FMS mechanism
in the standard model and beyond

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with
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Outline

[Törek and Maas, LATTICE2016, 1610.04188]

Physical states in the standard model

Standard description

Gauge-invariant perturbation theory

Physical states in a grand-unified setting

Physical states in the standard model

The problem in the standard model

- Consider gauge-Higgs sector of the standard model:

$$\mathcal{L} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \lambda \left(\phi^\dagger \phi - v^2\right)^2$$

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- Global $SU(2)$ Higgs flavor symmetry:
  Custodial symmetry

$$W^a_\mu \to W^a_\mu \qquad \phi_i \to M_{ij}\phi_j + N_{ij}\phi^\star_j$$

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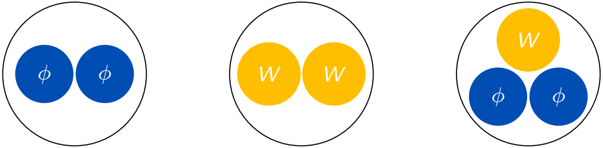
Higgs-Higgs W-W Higgs-Higgs-W



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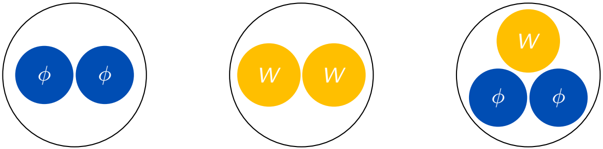

et cetera
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- What is the mass spectrum?
- Why does perturbation theory work?

Masses from propagators

- Poles of propagators $\Rightarrow$ Masses
- Two propagators:
  - W/Z: $D^{ab}_{\mu\nu}(x-y) = \langle W^a_\mu(x) W^b_\nu(y)\rangle$
    Degenerate without QED
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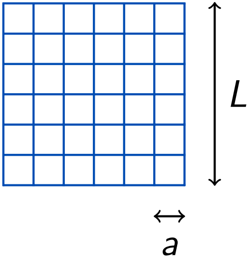
- For gauge-invariant states: Non-perturbative method

Lattice calculations

- Finite volume (hypercube)
- Discretization $\Rightarrow$ Finite hypercubic lattize



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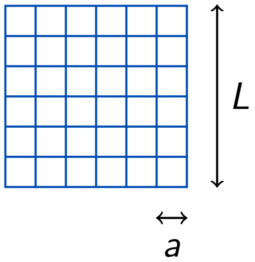

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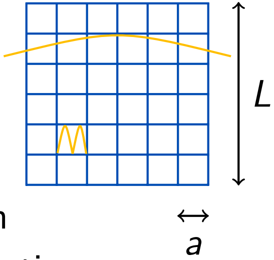
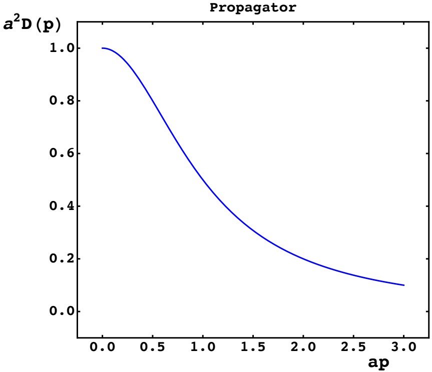


- Artifacts
  - Finite volume and discretization
  - Masses vs. wave lengths: Resolution
  - Euclidean formulation

Masses from Euclidean propagators



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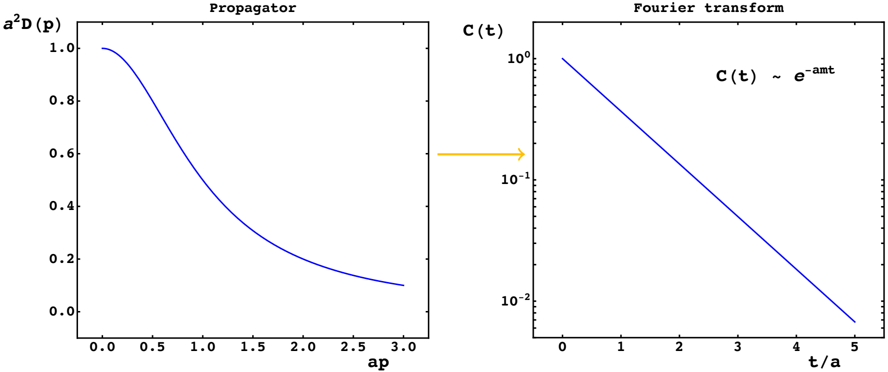

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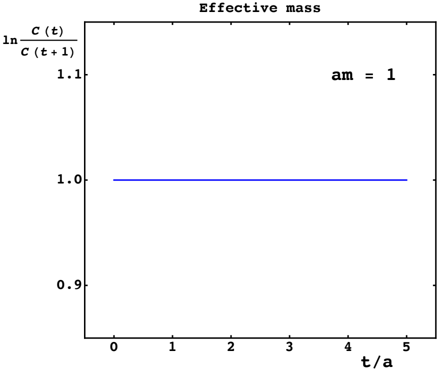

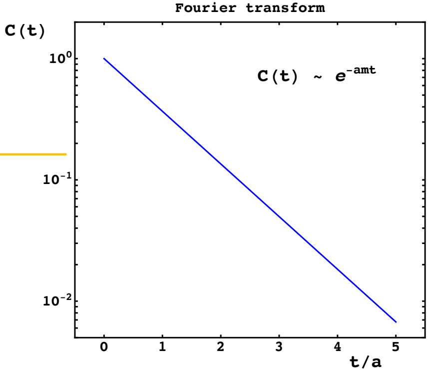

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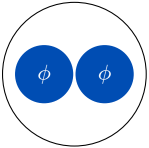
- Extract effective mass

Mass spectrum: Higgs-Higgs



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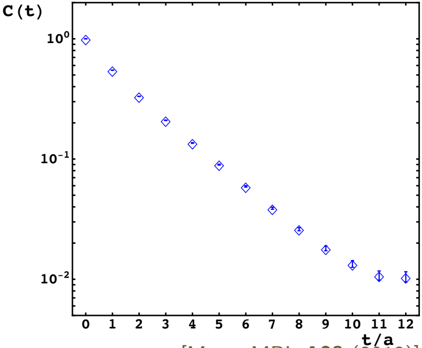

[Maas, MPL **A28** (2013)]

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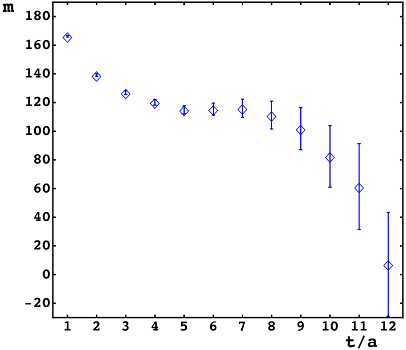

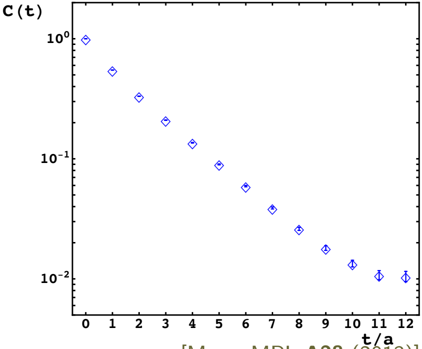

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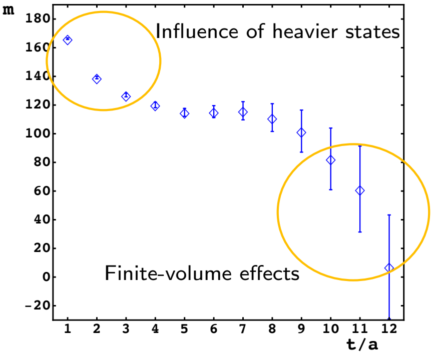

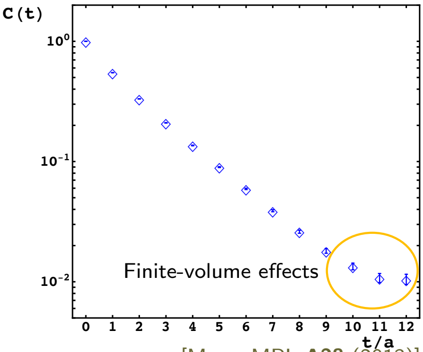

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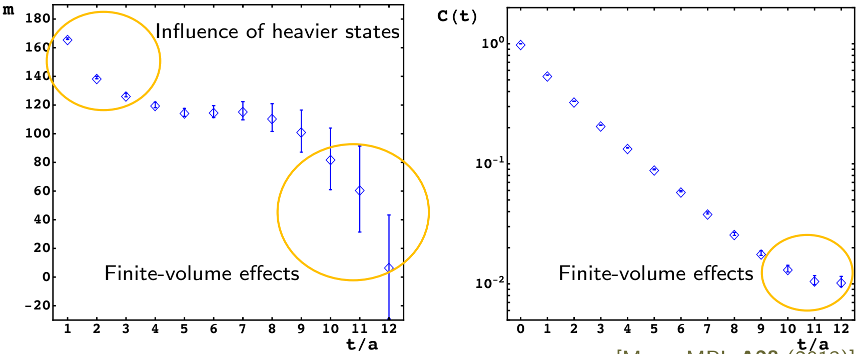

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- Mass is about 120 GeV: Same as Higgs

Gauge-invariant perturbation theory

[Fröhlich *et al.*, PL **B97** (1980) and NP **B190** (1981) /
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Bound state mass

2 x Higgs mass scattering state

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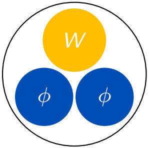
Mass spectrum: Vector state



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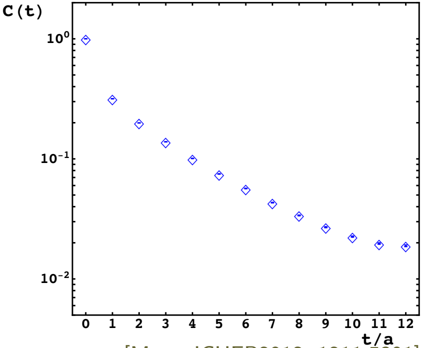

[Maas, ICHEP2012, 1211.5301]

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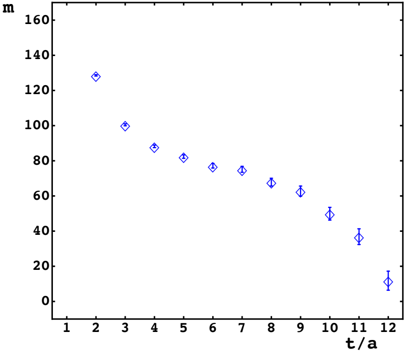

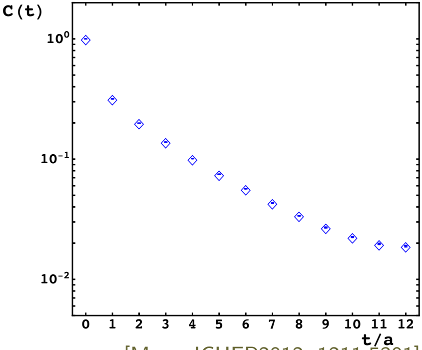

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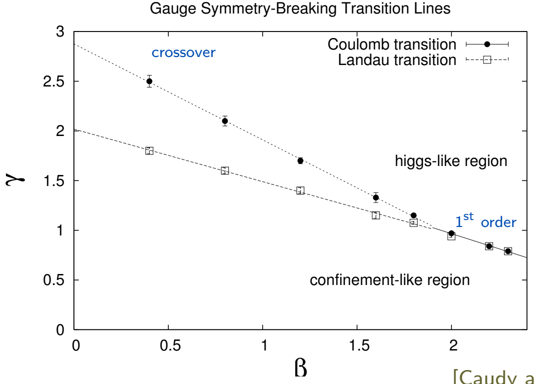
- Same poles to leading order
- Exchange of a gauge for a custodial triplet

Phase diagram: SU(2) gauge-Higgs model

- Depending on parameters (inverse gauge coupling β, classical Higgs mass γ) different regions

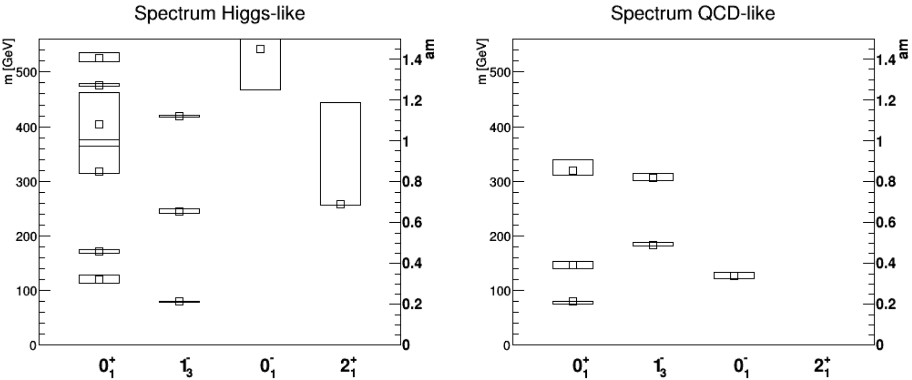


[Caudy and Greensite, PR **D78** (2008)]

- No unique transition line (depends on gauge)
- No phase transition in this model

[Osterwalder and Seiler, AP**110** (1978); Fradkin and Shenker, PR **D19** (1979)]

Typical spectra



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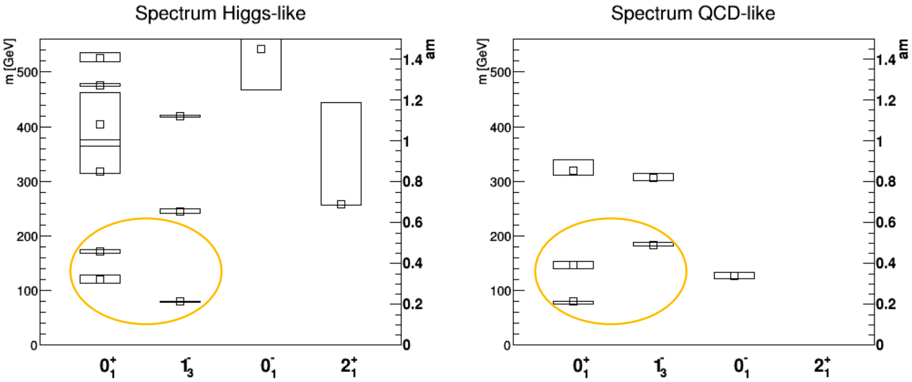

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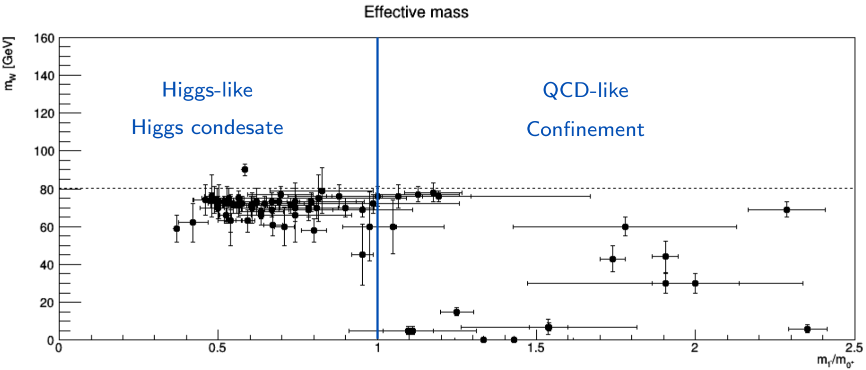
- 1^- lighter in Higgs-like region
- 0^+ lighter in QCD-like region

Limits



[Maas and Mufti, JHEP (2014)]

- At $m_{1^-} = m_{0^+}$ FMS stops working
- So does BEH effect

Rest of the standard model

[Fröhlich *et al.*, PL **B97** (1980) and NP **B190** (1981) / Egger *et al.*, 1701.02881]

- Quarks and gluons
  - Bound by confinement in bound states
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  - Except for right-handed neutrinos

$$\mathcal{O} = \tilde{\phi}^\dagger \begin{pmatrix} \nu \\ e \end{pmatrix} = \begin{pmatrix} \phi_2 \nu - \phi_1 e \\ \phi_1^\star \nu + \phi_2^\star e \end{pmatrix} \overset{\phi_i = v\delta_{i,2} + \eta_i}{=} v \begin{pmatrix} \nu \\ e \end{pmatrix} + O(\eta)$$

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- Photons
  - Can also be included

Status of the standard model

- Physical states are bound states
  - Observed in experiment
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- Has to be checked for BSM theories

Physical spectrum in a grand-unified setting

[Törek and Maas, PR**D95** (2017), 1607.05860]

Partially Higgsed gauge theory

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- Perturbative construction: $SU(3) \xrightarrow{\langle\phi\rangle} SU(2)$
- Perturbative spectrum:
  - $4+1$ massive and 3 massless gauge bosons
  - 1 massive Higgs boson

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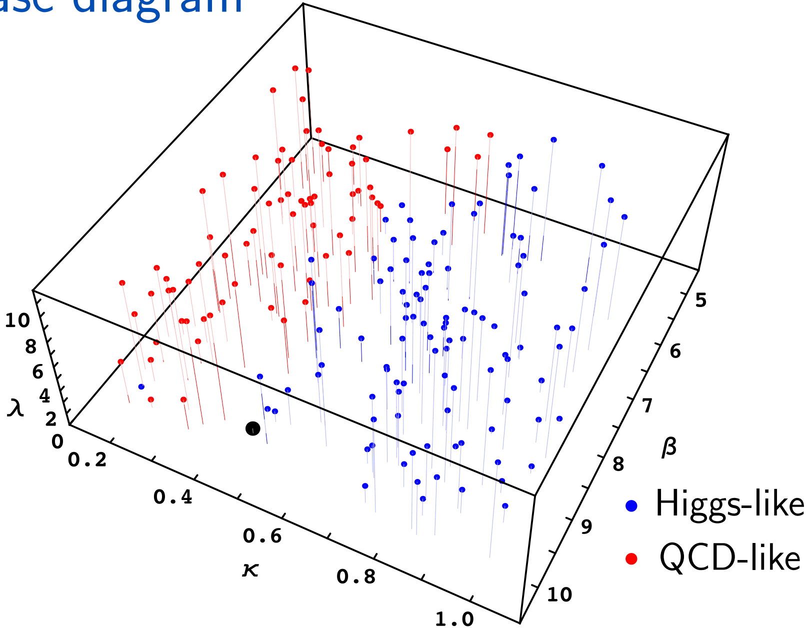
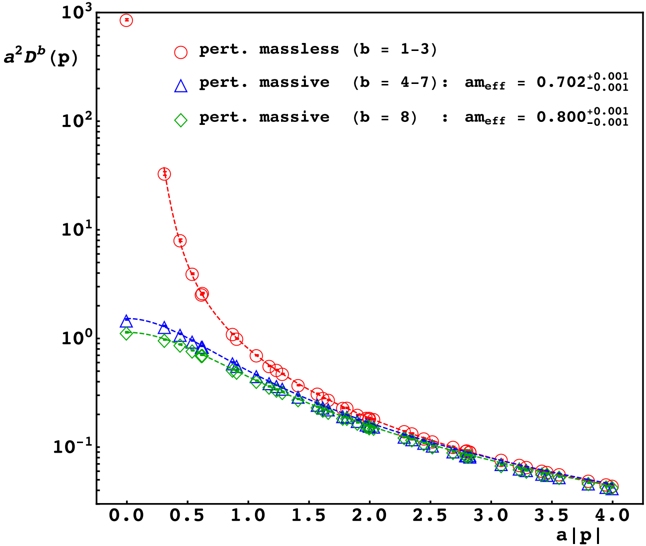
- Only a single massive particle is predicted
  $\Rightarrow$ Contradiction to perturbative spectrum

Phase diagram

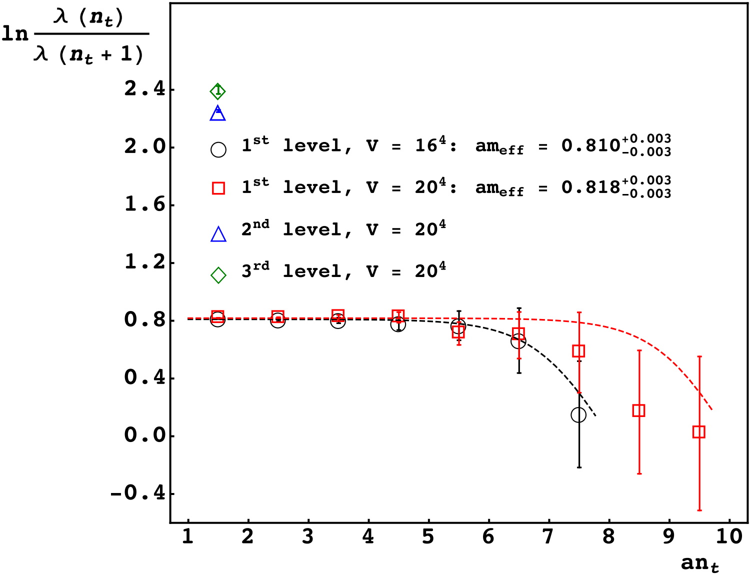


Propagators

- Good agreement with tree-level perturbation theory

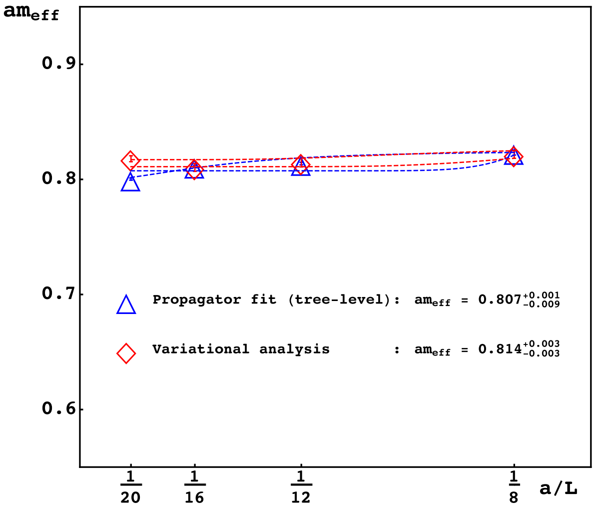


Spectroscopy in 1^- channel - Results



Volume dependency of m_{eff}

- Single massive ground state with mass of W^8
- Exactly like FMS mechanism predicts



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  - Same light d.o.f. as in standard model: Good candidate

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[Maas, Sondenheimer and Törek, work in progress]

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- More realistic GUT: $SU(5)$
  Higgs in adjoint and fundamental representation

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- Gauge-invariant perturbation theory as a tool
  - Requires BEH effect
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  - Mostly not much more complicated
- Applicable to BSM theories
  - Structural requirement: Multiplets must match
  - Dynamical requirement: Small fluctuations
  - Verification requires non-perturbative methods

Thank you!