

LEP 2 $e^+e^- \rightarrow f\bar{f}, \gamma\gamma (\gamma)$: results and interpretations

- Introduction

 - Data set + Reminder of event topologies & s'

 - The LEP combination

- Results and comparison with the Standard Model

- Indirect Search for New Physics

 - Z' bosons

 - Contact Interactions

 - Low Scale Gravity

- Determination of E_b through Radiative Returns

- Conclusions

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University of Oxford,
Moriond EW, March 2002

LEP 2 data set

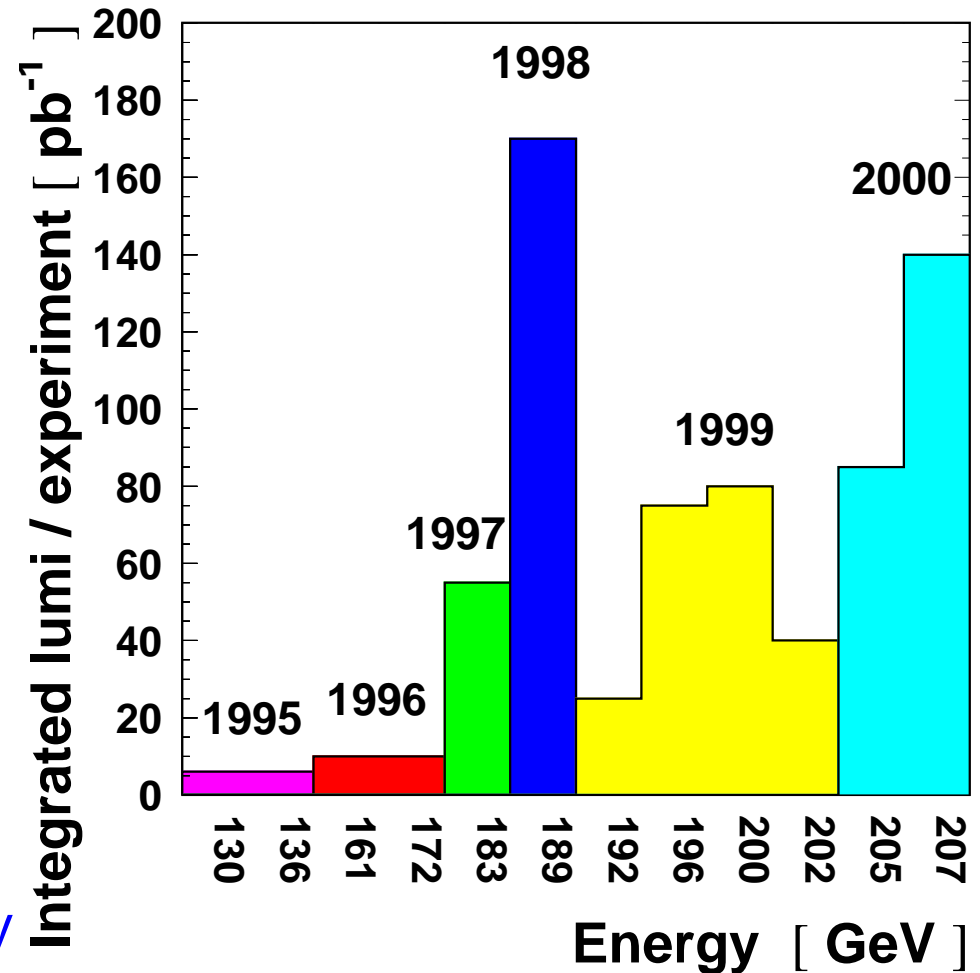
$\sim 700 \text{ pb}^{-1}$ per experiment
between 130 & 207 GeV.

Clean samples of $q\bar{q}$ & l^+l^-
with typical purities $> 90\%$

Residual background from
4-fermion & 2-photon collisions

$\sigma_{f\bar{f}}$ & $A_{\text{FB}}^{l^+l^-}$ results ≥ 99 preliminary


Additional results with flavour tagged quarks & $e^+e^- \rightarrow \gamma\gamma(\gamma)$



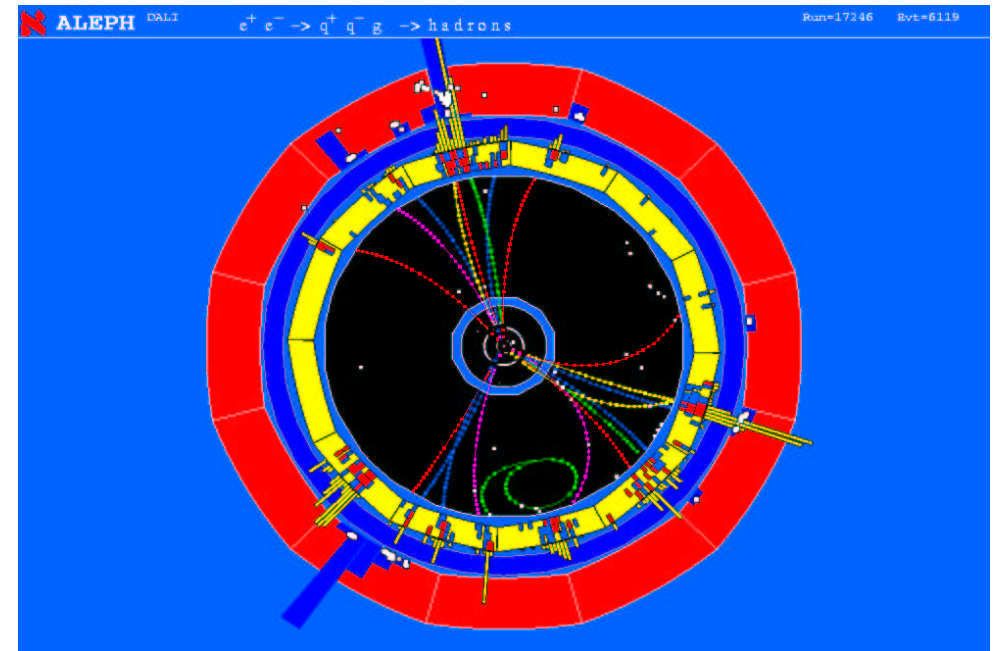
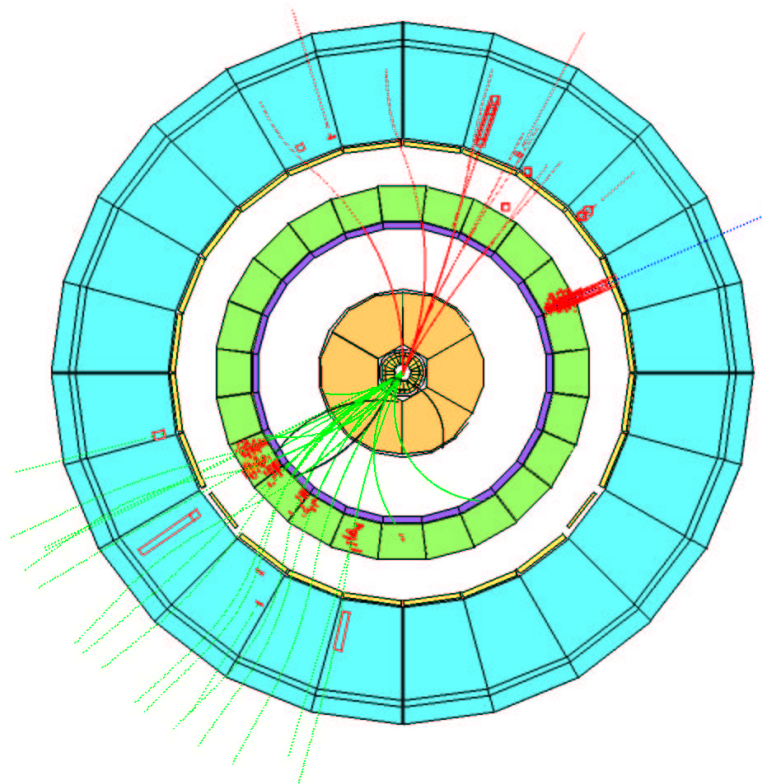
Hadronic events

$q\bar{q}\gamma$

3 jets

 DELPHI Interactive Analysis
Beam: 70.1 GeV Run: 64211 DAS: 11-Nov-1995
Proc: 11-Nov-1995 Ev t: 6137 05:45:07
Tan+DST Scan: 15-May-1996


	TD	TE	TS	TK	TV	ST	PA
Act	0	26	0	38	0	0	0
Deact	(0)	(217)	(0)	(39)	(0)	(0)	(0)
	(0)	(0)	(0)	(0)	(0)	(0)	(0)

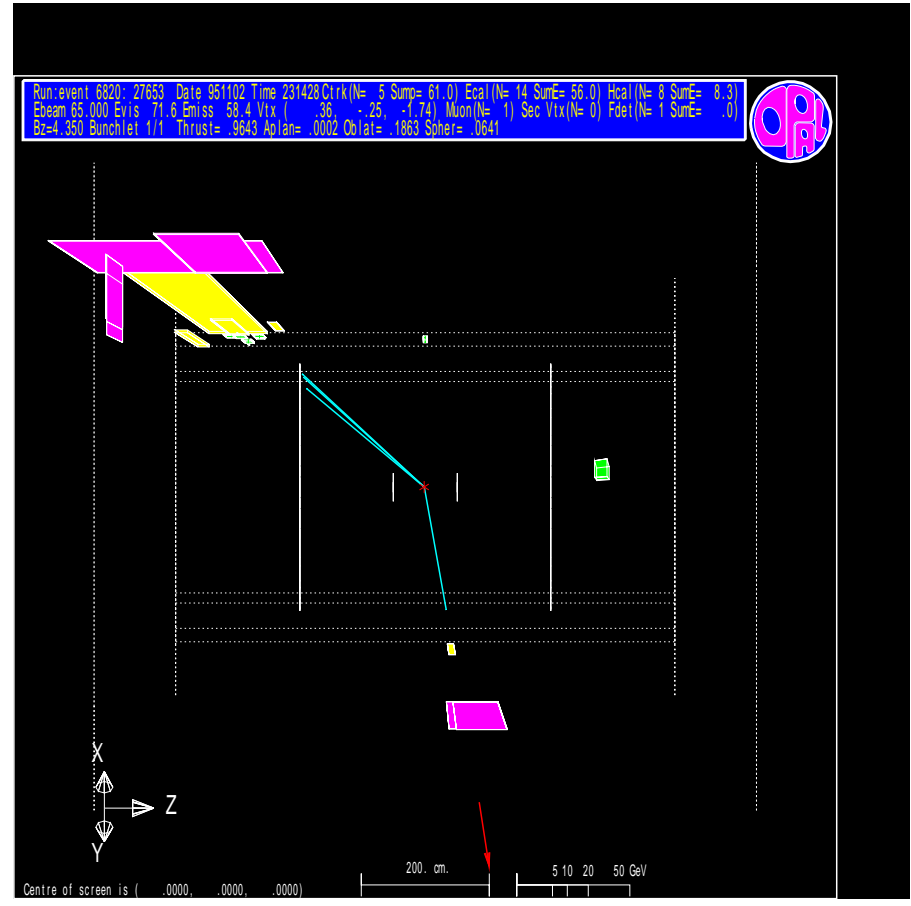
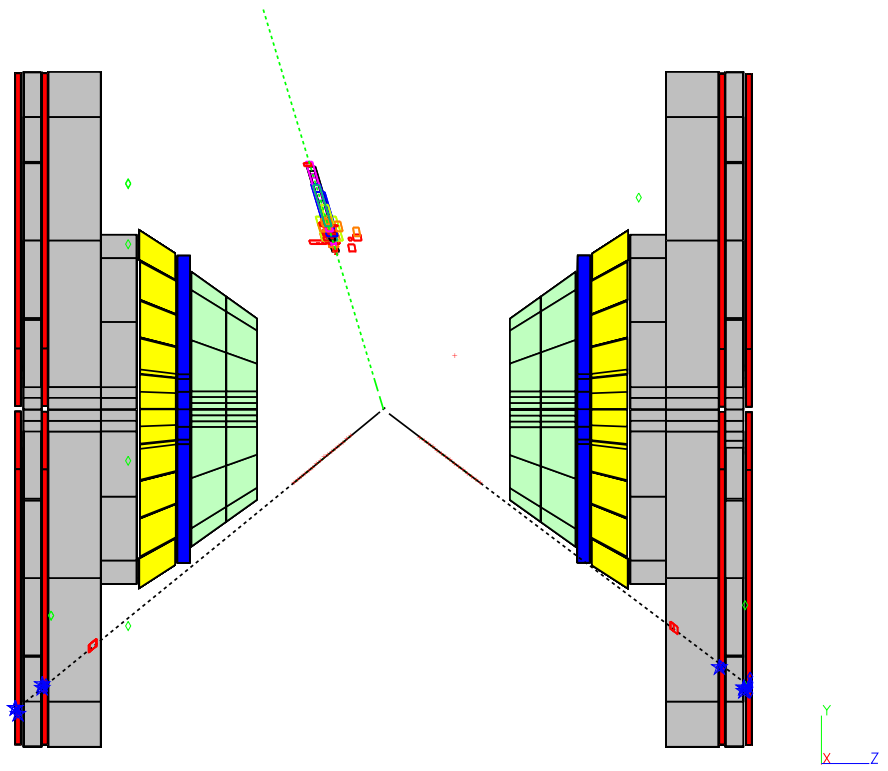


Leptonic events

$$\mu^+ \mu^- \gamma$$

$$\tau^+ \tau^- \text{ radiative return}$$

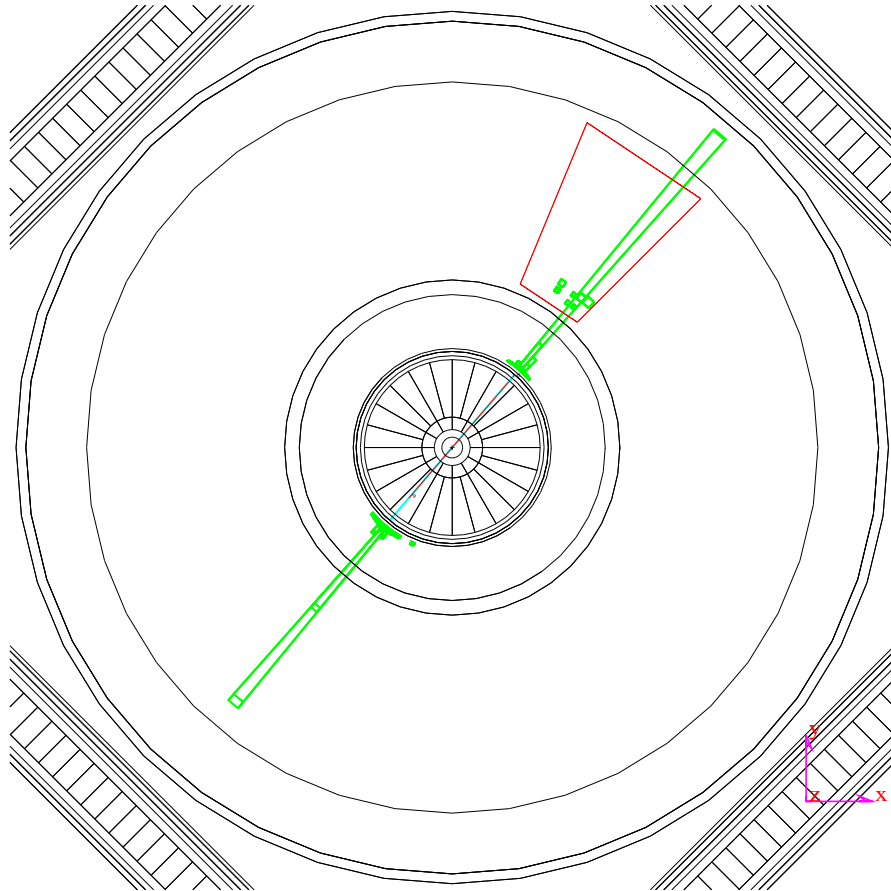
 DELPHI Run: 84844 Evt: 7203 Beam: 94.6 GeV Proc: 6-Jul-1998 DAS: 6-Jul-1998 Scan: 19-Nov-1998 17:36:02 Tan+DST	TD	TE	TS	TK	TV	ST	PA						
	Act	1	50	0	3	0	0	0					
		(82)	(118	X	0	X	4	X	0	X	0	X	0
	Deact	0	0	0	0	0	0	0					
	(0	X	0	X	0	X	0	X	0	X	0	X	



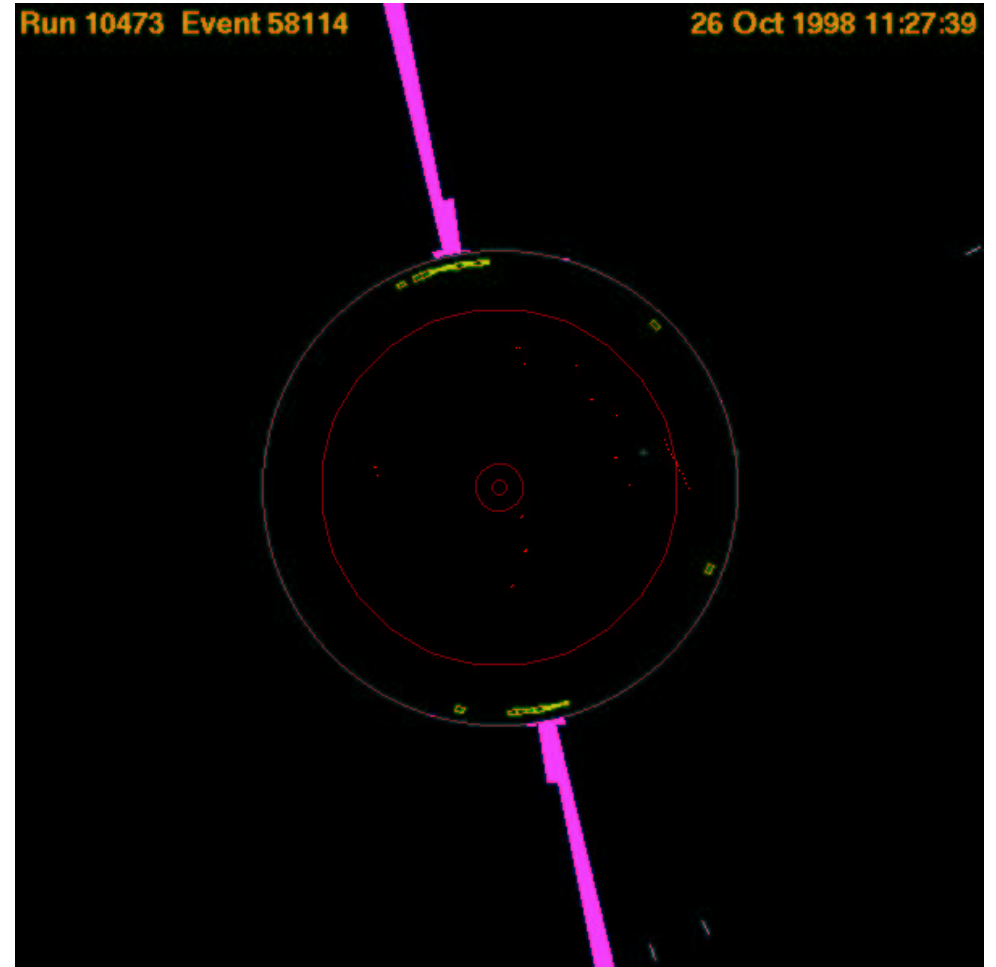
e^+e^-

$\gamma\gamma$

Run # 694301 Event # 3096 Total Energy : 136.63 GeV



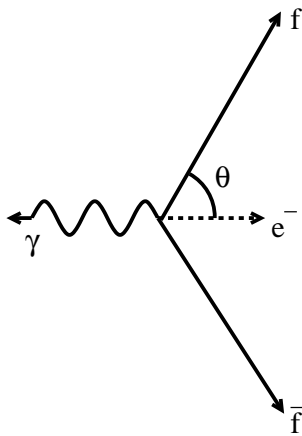
Transverse Imbalance :	.0052	Longitudinal Imbalance :	.4180		
Thrust :	.9180	Major :	.3931	Minor :	.0000
Event DAQ Time :	980528 204932				



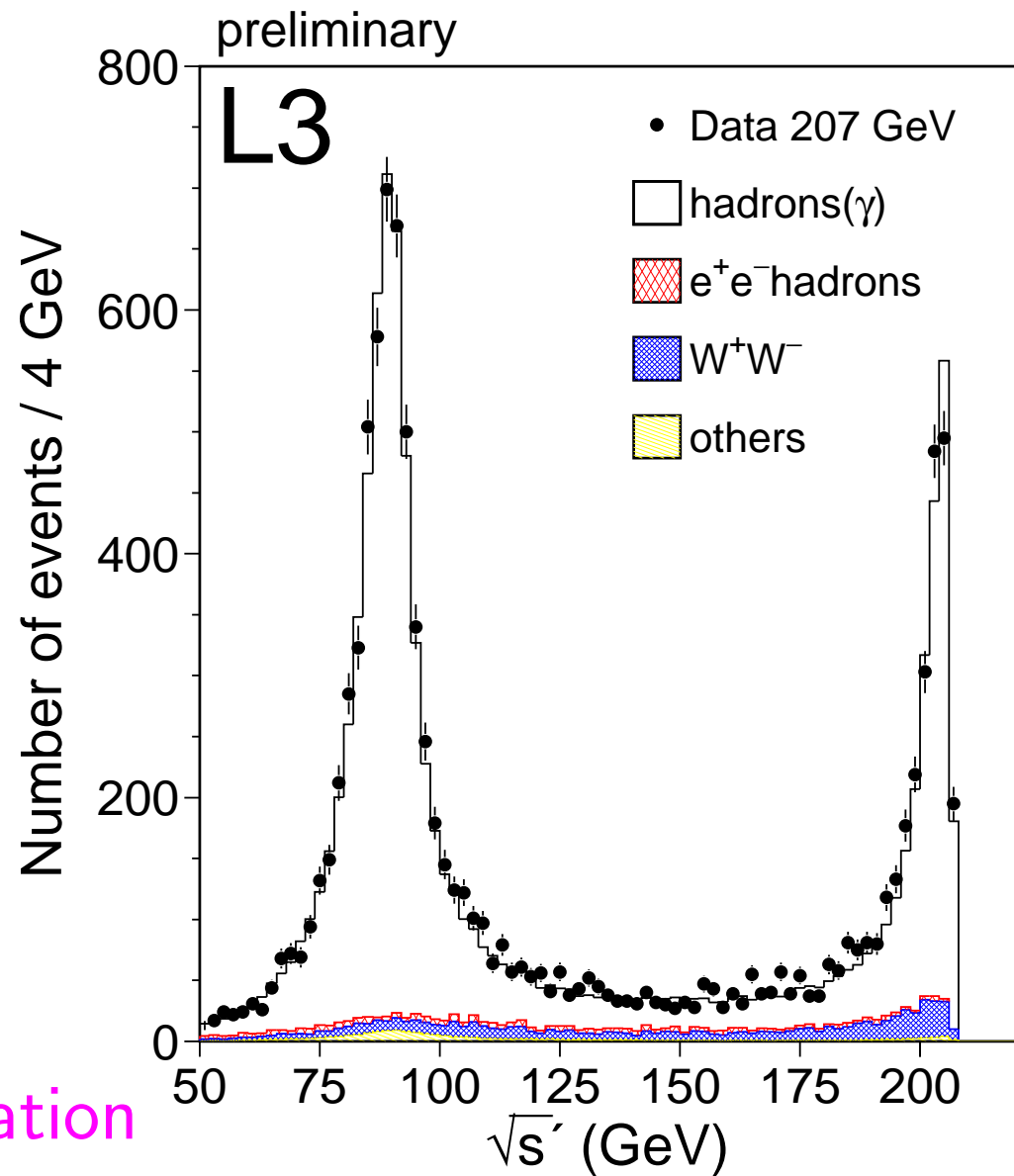
Radiative Return

ISR photon(s) \rightarrow a range of effective E_{cm} 's, or $\sqrt{s'}$, is sampled

$\sqrt{s'}$ generally obtained from fit to $f\bar{f}$ directions



High $\sqrt{s'}$ – test SM & look for New Physics
Z returns – calibration tool, eg. E_b determination



LEP combination

All available $q\bar{q}$, $\mu^+\mu^-$ and $\tau^+\tau^-$ cross-sections and asymmetries have been combined. (e^+e^- pending – presently a 2% theory error)

- Correct to common signal definitions before averaging
eg. definition of non-radiative sample
treatment of additional fermion pairs in event etc
- Correlations between channels, energies and experiments
eg. ISR modelling and fragmentation errors for $\sigma_{q\bar{q}}$

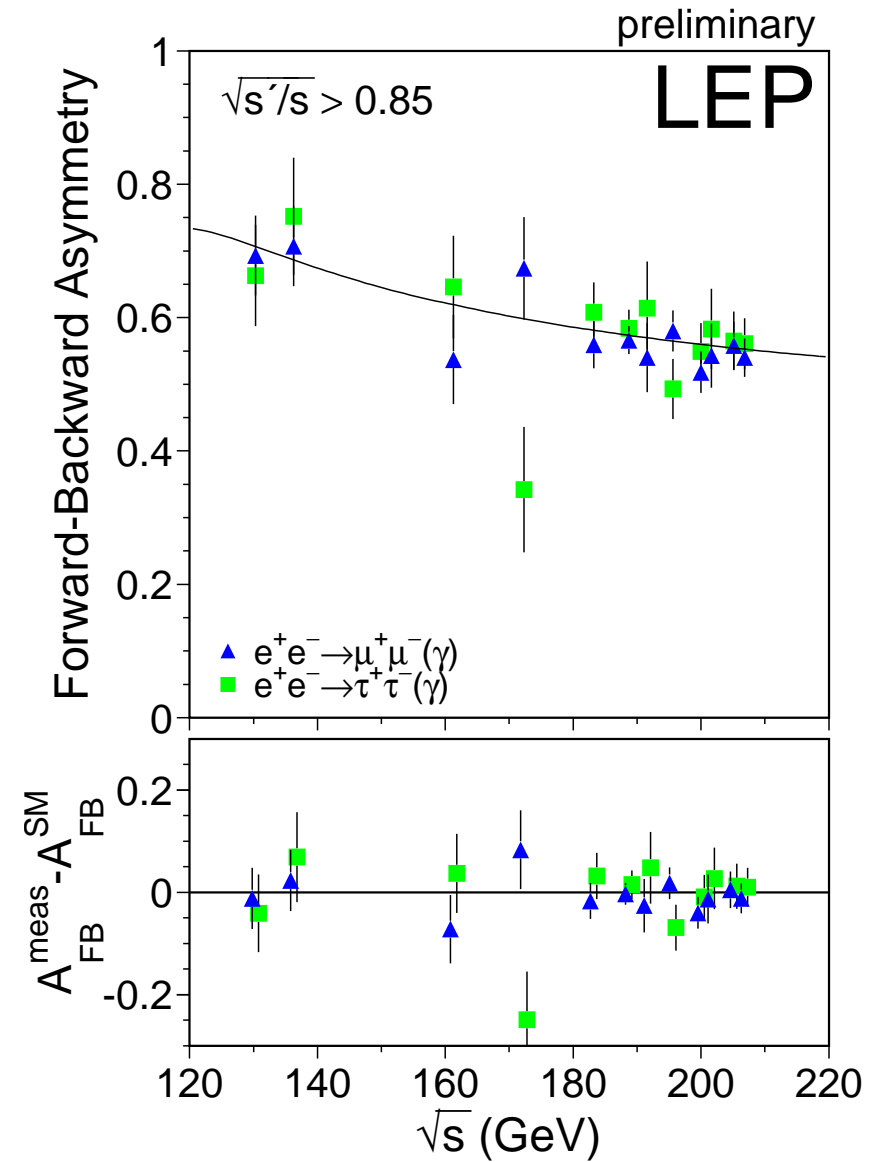
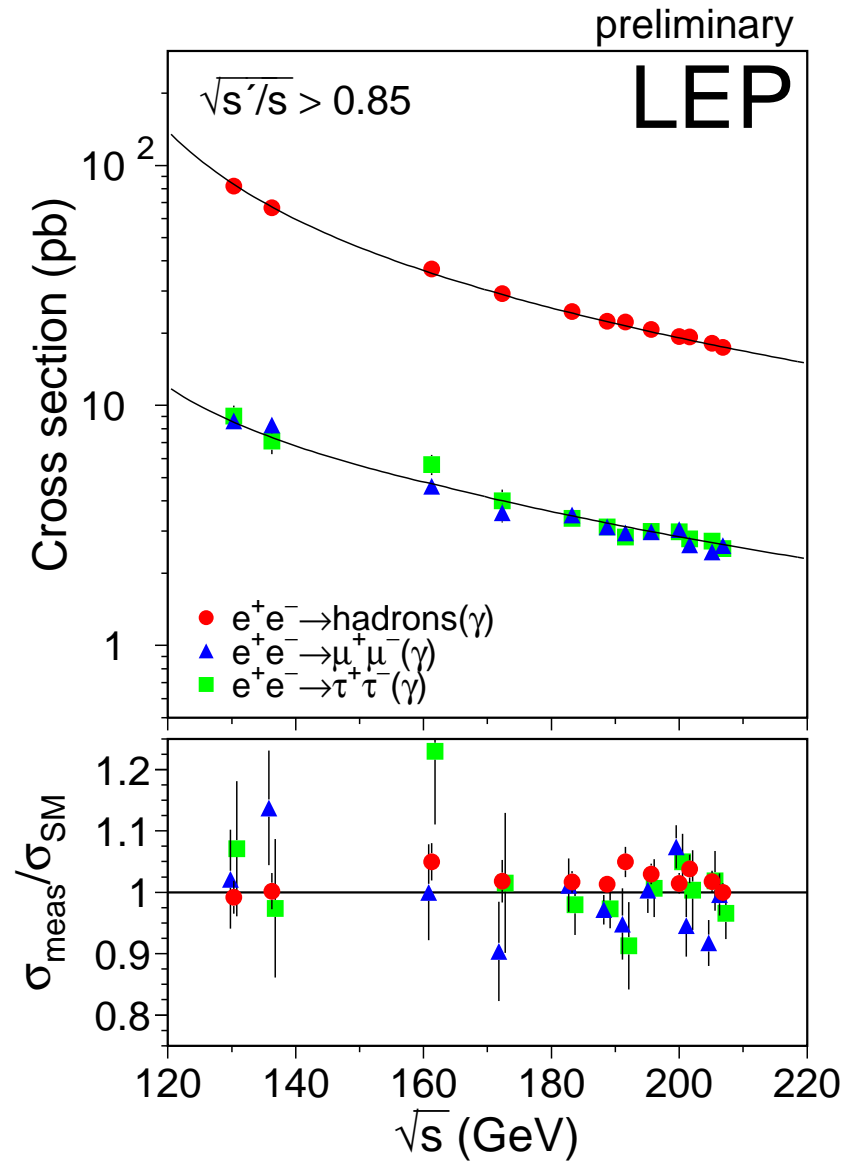
Total experimental precision on deviations from SM (x-sections):

$$q\bar{q} \sim 1.0\%, \quad \mu^+\mu^- \sim 1.6\%, \quad \tau^+\tau^- \sim 2.2\%$$

whereas theory uncertainties are:

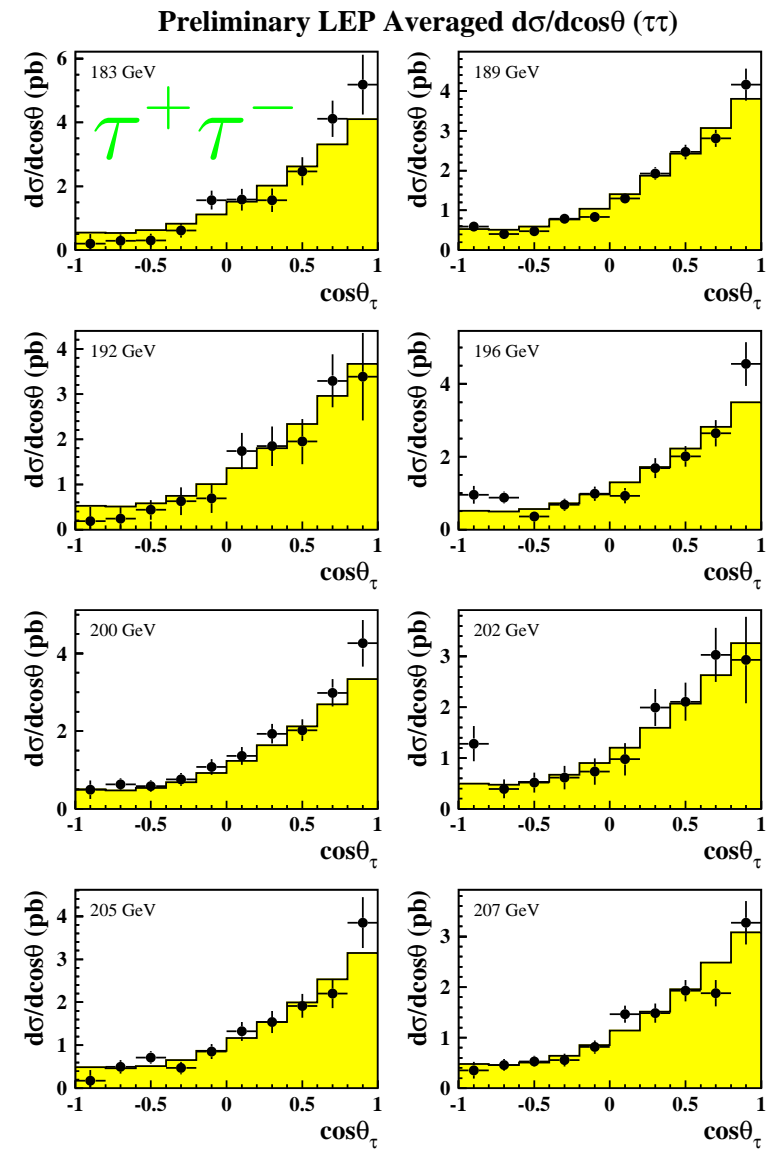
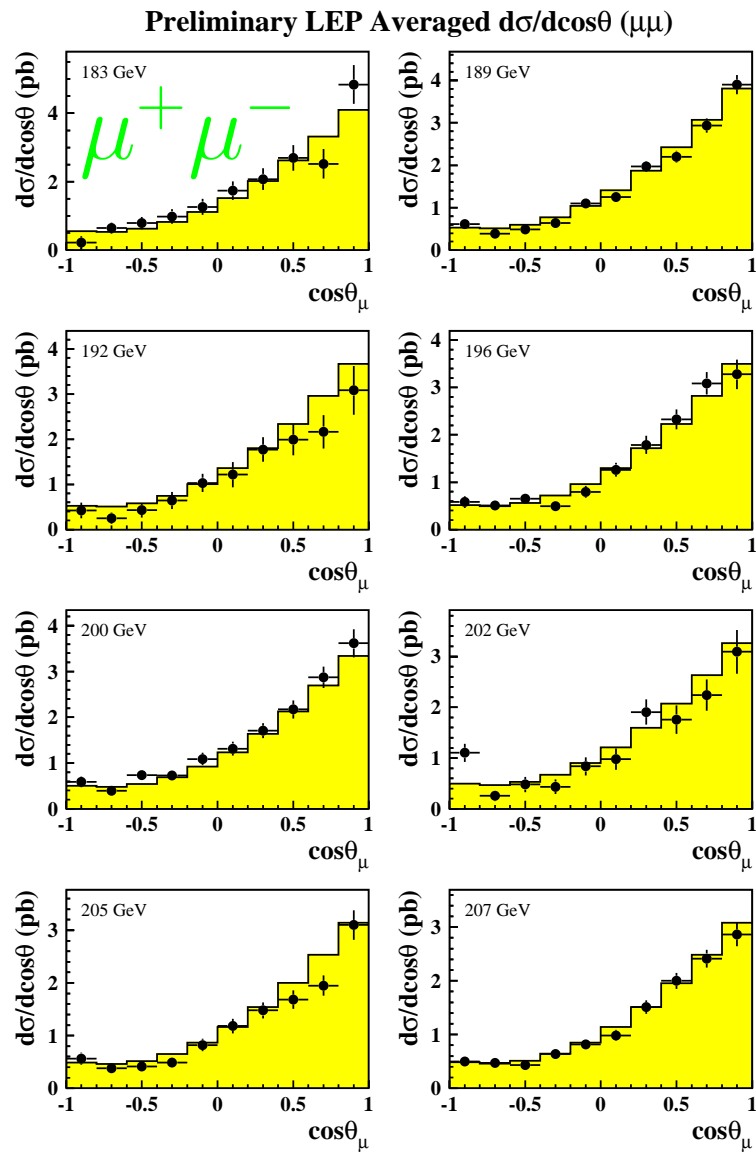
$$q\bar{q} \sim 0.3\%, \quad \mu^+\mu^- \sim 0.4\%, \quad \tau^+\tau^- \sim 0.4\%$$

LEP $f\bar{f}$ cross-sections and asymmetries



Agrees with SM – $q\bar{q}$ x-sec 1.8 sigma high averaged over all \sqrt{s}

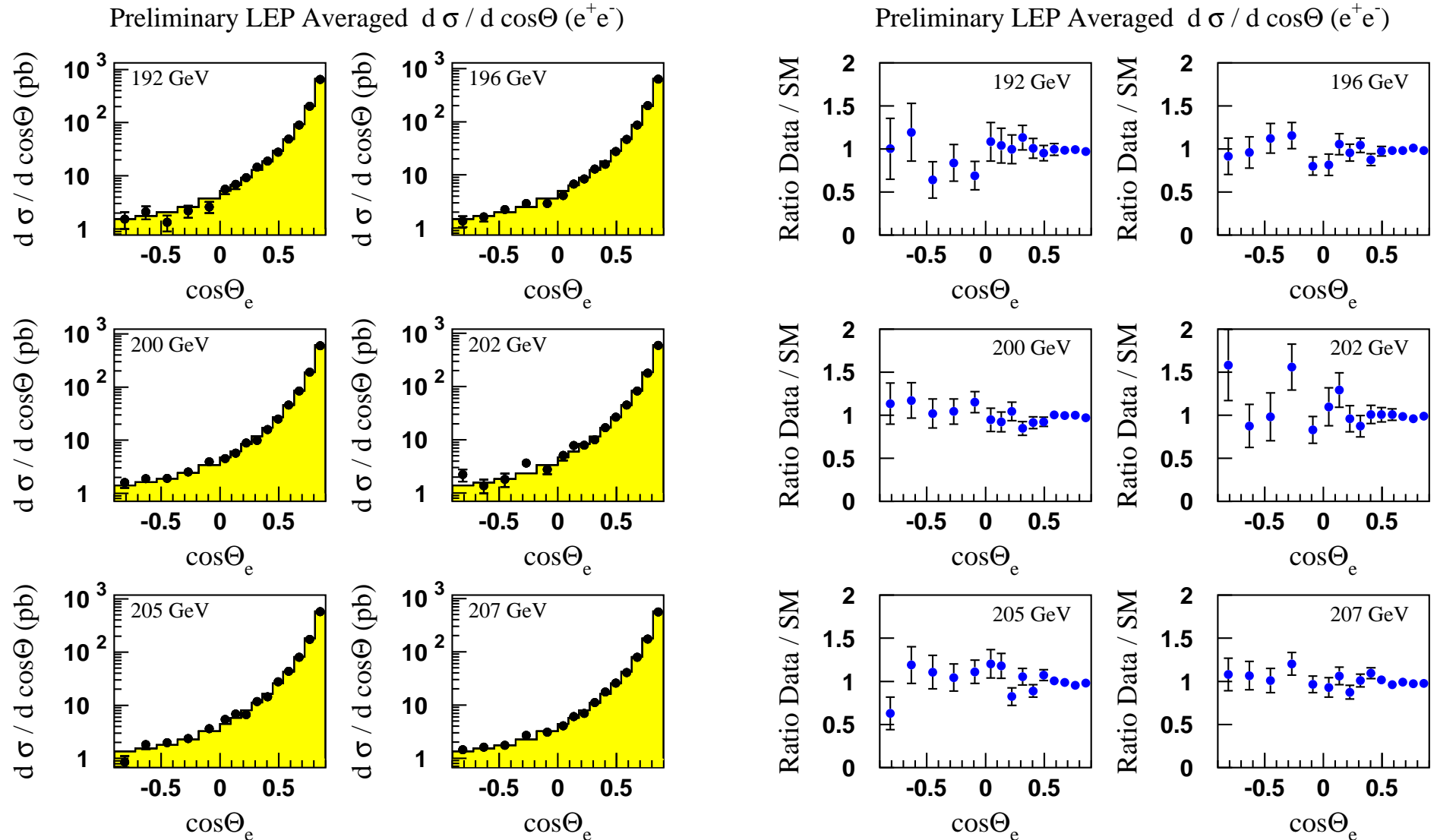
LEP combined differential cross-sections



(≥ 97 for OPAL & DELPHI; ≥ 98 for L3 (μ 's) & ALEPH; 98 for L3 τ 's)

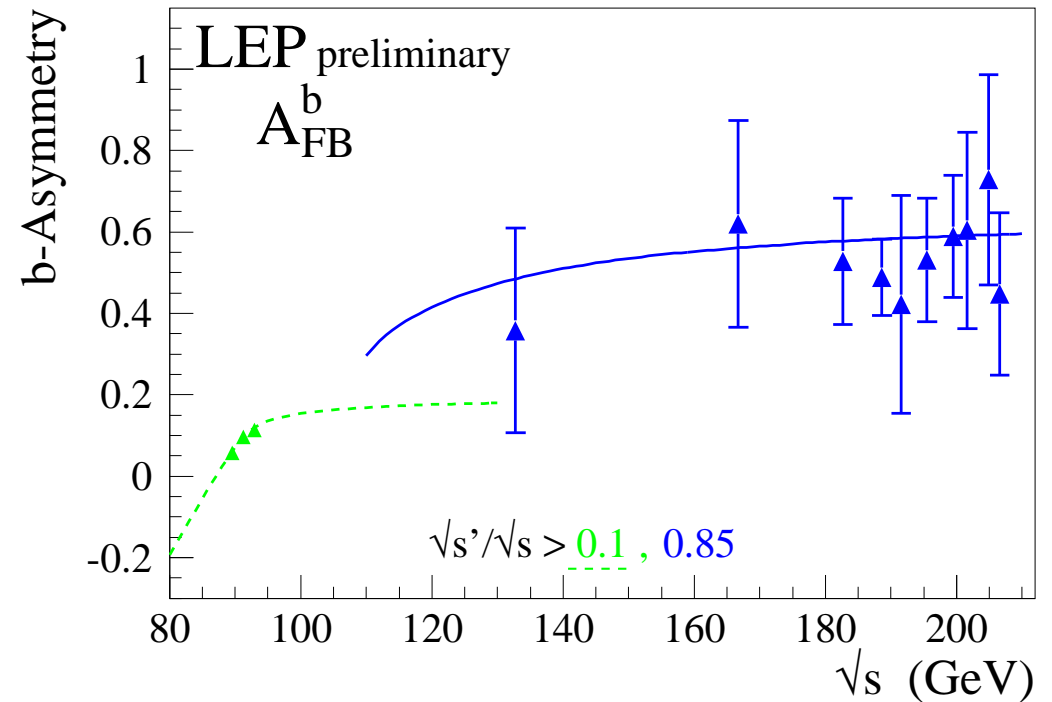
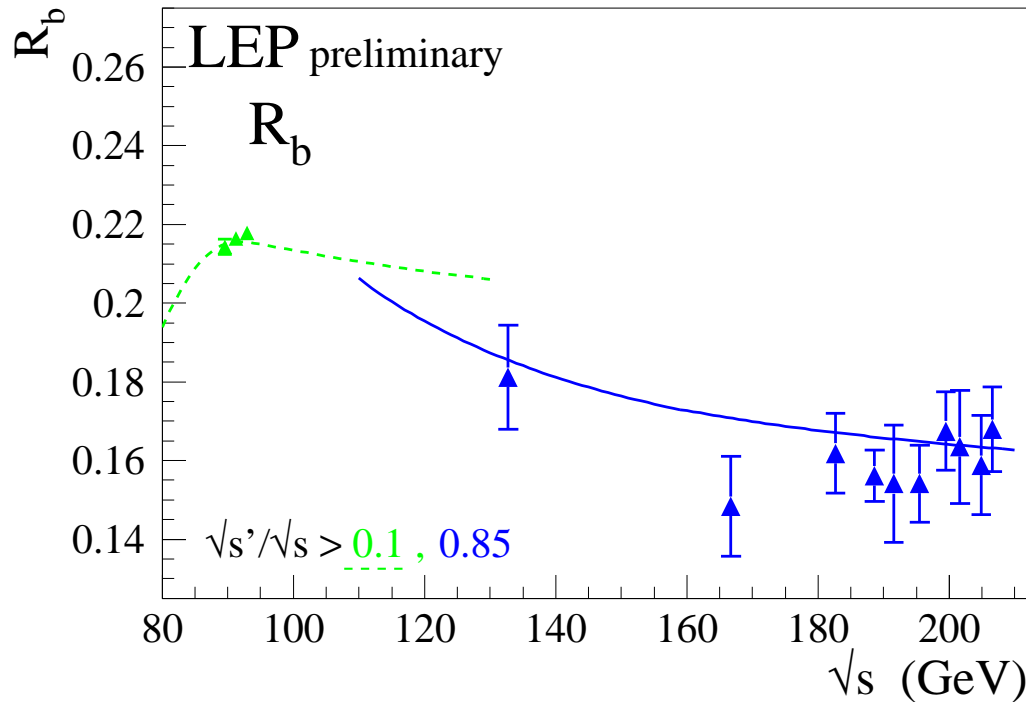
LEP combined differential cross-sections

New! Preliminary combination of OPAL and L3 1999 and 2000 e^+e^- results



LEP combined R_b and $A_{\text{FB}}^{b\bar{b}}$ results

Lifetime based tags used to select $b\bar{b}$ and measure R_b and $A_{\text{FB}}^{b\bar{b}}$

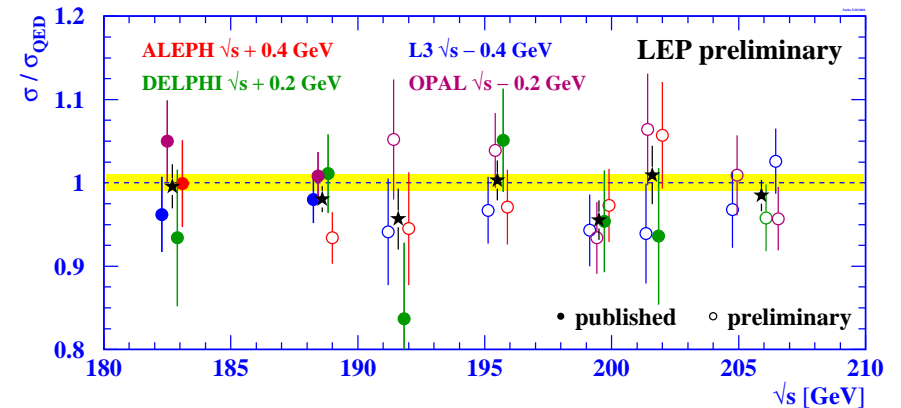
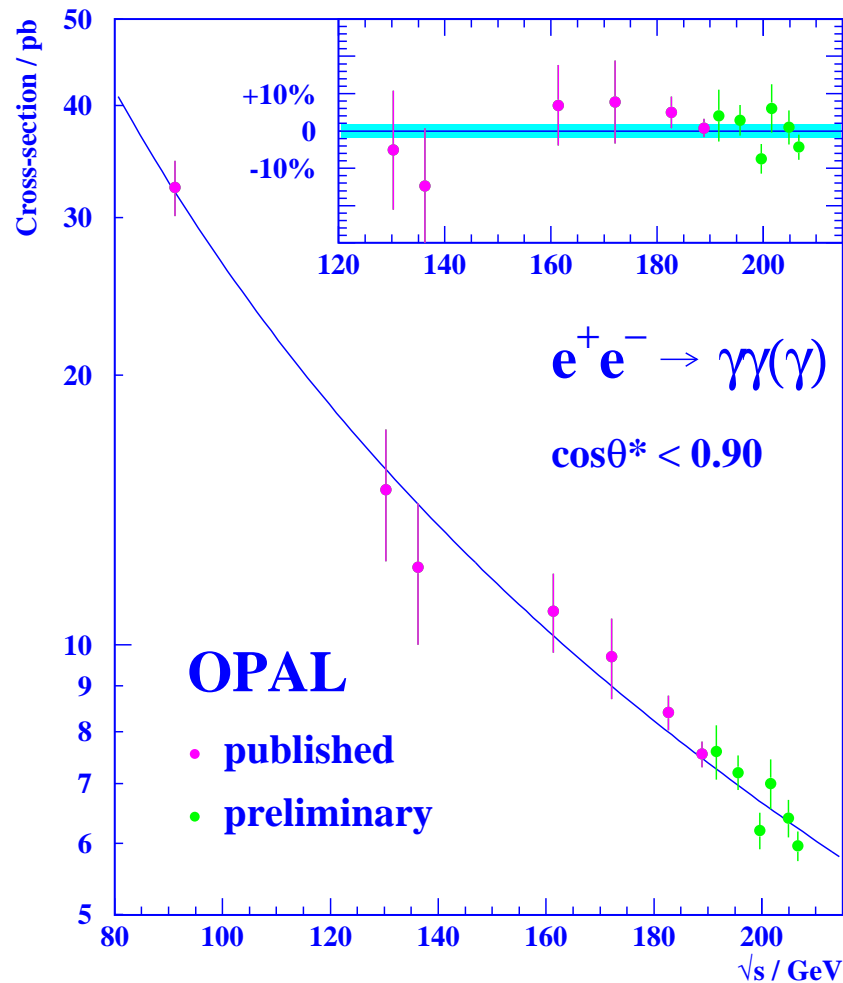


(R_b : ALEPH \leq '99, DELPHI & L3 complete but preliminary, OPAL \leq '98,
 $A_{\text{FB}}^{b\bar{b}}$: partial results from all. $c\bar{c}$ analyses underway – some results available.)

Averaged over \sqrt{s} : $\Delta R_b/R_b = 2.5\%$; $\Delta A_{\text{fb}}^{b\bar{b}} = 0.06$

LEP $e^+e^- \rightarrow \gamma\gamma(\gamma)$ cross-sections

Preliminary or final results for all significant data sets



Global average:

$$\sigma_{\text{meas}}/\sigma_{\text{QED}} = 0.982 \pm 0.012$$

theory error $\sim 1\%$

$e^+e^- \rightarrow \gamma\gamma(\gamma)$ differential cross-sections

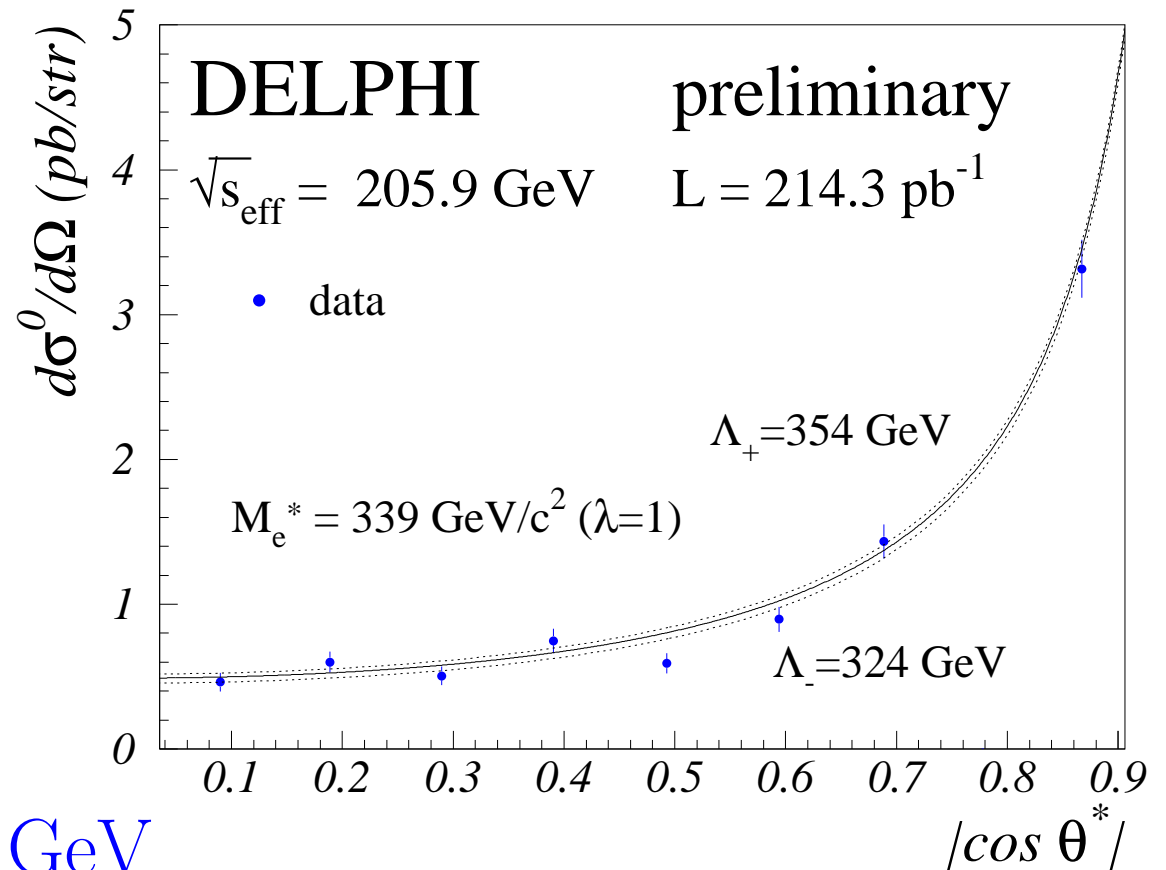
Differential cross-sections sensitive to New Physics

eg. fits to QED cut-off parameters, Λ_+ and Λ_-

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_{\pm}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} \pm \frac{\alpha^2 s}{2\Lambda_{\pm}^4} (1 + \cos^2 \theta)$$

LEP averaged 95% limits:

$$\Lambda_+ > 365 \text{ GeV}, \Lambda_- > 379 \text{ GeV}$$



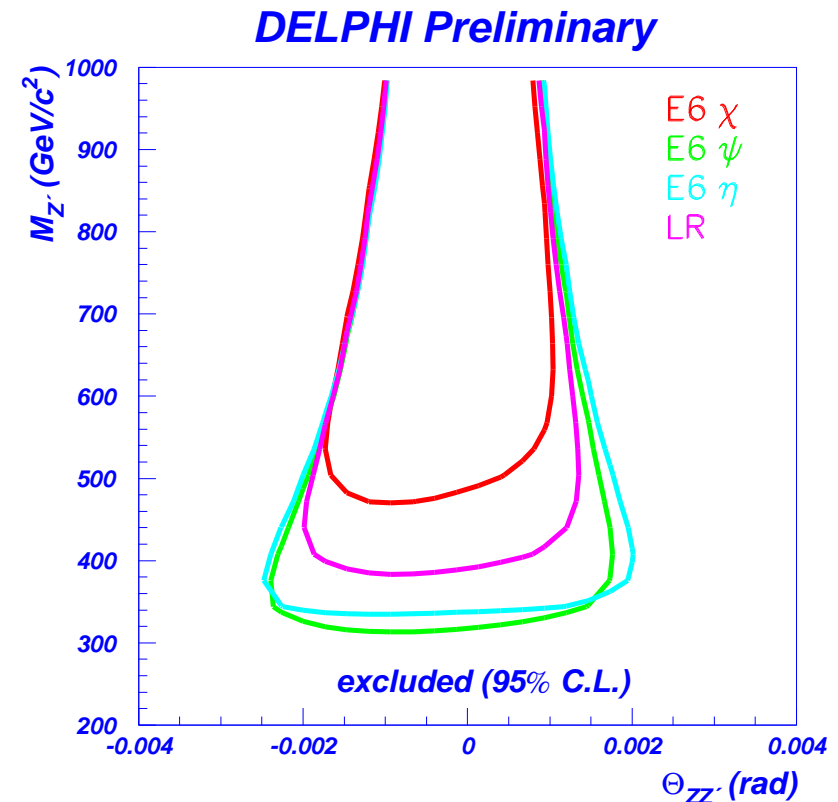
Also sensitive to Low Scale Quantum Gravity (see later)

Z' Bosons

Various New Physics models predict new neutral heavy bosons, Z' 's, and give the expected $f\bar{f} - Z'$ couplings

Fit for $M_{Z'}$, and use LEP 1 data to constrain $Z - Z'$ mixing, $\theta_{ZZ'} \rightarrow$

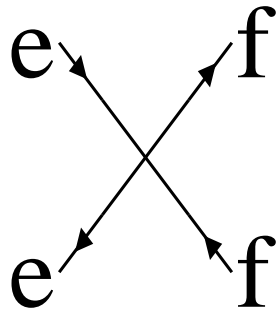
Global LEP fit: set $\theta_{ZZ'} = 0$



Model	χ	ψ	η	LR	SSM
$M_{Z'} > [\text{GeV}]$	678	463	436	800	1890

Contact Interactions

LEP results used to search for contact-interactions between leptons



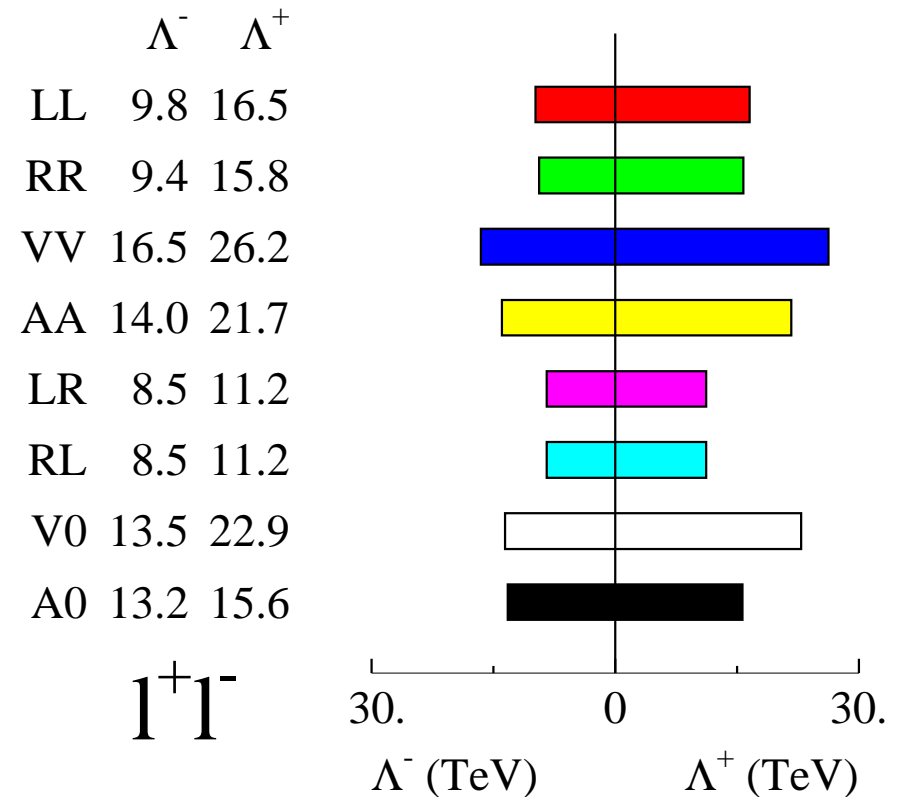
Parameterise with effective \mathcal{L} :

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

$i, j = L, R, \delta = 1$ (0) for $f=e$ ($f \neq e$)
and $g^2/4\pi = 1$ by convention

Fit $1/\Lambda^2$ ($=0$ in SM)

Preliminary LEP Combined



l^+l^-

95% CLs for $e^+e^- \rightarrow l^+l^-$

$\Lambda > 8.5 - 26.2$ TeV

Contact Interactions for quarks

Limits on contact interactions between electrons and b quarks have also been obtained

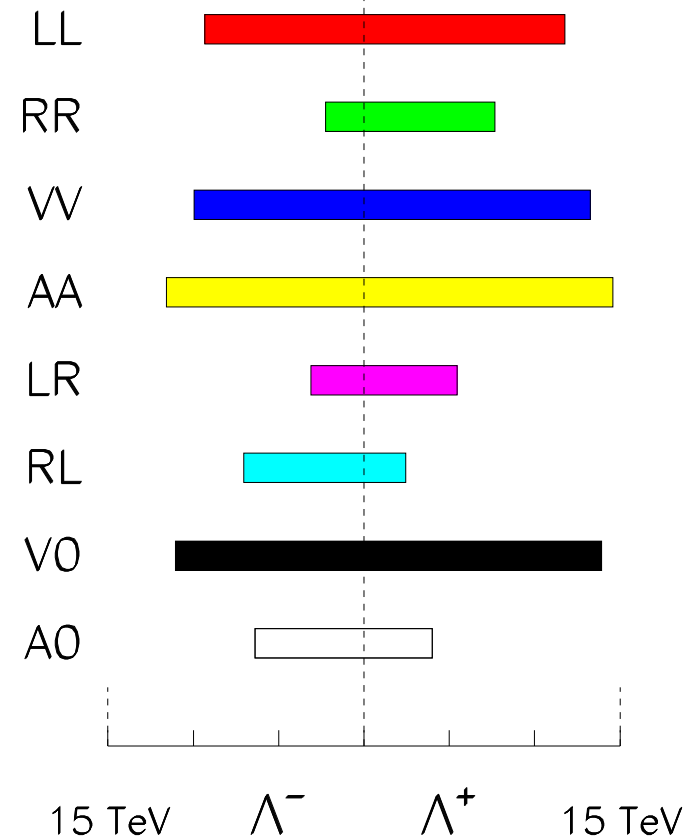
Of particular interest because inaccessible to $p\bar{p}$ & ep colliders

95% CLs for $e^+e^- \rightarrow b\bar{b}$

$\Lambda > 2.2 - 14.6$ TeV

(Equivalent limits on $c\bar{c}$ are $\Lambda > 1.4 - 7.4$ TeV – will improve)

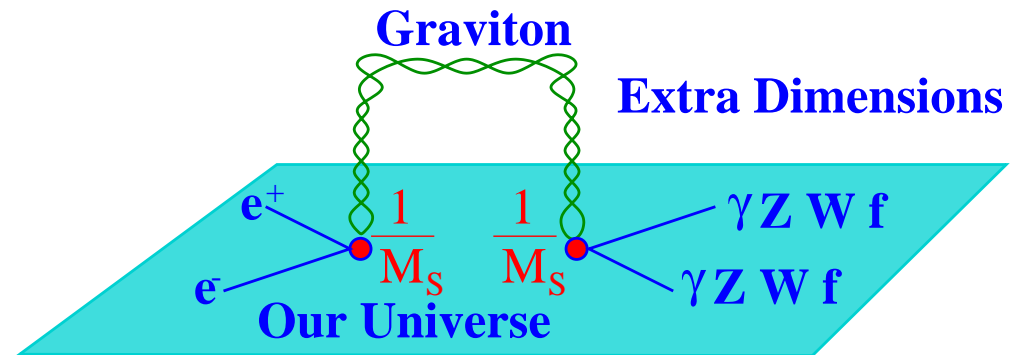
bb – LEP preliminary



Low Scale Gravity (LSG)

Hierarchy problem:

Why $M_{EW} \ll M_{Planck}$?
 $\sim 10^{2-3} \quad \sim 10^{18-19} \text{ GeV}$



Possible solutions: technicolour, SUSY
 or LSG in large extra dimensions ?

- n extra dimensions where gravity propagates
- SM fields in normal space-time
- No hierarchy problem by definition – true gravity scale $M_D \sim M_{EW}$, but appears ‘diluted’

$$M_{Planck}^2 = (M_D)^{2+n} R^n$$

here M_D is true scale for quantum gravity, say 1 TeV, and R = radius of compactified new dimensions

eg. if $n=2$, $R \sim 0.1 \text{ mm}$

‘large’ for string theories!

Low Scale Gravity and $f\bar{f}$ production

LSG in LEP $f\bar{f}$ production:

$$e^+e^- \rightarrow G^* \rightarrow f\bar{f}$$

Modifies diff cross-section:

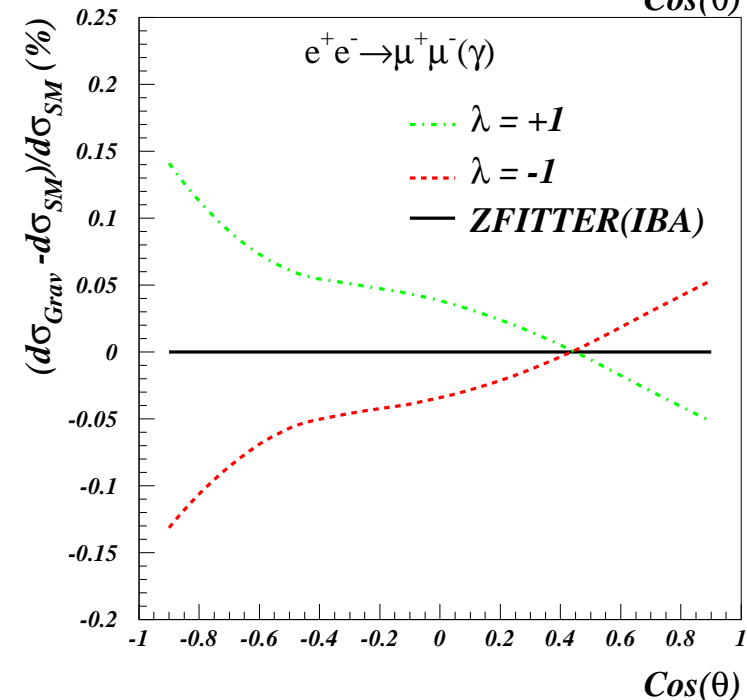
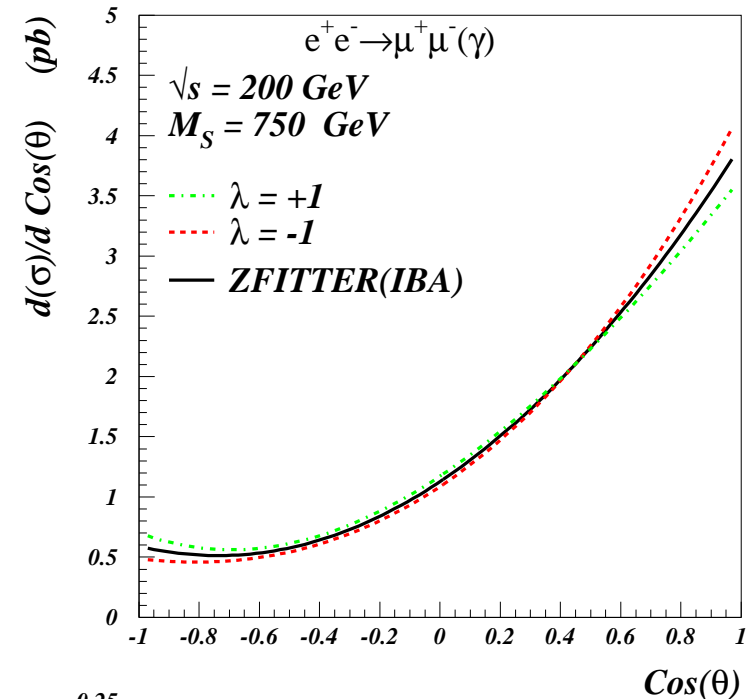
$$\begin{aligned} \frac{d\sigma}{d\cos\theta} &= A(\cos\theta) \\ &+ B(\cos\theta) \left[\frac{\lambda}{M_s^4} \right] \\ &+ C(\cos\theta) \left[\frac{\lambda}{M_s^4} \right]^2 \end{aligned}$$

$A = \text{SM}$, $B = \text{G-SM}$

interference, $C = \text{pure G}$

$\lambda = \text{inteference factor}$,

$M_s = \text{cut off scale} \sim M_D$

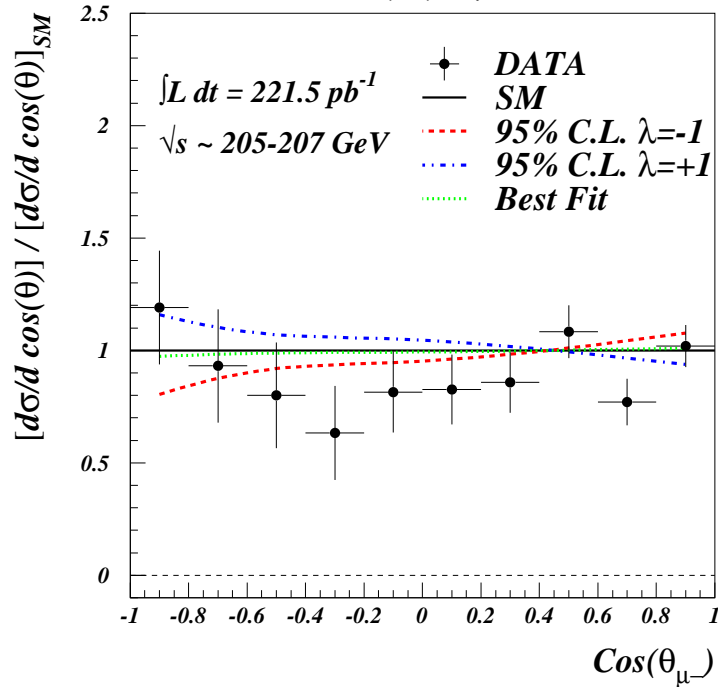


LEP Limits on LSG

No full LEP combined limits yet, but many interesting results

DELPHI PRELIMINARY

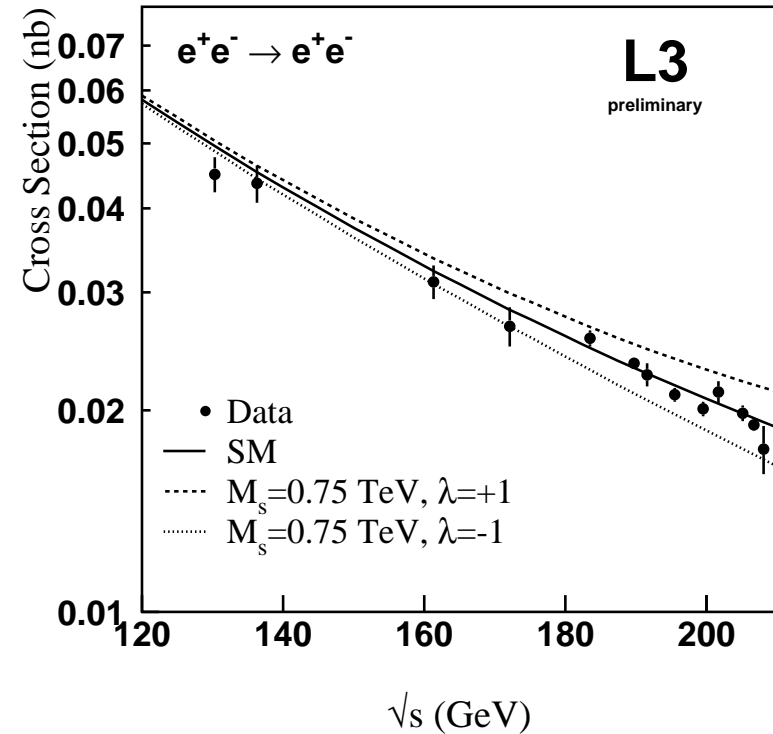
$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$



DELPHI, $\mu^+\mu^-$ & $\tau^+\tau^-$

$$M_s^{\lambda=+1} > 0.81 \text{ TeV}$$

$$M_s^{\lambda=-1} > 0.75 \text{ TeV}$$



L3, full $f\bar{f}$ analysis,
including e^+e^- x-secs

$$M_s^{\lambda=+1} > 1.06 \text{ TeV}$$

$$M_s^{\lambda=-1} > 0.98 \text{ TeV}$$

ALEPH – all $f\bar{f}$ analysed
 Best sensitivity with $\frac{d\sigma(e^+e^-)}{d\cos\theta}$

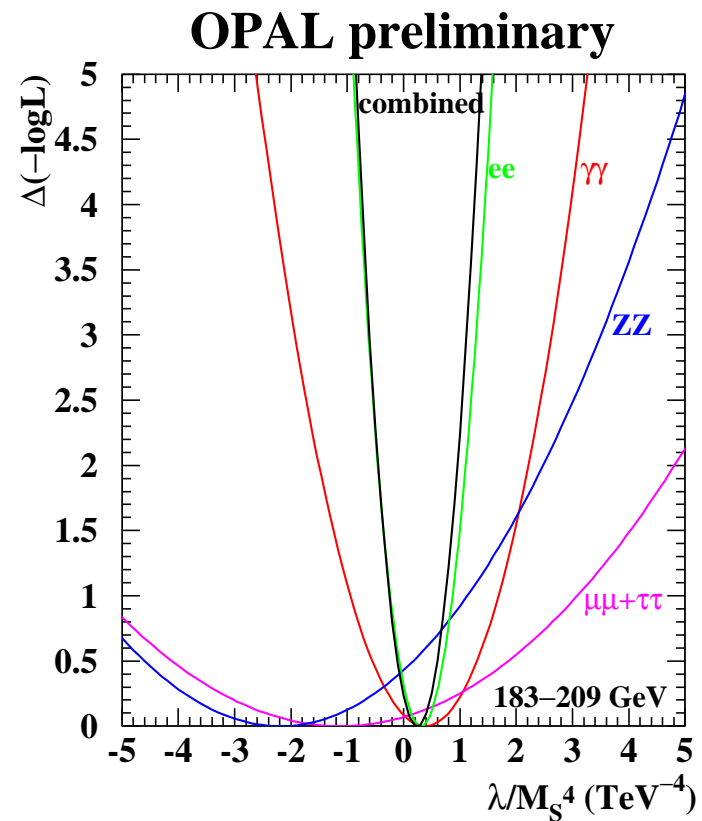
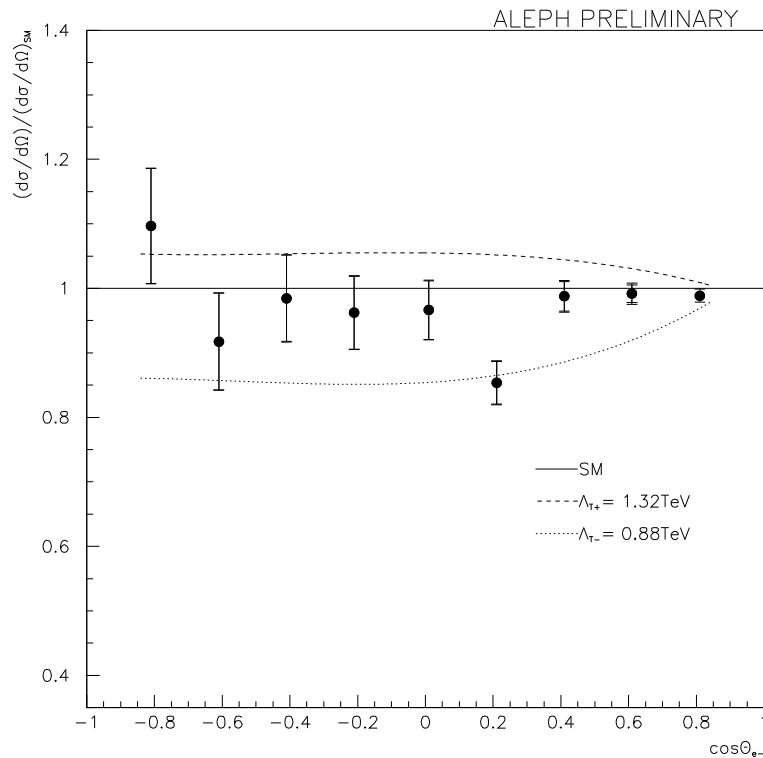
$$M_s^{\lambda=+1} > 1.18 \text{ TeV}$$

$$M_s^{\lambda=-1} > 0.81 \text{ TeV}$$

OPAL – all channels analysed
 2-bosons important, esp. $\gamma\gamma$

$$M_s^{\lambda=+1} > 1.03 \text{ TeV}$$

$$M_s^{\lambda=-1} > 1.17 \text{ TeV}$$



LEP combination of $\gamma\gamma$: $M_s^{\lambda=+1} > 0.97 \text{ TeV}$, $M_s^{\lambda=-1} > 0.94 \text{ TeV}$

Determination of E_b from Z returns

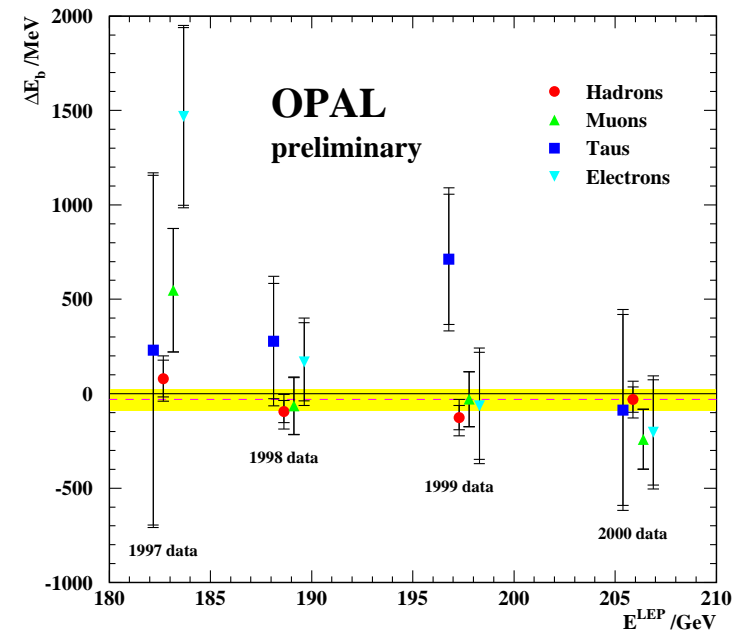
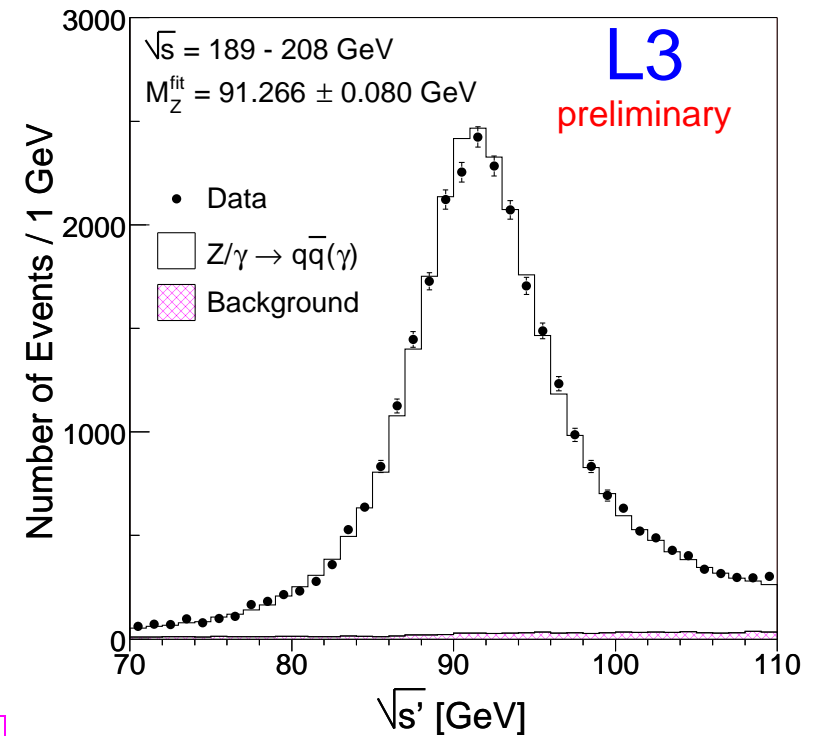
Knowledge of E_b an important systematic for m_W . Machine studies

→ ~ 20 MeV uncertainty

Possibility of cross-check from data!
Fit radiative return peak. Knowing M_Z , determine $\Delta E_b = (f\bar{f} - \text{LEP})$:

	ΔE_b [MeV]
ALEPH '97 $q\bar{q}$	-76 ± 103
OPAL all (prelim)	-31 ± 54
DELPHI $\mu^+\mu^-$ (prelim)	$+76 \pm 96$
L3 ≥ 98 $q\bar{q}$ (new prelim)	-83 ± 84

Systematics are very challenging!



Conclusions

LEP 2 $f\bar{f}$ and $\gamma\gamma$ are large and rich data sets which allow

Powerful tests of the Standard Model... sadly all passed (to date)

Diverse searches for New Physics, with very many interesting limits

Still much work to do in finalising analyses, in combining results and in improving theoretical understanding (eg. e^+e^-)

In particular watch out for:

- S-Matrix fits

- Final combined results on Low Scale Gravity

- Final analyses of E_b through radiative returns