



# Two-fermion Production at LEP(2)

measurements and interpretations

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## Summary

Channel description and Physics  
motivations

Data analysis

Results

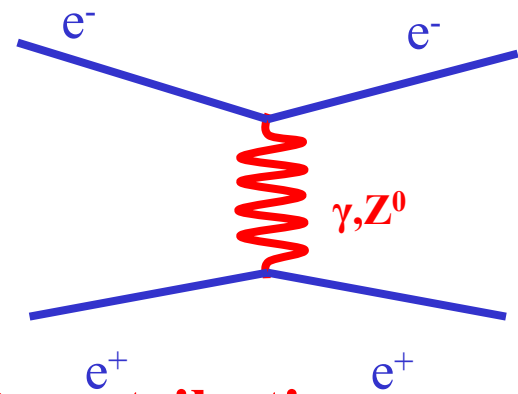
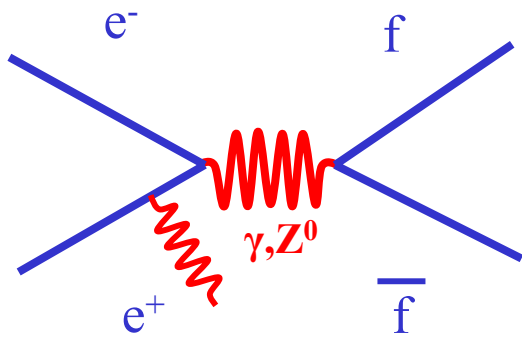
Excursus to two-photon production

Interpretations

Conclusions

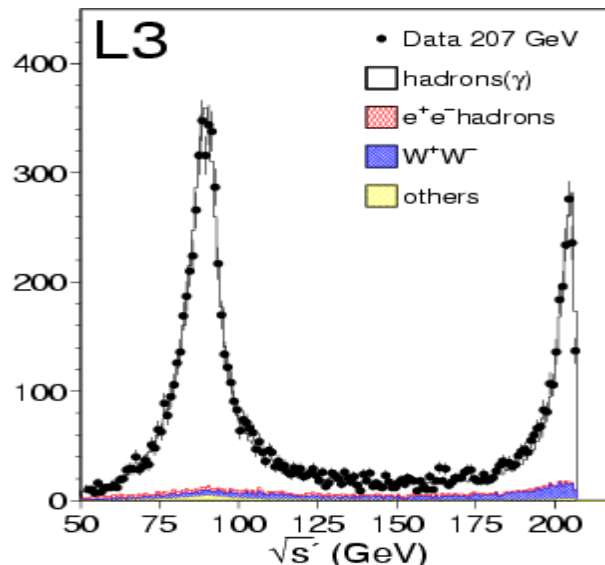
# Channel description and Physics motivations

## Standard Model production



but at LEP 2:

large ISR contribution



‘radiative  
return to  $Z^0$ ’

# Channel description and Physics motivations

$$e^+ e^- \rightarrow f \bar{f} (\gamma)$$

- **Test of Standard Model :**

- measured quantities ( $\sigma, d\sigma/d\cos(\theta), A_{FB}, \dots$ ) compared with SM predictions
- check of the  $Z\gamma$  interference (S-Matrix fit)

- **Search for Physics Beyond the SM**

- virtual effects  $\Rightarrow$  well above kinematic limit (sensitivity from interf.)
- test of specific models
- largest sensitivity on non radiative events

NB: 'clean' channel with signal much larger than expected backgrounds

# Data analysis

**LEP2 data set:  $\sim 700 \text{ pb}^{-1}$  per experiment**

**Final state measurements vs experiment**

$q\bar{q}$   $\sigma$  ADLO

$\mu^+\mu^-, \tau^+\tau^-$   $\sigma, A_{\text{FB}}, d\sigma/d\cos\theta$  ADLO

$e^+e^-$   $\sigma, A_{\text{FB}}, d\sigma/d\cos\theta$  ADLO

$b\bar{b}, c\bar{c}$   $R, A_{\text{FB}}$  ADLO

with

$$A_{\text{FB}} = \frac{N_{\cos\theta > 0} - N_{\cos\theta < 0}}{N_{\cos\theta > 0} + N_{\cos\theta < 0}}$$

$$R_{b,c} = \frac{\sigma_{b\bar{b}, c\bar{c}}}{\sigma_{q\bar{q}}}$$

$\sqrt{s}$ (GeV)	Year	$\sim \int \mathcal{L} dt$ ( $\text{pb}^{-1}$ )
130	95/97	6
136	95/97	6
161	96	10
172	96	10
183	97	55
189	98	155
192	99	25
196	99	75
200	99	85
202	99	40
205	00	85
207	00	140
<b>LEP2</b>	<b>95-00</b>	<b><math>\sim 700</math></b>

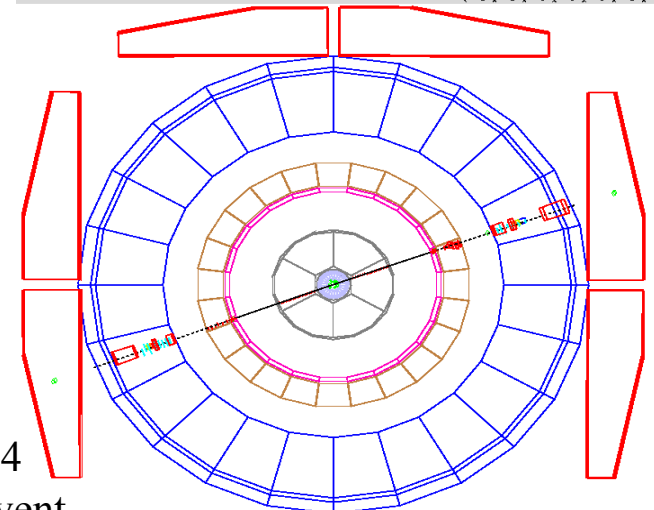
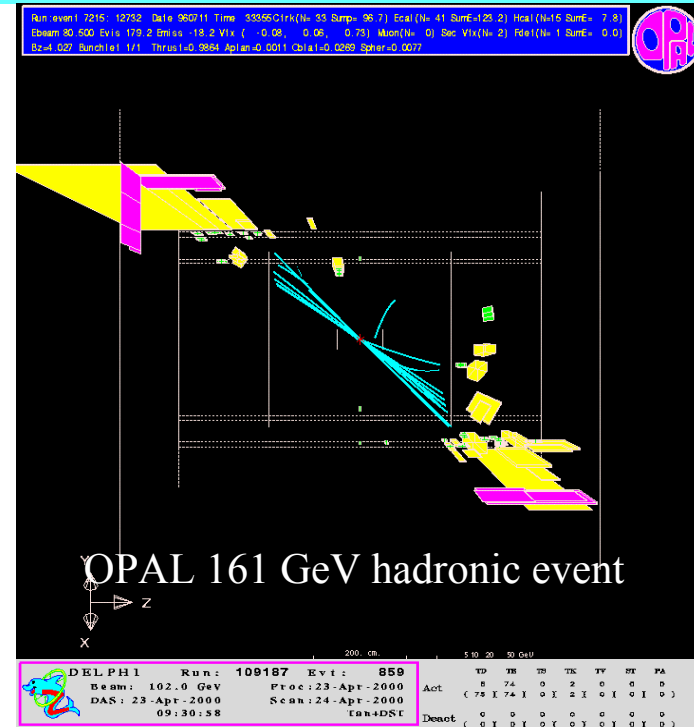
**LEP ElectroWeak Working Group:**  
**all measurements combined taking into account**  
**systematic effects and correlations**

results are still preliminary

# Data analysis

selection efficiencies and backgrounds given the clean topology and large signal:

$q\bar{q}$	eff. ~90%	bckg. 10-50% (WW,ZZ rejection)
$\mu^+\mu^-$	eff. ~90%	bckg. 1-3%
$\tau^+\tau^-$	eff. ~50%	bckg. ~10%
$e^+e^-$	eff. ~90%	bckg. <1%

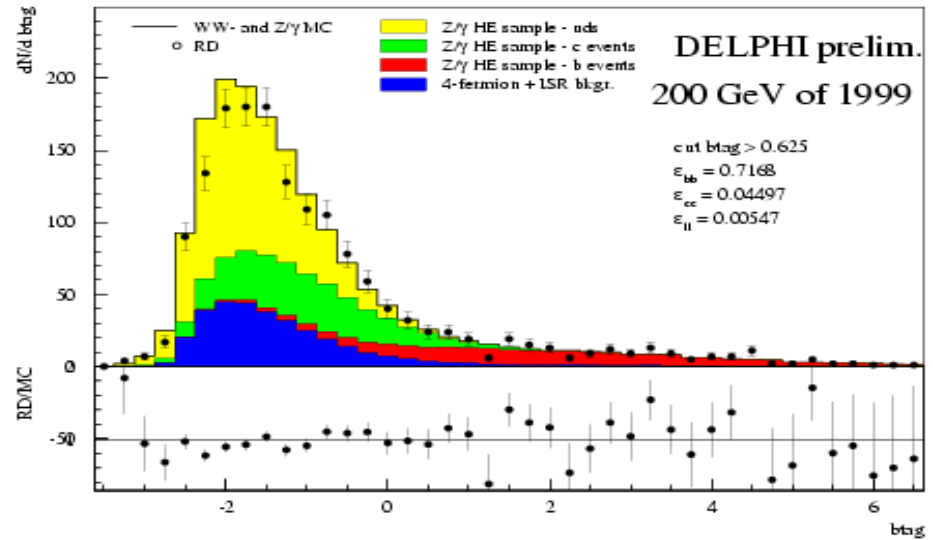


# Data analysis

## Flavour Tagging

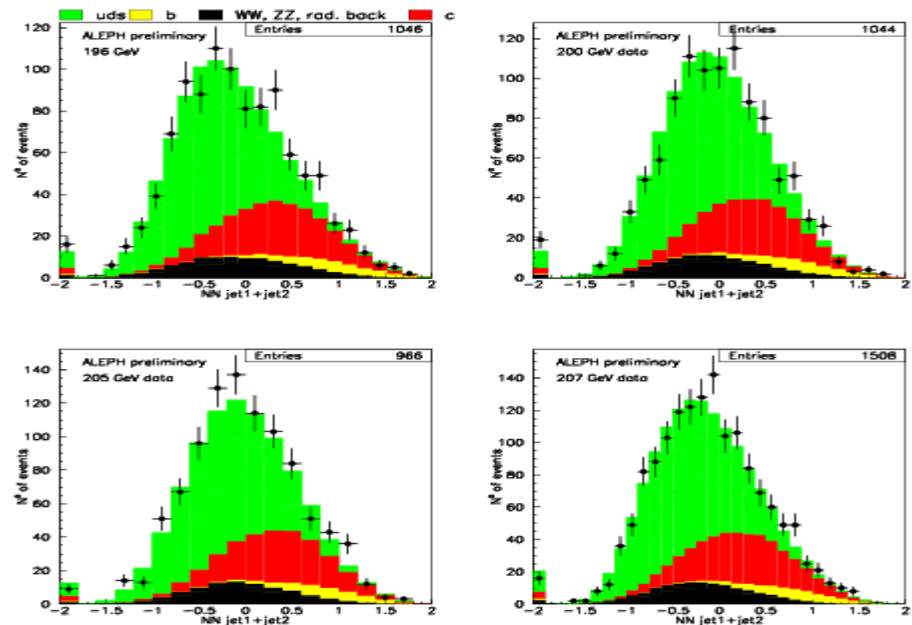
**b**

- lifetime variable
- mass of secondary vertex
- track rapidity
- jet, vertex charge



**c** ( $R_c:A$ )

- anti b tag
- multivariable NN to separate from light quarks
- NN+combined  $A_{fb}$  fit (O)



# Data analysis

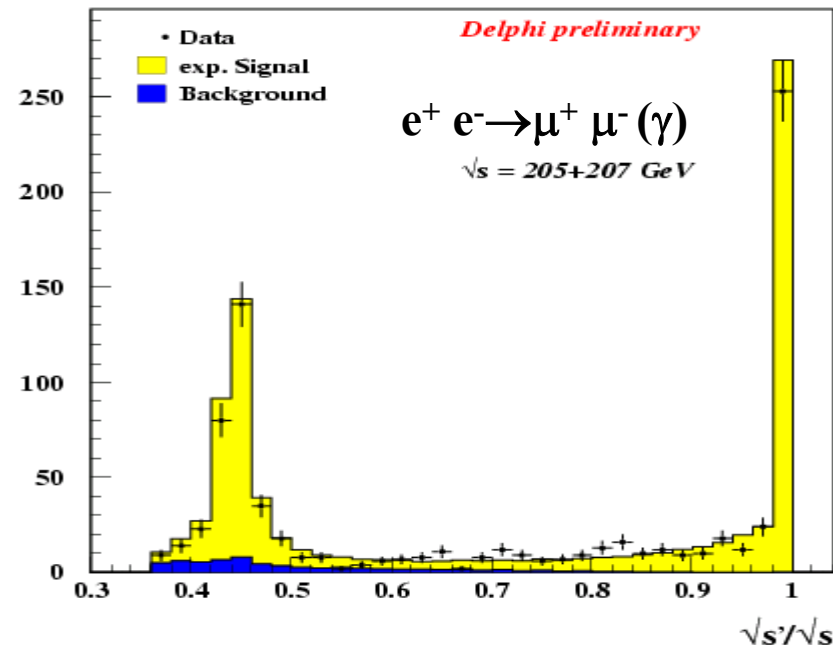
center of mass energy after initial state radiation ( $\sqrt{s}'$ )

in order to select high energy peak:  $\sqrt{s}' \sim \sqrt{s}$ :

- jet/lepton angles
- $\gamma$  detection
- $Z^0$  peak used as a cross check

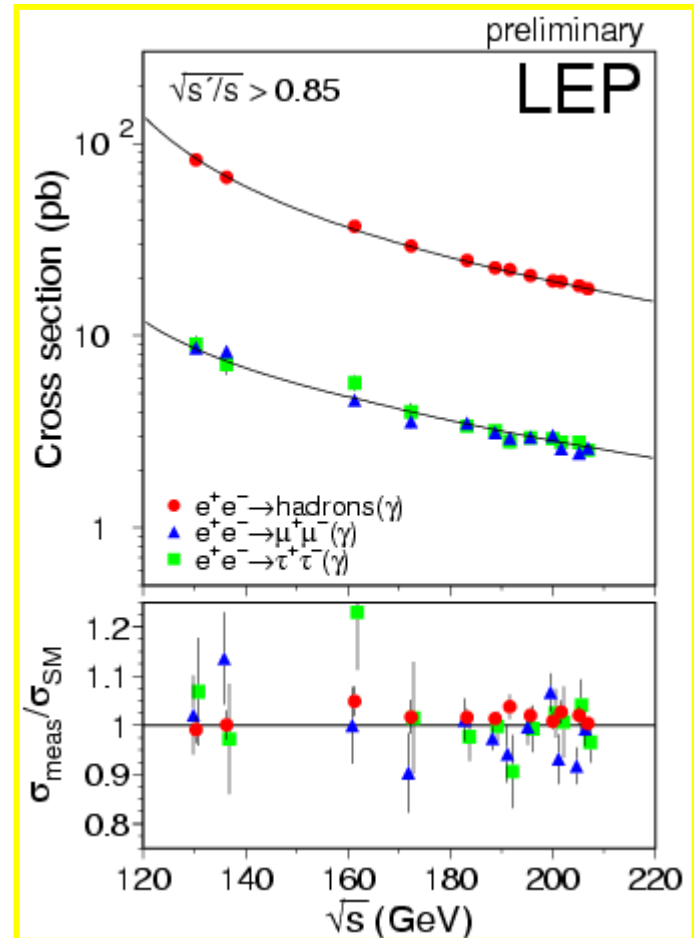
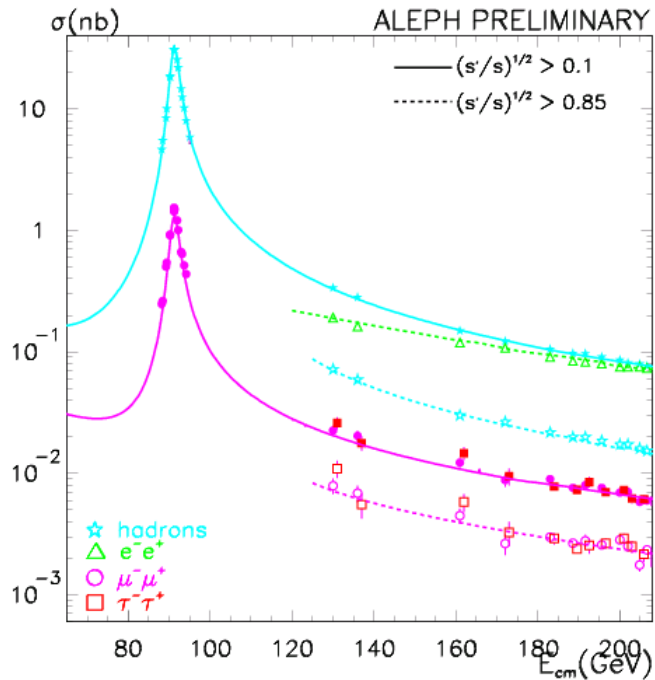
**non radiative:**

$\sqrt{s}' / \sqrt{s} > 0.85 - 0.90$   
or  $(e^+e^-)$  acol  $< 20^\circ$



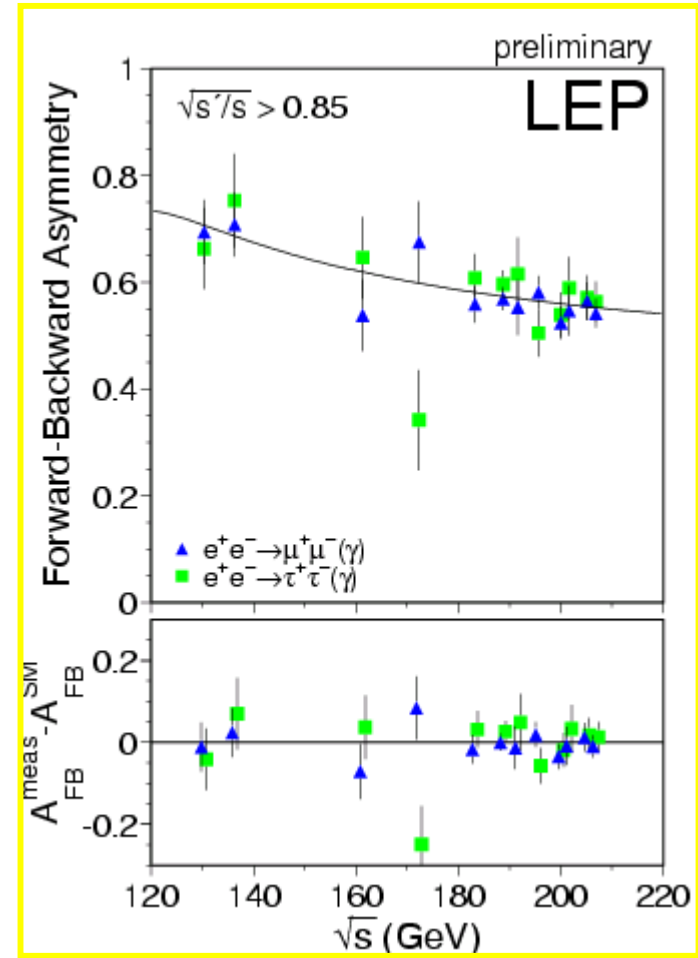
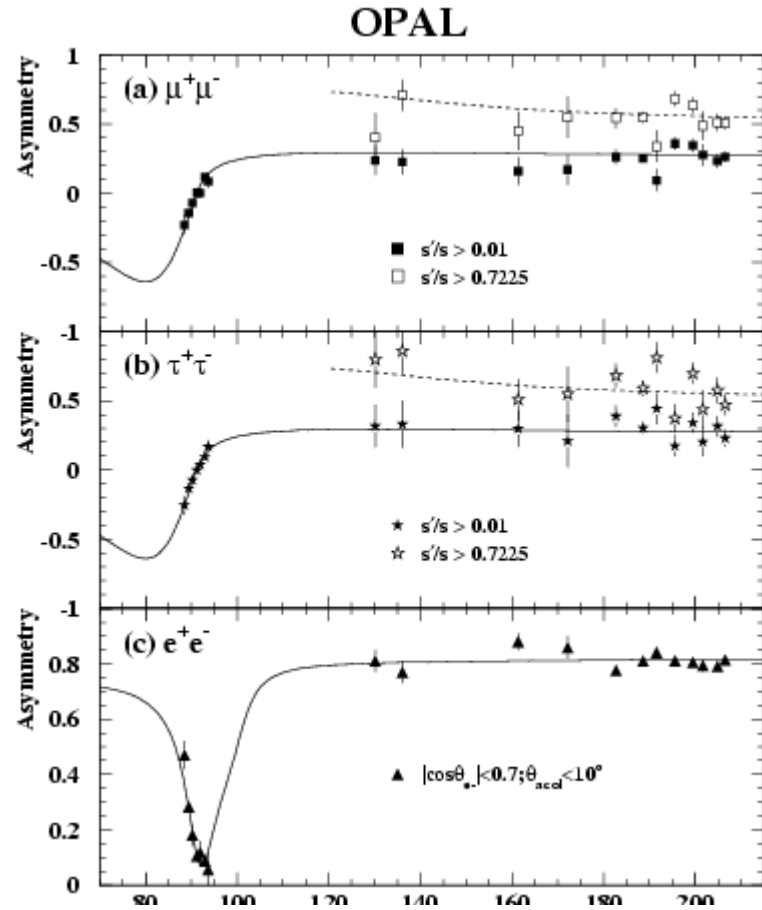
# Results

## Cross section and Asymmetries



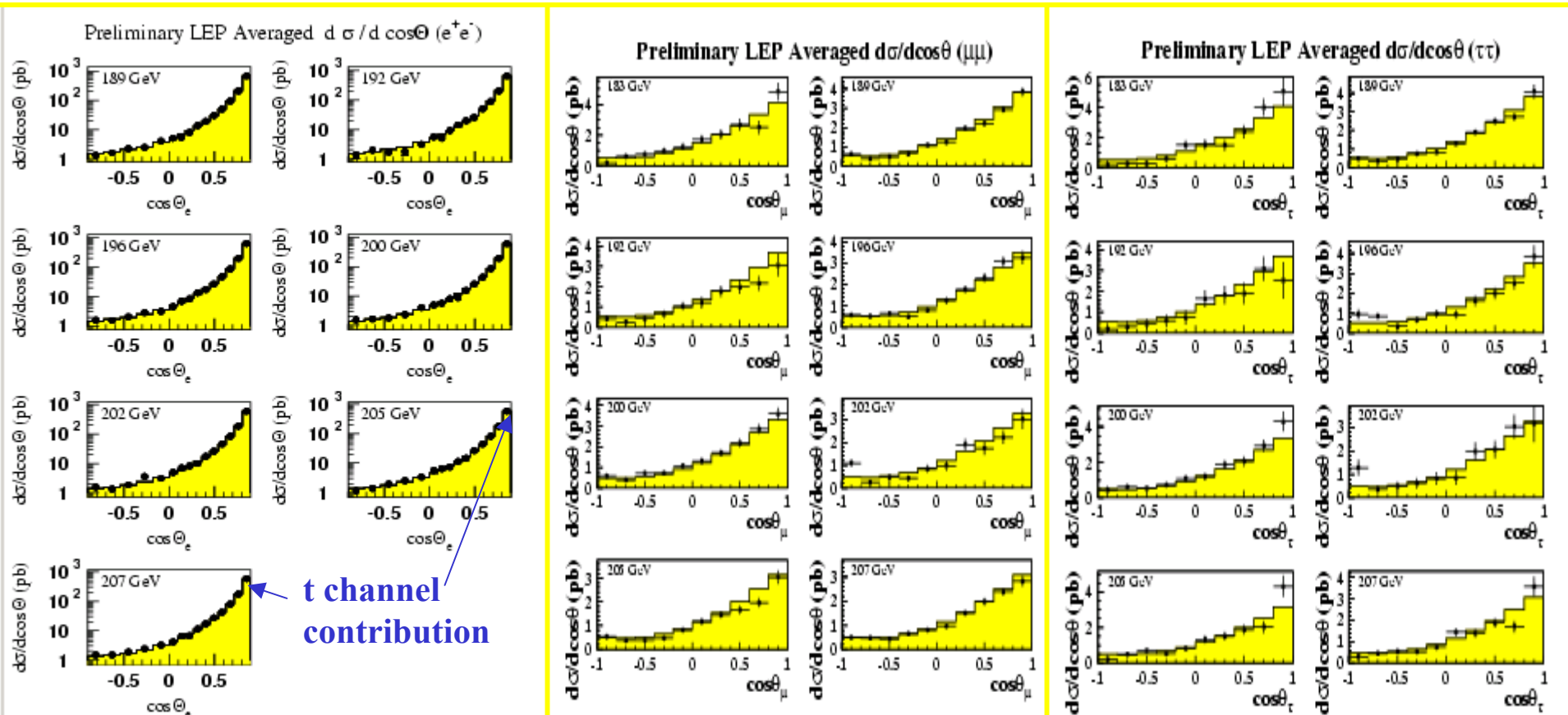
# Results

## Cross section and Asymmetries



# Results

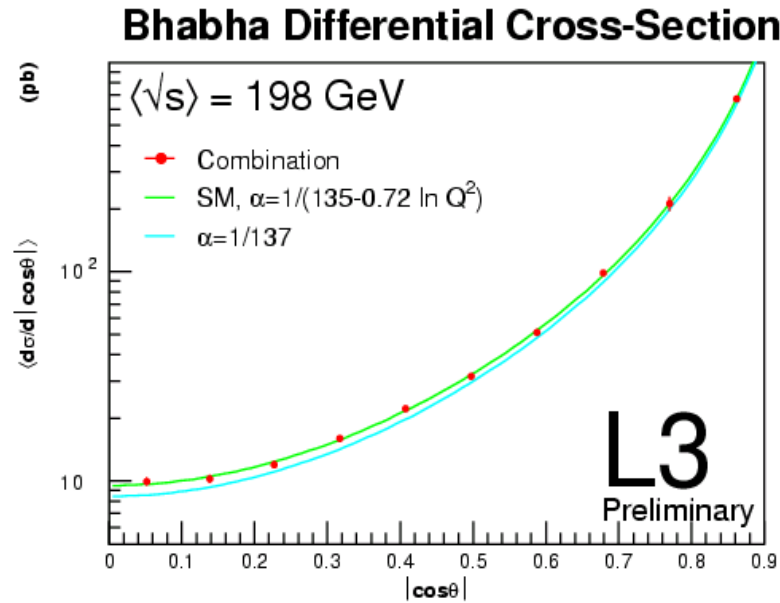
## Differential Cross section



Good agreement with the S.M. expectations

# Results

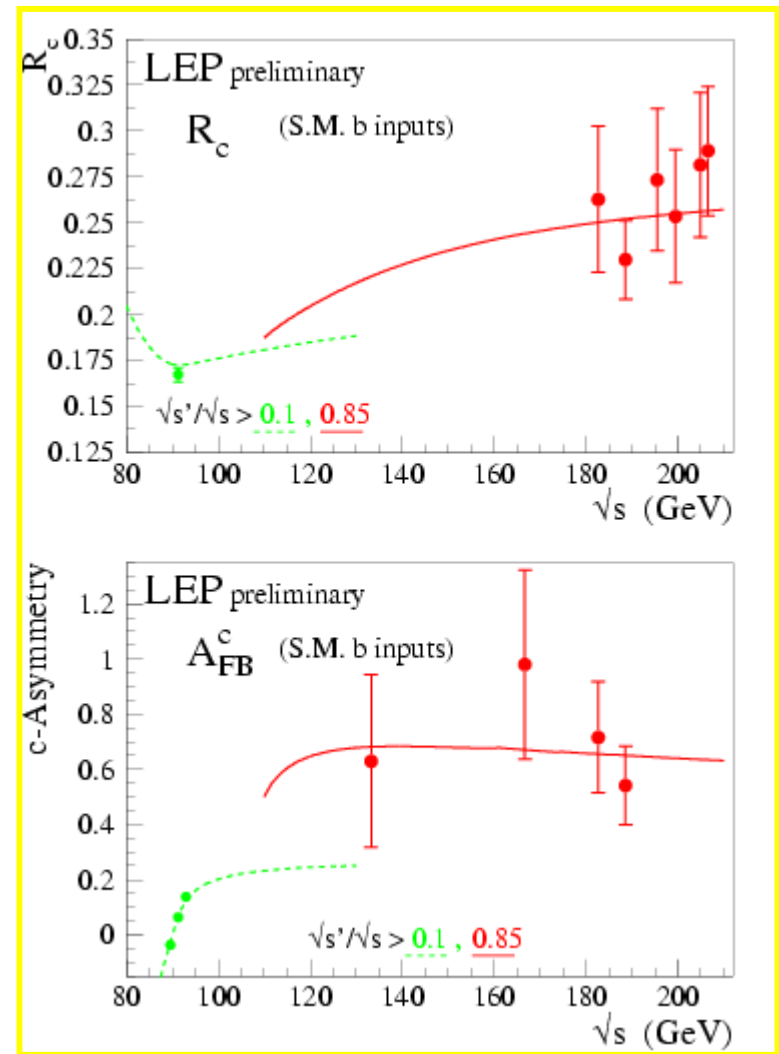
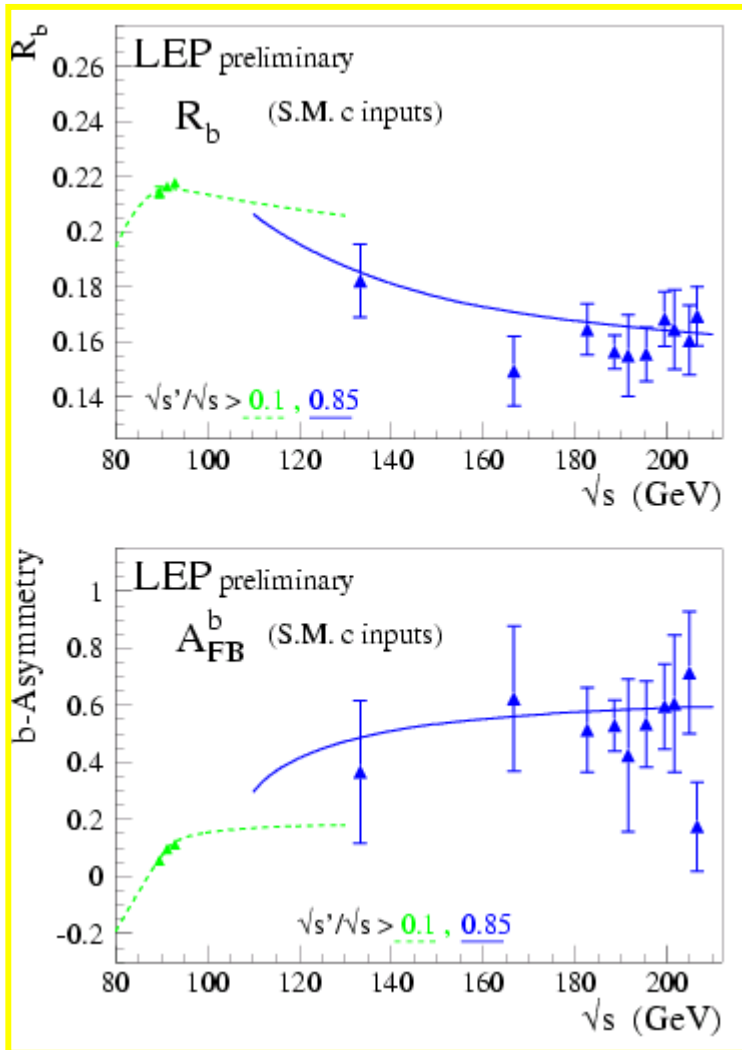
## Differential Cross section



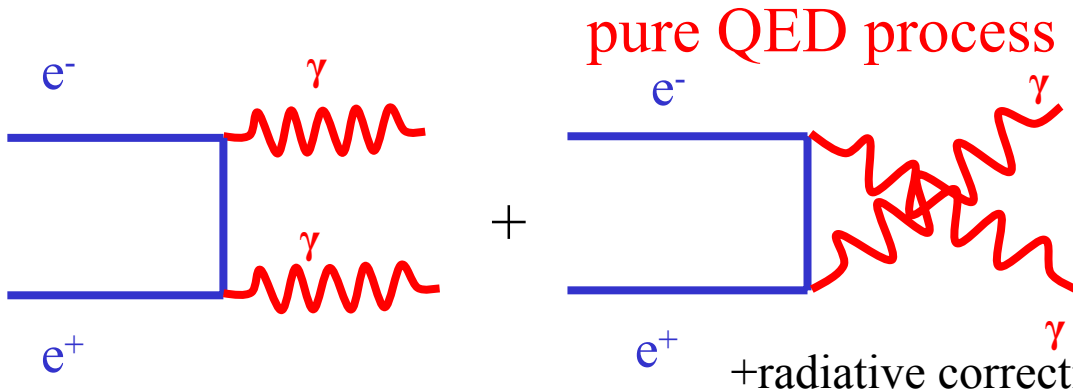
- ◆ No running ( $\alpha = 1/137$ ):  $\chi^2/\text{ndof} = 173/80$  (CL= $10^{-8}$ )
- ◆ Consistency with the running of  $\alpha$ :  $\chi^2/\text{ndof} = 81/80$

# Results

## Heavy quarks



# Excursus to two-photon production



$$\frac{d\sigma}{d\Omega_{\text{Born}}} = \frac{\alpha^2}{s} \frac{1 + \cos^2\theta}{\beta_e^{-2} - \cos^2\theta}$$

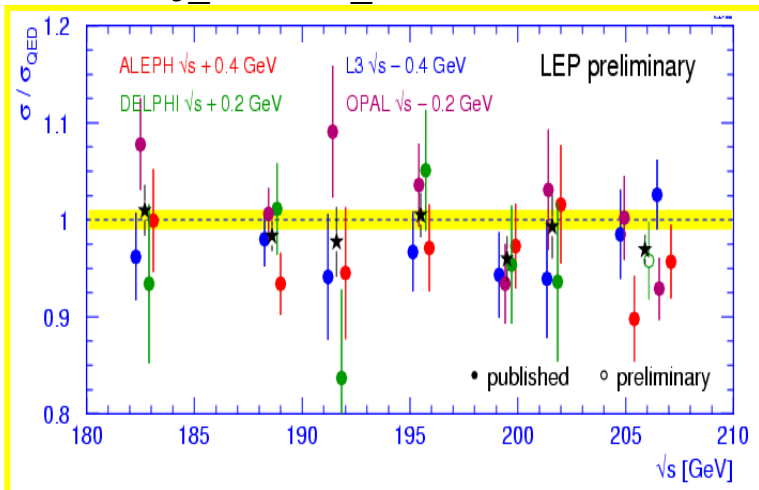
$$\frac{d\sigma}{d\Omega_{\text{QED}}} = \frac{d\sigma}{d\Omega_{\text{Born}}} (1 + \delta_{\text{QED}})$$

deviations parametrised as:  $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega_{\text{Born}}} \pm \frac{d\sigma}{d\Omega_{\text{D}}}$  and

i.e.  $\xi_{\pm} \propto 1/\Lambda_{\pm}^4$

$$\frac{d\sigma}{d\Omega_{\text{D}}} = s \xi (1 + \cos^2\theta)$$

high energies and high angles



$$\sigma_{\text{meas}}/\sigma_{\text{QED}} = 0.982 \pm 0.01_{\text{exp}} \pm 0.01_{\text{rad. corr}}$$

# Interpretations

## S-Matrix fit

LEP I 5 parameter fit to 2-fermion c.s. and asymm. provides a precise  $M_Z/\Gamma_Z$  determination but  $\gamma$ -Z interference as in SM. **In S-Mat. formalism boson exchange and interference contributions can vary independently  $\Rightarrow$  9  $\rightarrow$  16 parameters (5  $\rightarrow$  8 lept. universality)**

$$\sigma_{\text{tot},f}^0(s) = \frac{4}{3} \pi \alpha^2 \left( \frac{g_f^{\text{tot}}}{s} + \frac{j_f^{\text{tot}}(s - \overline{M}_Z^2) + r_f^{\text{tot}} s}{(s - \overline{M}_Z^2)^2 + \overline{M}_Z^2 \overline{\Gamma}_Z^2} \right)$$

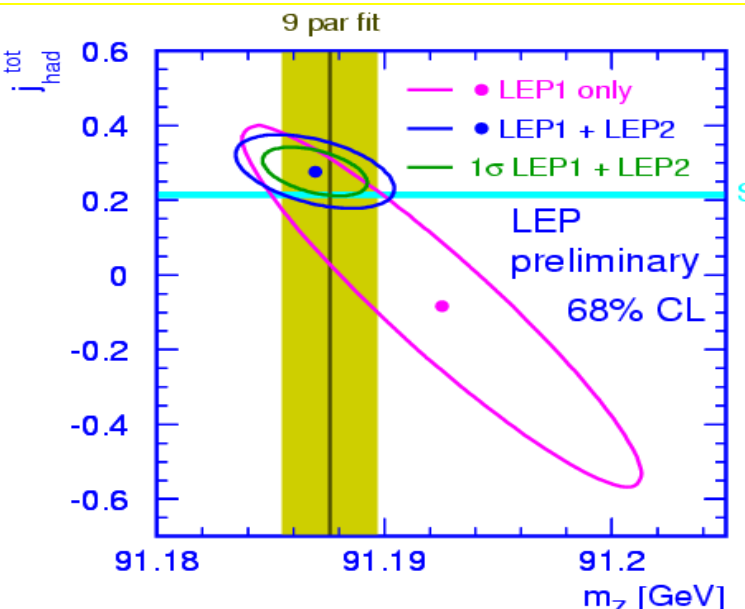
f=had,e, $\mu$ , $\tau$  or had,l

$$A_{\text{fb},f}^0(s) = \frac{\pi \alpha^2}{\sigma_{\text{tot},f}^0(s)} \left( \frac{g_f^{\text{fb}}}{s} + \frac{j_f^{\text{fb}}(s - \overline{M}_Z^2) + r_f^{\text{fb}} s}{(s - \overline{M}_Z^2)^2 + \overline{M}_Z^2 \overline{\Gamma}_Z^2} \right)$$

f=e, $\mu$ , $\tau$  or l

LEP I: only 3 precise points in had c.s.  $\Rightarrow$  large correlation  $M_Z \leftrightarrow j_{\text{had}}^{\text{tot}}$

LEP II data constrain the interference contributions



data	$M_Z$ (GeV)	$j_{\text{had}}^{\text{tot}}$	corr.	$\chi^2_{\text{/d.o.f}}$
LEP I only	91.1925 $\pm 0.0059$	-0.084 $\pm 0.324$	-0.935	62/48
LEP I + LEP II	91.1869* $\pm 0.0023$	0.277 $\pm 0.065$	-0.461	64/60

\*91.1876  $\pm$  0.0021 9-par. fit

# Interpretations

## Effective Lagrangian

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

$\Lambda$  energy scale of contact interactions

$g$  unknown coupling (usually  $g^2=4\pi$ )

$\delta = 1$  for  $e$  final state (0 elsewhere)

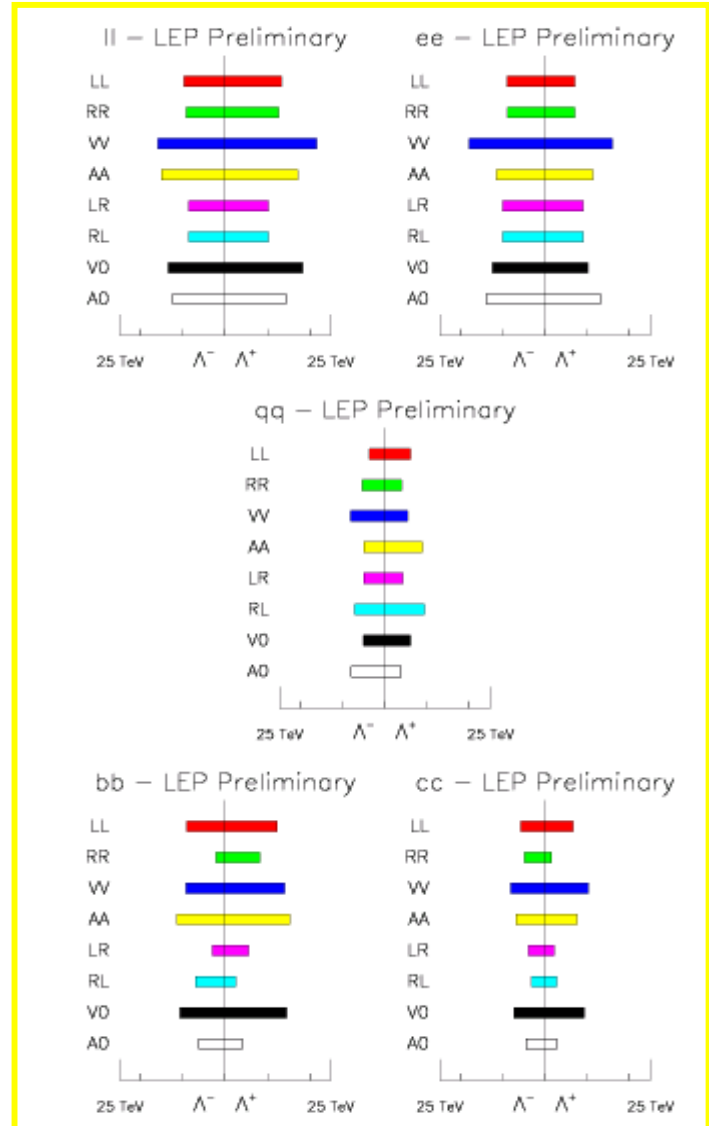
$\eta_{ij} = \pm 1, 0$  chiral structure of each model

fit  $\sigma, A_{\text{FB}}, d\sigma/d\cos\theta, R_{b,c}$

**For photons:**

$\Lambda_{\pm} > 392/364 \text{ GeV}$

## Contact Interactions\*



\* parametrization to describe deviations from SM

# Interpretations

## Z' bosons

### Several models:

- **GUT E6 models**(2 additional gauge groups;  $\chi, \psi, \eta$  depending on mixed state Z')
- **L-R symmetric models** (Additional  $SU(2)_R$ ; couplings to fermions  $\leftrightarrow \alpha_{LR}$ )
- **Sequential S.M** (Z' same couplings as Z)

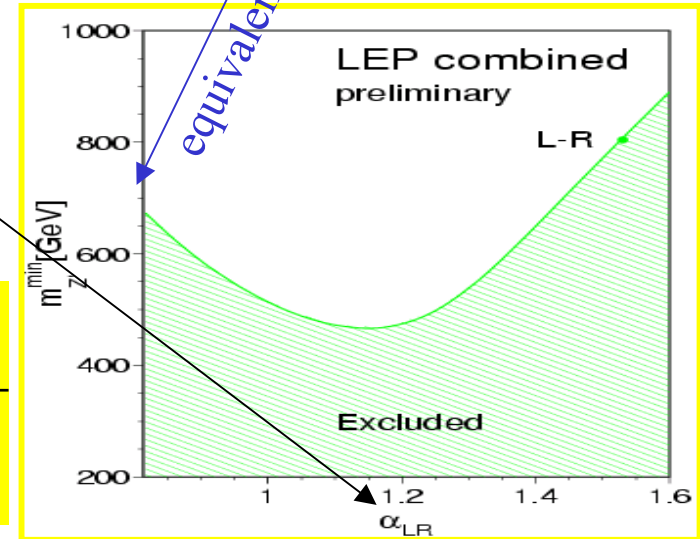
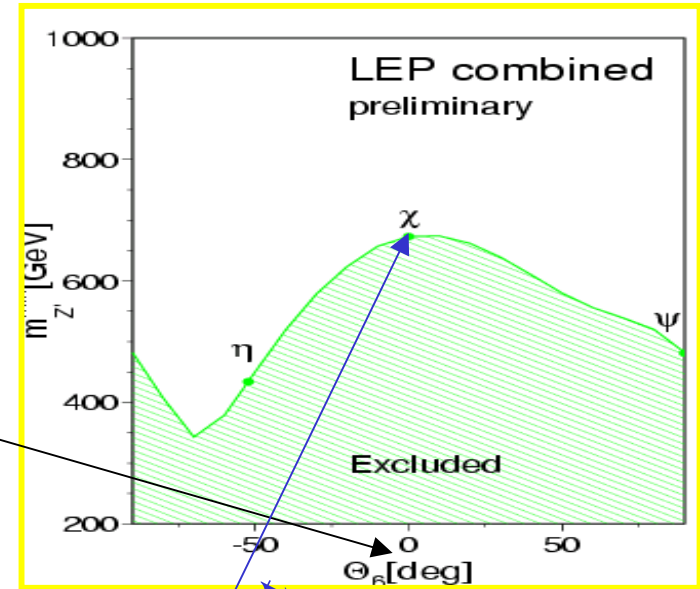
### Free parameters:

- Mixing angle  $\Theta_{ZZ'}$  ( $\sim 0$  from Lep I)
- Z' mass

fit  $\sigma, A_{FB}$

**No Z' evidence found, 95% C.L.  $M_{Z'}$  limits :**

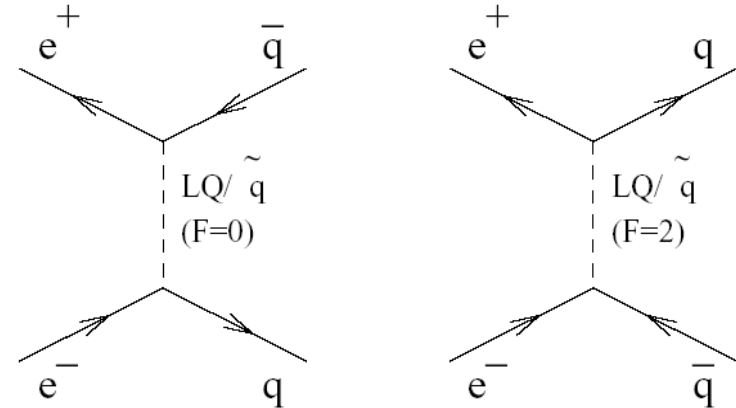
Model	$\chi$	$\psi$	$\eta$	L-R	SSM
Limit (GeV)	673	481	434	804	1787



# Interpretations

## Leptoquarks

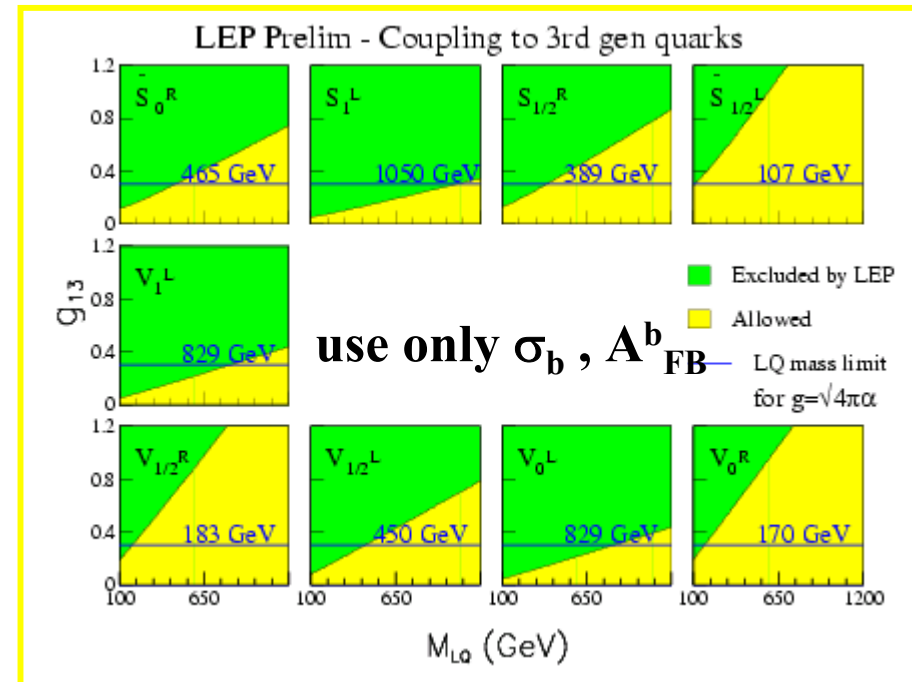
- quark-lepton transition:  $F=L+3B$
- scalar  $S_I$ , vectors  $V_I$ , hypercharge( $\sim$ )
- modify  $\sigma_{had}$ ,  $A_{FB}$  and  $R_{b,c}$
- limits on coupling to  $n^{th}$  q generation as function of  $M_{LQ}$



equivalent to  $R_p$  violating squarks

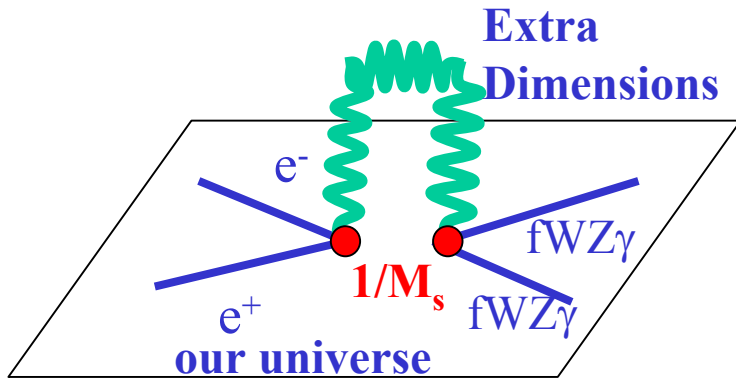
Limit on scalar LQ mass ( $\text{GeV}/c^2$ ) $g=\sqrt{4\pi\alpha}$							
	$S_0(L)$	$S_0(R)$	$\tilde{S}_0(R)$	$S_{\frac{1}{2}}(L)$	$S_{\frac{1}{2}}(R)$	$\tilde{S}_{\frac{1}{2}}(L)$	$S_1(L)$
$LQ_{1st}$	655	520	202	178	232	-	361
$LQ_{2nd}$	539	430	285	269	309	-	478
$LQ_{3rd}$	NA	NA	465	NA	389	107	1050

Limit on vector LQ mass ( $\text{GeV}/c^2$ )							
	$V_0(L)$	$V_0(R)$	$\tilde{V}_0(R)$	$V_{\frac{1}{2}}(L)$	$V_{\frac{1}{2}}(R)$	$\tilde{V}_{\frac{1}{2}}(L)$	$V_1(L)$
$LQ_{1st}$	917	165	489	303	227	176	659
$LQ_{2nd}$	692	183	630	357	256	187	873
$LQ_{3rd}$	829	170	NA	451	183	NA	829



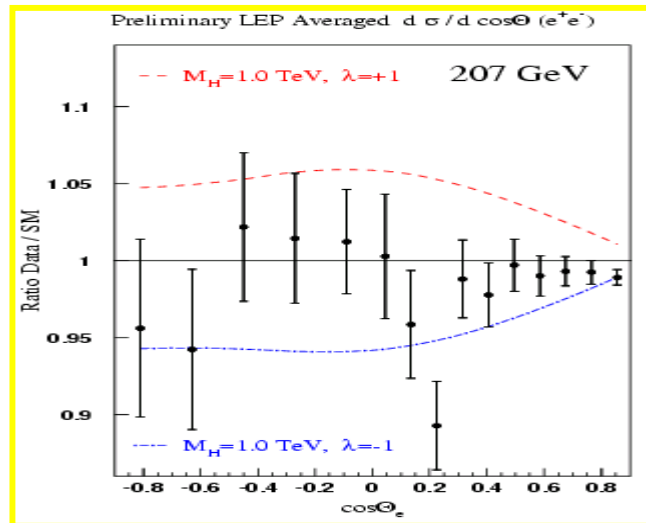
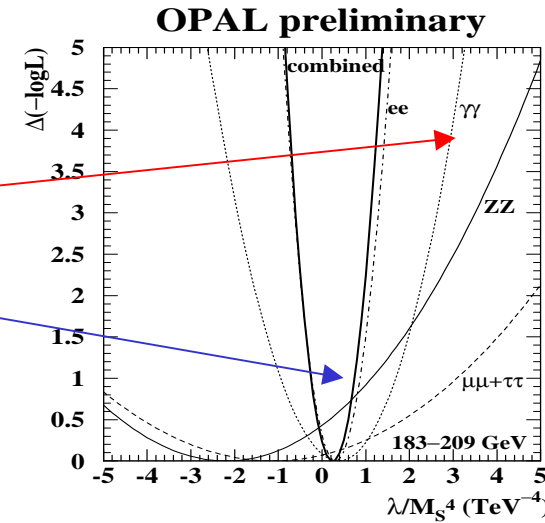
# Interpretations

## Quantum Gravity extra dimensions



contributions from virtual exchange of Kaluza Klein excitations of graviton

max sensitivity for  $e^+e^-, \gamma\gamma$  angular distribution



LEP  $e^+e^- \rightarrow e^+e^-$  :

$\lambda=+1: M_S > 1020 \text{ GeV}$

$\lambda=-1: M_S > 1009 \text{ GeV}$

LEP  $e^+e^- \rightarrow \gamma\gamma$  :

$\lambda=+1: M_S > 933 \text{ GeV}$

$\lambda=-1: M_S > 1010 \text{ GeV}$

# Conclusions

- Fermion (and photon) pair production studied at LEP in the whole energy range from  $Z^0$  to  $\sqrt{s} \sim 208$  GeV
- Good agreement with Standard Model both from the single experiments and the combined results
- S matrix fit  $\sim$  as precise as SM fit
- Limits on several models of Physics beyond Standard Model:  
Contact Interactions,  $Z'$ , Leptoquarks, Quantum Gravity

**Still preliminary but final results and combinations coming soon**

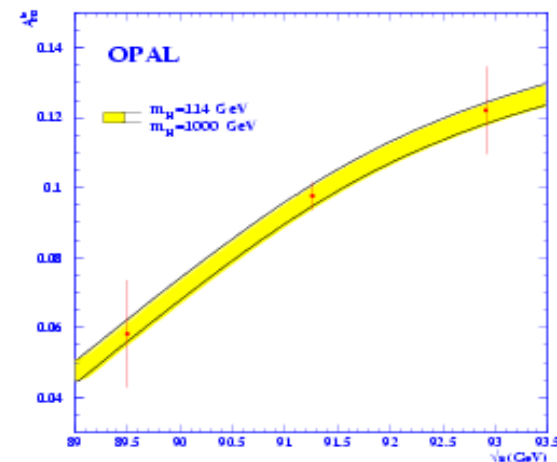
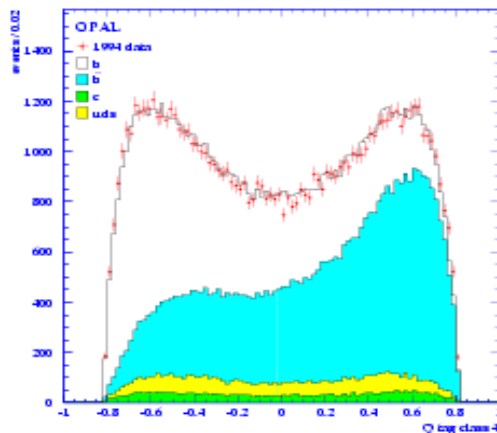
# Results

## LEP 1

T.K 4

### $A_{FB}(b)$ at Z

Combination of 4 charge tags  
using jet, vertex,  $K^\pm$



Sophisticated fitting procedure

$$\begin{aligned}
 A_{FB}^b &= 0.0582 \pm 0.0153 \pm 0.0012 & \text{pk} - 2 \\
 A_{FB}^b &= 0.0977 \pm 0.0036 \pm 0.0018 & \text{pk} \\
 A_{FB}^b &= 0.1221 \pm 0.0123 \pm 0.0025 & \text{pk} + 2
 \end{aligned}$$

New OPAL result

$$\begin{aligned}
 A_{FB}^{0,b} &= 0.1002 \pm 0.0034 \pm 0.0018 \\
 \sin^2 \theta_{\text{eff}}^e &= 0.23205 \pm 0.00068
 \end{aligned}$$

Previous OPAL result

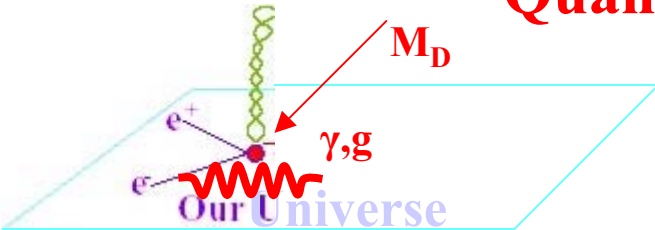
$$A_{FB}^{0,b} = 0.1007 \pm 0.0055 \pm 0.0040$$

Final  $A_{FB}^b$  using leptons will follow soon.

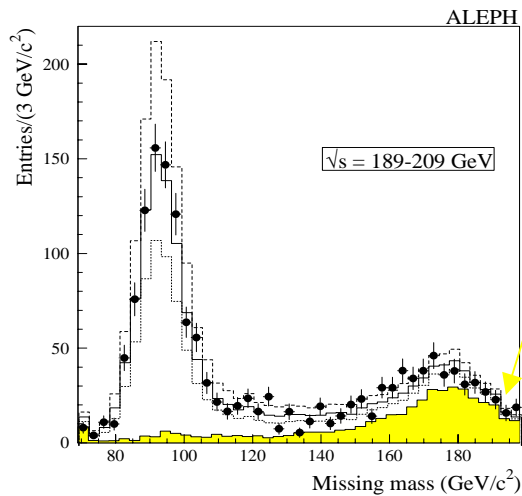
# Results

## Quantum Gravity extra dimensions

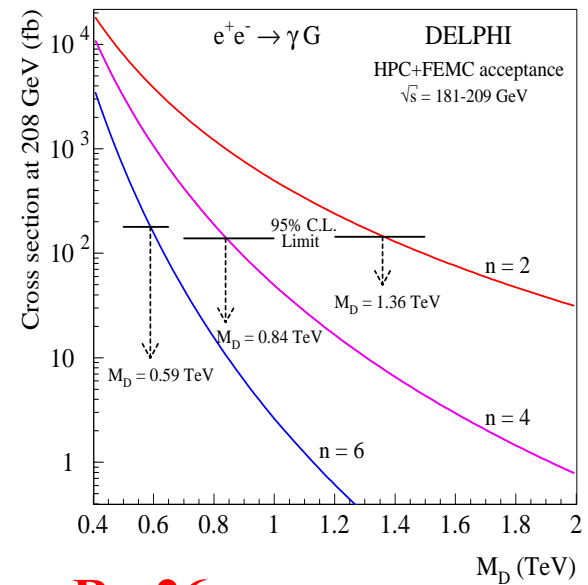
**Direct Effects**  
 $e^+e^- \rightarrow G\gamma$  : single photon (see also superlight  $\tilde{G}$ )



Produzione centrale e a bassa  $E_\gamma$



Limits depend on the number of extra dimensions



**ADLO: limiti  $M_D > 1 \div 1.35$  TeV per  $n=2$**   
 **$M_D > .51 \div .59$  TeV per  $n=6$**



**$R < .26$  mm**  
 **$R < 6 \times 10^{-12}$  m**