Bounds on Universal and Non Universal New Physics Effects from $f\bar{f}$ Production at LEP2

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Introduction and Outline

- Z-peak subtracted representation ($f \neq e$) of $e^+e^- \to f\bar{f}$ at LEP2 energies
- Universal (AGC, TC) and non Universal (CT, ED) New Physics models
- LEP2 combined data analysis **without** Bhabha $d\sigma/d\cos\theta$
- Z-peak representation of Bhabha scattering $e^+e^- \to e^+e^-$
- LEP2 combined data analysis **including** OPAL results on Bhabha

Experimental Results: LEP2 $f\bar{f}$ Combination

LEP2FF/99-01 + single experiments

LEP runs during 1995-99

year	1995		1996		1997	1998	1999	
E (GeV)	130.2	136.2	161.3	172.1	182.7	188.6	192	196

- **At** the Z peak: combination in terms of pseudo observables
- **Off** the Z-peak: averaged σ_5, $\sigma_{\mu,\tau}$, $A_{FB,\mu,\tau}$ at 183, 189 GeV
- Definition of the $f\bar{f}$ signal
  - 1: (L3, OPAL) $\sqrt{s'}$ is the mass of the s-channel propagator, $\sqrt{s'/s} > 0.85$, ISR-FSR γ interference subtracted
  - 2: (ALEPH, DELPHI) $\sqrt{s'}$ is the $f\bar{f}$ invariant mass for dileptons. $\sqrt{s'/s} > 0.85$, ISR-FSR included
- full 4π angular acceptance extrapolation

- Theoretical error estimated from ZFITTER, TOPAZ0, KK discrepancies 0.2% ($q\bar{q}$), 0.7% ($l\bar{l}$), 0.003 (A_l)
- Experimental measures

cms energy	quantity	average	SM	error %	deviation %
183 GeV	σ_5	24.54± 0.43 pb	24.20 pb	1.8	1.4
	σ_μ	3.44± 0.14 pb	3.45 pb	4.1	-0.29
	σ_τ	3.43± 0.18 pb	3.45 pb	5.2	-0.58
	$A_{FB,\mu}$	0.547± 0.034	0.576	6.2	-5
	$A_{FB,\tau}$	0.615± 0.044	0.576	7.2	6.8
189 GeV	σ_5	22.38± 0.25 pb	22.16 pb	1.1	0.99
	σ_μ	3.193± 0.083 pb	3.207 pb	2.6	-0.44
	σ_τ	3.135± 0.102 pb	3.207 pb	3.3	-2.2
	$A_{FB,\mu}$	0.562± 0.022	0.569	3.9	-1.2
	$A_{FB,\tau}$	0.597± 0.027	0.569	4.5	4.9

General Features of New Physics Effects off the Z Peak

- **At** the Z peak
  - Peskin - Takeuchi (S, T) or Altarelli - Barbieri ε_1, ε_3
  - New Physics is inherently **universal**
    - box diagrams can be neglected
    - s channel γ exchange can be neglected

- **Off** the Z peak (LEP2, LC, $\mu^+\mu^-$): Generic New Physics
  - Complicated dependence on the kinematical variables (s, θ)
  - box diagrams and s channel γ exchange are important

- **Off** the Z peak: Universal New Physics
  - **Only 3** functions $\delta_\gamma, \delta_s, \delta_Z$ of the energy (constants ?)

The Z-peak Subtracted Representation ($f \neq e$)

F.M. Renard and C. Verzegnassi, PRD52, 1369 (1995), PRD53, 1290 (1996)

- The general $e^+e^- \to f\bar{f}$ ($f \neq e$) scattering amplitude at one loop is the sum of an **effective photon** and an **effective Z amplitude** with couplings $g^{\gamma}_{Vj}(q^2,\theta)$, $g^{Z}_{Vj}(q^2,\theta)$, $g^{Z}_{Aj}(q^2,\theta)$ (j is the initial electron $j = e$ or the final fermion $j = f \neq e$)

$$\mathcal{A}(q^2,\theta) = \frac{i}{q^2}\bar{v}\gamma^{\mu} g^{(\gamma)}_{Ve}(q^2,\theta)u \cdot \bar{u}\gamma_{\mu} g^{(\gamma)}_{Vf}(q^2,\theta)v + \frac{i}{q^2 - M_Z^2 + iM_Z\Gamma_Z} \cdot$$
$$\bar{v}\gamma^{\mu}[g^{(Z)}_{Ve}(q^2,\theta) - g^{(Z)}_{Ae}(q^2,\theta)\gamma^5]u \cdot \bar{u}\gamma_{\mu}[g^{(Z)}_{Vf}(q^2,\theta) - g^{(Z)}_{Af}(q^2,\theta)\gamma^5]v$$

– Effective couplings ($\tilde{\Delta}_{\alpha,ef}$, R_{ef} and V_{ef} are **finite** and **gauge invariant**)

$$g^{\gamma}_{Ve}(q^2,\theta) = \sqrt{4\pi\alpha(0)}\; Q_e[1+\frac{1}{2}\tilde{\Delta}_{\alpha,ef}(q^2,\theta)]$$

$$g^{\gamma}_{Vf}(q^2,\theta) = \sqrt{4\pi\alpha(0)}\; Q_f[1+\frac{1}{2}\tilde{\Delta}_{\alpha,ef}(q^2,\theta)]$$

$$g^{\gamma}_{Ae}(q^2,\theta) = g^{\gamma}_{Af}(q^2,\theta) = 0$$

$$g^{Z}_{Ve} = \gamma_e^{\frac{1}{2}}\; I_{3e}\; \tilde{v}_e[1-\frac{1}{2}R_{ef}(q^2,\theta) - \frac{4\tilde{s}_e\tilde{c}_e}{\tilde{v}_e}|Q_f|V^{\gamma Z}_{ef}(q^2,\theta)]$$

$$g^{Z}_{Vf}(q^2,\theta) = \gamma_f^{\frac{1}{2}}\; I_{3f}\; \tilde{v}_f[1-\frac{1}{2}R_{ef}(q^2,\theta) - \frac{4\tilde{s}_e\tilde{c}_e}{\tilde{v}_f}|Q_f|V^{Z\gamma}_{ef}(q^2,\theta)]$$

$$g^{Z}_{Ae}(q^2,\theta) = \gamma_e^{\frac{1}{2}}\; I_{3e}[1-\frac{1}{2}R_{ef}(q^2,\theta)]$$

$$g^{Z}_{Af}(q^2,\theta) = \gamma_f^{\frac{1}{2}}\; I_{3f}[1-\frac{1}{2}R_{ef}(q^2,\theta)]$$

with the Z-**peak inputs**

$$\gamma_j^{\frac{1}{2}} = [\frac{48\pi\Gamma_j}{N_j M_Z(1+\tilde{v}_j^2)}]^{\frac{1}{2}} = \frac{e}{2sc} + \cdots$$

$$\tilde{v}_j = 1 - 4|Q_j|\tilde{s}_j^2$$

$\tilde{s}_j^2 = 1 - \tilde{c}_j^2$ is the **weak effective angle** measured through the forward-backward or polarization asymmetries in the final channel j, $\tilde{s}_e \equiv \tilde{s}_\mu \equiv \tilde{s}_\tau$

- The quantities $\tilde{\Delta}_{\alpha,ef}(q^2,\theta)$, $R_{ef}(q^2,\theta)$, $V_{ef}^{\gamma Z}(q^2,\theta)$, $V_{ef}^{Z\gamma}(q^2,\theta)$ contain all the q^2, θ dependent parts of the scattering amplitude due to SM or NP at one-loop.
- They are **finite, gauge independent** combinations of self-energies, vertices and boxes

– For an additional four fermion amplitude with Lorentz structure

$$\bar{v}(e^+)\gamma^\mu[a(q^2,\theta) - b(q^2,\theta)\gamma^5]u(e^-) \cdot \bar{u}(f)\gamma_\mu[c(q^2,\theta) - d(q^2,\theta)\gamma^5]v(f)$$

and a, b, c, d representing $\mathcal{O}(\alpha)$ effects, we have

$$\tilde{\Delta}_{\alpha,ef}(q^2,\theta) = \mathbf{q^2}\frac{[a(q^2,\theta) - b(q^2,\theta)\tilde{v}_e][c(q^2,\theta) - d(q^2,\theta)\tilde{v}_f]}{e^2 Q_e Q_f}$$

$$R_{ef}(q^2,\theta) = -(\mathbf{q^2} - \mathbf{M_Z^2})\frac{4\tilde{s}_e^2\tilde{c}_e^2 b(q^2,\theta)d(q^2,\theta)}{e^2 I_{3e} I_{3f}}$$

$$V_{ef}^{\gamma Z}(q^2,\theta) = -(\mathbf{q^2} - \mathbf{M_Z^2})\frac{[a(q^2,\theta) - b(q^2,\theta)\tilde{v}_e]2\tilde{s}_e\tilde{c}_e d(q^2,\theta)}{e^2 Q_e I_{3f}}$$

$$V_{ef}^{Z\gamma}(q^2,\theta) = -(\mathbf{q^2} - \mathbf{M_Z^2})\frac{[c(q^2,\theta) - d(q^2,\theta)\tilde{v}_f]2\tilde{s}_e\tilde{c}_e b(q^2,\theta)}{e^2 Q_f I_{3e}}$$

Differential Unpolarized Cross Sections

$$\frac{d\sigma_{lf}}{dcos\theta} = \frac{4\pi}{3} N_f q^2 \{\frac{3}{8}(1 + cos^2\theta)\mathbf{U_{11}} + \frac{3}{4} cos\theta \mathbf{U_{12}}\}$$

where (apart from α redefinition)

$$\begin{aligned} U_{11} &= \gamma\gamma + (\gamma Z + ZZ)(1 + \mathbf{A_e A_f} + \mathbf{A_e} + \mathbf{A_f}) \\ U_{12} &= \gamma Z(1 + \mathbf{A_e A_f}) + ZZ(1 + \mathbf{A_e A_f} + \mathbf{A_e} + \mathbf{A_f}) \end{aligned}$$

$$\begin{aligned} U_{11} = \quad & \frac{\alpha^2(0) Q_f^2}{q^4}[1 + 2\tilde{\Delta}_{\alpha,lf}(q^2,\theta)] \\ & +2[\alpha(0)|Q_f|]\frac{q^2 - M_Z^2}{q^2((q^2 - M_Z^2)^2 + M_Z^2\Gamma_Z^2)}[\frac{3\Gamma_l}{M_Z}]^{1/2}[\frac{3\Gamma_f}{N_f M_Z}]^{1/2}\frac{\tilde{v}_l\tilde{v}_f}{(1+\tilde{v}_l^2)^{1/2}(1+\tilde{v}_f^2)^{1/2}} \\ & \times[1 + \tilde{\Delta}_{\alpha,lf}(q^2,\theta) - R_{lf}(q^2,\theta) - 4\tilde{s}_l\tilde{c}_l\{\frac{1}{\tilde{v}_l}V_{lf}^{\gamma Z}(q^2,\theta) + \frac{|Q_f|}{\tilde{v}_f}V_{lf}^{Z\gamma}(q^2,\theta)\}] \end{aligned}$$

$$+\frac{[\frac{3\Gamma_l}{M_Z}][\frac{3\Gamma_f}{N_f M_Z}]}{(q^2-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

$$\times[1-2R_{lf}(q^2,\theta)-8\tilde{s}_l\tilde{c}_l\{\frac{\tilde{v}_l}{1+\tilde{v}_l^2}V_{lf}^{\gamma Z}(q^2,\theta)+\frac{\tilde{v}_f|Q_f|}{(1+\tilde{v}_f^2)}V_{lf}^{Z\gamma}(q^2,\theta)\}]$$

$$U_{12}= \quad 2[\alpha(0)|Q_f|]\frac{q^2-M_Z^2}{q^2((q^2-M_Z^2)^2+M_Z^2\Gamma_Z^2)}[\frac{3\Gamma_l}{M_Z}]^{1/2}[\frac{3\Gamma_f}{N_f M_Z}]^{1/2}\frac{1}{(1+\tilde{v}_l^2)^{1/2}(1+\tilde{v}_f^2)^{1/2}}$$

$$\times[1+\tilde{\Delta}_{\alpha,lf}(q^2,\theta)-R_{lf}(q^2,\theta)]$$

$$+\frac{[\frac{3\Gamma_l}{M_Z}][\frac{3\Gamma_f}{N_f M_Z}]}{(q^2-M_Z^2)^2+M_Z^2\Gamma_Z^2}[\frac{4\tilde{v}_l\tilde{v}_f}{(1+\tilde{v}_l^2)(1+\tilde{v}_f^2)}]$$

$$\times[1-2R_{lf}(q^2,\theta)-4\tilde{s}_l\tilde{c}_l\{\frac{1}{\tilde{v}_l}V_{lf}^{\gamma Z}(q^2,\theta)+\frac{|Q_f|}{\tilde{v}_f}V_{lf}^{Z\gamma}(q^2,\theta)\}]$$

New Physics Contributions

- For a general one loop New Physics effect the form factors $\tilde{\Delta}_{\alpha,lf}$, R_{lf}, $V_{lf}^{\gamma Z}$ and $V_{lf}^{Z\gamma}$ are shifted

$$\tilde{\Delta}_{\alpha,lf}(q^2,\theta) \to \tilde{\Delta}_{\alpha,lf}(q^2,\theta) + \tilde{\Delta}^{NP}_{\alpha,lf}(q^2,\theta)$$

- Explicit θ dependent terms (e.g. from SUSY boxes) introduce **new** parameters (# of terms $\cos^N\theta$)
- Simplifications occur for **Universal New Physics**
  - independent on the final fermion family f
  - independent on θ

$$\tilde{\Delta}^{UNP}_{\alpha}(q^2) \quad R^{UNP}(q^2) \quad V^{UNP}(q^2)$$

- If the q^2 dependence is **factorized**, then measurements at different q^2 can be combined

Definition of the Three δ Parameters

- By construction
$$\tilde{\Delta}_\alpha^{UNP}(0) = R^{UNP}(M_Z^2) = V^{UNP}(M_Z^2) = 0$$

- We therefore introduce the three dimensionless functions $\delta_{z,s,\gamma}(q^2)$

$$R^{UNP}(q^2) = \frac{(q^2 - M_Z^2)}{M_Z^2}\,\delta_z \quad V^{UNP}(q^2) = \frac{(q^2 - M_Z^2)}{M_Z^2}\,\delta_s \quad \tilde{\Delta}_\alpha^{UNP}(q^2) = \frac{q^2}{M_Z^2}\,\delta_\gamma$$

- For large New Physics scales ($\Lambda^2 >> q^2$), we find typically $\delta_i(q^2) = (q^2)^{m_i}\hat{\delta}_i(q^2)$ and, in some cases, $\hat{\delta}_i(q^2) \simeq \hat{\delta}_i(0)$

- Non Universality can occur by a θ dependence, a final flavour dependence, both.

Summary Table of Some Common New Physics Models

- AGC and TC are Universal
- CT are Universal in each flavour (e.g. $e^+e^- \to l\bar{l}$)
- For ED and SUSY, δ are functions of θ, not constants
- For SUSY, the condition $\Lambda^2 >> q^2$ is not interesting.

Model	Universal	θ	f	m
AGC	X			
TC	X			
CT			X	
ED		X	X	1
(SUSY)		X	X	?

Universal New Physics I: Anomalous gauge couplings

A. Blondel, F. M. Renard, L. Trentadue and C. Verzegnassi PRD 54 (1996)

dim=6, $SU(2) \times U(1)$ and CP conserving operators, linear Higgs (Hagiwara et al., PRD 48 (1993)

	W^2	Z^2	AZ	A^2	W^2Z	W^2A	W^4	W^2Z^2	W^2ZA	W^2A^2	Z^4
DW	x	x	x	x	x	x	x	x	x	x	
DB		x	x	x							
BW		x	x	x	x	x					
Φ,1		x									
WWW					x	x	x	x	x	x	
W					x	x	x	x	x		
B					x	x					

$e^+e^- \to f\bar{f}$ versus $e^+e^- \to W^+W^-$ at LEP2

– The effect of the "tree level" operators parametrized by f_{DW}, f_{DB}, f_{BW} and $f_{\Phi,1}$ receives contributions from the "one loop" operators, e.g.

$$
\begin{aligned}
f_{DW}^r &= f_{DW} - \frac{1}{192\pi^2}\left(f_W \log\frac{\Lambda^2}{M_W^2} + \frac{f_B - f_W}{4}\log\frac{M_H^2}{M_W^2}\right) \\
f_{DB}^r &= f_{DB} - \frac{1}{192\pi^2}\left(f_B \log\frac{\Lambda^2}{M_W^2} - \frac{f_B - f_W}{4}\log\frac{M_H^2}{M_W^2}\right)
\end{aligned}
$$

– The couplings f_{DW}, f_{DB}, f_{BW} and $f_{\Phi,1}$ are well constrained by amplitudes with external fermions at LEP1 and LEP2. Results from a 500 pb^{-1} @ 175 GeV conventional 4 parameters fit

	DW	DB	BW	Φ,1	WWW	W	B
$f\bar{f}$	0.22	1.9	0.46	0.042			
W^+W^-	2.1	12	1.5	0.19	10	7.1	46

– If they are excluded from $e^+e^- \to f\bar{f}$ then we can study

$$\frac{i\mathcal{L}}{g_{WWV}} = g_1^V V_\mu (W^{-\mu\nu} W_\nu^+ - W^{+\mu\nu} W_\nu^-) + \kappa_V V^{\mu\nu} W_\mu^- W^+ \nu + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^-$$

with ($SU(2) \times U(1)$ gives $g_1^\gamma = 1$, $\lambda_Z = \lambda_\gamma = \lambda$ and trades κ_Z)

$$\begin{aligned} \Delta\kappa_\gamma &= (f_B + f_W)\frac{M_W^2}{2\Lambda^2} \\ \Delta g_1^Z &= f_W \frac{M_Z^2}{2\Lambda^2} \\ \lambda &= f_{WWW} \frac{3M_W^2 g^2}{2\Lambda^2} \end{aligned}$$

LEP2 experimental results (C. Sbarra, Moriond 2000)

$$\Delta\kappa_\gamma = 0.021^{+0.063}_{-0.059}, \qquad \Delta g_1^Z = -0.024^{+0.024}_{-0.024}, \qquad \lambda_\gamma = -0.016^{+0.026}_{-0.026}$$

- Z-peak subtracted analysis: 2 parameters, f_{DW} and f_{DB}; they give q^2 dependent contributions.
- Expression of the δ parameters in terms of f_{DW} and f_{DB}

$$\delta_z = 8\pi\alpha\frac{M_Z^2}{\Lambda^2}\left(\frac{\tilde{c}_l^2}{\tilde{s}_l^2}f_{DW} + \frac{\tilde{s}_l^2}{\tilde{c}_l^2}f_{DB}\right), \quad \delta_s = 8\pi\alpha\frac{M_Z^2}{\Lambda^2}\left(\frac{\tilde{c}_l}{\tilde{s}_l}f_{DW} - \frac{\tilde{s}_l}{\tilde{c}_l}f_{DB}\right),$$

$$\delta_\gamma = -8\pi\alpha\frac{M_Z^2}{\Lambda^2}\left(f_{DW} + f_{DB}\right),$$

They satisfy the linear constraint:

$$\boxed{\delta_z - \frac{1-2\tilde{s}_l^2}{\tilde{s}_l\tilde{c}_l}\delta_s + \delta_\gamma = 0}$$

Universal New Physics II: Models of Technicolor type

R. S. Chivukula, F. M. Renard and C. Verzegnassi PRD 547 (1998)

- Strongly coupled Vector and Axial resonances. 2 parameters (ratios F/M^2)
- The Z-peak scheme leads naturally to the use of non perturbative dispersion relations
- δ parameters

$$\delta_z = M_Z^2 \frac{\pi\alpha}{\tilde{s}_l^2 \tilde{c}_l^2} \left((1 - 2\tilde{s}_l^2)^2 \frac{F_V^2}{M_V^4} + \frac{F_A^2}{M_A^4} \right),$$

$$\delta_s = M_Z^2 \frac{2\pi\alpha}{\tilde{s}_l \tilde{c}_l} (1 - 2\tilde{s}_l^2) \frac{F_V^2}{M_V^4}, \quad \delta_\gamma = -4\pi\alpha M_Z^2 \frac{F_V^2}{M_V^4}.$$

Again, we have a linear constraint in the $(\delta_z, \delta_s, \delta_\gamma)$ space:

$$\boxed{\delta_s = -\left(\frac{1-2\tilde{s}_l^2}{2\tilde{s}_l \tilde{c}_l} \right) \delta_\gamma} \qquad \delta_{z,s} > 0 \qquad \delta_\gamma < 0$$

Non Universal New Physics I: Contact Interactions

E. Eichten, K. Lane, M. Peskin, PRL 50 (1983)

- Composite models or any generic virtual NP effect with a high intrinsic scale (e.g., higher vector boson exchanges, satisfying chirality conservation)
- Interaction Lagrangian for $(i\bar{i} \to f\bar{f})$

$$\begin{aligned}\mathcal{L} &= k_{if}\frac{4\pi}{\Lambda^2}\{\eta_{LL}(\bar{\Psi}^i_L\gamma^\mu\Psi^i_L)(\bar{\Psi}^f_L\gamma_\mu\Psi^f_L) + \eta_{RR}(\bar{\Psi}^i_R\gamma^\mu\Psi^i_R)(\bar{\Psi}^f_R\gamma_\mu\Psi^f_R) \\ &\quad +\eta_{RL}(\bar{\Psi}^i_R\gamma^\mu\Psi^i_R)(\bar{\Psi}^f_L\gamma_\mu\Psi^f_L) + \eta_{LR}(\bar{\Psi}^i_L\gamma^\mu\Psi^i_L)(\bar{\Psi}^f_R\gamma_\mu\Psi^f_R)\}\end{aligned}$$

  where
  $k_{if} = \frac{1}{2}$ for $i \equiv f$, $k_{if} = 1$ otherwise; $\Psi_L = (1-\gamma^5)/2\ \Psi$, $\Psi_R = (1+\gamma^5)/2\ \Psi$; η_{ab} are phase factors defining the chirality structure of the interaction.
- Specific applications can be considered for pure chiral cases $(ij) = LL$ or RR or LR or RL (keeping only one $\eta_{ij} = \pm 1$), as well as for mixed cases like VV ($\eta_{LL} = \eta_{RR} = \eta_{RL} = \eta_{LR} = \pm 1$), AA ($\eta_{LL} = \eta_{RR} = -\eta_{RL} = -\eta_{LR} = \pm 1$), VA ($\eta_{LL} = -\eta_{RR} = \eta_{RL} = -\eta_{LR} = \pm 1$), AV ($\eta_{LL} = -\eta_{RR} = -\eta_{RL} = \eta_{LR} = \pm 1$);

– δ parameters

$$\delta_{\gamma,ef} = \frac{\pi M_Z^2}{e^2 Q_e Q_f \Lambda^2}[\eta_{LL}(1-v_e)(1-v_f) + \eta_{RR}(1+v_e)(1+v_f)$$
$$+\eta_{RL}(1+v_e)(1-v_f) + \eta_{LR}(1-v_e)(1+v_f)]$$
$$\delta_{Z,ef} = -\frac{4\tilde{s}_e^2 \tilde{c}_e^2 \pi M_Z^2}{e^2 I_{3e} I_{3f} \Lambda^2}[\eta_{LL} + \eta_{RR} - \eta_{RL} - \eta_{LR}]$$
$$\delta_{s,ef}^{\gamma Z} = -\frac{2\tilde{s}_e \tilde{c}_e \pi M_Z^2}{e^2 Q_e I_{3f} \Lambda^2}[\eta_{LL}(1-v_e) - \eta_{RR}(1+v_e) + \eta_{RL}(1+v_e) - \eta_{LR}(1-v_e)]$$
$$\delta_{s,ef}^{Z\gamma} = -\frac{2\tilde{s}_e \tilde{c}_e \pi M_Z^2}{e^2 Q_f I_{3e} \Lambda^2}[\eta_{LL}(1-v_f) - \eta_{RR}(1+v_f) - \eta_{RL}(1-v_f) + \eta_{LR}(1+v_f)]$$

– Since there is a single parameter, the bounds on $\delta_{Z,s,\gamma}$ translates into a bound on the New Physics coupling

Non Universal New Physics II: Extra Dimensions

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, PLB 429 (1998), PLB 436 (1998)

- Arkani-Hamed, Dimopoulos, Dvali model ($M_{Pl} \sim 10^{19}$GeV, $\quad M_S \sim 10^2$GeV)

$$M_{Pl}^2 \sim M_S^{n+2}\, R^n$$

- $n = 1$, $R \sim$ solar system;
  $n = 2$, $R = 0.1 - 1$mm
- Coupling to KK modes

$$\frac{1}{M_{Pl}} \times \#\ \text{modes} \sim \frac{1}{M_S}$$

- Lorentz structure of the matrix element

$$\frac{\lambda}{\Lambda^4}[\bar{e}\gamma^\mu e \bar{f}\gamma_\mu f(p_2 - p_1).(p_4 - p_3) - \bar{e}\gamma^\mu e \bar{f}\gamma^\nu f(p_2 - p_1)_\nu (p_4 - p_3)_\mu]$$

– δ parameters

$$\delta_{z,ef} = -(\frac{\lambda M_Z^2 q^2}{\Lambda^4})\frac{4\tilde{s}_l^2\tilde{c}_l^2}{e^2 I_{3e} I_{3f}}$$

$$\delta_{s,ef}^{\gamma Z} = (\frac{\lambda M_Z^2 q^2}{\Lambda^4})\frac{2\tilde{s}_l\tilde{c}_l\tilde{v}_l}{e^2 Q_e I_{3f}}$$

$$\delta_{s,ef}^{Z\gamma} = (\frac{\lambda M_Z^2 q^2}{\Lambda^4})\frac{2\tilde{s}_l\tilde{c}_l\tilde{v}_f}{e^2 Q_f I_{3e}}$$

$$\delta_{\gamma,ef} = (\frac{\lambda M_Z^2 q^2}{\Lambda^4})\frac{(\tilde{v}_l\tilde{v}_f - 2cos\theta)}{e^2 Q_e Q_f}$$

– The q^2 factor is purely kinematical and a consequence of the higher dimension of the interaction Lagrangian
– The term term proportional to $cos\theta$ gives a contribution in the t-**channel** with **large interference** effects **with** the standard **photon exchange** amplitude.

Corrections to the (non-Bhabha) Observables

- cross section for muon (or tau) production σ_μ; forward-backward asymmetry $A_{FB,\mu}$; cross section for five "light" (u, d, s, c, b) quark production σ_5; cross section for ($b\bar{b}$) production σ_b; forward-backward asymmetry $A_{FB,b}$.
- $\mathcal{O}_i = \mathcal{O}_i^{SM}[1 + d\mathcal{O}_i^{UNP}/\mathcal{O}_i^{SM}]$

$$\frac{d\sigma_\mu^{UNP}}{\sigma_\mu} = -1.43\ \delta_Z - 1.09\ \delta_s + 7.85\ \delta_\gamma$$

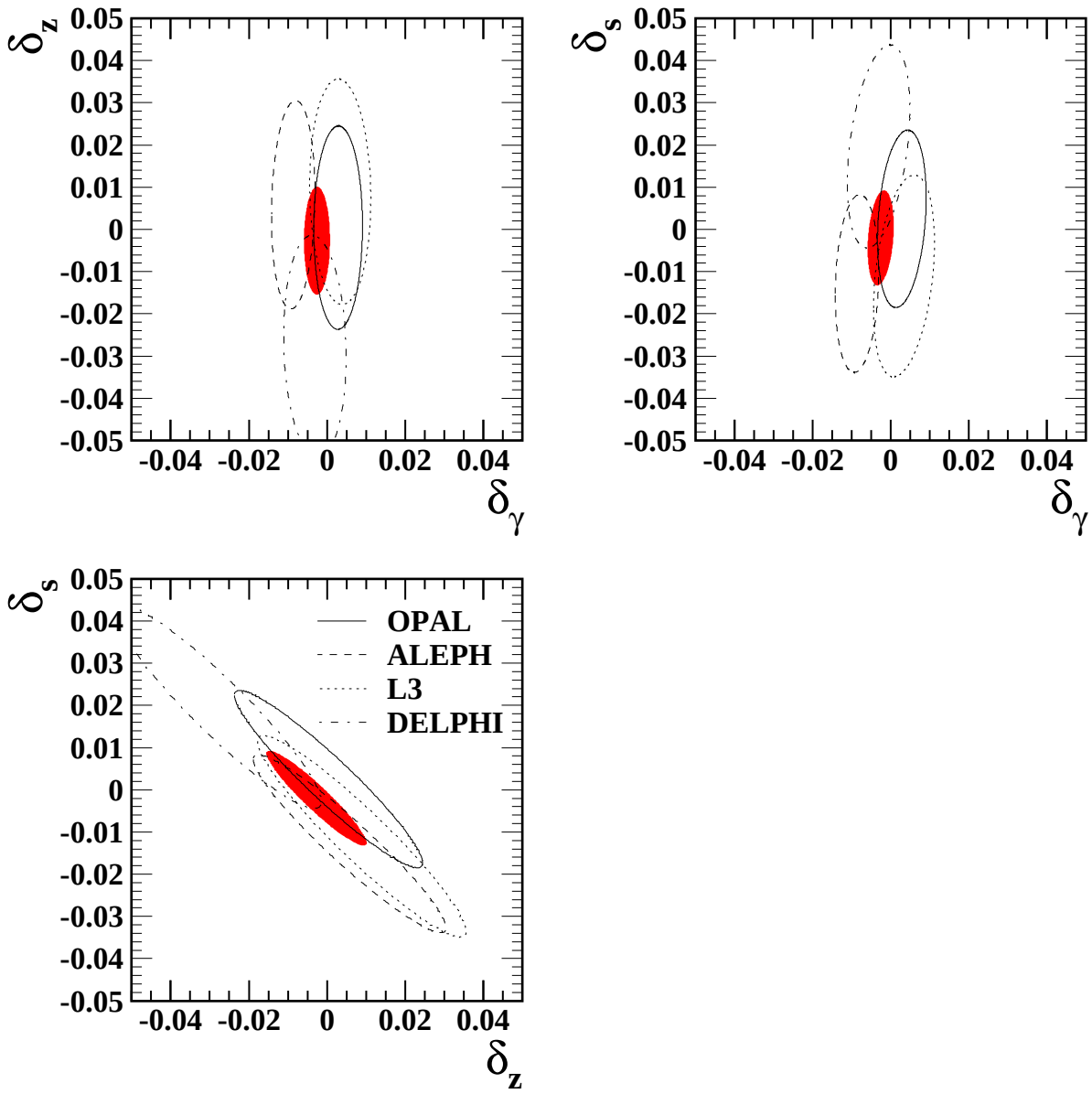
$$\frac{dA_{FB,\mu}^{UNP}}{A_{FB,\mu}} = -2.39\ \delta_Z - 0.19\ \delta_s - 3.02\ \delta_\gamma$$

$$\frac{d\sigma_5^{UNP}}{\sigma_5} = -4.28\ \delta_Z - 5.28\ \delta_s + 4.22\ \delta_\gamma$$

Combination of LEP2 Experiments

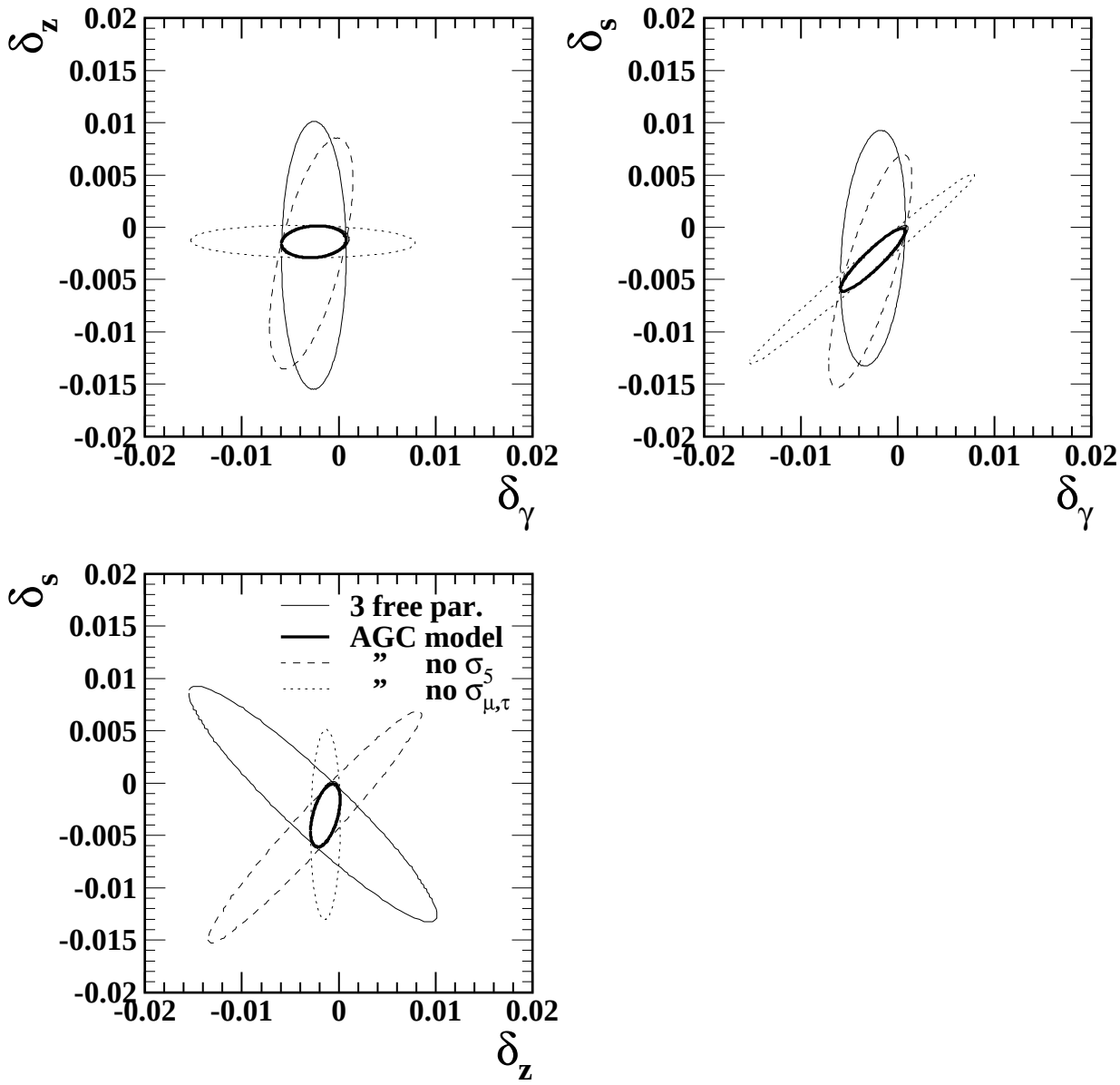
EPS-HEP99, $\sqrt{s} = 189$ GeV

$\Delta\chi^2 = 1$ contours



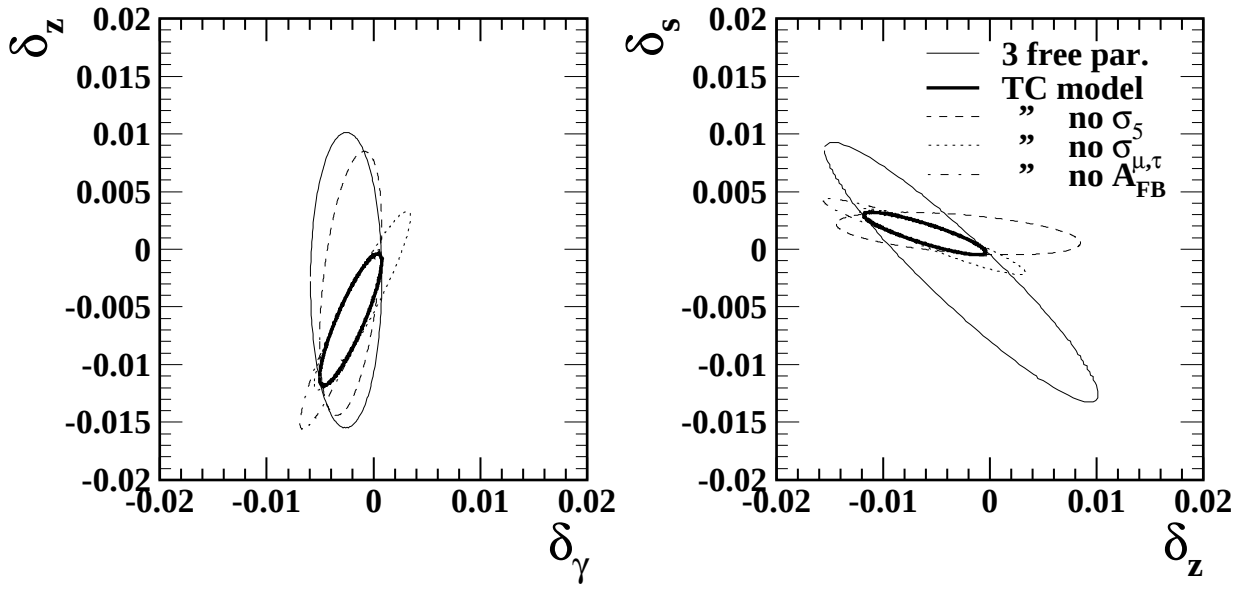
Role of the Different Observables: AGC case

σ_μ, σ_5 nearly orthogonal, $A_{FB,\mu}$ not important



Is Bhabha an additional **independent** and **precise** measurement ?

Role of the Different Observables: TC case

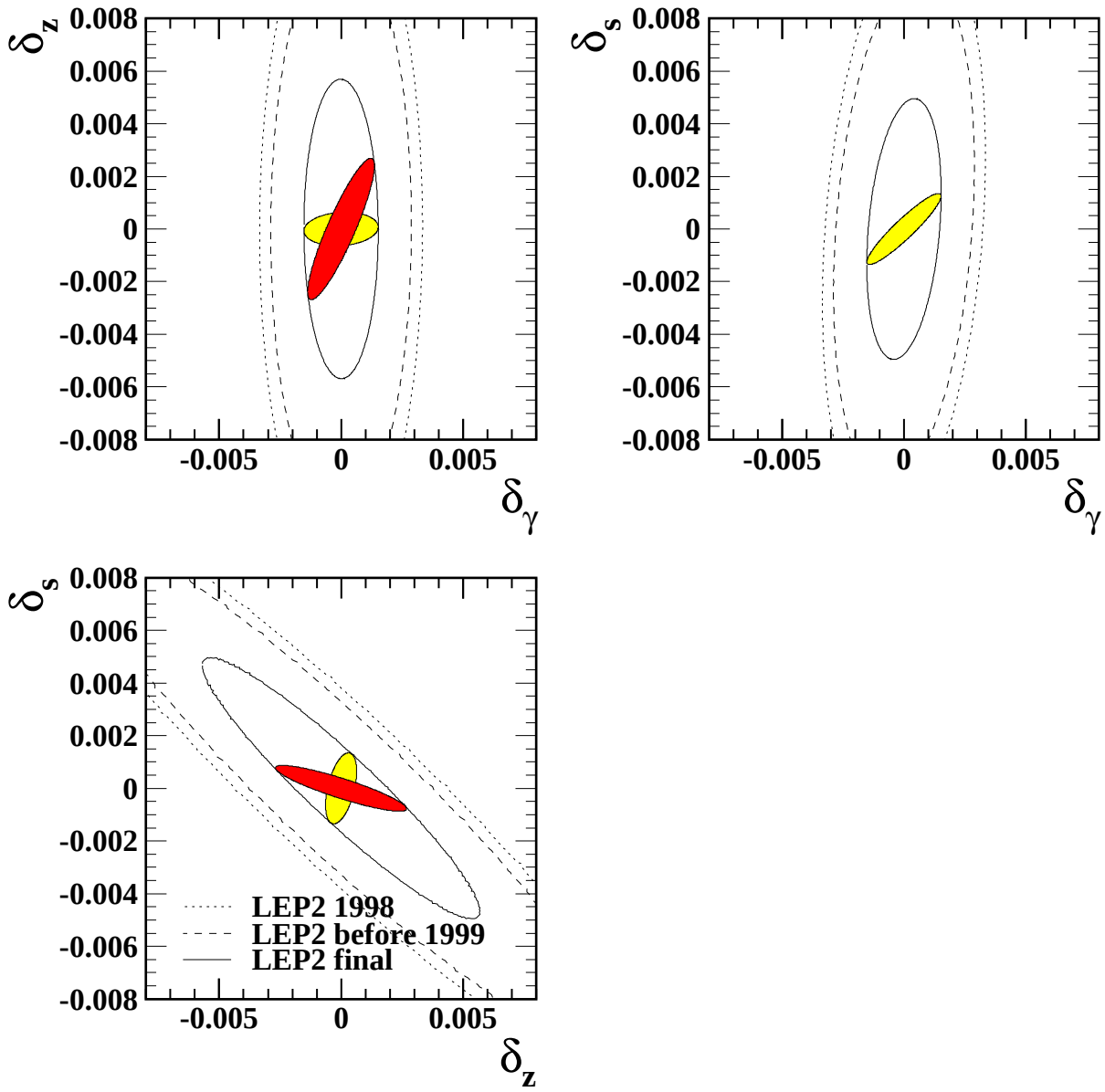


The additional constraint on TC is $\delta_{z,s} > 0$, $\delta_\gamma < 0$ but the C.L. here is low: 34%

Expected Final LEP2 Data

$\sqrt{s} = 183, 189$ GeV

$+$ simulated 400 pb^{-1} @ 200 GeV



Summary of the Bounds on δ for Universal New Physics

	DATA	δ_z		δ_s		δ_γ	
δ	189	$-0.0027^{+0.036}_{-0.036}$		$-0.0020^{+0.031}_{-0.031}$		$-0.0026^{+0.0094}_{-0.0094}$	
	183-189	$-0.0011^{+0.031}_{-0.031}$		$-0.0033^{+0.027}_{-0.027}$		$-0.0022^{+0.0081}_{-0.0081}$	
	Final	$\pm$ 0.016	**1.9**	$\pm$ 0.014	**1.9**	$\pm$0.0043	**1.9**
AGC	189	$-0.0014^{+0.0037}_{-0.0037}$		$-0.0031^{+0.0074}_{-0.0074}$		$-0.0026^{+0.0082}_{-0.0082}$	
	183-189	$-0.0015^{+0.0032}_{-0.0032}$		$-0.0029^{+0.0064}_{-0.0064}$		$-0.0022^{+0.0071}_{-0.0071}$	
	Final	$\pm$0.0016	**2**	$\pm$0.0033	**1.9**	$\pm$0.0037	**1.9**
TC	189	$-0.0061^{+0.015}_{-0.015}$		$0.0014^{+0.0047}_{-0.0047}$		$-0.0021^{-0.0075}_{-0.0075}$	
	183-189	$-0.0055^{+0.013}_{-0.013}$		$0.0010^{+0.0041}_{-0.0041}$		$-0.0016^{+0.0064}_{-0.0064}$	
	Final	$\pm$0.0066	**2**	$\pm$0.0021	**2**	$\pm$0.0034	**1.9**

Summary of the Bounds on Non Universal New Physics

Present Data

Λ_{CT} (TeV)	All	no σ_l	no σ_5	no $A_{FB,l}$
LL	2.9	**1.8**	2.8	2.9
RR	2.7	**1.6**	2.7	2.7
VV	4.7	**2.7**	4.6	4.6
AA	4.1	3.8	4.0	**3.3**
Λ_{ED} (TeV)	All	no σ_l	no σ_5	no $A_{FB,l}$
	0.78	0.78	0.78	**0.25**

Small AA contribution to δ_γ ($\sim v_l v_f$)

ED effect $\sim v_e^2 - 2\cos\theta \sim \cos\theta$

Summary of the Bounds on Non Universal New Physics

(Optimistic) Future Data

Λ_{CT} (TeV)	All		no σ_l		no σ_5		no $A_{FB,l}$	
LL	2.9	**4.0**	1.8	**2.5**	2.8	**3.9**	2.9	**3.9**
RR	2.7	**3.7**	1.6	**2.1**	2.7	**3.7**	2.7	**3.7**
VV	4.7	**6.4**	2.7	**3.6**	4.6	**6.3**	4.6	**6.3**
AA	4.1	**5.5**	3.8	**5.0**	4.0	**5.2**	3.3	**4.7**
Λ_{ED} (TeV)	All		no σ_l		no σ_5		no $A_{FB,l}$	
	0.78	**0.89**	0.78	**0.89**	0.78	**0.89**	0.25	**0.30**

$35 - 40\%$ improvement for CT

15% improvement for ED

Z-peak Representation of the Bhabha Process

- The scattering amplitude at one loop is the sum of two (s-channel and t-channel) components

$$\mathcal{A}_{ee} = \mathcal{A}_s(q^2, \theta) + \mathcal{A}_t(q^2, \theta)$$

- Definition of effective couplings in the t-channel component

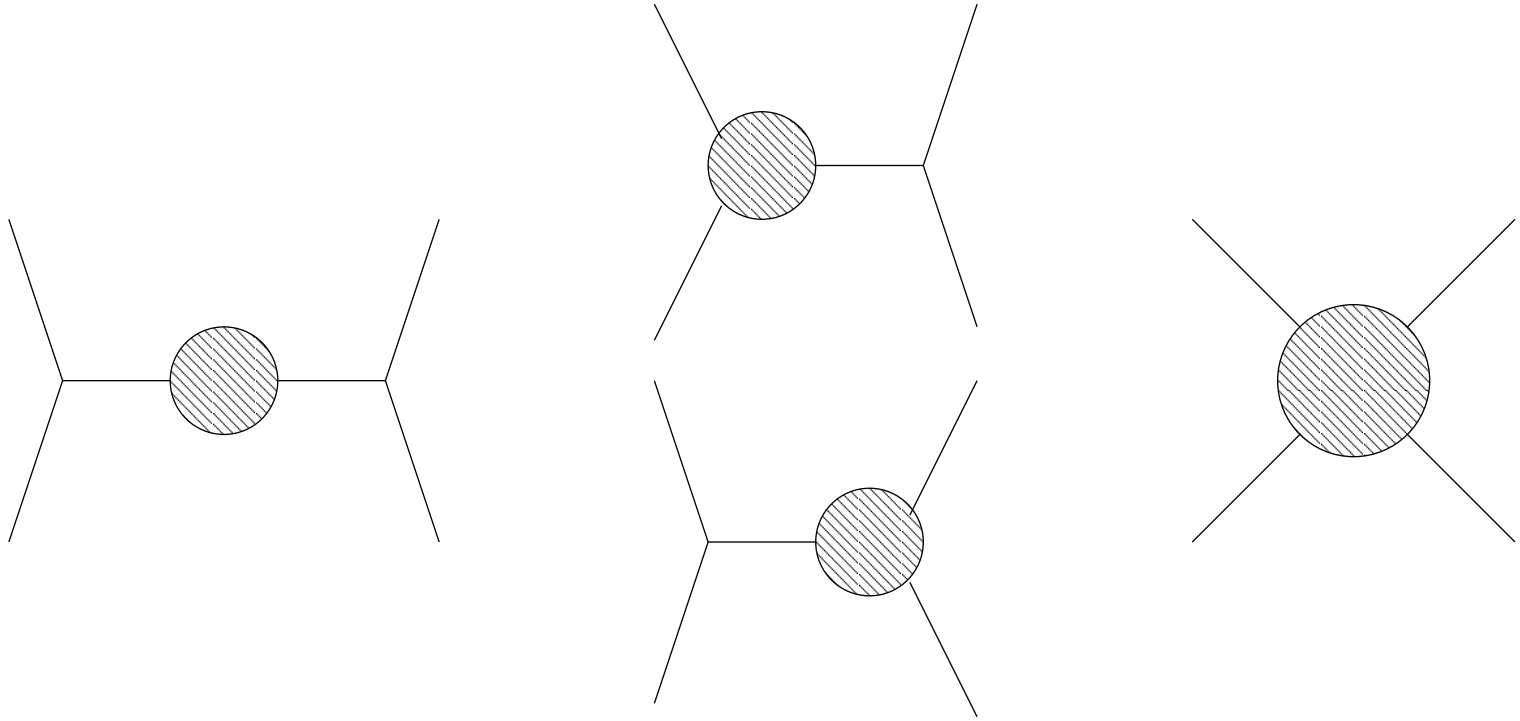
$$\mathcal{A}_t(q^2, \theta) = \frac{i}{t}\bar{v}\gamma^\mu \bar{g}_{Ve}^{(\gamma)}(q^2, \theta) v \cdot \bar{u}\gamma_\mu \bar{g}_{Vf}^{(\gamma)}(q^2, \theta) + \frac{i}{t - M_Z^2} \cdot$$
$$\bar{v}\gamma^\mu [\bar{g}_{Ve}^{(Z)}(q^2, \theta) - \bar{g}_{Ae}^{(Z)}(q^2, \theta)\gamma^5] \cdot \bar{u}\gamma_\mu [\bar{g}_{Vf}^{(Z)}(q^2, \theta) - \bar{g}_{Af}^{(Z)}(q^2, \theta)\gamma^5] u$$

– t-channel effective couplings

$$\bar{g}^{\gamma}_{Ve}(q^2,\theta) = \sqrt{4\pi\alpha(0)}\; Q_e[1+\frac{1}{2}\overline{\Delta}_{\alpha}(q^2,\theta)]$$
$$\bar{g}^{Z}_{Ve}(q^2,\theta) = \gamma_e^{\frac{1}{2}}\; I_{3e}\; \tilde{v}_e[1-\frac{1}{2}\overline{R}(q^2,\theta) - \frac{4\tilde{s}_e\tilde{c}_e}{\tilde{v}_e}|Q_f|\overline{V}(q^2,\theta)]$$
$$\bar{g}^{Z}_{Ae}(q^2,\theta) = \gamma_e^{\frac{1}{2}}\; I_{3e}[1-\frac{1}{2}\overline{R}(q^2,\theta)] \tag{1}$$

– The new functions $\overline{\Delta}_{\alpha}(q^2,\theta)$, $\overline{R}(q^2,\theta)$ and $\overline{V}(q^2,\theta)$ are obtained from the s-channel by crossing $s \longleftrightarrow t$

$$q^2 \longrightarrow t = -\frac{q^2}{2}(1-cos\theta) \qquad cos\theta \longrightarrow 1+\frac{2q^2}{t}$$



A rotated copy of the same diagrams occur in $e^+e^- \to e^+e^-$

- General expression of the polarized Bhabha differential cross section (P and P' are the initial e^-, e^+ polarizations)

$$\frac{d\sigma}{dcos\theta} = (1 - PP')\frac{d\sigma^1}{dcos\theta} + \underbrace{(1 + PP')\frac{d\sigma^2}{dcos\theta}}_{\text{t channel only}} + (P' - P)\frac{d\sigma^P}{dcos\theta}$$

- unpolarized angular distribution: relevant at LEP2

$$\frac{d\sigma}{dcos\theta} \equiv \frac{d\sigma^1}{dcos\theta} + \frac{d\sigma^2}{dcos\theta}$$

- LL-RR and LL+RR polarization asymmetries: relevant at LC

$$A_{LR}(q^2, \theta) = [\frac{d\sigma^P}{dcos\theta}]/[\frac{d\sigma}{dcos\theta}] \qquad A_{||}(q^2, \theta) = [\frac{d\sigma^2}{dcos\theta}]/[\frac{d\sigma}{dcos\theta}]$$

Parametrization of New Physics Effects in the Bhabha Observables

- General New Physics $\Longrightarrow$ duplication of the parameters
- Universal New Physics $\Longrightarrow$ the same set of three numbers
- General definition of δ, including contributions to Bhabha

$$R^{UNP}(z) = \frac{(z - M_Z^2)}{M_Z^2}\,\delta_Z$$

$$V^{UNP}(z) = \frac{(z - M_Z^2)}{M_Z^2}\,\delta_s$$

$$\tilde{\Delta}_\alpha^{UNP}(z) = \frac{z}{M_Z^2}\,\delta_\gamma$$

where $z = s, t$

Definition of the Observables for the Combined LEP2 + OPAL-Bhabha Fit

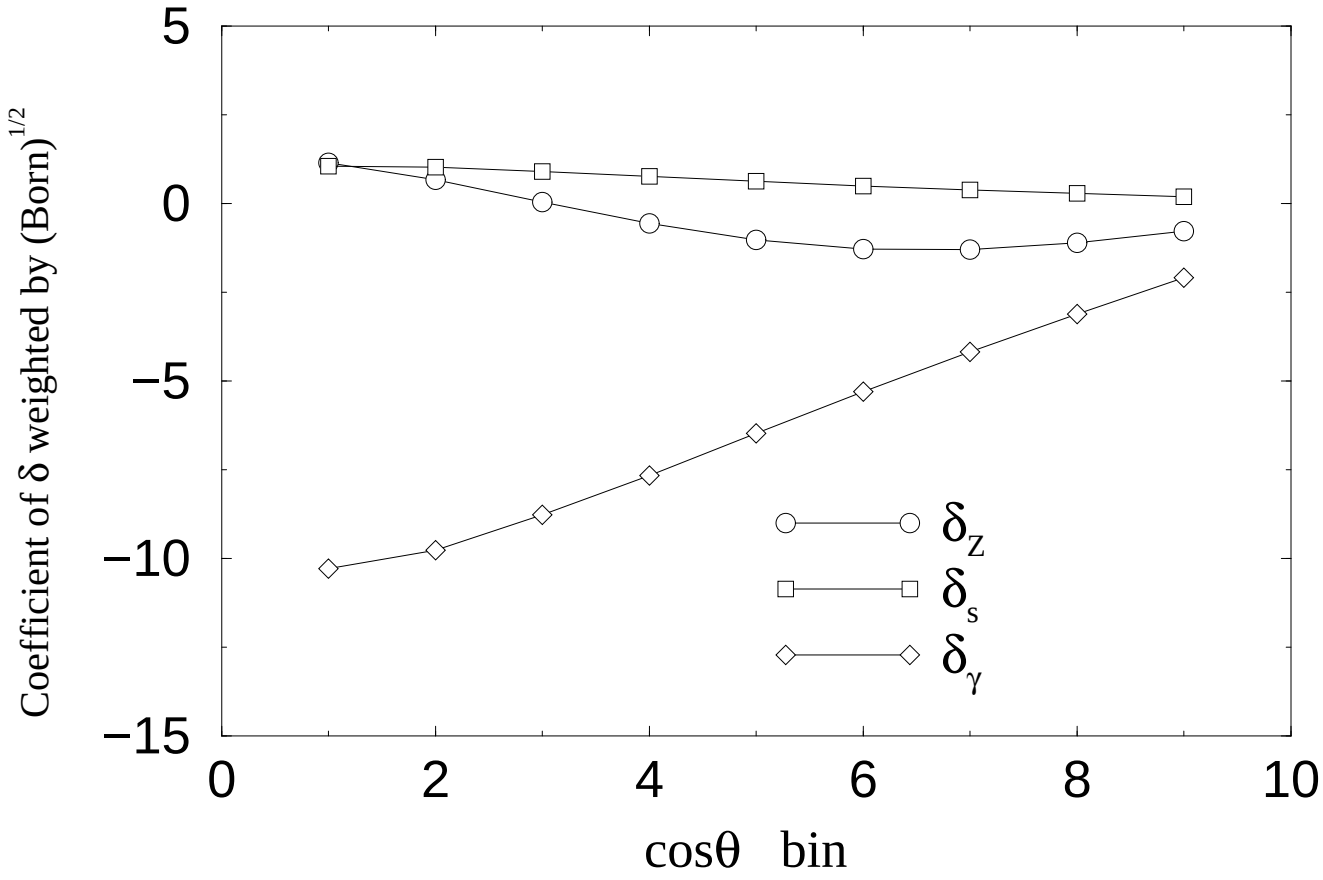
- Non Bhabha: σ_μ, σ_5, $A_{FB,\mu}$ @ $\sqrt{s} = 183, 189$ GeV

- Bhabha: unpolarized differential cross section from OPAL data (CERN-EP/99-097)
  - c.m. energy 189 GeV
  - 9 angular bins $-0.9 < \cos\theta_{e^-} < 0.9$
  - $\mathcal{L} = 180$ pb^{-1}
  - acol cut $< 10^o$ to discard radiative events

- For the non Bhabha observables, $\varepsilon_{th} < \varepsilon_{exp}$ is $< 1\%$, dominated by large QED corrections.

- For the Bhabha cross section, $\varepsilon_{th} \simeq 2\%$ larger than the experimental error in the very forward cone.

Relative contributions from Bhabha to δ



Bounds on δ

Present Data

	without Bhabha	with all Bhabha	forward	backward
δ_Z	-0.001 $\pm$ 0.031	0.0064 $\pm$ 0.028	0.006 $\pm$ 0.03	0.0011 $\pm$ 0.029
δ_s	-0.004 $\pm$ 0.032	-0.0087 $\pm$ 0.031	-0.0084 $\pm$ 0.032	-0.0057 $\pm$ 0.031
δ_γ	-0.0022 $\pm$ 0.0083	0.00019 $\pm$ 0.0074	0.00014 $\pm$ 0.0075	-0.0019 $\pm$ 0.0081

Not a spectacular improvement

Mainly in δ_γ and from the forward cone data

Bounds on δ

(Optimistic) Future Data including 400 pb^{-1} @ 200 GeV

	without Bhabha		all Bhabha, 2% th.		with all Bhabha	
δ_Z	0.031	**0.014**	0.028	**0.012**	0.03	**0.012**
δ_s	0.032	**0.015**	0.031	**0.013**	0.032	**0.013**
δ_γ	0.0083	**0.0038**	0.0074	**0.0034**	0.0075	**0.0028**

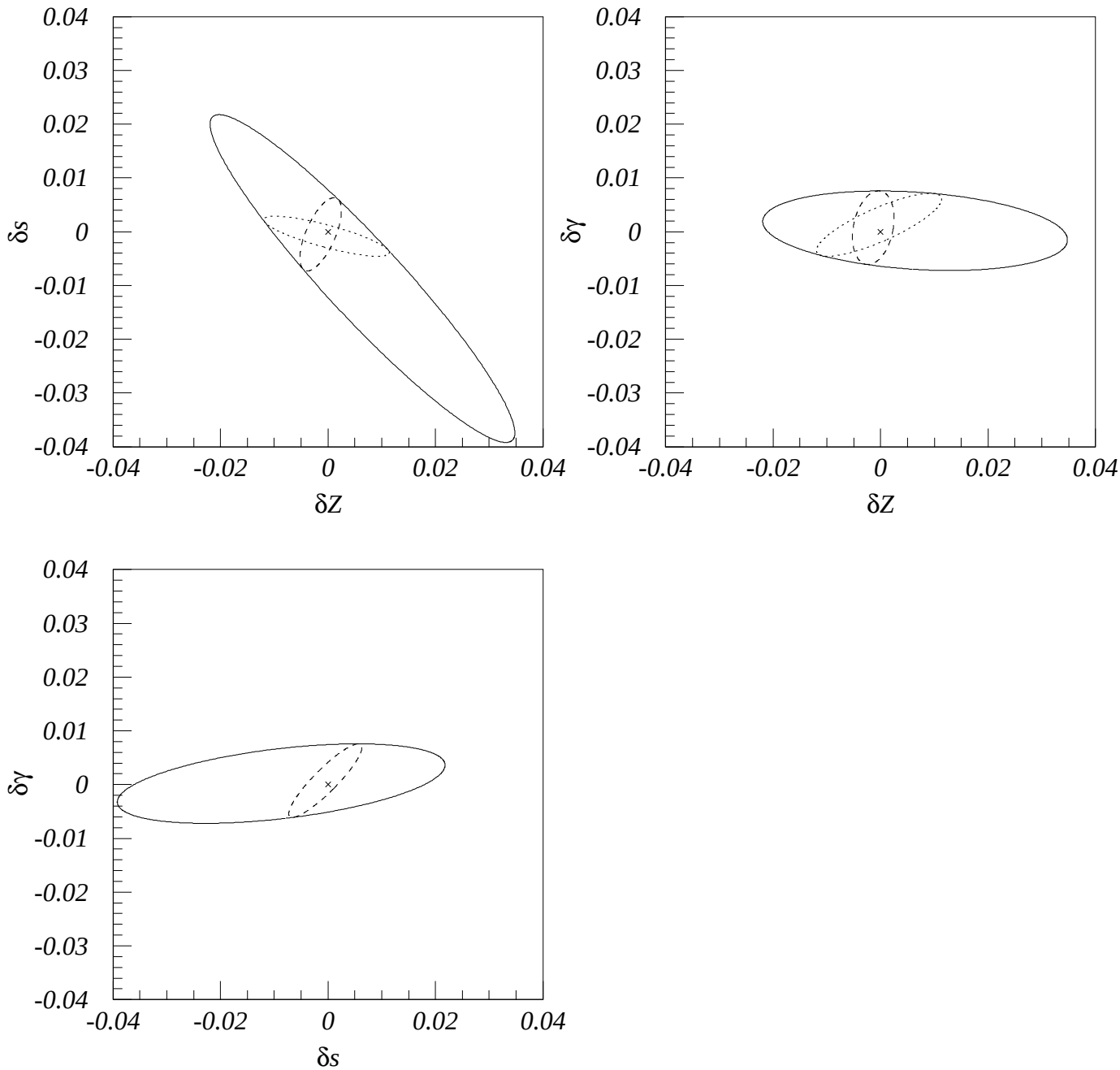
For AGC these results convert into

$$|\Delta f_{DW}| < 0.43, \qquad |\Delta f_{DB}| < 2.1$$

in agreement with Hagiwara et al.

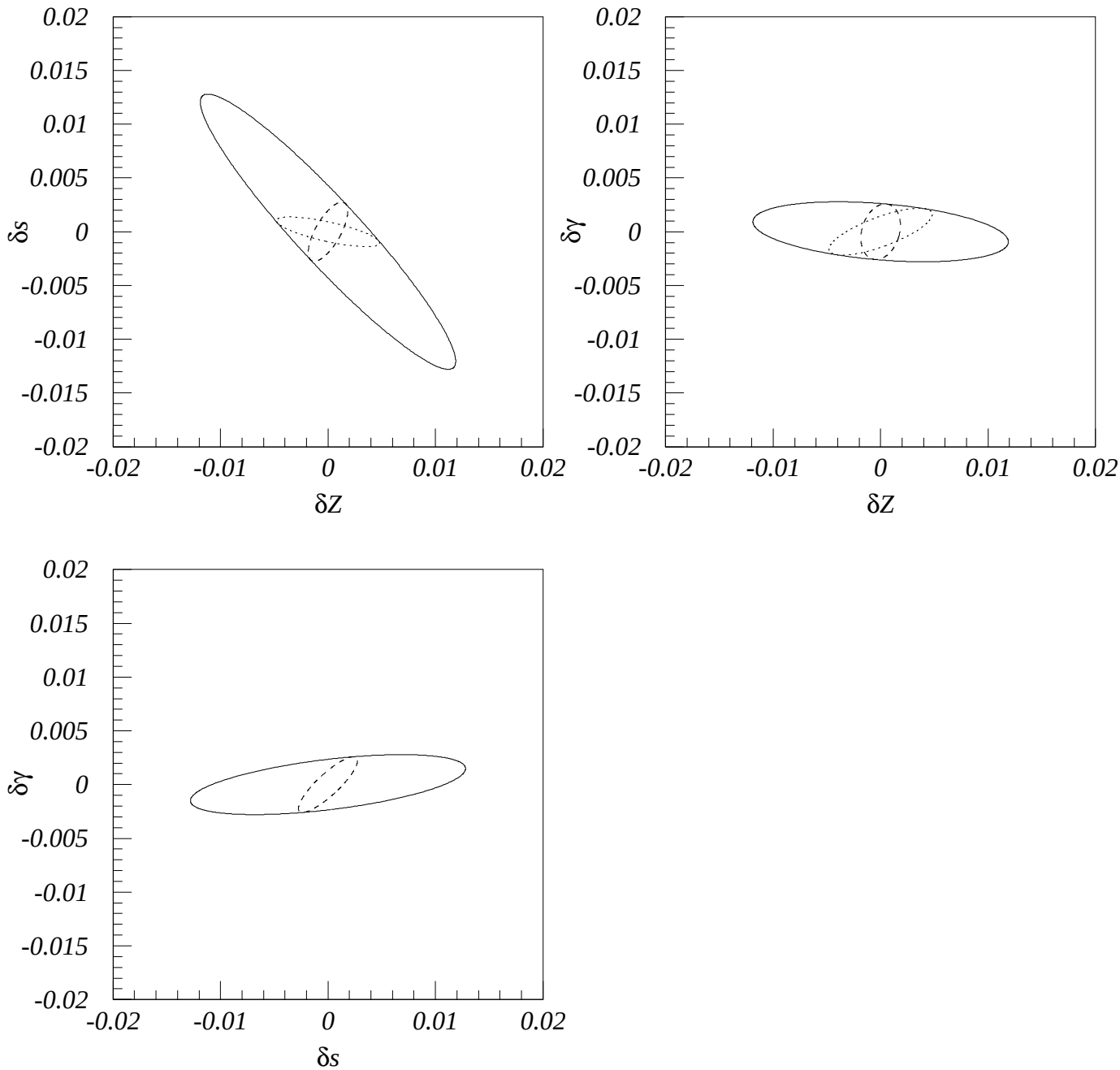
Bounds on δ: projected ellipses

Present Data



Bounds on δ: projected ellipses

(Optimistic) Future Data



Bounds on Non Universal New Physics: Extra Dimensions

Present data analysis L3, OPAL

- L3, 180 pb^{-1} at 189 GeV
- Bhabha in the cone $(44^o, 136^0)$

Process	syst %	M_S+	M_S-	MC
ZZ	10	0.77	0.76	EXCALIBUR
WW	4	0.79	0.68	KORALW
$\gamma\gamma$	1	0.79	0.80	
Bosons		0.89	0.82	
$\mu\mu$	2.4	0.69 (0.60)	0.56 (0.63)	KORALZ, ZFITTER
$\tau\tau$	3.5	0.54 (0.63)	0.58 (0.50)	
$q\bar{q}$	1.4	0.49	0.49	
ee	3	0.98	0.84	TOPAZ0
Fermions		1	0.84	
B + F		1.07	0.87	

Bounds on Non Universal New Physics

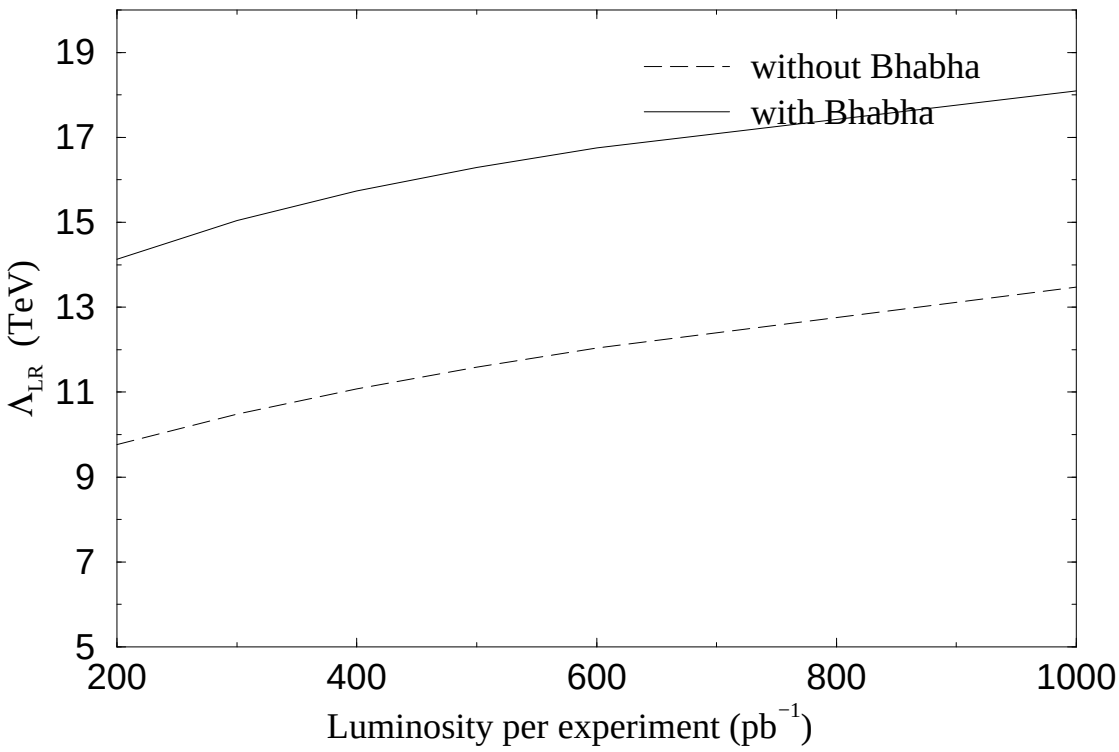
Present Data LEP2 Combined + OPAL

	without Bhabha	with all Bhabha	forward	backward
Λ_{LL}	10-9.9	11-9.2	11-9.2	10-9.8
Λ_{RR}	7.7-12	8.7-10	8.7-10	7.8-12
Λ_{LR}	6.5-9.2	16-7.8	14-7.3	8.2-9.2
Λ_{RL}	7.2-15	12-9.7	11-9.5	8.3-13
Λ_{VV}	13-20	17-16	16-16	13-20
Λ_{AA}	16-13	14-14	14-14	15-13
Λ_{AV}	17-8.7	17-8.7	17-8.7	17-8.7
Λ_{VA}	4-3.3	4.2-3.2	4.2-3.2	4-3.3
Λ_{ED}	0.69-0.75	0.82-2.2	0.8-1.9	0.77-0.9

ED: tt $>$ st $>$ ss

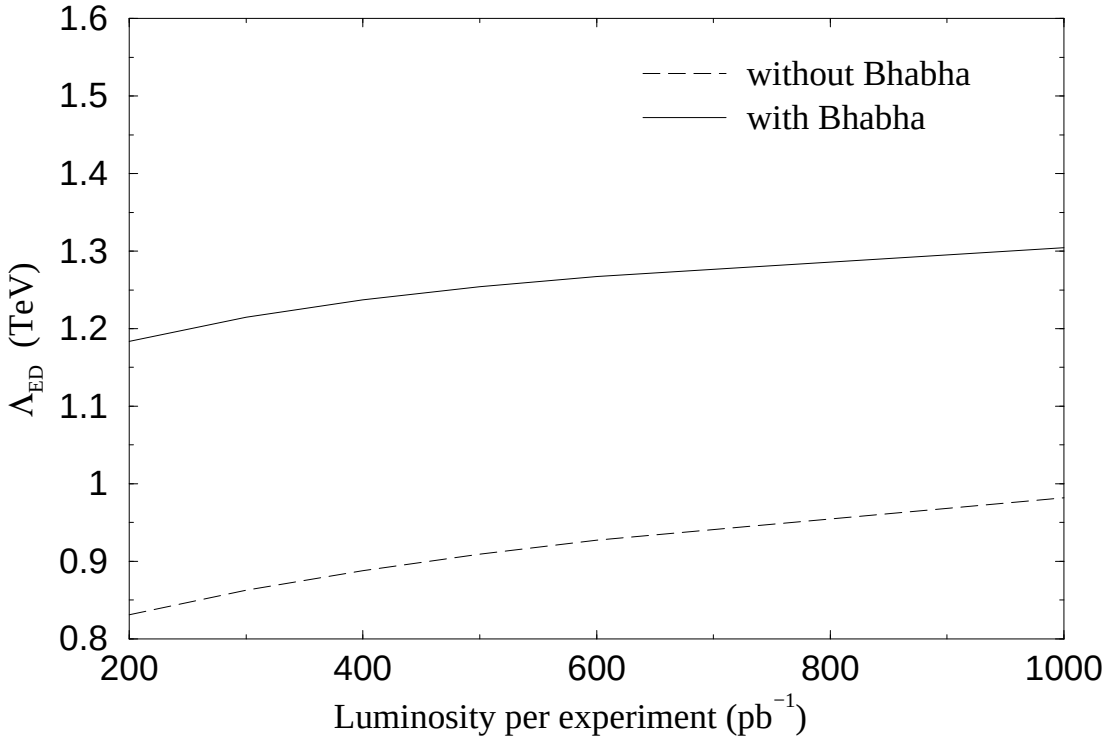
Bounds on Non Universal New Physics

Luminosity Dependence: Λ_{CT}



Bounds on Non Universal NP

Luminosity Dependence: Λ_{ED}



Bounds on Non Universal New Physics

(Optimistic) Future Data

	without Bhabha		all Bhabha, 2% th.		$\varepsilon_{th} = 0$
Λ_{LL}	10-9.9	**15**	11-9.2	**15**	**16**
Λ_{RR}	7.7-12	**13**	8.7-10	**14**	**15**
Λ_{LR}	6.5-9.2	**11**	16-7.8	**16**	**18**
Λ_{RL}	7.2-15	**13**	12-9.7	**17**	**18**
Λ_{VV}	13-20	**22**	17-16	**24**	**27**
Λ_{AA}	16-13	**21**	14-14	**21**	**22**
Λ_{AV}	17-8.7	**16**	17-8.7	**16**	**16**
Λ_{VA}	4-3.3	**5.2**	4.2-3.2	**5.2**	**5.3**
Λ_{ED}	0.69-0.75	**0.89**	0.82-2.2	**1.2**	**1.4**

Conclusions

- Simple parametrization of New Physics Effects in $e^+e^- \to f\bar{f}$ at present and future energies

- Exploitation of the Z-peak inputs in an automatic fashion for conventional combined observables and also for Bhabha

- Important Role of Bhabha scattering as a complementary measurement (such as A_{LR} at NLC) and as a probe for certain New Physics models