Electroweak and Alternative Theories
WG Summary

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Presentations in Vienna

- *Axel Bredenstein: Four-fermion production at □□colliders (hep-ph/0405169, hep-ph/0506005)*
- *Andre Utermann: Effective Lagrangian approach to WW production (hep-ph/0404006, hep-ph/0508132, hep-ph/0508133)*
- *Predrag Krstonosic: Quartic boson couplings*
- *Michael Beyer: Quartic gauge couplings from triple boson production*
- *Juan Antonio Aguilar-Saavedra: Single heavy neutrino production in e+e- colliders (hep-ph/0502189, hep-ph/0503026)*
- *Thomas Rizzo: Warped Univerzal Extra Dimensions (hep-ph/0508279, hep-ph/0509160)*
- *Stefania De Curtis: Playing with fermion couplings in Higgsless models (hep-ph/0405188, hep-ph/0502209)*

Four-fermion production at γγ colliders

Monte Carlo generator

A.B.,Dittmaier,
Roth '04-'05

Cofferγγ (COrrections to
Four-FERmion production in $\gamma\gamma$ collisions)

- complete Born matrix elements
  - ◇ $\gamma\gamma \to 4f$ and $\gamma\gamma \to 4f + \gamma$ with massless fermions
  - ◇ anomalous γWW, $\gamma\gamma$WW and $\gamma\gamma$ZZ couplings + effective γγH coupling
- radiative corrections to $\gamma\gamma \to \mathrm{WW} \to 4f$ in double-pole approximation

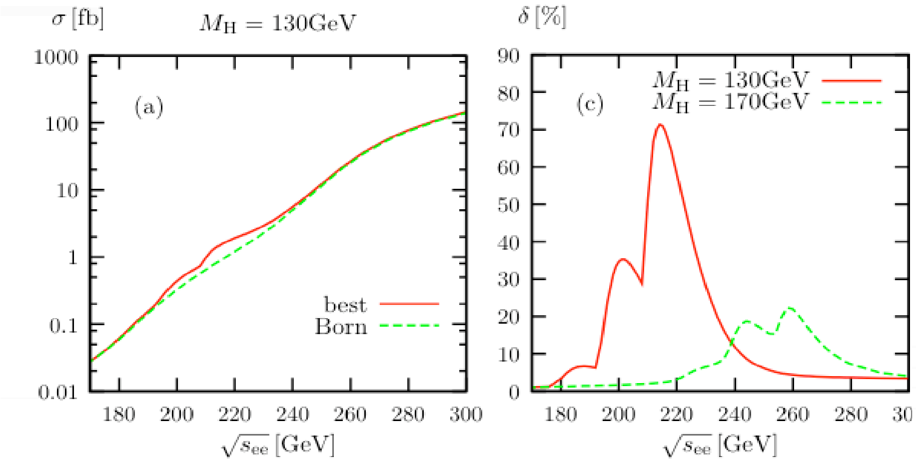
similar to e^+e^- case: Aeppli, v.Oldenborgh, Wyler '93; Beenakker, Berends, Chapovsky '98;
(RacoonWW) Jadach et al. '99; Denner, Dittmaier, Roth, Wackeroth '99

- integration with multi-channel Monte Carlo with adaptive optimization
- treatment of real corrections with dipole subtraction or phase-space slicing (including generalization to non-collinear observables)
- realistic photon spectrum e.g. CompAZ, Zarnecki '02

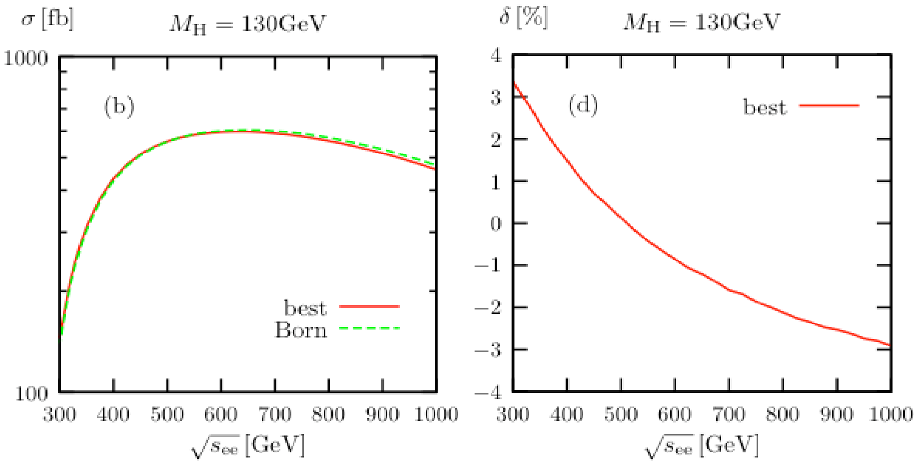
Bredenstein et al.

Impact of O(α) corrections

$\mathcal{O}(\alpha)$-corrected integrated cross section for $\gamma\gamma \to \nu_e e^+ d\bar{u}$ G_μ-scheme

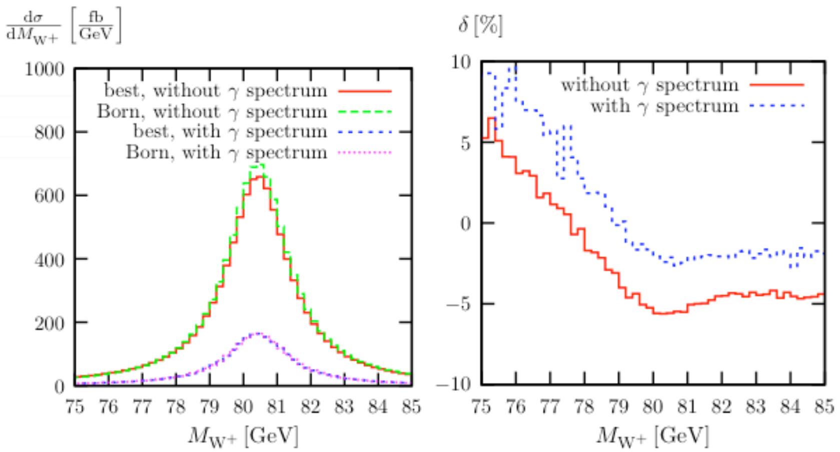


photon spectrum determines shape of Higgs resonance as function of e^-e^- CM energy $\sqrt{ee}$



$\mathcal{O}(\alpha)$ corrections $\sim 3\%$ away from Higgs resonance

$\mathcal{O}(\alpha)$-corrected W-invariant-mass distribution for $\gamma\gamma \to \nu_e e^+ d\bar{u}$ G_μ-scheme



important corrections to W-line shape

Bredenstein et al.

Effective Lagrangian approach to WW production

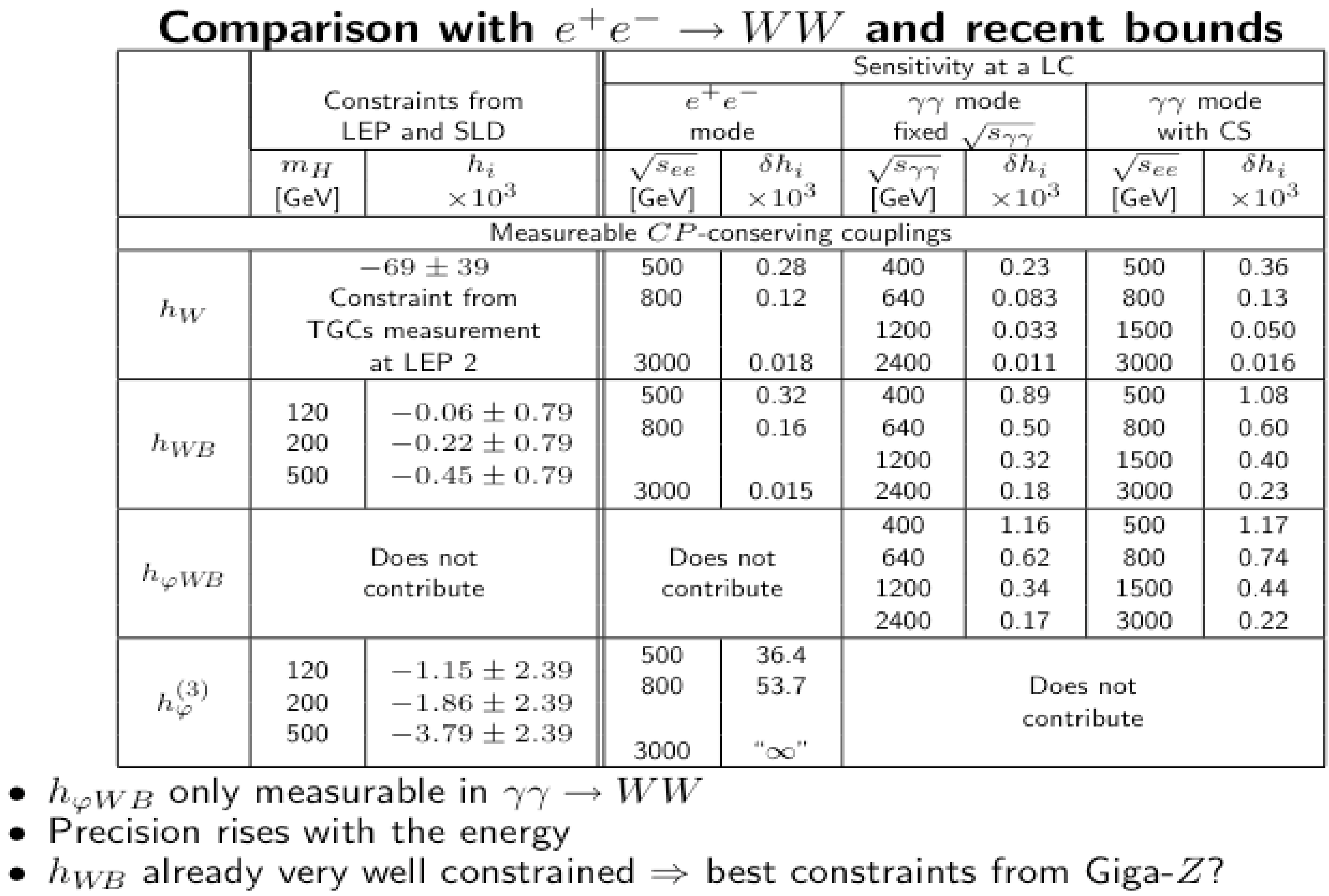
- Aim: consistent analysis of constraint from $e^+e^- \to W^+ W^-$, $\gamma\gamma \to W^+ W^-$ and high precision observables
- Idea: instead of the more general but less economic form factor approach (i.e. introducing form factors for every single vertex after EWSB), add terms satisfying certain symmetries to the SM Lagrangian before EWSB
- Restrictions:
  - * Only SM gauge boson and Higgs fields contribute
  - * SU(3)xSU(2)xU(1) invariant terms
  - * Operators up to dimension 6
- 10 non-SM terms - 10 anomalous coupling: h_i

	SM	h_W	$h_{\tilde W}$	$h_{\varphi W}$	$h_{\varphi \tilde W}$	$h_{\varphi B}$	$h_{\varphi \tilde B}$	h_{WB}	$h_{\tilde W B}$	$h_\varphi^{(1)}$	$h_\varphi^{(3)}$
γWW	✓	✓	✓					✓	✓		
ZWW	✓	✓	✓					✓	✓		P_Z
$\gamma\gamma WW$	✓	✓	✓								
$\gamma\gamma H$				✓	✓	✓	✓	✓	✓		

- Relation to the usual anomalous TGCs (g_1, □, □, □$^□$, □$^□$, g_4, g_5) can be established by identifying the terms in the effective Lagrangian after the EWSB
- Additional terms in Lagrangian before EWSB → redefine fields and parameters to get the physical quantities → anomalous couplings affect EW observables (m_W, Γ_W, σ^0_{had}, ...)

Utermann et al.

Expected sensitivity of optimal observable analyses



Comparison with $e^+e^- \to WW$ and recent bounds

	Constraints from LEP and SLD		Sensitivity at a LC					
			e^+e^- mode		$\gamma\gamma$ mode fixed $\sqrt{s_{\gamma\gamma}}$		$\gamma\gamma$ mode with CS	
	m_H [GeV]	h_i $\times 10^3$	$\sqrt{s_{ee}}$ [GeV]	δh_i $\times 10^3$	$\sqrt{s_{\gamma\gamma}}$ [GeV]	δh_i $\times 10^3$	$\sqrt{s_{ee}}$ [GeV]	δh_i $\times 10^3$
Measureable CP-conserving couplings								
h_W	-69 ± 39 Constraint from TGCs measurement at LEP 2		500	0.28	400	0.23	500	0.36
			800	0.12	640	0.083	800	0.13
					1200	0.033	1500	0.050
			3000	0.018	2400	0.011	3000	0.016
h_{WB}	120	-0.06 ± 0.79	500	0.32	400	0.89	500	1.08
	200	-0.22 ± 0.79	800	0.16	640	0.50	800	0.60
	500	-0.45 ± 0.79			1200	0.32	1500	0.40
			3000	0.015	2400	0.18	3000	0.23
$h_{\varphi WB}$	Does not contribute		Does not contribute		400	1.16	500	1.17
					640	0.62	800	0.74
					1200	0.34	1500	0.44
					2400	0.17	3000	0.22
$h_\varphi^{(3)}$	120	-1.15 ± 2.39	500	36.4	Does not contribute			
	200	-1.86 ± 2.39	800	53.7				
	500	-3.79 ± 2.39						
			3000	"∞"				

- $h_{\varphi WB}$ only measurable in $\gamma\gamma \to WW$
- Precision rises with the energy
- h_{WB} already very well constrained $\Rightarrow$ best constraints from Giga-Z?

Utermann et al.

Based on unpolarized □□□ WW calculation.
Desirable to calculate the polarized case.

Experimental study of gauge boson scattering

- ✘ Expected limits on the parameters $□_i$ (i=4-7,10) of the EW chiral Lagrangian from studies of gauge boson scattering were presented at LCWS05 (hep-ph/0508179)

Scattering processes
(only hadronic final states)

$e^+ e^□$ □	$e^□ e^□$ □	$□_4$	$□_5$	$□_6$	$□_7$	$□_{10}$
$W^+ W^□$ □ $W^+ W^□$	$W^□ W^□$ □ $W^□ W^□$	+	+			
$W^+ W^□$ □ $Z Z$		+	+	+	+	
$W^\pm Z$ □ $W^\pm Z$	$W^□ Z$ □ $W^□ Z$	+	+	+	+	
$Z Z$ □ $Z Z$	$Z Z$ □ $Z Z$	+	+	+	+	+

Expected limits
(1 ab^{-1} @ 1 TeV,
$P(e^-)=80\%$, $P(e^+)=40\%$)
$SU(2)_c$ violating →
conserving ↘

5D	□-	□+
$□_4$	-2.72	2.37
$□_5$	-2.46	2.35
$□_6$	-3.93	5.53
$□_7$	-3.22	3.31
$□_{10}$	-5.55	4.55

2D	□-	□+
$□_4$	-1.41	1.38
$□_5$	-1.16	1.09

Krstonosic et al.

- ✘ Relate these limits to the parameters of the underlying theory
- ✘ Consider all possible new heavy resonance (J=0,1,2; I=0,1,2) that may be involved in the scattering process and extract limits on their mass
- ✘ Resonance width limited from below by partial width to a vector boson pair, from above by its mass. This limits the resonance coupling and the scattering amplitude.

Limits on resonance mass

- By integrating the resonance out of the Lagrangian, one can relate the parameters of the theory (resonance mass) to measurable values (parameters of the chiral Lagrangian)
- Example: singlet scalar resonance has two independent linear couplings g (isospin conserving) and h (isospin violating).

$$\alpha_6 = 0$$

$$\alpha_4 = 0 \qquad \alpha_7 = 2gh\left(\frac{v^2}{8M^2}\right)$$

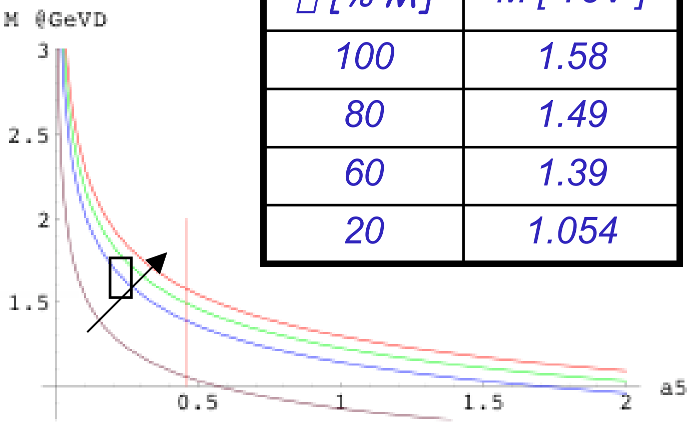
$$\alpha_5 = g^2\left(\frac{v^2}{8M^2}\right) \qquad \alpha_{10} = 2h^2\left(\frac{v^2}{8M^2}\right)$$

- in the high-mass limit partial width of the resonance to the WW and ZZ:

$$\Gamma = \frac{g^2 + \frac{1}{2}(g^2 + h^2)}{16\pi}\left(\frac{M^3}{v^2}\right)$$

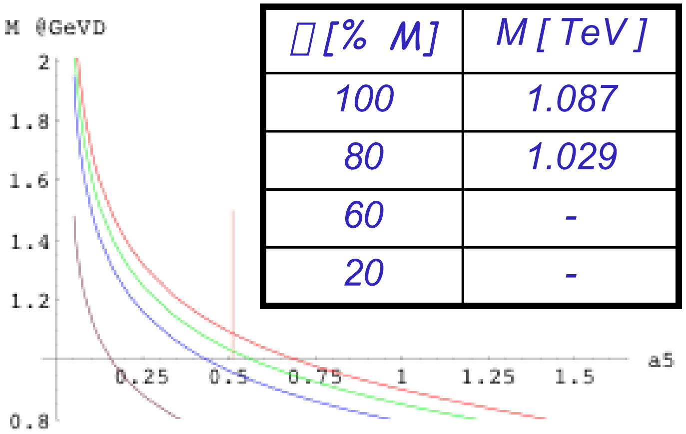
- Systematic extraction of mass limits on the basis of available limits on quartic boson couplings will be perfomed

Krstonosic et al.



Γ [% M]	M [TeV]
100	1.58
80	1.49
60	1.39
20	1.054

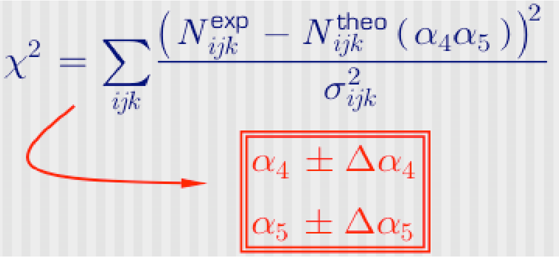
SU(2)$_c$ violating
conserving



Γ [% M]	M [TeV]
100	1.087
80	1.029
60	-
20	-

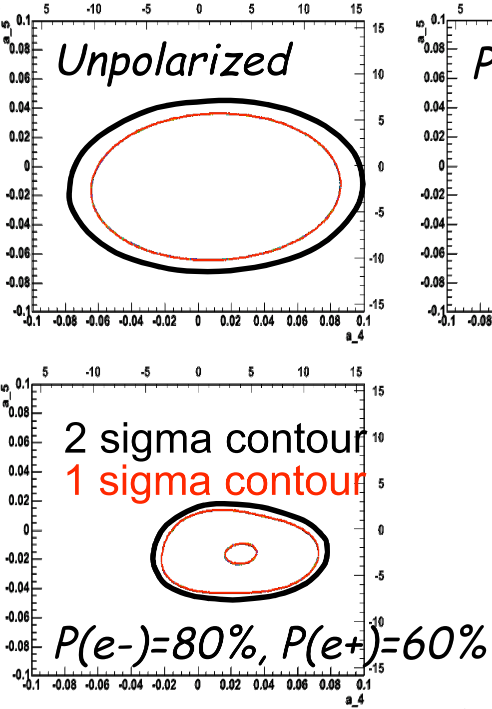
Triple gauge boson production

- Study e^+e^-□ $W^+ W^- Z$ @ 1 TeV with 1000 fb^{-1} with different polarization options
- Fifteen tree level processes, only 1 with QGC
- Polarization enchances the contribution with longitudinal gauge bosons that are sensitive to EWSB
- Study 6 jet final state , main background: tt □ bWbW□ 6j
- Bin events in 3 kinematic variables: m_{WW}, m_{WZ}, □(Z)
- Info comes from rate (not from shape)
- Minimize



$$\chi^2 = \sum_{ijk} \frac{\left(N^{\mathrm{exp}}_{ijk} - N^{\mathrm{theo}}_{ijk}\,(\alpha_4\alpha_5\,)\right)^2}{\sigma^2_{ijk}}$$

$$\boxed{\begin{array}{l}\alpha_4 \pm \Delta\alpha_4 \\ \alpha_5 \pm \Delta\alpha_5\end{array}}$$



N^{exp}: Whizard - Pythia - Simdet
N^{theo}: Whizard (reweighting events)

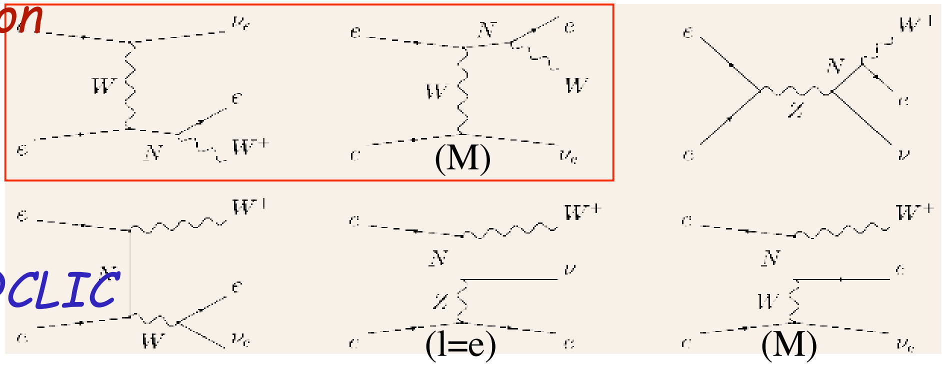
- Future:
  include final states with 4j
  include angular distribution of jets
  (sensitive to polarisation)

Beyer et al.

Single heavy neutrino production

Aguilar-Saavedra et al.

- Seesaw contribution to □ masses: $m_{\square} \sim Y^2 v^2 / m_N$
  small Yukawa couplings or cancellation with other source (symmetries)
- Model: additional neutrino singlets : N_{iR} (Majorana); N_{iL}, $\square_{iR}$, N_{iR} (Dirac) but no extra interactions
- N pair-production ~ $O(V^2)$ plus phase-space suppression
- N decay: $\square(Wl):\square(Z\square_l):G(H\square_l) = 2 : 1 : 1$ if $m_{H,} m_{Z,} m_W \ll m_N$ ($H\square_l$ ignored here),
- $\square_{Majorana}=2\square_{Dirac}$
- $e^+e^- \square\ lW\square\square\ \ ljj\square$ (only 1 N flavour to be produced) look for a peak in the ljj invariant mass distribution
- ILC(500 GeV, 345 fb^{-1}) and CLIC (3 TeV, 1000 fb^{-1}) with $P(e^+)=0.6$, $P(e^-)=-0.8$
- ISR and beamstrahlung included, parton level analysis with Gaussian smearing of charged lepton and jet energies
- Dominated by on-shell N□ production
- Observable if N-e coupling
- $\square_{Majorana}=\square_{Dirac}$
  2.4pb (m_N=300 GeV @ILC)
  550 fb (m_N=1.5 TeV @CLIC)
- Smaller SM background for l=□,□@CLIC

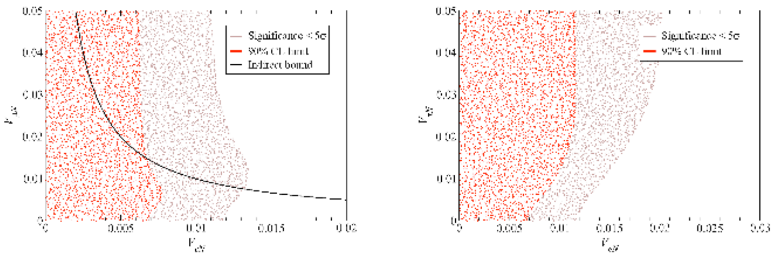


Single heavy neutrino production

Aguilar-Saavedra et al.

Combined limits on V_{eN} and $V_{\mu N}$ or $V_{\tau N}$ (ILC)

The statistical significances of the two channels are added



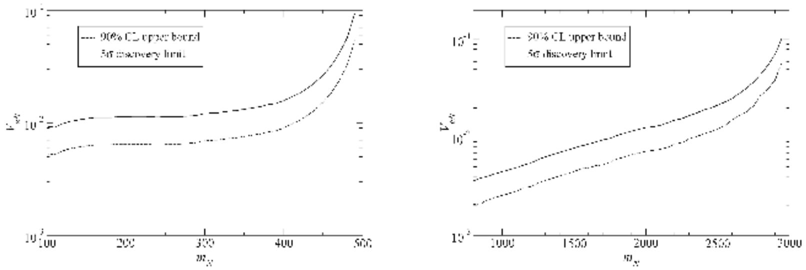
ILC

m_N = 300 GeV $V_{\tau N}$ = 0

ILC

m_N = 300 GeV $V_{\mu N}$ = 0

Discovery limits / upper bounds on V_{eN}, m_N



ILC

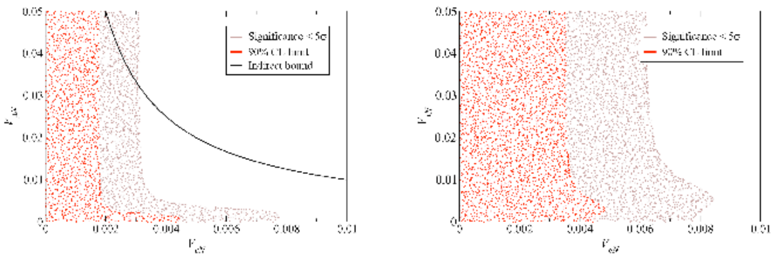
$V_{\mu N}$ = $V_{\tau N}$ = 0

CLIC

$V_{\mu N}$ = $V_{\tau N}$ = 0

Combined limits on V_{eN} and $V_{\mu N}$ or $V_{\tau N}$ (CLIC)

The statistical significances of the two channels are added



CLIC

m_N = 1.5 TeV $V_{\tau N}$ = 0

CLIC

m_N = 1.5 TeV $V_{\mu N}$ = 0

Determine Dirac/Majorana nature from angular distributions

Measurement of ℓNW couplings

S_e, S_μ, S_τ excess of events in the peak region

$$S_\ell = A_\ell \, V_{eN}^2 \frac{V_{\ell N}^2}{V_{eN}^2 + V_{\mu N}^2 + V_{\tau N}^2}, \quad A_\ell \text{ constants}$$

A_ℓ determined from MC simulation ☞

$$V_{eN}^2 = \frac{S_e}{A_e} + \frac{S_\mu}{A_\mu} + \frac{S_\tau}{A_\tau}$$

$$\frac{V_{\ell N}^2}{V_{eN}^2} = \frac{S_\ell}{A_\ell}\left(\frac{S_e}{A_e}\right)^{-1} \qquad \ell = \mu, \tau$$

Precision:

~5% (dominated by syst on A_l) for V_{eN}

2-3% for the ratios

Warped Universal Extra Dimensions

- Aim: put all SM fields including the Higgs into the bulk of the RS model
- Need: a single tachionic KK mode of the Higgs field in the low energy 4D theory (the remaining Higgs KK excitations should be normal, i.e. non-tachionic)
- Key to the solution: the Higgs wavefunction in the bulk depends on the 5th coordinate
- By scanning the parameter space of the Higgs sector (in the bulk and on the TeV and Planck branes), one finds two allowed regions where the usual SM like Higgs mechanism leads to EWSB
- Technical detail: equation of motion could not be solved analitically so far and even numerical solution is difficult so the $M_W=M_Z\cos\theta_W$ relation is not yet satisfied precisely (OK to 5-10%). Need to do better by enforcing custodial symmetry.
- Interesting realization - gravity induced EWSB: use the gravitational sector of RS model to provide the necessary bulk and brane mass scales. These scales are then related to the 5D curvature of RS geometry.
- New relations and constraints obtained among the parameters of the Higgs and gravitational sectors. Measuring both sectors (i.e. KK graviton states and Higgs+ radion) over-constrains the model. Other observations (fermion and gauge KK excitations) can also help.

Rizzo et al.

0.5

Phenomenological implications

- Reduced WWH coupling (by a factor of 1/2 - 2/3 w.r.t. the SM value)
- Higgs has heavy KK excitations with a mass comparable to the 1st graviton KK excitation but rather small couplings
- Higgs - radion sector completely different as the Higgs is now a bulk field with a vev that has profile.

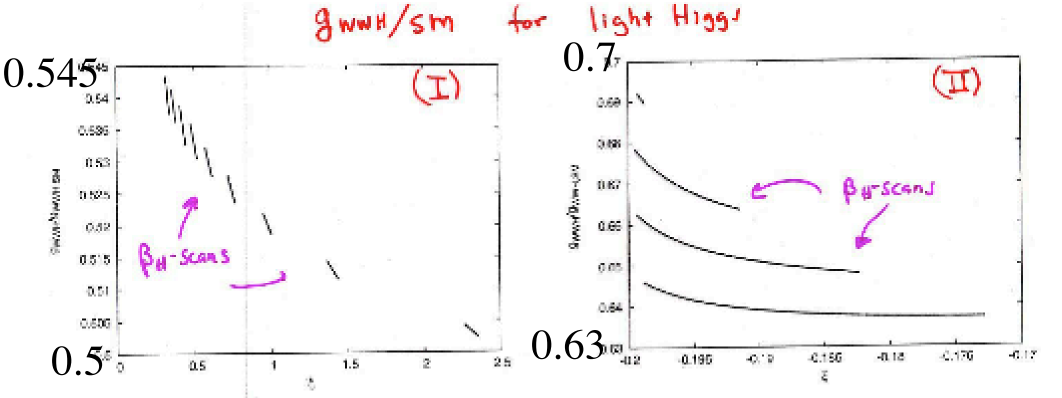
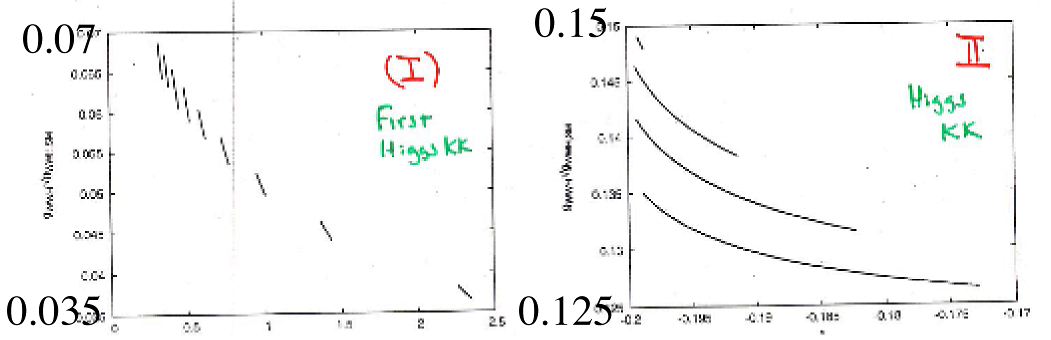


Figure 1: Values of the coupling ratio g_{WWH}/g^{SM}_{WWH} in regions I (left) and II (right) as functions of ξ for various β_H. In region I, from top from top to bottom, the curves correspond to $\beta_H = 1.4, 1.6, 1.8, 2.0$. A cut on the Higgs boson mass as described in the text has been imposed.



Rizzo et al.

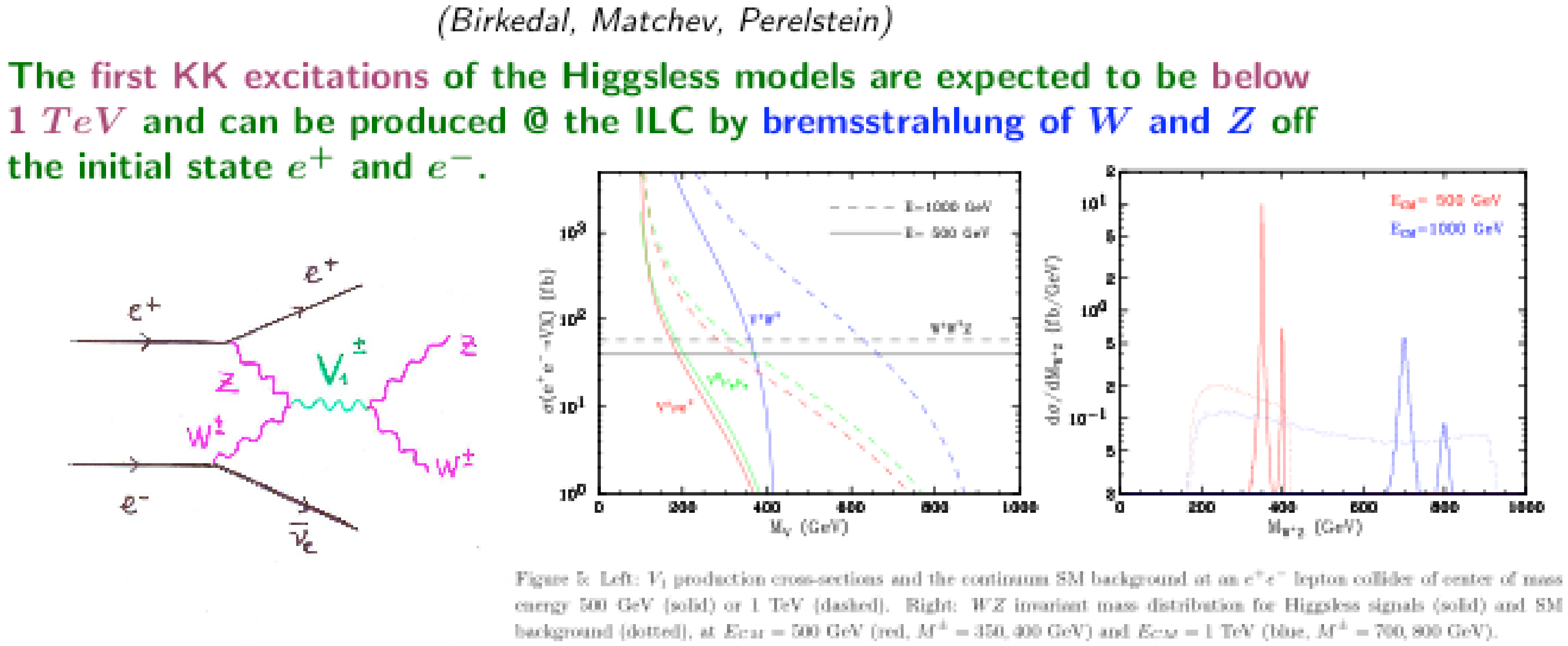
Higgsless models

- *Provide EWSB (including the unitarization of the scattering amplitude of longitudinal W and Z bosons) in a 4+1 dimensional SU(2)xSU(2)xU(1) gauge theory (to protect $\rho=1$) by boundary conditions of the gauge fields on the brane*
- *The scale, at which partial wave unitarity is lost, is delayed with respect to the SM without Higgs (~1.8 TeV) due to the exchange of KK excitation of gauge bosons*
- *The masses and couplings of the new massive vector bosons are constrained by unitarity sum rules*
- *If light fermions are allowed to leak into the bulk (delocalized) one can avoid constraints from EW precision measurements at the expense of fine tuning*
- *A particular realization using a linear moose model have been presented where the contribution from gauge bosons is compensated by fine tuning the fermion couplings at each site*

De Curtis et al.

Phenomenological implications

- ✘ *KK resonances of W and Z are fermiophobic (hep-ph/0508147)*
  - ✘ *Very narrow KK resonances (Γ/M ~ $10^{-3/-4}$)*
  - ✘ *Loose constraints from direct collider searches for new gauge bosons*
- ✘ *Anomalous gauge couplings can provide bounds on KK masses*
- ✘ *Direct observation of KK excitations may also be possible in WW → WW and WZ → WZ scattering (hep-ph/0508185)*



(Birkedal, Matchev, Perelstein)

The first KK excitations of the Higgsless models are expected to be below 1 TeV and can be produced @ the ILC by bremsstrahlung of W and Z off the initial state e^+ and e^-.

Figure 5: Left: V_1 production cross-sections and the continuum SM background at an e^+e^- lepton collider of center of mass energy 500 GeV (solid) or 1 TeV (dashed). Right: WZ invariant mass distribution for Higgsless signals (solid) and SM background (dotted), at E_{CM} = 500 GeV (red, $M^\pm$ = 350, 400 GeV) and E_{CM} = 1 TeV (blue, $M^\pm$ = 700, 800 GeV).