Recent progress for LC SM/BSM Higgs/EWSB calculations

Jürgen R. Reuter

DESY Hamburg

LCWS 2011, Granada, 27. Sept. 2011
Uli Baur Memorial

- Uli Baur, 24.5.1957-25.11.2010
- W, Z, Higgs physics
- mostly Tevatron/hadron collider physics
- always worked a lot for ILC....
- Measuring the Higgs Boson Self-Coupling at High-Energy $e^+e^-$ colliders PRD80 (09) 013012

- Uli Baur Memorial, Buffalo, last Saturday

Uli, we say Goodbye...
Overview: SM and BSM Higgs/EWSB calculations

General Remark: mass calculations not covered here ....

SM Calculations
- Precision calculations for Higgs mass (not covered)
- Precision calculations for EW processes (relevant to the EW sector)
- Higgs production processes (not covered)

Beyond/Besides the SM Calculations
- Little Higgs models
- Technicolor models and all that...
- Hidden Higgses
- Dark Matter at the ILC...
Triboson Production

- $e^+e^- \rightarrow WWZ, ZZZ$ important for EW sector ("WW successor")
  - Allow determination of (anomalous) quartic gauge couplings

- High precision SM prediction needed!
  - NLO corrections to $WWZ, ZZZ$
  - Finite width effects

$\frac{\alpha}{\pi}$ coupling strengths
$e^+e^- \rightarrow WWV$ @ NLO

- $WWZ$: 2700 diagrams, 109 pentagons; $ZZZ$: 1800 diagrams, 64 pentagons ('t Hooft-Feynman gauge)

- Two different codes, both based on FeynArts/FormCalc
- Calculation below $M_{WW}$ Higgs threshold
- Both groups successfully checked their results
- Onshell-renormalization scheme
- Denner-Dittmaier method to avoid Gram determ. (+ PV reduction)
- Catani-Seymour dipole subtraction vs. Phase space slicing
- Corrections dominated by QED ISR $\Rightarrow$ subtraction based on CS, or extracted from $ZZZ$
- $50 \text{ fb} \sim \sigma_{\text{peak}}(WWZ) > \sigma_{\text{peak}}(ZZZ) \sim 1.2 \text{ fb}$

- $1 \text{ ab}^{-1} \Rightarrow \text{per-mil precision needed}$

- Genuine EW corrections: -7 to -18 % (full EW: -30 %)

- Consistent with EW double-log. Sudakov corrections
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Vector Boson Scattering

- Even more powerful tool for checking EWSB  
  Beyer et al., 2006
- Top Yukawa plays special role in the SM \( \Rightarrow \) study \( VV \) scattering to a top pair
- EW/QCD NLO corrections to \( WW, ZZ \rightarrow t\bar{t} \)  
  Bouayed/Boudjema, PRD77 (08) 013004
- On-shell scheme
- Corrections grow with rising Higgs mass
- EW corrections most cancel QCD corrections \( WW \rightarrow t\bar{t} \)

- Beware: Full results in EWA only!
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NLO QCD/EW $e^+e^- \rightarrow t\bar{t}Z$

- $t\bar{t}Z$ is background for a light Higgs $t\bar{t}h$ associated production
- FeynArts/FormCalc have been used
- Onshell scheme, trivial CKM matrix, calculation for $M_h = 120$ GeV
- Photon/gluon mass to regulate IR singularities; phase space slicing
- QCD corr. dominate, positive, $\sim 40\%$; EW corrections negative, 4-8%
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SUSY QCD Corr. to Charged Higgs Production

Kniehl/Maniatis/Weber, PRD 83 (11) 015011

- $e^+e^- \rightarrow t\bar{b}H^-$ Important process for charged Higgs in the high mass region

- SM QCD corrections  
  Kniehl/Madricardo/Steinhauser, 02

- Large $\tan \beta$ enhanced corrections $\Rightarrow$ resummed bottom Yukawa

- Residual SUSY QCD corrections: -10 to -15 %

- Comparison of numerical Bernstein-Tkachov method with analytical approach (first one with non-trivial phase space)
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Triple Higgs Coupling

- Main recent focus on investigations in SM Higgs physics
- Study of processes: $b\bar{b}HH$, $t\bar{t}HH$
  
  No interferences found there (order 3 %)

- New extensive study

- $\nu\bar{\nu}HH$ dominates over $ZH H$ for high energies

- Conclusion for $m_H \sim 120 - 180$ GeV: $\lambda_{HHH}$ can be measured with precision $20 - 80$ % (1 TeV) and $10 - 20$ % (3 TeV)

- Caveat: no ISR and beamstrahlung used (!)

- Largest bkgd.: $jjb\bar{b}cc$ with mistagged charm
Beyond/Besides the Standard Model
Supersymmetry

No SUSY (dis)covered here ⇒ Sven’s talk after this one
4th Generation

- 4th generation already constrained by LHC Higgs searches


\[ \mathcal{L} = \sum_u \frac{\kappa}{\Lambda} \bar{t'} \sigma_{\mu\nu} q_u F^{\mu\nu} \]

(they could dominate the chiral SM interactions)

- Allows for single production of \( t' \) states: \( ee \rightarrow t'q \rightarrow Wbq \)

![Graphs showing production cross-sections at √s = 0.5 TeV and √s = 3 TeV for different \( m_{t'} \) values.](image)
4th Generation

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- Introduce special magnetic moment type interactions: Senol/Tasci/Ustabas, NPB 851 (2011) 289

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![Graph showing the dependence of m_t' on (κ/Λ) TeV^(-1)]
Technicolor (with Assistance from Topcolor)
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- **New strong interactions (techniquarks, -gluons, etc.)** break EW interactions  
  \( \text{Weinberg, 1976; Susskind, 1977} \)

- **Difficulties with EW precision observables, flavor, fermion masses**

- **Big revival in the context of dual models (adS/CFT picture)**

- **Topcolor**: new strong coupling of top quarks makes top quarks condense and generates EWSB  
  \( \text{Pendleton/Ross/Hill/Bardeen,Lindner; 1981-85} \)

- **Topcolor-Assisted Technicolor (TC2)**: mixture of E(TC) and TopC

- "Tilting" the vacuum \((U(1)')\ charges\) to avoid \(\langle b\bar{b} \rangle\) condensate

- **Emergent Top-Pions** \(m_\pi \sim m_t, f_\pi \sim 60 \text{ GeV}, g_{tb\pi} \sim m_t/\sqrt{2} f_\pi \sim 2.5\)

- **Basically 2HDM**: pseudoscalar top-pions and scalar top-Higgs decoupled states
TC/TopC: $\pi_t^+\pi_t^-$ and $\pi_t^+h_t^0$ production

- Calculation of $\pi_t^+/h_t$ pair production at ILC (and LHC)  
  
  - Indirect bounds + Tevatron: $m_{\pi}, m_h \gtrsim 220$ GeV

- LHC presumably only leaves the low-mass region (but difficult)

- Remember: Tevatron can almost not see these states....

- NLO vertex corrections calculated, LoopTools

- K-factor 1.05, $e^+e^- \rightarrow \pi_t^+\pi_t^-$: 20 fb @ 1.5 TeV $e^+e^-$ machine
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  Han/Wang, 1105.5513
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- K-factor 1.05, $e^+ e^- \rightarrow \pi_t h_t$: $\lesssim 10$ fb @ 1.5 TeV $e^+ e^-$ machine
TC/TopC: $\pi_t \pi_t$ and $\pi_t h_t$ production

- Discrepancy for $ee \rightarrow \pi_t \pi_t$ and $ee \rightarrow \pi_t h_t$ with earlier NLO calculation:
  Wang/Qiao/Zhang, PRD 71 (05) 095012 ; Qiao/Li/Li/Wang, Commun. Theor. Phys. 52 (09) 311

- Main backgrounds: triboson production can be effectively suppressed by a cut-based analysis

- Pair production in photon collisions:
  K-factor 1.05, $e^+ e^- \rightarrow \pi_t \pi_t$: 1 pb @ 1.5 TeV $e^+ e^-$ machine

*Conclusion:* ILC can detect top-pions, but cannot outdo LHC

*Realistic study on ILC capabilities missing*

*Independent NLO calculation for $\gamma \gamma \rightarrow \pi_t^+ \pi_t^-$*  
Han/Wang, 1105.5513
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TC/TopC: $Z/W + \pi\pi$ and $t\bar{t}H_{TC}$ production

- Calculation of $e^+e^- \to W^+\pi^-\pi^0$ xsecs
  Liu/Wang, Int.J.Mod.Phys. A32 (08) 5173
- Cross sections are in the range of a few femtobarn
- Background is $ttbc + W$ (!)
- Difficult to dig out of the background
- Cross sections are not reliable any more for $\sqrt{s} \gtrsim 1$ TeV
  (non-unitarized multi-pion scattering)
- Associated production $e^+e^- \to Z\pi_t^+\pi_t^-$
- Again, Xsecs. are $\mathcal{O}(1 \, \text{fb})$, marginally visible
- All calculations also done for photon collisions ($ee \to \gamma\gamma \to X$)
- Also: $e^+e^- \to \gamma\gamma \to t\bar{t}h_t$
  Huang/Lu/Xu/Wang, Chin.Phys. C34 (10) 1057-1060
Little Higgs Models
Little Higgs Models

- Strongly interacting models with weak sector at the terascale
  Arkani-Hamed et al., 2001
- Extended global symmetry (extended scalar sector)
- Extended gauge symmetry: $\gamma', Z', W'_{\pm}$
- New heavy fermions: $T$, but also $U, C, \ldots$
- Discrete symmetry: $T$ (TeV scale) parity, ameliorates EW precision data (lowers scale), allows for dark matter

Analogous: QCD

Scale $\Lambda$: chiral symmetry breaking, quarks, $SU(3)_c$
Scale $v$: pions, kaons, \ldots
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Scale $\Lambda$: global symmetry breaking, new particles, new (gauge) IA
Scale $v$: Higgs, $W/Z, \ell^\pm, \ldots$
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Scale $\Lambda$: global SB, new IA
Scale $F$: Pseudo-Goldstone boson, new vectors/fermions
Scale $v$: Higgs, $W/Z$, $\ell^\pm$, $\ldots$
Product Group Models
(e.g. Littlest Higgs)

\[ \mathcal{H} \rightarrow \mathcal{H}' \]

\[ \mathcal{G}_1 \rightarrow \mathcal{G}_1' \]

\[ \mathcal{G}_2 \rightarrow \mathcal{G}_2' \]

\[ \mathcal{H}_1 \subset \mathcal{H} \cap \mathcal{H}_2 \subset \mathcal{H} \]

\[ g_1 \neq 0 \]

\[ g_2 \neq 0 \]

Simple Group Models
(e.g. Simplest Little Higgs)

\[ \mathcal{H}_1 \rightarrow \mathcal{H}_1' \]

\[ \mathcal{H}_2 \rightarrow \mathcal{H}_2' \]

\[ \mathcal{H}_1 \ni h \in \mathcal{H}_2 \]

\[ \mathcal{G}_{\text{diag}} \rightarrow \mathcal{G}' \]

Little Higgs models tests at LCs: ⇒ Shigeki Matsumoto’s talk
Product Group Models
(e.g. Littlest Higgs)

\[
\mathcal{H} \rightarrow \mathcal{H}'
\]

\[
\mathcal{G}_1 \rightarrow \mathcal{G}_1'
\]

\[
\mathcal{H}_1, \mathcal{H}_2 \neq 0
\]

\[
\mathcal{H}_1 \subset \mathcal{H}, \mathcal{H}_2 \subset \mathcal{H}
\]

\[
g_1 \neq 0
\]

\[
g_2 \neq 0
\]

Moose Models
(e.g. Minimal Moose Model)

\[
\mathcal{H}_1 \rightarrow \mathcal{H}_1'
\]

\[
\mathcal{H}_2 \rightarrow \mathcal{H}_2'
\]

\[
\mathcal{H}_3 \rightarrow \mathcal{H}_3'
\]

\[
\mathcal{H}_4 \rightarrow \mathcal{H}_4'
\]

\[
\mathcal{H}_5 \rightarrow \mathcal{H}_5'
\]

\[
\mathcal{H}_n \rightarrow \mathcal{H}_n'
\]

Little Higgs models tests at LCs: \(\Rightarrow\) Shigeki Matsumoto’s talk
Little Higgs spectra

\[ \mathcal{H} = \frac{SU(5)}{SO(5)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)} \]

Arkani-Hamed/Cohen/Katz/Nelson, 2002

\[ \mathcal{H} = \frac{SO(6)}{Sp(6)}, \mathcal{G} = \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)} \]

Low/Skiba/Smith, 2002

\[ \mathcal{H} = \frac{[SU(3)]^2}{[SU(2)]^2}, \mathcal{G} = \frac{SU(3) \times U(1)}{SU(2) \times U(1)} \]

Schmaltz, 2004

\[ [SU(4)]^4 \rightarrow [SU(3)]^4 \]

Kaplan/Schmaltz, 2003

2HDM, \( h_{1/2}, \Phi_{1,2,3}, \Phi'_P, 1,2,3, Z'_1,...,8, W'_{1,2}, q', \ell' \)

\[ U, C \]

\[ X^0/Y^0 \]

\[ \eta \]

\[ W^\pm \]
Associated $Z\Phi$ production in Littlest Higgs

- Essential parameters:
  intermediate scale $f \sim 1$ TeV, $v'$ Higgs triplet VEV

- Electroweak precision observables: $f \gtrsim 3-4$ TeV, $v' \lesssim 10^{-2}$ GeV

  Csaki et al.; Hewett/Rizzo/Petriello; Kilian/JRR, 2003

- Goldstone bosons from complex Higgs triplet difficult to see at LHC

- Associated production calculated

  Cagil/Zeyrek, Acta Phys. Pol. B42 (11), 45

- Cross section largely suffers from phase space and decoupling limit

- Focus on a fermiophobic limit which is favored by EWPO

- SM backgrounds: $Ztt$; no study about visibility (yet)
$e^+ e^- \rightarrow t\bar{t}\eta$ in Simplest Little Higgs

- $U(1)$ factors in Little Higgs models need not be gauged $\Rightarrow$ new light pseudoscalar states
  
  Kilian/Rainwater/JRR, 2005

- Has discriminating power for Little Higgs models
  
  Kilian/Rainwater/JRR, 2006

- $e^+ e^- \rightarrow t\bar{t}\eta$ revisited for $T$ parity recently
  
  Han/Yang/Wang, Mod.Phys.Lett. A26 (2011)

- Xsecs. compatible with $tth$ in SM/MSSM: $\sim 1 \text{ fb}^{-1}$

- Adding $t\bar{t}\eta$ from $\gamma\gamma$ interactions

- Small ballpark, but additional source for SLH measurements
Twin Higgs Model (Mirror/Left-Right)
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- Extend the SM by a parity symmetry: mirror symmetry left-right models. Lee/Yang
  Pati/Salam, Mohapatra/Pati, Senjanovic/Mohapatra

- Similar to Little Higgs: pseudo-Goldstone bosons from breaking a large(r) global symmetry

- Parity doubling cancels quadratic divergencies

- No new colored states in the model $\Rightarrow$ notoriously difficult to discover at LHC

- Communication to mirror sector only through the Higgs

- Drell-Yan is a possibility (via $Z_M$, $W_H$) (but large backgrounds)
Higgs production in LR Twin Higgs Model

- Left-right symmetric Twin Higgs model
  - $U(4)_1 \times U(4)_2$ global symmetry
  - $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

- Higgs spectrum: $h, \phi^\pm$, pseudoscalar $\phi^0$, doublet ($h^+_1, h^0_2$)

- Calculation of pair production $h\phi^0$ in LRTH model
  
  
  Liu, PLB 698 (11) 157

- Predominant decay $\phi^0 \rightarrow b\bar{b}$, only determined by detector resolution
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(Multiple) Higgsstrahlung in LR Twin Higgs Model

- Corrections to Higgsstrahlung (single and double) in LR Twin Higgs Model estimated
  Liu/Wang/Han, EPL 81 (08) 31001

- Extensions of electroweak Higgs sector can drastically enhance these processes
  cf. Kilian/Rainwater/JRR, 06

- Corrections to Higgsstrahlung $e^+e^- \rightarrow ZH$, $e^+e^- \rightarrow ZHH$

- Enhancement of SM xsecs makes these processes accessible
Summary and Conclusions

- We are well prepared!
- Relevant calculations done a long time before
  SM calculations focusing on high-luminosity/high-energy processes at the heart of EWSB: $\text{triboson/VV scattering}$
- Mapping out the Higgs potential:
  Higgs self-couplings
- **BSM models:** En attendant l’LHC
- Almost no (more) SUSY calculations
- Focus on EWSB-related processes in strongly interacting models:
  Little Higgs, Technicolor, Topcolor, Twin Higgs

General feeling: guidance from LHC is needed
Linear Collider IS helpful...
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Muchas gracias por esto lugar fantástico!