Combination of LEP II Fermion/Photon Pair Results

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LEP Jamboree

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LEP II $\mathrm{f\bar{f}}/\gamma\gamma$ Group

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LEP II $e^+e^- \to f\bar{f}$ and $e^+e^- \to \gamma\gamma$ Measurements

$\sim\sqrt{s}$ [GeV]	Year	$\sim\int\mathcal{L}dt$ [pb^{-1}/expt]
130	95/97	6
136	95/97	6
161	96	10
172	96	10
183	97	55
189	98	170
192	99	25
196	99	75
200	99	80
202	99	40
205	00	85
207	00	140
LEP II	95-00	700

- Measurements of

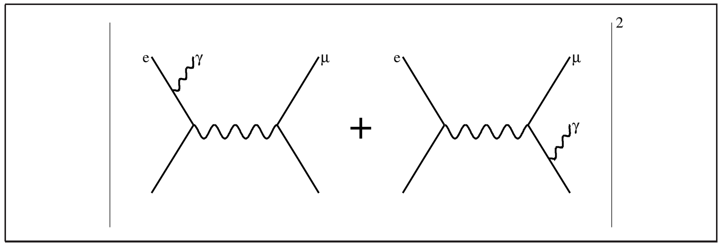
σ	(e^+e^- / $\mu^+\mu^-$ / $\tau^+\tau^-$ / $q\bar{q}$)	*non-rad.* and *incl.*
A_{FB}	(e^+e^- / $\mu^+\mu^-$ / $\tau^+\tau^-$)	*non-rad.* and *incl.*
$\frac{d\sigma}{d\cos\theta}$	(e^+e^- / $\mu^+\mu^-$ / $\tau^+\tau^-$)	*non-rad.*
$R_{\mathrm{q}} = \frac{\sigma_{q\bar{q}}}{\sigma_{\mathrm{had}}}$	(b / c)	*non-rad.*
$A_{\mathrm{FB}}^{\mathrm{qq}}$	(b / c)	*non-rad.*
σ	($\gamma\gamma$)	
$\frac{d\sigma}{d\cos\theta}$	($\gamma\gamma$)	

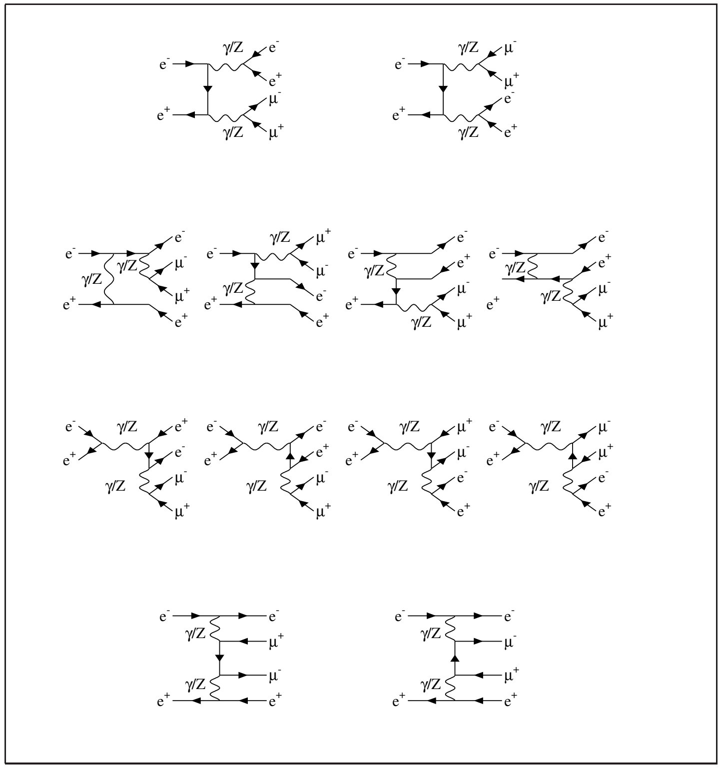
- Contents
  - Combination of σ and A_{FB}
  - Combination of $d\sigma/d\cos\theta$
  - Combination of R_{q} and $A_{\mathrm{FB}}^{\mathrm{qq}}$
  - Combination of $e^+e^- \to \gamma\gamma$ results
  - Interpretation
- RESULTS ARE BASED ON PRELIMINARY DATA

Combination of σ and A_{FB}

- Aim to provide a set of data that can be used for searches $\mathcal{BSM}$ after LEP era
- Concentrate on combining *non-radiative* samples (e^+e^- not yet combined)
- Corrections are applied to data before averaging so that data correspond to a common signal definition
- Correlations: systematics are broken down into 5 classes
  - Uncorrelated errors
  - Errors correlated between energies
  - Errors correlated between channels
  - Errors correlated between energies and experiments
  - Error correlated between energies, experiments and channels
  - Most important are correlations between experiments, eg
    - ISR modelling and Fragmentation errors for $\sigma_{q\bar{q}}$
- Web page: `http://lepewwg.web.cern.ch/LEPEWWG/lep2/`

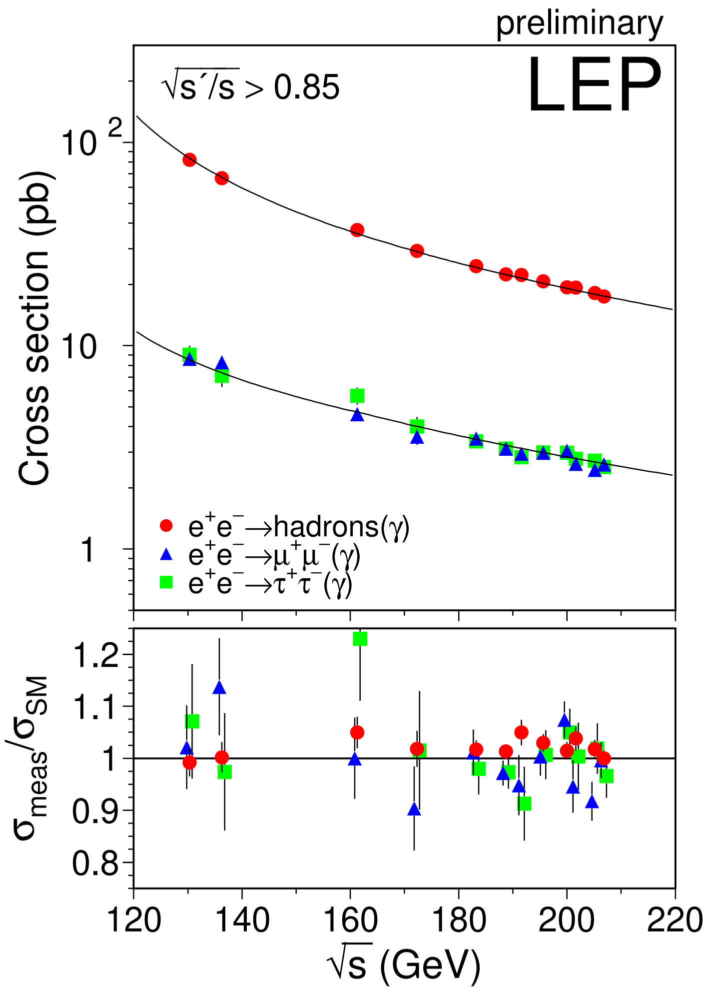
Signal Definition

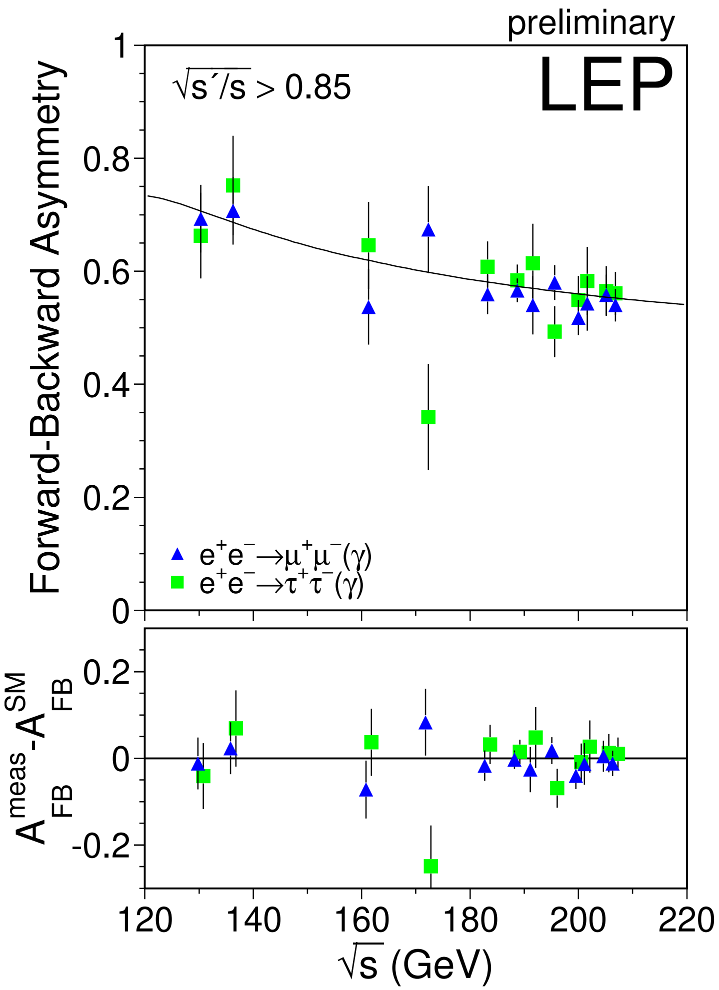




- Exact signal definition differs between experiments
  - Definition of $\sqrt{s'}$
    - $\sqrt{s'} = Q$: invariant mass of propagator
    - $\sqrt{s'} = M_{ff}$: invariant mass $f\bar{f}$
  - Ranges of $\sqrt{s'}$
    - *non-radiative* selection $\sqrt{s'} > 0.85 - 0.9\sqrt{s}$
  - Extrapolation to 4π acceptance
  - Treatments of interference between ISR and FSR
    - subtract ISR*FSR interference or not
  - Treatment of additional fermion pairs in events

Cross-section and Forward-Backward Asymmetry Results





Good agreement with $\mathcal{SM}$ - Hadronic σ 1.8 s.d. excess averaged over all $\sqrt{s}$

Uncertainties and Correlations

- Averaging procedure gives the full errors matrix for all measurements
- Correlations between uncertainties on hadronic σ at different energies are significant

$$\mathcal{O}(15 - 30\%)$$

- Total experimental precision on deviations from $\mathcal{SM}$ averaged over all energies

$$\begin{array}{llll} \text{hadrons} & \Delta(\sigma - \sigma_{\mathcal{SM}})/\sigma_{\mathcal{SM}} \sim 1.0\% & & \\ \mu^+\mu^- & \Delta(\sigma - \sigma_{\mathcal{SM}})/\sigma_{\mathcal{SM}} \sim 1.6\% & \Delta A_{FB} - A_{FB\ \mathcal{SM}} & \sim 0.012 \\ \tau^+\tau^- & \Delta(\sigma - \sigma_{\mathcal{SM}})/\sigma_{\mathcal{SM}} \sim 2.2\% & \Delta A_{FB} - A_{FB\ \mathcal{SM}} & \sim 0.015 \end{array}$$

- Theoretical uncertainty on σ in $\mathcal{SM}$

Non-radiative: hadrons 0.3%; $\mu^+\mu^-$ 0.4%; $\tau^+\tau^-$ 0.4%; e^+e^- (central) 2.0%

(*"LEP II Monte Carlo Workshop"* Yellow Report CERN 2000-09)

Combination of $\mathbf{d}\sigma/\mathbf{d}\cos\theta$

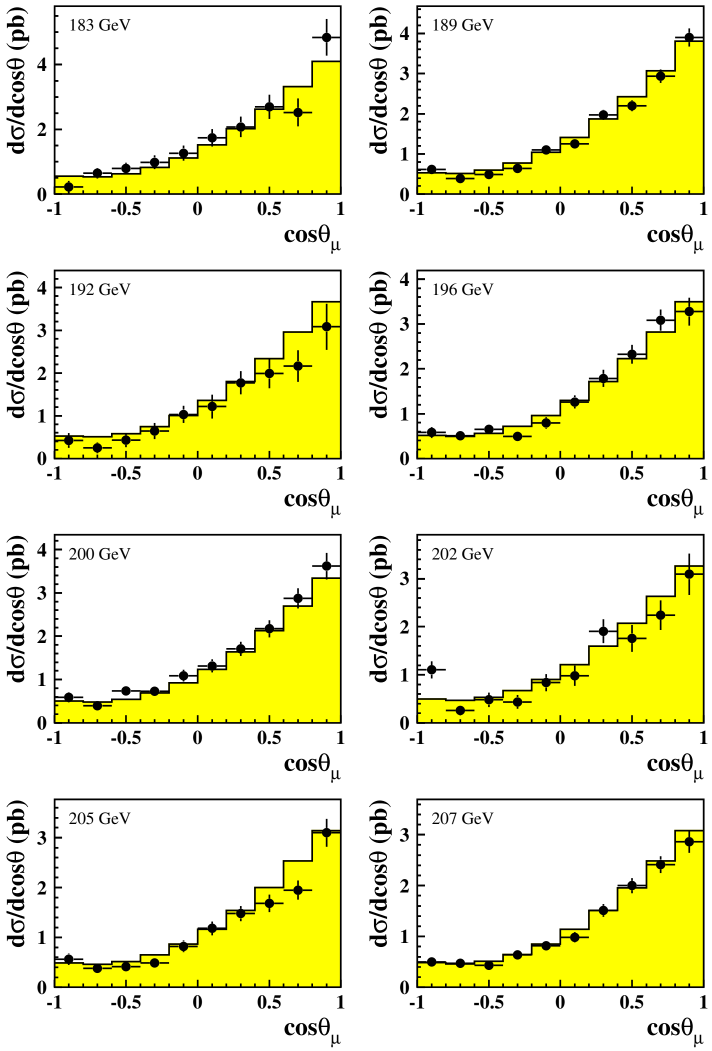
- Combination method very similar to σ and A_{FB}
- Extrapolation to $|\cos\theta| = 1.0$ in forward and backward bins
- Some bins have low statistics at some energies
  - Using likelihood fit to number of observed events not possible - data not published
  - Use expected error on $d\sigma/d\cos\theta$ in each bin to average results
  - Based on $\mathcal{SM}$ expectation in bin
  - Method was cross-checked against likelihood fit for backward bin at energy with low statistics

$\sqrt{s}$ (GeV)	μ				τ			
	A	D	L	O	A	D	L	O
183	-	F	-	F	-	F	-	F
189	P	F	F	F	P	F	F	F
192-202	P	P	P	P	P	P	-	P
205-207	P	P	P	P	P	P	-	P

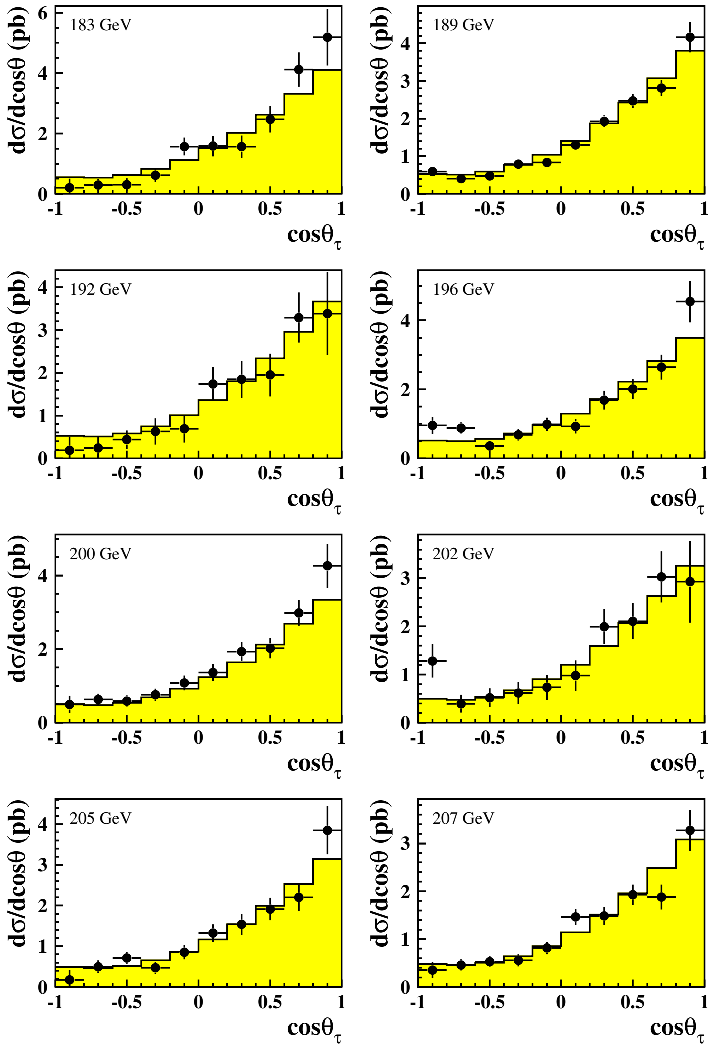
P = preliminary F = Final

Combination of $\mathrm{d}\sigma/\mathrm{d}\cos\theta$

Preliminary LEP Averaged dσ/dcosθ (μμ)



Preliminary LEP Averaged dσ/dcosθ (ττ)



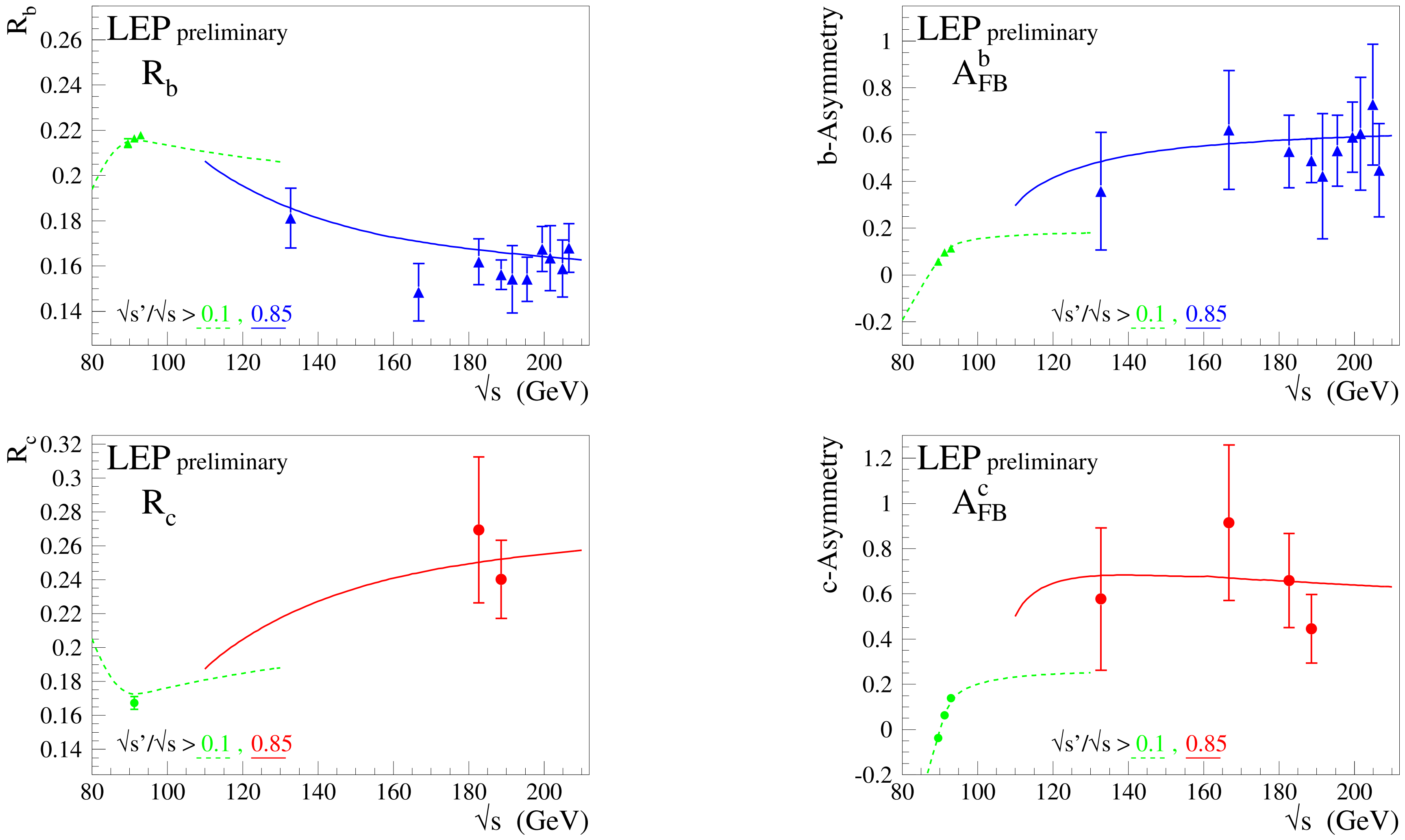
Combination of R_q and A_{fb}^{qq}

$\sqrt{s}$ (GeV)	R_b				R_c				A_{FB}^{bb}				A_{FB}^{cc}			
	A	D	L	O	A	D	L	O	A	D	L	O	A	D	L	O
133	F	F	F	F	-	-	-	-	-	F	-	F	-	F	-	F
167	F	F	F	F	-	-	-	-	-	F	-	F	-	F	-	F
183	F	P	F	F	F	-	-	-	F	-	-	F	P	-	-	F
189	P	P	F	F	P	-	-	-	P	P	F	F	P	-	-	F
192-202	P	P	P	-	-	-	-	-	P	P	-	-	-	-	-	-
205-207	-	P	P	-	-	-	-	-	-	P	-	-	-	-	-	-

F = Final P = Preliminary

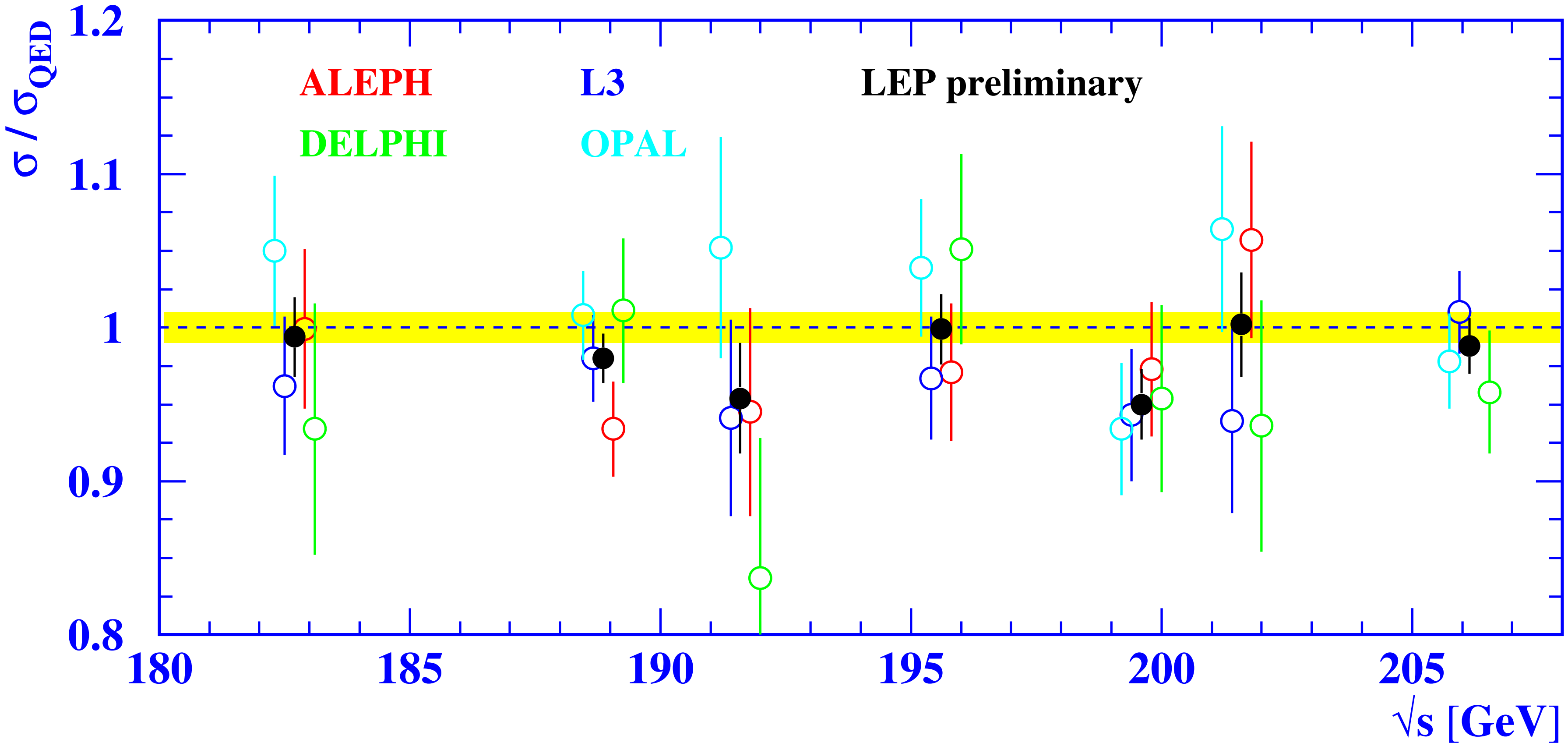
Combination follows the heavy flavour averaging procedure used at LEP I

Combination of R_q and A_{fb}^{qq}



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

Combination of $e^+e^- \to \gamma\gamma$ Results



New activity since spring

Interpretation of Combined Results

Examples of Models Studied
$e^+e^- \to f\bar{f}$

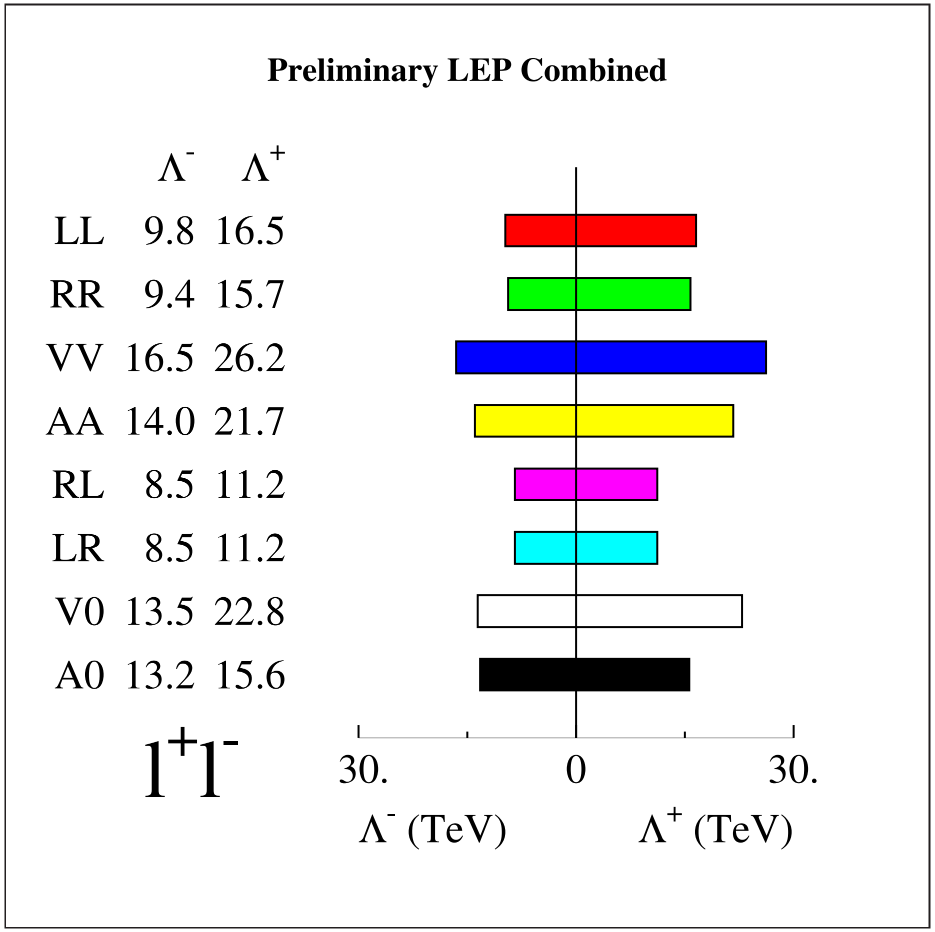
model	A	D	L	O	LEP
S-Matrix	$\odot$	$\odot$	$\oplus$	$\oplus$	
Contact	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
$\tilde{\nu}$	$\oplus$	$\odot$	$\odot$	$\odot$	
$\tilde{q}$	$\oplus$	$\odot$	$\oplus$	$\odot$	$\odot$
Z'	$\odot$	$\oplus$	$\oplus$	$\oplus$	$\oplus$
Gravity	$\oplus$	$\odot$	$\oplus$	$\oplus$	
Strings			$\oplus$		

$\odot$ = analysis performed

$\oplus$ = results with 2000 data

- Combined LEP $e^+e^- \to f\bar{f}$ and $e^+e^- \to \gamma\gamma$ data can be used to constrain physics $\mathcal{BSM}$
- Effects of physics $\mathcal{BSM}$ are from virtual interactions
- Usually sensitivity comes from interference of $\mathcal{BSM}$ with $\mathcal{SM}$.
- The *non-radiative* peak usually has highest sensitivity
- Can usually reach higher energy scales than direct searches in e^+e^- collisions at same energy

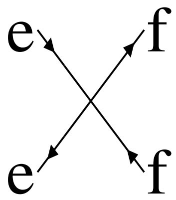
Contact Interactions



95% confidence limits for $e^+e^- \to l^+l^-$

$\Lambda > 8.5 - 26.2$ TeV

LEP (Data 130 - 207 GeV ; Summer 2001)



- Λ is scale of contact interactions in effective Lagrangian

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

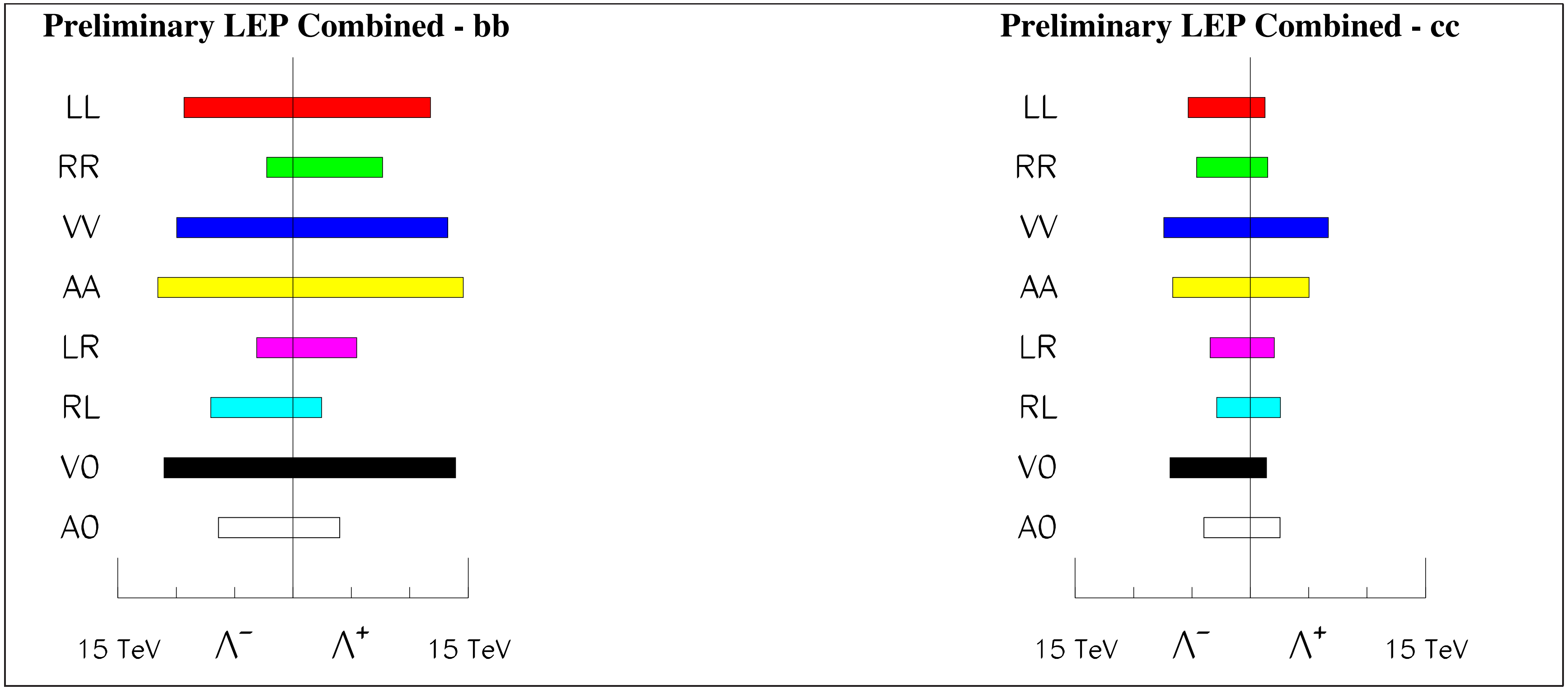
where $i, j = L, R$. Take $g^2 = 4\pi$

- Fit $\epsilon = 1/\Lambda^2$; ($\mathcal{SM}$ $\epsilon = 0$)
- Fermi Theory with this ansatz:

$$\frac{e^2}{8\mathrm{M_W}^2 \sin^2\theta_\mathrm{W}} = \frac{G_{\mathrm{F}}}{\sqrt{2}} \to \frac{4\pi}{\Lambda^2}$$

$\mathrm{M_W} \sim \mathcal{O}(0.1\mathrm{TeV})$ but $\Lambda \sim \mathcal{O}(1\mathrm{TeV})$

Contact Interactions for quarks



- Assume $\times$ only affects one flavour
- Fit R_b, R_c, A_{FB}^{bb}, A_{FB}^{cc} and σ_{had}

95% confidence limits for $e^+e^- \rightarrow q\bar{q}$

$b\bar{b}$ $\Lambda > 2.2 - 14.6$ TeV

$c\bar{c}$ $\Lambda > 1.4 - 7.4$ TeV

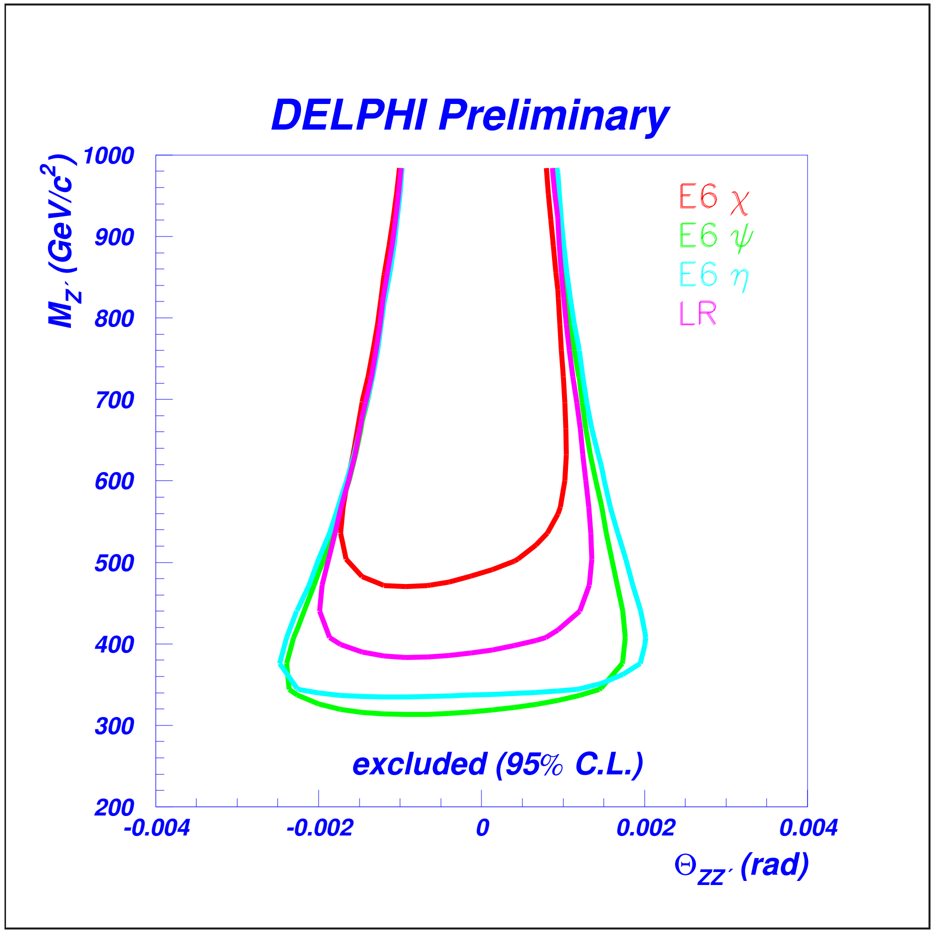
LEP (Data 130 - 207 GeV ; Summer 2001)

Z′ Bosons

- Various models predict the existence of new neutral, heavy bosons: Z′s
- Models set couplings of Z′ to $f\bar{f}$
- Individual experiments use
  - LEP I: constrains mixing $\theta_{ZZ'}$
  - LEP II: constrains mass $M_{Z'}$
- LEP II combined σ and A_{FB}. assume $\theta_{ZZ'} = 0$.
- LEP 95% confidence limits

Model	χ	ψ	η	LR	SSM
$M_{Z'} >$ (GeV)	678	463	436	800	1890

(Data 130-207 GeV; Summer 2001)



DELPHI (Data LEP I + 130-207 GeV ; Summer 2001)

Summary and Outlook

- The LEP II $e^+e^- \rightarrow f\bar{f}$ and $e^+e^- \rightarrow \gamma\gamma$ data provides a test of the $\mathcal{SM}$ at the % level
- The data is in good agreement with $\mathcal{SM}$
- Tight constraints on the physics $\mathcal{BSM}$

- Experiments aiming to complete analysis within 12-18 months
- Will combine final data
- Will work on those important areas that we have not yet covered
  - electron $\frac{d\sigma}{d\cos\theta}$
  - gravity in extra dimensions
  - $\gamma\gamma$ final states