Electroweak Interactions: Summary

Wolfgang Kilian (Karlsruhe)

LCWS 2000
Fermilab

WG Contact Persons:

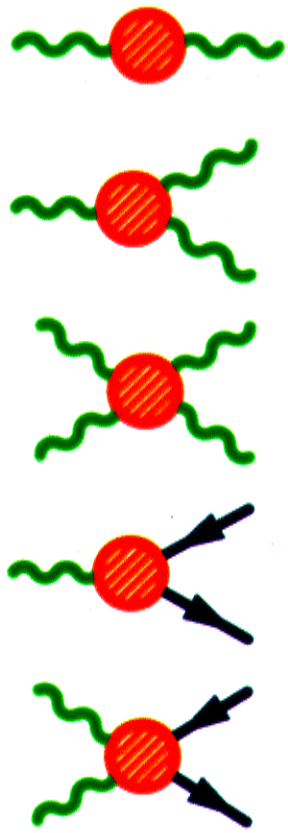
Tim Barklow
Kaoru Hagiwara
Klaus Moenig

Thanks to all speakers & participants!

The Task

Precision measurements
of Electroweak interactions:

New contributions
at LCWS 2000:



- "Classical" domain of e^+e^- physics
- But many new ideas & developments since Sitges 99

The Challenge

Deviations expected at the level of SM loop corrections:

Magic Number

$$\frac{1}{16\pi^2} = 0.0063$$

⇒ Measure to better than a percent

→ Machine energy & luminosity

→ Detector resolution, hermeticity ...

⇒ Predict signal to better than a percent

→ Theory: Radiative corrections

→ Theory: Resummation

⇒ Understand background to better than a percent

→ Simulation: Complete matrix elements

→ Simulation: Phase space for multiparticle processes

The Big IF

IF (a light Higgs exists) THEN

- We are testing the nonabelian symmetry
- The SM predicts observables to all orders

  ⇒ Deviations give hints for SM extensions/breakdown (New weakly interacting matter, compositeness, extra dimensions, ...)

ELSE

- We are probing the mechanism of electroweak symmetry breaking
- We have predictions only to leading order in low-energy expansion

  ⇒ Deviations give hints to the underlying "true" theory.

END IF

New Opportunity at the LC:

Giga-Z

→ Klaus Mönig's talk

Electroweak Precision Tests at GigaZ

S. Heinemeyer, Brookhaven Natl. Lab.

Fermilab, 10/00

based on collaboration with
J. Erler, W. Hollik, G. Weiglein and *P. Zerwas*

1. Introduction

2. Precision Tests of the SM

3. Precision Tests of the MSSM

4. Conclusions

1. Introduction

Definition:

LC at low energies: high precision
high luminosity $(\sim 10^9\,Z/\text{year})$ } **GigaZ**

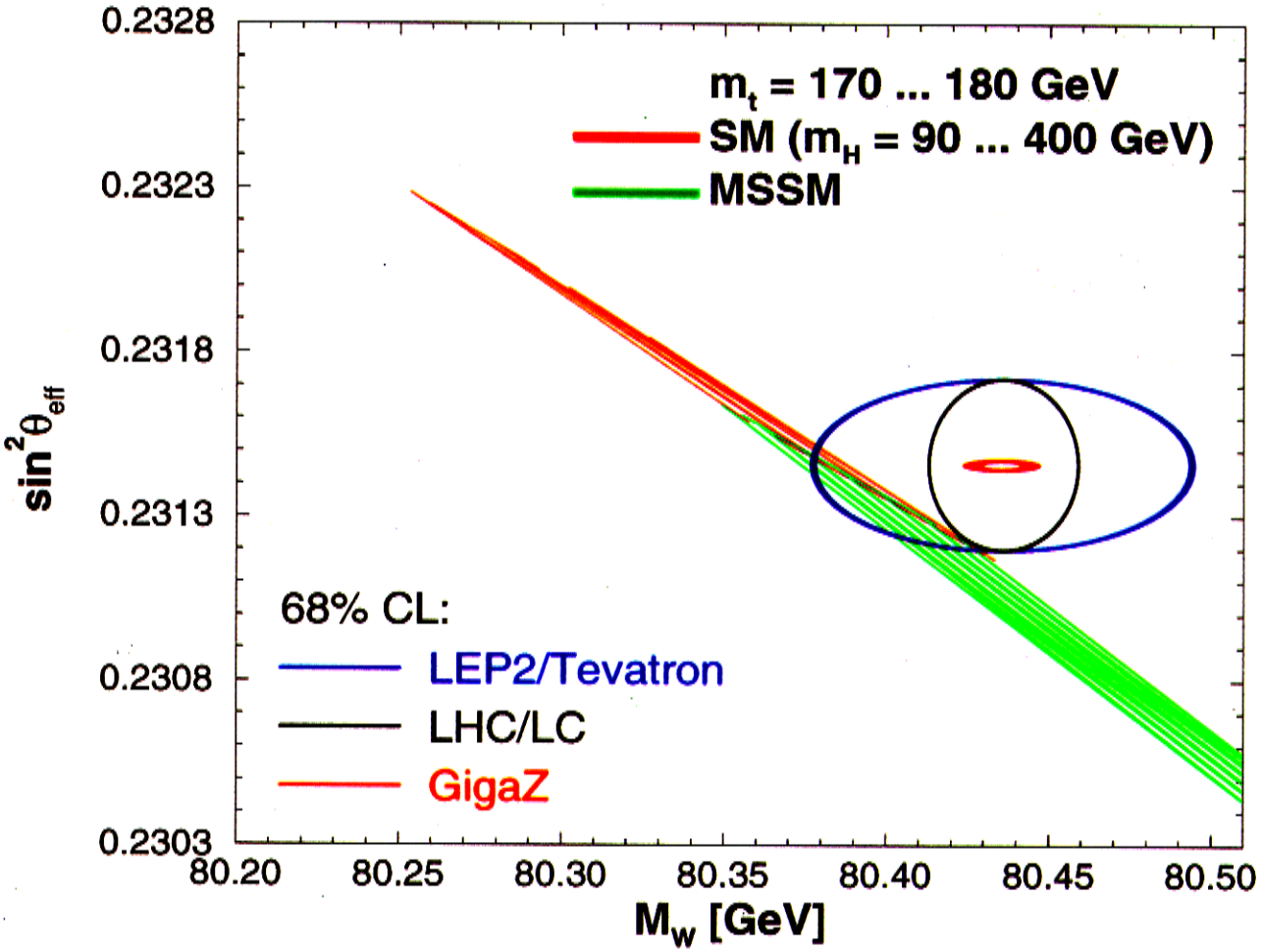
- at the Z peak (one year): 6×10^8 b quarks
- at the Z peak (via A_{LR}): $\Delta \sin^2\theta_{\text{eff}}$
- at the 2 W threshold (one year): ΔM_W

Expected accuracy:

	LEP2/Tev.	LHC	LC	GigaZ
M_W	30 MeV	15 MeV	15 MeV	6 MeV
$\sin^2\theta_{\text{eff}}$	0.00018	0.00018	0.00018	0.00001
m_t	3 GeV	2 GeV	0.2 GeV	0.2 GeV
m_h	?	0.2 GeV	0.05 GeV	0.05 GeV
M_{SUSY}	?	10%	0.1%	0.1%

What can we learn from improved accuracy in M_W and $\sin^2\theta_{\text{eff}}$?

Prediction for M_W, $\sin^2\theta_{\rm eff}$ in the SM and MSSM vs. prospective accuracies at LEP2/SLD/Tevatron , LHC/LC, GigaZ:



⇒ large improvement of experimental accuracy:

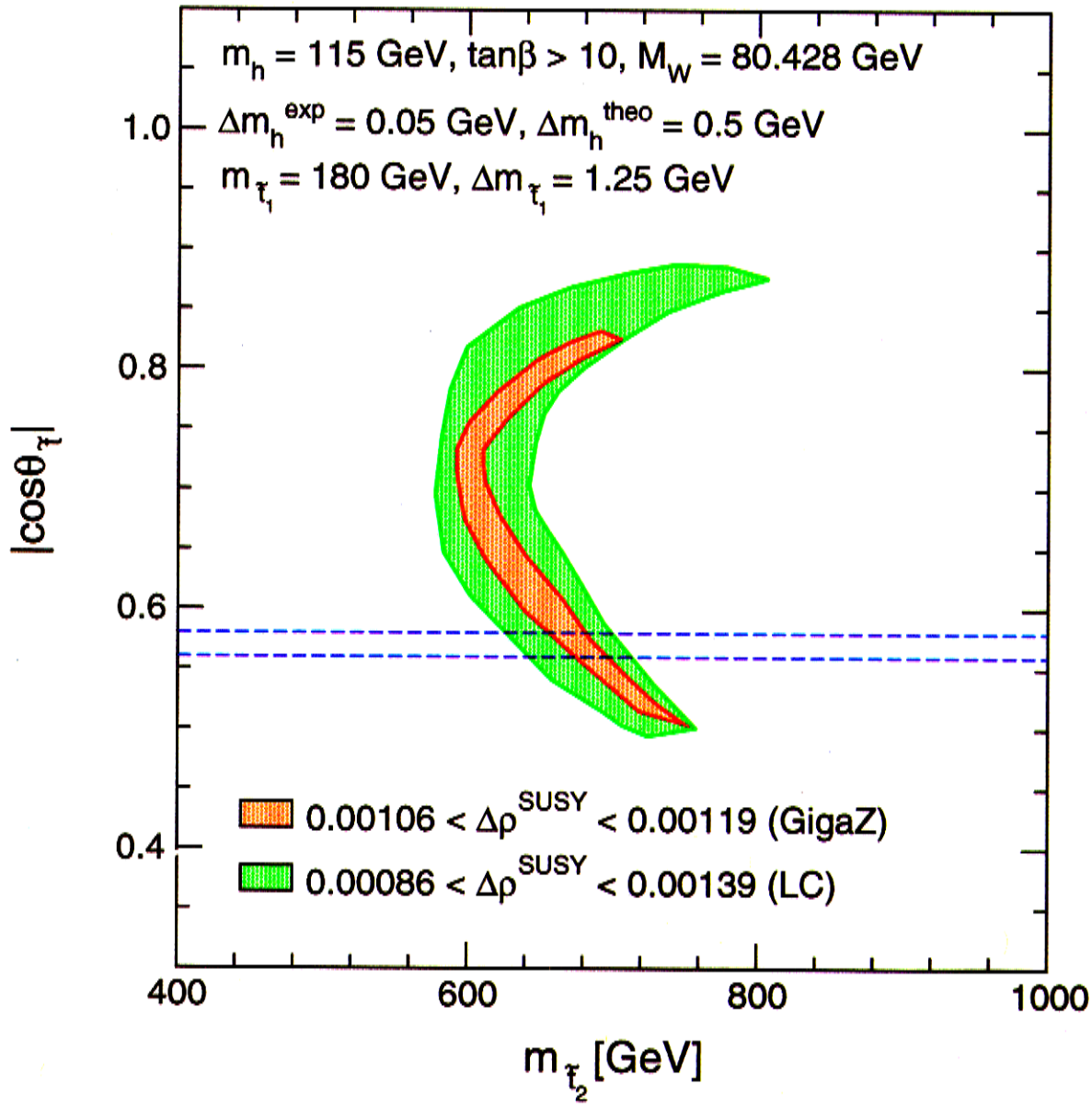
LEP2/SLD/Tevatron → LHC/LC → GigaZ

⇒ Very sensitive test of theory

Indirect information:

Constraints on $m_{\tilde{t}_2}$, $\theta_{\tilde{t}}$ from precision observables $m_h, M_W, \sin^2\theta_{\text{eff}}$ at LC and GigaZ :
[S.H., G. Weiglein '00]

Allowed region in $m_{\tilde{t}_2}$-$\cos\theta_{\tilde{t}}$ plane:
($M_A = 257 \pm 10$ GeV, $\tan\beta > 10$):



Complementary of direct and indirect information

⇒ Indirect determination of $m_{\tilde{t}_2}$ with high precision

Experimental Issues for Precision Electroweak Physics at a high luminosity Z factory

October 25th, 2000

P.C. Rowson, SLAC (presenter) and M. Woods, SLAC

Focus will be on the measurement of $sin^2\theta_W^{eff}$ by the A_{LR} technique, drawing on experience gained at the SLC.

Comments regarding other important observables, such as M_Z, Γ_Z, m_W, and m_{top} are possible as well, although these are covered in more detail elsewhere.

Our main conclusions in advance :

Along with **polarization, energy measurement** will play a central role.

There will likely be an interplay between machine parameters and the precision measurements - a **luminosity/precision trade-off**.

SUMMARY

With only the electron beam polarized, 90%,

→ can improve SLD's A_{LR} measurement by a factor of 5

With 0.25% polarimetry (plausible SLC extrapolation) and with modest luminosity (use $L=4 \times 10^{32}\ cm^{-2}\ s^{-1}$) to accumulate 50M Zs in 0.4 Snowmass-years. Beamstrahlung correction for $E_{CM}^{lum\text{-}wt}$ should only be about 40 MeV and one needs to know this with 10 MeV accuracy. But still need to study problem of understanding the Z multiplicity (to approx 0.2%). (This measurement is much easier at TESLA-90.)

With $P^- = 90\%$ and $P^+ = 50\%$,

→ to improve SLD's A_{LR} measurement by a factor of 10 or more,

Need to understand $E_{CM}^{lum\text{-}wt}$ at 5 MeV level and to understand Z multiplicity at level of 0.02% at NLC (5% at TESLA-90). This measurement probably only makes sense at TESLA-90, or perhaps the new lowbeamstrahlung NLC configuration from T.Raubenheimer (@180 Hz rep.rate).

A_{LR} with Positron Polarization (Comment)

Keisuke Fujii, KEK
in place of
Tsunehiko Omori, KEK

This is to call your attention to the usefulness of positron polarization in reducing the systematic error on A_{LR} as described in our old note: KEK Preprint 95-127

Combined Polarization

$$P_{comb} \equiv \frac{P_- - P_+}{1 - P_- P_+}$$

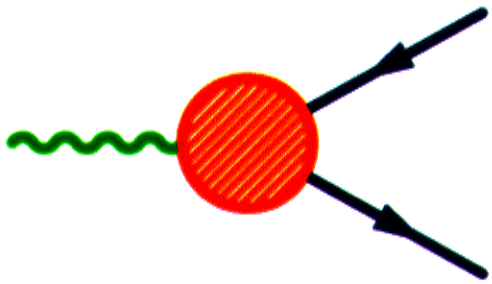
right-handed helicity basis:
P=-1 means 100% left-handed

A_{LR}

$$A_{obs} \equiv \frac{N_L - N_R}{N_L + N_R} = -P_{comb}\, A_{LR}$$

$$\frac{\Delta A_{LR}}{A_{LR}} \simeq \sqrt{\left(\frac{\Delta P_{comb}}{P_{comb}}\right)^2 + \frac{1}{N\,(P_{comb} A_{LR})^2}}$$

Systematic Error on P_{comb} dominates if N >>1



Combine LC (high energy) & Giga-Z

Can we improve on low-energy precision data?

→ B Physics

→ CKM in W decays

B Physics with a Giga-Z Sample

Bruce Schumm
Santa Cruz Institute for Particle Physics
and the
University of California, Santa Cruz

Presented at:

LCWS 2000 Linear Collider Workshop
Electroweak Parallel Session
October 25, 2000

Tentative Conclusions

Unique opportunity for heavy quark EW couplings

Natural environment for exclusive CKM asymnmetries (low backgrounds, polarization) but running $\sim \times 10$ behind BTEV, LHCB

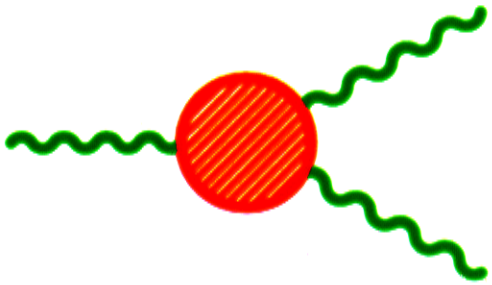
May have unique shot at V_{ub}

Difficult exclusive modes: $B \to s\nu\bar{\nu}$, $B \to \pi^0\pi^0$, multi-prong modes w/out narrow intermediate states

Possible Studies:

- V_{ub} with full vertexing (PRECISE, ZVTOP)
- B_s mixing precision (rather than reach)
- Difficult exclusive modes (continue)
- Aggressive vertexing scenarios
- Suggestions?

Trilinear Interactions



Precision measurements at the LC

Improvements in theoretical understanding

Triple Gauge Couplings at TESLA

Wolfgang Menges
II. Institut für Experimentalphysik
Universität Hamburg

25.10.2000

- TGC's at 500 GeV
- TGC's at 800 GeV
- Polarised Electrons/Positrons

Linear Collider Workshop 2000 - LCWS 2000
Fermi National Accelerator Laboratory
October 24-28, 2000

Properties of the Couplings

14 couplings in total (7 WWγ, 7 WWZ)

$\Rightarrow$ std. couplings: (C, P, CP conserving)

g_1^γ, g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z 6

el. mag. gauge invariance:

g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z 5

$SU(2) \times U(1)_Y$ gauge invariance:

g_1^Z, κ_γ, λ_γ 3

$\Rightarrow$ non std. couplings:

	g_4^V	g_5^V	$\tilde{\kappa}_V$	$\tilde{\lambda}_V$
C	–	–	√	√
P	√	–	–	–
CP	–	√	–	–

- only WWZ-couplings 4
- limits for WWγ-couplings from other processes

Fit

Generator: Wopper 1.5

- W-pair generator CC03/CC11
- including ISR
- including beamstrahlung (CIRCE)

Detector Simulation: Simdet

- no update on detector effects
- old studie from S. Petzold and C. Burgard
- detector effects are small

	$\Delta\kappa_\gamma$
generator level	3.52×10^{-4}
measured level	3.54×10^{-4}
kinematic fit	3.55×10^{-4}

Fitting procedure:

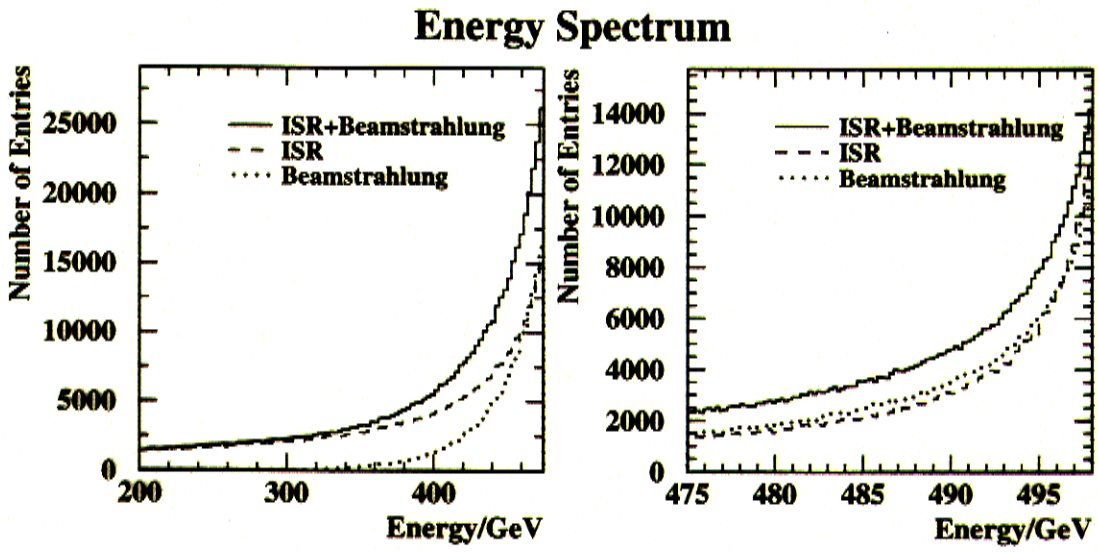
- χ^2 fit with MC reweighting
- using $\cos\theta$, spin density matrix and cross section
- includes detector effects (no yet done)
- good for 1d, 2d, 3d, ... fits

Results

- **1 σ errors (10^{-4}) for 1d fits**
- **Energy**: 500 GeV
- **Polarisation**: LR ($P_{e^-} = -0.8, P_{e^+} = +0.6$)
  RL ($P_{e^-} = +0.8, P_{e^+} = -0.6$)

	no pol. $500\,\mathrm{fb}^{-1}$	RL $250\,\mathrm{fb}^{-1}$	LR $250\,\mathrm{fb}^{-1}$	RL+LR $250+250\,\mathrm{fb}^{-1}$
Δg_1^Z	7.3	4.0	3.7	2.8
$\Delta\kappa_\gamma$	5.7	3.4	7.9	3.1
λ_γ	6.1	32.6	4.4	4.3
Δg_1^Z	38.1	20.3	21.0	15.5
$\Delta\kappa_\gamma$	4.8	4.3	5.2	3.3
λ_γ	12.1	11.4	9.6	5.9
$\Delta\kappa_Z$	8.7	4.7	4.4	3.2
λ_Z	11.5	14.1	7.9	6.7

First Estimate of ISR & Beamstrahlung Systematics



very simple test:

- switch off ISR in "data", leave reweighting MC unchanged
- switch off beamstrahlung in "data", leave reweighting MC unchanged

ISR:

- 500 GeV: biases of $\mathcal{O}(100 * stat.error)$
- 800 GeV: biases of $\mathcal{O}(100 * stat.error)$

$\Rightarrow$ need to understand to order of 1 %

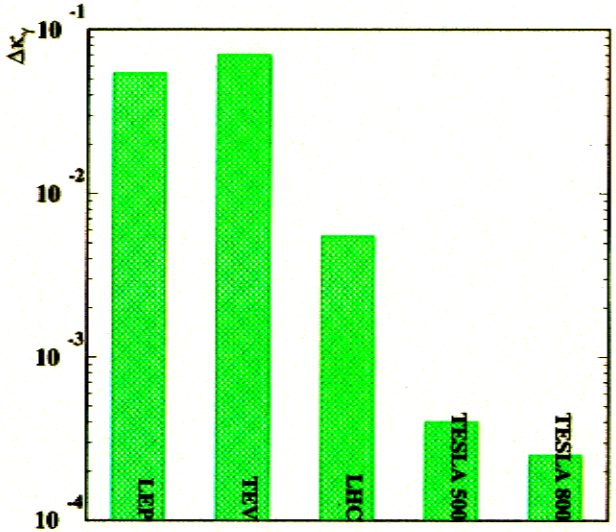
Beamstrahlung:

- 500 GeV: biases of $\mathcal{O}(10 * stat.error)$
- 800 GeV: biases of $\mathcal{O}(10 * stat.error)$

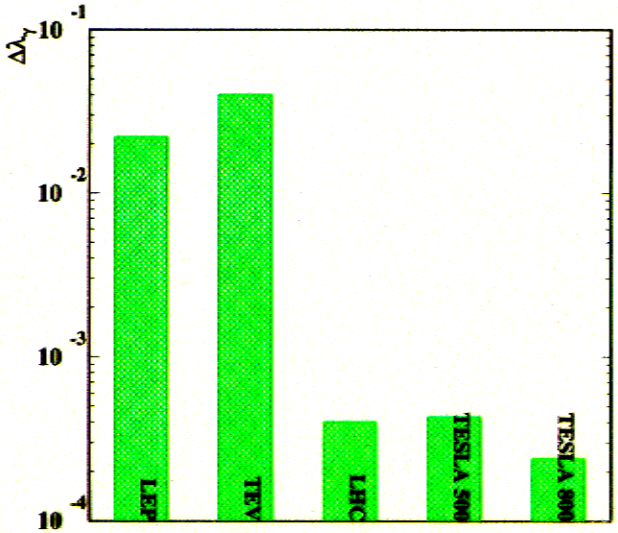
$\Rightarrow$ need to understand to better than 10 %

Comparison

- exp. error of std. couplings in order of 10^{-4}
- exp. error of CP violating couplings in order of 10^{-3}
- polarisation improves results
- polarisation will disentagle WWγ-WWZcouplings
- systematics look okay!



	LEP limits (ICHEP 2000)			TESLA 500	TESLA 800
Δg_1^Z	-0.025	+0.026	-0.026	$\pm$ 0.00073	$\pm$ 0.00045
$\Delta\kappa_\gamma$	-0.002	+0.067	-0.065	$\pm$ 0.00057	$\pm$ 0.00031
λ_γ	-0.036	+0.028	-0.027	$\pm$ 0.00061	$\pm$ 0.00029
g_5^Z	+0.05	+0.16	-0.17	$\pm$ 0.0028	$\pm$ 0.0029



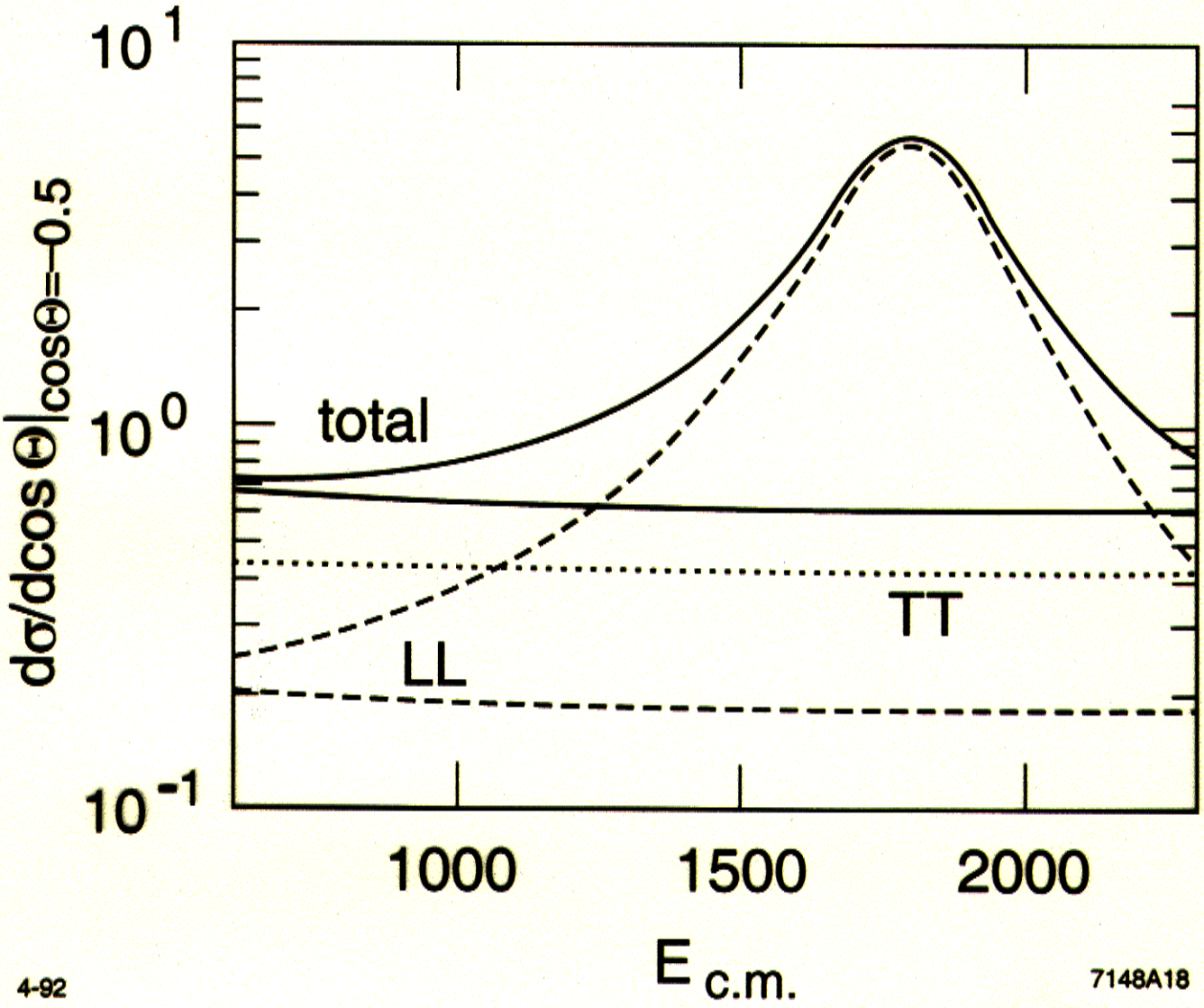
Strong Symmetry Breaking Signals in $e^+e^- \to W^+W^-$ at $\sqrt{s} = 800$ GeV

LCWS 2000

Oct 26, 2000

Tim Barklow
SLAC

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



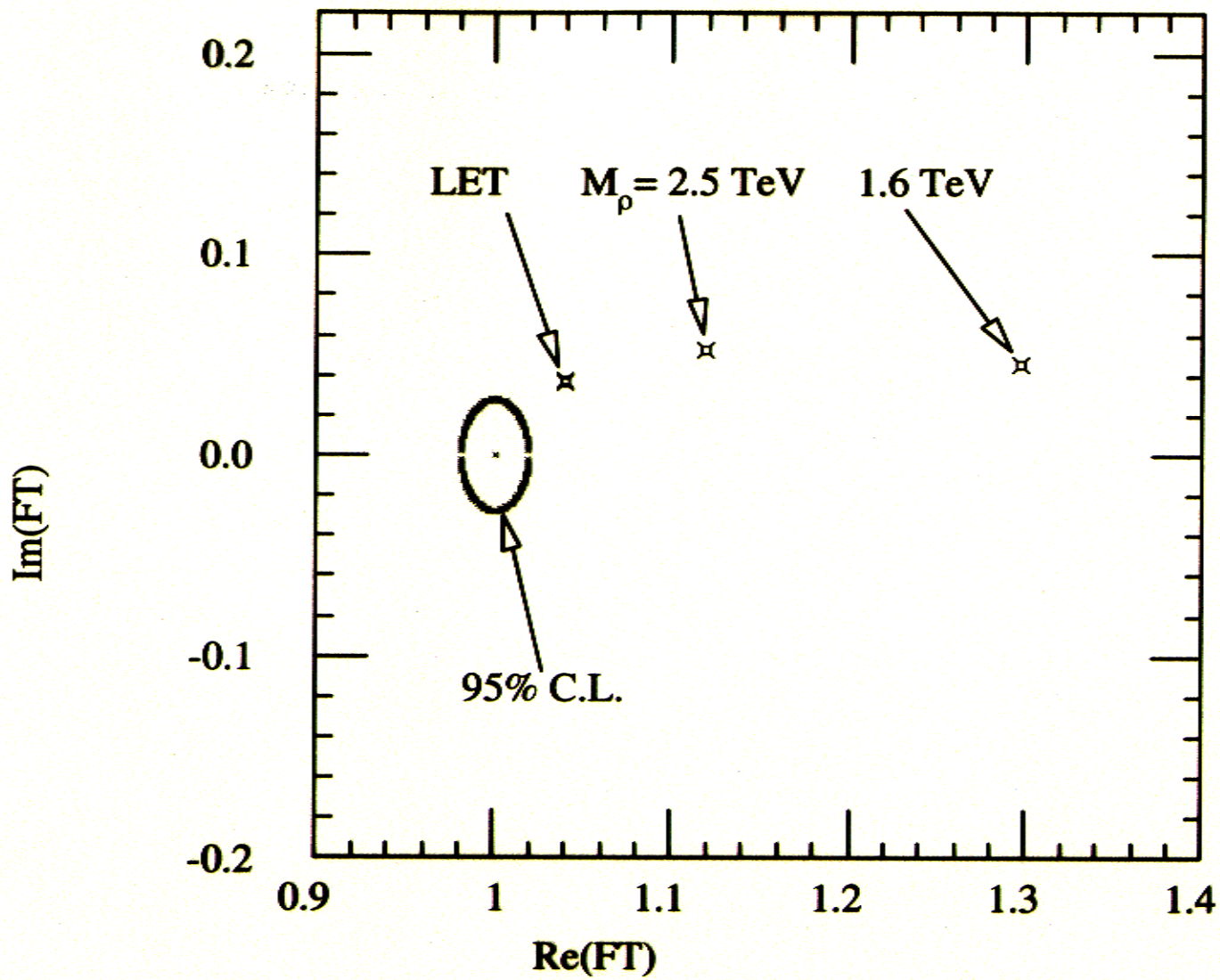
4-92

7148A18

$e^+e^- \to W^+W^-$ Analysis

- 80/0% e^-/e^+ polarization – all e^-_L
- Likelihood fit of production angle & 4 decay angles
- $e\nu q\overline{q}$ and $\mu\nu q\overline{q}$ channels only
- Charm jets tagged with 100/65% purity/efficiency
- Solid angle $|\cos\Theta| < 0.9$
- Statistical errors only

ECM=800 GEV L=500 fb^{-1}



Conclusions

- e^+e^- Linear Colliders provide a significant enhancement over LHC in I=J=1 W^+W^- scattering channel. Even at $\sqrt{s} = 500$ GeV TESLA outperforms LHC in this scattering channel.
- TESLA with 500 fb^{-1} at $\sqrt{s} = 800$ GeV gives a larger LET signal than LHC with 100 fb^{-1}
- TESLA with 500 fb^{-1} at $\sqrt{s} = 800$ GeV gives a larger LET signal than NLC with 200 fb^{-1} at $\sqrt{s} = 1500$ GeV.
- Charm tagging in $e\nu q\bar{q}$ & $\mu\nu q\bar{q}$ channels improves LET signal; improvement is equivalent to a 50% increase in luminosity.

Vertex detection in strong electroweak symmetry breaking

Wolfgang Walkowiak,

UC Santa Cruz

Linear Collider Workshop 2000,

Fermilab,

26 Oct 2000

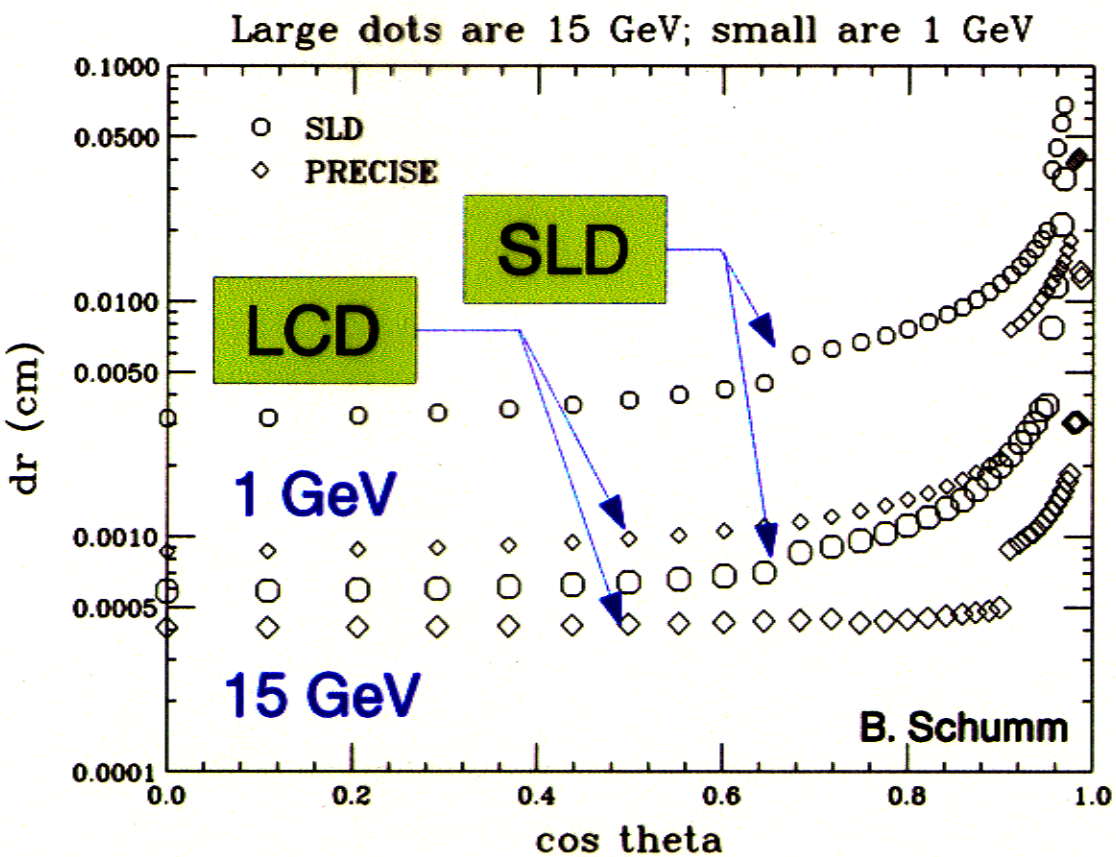
Flavor tagging

- Lepton is expected to be identified, but there is an ambiguity on hadronic side in W decay tensor:

$$\bar{H}^{\bar{\lambda}}_{\bar{\lambda}'} = \left[\bar{D}^{\bar{\lambda}}_{\bar{\lambda}'}(\cos(\bar{\theta}^*), \bar{\phi}^*) + \bar{D}^{\bar{\lambda}}_{\bar{\lambda}'}(-\cos(\bar{\theta}^*), \bar{\phi}^* + \pi) \right]$$

- Loosing information by 'averaging' over these two states.
- Need flavor tagging to make this information accessible.

LCD vs SLD resolution



- Better tracking resolution for LCD detector.
- Higher c-tagging efficiency expected!
- Aggressive vertexing?

Plans for $e^+e^- \rightarrow W^+W^-$ analysis

- Study c-tagging efficiency for $e^+e^- \rightarrow W^+W^-$ events using Fast MC and ZvTopVertexer:
  Which level of equivalent lumi gain is reachable?
- W_L W_L analysis: Begin with having one W decay leptonically, the other one hadronically.
- Then, in addition use events with both Ws decaying hadronically with c-tags at both sides:
  - Study influence of mistags.
  - Study feasibility with respect to backgrounds.
- Consider aggressive vertexing.

W-Pair Production With YFSWW/KORALW

WIESŁAW PŁACZEK
Jagiellonian University, Cracow, Poland
and
CERN, Geneva, Switzerland

Outline:

- **Introduction.**
- **WW Physics with YFSWW/KORALW.**
- **Numerical results.**
- **Conclusions and outlook.**

LC workshop 2000, Fermilab, October 25, 2000

Predictions for $e^+e^- \to WW \to 4f$ and $e^+e^- \to 4f + \gamma$ at a future linear collider

Doreen Wackeroth

University of Rochester

in collaboration with

A. Denner, S. Dittmaier, and M. Roth

Literature:

[1] *Predictions for all processes $e^+e^- \to$ 4fermions $+\gamma$*, Nucl. Phys. **B560**, 33 (1999), hep-ph/9904472.

[2] *Four-fermion production in electron positron colliders*, LEP2MC workshop report, hep-ph/0005309.

[3] *Electroweak radiative corrections to $e^+e^- \to WW \to$ 4 fermions in DPA - the RacoonWW approach*, Nucl. Phys. **B587**, 67 (2000), hep-ph/0006307.

[4] *W pair production at future e^+e^- colliders: Precise predictions from RacoonWW*, EPJdirect Vol.2 C4 (2000), hep-ph/9912447.

[5] *$\mathcal{O}(\alpha)$ corrections to $e^+e^- \to WW \to$ 4fermions ($+\gamma$): First numerical results from RacoonWW*, Phys. Lett. **B475**, 127 (2000), hep-ph/9912261.

Introduction

⇒ **EXPERIMENTALLY:**

W-pairs observed through **4f** final states + radiative photons

- **GENERAL PROCESS:**

$$e^+ + e^- \longrightarrow f_1 + \bar{f}_2 + f_3 + \bar{f}_4 + n\gamma\,, \quad (n = 0, 1, \ldots)$$

⇒ **THEORETICALLY:** also LOOP corrections necessary!

- **Exclusive Yennie-Frautschi-Suura Exponentiation:**

$$\sigma = \sum_{n=0}^{\infty} \frac{1}{n!} \int \prod_{j=1}^{4} \frac{d^3 q_j}{q_j^0} \left\{ \prod_{i=1}^{n} \frac{d^3 k_i}{k_i^0} \tilde{S}(\{p\},\{q\},k_i) \Theta\left(\frac{2k_i^0}{\sqrt{s}} - \epsilon\right) \right\}$$
$$\times \delta^{(4)}\left(p_1 + p_2 - \sum_{j=1}^{4} q_i - \sum_{j=1}^{n} k_i\right) e^{Y(\{p\},\{q\};\epsilon)}$$
$$\times \left[\bar{\beta}_0^{(m)}(\{p\},\{q\}) + \sum_{i=1}^{n} \frac{\bar{\beta}_1^{(m)}(\{p\},\{q\},k_i)}{\tilde{S}(\{p\},\{q\},k_i)} + \ldots \right],$$

where

$\tilde{S}(\{p\},\{q\},k)$ — Soft Photon Radiation Factor

$Y(\{p\},\{q\};\epsilon)$ — YFS FormFactor

$\bar{\beta}_n^{(m)}(\ldots)$ — $\mathcal{O}(\alpha^m)$ YFS Residuals for n Real Photons

COMPLICATED !!!

Precise predictions for $e^+e^- \to WW \to 4f$

LEP2MC workshop (1999-2000) [2]:
→ improved predictions, i.e. beyond leading universal corrections !
→ estimate of the theoretical uncertainty !

Complete calculation of $\mathcal{O}(\alpha)$ corrections to all processes $e^+e^- \to 4f$ not feasible (yet).
(work in progress: A. Vicini 1998)

Good starting point to go beyond leading $\mathcal{O}(\alpha)$ corrections to off-shell W pair production:

Double-pole approximation (DPA)

All present calculations of radiative corrections to $e^+e^- \to WW \to 4f$
Beenakker et al. (semi-analytic), Denner et al. (RacoonWW), Jadach et al. (YFSWW3), Kurihara et al. (GRACE)
rely on a DPA:

the matrix element to $e^+e^- \to W^+(k_+)W^-(k_-) \to 4f$ is of the form:

$$\mathcal{M} = \frac{R_{+-}(k_+^2,k_-^2)}{(k_+^2-M_W^2)(k_-^2-M_W^2)} + \frac{R_+(k_+^2,k_-^2)}{(k_+^2-M_W^2)} + \frac{R_-(k_+^2,k_-^2)}{(k_-^2-M_W^2)} + N(k_+^2,k_-^2)$$

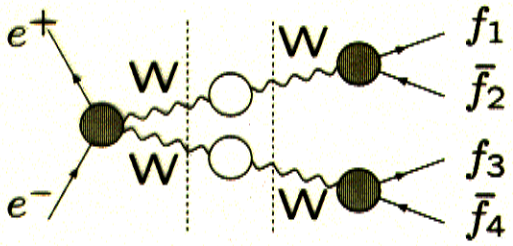
DPA: Sufficiently above the W pair production threshold, W-pair production is dominated by the doubly-resonant contributions:

$$\mathcal{M} \to \frac{R_{+-}(M_W^2,M_W^2)}{(k_+^2-M_W^2+iM_W\Gamma_W)(k_-^2-M_W^2+iM_W\Gamma_W)}$$

$\mathcal{O}(\alpha)$ corrections to $e^+e^- \to WW \to 4f$: the RacoonWW approach [3]

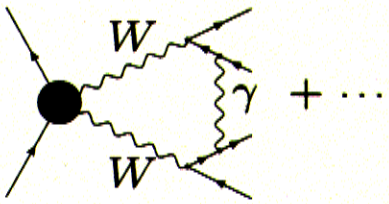
→ complete virtual corrections in DPA:

factorizable



building blocks:
RCs to on-shell production
Böhm et al., Fleischer et al.
RCs to W decay Bardin et al., Denner et al., Jegerlehner et al.

non-factorizable



γ exchange between production and decay subprocesses ($E_\gamma < \Gamma_W$)
Beenakker et al., Denner et al., Melnikov et al.

→ real photon corrections:

full matrix element calculation for real photons in $e^+e^- \to 4f + \gamma$:

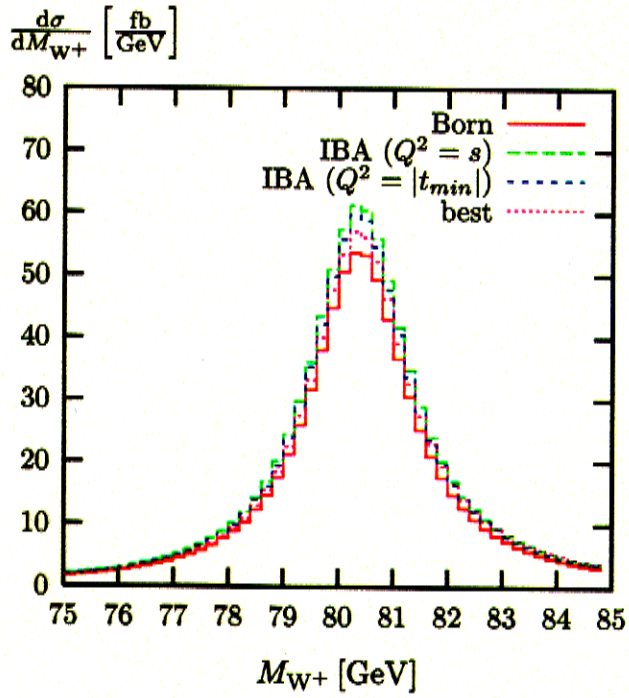
+ Exact five particle phase space ⇒ full information on photon kinematics !

− Careful matching of virtual photonic corrections calculated in DPA with exact real contribution is needed, so that the IR and collinear singularities cancel.
singular parts are extracted from real photon contribution, full Born → DPA Born in those parts which match the virtual singular part ⇒ DPA is only applied to the finite part of the virtual corrections.

⇒ Naively expected accuracy of the DPA (whenever W-pair production is dominant)

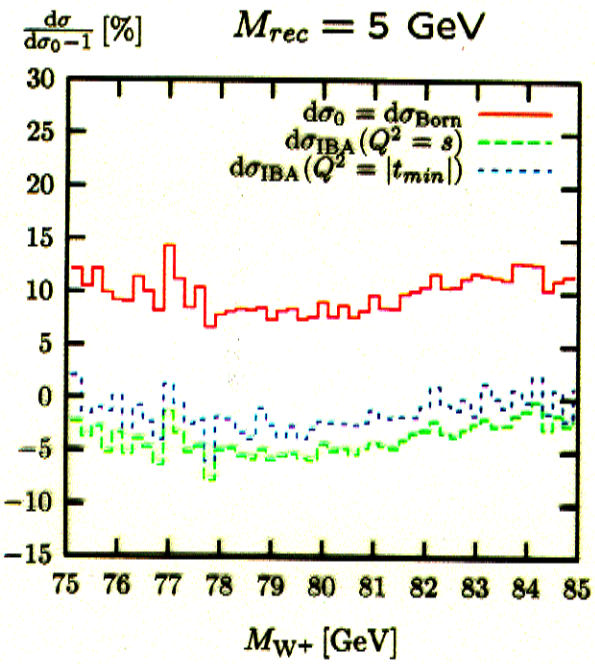
$$\frac{\alpha}{\pi}\frac{\Gamma_W}{M_W} < 0.5\%$$

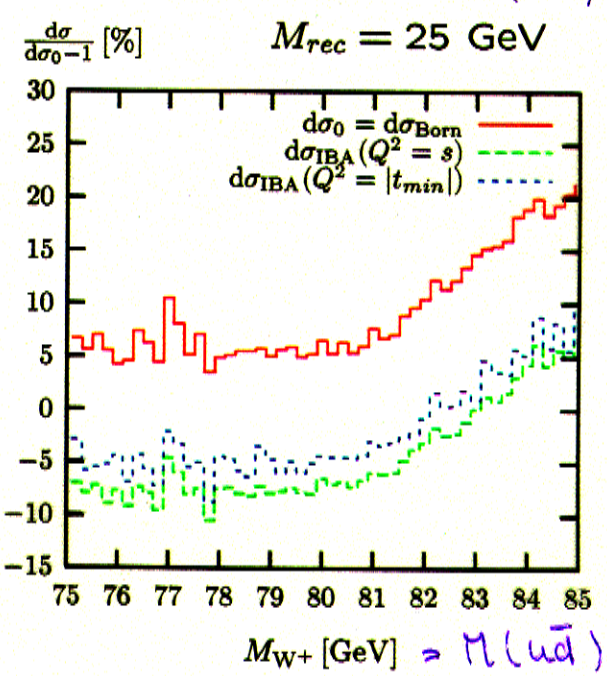
The impact of the radiative corrections to $e^+e^- \to u\bar{d}\mu^-\bar{\nu}_\mu$ on the W^+ invariant-mass distributions at 500 GeV with RacoonWW (preliminary):



Q^2: scale in ISR structure functions!

$d\sigma$: best (O(α) DPA calc.)





shape due to FSR!

Not described by IBA!

⇒ W invariant-mass distributions strongly depend on the recombination cuts, i.e. on the treatment of the photons !

⇒ **OUR SOLUTION:**

TWO MC EVENT GENERATORS

⇓ ⇓

YFSWW | **KORALW**

Simplified Process (Double-Resonant W) | **Full Process** (All 4f Channels)

⊕ ⊕

As Much Rad. Corr. As Possible (Needed) | **Simplified Rad. Corr. (ISR, Coulomb, ...)**

δ_{WW}^{NL}

* $\mathcal{O}(\alpha)$ NL EW Corr.
* "Screened" Coul. Corr. (Approximation For Non-Factorizable Corr.)

WW-Process

* YFS $\mathcal{O}(\alpha^3)$LL ISR
* Coulomb Correction
* "Naive" QCD Corr.
* Full CKM Matrix
* W-BR's Incl. Rad Corr.
* Anomalous TGC's
* FSR by PHOTOS
* τ Decays by TAUOLA
* Hadronization by JETSET
* Semi-An. Code: KORWAN

δ_{4f}

* Non-WW 4f Contrib.
* YFS $\mathcal{O}(\alpha^3)$LL ISR

Results

YFSWW3-1.14 ↔ RACOONWW

A. Denner, S. Dittmaier, M. Roth, D. Wackeroth

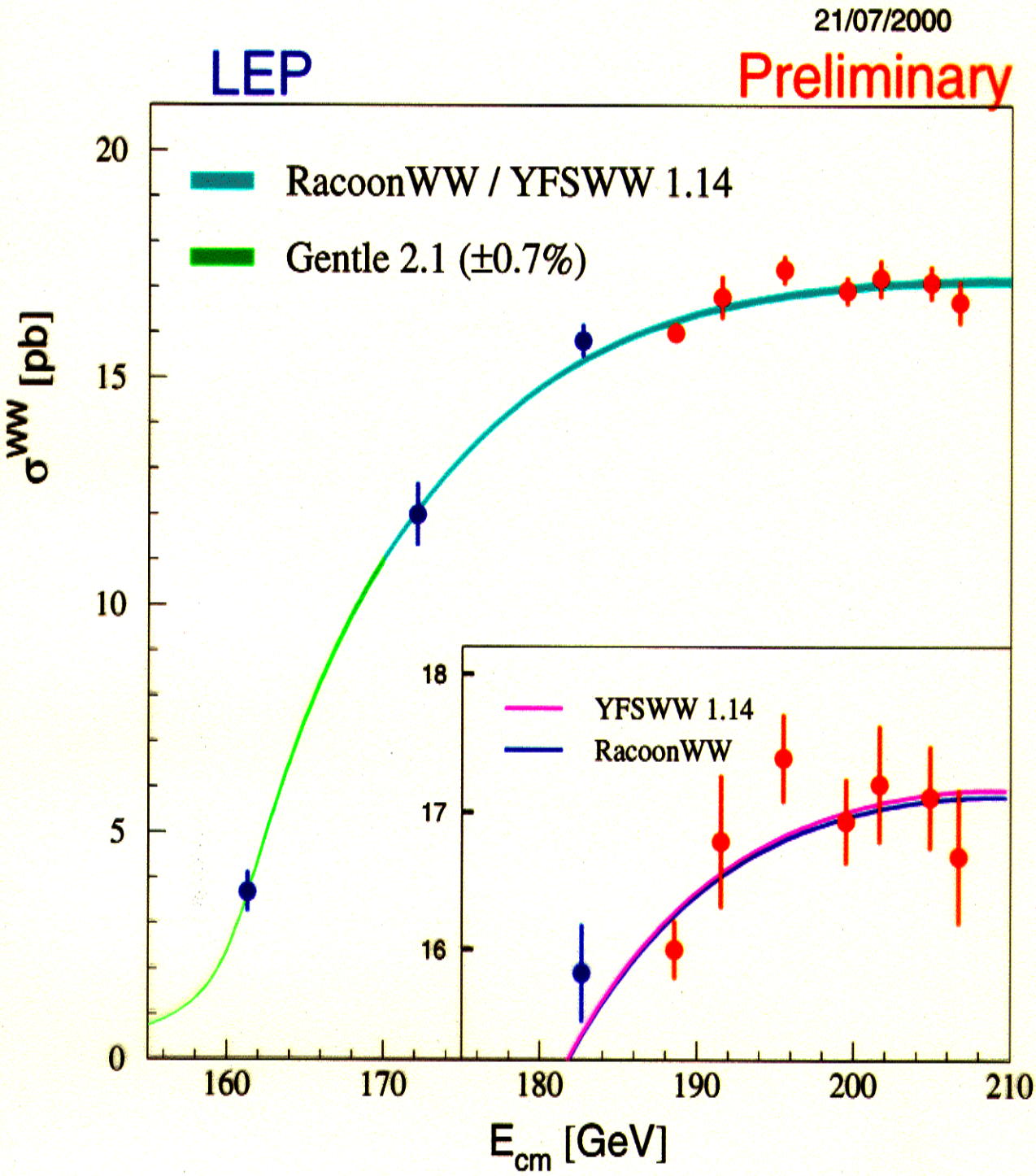
@ LEP2 Energies

$\sqrt{s}\,[GeV]$	$\sigma_{WW}\,[pb]$		(Y − R)/Y [%]
	YFSWW3	RACOONWW	
168.000	9.8302 (34)	9.8392 (49)	−0.09 (6)
172.086	12.0988 (41)	12.0896 (76)	0.08 (7)
176.000	13.6360 (45)	13.6271 (66)	0.07 (6)
180.000	14.7791 (49)	14.7585 (72)	0.14 (6)
182.655	15.3610 (50)	15.3684 (76)	−0.05 (6)
185.000	15.7755 (48)	15.7716 (78)	0.25 (6)
188.628	16.2664 (53)	16.2486 (111)	0.11 (8)
191.583	16.5680 (57)	16.5188 (85)	0.30 (6)
195.519	16.8409 (61)	16.8009 (87)	0.24 (6)
199.516	17.0167 (68)	16.9791 (88)	0.22 (6)
201.624	17.0755 (62)	17.0316 (89)	0.26 (6)
205.000	17.1279 (55)	17.0792 (89)	0.28 (6)
208.000	17.1507 (67)	17.0942 (90)	0.33 (7)
210.000	17.1467 (66)	17.0858 (91)	0.34 (7)
215.000	17.0786 (70)	17.0378 (91)	0.24 (7)

Agreement Within 0.4%

Results

Versus LEP2 Data



Electroweak Sudakov Corrections

Michael Melles*

Introduction

DL-corrections in Non-Abelian theories

Subleading Corrections in Non-Abelian theories

Leading and Subleading EW Sudakov Logarithms

Comparison with existing calculations

Conclusions

* work based on Phys. Rev. D 61 (2000) 094002, hep-ph/0004056 and ongoing work.

Introduction

Precision NLC physics (<1%) to disentangle new physics.

At 1 Loop, EW DL's 10-20 %, at 2 Loops few %. Subleading could be significant too.

$\longrightarrow$ Need a complete leading & subl. log analysis through 2 Loops!

In addition:

Theoretical understanding of IR-structure of broken gauge theories.

Strategy:

Calculate in terms of massless fields for $\mu \geq M$ (where $M_Z \sim M_W \sim M_{\text{Higgs}} \sim M$)

Then solve IR evolution equation:

$$\left(\frac{\partial}{\partial t} + \beta\frac{\partial}{\partial g} + \beta'\frac{\partial}{\partial g'} + \sum_{i=1}^{n_g}\Gamma_g^i(t) - n_{\mathrm{W}}\frac{1}{2}\frac{\alpha}{\pi}\beta_0 - n_{\mathrm{B}}\frac{1}{2}\frac{\alpha'}{\pi}\beta_0' + \sum_{k=1}^{n_f}\left(\Gamma_f^k(t) + \frac{1}{2}\gamma_{q\bar{q}}^k\right)\right)\mathcal{M}^{\perp}(p_1, ..., p_n, g, g', \mu) = 0$$

with
$$\beta(g(\overline{\mu}^2)) = \frac{\partial g(\overline{\mu}^2)}{\partial \log \overline{\mu}^2} \approx -\beta_0\frac{g^3(\overline{\mu}^2)}{8\pi^2}$$
$$\beta'(g'(\overline{\mu}^2)) = \frac{\partial g'(\overline{\mu}^2)}{\partial \log \overline{\mu}^2} \approx -\beta_0'\frac{g'^3(\overline{\mu}^2)}{8\pi^2}$$

and
$$\beta_0 = \frac{11}{12}C_A - \frac{1}{3}n_{gen} - \frac{1}{24}n_h$$
$$\beta_0' = -\frac{5}{9}n_{gen} - \frac{1}{24}n_h$$
$$\Gamma_{f,g}^i(t) = \left(\frac{\alpha}{4\pi}T_i(T_i+1) + \frac{\alpha'}{4\pi}\left(\frac{Y_i}{2}\right)^2\right)t$$
$$\gamma_{q\bar{q}}^i = -3\left(\frac{\alpha}{4\pi}T_i(T_i+1) + \frac{\alpha'}{4\pi}\left(\frac{Y_i}{2}\right)^2\right)$$

Conclusions

NLO Sudakov logarithms in broken gauge theories are calculated to all orders using fields of the effective high energy theory and the gauge invariant IR evolution equation method.

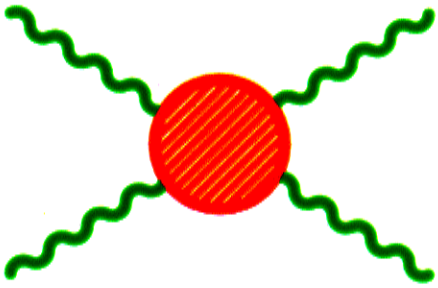
They *factorize* and *exponentiate* (with reasonable experimental cuts, mixing).

$\log \frac{s}{M^2} \log \frac{t}{u}$ should be calculated at least at one loop.

Agreement at one loop up to NLO , to two loops for DL with calculation using physical fields!

The method is universal for all processes at a future collider (NLC, LHC).

Quartic Interactions



Strongly interacting W bosons?

New tools allow for detailed simulations

WW Scattering at Tesla

Roberto Chierici
CERN

Stefano Rosati, Michael Kobel
Bonn University

- ✔ Motivations
- ✔ Setup of the study
- ✔ Generators
- ✔ $ee \to \nu\nu WW$
- ✔ $ee \to \nu\nu ZZ$
- ✔ Results
- ✔ Conclusions and plans

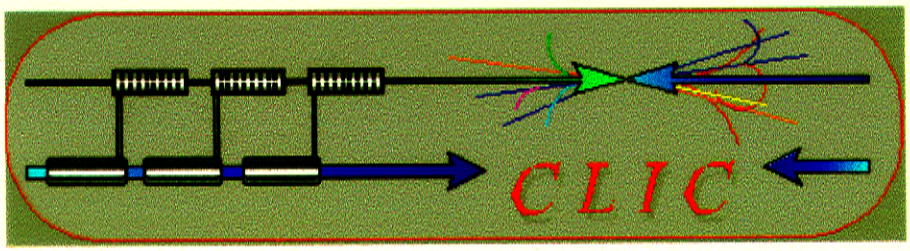
WW Scattering at CLIC

Albert De Roeck, CERN

LCWS2000, FNAL, October 2000

- Introduction
- Cuts & Cross Sections
- SIMDET Level Studies
- Summary

e^+e^- collider $\sqrt{s} = 3$ TeV

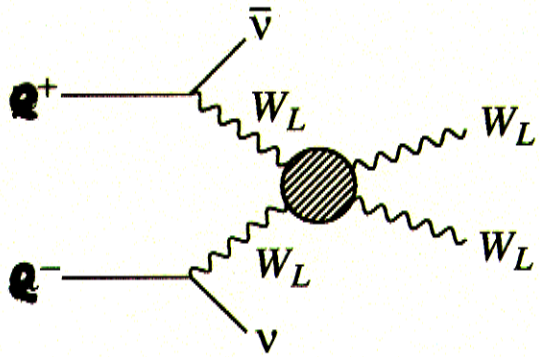


INTRODUCTION

IF NO LIGHT HIGGS ($M_H < 700$ GEV)

$\Rightarrow$ $W^{\pm}, Z$ BOSONS DEVELOP STRONG INTERACTIONS AT SCALES OF ORDER 1-2 TEV

LONGITUDINAL GAUGE BOSON SCATTERING



$\Rightarrow$ MEASURE THE WW MASS SPECTRUM

TECHNIQUES (Barger et al.: hep-ph/9501379,hep-ph/9606417; Forshaw et al., to be published) DOBADO ET AL, ...)

- EXCESS OF EVENTS BEYOND THE SM BACKGROUND
- MEASURE $W_T W_T, W_L W_T$ AND $W_L W_L$ CONTRIBUTIONS.
- CLIC: HIGH CMS ENERGY (3TEV) $\rightarrow$ SEARCH FOR RESONANCE STRUCTURES

Formalism

- The EW interactions at low energies can be described by the EW chiral lagrangian:

  ⇒ effective field theory coupling the 3 Goldstones to fermions and bosons in a SU(2)xU(1) invariant way.

  ⇒ effective operators of increasing dimension.

- Besides the gauge interaction, the theory has only two $SU(2)_C$, 4-D interaction terms, with the following four-boson vertices:

$$L_4 = \alpha_4\left[\frac{g^4}{2}\left(W^+_\mu W^{\mu-}\right)^2 + \frac{g^4}{4c_W^4}\left(Z_\mu Z^\mu\right)^2 + \frac{g^4}{2}W^+_\mu W^{\mu+} W^-_\nu W^{\nu-} + \frac{g^4}{c_W^2}W^+_\mu Z^\mu W^-_\nu Z^\nu\right]$$

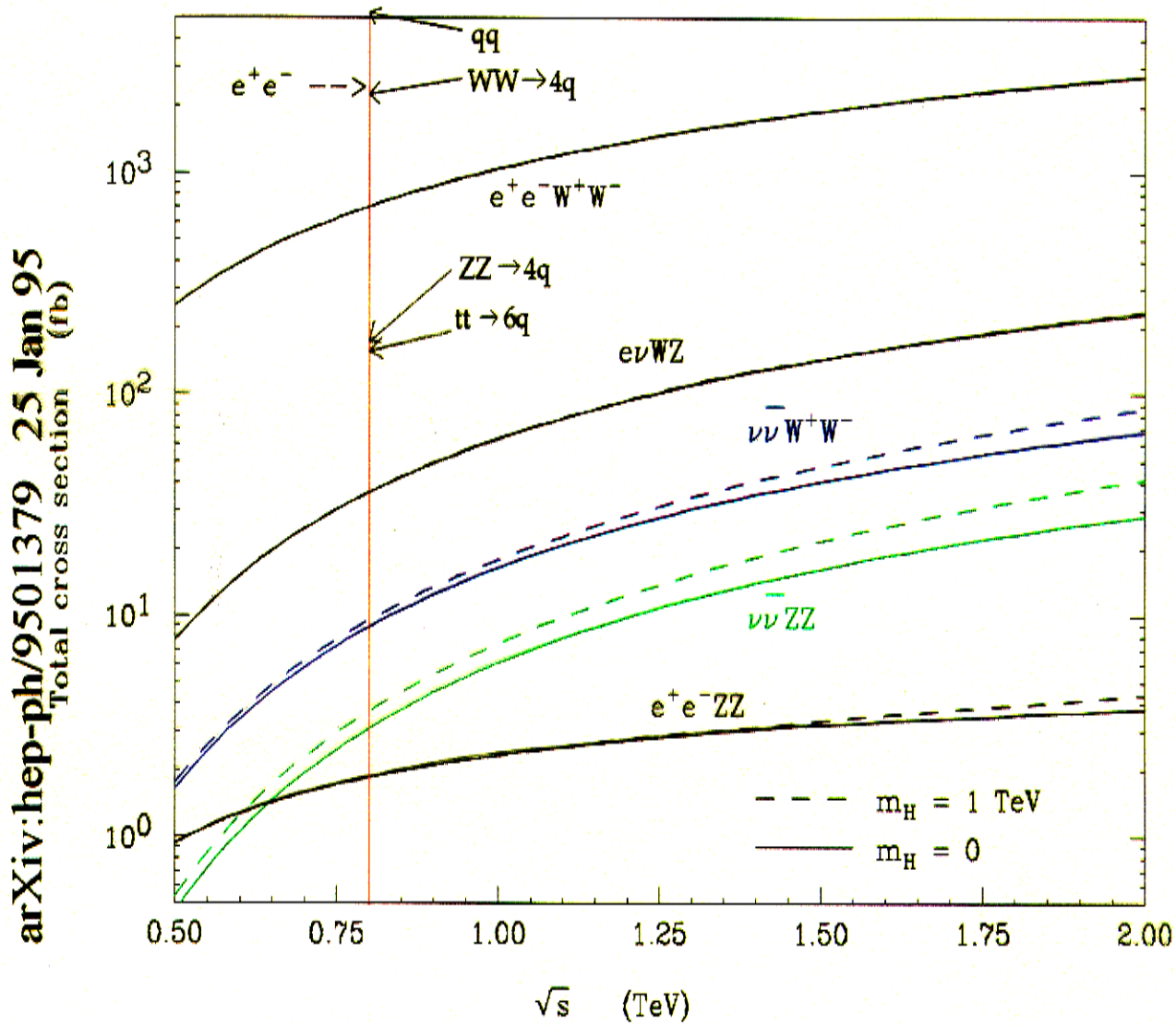
$$L_5 = \alpha_5\left[g^4\left(W^+_\mu W^{\mu-}\right)^2 + \frac{g^4}{c_W^2}W^+_\mu W^{\mu-} Z_\nu Z^\nu + \frac{g^4}{4c_W^4}\left(Z_\mu Z^\mu\right)^2\right]$$

- α_4 and α_5 (both 0 in the SM) are model dependent.

- What's the sensitivity to the αs that can be reached at TESLA?

Cross Sections

- $\sqrt{s}$ =800 GeV and $\int \mathcal{L}$ dt=1000 fb^{-1} are assumed in this study. No beam polarisation yet.
- ISR included, beamstrahlung neglected.



Detector Setup

- SIMDET V3 is used (Pohl,Schreiber).
- Basic layout taken from CDR:

TRACKING:	**CCD 2 cm + FT + TPC** $\lvert\vec{B}\rvert = 3T$
	TPC coverage down to approx. 10°
	overall tracking coverage down to ~5°
CALORIMETRY:	**E.M.** $0.6\%+10\%/\sqrt{E}$
	HAD $4\%+40\%/\sqrt{E}$
	calorimetry acceptance down to ~5°
VERY FORWARD:	**instrumented mask from 5 to 83 mrad**
	no dead regions from 50 to 80 mrad
	LAT from 23.5 to 83.1 mrad

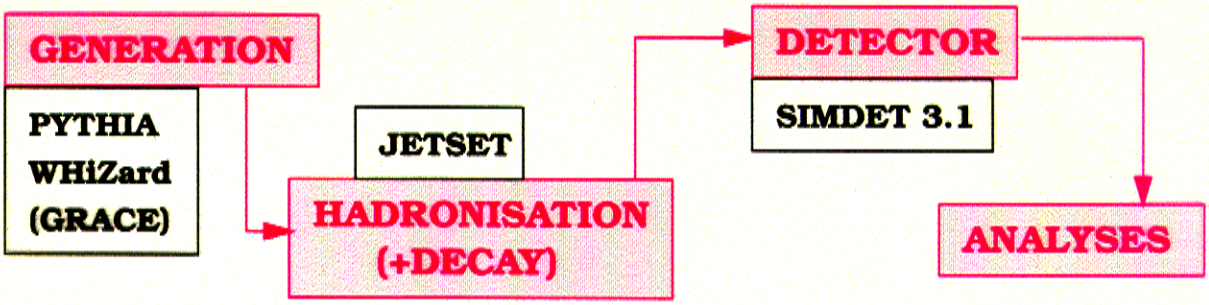
- Key points of these analyses:

✗ hermeticity + forward coverage

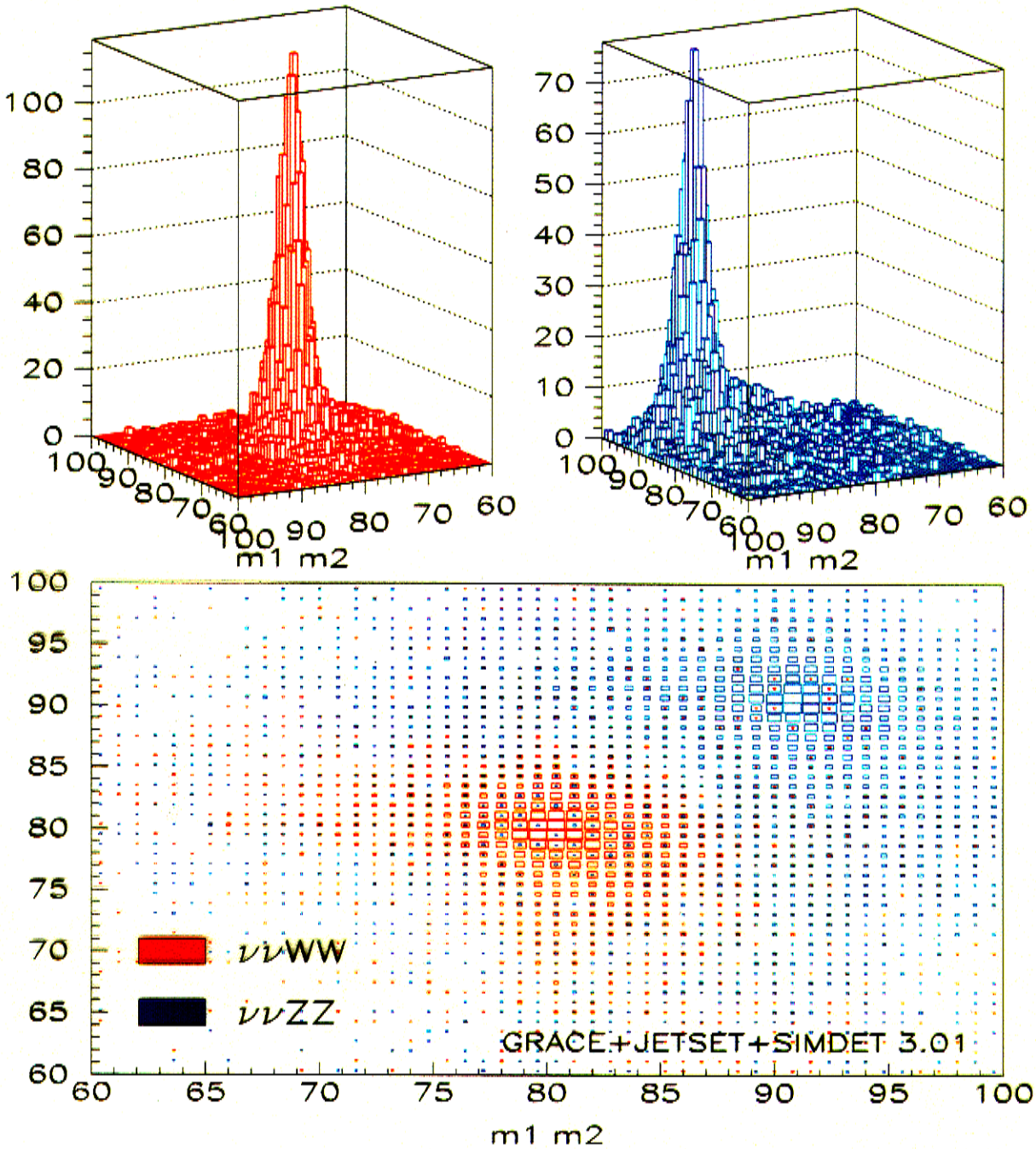
⇒ p_T determination, missing E, forward $e^{+/-}$

✗ tracking, calorimetry

⇒ excellent mass resolution, b tagging



Detector performance



- Mass resolution ~4%.

Performance of the selections

Channel*	Exp. events** ($\nu\nu ZZ$)	Exp. events** ($\nu\nu WW$)
$ee \rightarrow \nu\nu ZZ$***	844 ± 10	
$ee \rightarrow \nu\nu WW$***		2550 ± 30
$ee \rightarrow \nu\nu q\bar{q}q\bar{q}$	88 ± 5	151 ± 5
$ee \rightarrow \nu e ZW$	570 ± 20	350 ± 10
$ee \rightarrow eeWW,ZZ$	negligible	130 ± 20
$ee \rightarrow t\bar{t}$	83 ± 5	400 ± 70
$ee \rightarrow WW,ZZ$	23 ± 10	negligible
$ee \rightarrow q\bar{q}$	negligible	negligible
efficiency***	0.522 ± 0.006	0.401 ± 0.004
purity***	52.3%	71.2%
$\Delta\sigma/\sigma$	3.2%	2.0%

(*) Only final states leading to four quarks at least are considered.

(**) A centre of mass energy of 800 GeV and an integrated luminosity of 1000 fb^{-1} are assumed.

(***) Double resonant regions of the signal are defined with the following cuts:

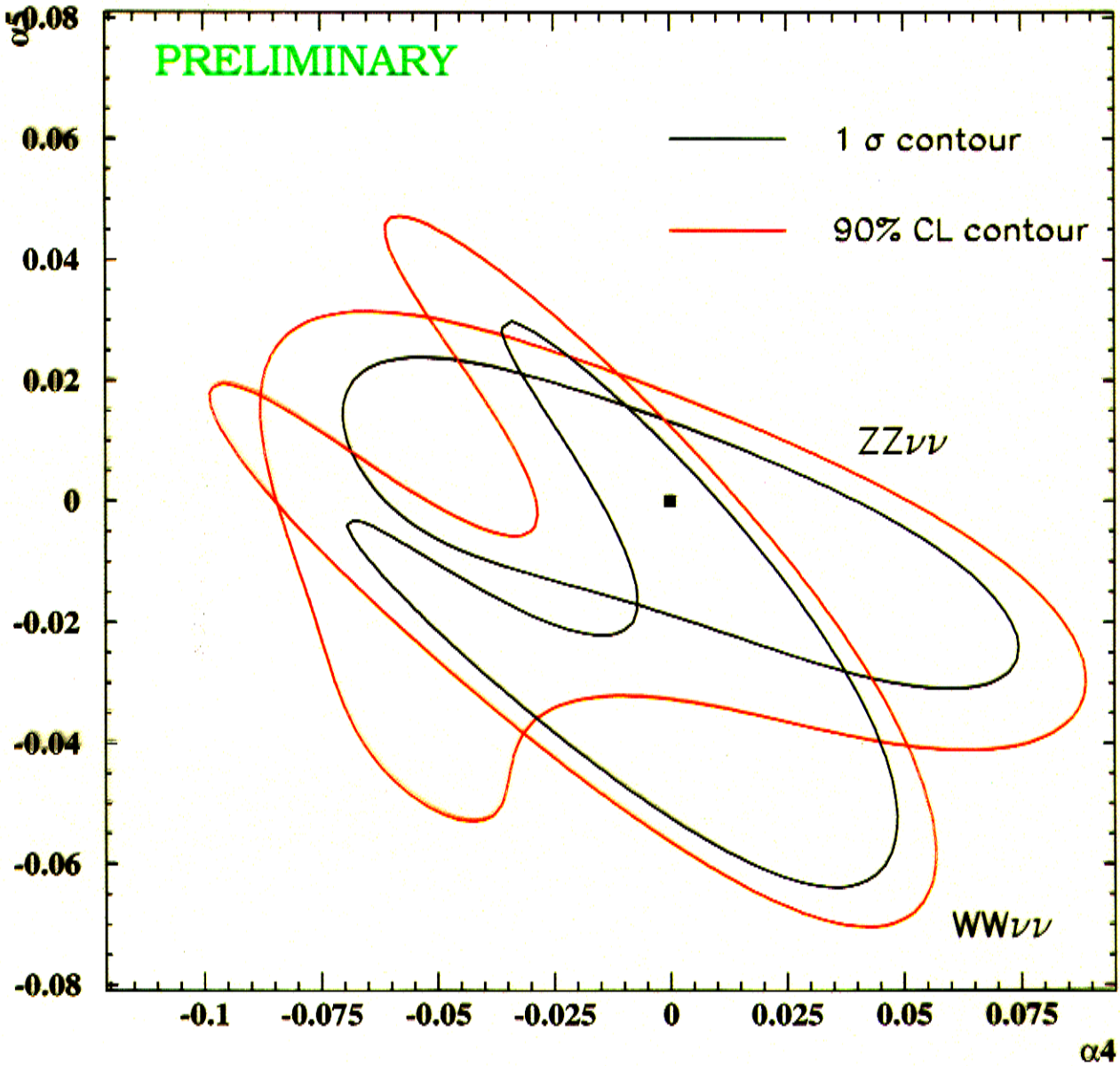
$\nu\nu ZZ$: 170 GeV$<m_1+m_2<$195 GeV $|m_1-m_2|<$20 GeV

$\nu\nu WW$: 75 GeV$<m_1, m_2<$85 GeV

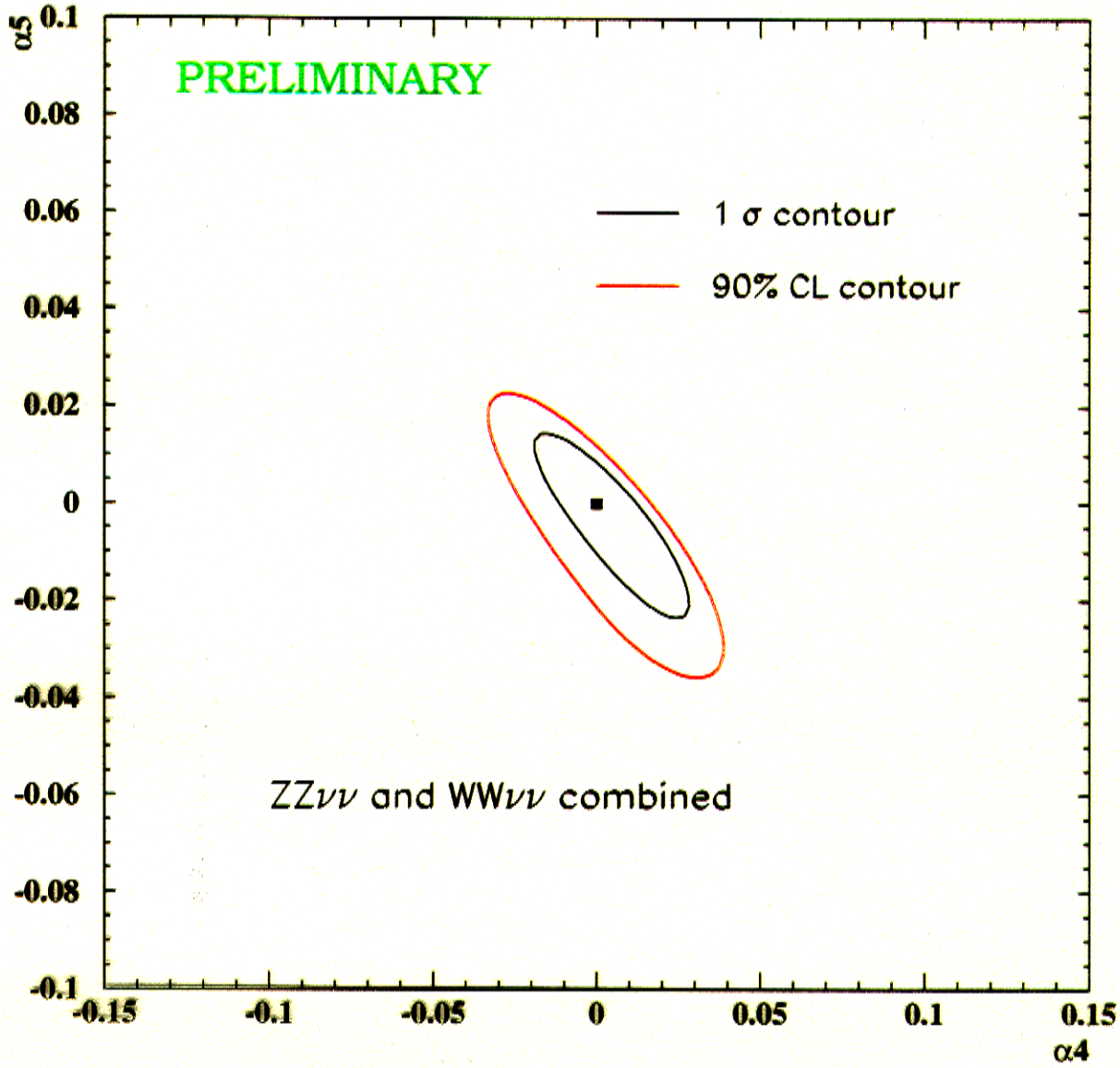
Likelihood outputs for ννZZ and ννWW

- Double minimum structures, more evident for ννWW.

  ⇒ Effect depending upon the structure of $\sigma(\alpha_4, \alpha_5)$.



Combined Likelihood



- Expected limits are of the order of 10^{-2}.
- Not directly comparable with LHC...

Possible Improvements

- Inclusion of other final states ($\nu\nu q\bar{q}l\nu$, $\nu\nu q\bar{q}ll$).
  - ✗ different selection, cleaner signature.
- Use of other tools in the analyses.
  - ✗ lepton identification.
- Use even more information in the event.
  - ✗ W-pair invariant mass. One extra-dimension for our likelihood.
- Exploit initial state polarisation for S/N enhancement.
  - ✗ the signal is enhanced by $(1+P_+)(1+P_-)$.
  - ✗ $e\nu WZ$ is enhanced by $1+(P_++P_-)/2$. The other backgrounds are not modified.

    ⇒ polarisation of both electrons and positrons is important.

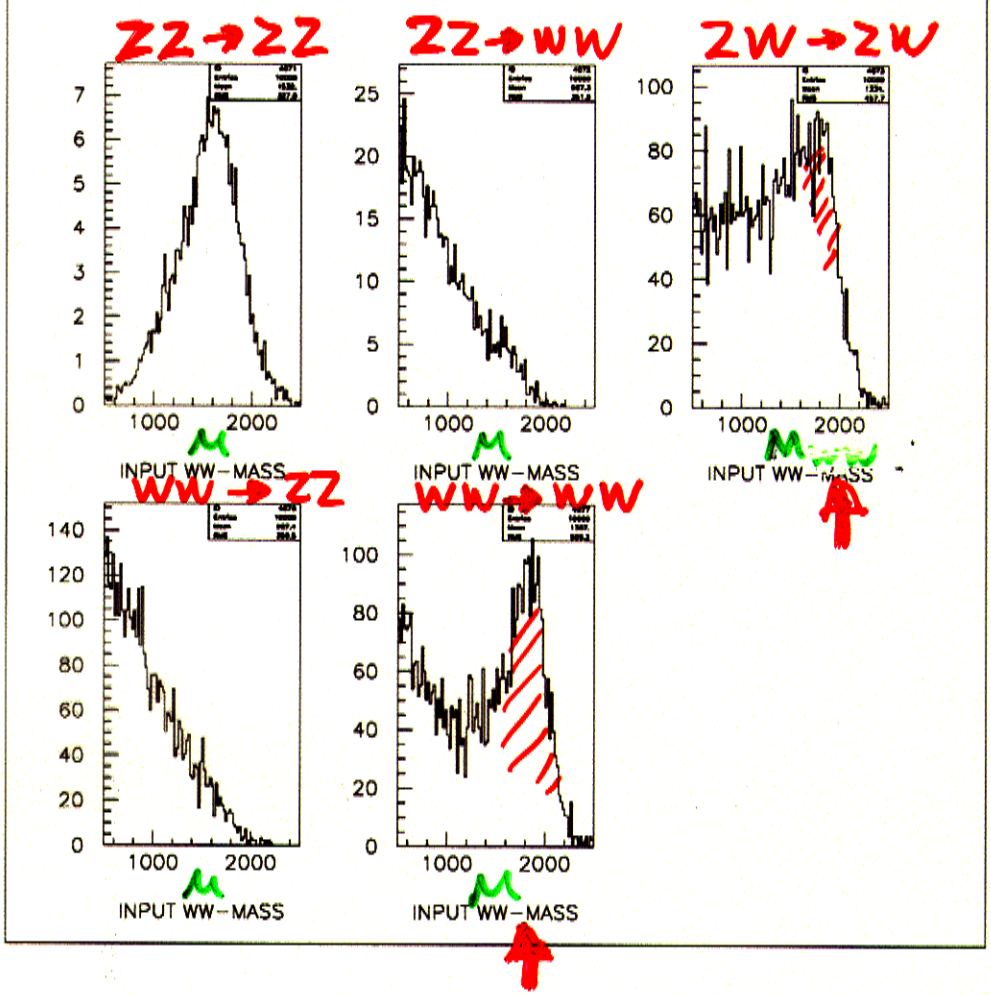
PLANS FOR A NEAR FUTURE (in time for TDR?):

- Redo everything including IS polarisation, assuming 80%e^-/40%e^+.
- Use WHiZard as unique 6f generator.
- Fit m(WW) together with the angular distributions.

THEORETICAL FRAMEWORK

- ZZ, WW AND WZ CROSS SECTIONS (EVENTS/500 FB^{-1}/20 GEV)

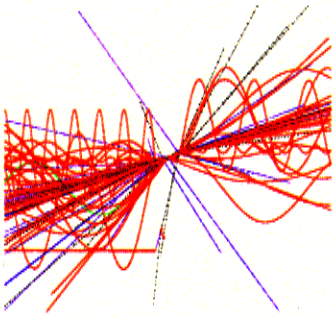
$a_5 = -0.002$, $a_4 = 0.0$, BROAD REASONANCE AROUND 2 TEV.

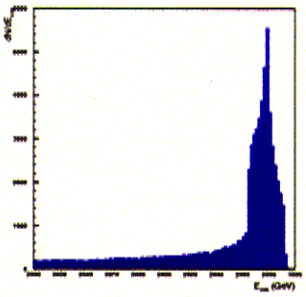


IMPLEMENTED IN PYTHIA (PROCS 71 → 77) (B. COX, J. FORSHAW)

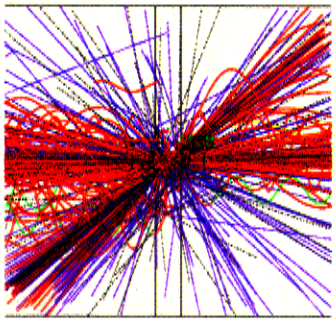
Analysis Tools

Physics Generator ((CompHep +) Pythia 6)
+ CLIC Beamstralhung Spectrum (Calypso)



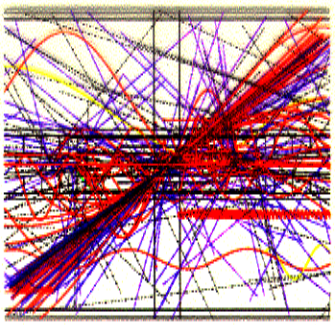


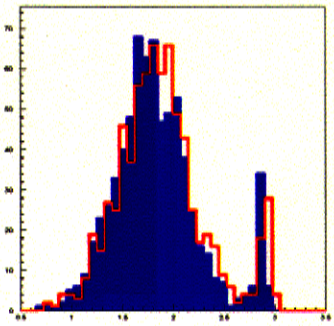
+ $\gamma\gamma \rightarrow$ **hadron Background** (Hades)



$\rightarrow$ Hepevt File

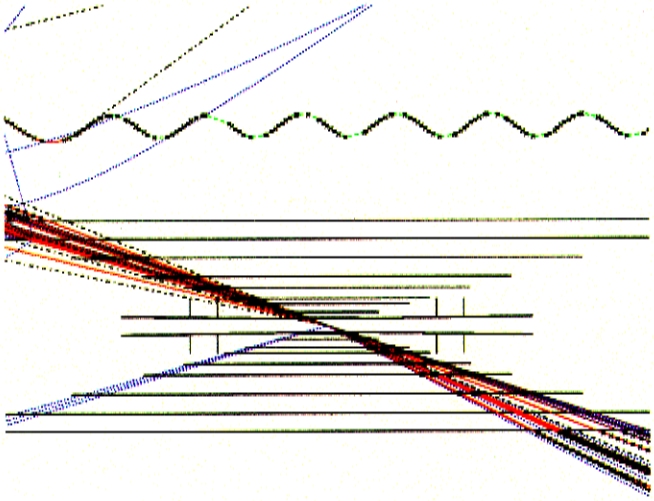
Geant **Full Sim**	Simdet **Par. Smear**
(TESLA CDR Det.)	**(TESLA CDR Det.)**
(Brahms v.1)	**B = 4-6 T**

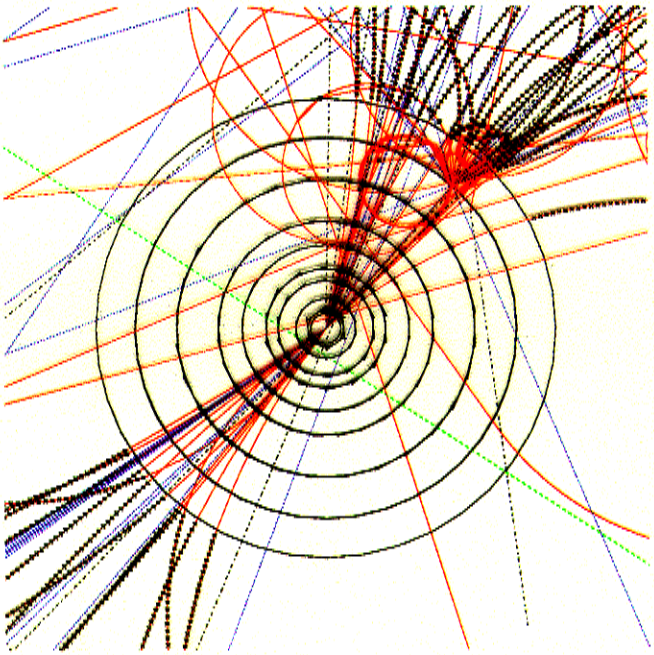




Events

Case Study: $M_{WW} = 2$ TeV, $\Gamma = 85$ GeV





MEASURED SPECTRUM

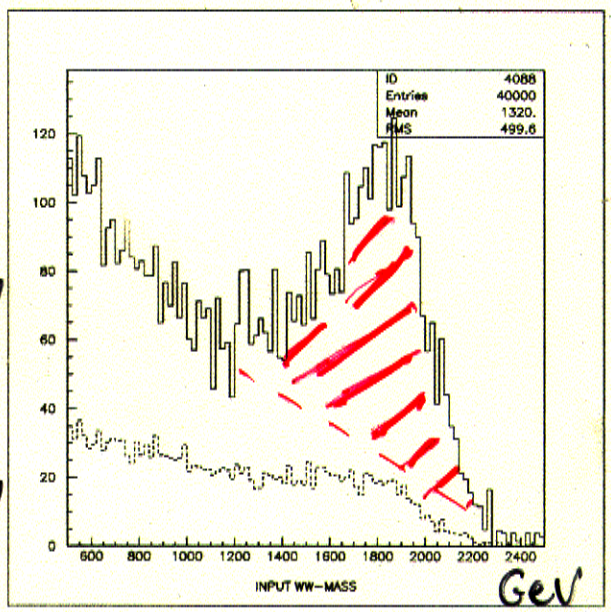
FORSHAW ET AL. MODEL ALL CHANNELS

a_5=−0.002, a_4=0.0, PADDE UNITARIZATION

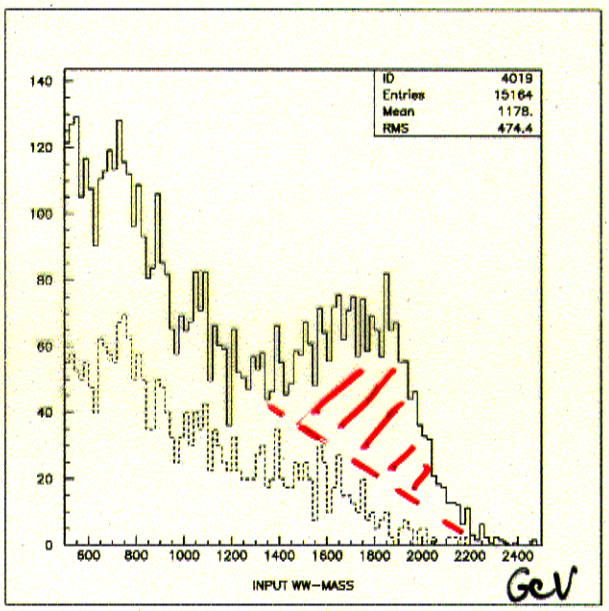
BEFORE DETECTOR

1600 fb^{-1}

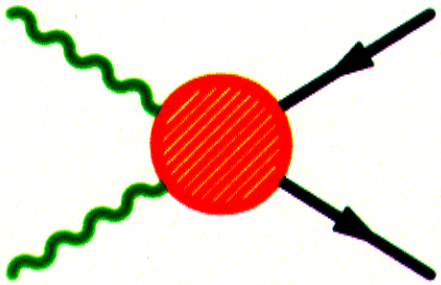
ZZ → WW
ZW → ZW
WW → ZZ
WW → WW



AFTER DETECTOR



Top Quark Interaction



Role of the top quark in EWSB?

$W_L W_L \to t\bar{t}$ and $W_L Z_L \to t\bar{b}$ at Future e^+e^- Colliders – Probing TeV-scale new physics*

Tao Han, UW - Madison

(The 5th Linear Collider Workshop, FNAL, Oct. 26, 2000)

I. Top-SEWS sector:

General parameterization

Constraints on model parameters

II. Signal/background calculations:

Effective W Approximation

Signal identification

III. Sensitivity on the models

Cases for $\sqrt{s} = 1.5,\ 4$ TeV

*T. Han, Y.-J. Kim, A. Likhoded, and G. Valencia, hep-ph/0005306, to appear in NPB.

Study of the $WW \to H \to t\bar{t}$ Process at TESLA

Juan Alcaraz
CIEMAT, Madrid

Ester Ruiz Morales
UAM, Madrid

5th International e^+e^- Linear Collider Workshop
Fermilab, 24-28 October 2000

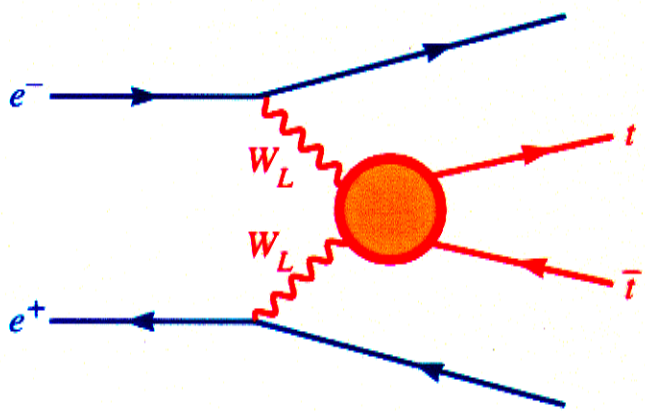
- Motivation
- At the generator level
- At the reconstruction level: selection cuts
- Results
- Conclusions and Outlook

Top quark and the EWSB:

$$M_W = \frac{1}{2} g v, \quad m_t \approx \frac{v}{\sqrt{2}} \quad ?!$$

Consider the processes: †

$$e^+e^- \to \bar{\nu}\nu W^* W^* \to \bar{\nu}\nu\ \bar{t}t,$$
$$e^+e^- \to \bar{\nu}e^- W^* Z^* \to \bar{\nu}e^-\ t\bar{b}.$$

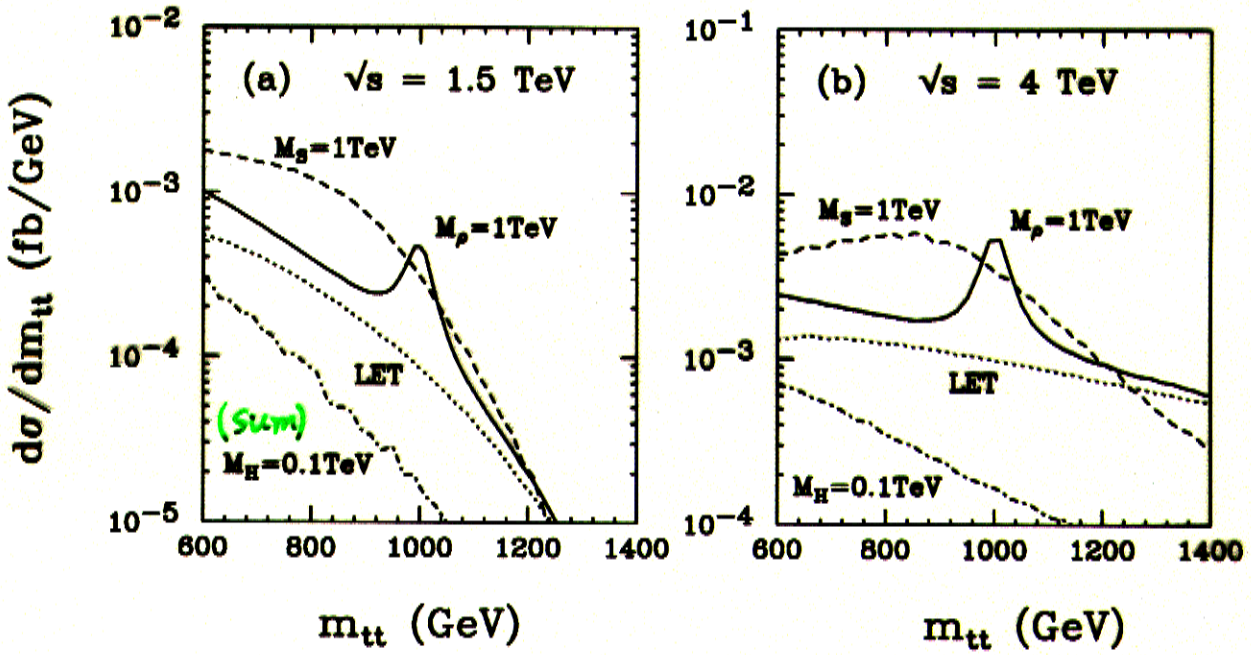


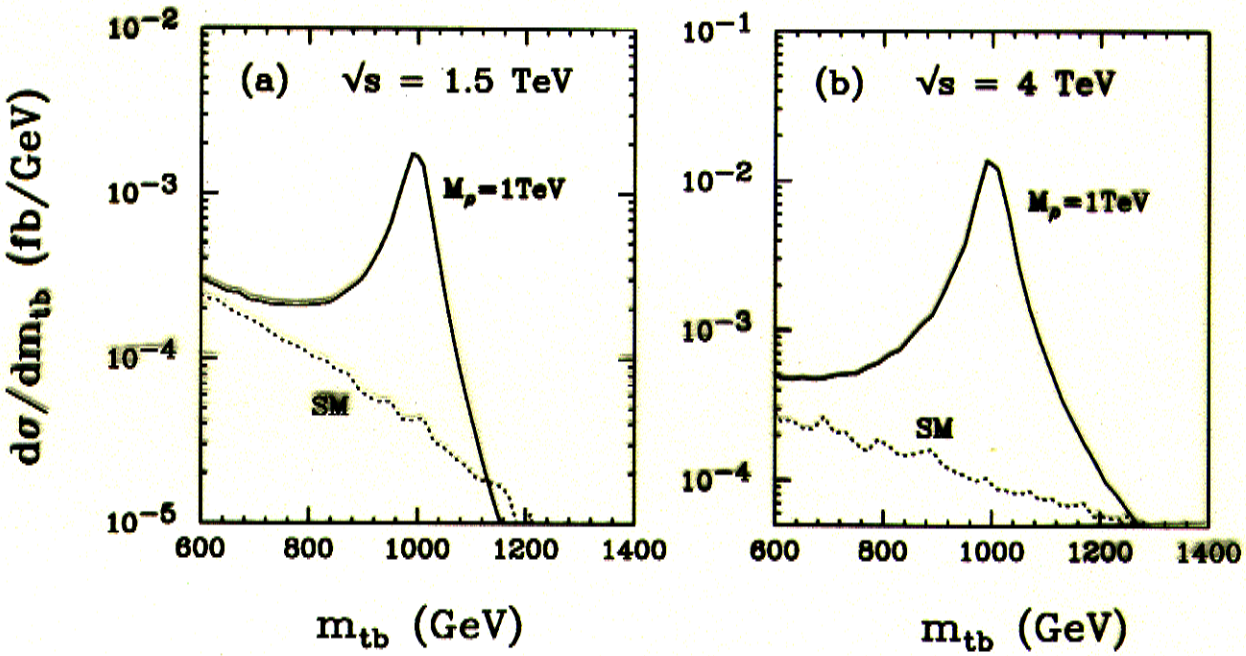
which can test

$$W_L^+ W_L^- \to H^0, \ \rho_T^0 \to \bar{t}t$$
$$W_L^\pm Z_L \to \rho_T^\pm \to tb.$$

†Kauffman; Barklow; Gintner and Godfrey; Larios, Tait and Yuan; Morales and Peskin.

Clear signals:





Previous Studies

Theoretical Studies

- E. Ruiz Morales and M. Peskin, Sitges 99
  - $WW \to t\bar{t}$ in different strong-interaction scenarios
  - $\sqrt{s} = 1.5$ TeV
  - Polarization analysis based on experimental "guesses"
- T. Han *et al.*, 2000
  - $WW \to t\bar{t}$, and also $WZ \to tb$
  - $\sqrt{s} \gtrsim 1.5$ TeV

Simulation Studies

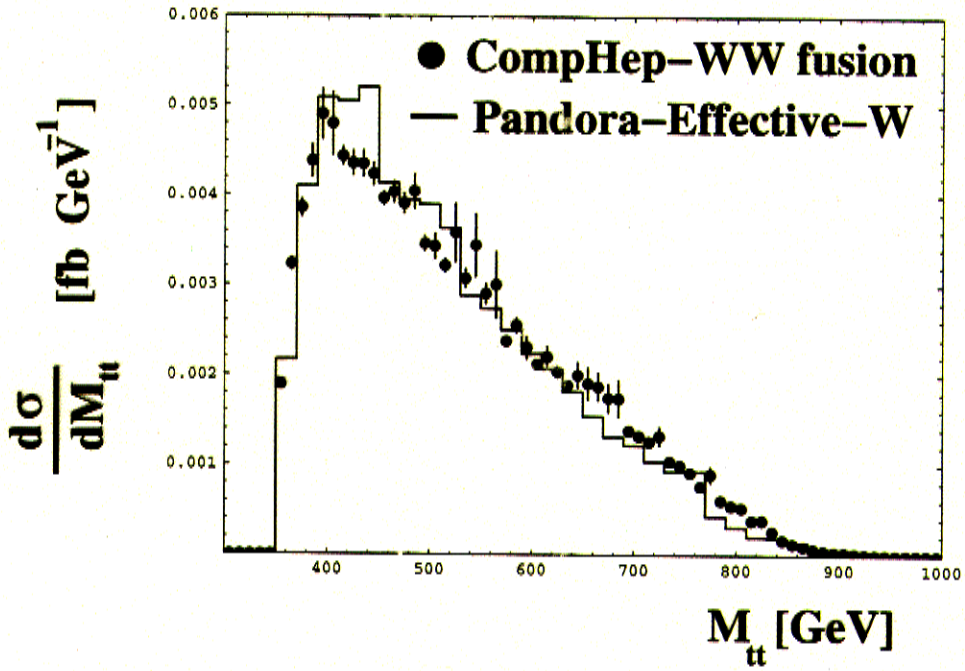
- T. Barklow at Snowmass (1996), $\sqrt{s} = 1.5$ TeV
- Tsukamoto, JLC study (1991)

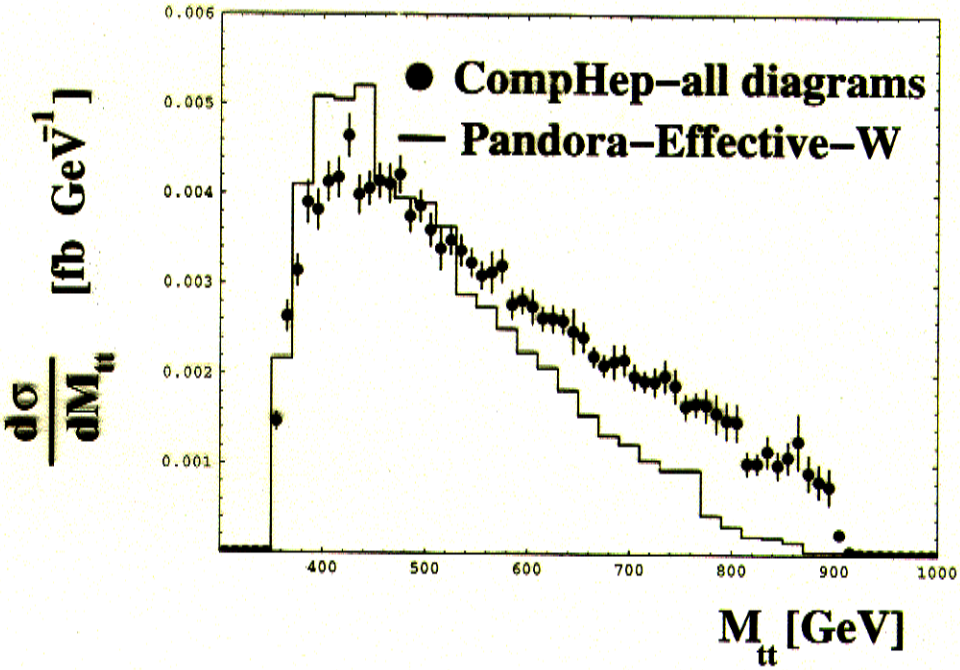
Our Analysis

- Realistic simulation study for TESLA: $\mathcal{L} = 1$ ab^{-1}, $\sqrt{s} = 1$ TeV, 800 GeV.
- Full calculation including reducible and irreducible backgrounds. Need reliable event generators.
- Include ISR and Beamstrahlung (CIRCE).
- Realistic Detector Simulation and reconstruction (SIMDET, V3.02).
- Reliable conclusions $\Rightarrow$ cut-based analysis, do not push performance to the limit.

$$\sqrt{s} = 1 \text{ TeV}, \; m_{\mathrm{H}} = 800 \text{ GeV}$$

Generator Level, no ISR, no Beamstrahlung





Results: Signal Sensitivity

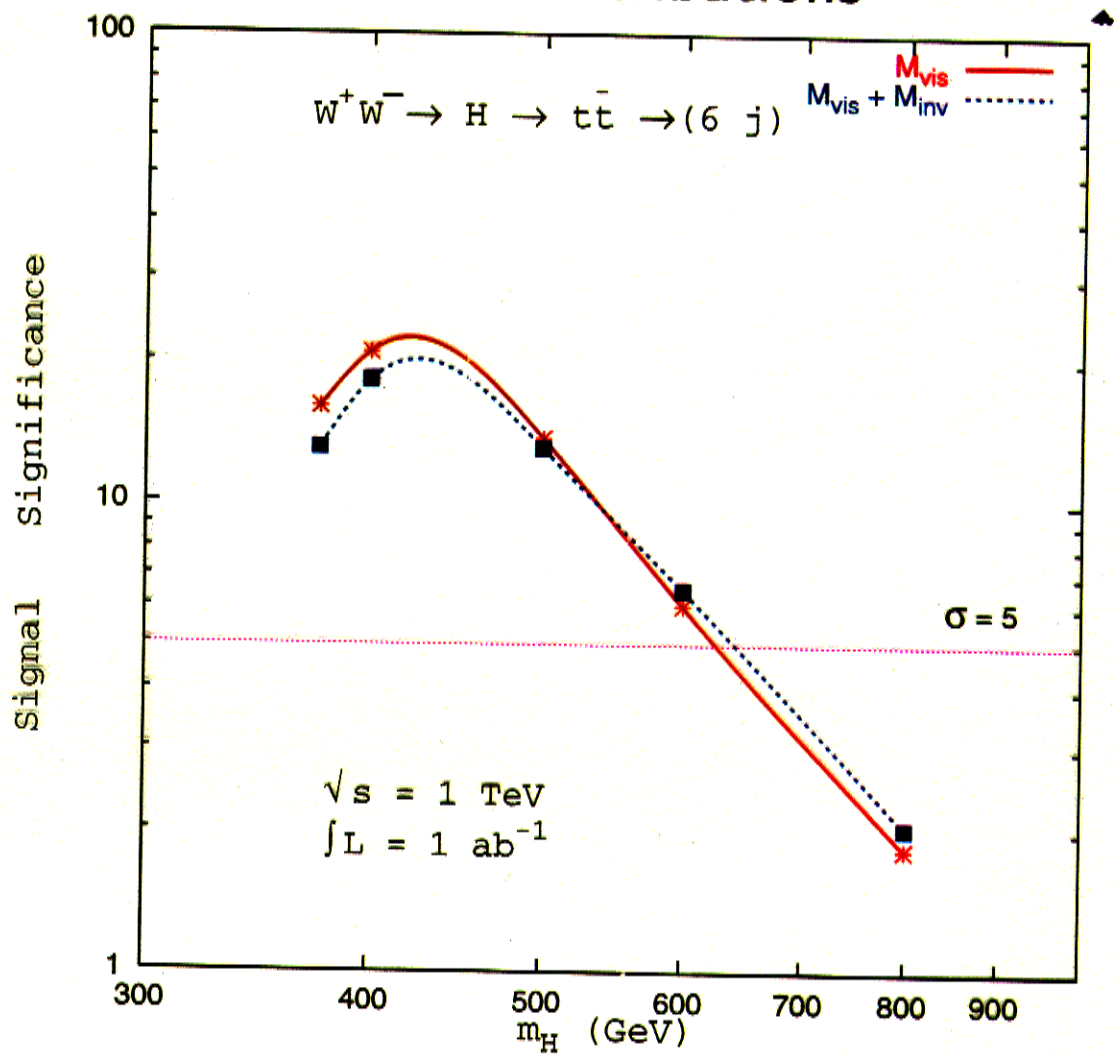
$$\sqrt{s} = 1 \text{ TeV}$$

Events with $M_{\text{vis}} + M_{\text{miss}} > 900$ GeV

m_{H}(GeV)	375	400	500	600	800
Signal	342	542	351	158	41

Background $\equiv N_{\text{expected}}(m_{\text{H}} = 100 \text{ GeV})$: 519

Fit to the distributions



Conclusions

- $WW \to H \to t\bar{t}$ interesting if there is no light Higgs boson.

- It will be observable ($> 5\sigma$) and it will lead to a precise Higgs-top Yukawa measurement ($\frac{\Delta y_t}{y_t} < 10\%$) at the TESLA e^+e^- collider, provided that:

$$350 \text{ GeV} < m_H < 650 \text{ GeV}, (\sqrt{s} = 1 \text{ TeV}, \mathcal{L} = 1 \text{ ab}^{-1})$$

$$350 \text{ GeV} < m_H < 500 \text{ GeV}, (\sqrt{s} = 800 \text{ GeV}, \mathcal{L} = 1 \text{ ab}^{-1})$$

- Similar sensitivities are expected in other scenarios of strong symmetry breaking (i.e. technicolor).

- Extensions of this analysis under study:
  - Include semileptonic $t\bar{t}$ decays,
  - Top polarization studies,
  - Higher $\sqrt{s}$.

Conclusions

Giga-Z: most precise EW measurements

(! polarization, E !)

TGC: high precision measurements

→ new physics sensitivity

(! radiative corrections !)

$WW \to WW, ZZ, t\bar{t}$: detailed simulations

→ strong EWSB visible

(! high lumi for threshold !)

(! high energy for looking beyond !)