The Physics Of Yang-Mills-Higgs Systems

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Overview

- Yang-Mills-Higgs theory
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- Yang-Mills-Higgs theory
- Physical states from the lattice
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- Yang-Mills-Higgs theory
- Physical states from the lattice
- Quantum phase diagram
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- Excited states from the lattice
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- Yang-Mills-Higgs theory
- Physical states from the lattice
- Quantum phase diagram
- Excited states from the lattice
- Experimental signatures
- Summary
Yang-Mills-Higgs Theory
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

\[ L = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a \]

\[ W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu \]

- Ws

\[ W^a_\mu \]
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\[ W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^{a}_{bc} W^b_\mu W^c_\nu \]

- \( W^a_\mu \)

- Coupling \( g \) and some numbers \( f^{abc} \)
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  \[ W^a_\mu \]

- No QED: Ws and Zs are degenerate

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  \[ L = -\frac{1}{4} W^a_{\mu\nu} W_{a}^{\mu\nu} + (D^i_\mu h^j) + D^u_{ik} h_k \]
  \[ W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{bc} W^b_\mu W^c_\nu \]
  \[ D^{ij}_\mu = \delta^{ij} \partial_\mu \]
- Ws \( W^a_\mu \)
- Higgs \( h_i \)
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\[ D^{ij}_\mu = \delta^{ij} \partial_\mu - ig W^a_\mu t^{ij}_a \]

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\[ L = -\frac{1}{4} W^a_{\mu \nu} W^{\mu \nu}_a + (D^j_i h^j) + D^\mu_{ik} h^k + \lambda (h^a h^a + - \nu^2)^2 \]

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\[ D^i_j = \delta^i_j \partial^\mu - ig W^a_{\mu} t^i_j \]

- Ws \[ W^a_{\mu} \]

- Higgs \[ h_i \]

- No QED: Ws and Zs are degenerate

- Couplings \( g, \nu, \lambda \) and some numbers \( f^{abc} \) and \( t^i_j \)
Symmetries

\[ L = -\frac{1}{4} W^a_{\mu \nu} W^{\mu \nu}_a + (D^i_{\mu} h^j) + D^a_{\mu} h_k + \lambda (h^a h^+_a - v^2)^2 \]

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- Local SU(2) gauge symmetry
  - Invariant under arbitrary gauge transformations \( \phi^a(x) \)

\[ W^a_\mu \rightarrow W^a_\mu + (\delta^a_b \partial_\mu - gf^a_{bc} W^c_\mu) \phi^b \]

\[ h_i \rightarrow h_i + g t^i_j \phi^a h_j \]
Symmetries

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    \[
    h_i \rightarrow h_i + g t^i_{a} \phi^a h_j
    \]
- Global SU(2) Higgs flavor symmetry
  - Acts as right-transformation on the Higgs field only
    \[
    W^a_{\mu} \rightarrow W^a_{\mu} \quad h_i \rightarrow h_i + a^i_{j} h_j + b^i_{j} h_j^*
    \]
Classical analysis

\[ L = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} + (D^i_\mu h^j) + D^\mu_{ik} h_k + \lambda (h^a h^a + - \nu^2)^2 \]

[Bohm et al. 2001]
Classical analysis

\[ L = \lambda \left( h^a h_a^+ - \nu^2 \right)^2 \]

- Classical analysis of the Higgs sector
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The shape of the Higgs potential depends on parameters. 

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- Experiments decides
  - Higgs mass is tachyonic

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- Classical analysis of the Higgs sector
- Non-zero condensate shifts Higgs mass to an ordinary mass
- Perform perturbative expansion around the classical vacuum

Shape depends on parameters
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Standard approach

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h(x) = \begin{pmatrix} \varphi^1(x) + i \varphi^2(x) \\ v + \eta(x) + i \varphi^3(x) \end{pmatrix} \Rightarrow \langle h \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}
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- Perform perturbation theory
Implications of global transformation

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  • Local symmetry intact and cannot be broken

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  - Symmetry expressed in STIs/WTIs
Masses from propagators

• Masses are determined by poles of propagators
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• 2 propagators
  • $W/Z$ \( D^{ab}_{\mu\nu}(x-y) = \langle W^a_{\mu}(x) W^b_{\nu}(y) \rangle \)
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  - Without gauge fixing propagators are $\sim \delta(x-y)$
Physical states

• Elementary fields depend on the gauge
  • Except right-handed neutrinos

[Fröhlich et al. PLB 80, 't Hooft ASIB 80, Bank et al. NPB 79]
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  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.

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Lattice and Physical States
Lattice calculations

• Take a finite volume – usually a hypercube
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  - Euclidean formulation
Masses from Euclidean propagators
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Masses from Euclidean propagators

\[ D(p) = \langle O^+(p)O(-p) \rangle \sim \sum \frac{a_i}{p^2 + m_i^2} \]

\[ C(t) = \langle O^+(x)O(y) \rangle \sim \sum a_i \exp(-m_i \Delta t) \]

\[ \sum a_i = 1 \land m_0 < m_1 < \ldots \]

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  - No exact results on time-like momenta
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Higgsonium

- Simpelst $0^+$ bound state $h^+ (x) h(x)$
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- Simplest $0^+$ bound state: $h^+(x)h(x)$
- Same quantum numbers as the Higgs
- No weak or flavor charge
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Finite-volume effects

[Maas et al. '13]

Effective mass

Fourier transform
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Mass relation - Higgs

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV

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\[ \langle (h^+ h)(x)(h^+ h)(y) \rangle \]
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\[
\langle (h^+ h)(x)(h^+ h)(y) \rangle \approx h = v + \eta
\]
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\[ h = v + \eta \approx \text{const.} + \langle h^+ (x) h(y) \rangle + O(\eta^3) \]

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    \( h = v + \eta \)
    \[ \langle (h^+ h)(x)(h^+ h)(y) \rangle \approx \text{const.} + \langle h^+ (x)h(y) \rangle + O(\eta^3) \]
  - Same poles to leading order
- Deeply-bound relativistic state
  - Mass defect\(\sim\)constituent mass
  - Cannot describe with quantum mechanics
  - Very different from QCD bound states

[Fröhlich et al. PLB 80
Maas'12, Maas & Mufti'13]
Comparison to Higgs

[Maas et al. '13]
Comparison to Higgs

- Same mass
- Different influence at short times
  - Can be traced back to Higgs mechanism
Isovector-vector state

- Vector state $1^-$ with operator $\text{tr} t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$
- Only in a Higgs phase close to a simple particle
- Higgs-flavor triplet, instead of gauge triplet
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  - Only in a Higgs phase close to a simple particle
  - Higgs-flavor triplet, instead of gauge triplet
  - Mass about 80 GeV
Mass relation - W

• Vector state: 80 GeV
• $W$ at tree-level: 80 GeV
  • $W$ not scale or scheme dependent
Mass relation - W

- Vector state: 80 GeV
- W at tree-level: 80 GeV
  - W not scale or scheme dependent
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\[
\langle (h^+ D_{\mu} h)(x)(h^+ D_{\mu} h)(y) \rangle
\]
Mass relation - W

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- W at tree-level: 80 GeV
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\[ \langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y) \rangle \]

\[ h = v + \eta \approx \text{const.} + \langle W_\mu(x)W_\mu(y) \rangle + O(\eta^3) \]

\[ \partial v = 0 \]
Mass relation - W

• Vector state: 80 GeV
• W at tree-level: 80 GeV
  • W not scale or scheme dependent
• Same mechanism

\begin{equation}
\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y) \rangle \\
h = v + \eta \\
\approx \text{const.} + \langle W_\mu(x) W_\mu(y) \rangle + O(\eta^3) \\
\partial v = 0
\end{equation}

• Same poles at leading order
  • At least for a light Higgs
Mass relation - W

- Vector state: 80 GeV
- W at tree-level: 80 GeV
  - W not scale or scheme dependent
- Same mechanism
  \[
  \left\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y) \right\rangle
  \]
  \[
  h = v + \eta \\
  \approx \text{const.} + \left\langle W_\mu(x) W_\mu(y) \right\rangle + O(\eta^3)
  \]
  \[
  \partial v = 0
  \]
- Same poles at leading order
  - At least for a light Higgs
  - Remains true beyond leading order

[Fröhlich et al. PLB 80 Maas'12]
Comparison to W

[Maas et al. '13]
Comparison to W

- Same mass
- Different influence at short times
  - Not a hard mass, but decreases at high energies

[Maas et al. '13]
Ground state spectrum

[Maas et al. Unpublished, PoS'12]
Ground state spectrum

- Many states
- No simple relation to elementary states besides Higgs and W

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Ground state spectrum

- Many states
  - No simple relation to elementary states besides Higgs and W
- Can mimic new physics
  - Note: Depends on parameters

[Maas et al. Unpublished, PoS'12]
Ground states

- For W and Higgs exist gauge-invariant composite/bound states of the same mass
  - Play the role of the experimental signatures
  - “True” physical states
  - Reason for the applicability of perturbation theory for electroweak physics
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- For $W$ and Higgs exist gauge-invariant composite/bound states of the same mass
  - Play the role of the experimental signatures
  - "True" physical states
  - Reason for the applicability of perturbation theory for electroweak physics

- Is this always true?
  - Full standard model: Probably
  - Other parameters?
Quantum Phase Diagram
Lines of constant physics

• Lattice simulations have an intrinsic cutoff – the lattice spacing a
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  - Full theory reached at zero lattice spacing
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  - Different starting points yield different physics
Phase diagram

- (Lattice-regularized) phase diagram

![Phase diagram](image)

\[ f(\text{Classical Higgs mass}) \]

\[ g(\text{Classical gauge coupling}) \]

[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]
Phase diagram

- (Lattice-regularized) phase diagram

![Diagram with axes labeled $f$ (Classical Higgs mass) and $g$ (Classical gauge coupling), and a note indicating a Higgs "phase".]

[Fradkin & Shenker PRD'79, Caudy & Greensite PRD'07]
Phase diagram

• (Lattice-regularized) phase diagram

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Phase diagram

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![Phase diagram with Higgs and Confinement phases]

[Phadkin & Shenker PRD’79 Caudy & Greensite PRD’07]
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[Fradkin & Shenker PRD’79, Caudy & Greensite PRD’07]
Phase diagram

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  - Separation only in fixed gauges

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- Same asymptotic states in confinement and Higgs pseudo-phases

\[(\text{f(Classical Higgs mass)})\]
\[(\text{g(Classical gauge coupling)})\]

[Fradkin & Shenker PRD’79
Caudy & Greensite PRD’07]

1\text{st order}
Phase diagram

- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges
- Same asymptotic states in confinement and Higgs pseudo-phases
- Same asymptotic states irrespective of coupling strengths

[Fradkin & Shenker PRD’79 Caudy & Greensite PRD’07]
Typical spectra

[Maas, Mufti PoS'12, unpublished, Evertz et al.'86, Langguth et al.'85,'86]
Typical spectra

Higgs

W

“Higgs”

“QCD”

[Maas, Mufti PoS'12, unpublished, Evertz et al.'86, Langguth et al.'85,'86]
Typical spectra

- Generically different low-lying spectra
  - $0^{++}$ lighter in QCD-like region
  - $1^{--}$ lighter in Higgs-like region

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Typical spectra

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  - $0^{++}$ lighter in QCD-like region
  - $1^{--}$ lighter in Higgs-like region
- Use as operational definition of phase

[Maas, Mufti PoS'12, unpublished, Evertz et al.'86, Langguth et al.'85,'86]
Phase diagram
Phase diagram

“Higgs”

“QCD”

- Complicated real phase diagram

[Maas, Mufti, unpublished]
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- Similar bare couplings for both physics types

[Maas, Mufti, unpublished]
Phase diagram

- Complicated real phase diagram
- QCD-like behavior even for negative bare mass
- Similar bare couplings for both physics types
- Lower "Higgs" ($0^+$) mass bound: "W" ($1^-$) mass

[Maas, Mufti, unpublished]
Limits of perturbation theory

- Naively: Too “large” couplings
  - Landau poles around electroweak scale
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  - No reliable identification of asymptotic states

QCD-like
Limits of perturbation theory

- Naively: Too “large” couplings
  - Landau poles around electroweak scale
- Mass relation $W$ to $1^-$ may break earlier
  - Threshold in the $0^+$ channel at twice the $1^-$ mass
  - No reliable identification of asymptotic states
  - Depends on dynamics – right LCP?

QCD-like

---

[Maas, Mufti'13]
Comparability to the standard model

- 2 correct masses only fix two parameters, but 3 parameters needed
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- Comparison to standard model complicated
  - States stable, no W/Z splitting
Comparability to the standard model

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- Comparison to standard model complicated
  - States stable, no W/Z splitting
  - Couplings run differently – proceed with caution

[Maas, Mufti'13]
Lattice and Excited States
(Speculative) Consequences

• Composite states can have excitations
• Not necessarily [Wurtz et al. '13]
(Speculative) Consequences

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    [Wurtz et al. '13]
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    • Will be suppressed as higher orders in the expansion around the vacuum field
    • Small couplings, perhaps 1% or less of gauge couplings
    • Consistent with experimental bounds
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    - Distinction from scattering states
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      • Consistent with experimental bounds
  • Possibly only sigma-like bumps
    • Distinction from scattering states
  • Requires confirmation or exclusion
Excited states on the lattice

• Each quantum number channel has a spectrum

• Discreet in a finite volume
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- States can be either stable, excited states,
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Excited states on the lattice

Exponential volume dependency
- if stable against decays into other channels

[Luescher'85,'86,'90,'91]
Excited states on the lattice

- Excited state
- Resonances or scattering states
- Inelastic
- Elastic
- Ground state

- Exponential volume dependency
  - if stable against decays into other channels
- Polynominal (inverse) volume dependence
- Width and nature from phase shifts below the inelastic threshold

[Luescher'85,'86,'90,'91]
Excited states on the lattice

Above inelastic threshold still complicated

- Polynomial (inverse) volume dependence
- Width and nature from phase shifts below the inelastic threshold

Exponential volume dependency - if stable against decays into other channels

[Luescher'85,'86,'90,'91]
Excited states on the lattice

Spectrum

\[ \text{Luescher'85,'86,'90,'91} \]
Excited states on the lattice

Ground state

[Spectrum]

[Luescher'85,'86,'90,'91]
Excited states on the lattice

Spectrum

Inelastic threshold: $H \rightarrow 2H$

Elastic threshold: $H \rightarrow 2W$

Ground state

[Luescher'85,'86,'90,'91]
Excited states on the lattice

Scattering states

Inelastic threshold: $H \rightarrow 2H$

Elastic threshold: $H \rightarrow 2W$

Ground state

[Luescher'85,'86,'90,'91]
Excited states on the lattice

Scattering states
- Inelastic threshold: $H \rightarrow 2H$
- Avoided level crossing
- Identification and widths from phase shifts
- Elastic threshold: $H \rightarrow 2W$

Ground state

[Luescher'85,'86,'90,'91]
Excited Higgs

Scattering states

Inelastic threshold

Elastic threshold

Ground state

NB: weakly coupled

[Spectrum $0^+_1$]

[Maas et al. unpublished]
Excited Higgs

Scattering states

Inelastic threshold

Elastic threshold

Possible excited Higgs $\sim 150$ GeV

Ground state

NB: weakly coupled

[Spectrum $0^+_1$]
Scattering states

Inelastic threshold

Elastic threshold

Ground state

NB: weakly coupled
Scattering states

Inelastic threshold

Identification unclear

Elastic threshold

Ground state

NB: weakly coupled
Experimental Signals
Weakly coupled experimental signals?

• Similar or identical to standard model Higgs sector
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  - Excited states or different quantum numbers possible best signal channel
- Example experimental signal: Excited Higgs
  - 190 GeV mass, 19 GeV width
Impact on quartic gauge coupling
Impact on quartic gauge coupling

• (Singlet) quartic gauge coupling and resonance formation in the same channel

[Maas et al. Unpublished]
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Impact on quartic gauge coupling

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- Resonance peak in final state invariant mass?

[Maas et al. Unpublished]
Impact on quartic gauge coupling

• (Singlet) quartic gauge coupling and resonance formation in the same channel

• Resonance peak in final state invariant mass?
  • Estimate using effective theory + Sherpa: Too small to be seen (less than 1% at peak)
Experimental accessibility

[Maas et al. Unpublished]
Experimental accessibility

Parton 1 → Z → Z → W^+ → W^-

Parton 2

Ordinary: e.g. Higgs

[Maas et al. Unpublished]
Experimental accessibility  [Maas et al. Unpublished]

- E.g. excited Higgs: Decay channel: 2W
Experimental accessibility

- Non-perturbative: \(0^{++},...,\) Additional 1% effect

- Ordinary: e.g. Higgs

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E.g. excited Higgs: Decay channel: 2W
Experimental accessibility

\[ \text{pp} \rightarrow Z W^+ W^- + <3 \text{ jets} > \rightarrow \text{anything at } \sqrt{s} = 8 \text{ TeV} \]

\[ \text{pp} \rightarrow Z W^+ W^- + <3 \text{ jets} > \rightarrow \text{anything at } \sqrt{s} = 14 \text{ TeV} \]

- E.g. excited Higgs: Decay channel: 2W

[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]
Experimental accessibility

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp \to Z W^+ W^- + &lt;3$ jets $\to$ anything</td>
<td>8</td>
</tr>
<tr>
<td>$pp \to Z W^+ W^- + &lt;3$ jets $\to$ anything</td>
<td>14</td>
</tr>
<tr>
<td>$e^+ e^- \to Z W W^- + &lt;3$ jets $\to$ anything</td>
<td>500</td>
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- E.g. excited Higgs: Decay channel: $2W$
- Decides whether present in the standard model
- If present standard-model physics this would be a gateway to new physics

[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

[Maas et al. Unpublished]
Experimental accessibility

**Perturbative:** Higgs, Z, $\gamma$

**Non-perturbative:** $\gamma^{\ast\ast\ast}$, ...

**Additional 1% effect**

- E.g. excited Higgs: Decay channel: 2W
- Decides whether present in the standard model
- If present standard-model physics this would be a gateway to new physics

---

**Speculative**

- Low-energy effective Lagrangian, MC by Sherpa 1.4.2

- 20 fb$^{-1}$
- 1000 fb$^{-1}$
- 500 fb$^{-1}$
Summary

- Higgs sector with light Higgs successfully described by perturbation theory around classical physics.
Summary

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- Bound-state/elementary state duality
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  • Highly relativistic bound states
    • Unusual structure
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- Bound-state/elementary state duality
  - Highly relativistic bound states
    - Unusual structure
  - Permits physical interpretation of resonances in cross sections
- Possibility of new excitations of bound states
  - Background for new physics searches
- If existing likely accessible at LHC/ILC
  - New experimental perspective/program
- Non-perturbatively interesting even for a light Higgs