Gauge Invariance and Particles

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Vienna
Austria

UNI GRAZ
NAWI Graz Natural Sciences
FWF Österreichischer Wissenschaftsfonds

What is this talk about?

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Gauge symmetry needs to be respected:
Elementary particles are not observables

Review: 1712.04721 Update: 2305.01960

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- Brout-Englert-Higgs Physics
- Fröhlich-Morchio-Strocchi mechanism
  - Standard Model
    - Experimental signatures

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- Brout-Englert-Higgs Physics
- Fröhlich-Morchio-Strocchi mechanism
  - Standard Model
    - Experimental signatures
  - Beyond the Standard Model
    - Qualitative changes

Review: 1712.04721 Update: 2305.01960

Brout-Englert-Higgs Physics
-
The Standard Model

A toy model

A toy model: Higgs sector of the SM

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- Essentially the standard model Higgs

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

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- Ws W^{a}_{μ} 

- Coupling g and some numbers f^{abc}

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

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- Local SU(2) gauge symmetry

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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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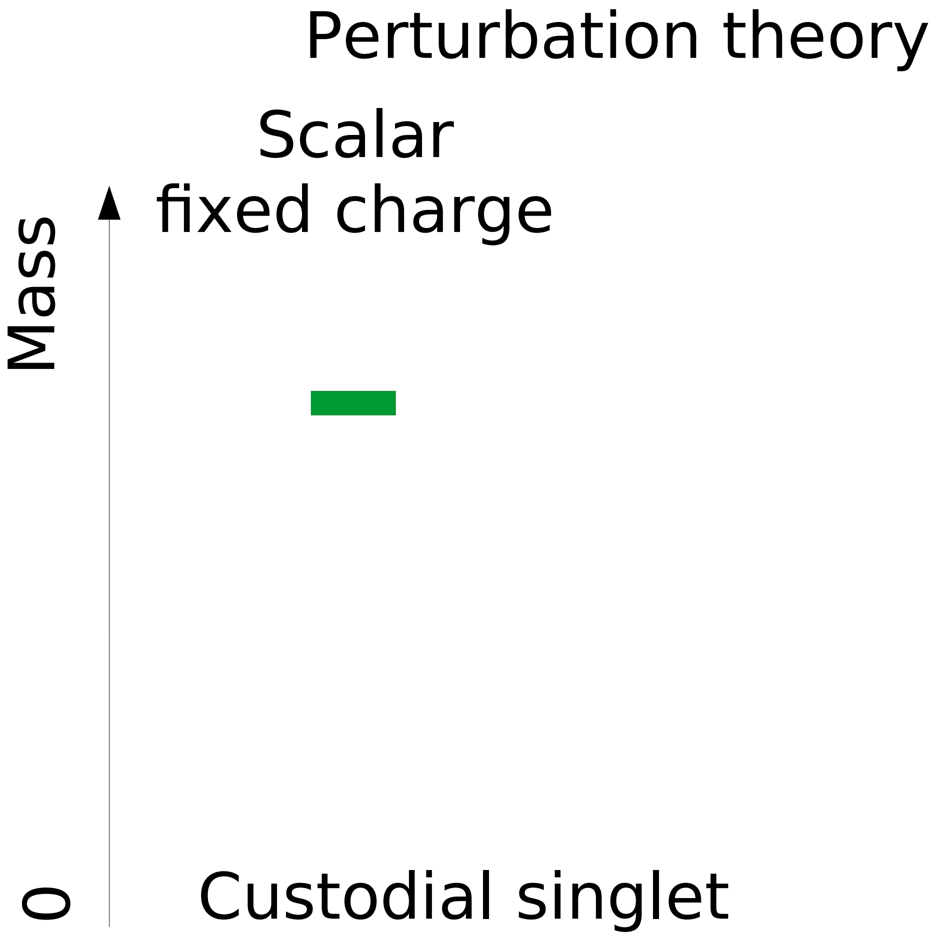
- Choose a suitable gauge and obtain ‘spontaneous gauge symmetry breaking’: SU(2) → 1
- Get masses and degeneracies at tree-level
- Perform perturbation theory

Physical spectrum

Perturbation theory

Physical spectrum



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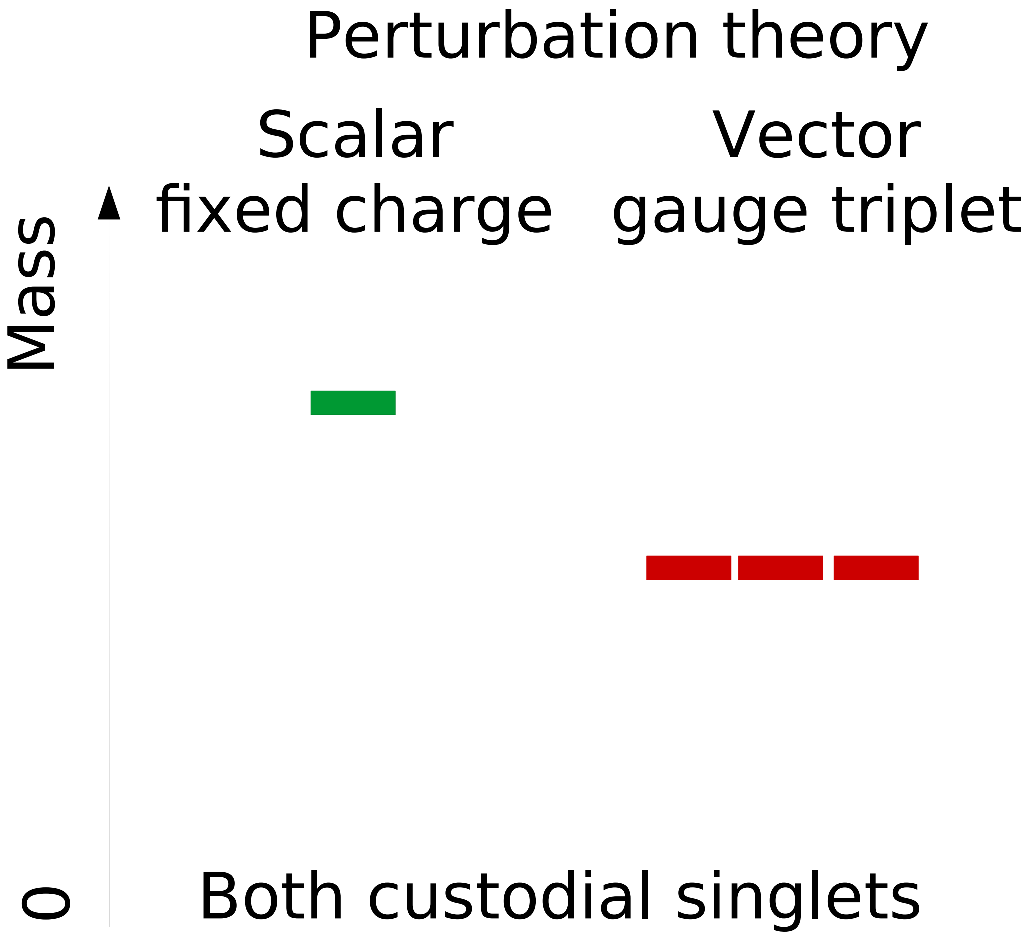

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  - And this includes non-perturbative aspects...
  - ...even at weak coupling [Gribov'78,Singer'78,Fujikawa'82]

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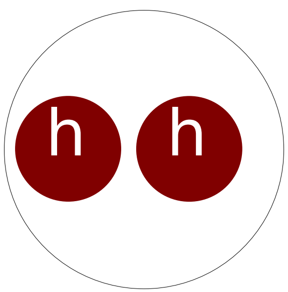

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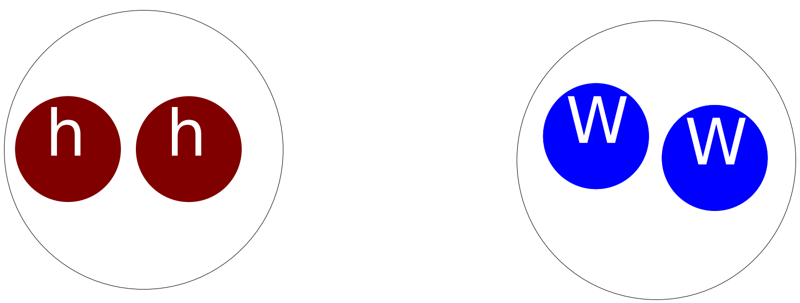

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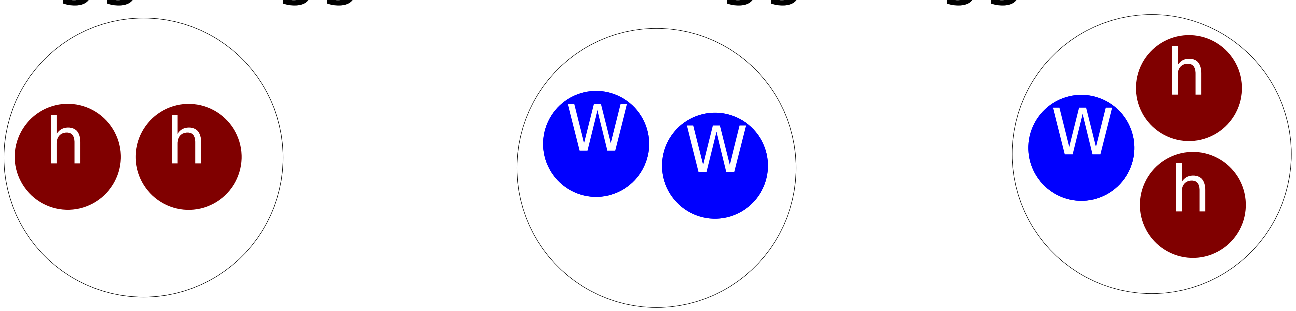

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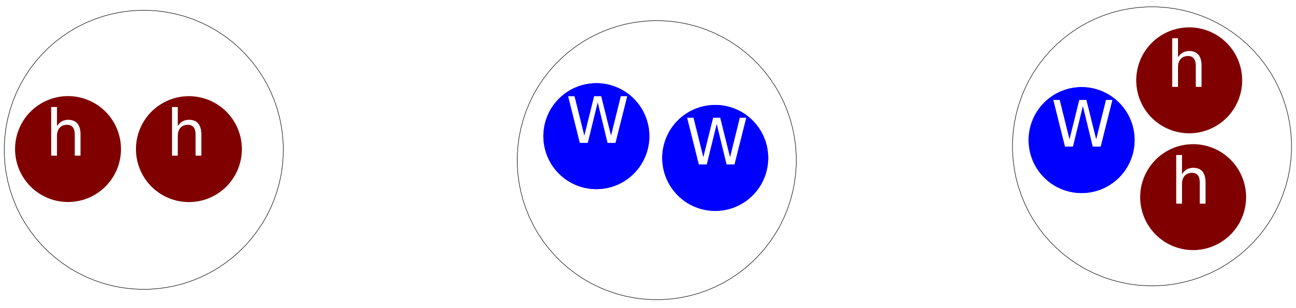

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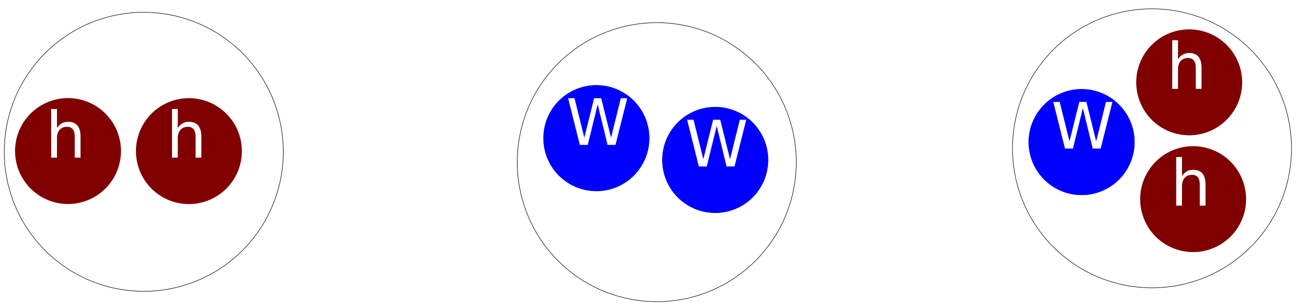

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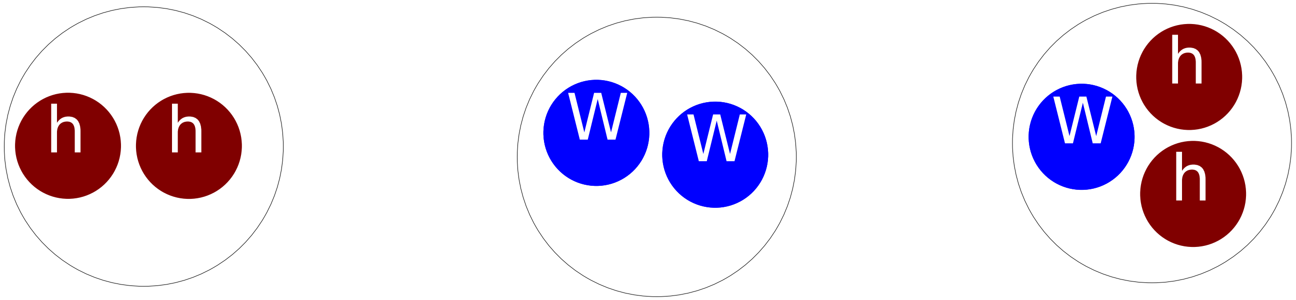

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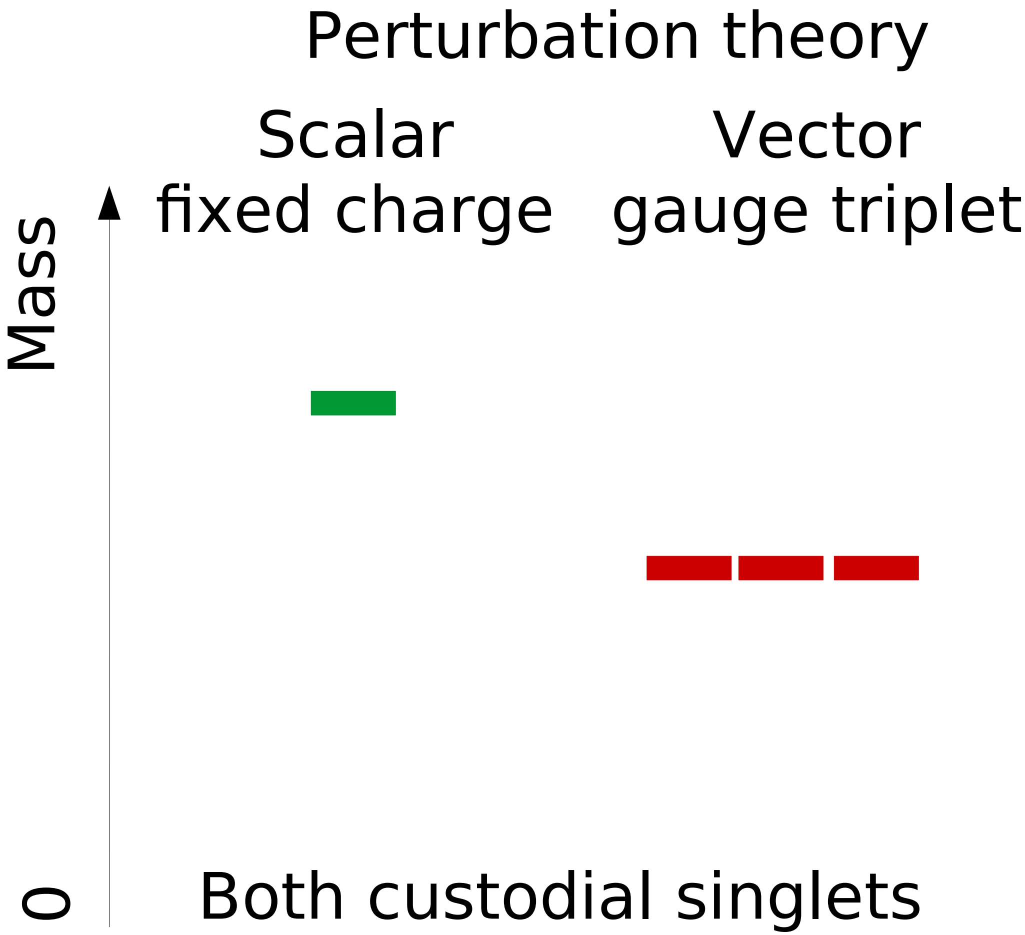
  - Think QED (hydrogen atom!)
- Can this matter?

Physical spectrum



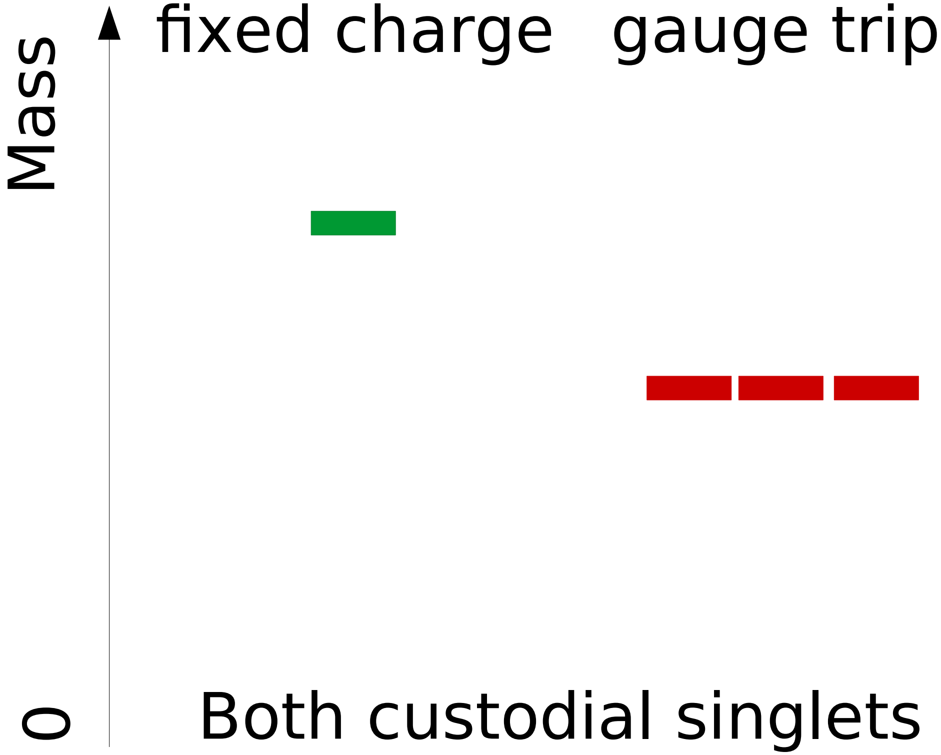
Remember: Experiment tells that somehow the left is correct!

Physical spectrum

Perturbation theory

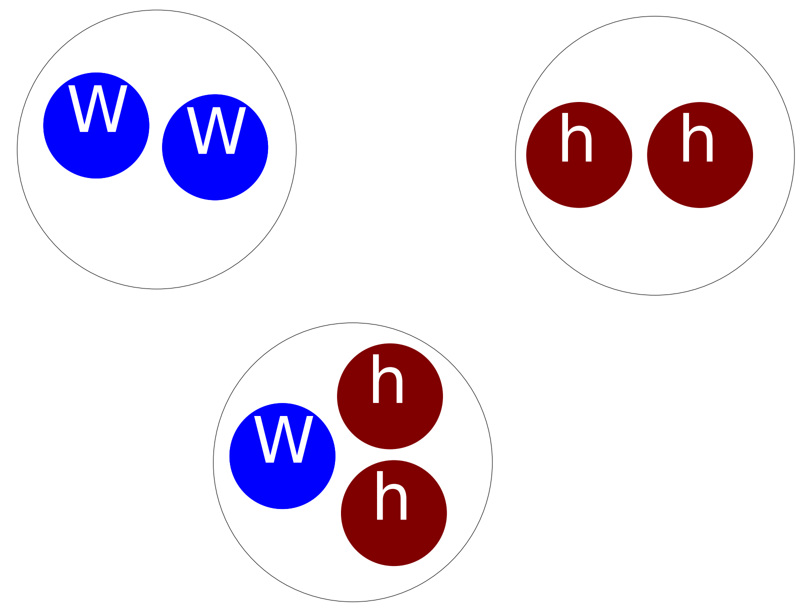
Scalar
fixed charge

Vector
gauge triplet



Both custodial singlets

Composite (bound) states



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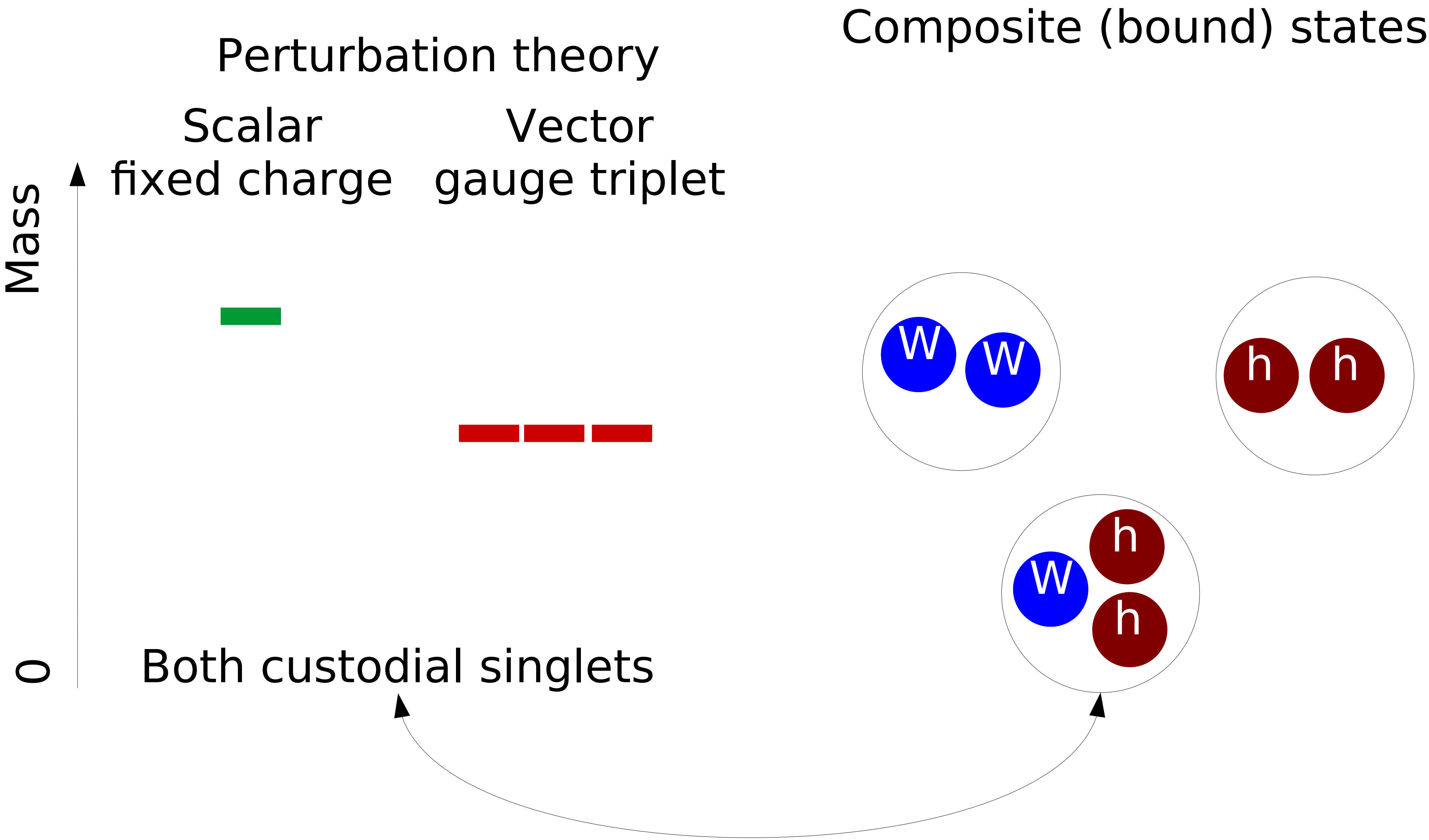
Physical spectrum



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

Physical particles

[Fröhlich et al.'80,'81,
Maas & Törek'16,'18,
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    - Operators limited to asymptotic, elementary, gauge-dependent states

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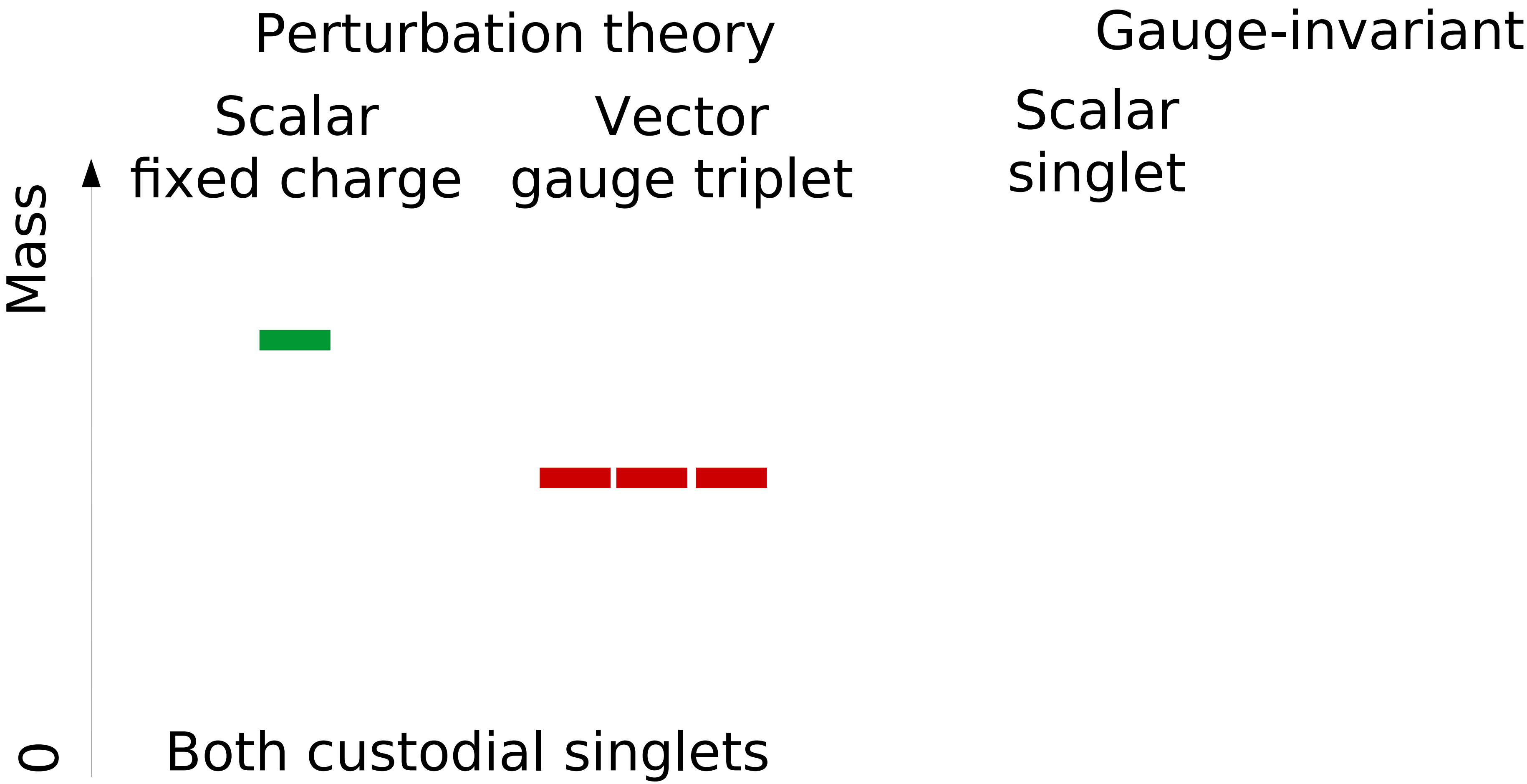
    - Standard lattice spectroscopy problem
    - Standard methods
      - Smearing, variational analysis, systematic error analysis etc.
    - Very large statistics (>10^5 configurations)

Physical spectrum

[Maas'12, Maas & Mufti'14]



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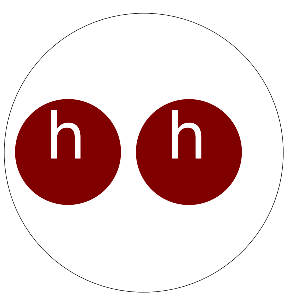

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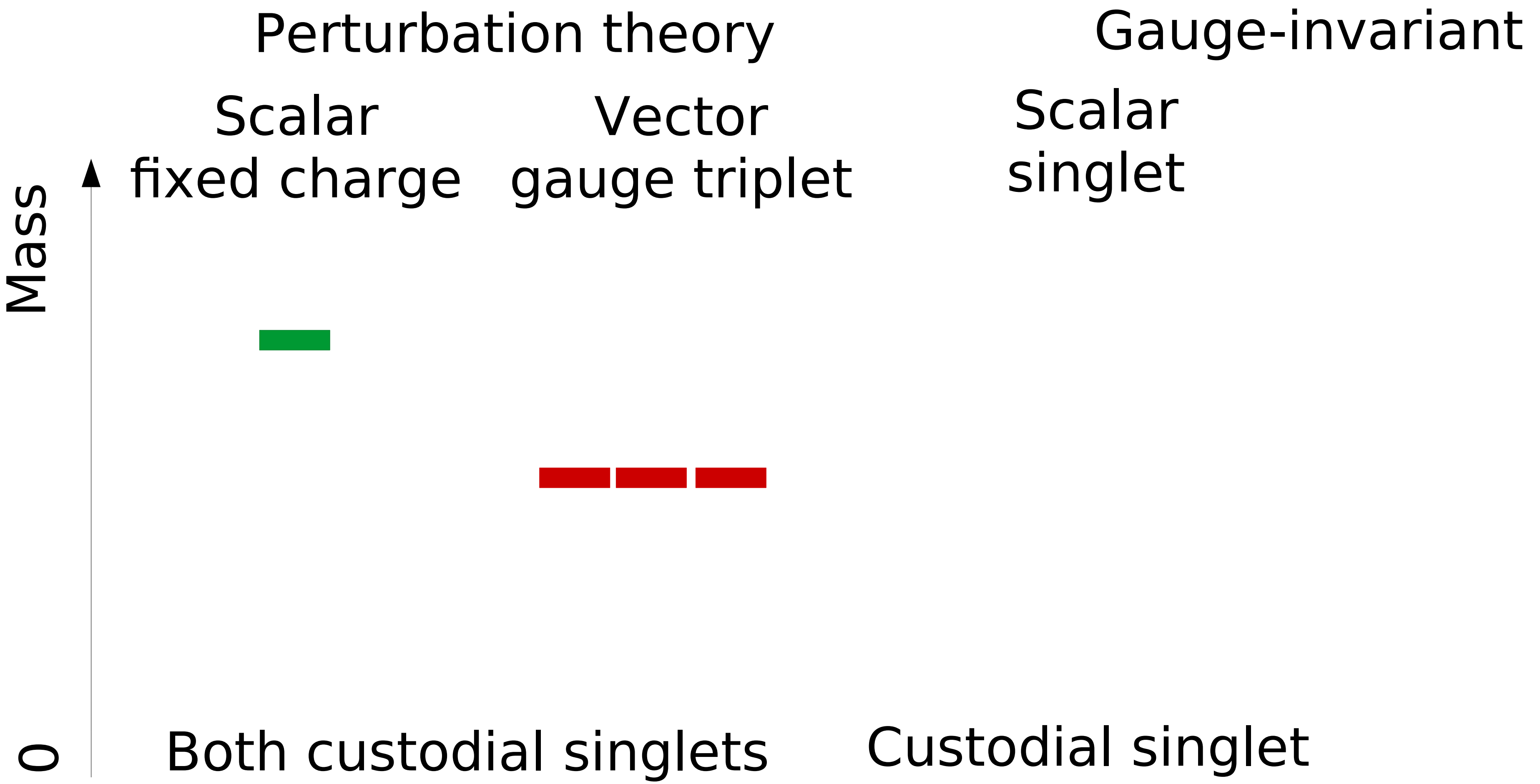

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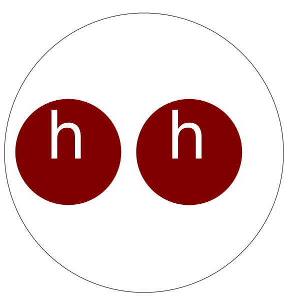

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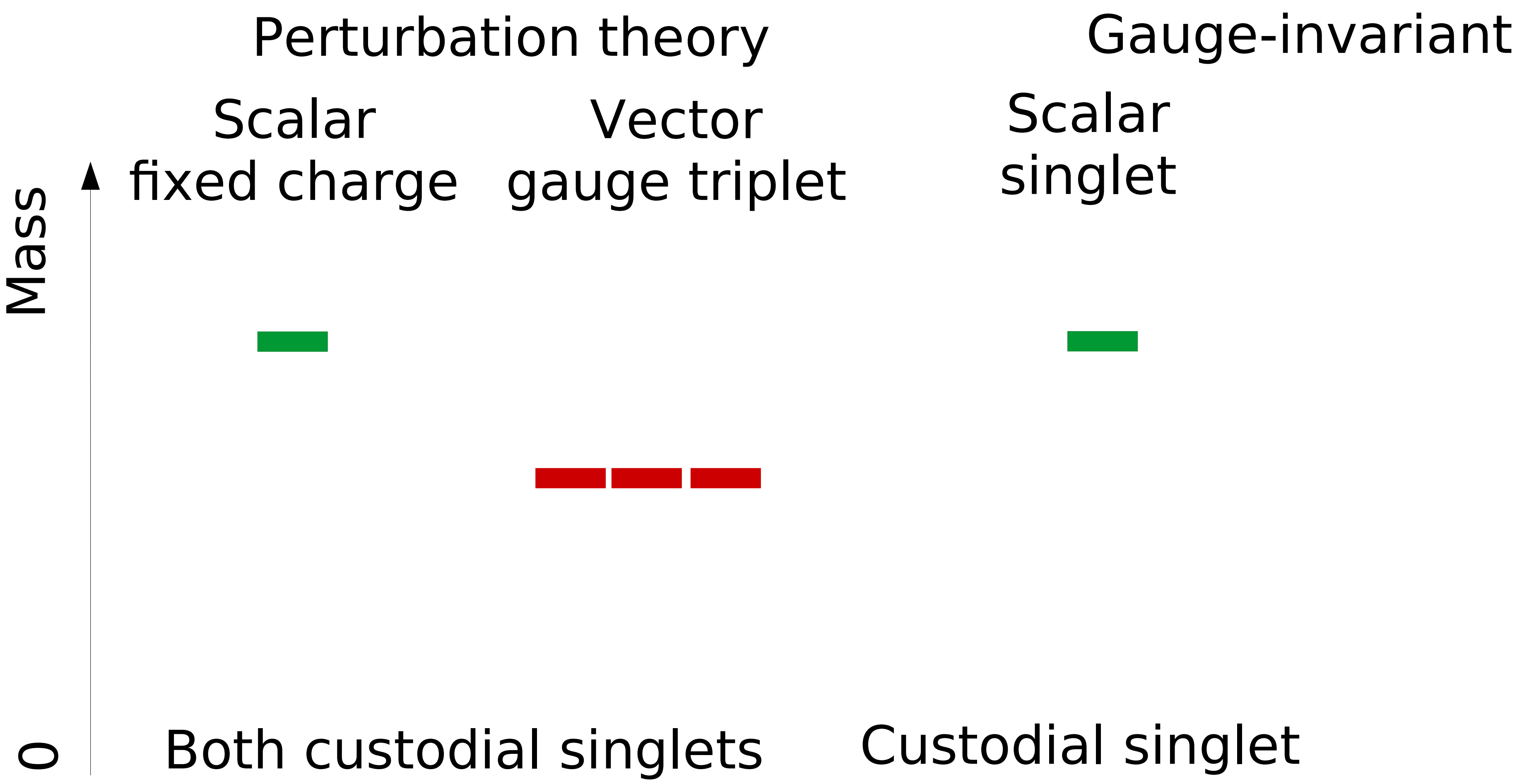

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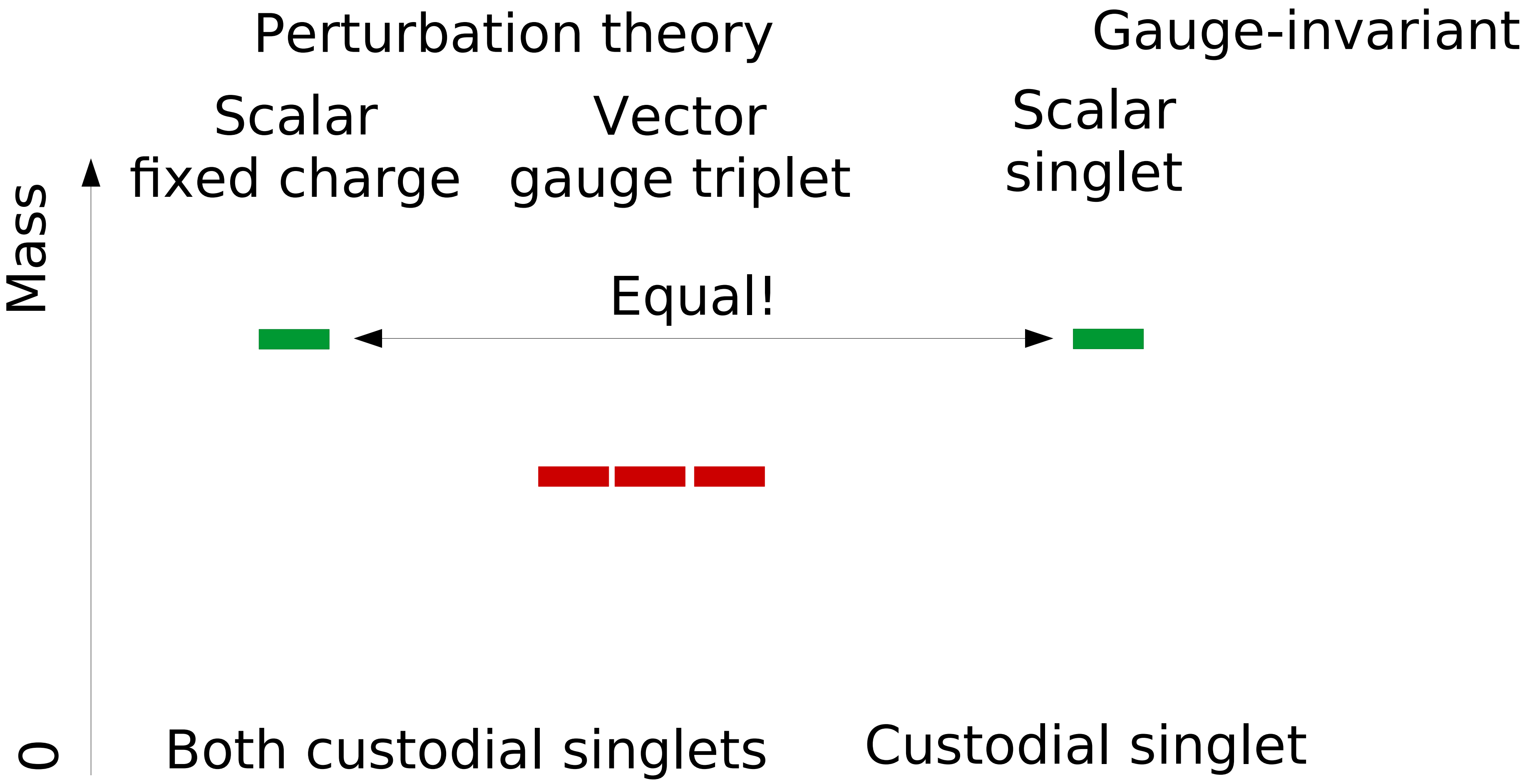

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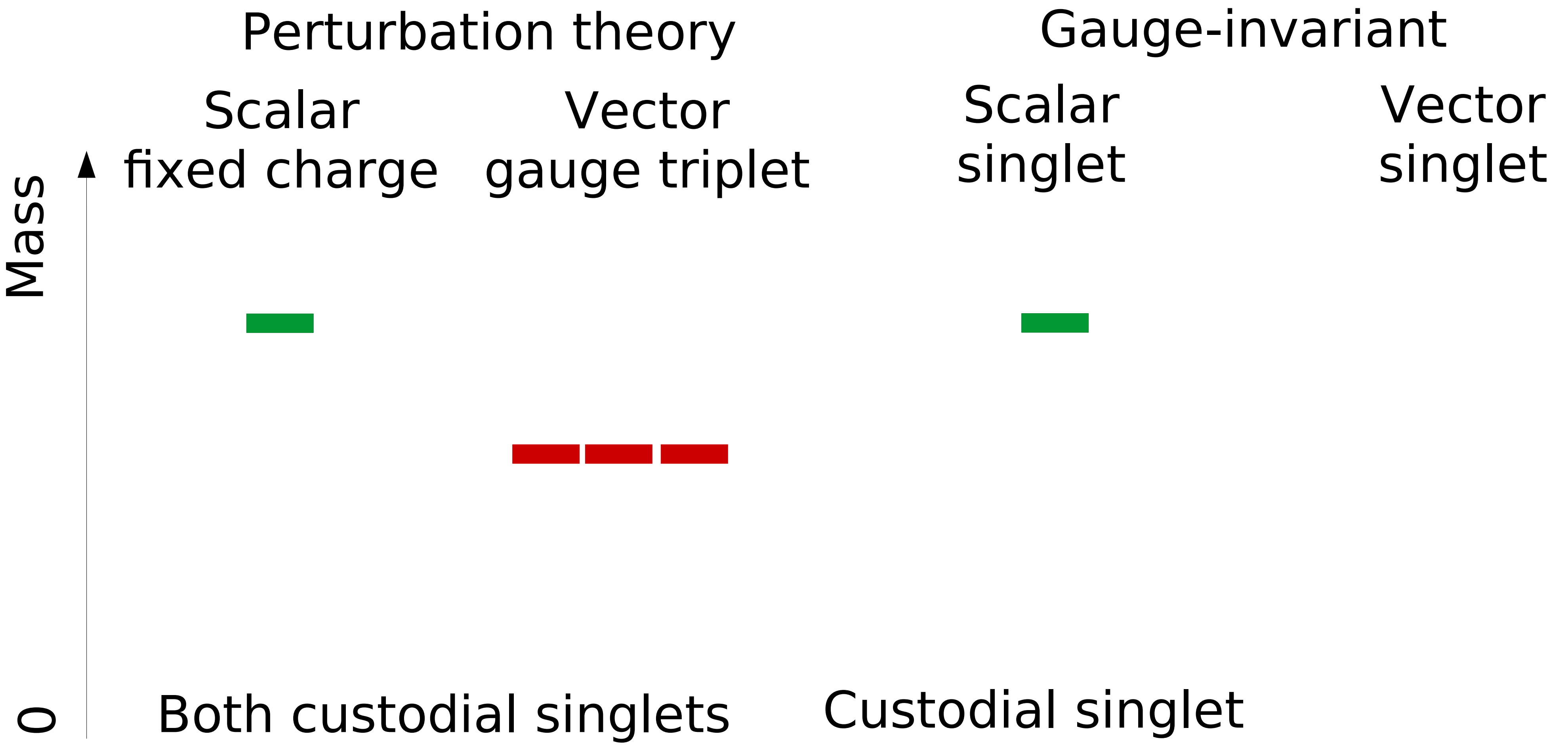

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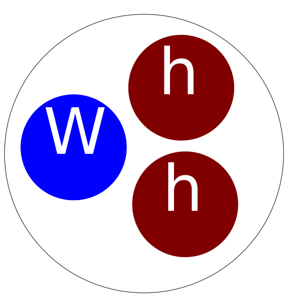


Physical spectrum

[Maas'12, Maas & Mufti'14]

Perturbation theory

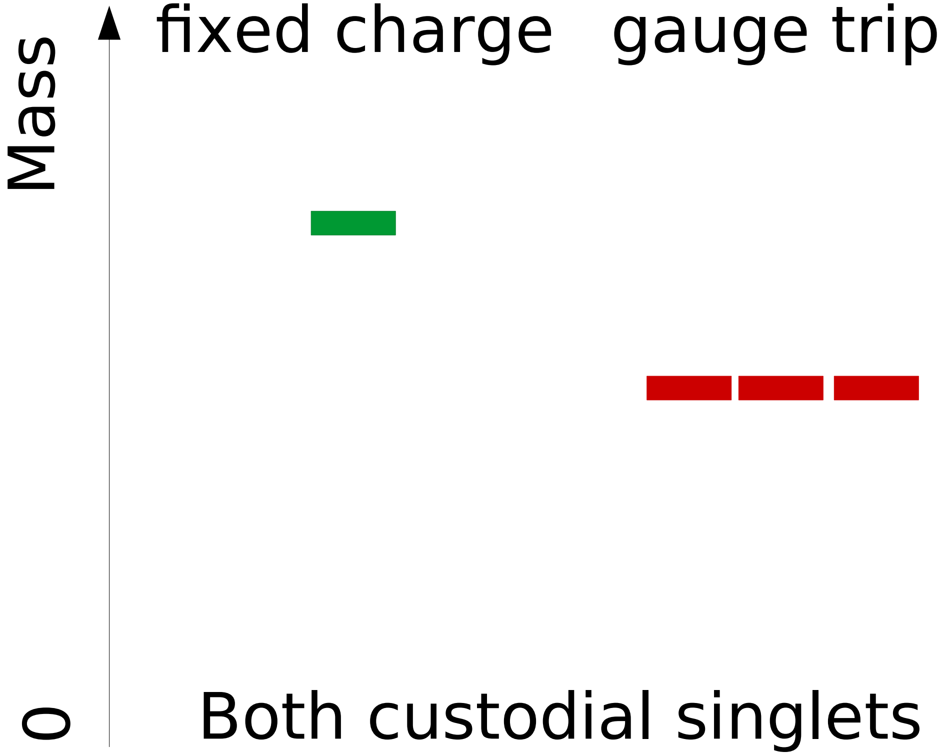
Scalar fixed charge

Vector gauge triplet

Gauge-invariant

Scalar singlet

Vector singlet



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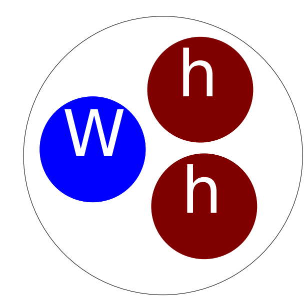

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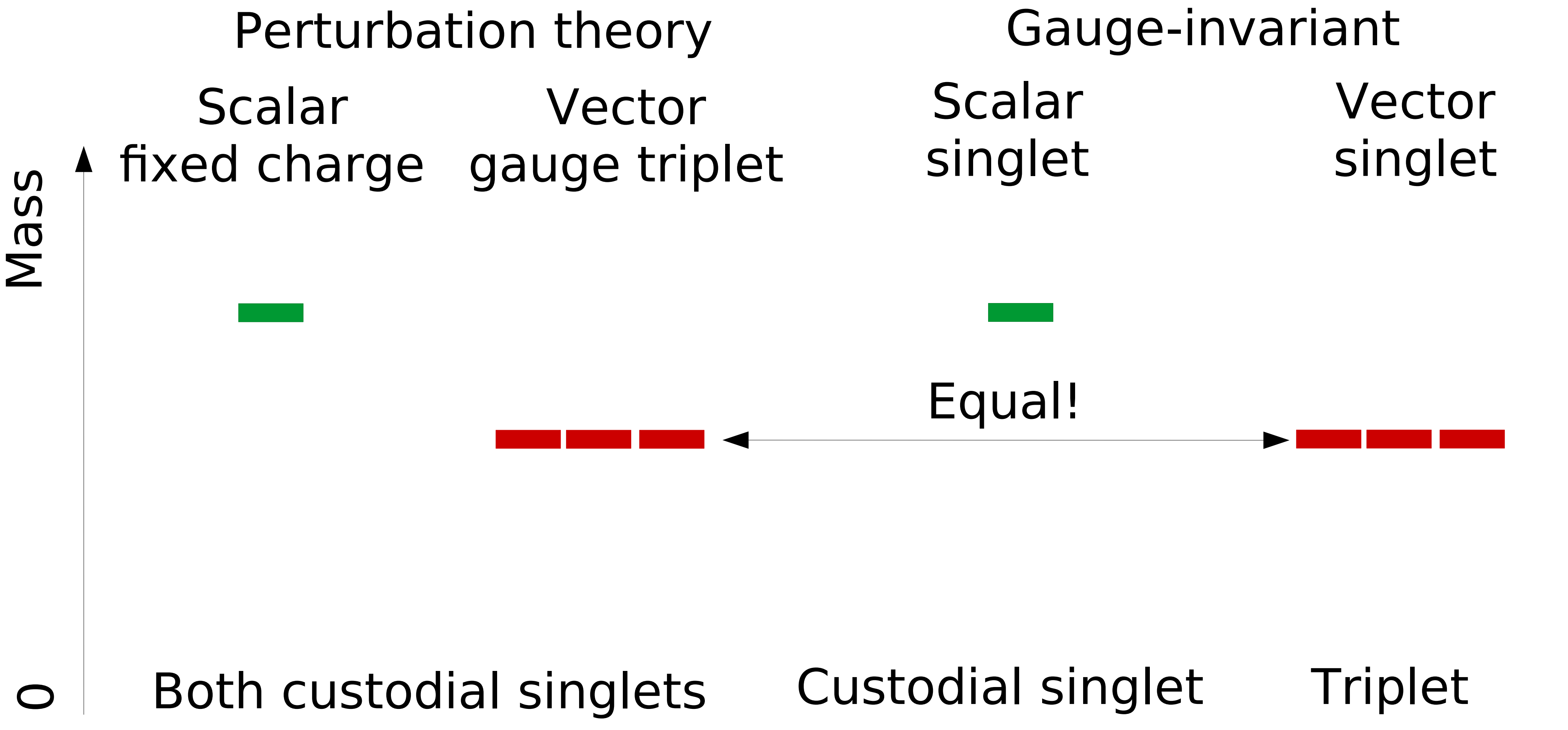

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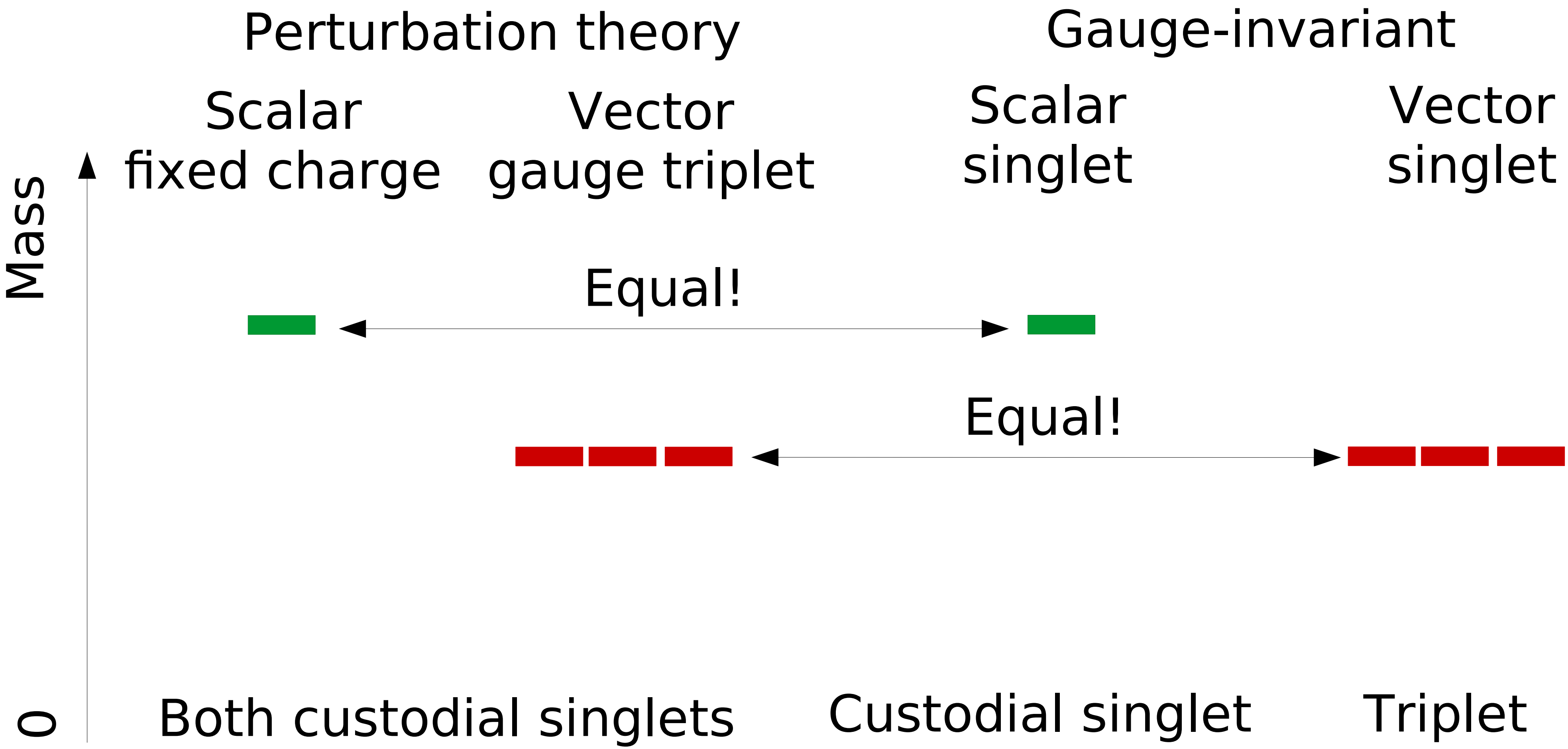

Why?

A microscopic origin
-
Fröhlich-Morchio-Strocchi mechanism

How to make predictions

[Fröhlich et al.'80,'81,
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Maas & Sondenheimer '20]

- J^{PC} and custodial charge only quantum numbers
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  - Bound state structure – non-perturbative methods?
  - 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]

1) Formulate gauge-invariant operator

Augmented perturbation theory

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

Higgs field

Augmented perturbation theory

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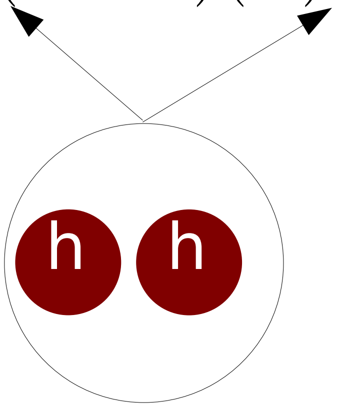

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Trivial two-particle state

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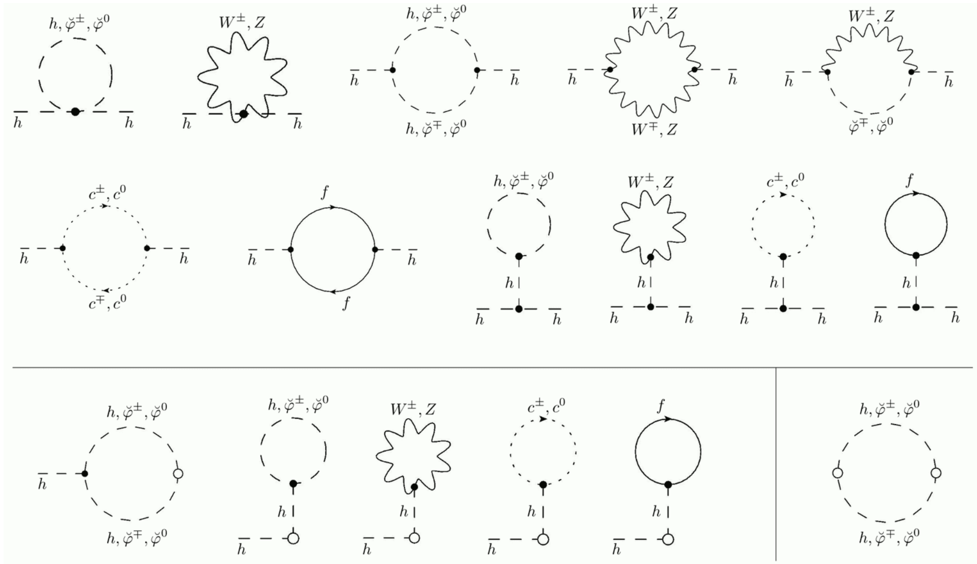

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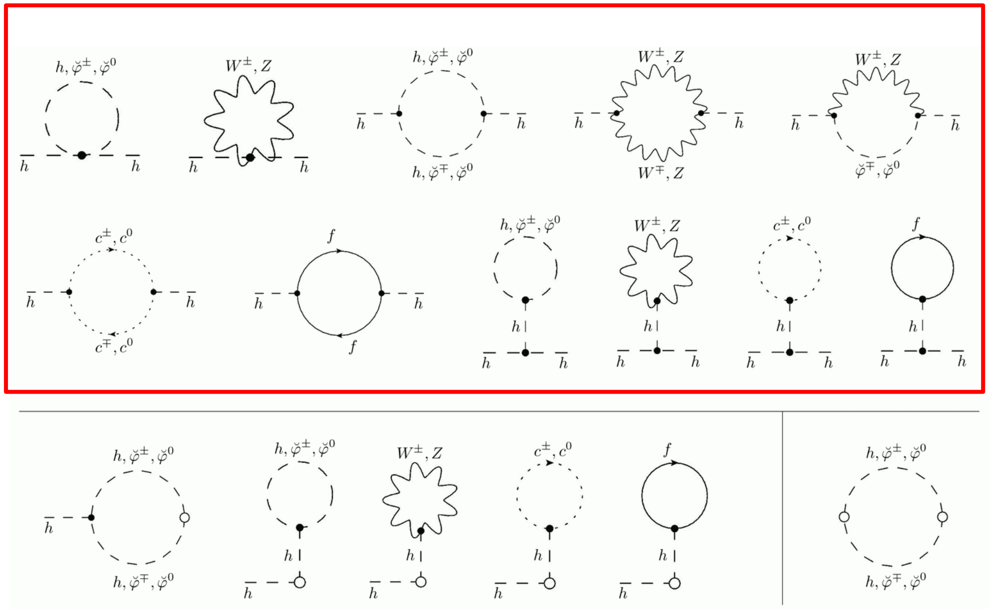

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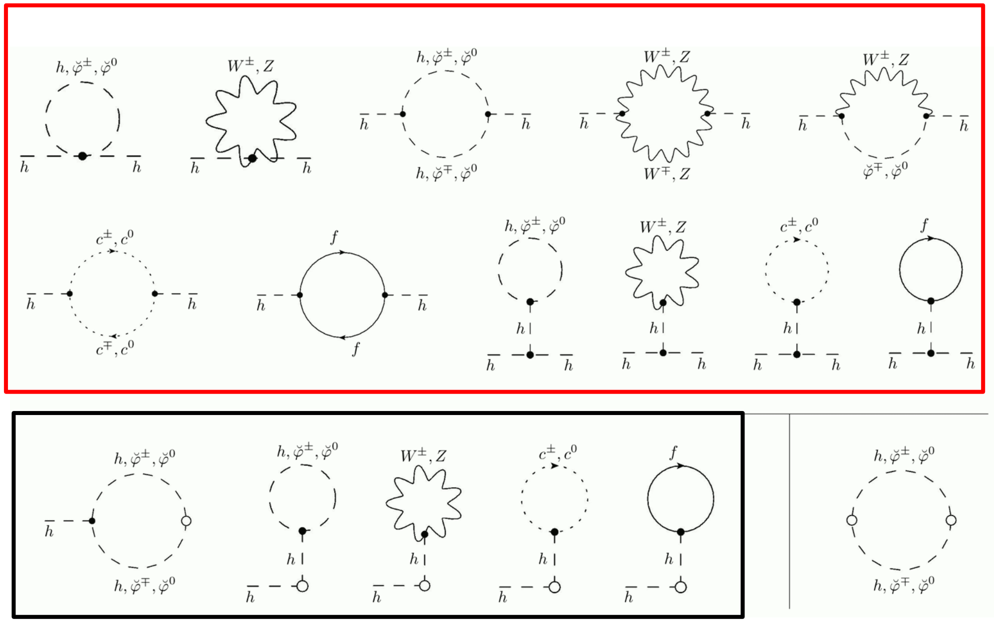

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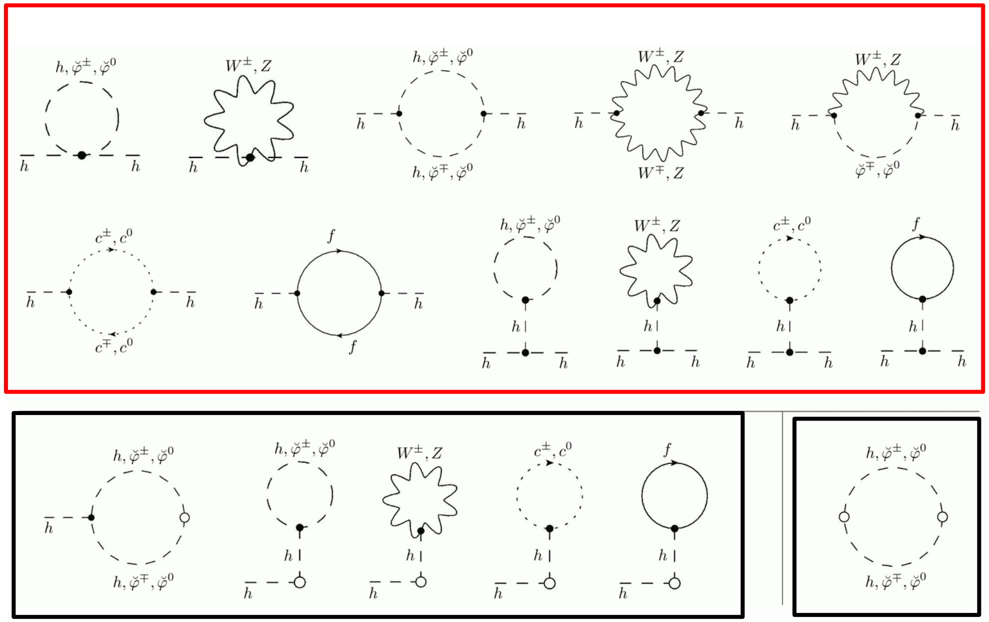

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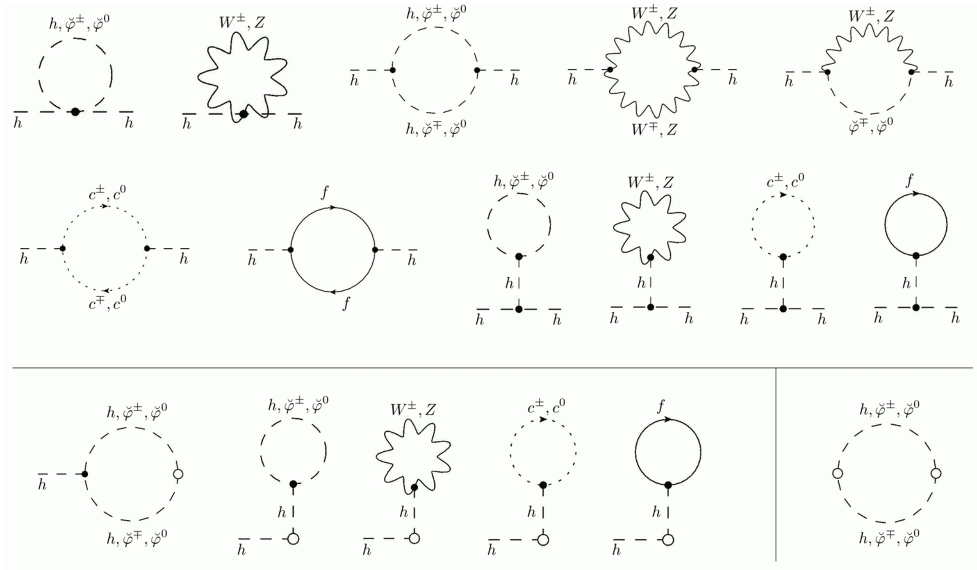

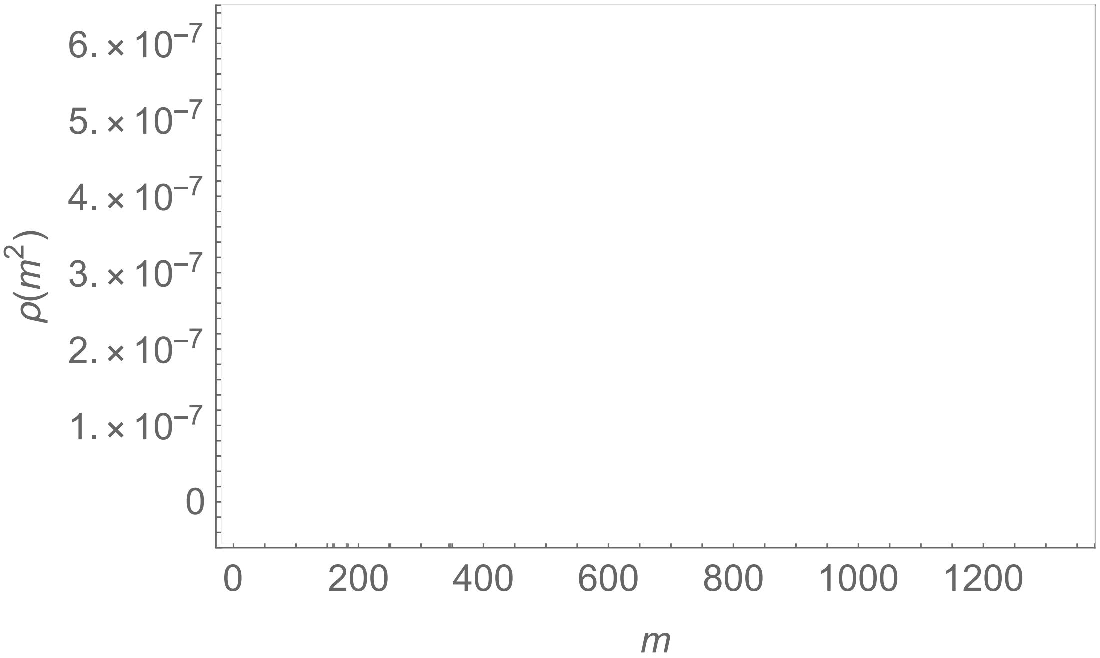

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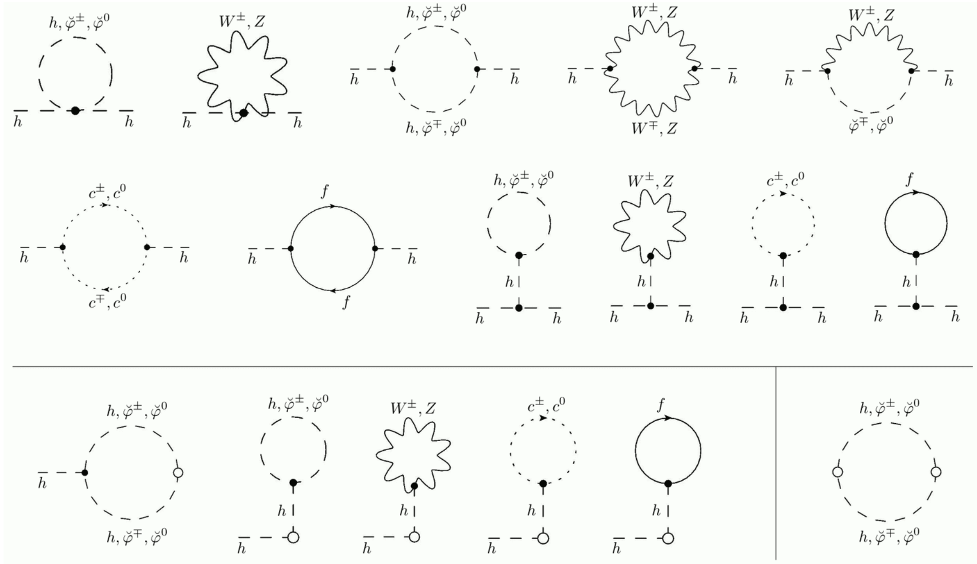

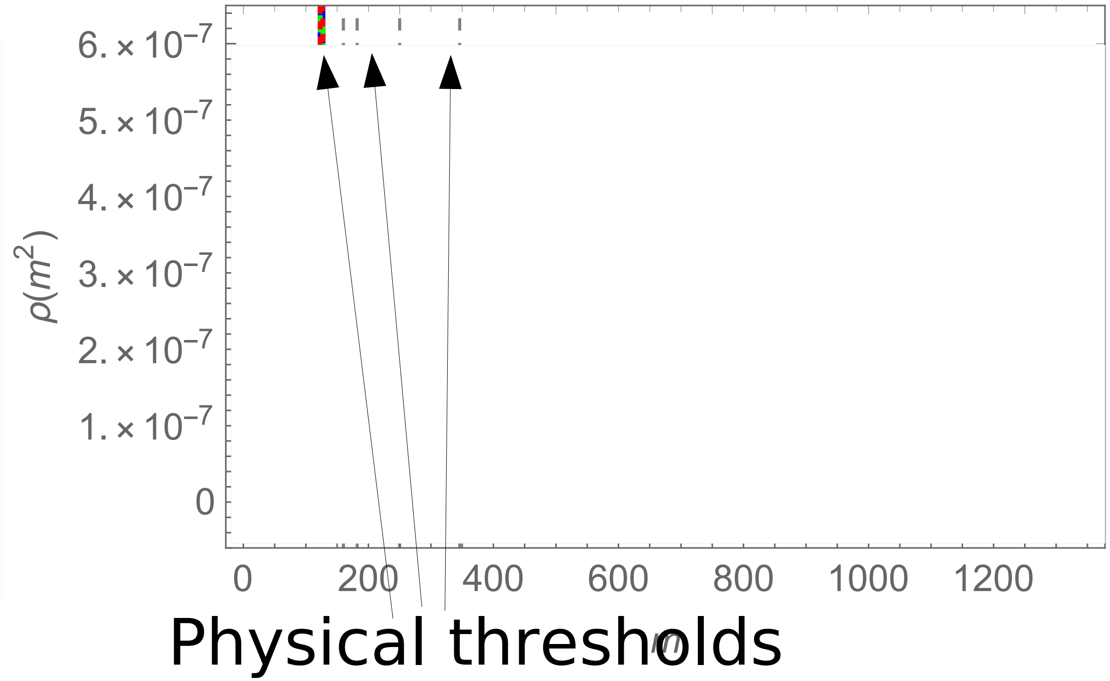

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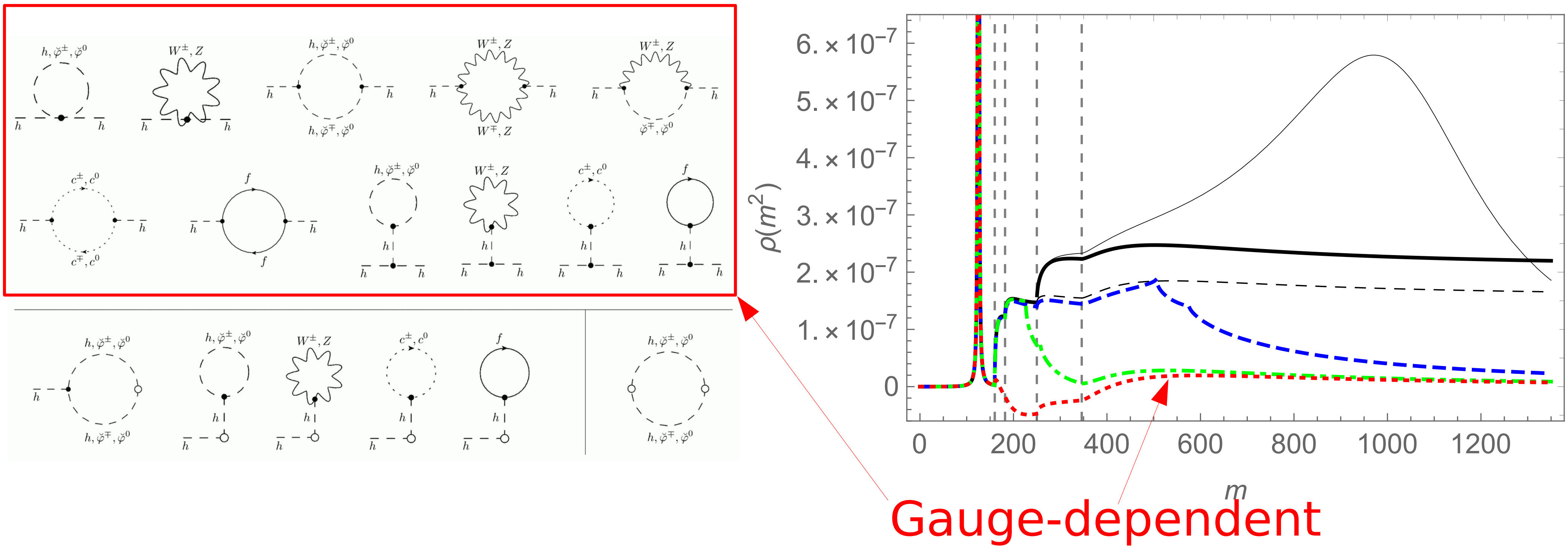

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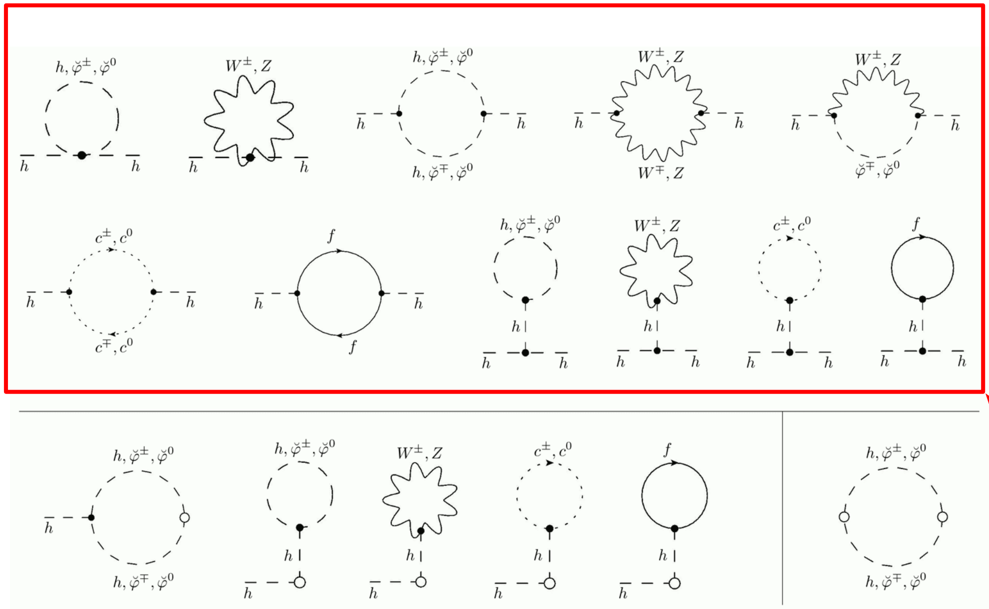

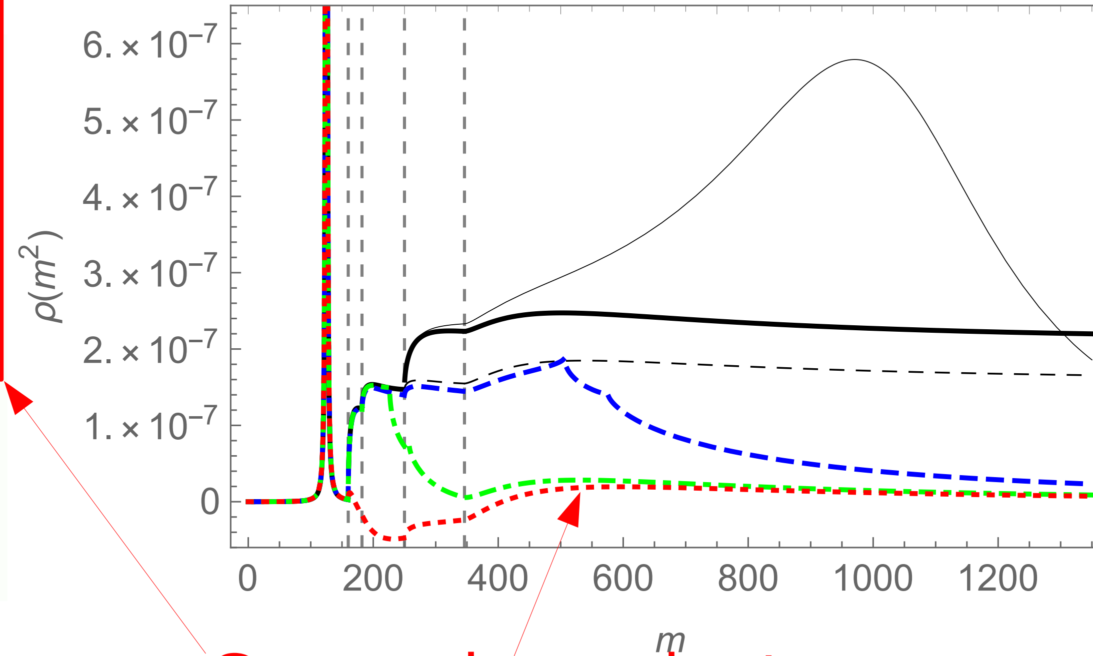

Gauge-dependent

Unphysical features:

Positivity violation

Additional thresholds

Consequences: The Higgs

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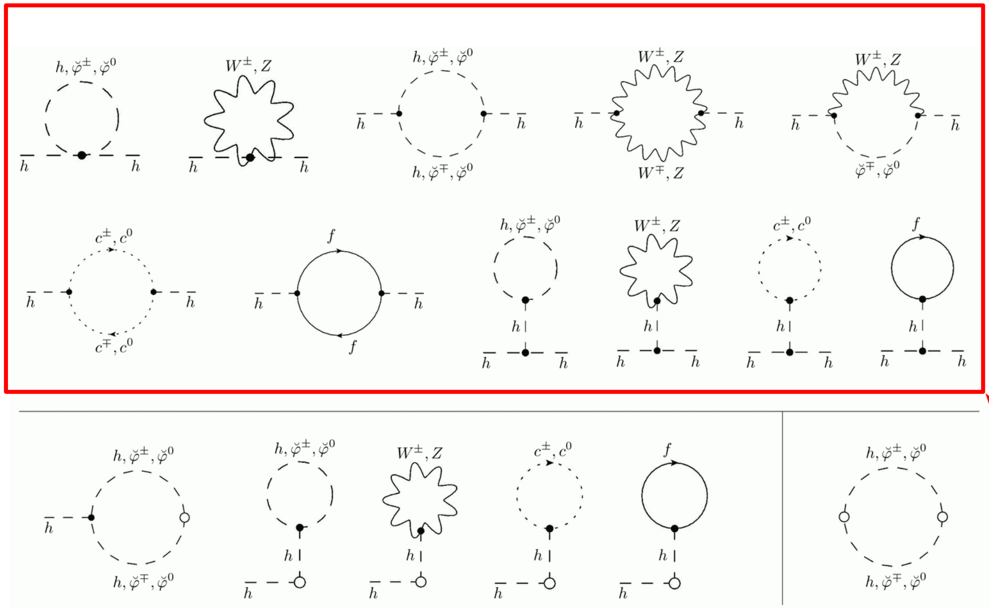

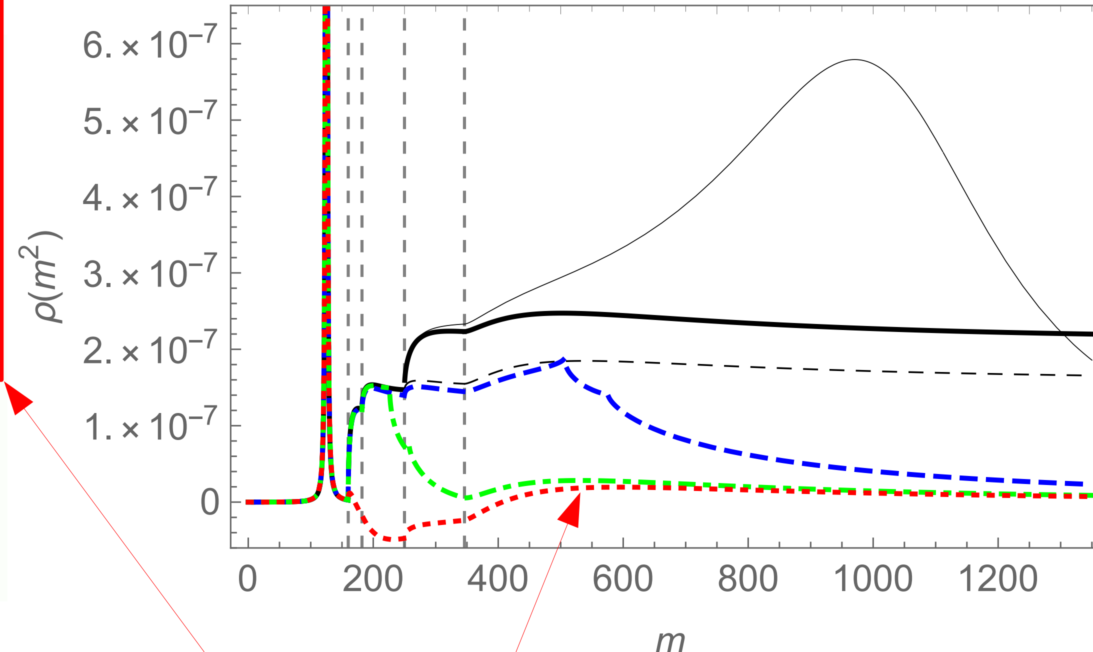

Gauge-dependent
Unphysical features:
Positivity violation
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Not a consequence of instability: Occurs even for an asymptotically stable Higgs in a toy theory

Consequences: The Higgs

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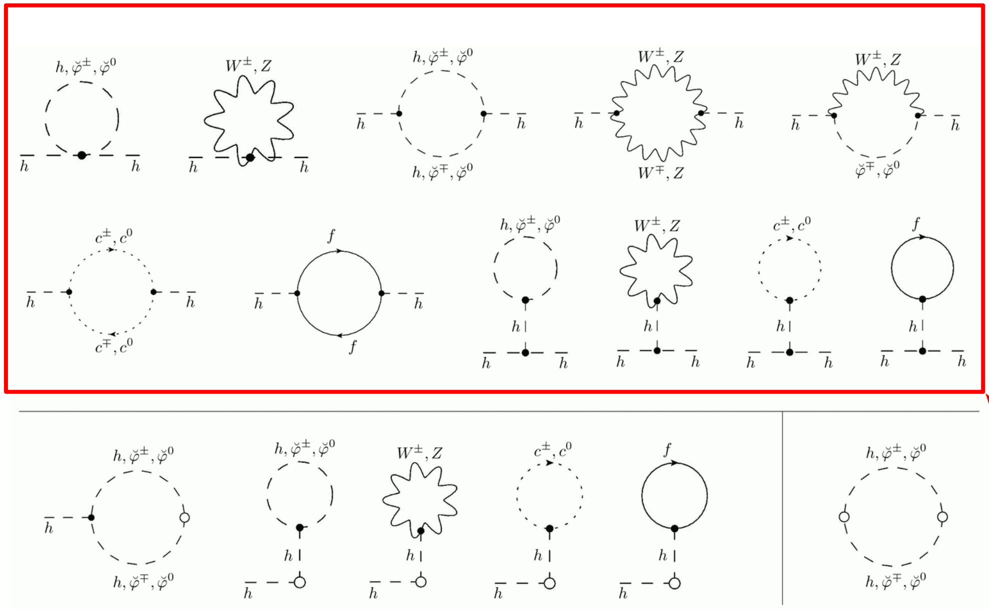

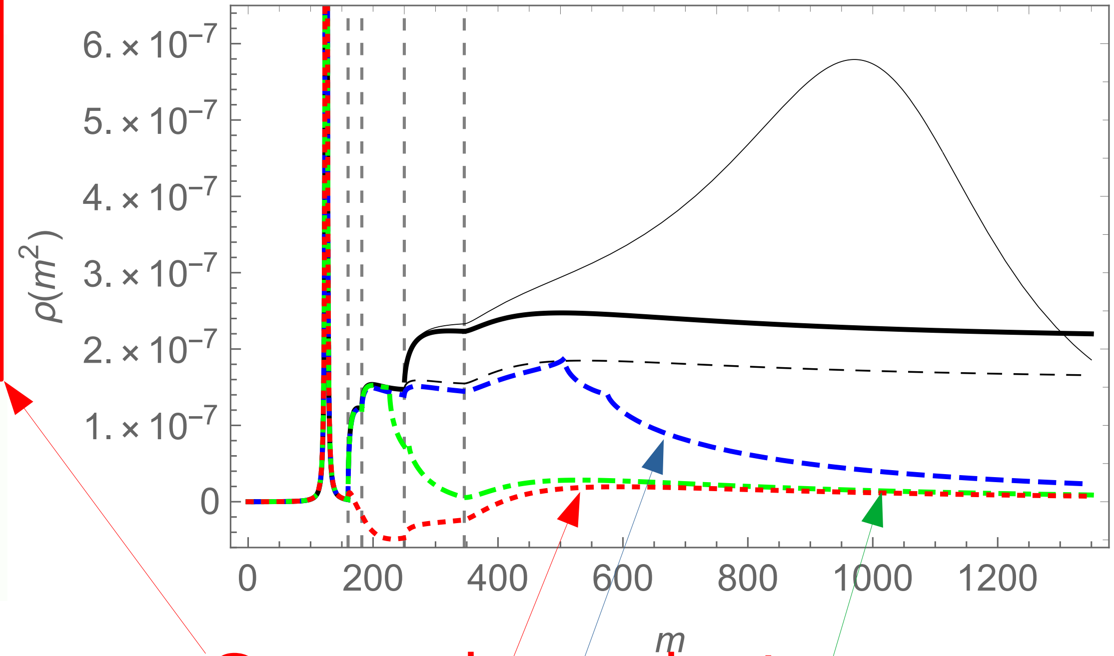

Gauge-dependent
Other gauge choices

Consequences: The Higgs

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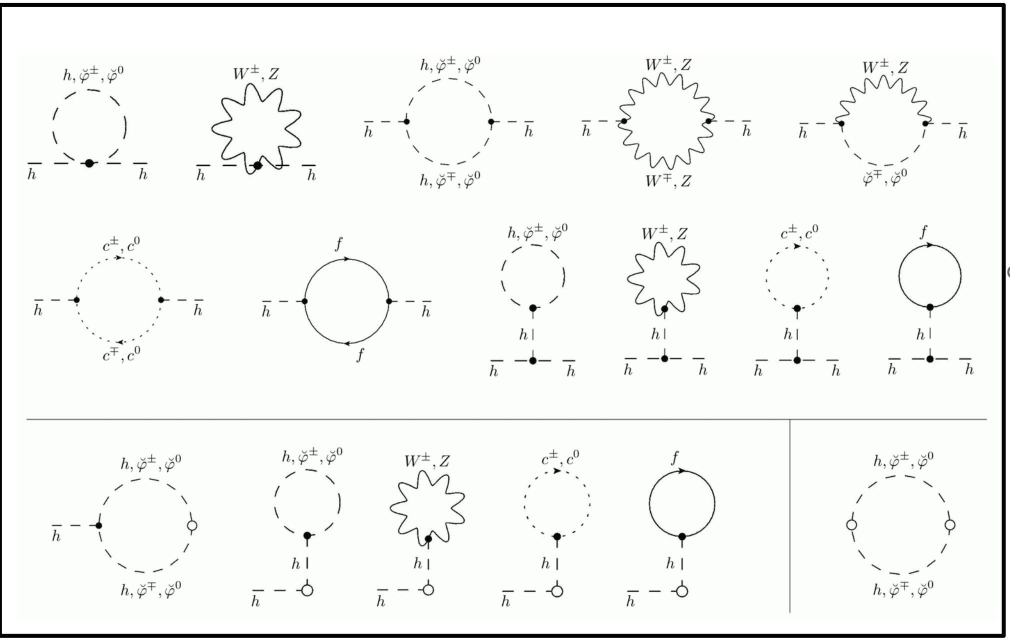

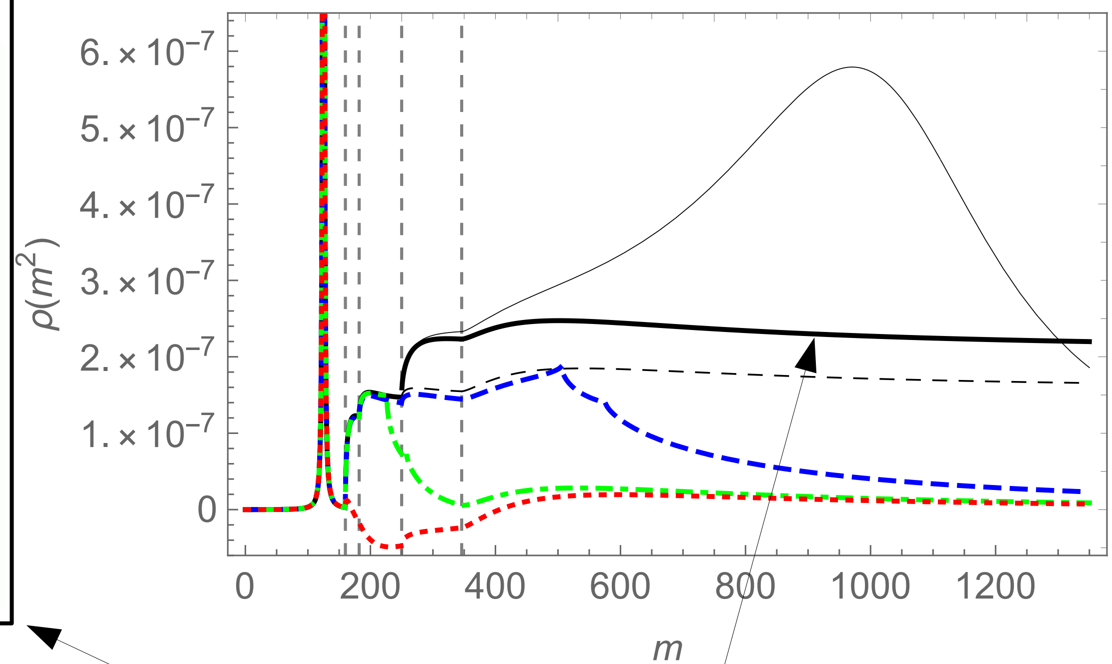

Physical – same for all gauge choices

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What about the vector?

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Exactly one gauge boson for every physical state

Phenomenological Implications
-
Can we measure this?

Bound states as extended objects

Bound states as extended objects

- Two possibilities to measure extension

Bound states as extended objects

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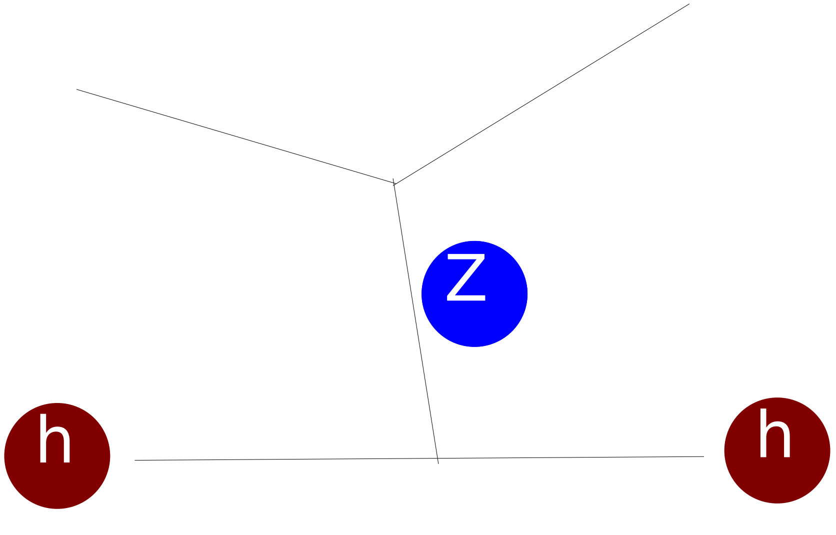
  - Form factor
    - Difficult
      - Higgs and Z need to be both produced in the same process

[Maas, Raubitzek, Törek'18]



Bound states as extended objects

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    - Standard vector boson scattering process at low energies
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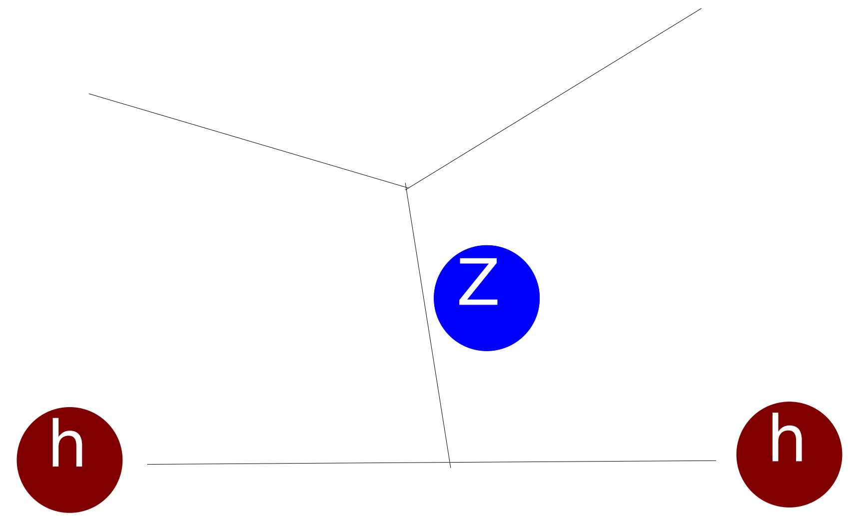

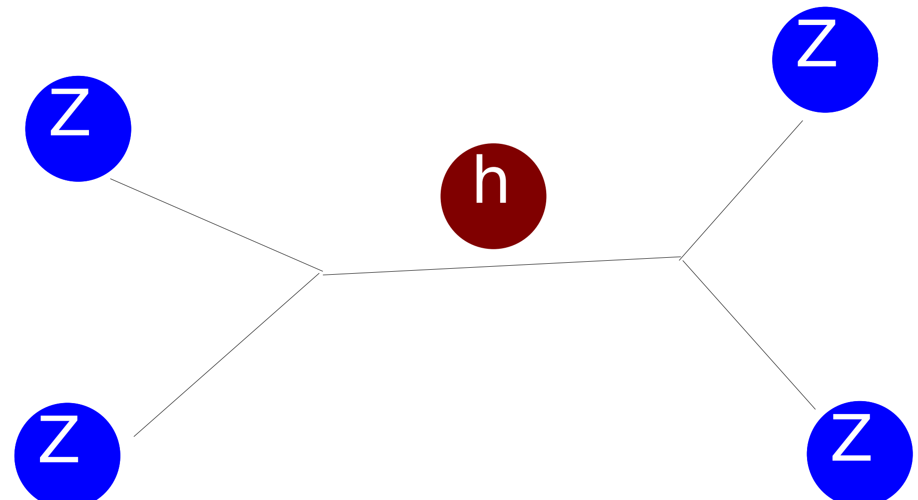

[Jenny, Maas, Riederer’22]

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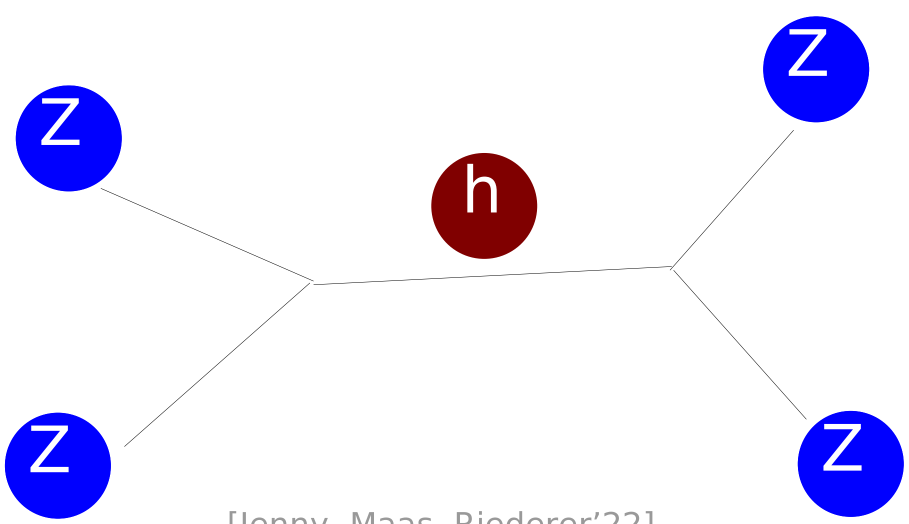

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Radius from elastic scattering in VBS

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Legendre polynom

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Scattering length~"size"

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→ Lattice Lüscher analysis

Impact of a finite size of the Higgs

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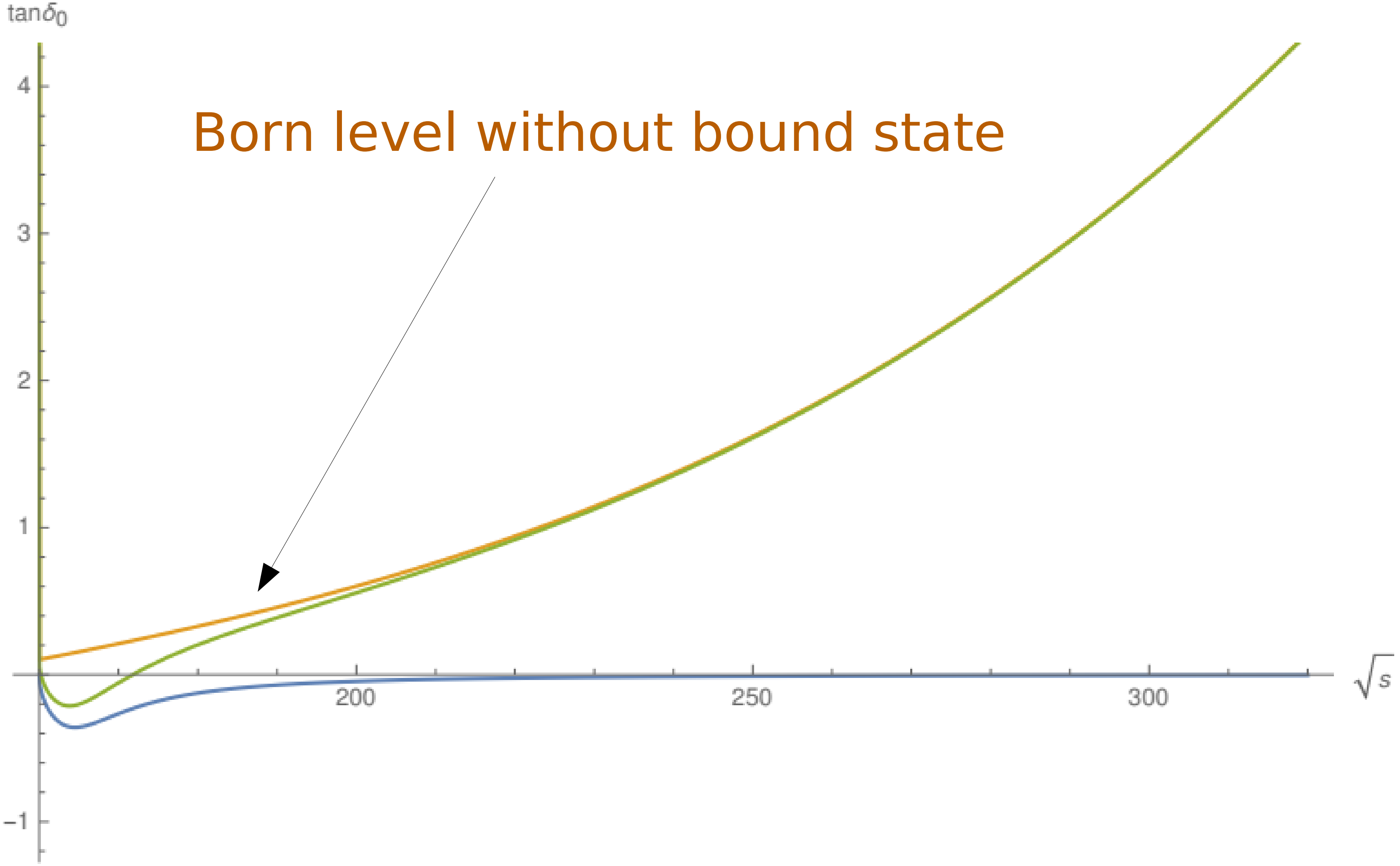

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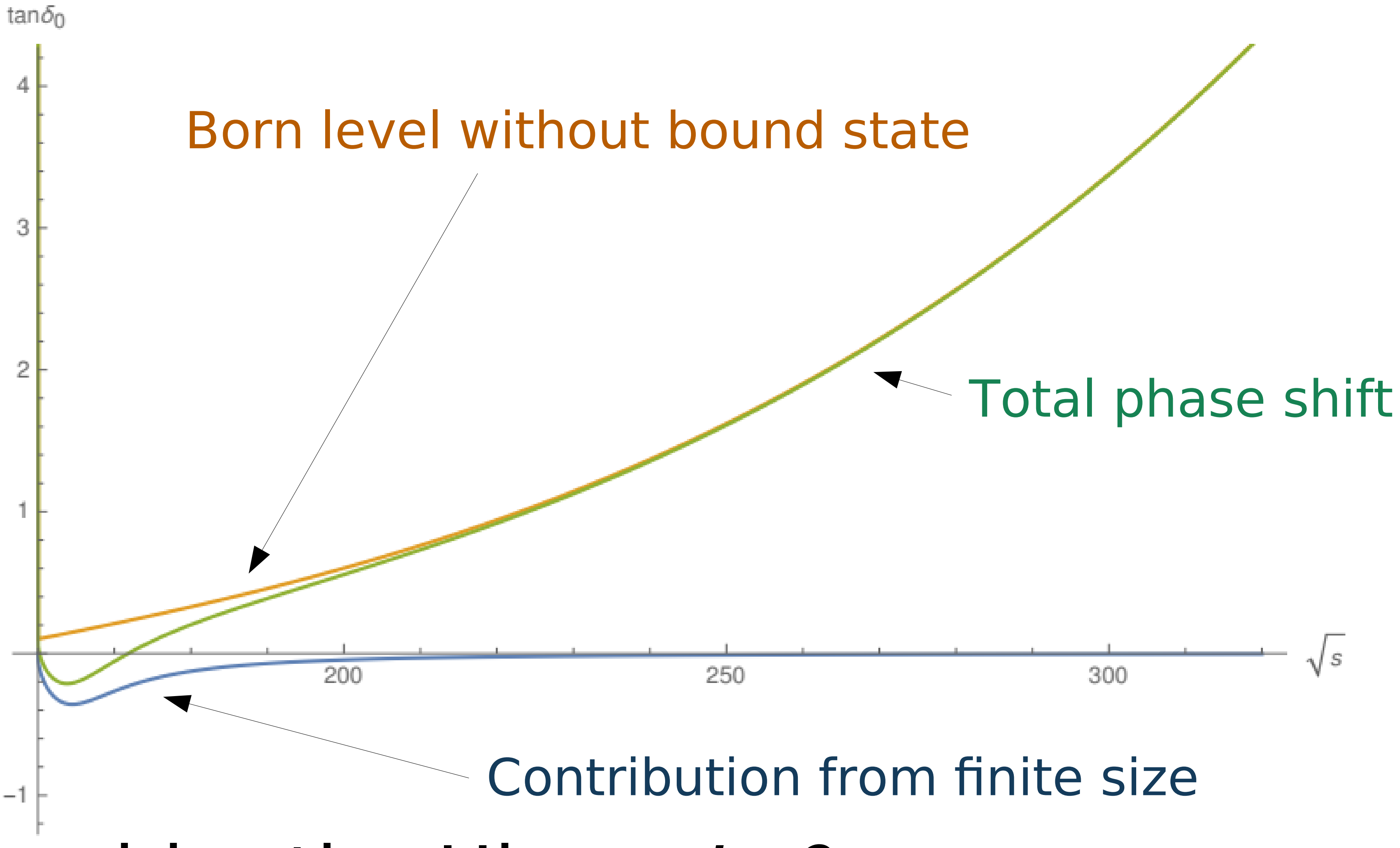

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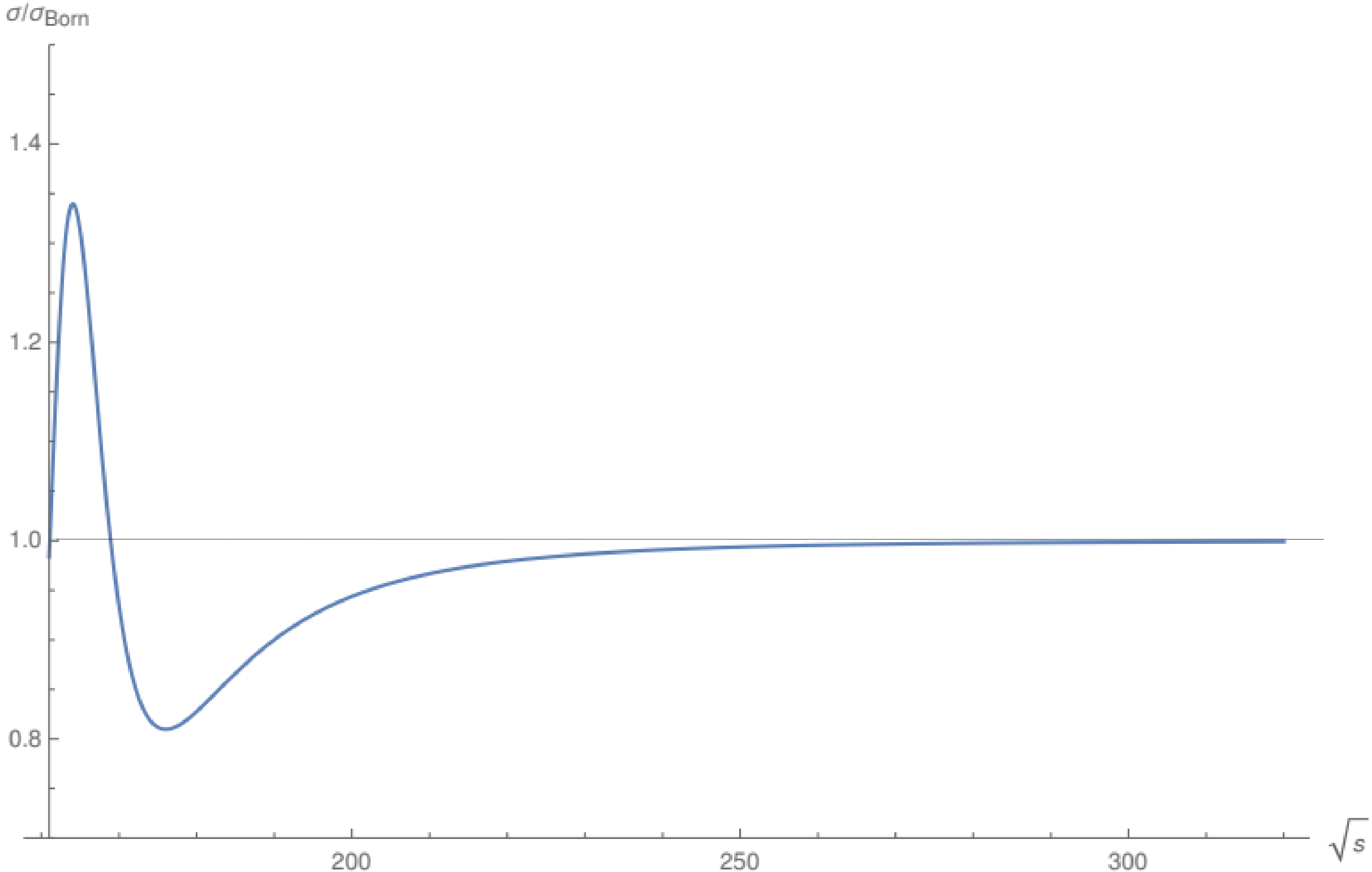

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Impact on the radius of the Higgs

- Reduced SM: Only W/Z and the Higgs
  - Parameters slightly different
    - Higgs 145 GeV and weak coupling larger

[Jenny, Maas, Riederer'22]

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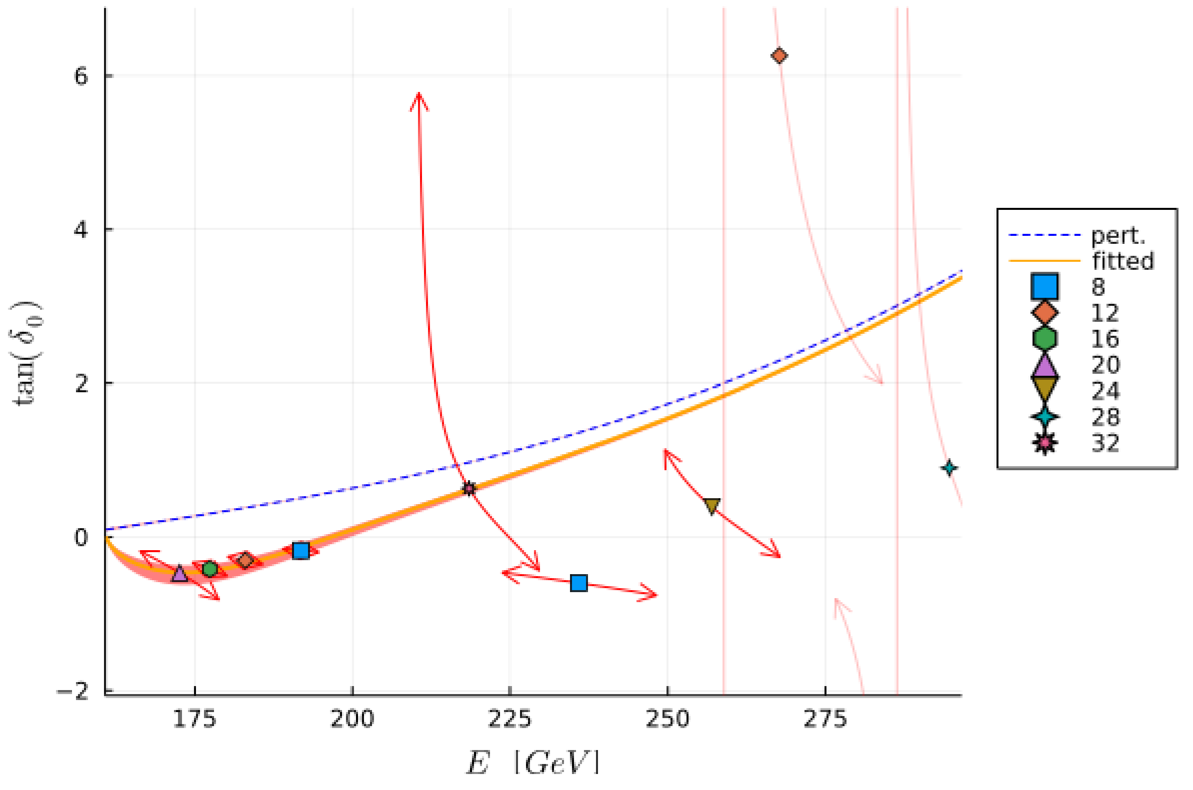

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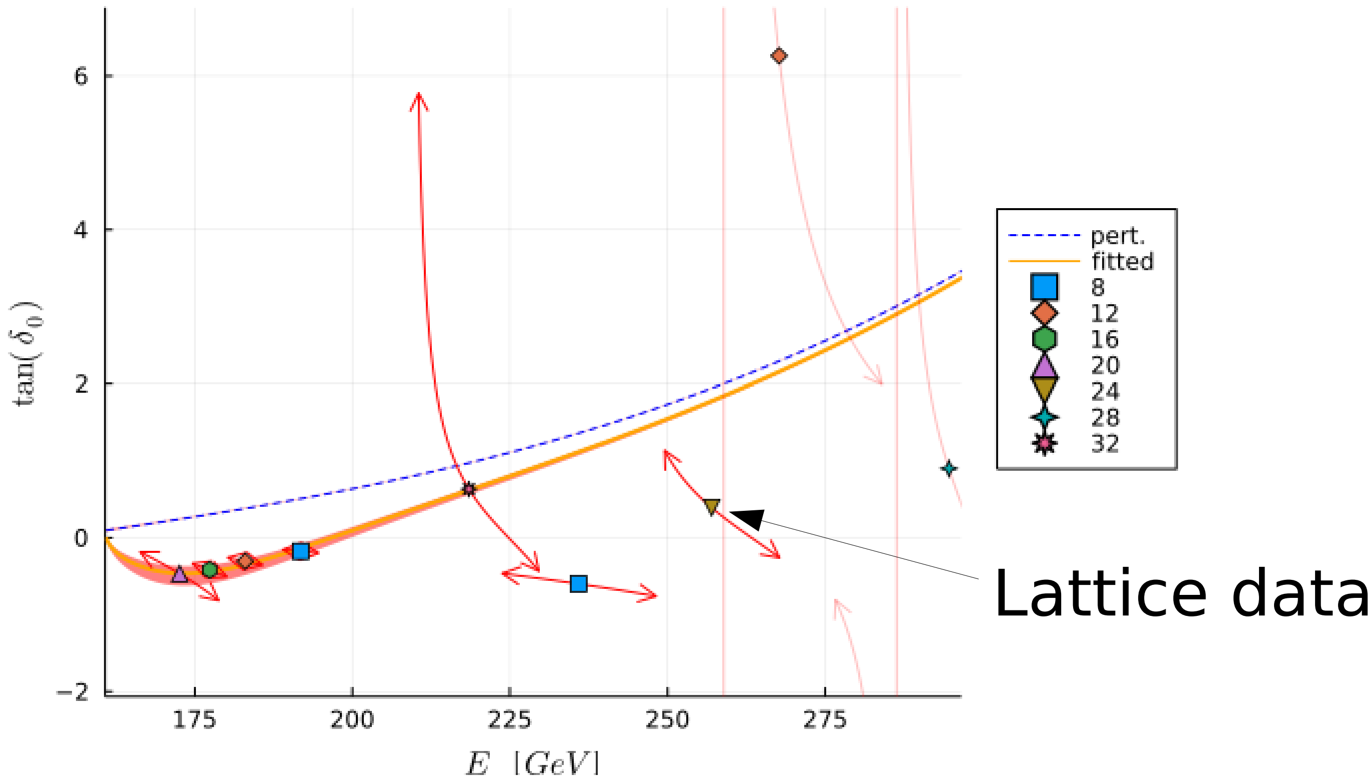

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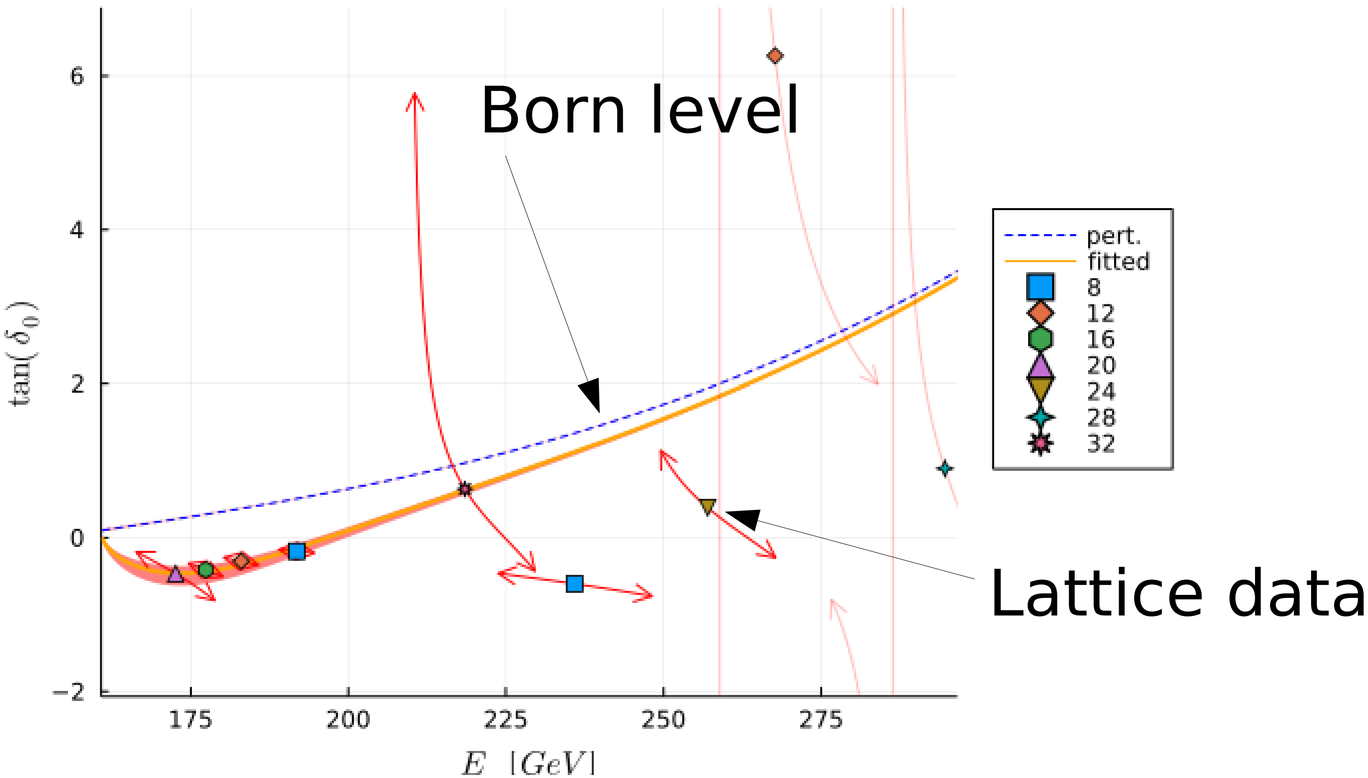

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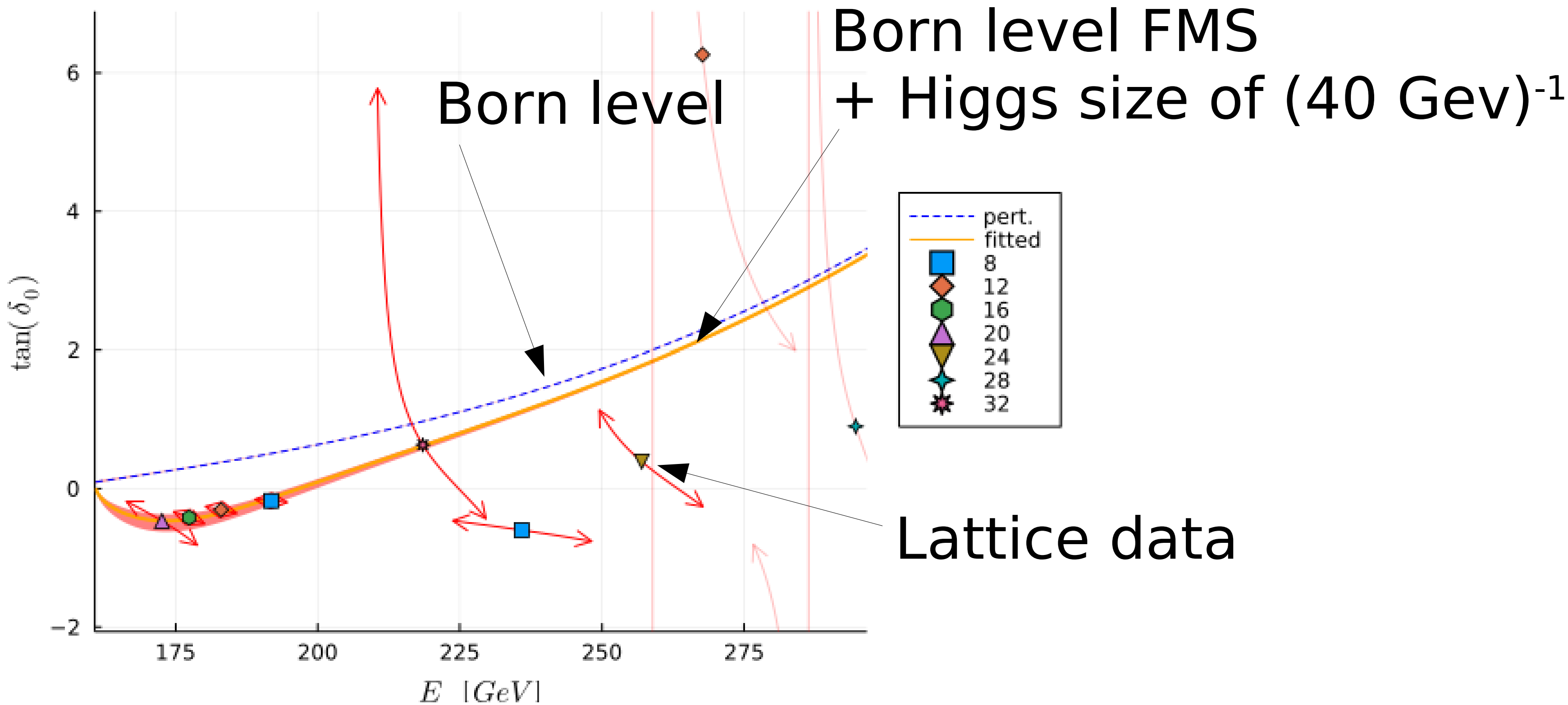

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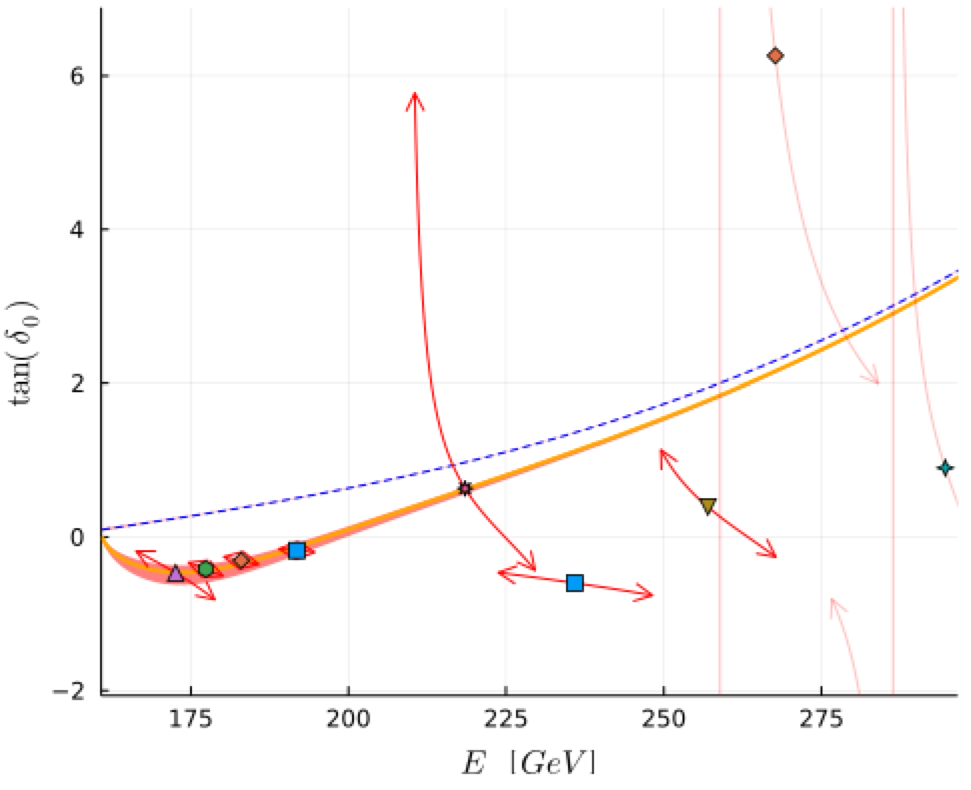

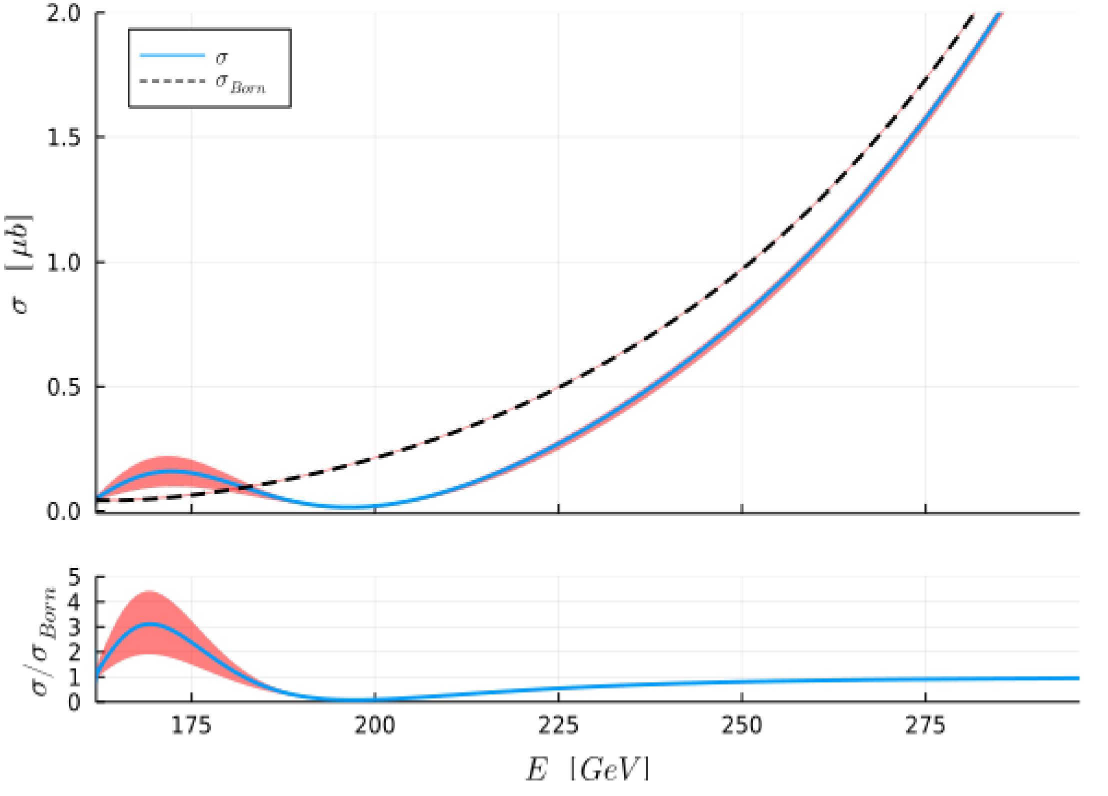

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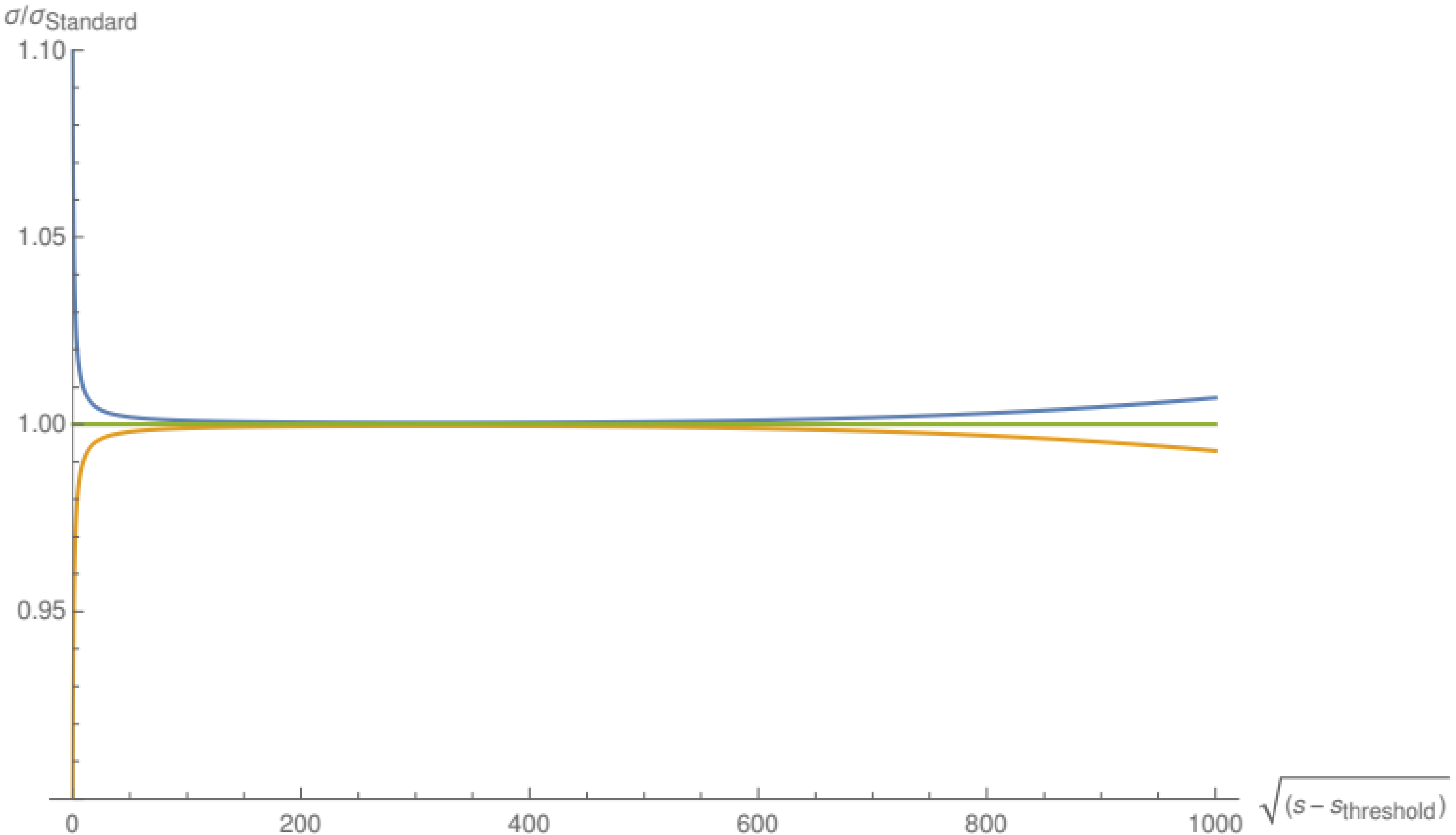
Generic behavior

Has been done for several observables

Generic behavior: DIS-like



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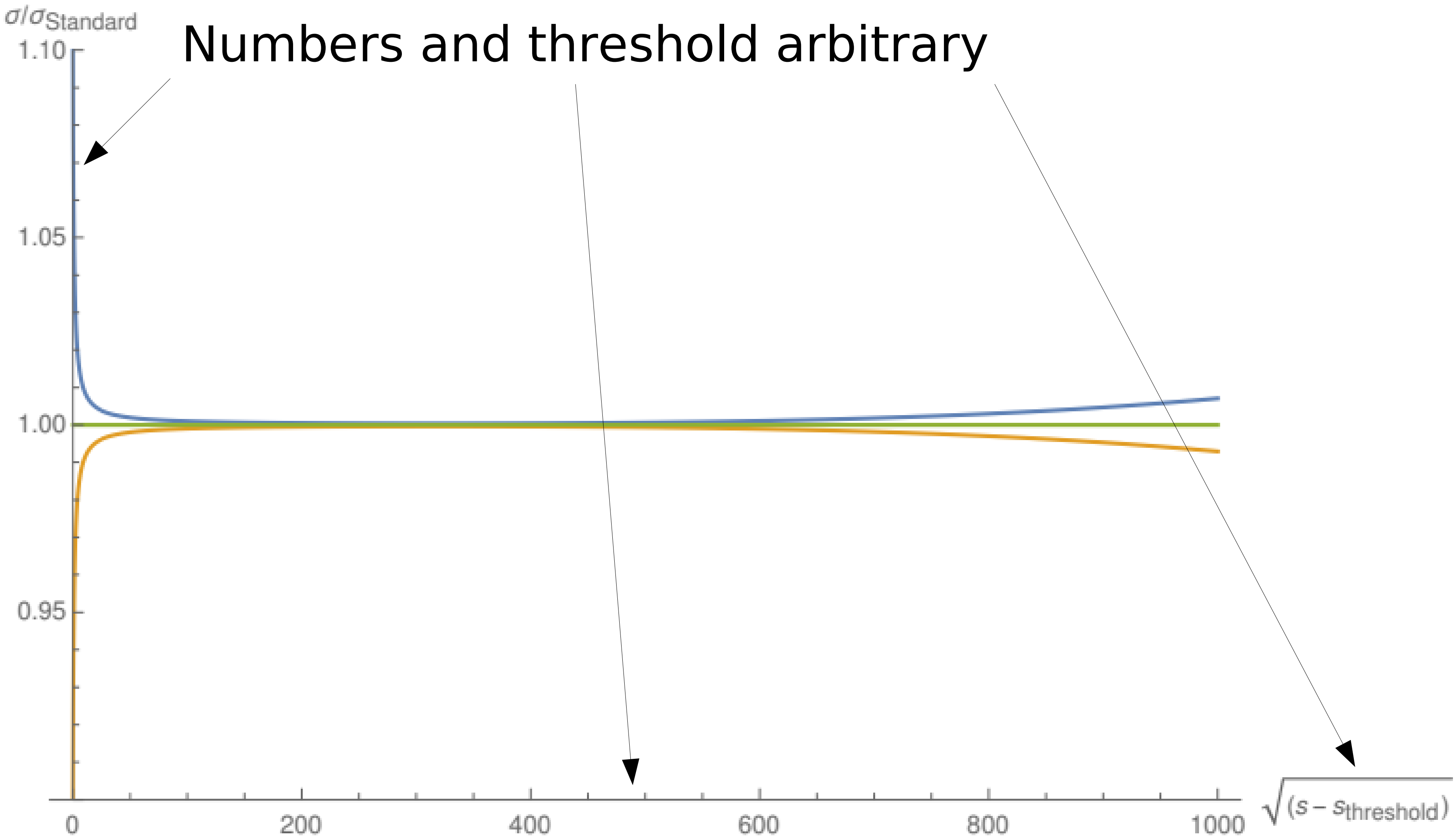
Generic behavior: DIS-like

Numbers and threshold arbitrary



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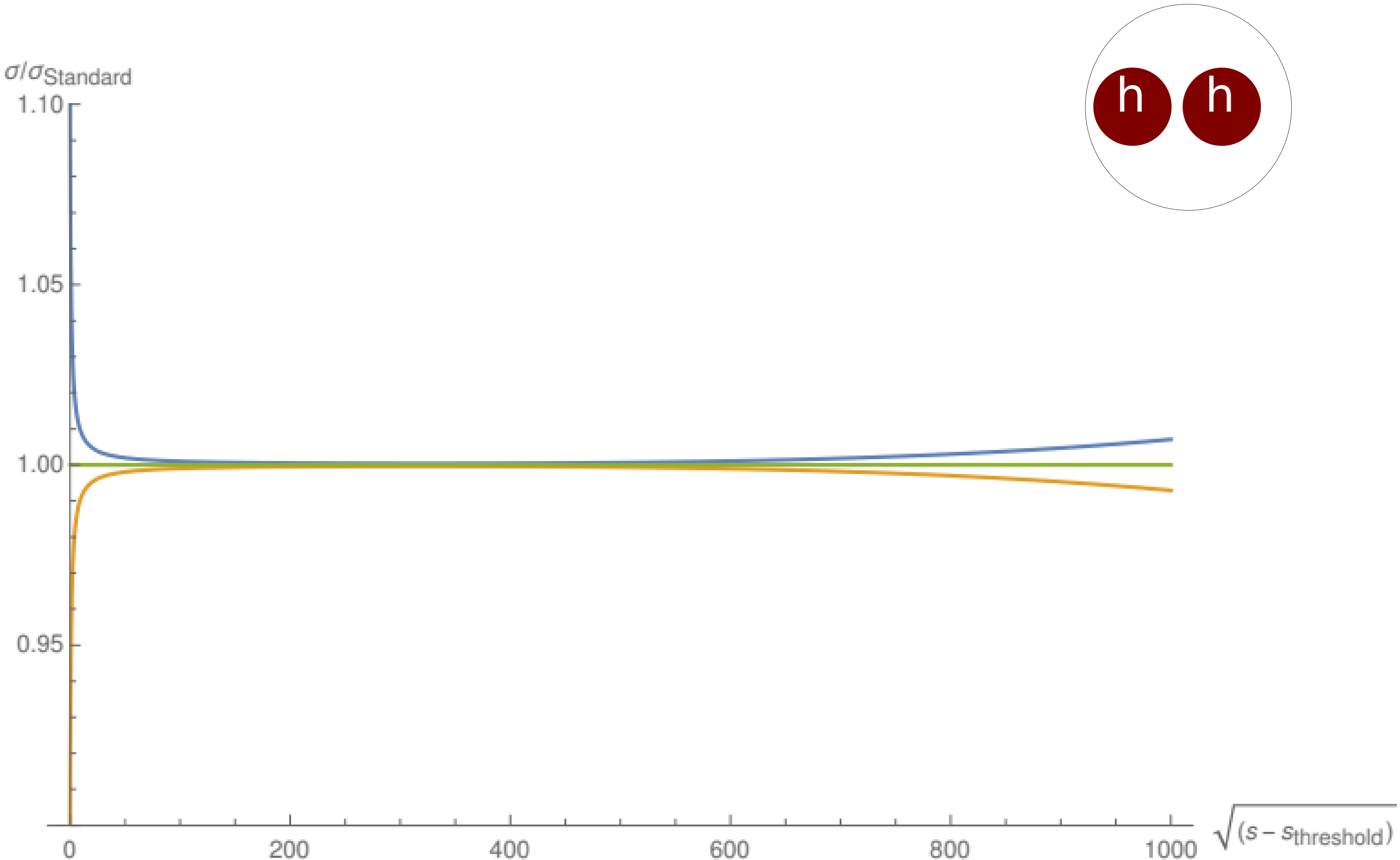

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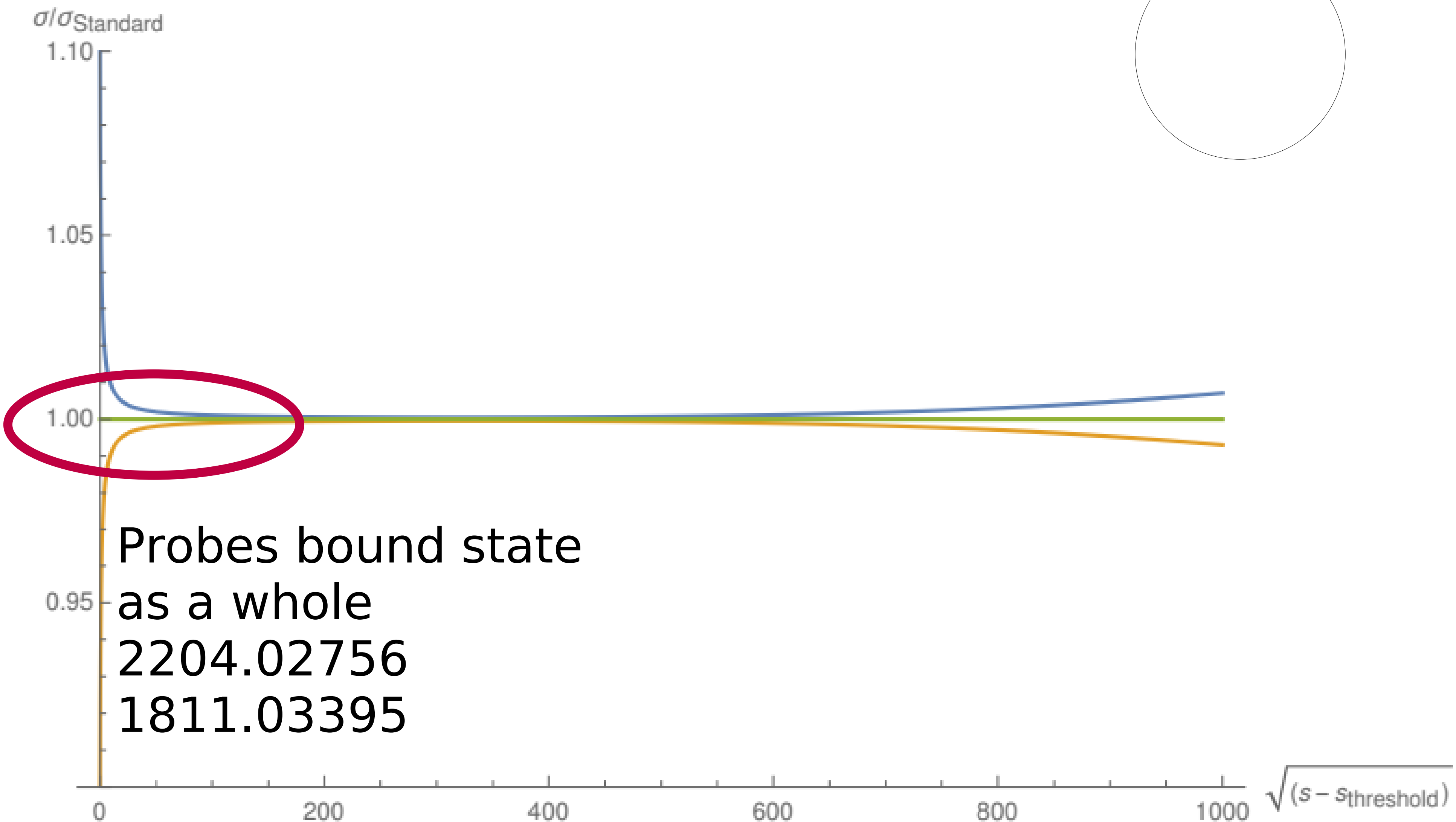
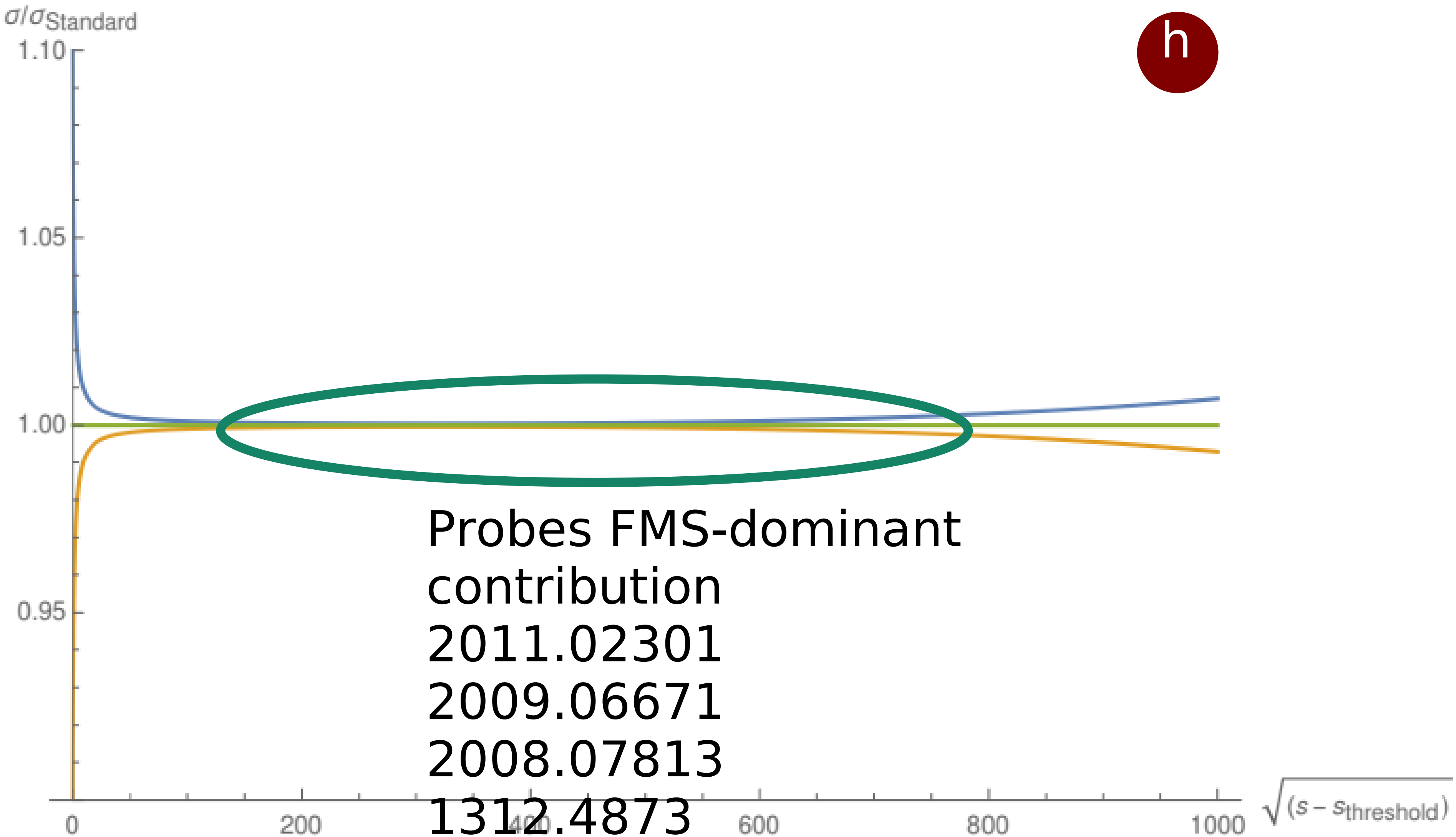


Probes bound state
as a whole
2204.02756
1811.03395

Has been done for several observables

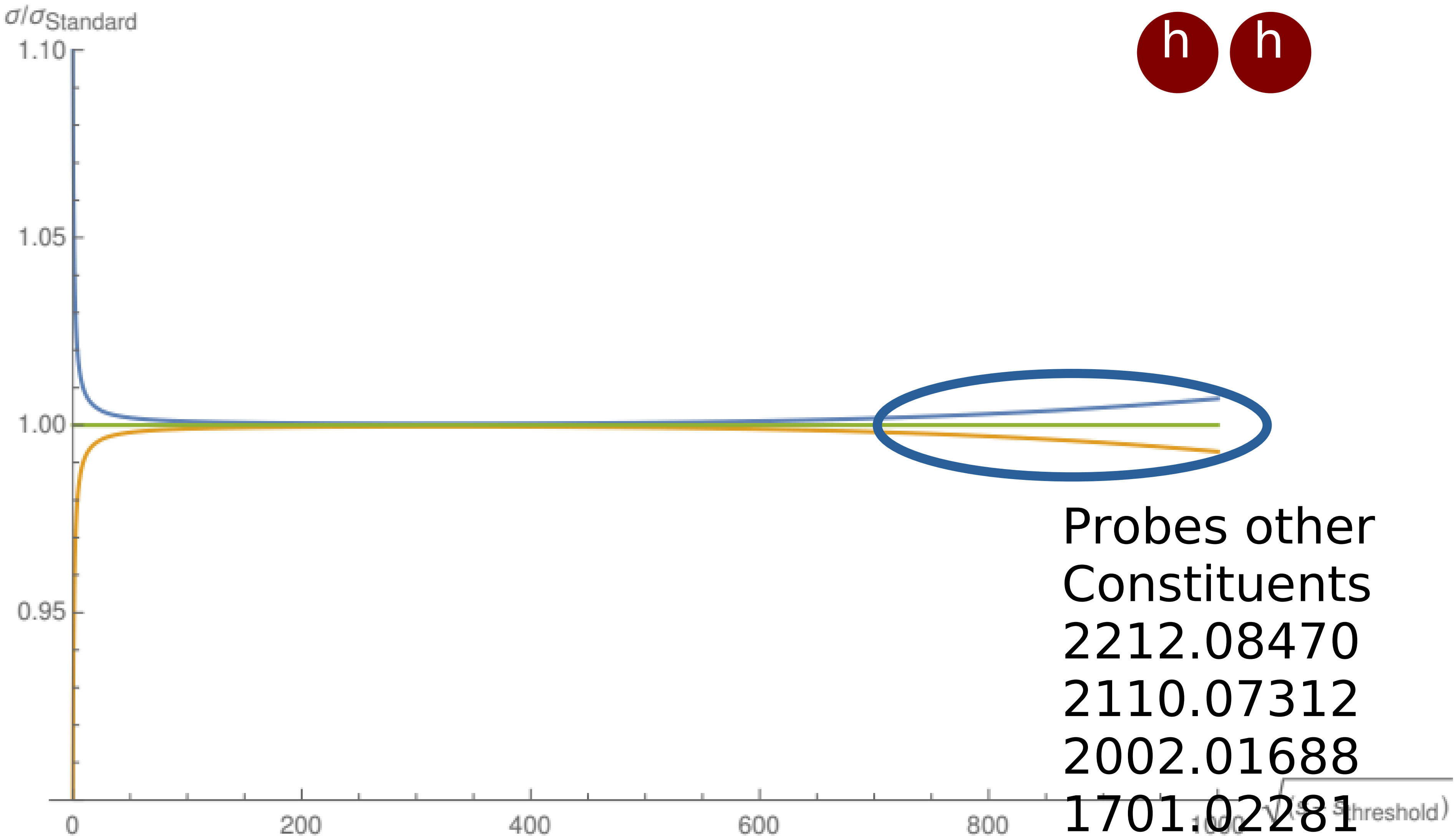
Generic behavior: DIS-like



Probes FMS-dominant contribution
2011.02301
2009.06671
2008.07813
1312.4873

Has been done for several observables

Generic behavior: DIS-like



Probes other
Constituents
2212.08470
2110.07312
2002.01688
1701.02281

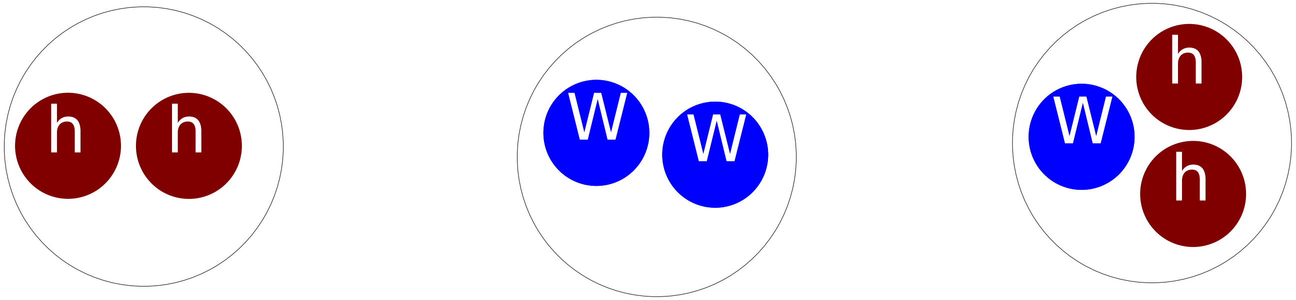
Has been done for several observables

Phenomenological Implications
-
Adding matter

Physical states

[Fröhlich et al.'80, Banks et al.'79]

- Need physical, 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!)
- Can this matter?

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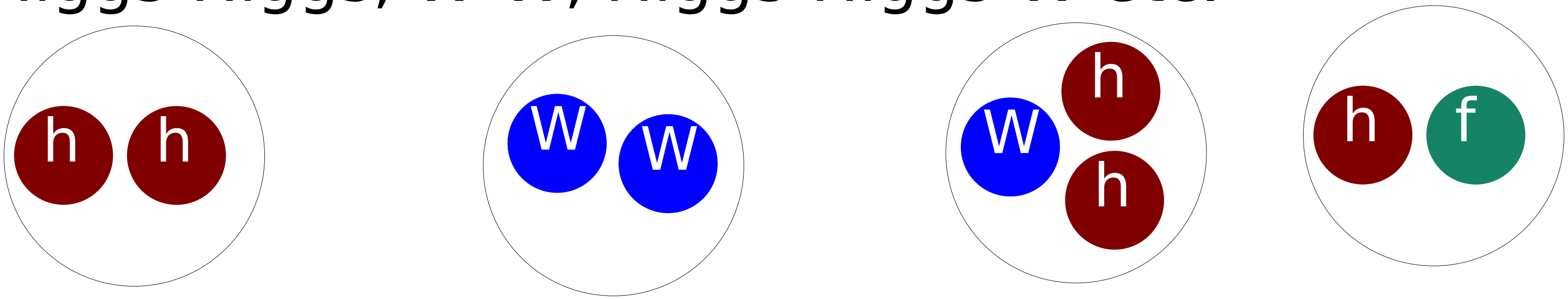

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Flavor

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

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

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$$\left(\begin{pmatrix} h_2 & -h_1 \\ h_1^* & h_2^* \end{pmatrix}\begin{pmatrix} \nu_L \\ l_L \end{pmatrix}\right)_i (x)$$

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[Afferrante,Maas,Sondenheimer,Törek'20]

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  - Compressed mass scales
  - One generation
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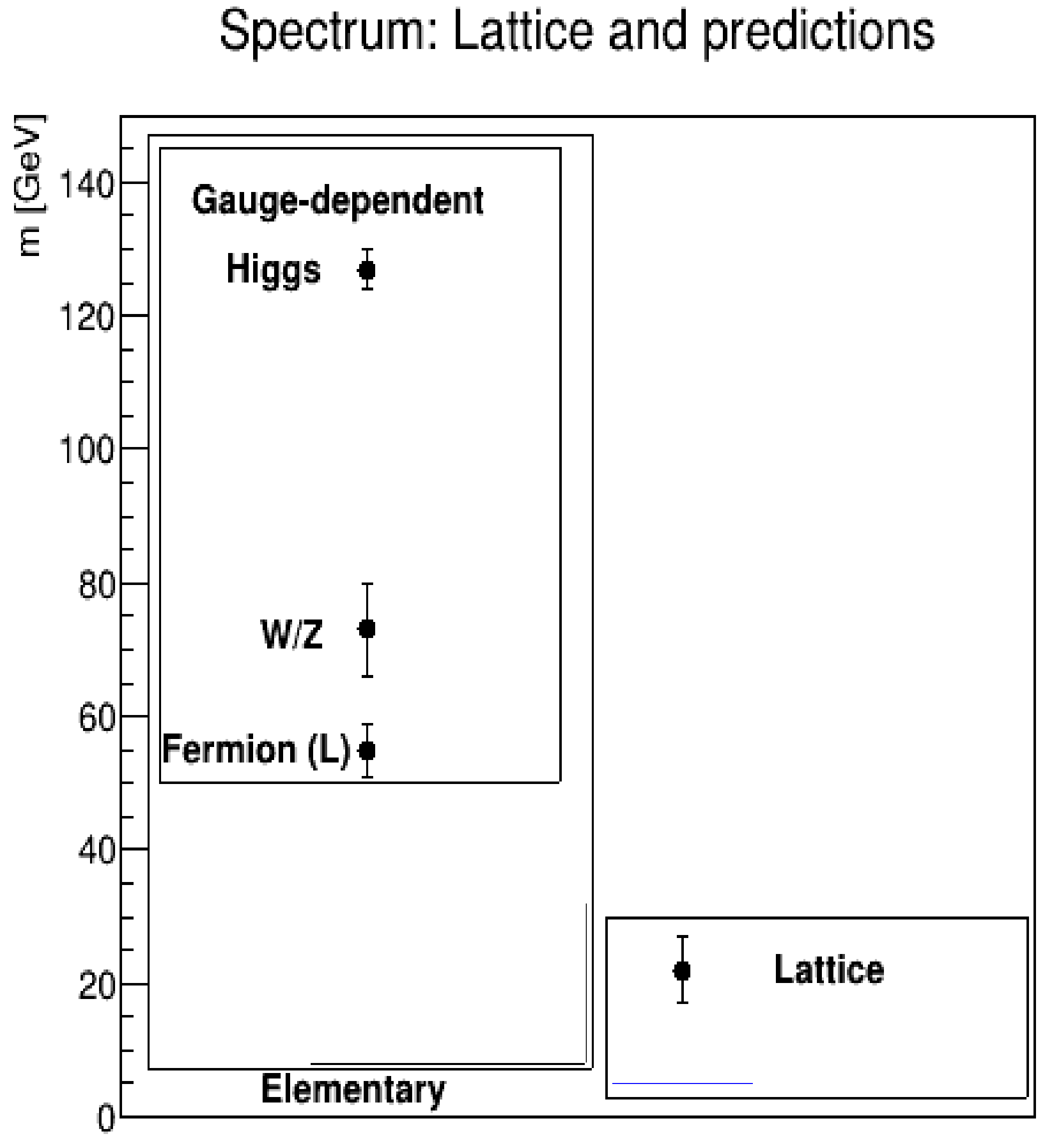

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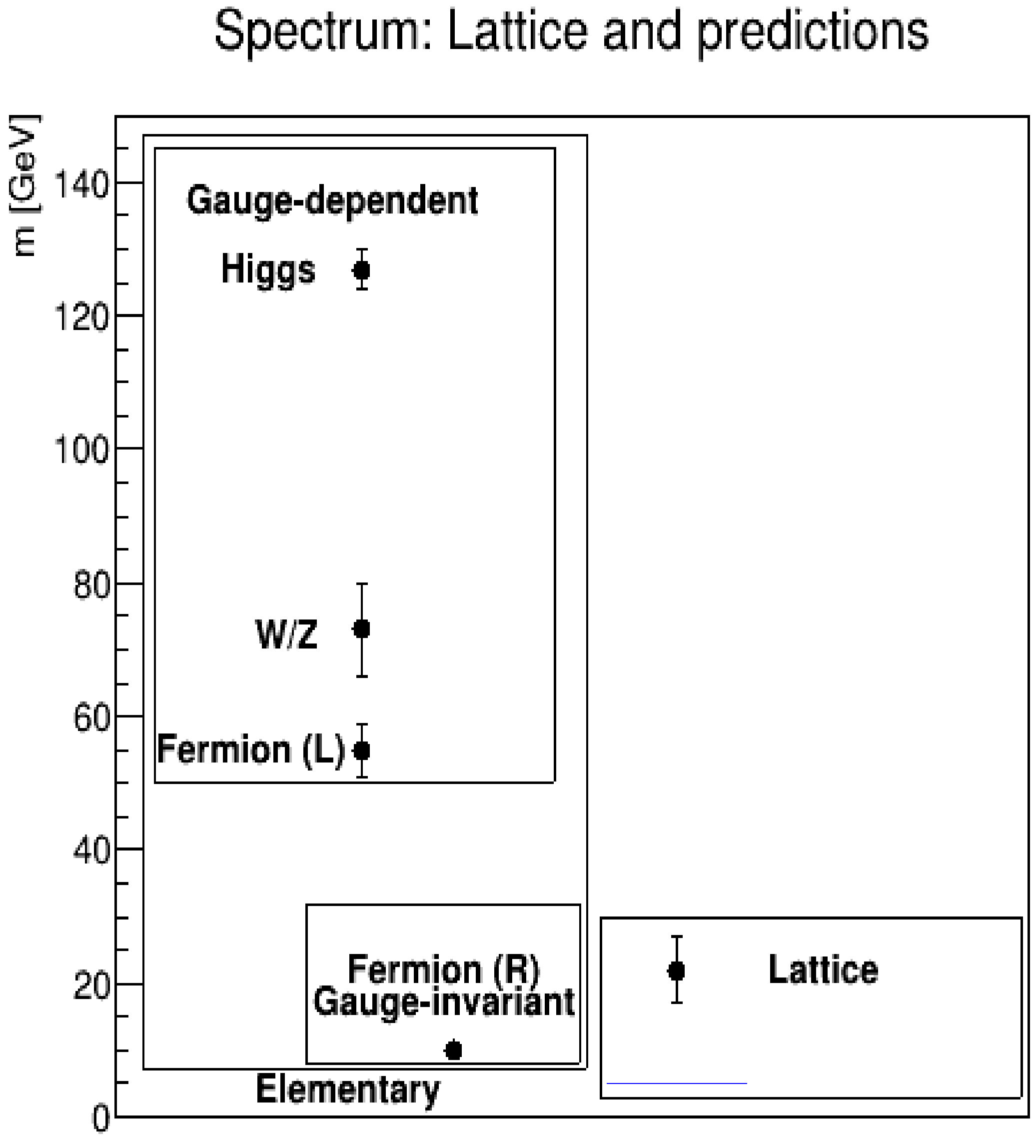

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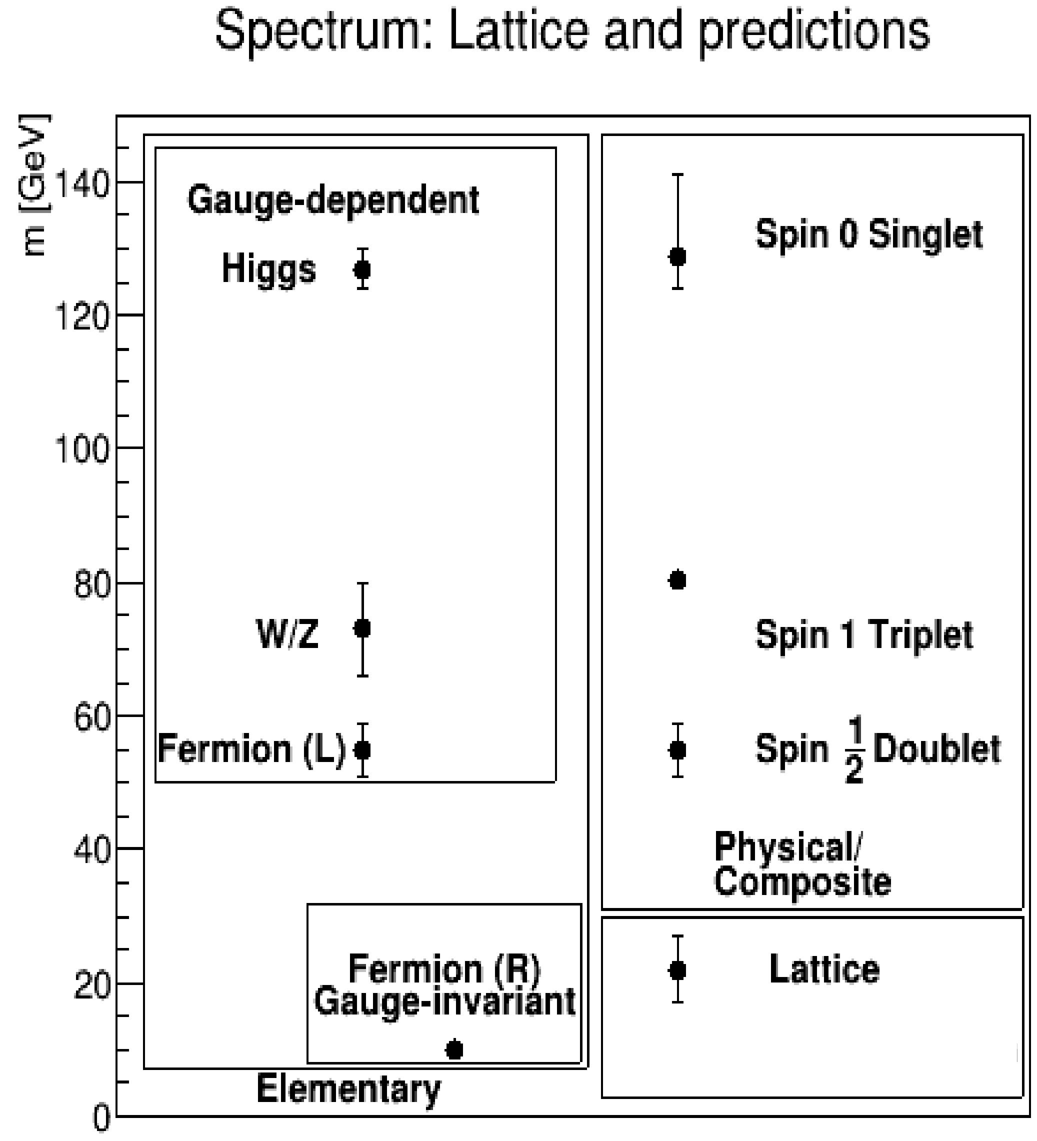

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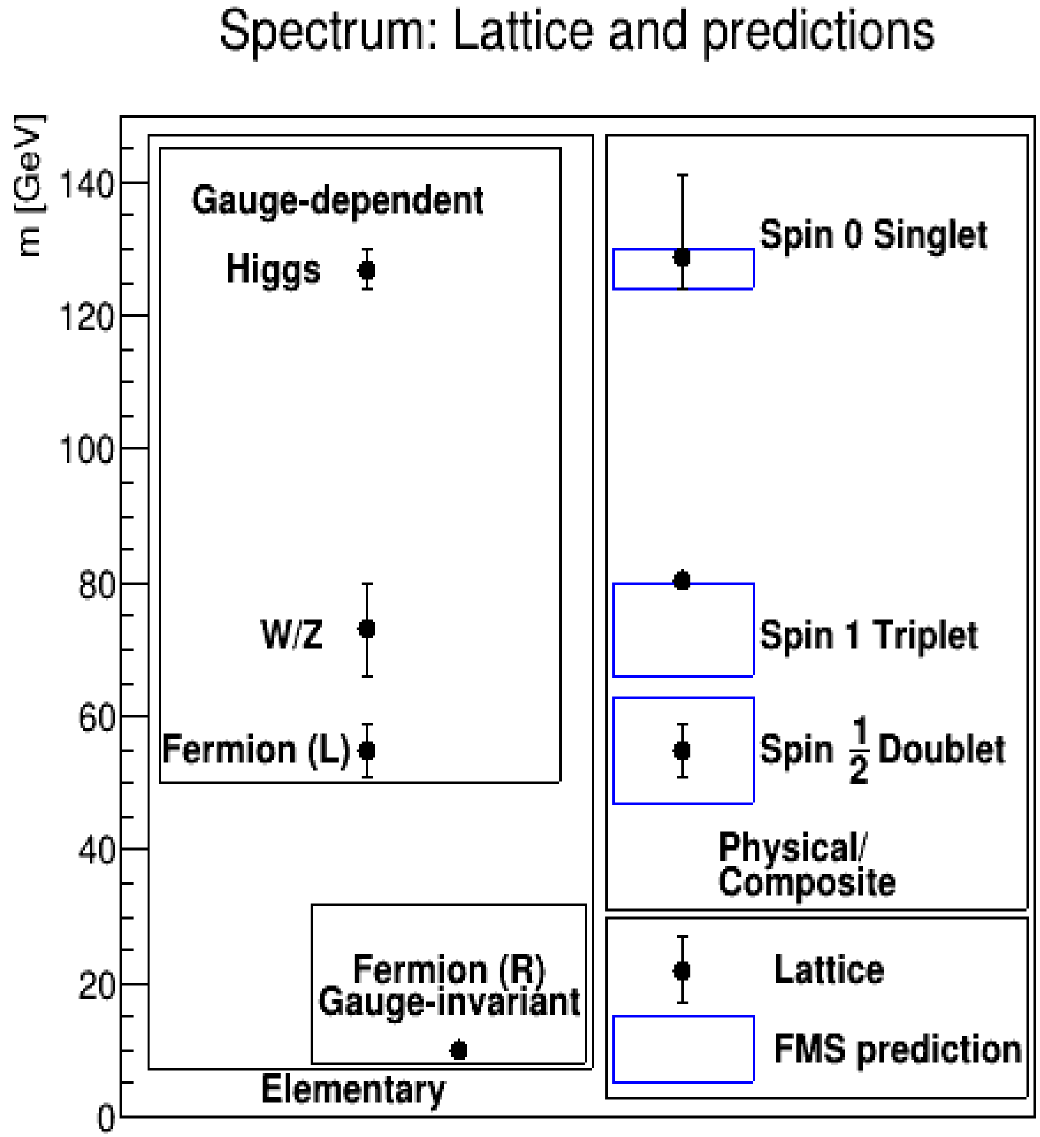
- Supports FMS prediction



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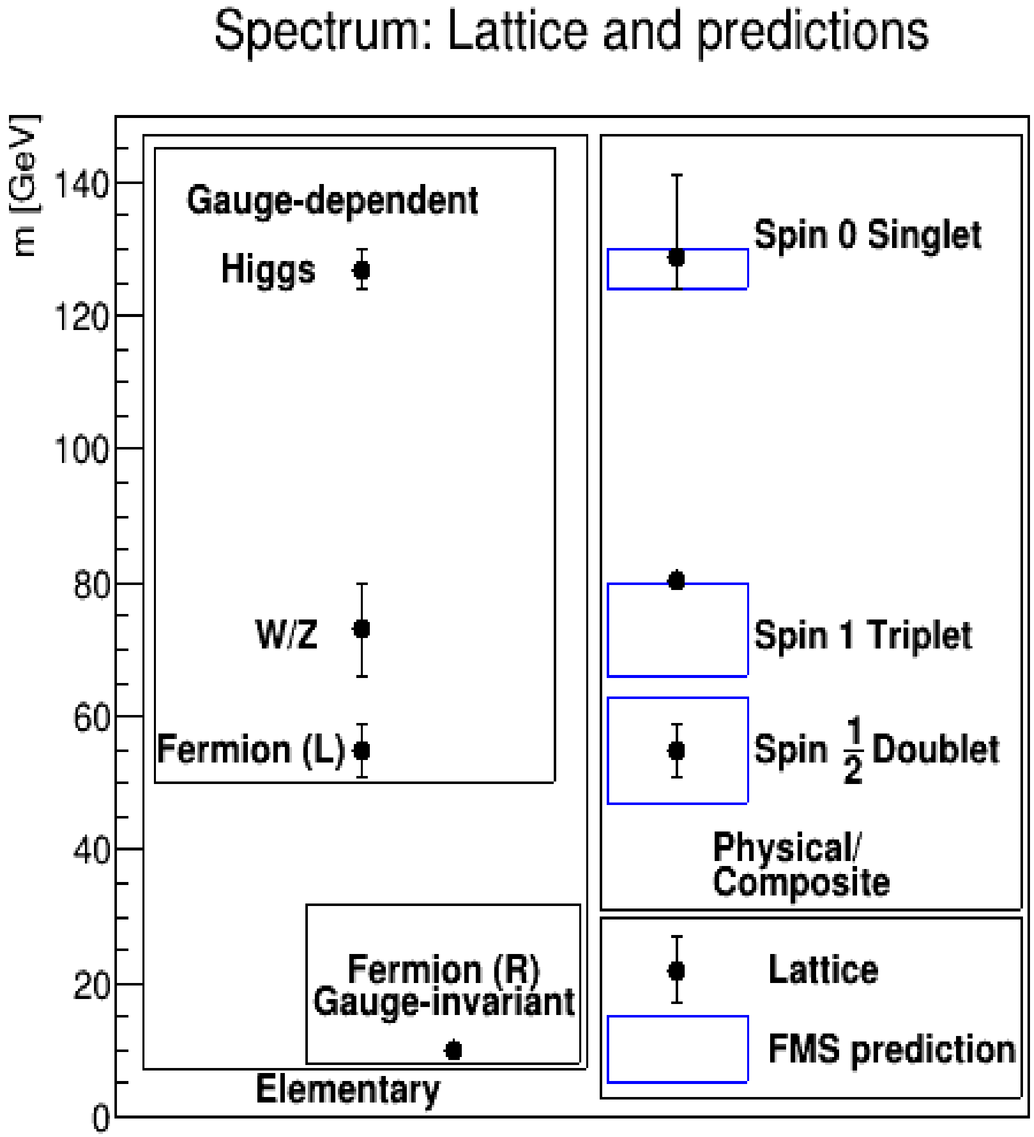
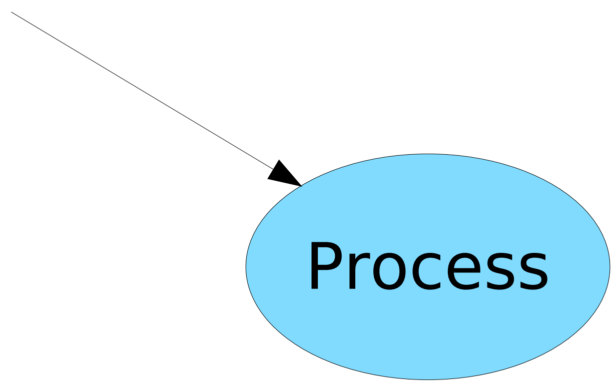


- Supports FMS prediction – grant for unquenching '24-'28

Scattering

[Maas et al.'17
Maas & Reiner '22
Maas, Plätzer et al.' unpublished]

Incoming (asymptotic) particle
Standard LSZ: Elementary particle



$$\langle f(p)\ldots\rangle$$

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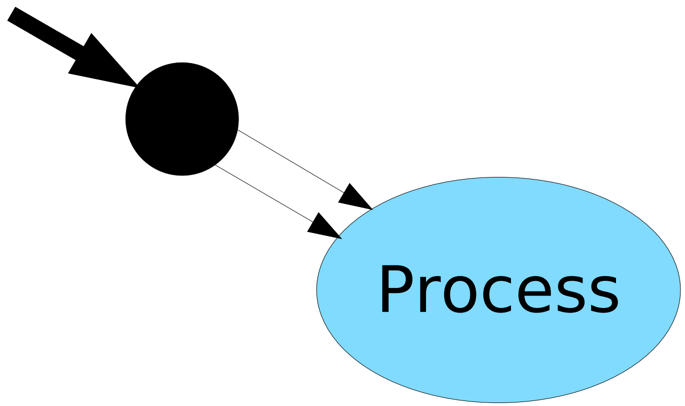
Gauge-invariant LSZ: Bound state



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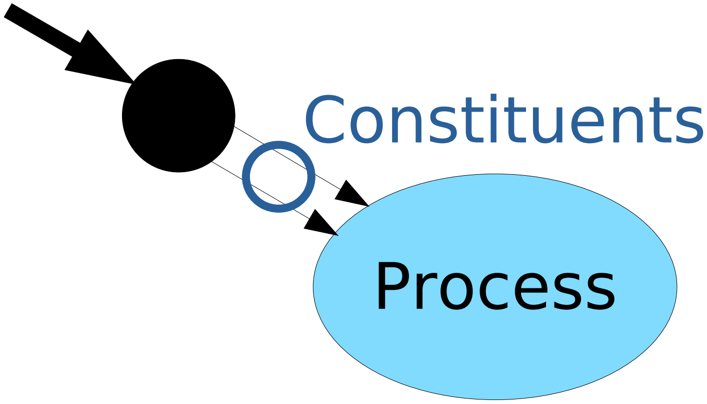

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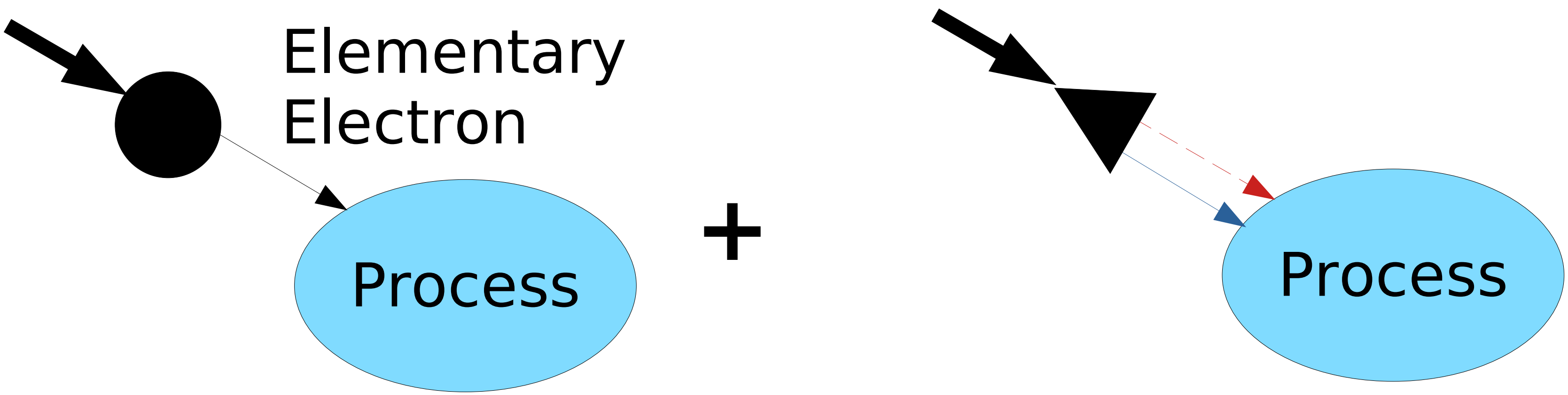

$$v\langle f(p)\ldots\rangle+\int dq\,\Gamma(P,q)\,D_f(p-q)\,D_h(q)\langle h(q)f(P-q)\ldots\rangle$$

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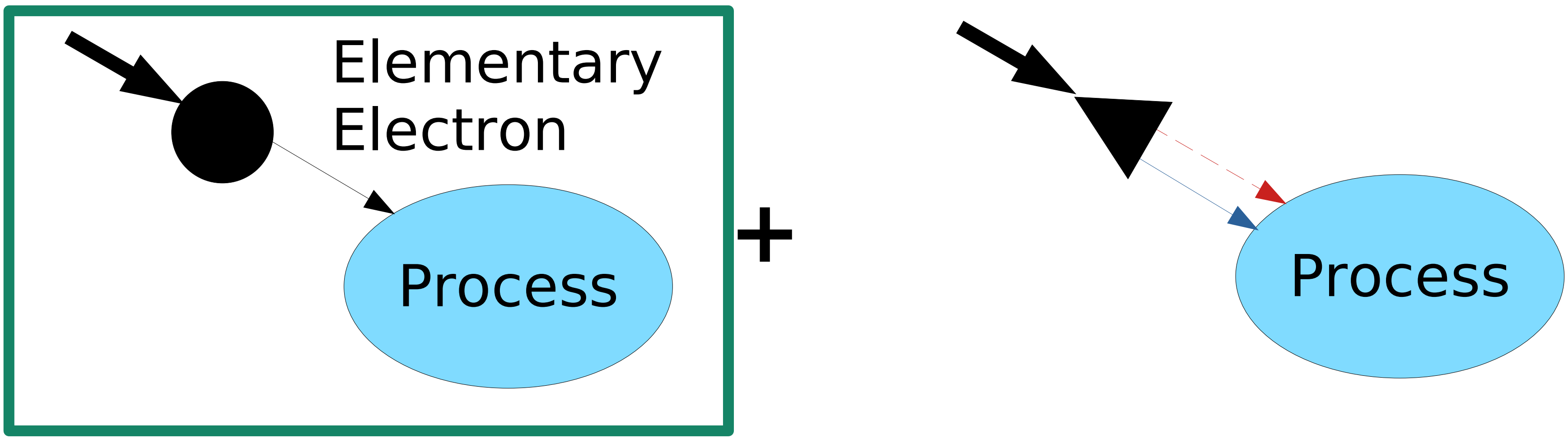

Standard perturbation theory

$$v\langle f(p)...\rangle + \int dq\,\Gamma(P,q)\,D_f(p-q)\,D_h(q)\langle h(q)\,f(P-q)...\rangle$$

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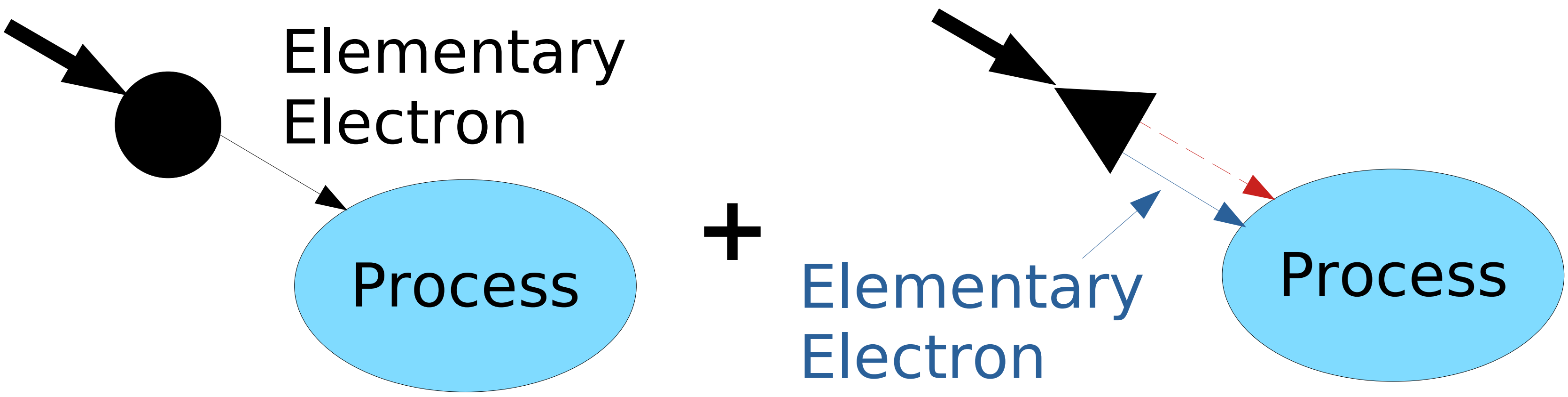

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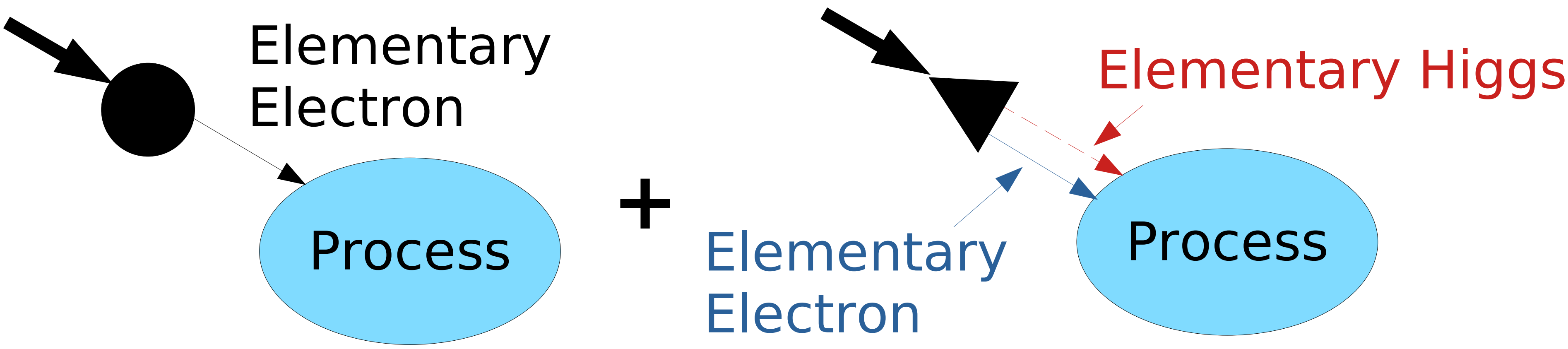

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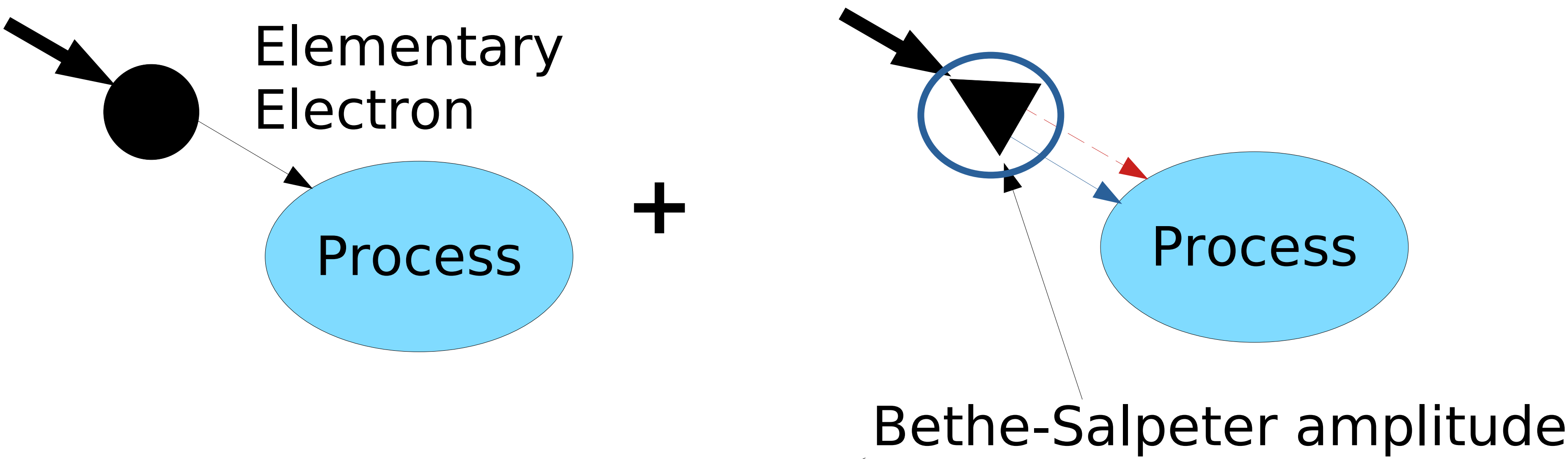

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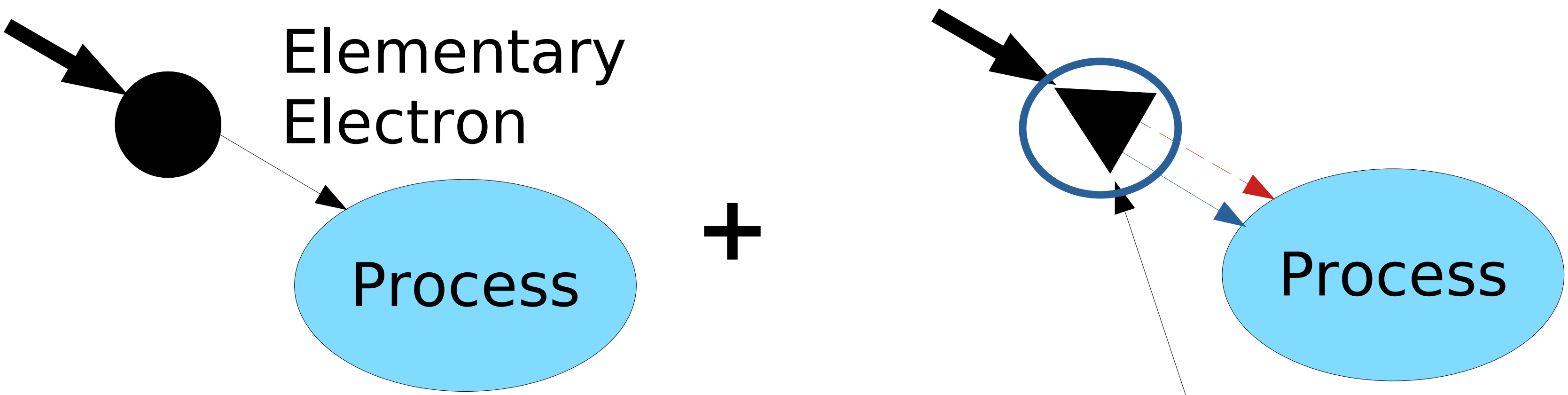

Bethe-Salpeter amplitude:
Calculabe in augmented PT

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Bethe-Salpeter Amplitude

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Calculable itself in augmented perturbation theory

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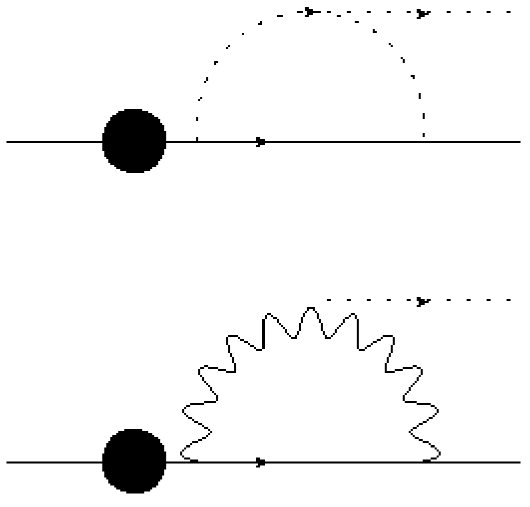

$$v_i \Gamma_{ijk}^{ffh}(P, P-q, q)$$

Bethe-Salpeter Amplitude

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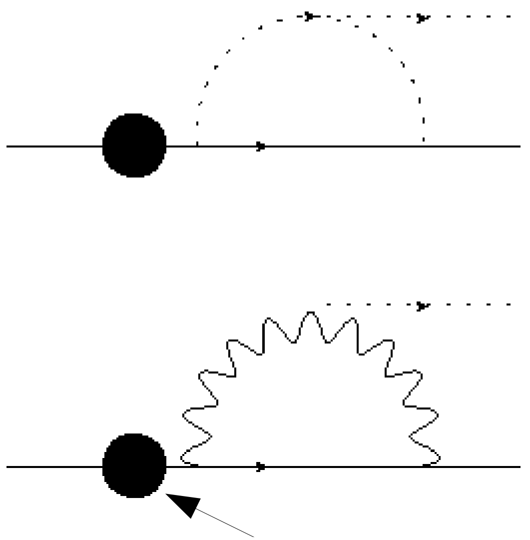

$$v_i \Gamma_{ijk}^{ffh}(P, P-q, q)$$

Binding-to-constituent transition

Bethe-Salpeter Amplitude

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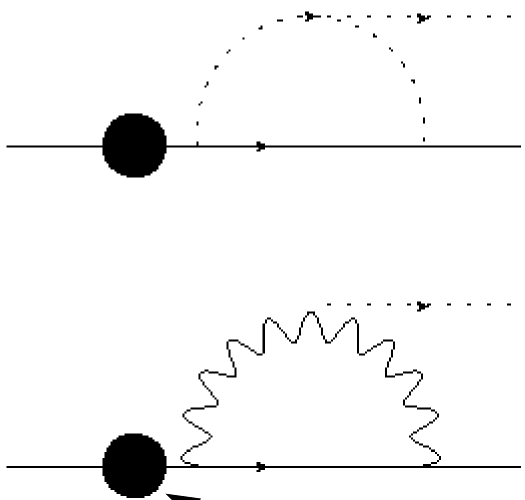
Calculable itself in augmented perturbation theory



$$v_i \Gamma_{ijk}^{ffh}(P, P-q, q)$$

Binding-to-constituent transition

Reweights standard diagrams @N(N)LO

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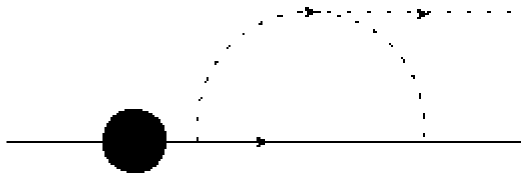

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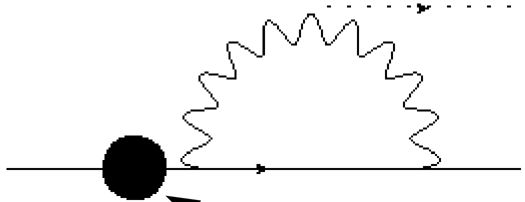

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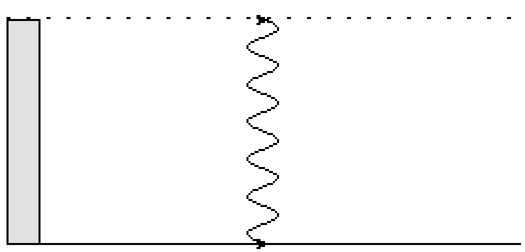

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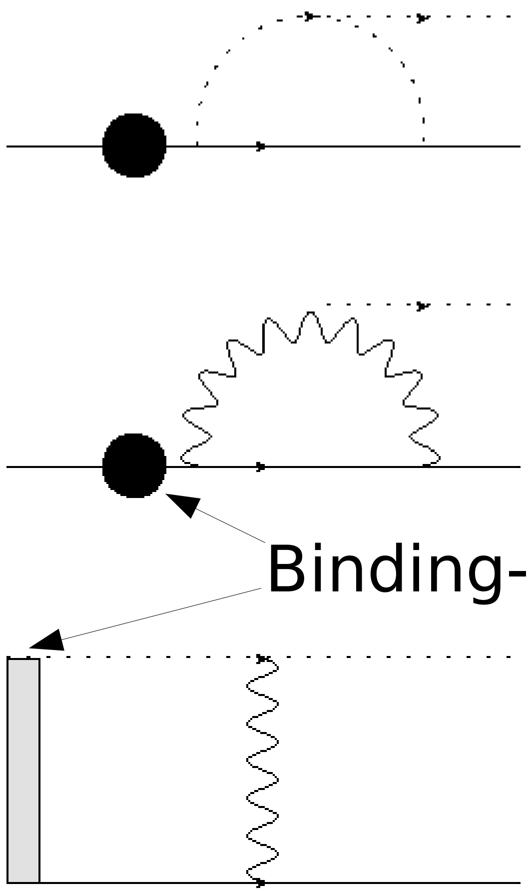

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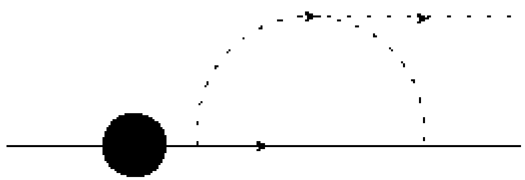

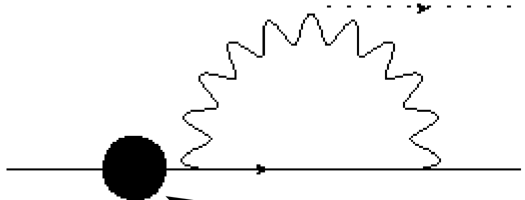

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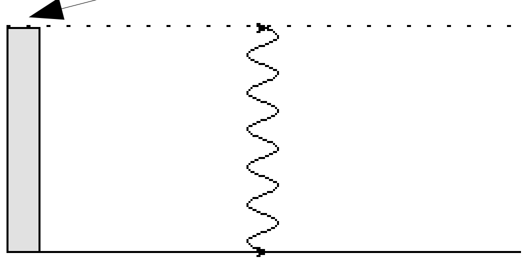

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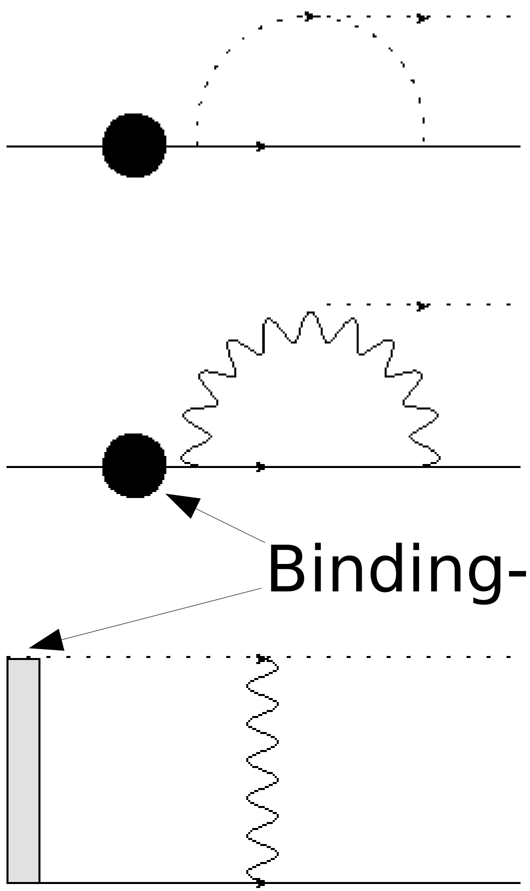

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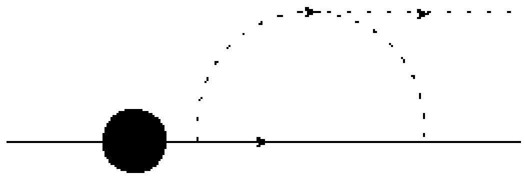

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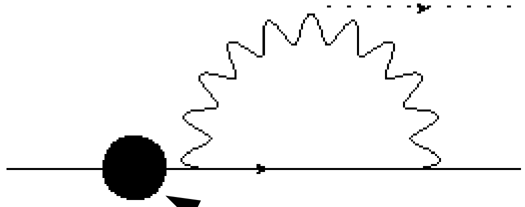

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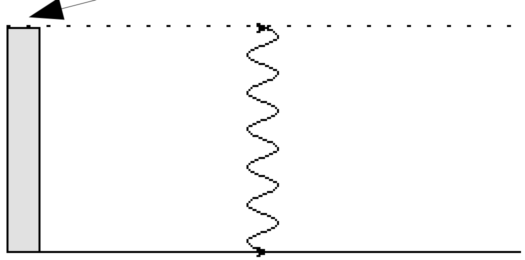

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Impact on processes

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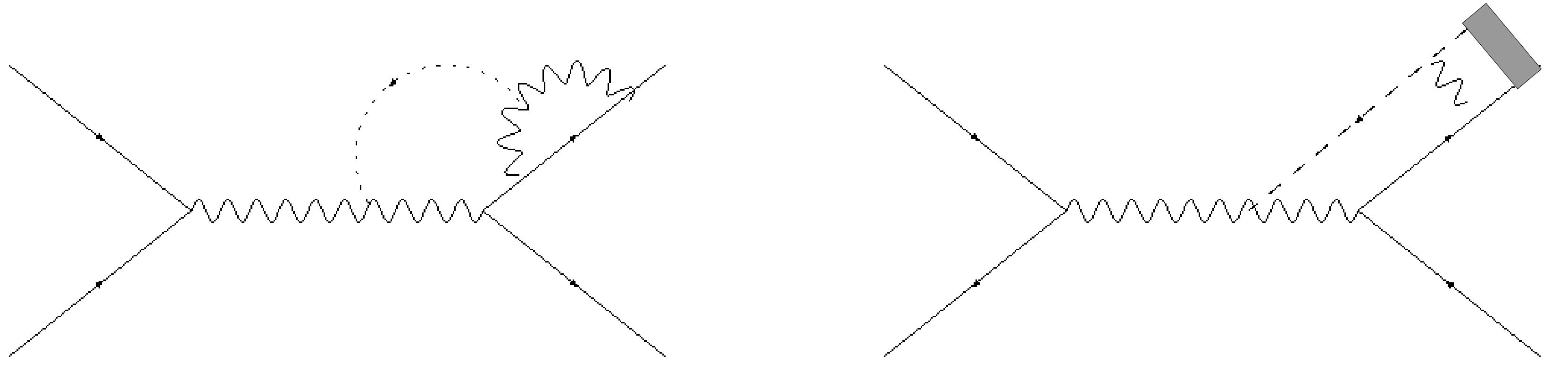

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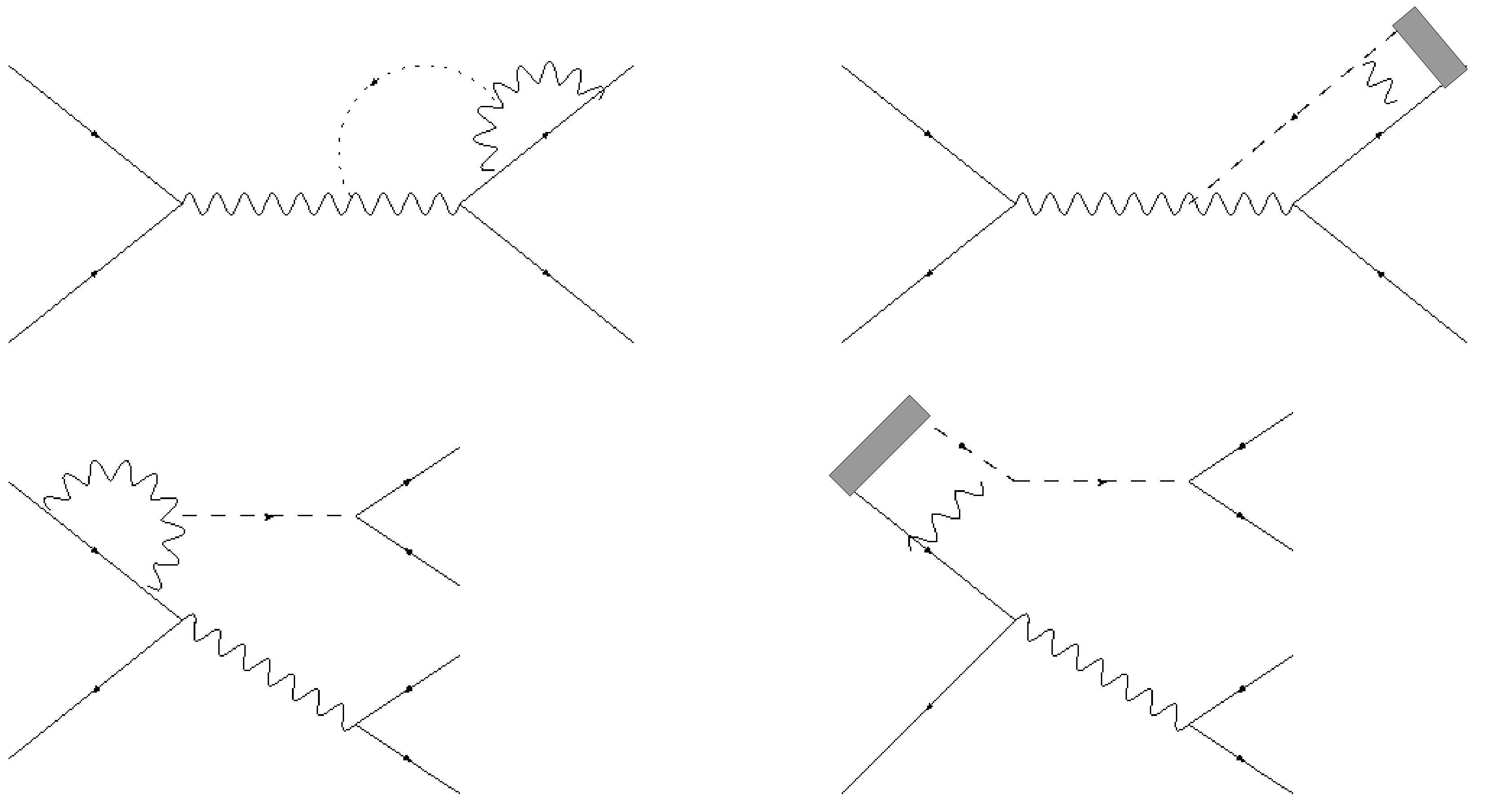

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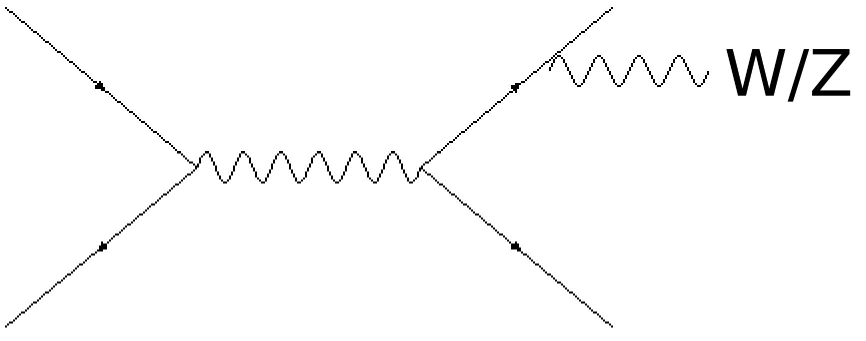

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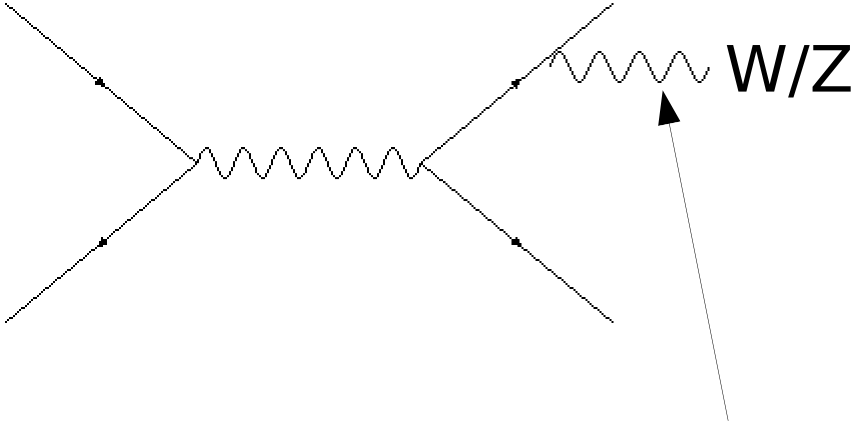

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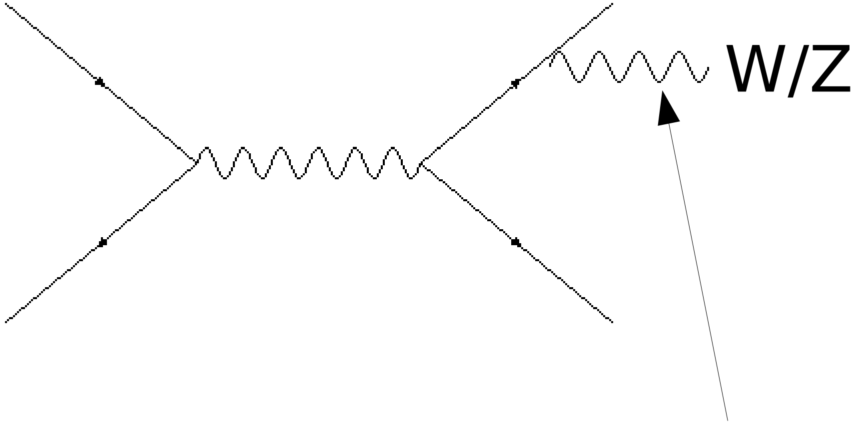

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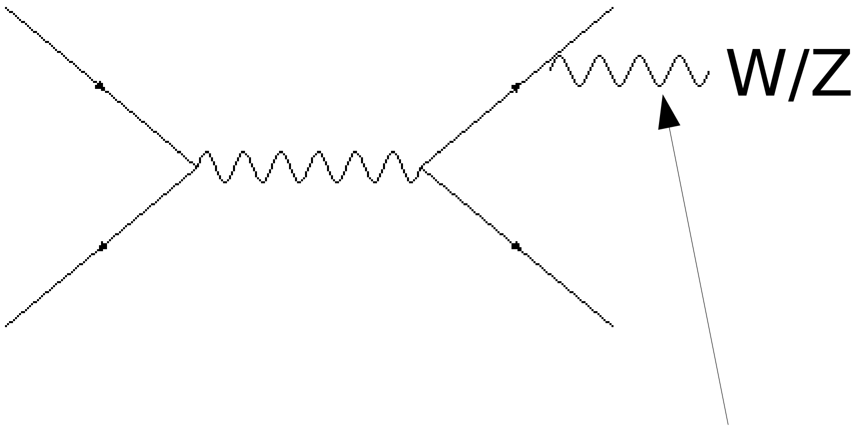

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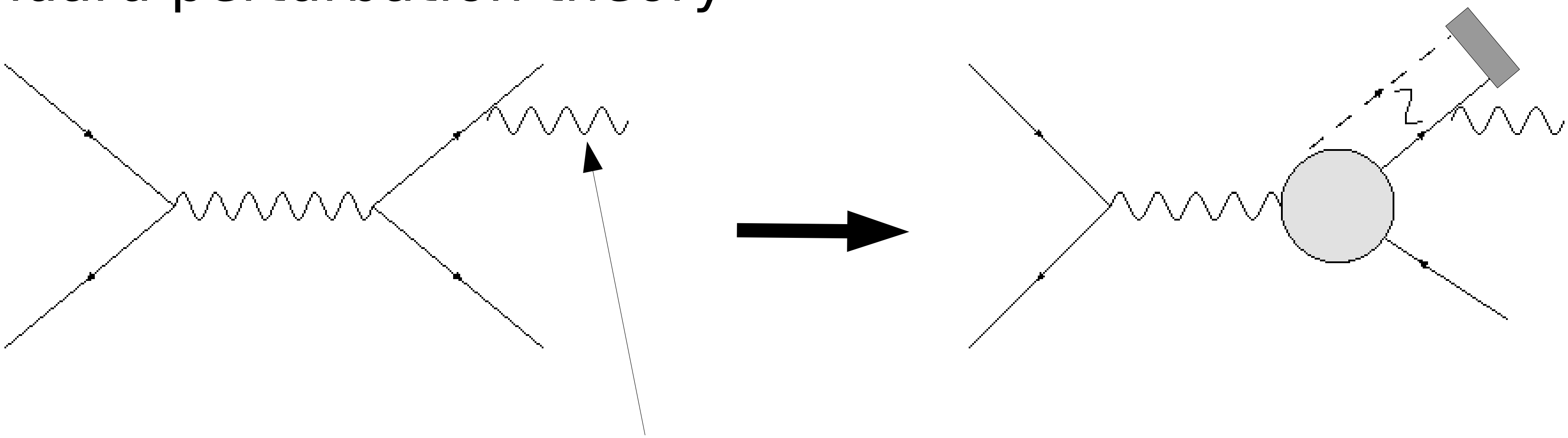

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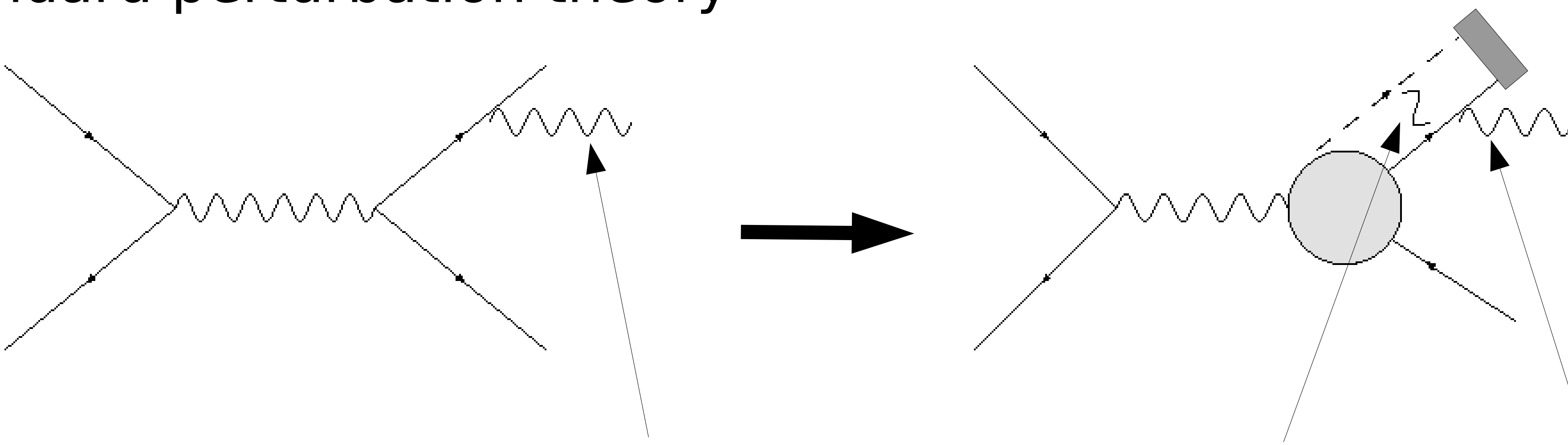

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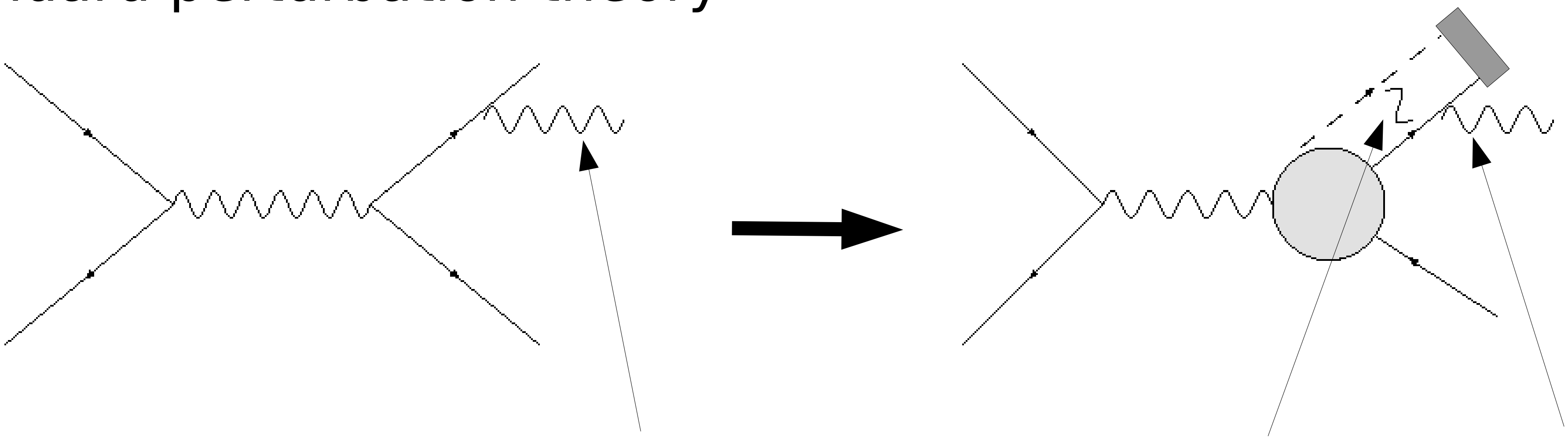

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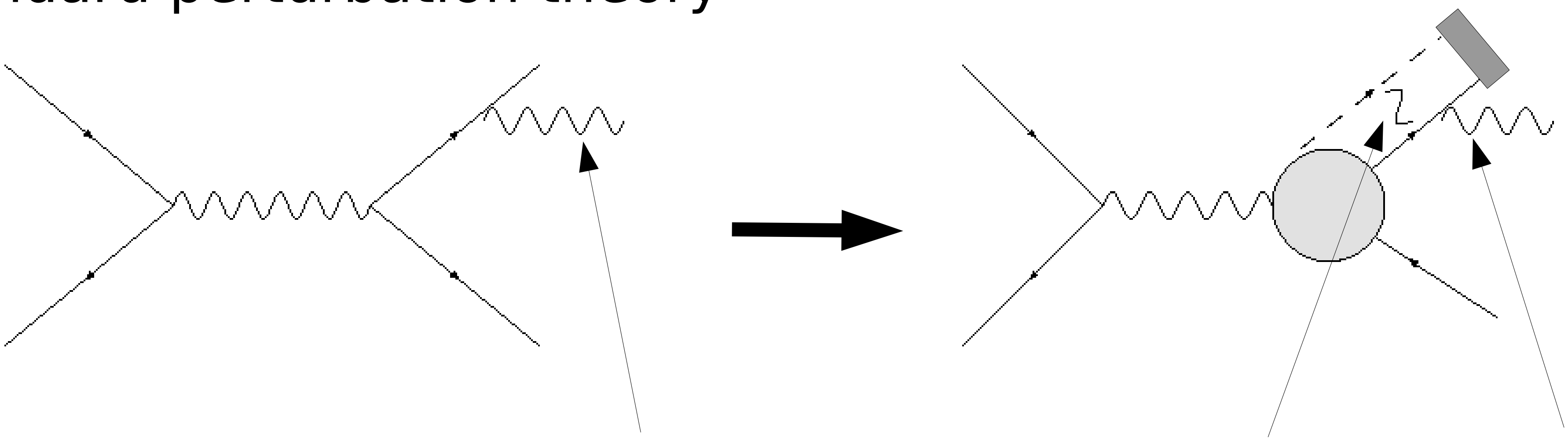

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Cancel this effect:
Less weak jets

New physics
-
Qualitative changes

Beyond the standard model

[Maas'15
Maas, Sondenheimer, Törek'17]

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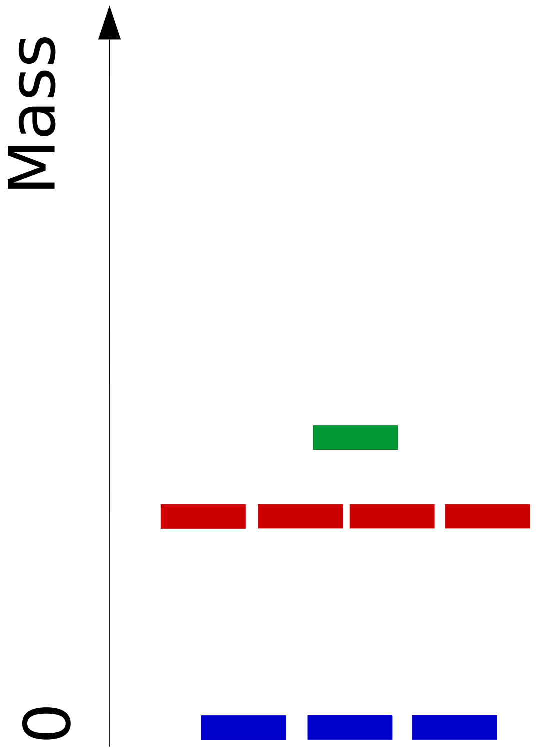
- Global U(1) custodial (flavor) symmetry
  - Acts as (right-)transformation on the scalar field only

$$W_\mu^a\rightarrow W_\mu^a \qquad h\rightarrow \exp(ia)h$$

Spectrum

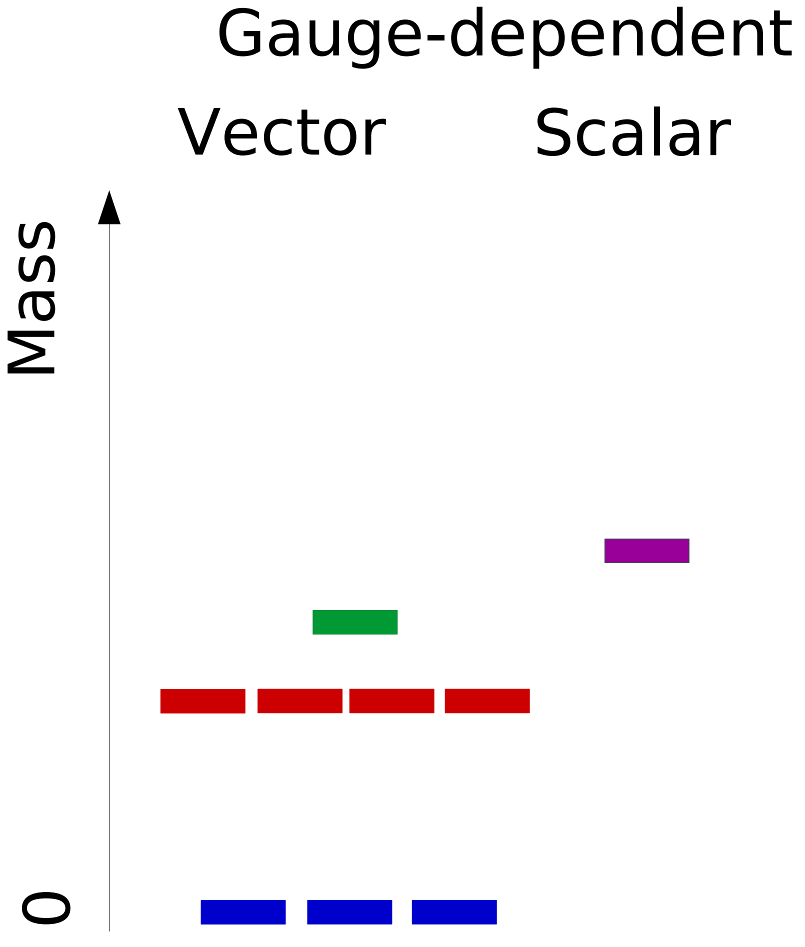
Gauge-dependent

Vector



‘SU(3)→ SU(2)’

Spectrum



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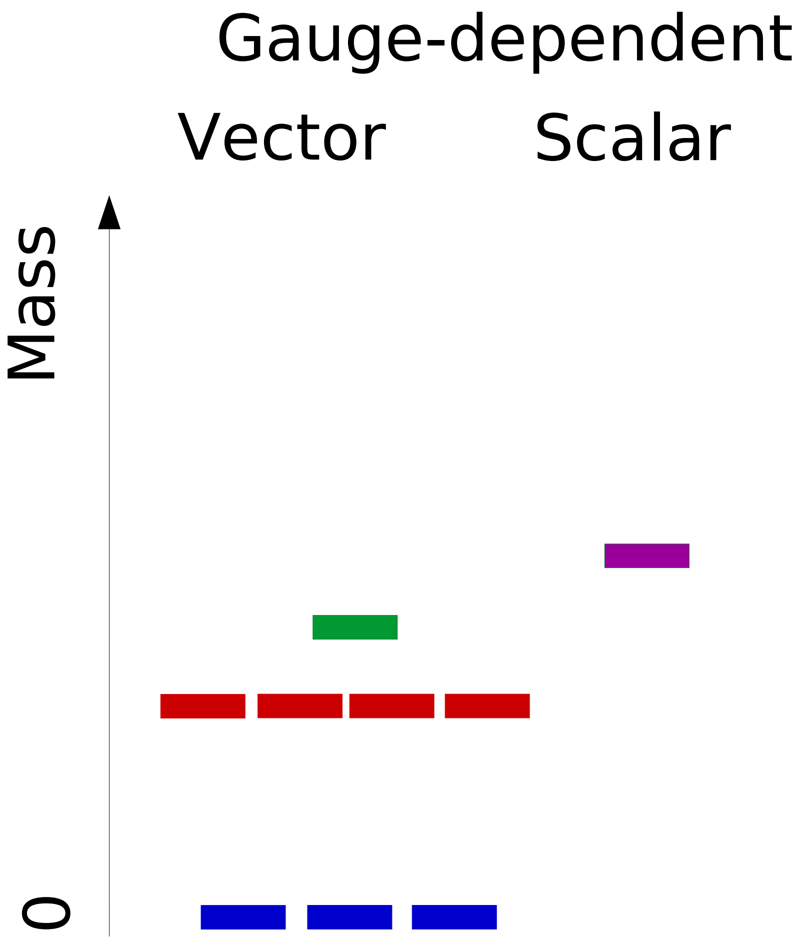

Confirmed in gauge-fixed lattice calculations [Maas et al.'16]

Spectrum

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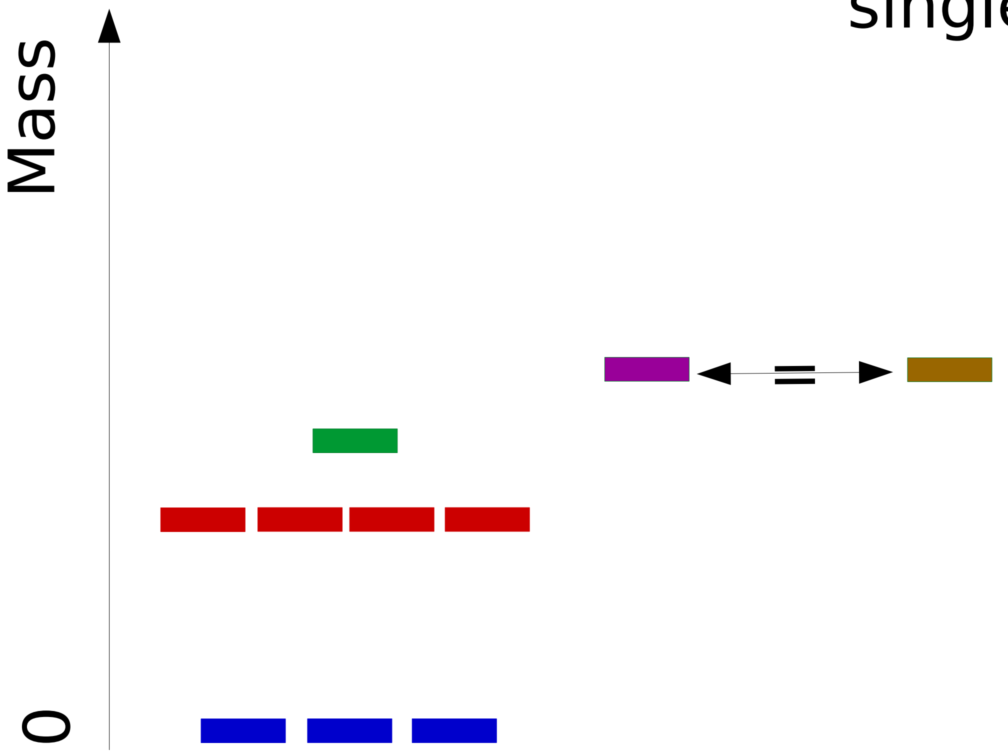
Gauge-dependent

Gauge-invariant

Vector Scalar Scalar singlet



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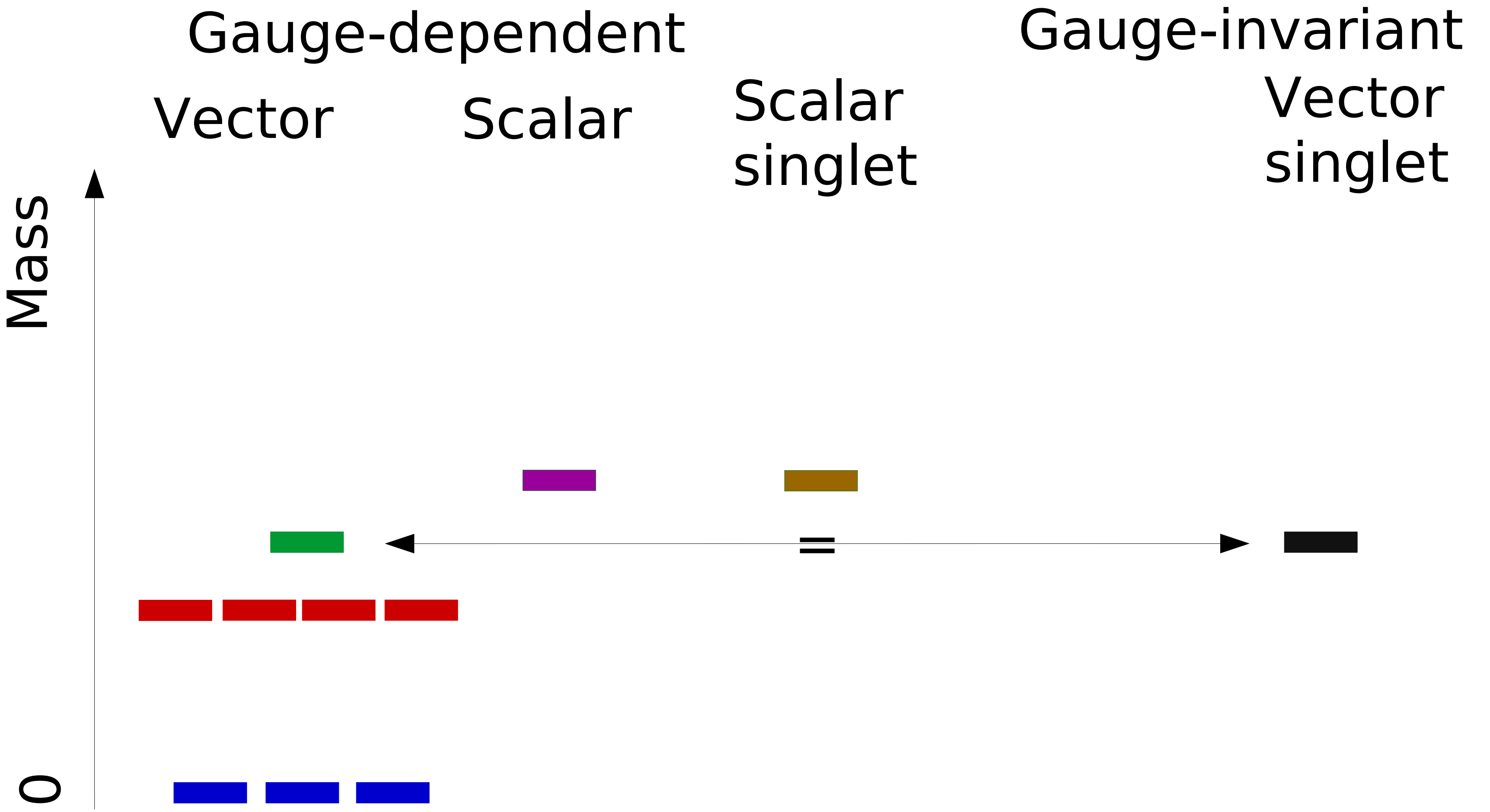

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Only one state remains in the spectrum at mass of gauge boson 8 (heavy singlet)

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- Now: States without elementary analouge
  - Gauge-invariant states from 3 Higgs fields
  - Baryon analogue – U(1) acts as baryon number
  - Lightest must exist and be absolutely stable

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- What is the lightest state?
  - Prediction with constituent model

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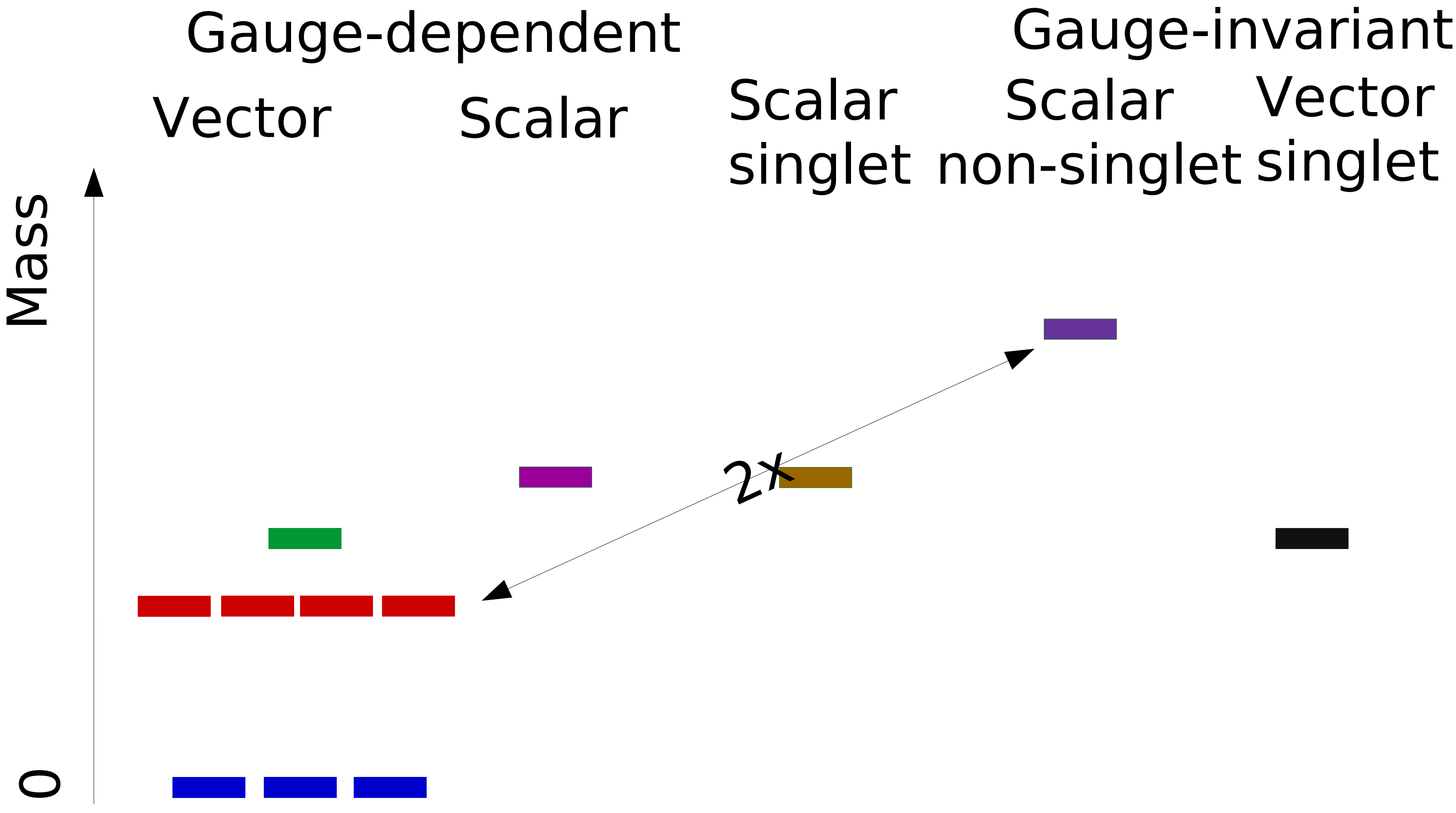

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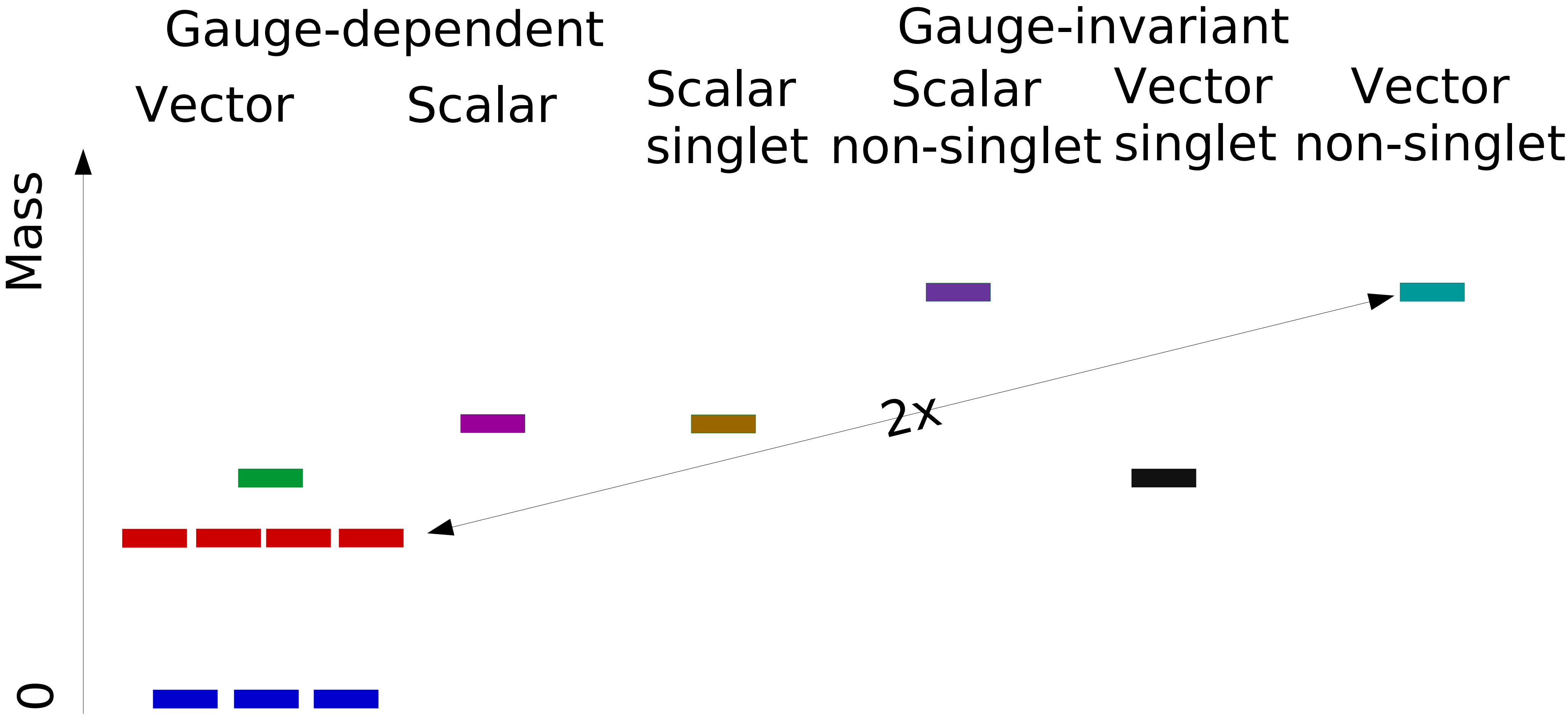
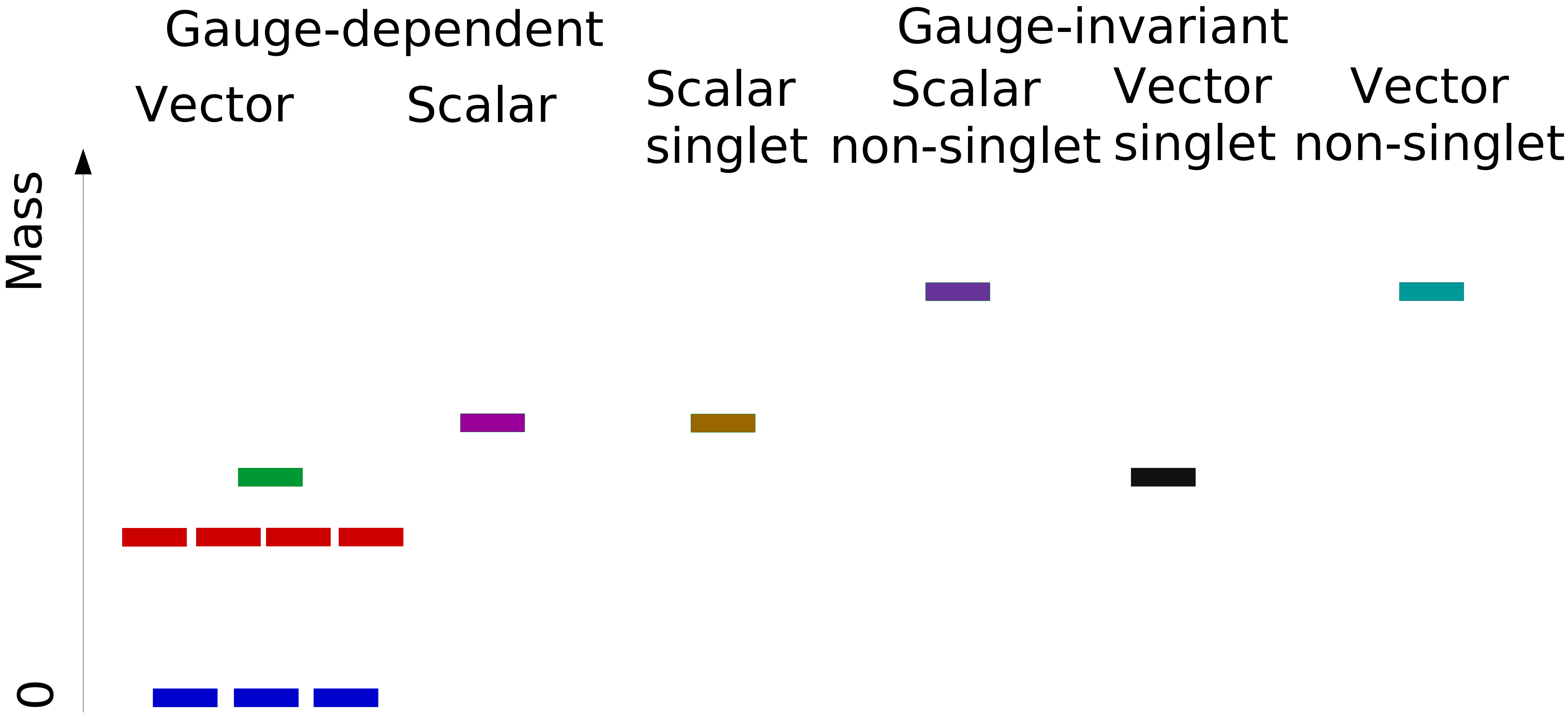


Spectrum

[Maas & Törek'16,'18
Maas, Sondenheimer & Törek'17]



- Qualitatively different spectrum
- No mass gap!

Possible states

- Quantum numbers are $J^{PC}{}_{\text{Custodial}}$
  - Simpelst non-trivial state operator: $0^{++}{}_{1}$
  - $\epsilon_{abc}\phi^a D_\mu \phi^b D_\nu D^\nu D^\mu \phi^c$
- What is the lightest state?
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- What is the lightest state?
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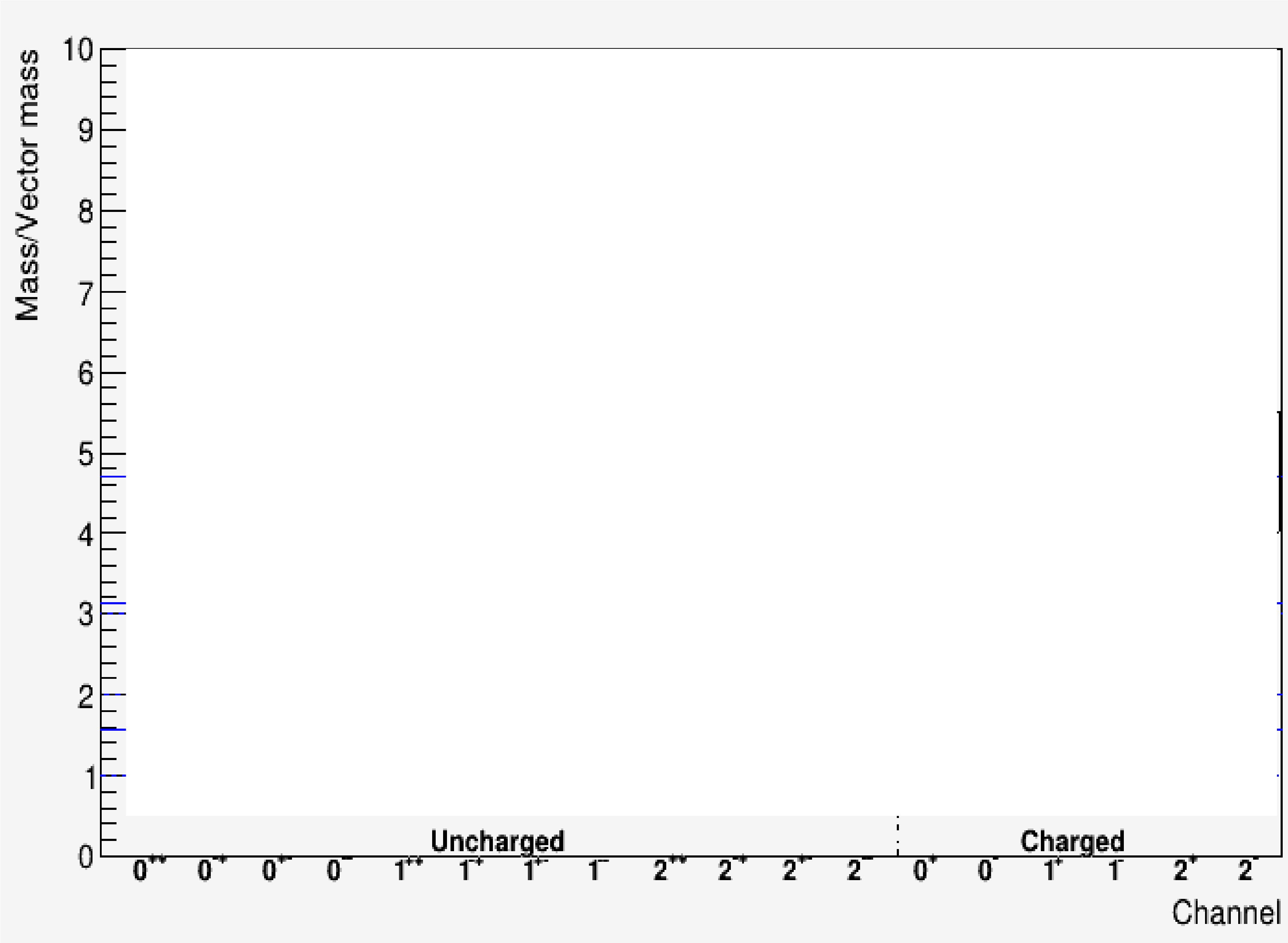
  - All channels: J<3
  - Aim: Ground state for each channel
    - Characterization through scattering states

Typical spectrum

PRELIMINARY

[Dobson et al.’25]



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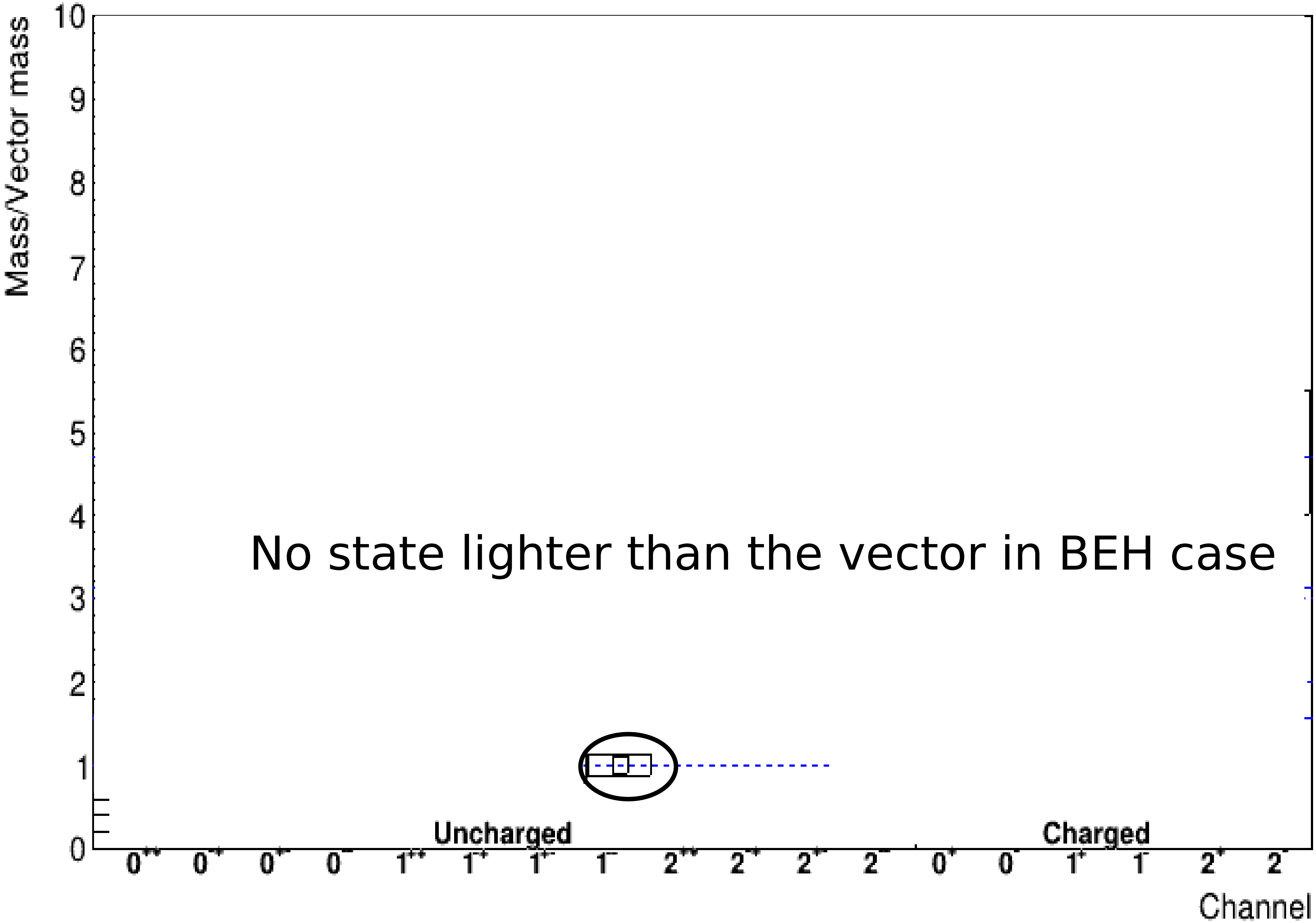

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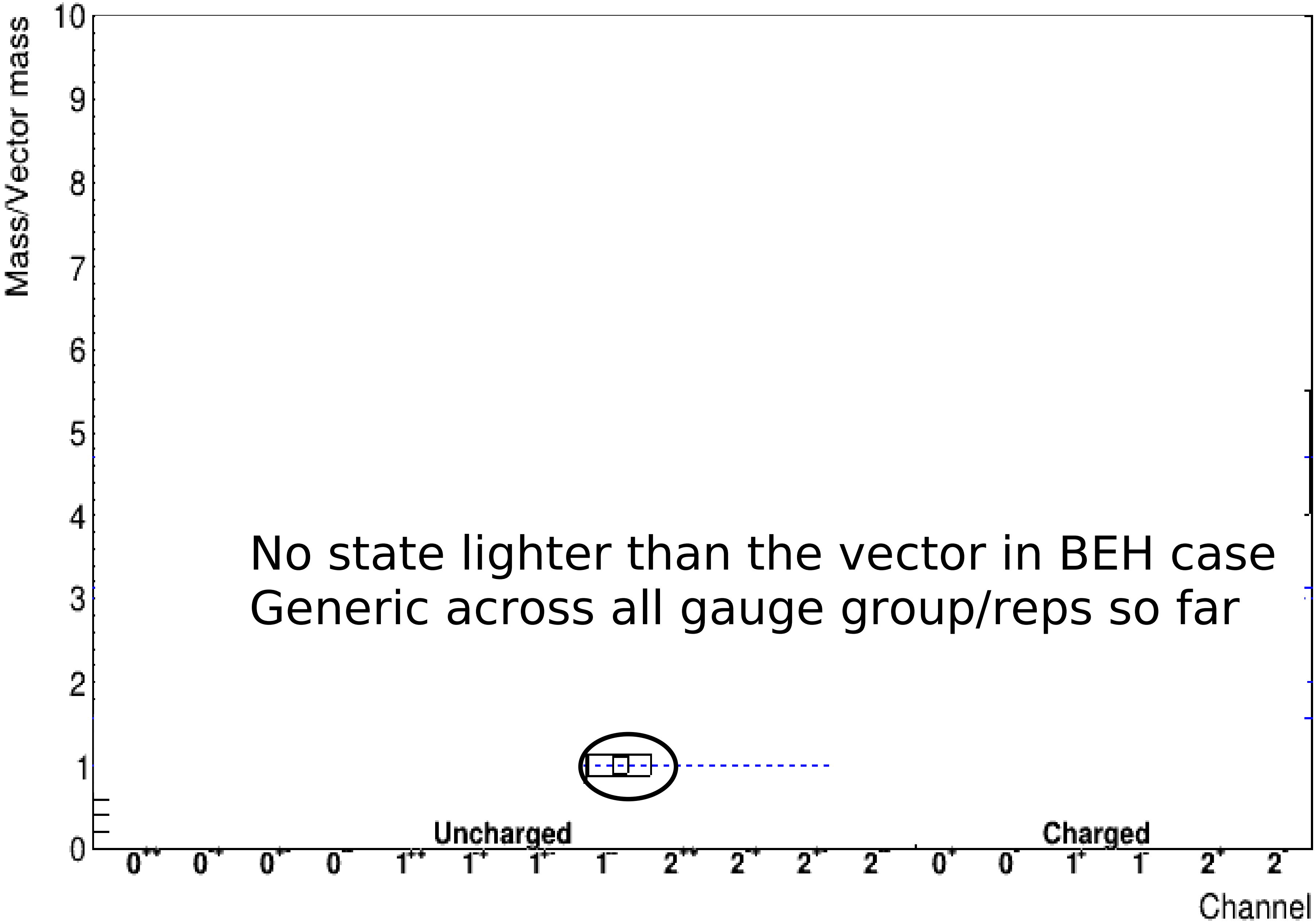

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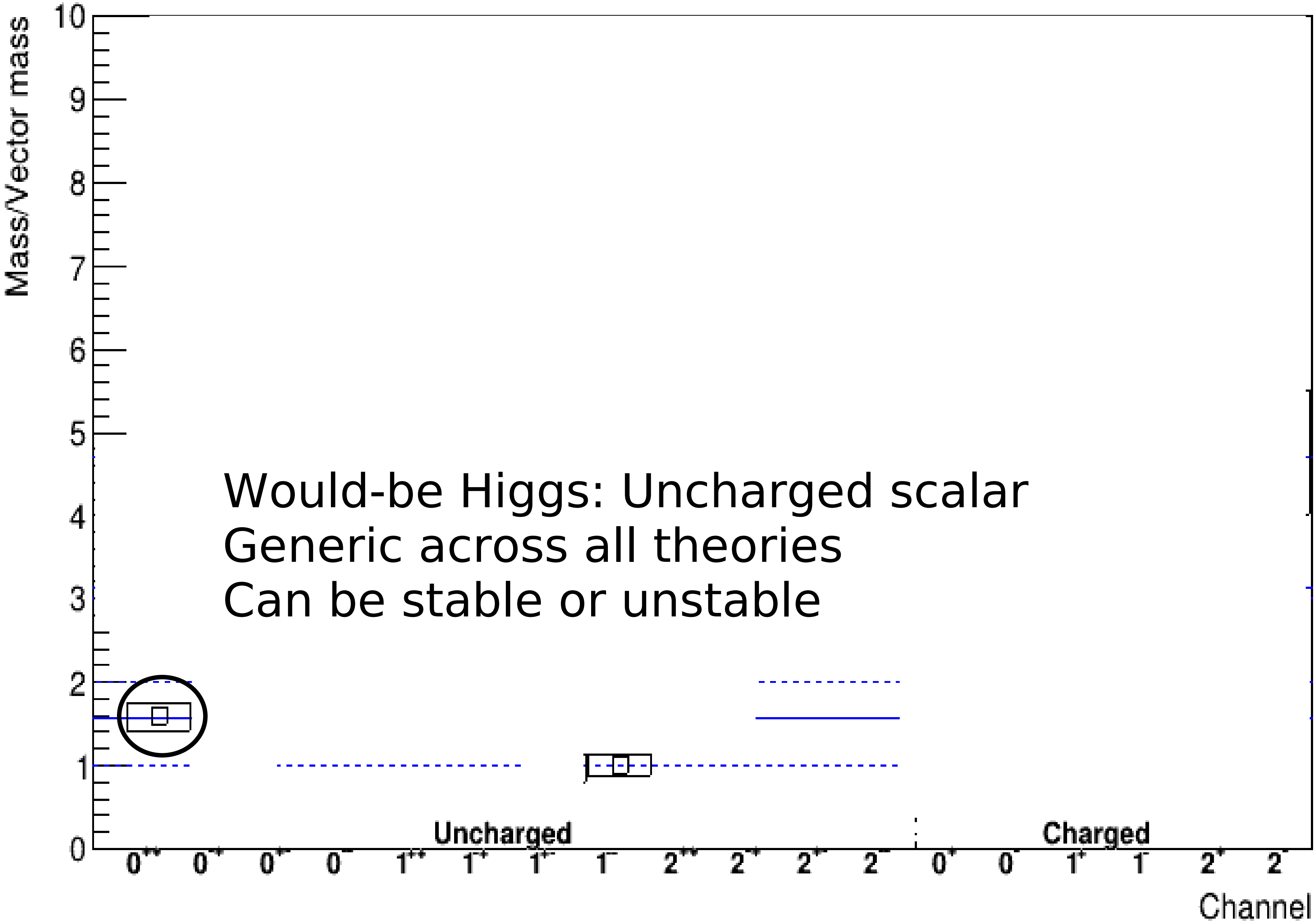

Would-be Higgs: Uncharged scalar
Generic across all theories
Can be stable or unstable

Typical spectrum

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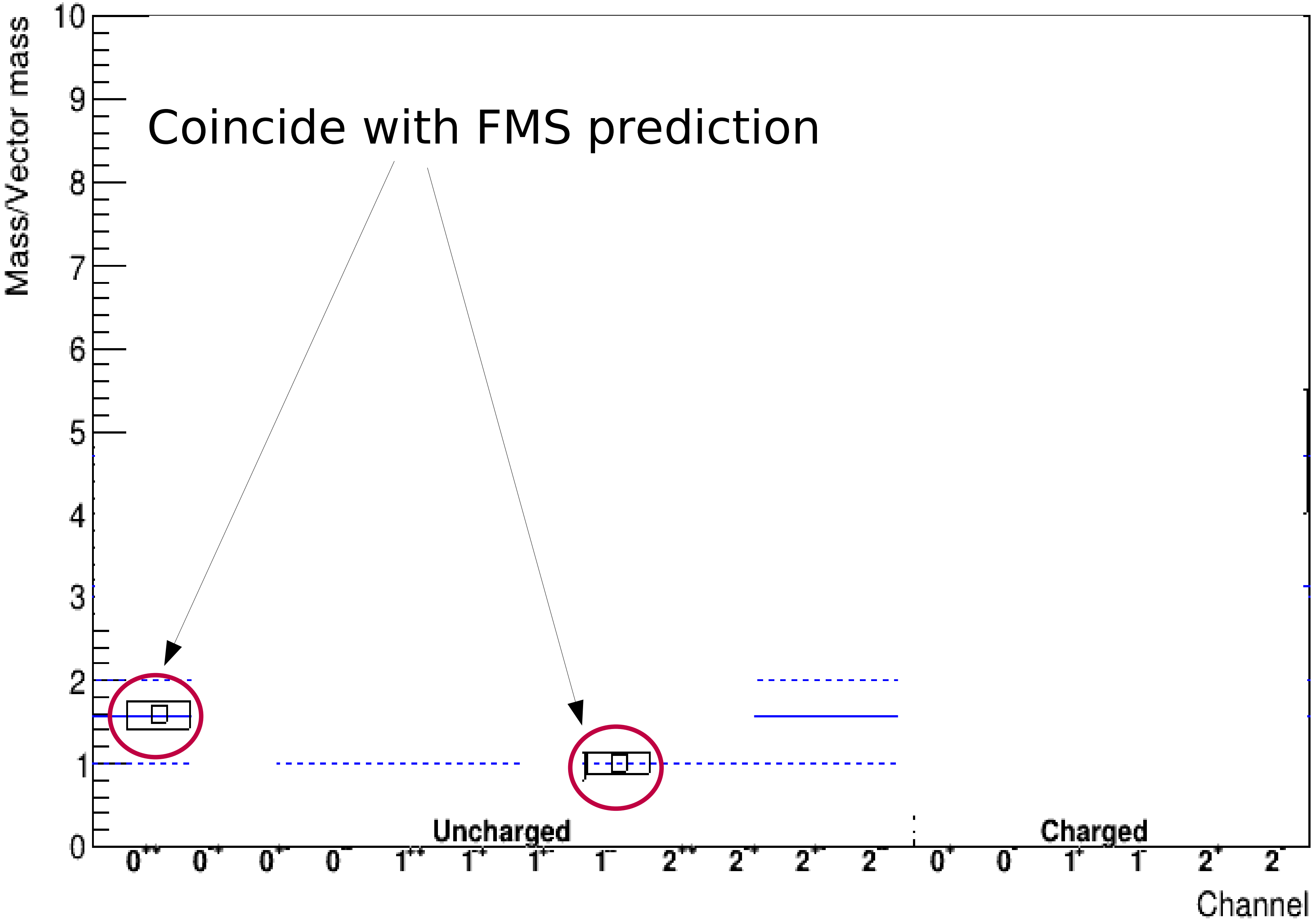

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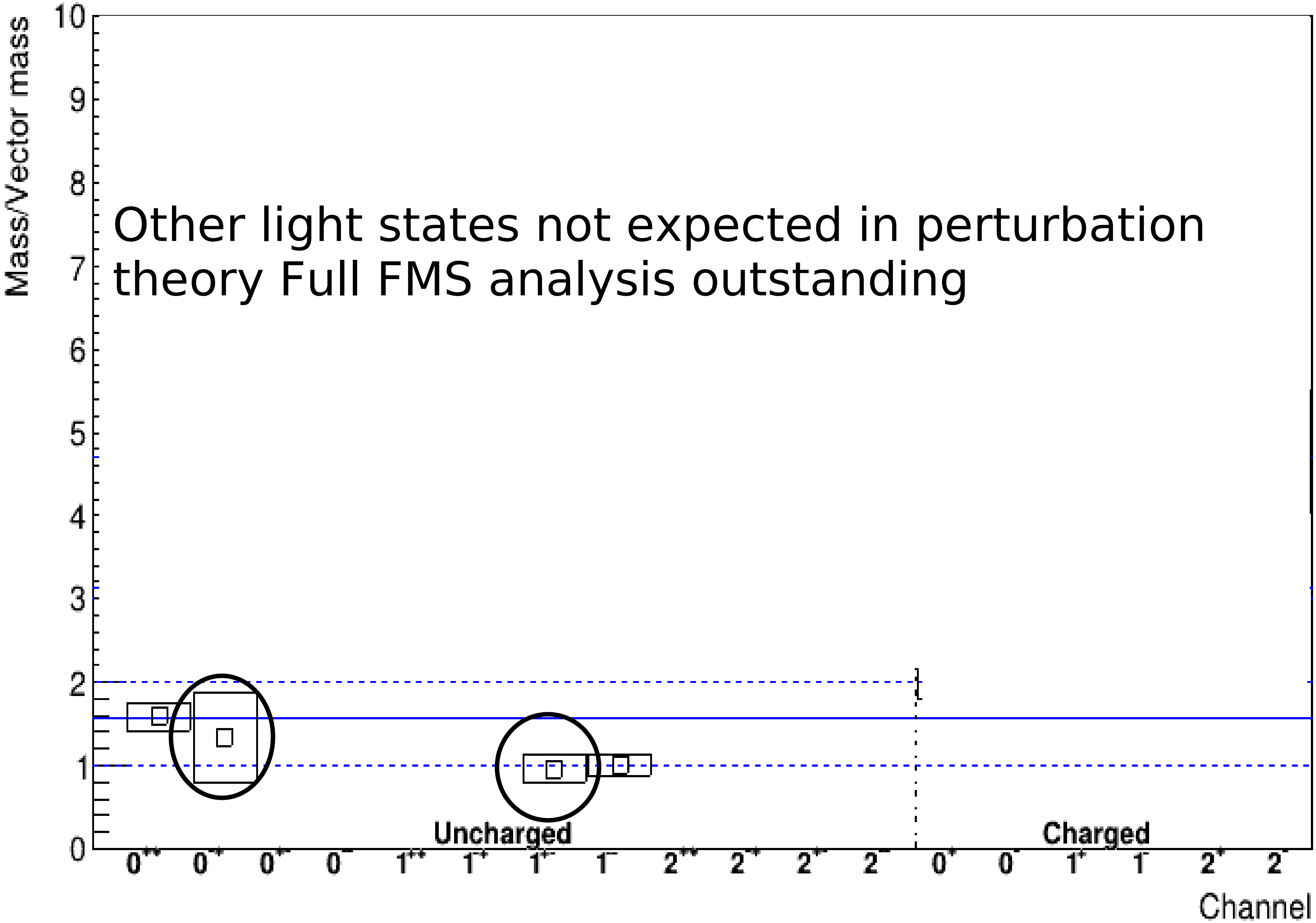
Other light states not expected in perturbation theory Full FMS analysis outstanding



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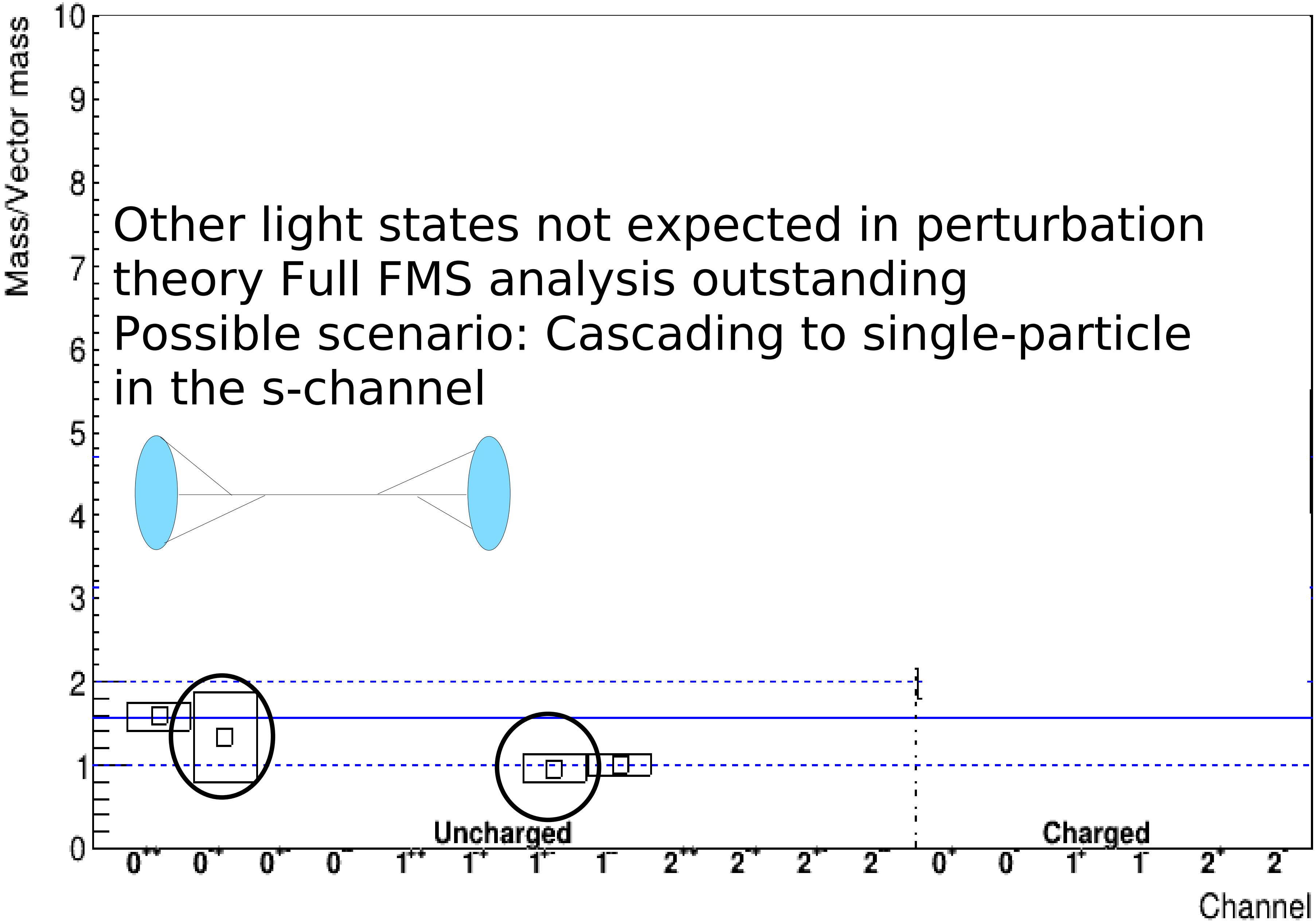
Possible scenario: Cascading to single-particle in the s-channel



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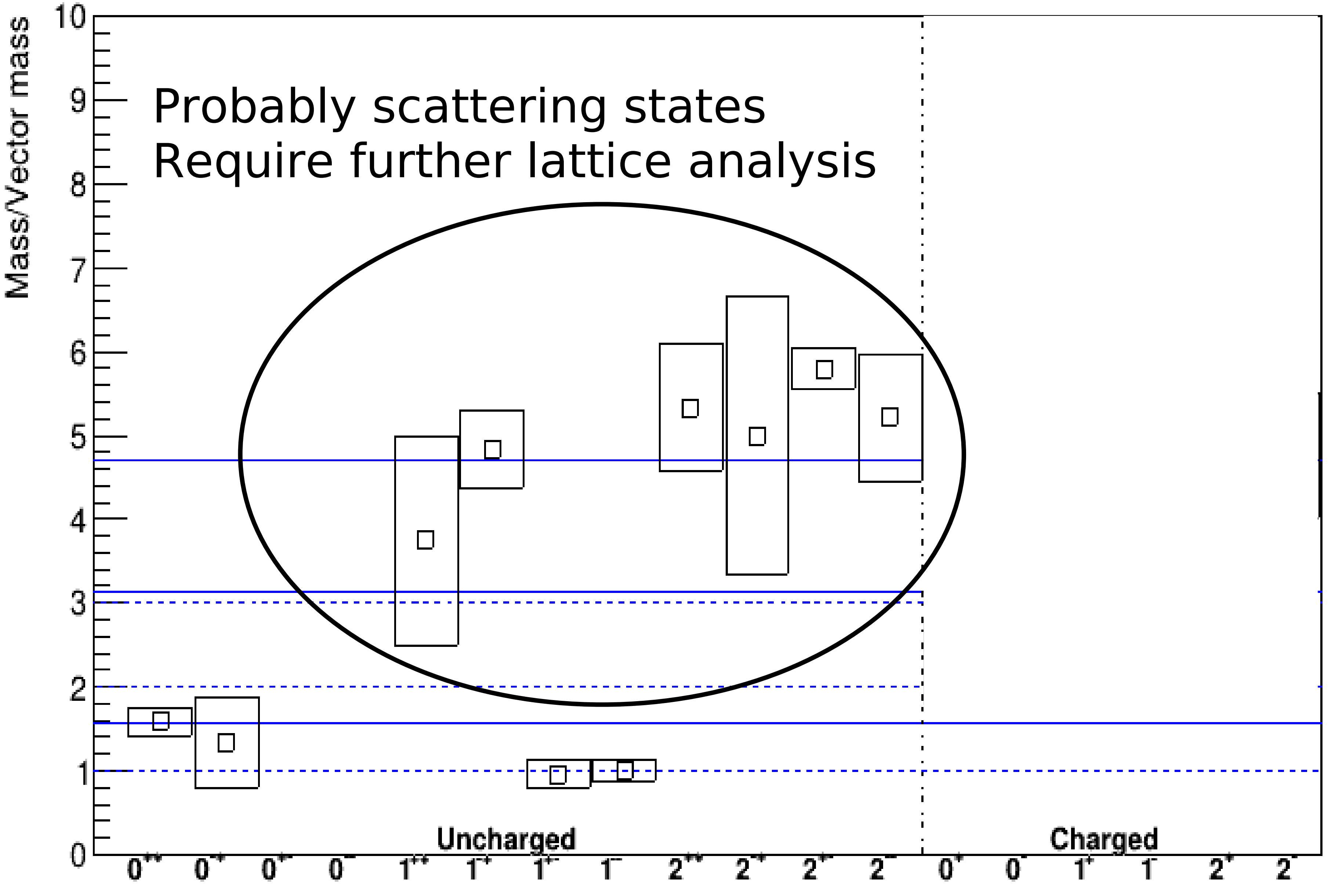

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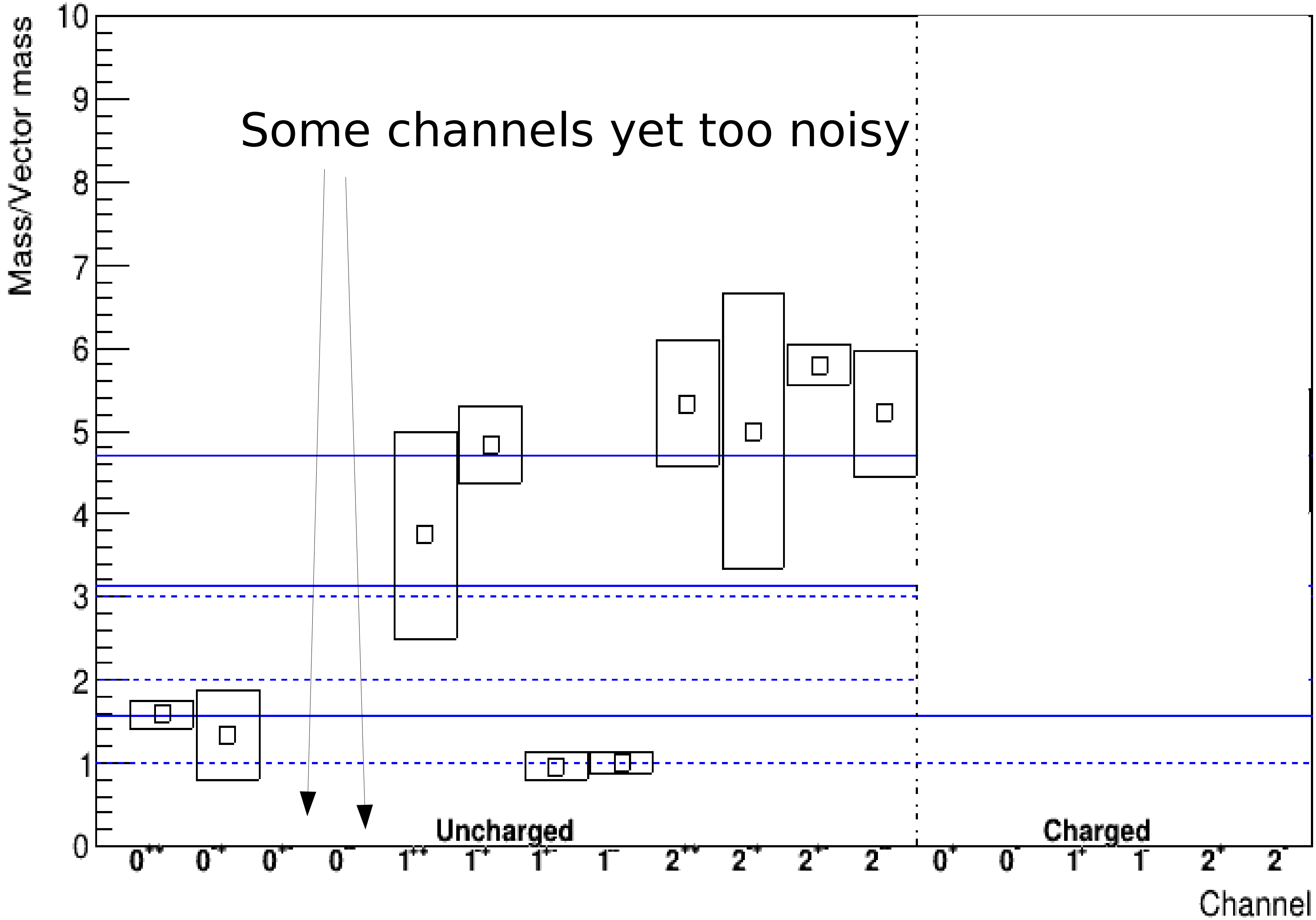

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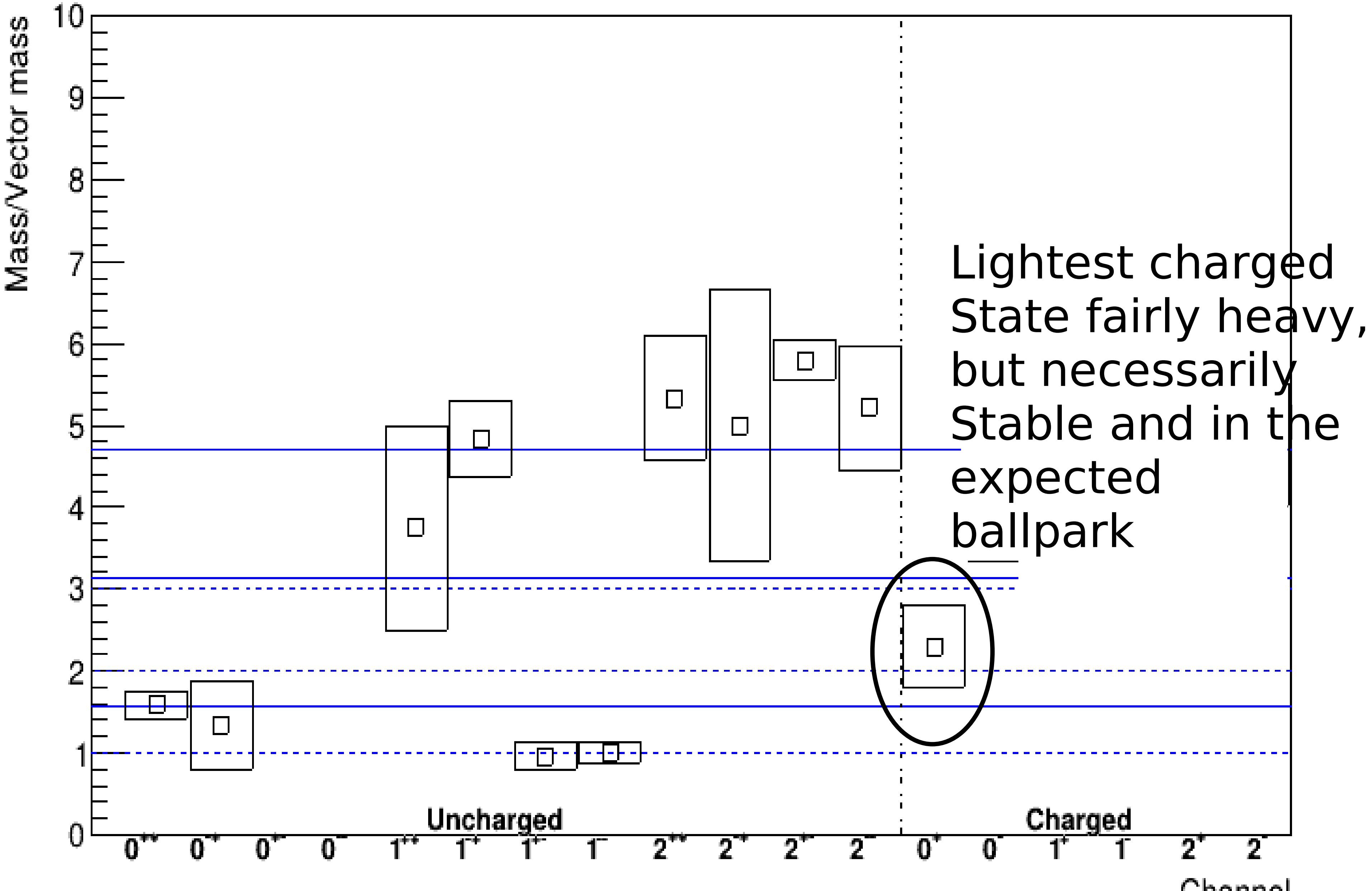

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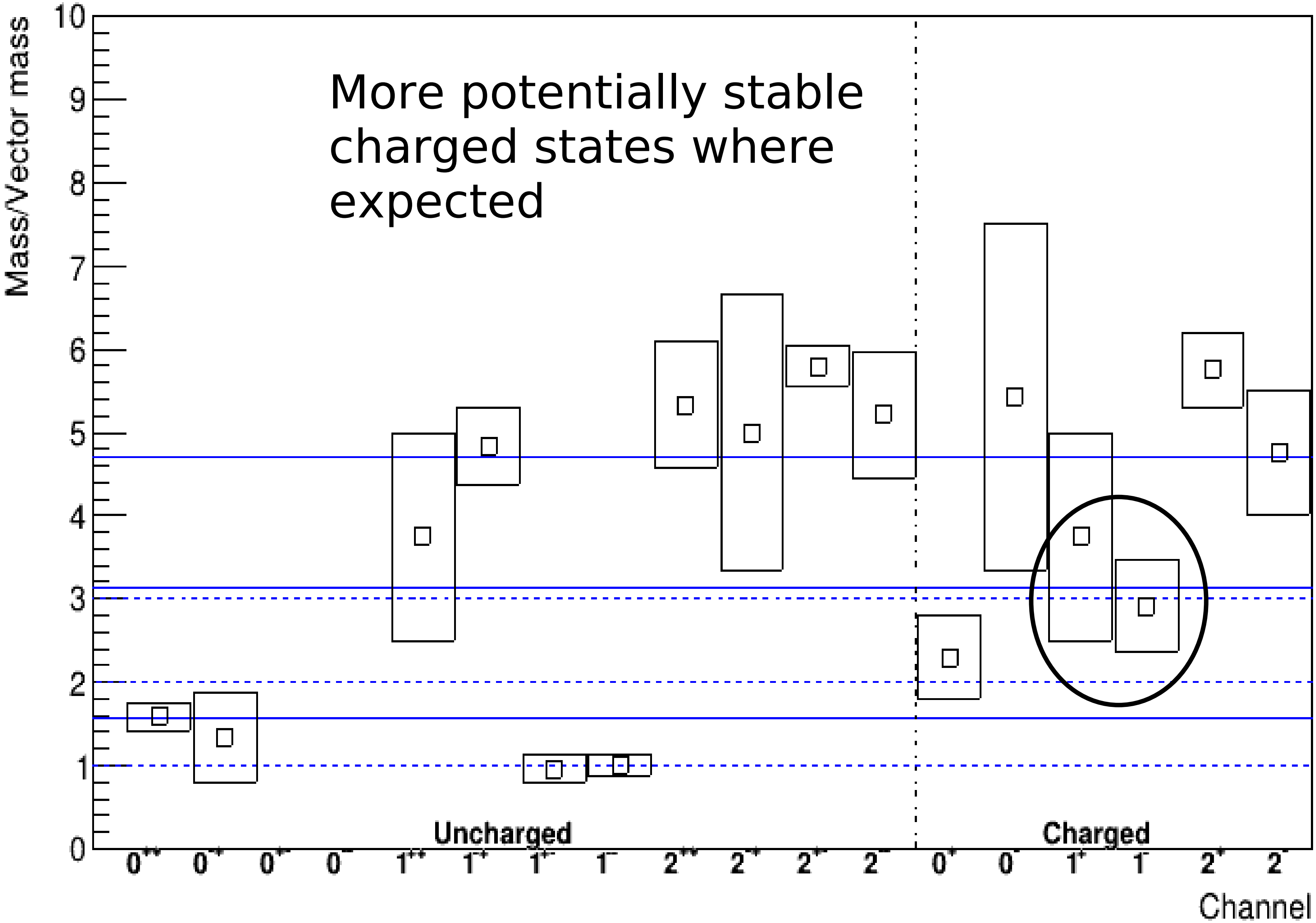

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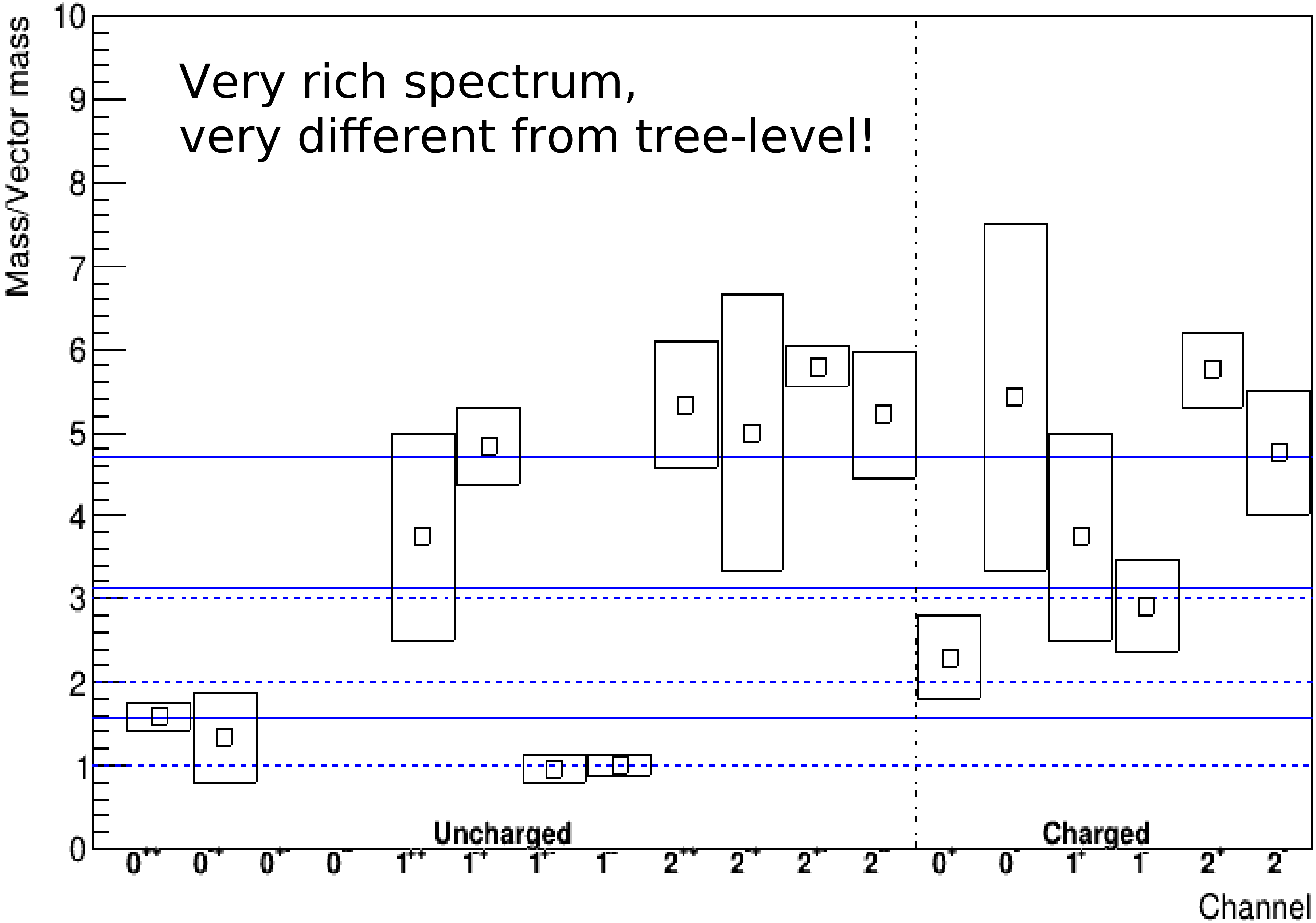

Experimental consequences

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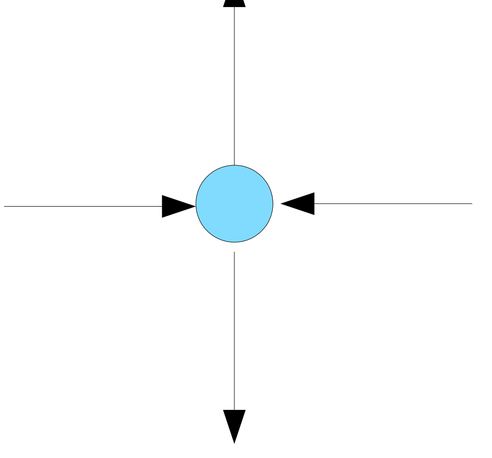

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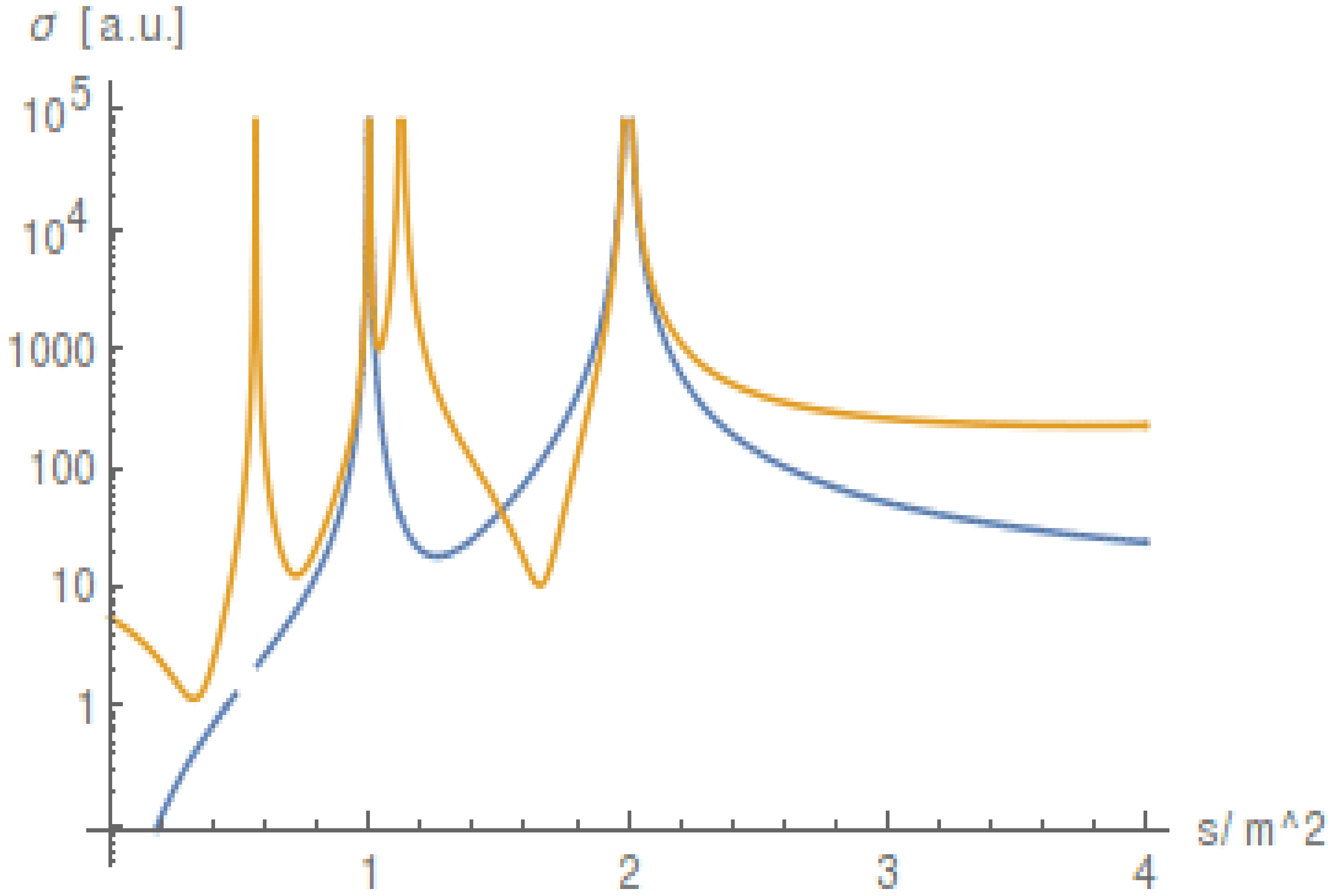

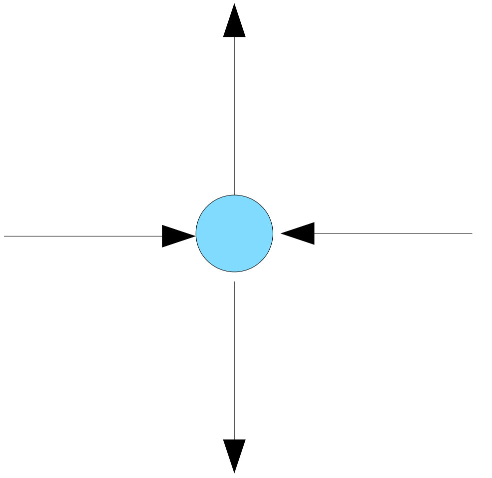

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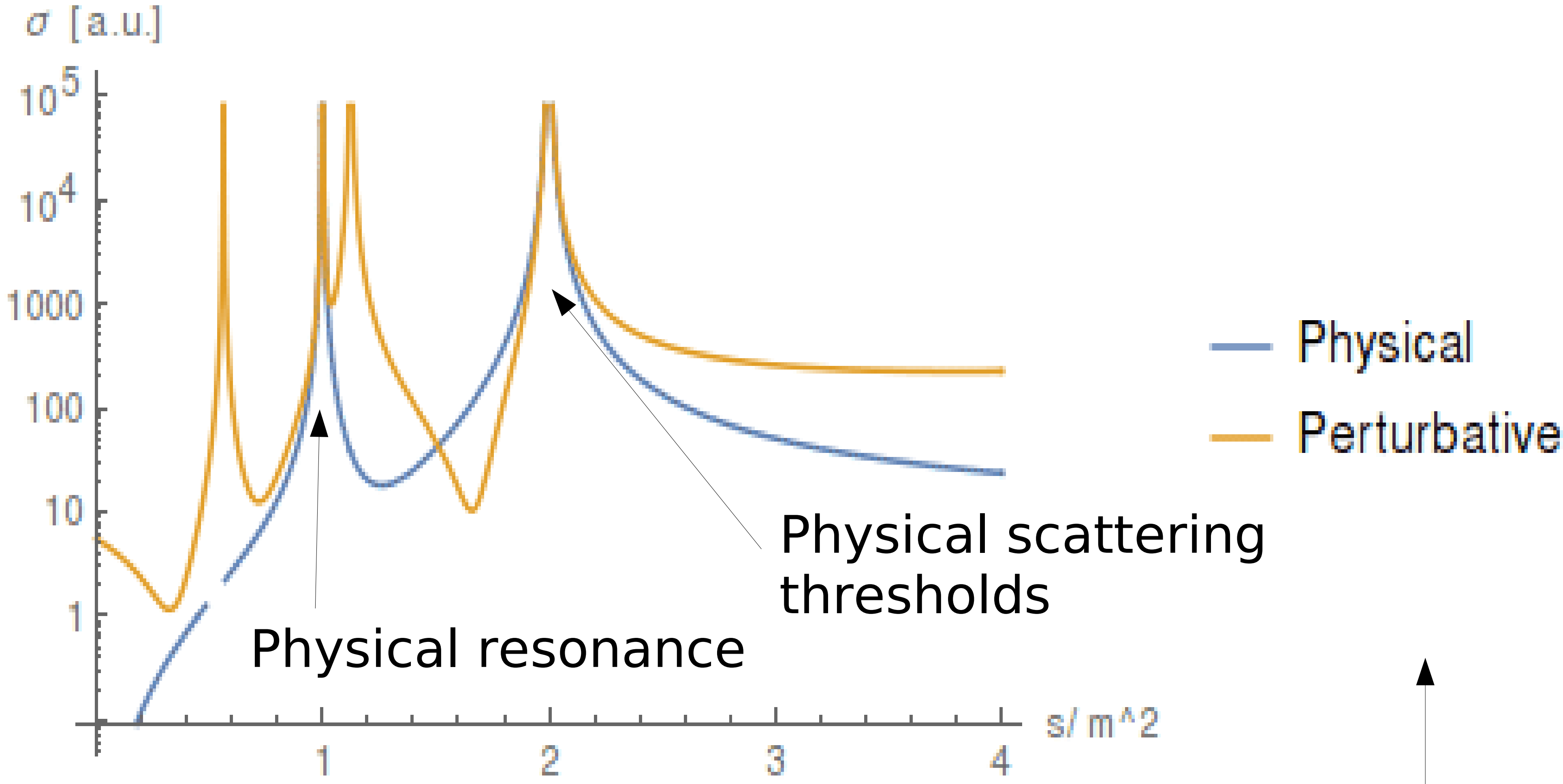

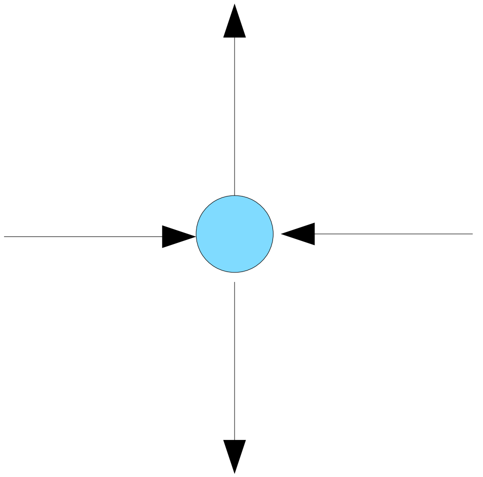

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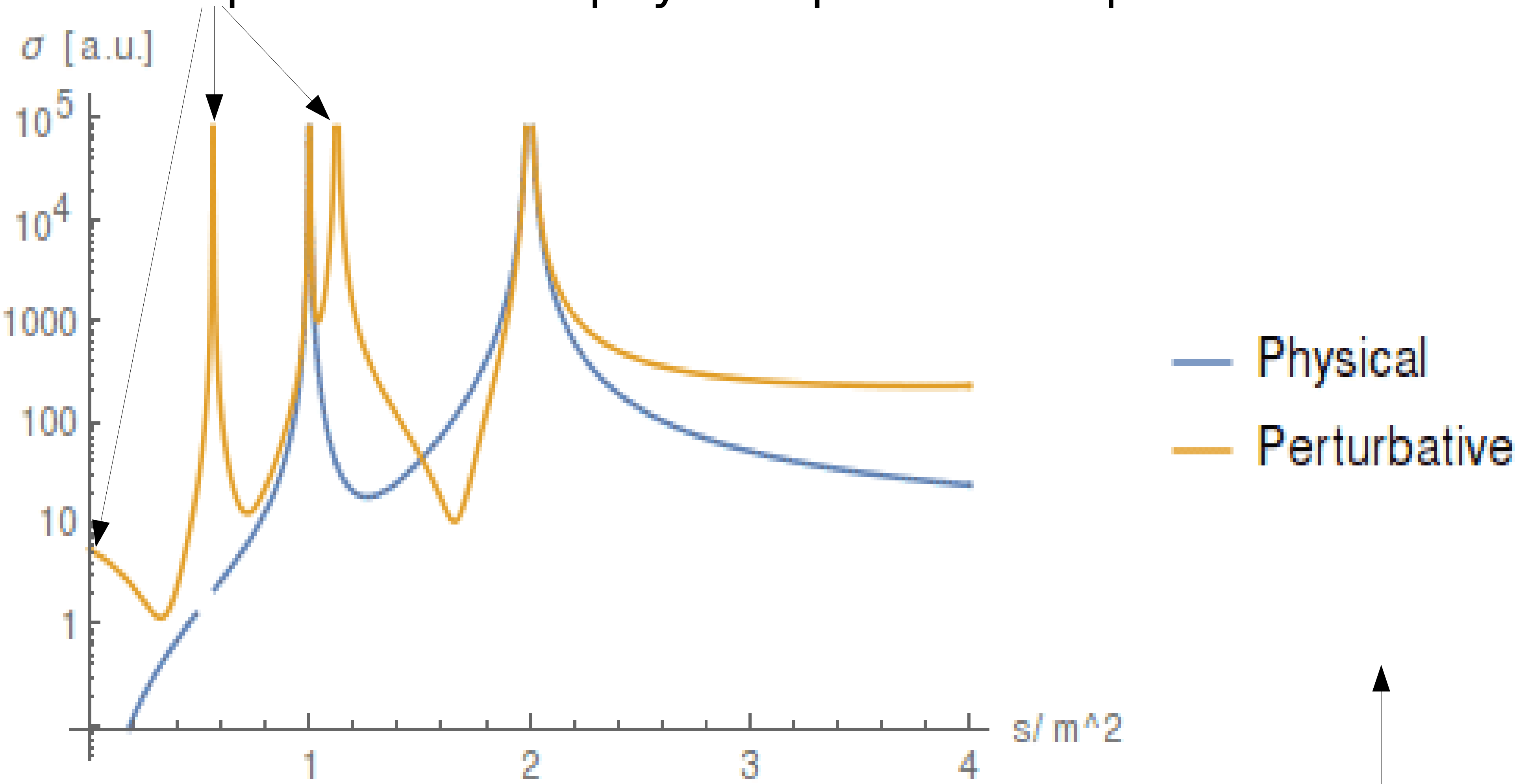
Ghost peaks from unphysical particles in perturbation theory



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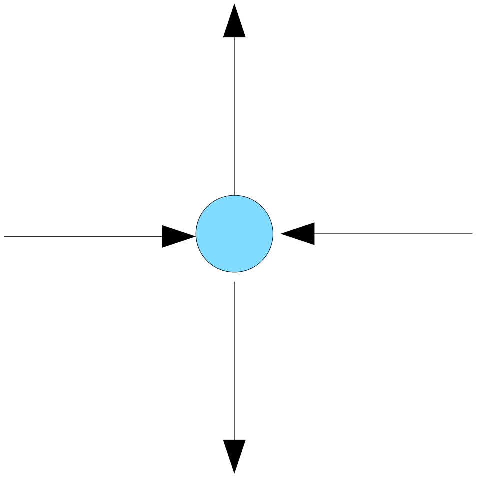

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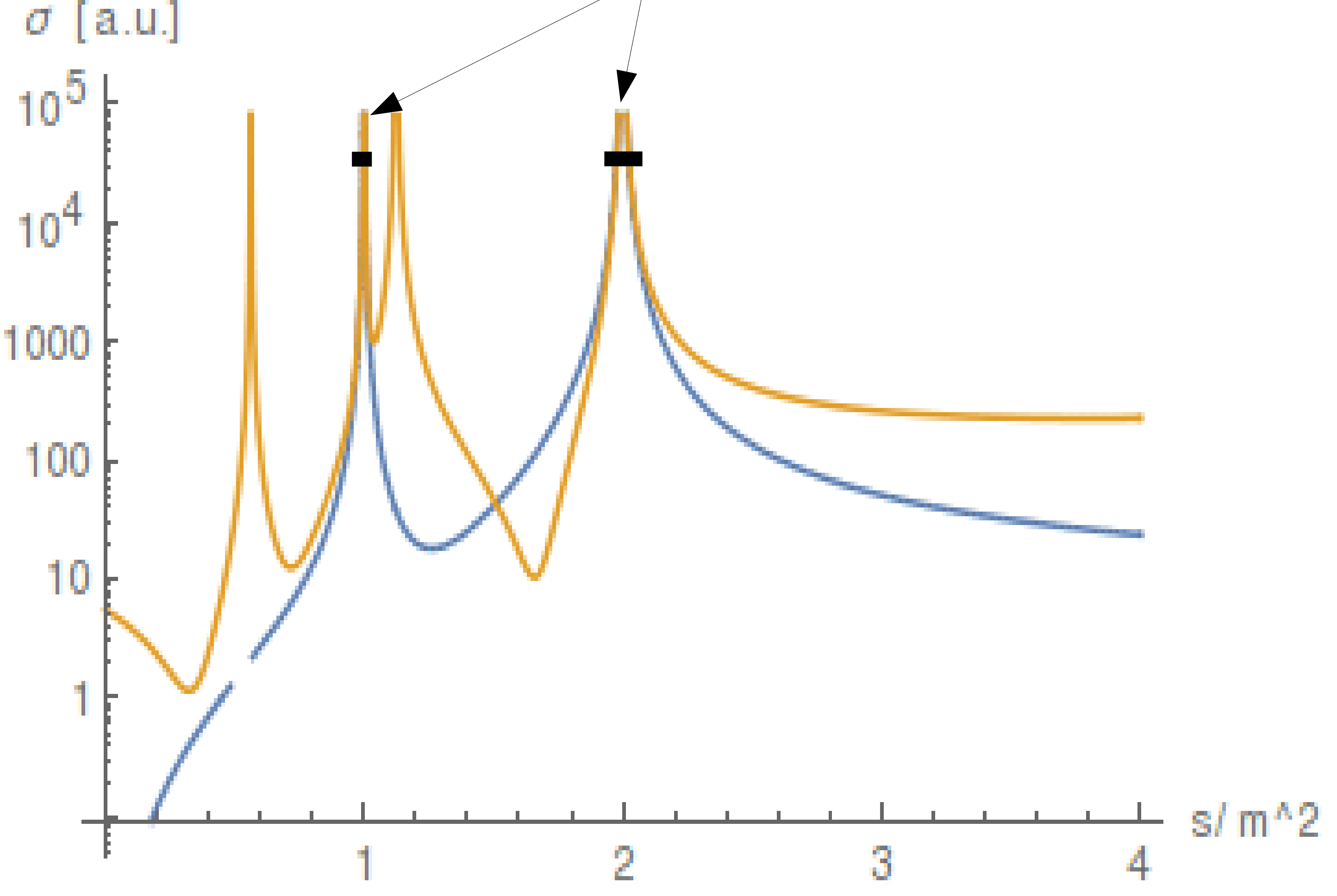
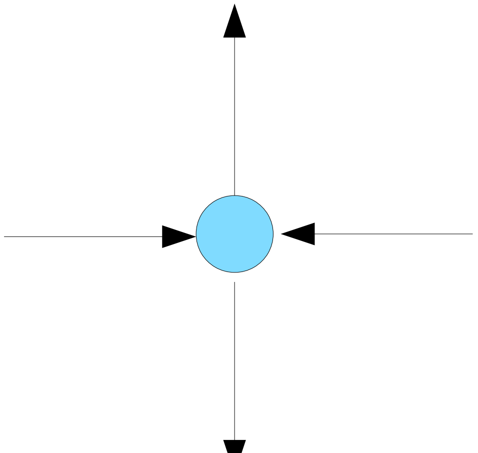
Close to true structures identical!





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[Maas’19,
Maas, Markl, Müller’22]

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  - Hints for such states seen in CDT [Maas, Plätzer, Pressler'25]

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Review: 1712.04721 Update: 2305.01960

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Review: 1712.04721 Update: 2305.01960