Electroweak Sudakov Logarithms

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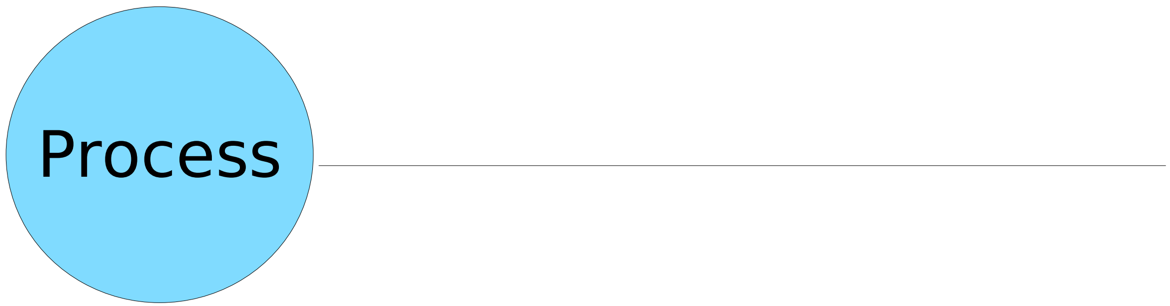
2nd of July 2024
Parton Showers and Resummation
Graz
Austria

UNI GRAZ
NAWI Graz Natural Sciences
FWF Österreichischer Wissenschaftsfonds

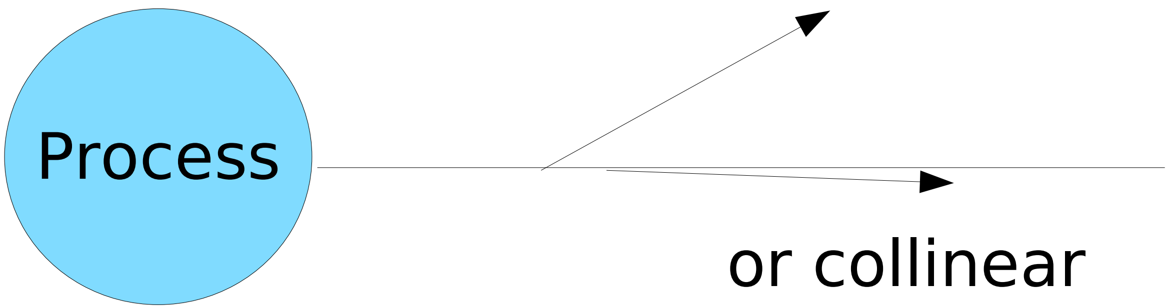
The issue in gauge theories



Incoming or outgoing gauged particle

The issue in gauge theories

Can emit soft



Incoming or outgoing gauged particle

or collinear radiation, especially massless gauge bosons

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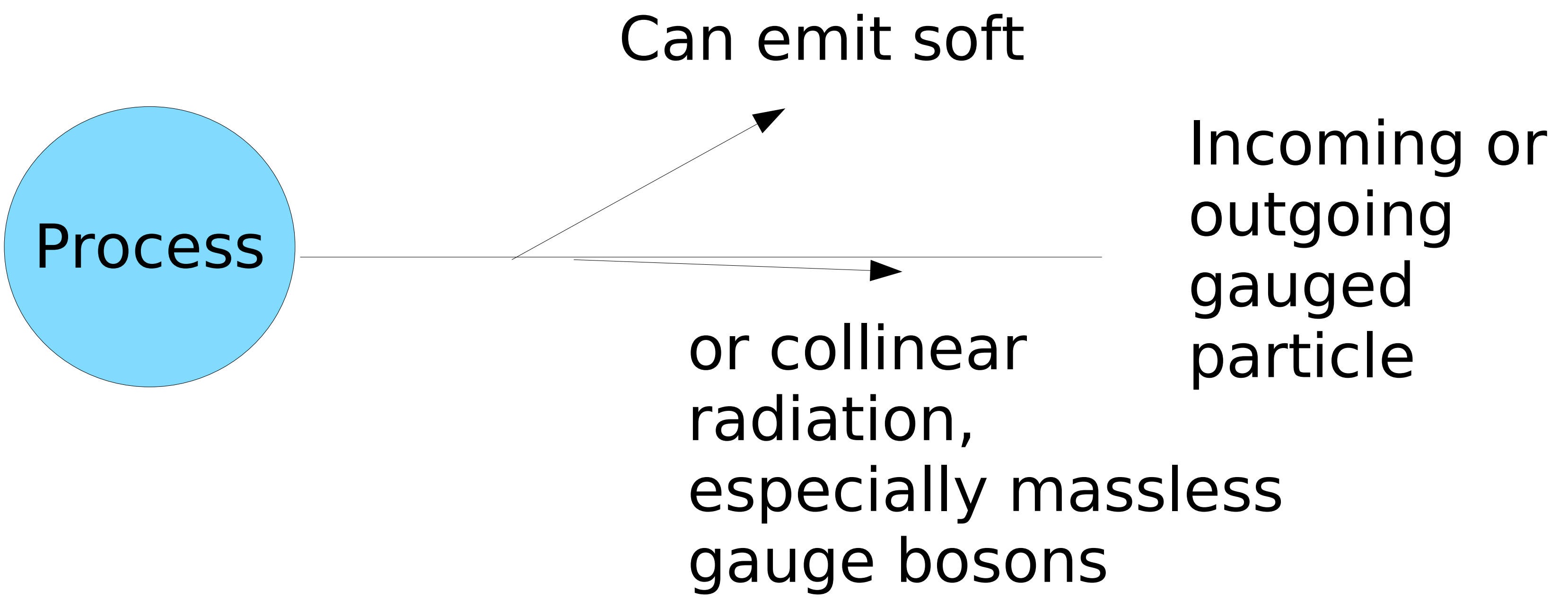
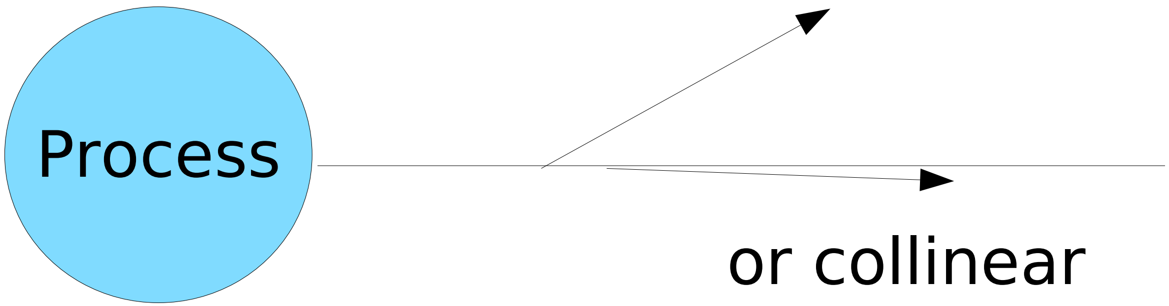


- Resummation yields (double) Sudakov logarithms: $\ln^2 \frac{s}{\Lambda}$
- Can dominate the cross sections
- Quick rise can obstruct convergence

Resolution in gauge theories

Can emit soft



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- Involved particle is a gauge singlet

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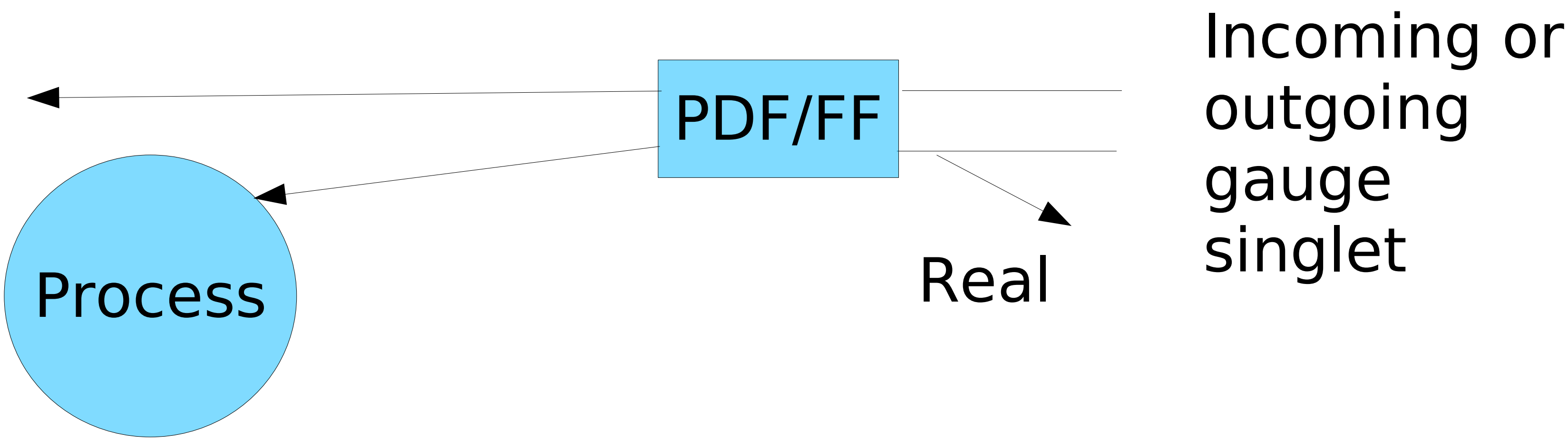

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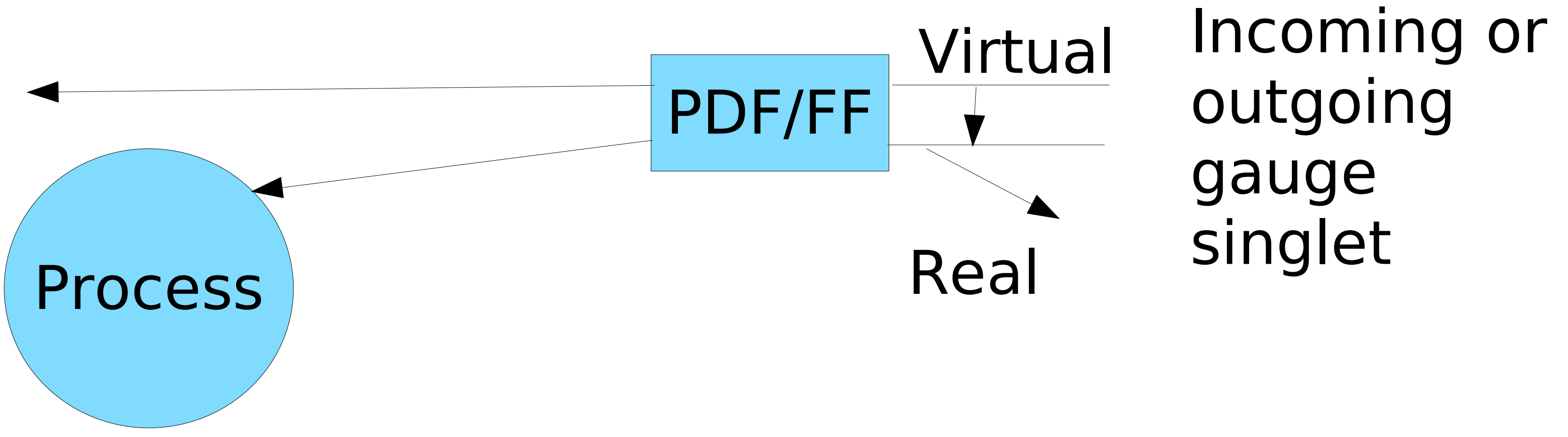

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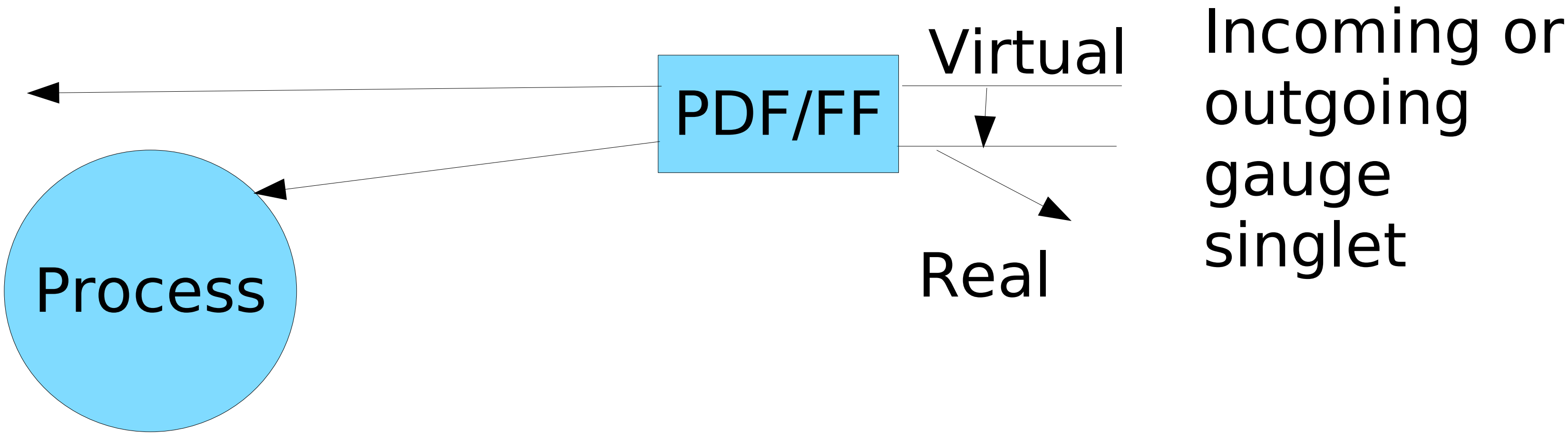

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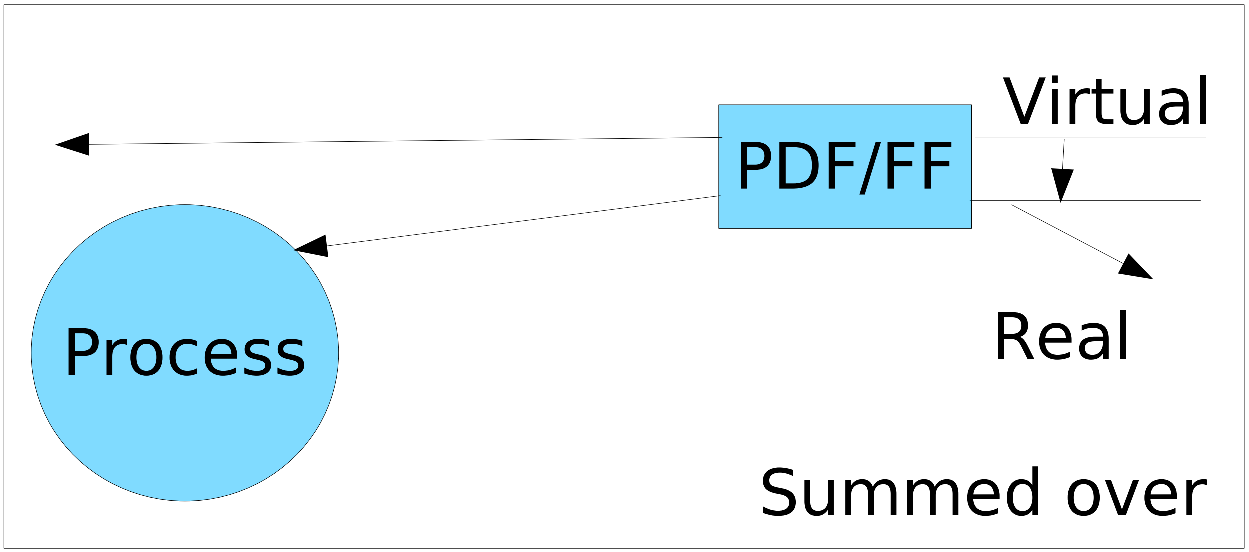

Incoming or outgoing gauge singlet

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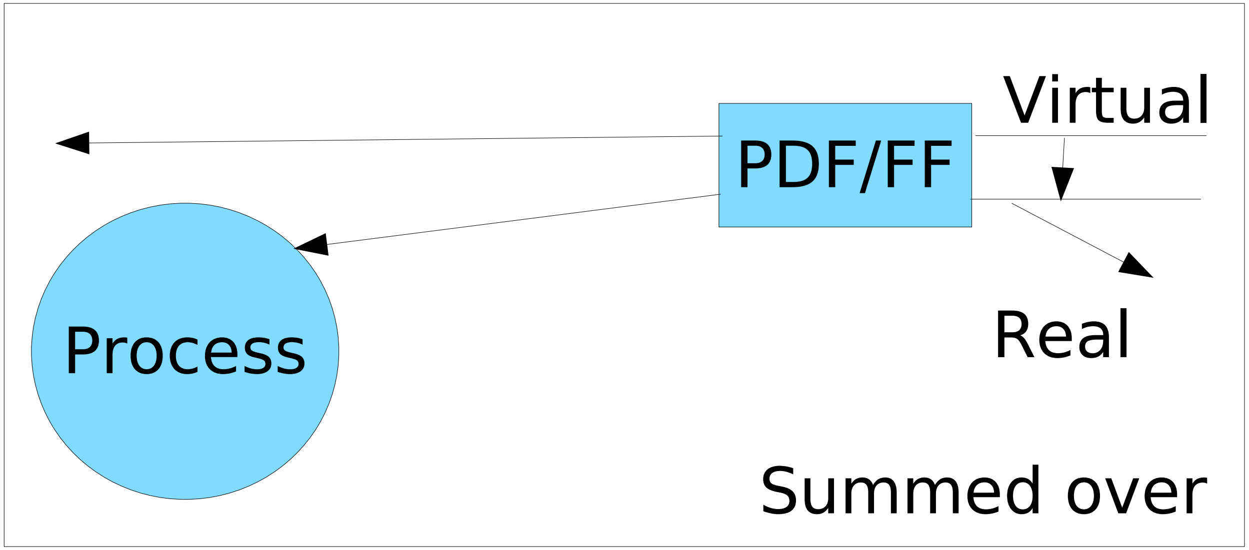
  - Cancellations between real and virtual corrections
  - Cancel Sudakov logarithms
- Initial state: Bloch-Nordsieck theorem/Initial state and final state: Kinoshita-Lee-Naunberg theorem
  - Required: Inclusive in the gauge charge

Invalidation in electroweak physics

[Ciafaloni et al.'00,'22
Bauer et al.'18]



Incoming or outgoing gauge singlet

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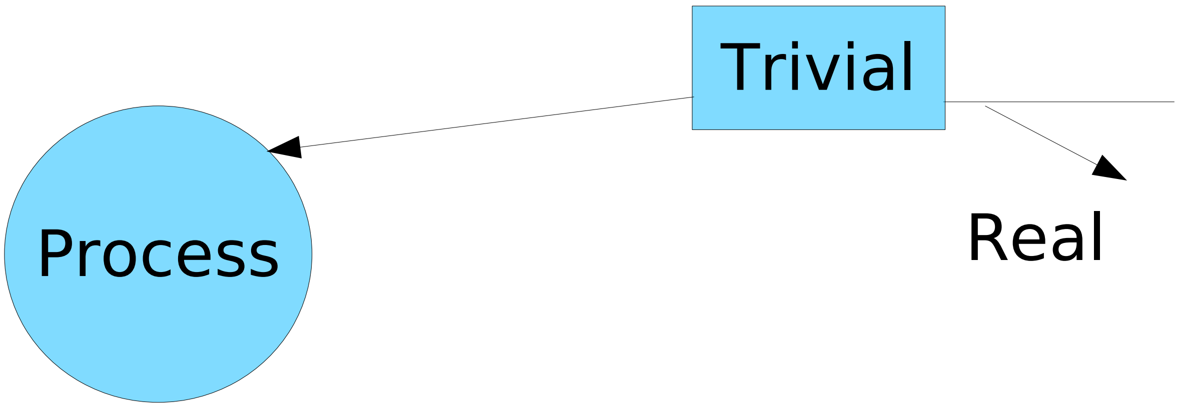

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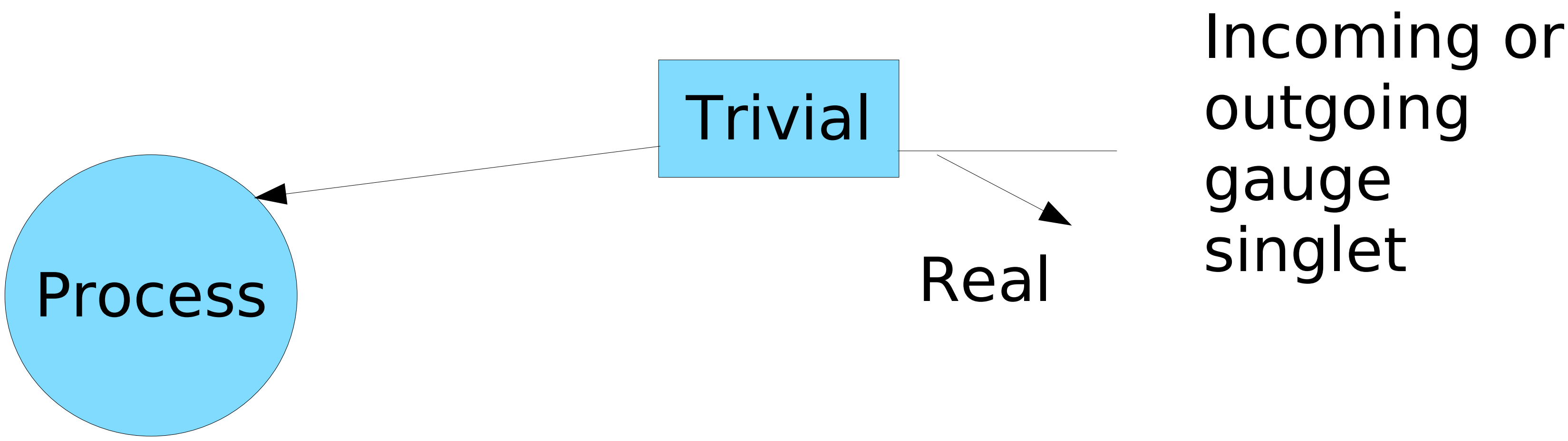

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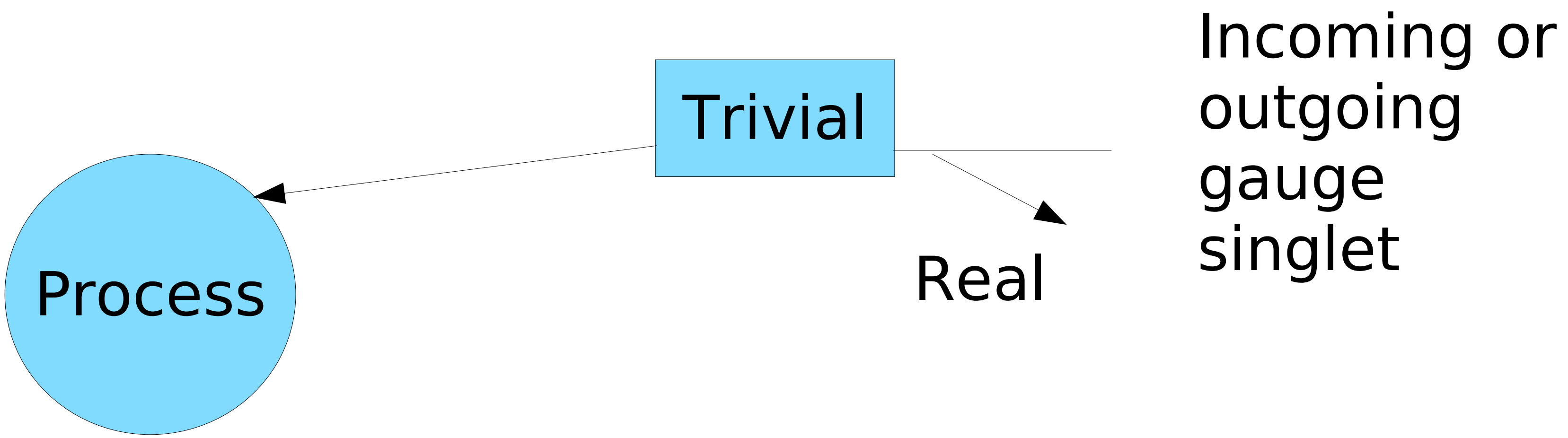

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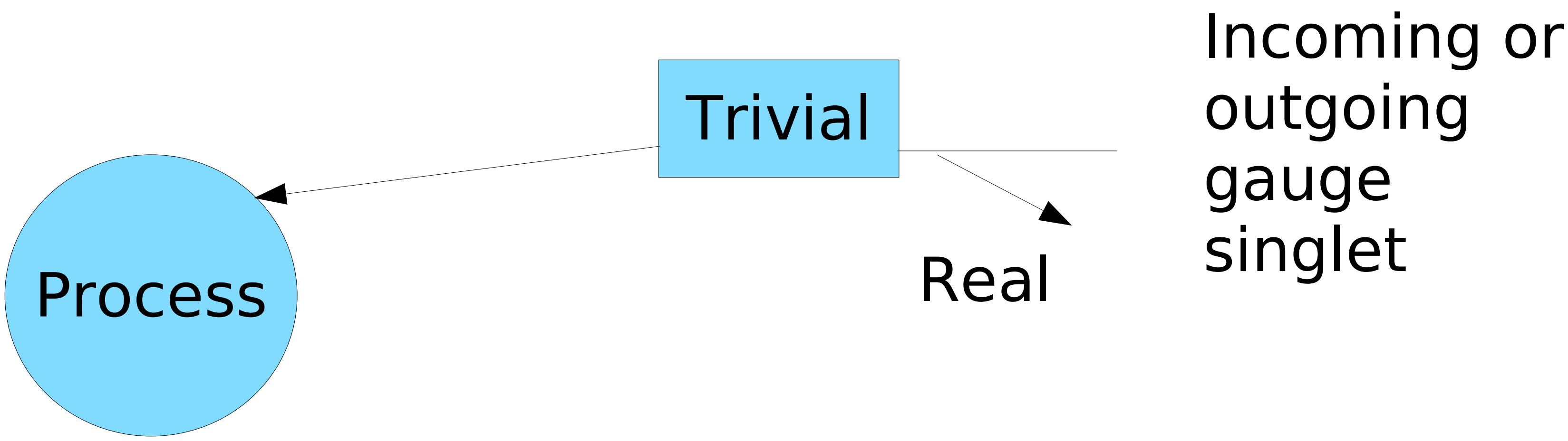

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- Double Sudakov logarithms suppressed: $\ln^2 \frac{s}{m_W^2}$
- Negligble at small energies
- At LC@TeV: Same order as strong interactions
  - Swamped by jets of vector bosons and Higgs

Is this inevitable?

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  - Because of breaking the gauge symmetry

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  - But there is no physical gauge-symmetry breaking [Elitzur’75, Osterwalder & Seiler’77, Fradkin & Shenker’78]
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    - Just a figure of speech
    - Actually just ordinary gauge-fixing

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[Review: 1712.04721 Update: 2305.01960]

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- But it is well established?
  - Actually, a coincidence of the standard model
  - Subleading effects save the day

[Review: 1712.04721 Update: 2305.01960]

A toy model

A toy model: Higgs sector of the SM

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

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- Ws W^{a}_{μ} 

- Coupling g and some numbers f^{abc}

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- Ws W_{μ}^{a}
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- Couplings g, v, λ and some numbers f^{abc} and t_{a}^{ij}
- Parameters selected for a BEH effect

A toy model: Symmetries

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- Local SU(2) gauge symmetry

$$W_{\mu}^{a} \rightarrow W_{\mu}^{a} + \left(\delta_{b}^{a} \partial_{\mu} - g f_{bc}^{a} W_{\mu}^{c} \right) \phi^{b}$$

$$h_{i} \rightarrow h_{i} + g t_{a}^{ij} \phi^{a} h_{j}$$

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

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a} \qquad h\rightarrow h\Omega$$

Textbook approach

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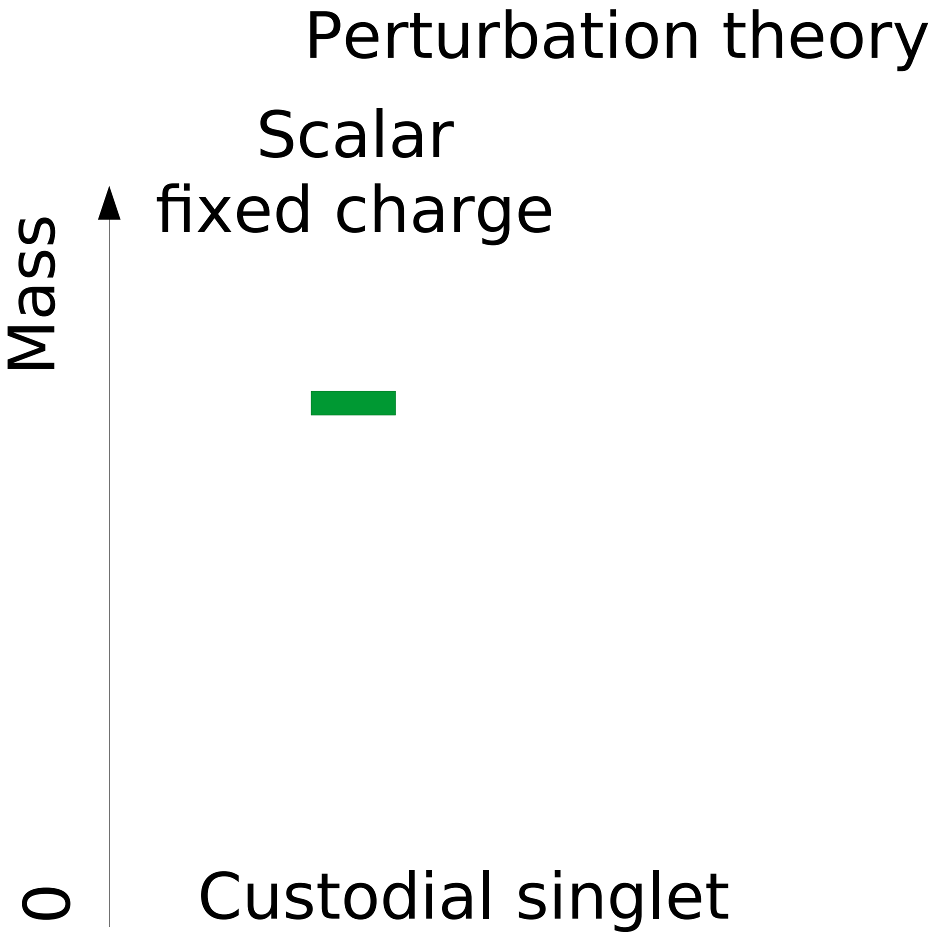
- Get masses and degeneracies at tree-level
- Perform perturbation theory

Physical spectrum

Perturbation theory

Physical spectrum



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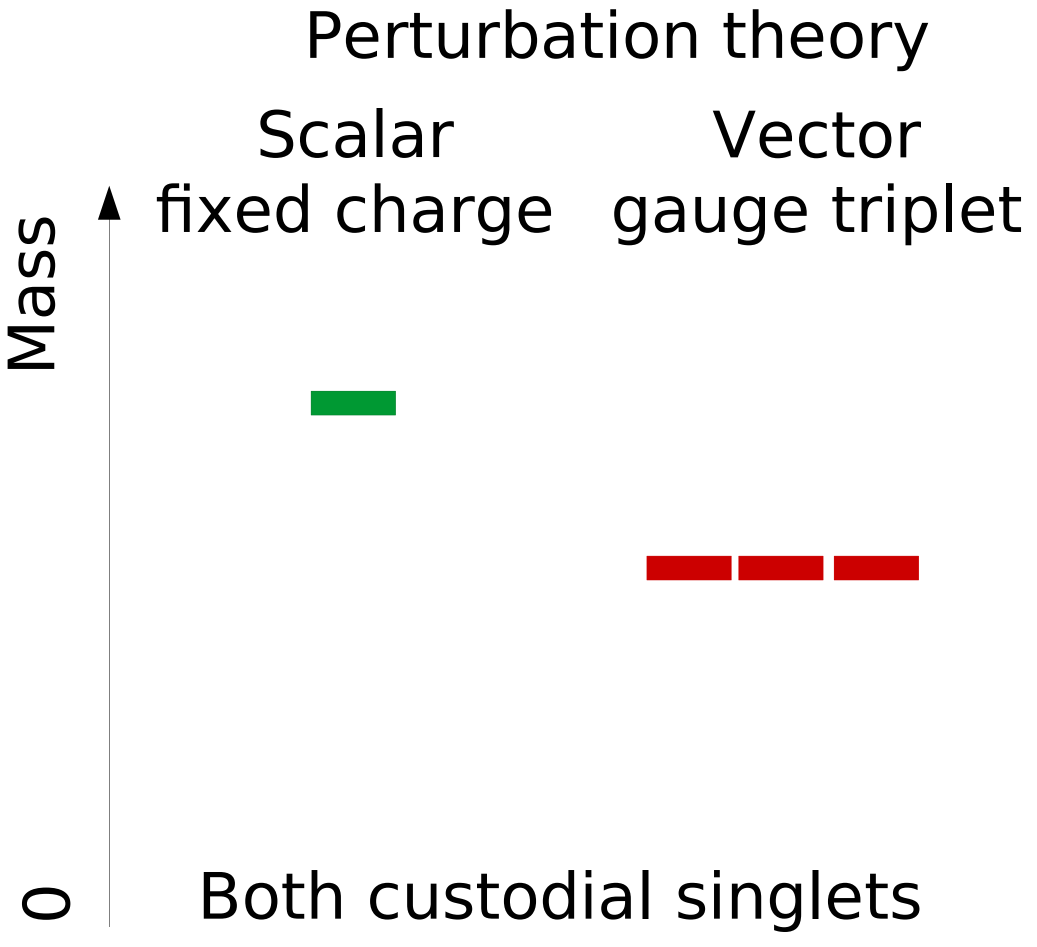

Physical states

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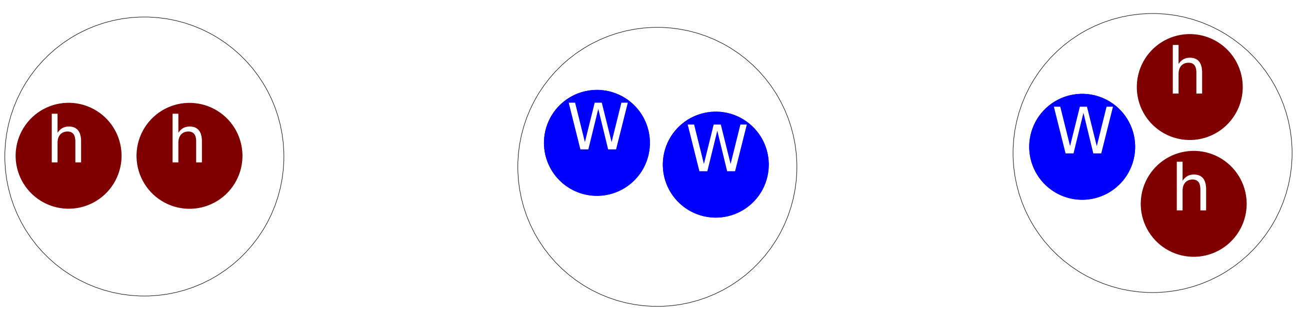
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



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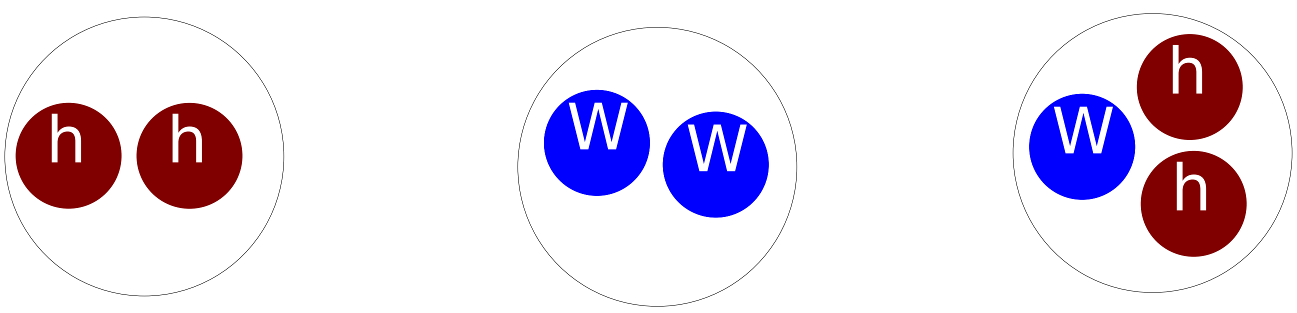
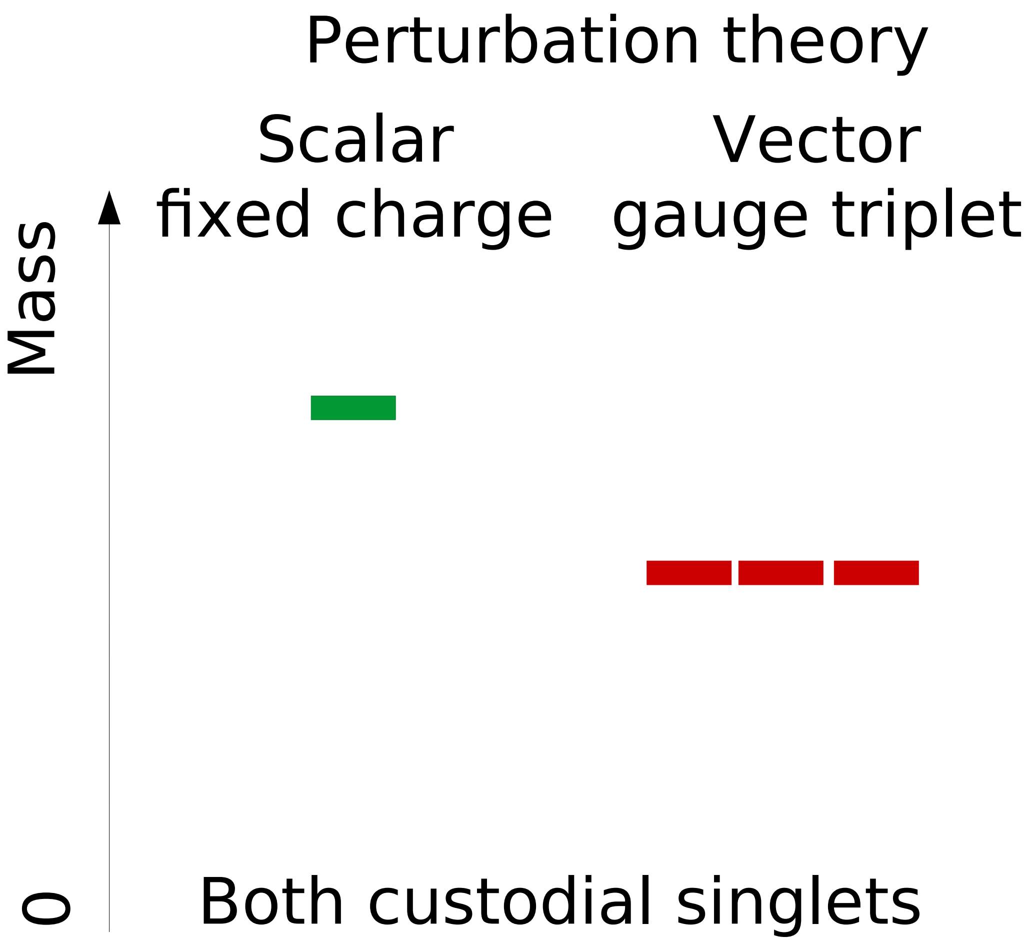


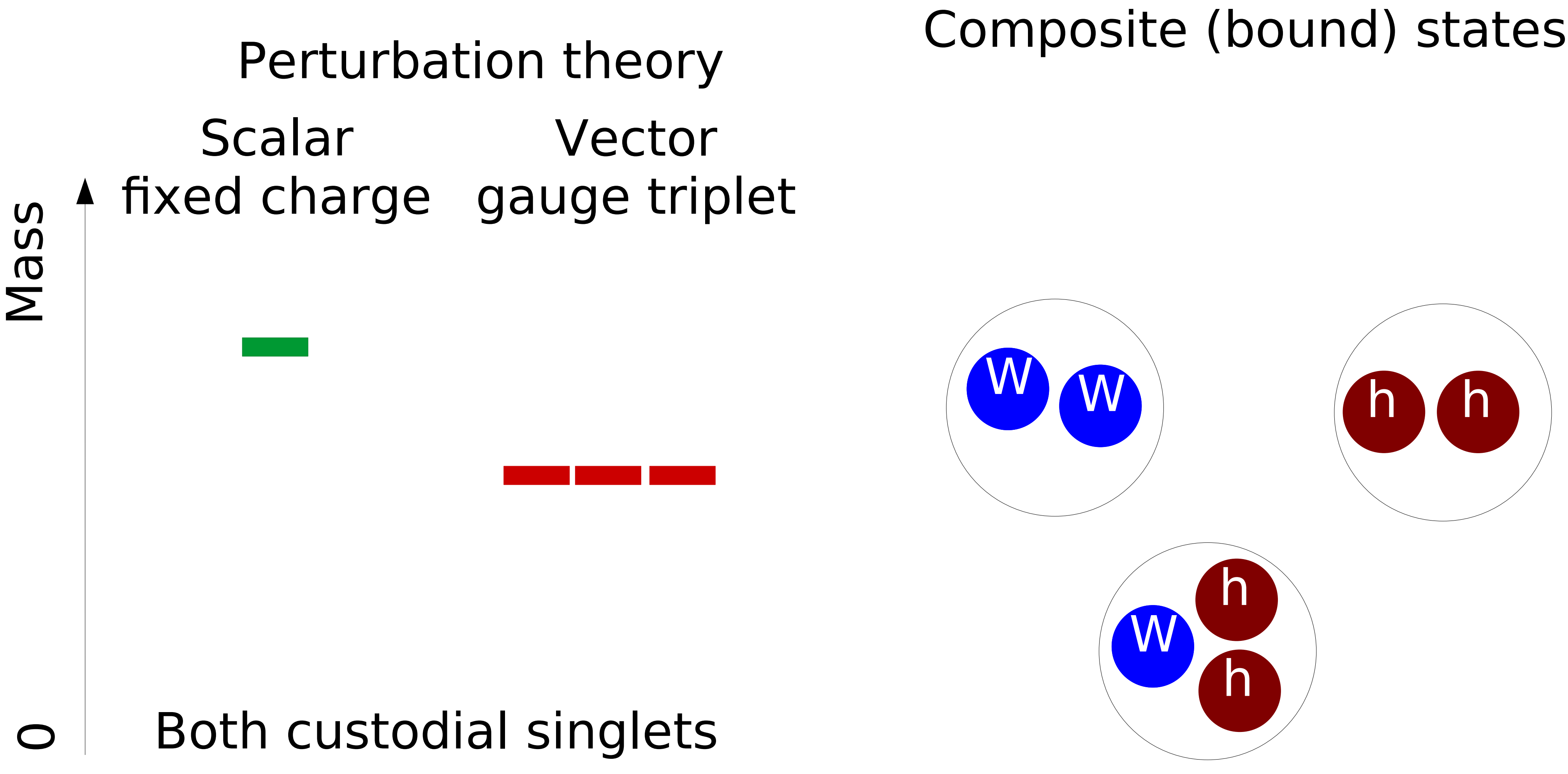
- Has nothing to do with weak coupling
  - Think QED (hydrogen atom!)

Physical spectrum



Remember: Experiment tells that somehow the left is correct!

Physical spectrum



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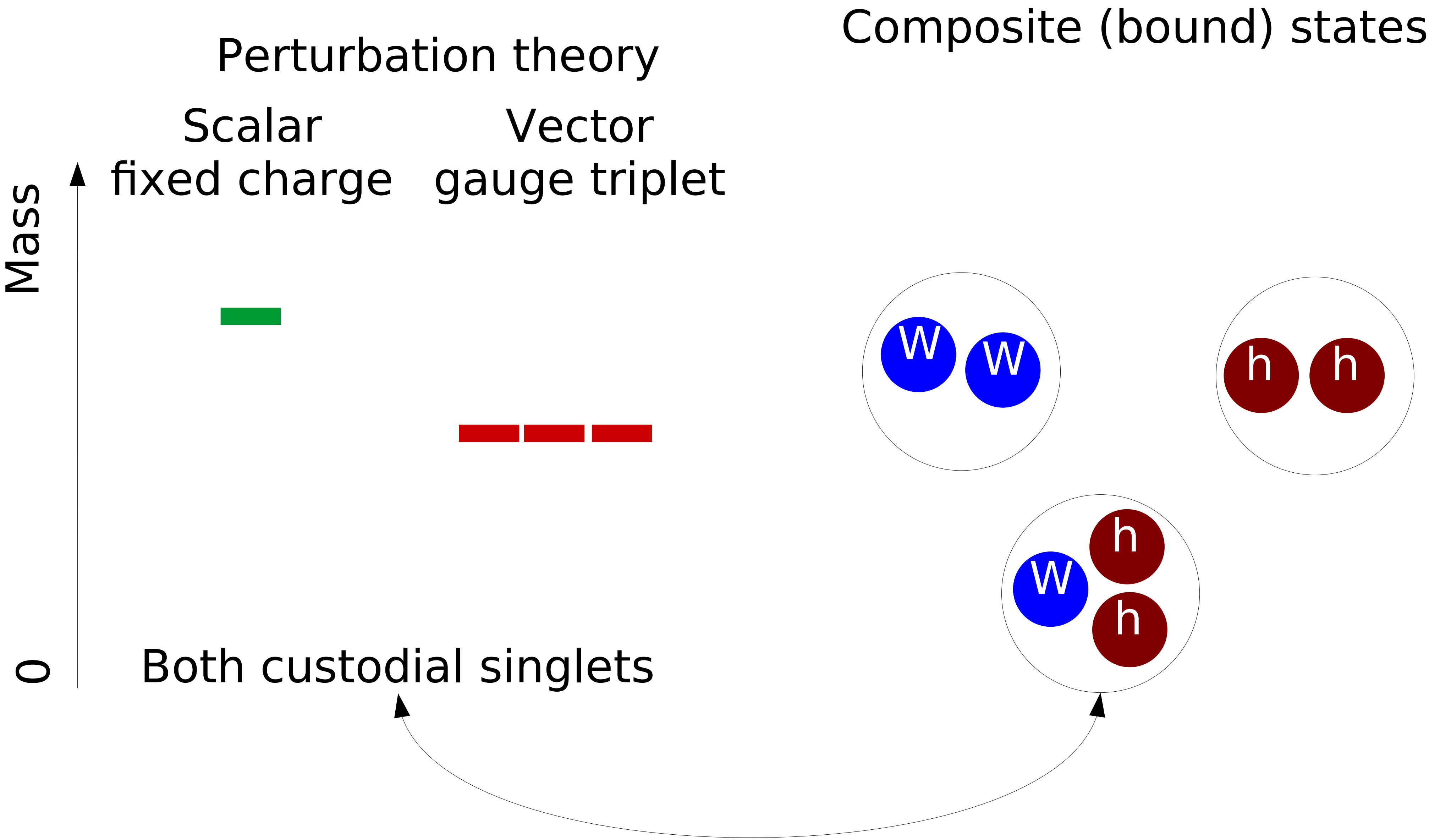

Experiment tells that somehow the left is correct
Theory say the right is correct
There must exist a relation that both are correct

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[Fröhlich et al.'80,'81,
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    - Standard lattice spectroscopy problem
    - Standard methods
      - Smearing, variational analysis, systematic error analysis etc.
    - Very large statistics (>10^5 configurations)

Physical spectrum

[Maas'12, Maas & Mufti'14]

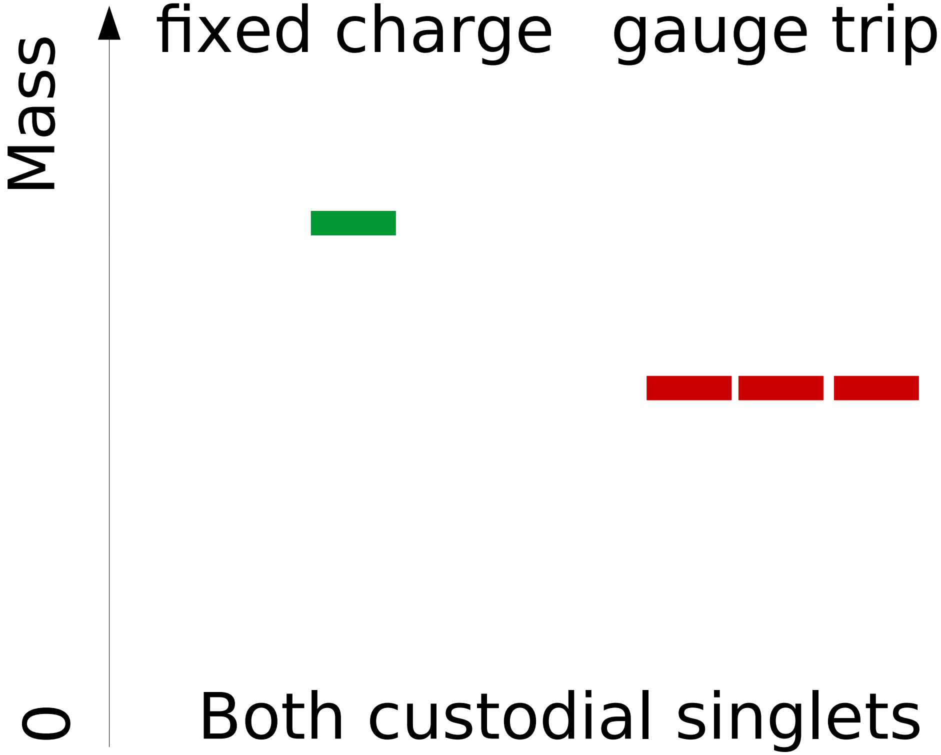
Perturbation theory

Gauge-invariant

Scalar
fixed charge

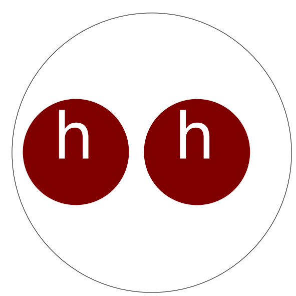
Vector
gauge triplet

Scalar
singlet



Both custodial singlets

$$h(x)^{+}\,h(x)$$



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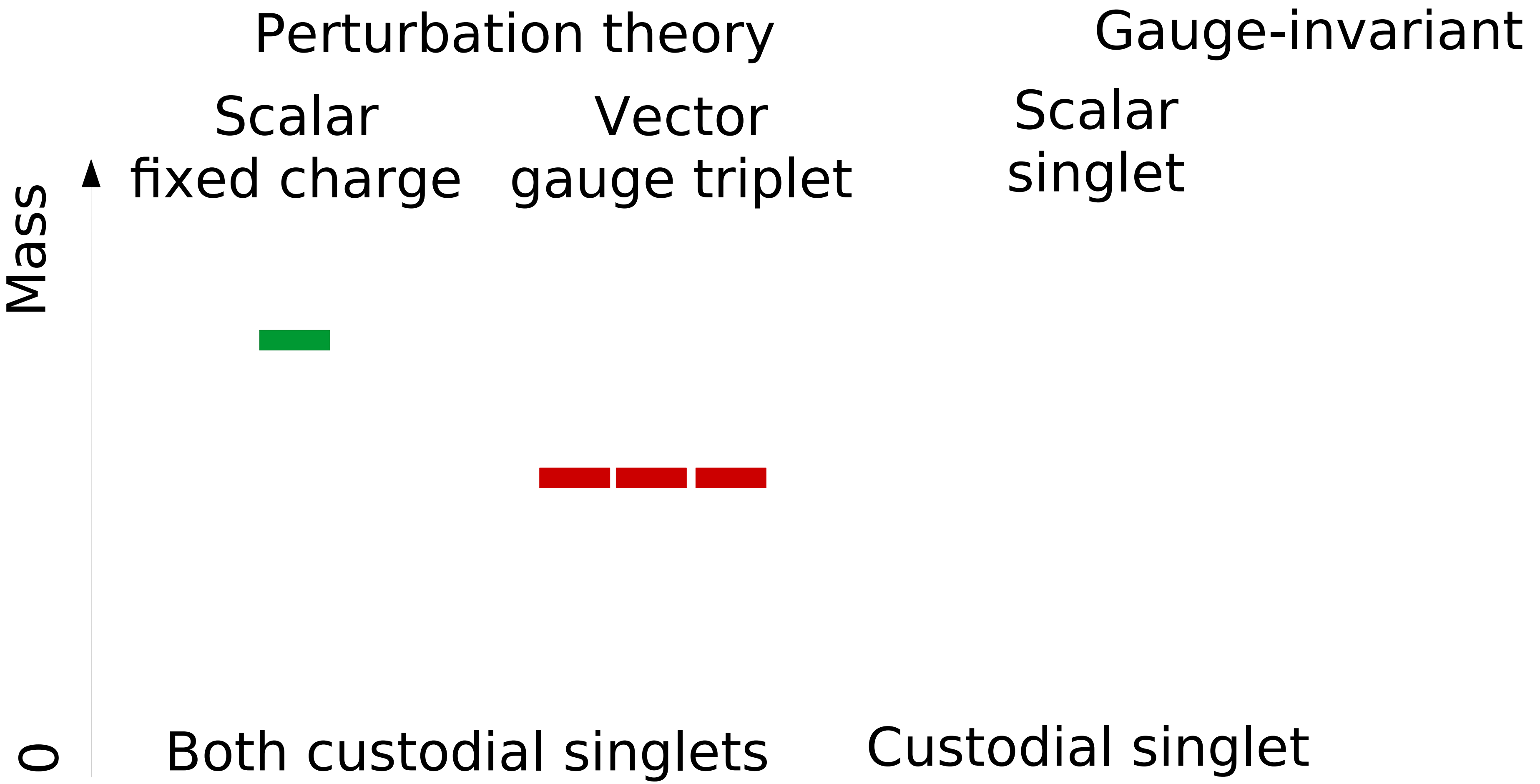

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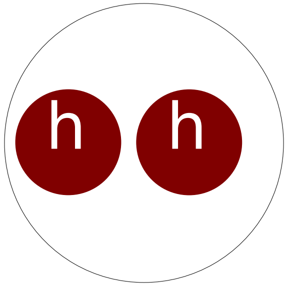

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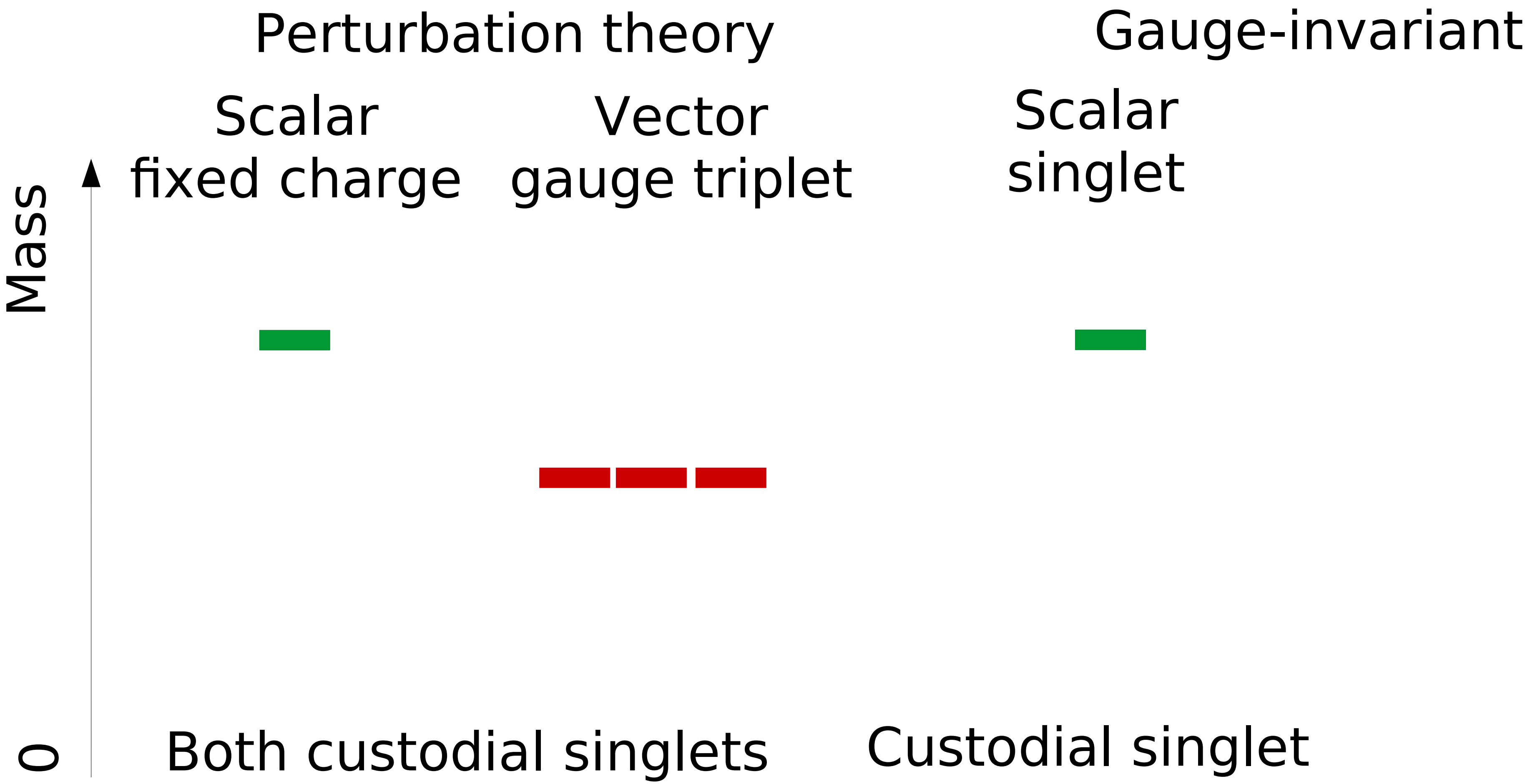

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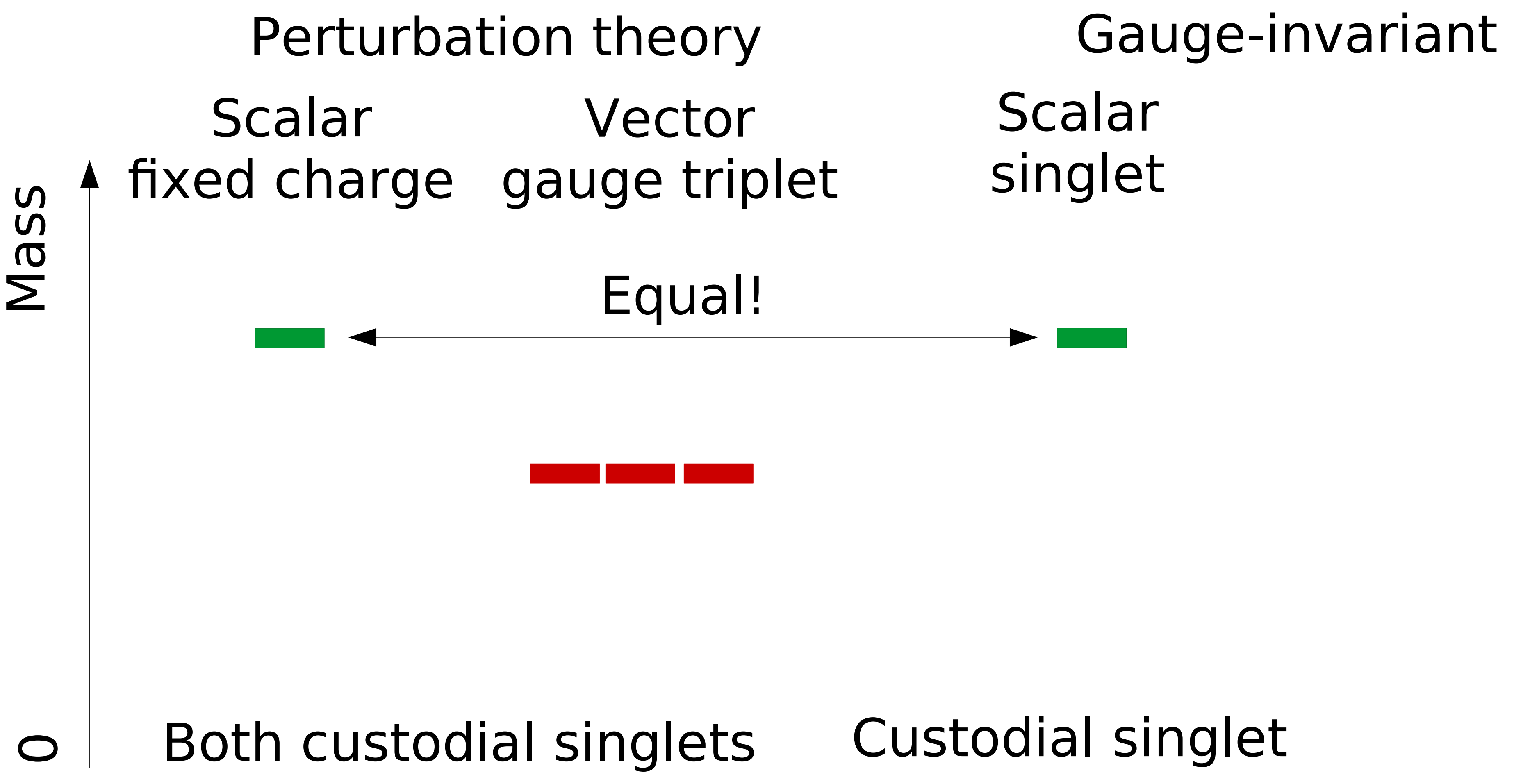

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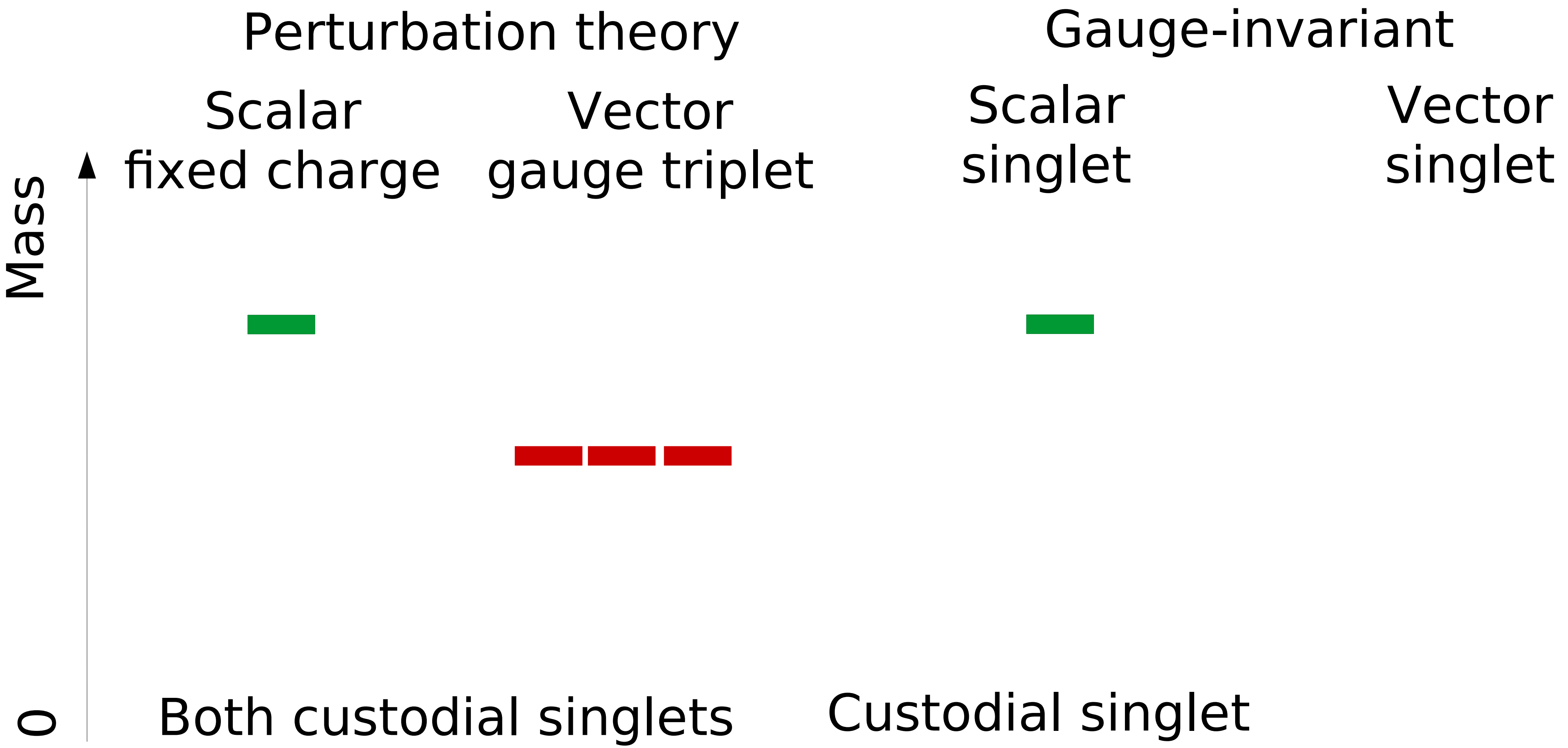
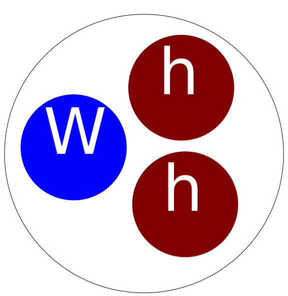


$$tr\, t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$$



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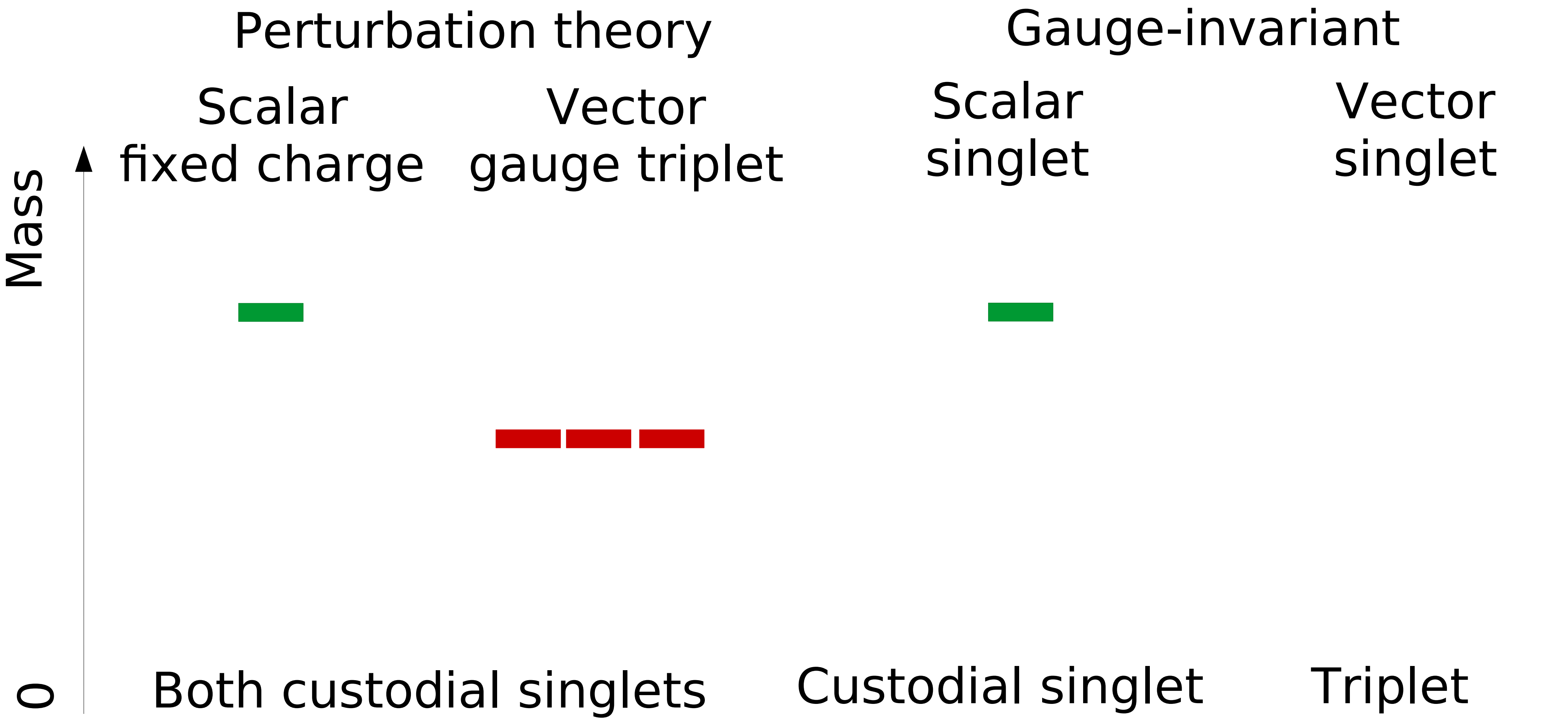

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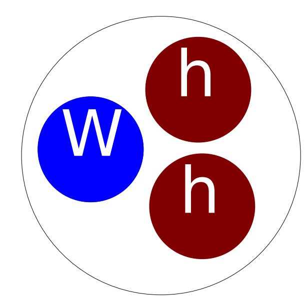

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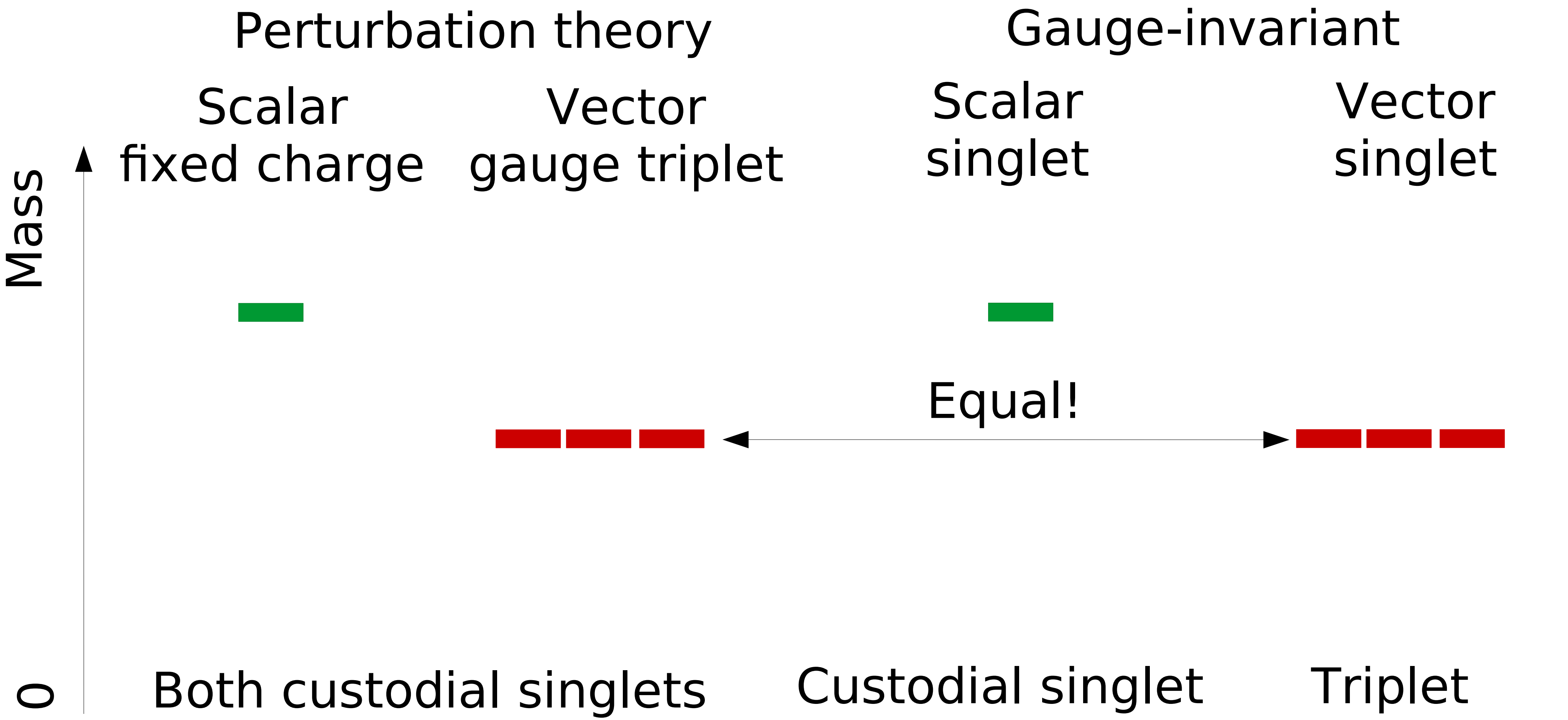

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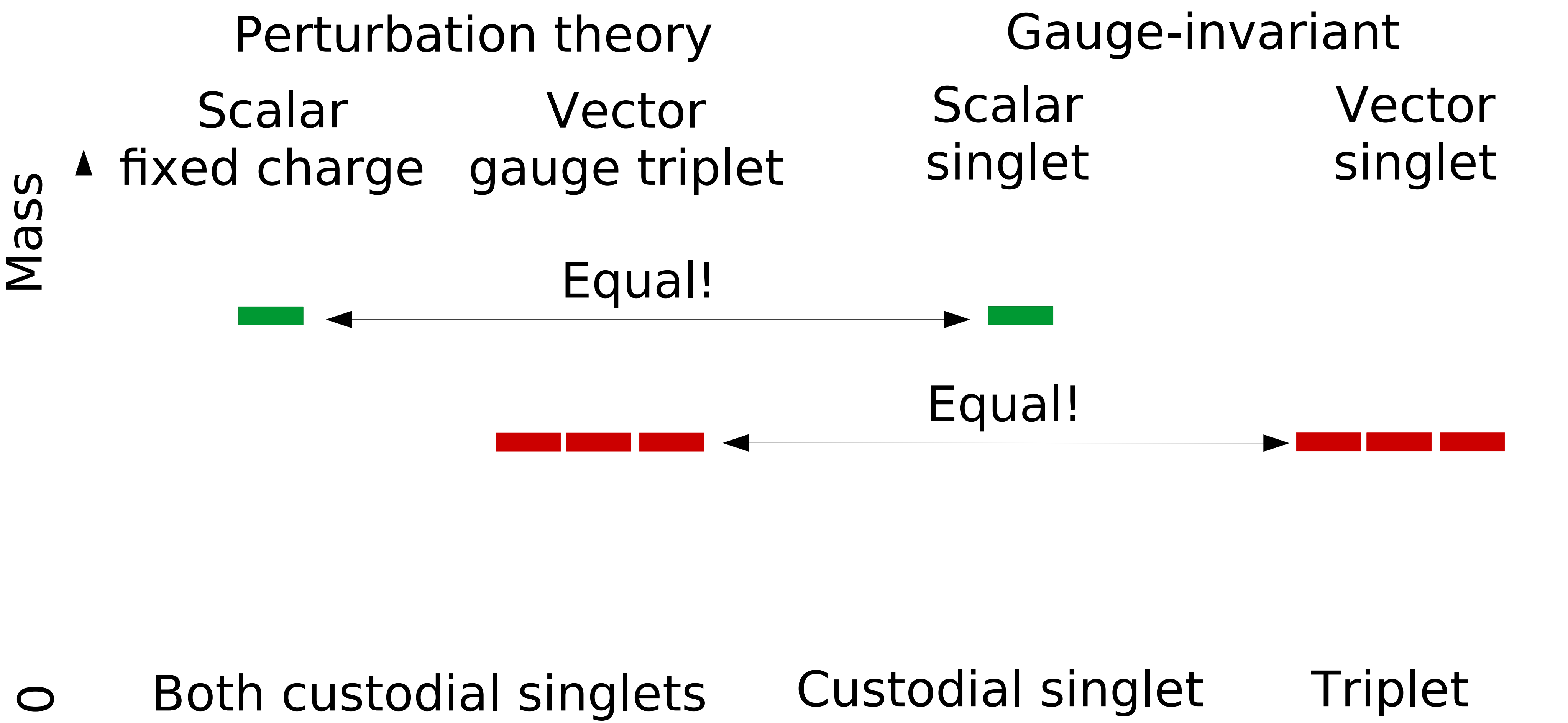

Why?

How to make predictions

[Fröhlich et al.'80,'81,
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Maas & Törek'16,’18,
Maas, Sondenheimer & Törek'17
Maas & Sondenheimer ‘20]

- J^{PC} and custodial charge only quantum numbers
  - Different from perturbation theory
    - Operators limited to asymptotic, elementary, gauge-dependent states
- Formulate gauge-invariant, composite operators
  - Bound state structure – non-perturbative methods?
  - But coupling is still weak and there is a BEH

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    - But coupling is still weak and there is a BEH
    - Perform double expansion [Fröhlich et al.'80, Maas’12]
        - Vacuum expectation value (FMS mechanism)
        - Standard expansion in couplings
        - Together: Augmented perturbation theory

Augmented perturbation theory

[Fröhlich et al.’80,’81
Maas'12,’17]

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Higgs field

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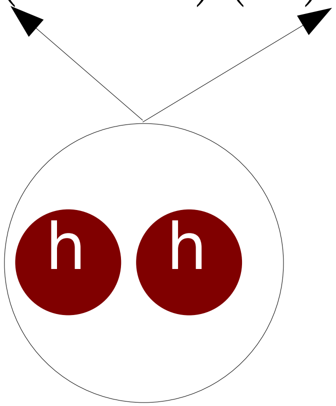

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Trivial two-particle state

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Bound state mass → $\langle (h^+ h)(x)(h^+ h)(y)\rangle$ $= v^2$ $\langle \eta^+(x)\eta(y)\rangle$ ← Higgs mass

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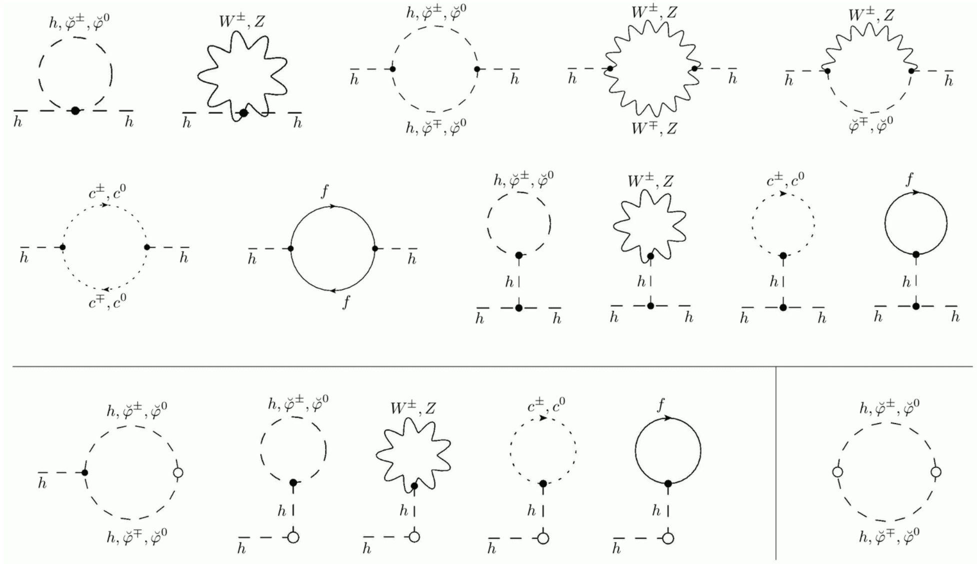

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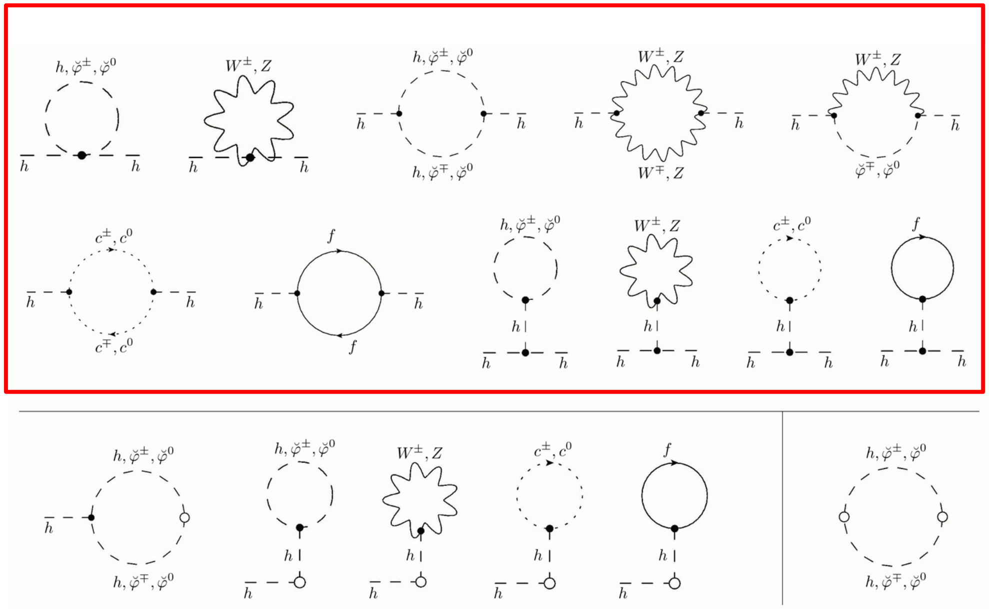

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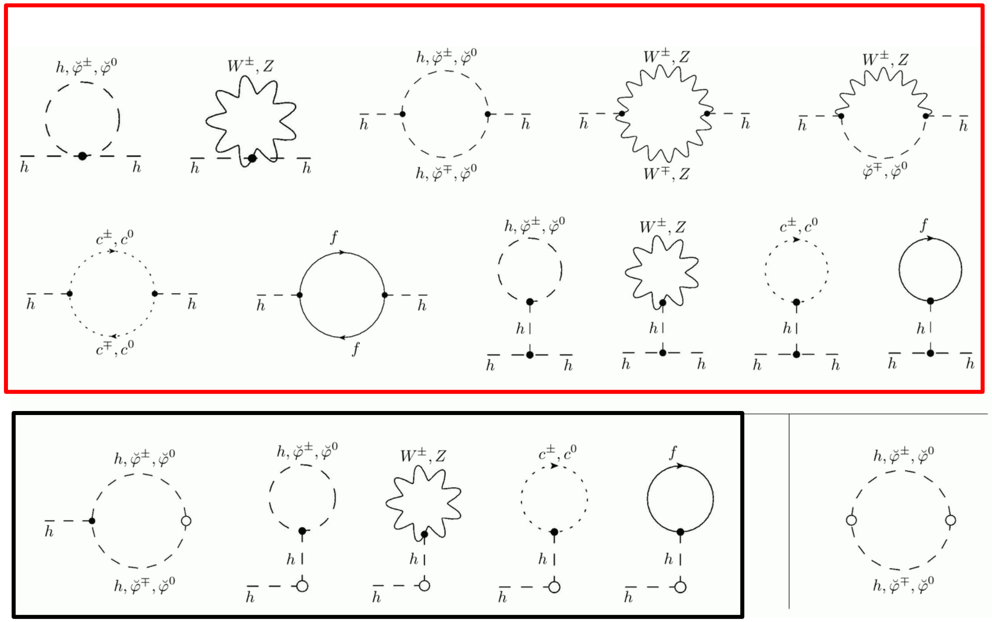

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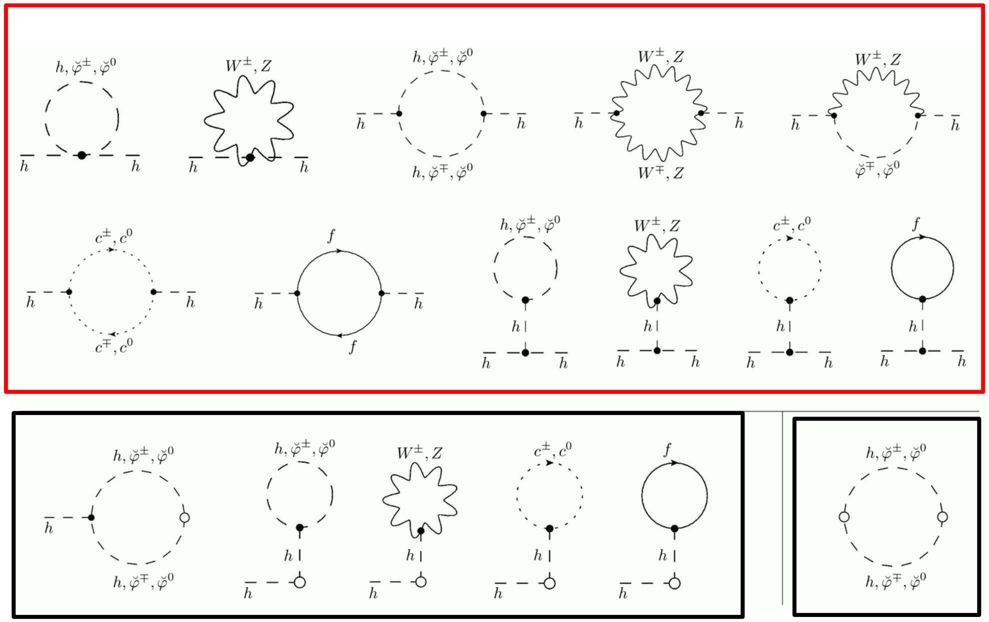

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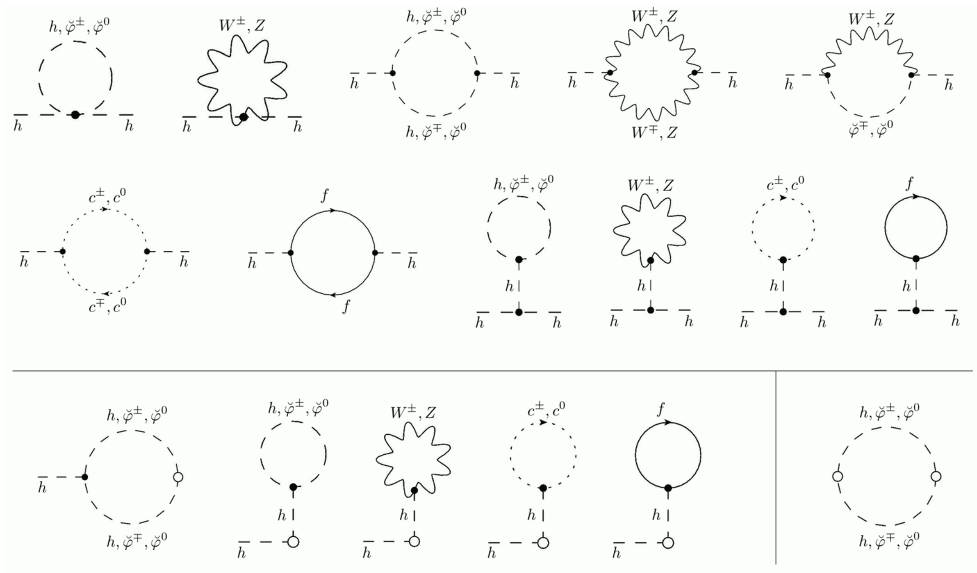

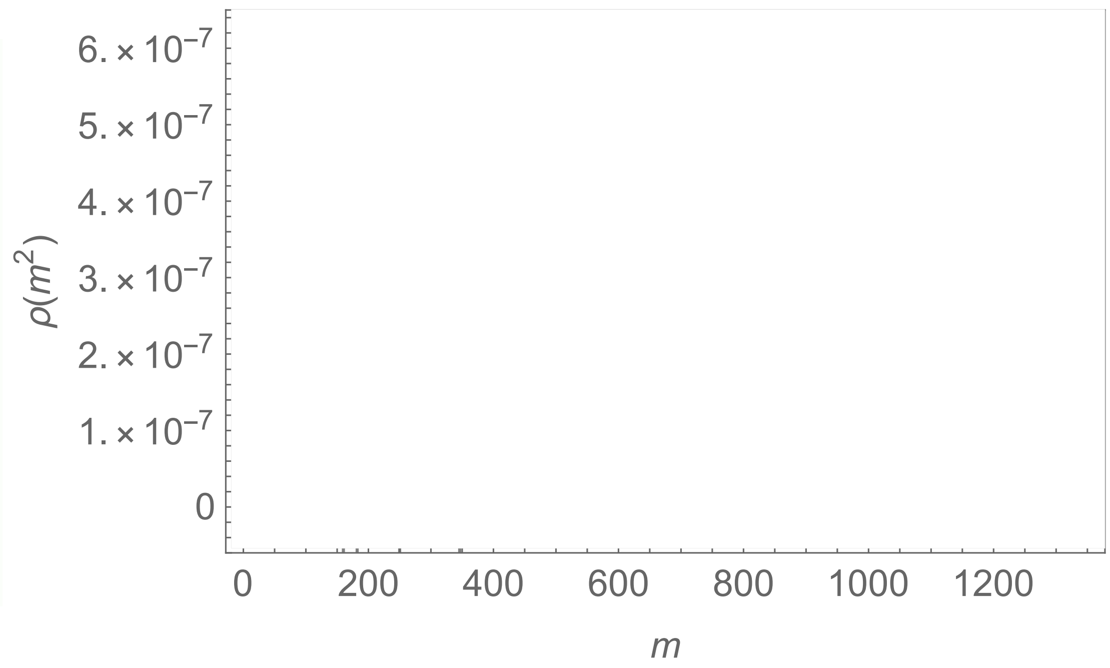

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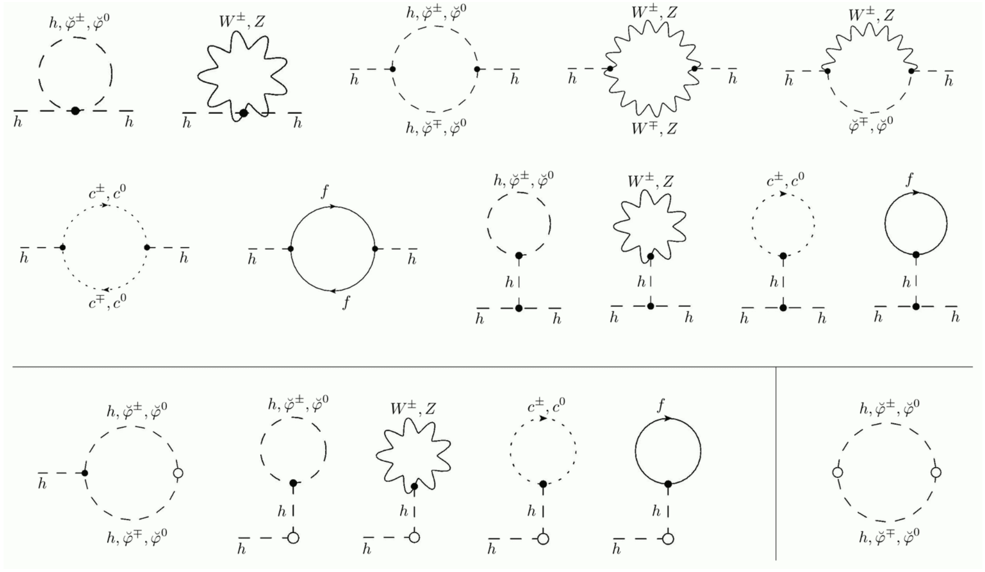

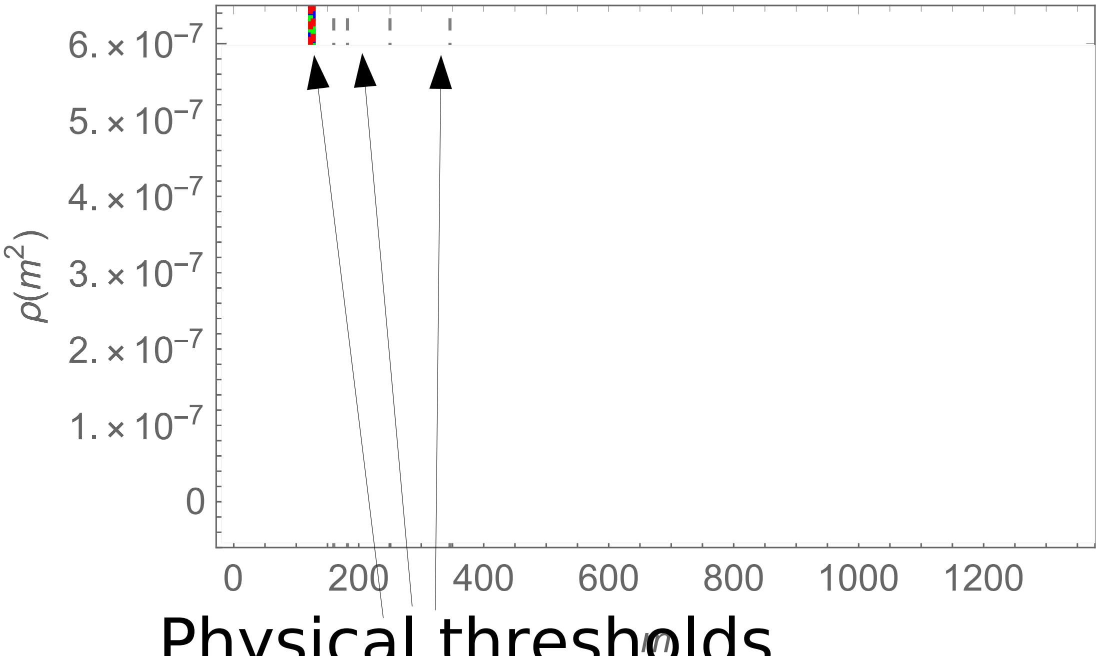

Physical thresholds

Consequences: The Higgs

[Maas'12,'17
Maas & Sondenheimer'20
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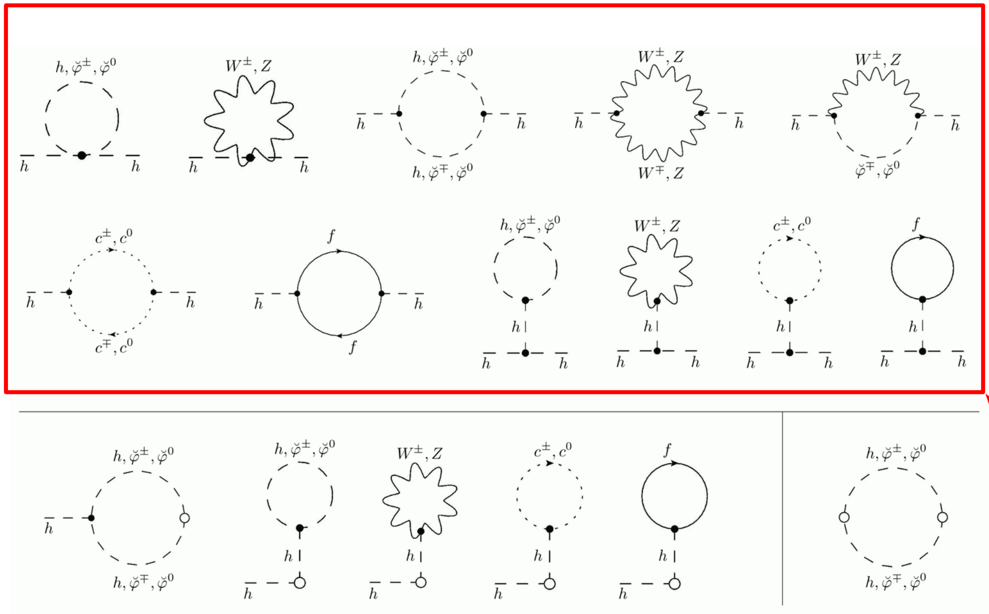

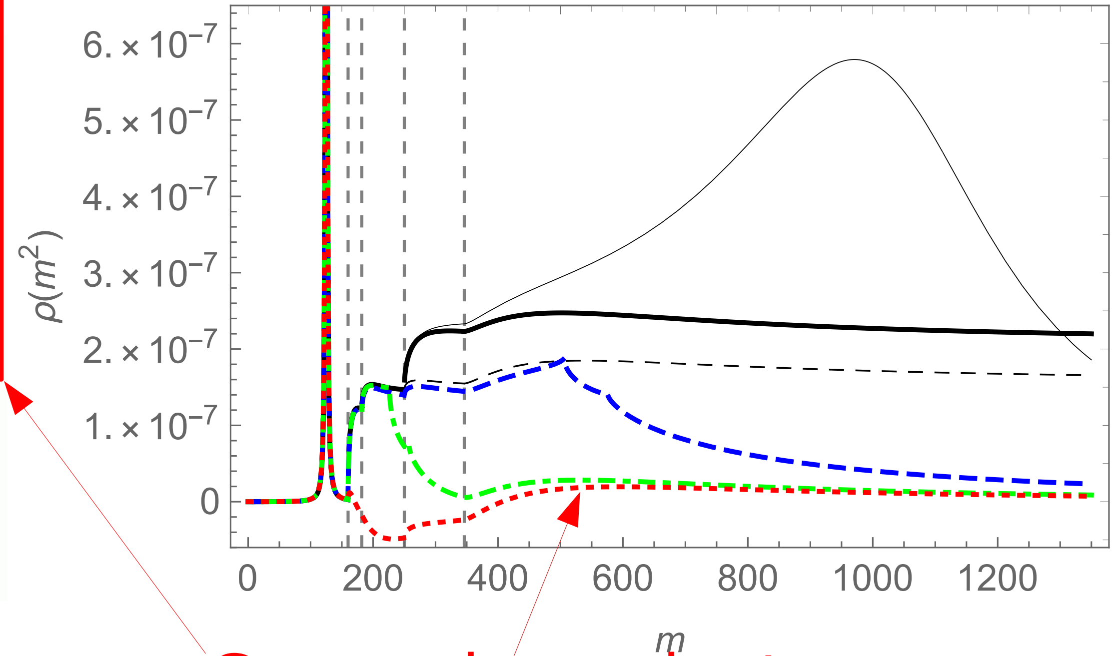

Gauge-dependent

Consequences: The Higgs

[Maas'12,'17
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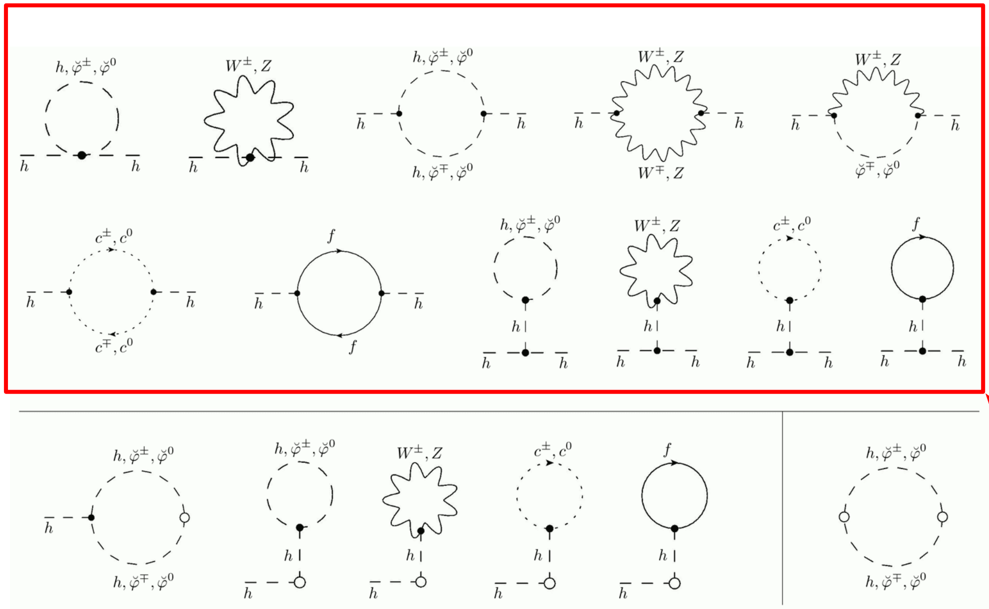

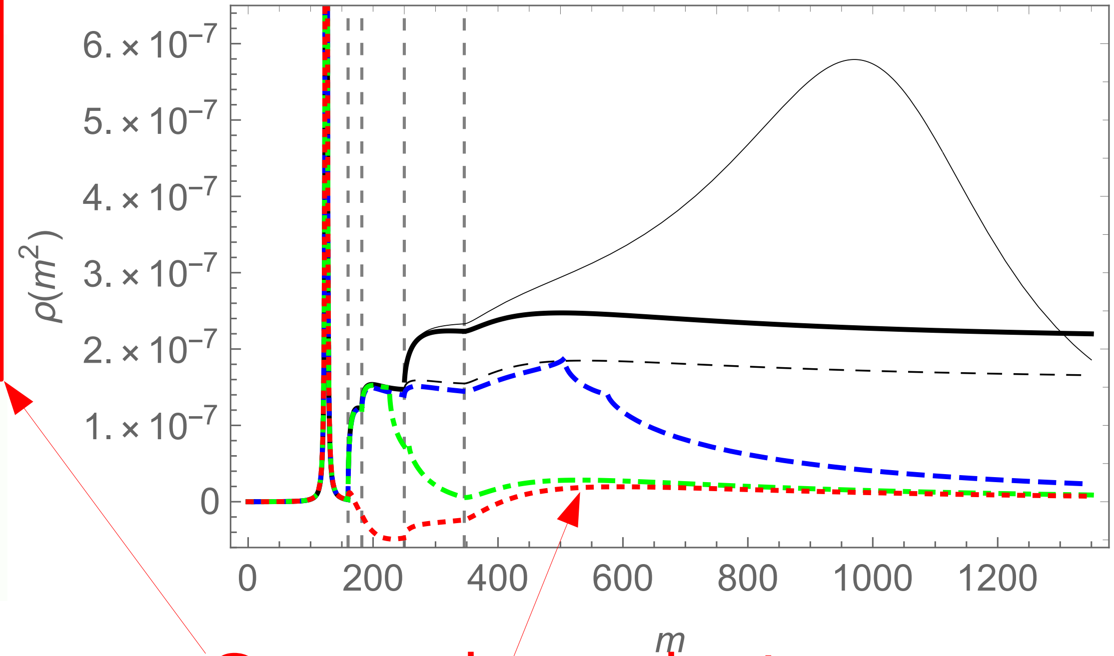

Gauge-dependent

Unphysical features:

Positivity violation

Additional thresholds

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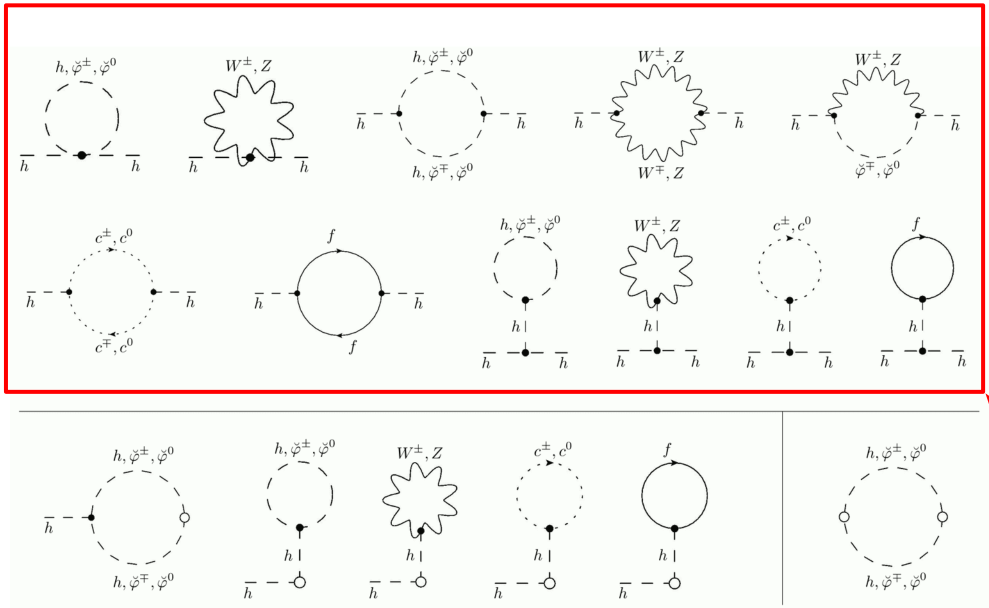

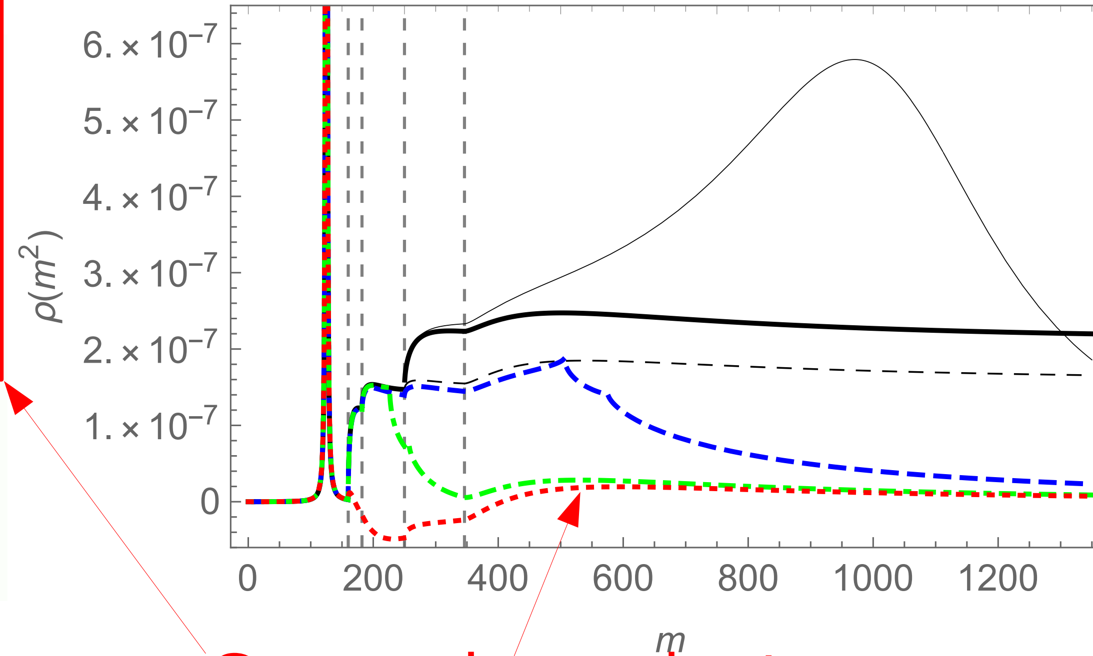

Gauge-dependent
Unphysical features:
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Not a consequence
of instability: Occurs even
for an asymptotically stable
Higgs in a toy theory

Consequences: The Higgs

[Maas'12,'17
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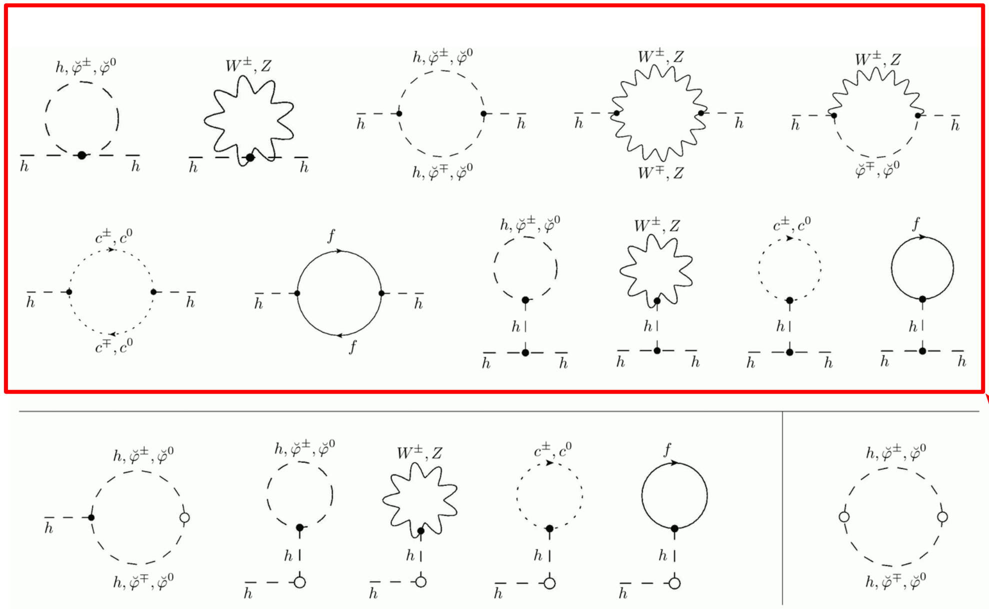

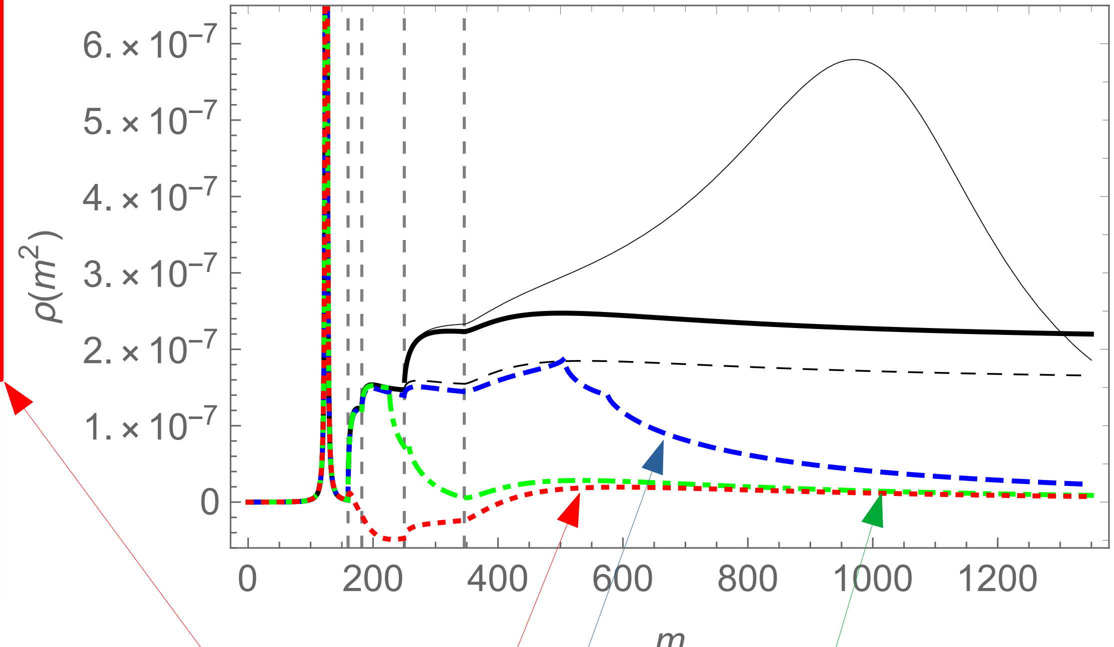

Gauge-dependent

Other gauge choices

Consequences: The Higgs

[Maas'12,'17
Maas & Sondenheimer'20
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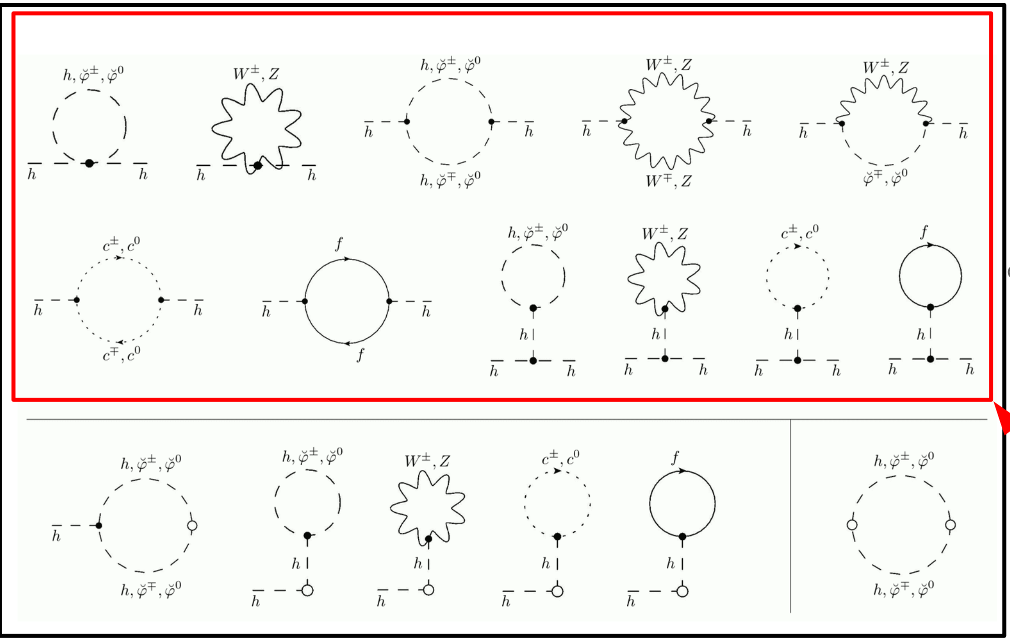

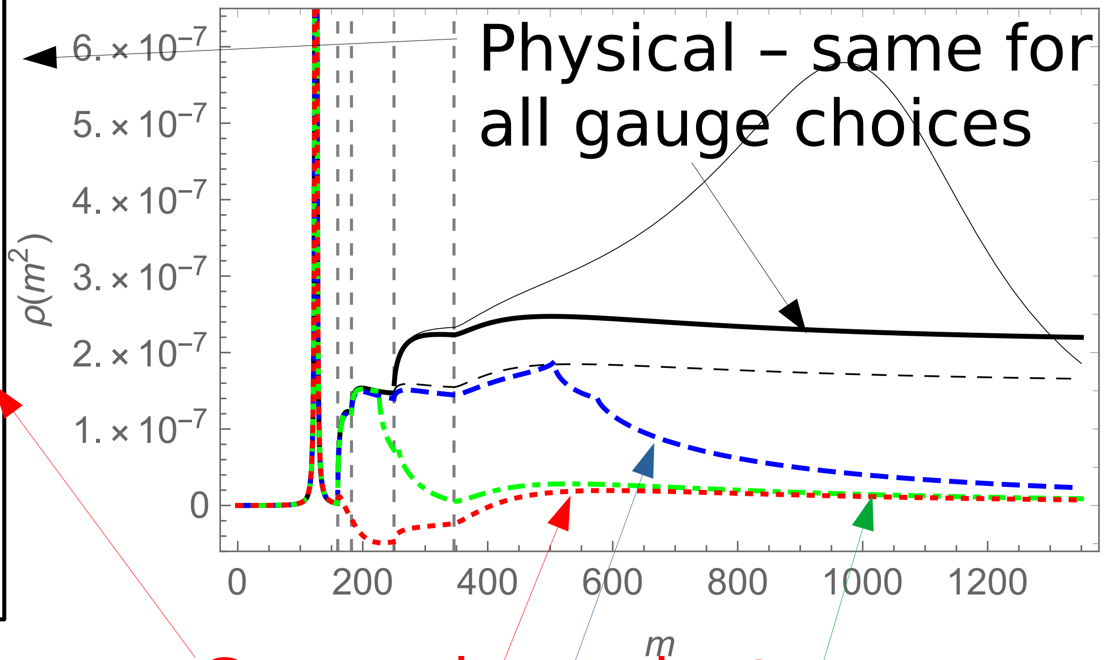

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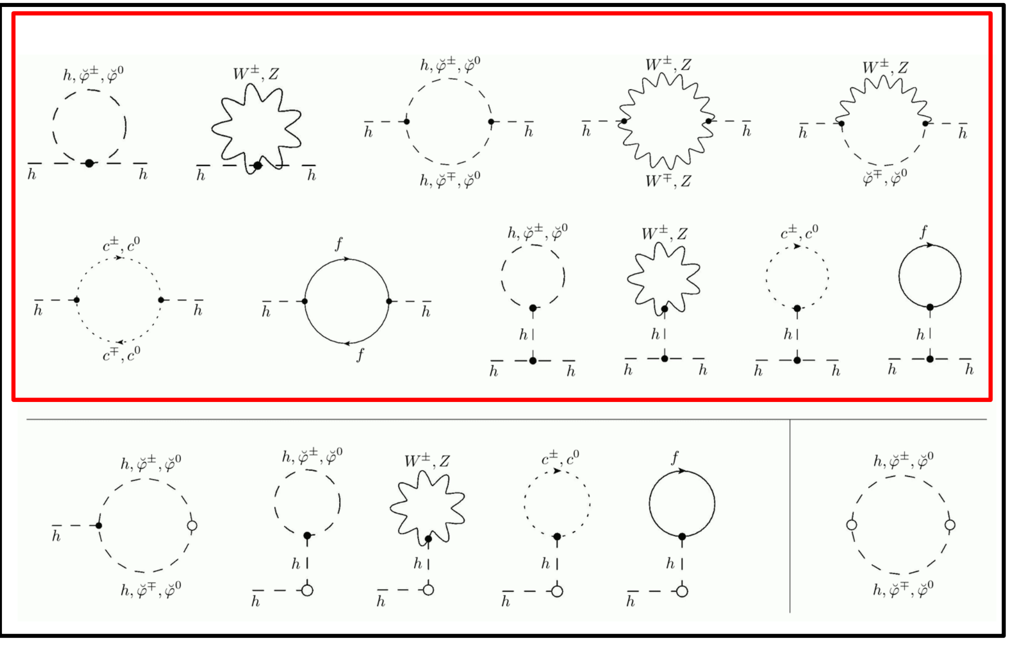

Same structure repeats itself in decays and scattering processes

Consequences: The Higgs

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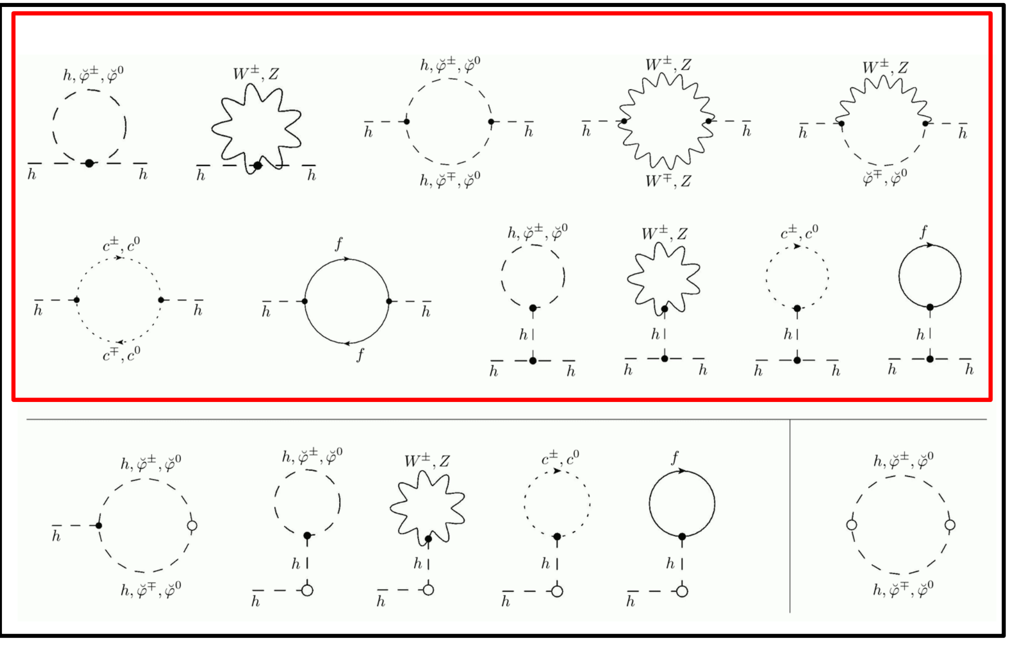

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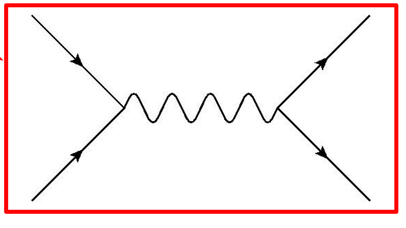
LO: Standard perturbation theory



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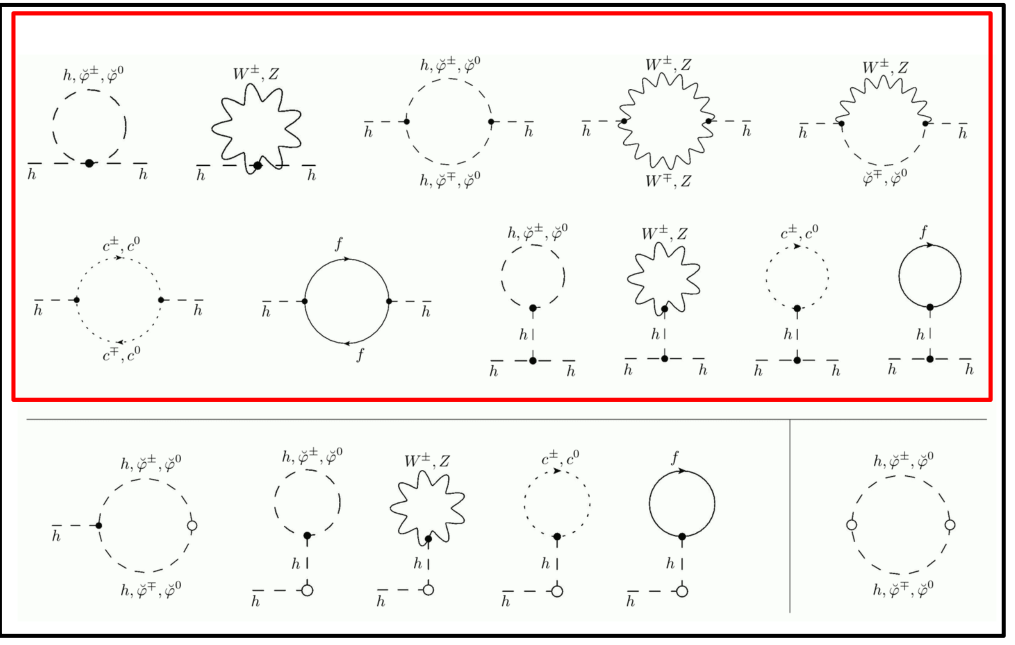

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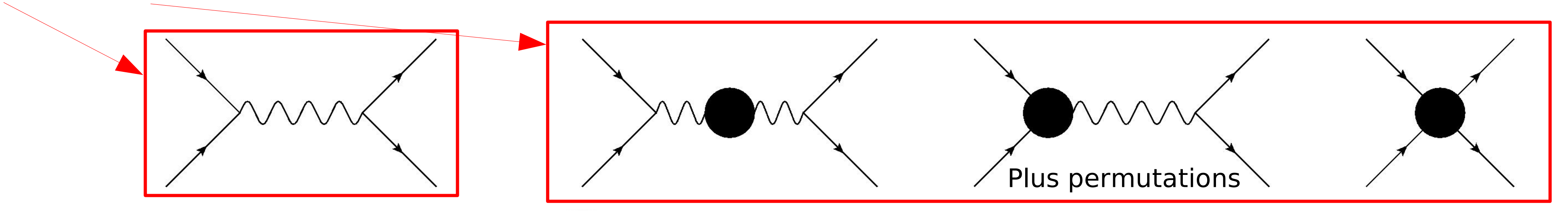
LO, NLO: Standard perturbation theory



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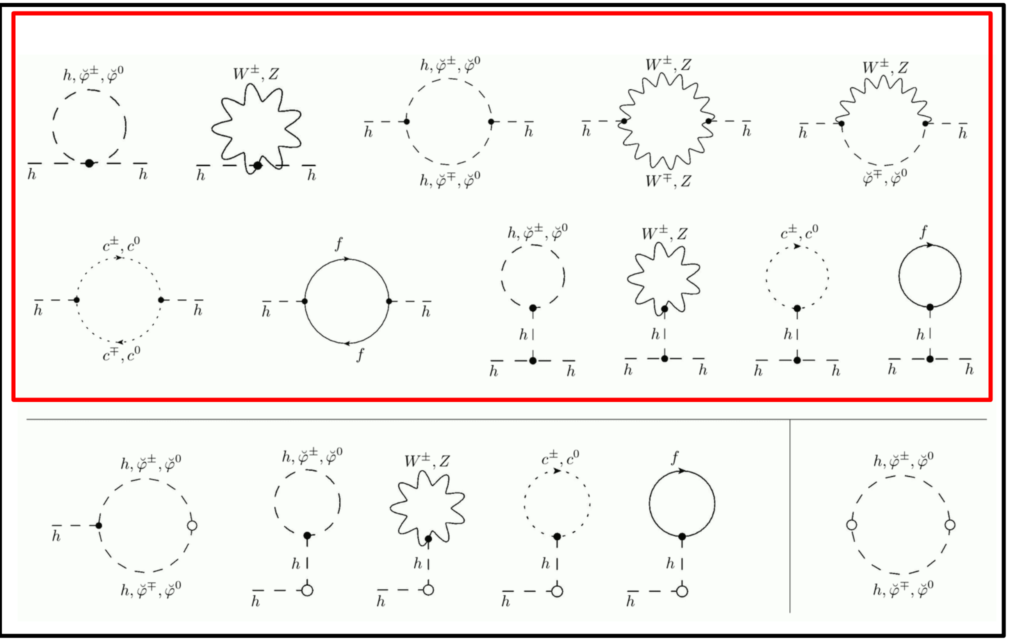

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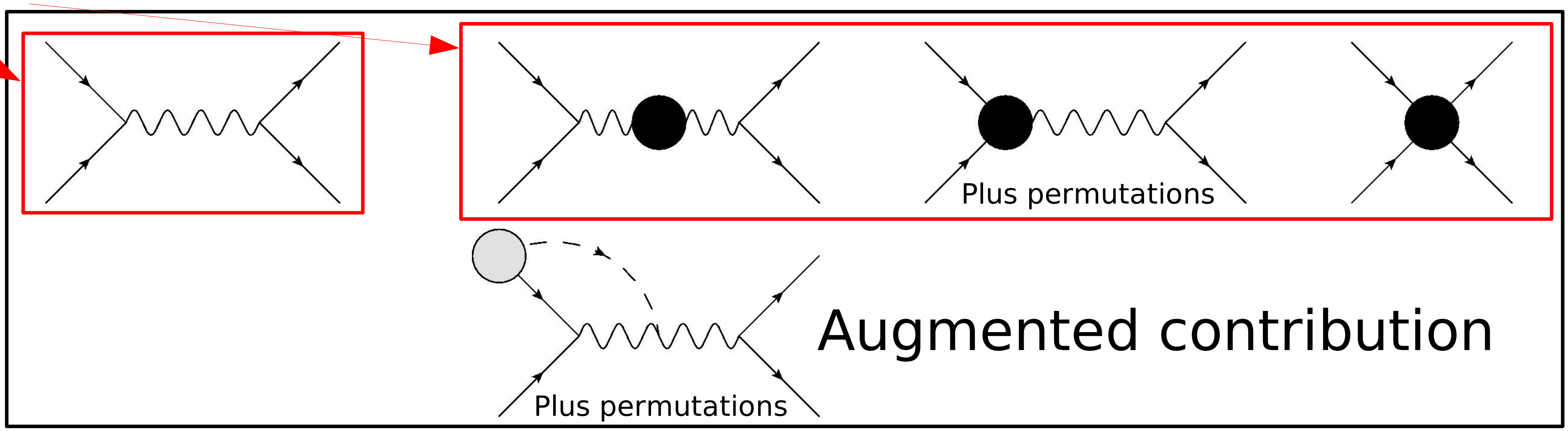

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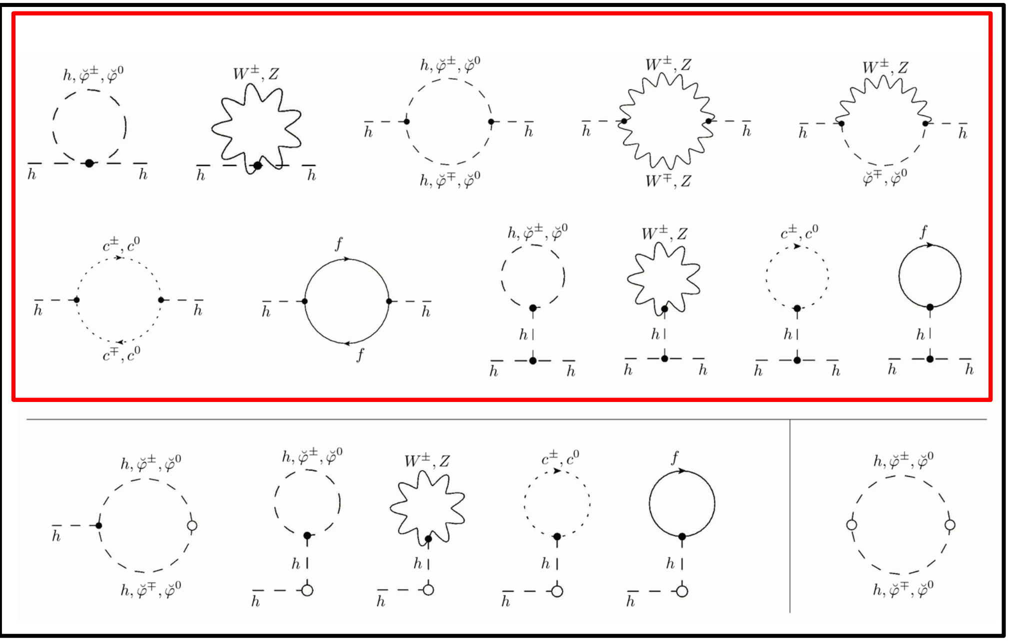

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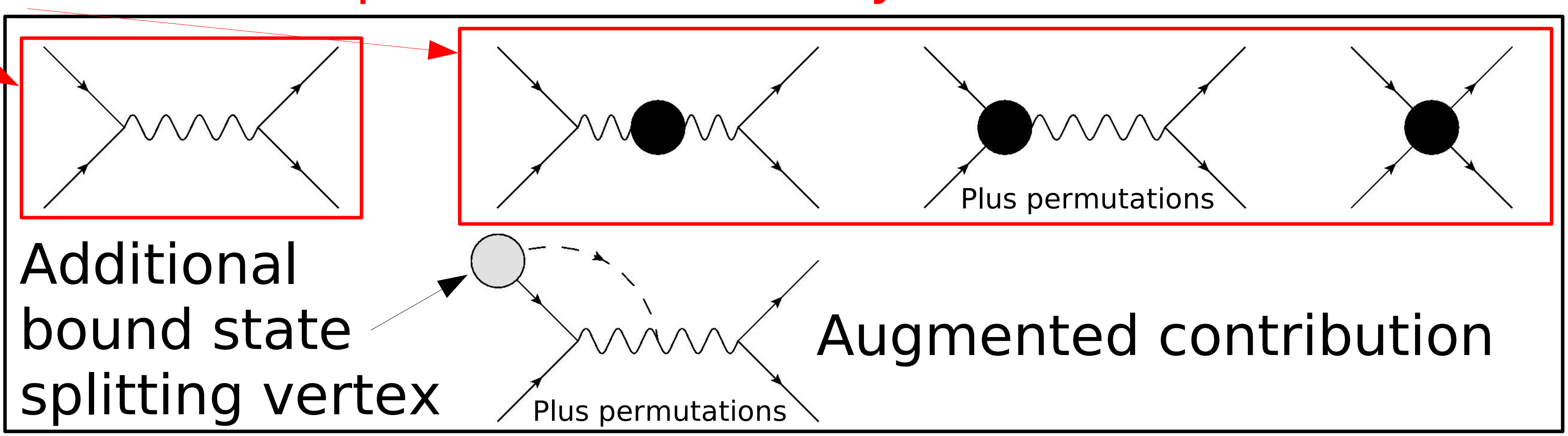

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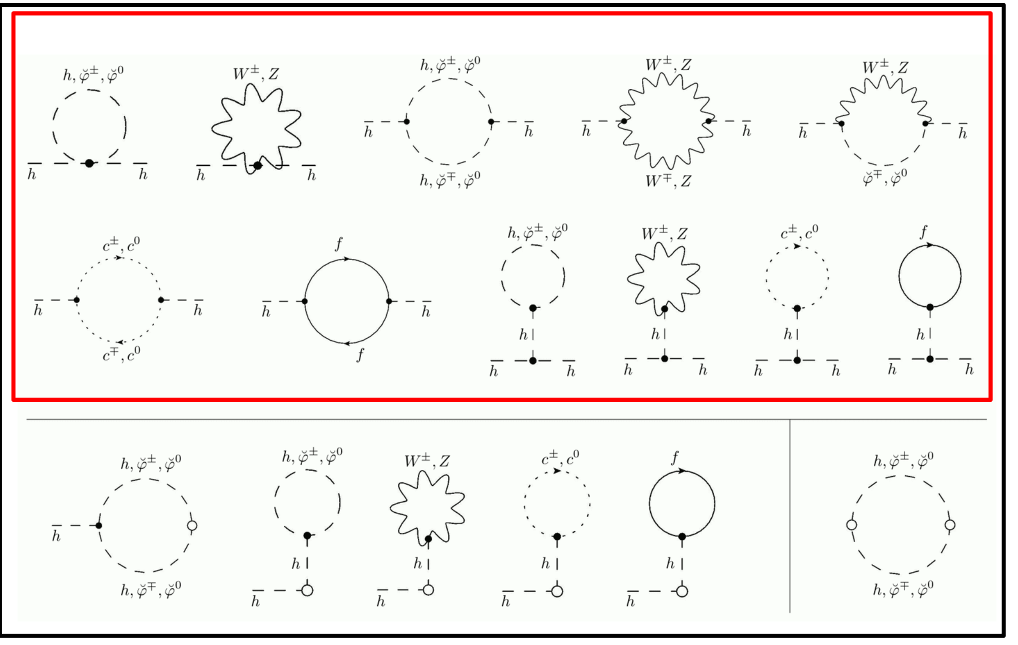

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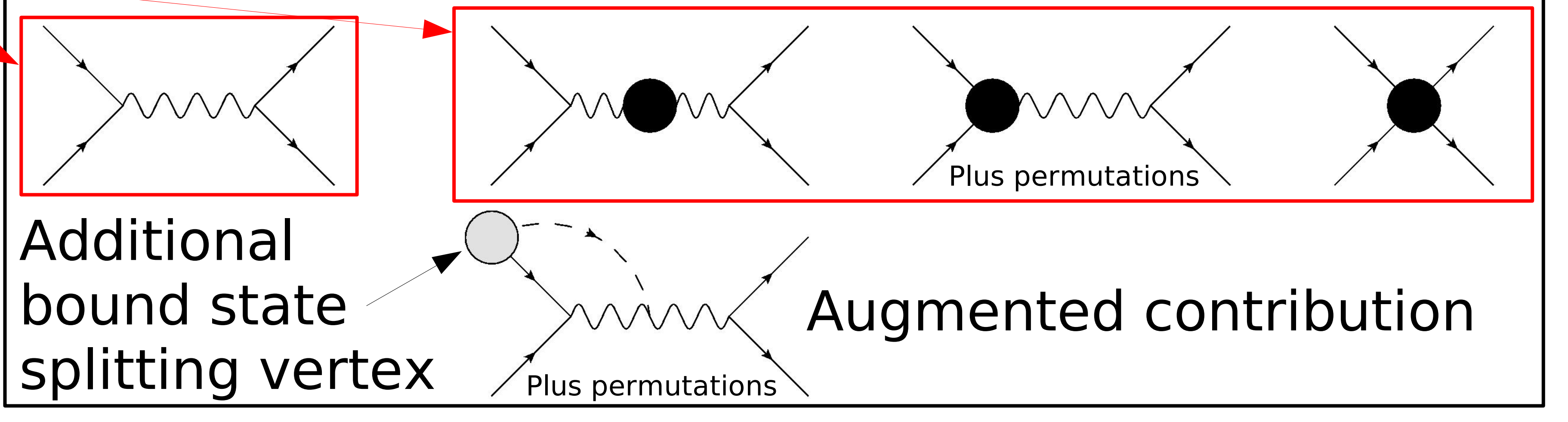

Augmented perturbation theory only augments Feynman rules

What about the vector?

[Fröhlich et al.’80,’81
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Matrix from group structure

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Matrix from group structure

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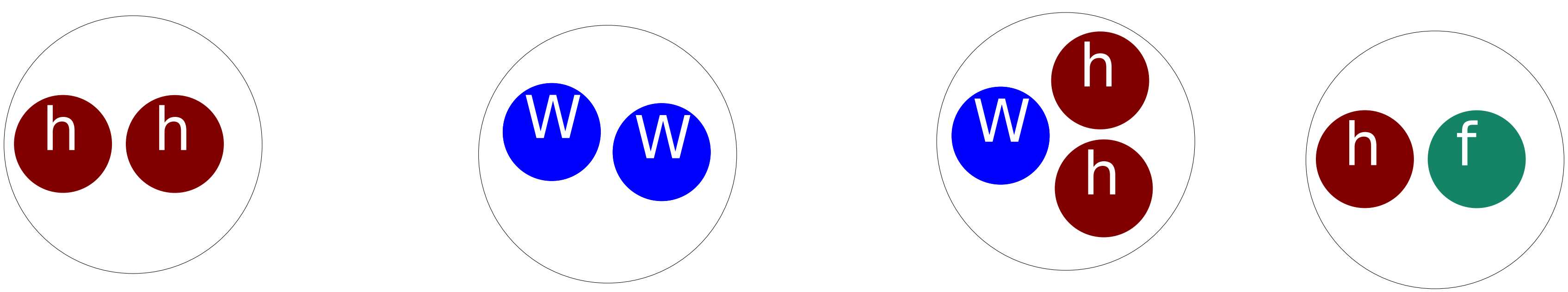
Exactly one gauge boson for every physical state

Physical states

[Fröhlich et al.'80,
Banks et al.'79]

- No “real” breaking
- Physical particles are gauge-invariant particles
  - **Cannot** be the elementary particles
  - Non-Abelian nature is relevant
- Need more than one particle: Composite particles
  - Higgs-Higgs, W-W, Higgs-Higgs-W etc.



- Has nothing to do with weak coupling
  - Think QED (hydrogen atom!)

Flavor

[Fröhlich et al.'80,
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- Extends non-trivially to hadrons

Flavor on the lattice

[Afferrante,Maas,Sondenheimer,Törek'20]

- Only mock-up standard model
  - Compressed mass scales
  - One generation
  - Degenerate leptons and neutrinos
  - Dirac fermions: left/right-handed non-degenerate
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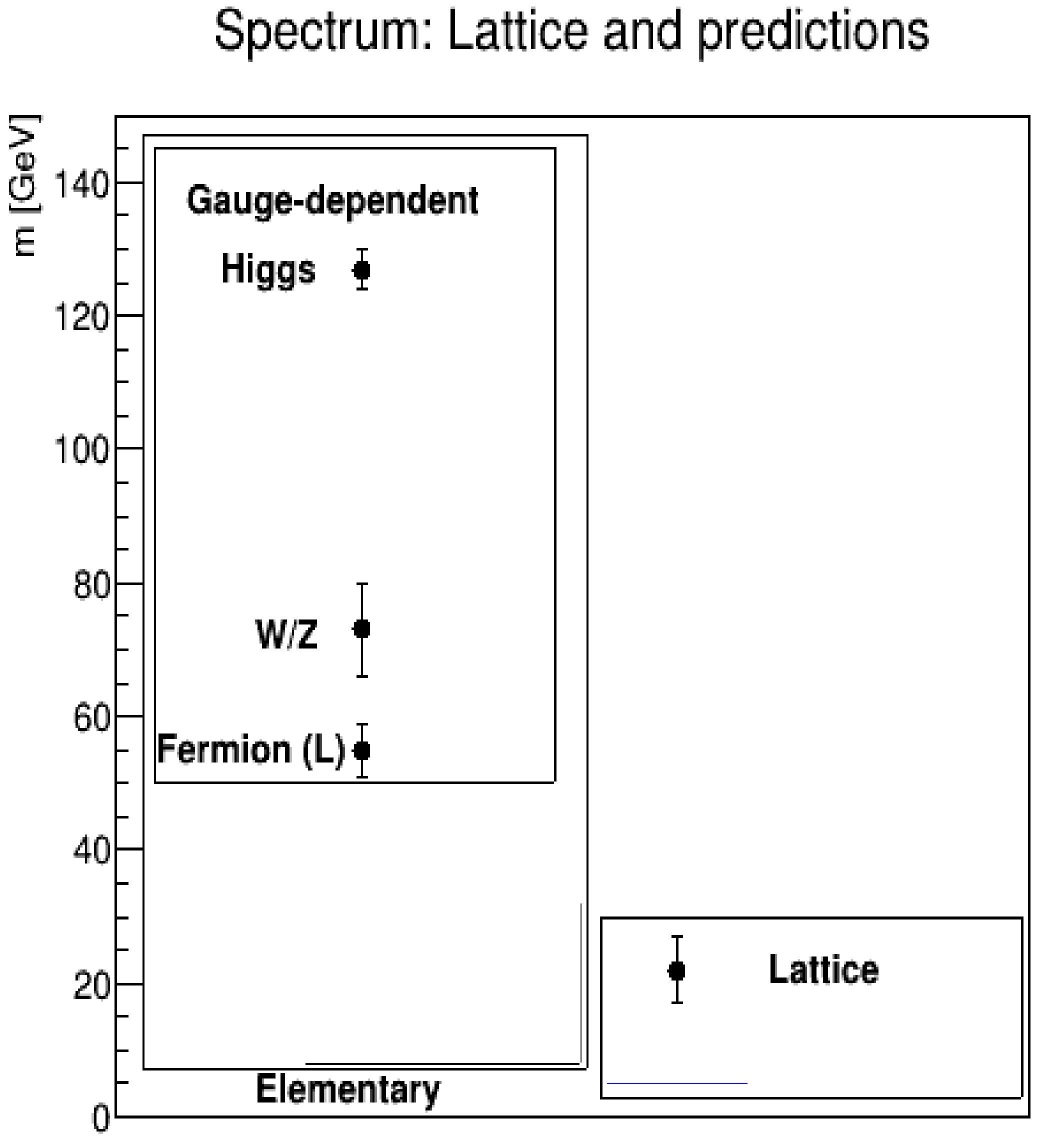

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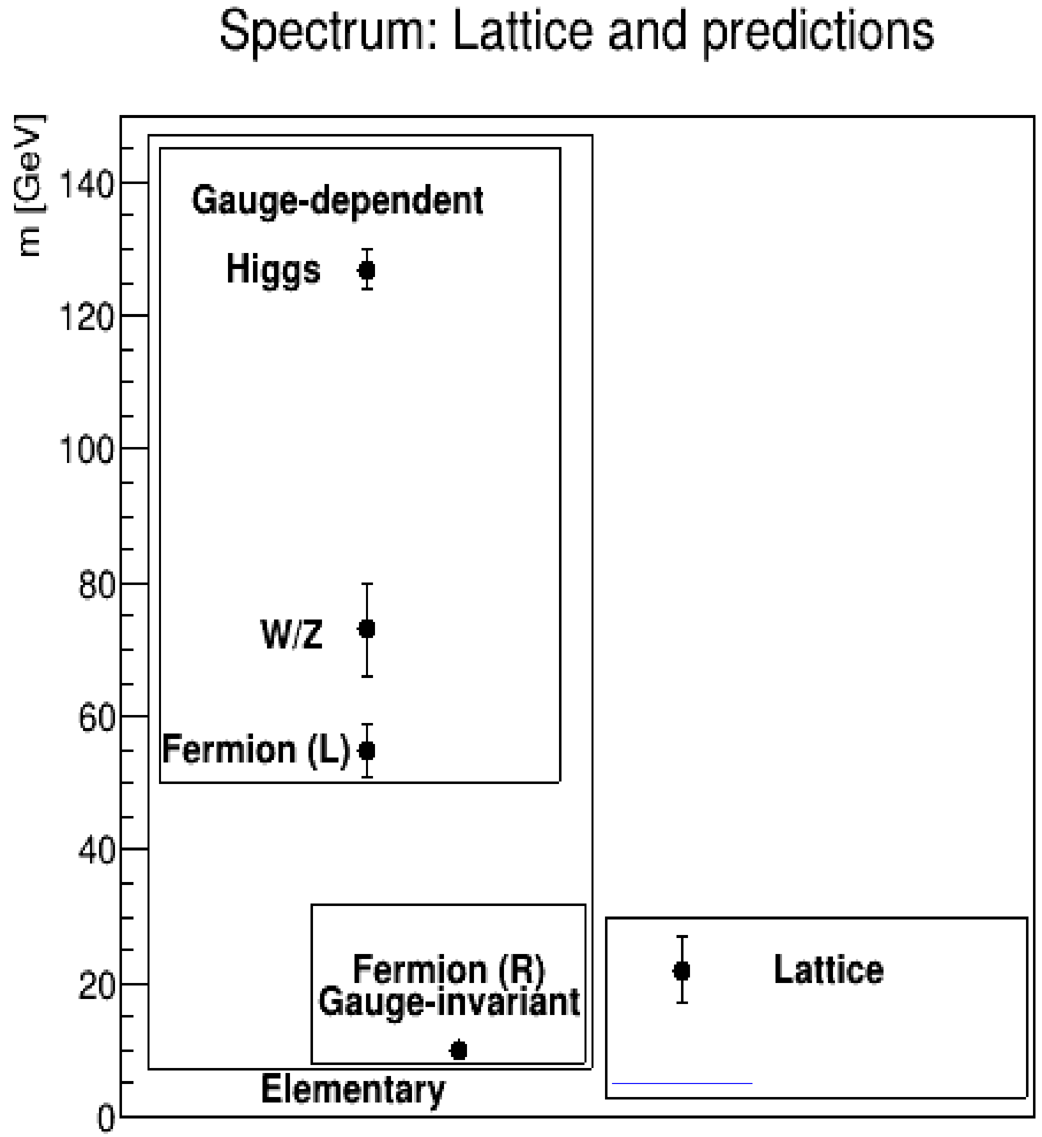

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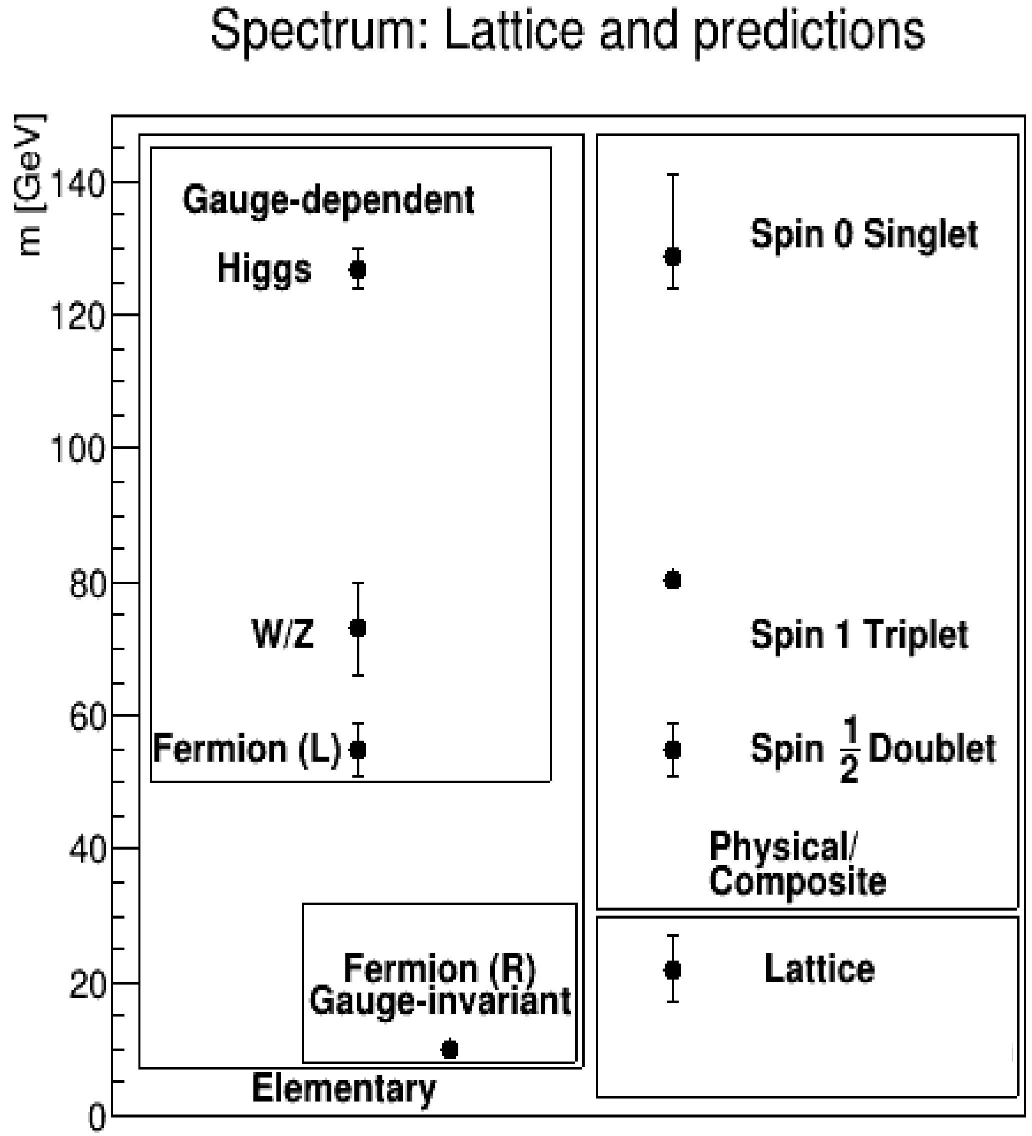

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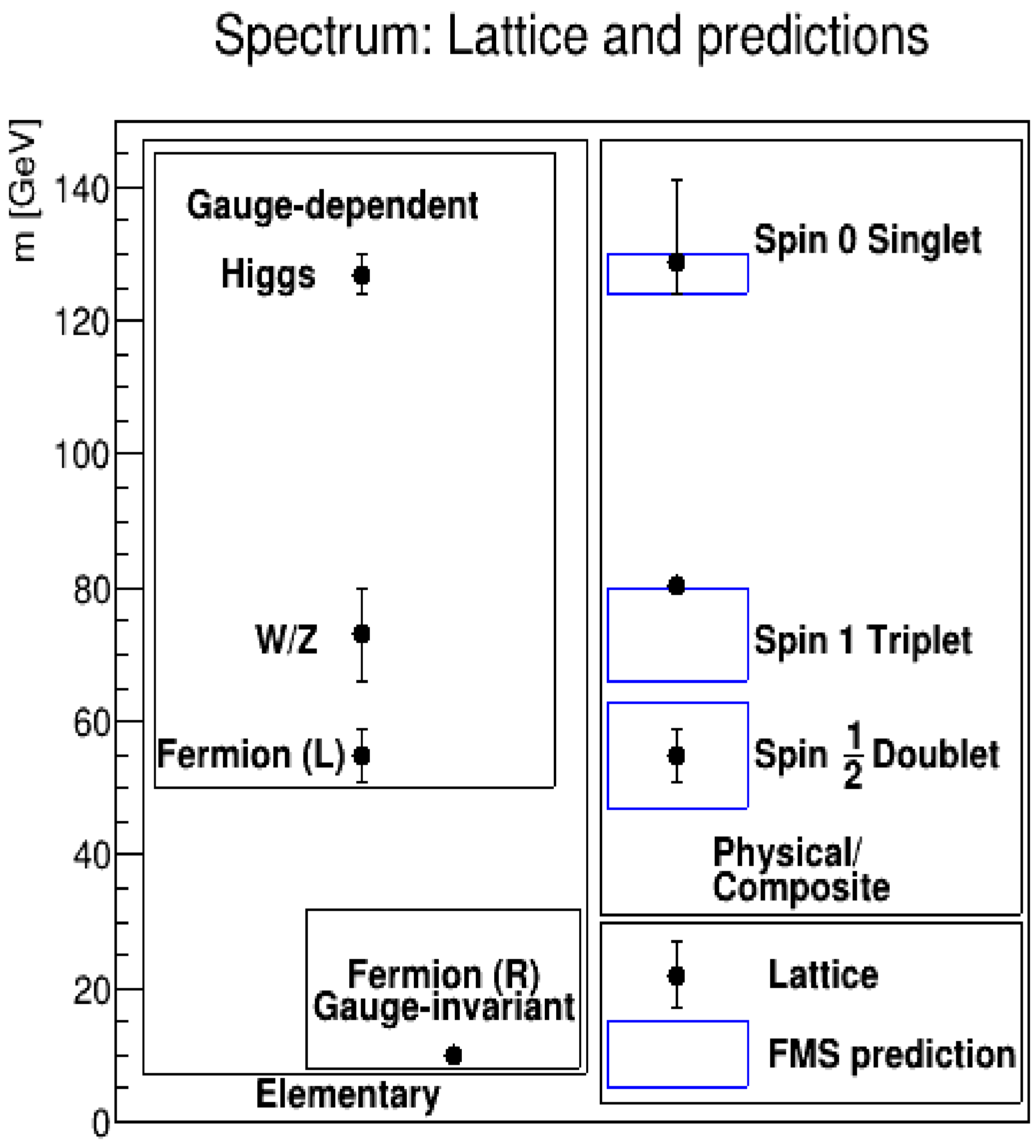
- Supports FMS prediction



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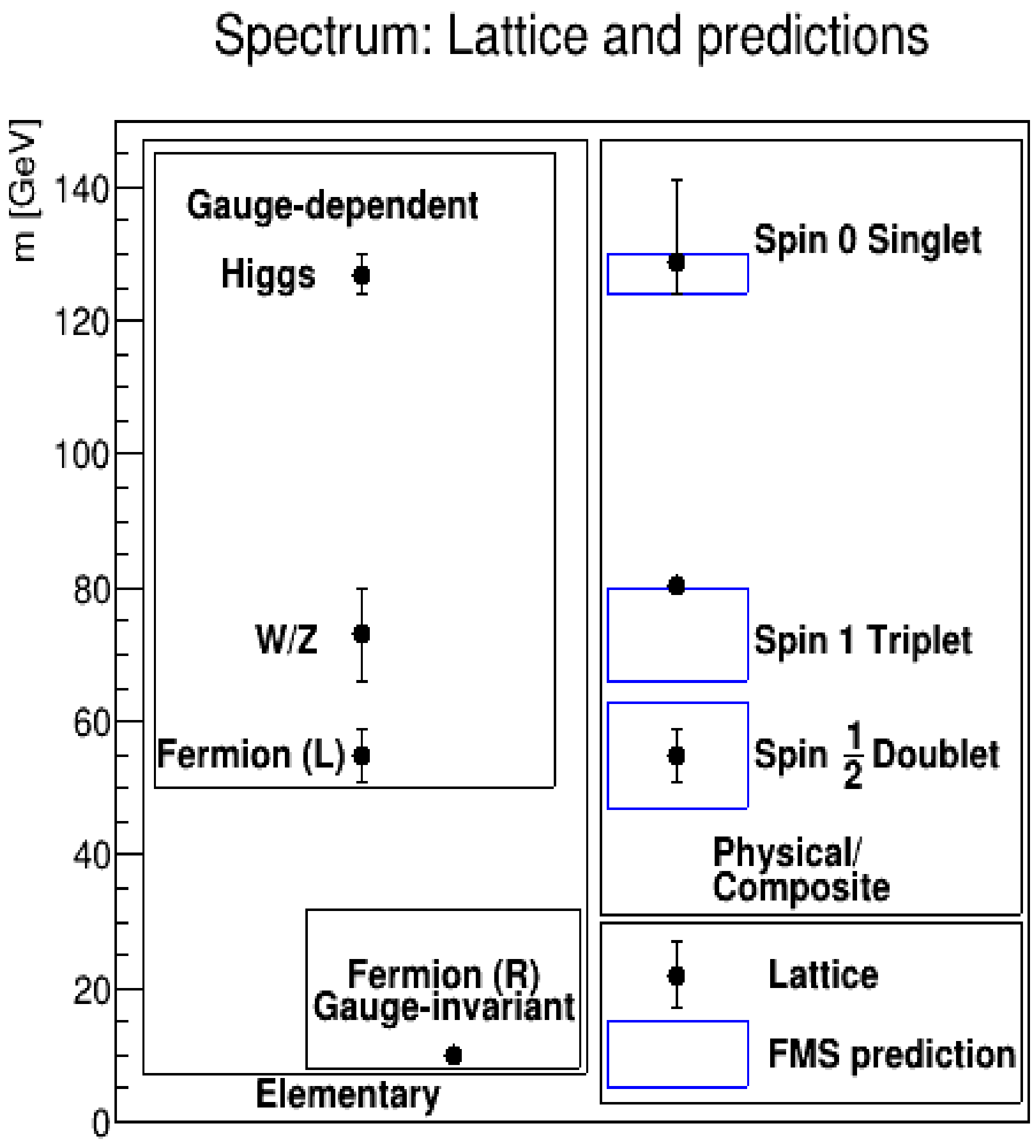
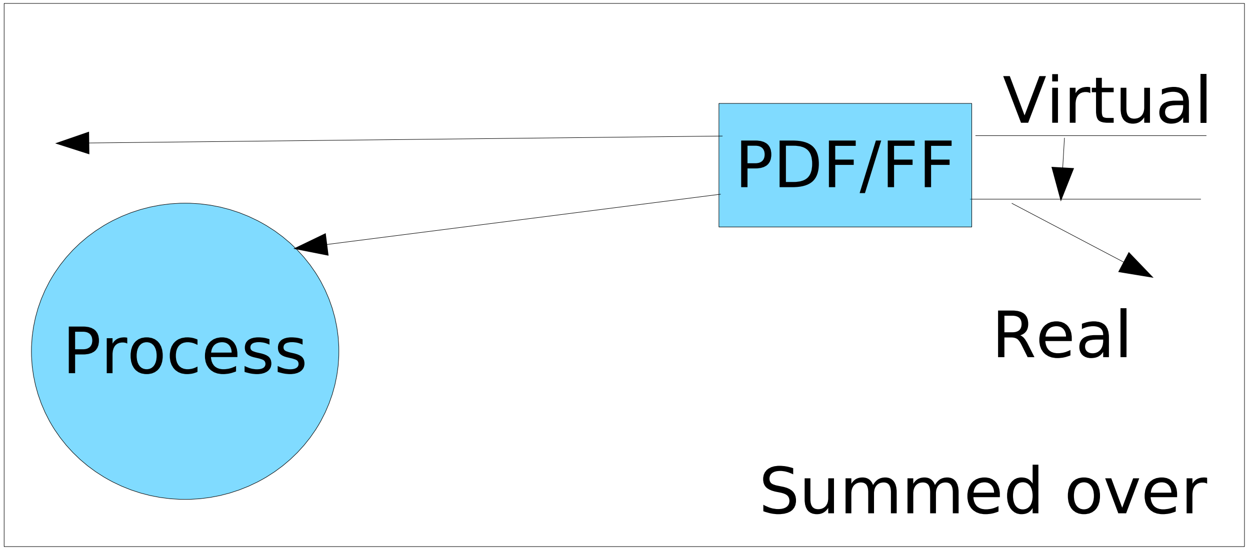


- Supports FMS prediction – grant for unquenching '24-'28

Invalidation in electroweak physics

[Maas et al.'22]



Incoming or outgoing gauge singlet

- Particles are again (electroweak) gauge-singlets

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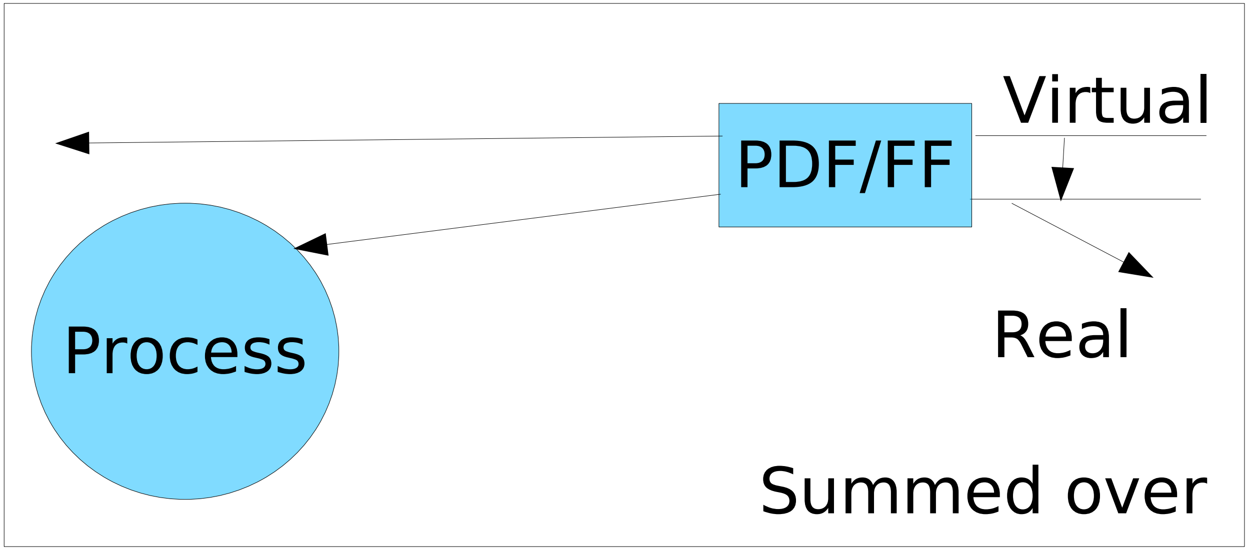

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$$\langle hehe|h\mu\, h\mu\rangle = \langle ee|\mu\,\mu\rangle + \langle\eta\,\eta\rangle\langle ee|\mu\,\mu\rangle + \langle ee\rangle\langle\eta\,\eta|\mu\,\mu\rangle + \ldots$$

Standard result

Irrelevant at low energies

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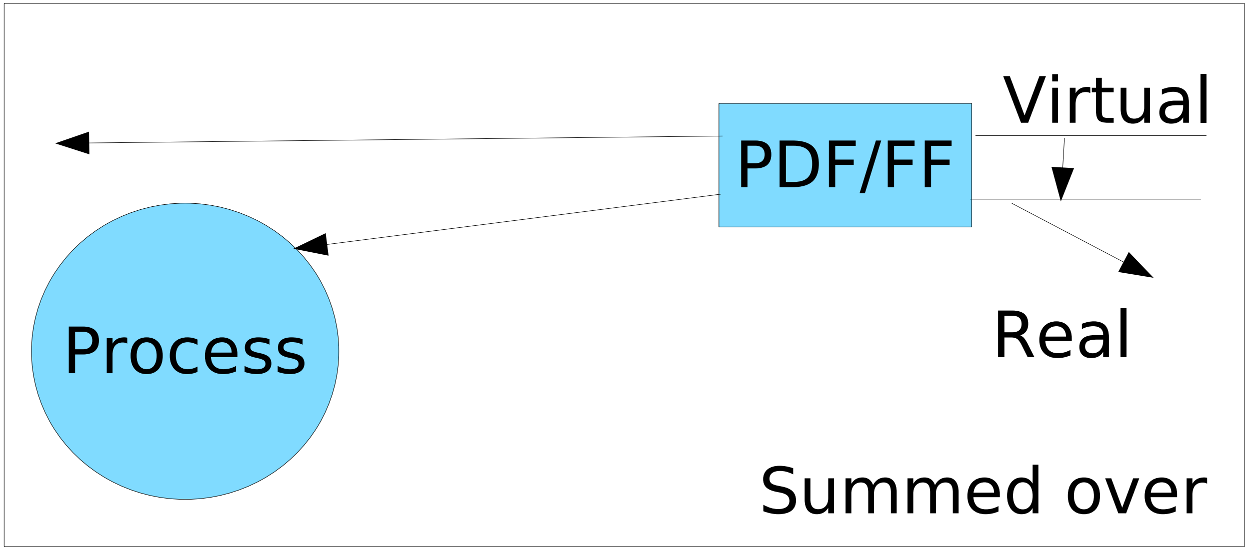

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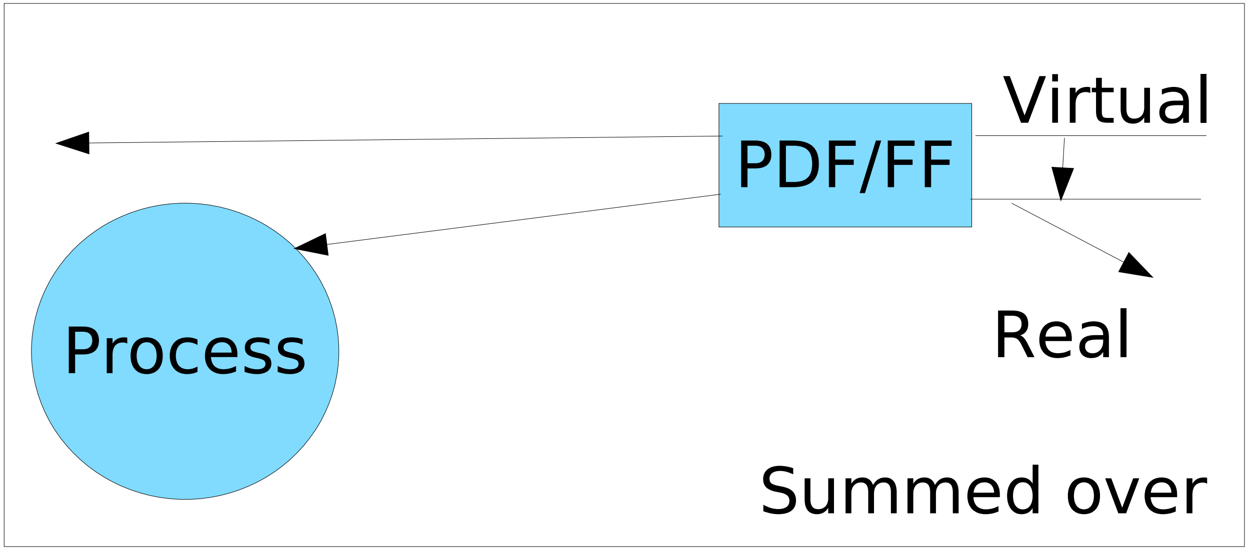

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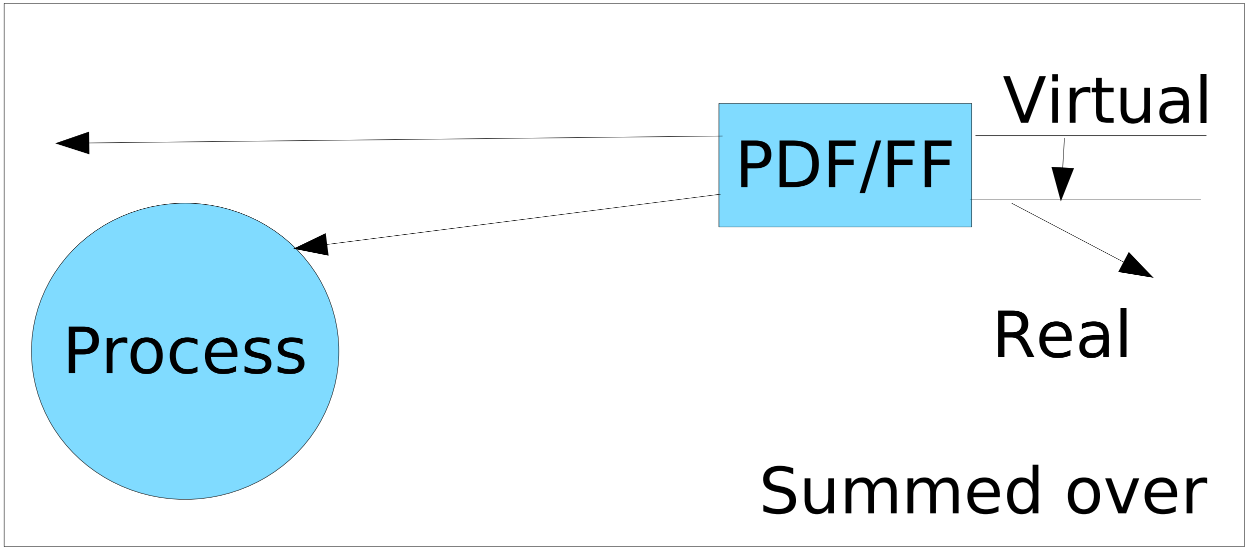

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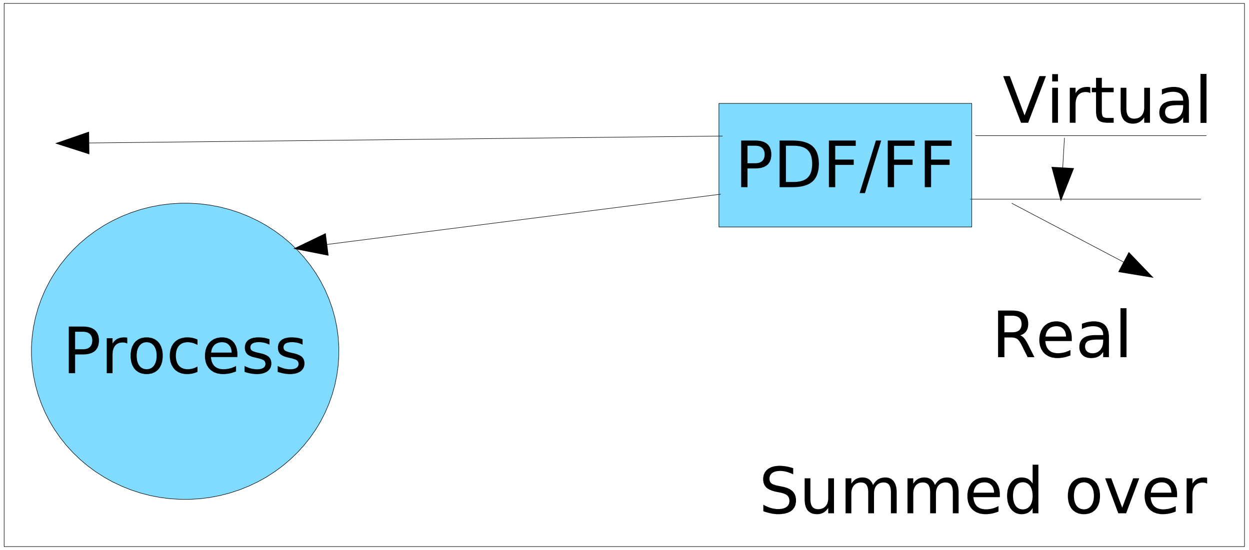

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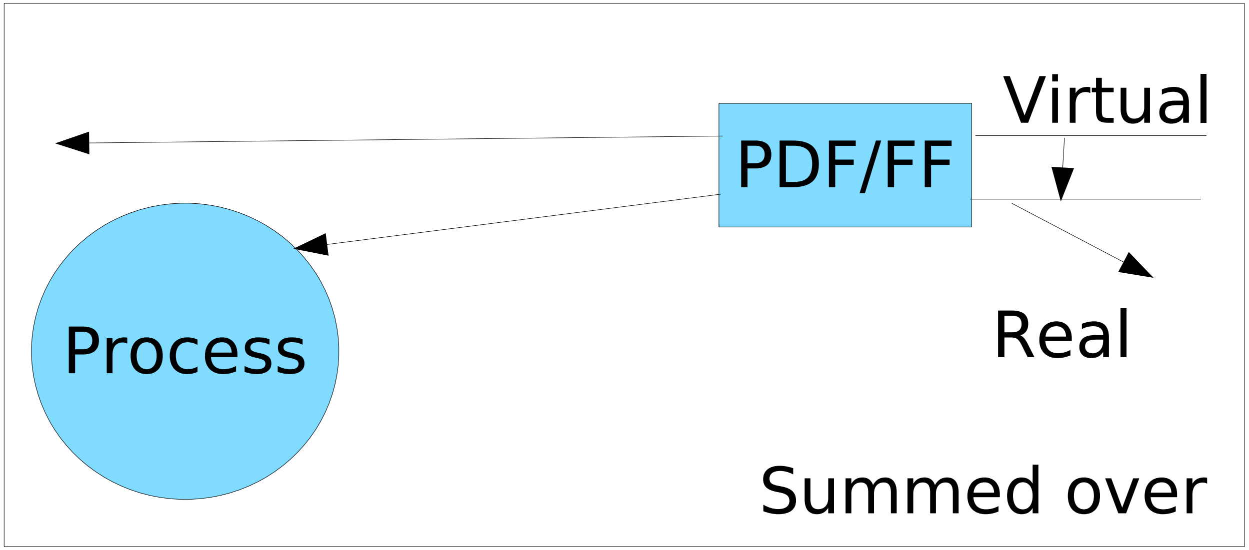

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  - Comparable to strong corrections

Review: 1712.04721 Update: 2305.01960

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  - Comparable to strong corrections

- Effect suppressed at low energies because of standard model structure
  - Different in BSM physics

Review: 1712.04721 Update: 2305.01960