ElectroWeak Symmetry Breaking (assuming that ALEPH is wrong . . .)

↳ "Alternative" Chapter of TDR

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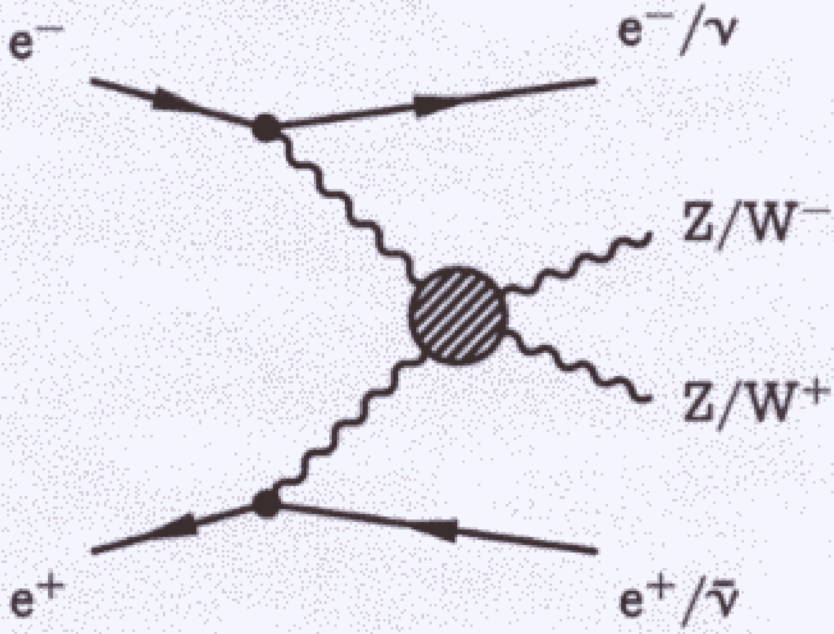


- Cross sections for $e^+e^- \to VVf\bar{f}$ around 1 TeV are typically $\mathcal{O}(1\,\text{fb})$

∴ with $\mathcal{L} \approx 1000\,\text{fb}^{-1}$, there will typically be $\mathcal{O}(1000)$ events per channel (before branching ratios, efficiency and event selection)

- NB: the LHC expects $\mathcal{O}(100)$ observed events per channel

∴ … if there was a competition, there would be a little breathing room, but not much …

$\boxed{\rho \approx 1}$ $T \approx 0,\ \epsilon_1 \approx 0$

- SU(2)$_c$-**invariant** dimension-4 interactions (other than the gauge interaction)

$\alpha_i = \left(\frac{v}{\Lambda}\right)^2$

Gauge bosons

$$\mathcal{L}_4 = \alpha_4\, \mathrm{tr}\,[V_\mu V_\nu]\, \mathrm{tr}\,[V^\mu V^\nu]$$
$$\mathcal{L}_5 = \alpha_5\, \mathrm{tr}\,[V_\mu V^\mu]\, \mathrm{tr}\,[V_\nu V^\nu]\,,$$

$v = 246\,\mathrm{GeV}$

- SU(2)$_c$-**violating** dimension-4 interactions are

naturally $\Lambda \approx 4\pi v \Rightarrow \alpha \approx \frac{1}{16\pi^2}$

Flavor physics

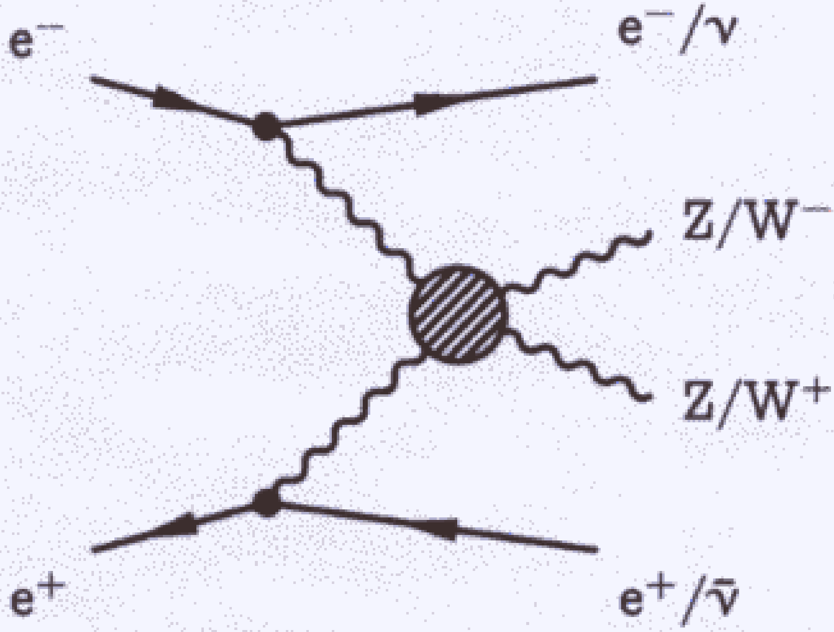
$$\mathcal{L}_6 = \alpha_6\, \mathrm{tr}\,[V_\mu V_\nu]\, \mathrm{tr}\,[\sigma_3 V^\mu]\, \mathrm{tr}\,[\sigma_3 V^\nu]$$
$$\mathcal{L}_7 = \alpha_7\, \mathrm{tr}\,[V_\mu V^\mu]\, \mathrm{tr}\,[\sigma_3 V_\nu]\, \mathrm{tr}\,[\sigma_3 V^\nu]$$
$$\mathcal{L}_{10} = \alpha_{10}\, \mathrm{tr}\,[\sigma_3 V_\mu]\, \mathrm{tr}\,[\sigma_3 V_\nu]\, \mathrm{tr}\,[\sigma_3 V^\mu]\, \mathrm{tr}\,[\sigma_3 V^\nu]\,.$$

SU(2)$_c$-**invariant** four gauge boson vertices

$$\mathcal{L}_4 = \alpha_4 \left[\frac{g^4}{2}\left((W^+_\mu W^{-,\mu})^2 + W^+_\mu W^{+,\mu} W^-_\mu W^{-,\mu}\right) + \frac{g^4}{\cos^2\theta_w} W^+_\mu Z^\mu W^-_\nu Z^\nu + \frac{g^4}{4\cos^4\theta_w}(Z_\mu Z^\mu)^2\right.$$

$$\mathcal{L}_5 = \alpha_5 \left[g^4 (W^+_\mu W^{-,\mu})^2 + \frac{g^4}{\cos^2\theta_w} W^+_\mu W^{-,\mu} Z_\nu Z^\nu + \frac{g^4}{4\cos^4\theta_w}(Z_\mu Z^\mu)^2\right]$$

comprehensive study (including $SU(2)_c$-violating interactions) of



by E. Boos, H. J. He, W. Kilian, A. Pukhov, C. P. Yuan and P. M. Zerwas in 1998 (high energy) & 2000 (high luminosity).

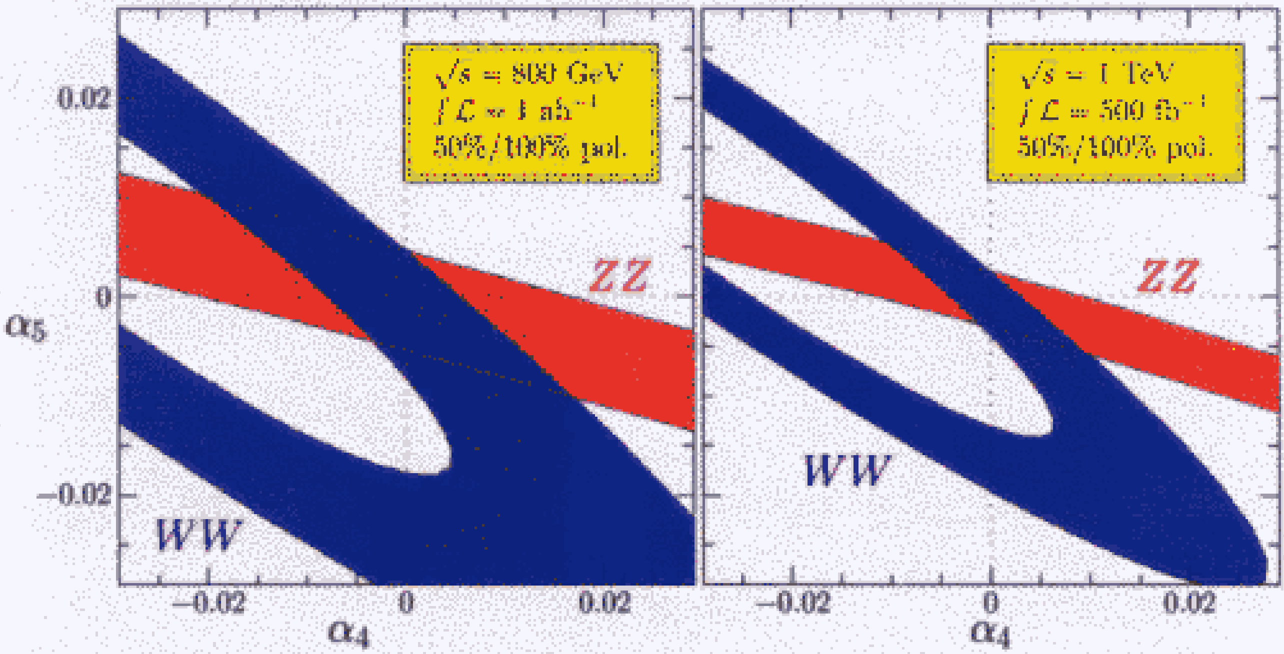
- both high luminosity ($1000\,\text{fb}^{-1}$ at $800\,\text{GeV}$) and high energy ($1.6\,\text{TeV}$) will probe the couplings at their natural size $1/(16\pi^2)$

Shortcomings (not the author's fault, reflects calculational state of the art at the time):

- no irreducible backgrounds for W and Z decays
- W and Z not polarized, decay distributions incorrect

WW scattering

Sensitivity estimate from simulation of $e^+e^- \to \bar{\nu}\nu W^+W^-$ and ZZ (including backgrounds), two-parameter fit:



800 GeV,	$1000\ \mathrm{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.015$	$\to \Lambda > 2$ TeV
1 TeV,	$500\ \mathrm{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.009$	$\to \Lambda > 2.5$ TeV
LHC,	$100\ \mathrm{fb}^{-1}$:	$\lvert\Delta\alpha_5\rvert < 0.025$	$\to \Lambda > 1.5$ TeV

LC at 500 GeV, $100\ \mathrm{fb}^{-1}$: [S. Rosati → EW Session]

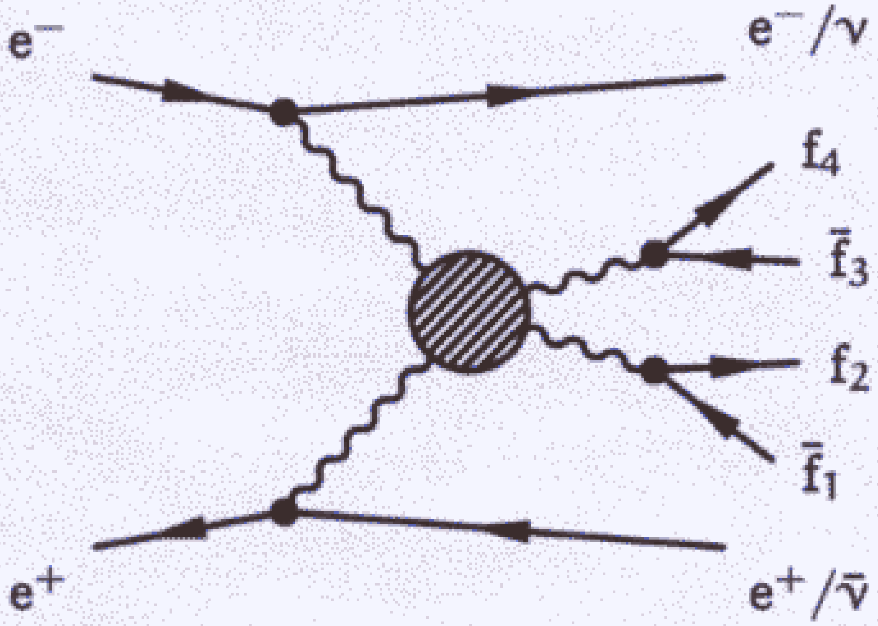
$-0.43 < \alpha_4 < 0.43$ $\quad -0.40 < \alpha_5 < 0.24$ (95%)

WWZ/ZZZ: [Han/He/Yuan]

500 GeV, $50\ \mathrm{fb}^{-1}$: $\lvert\Delta\alpha_5\rvert < 0.2$

New Calculations

The "real" physics process



can be simulated including all irreducible backgrounds thanks to recently matured tools:

- WHIZARD: phase space generation and a unweighted event generation (Wolfgang Kilian)
- O'Mega: fast factorized matrix element calculation (SM and extensions) (Mauro Moretti, T. O., et al)
- VAMP: adaptive multi channel sampling (T. O.)

Currently only $SU(2)_c$-conserving interactions are included in the analysis

- only a problem of limited resources ...

$ZZ\nu\nu$ signal and backgrounds

For each process, all diagrams, including interference, are generated.

$ZZ\nu\nu \to qqqq\nu\nu$ (SIGNAL) BR=49%	Signal definition: cut on di-quark masses $170<M_1+M_2<195$ and $\|M_1-M_2\|<20$ GeV Whizard + Jetset hadronization (σ =3.7 fb)
$qqqq\nu\nu$ background	$WW\nu\nu$ and other non-resonant diagrams Whizard+Jetset (σ =12.9 fb)
Other 6-fermion backgnd. $WZe\nu$, WWee,ZZee and non resonant $qqqqe\nu$, qqqqee	Whizard + Jetset hadronization (σ=32, 492, 2 fb)
4-fermion (WW,ZZ + ISR)	Pythia (σ = 5280 fb)
$t\bar{t}$	Pythia (σ =346 fb)

Detector

Optimal mass resolution and forward coverage (P_t, Emis, forward leptons ID)

- Detector simulation with SIMDET V3.1

SETUP

- Tracking: CCD 2cm+FT+TPC, $|\vec{B}|$=3T.
- TPC acceptance $\rightarrow$ 10^o, overall tracking acceptance $\rightarrow$ 5^o
- Calorimetry: EM (0.6%+10%/$\sqrt{E}$ resolution), HAD (4%+40%/$\sqrt{E}$ resolution) acceptance $\rightarrow$ 4.6^o
- Instrumented mask in the very forward region
- Instrumentation up to 23.7 mrad in SIMDET$\rightarrow$(important for WWee,WZeν background)

$ZZ\nu\nu$ selection

Preselection cuts

200<E_{mis}<650 GeV E_{track}^{max}<200 GeV

$|\cos(\theta_{pmis})|$<0.99 $|\cos(\theta_{Emax})|$<0.99

- Cut the event if one of the four most energetic charged tracks is isolated (less then 2 GeV in a 10 degrees cone). Effective against $t\bar{t} \to b\bar{b}l\nu l\nu$ background.

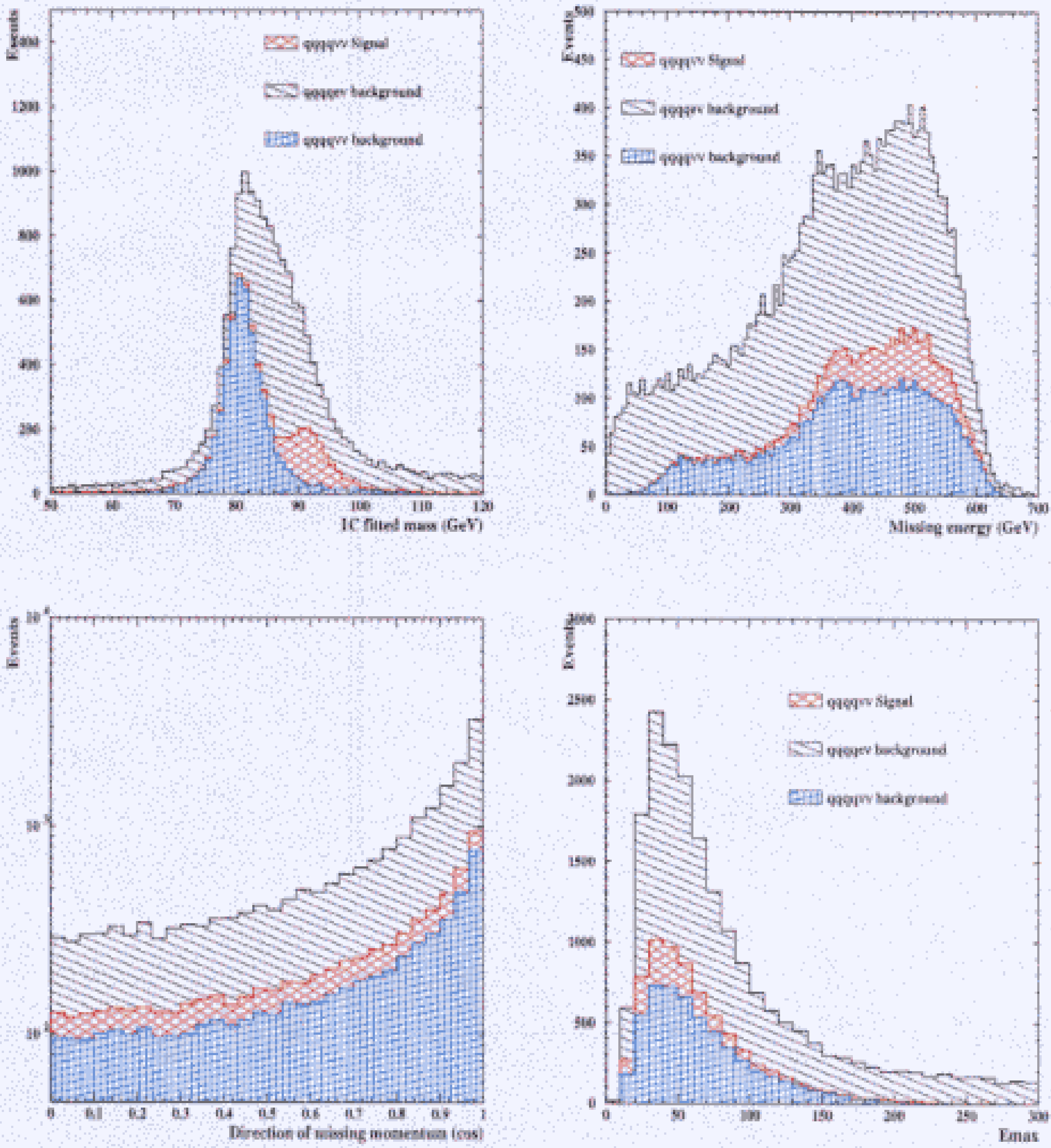
Likelihood variables

E_{mis} E_{track}^{max}

$|\cos(\theta_{Pmis})|$ $|\cos(\theta_{Emax})|$

Fitted mass   Jet pairing likelihood

Selection variables



Selection results

Expected number of events at $\sqrt{s}$ =800 GeV
1000 fb^{-1} integrated luminosity

Channel	Events	
$ZZ\nu\nu \to qqqq\nu\nu$	844±10	$\epsilon = 52.2 \pm 0.6\%$
$qqqq\nu\nu$ backgnd	88±5	
$WZe\nu$	570 ± 20	
ZZee,WWee	≃0	
$t\bar{t}$	83 ±5	
$q\bar{q}$	≃0	
4 fermion	23±10	

The purity is 52.3 %

→ this results in $\frac{\Delta\sigma}{\sigma}$=3.2%

$WW\nu\nu$ selection

From R.Chierici

Event treatment

The event is forced into 4 jets (if possible)

Jet pairing chosen such that $|M_{ij}-M_W|\cdot|M_{kl}-M_W|$ is minimum

Rejection of ee→2f,4f

N_{jet} (LUCLUS, d_{join}=7GeV) = 4,5

120 GeV < E_{trans} < 600 GeV

M_{recoil} > 200 GeV (also effective for irr. $WW\nu\nu$)

Rejection of small P_T events (removes e, μ, τ ...)

P_T (WW)>40 GeV

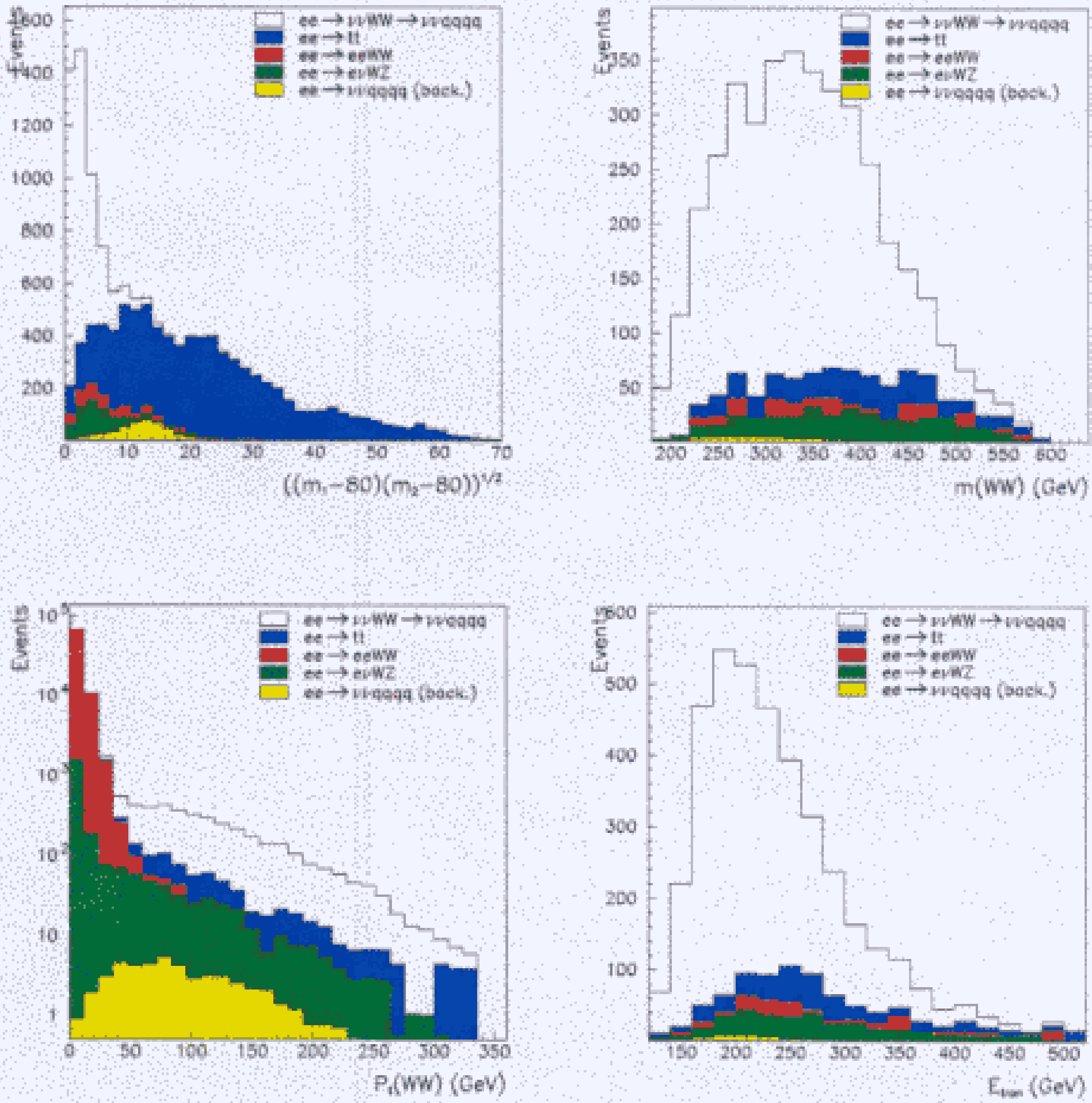
N_{ch}^{jet}(min)=3

Invariant mass (loose) cuts (very effective for $t\bar{t}$ and $ZZ\nu\nu$)

60 GeV<$M(W^+)$, $M(W^-)$<100 GeV

$|M_1-M_W|\cdot|M_2-M_W|$<50 GeV^2

AND b-TAG


Events
ee → ννWW → ννqqqq
ee → tt
ee → eeWW
ee → eνWZ
ee → ννqqqq (back.)
((m1−80)(m2−80))^1/2
m(WW) (GeV)
Pt(WW) (GeV)
Etran (GeV)

WW$\nu\nu$ selection results

Expected number of events at $\sqrt{s}$ =800 GeV
1000 fb^{-1} integrated luminosity

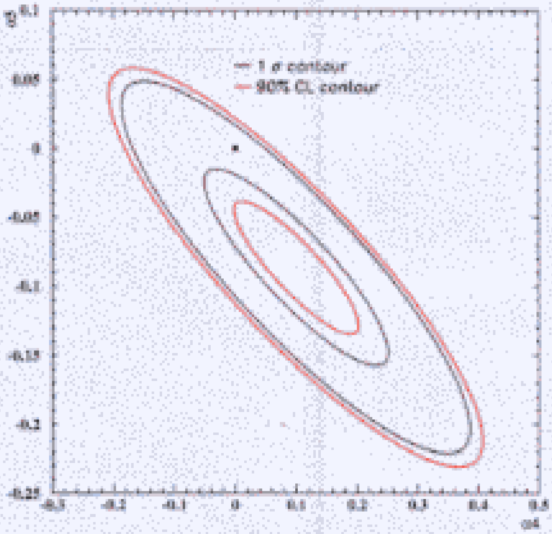
Channel	Events	
WW$\nu\nu$ $\rightarrow$qqqq$\nu\nu$	2550$\pm$30	$\epsilon = 40.1 \pm 0.4\%$
qqqq$\nu\nu$ backgnd	151$\pm$5	
WZeν	350$\pm$ 10	
WWee	130$\pm$20	
$t\bar{t}$	400$\pm$ 70	
$q\bar{q}$	$\simeq$0	
4 fermion	$\simeq$0	

$\rightarrow$ this results in $\frac{\Delta\sigma}{\sigma}$=2.0%

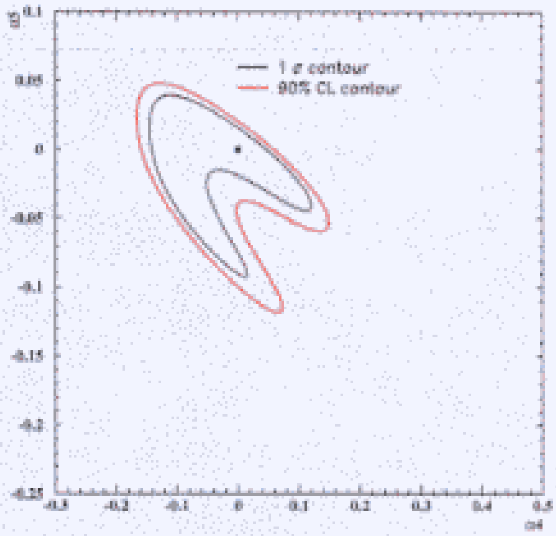
ZZ$\nu\nu$ fits

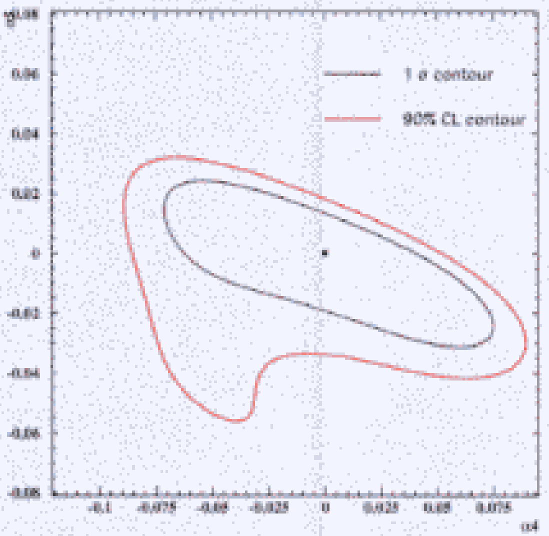
Effects of the angular distributions on the fit

EVENT RATE



EV. RATE + Z ANGLE





→ ALSO FERMION

- Roberto Chierici and Stefano Rosati: full simulation of
  + Michael Kobel

$$e^+e^- \to \nu\bar{\nu}WW \to \nu\bar{\nu}q\bar{q}q\bar{q}$$

$$e^+e^- \to \nu\bar{\nu}ZZ \to \nu\bar{\nu}q\bar{q}q\bar{q}$$

  including backgrounds and SIMDET V3.1.

$e^+e^- \to \nu\bar{\nu}W^+W^- \to 6f$:

Channel	σ/fb generated	MC	σ/fb selected
$ee \to qq$	5100.00	PY	negl.
$ee \to WW \to 4q$	2300.00	PY	negl.
$ee \to ZZ \to 4q$	168.00	PY	negl.
$ee \to tt \to 6q$	349.00	PY	0.40 ± 0.07
$ee \to eeWW \to ee4q$	198.00	GR	0.13 ± 0.02
$ee \to e\nu WZ \to e\nu 4q$	14.70	GR	0.35 ± 0.01
$ee \to \nu\nu uuss + \ldots$	0.90	WH	0.041 ± 0.001
$ee \to \nu\nu uucc + \ldots$	0.25	WH	0.017 ± 0.0004
$ee \to \nu\nu ddss + \ldots$	0.82	WH	0.043 ± 0.001
$ee \to \nu\nu udcs + \ldots$	8.34	WH	3.03 ± 0.03
dto. w/ inv. mass cuts	6.36	WH	2.55 ± 0.03

LHC & Polarization

- LHC expectation (not full simulations)

(1-d)

$$-0.0035 \le \alpha_4^{LHC} \le 0.015$$
$$-0.0072 \le \alpha_5^{LHC} \le 0.013$$

$\Lambda \approx 10 \sim 2.5$ TeV

(the asymmetrical errors are not typos)

- TESLA sans polarization (full simulations)

(1-d)

$$-0.022 \le \alpha_4 \le 0.017$$
$$-0.022 \le \alpha_5 \le 0.012$$

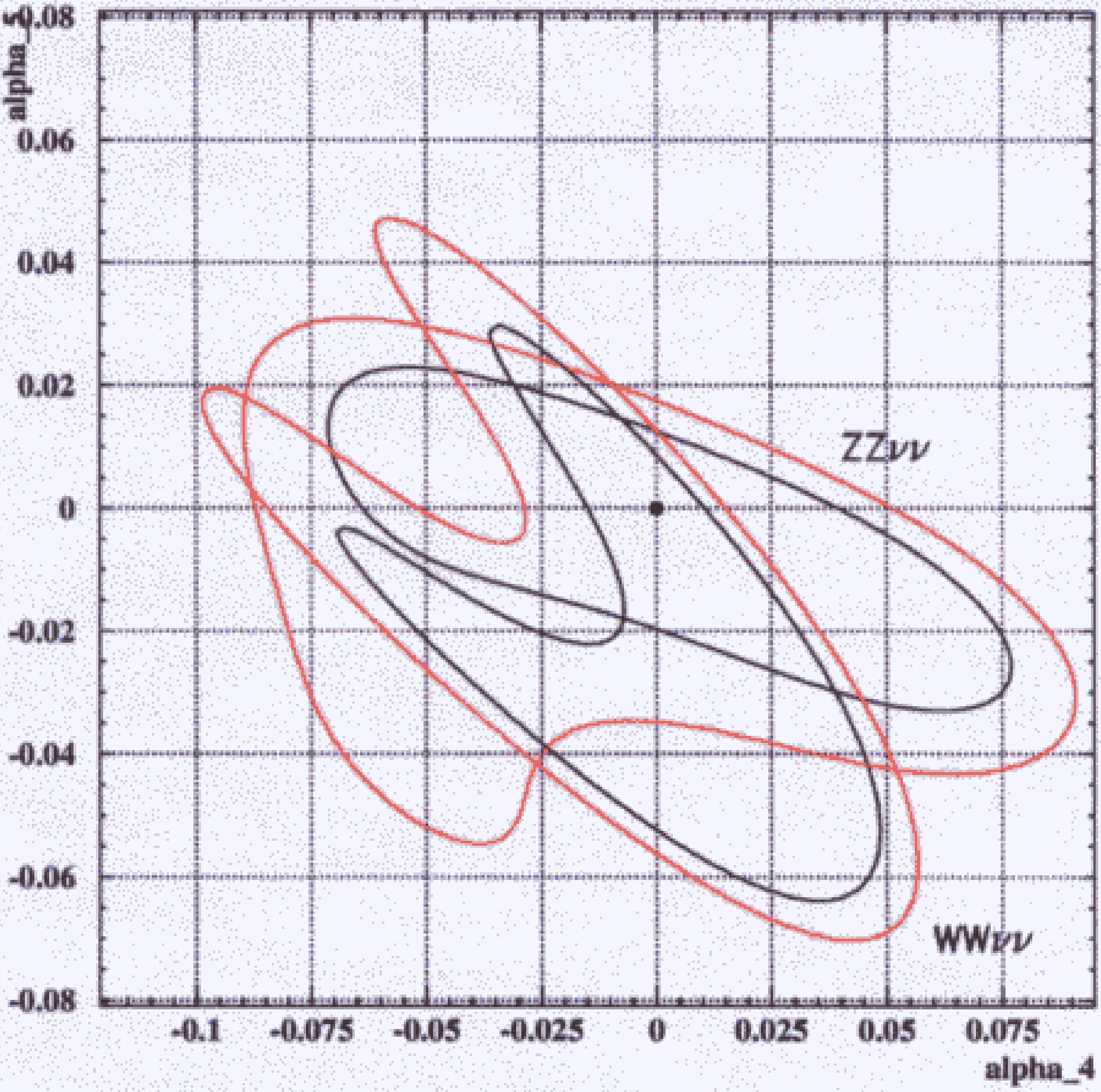
at face value, TESLA is not better than LHC

∵ whining about the LHC expectations is not an option

∴ include beam polarization in TESLA numbers

- full simulations are possible (calculations are done and avalaible as Monte Carlo, at least for the signal), but take (too much?) time (physicist's wall clock time, not computer time). add M(jjjj) to likelihood ?
- a shortcut could extrapolate using numbers from Boos etal., since beam polarization is mostly relevant for signal/background relations

α_4–α_5 Limits

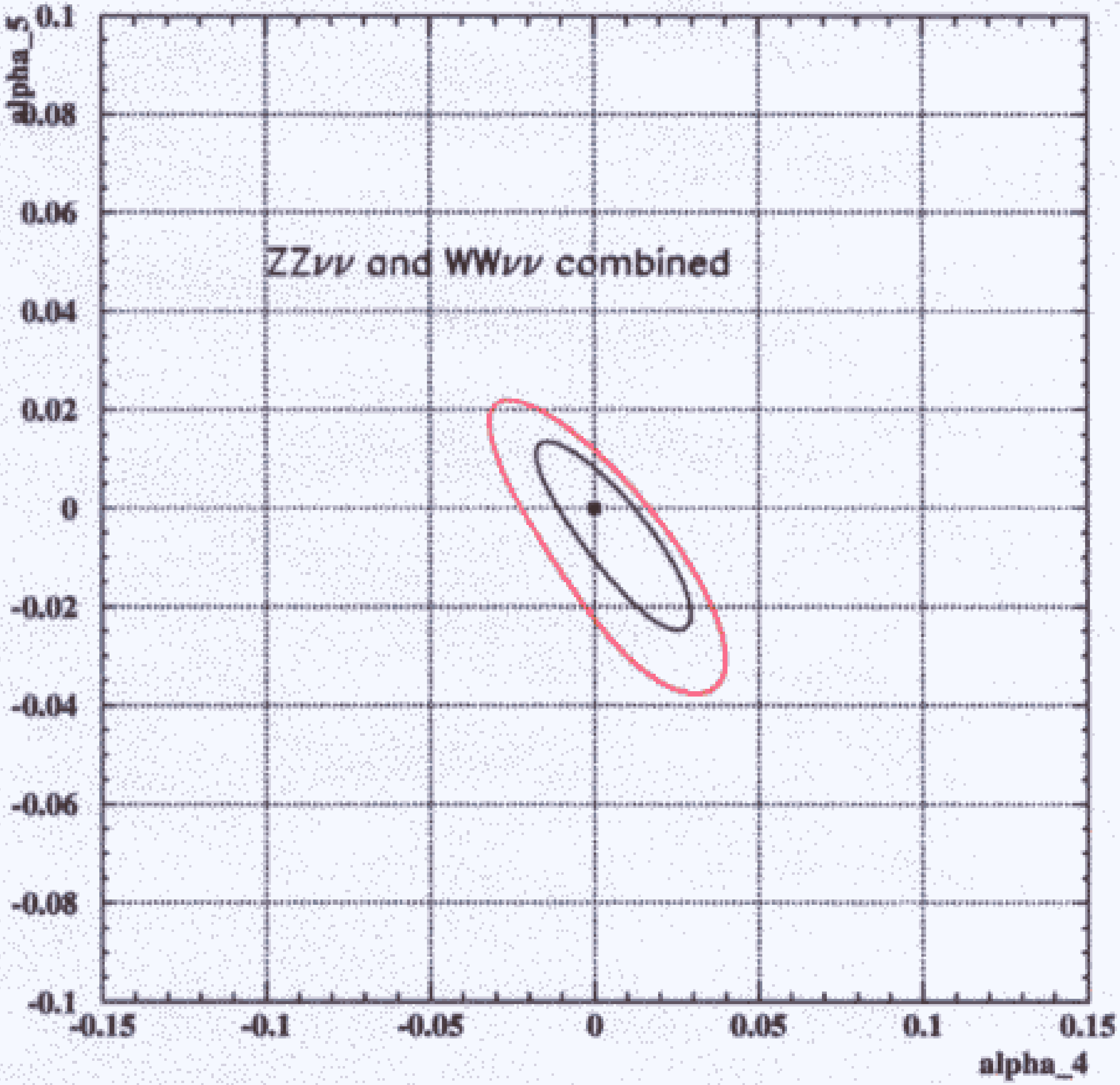


- red contour: 95% C.L.
- black contour: 1σ

Observations:

- shapes are retained w. r. t. Boos et al.
- shapes are fattened by background and full simulation
- second minimum is removed by angular dependence (production and decay, a. k. a. polarization)

α_4–α_5 Limits



- red contour: 95% C.L.
- black contour: 1σ

Conclusion:

- $e^- e^- \to W^- W^- \nu\nu$ not needed for removing the second minimum