Rethinking Brout-Englert-Higgs Physics

Axel Maas

22nd of April 2017
Alps 2017
Austria

Why rethinking?

Why rethinking?

- The Higgs is there (and not much else)

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?
  - Experiment says yes

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?
  - Experiment says yes
  - Fundamental considerations say no
    - Lots of work from the late 70ier/early 80ies
    - Lots of recent work

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?
    - Experiment says yes
    - Fundamental considerations say no
        - Lots of work from the late 70ier/early 80ies
        - Lots of recent work
        - But: Not at odds with experiment

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?
  - Experiment says yes
  - Fundamental considerations say no
    - Lots of work from the late 70ier/early 80ies
    - Lots of recent work
    - But: Not at odds with experiment
  - At odds beyond the standard model

Why rethinking?

- The Higgs is there (and not much else)
- The theory is there (and much else)
- But: Do we really understand it?
    - Experiment says yes
    - Fundamental considerations say no
        - Lots of work from the late 70ier/early 80ies
        - Lots of recent work
        - But: Not at odds with experiment
    - At odds beyond the standard model
- Need to make sure we know what we do

Three examples

Three examples

- W/Z mass corrections from QCD
  - Of the order of the experimental error

Three examples

- W/Z mass corrections from QCD
  - Of the order of the experimental error
- Ultraviolet structure as guide for new physics
  - Why there are many more possibilities

Three examples

- W/Z mass corrections from QCD
  - Of the order of the experimental error
- Ultraviolet structure as guide for new physics
  - Why there are many more possibilities
- Constraints from theory
  - Why the standard model is special
  - Why this can be a game changer beyond the standard model

Example 1

Corrections from QCD

Inverting the technicolor argument

[Quigg & Shrock'09]

Inverting the technicolor argument

[Quigg & Shrock'09]

- In the same way as technicolor QCD 'breaks' the electroweak gauge symmetry

Inverting the technicolor argument

[Quigg & Shrock'09]

- In the same way as technicolor QCD 'breaks' the electroweak gauge symmetry
  - Origin: Dynamically chiral symmetry breaking
    - Purely non-perturbative effect
  - Quark-Antiquark condensate

Inverting the technicolor argument

[Quigg & Shrock'09]

- In the same way as technicolor QCD 'breaks' the electroweak gauge symmetry
  - Origin: Dynamically chiral symmetry breaking
    - Purely non-perturbative effect
  - Quark-Antiquark condensate
- Acts exactly like the Higgs condensate

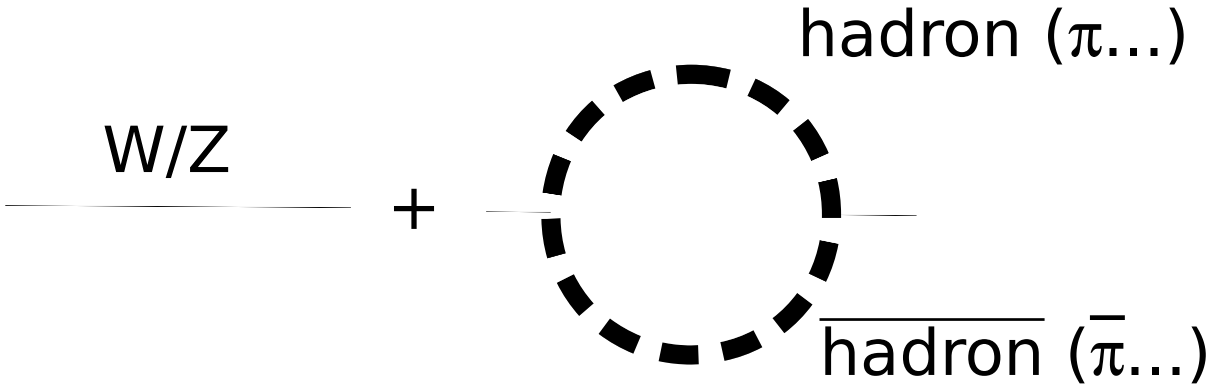
Inverting the technicolor argument

[Quigg & Shrock'09]

- In the same way as technicolor QCD 'breaks' the electroweak gauge symmetry
  - Origin: Dynamically chiral symmetry breaking
    - Purely non-perturbative effect
  - Quark-Antiquark condensate
- Acts exactly like the Higgs condensate
- Will create (additional) mass for the W/Z

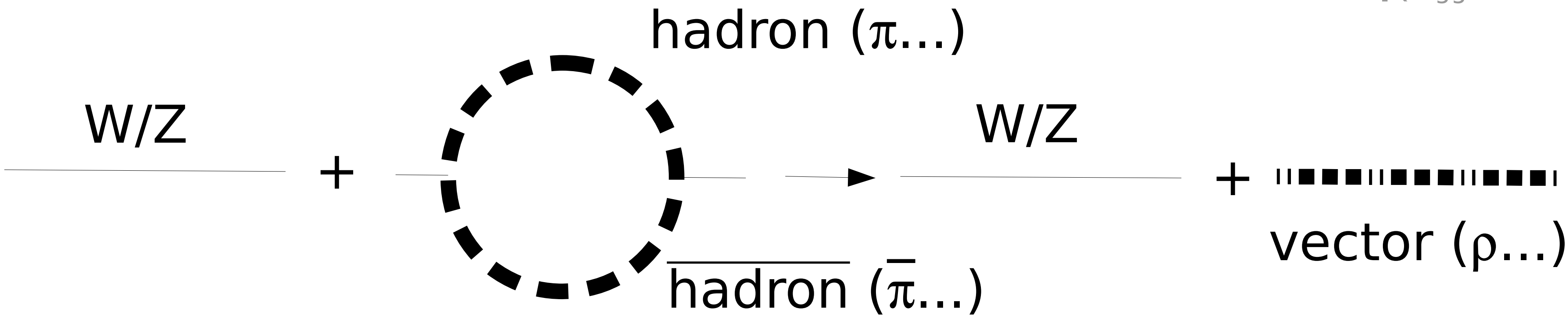
Contribution to the W/Z mass

[Quigg & Shrock'09]



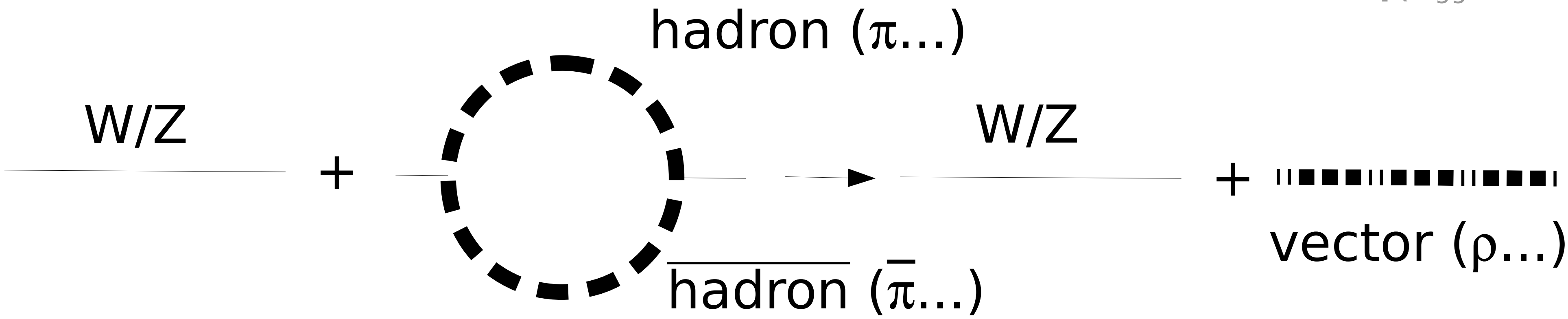
Contribution to the W/Z mass

[Quigg & Shrock'09]



Contribution to the W/Z mass

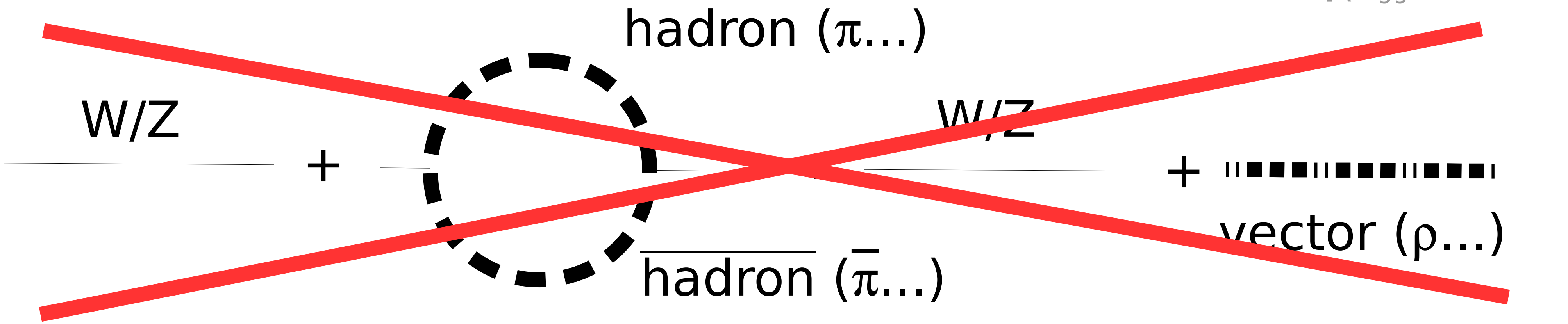
[Quigg & Shrock'09]



- Is it like this?

Contribution to the W/Z mass

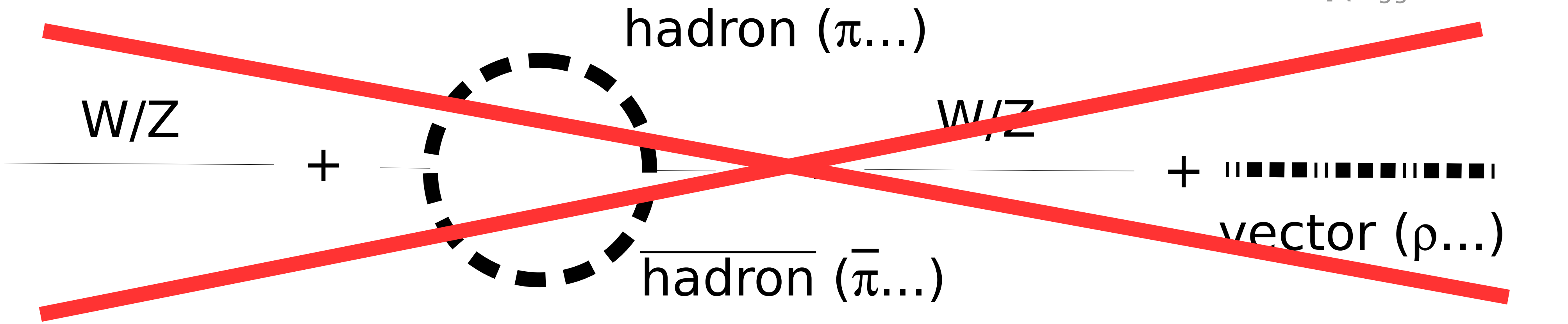
[Quigg & Shrock'09]



- Is it like this? No!

Contribution to the W/Z mass

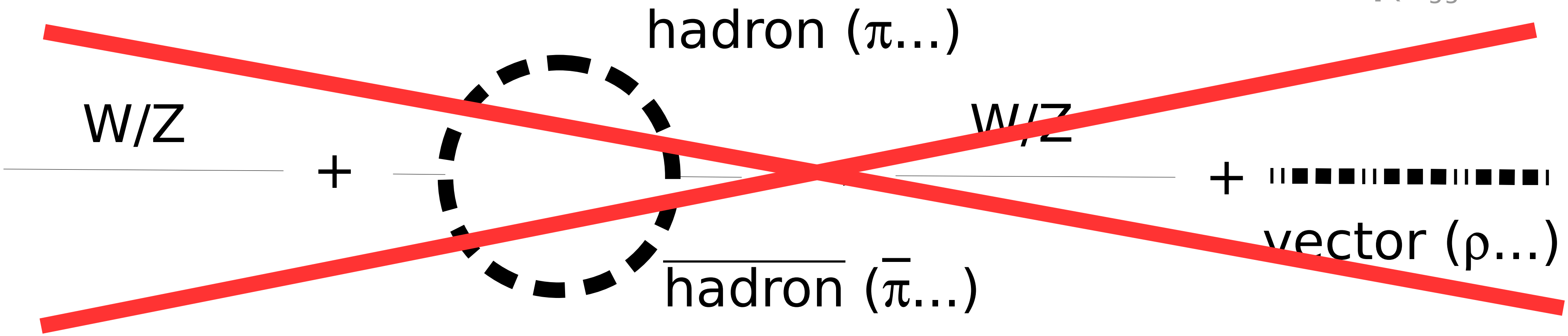
[Quigg & Shrock'09]



- Is it like this? No! Cannot create mass.

Contribution to the W/Z mass

[Quigg & Shrock'09]



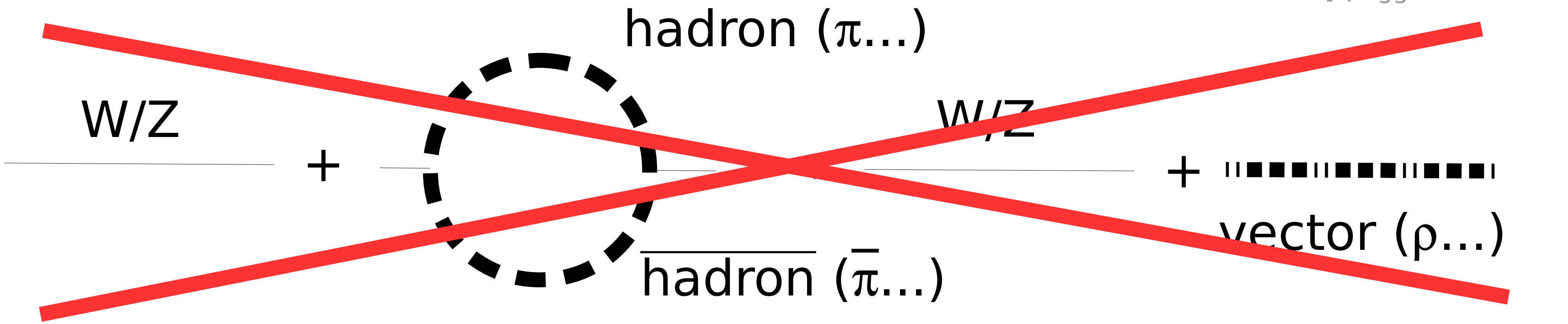
- Is it like this? No! Cannot create mass.
- Acts like an additional contribution to the condensate

$$M_W^2 \sim g^2_{weak} v^2_{Higgs} \rightarrow g^2_{weak}(v^2_{Higgs} + N_f \langle \bar{q}q \rangle^{3/2})$$

  - Essentially quark condensate
  - Expected size : Typical effect: 30-50 MeV

Contribution to the W/Z mass

[Quigg & Shrock'09]



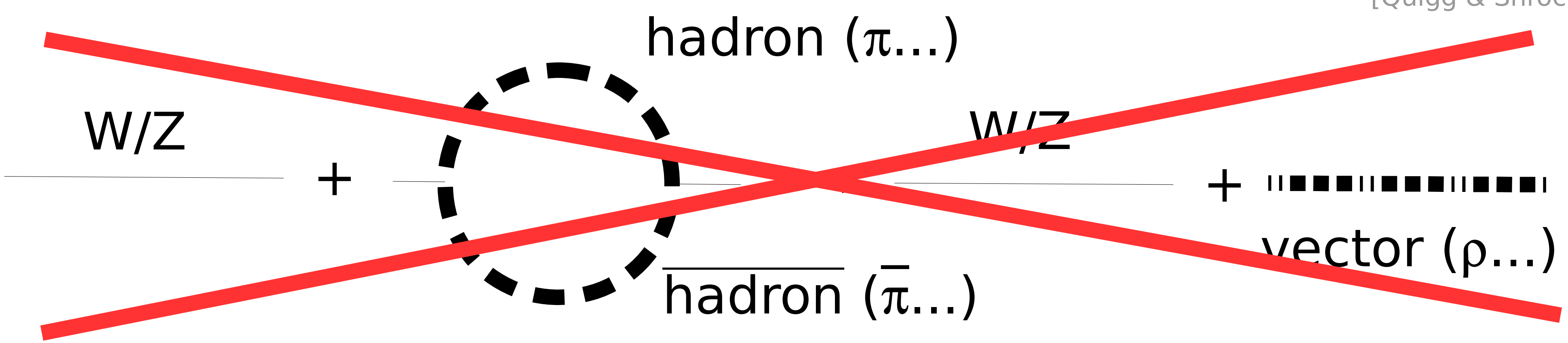
- Is it like this? No! Cannot create mass.
- Acts like an additional contribution to the condensate

$$M_W^2 \sim g^2_{weak} v^2_{Higgs} \rightarrow g^2_{weak}(v^2_{Higgs} + N_f \langle \bar{q}q \rangle^{3/2})$$

  - Essentially quark condensate
  - Expected size : Typical effect: 30-50 MeV
  - Larger as current experimental error of ~20 MeV

Contribution to the W/Z mass

[Quigg & Shrock'09]



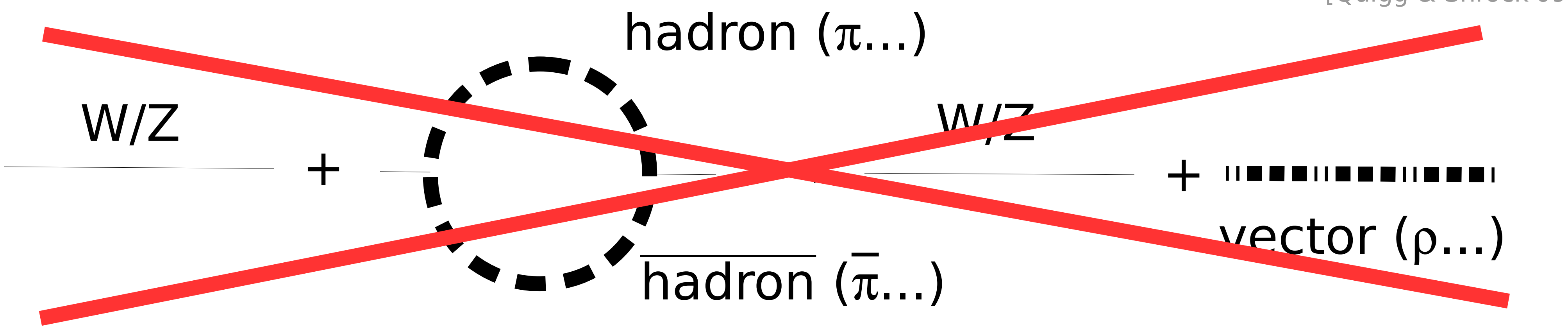
- Is it like this? No! Cannot create mass.
- Acts like an additional contribution to the condensate

$$M_W^2 \sim g^2_{weak} v^2_{Higgs} \rightarrow g^2_{weak}(v^2_{Higgs} + N_f \langle \bar{q}q \rangle^{3/2})$$

  - Essentially quark condensate
  - Expected size : Typical effect: 30-50 MeV
  - Larger as current experimental error of ~20 MeV
- Acts like a static mass when added at tree-level

Contribution to the W/Z mass

[Quigg & Shrock'09]



- Is it like this? No! Cannot create mass.
- Acts like an additional contribution to the condensate

$$M_W^2 \sim g^2_{weak} v^2_{Higgs} \to g^2_{weak}(v^2_{Higgs} + N_f \langle \bar{q}q \rangle^{3/2})$$

  - Essentially quark condensate
  - Expected size : Typical effect: 30-50 MeV
  - Larger as current experimental error of ~20 MeV
- Acts like a static mass when added at tree-level
  - Unitarity violation is canceled non-perturbatively

Implications

- Needs to be accounted for

Implications

- Needs to be accounted for
- Same order as new physics effects
    - E.g. in 2HDM models
    - Could lead to 'false' new physics claims

Implications

- Needs to be accounted for
- Same order as new physics effects
  - E.g. in 2HDM models
  - Could lead to 'false' new physics claims
- Other non-perturbative QCD corrections exist
  - 300 MeV mass for the top (and bottom) quark
  - Higgs mixes with (heavy) mesons

Implications

- Needs to be accounted for
- Same order as new physics effects
  - E.g. in 2HDM models
  - Could lead to 'false' new physics claims
- Other non-perturbative QCD corrections exist
  - 300 MeV mass for the top (and bottom) quark
  - Higgs mixes with (heavy) mesons
- New particle with color affected
- New non-perturbative condensates contribute

Example 2

Non-trivial UV structure

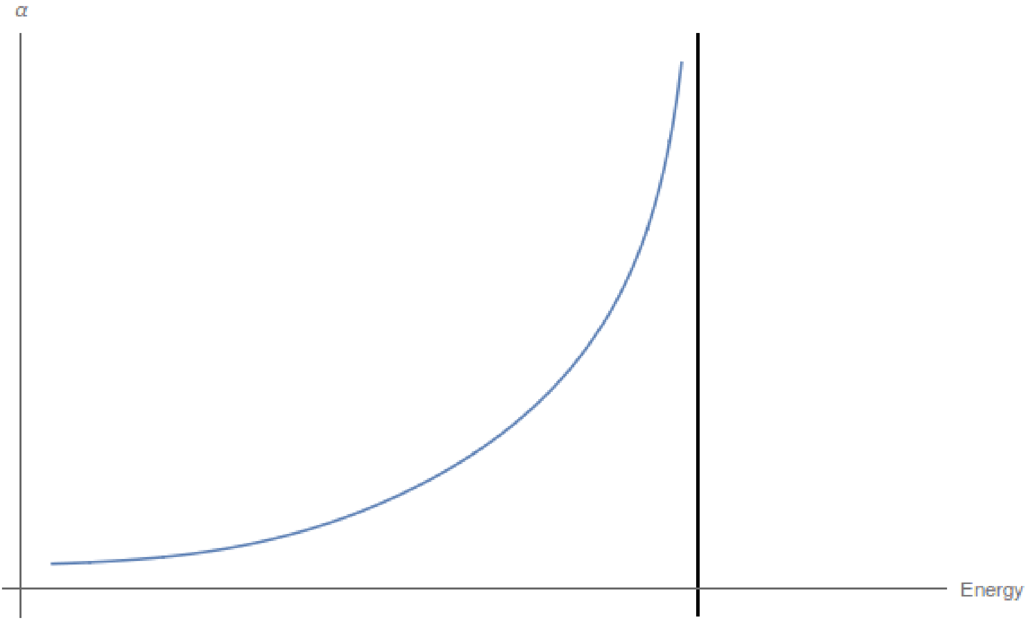
Ultraviolet structure

- Selection criterion for candidate new physics

Ultraviolet structure

- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings

Ultraviolet structure

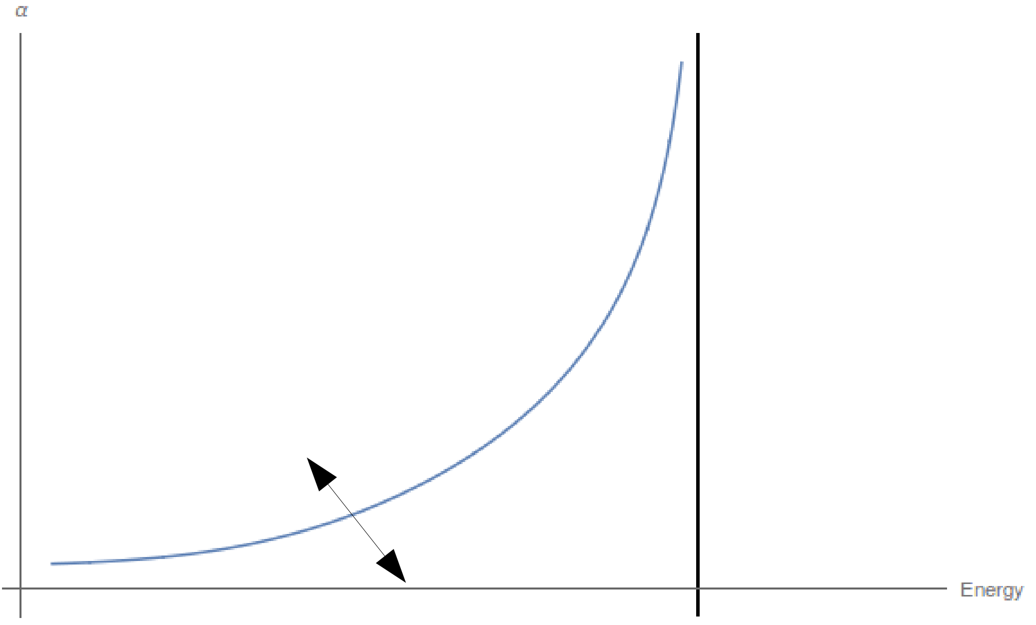


- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings
  - "Better" behavior than the standard model

    (1)No Landau poles (small coupling)

    (2)No triviality problem

Ultraviolet structure



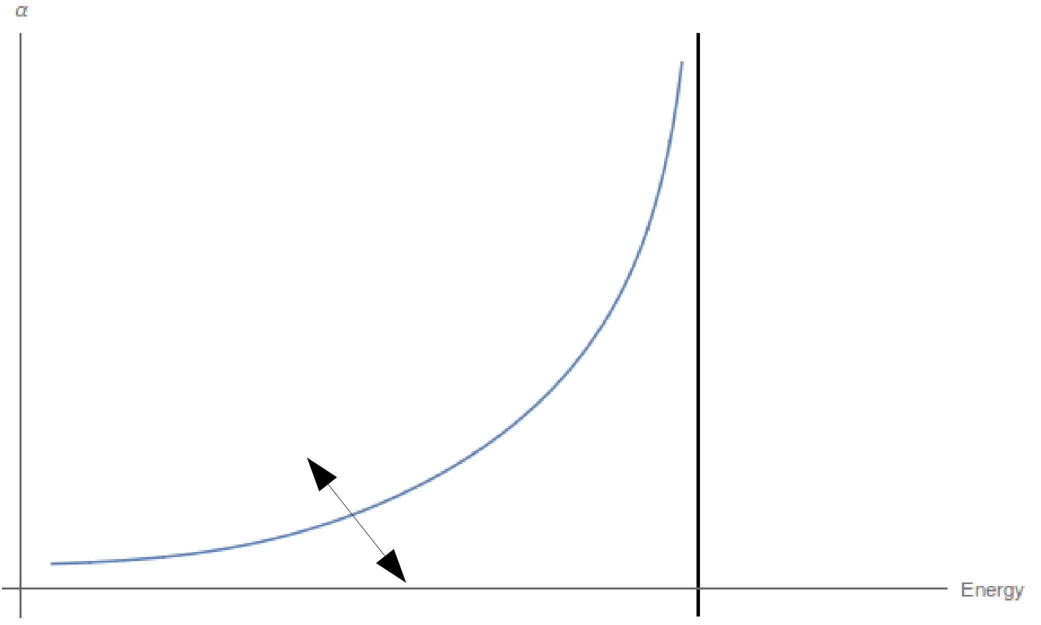
- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings
  - “Better” behavior than the standard model

    (1) No Landau poles (small coupling)

    (2) No triviality problem

    (3) No or little fine-tuning

Ultraviolet structure



- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings
  - “Better” behavior than the standard model

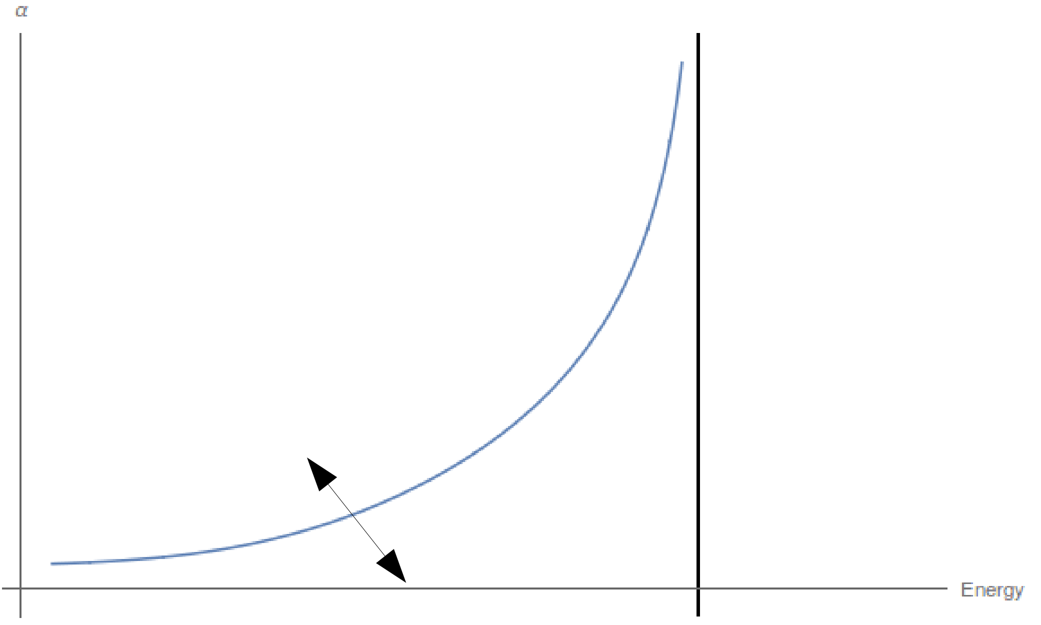
    (1)No Landau poles (small coupling)

    (2)No triviality problem

    (3)No or little fine-tuning

    - Violated by QED (1,2), Yukawa (1,2), Higgs (1-3)

Ultraviolet structure



- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings
  - “Better” behavior than the standard model

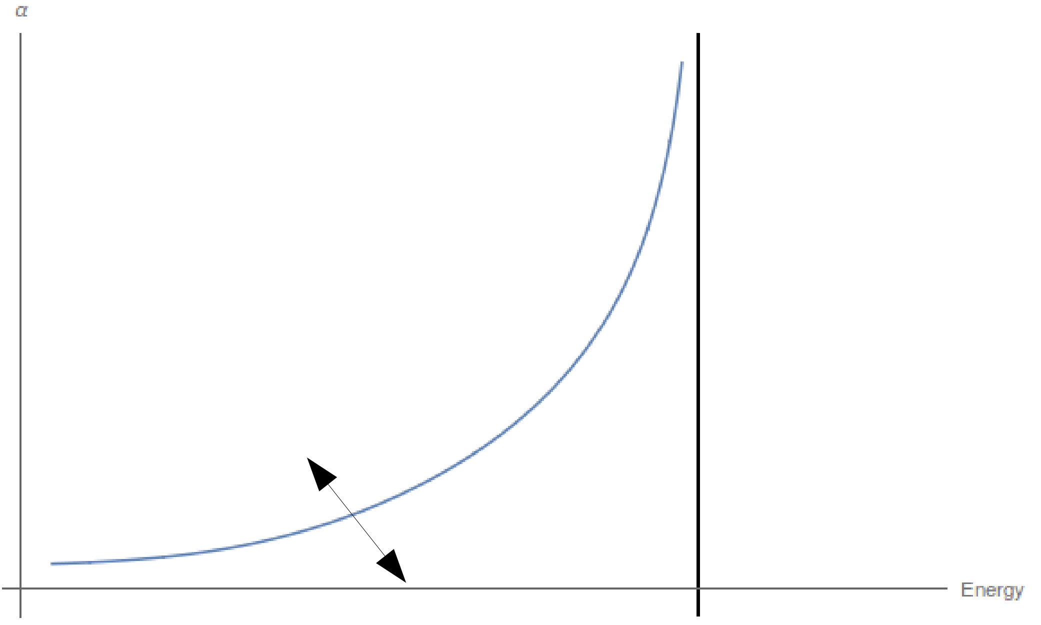
    (1)No Landau poles (small coupling)

    (2)No triviality problem

    (3)No or little fine-tuning

    - Violated by QED (1,2), Yukawa (1,2), Higgs (1-3)
- Sufficient?

Ultraviolet structure



- Selection criterion for candidate new physics
  - Usual test: Perturbative running of couplings
  - “Better” behavior than the standard model

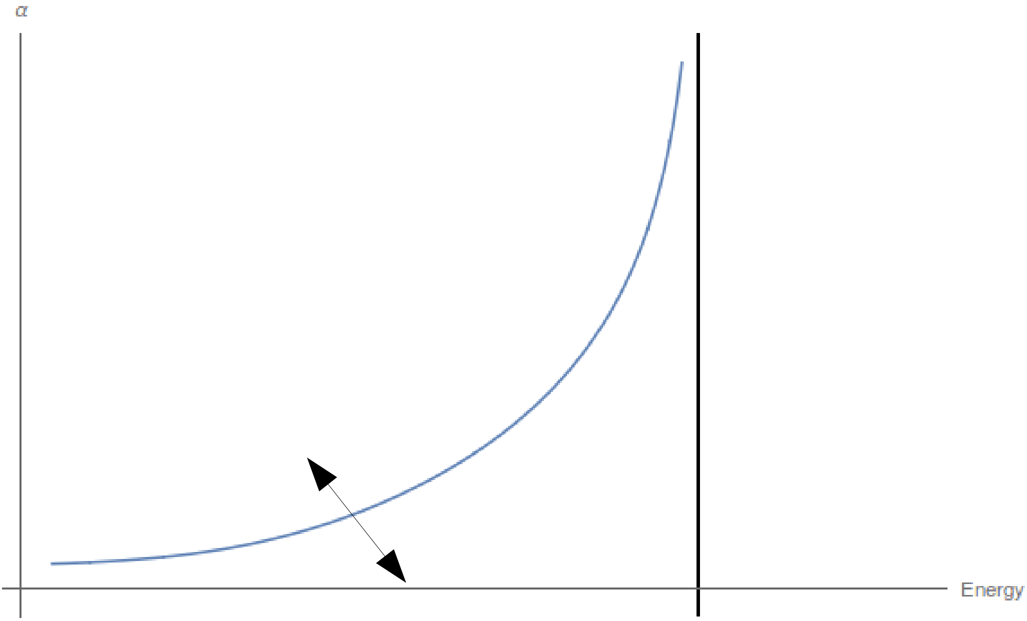
    (1)No Landau poles (small coupling)

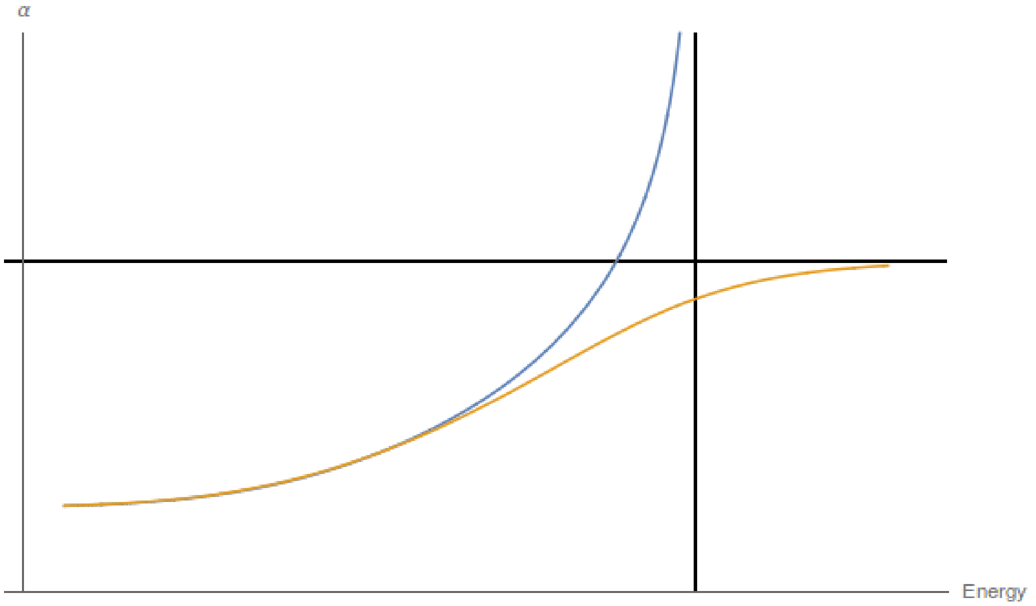
    (2)No triviality problem

    (3)No or little fine-tuning

    - Violated by QED (1,2), Yukawa (1,2), Higgs (1-3)
- Sufficient? No.

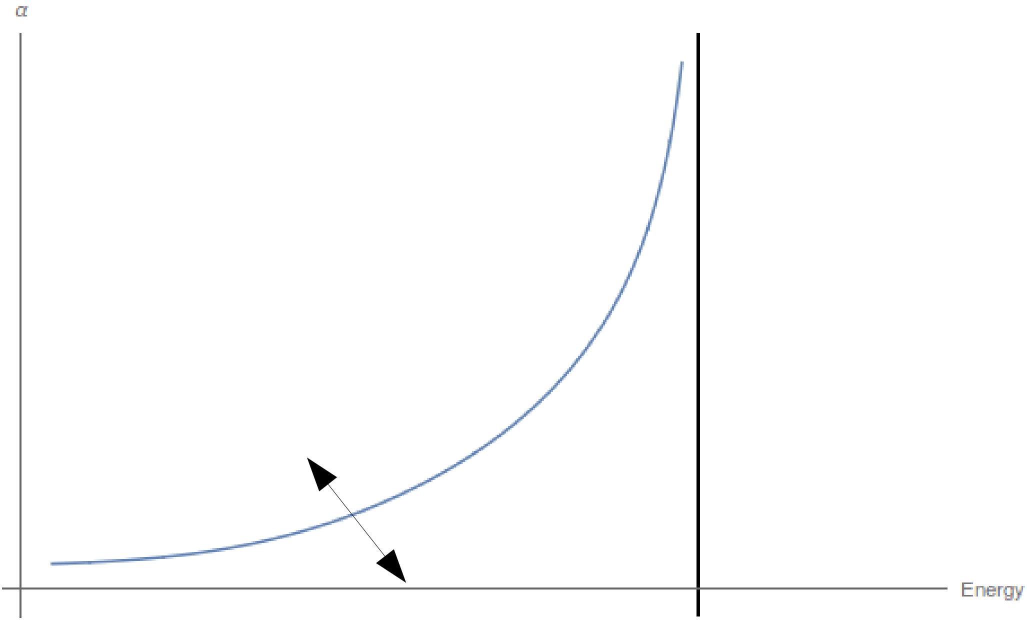
Possible scenarios

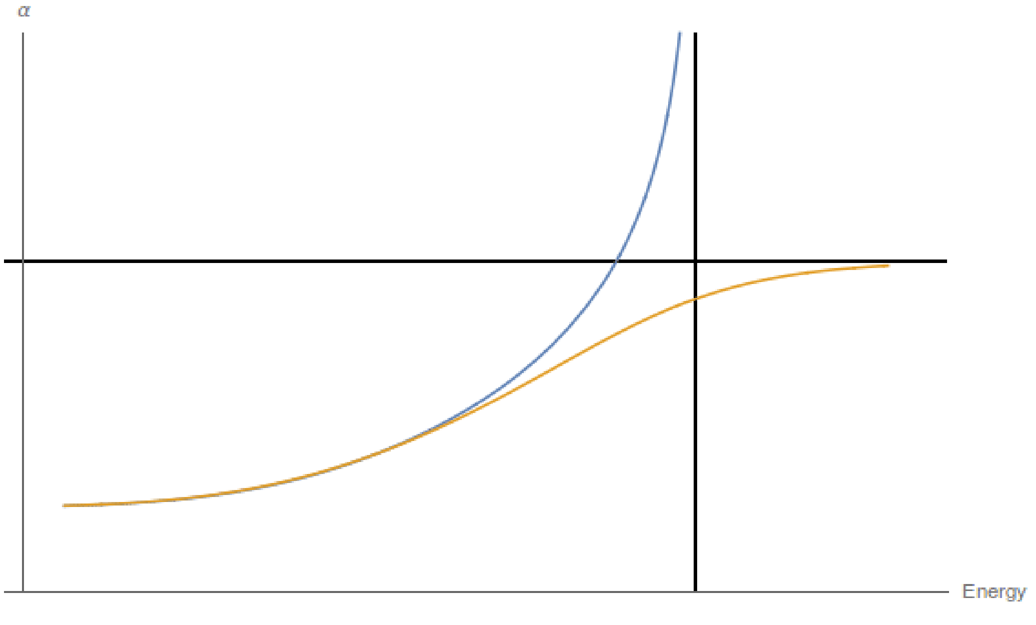




- Asymptotic safety [Weinberg'79,Gies et al.'13-'17,Litim et al.'14-'17]
  - Sufficient to have a (small) finite coupling
  - From (non-)perturbative cancellations in β-functions

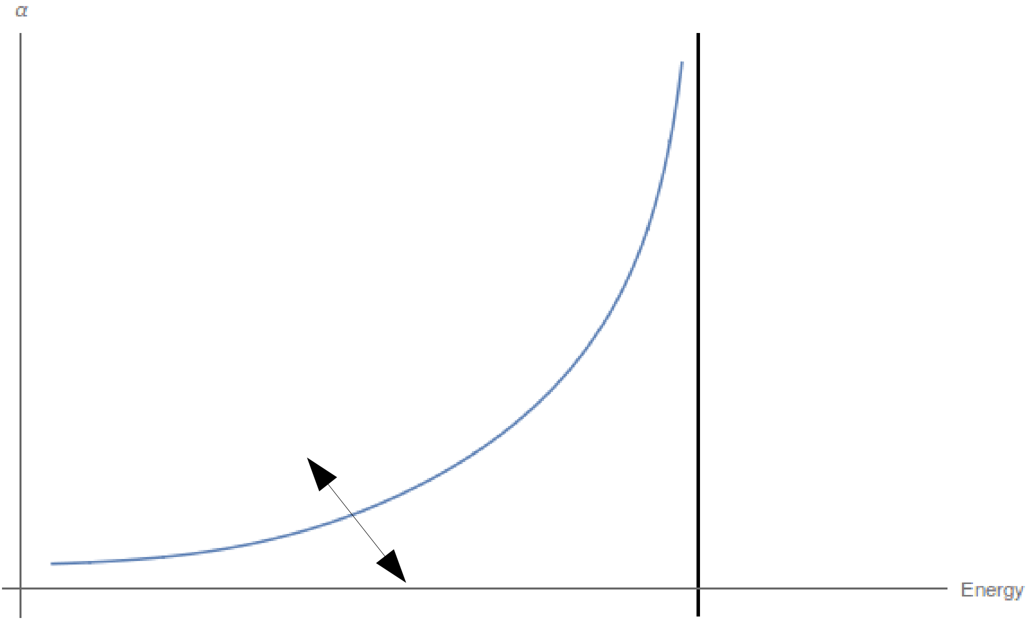
Possible scenarios

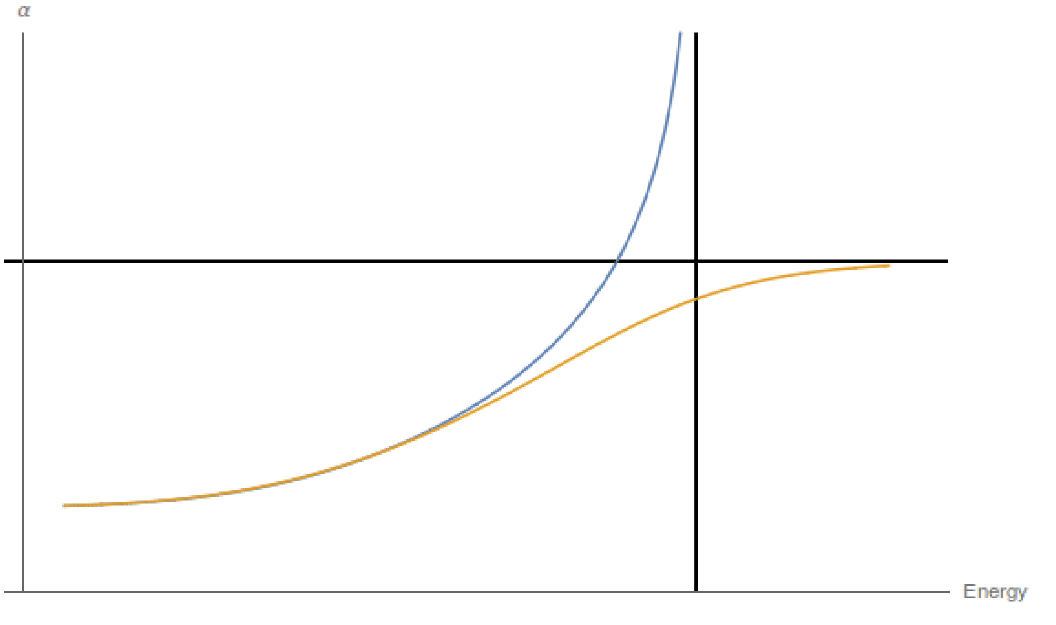




- Asymptotic safety [Weinberg'79,Gies et al.'13-'17,Litim et al.'14-'17]
    - Sufficient to have a (small) finite coupling
    - From (non-)perturbative cancellations in β-functions
- Quantum gravity can backcouple [Wetterich et al.'09,Eichhorn et al.'13-'17]
    - May solve all of these problems

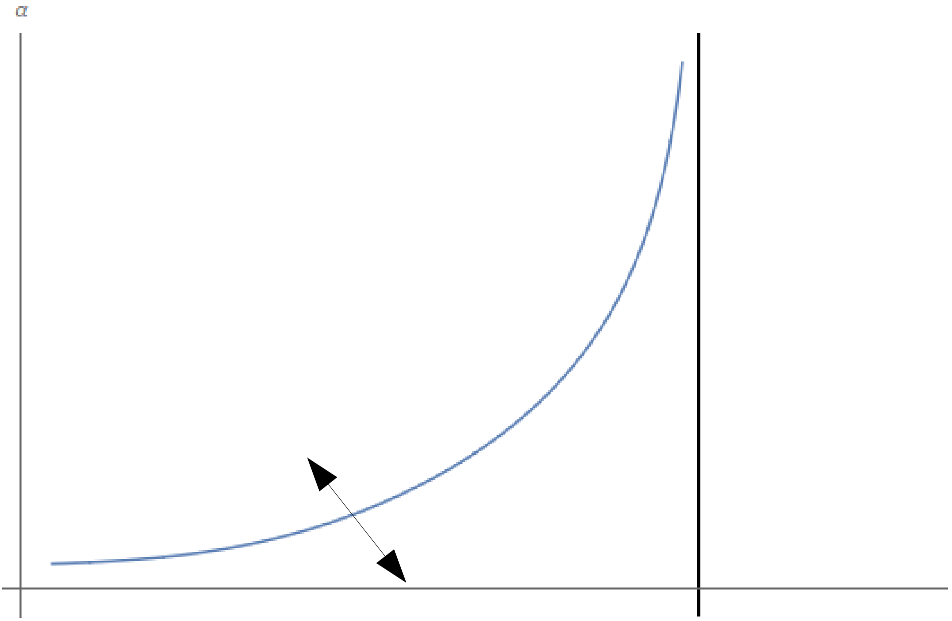
Possible scenarios

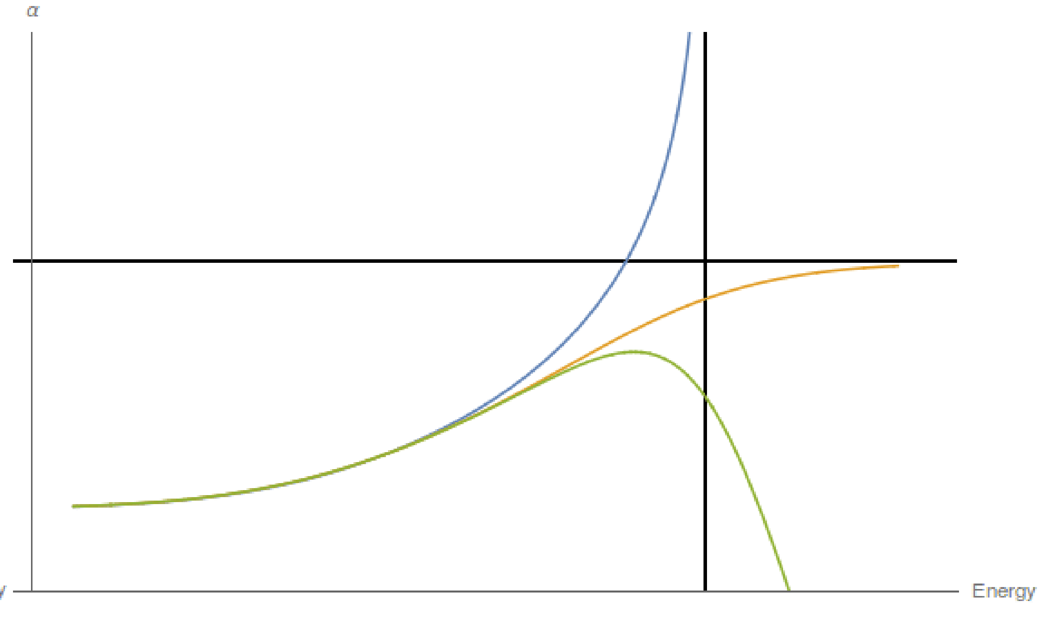




- Asymptotic safety [Weinberg'79,Gies et al.'13-'17,Litim et al.'14-'17]
  - Sufficient to have a (small) finite coupling
  - From (non-)perturbative cancellations in β-functions
- Quantum gravity can backcouple [Wetterich et al.'09,Eichhorn et al.'13-'17]
  - May solve all of these problems
- Fine-tuned special trajectories [Callaway'88,Litim et al.'14-'17]
  - All order cancellations solve problem

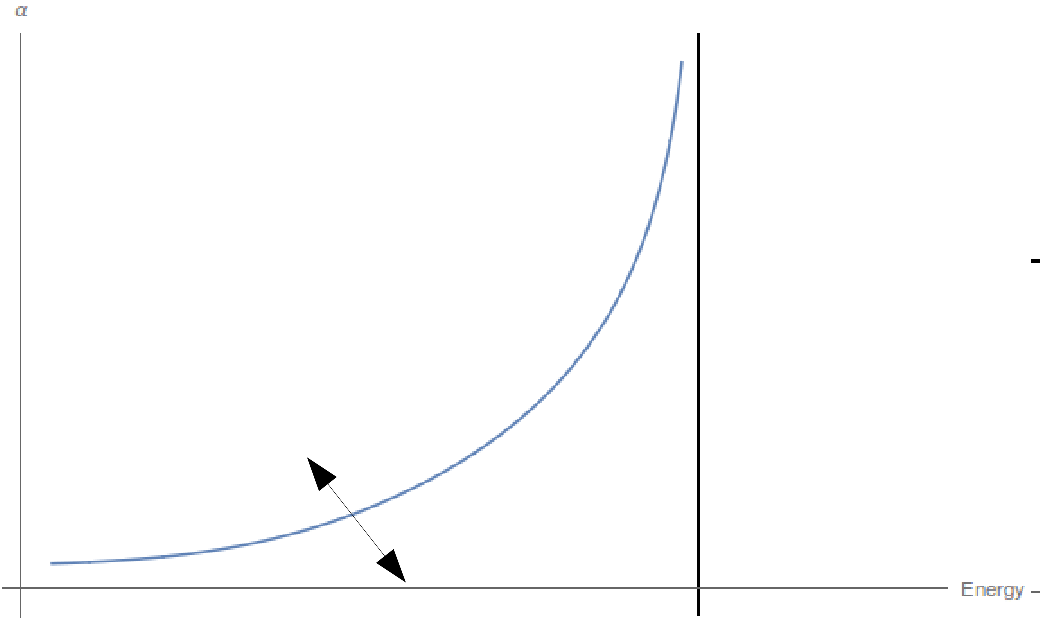
Possible scenarios

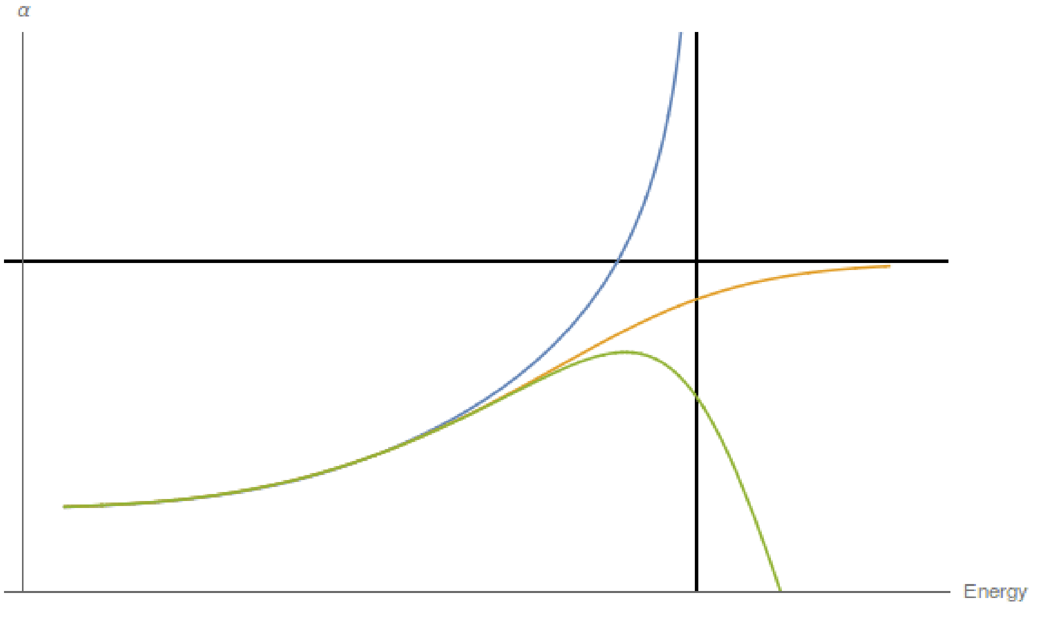




- Asymptotic safety [Weinberg'79,Gies et al.'13-'17,Litim et al.'14-'17]
  - Sufficient to have a (small) finite coupling
  - From (non-)perturbative cancellations in β-functions
- Quantum gravity can backcouple [Wetterich et al.'09,Eichhorn et al.'13-'17]
  - May solve all of these problems
- Fine-tuned special trajectories [Callaway'88,Litim et al.'14-'17,Gies et al.'15,'16]
  - All order cancellations solve problem

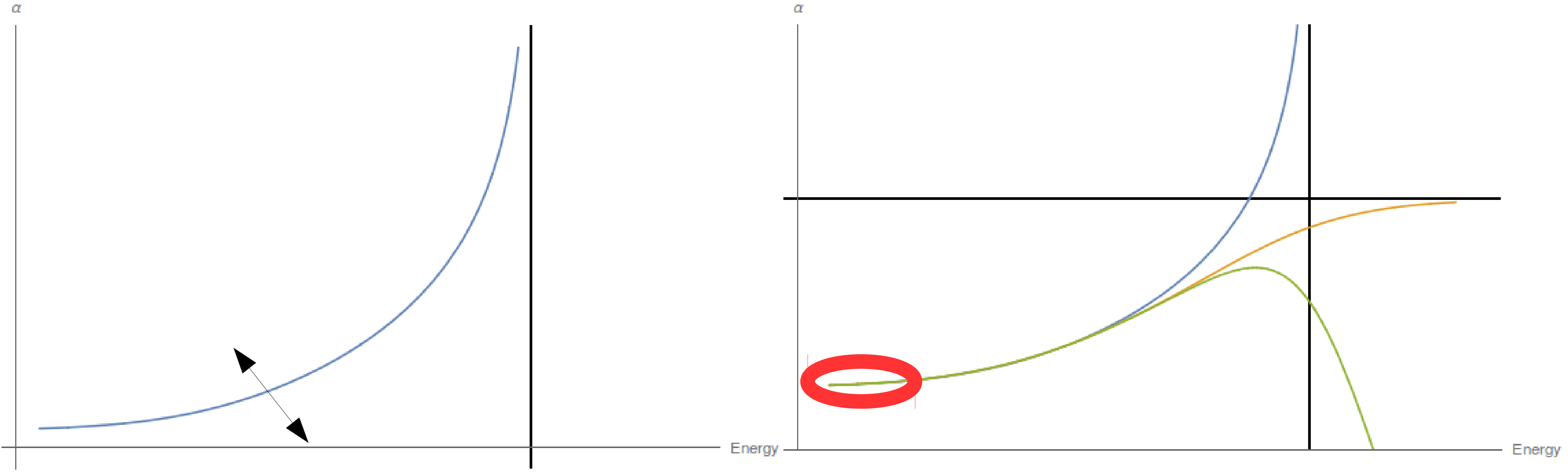
Where to look for it





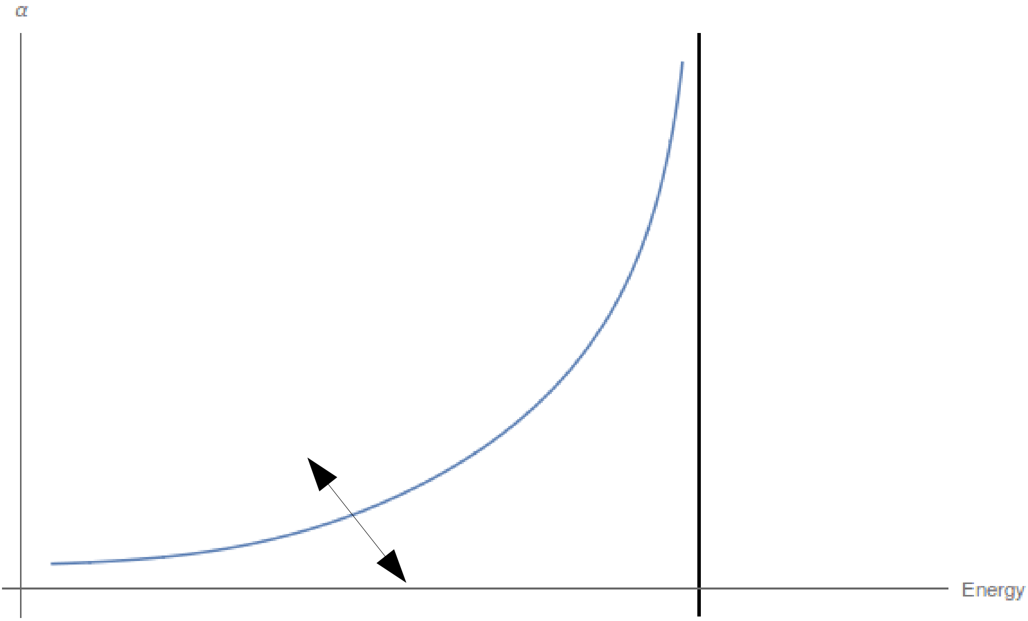
- Experimentally hard to find
  - Energy-dependence of running couplings
    - Tiny deviations at accessible energies: Precision tests

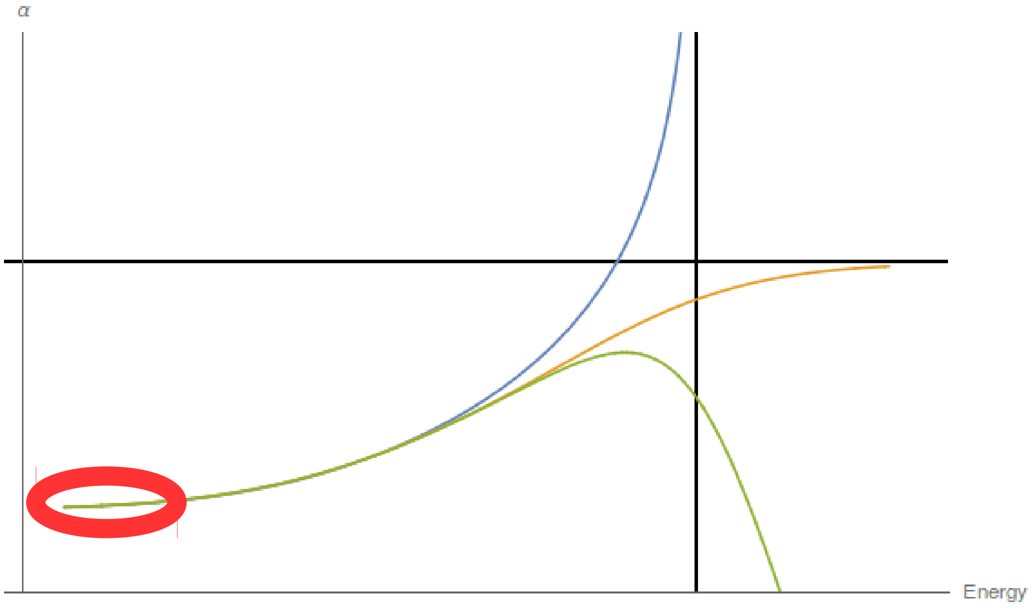
Where to look for it



- Experimentally hard to find
  - Energy-dependence of running couplings
    - Tiny deviations at accessible energies: Precision tests

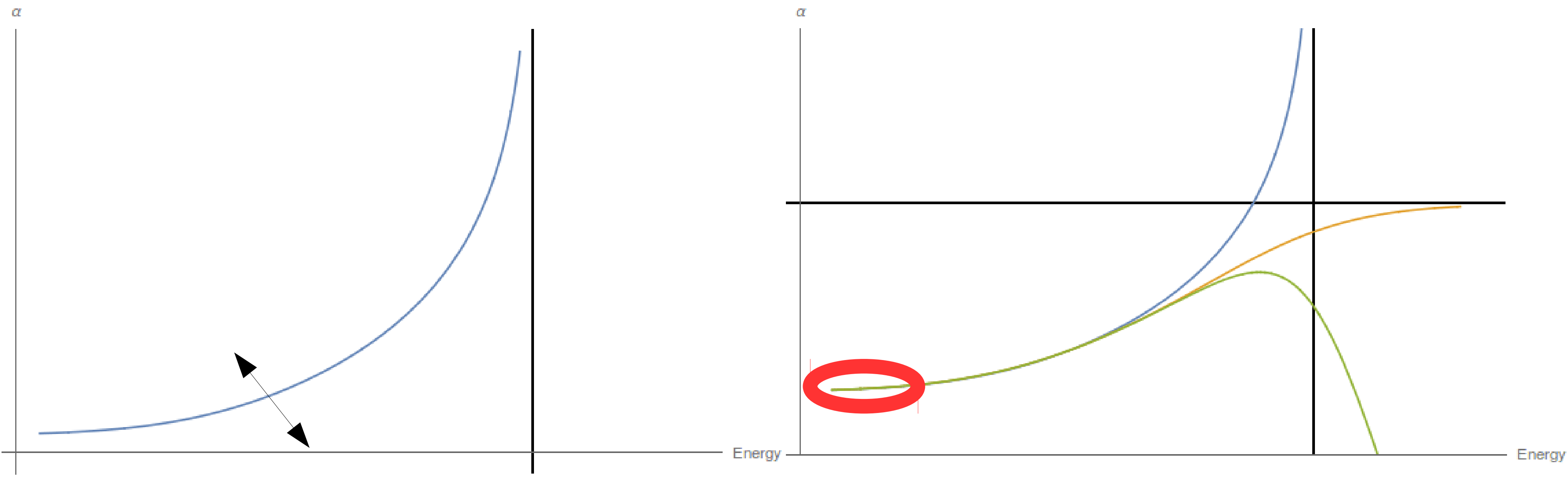
Where to look for it





- Experimentally hard to find
    - Energy-dependence of running couplings
        - Tiny deviations at accessible energies: Precision tests
    - Particle content constrained

Where to look for it



- Experimentally hard to find
  - Energy-dependence of running couplings
    - Tiny deviations at accessible energies: Precision tests
  - Particle content constrained
- Quantum gravity has implications for cosmology
  - Cosmological constant becomes running
  - Tests against astrophysical data

Example 3

Theory constraints

The Problem

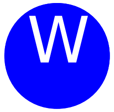
- Consider the Higgs sector of the standard model

The Problem

- Consider the Higgs sector of the standard model
- The Higgs sector is a gauge theory

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

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

- Ws W^a_μ 

- Coupling g and some numbers f^{abc}

The Problem

- Consider the Higgs sector of the standard model
- 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 W
- Higgs h_i h

- Coupling g and some numbers f^{abc} and t_a^{ij}

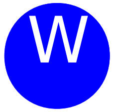
The Problem

- Consider the Higgs sector of the standard model
- The Higgs sector is a gauge theory

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

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

$$D_{\mu}^{ij}=\delta^{ij}\partial_{\mu}-igW_{\mu}^{a}t_{a}^{ij}$$

- Ws W_{μ}^{a} 

- Higgs h_i 

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

The Problem

- Consider the Higgs sector of the standard model
- The Higgs sector is a gauge theory

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

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

$$D_{\mu}^{ij}=\delta^{ij}\partial_{\mu}-igW_{\mu}^{a}t_{a}^{ij}$$

The Problem

- Consider the Higgs sector of the standard model
- The Higgs sector is a gauge theory

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

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

$$D_{\mu}^{ij}=\delta^{ij}\partial_{\mu}-igW_{\mu}^{a}t_{a}^{ij}$$

- Local SU(2) gauge symmetry

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a}+\left(\delta_{b}^{a}\partial_{\mu}-gf_{bc}^{a}W_{\mu}^{c}\right)\phi^{b} \qquad h_{i}\rightarrow h_{i}+g\,t_{a}^{ij}\phi^{a}h_{j}$$

The Problem

- Consider the Higgs sector of the standard model
- The Higgs sector is a gauge theory

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

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

$$D_{\mu}^{ij}=\delta^{ij}\partial_{\mu}-igW_{\mu}^{a}t_{a}^{ij}$$

- Local SU(2) gauge symmetry

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a}+(\delta_{b}^{a}\partial_{\mu}-gf_{bc}^{a}W_{\mu}^{c})\phi^{b} \qquad h_{i}\rightarrow h_{i}+g\,t_{a}^{ij}\phi^{a}h_{j}$$

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

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a} \qquad h_{i}\rightarrow h_{i}+a^{ij}h_{j}+b^{ij}h_{j}^{*}$$

Gauge symmetry broken

- Standard approach: Perturbation theory
    - Requires a choice of gauge

Gauge symmetry (un)broken

- Standard approach: Perturbation theory
  - Requires a choice of gauge
- Only in some gauges exist a Higgs condensate
  [Lee et al.'72, Osterwalder & Seiler'77, Fröhlich et al.'80]

Gauge symmetry (un)broken

- Standard approach: Perturbation theory
  - Requires a choice of gauge
- Only in some gauges exist a Higgs condensate
  [Lee et al.'72, Osterwalder & Seiler'77, Fröhlich et al.'80]
  - Only in these is perturbation theory possible

Gauge symmetry (un)broken

- Standard approach: Perturbation theory
  - Requires a choice of gauge
- Only in some gauges exist a Higgs condensate
  [Lee et al.'72, Osterwalder & Seiler'77, Fröhlich et al.'80]
  - Only in these is perturbation theory possible
  - “Spontaneous gauge symmetry breaking”

Gauge symmetry unbroken

- Standard approach: Perturbation theory
  - Requires a choice of gauge
- Only in some gauges exist a Higgs condensate [Lee et al.'72, Osterwalder & Seiler'77, Fröhlich et al.'80]
  - Only in these is perturbation theory possible
  - “Spontaneous gauge symmetry breaking”
    - Broken by the gauge choice, not by the dynamics
    - Non-perturbative calculations in other gauges possible [Maas'13]
    - Local symmetry intact and cannot be broken [Elitzur'75]

Gauge symmetry unbroken

- Standard approach: Perturbation theory
  - Requires a choice of gauge
- Only in some gauges exist a Higgs condensate
  [Lee et al.'72, Osterwalder & Seiler'77, Fröhlich et al.'80]
  - Only in these is perturbation theory possible
  - “Spontaneous gauge symmetry breaking”
    - Broken by the gauge choice, not by the dynamics
    - Non-perturbative calculations in other gauges possible [Maas'13]
    - Local symmetry intact and cannot be broken
      [Elitzur'75]
- Gauge invariance as primary construction principle much broader

Physical states

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

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections

Physical states

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

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable

Physical states

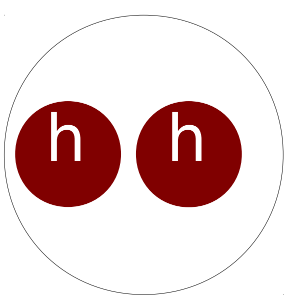
[Fröhlich et al.'80,
't Hooft'80,
Bank et al.'79]

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory

Physical states

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

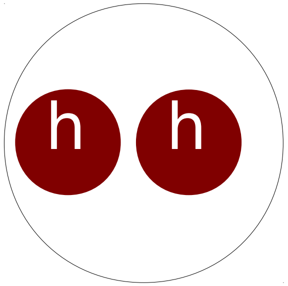
- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs

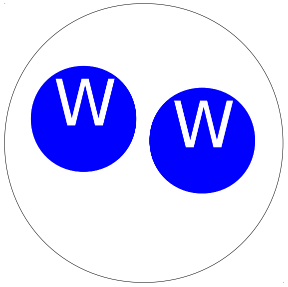


Physical states

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

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs, W-W

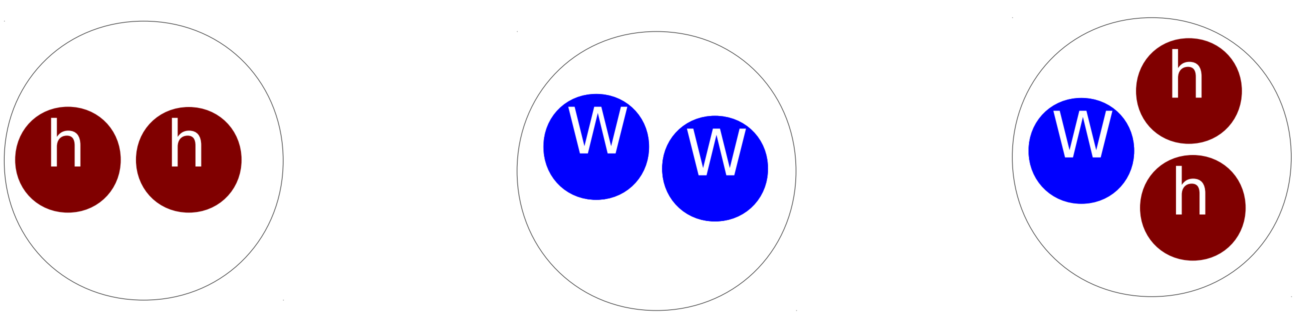




Physical states

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

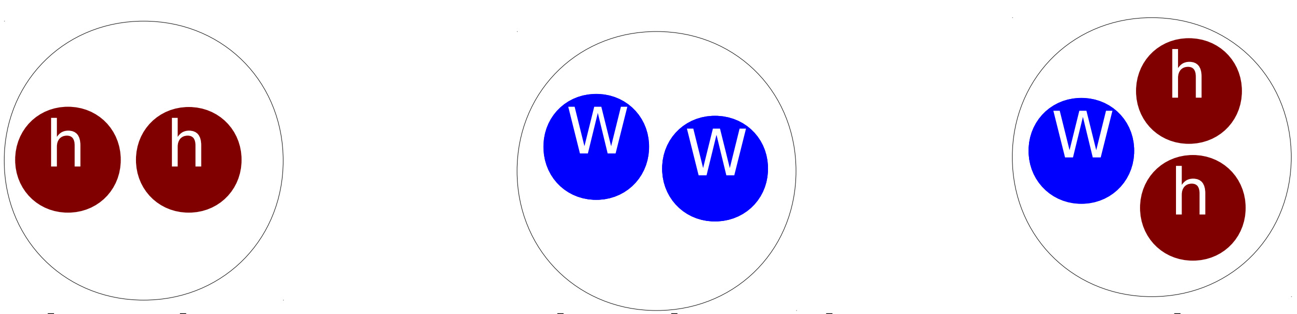
- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



Physical states

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

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.

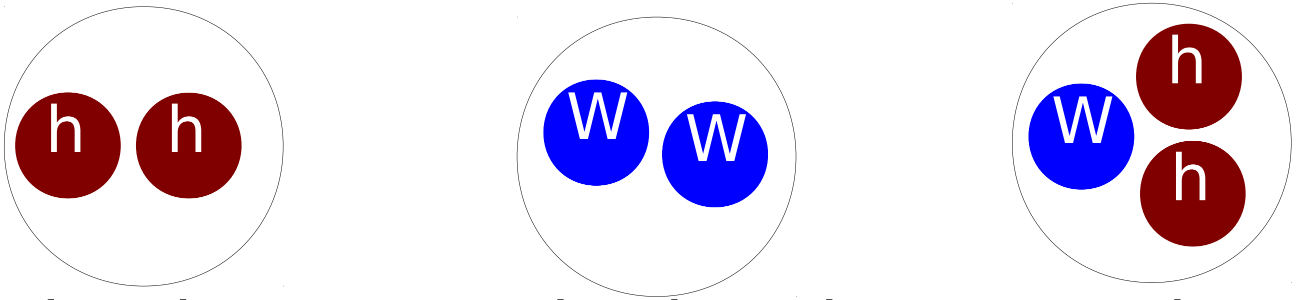


  - Why does perturbation theory work?

Physical states

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

- Physical spectrum: Observable particles
  - Experiments measure peaks in cross-sections
- Elementary fields depend on the gauge
  - Cannot be observable
- Gauge-invariant states are composite
  - Not asymptotic states in perturbation theory
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



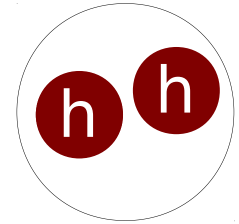
  - Why does perturbation theory work?
  - Mass spectrum

Mass relation - Higgs

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

- Mass spectrum can be measured on the lattice

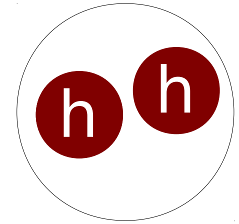
Mass relation - Higgs



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

- Mass spectrum can be measured on the lattice
- Mass of the scalar bound state and Higgs same
  [Maas et al., '12-'16]
  - Issues with scheme dependencies

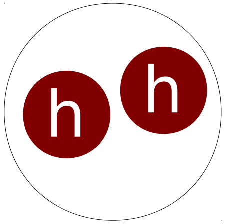
Mass relation - Higgs



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

- Mass spectrum can be measured on the lattice
- Mass of the scalar bound state and Higgs same
  [Maas et al., '12-'16]
  - Issues with scheme dependencies
- Coincidence?

Mass relation - Higgs



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

- Mass spectrum can be measured on the lattice
- Mass of the scalar bound state and Higgs same
  [Maas et al., '12-'16]
  - Issues with scheme dependencies
- Coincidence? No.

Gauge-invariant perturbation theory

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y) \rangle$

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y)\rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2 \langle \eta^+(x)\eta(y)\rangle$$
$$+ v\langle \eta^+ \eta^2 + \eta^{+2}\eta\rangle + \langle \eta^{+2}\eta^2\rangle$$

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y) \rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = c + v^2 \langle \eta^+ (x) \eta(y) \rangle$$
$$+ v \langle \eta^+ \eta^2 + \eta^{+2} \eta \rangle + \langle \eta^{+2} \eta^2 \rangle$$

3) Standard perturbation theory

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = c + v^2 \langle \eta^+ (x) \eta(y) \rangle$$
$$+ \langle \eta^+ (x) \eta(y) \rangle \langle \eta^+ (x) \eta(y) \rangle + O(g, \lambda)$$

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y)\rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2 \langle \eta^+(x)\eta(y)\rangle$$
$$+ v\langle \eta^+ \eta^2 + \eta^{+2}\eta\rangle + \langle \eta^{+2}\eta^2\rangle$$

3) Standard perturbation theory

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2 \langle \eta^+(x)\eta(y)\rangle$$
$$+ \langle \eta^+(x)\eta(y)\rangle\langle \eta^+(x)\eta(y)\rangle + O(g,\lambda)$$

4) Compare poles on both sides

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0⁺ singlet: $\langle (h^+ h)(x)(h^+ h)(y) \rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = c + v^2 \langle \eta^+ (x) \eta(y) \rangle + v \langle \eta^+ \eta^2 + \eta^{+2} \eta \rangle + \langle \eta^{+2} \eta^2 \rangle$$

3) Standard perturbation theory

Bound state mass

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = c + v^2 \langle \eta^+ (x) \eta(y) \rangle + \langle \eta^+ (x) \eta(y) \rangle \langle \eta^+ (x) \eta(y) \rangle + O(g, \lambda)$$

4) Compare poles on both sides

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0$^+$ singlet: $\langle (h^+ h)(x)(h^+ h)(y)\rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2 \langle \eta^+(x)\eta(y)\rangle$$
$$+ v\langle \eta^+ \eta^2 + \eta^{+2}\eta\rangle + \langle \eta^{+2}\eta^2\rangle$$

3) Standard perturbation theory

Bound state mass

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2 \langle \eta^+(x)\eta(y)\rangle$$
$$+ \langle \eta^+(x)\eta(y)\rangle\langle \eta^+(x)\eta(y)\rangle + O(g,\lambda)$$

2 x Higgs mass: Scattering state

4) Compare poles on both sides

Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y)\rangle$

2) Expand Higgs field around fluctuations

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2\langle \eta^+(x)\eta(y)\rangle + v\langle \eta^+\eta^2 + \eta^{+2}\eta\rangle + \langle \eta^{+2}\eta^2\rangle$$

3) Standard perturbation theory

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle = c + v^2\langle \eta^+(x)\eta(y)\rangle + \langle \eta^+(x)\eta(y)\rangle\langle \eta^+(x)\eta(y)\rangle + O(g,\lambda)$$

Bound state mass

Higgs mass

2 x Higgs mass: Scattering state

4) Compare poles on both sides

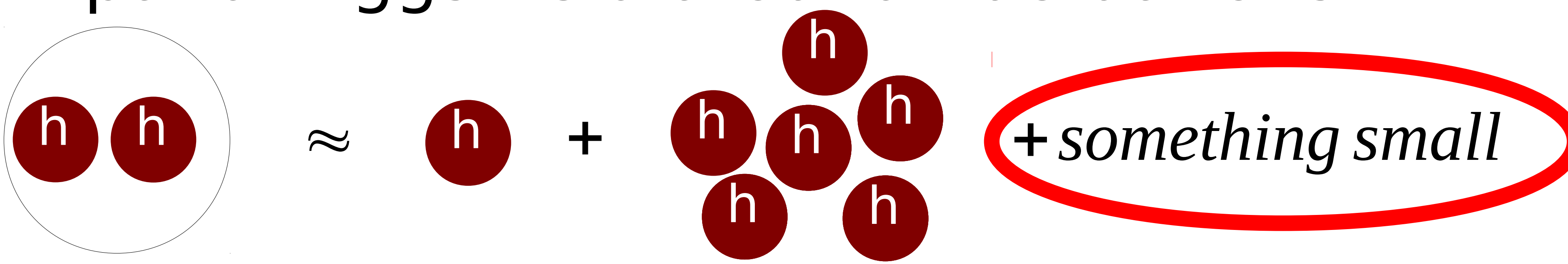
Gauge-invariant perturbation theory

[Fröhlich et al. PLB 80
Maas'12, Törek & Maas'16]

1) Formulate gauge-invariant operator

0^+ singlet: $\langle (h^+ h)(x)(h^+ h)(y) \rangle$

2) Expand Higgs field around fluctuations



3) Standard perturbation theory

$$\langle (h^+ h)(x)(h^+ h)(y) \rangle = c + v^2 \langle \eta^+(x)\eta(y) \rangle + \langle \eta^+(x)\eta(y) \rangle \langle \eta^+(x)\eta(y) \rangle + O(g, \lambda)$$

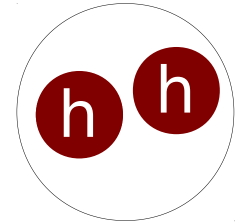
Bound state mass

Higgs mass

2 x Higgs mass: Scattering state

4) Compare poles on both sides

Mass relation - Higgs



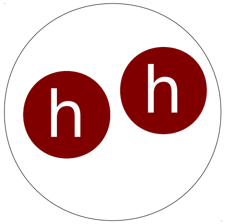
[Fröhlich et al.'80
Maas'12, Maas & Mufti'13]

- Mass spectrum can be measured on the lattice
- Mass of the scalar bound state and Higgs same
  [Maas et al., '12-'16]
  - Issues with scheme dependencies
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al.'80]

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

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

Mass relation - Higgs



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

- Mass spectrum can be measured on the lattice
- Mass of the scalar bound state and Higgs same
  [Maas et al., '12-'16]
  - Issues with scheme dependencies
- Coincidence? No.
  - Duality between elementary states and bound states
    [Fröhlich et al.'80]

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

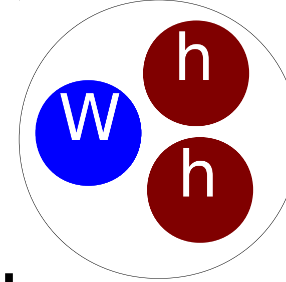
  - Same poles to leading order
- Fröhlich-Morchio-Strocchi (FMS) mechanism
- Deeply-bound relativistic state -not like QCD
- Mass defect~constituent mass – requires QFT

Mass relation - W

[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers

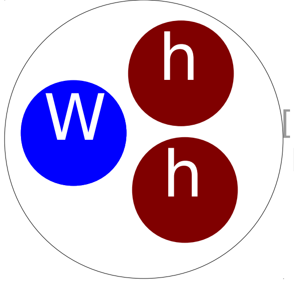
Mass relation - W



[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers
- 1^- custodial triplet

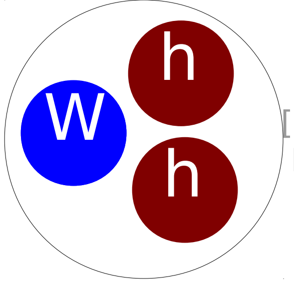
Mass relation - W



[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers
- 1^- custodial triplet: Same mass as W
  [Maas et al., '12-'16]

Mass relation - W



[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers
- 1^- custodial triplet: Same mass as W
  [Maas et al., '12-'16]
- Same mechanism

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

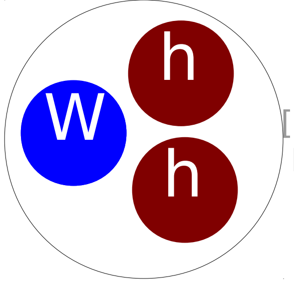
$$h = v + \eta$$

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

$$\partial v = 0$$

- Same poles at leading order

Mass relation - W



[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers
- 1^- custodial triplet: Same mass as W

  [Maas et al., '12-'16]

- Same mechanism

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

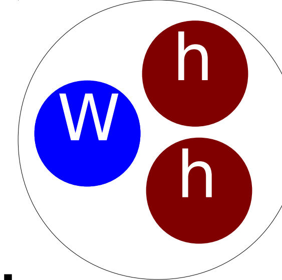
$$h = v + \eta$$

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

$$\partial v = 0$$

- Same poles at leading order
- Weak charge not observable

Mass relation - W



[Fröhlich et al.'80
Maas'12]

- Can be done for arbitrary quantum numbers
- 1^- custodial triplet: Same mass as W
  [Maas et al., '12-'16]
- Same mechanism

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

$$h = v + \eta$$

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

$$\partial v = 0$$

- Same poles at leading order
- Weak charge not observable
  - Weak triplet transformed to custodial triplet

Grand-unified theories

Grand-unified theories

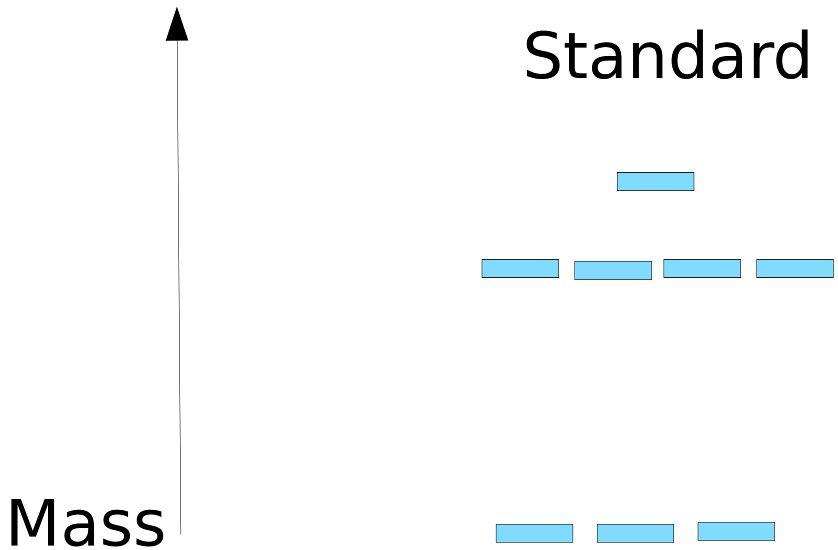
[Maas'15,
Maas & Törek'16]

- Toy example: SU(3)+fundamental Higgs

Grand-unified theories

[Maas'15, Maas & Törek'16]

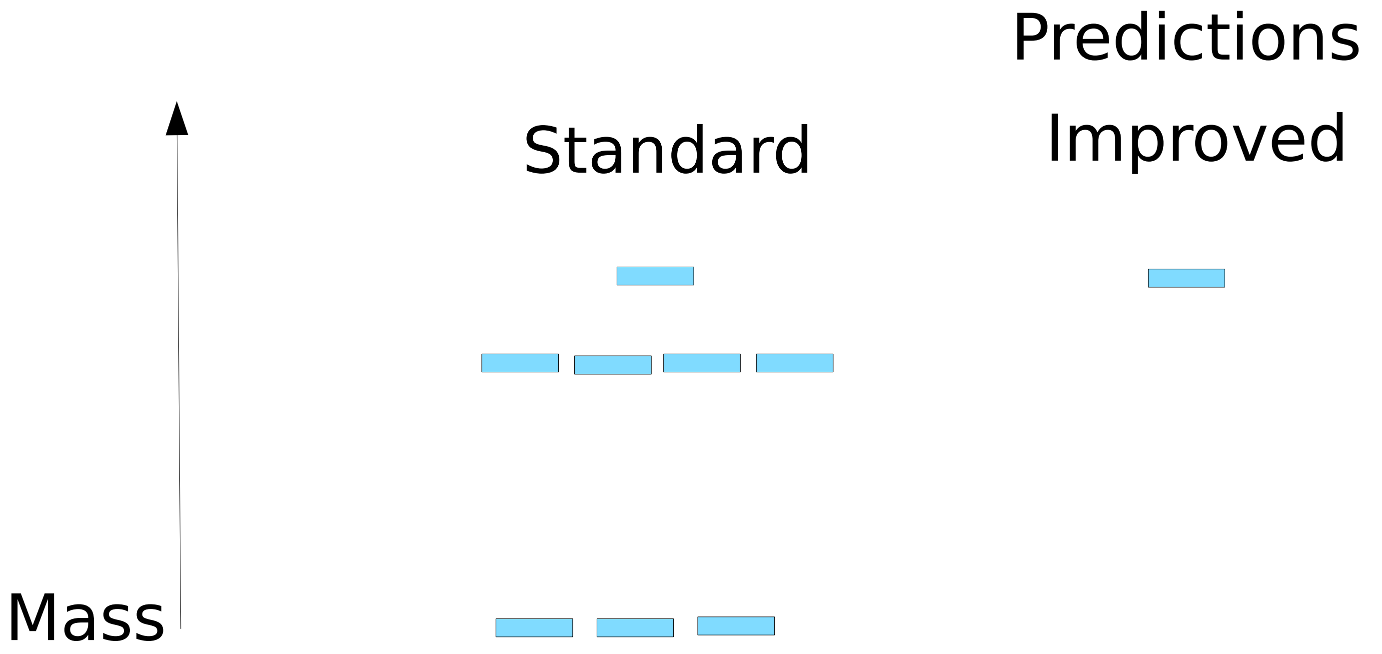
Predictions



- Toy example: SU(3)+fundamental Higgs
- Standard (perturbative) spectrum for the vectors

Grand-unified theories

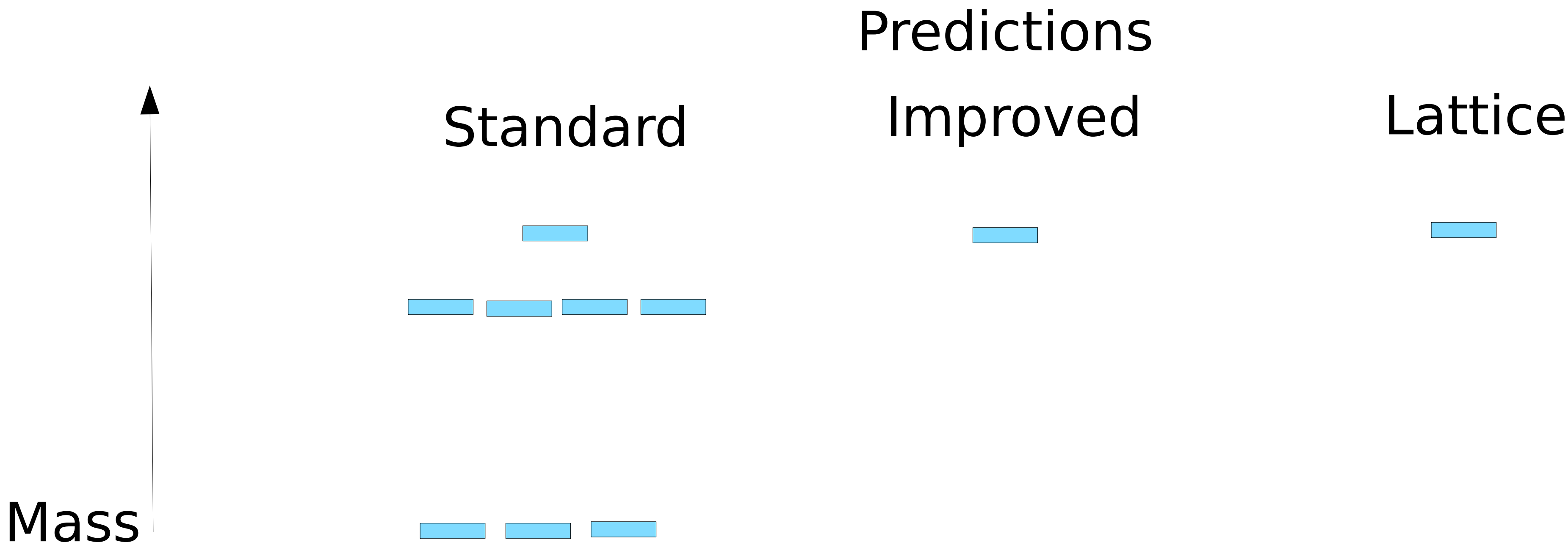
[Maas'15,
Maas & Törek'16]



- Toy example: SU(3)+fundamental Higgs
- Standard (perturbative) spectrum for the vectors
- Prediction from gauge-invariant perturbation theory

Grand-unified theories

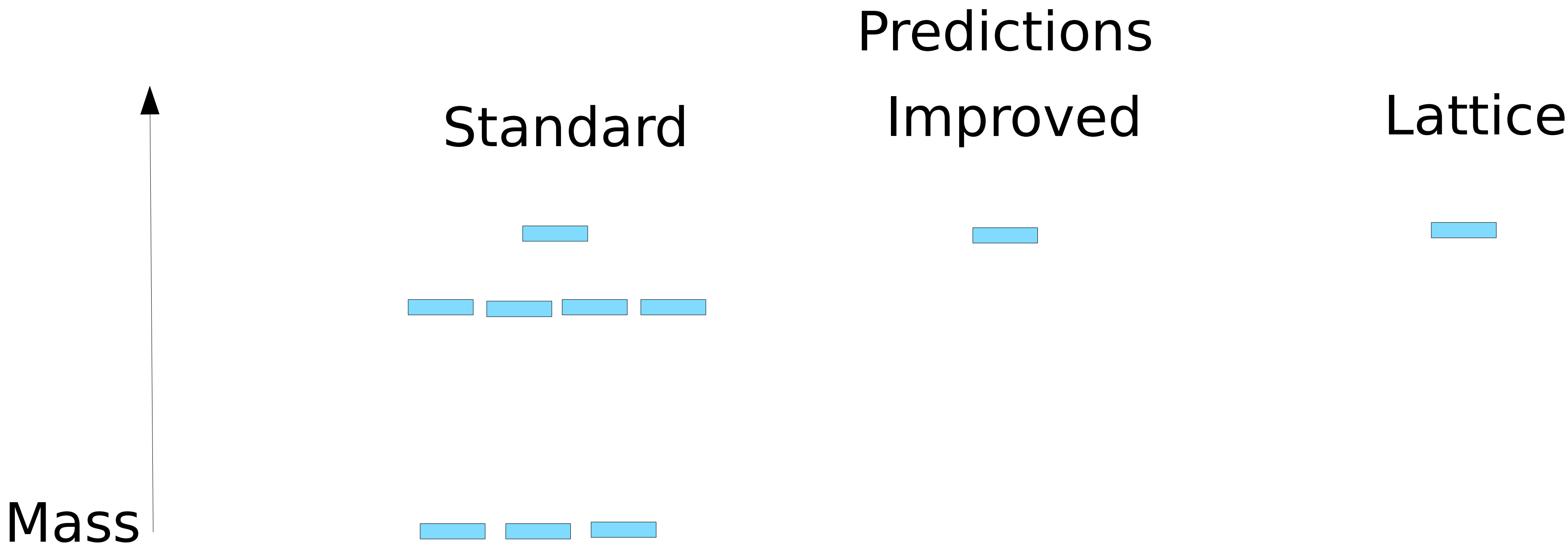
[Maas'15, Maas & Törek'16]



- Toy example: SU(3)+fundamental Higgs
- Standard (perturbative) spectrum for the vectors
- Prediction from gauge-invariant perturbation theory
- Lattice results – favor non-standard results

Grand-unified theories

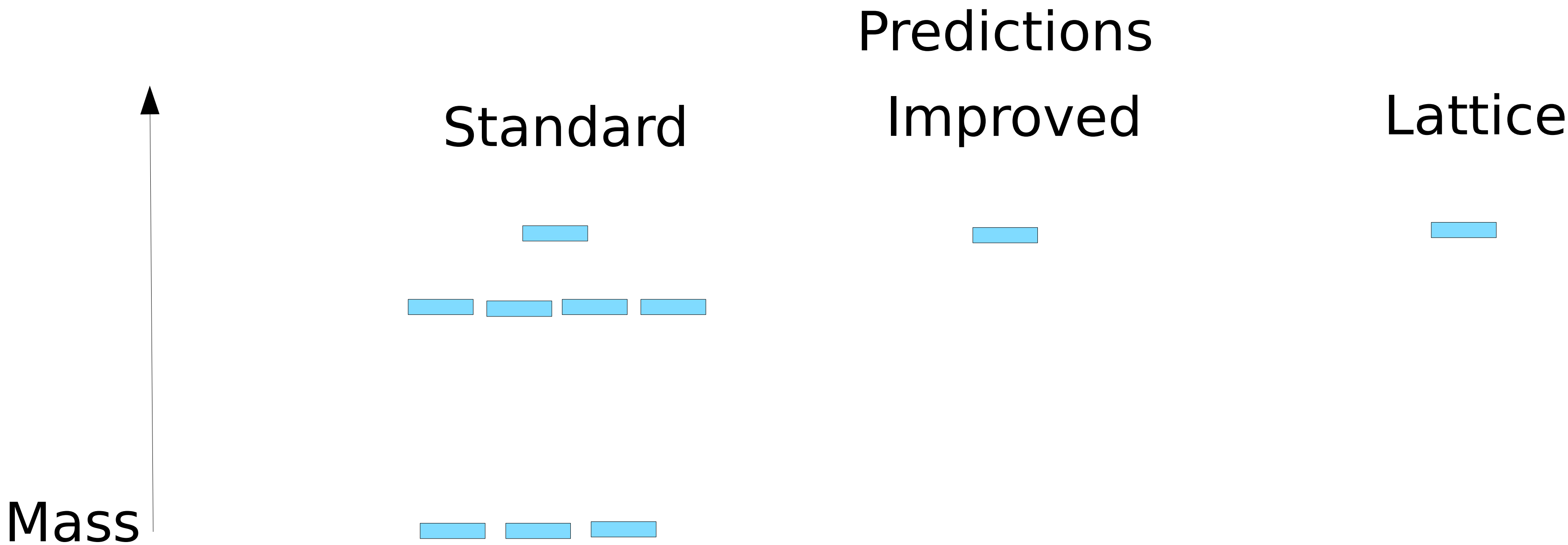
[Maas'15,
Maas & Törek'16]



- Toy example: SU(3)+fundamental Higgs
- Standard (perturbative) spectrum for the vectors
- Prediction from gauge-invariant perturbation theory
- Lattice results – favor non-standard results
- Generic pattern with a single Higgs

Grand-unified theories

[Maas'15, Maas & Török'16]



- Toy example: SU(3)+fundamental Higgs
- Standard (perturbative) spectrum for the vectors
- Prediction from gauge-invariant perturbation theory
- Lattice results – favor non-standard results
- Generic pattern with a single Higgs
- General case under investigation

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]
- 2-Higgs-doublet models
  - Same gauge group, but larger custodial group
  - FMS works like in the standard model [Maas & Pedro'16]

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]
- 2-Higgs-doublet models
  - Same gauge group, but larger custodial group
  - FMS works like in the standard model [Maas & Pedro'16]
- Implications for Technicolor [Maas'15]
  - Gauge invariance must still be maintained
  - Lightest gauge-invariant state: Vectors?

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]
- 2-Higgs-doublet models
  - Same gauge group, but larger custodial group
  - FMS works like in the standard model [Maas & Pedro'16]
- Implications for Technicolor [Maas'15]
  - Gauge invariance must still be maintained
  - Lightest gauge-invariant state: Vectors?
- What about the rest of the standard model?

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]
- 2-Higgs-doublet models
  - Same gauge group, but larger custodial group
  - FMS works like in the standard model [Maas & Pedro'16]
- Implications for Technicolor [Maas'15]
  - Gauge invariance must still be maintained
  - Lightest gauge-invariant state: Vectors?
- What about the rest of the standard model?
  - QED and QCD no problem

Implications

[Maas'15]

- Grand-unified theories
  - Gauge group larger than custodial group
  - Serious problems [Maas & Törek'16]
- 2-Higgs-doublet models
  - Same gauge group, but larger custodial group
  - FMS works like in the standard model [Maas & Pedro'16]
- Implications for Technicolor [Maas'15]
  - Gauge invariance must still be maintained
  - Lightest gauge-invariant state: Vectors?
- What about the rest of the standard model?
  - QED and QCD no problem – but flavor

Flavor of leptons

[Fröhlich et al.'80, Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)

Flavor of leptons

[Fröhlich et al.'80,
Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable

Flavor of leptons

[Fröhlich et al.'80, Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable
- Replaced by bound state – FMS applicable

$$\langle (h_{ia}^{+} f_a)(x)^{+} (h_{ib}^{+} f_b)(y) \rangle \overset{h=v+\eta}{\approx} \langle f_a^{+}(x) f_a(y) \rangle + O(\eta)$$

Flavor of leptons

[Fröhlich et al.'80,
Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable
- Replaced by bound state – FMS applicable

$$\left\langle \left(h_{ia}^{+} f_a\right)(x)^{+} \left(h_{ib}^{+} f_b\right)(y)\right\rangle \overset{h=v+\eta}{\approx} \left\langle f_a^{+}(x) f_a(y)\right\rangle + O(\eta)$$

- Gauge-invariant state, but custodial doublet

Flavor of leptons

[Fröhlich et al.'80,
Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable
- Replaced by bound state – FMS applicable

$$\langle (h_{ia}^{+} f_a)(x)^{+} (h_{ib}^{+} f_b)(y) \rangle \overset{h=v+\eta}{\approx} \langle f_a^{+}(x) f_a(y) \rangle + O(\eta)$$

- Gauge-invariant state, but custodial doublet
- Yukawa terms break custodial symmetry
  - Different masses for doublet members

Flavor of leptons

[Fröhlich et al.'80,
Egger, Maas, Sondenheimer'17]

- Flavor has two components
  - Global SU(3) generation
  - Local SU(2) weak gauge (up/down distinction)
- Same argument: Weak gauge not observable
- Replaced by bound state – FMS applicable

$$\langle (h_{ia}^{+} f_{a})(x)^{+} (h_{ib}^{+} f_{b})(y) \rangle \overset{h=v+\eta}{\approx} \langle f_{a}^{+}(x) f_{a}(y) \rangle + O(\eta)$$

- Gauge-invariant state, but custodial doublet
- Yukawa terms break custodial symmetry
  - Different masses for doublet members
- Possibly observable at CEPC/ILC

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
- Consider nucleon
- qqq open flavor, cannot be gauge invariant
  - Impossible to build a gauge-invariant 3-quark state

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
- Consider nucleon
- qqq open flavor, cannot be gauge invariant
  - Impossible to build a gauge-invariant 3-quark state
- Replacement: qqq**h**

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
- Consider nucleon
- qqq open flavor, cannot be gauge invariant
  - Impossible to build a gauge-invariant 3-quark state
- Replacement: qqq**h**
  - FMS mechanism as usual yields QCD

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
- Consider nucleon
- qqq open flavor, cannot be gauge invariant
  - Impossible to build a gauge-invariant 3-quark state
- Replacement: qqq**h**
  - FMS mechanism as usual yields QCD
  - Detectable at LHC? Large QCD background

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
- Consider nucleon
- qqq open flavor, cannot be gauge invariant
  - Impossible to build a gauge-invariant 3-quark state
- Replacement: qqq**h**
  - FMS mechanism as usual yields QCD
  - Detectable at LHC? Large QCD background! Unknown.

Summary

[Maas'12,'15
Törek & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open

Summary

[Maas'12,'15
Törek & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open
- Subtle interplay with the rest of the standard model
  - Additional mass from QCD detectable

Summary

[Maas'12,'15
Törek & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open
- Subtle interplay with the rest of the standard model
  - Additional mass from QCD detectable
- Ultraviolet properties may be richer than expected
  - Hard to measure

Summary

[Maas'12,'15
Törek & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open
- Subtle interplay with the rest of the standard model
  - Additional mass from QCD detectable
- Ultraviolet properties may be richer than expected
  - Hard to measure
- Formal aspects have interesting implications
  - Standard model very special
    - ...but perhaps still measurable impact

Summary

[Maas'12,'15
Törek & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open
- Subtle interplay with the rest of the standard model
  - Additional mass from QCD detectable
- Ultraviolet properties may be richer than expected
  - Hard to measure
- Formal aspects have interesting implications
  - Standard model very special
    - ...but perhaps still measurable impact
  - BSM model building may be affected

Summary

[Maas'12,'15
Török & Maas'16
Egger, Maas, Sondenheimer'17]

- BEH theory is still wide open
- Subtle interplay with the rest of the standard model
  - Additional mass from QCD detectable
- Ultraviolet properties may be richer than expected
  - Hard to measure
- Formal aspects have interesting implications
  - Standard model very special
    - ...but perhaps still measurable impact
  - BSM model building may be affected
- BEH physics needs rethinking