LEP II $f\bar{f}$ averages

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CERN

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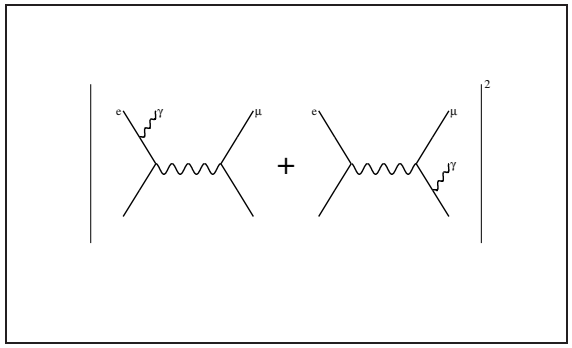
LEP II $f\bar{f}$ averaging group

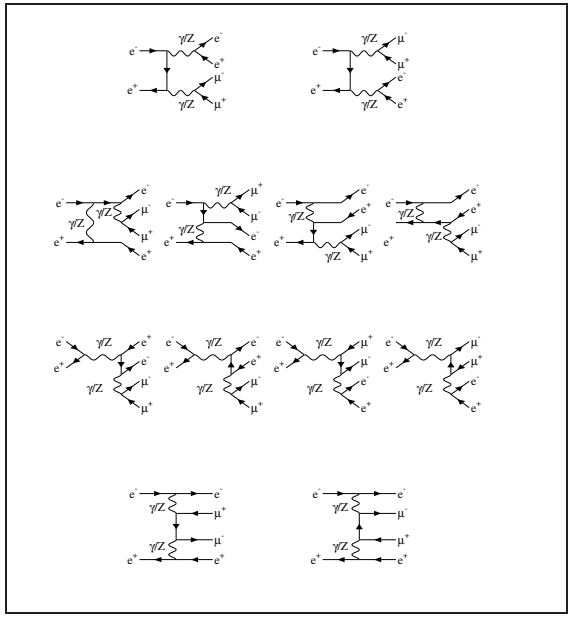
- DELPHI members
  Markus Elsing, PJH, Wolfgang Leibig, Peter Renton (chair)
  Members from each of the other collaboration
- Aim
  - Combine results from the LEP experiments to provide a set of results that can be used in the future to search for new physics Beyond the Standard Model in new models.
  - Thus concentrate on combining measurements with high $\sqrt{s'}/\sqrt{s}$
  - Combine measurements of

σ		($\mu^+\mu^-$ / $\tau^+\tau^-$ /$q\bar{q}$)
A_{FB}		($\mu^+\mu^-$ / $\tau^+\tau^-$)
$\frac{d\sigma}{d\cos\theta}$		(e^+e^- / $\mu^+\mu^-$ / $\tau^+\tau^-$)
$R_{\text{Q}} = \frac{\sigma_{Q\bar{Q}}}{\sigma_{\text{had}}}$		(b / c)
$A_{\text{FB}}^{Q\bar{Q}}$		(b / c)

- Web page: http://lepewwg.web.cern.ch/LEPEWWG/lep2/

Signal Definition





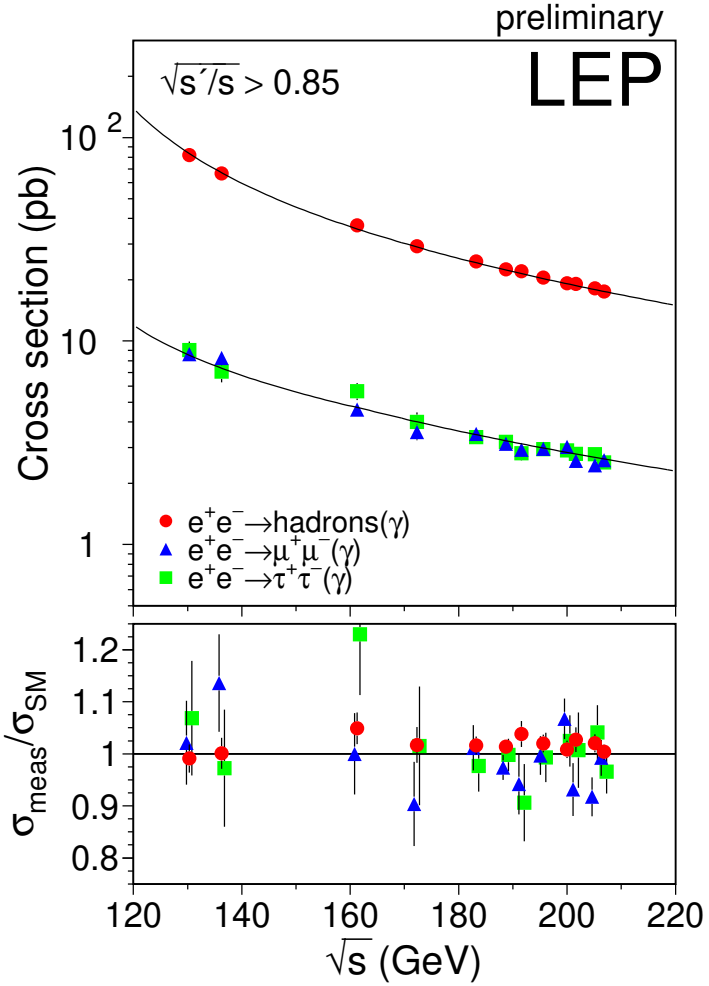
- Exact signal definition differs between experiments
  - Definition of $\sqrt{s'}$
    - $\sqrt{s'} = Q$: invariant mass of propagator
    - $\sqrt{s'} = M_{ff}$: invariant mass of final state fermions
  - Extrapolation to 4π acceptance
  - Treatments of interference between ISR and FSR
    - apply correction to subtract ISR*FSR interference or not
  - Treatment of additional fermion pairs in events
    - which events to count as signal which as background
- Correct to a common signal definition

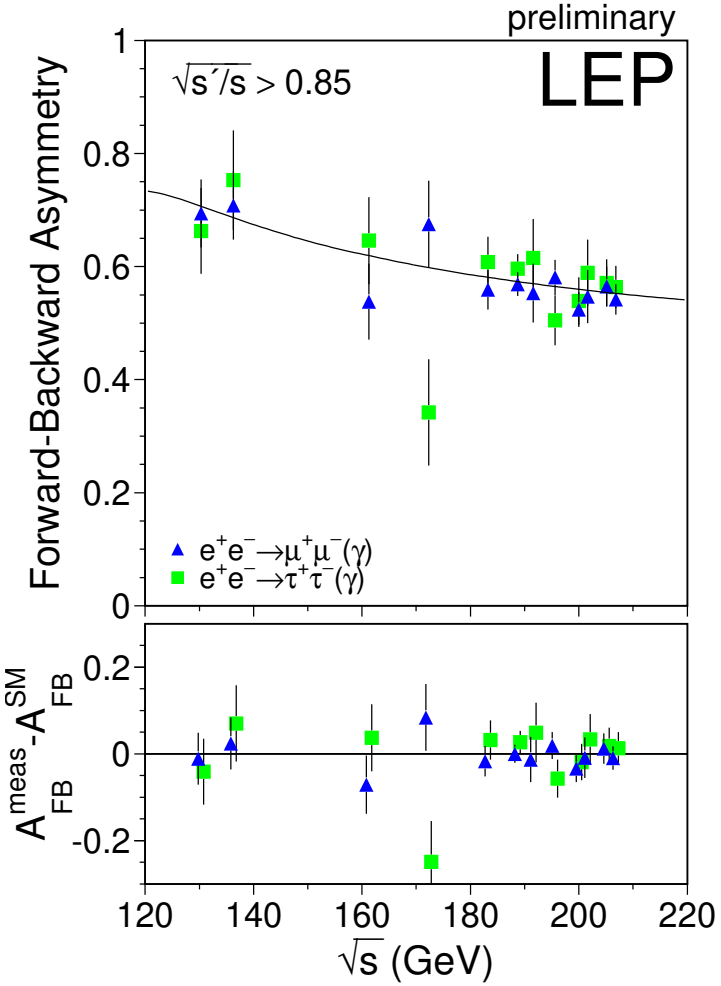
$$\mathrm{M_{corr}} = \mathrm{M_{exp}} - \mathrm{P_{exp}} + \mathrm{P_{LEP}}$$

Correlations

- 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 $\sigma_{q\bar{q}}$
- Average is done with the BLUE technique
  - Equivalent to a χ^2
  - Gives the full errors matrix for all measurements
  - Can get breakdown of errors on the averages
- Uncorrelated systematics and statistical errors are lumped together
  Will be split for final combination

Results





Good agreement with $\mathcal{SM}$ - $\sigma_{q\bar{q}}/\sigma_{SM}$ 1.7 s.d. excess averaged over all $\sqrt{s}$

Results: Uncertainties and Correlations

- 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

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

- 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)

$$\frac{d\sigma}{d\cos\theta}(e^+e^-)$$

- Correct for different signal definitions
  - acolinearity
- Binning
  - Forward: 10 bins $\cos\theta$ 0.0–0.9
  - Backward: 5 bins $\cos\theta$ -0.9–0.0

  Different experiments cover different angular ranges
- Consider correlations between
  - Experiments, energies and bins from normalization
  - Bins in opposite hemisphere due to charge confusion
- Combine using BLUE

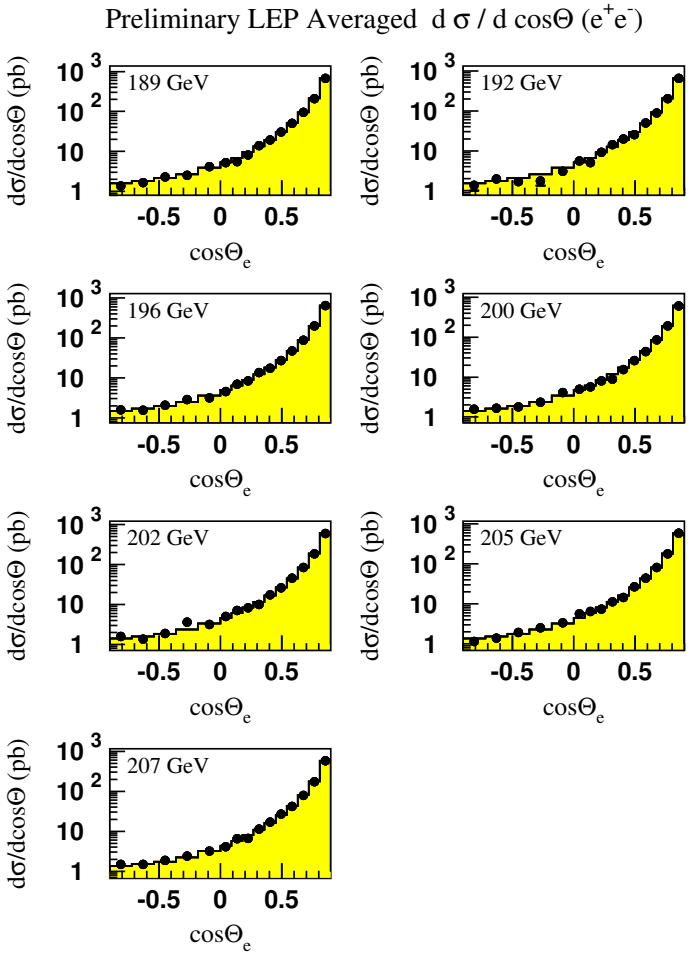
  χ^2/D.O.F 191/189

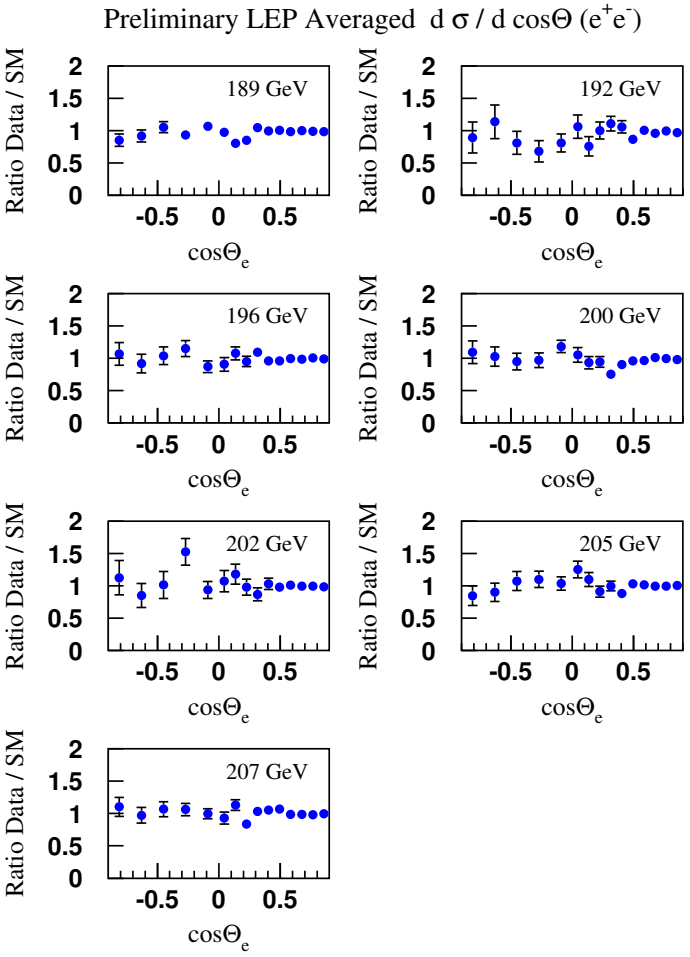
	$\sqrt{s}$
A	189-207
L	189-207
O	183-207

	cut
A	$\sqrt{s}/\sqrt{s'} < .85$
L	$\theta_{acol} < 25°$
O	$\theta_{acol} < 10°$

	$\lvert\cos\theta\rvert$
A	< 0.9
L	< 0.72
O	< 0.9

Results $\frac{d\sigma}{d\cos\theta}(e^+e^-)$





Good agreement with BHWIDE

Correlations important in forward bins

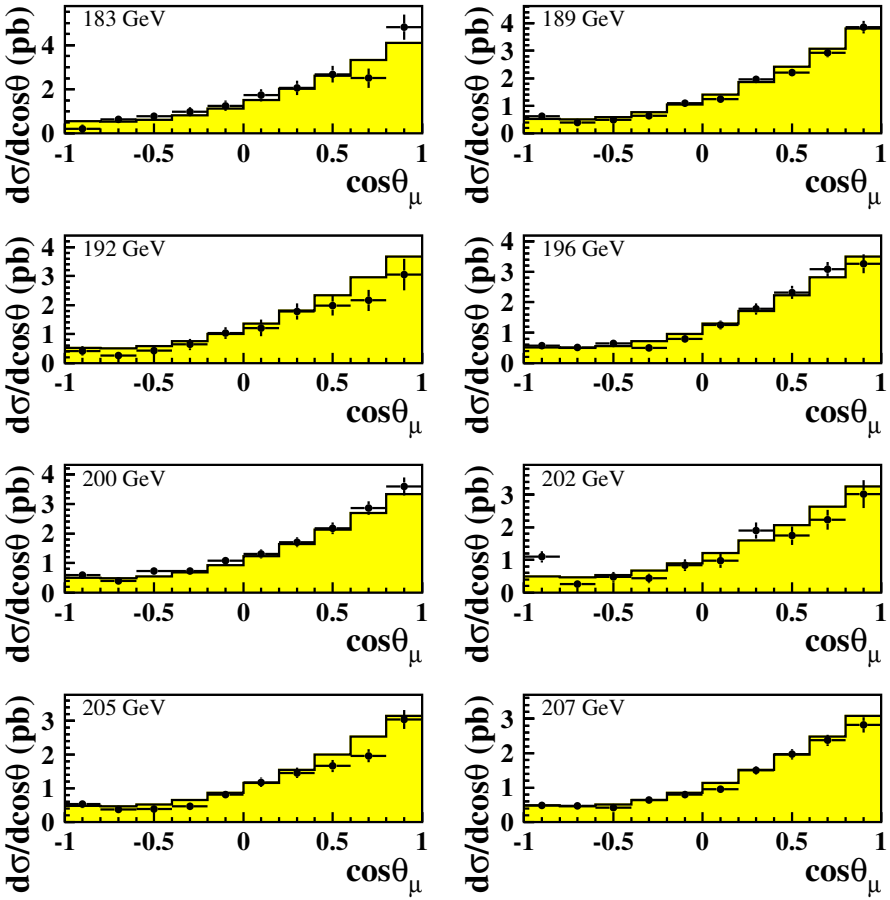
$$\frac{d\sigma}{d\cos\theta}(\mu^+\mu^-/\tau^+\tau^-)$$

	Channel	$\sqrt{s}$	$\lvert\cos\theta\rvert$
A	$e^+e^- \to l^+l^-$	189–207	0.95
D	$e^+e^- \to \mu^+\mu^-$	183	0.94
	$e^+e^- \to \mu^+\mu^-$	189–207	0.97
	$e^+e^- \to \tau^+\tau^-$	183–207	0.96
L	$e^+e^- \to \mu^+\mu^-$	189–207	0.90
	$e^+e^- \to \mu^+\mu^-$	189	0.90
O	$e^+e^- \to l^+l^-$	183–207	1.00
LEP Average			1.00

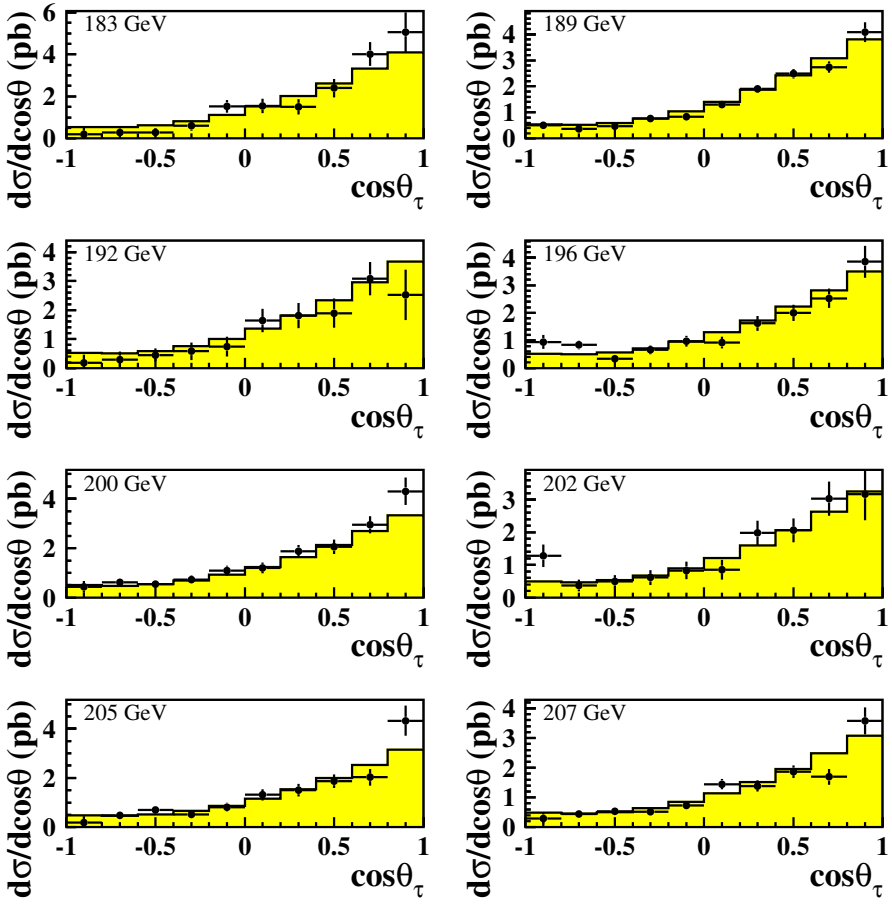
- Binning
  - 10 bins $-1 < \cos\theta < 1$
- Signal Definition
  - also correct to $\lvert\cos\theta\rvert < 1$
- Errors
  - consider correlations on normalization
  - use expected statistical error
- Combine using BLUE

Results $\frac{d\sigma}{d\cos\theta}(\mu^+\mu^-/\tau^+\tau^-)$

Preliminary LEP Averaged dσ/dcosθ (μμ)



Preliminary LEP Averaged dσ/dcosθ (ττ)



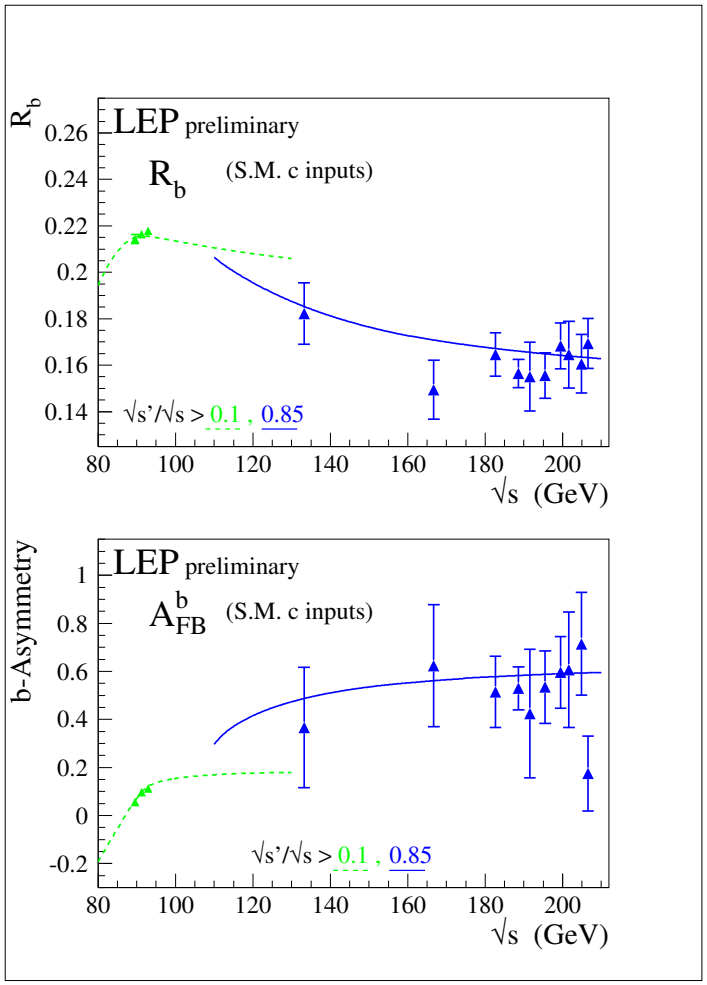
Heavy Flavour Averages

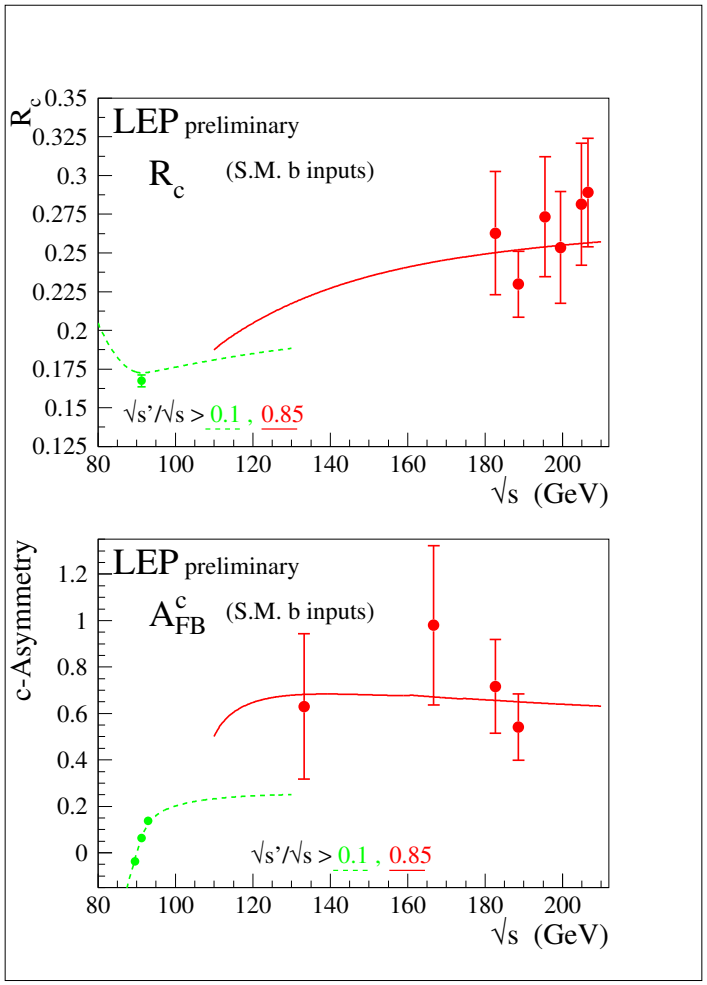
- Combine using the LEP I heavy flavour method
  - specific errors identified
- Quote results for
  - b with c content fixed to SM prediction
  - c with b content fixed to SM prediction
- For errors
  - b/c correlations included
- Much data is still to be included in combination
  - R_{c} and $A_{\mathrm{FB}}^{c\bar{c}}$ data is sparce

R_{b}	R_{c}
$A_{\mathrm{FB}}^{b\bar{b}}$	$A_{\mathrm{FB}}^{c\bar{c}}$

$$R_{\mathrm{Q}} = \frac{\sigma_{Q\bar{Q}}}{\sigma_{\mathrm{had}}}$$

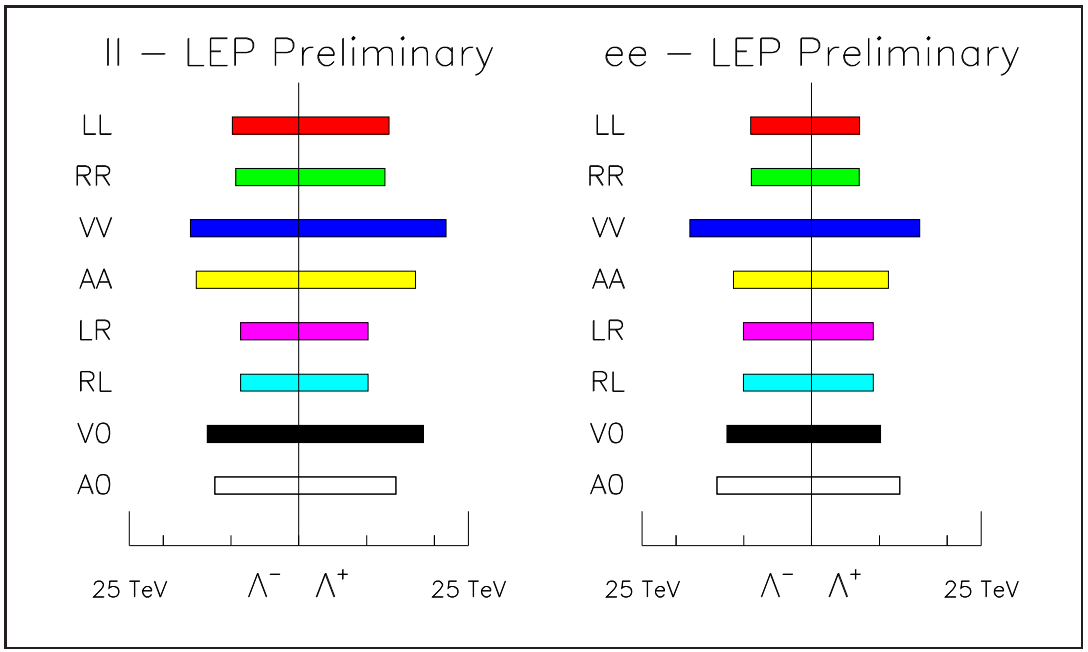
Results for Heavy Flavours





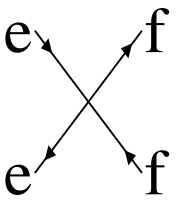
$R_b/R_{bSM} \sim 2$ s.d. below unity

Contact Interactions



95% confidence limits

$$e^+e^- \to l^+l^- \quad \sigma, A_{FB} \quad \Lambda > 8.6 - 21.7 \text{ TeV}$$
$$e^+e^- \to e^+e^- \quad \frac{d\sigma}{d\cos\theta} \quad \Lambda > 7.0 - 18.0 \text{ TeV}$$



- Λ is scale of contact interactions in effective Lagrangian

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

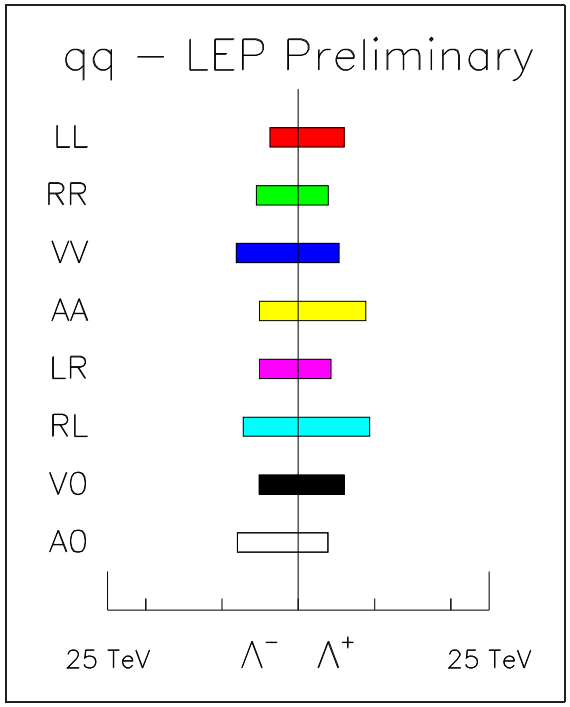
  where $i, j = L, R$. Take $g^2 = 4\pi$

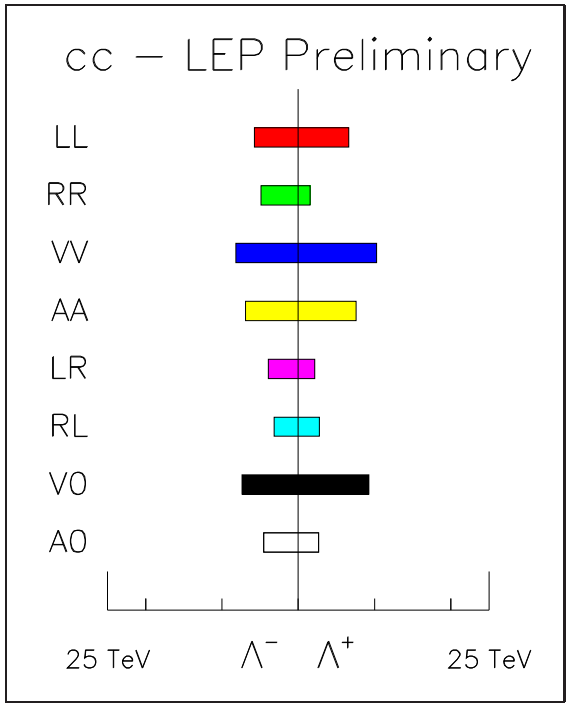
- Fit $\epsilon = 1/\Lambda^2$; $(\mathcal{SM}\ \epsilon = 0)$
- Fermi Theory with this ansatz:

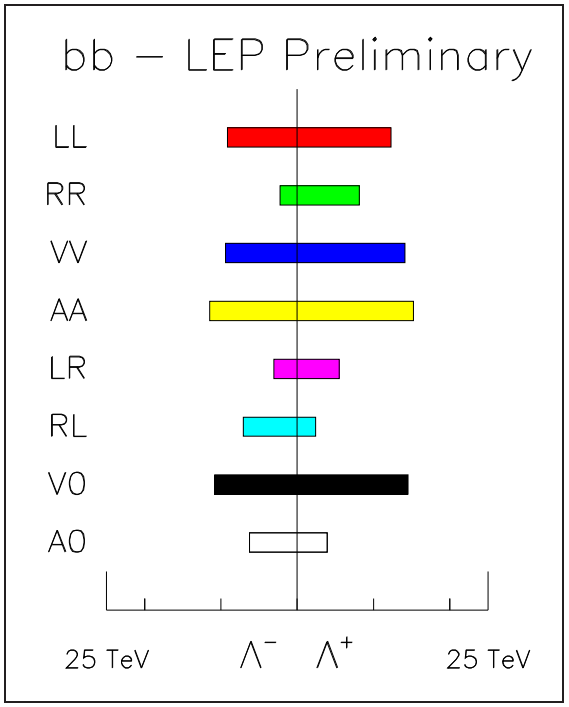
$$\frac{e^2}{8 M_W{}^2 \sin^2\theta_W} = \frac{G_F}{\sqrt{2}} \to \frac{4\pi}{\Lambda^2}$$

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

Contact Interactions for quarks







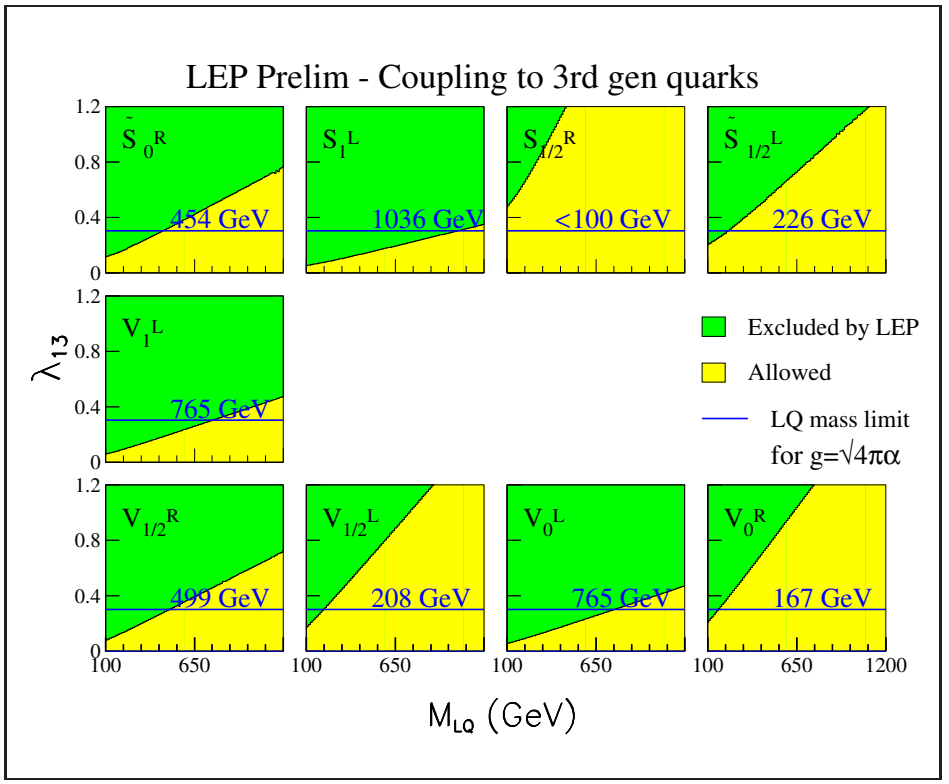
- × couples to all $q\bar{q}$
- Fit $\sigma_{\rm had}$
- $\Lambda > 3.7 - 9.3$ TeV (95% CL)

- × only couples to $c\bar{c}$
- Fit $\sigma_{\rm had}$, $R_{\rm c}$ and $A_{\rm FB}^{c\bar{c}}$
- $\Lambda > 1.5 - 6.9$ TeV (95% CL)

- × only couples to $b\bar{b}$
- Fit $\sigma_{\rm had}$, $R_{\rm b}$ and $A_{\rm FB}^{b\bar{b}}$
- $\Lambda > 2.2 - 15.3$ TeV (95% CL)

Leptoquarks/Squarks

- Leptoquarks:
  - conserve B and L (proton decay)
  - classification:
    - spin (S or V)
    - weak isospin (subscript)
    - hypercharge (tildes)
    - L/R coupling (L/R)
    - Quark generation 1^{st},2^{nd},3^{rd}
- Certain ($\not{R}$) squarks would be identical to certain leptoquarks, eg: $\tilde{d}_R \leftrightarrow S_{0(L)}$; $\tilde{u}_L \leftrightarrow \tilde{S}_{1/2}$
- t/u-channel leptoquark exchange would effect $\sigma(q\bar{q})$, R_{Q} and $A_{\text{FB}}^{Q\bar{Q}}$



For coupling $\lambda_{1j} = \sqrt{4\pi\alpha}$:

$\tilde{S}_{0(R)}$ 1^{st} generation: $M > 202$ GeV

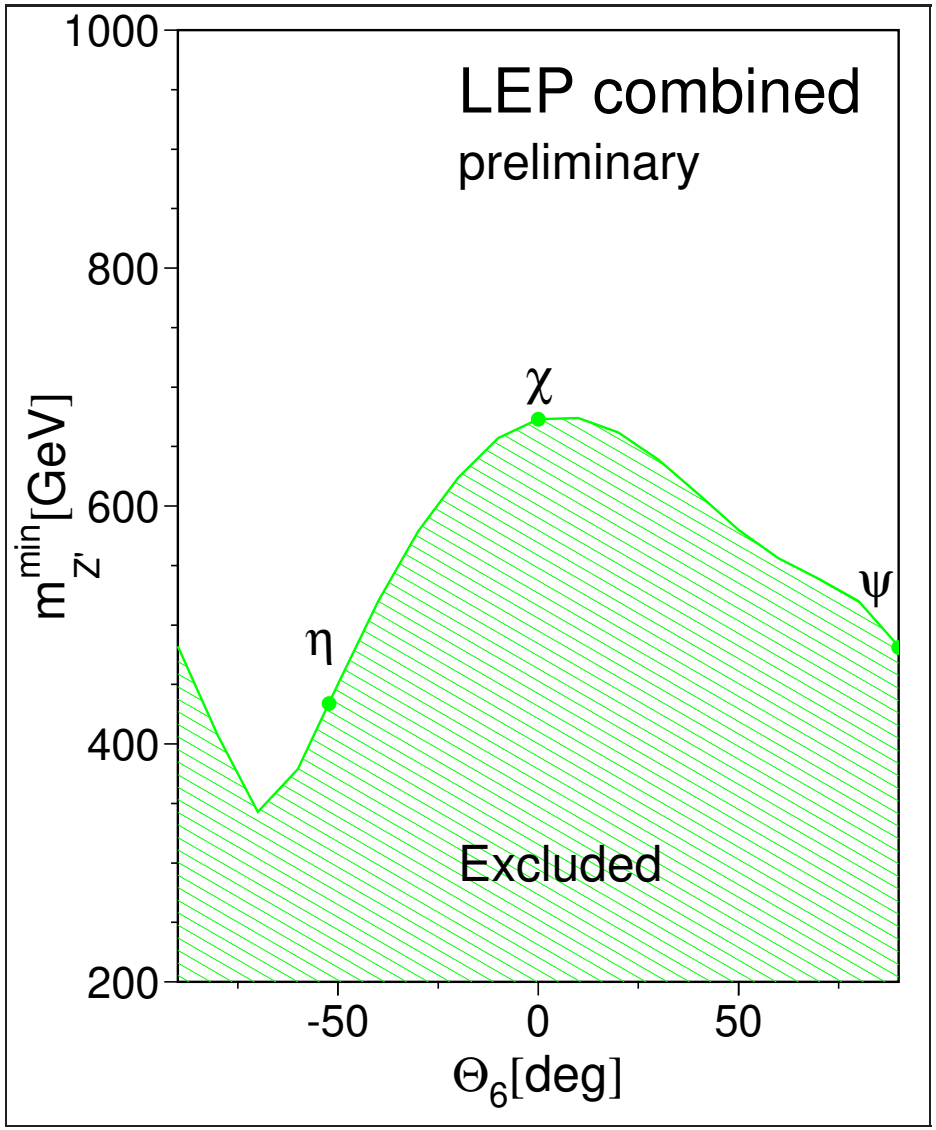
$\tilde{S}_{0(R)}$ 2^{nd} generation: $M > 209$ GeV

$\tilde{S}_{0(R)}$ 3^{rd} generation: $M > 454$ GeV

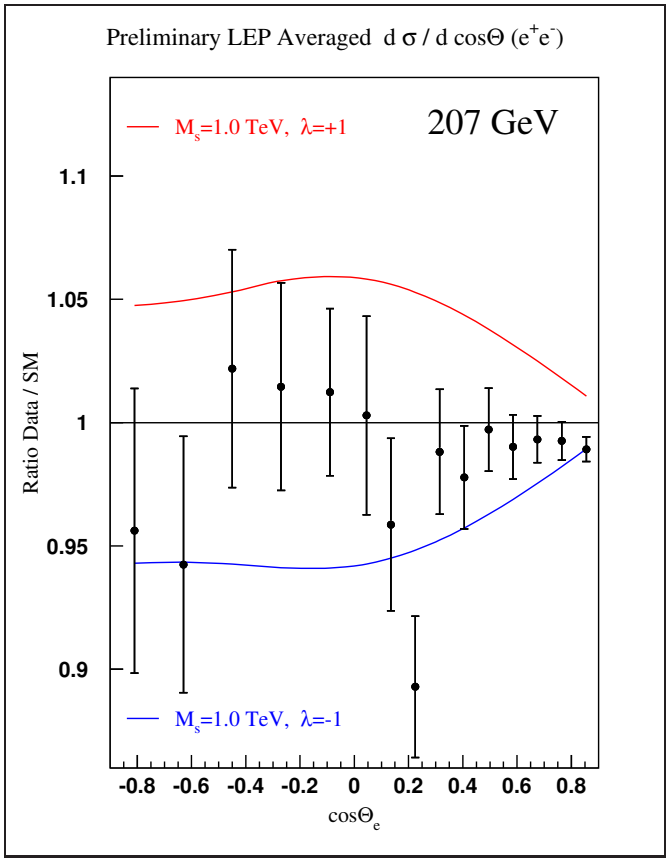
Z′ Bosons

- 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)	673	481	434	804	1787



Gravity in Large Compactified Extra Dimensions



	M_s[TeV] (95% C.L.)	
	$\lambda = -1$	$\lambda = +1$
e^+e^-	> 1.09	> 1.20

- Original ADD scheme: possible for quantum gravity scale $M_D \sim M_{EW} \ll M_{planck}$
  $R << 1$ mm for $M_D \sim M_{EW}$ for $n \geq 3$
- Exchange of a large number of graviton modes in extra dimensions could change $e^+e^- \to f\bar{f}$.
- In parameterisation of Hewett:

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

  allows for + and − interference with $\mathcal{SM}$; $\lambda = \pm 1$
- Fit $\epsilon = 1/M_s^4$ with $M_s = \mathcal{O}(M_D)$
- Best reach from $e^+e^- \to e^+e^-$