Strong Electroweak Symmetry Breaking

M. Arneodo, T. Barklow, S. Boogert, J.M. Butterworth, G. Cerminara,
W. Kilian, C. Mariotti, K. Mönig, A.F. Osorio, G. Passarino

Wolfgang Kilian

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Electroweak symmetry breaking: Alternative solutions

(1) Light Higgs boson: Weakly-interacting model (SM + extensions)

- Consistent with electroweak precision data
  (*but best fit for Higgs mass in excluded region*)
- Weak interactions $\Rightarrow$ everything calculable
- Embedding in MSSM $\Rightarrow$ EW scale generated by SUSY breaking?

(2) No light Higgs boson: Strongly-interacting model

- New physics in TeV range $\Rightarrow$ extra contributions could mimic light Higgs
- Strong interactions $\Rightarrow$ no reliable predictions
- Higgs mechanism by field condensation $\Rightarrow$ EW scale analogous to QCD scale?

We can't be sure that (1) is true . . . better be prepared for (2)!

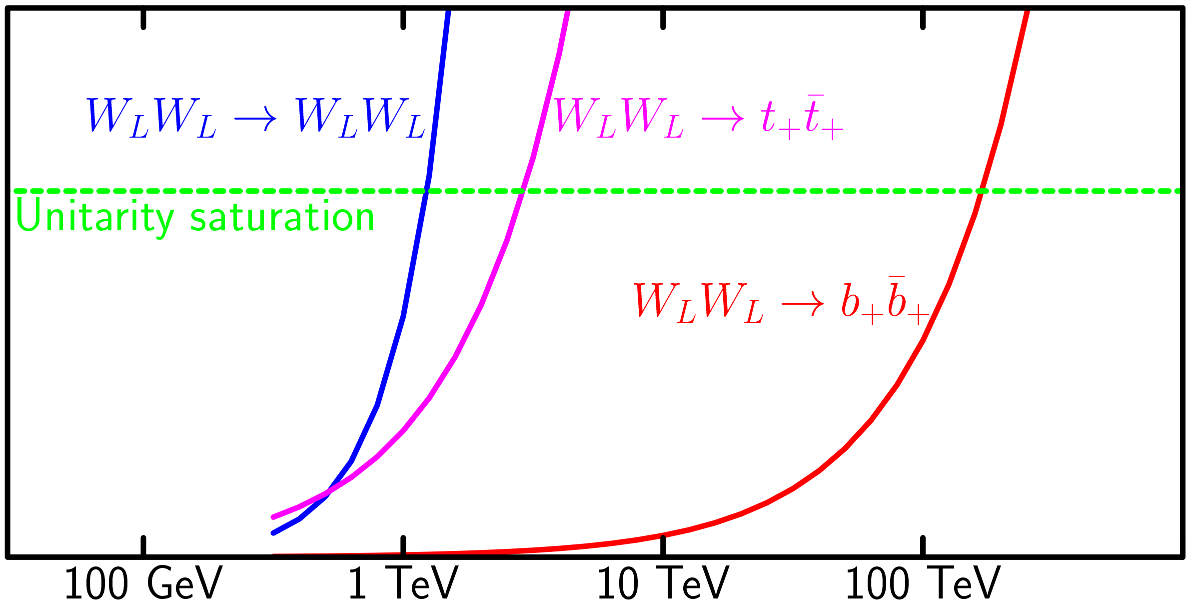
Assumption: No Higgs

- (Theory) Model is non-renormalizable ⇒ New physics at $\Lambda = 4\pi v = 3\,\mathrm{TeV}$ or below
- (Phenomenology) Scattering amplitudes involving massive particles are unbounded

⇒ Unitarity saturation within reach for WW, WZ, ZZ (and $t\bar{t}$) scattering

⇒ *Strongly interacting* W*s*

Naively extrapolated:



⇒ New effects must come in at $E \lesssim 1.2\,\mathrm{TeV}$!

Dynamical EWSB:

- Technicolor: QCD analog (longitudinal W/Z are composite)

  Problems: *no fermion masses, bad fit to EW data*

- Refinements: many models (Extended TC, Walking TC, Topcolor-Assisted TC, . . .)

- New developments: Topcolor-type models, Little-Higgs models, . . .

Predictions:

- WW scattering: Many possibilities

  Vector resonance, medium or heavy scalar (Higgs) resonance, structureless amplitude, . . .

- Extra states: *Pseudo-Goldstone bosons ("technipions"), extra heavy quarks, . . .*

$\Rightarrow$ WW scattering is sensitive probe

+ should be combined with generic new-particle searches

WW scattering processes:

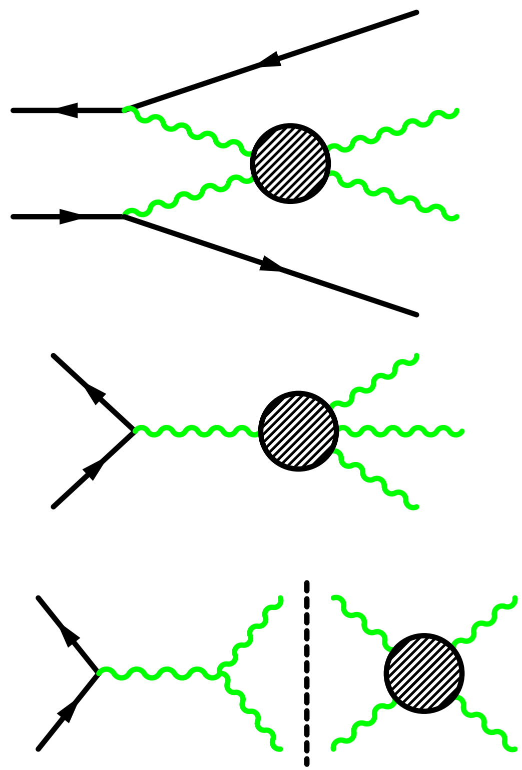
- Which signatures are measurable at LHC and LC?
- How can the LHC/LC results be combined, and what is gained?
- Collecting all information, how well can we reconstruct the amplitudes (all channels, all energies)?

Further Questions:

- Assuming the strong EWSB scenario, what else is needed to complete the picture (heavy-particle form factors, new particles, ...)?
- What do we learn from this about the underlying theory?

Processes at LHC and LC:

1. Quasielastic vector boson scattering:
   - cross section rises with energy
   - but WW energy less than collider energy
2. Triple vector boson production:
   - cross section falls off with energy
3. Rescattering in vector boson pair production:
   - need imaginary part of form factor
   - only $J = 1$ amplitude accessible



This talk: concentrate on (1) [as most studies have done].

Full analysis: need to combine (1) with (2) and (3)

LHC: Process $qq \to qqVV \to qq + 4f$

- Two hard forward jets
- Leptonic W/Z decays easier than hadronic decays (QCD background)
- ... but low branching ratios
- WW and ZZ scattering [initial state] indistinguishable

LC: Process $e^+e^- \to \nu\bar{\nu}VV \to \nu\bar{\nu} + 4f$

- Large missing invariant mass (neutrinos)
- Hadronic W/Z decays no problem
- ... but need good W/Z separation in dijet mode
- Easy channels: $W^+W^- \to W^+W^-$ and $W^+W^- \to ZZ$
- ZZ scattering distinguishable but suppressed

Calculation: Framework

Low-energy effective theory describes rise of scattering amplitudes up to $\sim 1\,\mathrm{TeV}$

- Model-independent framework for complete calculations
- 5 independent parameters in VV scattering

High-energy: models describe possible scenarios beyond $\sim 1\,\mathrm{TeV}$

- Assume generic resonances or nonresonant behavior
- Resonance masses and widths are free parameters

Unitarization prescriptions for extrapolating low-energy amplitudes:

- Examples:
  - Padé: one resonance (or dip) per channel
  - K-matrix: no resonances

$\Rightarrow$ Equivalent to matching high-energy models to low-energy parameterization

Full calculation: typically 1,000-10,000 diagrams in $ff \to 6f$ (leading order!)

Approximations:

On-shell vector bosons

- reduces problem to less than 100 diagrams per channel
- off-shell effects and irreducible background under control?

Effective W approximation

- simplifies to on-shell $VV \to VV$ scattering with vector boson structure functions
- neglected diagrams do give large corrections
- p_T distribution neglected, but important for experimental analysis

Equivalence Theorem

- replaces vector bosons (longitudinal) by Goldstone scalars, neglects transversal Ws
- corrections formally subleading, but dominant for finite energy

$\Rightarrow$ Approximations questionable for quantitative studies (LHC/LC)

Studies of WW scattering processes:

LHC

[1994/95] BAGGER ET AL.: Resonant and nonresonant models

[1995] DOBADO ET AL.: Parameter determination

[1994/99] ATLAS/CMS: Heavy Higgs resonance [with detector sim.]

[1998] BELYAEV ET AL.: Parameter determination [with refined calculation]

[2002] BUTTERWORTH ET AL.: Resonant models, semihadronic WW decays

LC

[1995] BARGER ET AL.: Resonant and nonresonant models

[1997/00] BOOS ET AL.: Parameter determination

[2001] CHIERICI ET AL.: Parameter determination [with detector sim.]

What is missing?

Most results obtained so far:

- Parton level
- Questionable approximations (EWA, ET, on-shell Ws, . . .)
- Backgrounds partly neglected

Needed:

Common basis (effective theory/models), complete simulations (6-fermion matrix elements), all backgrounds, detector simulation.

$\Rightarrow$ Quantitative comparison or combination of LHC and LC results not (yet) possible!

Working-Group Document for the present LHC/LC report:

- Review of theory & phenomenology
- Compilation of existing results & overview of ongoing study

CMS: New simulation & analysis of WW scattering at LHC

- Plan to use full 6f generator (under development)
- GEANT simulation
- Current status: preparatory studies using simplified matrix elements (PYTHIA, CompHEP) and fast detector simulation

ATLAS:

- Extension of the recent study (BUTTERWORTH ET AL.) of resonances in WW scattering: include detector simulation

LC:

Recent analysis by CHIERICI ET AL. used full 6-f generator and fast detector simulation

Plans:

- Refine background study and make contact with resonance models
- Analyze also triple vector boson production and WW rescattering

What Next?

With new results for WW scattering at LHC (and refinements of LC studies):

1. Quantitative conclusions on the sensitivity of the two machines
2. Combine results to disentangle the low-energy parameters in all channels
3. Improve information about high-energy region (resonances) by precision results on low-energy parameters
4. Combine with information from other processes (triple-gauge couplings!) to get complete picture

Further options for LHC/LC combination study:

- Dedicated study of specific scenarios (e.g., vector resonance seen at LHC. . .)
- Other signatures associated with strong EWSB (new particles)