Observables in Higgsed Theories

Axel Maas

12th of November 2014
Strong Interactions in the LHC Era
Bad Honnef
Germany

Overview

- Yang-Mills-Higgs theory

Overview

- Yang-Mills-Higgs theory
- Fröhlich-Morchio-Strocchi mechanism

Overview

- Yang-Mills-Higgs theory
- Fröhlich-Morchio-Strocchi mechanism
- Experimental signatures

Overview

- Yang-Mills-Higgs theory
- Fröhlich-Morchio-Strocchi mechanism
- Experimental signatures
- Quantum phase diagram

Overview

- Yang-Mills-Higgs theory
- Fröhlich-Morchio-Strocchi mechanism
- Experimental signatures
- Quantum phase diagram
- Impact beyond the standard model
- Summary

What is non-perturbative?

- Strong interactions are non-perturbative
  - Like QCD
  - But not always: Asymptotic freedom

What is non-perturbative?

- Strong interactions are non-perturbative
  - Like QCD
  - But not always: Asymptotic freedom
- Weak interactions can be non-perturbative
  - QED is weakly interacting, but has non-perturbative features like atoms, molecules, matter with phase structure,...
  - Bound states, phase transitions,...

What is non-perturbative?

- Strong interactions are non-perturbative
  - Like QCD
  - But not always: Asymptotic freedom
- Weak interactions can be non-perturbative
  - QED is weakly interacting, but has non-perturbative features like atoms, molecules, matter with phase structure,...
  - Bound states, phase transitions,...
- Are there (relevant) non-perturbative effects in the weak interactions and the Higgs?

The Higgs sector as a gauge theory

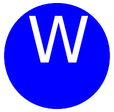
- The Higgs sector is a gauge theory

The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W_{\mu\nu}^{a}W_{a}^{\mu\nu}$$

$$W_{\mu\nu}^{a}=\partial_{\mu}W_{\nu}^{a}-\partial_{\nu}W_{\mu}^{a}$$



- Ws W_{μ}^{a}

The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu}$$

$$W^a_{\mu\nu}=\partial_\mu W^a_\nu-\partial_\nu W^a_\mu+gf^a_{bc}W^b_\mu W^c_\nu$$

- Ws W^a_μ

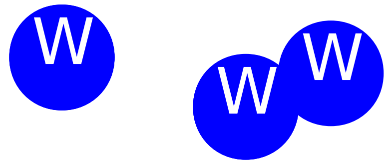
- Coupling g and some numbers f^{abc}

The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu}$$

$$W^a_{\mu\nu}=\partial_\mu W^a_\nu-\partial_\nu W^a_\mu+gf^a_{bc}W^b_\mu W^c_\nu$$



- Ws W^a_μ

- No QED: Ws and Zs are degenerate
- Coupling g and some numbers f^{abc}

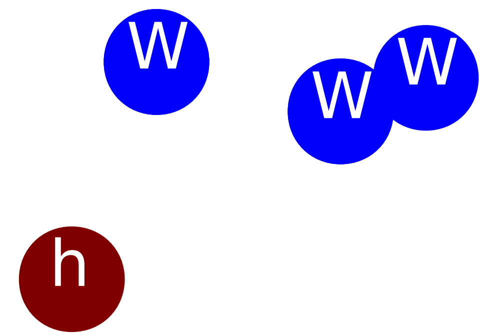
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W_{\mu\nu}^{a}W_{a}^{\mu\nu}+\left(D_{\mu}^{ij}h^{j}\right)^{+}D_{ik}^{\mu}h_{k}$$

$$W_{\mu\nu}^{a}=\partial_{\mu}W_{\nu}^{a}-\partial_{\nu}W_{\mu}^{a}+gf_{bc}^{a}W_{\mu}^{b}W_{\nu}^{c}$$

$$D_{\mu}^{ij}=\delta^{ij}\partial_{\mu}$$



- Ws W_{μ}^{a}
- Higgs h_i
- No QED: Ws and Zs are degenerate
- Coupling g and some numbers f^{abc}

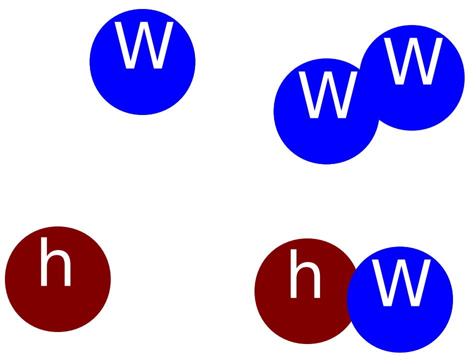
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W^a_{\mu\nu}W_a^{\mu\nu}+\left(D^{ij}_\mu h^j\right)^+ D^\mu_{ik}h_k$$

$$W^a_{\mu\nu}=\partial_\mu W^a_\nu-\partial_\nu W^a_\mu+gf^a_{bc}W^b_\mu W^c_\nu$$

$$D^{ij}_\mu=\delta^{ij}\partial_\mu-igW^a_\mu t^{ij}_a$$



- Ws W^a_μ
- Higgs h_i
- No QED: Ws and Zs are degenerate
- Coupling g and some numbers f^{abc} and t_a^{ij}

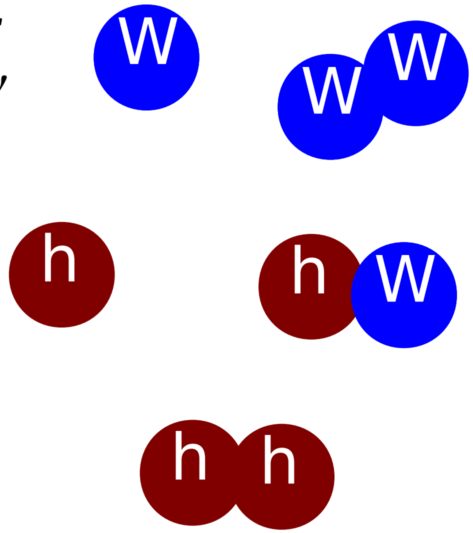
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} + \left(D_\mu^{ij} h^j\right)^+ D^\mu_{ik} h_k + \lambda\left(h^a h_a^+ - v^2\right)^2$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{bc} W^b_\mu W^c_\nu$$

$$D^{ij}_\mu = \delta^{ij}\partial_\mu - igW^a_\mu t^{ij}_a$$



- Ws W^a_μ
- Higgs h_i
- No QED: Ws and Zs are degenerate
- Couplings g, v, λ and some numbers f^{abc} and t_a^{ij}

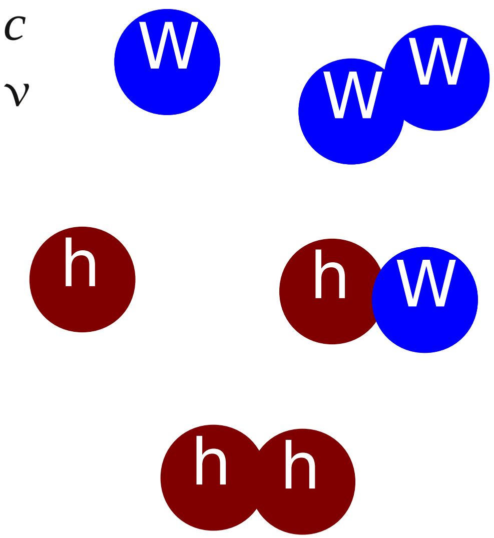
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L = -\frac{1}{4} W^{a}_{\mu\nu} W_{a}^{\mu\nu} + \left(D^{ij}_{\mu} h^{j} \right)^{+} D^{\mu}_{ik} h_{k} + \lambda \left(h^{a} h_{a}^{+} - v^{2} \right)^{2}$$

$$W^{a}_{\mu\nu} = \partial_{\mu} W^{a}_{\nu} - \partial_{\nu} W^{a}_{\mu} + g f^{a}_{bc} W^{b}_{\mu} W^{c}_{\nu}$$

$$D^{ij}_{\mu} = \delta^{ij} \partial_{\mu} - i g W^{a}_{\mu} t^{ij}_{a}$$



- Ws W^{a}_{μ}
- Higgs h_{i}
- No QED: Ws and Zs are degenerate
- Couplings g, v, λ and some numbers f^{abc} and t^{ij}_{a}
- If not stated differently: Tree-level masses as in SM

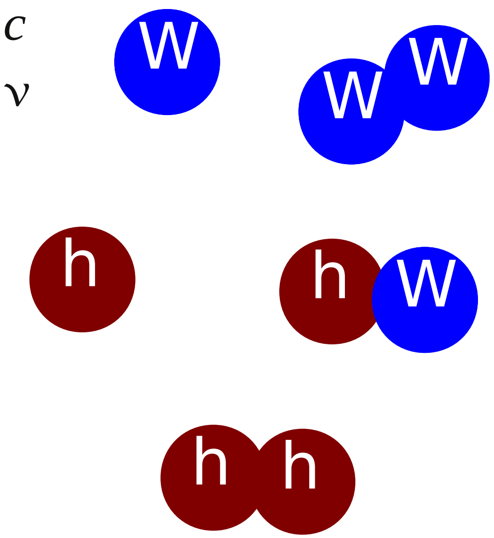
The Higgs sector as a gauge theory

- The Higgs sector is a gauge theory

$$L=-\frac{1}{4}W^{a}_{\mu\nu}W_{a}^{\mu\nu}+\left(D^{ij}_{\mu}h^{j}\right)^{+}D^{\mu}_{ik}h_{k}+\lambda\left(h^{a}h_{a}^{+}-v^{2}\right)^{2}$$

$$W^{a}_{\mu\nu}=\partial_{\mu}W^{a}_{\nu}-\partial_{\nu}W^{a}_{\mu}+gf^{a}_{bc}W^{b}_{\mu}W^{c}_{\nu}$$

$$D^{ij}_{\mu}=\delta^{ij}\partial_{\mu}-igW^{a}_{\mu}t^{ij}_{a}$$



- Ws W^{a}_{μ}
- Higgs h_{i}
- No QED: Ws and Zs are degenerate
- Couplings g, v, λ and some numbers f^{abc} and t_{a}^{ij}
- If not stated differently: Tree-level masses as in SM
- Calculations will be performed using lattice

Symmetries

$$L = -\frac{1}{4} W^a_{\mu\nu} W^{\mu\nu}_a + \left(D^{ij}_\mu h^j \right)^+ D^\mu_{ik} h_k + \lambda \left(h^a h^+_a - v^2 \right)^2$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{\ bc} W^b_\mu W^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - i g W^a_\mu t^{ij}_a$$

Symmetries

$$L = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} + \left(D^{ij}_\mu h^j\right)^+ D^\mu_{ik} h_k + \lambda\left(h^a h_a^+ - v^2\right)^2$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{\ bc} W^b_\mu W^c_\nu$$

$$D^{ij}_\mu = \delta^{ij}\partial_\mu - igW^a_\mu t^{ij}_a$$

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

$$W^a_\mu \rightarrow W^a_\mu + (\delta^a_b \partial_\mu - g f^a_{bc} W^c_\mu)\phi^b \qquad h_i \rightarrow h_i + g\, t^{ij}_a \phi^a h_j$$

Symmetries

$$L = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu} + \left(D^{ij}_\mu h^j\right)^+ D^\mu_{ik} h_k + \lambda\left(h^a h_a^+ - v^2\right)^2$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{\ bc} W^b_\mu W^c_\nu$$

$$D^{ij}_\mu = \delta^{ij} \partial_\mu - i g W^a_\mu t^{ij}_a$$

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

$$W^a_\mu \rightarrow W^a_\mu + (\delta^a_b \partial_\mu - g f^a_{\ bc} W^c_\mu) \phi^b \qquad h_i \rightarrow h_i + g t^{ij}_a \phi^a h_j$$

- Global SU(2) Higgs custodial (flavor) symmetry
  - Acts as right-transformation on the Higgs field only

$$W^a_\mu \rightarrow W^a_\mu \qquad h_i \rightarrow h_i + a^{ij} h_j + b^{ij} h_j^*$$

Standard approach

[Bohm et al. 2001]

- Minimize action classically
  - Yields $hh^{+} = v^2$ - Higgs vev

Standard approach

[Bohm et al. 2001]

- Minimize action classically
  - Yields $hh^{+} = v^2$ - Higgs vev
  - Assume quantum corrections to this are small

Standard approach

[Bohm et al. 2001]

- Minimize action classically
  - Yields $hh^{+}=v^2$ - Higgs vev
  - Assume quantum corrections to this are small
- Perform global gauge transformation such that

$$h(x)=\begin{pmatrix}\varphi^1(x)+i\varphi^2(x)\\ v+\eta(x)+i\varphi^3(x)\end{pmatrix}\Rightarrow\langle h\rangle=\begin{pmatrix}0\\ v\end{pmatrix}$$

  - η mass depends at tree-level on v

Standard approach

[Bohm et al. 2001]

- Minimize action classically
  - Yields $hh^{+}=v^2$ - Higgs vev
  - Assume quantum corrections to this are small
- Perform global gauge transformation such that

$$h(x)=\begin{pmatrix}\varphi^1(x)+i\varphi^2(x)\\ v+\eta(x)+i\varphi^3(x)\end{pmatrix}\Rightarrow\langle h\rangle=\begin{pmatrix}0\\ v\end{pmatrix}$$

  - η mass depends at tree-level on v
- Perform perturbation theory

Implications of global transformation

- Not all charge directions equal
    - This is not physical, but merely a choice of gauge

Implications of global transformation

- Not all charge directions equal
  - This is not physical, but merely a choice of gauge
  - “Spontaneous gauge symmetry breaking”
    - Broken by the transformation, not by the dynamics
    - Dynamics only affect the length of the Higgs field
    - Local symmetry intact and cannot be broken

      [Elitzur PR'75]

Implications of global transformation

- Not all charge directions equal
  - This is not physical, but merely a choice of gauge
  - “Spontaneous gauge symmetry breaking”
    - Broken by the transformation, not by the dynamics
    - Dynamics only affect the length of the Higgs field
    - Local symmetry intact and cannot be broken [Elitzur PR'75]
  - There are gauge where the vev always vanishes [Maas'13]
    - Perturbation theory not sensible [Lee et al.'72]

Implications of global transformation

- Not all charge directions equal
  - This is not physical, but merely a choice of gauge
  - “Spontaneous gauge symmetry breaking”
    - Broken by the transformation, not by the dynamics
    - Dynamics only affect the length of the Higgs field
    - Local symmetry intact and cannot be broken [Elitzur PR'75]
  - There are gauge where the vev always vanishes [Maas'13]
    - Perturbation theory not sensible [Lee et al.'72]
- Consequence: Symmetry in charge space not manifest (hidden)
  - Symmetry expressed in STIs/WTIs

Masses from propagators

- Masses are determined by poles of propagators

Masses from propagators

- Masses are determined by poles of propagators
- 2 propagators
  - W/Z $D^{ab}_{\mu\nu}(x-y) = <W^a_\mu(x) W^b_\nu(y)>$
    - Degenerate without QED
  - Scalar $D^{ij}_H(x-y) = <h^i(x) h^{j+}(y)>$

Masses from propagators

- Masses are determined by poles of propagators
- 2 propagators
  - W/Z $D_{\mu\nu}^{ab}(x-y) = <W_\mu^a(x) W_\nu^b(y)>$
    - Degenerate without QED
  - Scalar $D_H^{ij}(x-y) = <h^i(x) h^{j+}(y)>$
- (Tree-level/perturbative) poles at Higgs and W mass

Masses from propagators

- Masses are determined by poles of propagators
- 2 propagators
  - W/Z $D^{ab}_{\mu\nu}(x-y) = \langle W^a_\mu(x) W^b_\nu(y) \rangle$
    - Degenerate without QED
  - Scalar $D^{ij}_H(x-y) = \langle h^i(x) h^{j+}(y) \rangle$
- (Tree-level/perturbative) poles at Higgs and W mass
  - But only in a fixed gauge
  - Elementary fields are gauge-dependent
  - Without gauge fixing propagators are $\sim\delta(x-y)$

Physical states

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

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

Physical states

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

- Elementary fields depend on the gauge
  - Except right-handed neutrinos
- Experiments measure peaks in cross-sections for particular quantum numbers
  - E.g. hadrons in QCD

Physical states

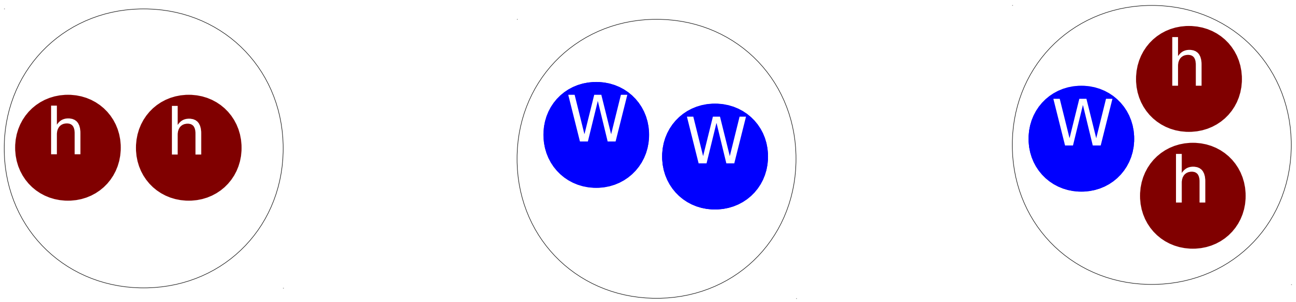
[Fröhlich et al. PLB 80,
't Hooft ASIB 80,
Bank et al. NPB 79]

- Elementary fields depend on the gauge
  - Except right-handed neutrinos
- Experiments measure peaks in cross-sections for particular quantum numbers
  - E.g. hadrons in QCD
- Gauge-invariance requires composite operators in gauge theories
  - Not asymptotic states in perturbation theory

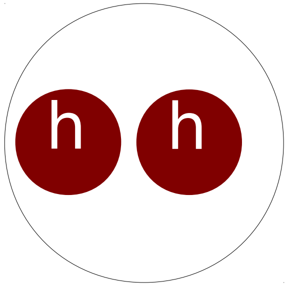
Physical states

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

- Elementary fields depend on the gauge
  - Except right-handed neutrinos
- Experiments measure peaks in cross-sections for particular quantum numbers
  - E.g. hadrons in QCD
- Gauge-invariance requires composite operators in gauge theories
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.

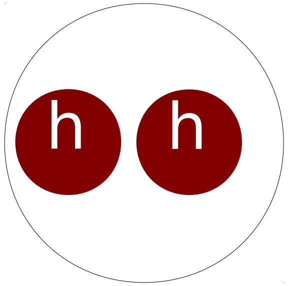


Higgsonium



- Simpelst 0^+ bound state $h^+(x)h(x)$

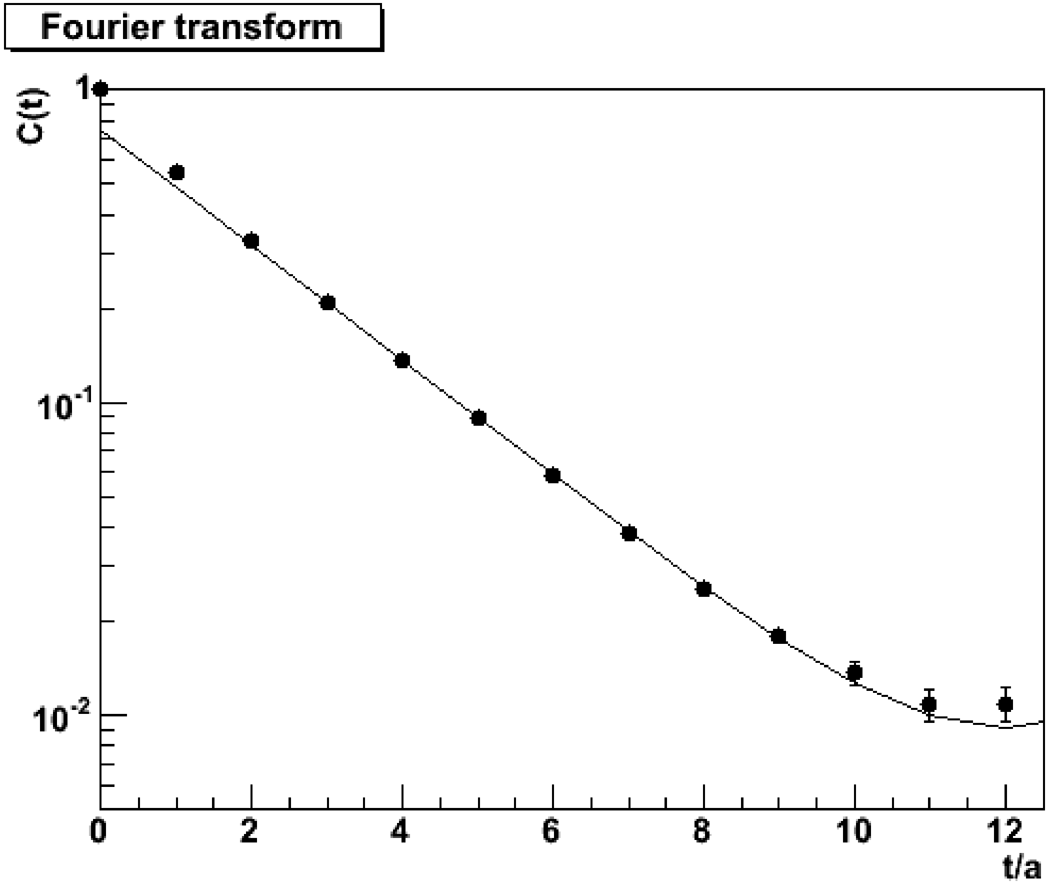
Higgsonium



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

Higgsonium

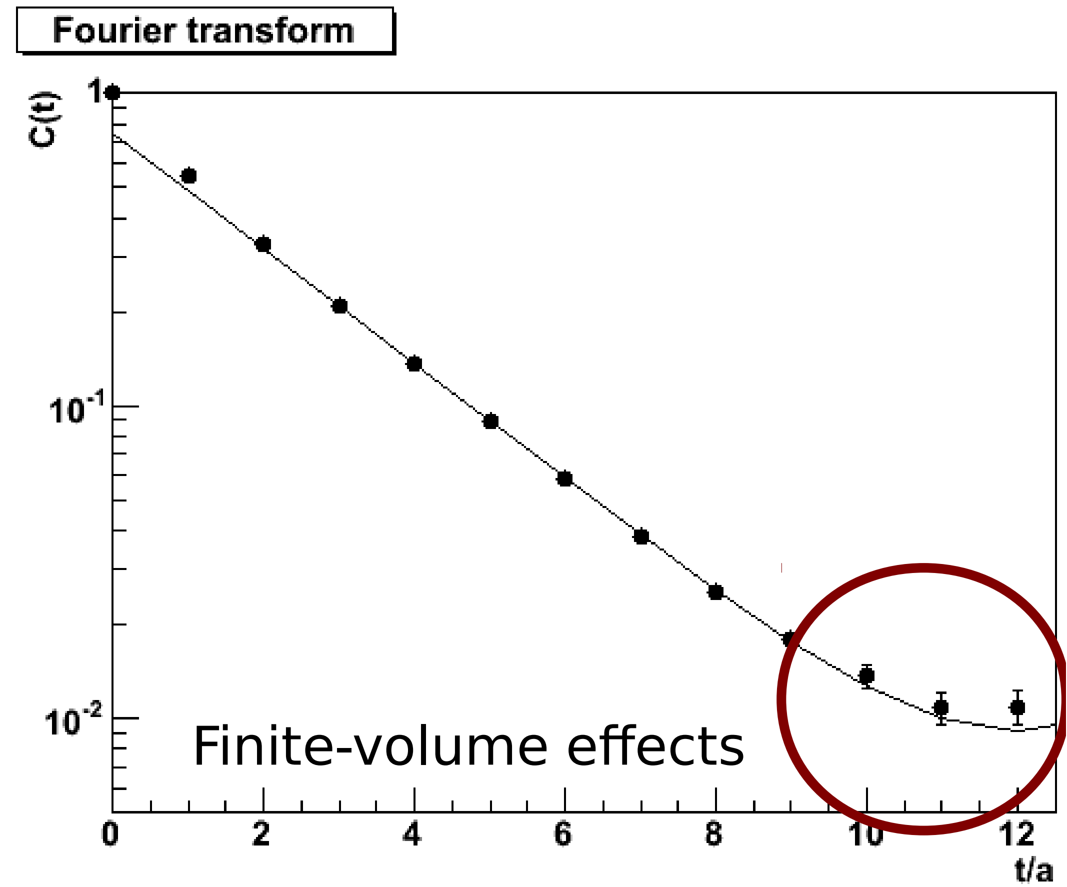
[Maas et al. '13]



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

Higgsonium

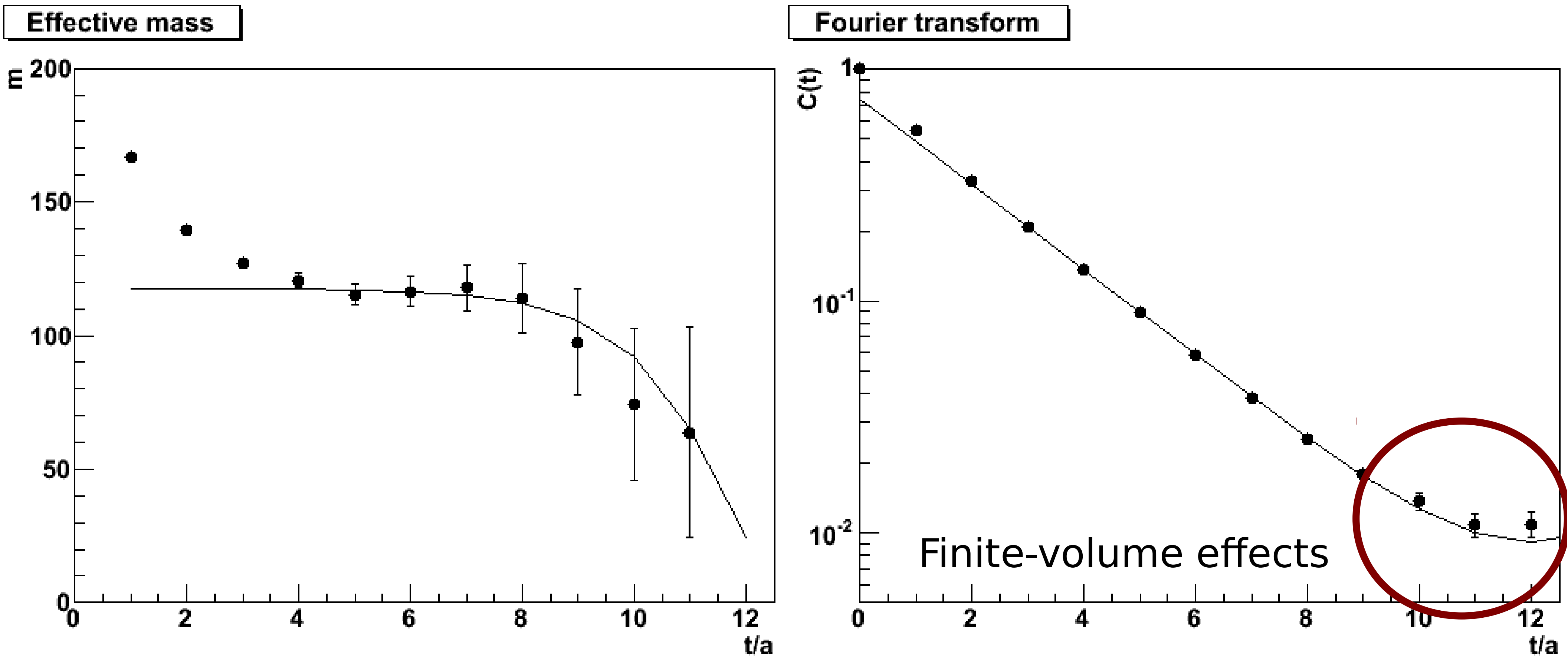
[Maas et al. '13]



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

Higgsonium

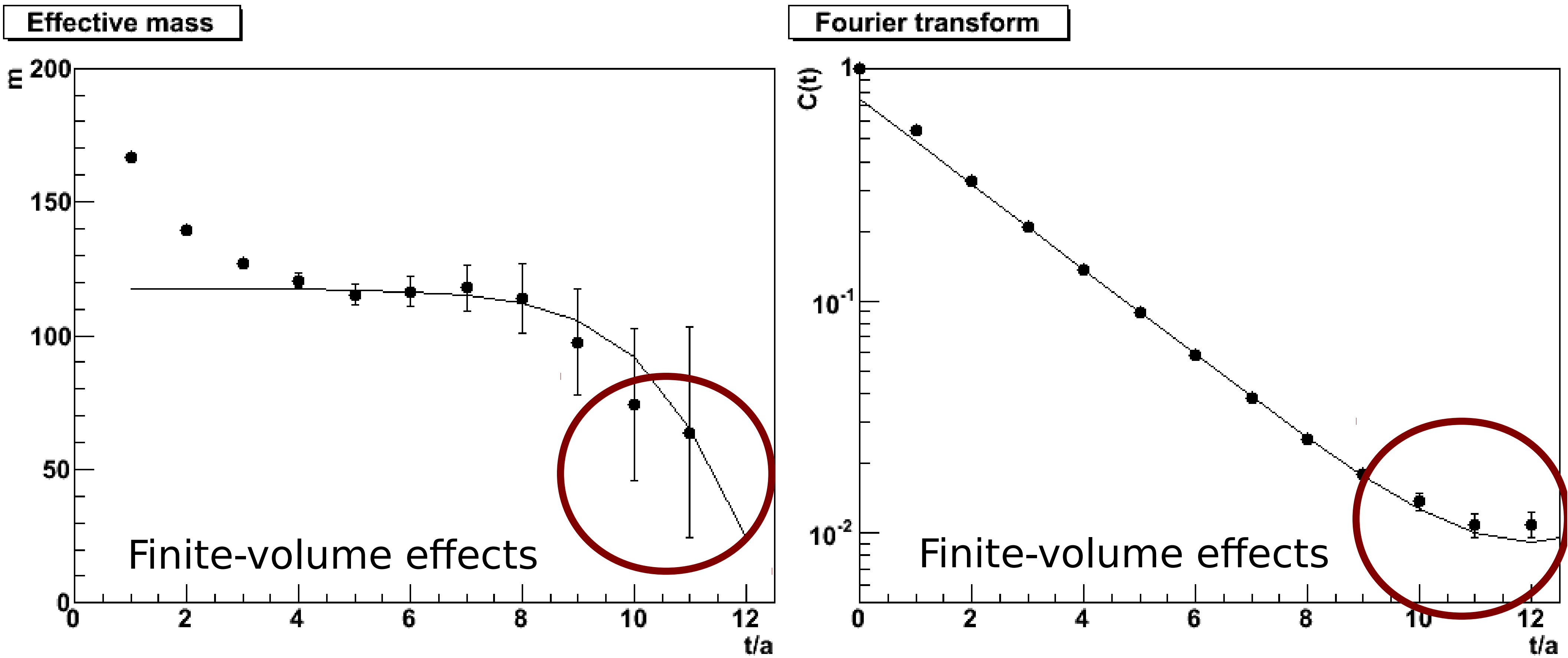
[Maas et al. '13]



- Simpelst 0^+ bound state $h^+(x)h(x)$
  - Same quantum numbers as the Higgs
    - No weak or flavor charge
  - Mass is about 120 GeV

Higgsonium

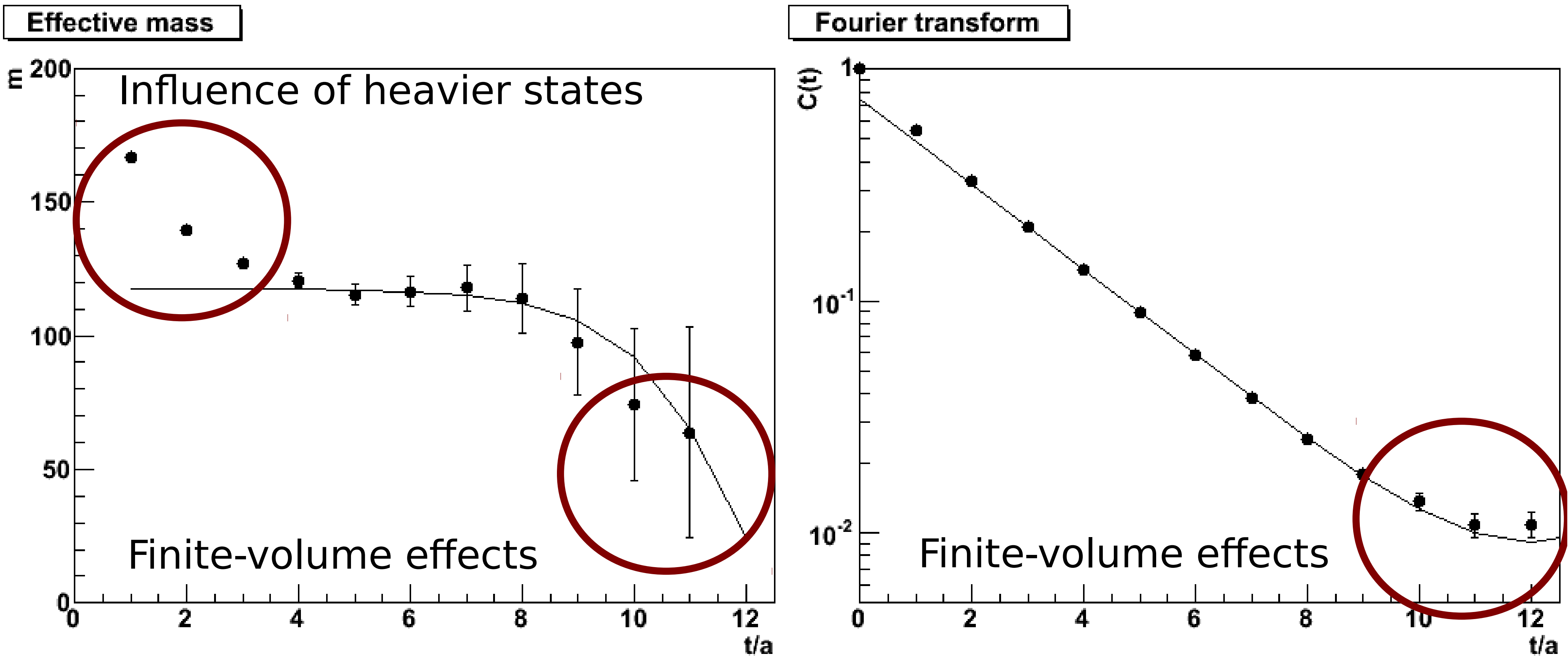
[Maas et al. '13]



- Simpelst 0^+ bound state $h^+(x)h(x)$
  - Same quantum numbers as the Higgs
    - No weak or flavor charge
  - Mass is about 120 GeV

Higgsonium

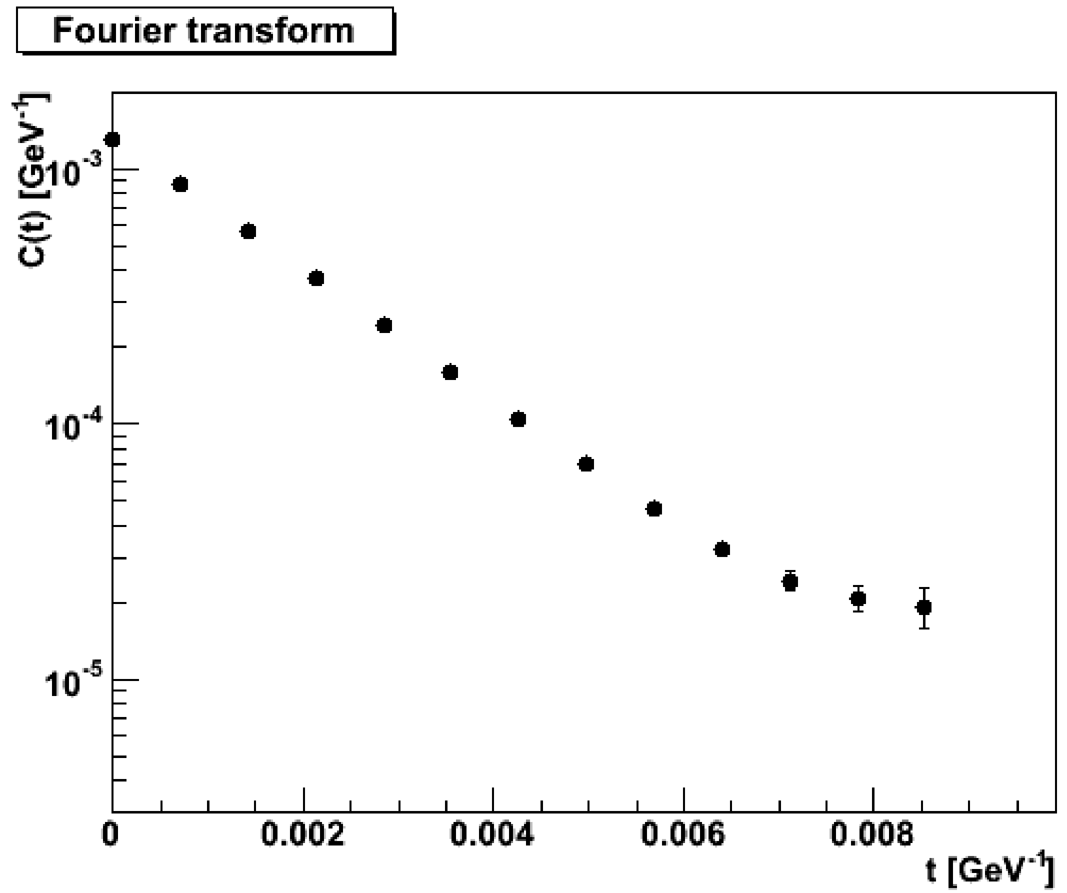
[Maas et al. '13]



- Simpelst 0^+ bound state $h^+(x)h(x)$
  - Same quantum numbers as the Higgs
    - No weak or flavor charge
  - Mass is about 120 GeV

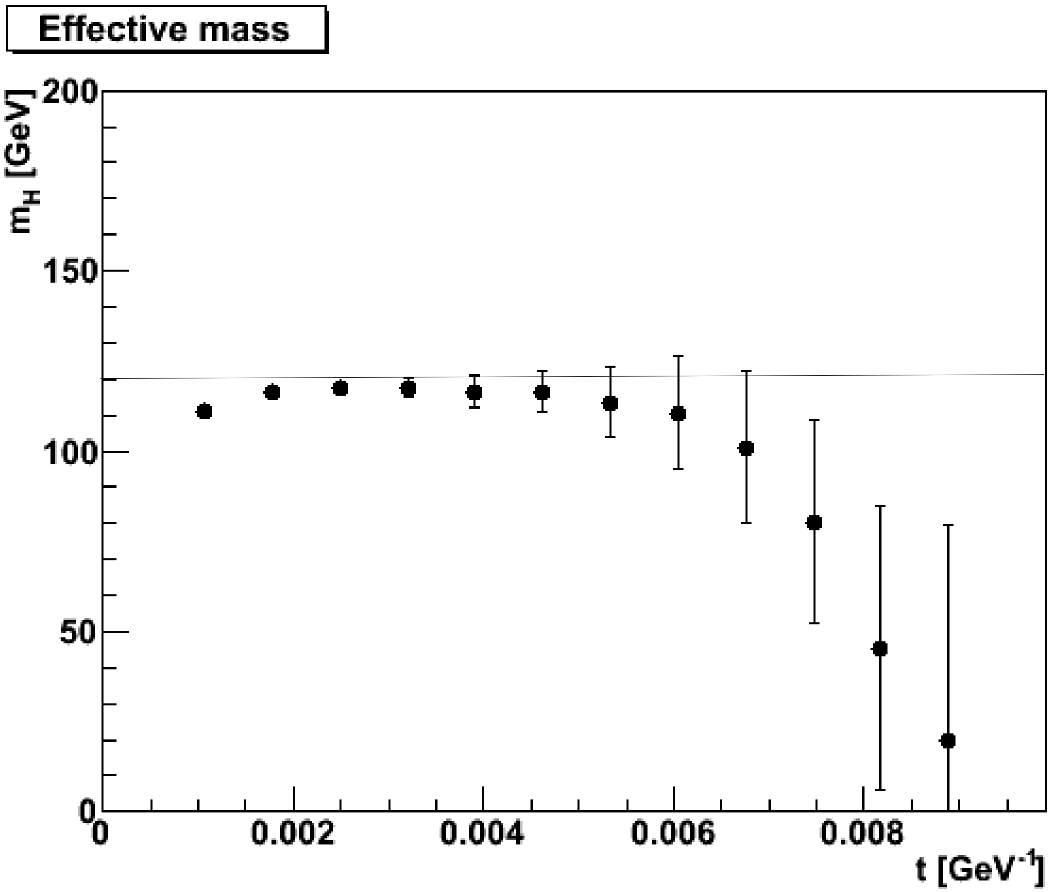
Comparison to Higgs

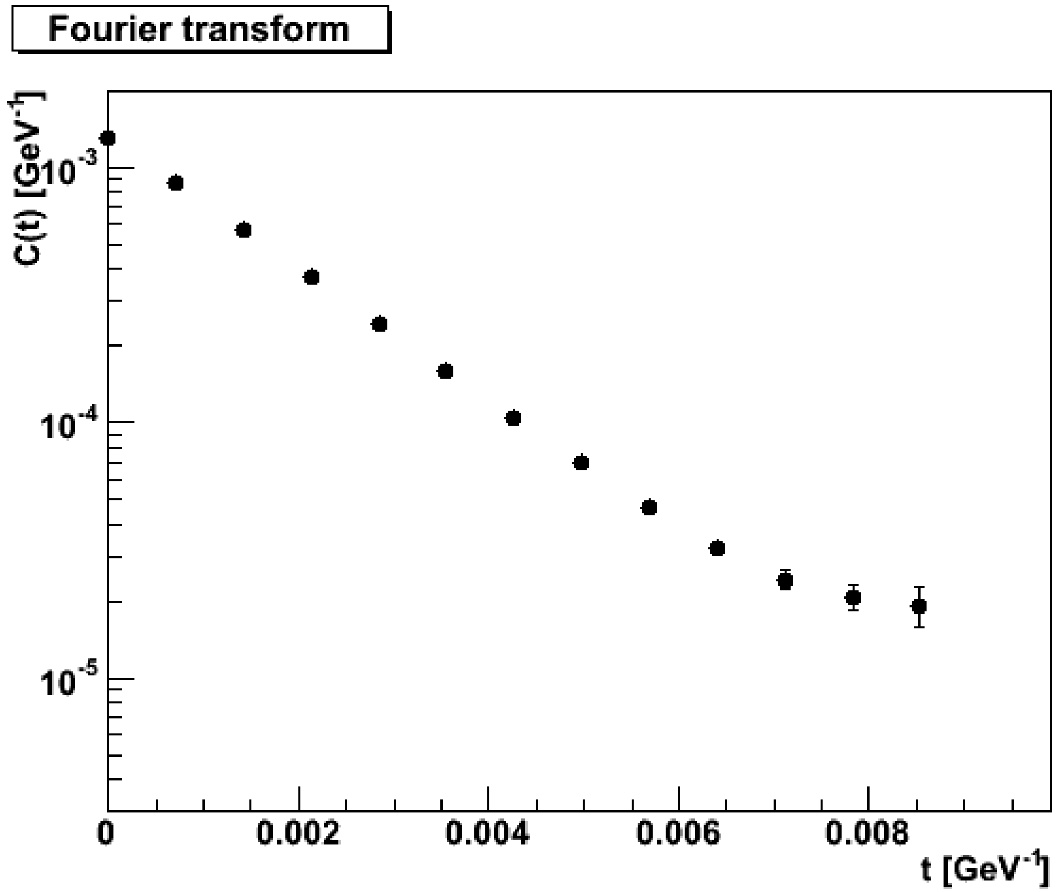
[Maas et al. '13]



Comparison to Higgs

[Maas et al. '13]





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

Mass relation - Higgs

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

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

Mass relation - Higgs

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

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

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al. PLB 80]

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al. PLB 80]

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle$$

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al. PLB 80]

$$h = v + \eta$$

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle \approx$$

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states

[Fröhlich et al. PLB 80]

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

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al. PLB 80]

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

  - Same poles to leading order

Mass relation - Higgs

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

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al. PLB 80]

$$\left\langle \left(h^+ h\right)(x)\left(h^+ h\right)(y)\right\rangle \overset{h=v+\eta}{\approx} const. + \left\langle h^+(x) h(y)\right\rangle + O\left(\eta^3\right)$$

  - Same poles to leading order
- Fröhlich-Morchio-Strocchi (FMS) mechanism

Mass relation - Higgs

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

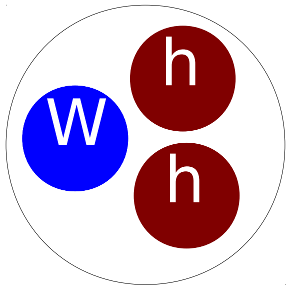
- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states

[Fröhlich et al. PLB 80]

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

  - Same poles to leading order
- Fröhlich-Morchio-Strocchi (FMS) mechanism
- Deeply-bound relativistic state
  - Mass defect~constituent mass
  - Cannot describe with quantum mechanics
  - Very different from QCD bound states

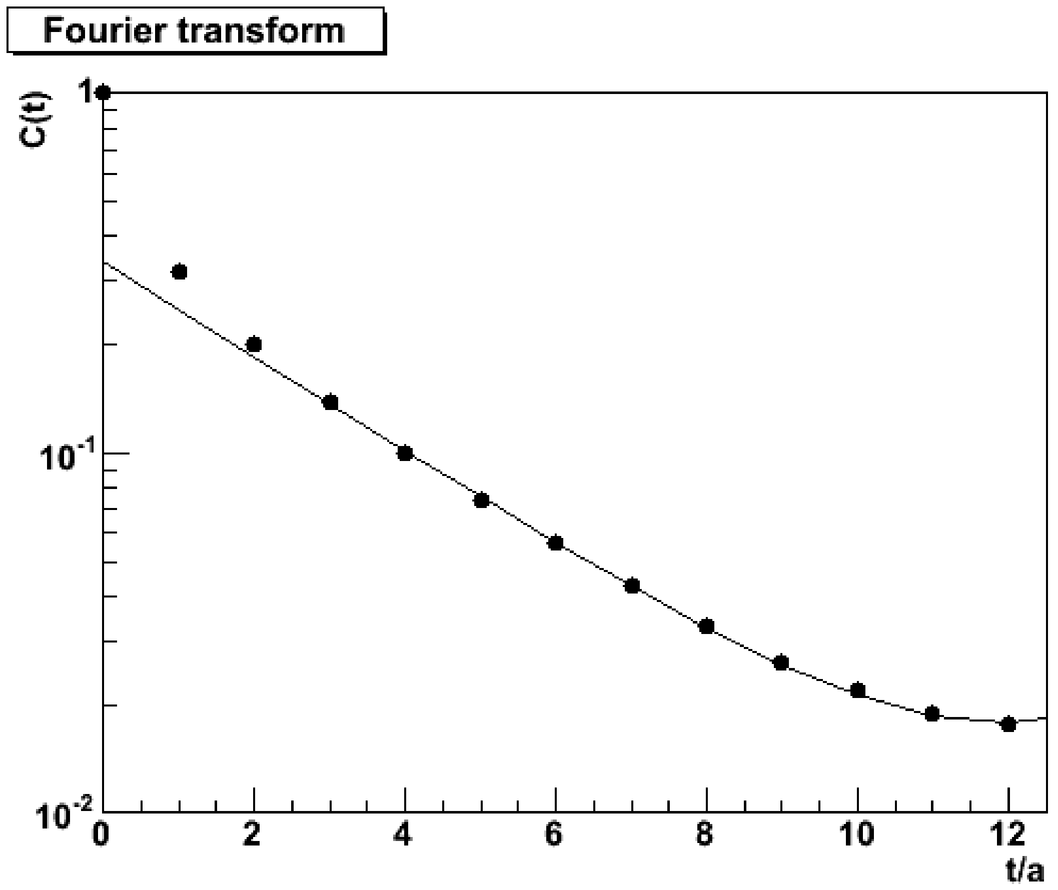
Isovector-vector state



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

Isovector-vector state

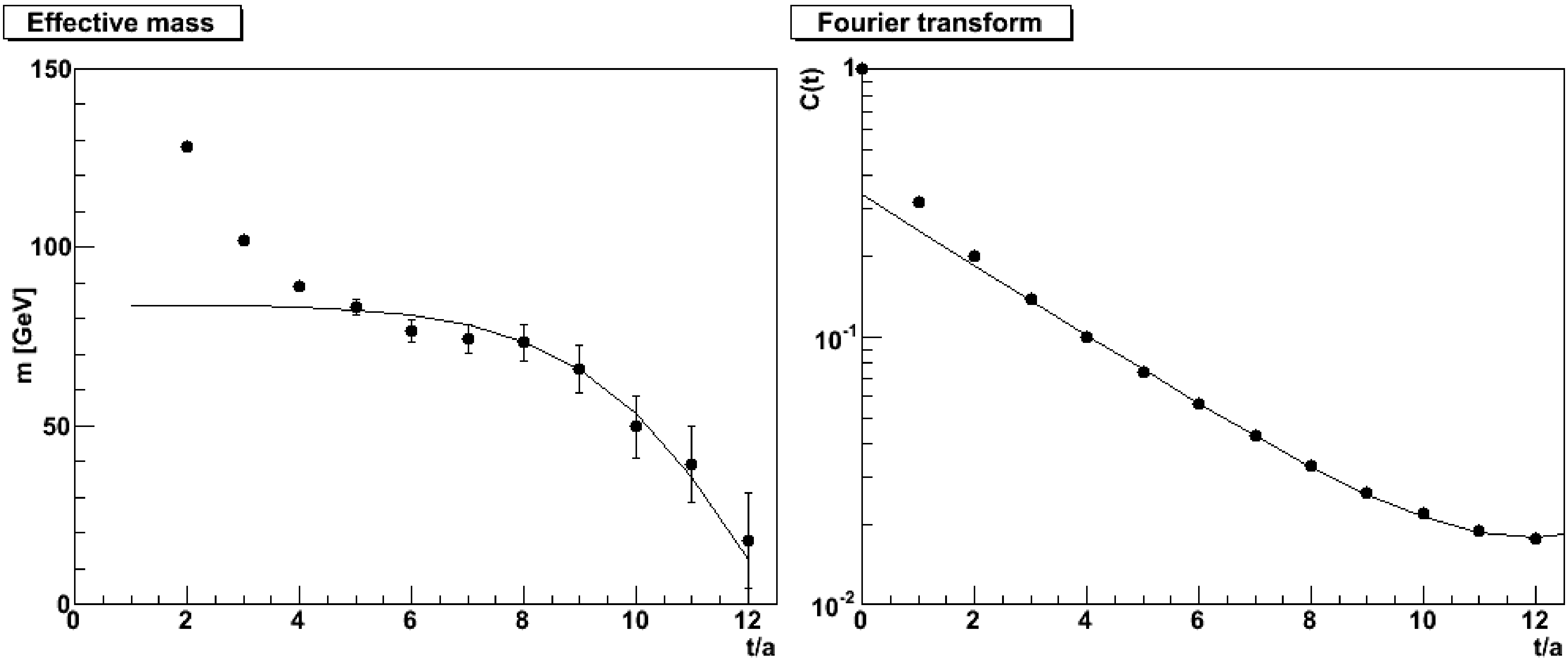
[Maas et al. '13]



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

Isovector-vector state

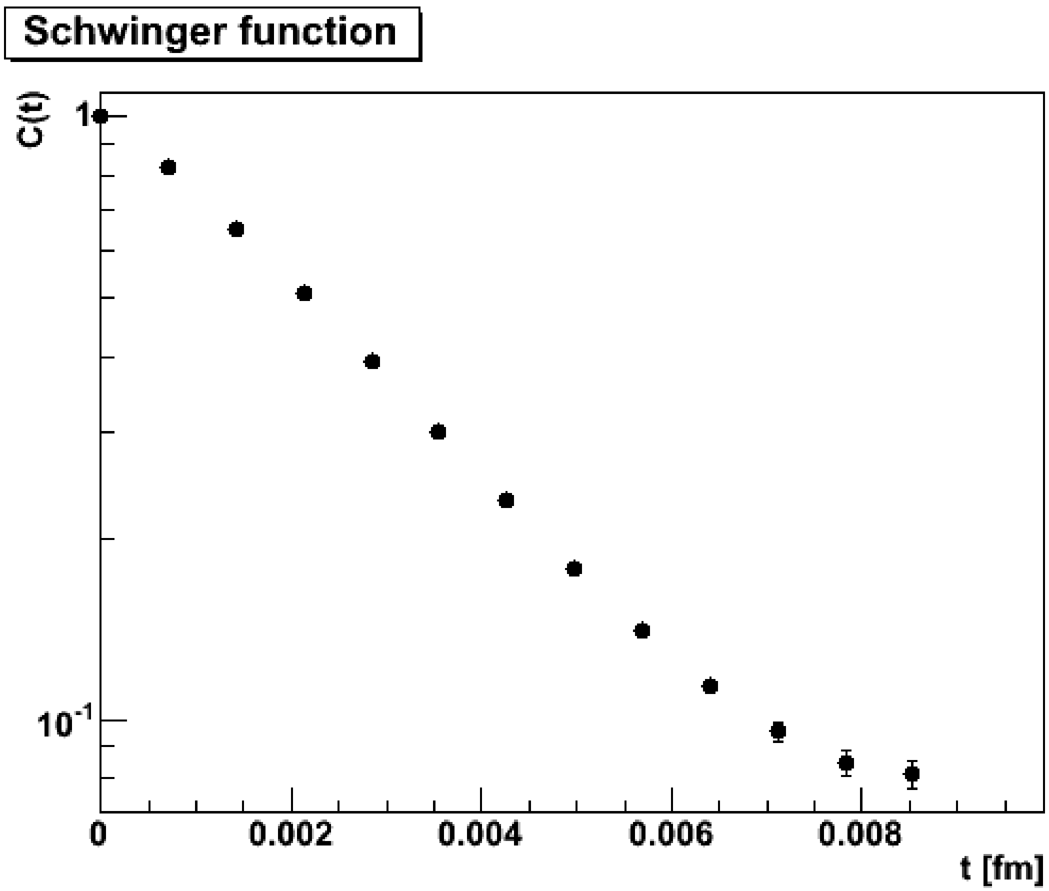
[Maas et al. '13]



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

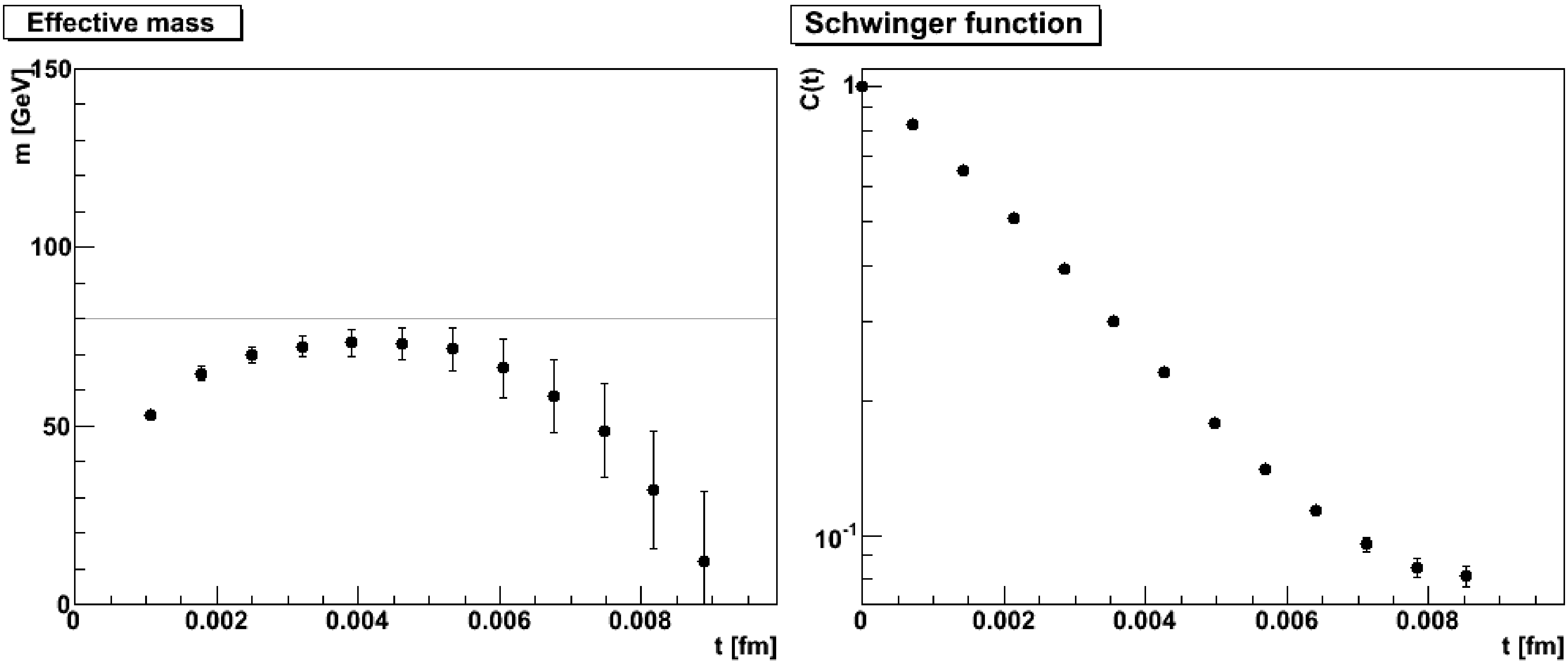
Comparison to W

[Maas et al. '13]



Comparison to W

[Maas et al. '13]



- Essentially same mass, up to artifacts
- Different influence at short times
  - Not a hard mass, but decreases at high energies

Mass relation - W

[Fröhlich et al. PLB 80
Maas'12]

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

Mass relation - W

[Fröhlich et al. PLB 80
Maas'12]

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

$$\left\langle \left(h^{+} D_{\mu} h\right)(x) \left(h^{+} D_{\mu} h\right)(y) \right\rangle$$

Mass relation - W

[Fröhlich et al. PLB 80
Maas'12]

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

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y)\rangle$$

$$h = v + \eta$$

$$\approx \quad const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta^3)$$

$$\partial v = 0$$

Mass relation - W

[Fröhlich et al. PLB 80
Maas'12]

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

$$\left\langle \left(h^+ D_\mu h\right)(x)\left(h^+ D_\mu h\right)(y)\right\rangle$$

$$h = v + \eta$$

$$\approx \quad const. + \left\langle W_\mu(x) W_\mu(y)\right\rangle + O\left(\eta^3\right)$$

$$\partial v = 0$$

- Same poles at leading order
  - At least for a light Higgs

Mass relation - W

[Fröhlich et al. PLB 80
Maas'12]

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

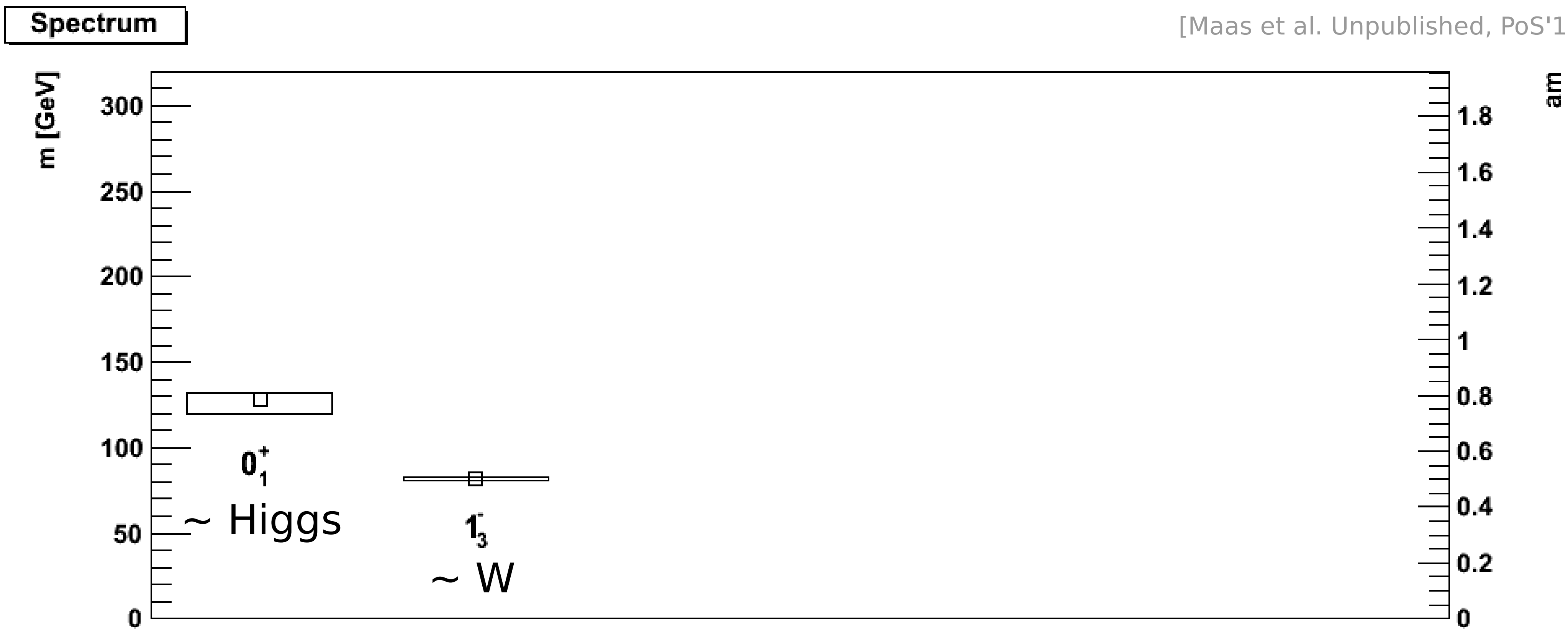
$$\left\langle \left(h^+ D_\mu h\right)(x) \left(h^+ D_\mu h\right)(y) \right\rangle$$

$$\underset{\partial v = 0}{\overset{h=v+\eta}{\approx}} const. + \left\langle W_\mu(x) W_\mu(y) \right\rangle + O\left(\eta^3\right)$$

- Same poles at leading order
  - At least for a light Higgs
  - Remains true beyond leading order

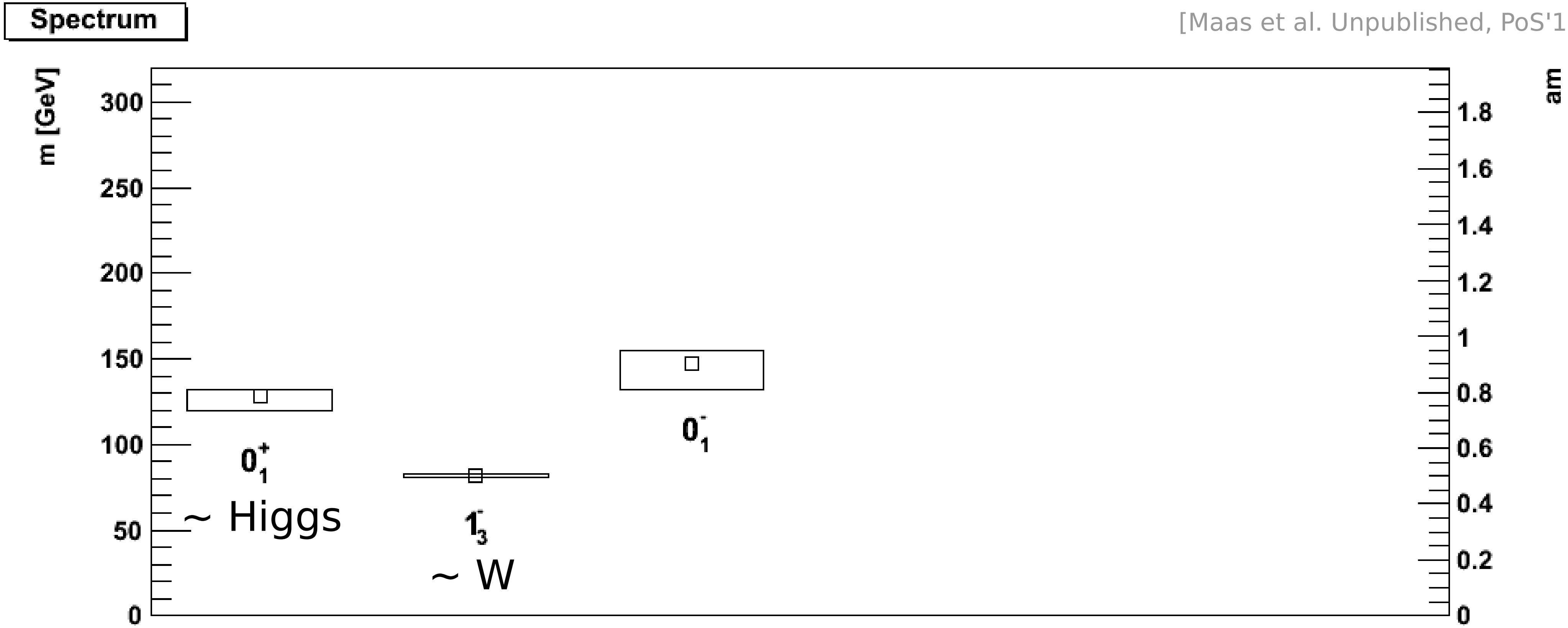
Ground state spectrum

[Maas et al. Unpublished, PoS'12]



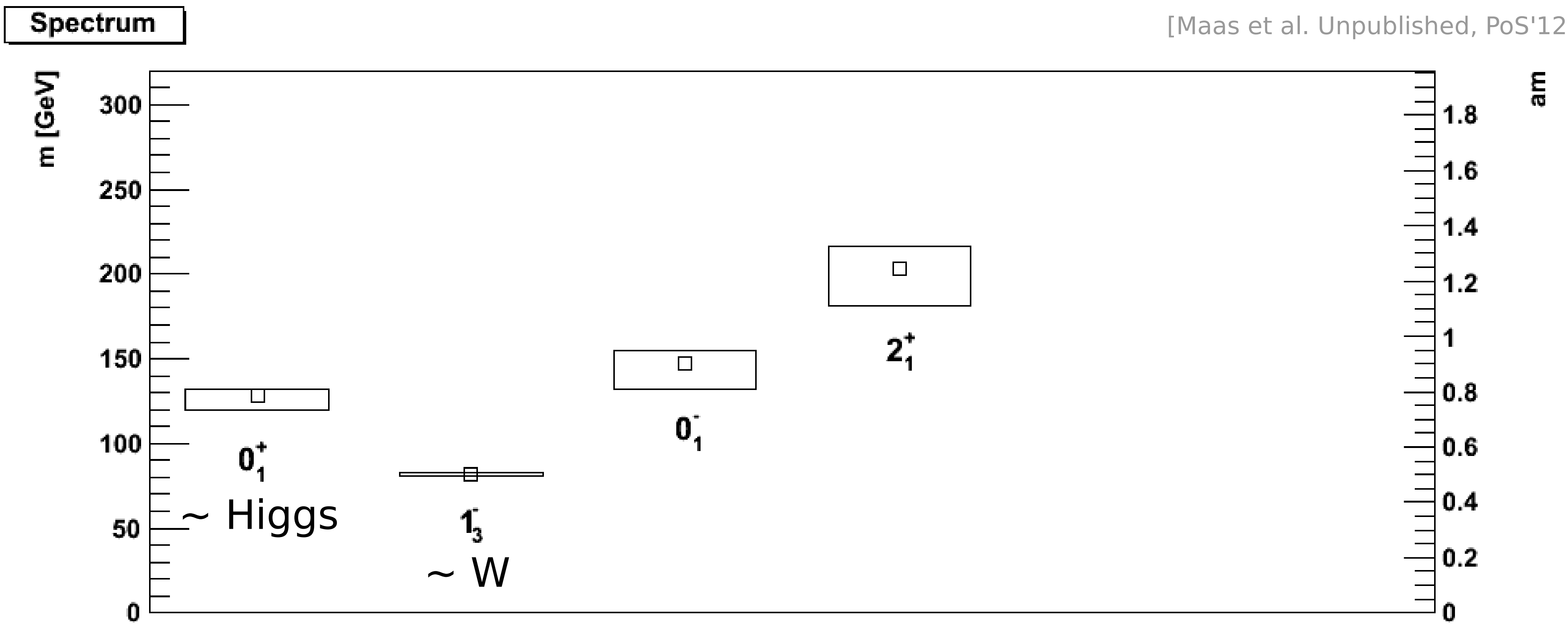
Ground state spectrum

[Maas et al. Unpublished, PoS'12]



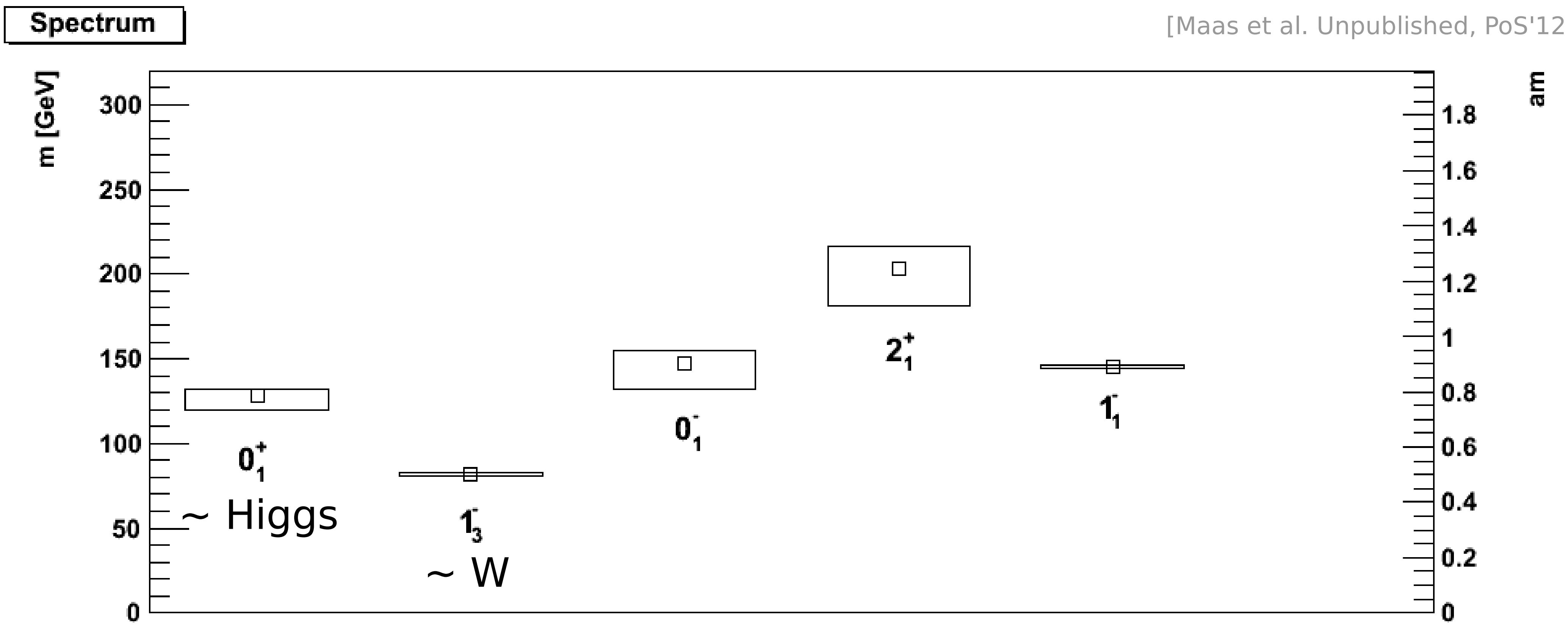
- Many states
  - No simple relation to elementary states besides Higgs and W

Ground state spectrum



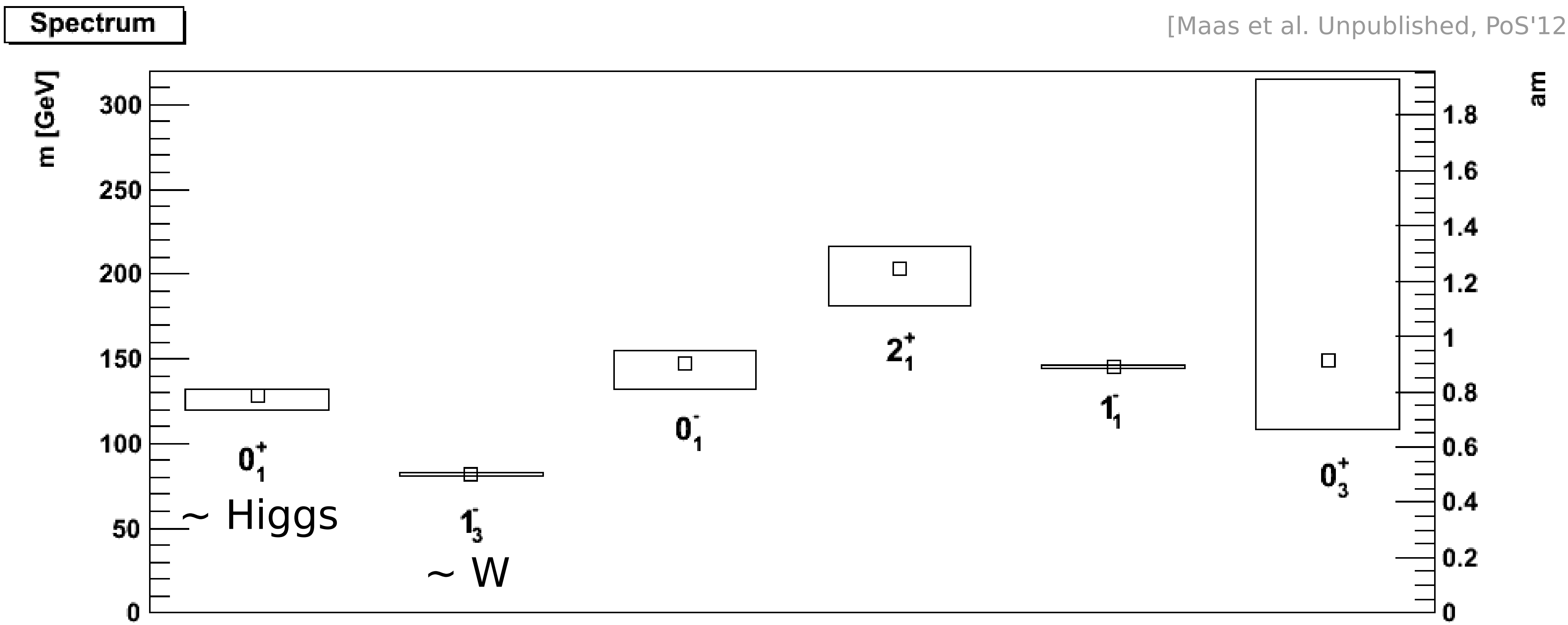
- Many states
  - No simple relation to elementary states besides Higgs and W

Ground state spectrum



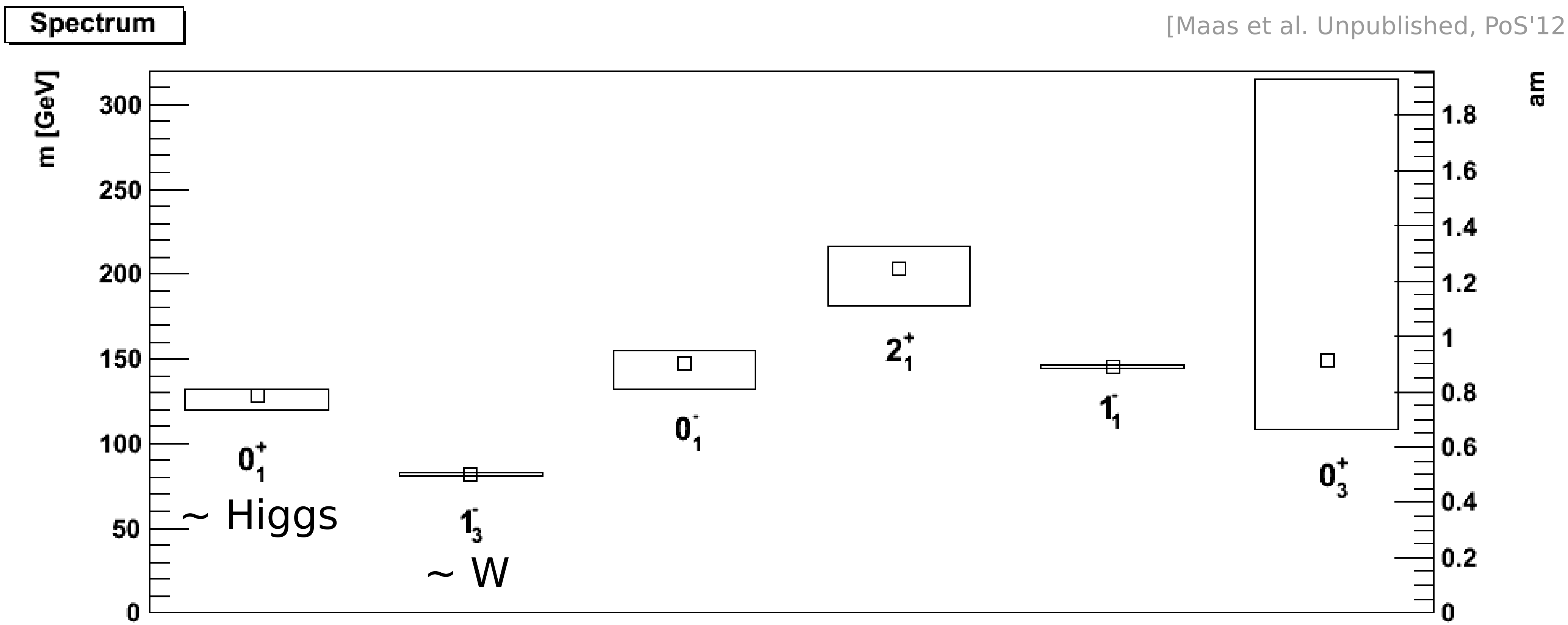
- Many states
  - No simple relation to elementary states besides Higgs and W

Ground state spectrum



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

Ground state spectrum



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

(Speculative) Consequences

- Composite states can have excitations
  - Not necessarily [Wurtz et al. '13]

(Speculative) Consequences

- Composite states can have excitations
  - Not necessarily [Wurtz et al. '13]
  - Could mimic additional Higgs or Z'

(Speculative) Consequences

- Composite states can have excitations
  - Not necessarily [Wurtz et al. '13]
  - Could mimic additional Higgs or Z'
    - 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

(Speculative) Consequences

- Composite states can have excitations
  - Not necessarily [Wurtz et al. '13]
  - Could mimic additional Higgs or Z'
    - 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
  - Possibly only sigma-like bumps
    - Distinction from scattering states

(Speculative) Consequences

- Composite states can have excitations
  - Not necessarily [Wurtz et al. '13]
  - Could mimic additional Higgs or Z'
    - 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
  - Possibly only sigma-like bumps
    - Distinction from scattering states
  - Requires confirmation or exclusion

Comparability to the standard model

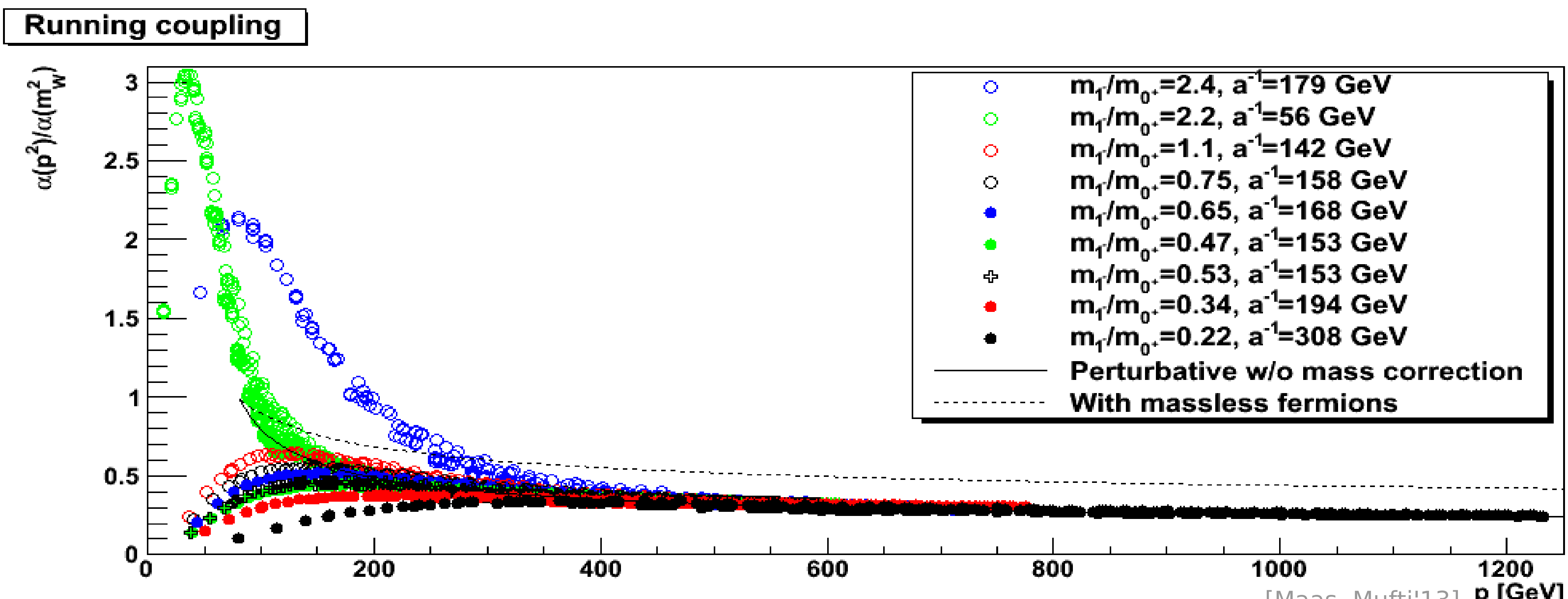
- 2 correct masses only fix two parameters, but 3 parameters needed

Comparability to the standard model

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

Comparability to the standard model

- 2 correct masses only fix two parameters, but 3 parameters needed
- Comparison to standard model complicated
  - States stable, no W/Z splitting
  - Couplings run differently – proceed with caution



[Maas, Mufti'13]

Weakly coupled experimental signals?

- Similar or identical to standard model Higgs sector

Weakly coupled experimental signals?

- Similar or identical to standard model Higgs sector
- Full non-perturbative matrix elements can be expanded in Higgs quantum fluctuations

Weakly coupled experimental signals?

- Similar or identical to standard model Higgs sector
- Full non-perturbative matrix elements can be expanded in Higgs quantum fluctuations
  - Order <~1% in the standard model – weakly coupled and thus strongly suppressed

Weakly coupled experimental signals?

- Similar or identical to standard model Higgs sector
- Full non-perturbative matrix elements can be expanded in Higgs quantum fluctuations
  - Order <~1% in the standard model – weakly coupled and thus strongly suppressed
  - Near W/Z or Higgs pole by construction identical to the perturbative result

Weakly coupled experimental signals?

- Similar or identical to standard model Higgs sector
- Full non-perturbative matrix elements can be expanded in Higgs quantum fluctuations
  - Order <~1% in the standard model – weakly coupled and thus strongly suppressed
  - Near W/Z or Higgs pole by construction identical to the perturbative result
  - Excited states or different quantum numbers possible best signal channel

Weakly coupled experimental signals?

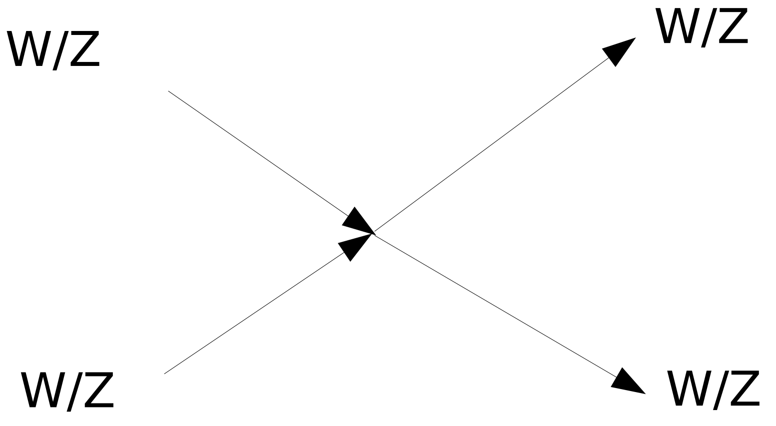
- Similar or identical to standard model Higgs sector
- Full non-perturbative matrix elements can be expanded in Higgs quantum fluctuations
  - Order <~1% in the standard model – weakly coupled and thus strongly suppressed
  - Near W/Z or Higgs pole by construction identical to the perturbative result
  - 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

[Maas et al. Unpublished]

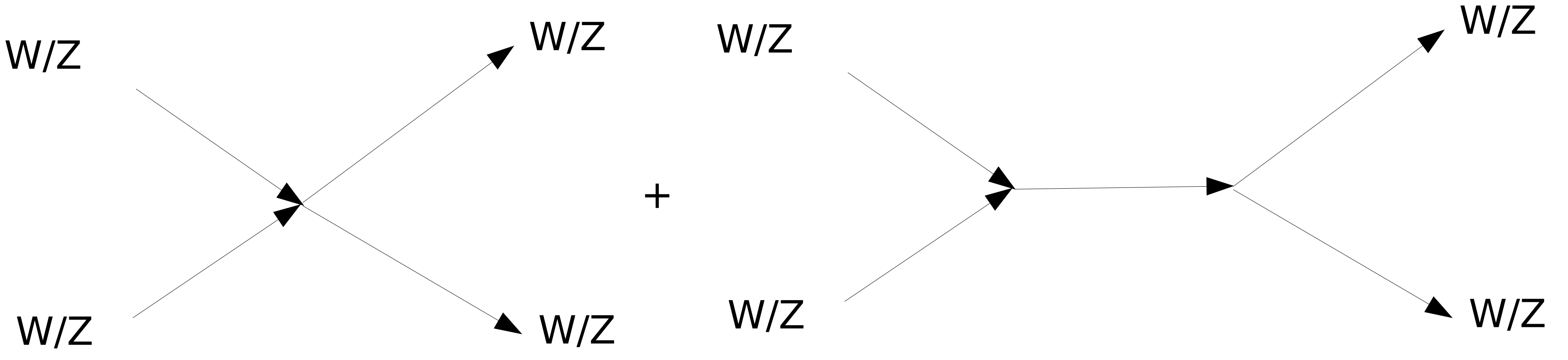
- (Singlet) quartic gauge coupling and resonance formation in the same channel



Impact on quartic gauge coupling

[Maas et al. Unpublished]

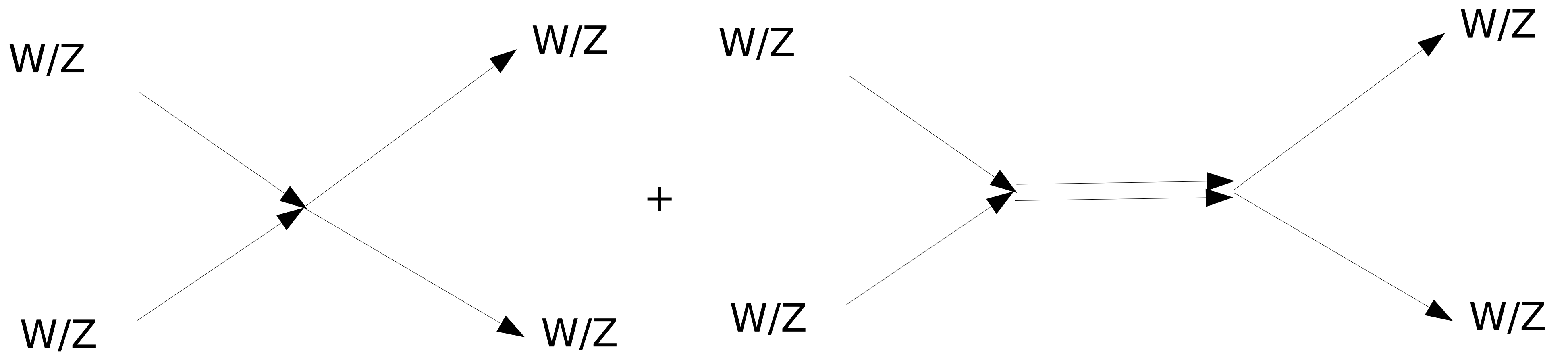
- (Singlet) quartic gauge coupling and resonance formation in the same channel



Impact on quartic gauge coupling

[Maas et al. Unpublished]

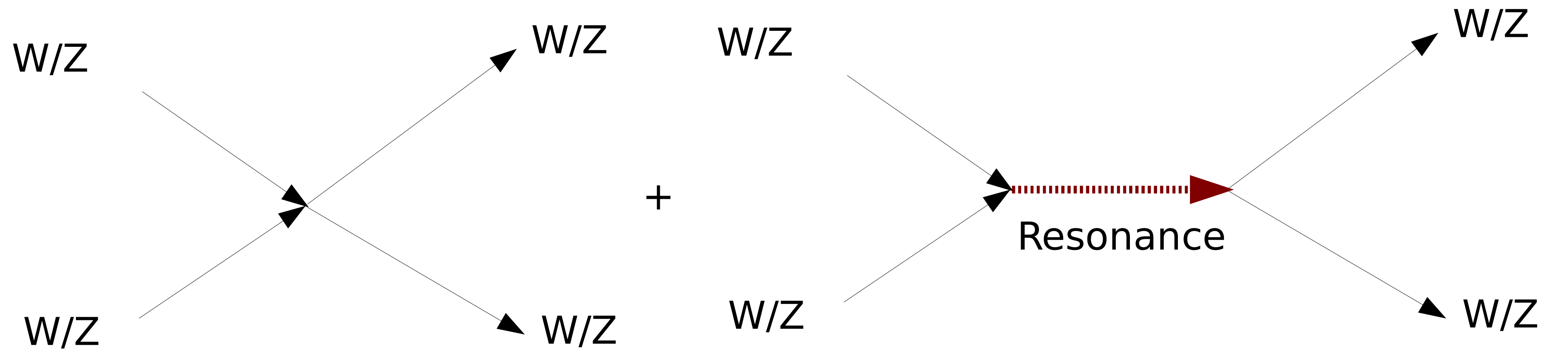
- (Singlet) quartic gauge coupling and resonance formation in the same channel



Impact on quartic gauge coupling

[Maas et al. Unpublished]

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

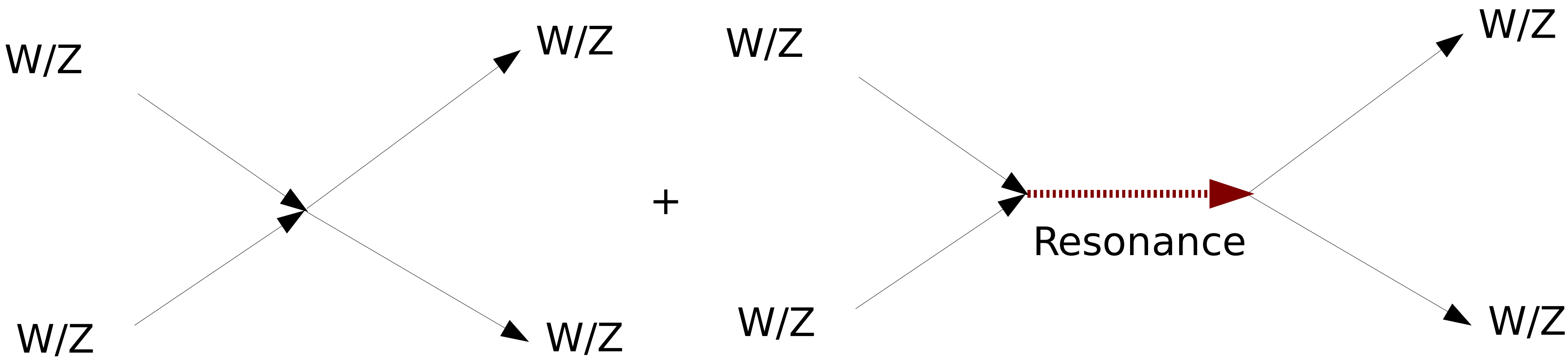


- Resonance peak in final state invariant mass?

Impact on quartic gauge coupling

[Maas et al. Unpublished]

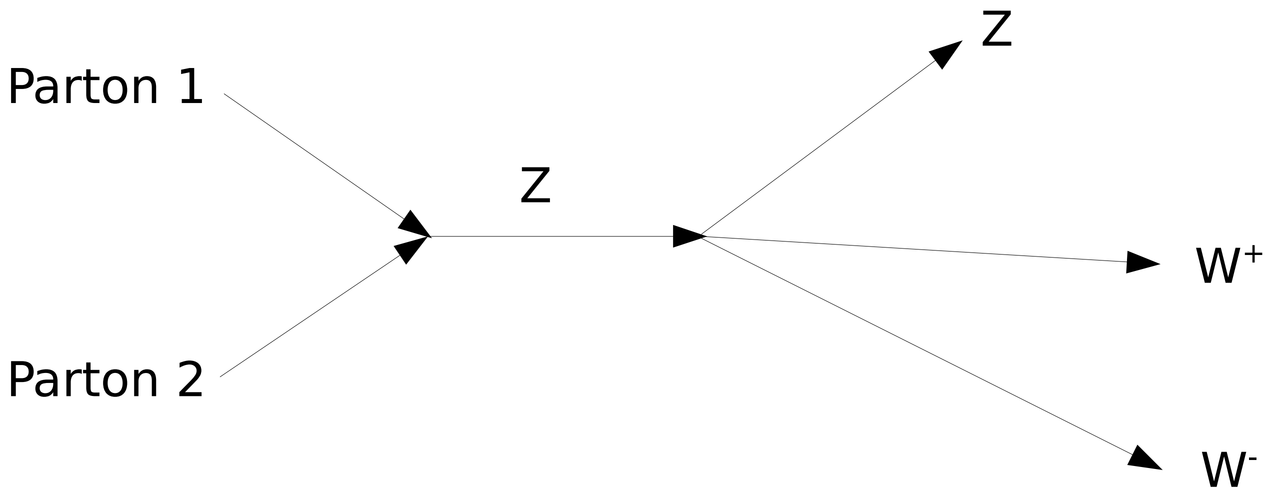
- (Singlet) quartic gauge coupling and resonance formation in the same channel



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

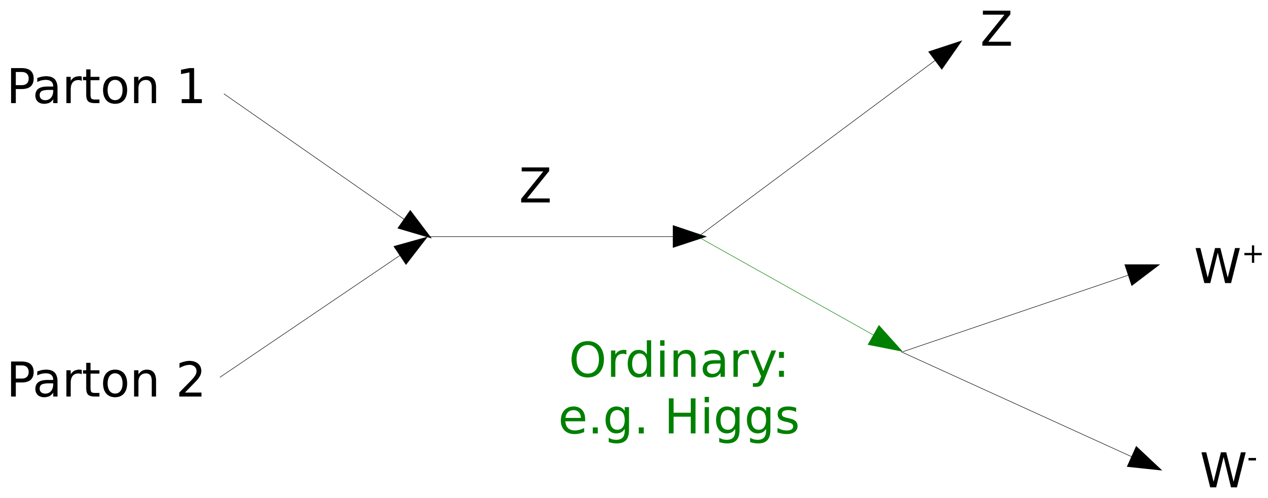
Experimental accessibility

[Maas et al. Unpublished]



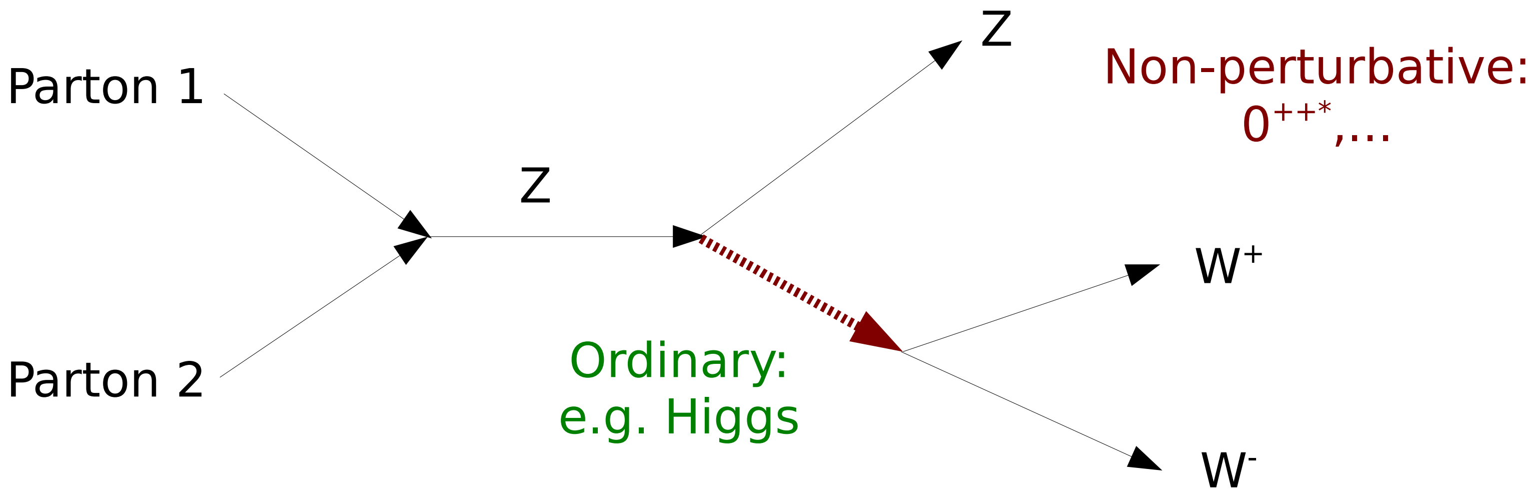
Experimental accessibility

[Maas et al. Unpublished]



Experimental accessibility

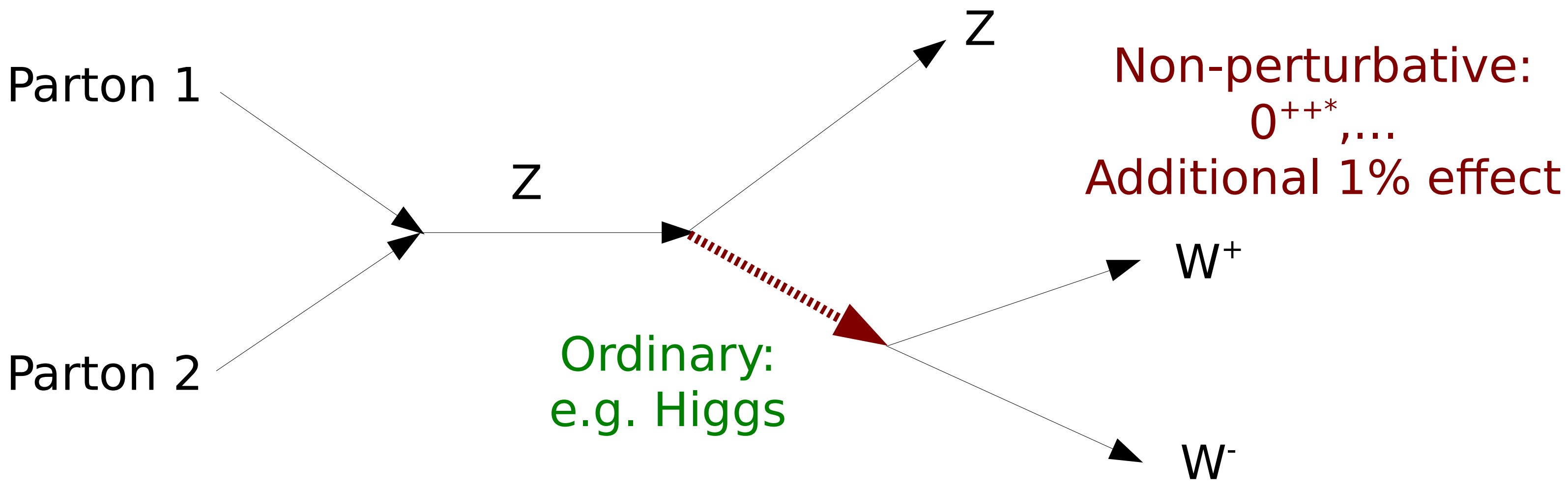
[Maas et al. Unpublished]



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

Experimental accessibility

[Maas et al. Unpublished]

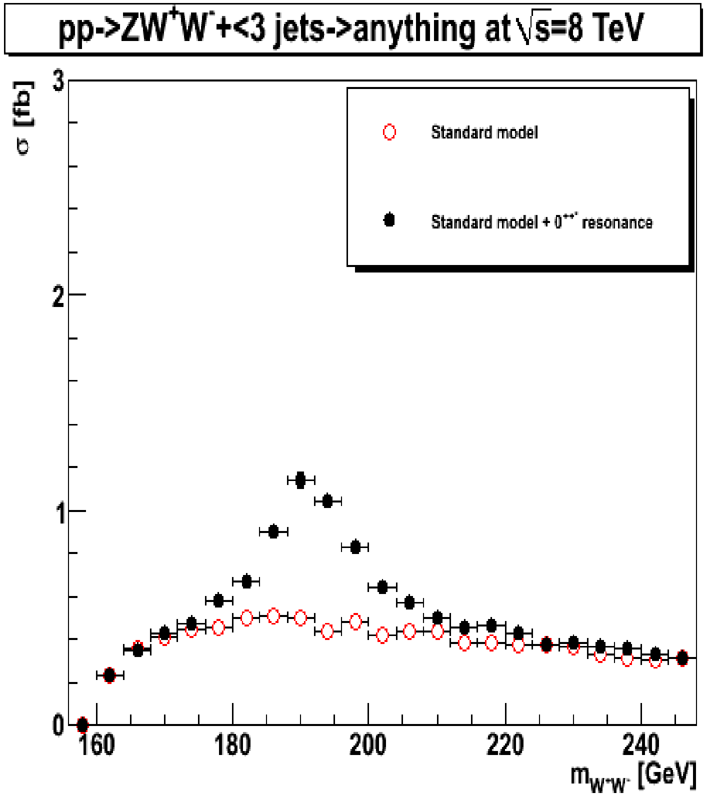


- E.g. excited Higgs: Decay channel: 2W

Experimental accessibility

[Maas et al. Unpublished]

SPECULATIVE



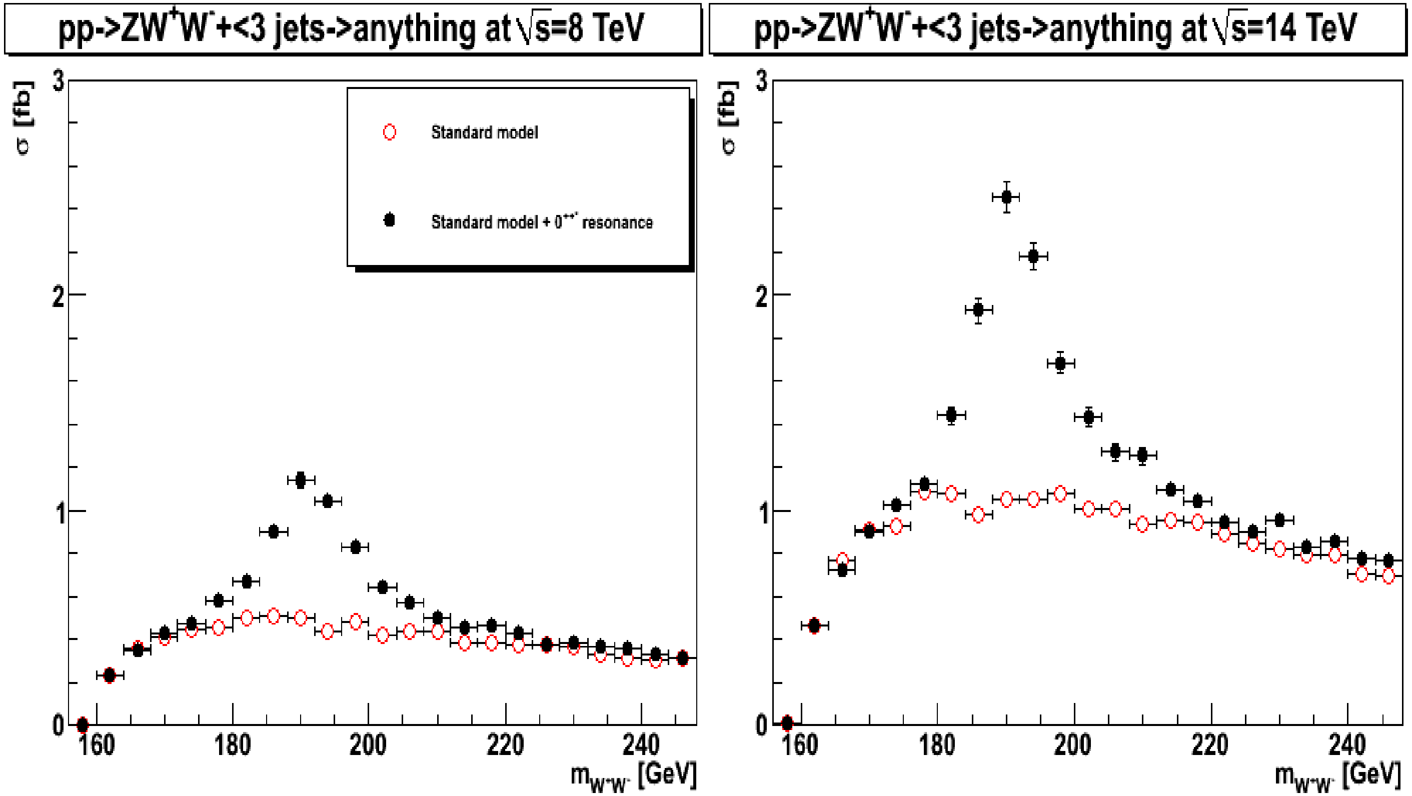
[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

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

Experimental accessibility

[Maas et al. Unpublished]

SPECULATIVE



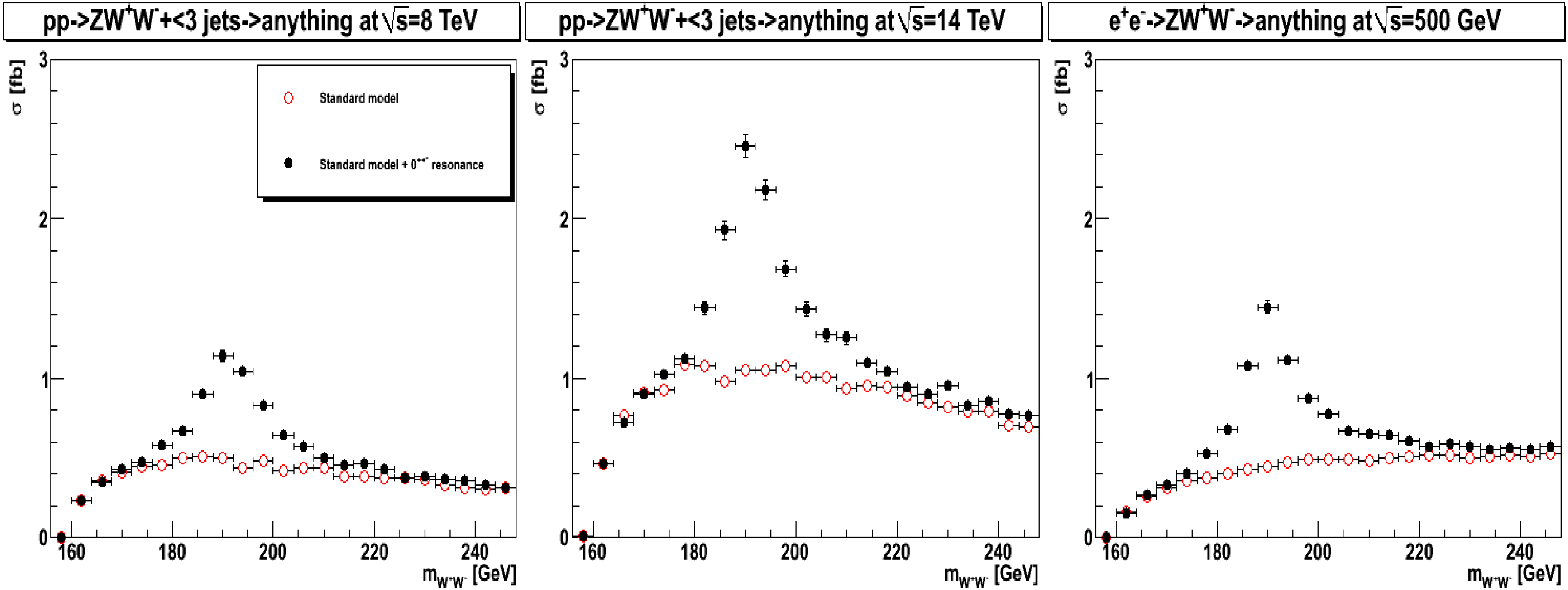
[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

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

Experimental accessibility

[Maas et al. Unpublished]

SPECULATIVE



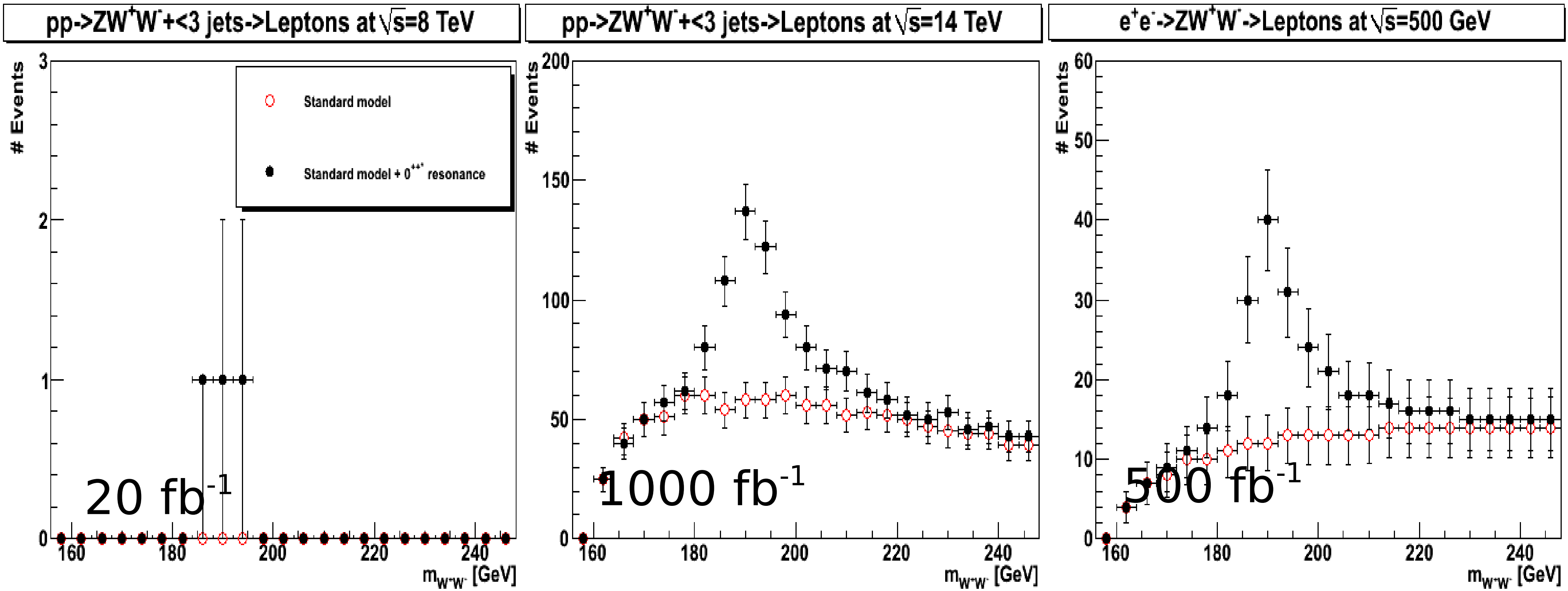
[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

- 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

Experimental accessibility

[Maas et al. Unpublished]

SPECULATIVE



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

- 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

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

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
- Is this always true?
  - Full standard model: Probably
  - Other parameters?

Phase diagram

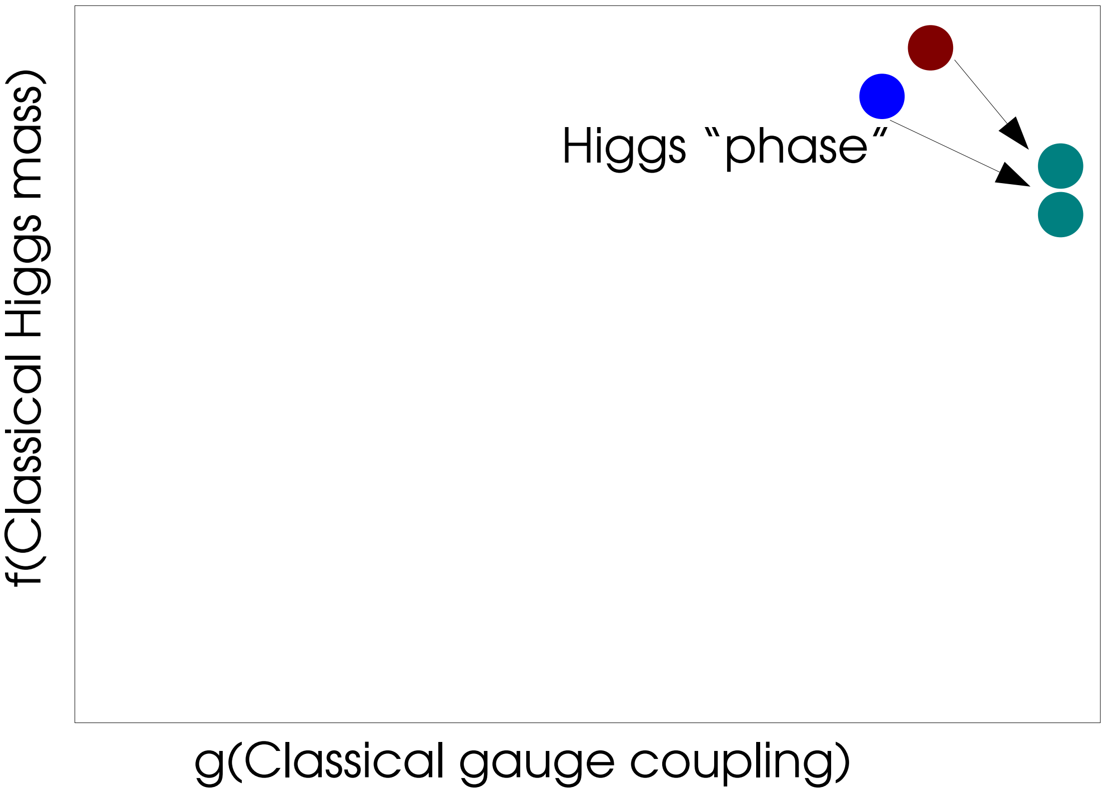
[Fradkin & Shenker PRD'79
Caudy & Greensite PRD'07]

- (Lattice-regularized) phase diagram

Phase diagram

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

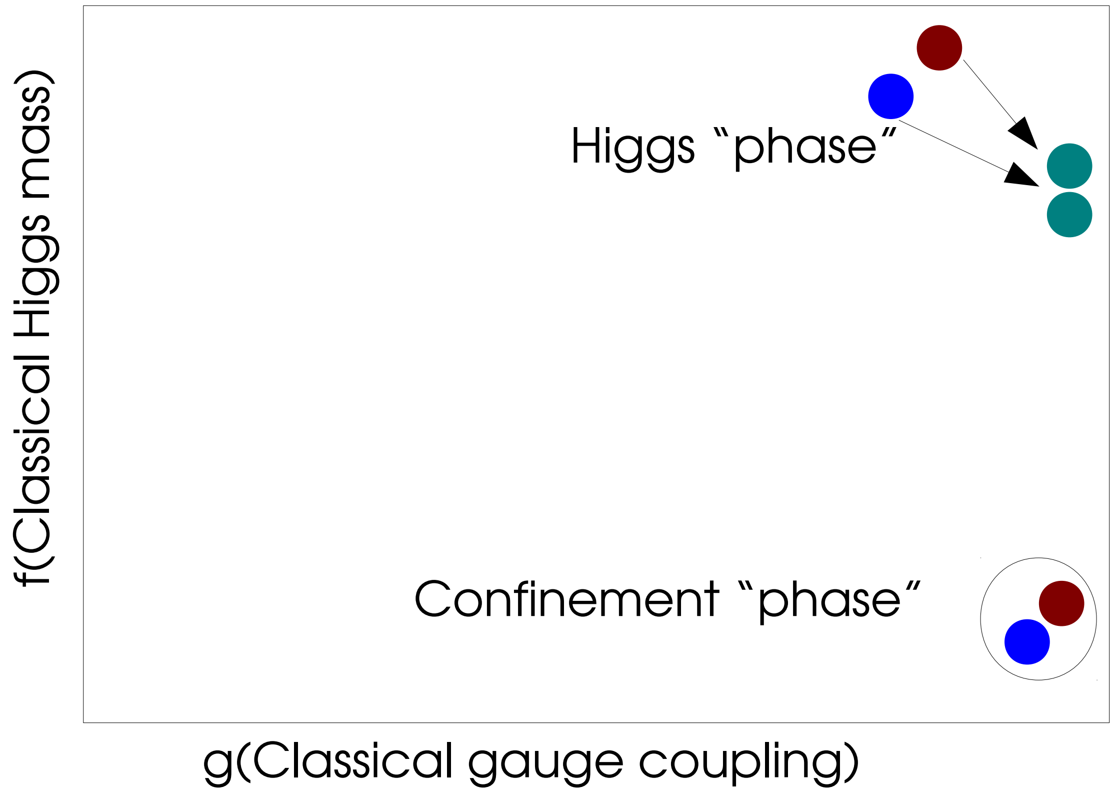
- (Lattice-regularized) phase diagram



Phase diagram

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

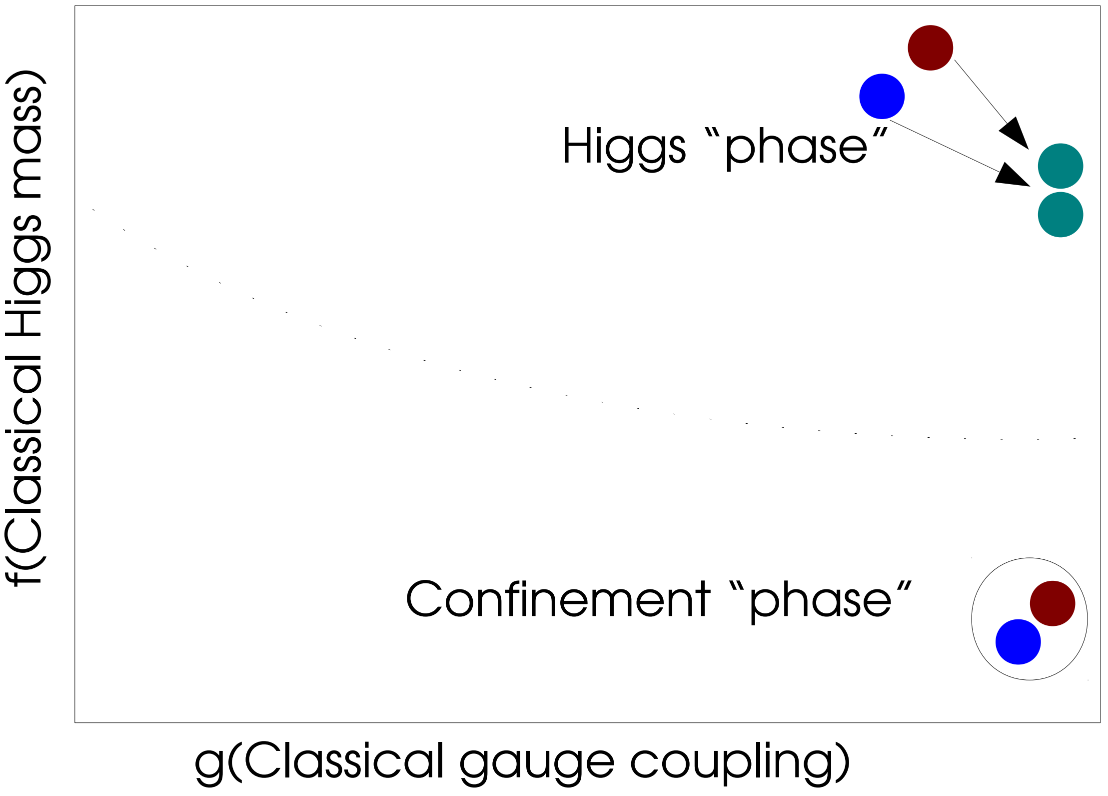
- (Lattice-regularized) phase diagram



Phase diagram

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

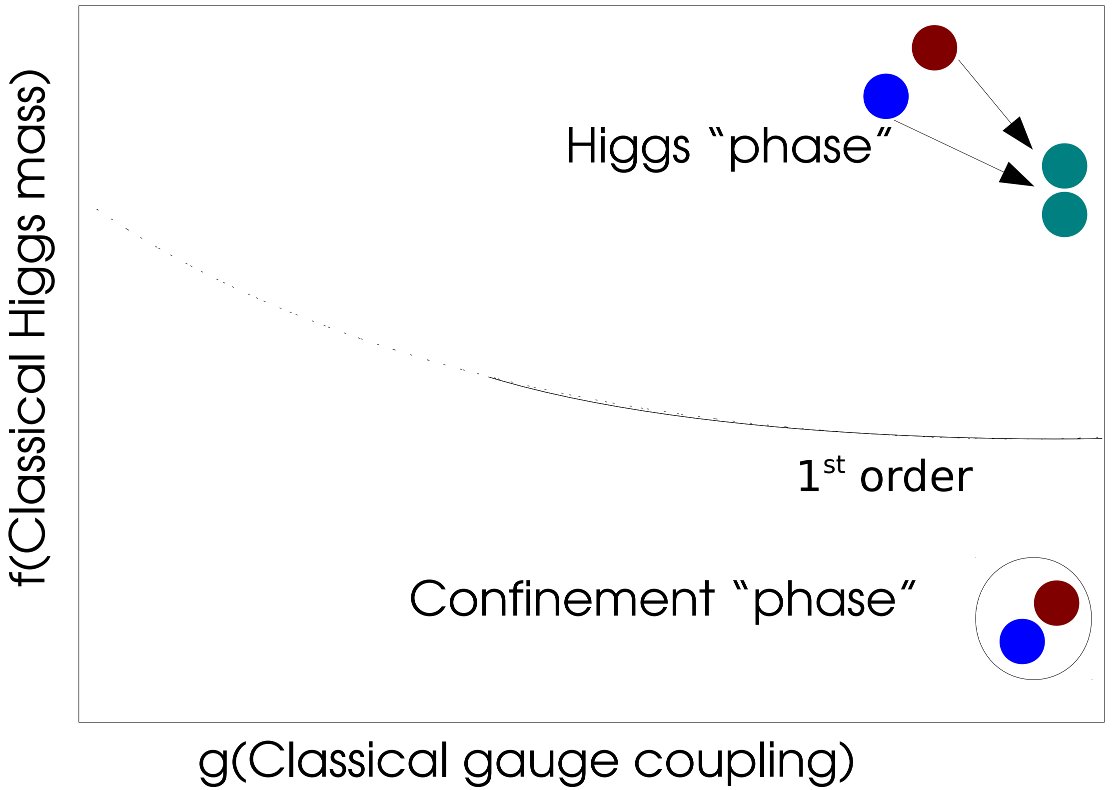
- (Lattice-regularized) phase diagram



Phase diagram

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

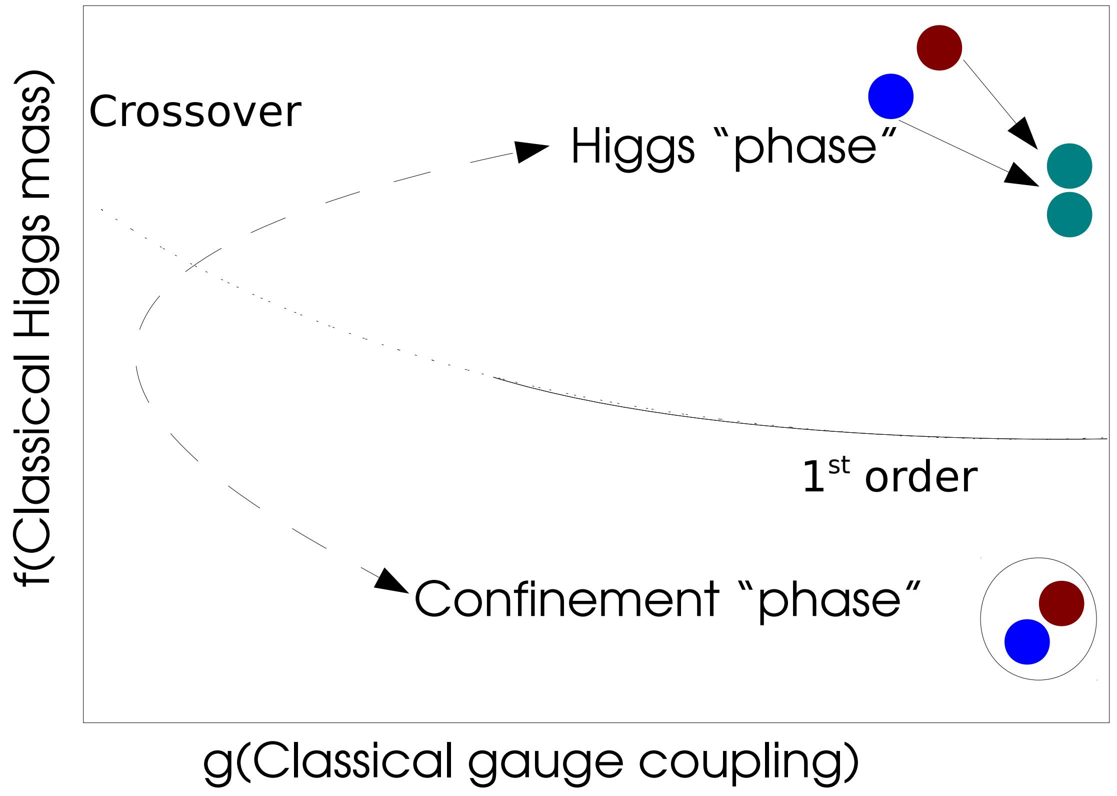
- (Lattice-regularized) phase diagram



Phase diagram

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

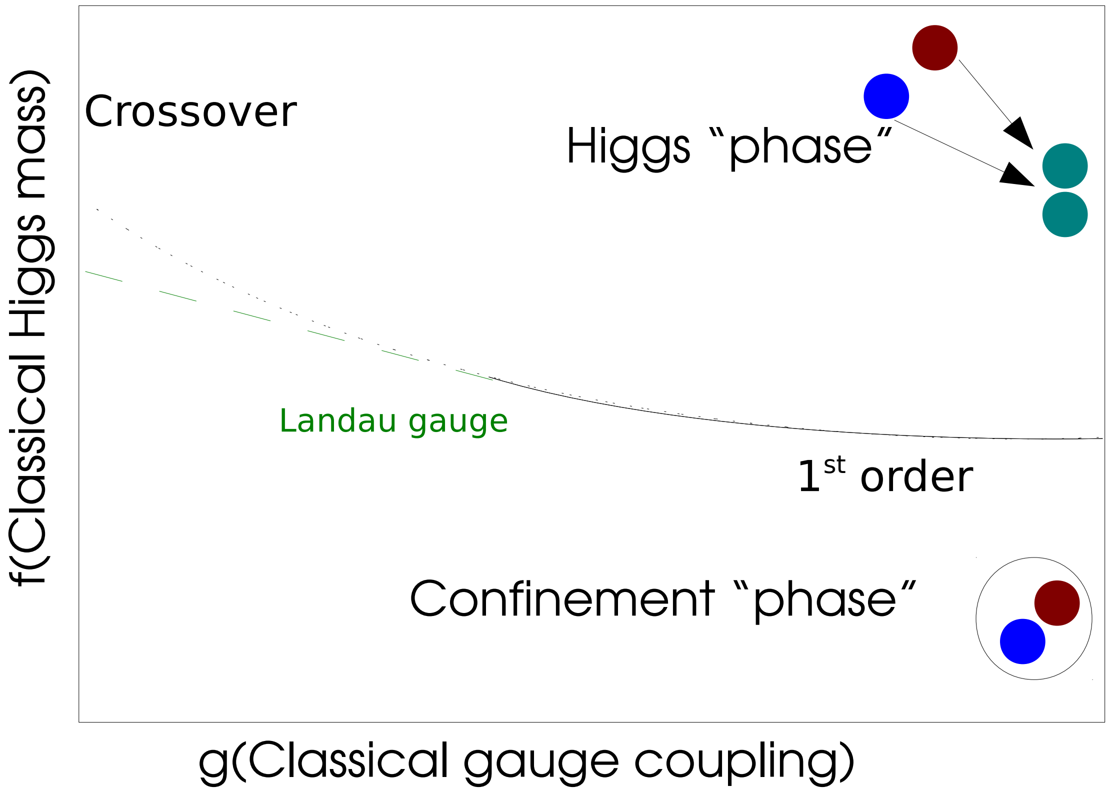
- (Lattice-regularized) phase diagram continuous



Phase diagram

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

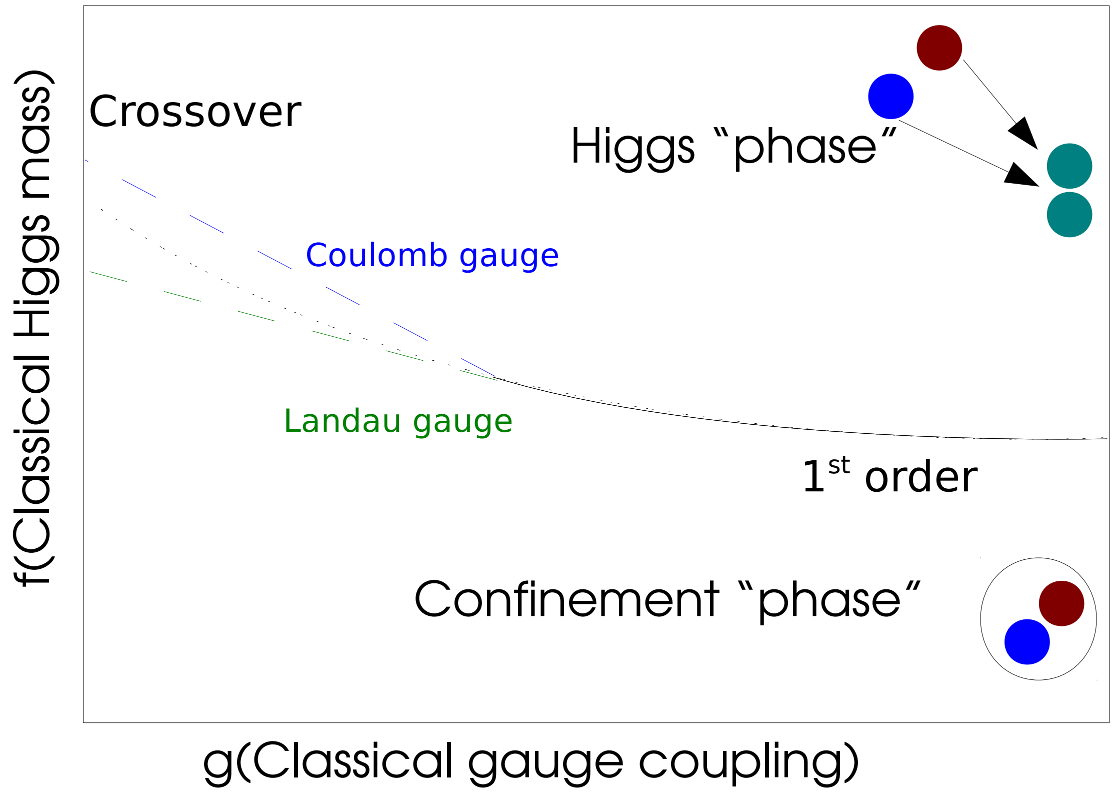
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges



Phase diagram

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

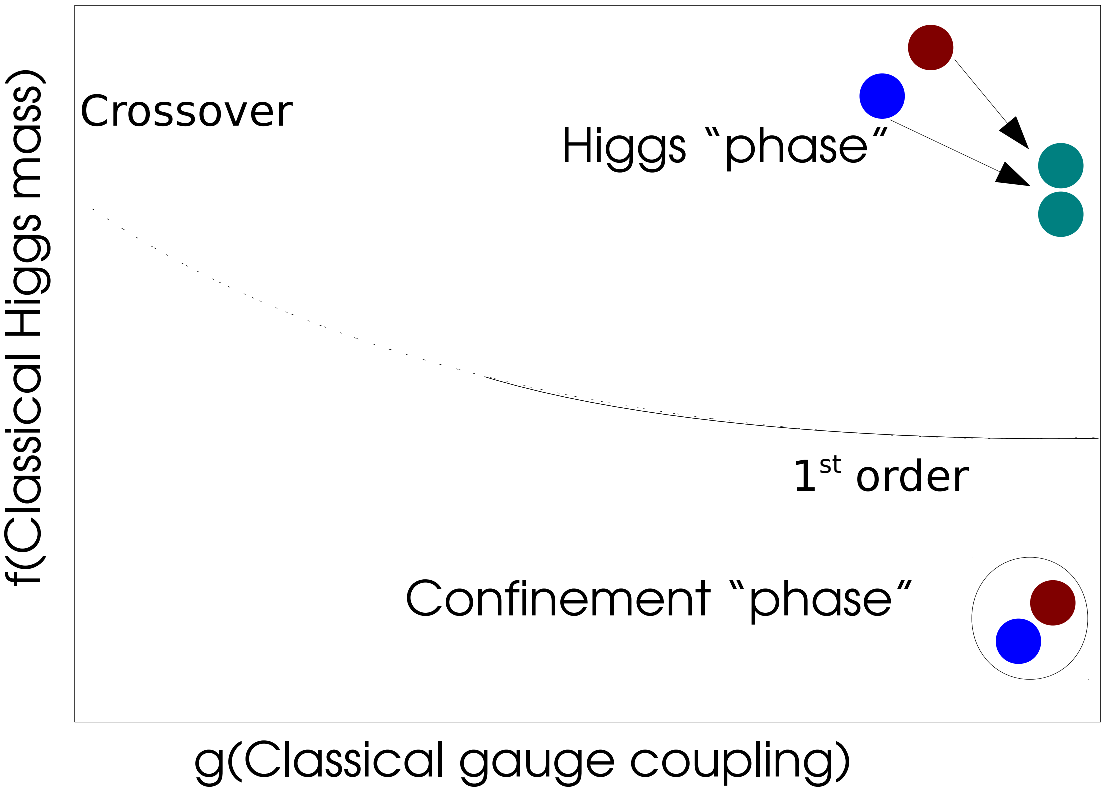
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges



Phase diagram

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

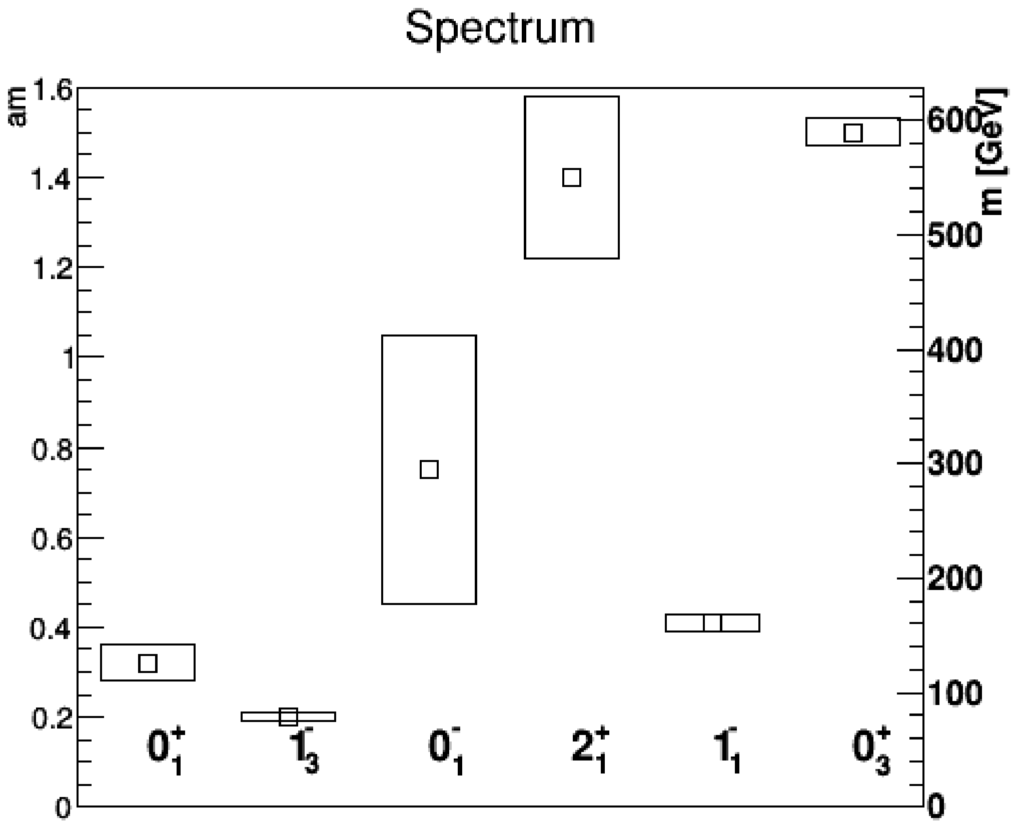
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges
- Same asymptotic states in confinement and Higgs pseudo-phases



- Same asymptotic states irrespective of coupling strengths

Typical spectra

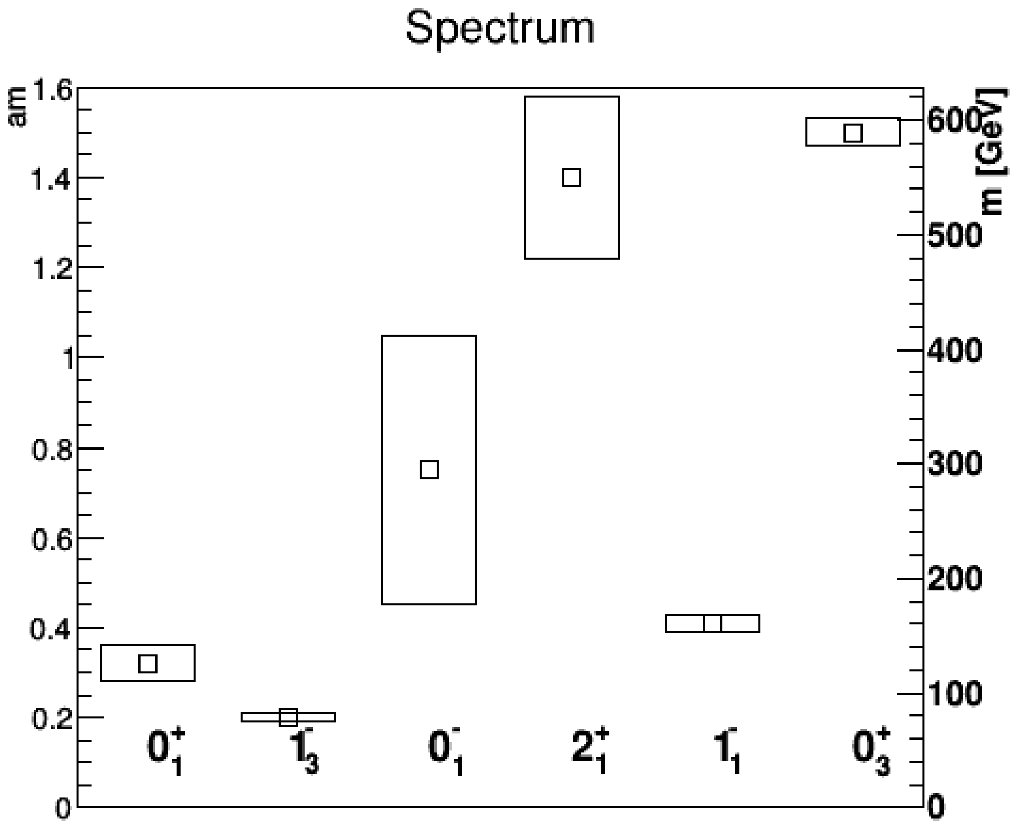
[Maas, Mufti PoS'12, unpublished, Evertz et al.'86, Langguth et al.'85,'86]

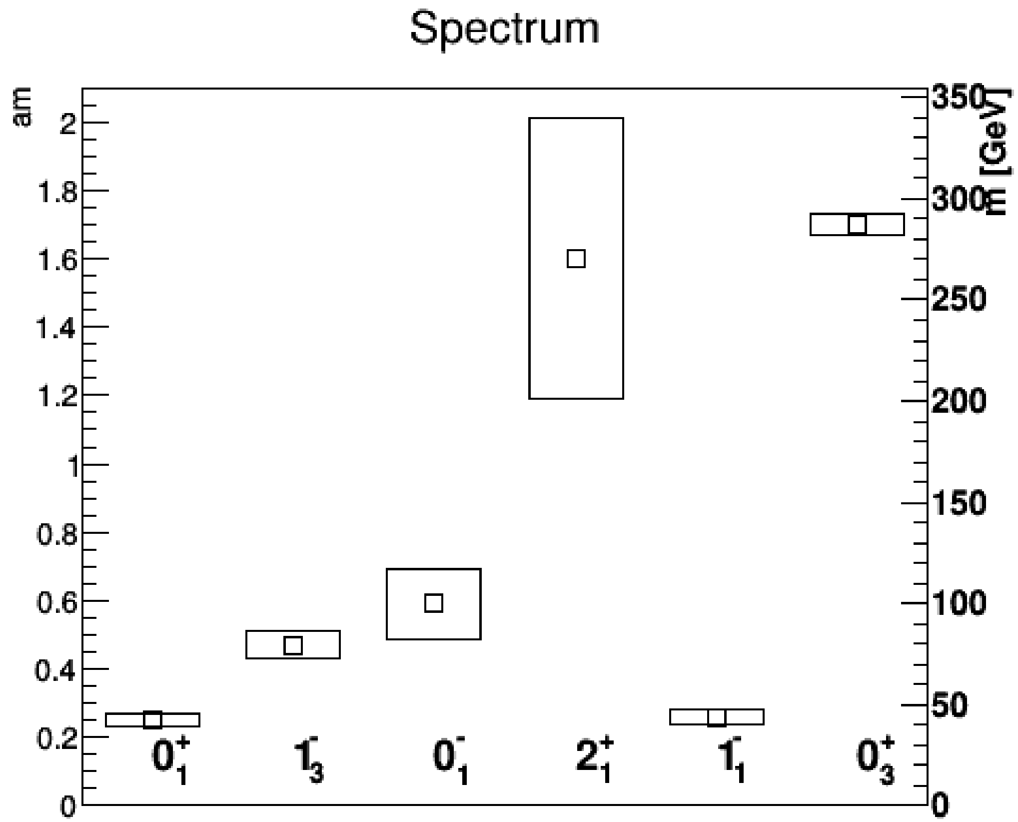


- Generically different low-lying spectra

Typical spectra

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

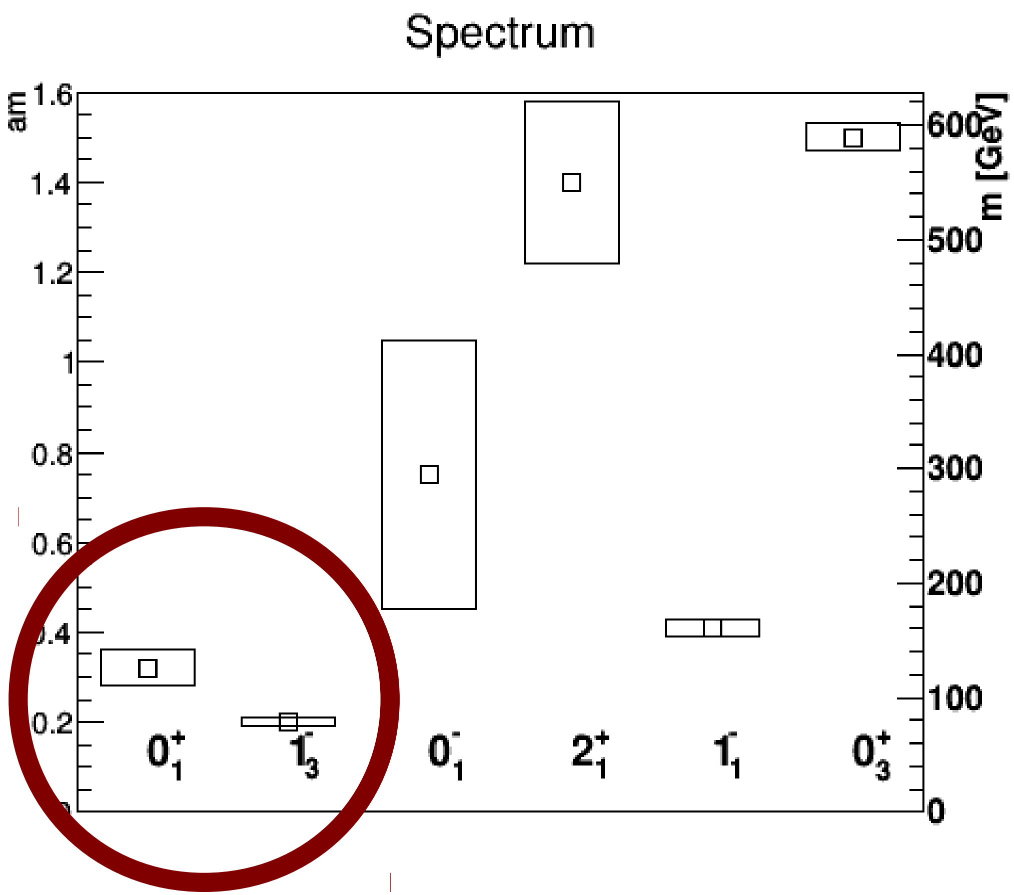


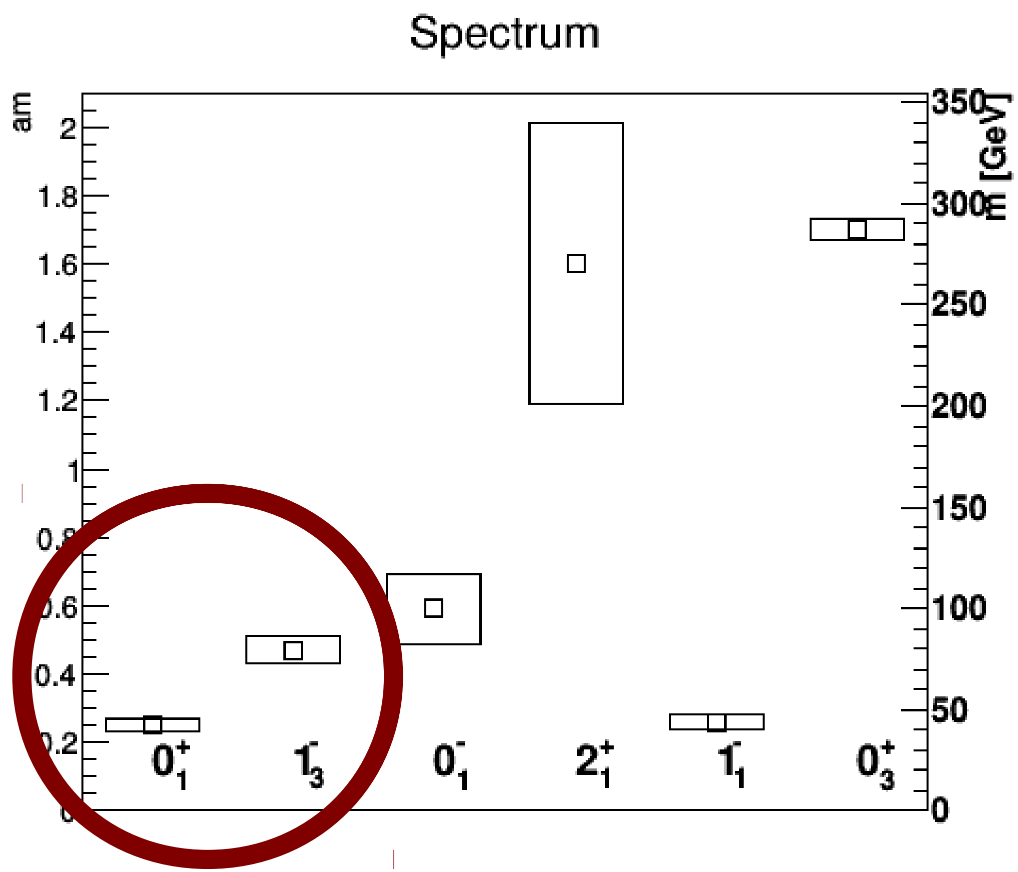


- Generically different low-lying spectra

Typical spectra

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

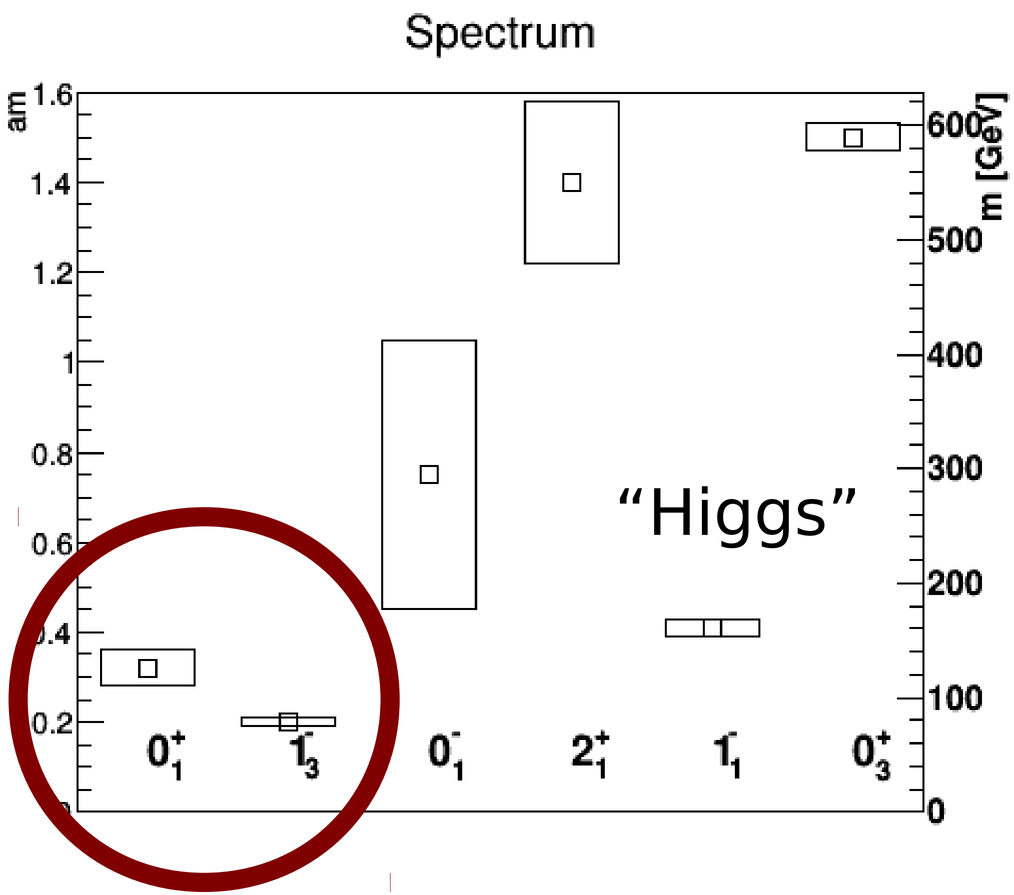


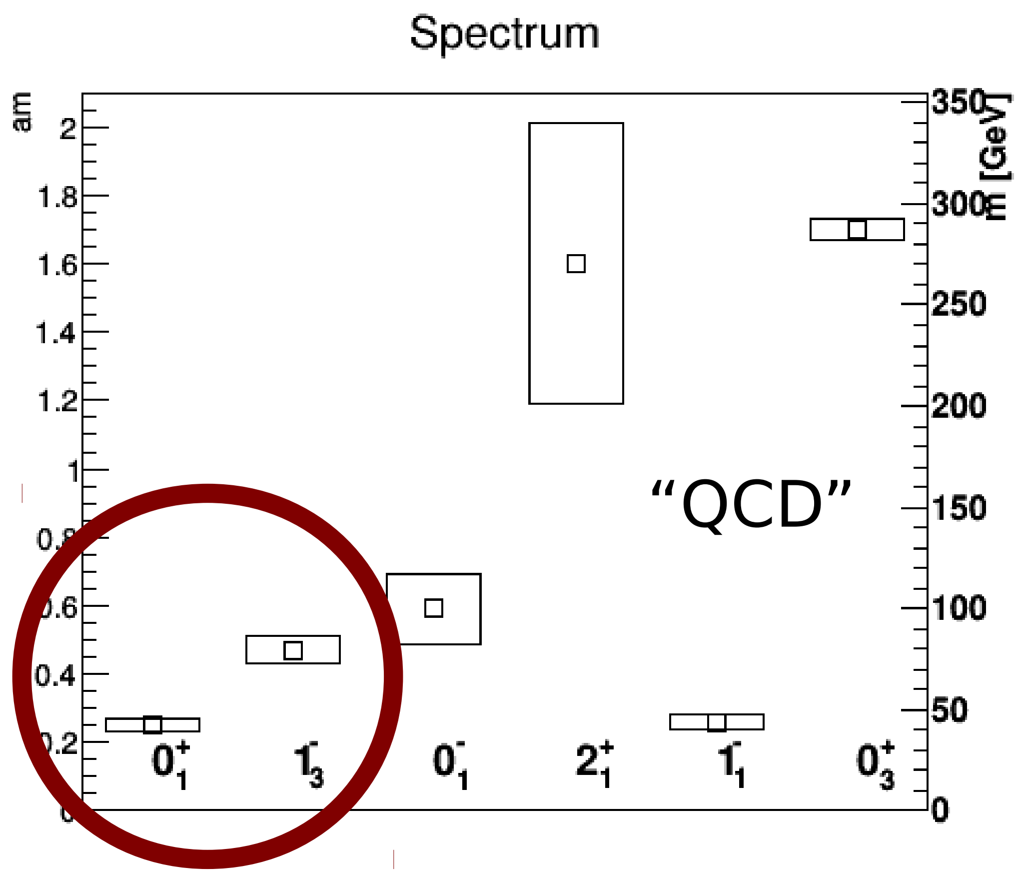


- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
  - 1^- lighter in Higgs-like region

Typical spectra

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

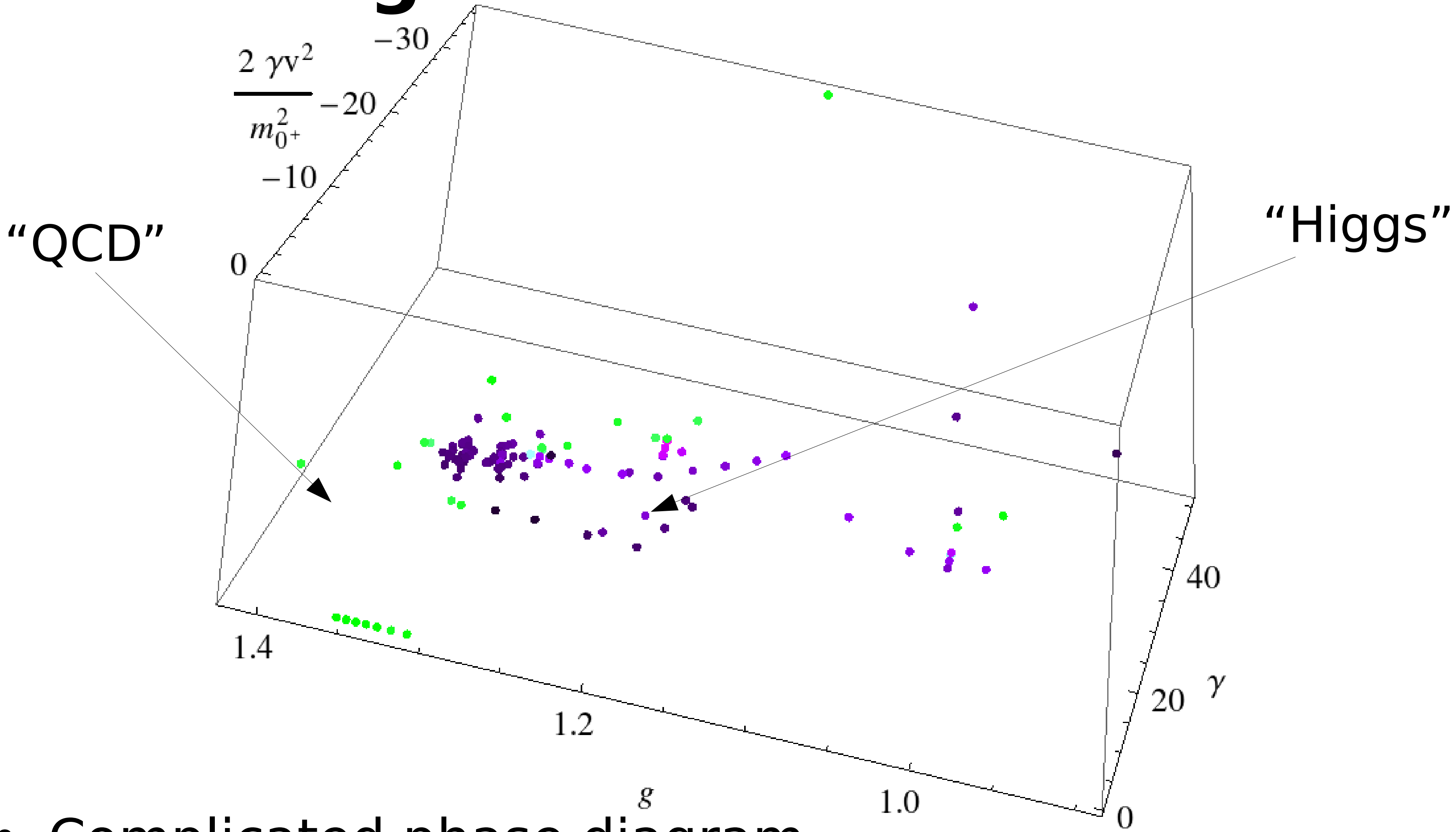




- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
  - 1^- lighter in Higgs-like region
- Use as operational definition of phase

Phase diagram

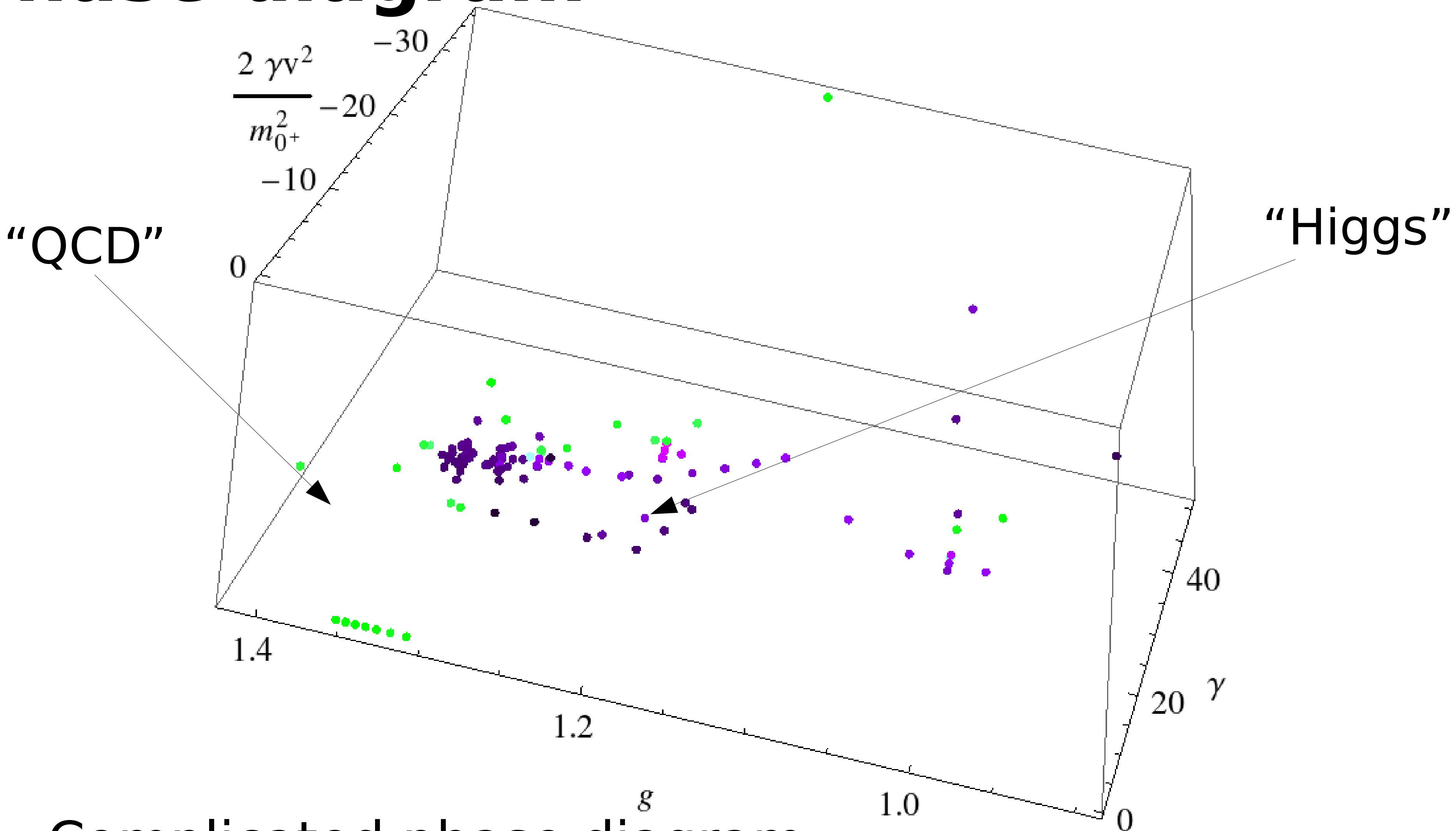
[Maas, Mufti, unpublished]



- Complicated phase diagram

Phase diagram

[Maas, Mufti, unpublished]

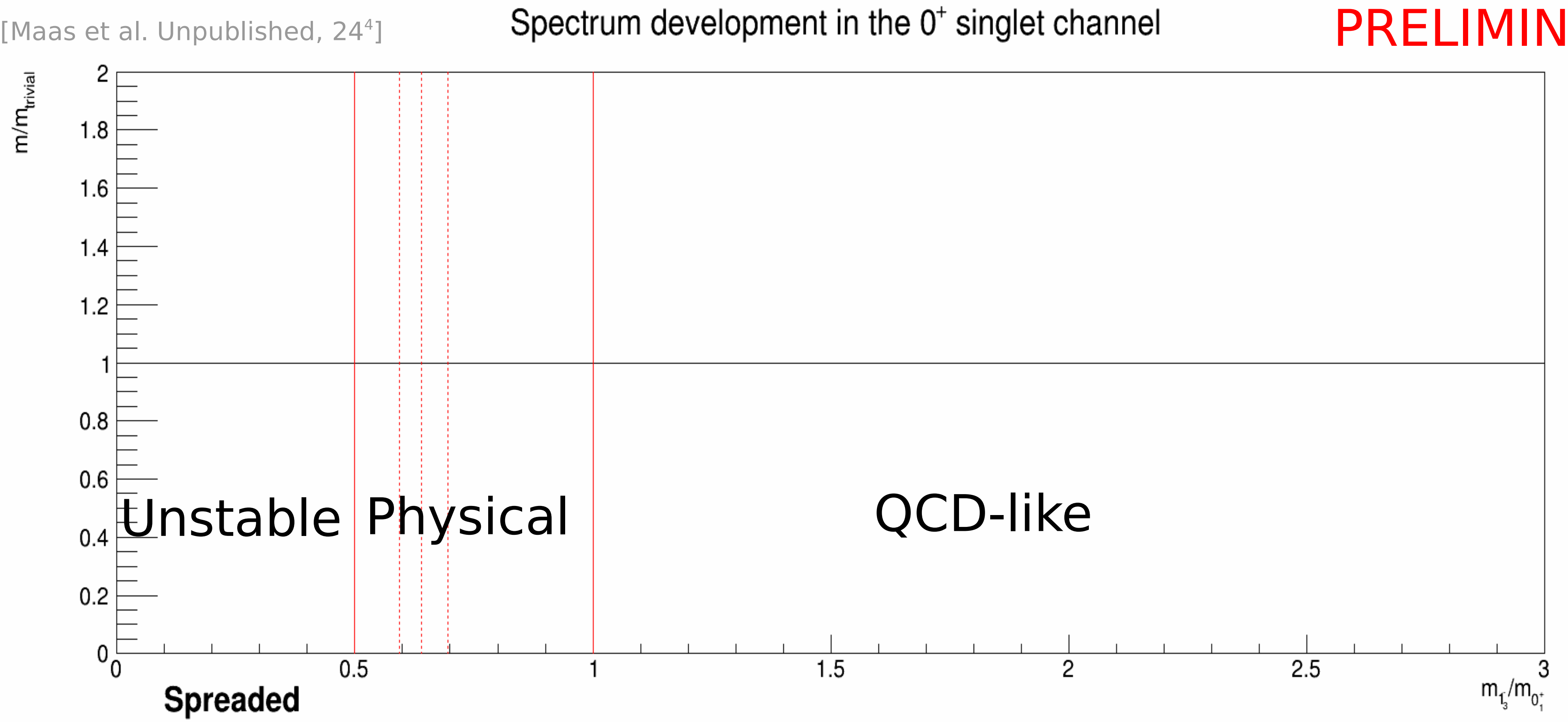


- Complicated phase diagram
- QCD-like behavior even for negative bare mass
- Similar bare couplings for both physics types

Development in the Higgs channel

[Maas et al. Unpublished, 24[4]]

PRELIMINARY

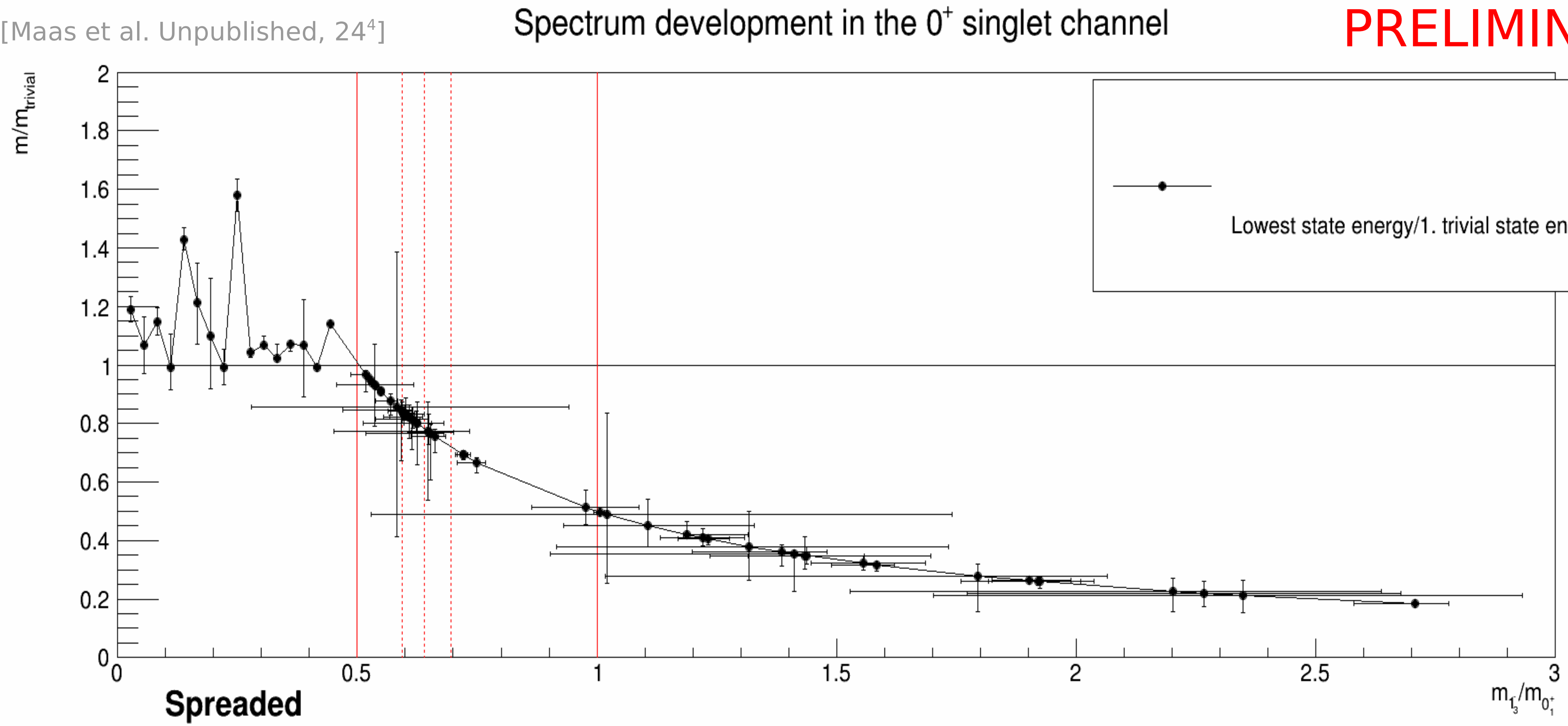


- Three distinct regions

Development in the Higgs channel

[Maas et al. Unpublished, 24[4]]

PRELIMINARY

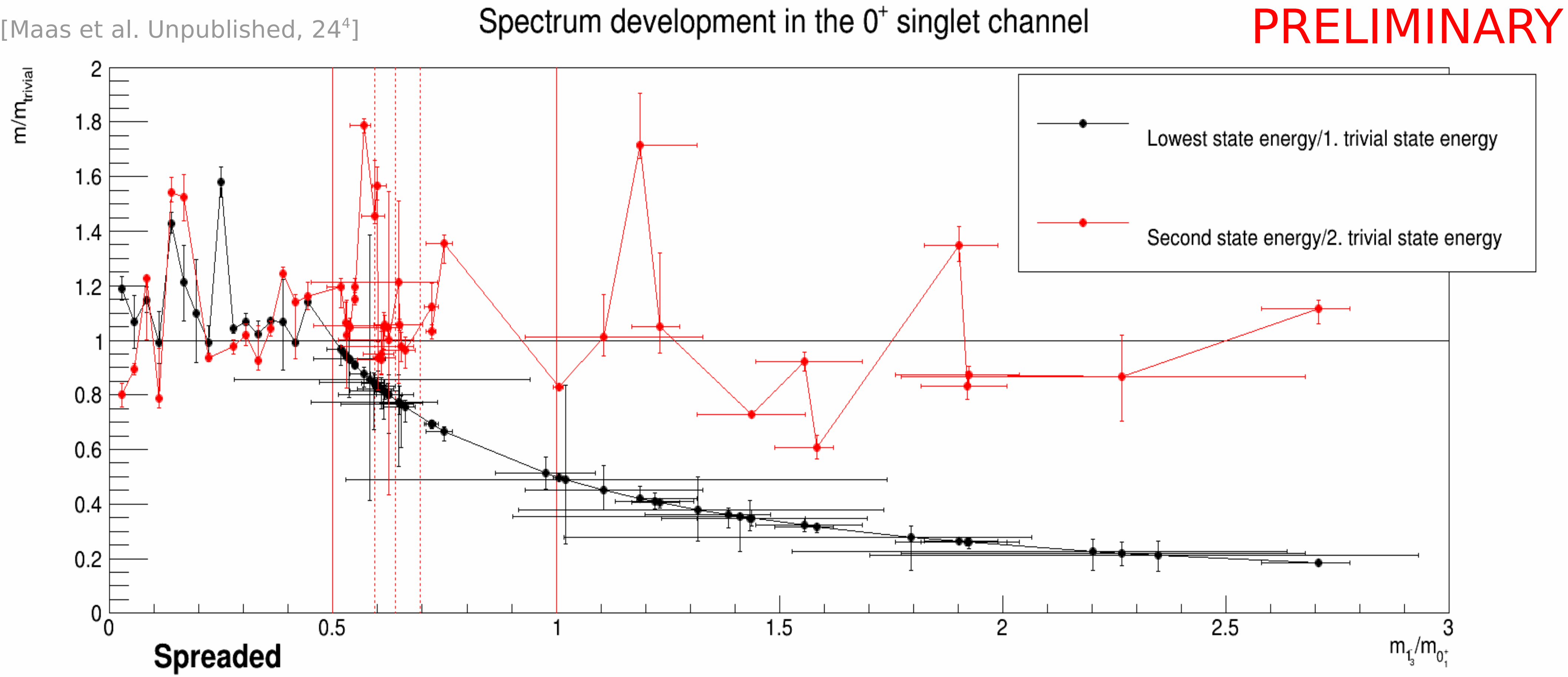


- Base-line
- Lowest state as expected above threshold: 2 almost non-interacting "Ws"

Development in the Higgs channel

[Maas et al. Unpublished, 24[4]]

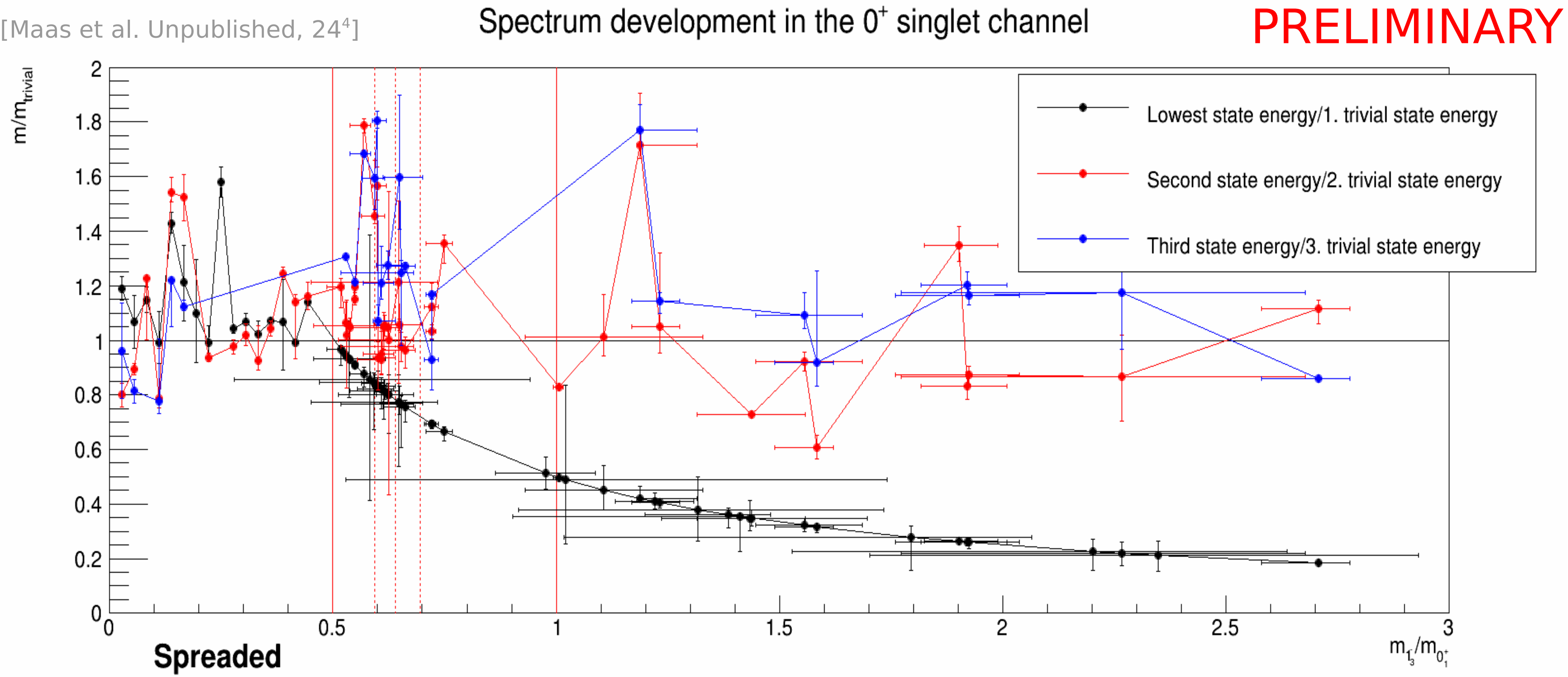
PRELIMINARY



- Next state within errors essentially trivial throughout
- No discernible resonances

Development in the Higgs channel

[Maas et al. Unpublished, 24[4]]



- Next state within errors essentially trivial throughout
- No discernible resonances
- Also true for the next level
- Different from perturbation theory

Implications for Higgsed theories

- Higgsed theories appear a lot in BSM
    - GUTs, 2HDM, (some) SUSY models,...

Implications for Higgsed theories

- Higgsed theories appear a lot in BSM
  - GUTs, 2HDM, (some) SUSY models,...
- Structure observed here is not generic
  - Mass relation of elementary states and observable states only possible for light but not too light Higgs
  - Global symmetries determines observable state spectrum
    - SM Higgs sector is special because custodial and gauge group are the same

Implications for Higgsed theories

- Higgsed theories appear a lot in BSM
  - GUTs, 2HDM, (some) SUSY models,...
- Structure observed here is not generic
  - Mass relation of elementary states and observable states only possible for light but not too light Higgs
  - Global symmetries determines observable state spectrum
    - SM Higgs sector is special because custodial and gauge group are the same
- Each case may be different

Implications for 2HDM

[Maas'14]

- Simple example: Additional Higgs doublet a

Implications for 2HDM

[Maas'14]

- Simple example: Additional Higgs doublet a
- Standard scenario: Both Higgs condense
  - SM condensate is a mixture
  - All additional Higgs particles are states, but heavier than the SM Higgs

Implications for 2HDM

[Maas'14]

- Simple example: Additional Higgs doublet a
- Standard scenario: Both Higgs condense
  - SM condensate is a mixture
  - All additional Higgs particles are states, but heavier than the SM Higgs
- Perturbatively, the state space has just four more (heavier) Higgs

Implications for 2HDM

[Maas'14]

- Simple example: Additional Higgs doublet a
- Standard scenario: Both Higgs condense
  - SM condensate is a mixture
  - All additional Higgs particles are states, but heavier than the SM Higgs
- Perturbatively, the state space has just four more (heavier) Higgs
- Non-perturbative?

Implications for 2HDM

[Maas'14]

- FMS states

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle h^+(x) h(y)\rangle + O(\eta_h^3)$$

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle h^+(x) h(y)\rangle + O(\eta_h^3)$$

  - Higgs 2:

$$\langle (a^+ a)(x)(a^+ a)(y)\rangle \approx const. + \langle a^+(x) a(y)\rangle + O(\eta_a^3)$$

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle h^+(x) h(y)\rangle + O(\eta_h^3)$$

  - Higgs 2:

$$\langle (a^+ a)(x)(a^+ a)(y)\rangle \approx const. + \langle a^+(x) a(y)\rangle + O(\eta_a^3)$$

  - W 1:

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y)\rangle \approx const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta_h^3)$$

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle h^+(x) h(y)\rangle + O(\eta_h^3)$$

  - Higgs 2:

$$\langle (a^+ a)(x)(a^+ a)(y)\rangle \approx const. + \langle a^+(x) a(y)\rangle + O(\eta_a^3)$$

  - W 1:

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y)\rangle \approx const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta_h^3)$$

  - W 2:

$$\langle (a^+ D_\mu a)(x)(a^+ D_\mu a)(y)\rangle \approx const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta_a^3)$$

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle h^+(x) h(y)\rangle + O(\eta_h^3)$$

  - Higgs 2:

$$\langle (a^+ a)(x)(a^+ a)(y)\rangle \approx const. + \langle a^+(x) a(y)\rangle + O(\eta_a^3)$$

  - W 1:

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y)\rangle \approx const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta_h^3)$$

  - W 2:

$$\langle (a^+ D_\mu a)(x)(a^+ D_\mu a)(y)\rangle \approx const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta_a^3)$$

- Twice as many W

Implications for 2HDM

[Maas'14]

- FMS states:
  - Higgs 1:

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const.+\langle h^+(x)h(y)\rangle + O(\eta_h^3)$$

  - Higgs 2:

$$\langle (a^+ a)(x)(a^+ a)(y)\rangle \approx const.+\langle a^+(x)a(y)\rangle + O(\eta_a^3)$$

  - W 1:

$$\langle (h^+ D_\mu h)(x)(h^+ D_\mu h)(y)\rangle \approx const.+\langle W_\mu(x)W_\mu(y)\rangle + O(\eta_h^3)$$

  - W 2:

$$\langle (a^+ D_\mu a)(x)(a^+ D_\mu a)(y)\rangle \approx const.+\langle W_\mu(x)W_\mu(y)\rangle + O(\eta_a^3)$$

- Twice as many W
  - Beyond expansion: Lattice is running

Summary

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

Summary

- Higgs sector with light Higgs successfully described by perturbation theory around classical physics
- Bound-state/elementary state duality
  - Highly relativistic bound states
- Permits physical interpretation of resonances in cross sections

Summary

- Higgs sector with light Higgs successfully described by perturbation theory around classical physics
- Bound-state/elementary state duality
  - Highly relativistic bound states
- Permits physical interpretation of resonances in cross sections
- Could create new background for BSM searches
- Generalizations to other BSM theories with Higgs effect possible
  - Required to understand observable spectrum
  - Can it differ from the perturbative/tree-level one?

Summary

- Higgs sector with light Higgs successfully described by perturbation theory around classical physics
- Bound-state/elementary state duality
  - Highly relativistic bound states
- Permits physical interpretation of resonances in cross sections
- Could create new background for BSM searches
- Generalizations to other BSM theories with Higgs effect possible
  - Required to understand observable spectrum
  - Can it differ from the perturbative/tree-level one?
- Non-perturbatively interesting even for a light Higgs