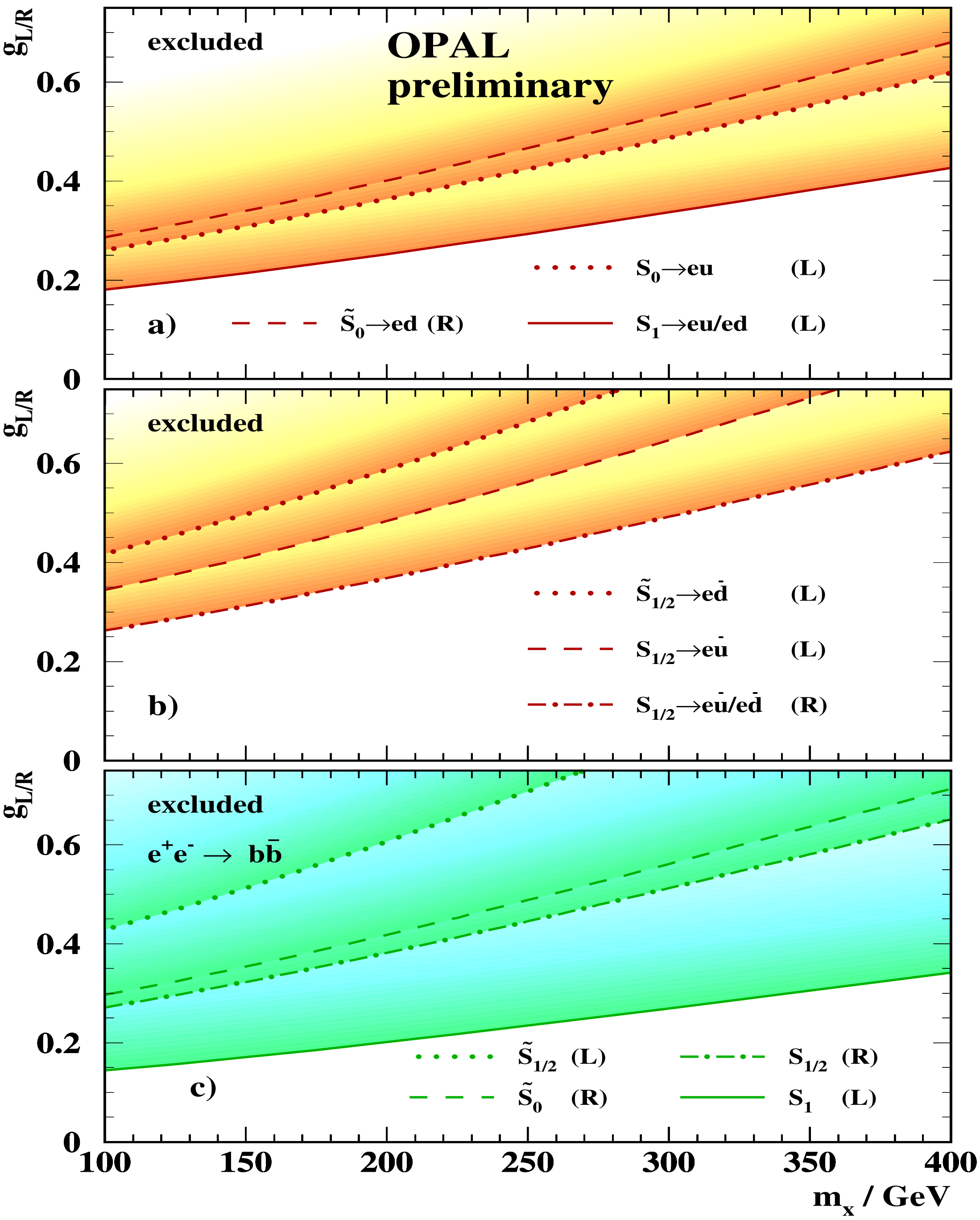


- CDF and DØ exclude scalar LQ with mass below 225 GeV and $\beta(\mathrm{LQ} \to \mathrm{lq}) = 1$
- at LEP2 we can search for higher LQ masses if the coupling is sizeable

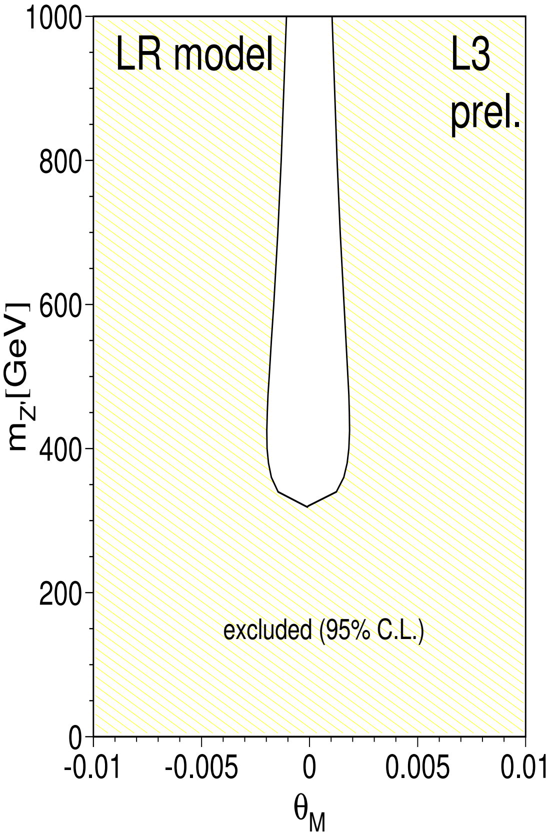
$\widetilde{\mathrm{S}}_{1/2}$ - limit on $\lambda'_{1\mathrm{jk}}$, $(j = 1, 2, 3)$ - exchanged $\tilde{u}_L - type$,
$(k = 1, 2, 3)$ - final state $d - type$

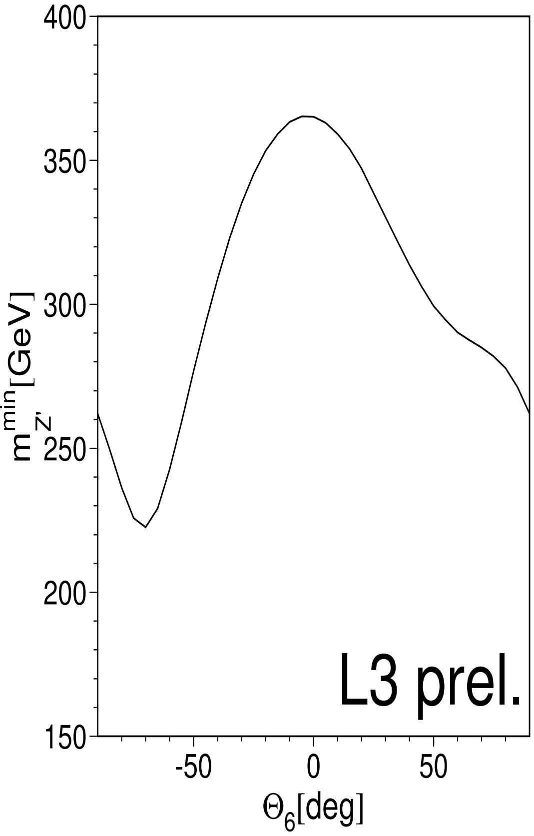
$\mathrm{S}_0(\mathrm{L})$ - limit on $\lambda'_{1\mathrm{jk}}$, $(j = 1, 2)$ - final state $u - type$,
$(k = 1, 2, 3)$ - exchanged $\tilde{d}_R - type$

Limits on the coupling for Scalar Leptoquarks



- mass $m_{Z'}$, Z' couplings, $Z - Z'$ mixing θ_M
- E$_6$ models ($\chi,\ \psi,\ \eta$ - $\Theta_6 = 0;\ \frac{\pi}{2};\ \arctan\sqrt{\frac{5}{3}}$)
  LR models (α_{LR})





- if $\theta_M = 0$ and SM couplings, $m_{Z'} > 805\ GeV$ @ 95 % CL (similar CDF limit 690 GeV)
- do not fix Z' model $\Rightarrow$
  model independent limits on the couplings $Z'l\bar{l}$ -
  $|\mathrm{v}'_\mathrm{l}|, |\mathrm{a}'_\mathrm{l}| < 0.7$ for $m_{Z'} = 500\ GeV$

Outlook

- the Standard Model describes all fermion-pair production measurements up to 183 GeV

- no hint for new phenomena so far

- new or improved limits obtained:
  contact interactions, $\widetilde{\nu}/\widetilde{\mathrm{q}}$, leptoquarks, Z'

- the LEP2 discovery potential is large; we are looking forward to more data at higher energies

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