WW Physics at Present and Future e^+e^- Colliders

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SLAC

OUTLINE

TGC's at LEP2

TGC's at Future e^+e^- Colliders

Strong EWSB at Future e^+e^- Colliders

General WWV Vertex

$$\begin{aligned}\mathcal{L}_{WWV}/g_{WWV} = & \; ig_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} \\ & + \frac{i\lambda_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\ & + g_5^V \varepsilon^{\mu\nu\rho\sigma} (W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma + i\tilde{\kappa_V} W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\tilde{\lambda}_V}{m_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda}\end{aligned}$$

EM Gauge Invariance, C & P Conservation Reduces
TGC Parameter Set to g_1^Z κ_Z λ_Z κ_γ λ_γ

Light Higgs, No Operators With Dim$\geq$ 8, LEP1 Data $\Longrightarrow$

$$\Delta\kappa_{\mathrm{Z}} = -\Delta\kappa_\gamma \tan^2\theta_{\mathrm{w}} + \Delta \mathrm{g}_1^{\mathrm{Z}}$$

$$\lambda_{\mathrm{Z}} = \lambda_\gamma$$

In SM at Tree-Level All TGC's=0 Except $g_1^V = \kappa_V = 1$

Chiral Lagrangian

$$\mathcal{L}_{SB} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \cdots$$

where

$$\begin{aligned}
\mathcal{L}^{(2)} &= \frac{1}{4} v^2 \mathrm{Tr} D^\mu \Sigma^\dagger D_\mu \Sigma, \\
\mathcal{L}^{(4)} &= \frac{L_1}{16\pi^2} [\mathrm{Tr}(D^\mu \Sigma^\dagger D_\mu \Sigma)]^2 + \frac{L_2}{16\pi^2} \mathrm{Tr}(D_\mu \Sigma^\dagger D_\nu \Sigma) \mathrm{Tr}(D^\mu \Sigma^\dagger D^\nu \Sigma) \\
&\quad - ig \frac{L_{9L}}{16\pi^2} \mathrm{Tr}(W^{\mu\nu} D_\mu \Sigma D_\mu \Sigma^\dagger) - ig' \frac{L_{9R}}{16\pi^2} \mathrm{Tr}(B^{\mu\nu} D_\mu \Sigma^\dagger D_\nu \Sigma) \\
&\quad + gg' \frac{L_{10}}{16\pi^2} \mathrm{Tr}(\Sigma B^{\mu\nu} \Sigma^\dagger W_{\mu\nu}) \quad .
\end{aligned}$$

$$\begin{aligned}
\kappa_\gamma &= 1 + \frac{e^2}{32\pi^2 s_w^2} (L_{9L} + L_{9R}) \\
\kappa_Z &= 1 + \frac{e^2}{32\pi^2 s_w^2} \left(L_{9L} - \frac{s_w^2}{c_w^2} L_{9R}\right) \\
g_1^Z &= 1 + \frac{e^2}{32\pi^2 s_w^2} \frac{L_{9L}}{c_w^2}
\end{aligned}$$

QCD values for L_{9L}, $L_{9R} \Rightarrow \Delta\kappa_\gamma \sim -3 \times 10^{-3}$

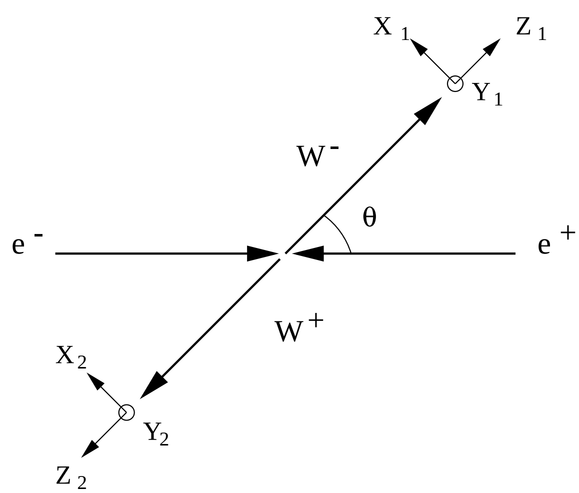
SM loop corrections also $\mathcal{O}(10^{-3})$

Indirect vs. LEP2 Limits

68% C.L.

	Indirect Limits					ALEPH 470 pb^{-1}	
	oblique params	$(g-2)_\mu$	d_n	d_e	$b \to s\gamma$	Re	Im
$\Delta\kappa_\gamma$	0.05	1.00	-	-	2.00	0.10	-
$\Delta\kappa_Z$	0.40	-	-	-	2	-	-
λ_γ	0.20	2.00	-	-	7.00	0.04	-
λ_Z	0.20	-	-	-	-	-	-
$\tilde{\kappa}_\gamma$	-	-	-	0.14	0.40	0.16	0.09
$\tilde{\kappa}_Z$	-	-	-	0.04	-	0.09	0.06
$\tilde{\lambda}_\gamma$	-	-	0.00025	-	1.30	0.12	0.07
g_4^Z	-	-	-	0.80	-	0.16	0.14
$\tilde{\lambda}_Z$	-	-	-	-	-	0.07	0.05
g_4^γ	-	-	-	-	-	0.23	0.20
g_5^γ	-	-	-	-	-	0.33	0.37
g_5^Z	-	-	-	-	-	0.21	0.23

W^+W^- Event Reconstruction and Analysis



Reconstruct Production Angle and 4 Decay Angles

Utilize All Decay Modes: $l\nu q\overline{q}$, $q\overline{q}q\overline{q}$, $l\nu l\nu$

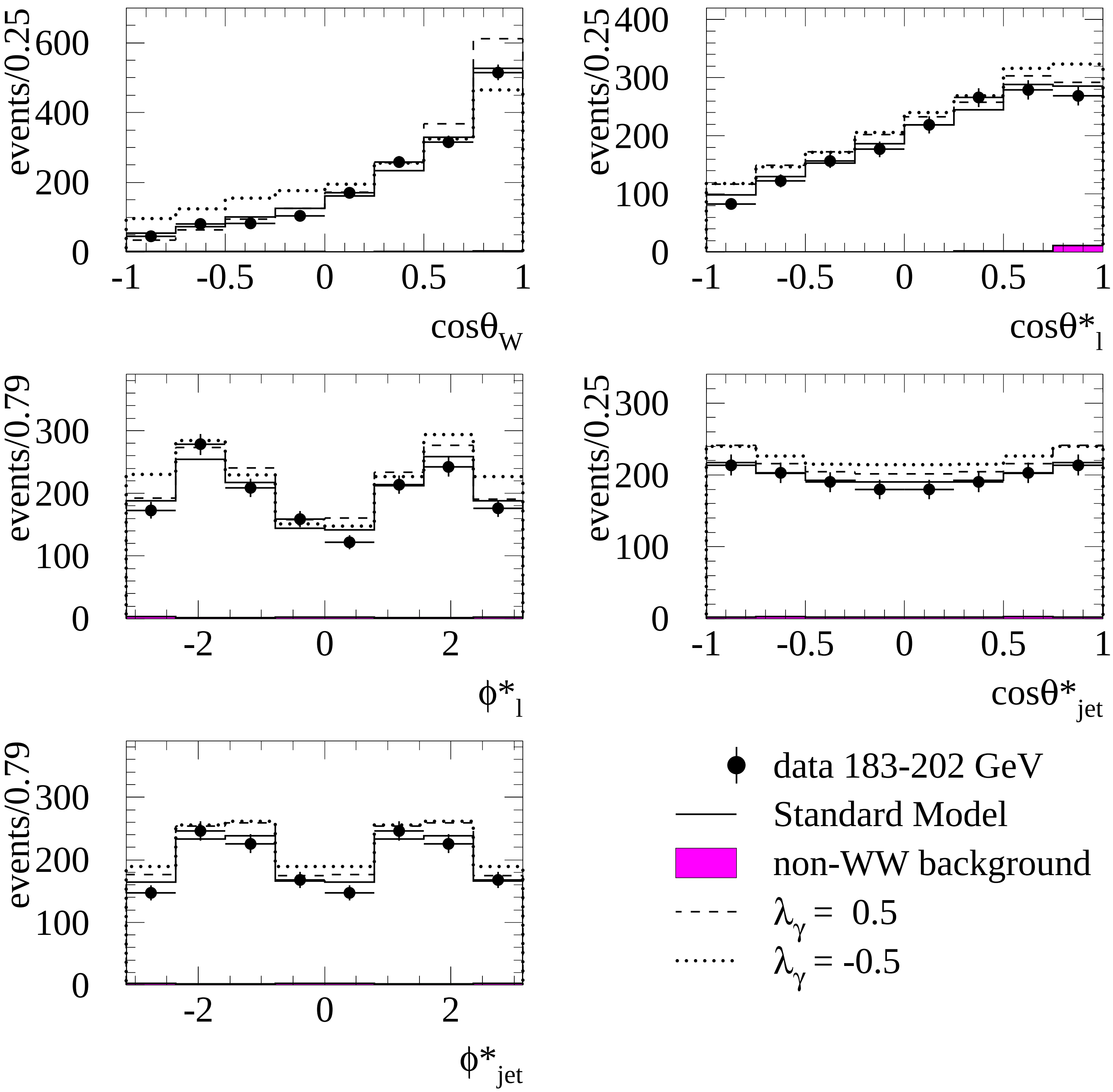
Include Cross Section Information

TGC Fit: Max Likelihood Analysis of 5 Angles

or

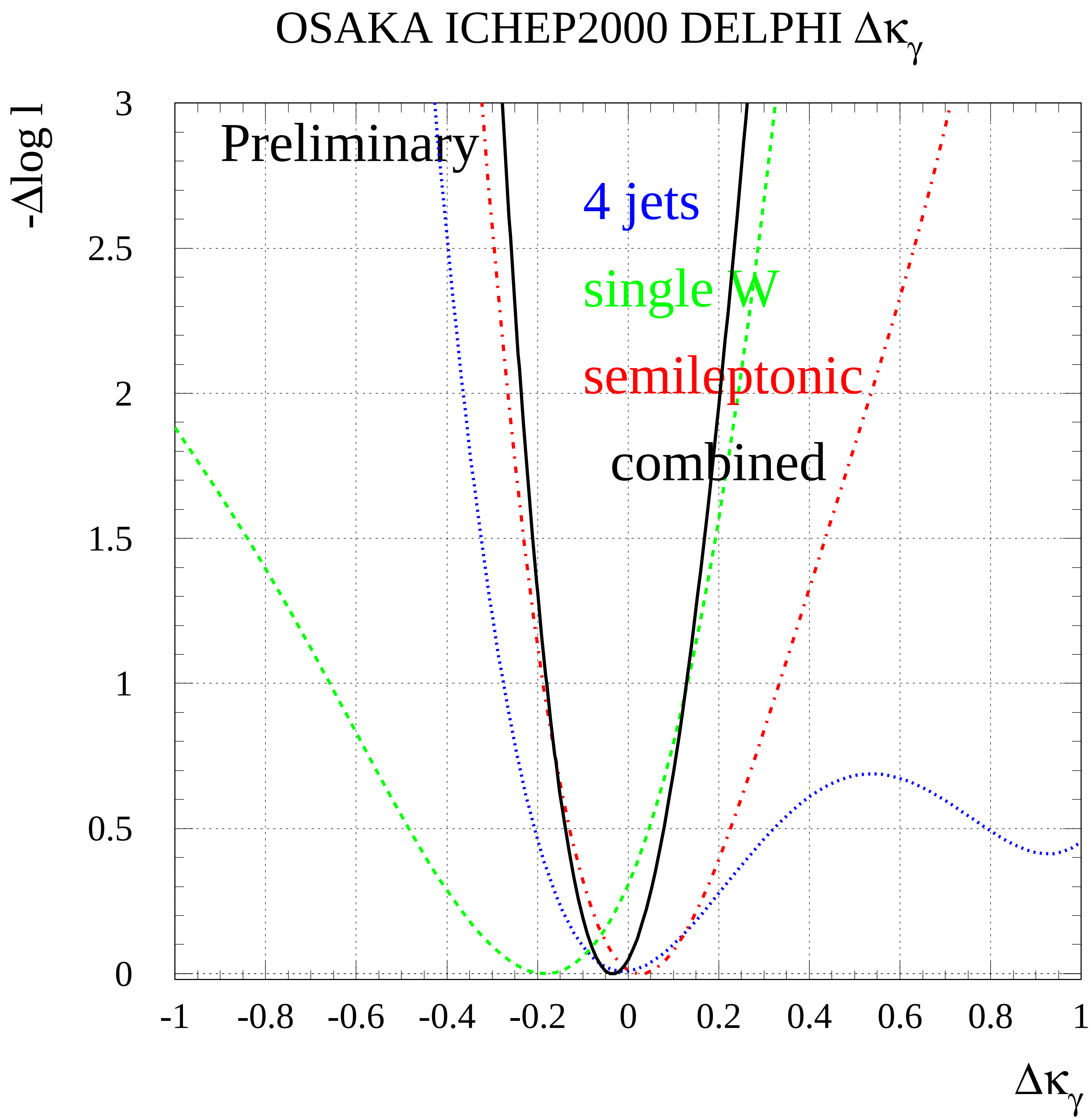
Measure ⟨Optimal Observable⟩ Based on TGC, 5 Angles

ALEPH Preliminary

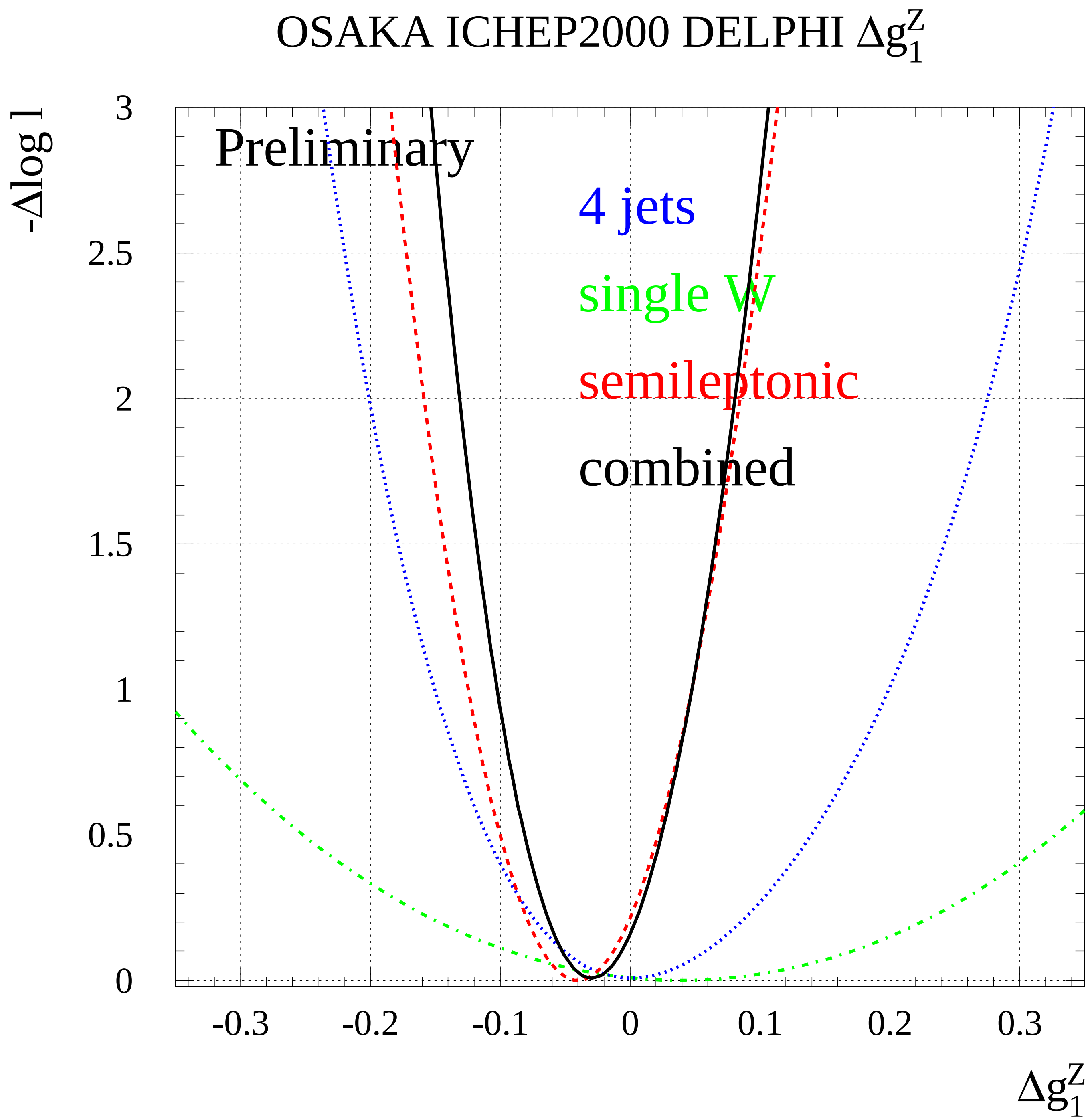


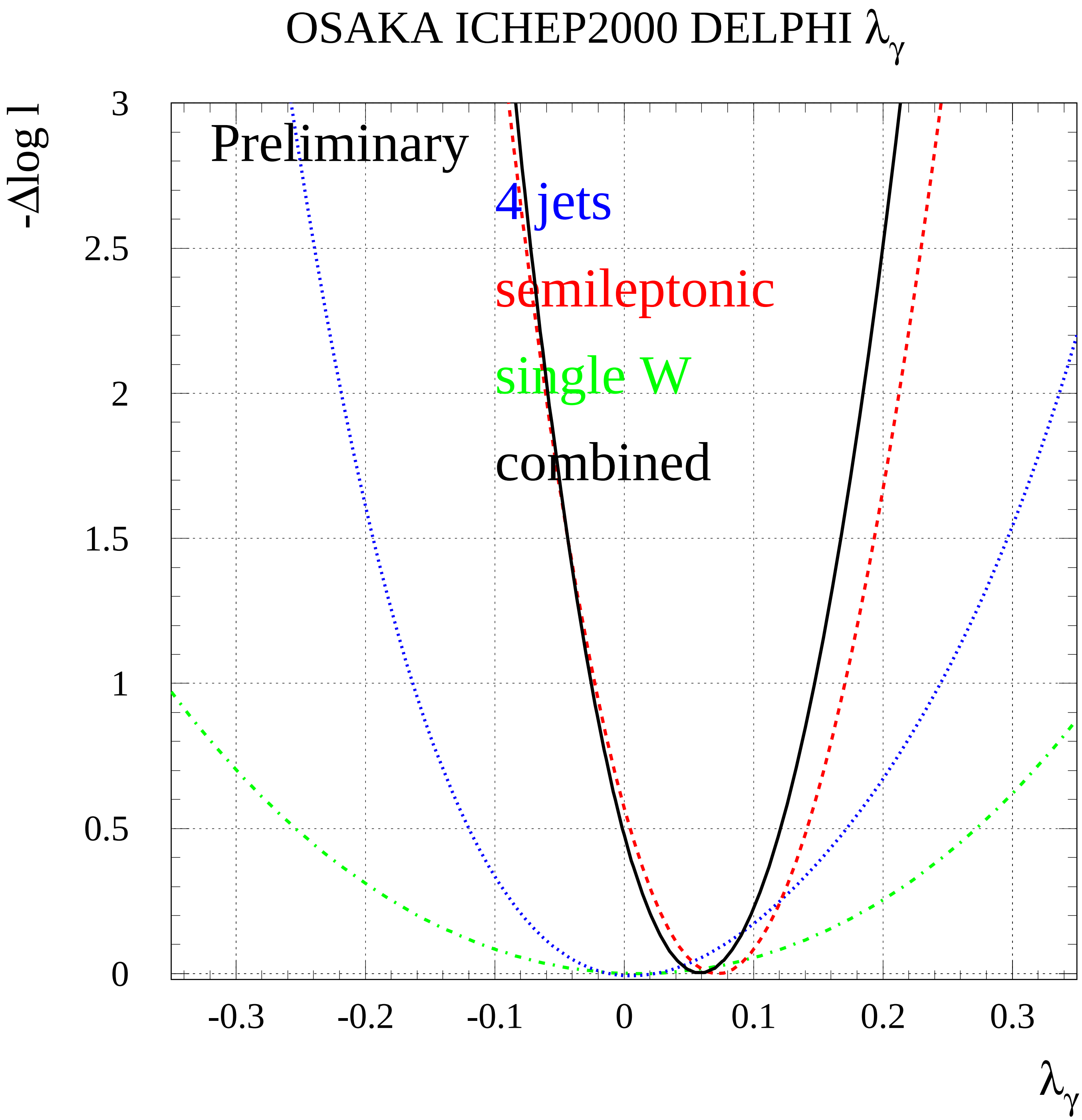
Example of Systematic Errors at LEP2

	λ_γ				
Source	$q\bar{q}q\bar{q}$	$e\nu q\bar{q}$	$\mu\nu q\bar{q}$	$\tau\nu q\bar{q}$	$\ell\nu\ell\nu$
Correlated errors					
LEP energy	-	-	-	-	-
Luminosity	0.04	-	-	-	0.01
W mass	0.01	-	-	0.06	0.03
W^+W^- cross section	0.05	0.03	0.01	-	-
Initial state Radiation	0.02	-	-	0.14	-
MC fragmentation	0.12	0.04	0.03	0.15	-
Calorimeter scale	0.03	0.05	0.05	0.03	0.03
Tracking	-	0.06	0.08	-	0.01
Jet corrections	-	0.02	0.05	-	-
Uncorrelated errors					
Background estimation	0.03	0.01	-	-	-
Reference MC statistics	0.02	0.01	0.01	0.17	0.06
Four-fermion reweighting	-	0.03	0.01	0.04	-
Jet charge	-	-	0.03	-	-
Colour reconnection	0.01	-	-	-	-
Bose-Einstein effects	0.02	-	-	-	-
Statistical error 175 pb^{-1}	0.13	0.11	0.09	0.16	0.13



OSAKA ICHEP2000 DELPHI Δκ_γ
-Δlog l
Preliminary
4 jets
single W
semileptonic
combined
3
2.5
2
1.5
1
0.5
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Δκ_γ

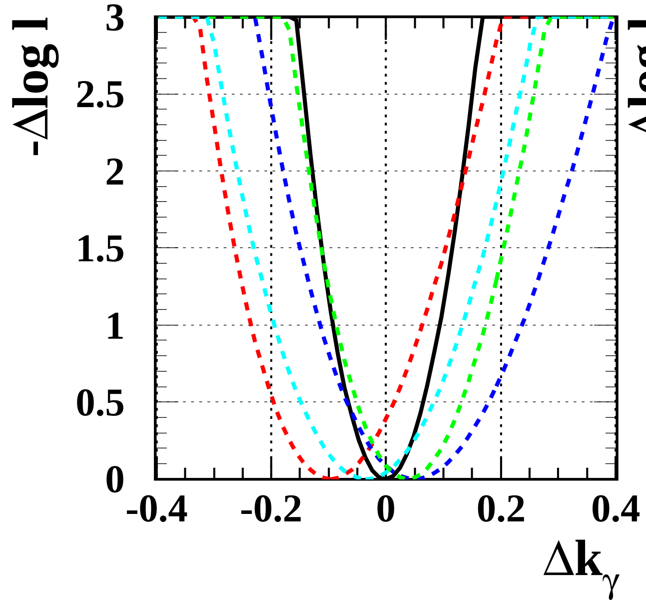

OSAKA ICHEP2000 DELPHI Δg_1^Z
Preliminary
4 jets
single W
semileptonic
combined
$-\Delta \log l$
3
2.5
2
1.5
1
0.5
0
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
Δg_1^Z

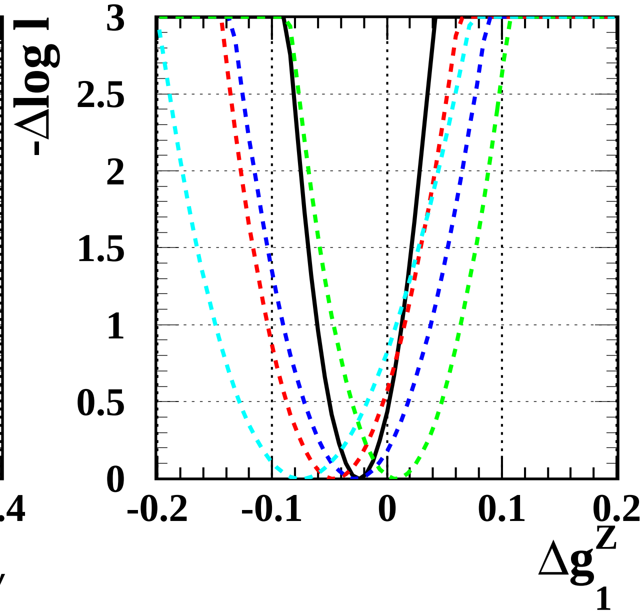


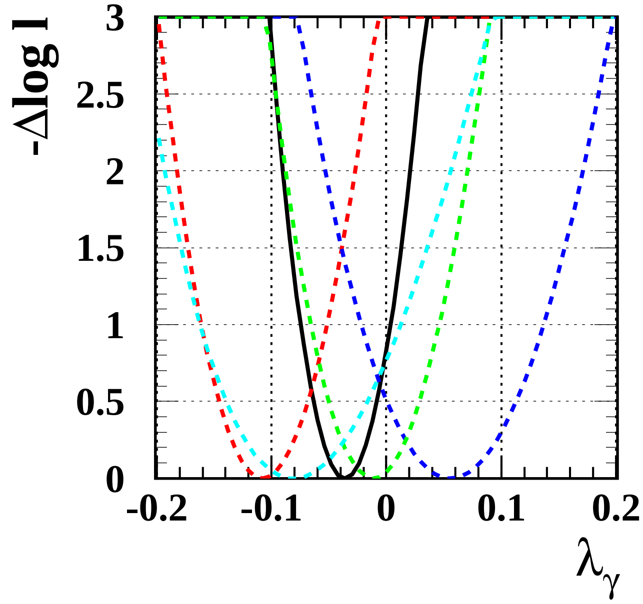
OSAKA ICHEP2000 DELPHI λ_γ
Preliminary
4 jets
semileptonic
single W
combined
$-\Delta \log l$
λ_γ
0
0.5
1
1.5
2
2.5
3
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

W^+W^- and $e\nu W$ Final States
$\sqrt{s}$ =161-202 GeV, 475 pb^{-1} per exp

ALEPH + DELPHI + L3 + OPAL







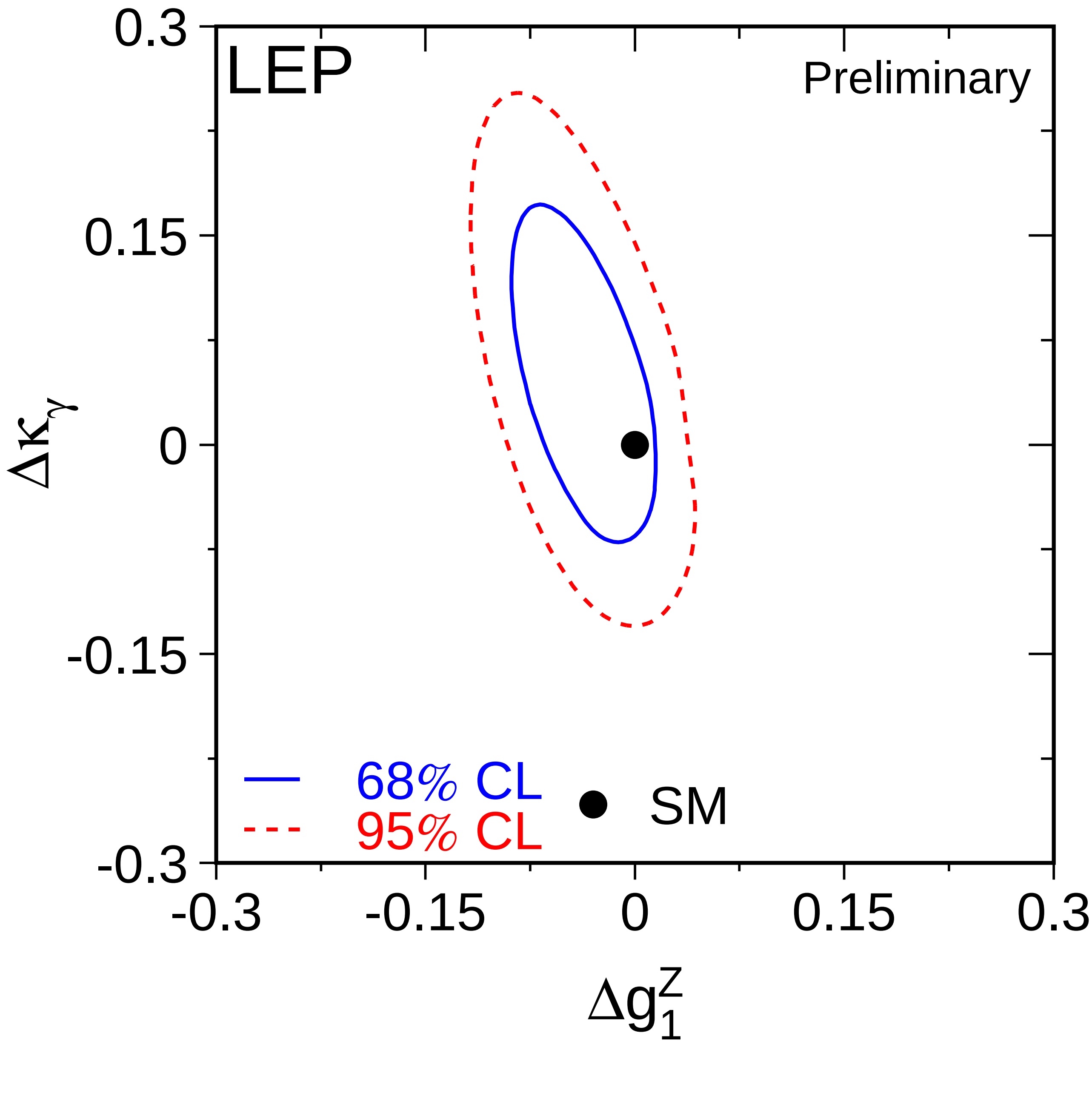
$\Delta k_\gamma = -0.002^{+0.067}_{-0.065}$

$\Delta g_1^Z = -0.025^{+0.026}_{-0.026}$

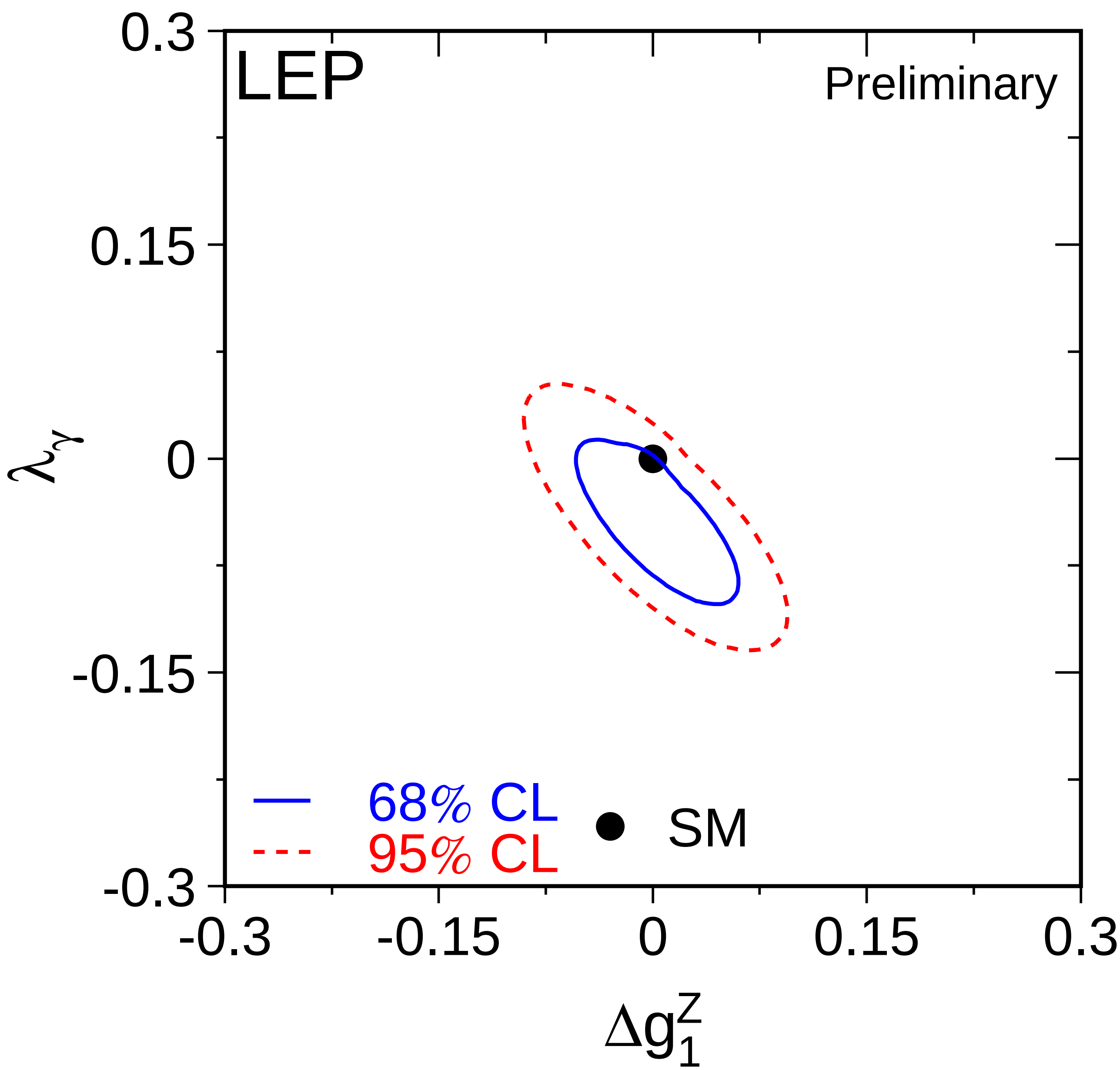
$\lambda_\gamma = -0.036^{+0.028}_{-0.027}$

Preliminary

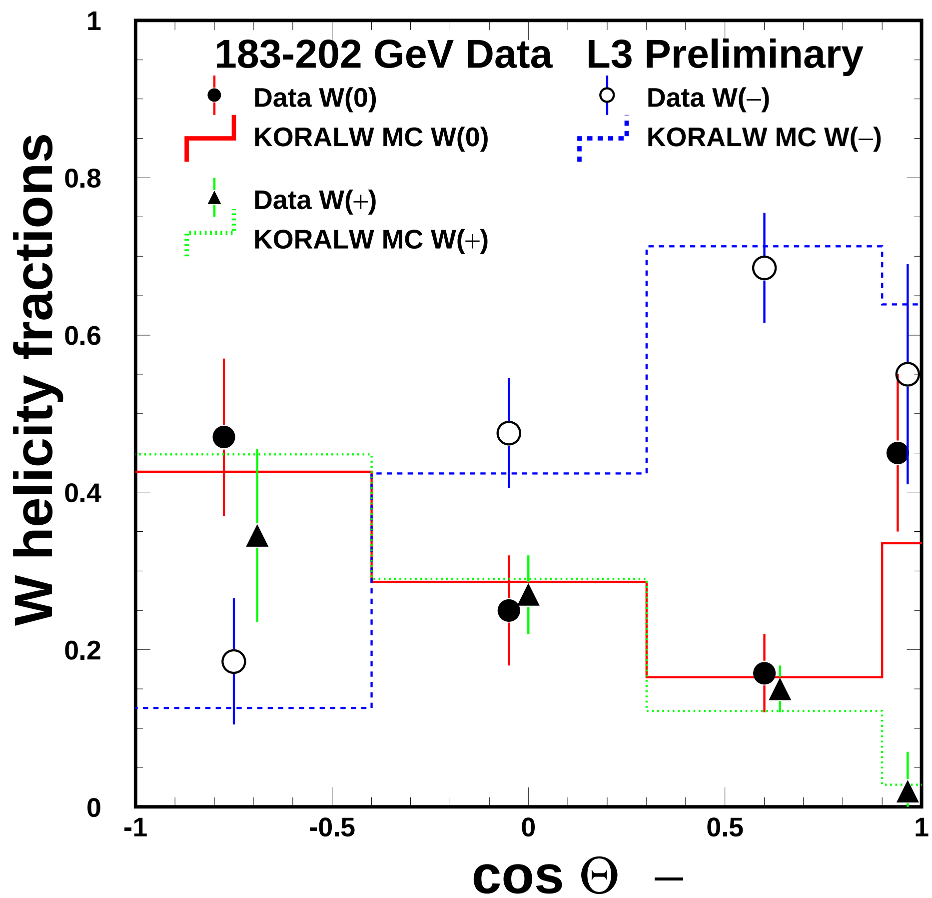
W^+W^- and $e\nu W$ Final States
$\sqrt{s}$ =161-202 GeV, 475 pb^{-1} per exp



W^+W^- and $e\nu W$ Final States
$\sqrt{s}$ =161-202 GeV, 475 pb^{-1} per exp



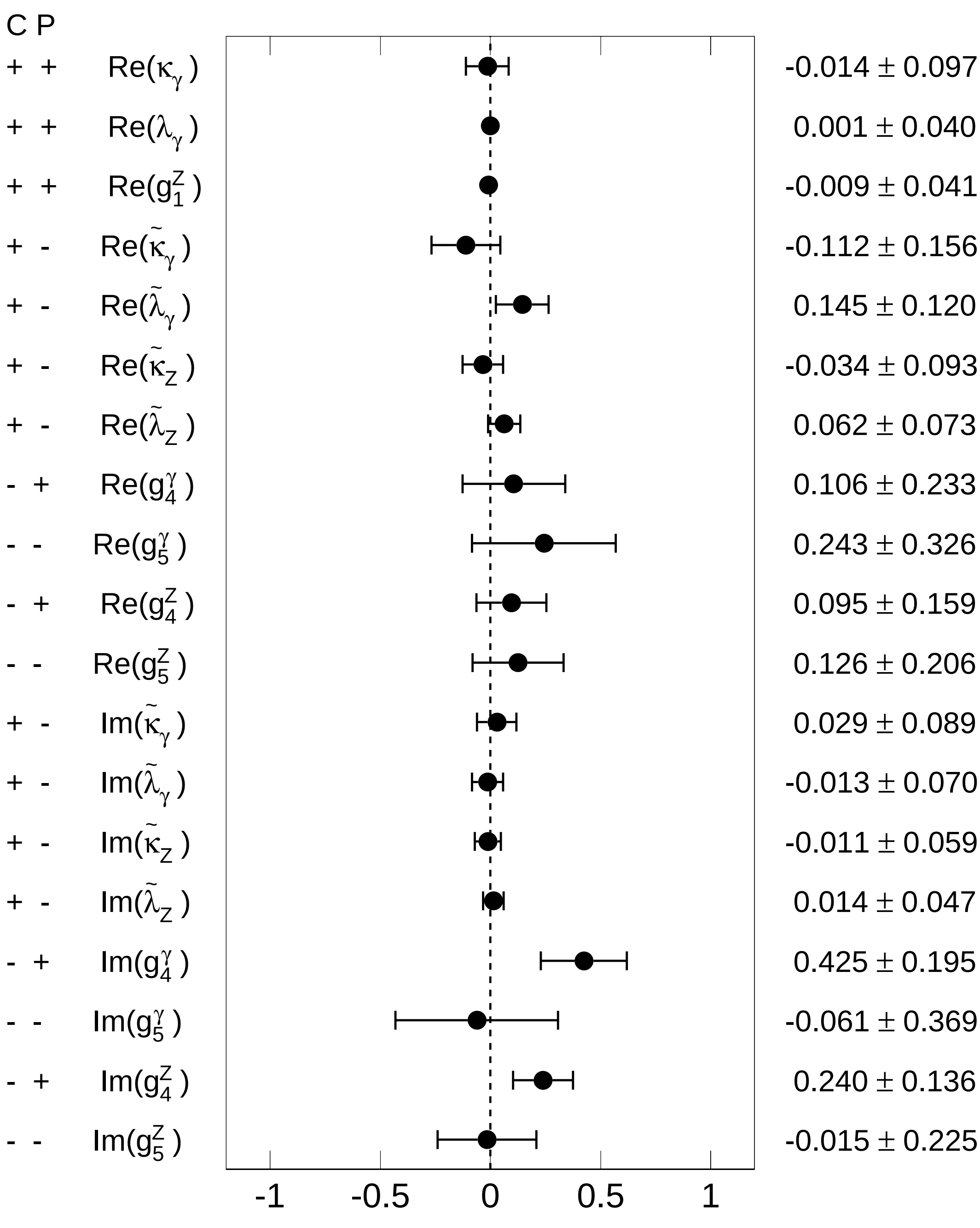
W Polarization Measurements

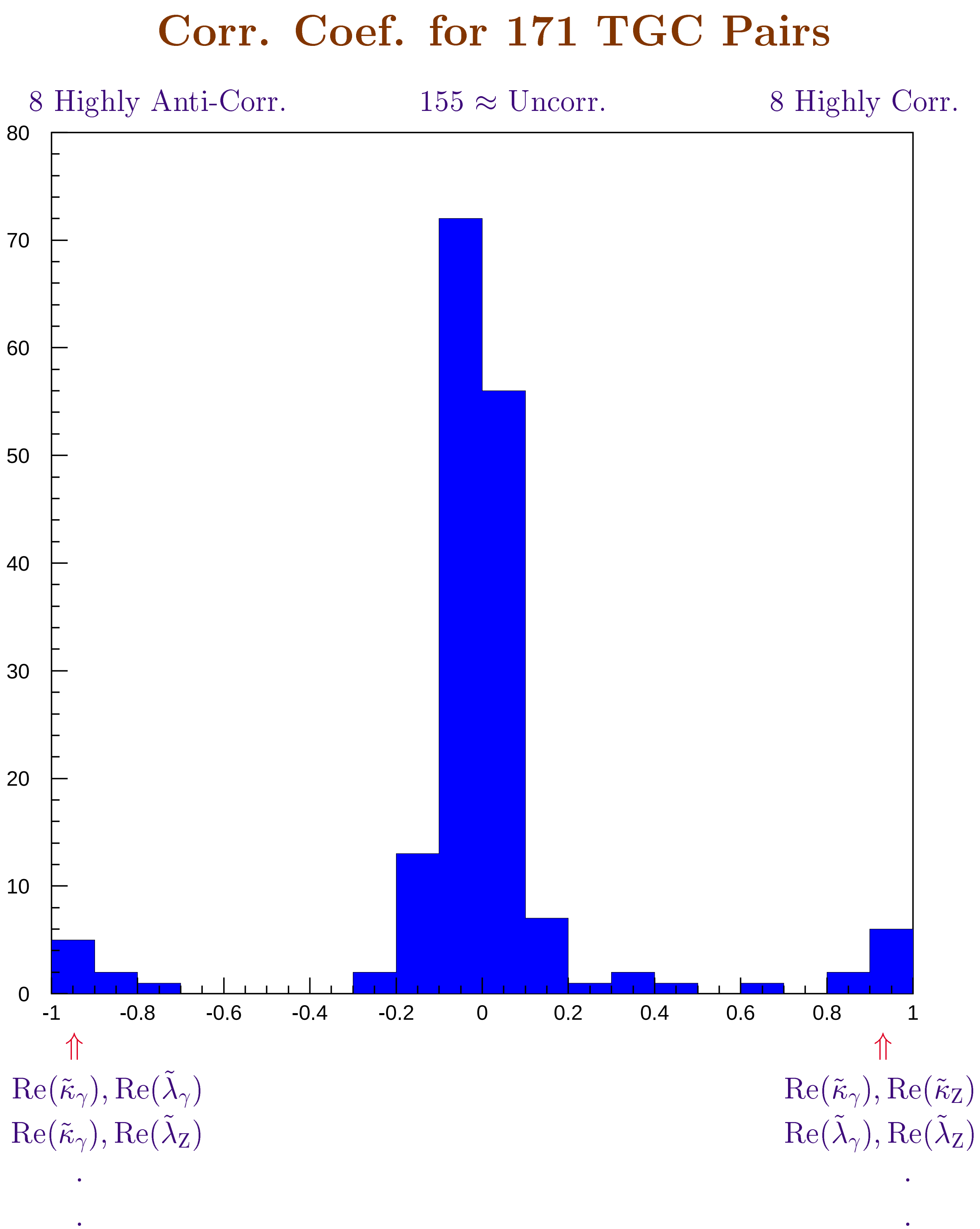


	σ_L/σ_{tot} (%)	
	Meas.	**SM**
L3	25.9 ± 3.5	**24.8**
OPAL	21.0 ± 3.6	**25.7**

ALEPH Preliminary

183-202 GeV Data (468.32 pb^{-1})





Corr. Coef. for 171 TGC Pairs
8 Highly Anti-Corr.
155 ≈ Uncorr.
8 Highly Corr.
80
70
60
50
40
30
20
10
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
⇑
⇑
$\mathrm{Re}(\tilde{\kappa}_\gamma), \mathrm{Re}(\tilde{\lambda}_\gamma)$
$\mathrm{Re}(\tilde{\kappa}_\gamma), \mathrm{Re}(\tilde{\lambda}_\mathrm{Z})$
$\mathrm{Re}(\tilde{\kappa}_\gamma), \mathrm{Re}(\tilde{\kappa}_\mathrm{Z})$
$\mathrm{Re}(\tilde{\lambda}_\gamma), \mathrm{Re}(\tilde{\lambda}_\mathrm{Z})$

W^+W^- Analysis at Future LC

- 80/0% e^-/e^+ polarization (NLC), 80/50% e^-/e^+ polarization (TESLA)
- Likelihood fit of production angle & 4 decay angles
- $e\nu q\bar{q}$ and $\mu\nu q\bar{q}$ channels only
- Solid angle $|\cos\Theta| < 0.9$
- Statistical errors only

TGC Systematics at $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500$ fb^{-1}

(From C. Burgard, LCWS Sitges 1999)

The following uncertainties produce TGC biases of $\mathcal{O}$(stat. error) :

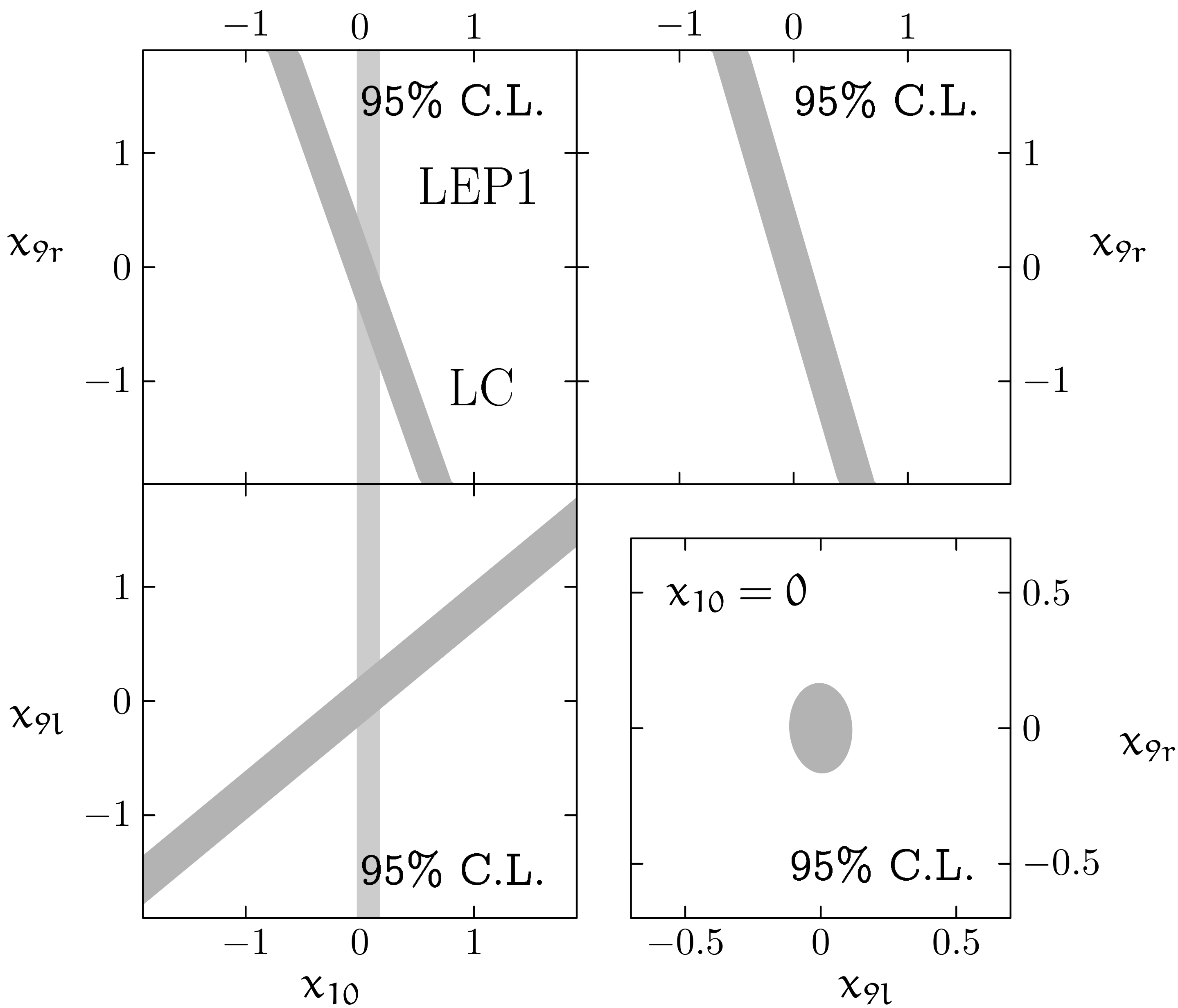
1% Uncertainty in Detector Resolution

1% Uncertainty in ISR

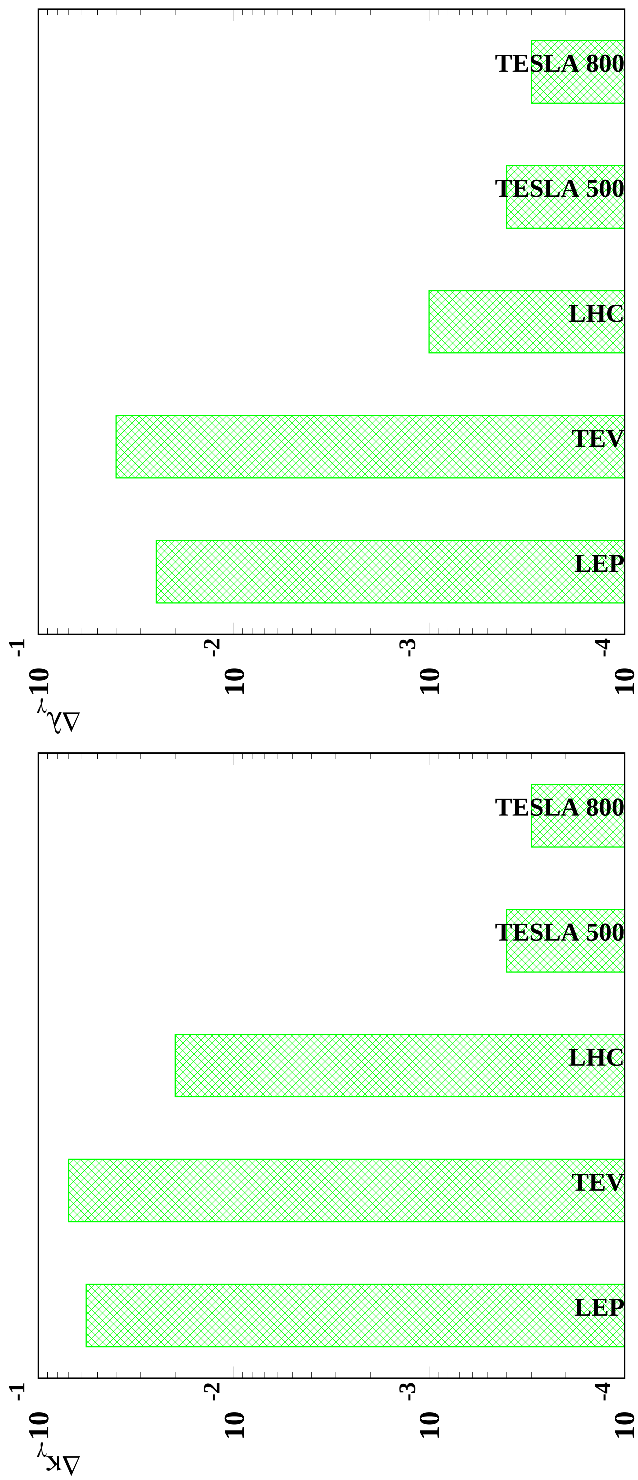
10% Uncertainty in Beamstrahlung Spectrum

$\Longrightarrow$ Systematics Are Controllable

Future e^+e^- LC
$\sqrt{s}$ =500 GeV, $\mathcal{L}$=300 fb^{-1}



New physics ⇒ $x_{9L}, x_{9R} \sim \mathcal{O}(1)$



$\Delta\lambda_\gamma$
$\Delta\kappa_\gamma$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LEP
TEV
LHC
TESLA 500
TESLA 800

The process $e^+e^- \rightarrow W^+W^-$is affected in two ways as $M_H \rightarrow \infty$

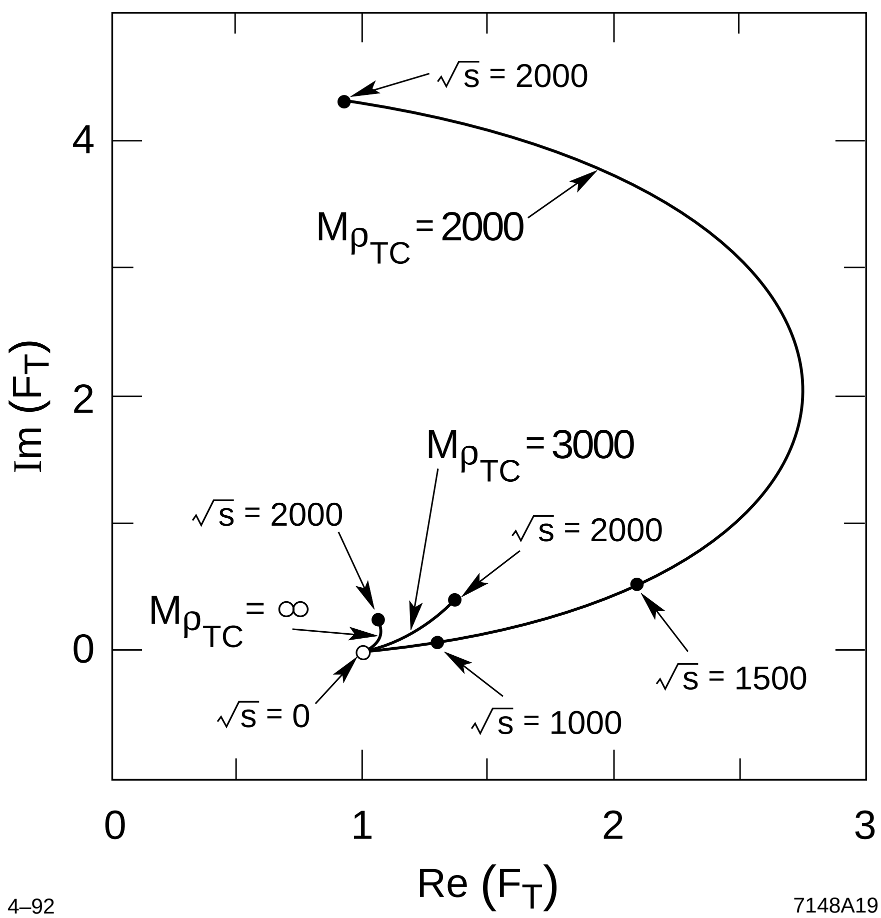
1. **Non-SM TGC's induced**

2. **$e^+e^- \rightarrow W_L^+W_L^-$ amplitude modified**

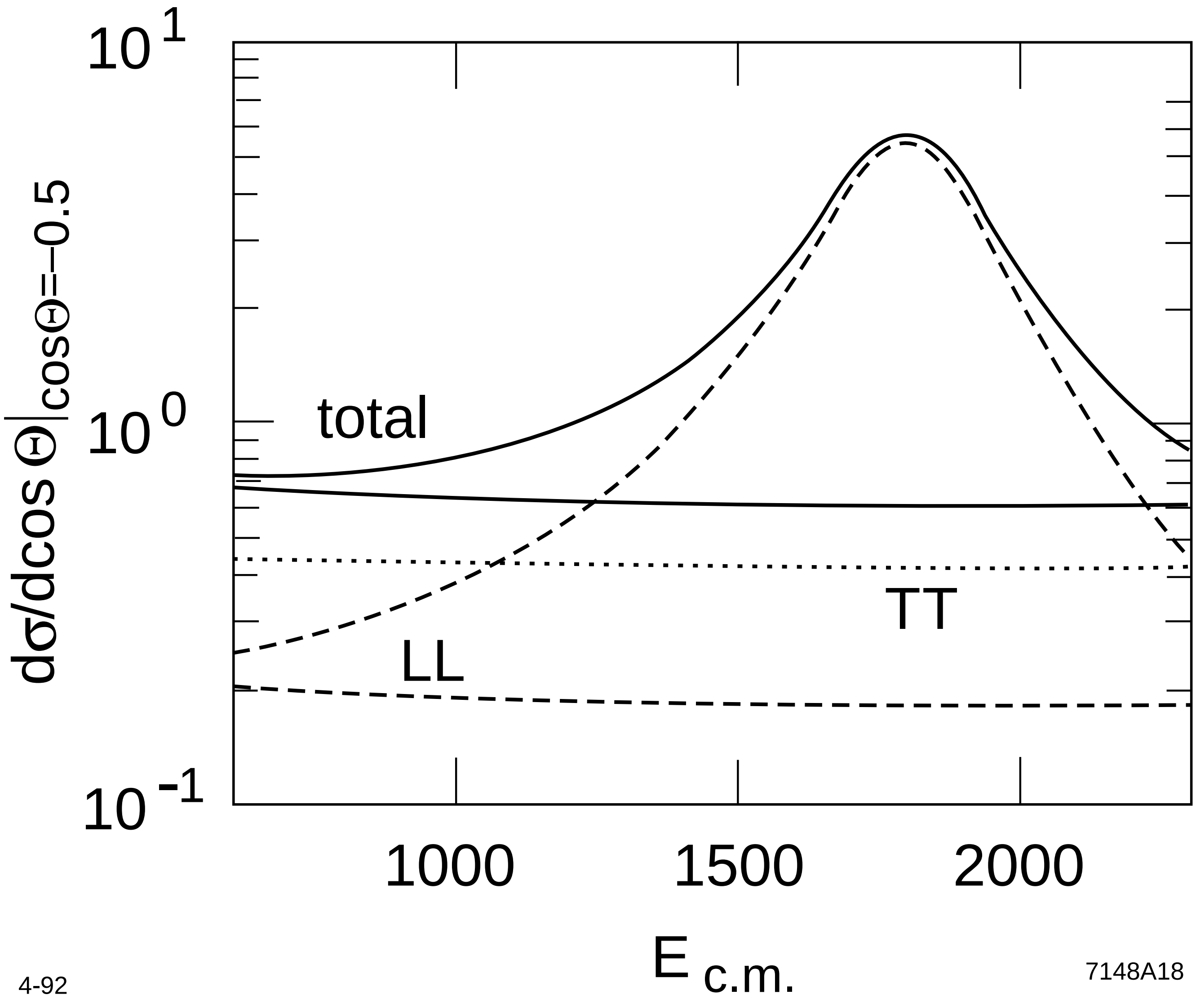
$e^+e^- \rightarrow W_L^+W_L^-$ Amplitude

$$F_T = \exp[\frac{1}{\pi}\int_0^\infty ds'\delta(s', M_\rho, \Gamma_\rho)\{\frac{1}{s'-s-i\epsilon} - \frac{1}{s'}\}]$$

$$\delta(s) = \frac{1}{96\pi}\frac{s}{v^2} + \frac{3\pi}{8}\left[tanh(\frac{s-M_\rho^2}{M_\rho\Gamma_\rho}) + 1\right]$$



$e^+e^- \to W^+W^-$ Cross-section in the Presence of 1.8 TeV Technirho



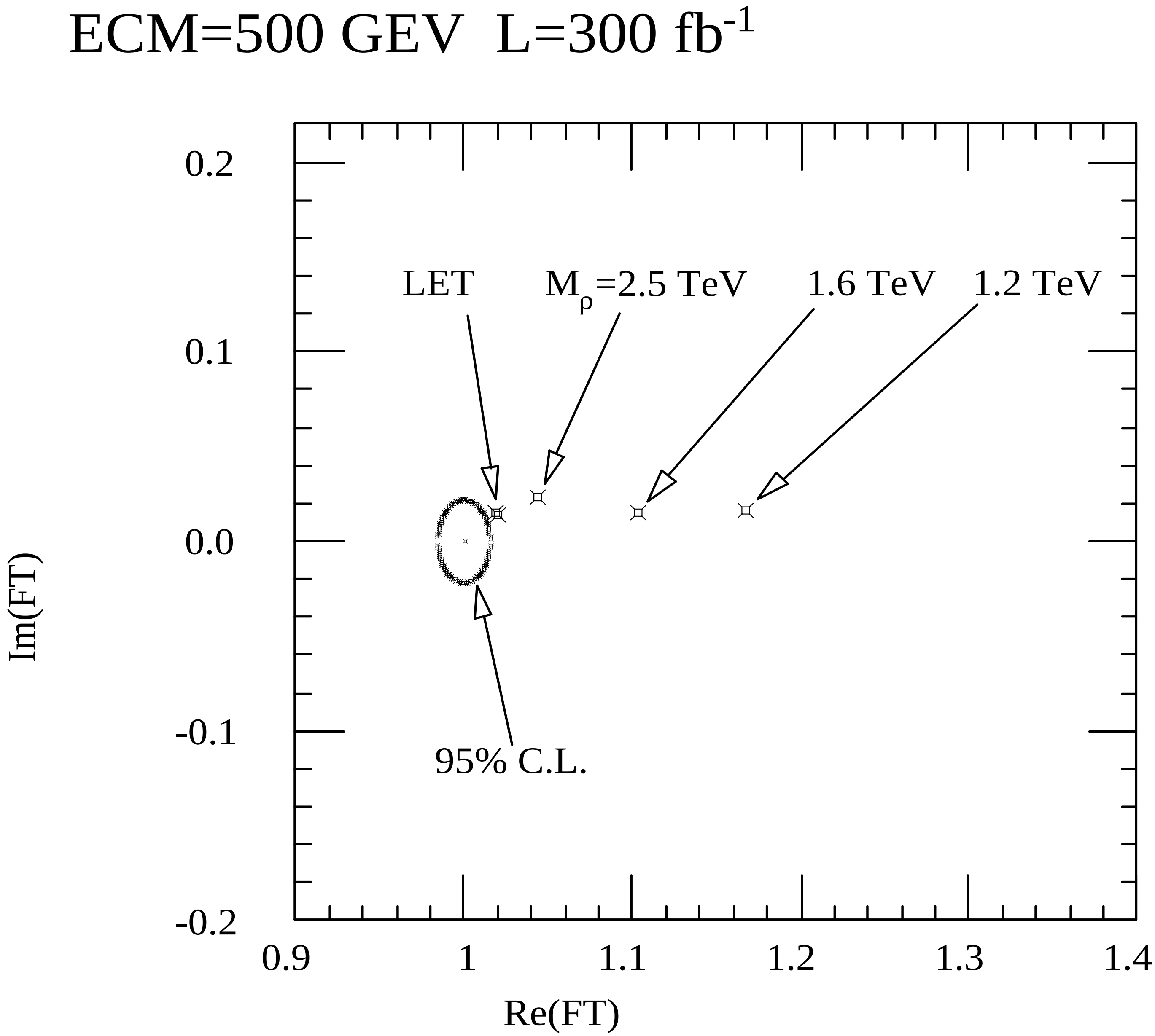
vector resonance widths (same as ATLAS TDR):

M_ρ (TeV)	Γ_ρ (TeV)
1.234	0.104
1.600	0.224
2.500	0.844

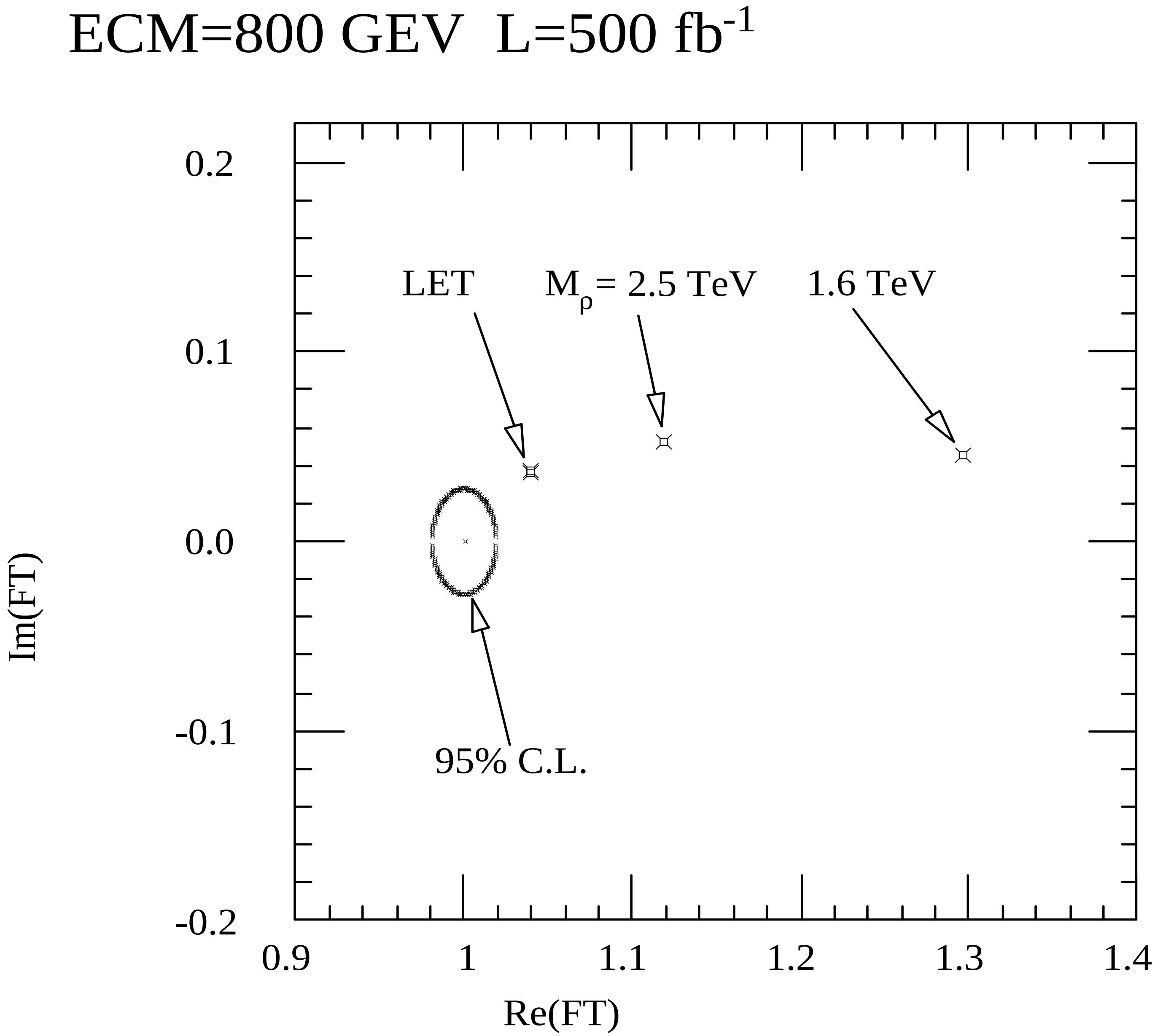
unitarization scheme:

$$\delta(s) = \begin{cases} \frac{s}{96\pi v^2} \text{ if } s < s^0 \\ \\ \frac{s^0}{96\pi v^2} \text{ if } s \geq s^0 \end{cases}$$

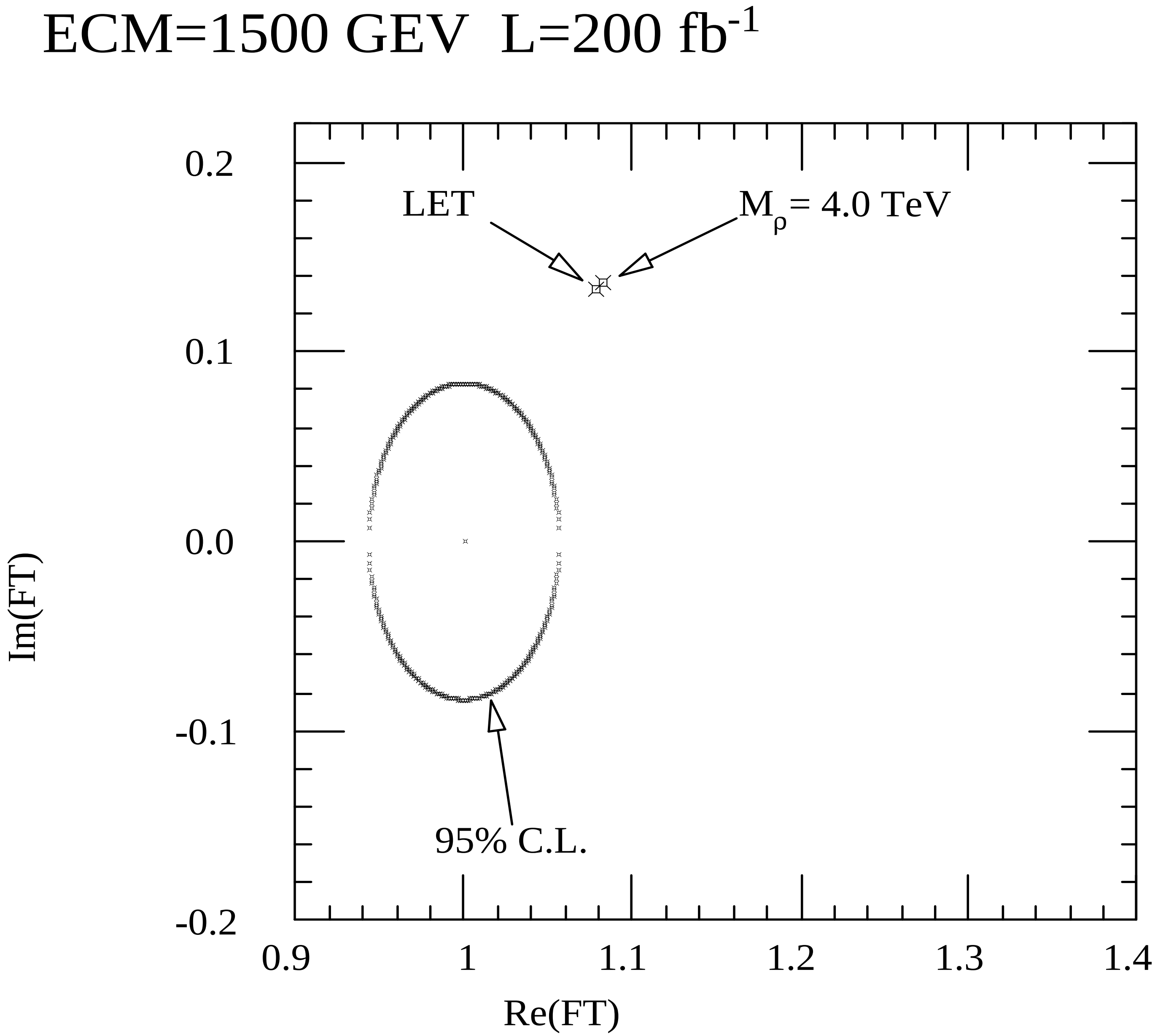
where $s^0 = (2.8 \text{ TeV})^2$.



ECM=500 GEV L=300 fb-1
LET
Mρ=2.5 TeV
1.6 TeV
1.2 TeV
95% C.L.
0.2
0.1
0.0
-0.1
-0.2
0.9
1
1.1
1.2
1.3
1.4
Re(FT)
Im(FT)



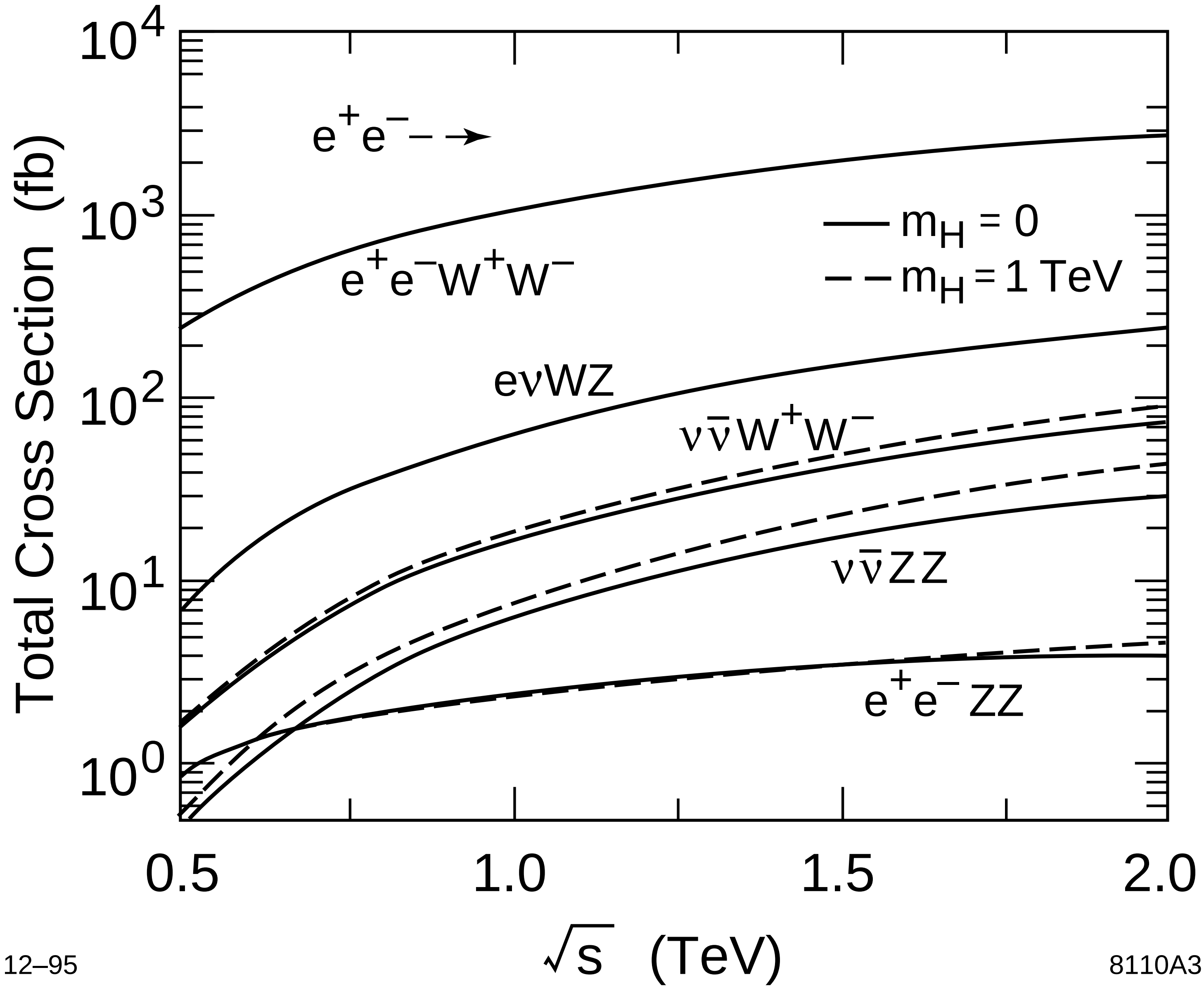
ECM=800 GEV L=500 fb-1
LET
Mρ= 2.5 TeV
1.6 TeV
95% C.L.
0.2
0.1
0.0
-0.1
-0.2
0.9
1
1.1
1.2
1.3
1.4
Im(FT)
Re(FT)


ECM=1500 GEV L=200 fb-1
LET
Mρ = 4.0 TeV
95% C.L.
0.2
0.1
0.0
-0.1
-0.2
0.9
1
1.1
1.2
1.3
1.4
Im(FT)
Re(FT)

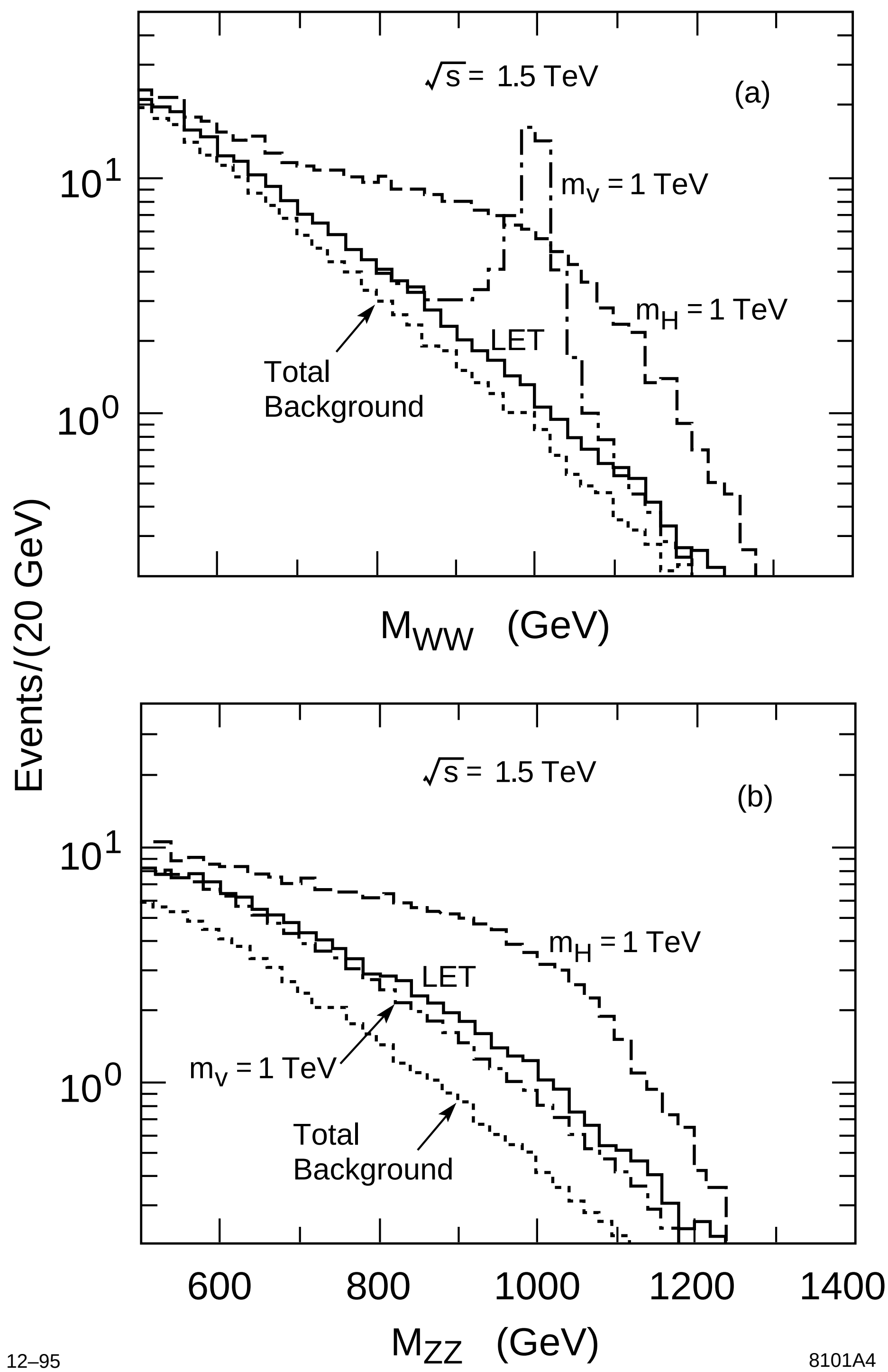
LC / LHC Comparison

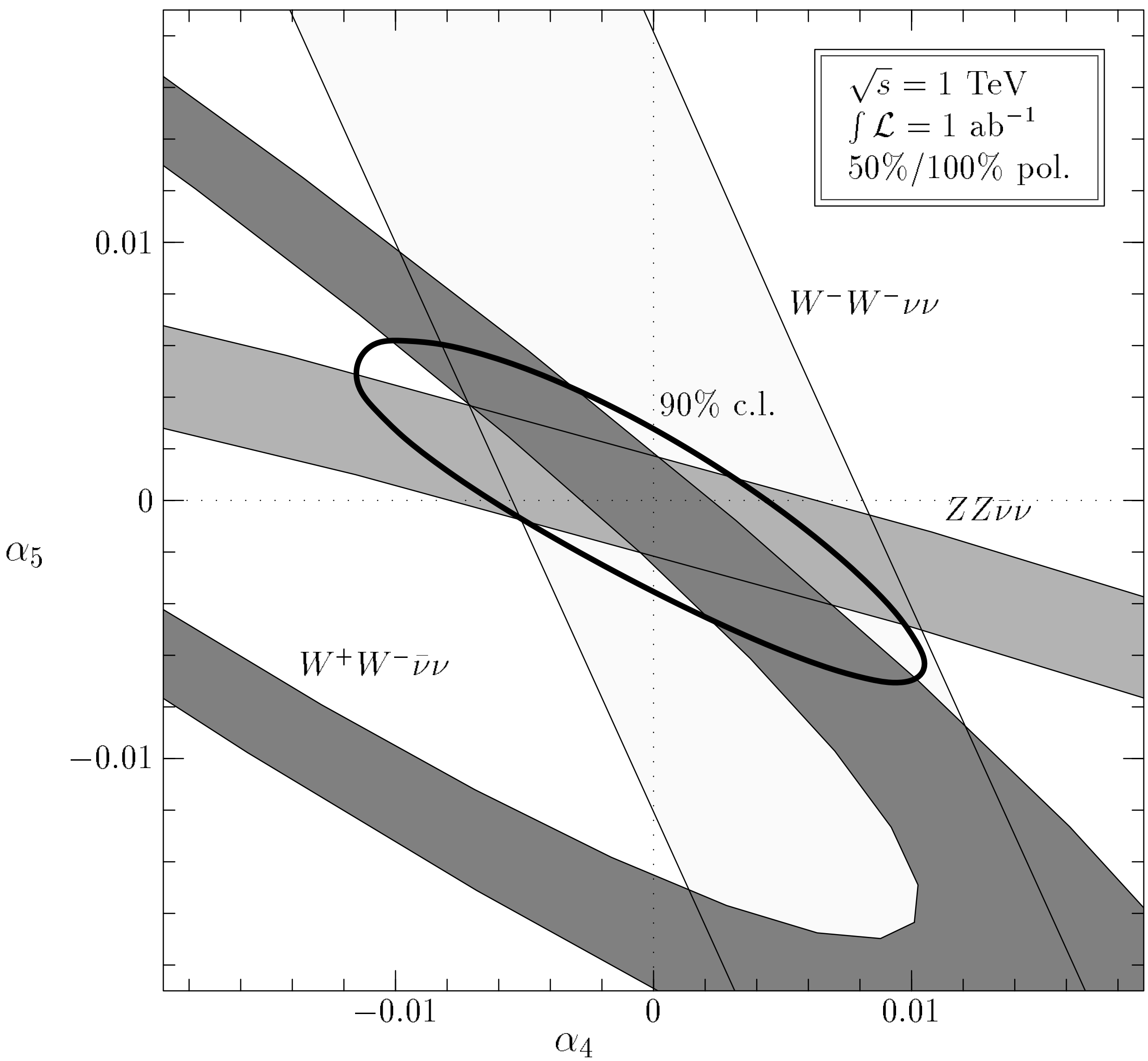
	Final State	$\sqrt{s}$ TeV	$\mathcal{L}$ fb^{-1}	$M_\rho =$ 1.2 TeV	$M_\rho =$ 1.6 TeV	$M_\rho =$ 2.5 TeV	LET
TESLA	W^+W^-	0.5	300	27σ	16σ	7σ	3σ
TESLA	W^+W^-	0.8	500	73σ	38σ	16σ	6σ
NLC	W^+W^-	1.5	200	114σ	204σ	24σ	5σ
LHC	qqW^+Z	14	100	8σ	6σ	–	–
LHC	qqW^+W^+	14	100	1σ	1σ	–	5σ

$e^+e^- \to \cdots$ Before Cuts



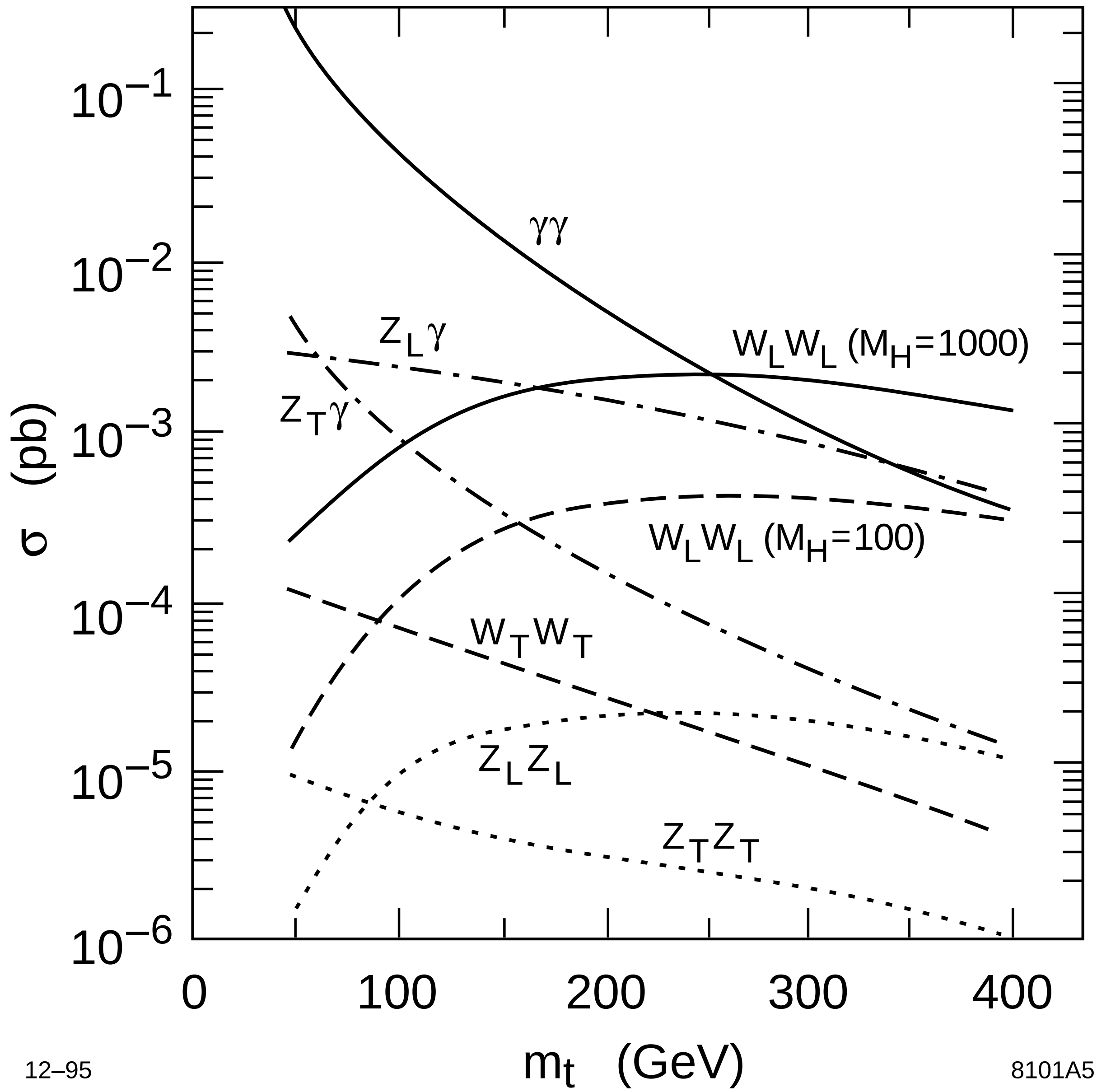
$e^+e^- \to \nu\nu W^+W^-,\ \nu\nu ZZ$ After Cuts



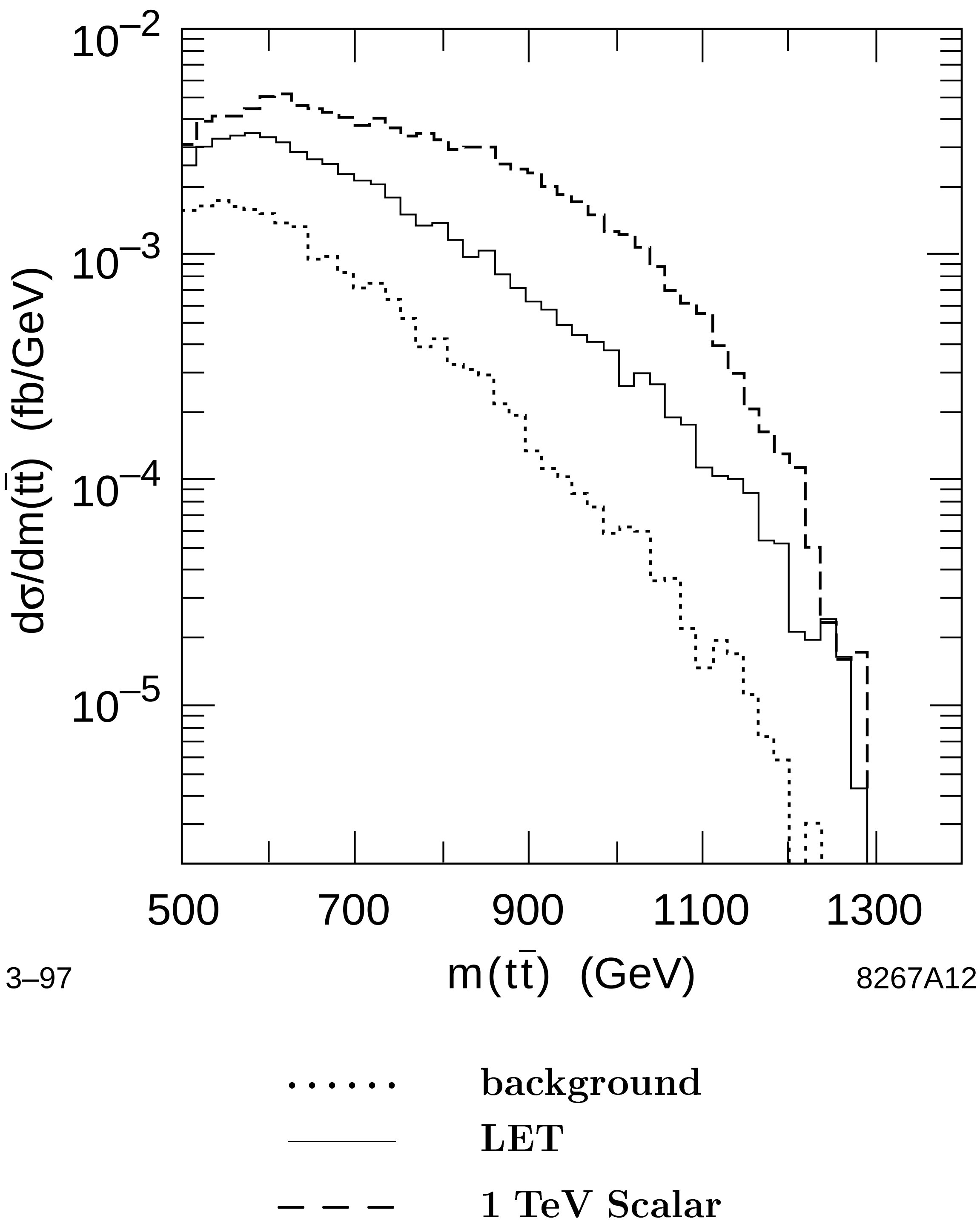


α_4, α_5 are chiral lagrangian params
corresponds to $\approx$ 5σ LET signal

$e^+e^- \to \nu\nu t\bar{t}$, ... , Before Cuts



$e^+e^- \to \nu\nu t\bar{t}$ After Cuts



Summary

LEP2 TGC sens. $\rightarrow \mathcal{O}(\text{few} \times 10^{-2})$

Future e^+e^- LC TGC sens. $\rightarrow \mathcal{O}(\text{few} \times 10^{-4})$

Studies of Strong EWSB Enhanced Considerably by e^+e^- LC with $\sqrt{s} = 500$ — 1000 GeV:

- Backgrounds to $W^+W^- \rightarrow W^+W^-, ZZ$ limited to electroweak processes
- Unique access to $W^+W^- \rightarrow t\bar{t}$.
- Powerful probe of I=J=1 W^+W^- scattering channel
- If far from resonances, high $\mathcal{L}$ @ 1 TeV may be as good or better than avg. $\mathcal{L}$ @ 1.5 TeV