Searches for Physics $\mathcal{BSM}$ in $f\bar{f}$ Production at LEP II

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CERN

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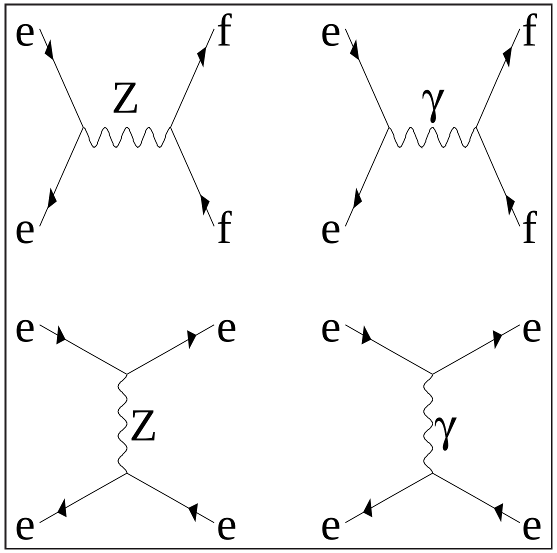
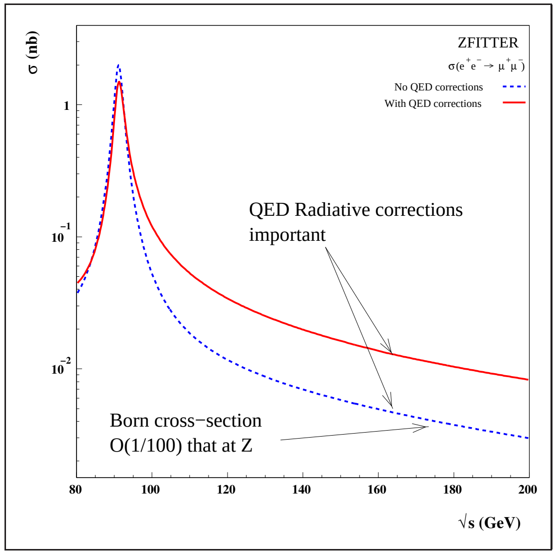
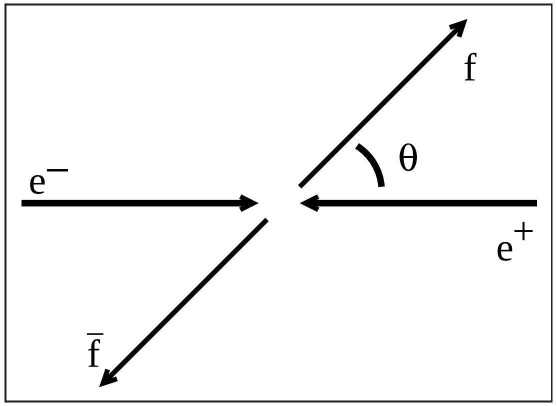
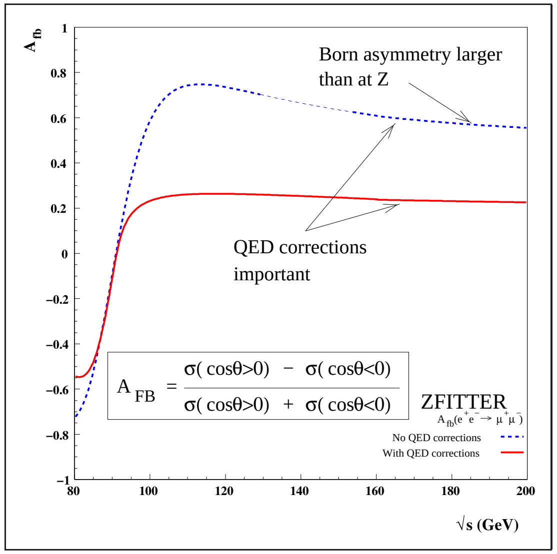
Fermion Pair production in $\mathcal{SM}$

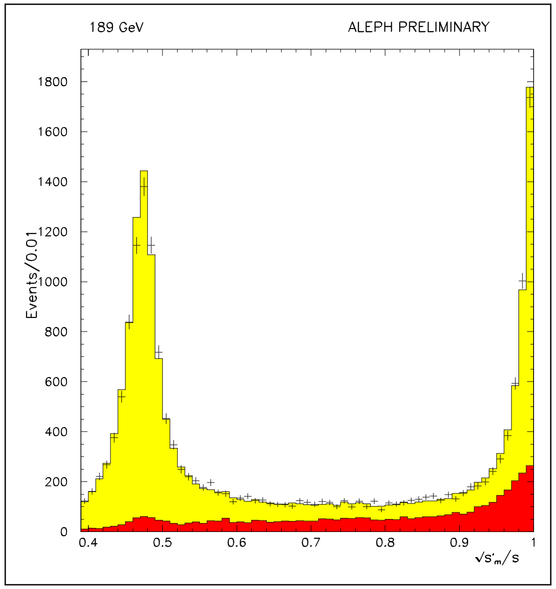


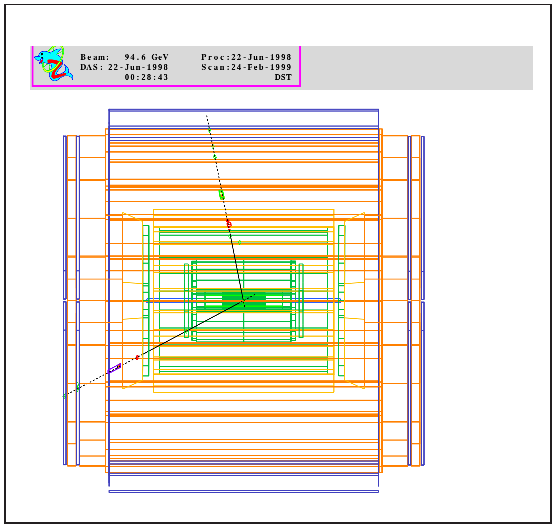






Radiative Return

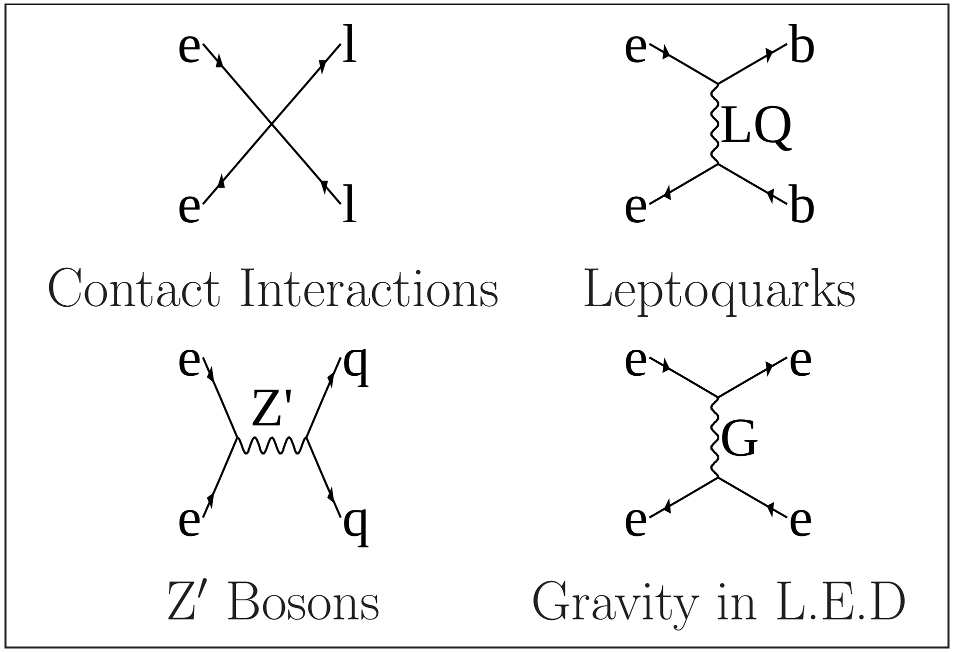




- Two clear peaks in differential distribution of reduced centre of mass energy $\sqrt{s'}$.
  - *Non radiative peak* at $\sqrt{s'} \sim \sqrt{s}$
    Fermions approximately back-to-back.
  - *Radiative return* peak at $\sqrt{s'} \sim \mathrm{M_Z}$
    Fermions tend to be highly acollinear with missing energy down beam pipe due to hard ISR photons
- Experiments have different algorithms to determine $\sqrt{s'}$

Test of $\mathcal{SM}$ with $e^+e^- \to f\bar{f}$

Examples of Models Studied



Contact Interactions

Leptoquarks

Z' Bosons

Gravity in L.E.D

- Can use $e^+e^- \to f\bar{f}$ to Search for 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

LEP Averages

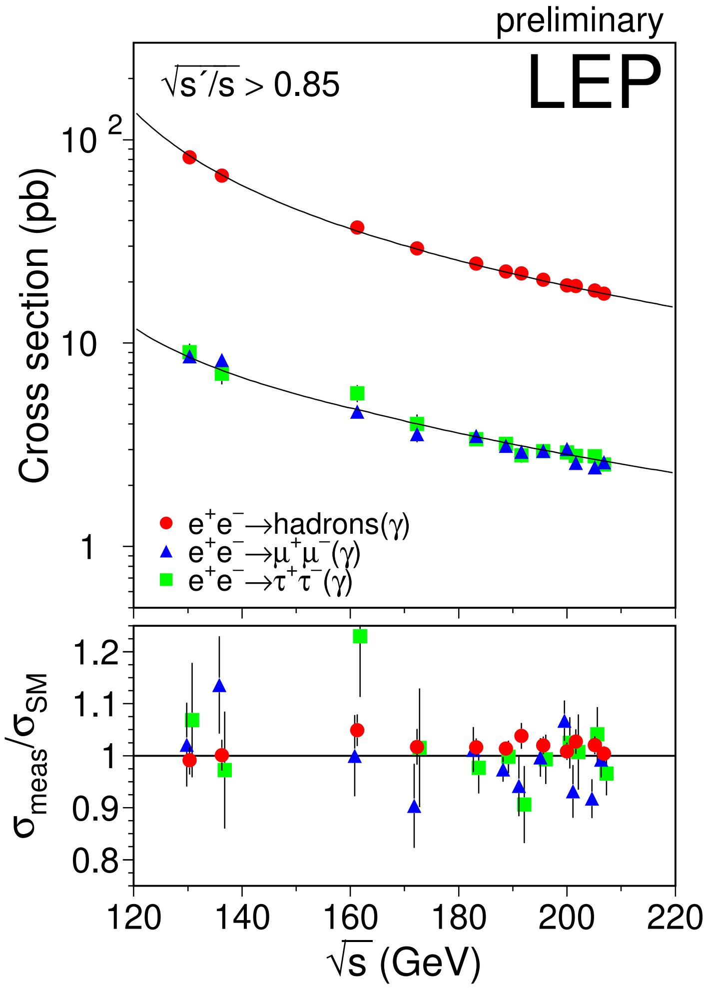
$\sim \sqrt{s}$ [GeV]	130	136	161	172	183	189
$\sim \int \mathcal{L}dt$ [pb^{-1}]	6	6	10	10	55	170
$\sim \sqrt{s}$ [GeV]	192	196	200	202	205	207
$\sim \int \mathcal{L}dt$ [pb^{-1}]	25	75	80	40	85	140

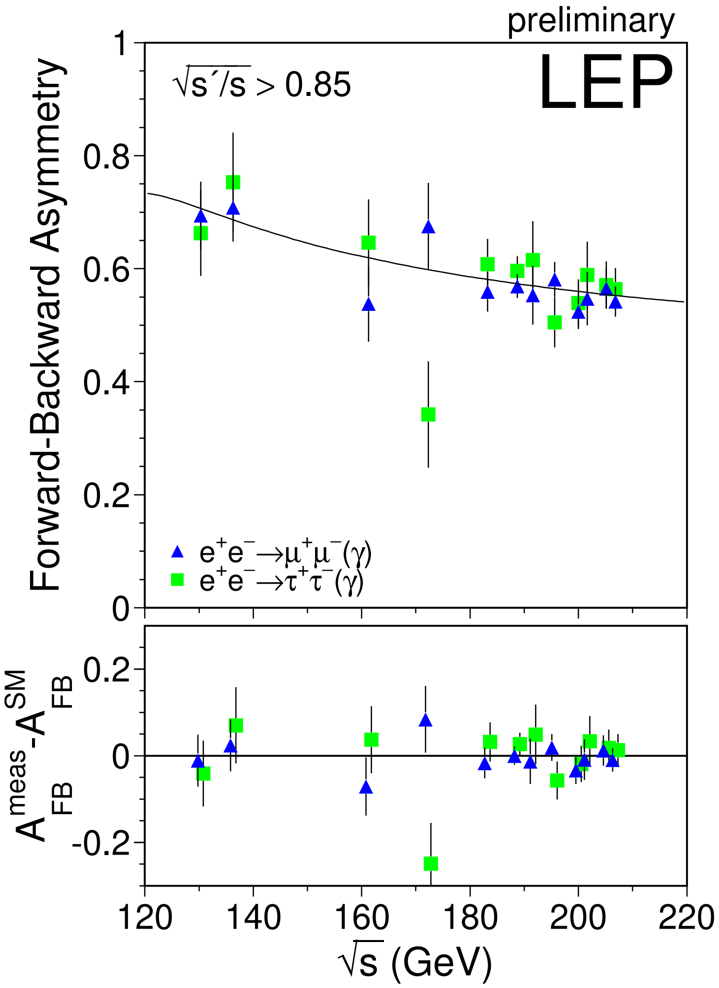
		A	D	L	O
σ, A_{FB}	$\mu^+\mu^-$	130-207	130-207	130-207	130-207
	$\tau^+\tau^-$	130-207	130-207	130-207	130-207
	$q\bar{q}$	130-207	130-207	130-207	130-207
$\frac{d\sigma}{d\cos\theta}$	e^+e^-	189-207	-	189-207	189-207
$\frac{d\sigma}{d\cos\theta}$	$\mu^+\mu^-$	189-207	183-207	189-207	183-207
	$\tau^+\tau^-$	189-207	183-207	189	183-207
R_Q	b	130-202	130-207	120-207	130-189
	c	183-207	-	-	-
A_{FB}^{QQ}	b	130-207	130-207	189	130-189
	c	183-189	130-172	-	130-189

- Data taken at 12 energies $\sqrt{s} \sim 130 - 207$ GeV
- Total luminosity $\sim 700\text{pb}^{-1}$ per experiment
- Combine data from 4 experiments
- Combine data at high $\sqrt{s'}/\sqrt{s}$
- Corrections applied to bring data to common signal definitions
- Combination procedure takes into account correlations between measurements

http://lepewwg.web.cern.ch/LEPEWWG/lep2/

Results for σ and A_{FB}





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

Results for σ and A_{FB}: 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

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

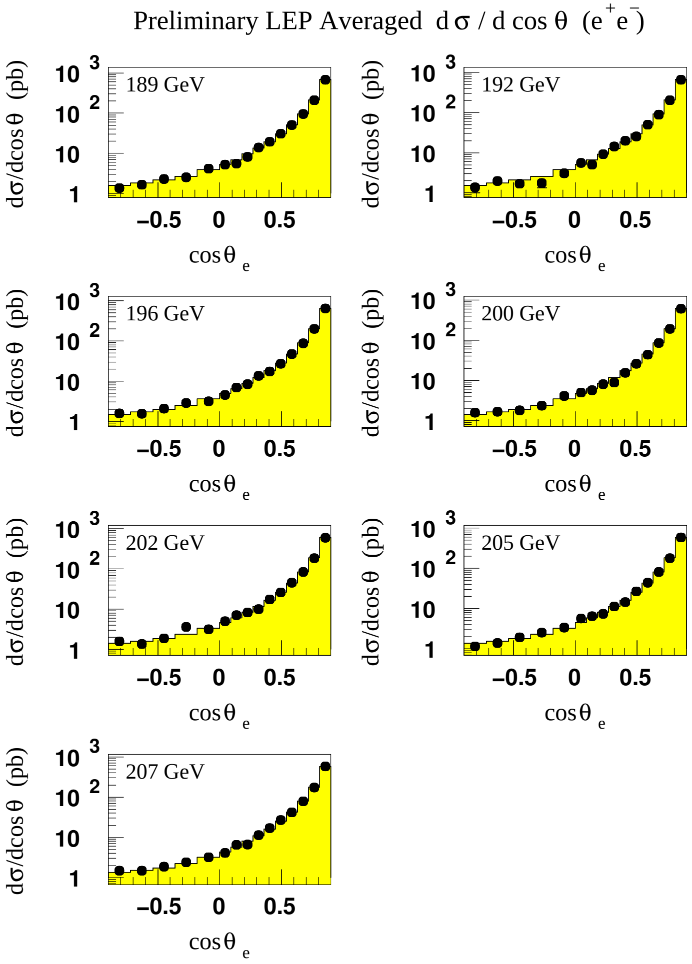
- Theoretical uncertainty on σ in $\mathcal{SM}$

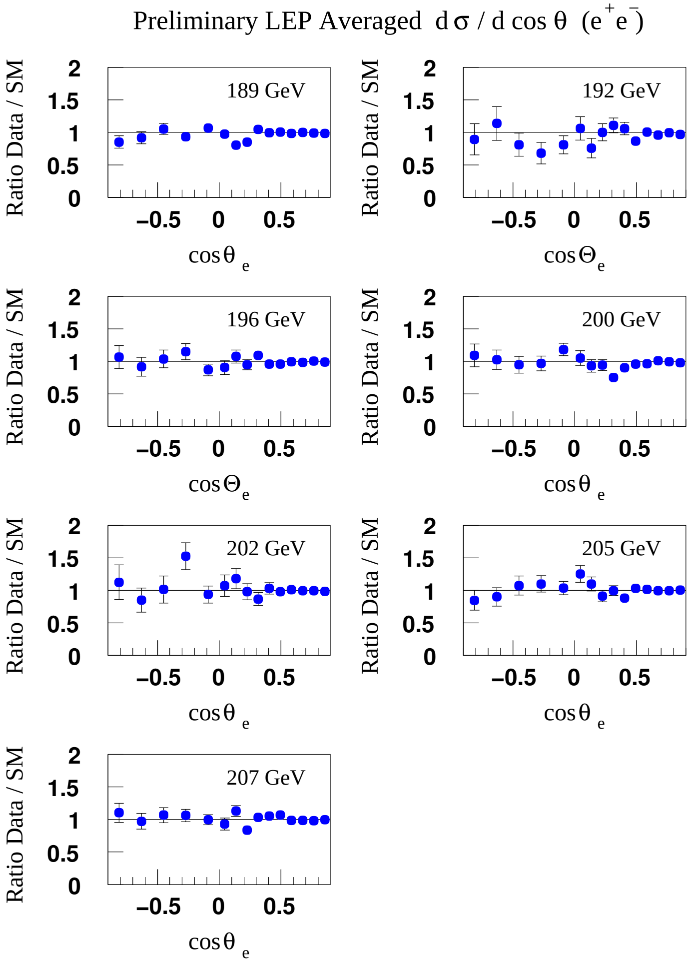
Non-radiative: hadrons 0.3%; $\mu^+\mu^-$ 0.4%; $\tau^+\tau^-$ 0.4%; e^+e^- (central) 2.0%

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

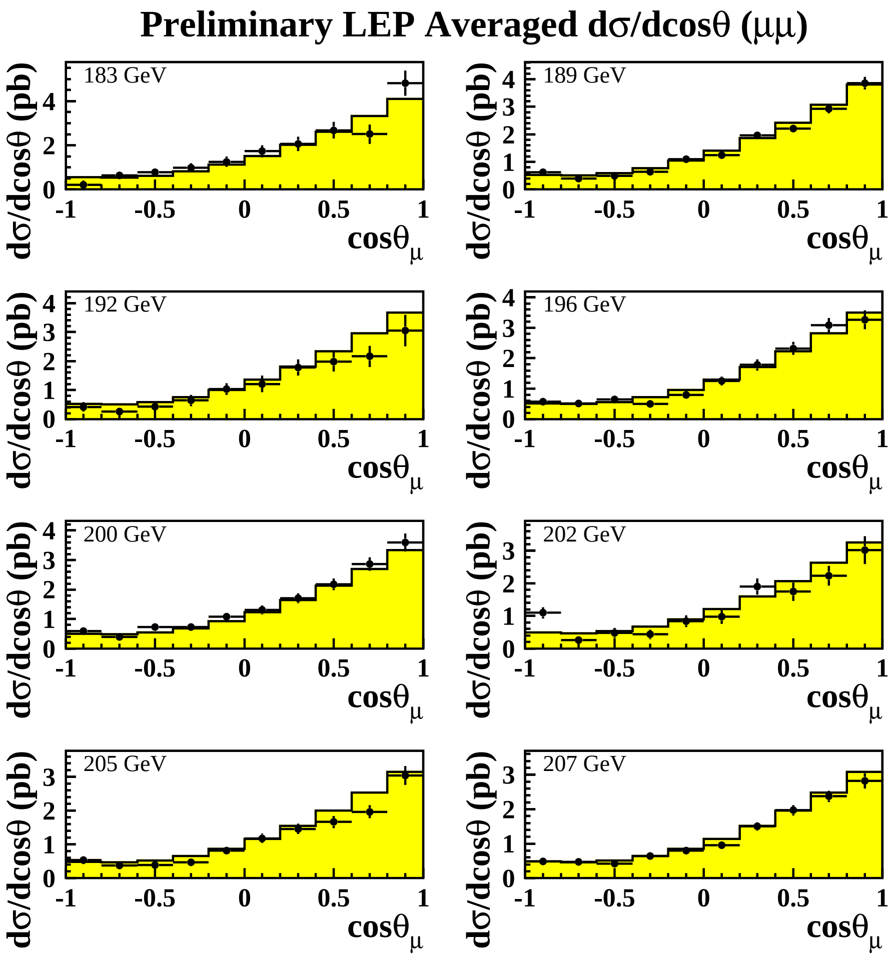
Results for $\frac{d\sigma}{d\cos\theta}(e^+e^-)$

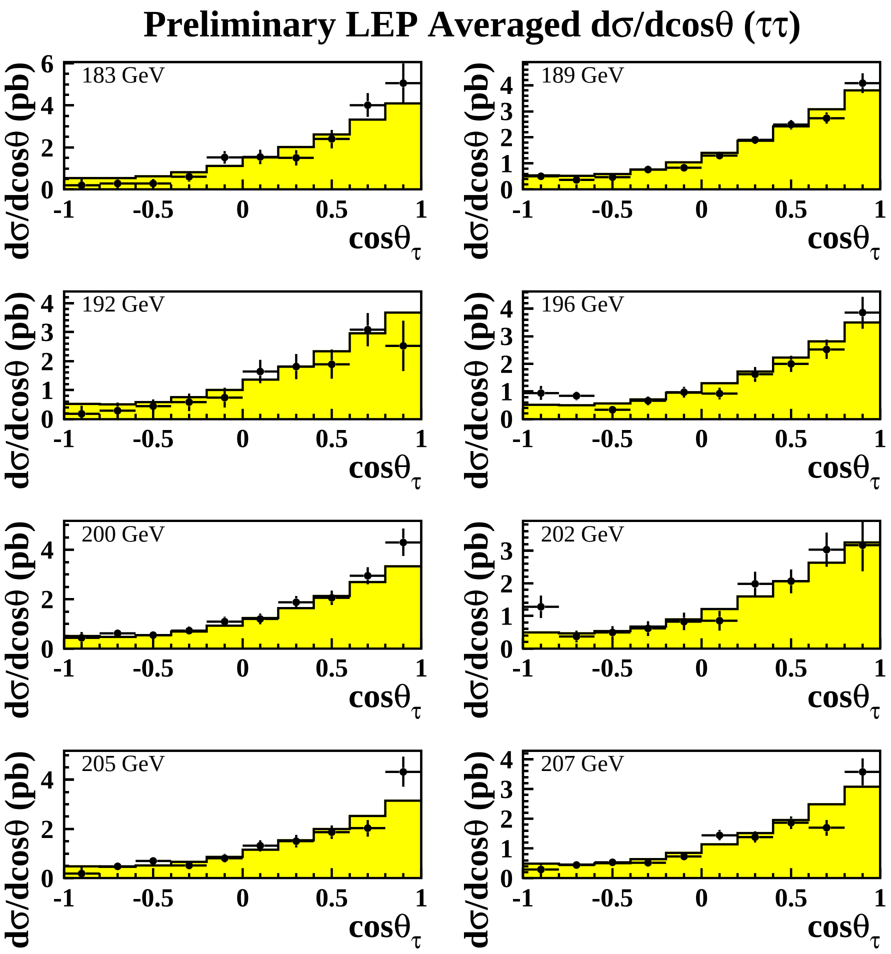
- Combine $\frac{d\sigma}{d\cos\theta}$ not σ since acceptances for σ very different
- Good agreement with $\mathcal{SM}$ predictions of BHWIDE
- Theory uncertainty $\sim 2\%$
- Bin-to-bin correlations significant in forward bins





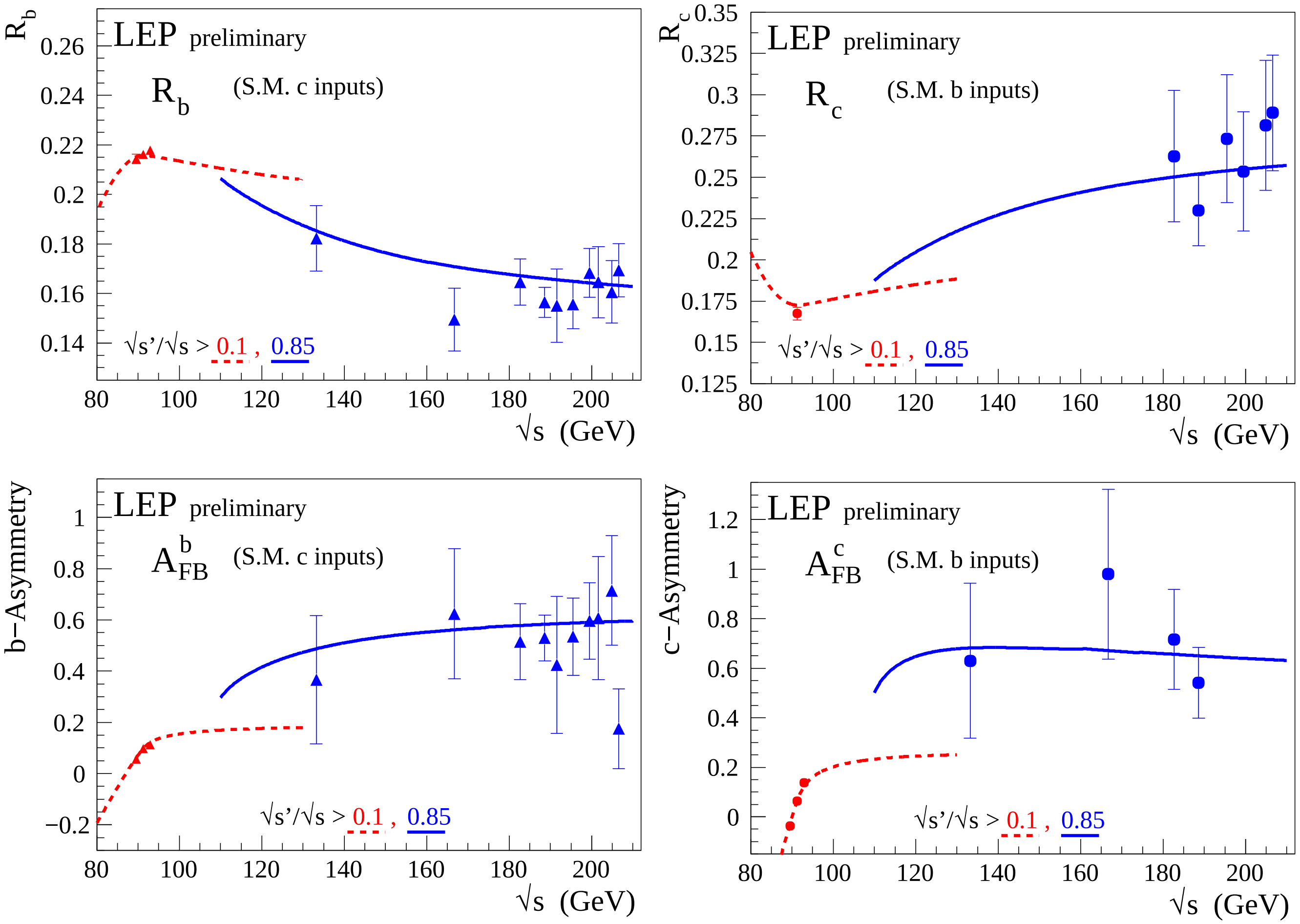
Results for $\frac{d\sigma}{d\cos\theta}(\mu^+\mu^-/\tau^+\tau^-)$



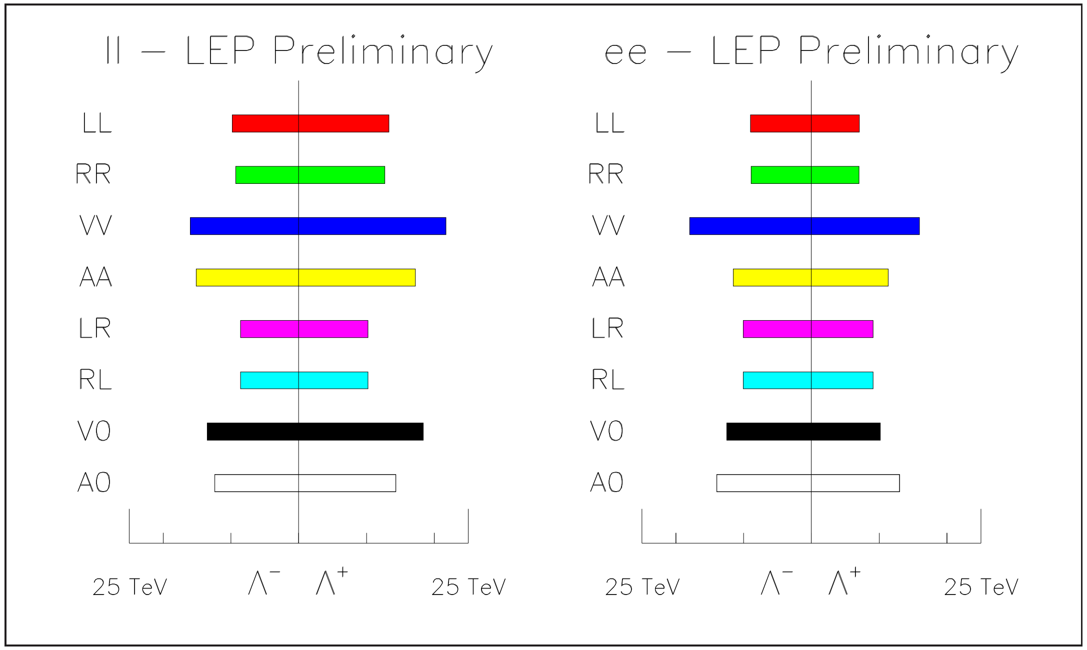


Results for Heavy Flavours

- $R_{\mathrm{Q}} = \frac{\sigma_{QQ}}{\sigma_{\mathrm{had}}}$
- Quote results for
  - b with c content fixed to SM prediction
  - c with b content fixed to SM prediction
- $R_{\mathrm{b}}/R_{\mathrm{b}SM} \sim 2$ s.d. below unity



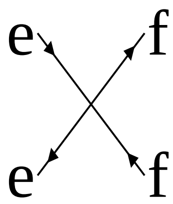
Contact Interactions



95% exclusion limits

$e^+e^- \rightarrow l^+l^-$ σ, A_{FB} $\Lambda > 8.6 - 21.7$ TeV

$e^+e^- \rightarrow e^+e^-$ $\frac{d\sigma}{d\cos\theta}$ $\Lambda > 7.0 - 18.0$ TeV



- Λ is scale of contact interactions in effective Lagrangian

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

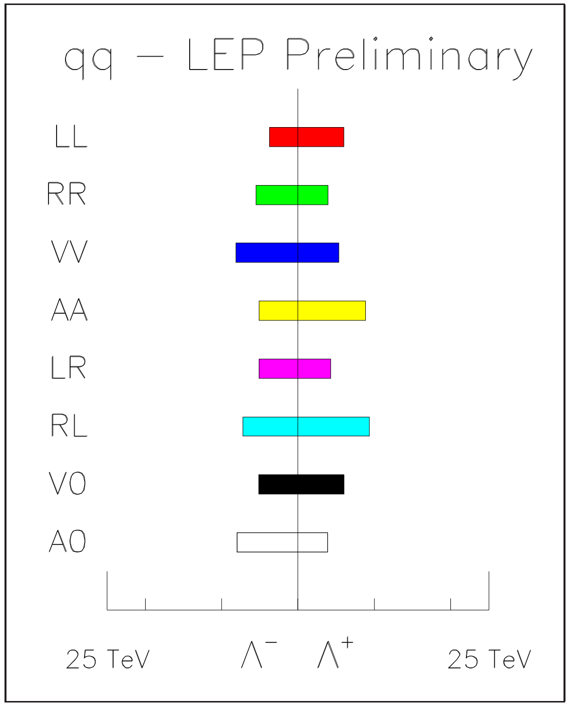
where $i, j = L, R$. Take $g^2 = 4\pi$

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

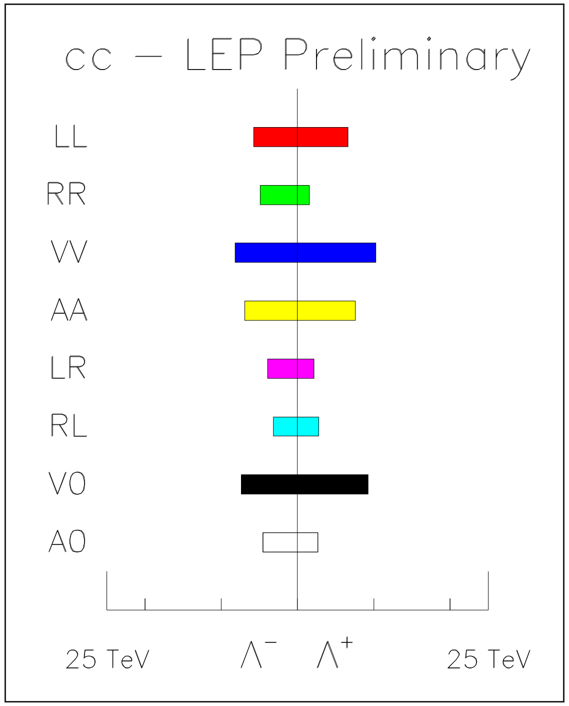
$$\frac{e^2}{8\mathrm{M_W}^2 \sin^2\theta_\mathrm{W}} = \frac{G_\mathrm{F}}{\sqrt{2}} \rightarrow \frac{4\pi}{\Lambda^2}$$

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

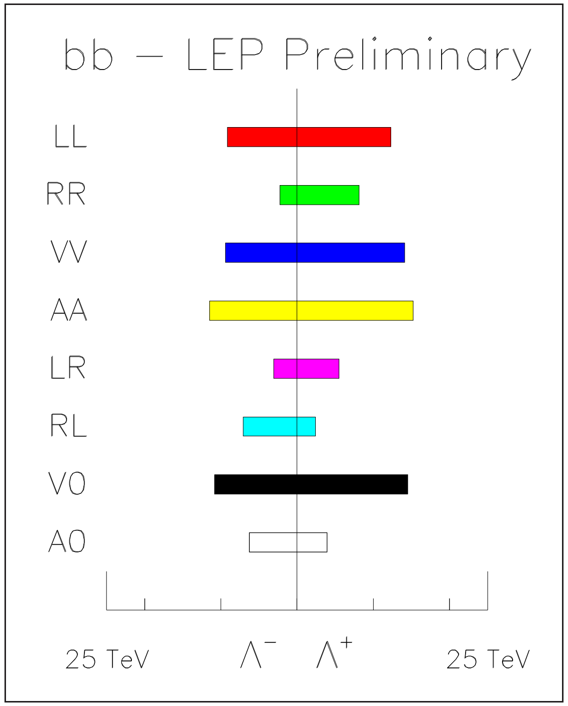
Contact Interactions for quarks



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



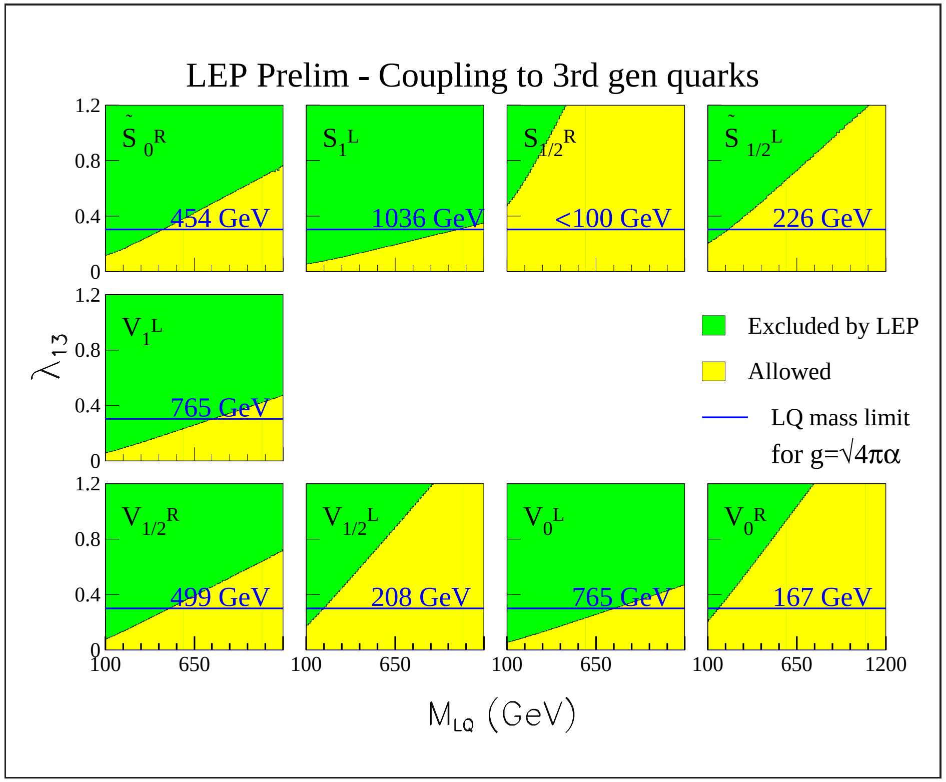
- × only couples to $c\bar{c}$
- Fit σ_{had}, R_{c} and $A_{\mathrm{FB}}^{c\bar{c}}$
- $\Lambda > 1.5 - 6.9$ TeV (95% CL)



- × only couples to $b\bar{b}$
- Fit σ_{had}, R_{b} and $A_{\mathrm{FB}}^{b\bar{b}}$
- $\Lambda > 2.2 - 15.3$ 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 $\sigma(q\bar{q})$, $R_{\rm Q}$ and $A_{\rm FB}^{QQ}$



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

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

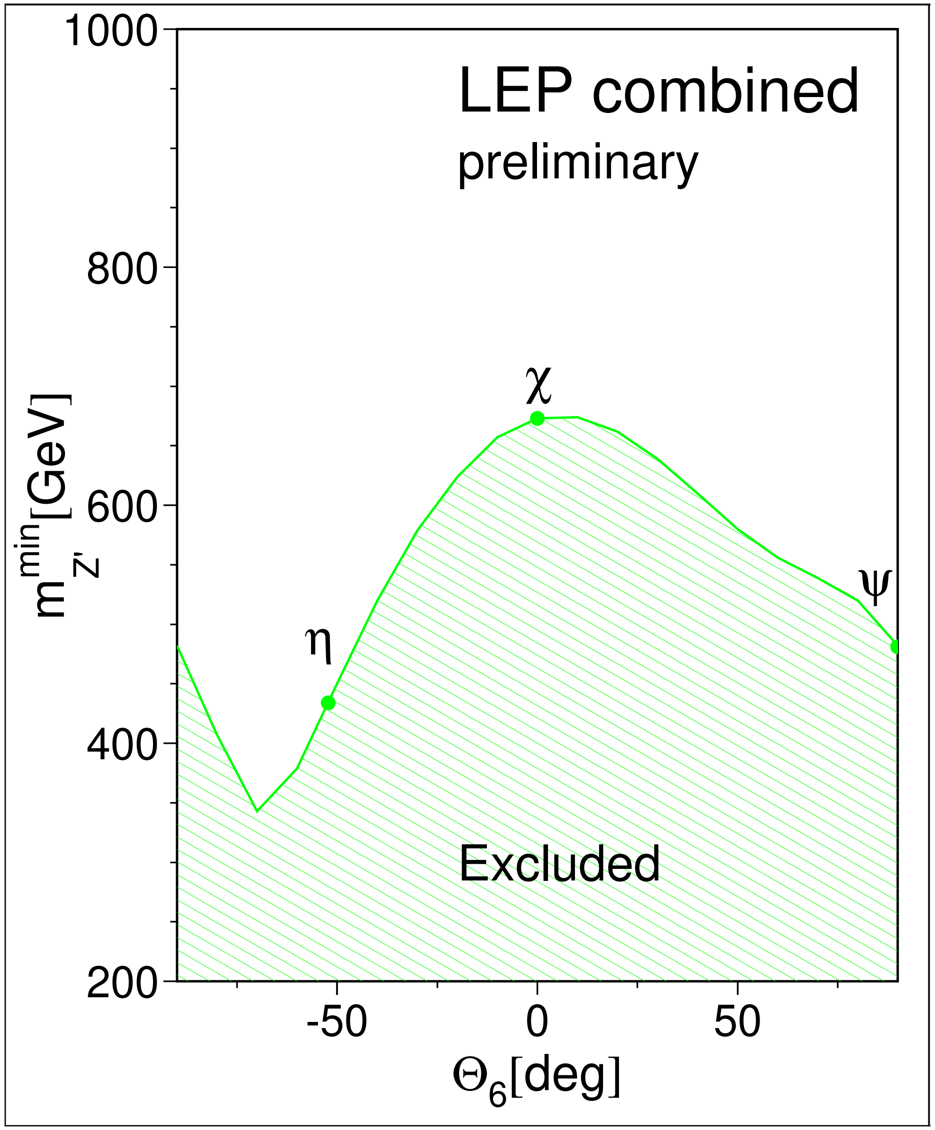
$\tilde{S}_{0(R)}$ 2^{nd} generation: $M > 209$ GeV

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

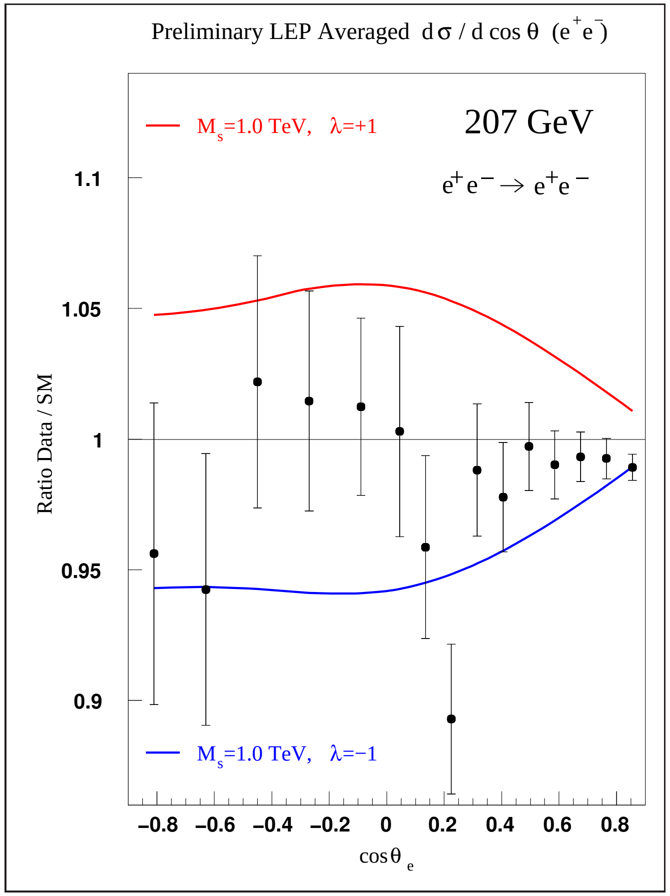
Z' Bosons

- 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 $e^+e^- \rightarrow f\bar{f}$.
- In parametrisation of Hewett:

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

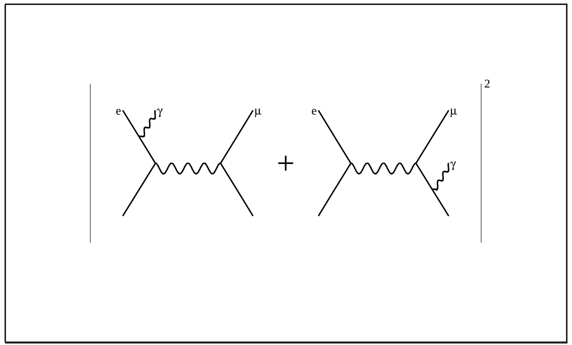
  allows for $+$ and $-$ interference with $\mathcal{SM}$; $\lambda = \pm 1$
- Fit $\epsilon = 1/M_s^4$ with $M_s = \mathcal{O}(M_D)$
- Best reach from $e^+e^- \rightarrow e^+e^-$

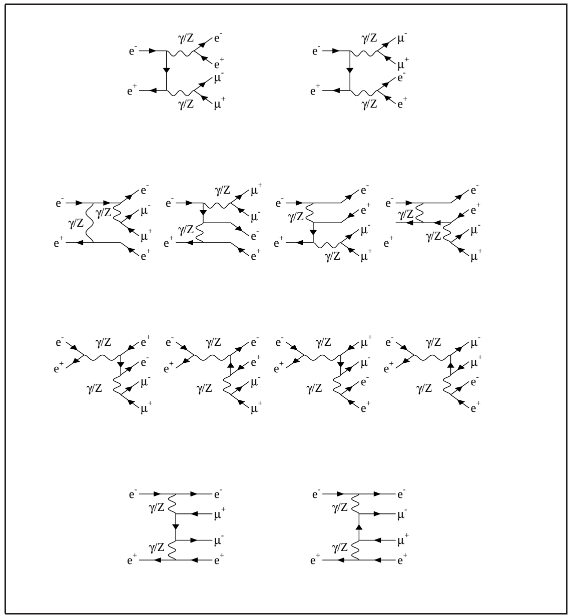
Summary and Outlook

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

- Experiments aiming to complete analysis within 6-12 months
- Final published results will be combined
- Constraints placed on $\mathcal{BSM}$physics

Average of σ and A_{FB}: 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

$$\mathrm{M}_{\mathrm{corr}} = \mathrm{M}_{\mathrm{exp}} - \mathrm{P}_{\mathrm{exp}} + \mathrm{P}_{\mathrm{LEP}}$$

Average of σ and A_{FB}: 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

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

- 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	$\theta_{acol} < 25^\circ$
O	$\theta_{acol} < 10^\circ$

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

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

	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 $|\cos\theta| < 1$
- Errors
  - consider correlations on normalization
  - use expected statistical error
- Combine using BLUE