New effects in precision Brout-Englert-Higgs physics

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What is this talk about?

- Gauge invariance and the Brout-Englert Higgs effect
- Physical states
- Deviations and signals at experiments
- Implications beyond the standard model

Review: 1712.04721

What's the deal?

-

Gauge symmetry

A toy model

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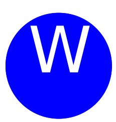
- Ws W_{μ}^{a} 

- 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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- 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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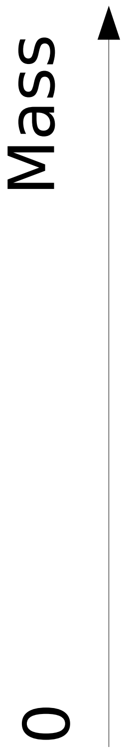
- Perform perturbation theory

Physical spectrum

Perturbation theory



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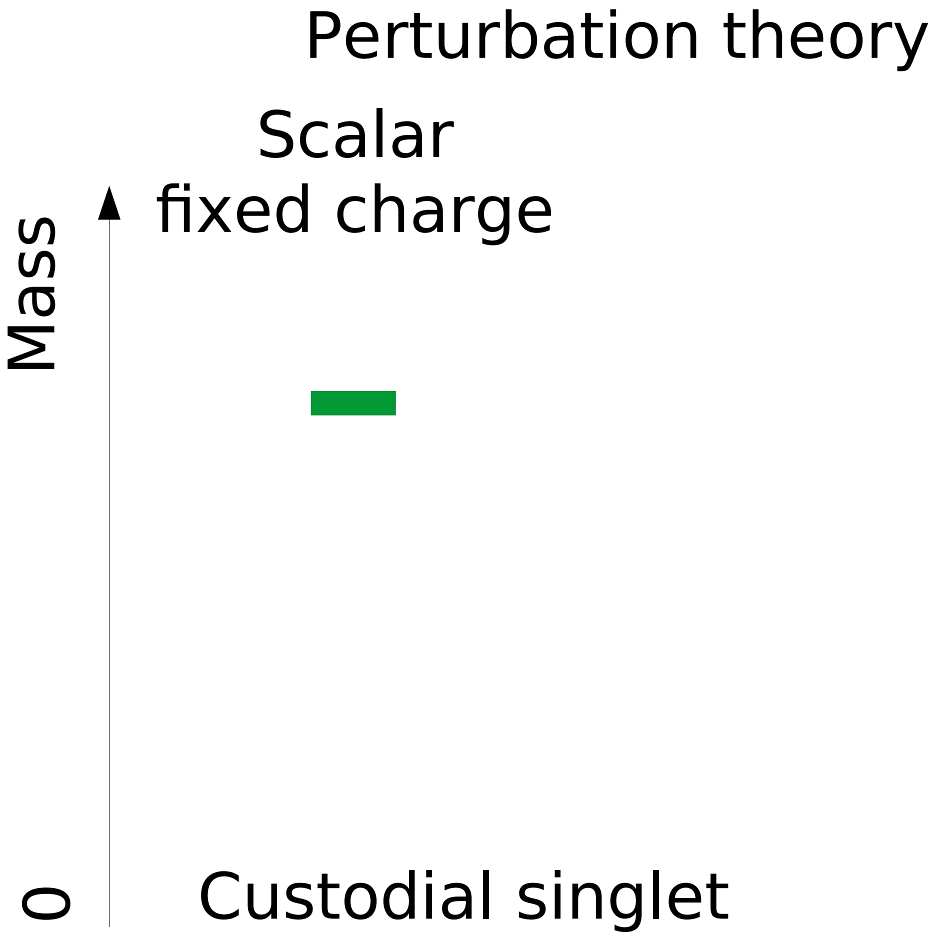

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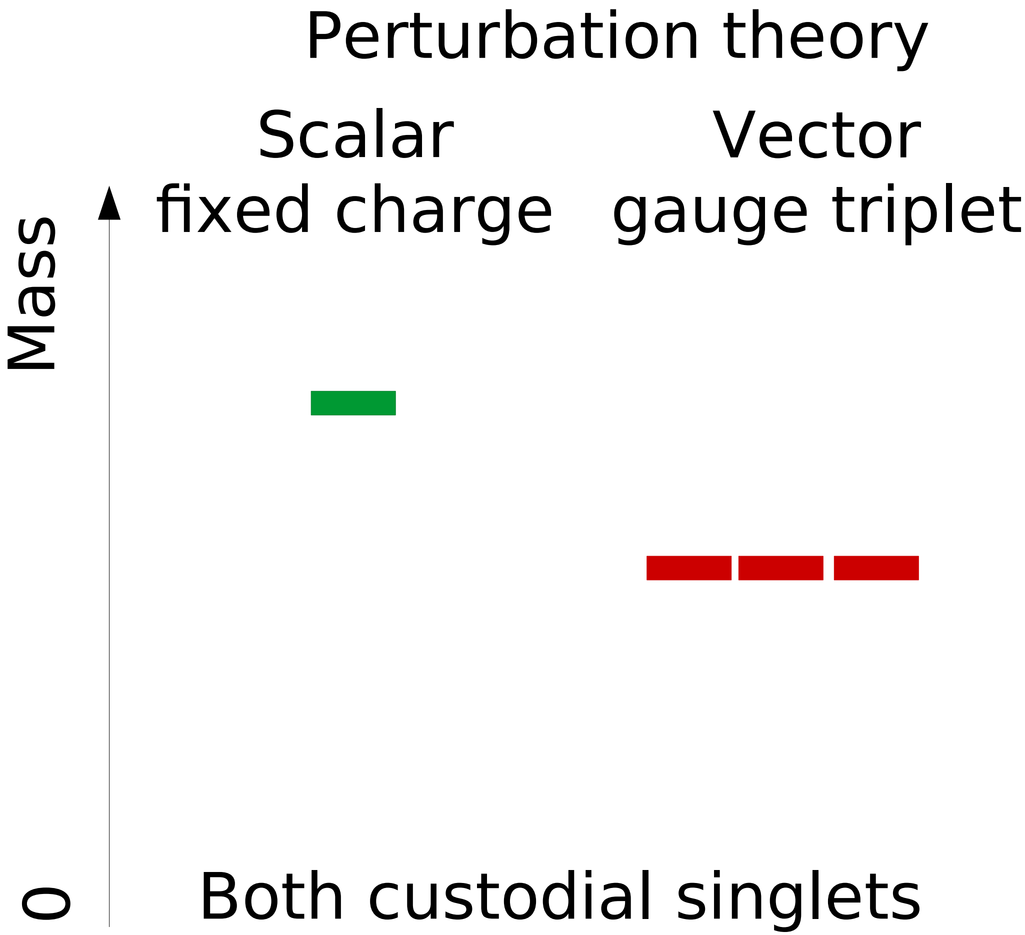

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  - And this includes non-perturbative aspects...
  - ...even at weak coupling [Gribov'78,Singer'78,Fujikawa'82]

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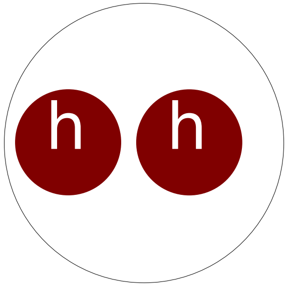

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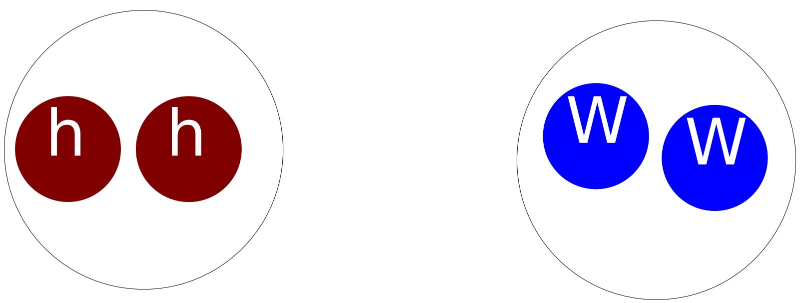

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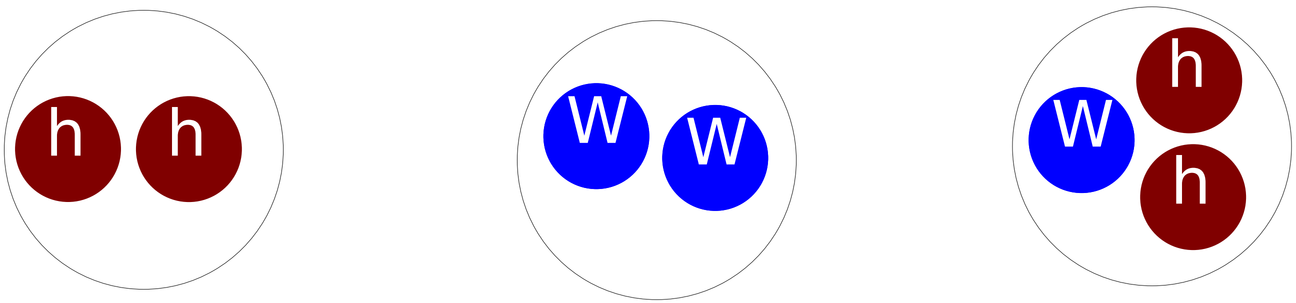

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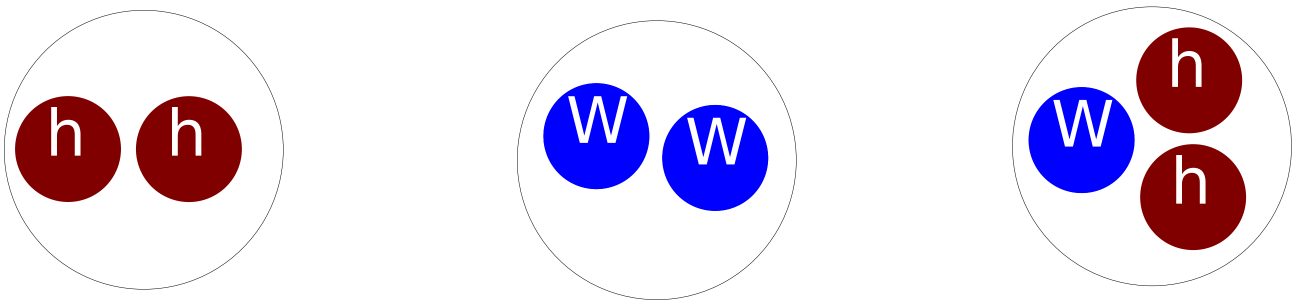

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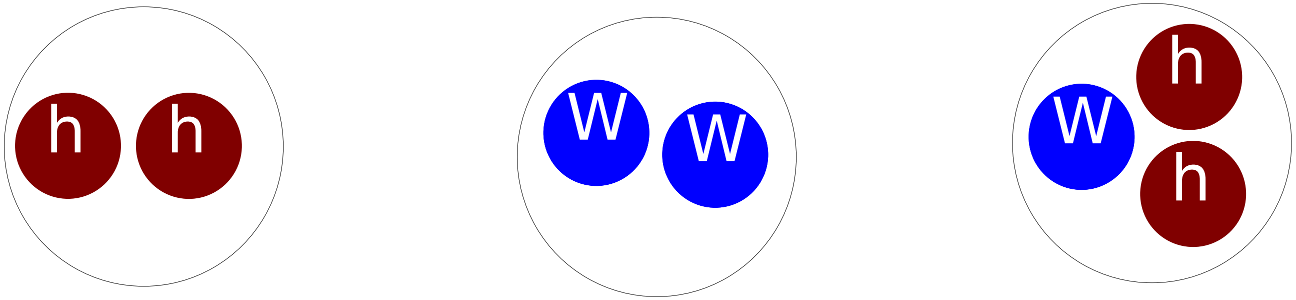

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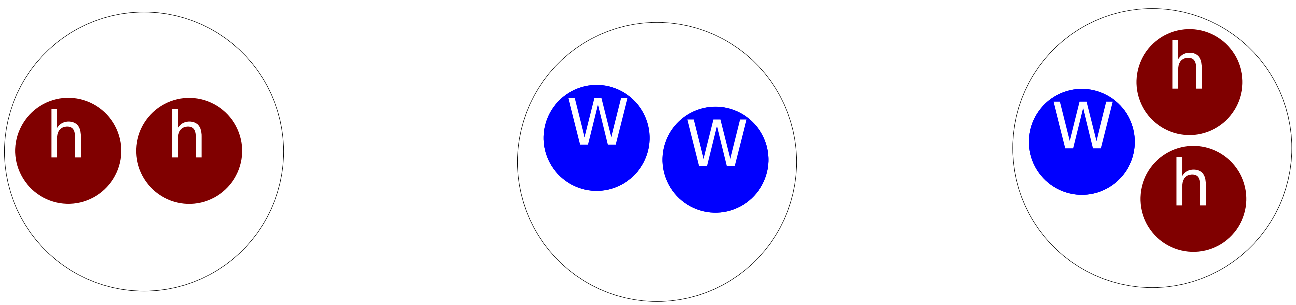

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- Can this matter?

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Lattice calculations

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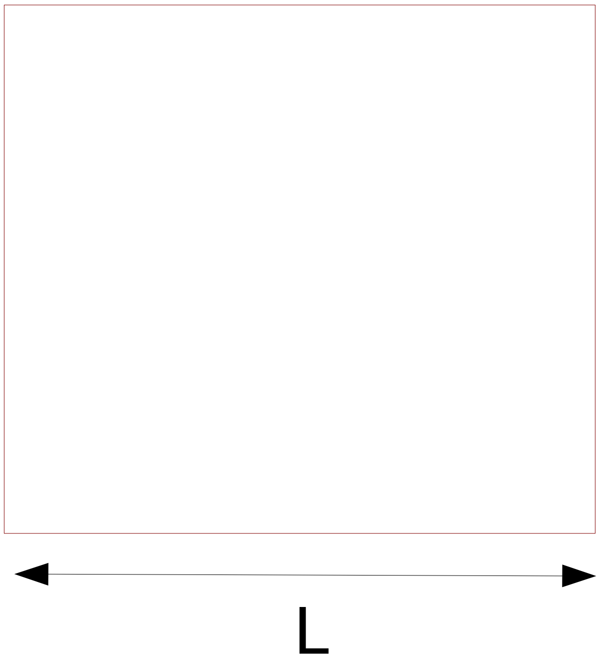

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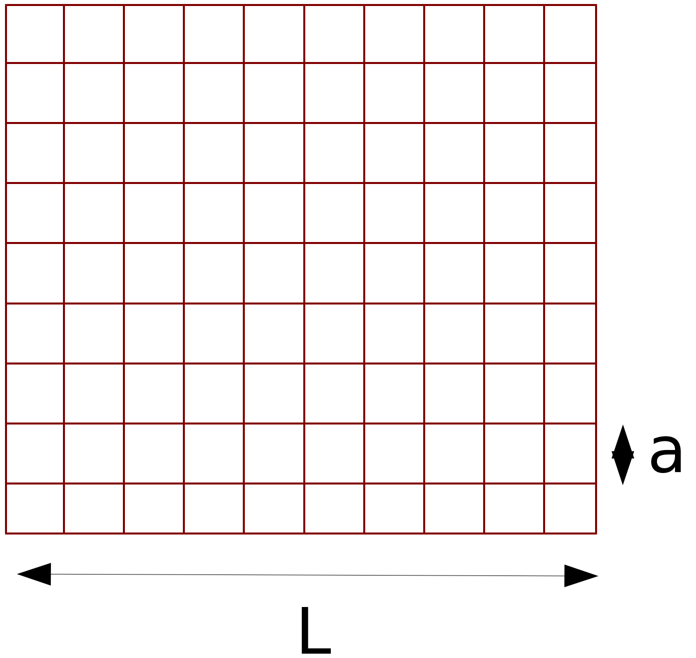

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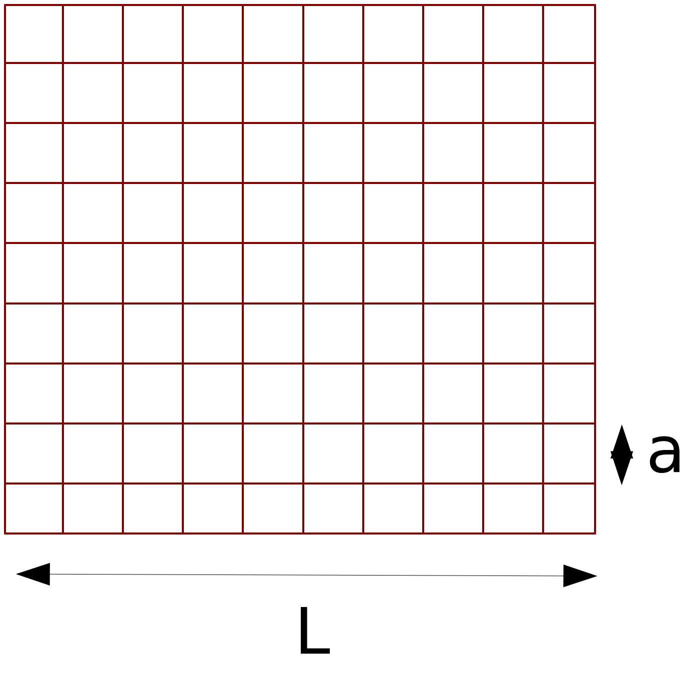

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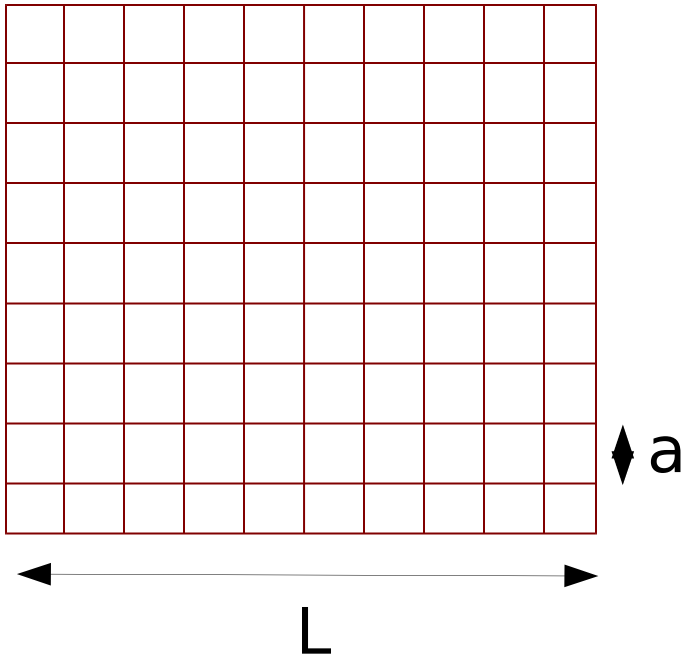

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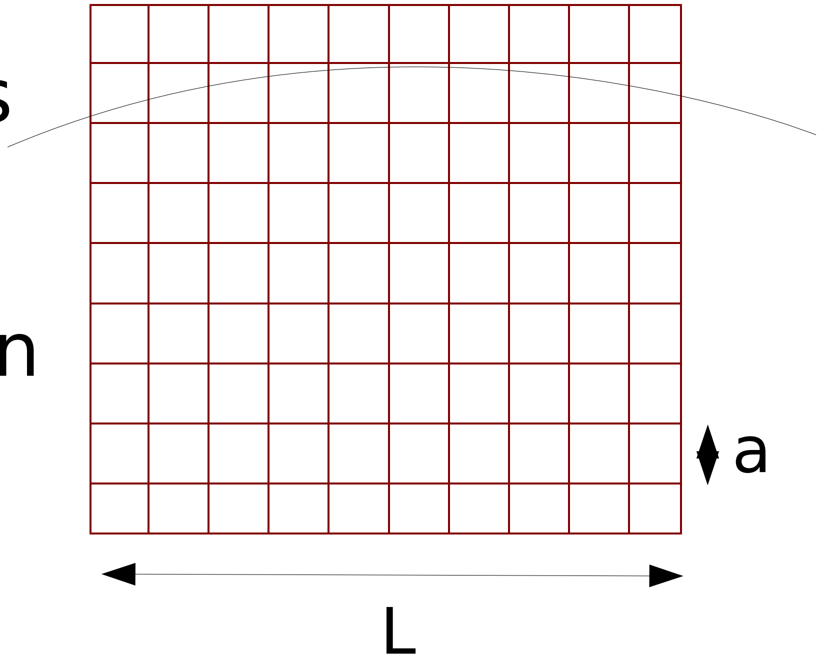

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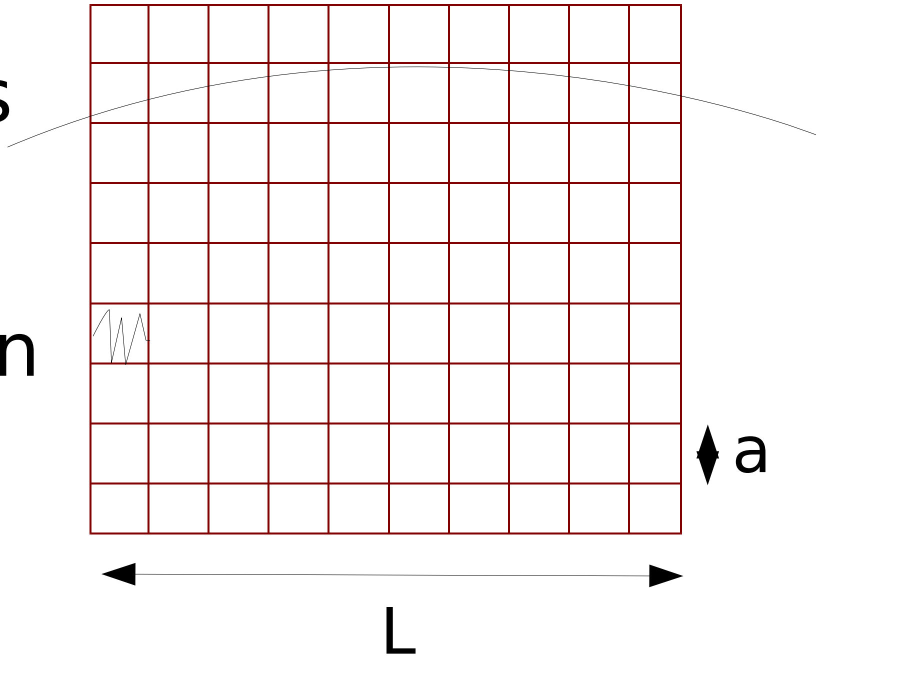

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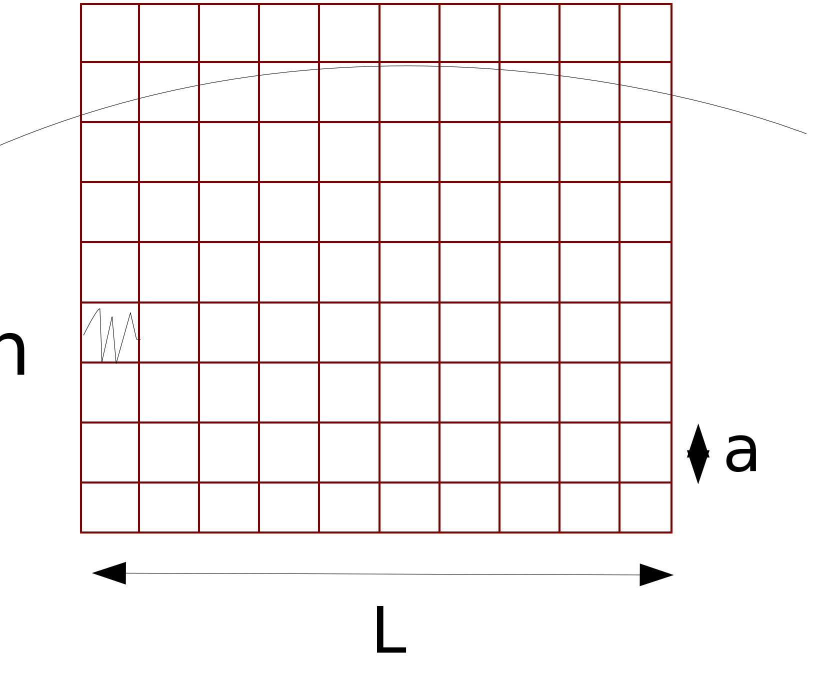
  - Euclidean formulation



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Masses from Euclidean propagators

$$D(p)=\langle O^+(p)O(-p)\rangle \sim \sum \frac{a_i}{p^2+m_i^2}$$

$$C(t)=\langle O^+(x)O(y)\rangle \sim \sum a_i \exp(-m_i \Delta t)$$

$$\sum a_i = 1 \wedge m_0 < m_1 < \ldots$$

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- Long-time behavior relevant
  - No exact results on time-like momenta

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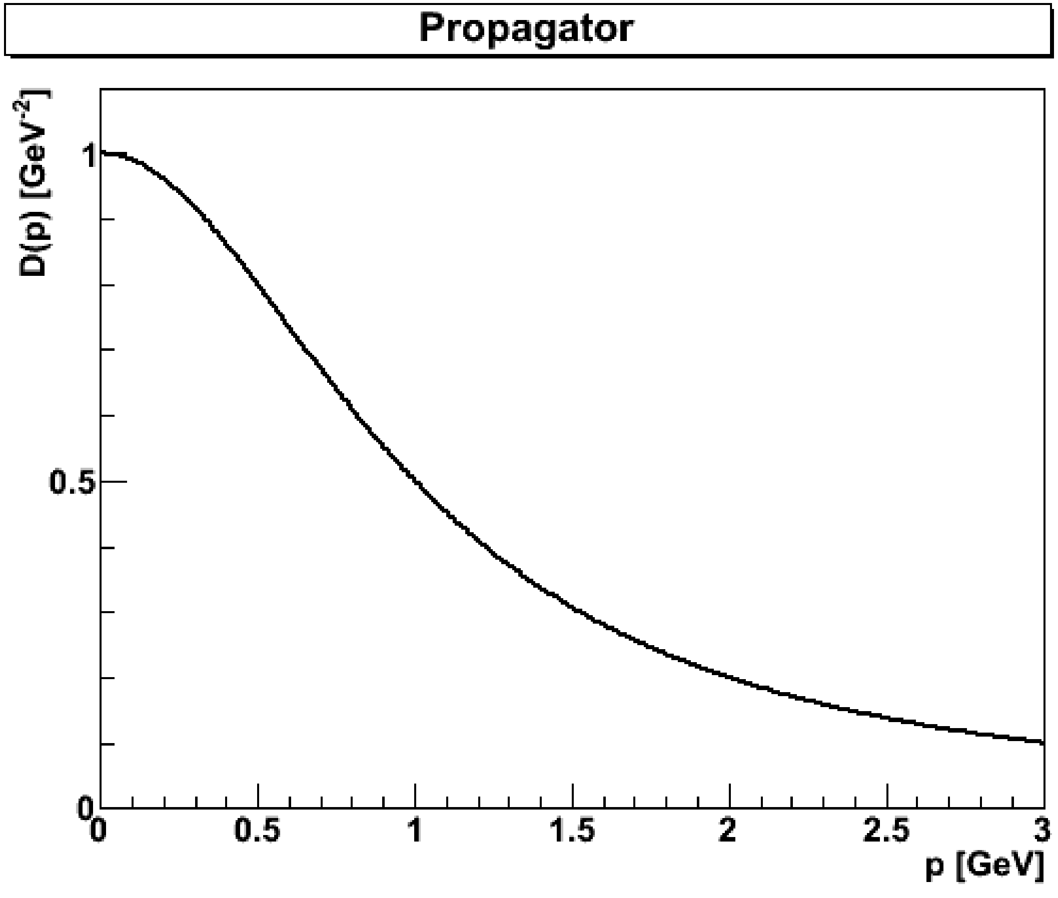

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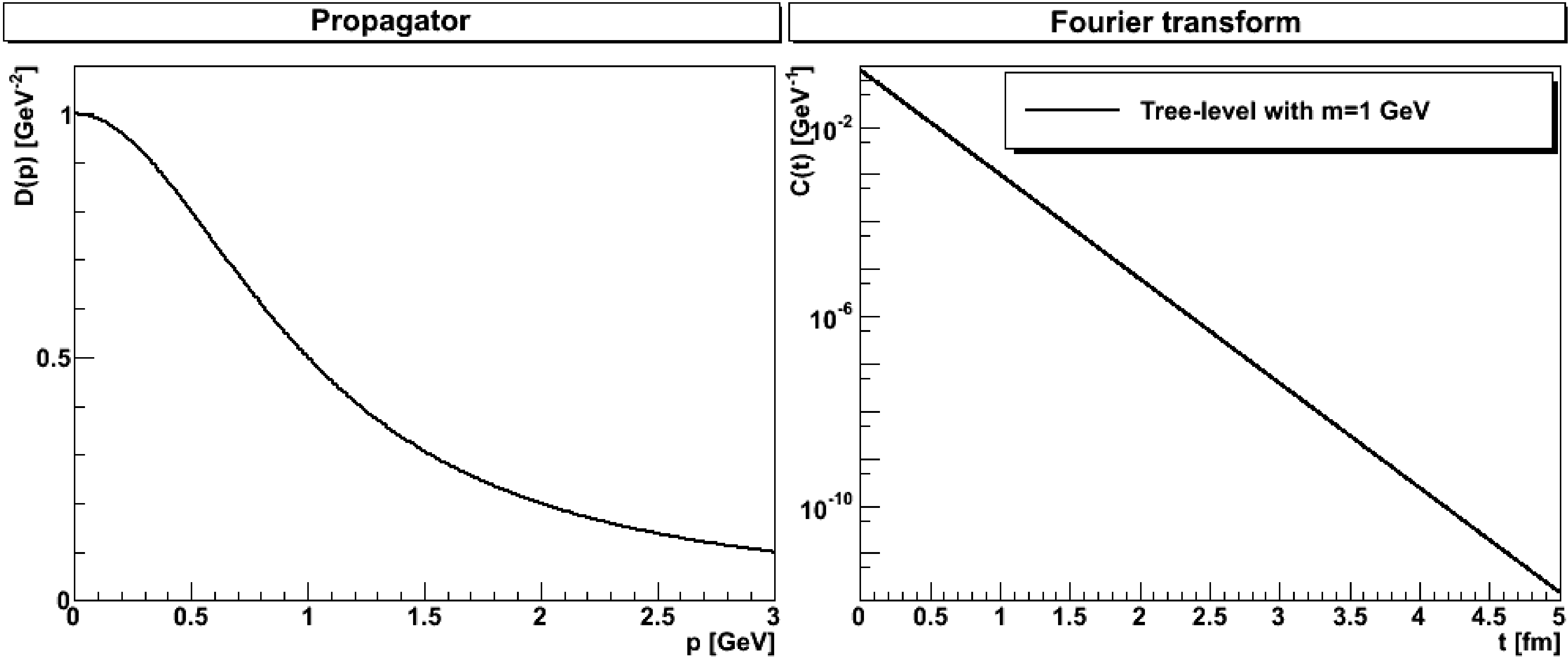

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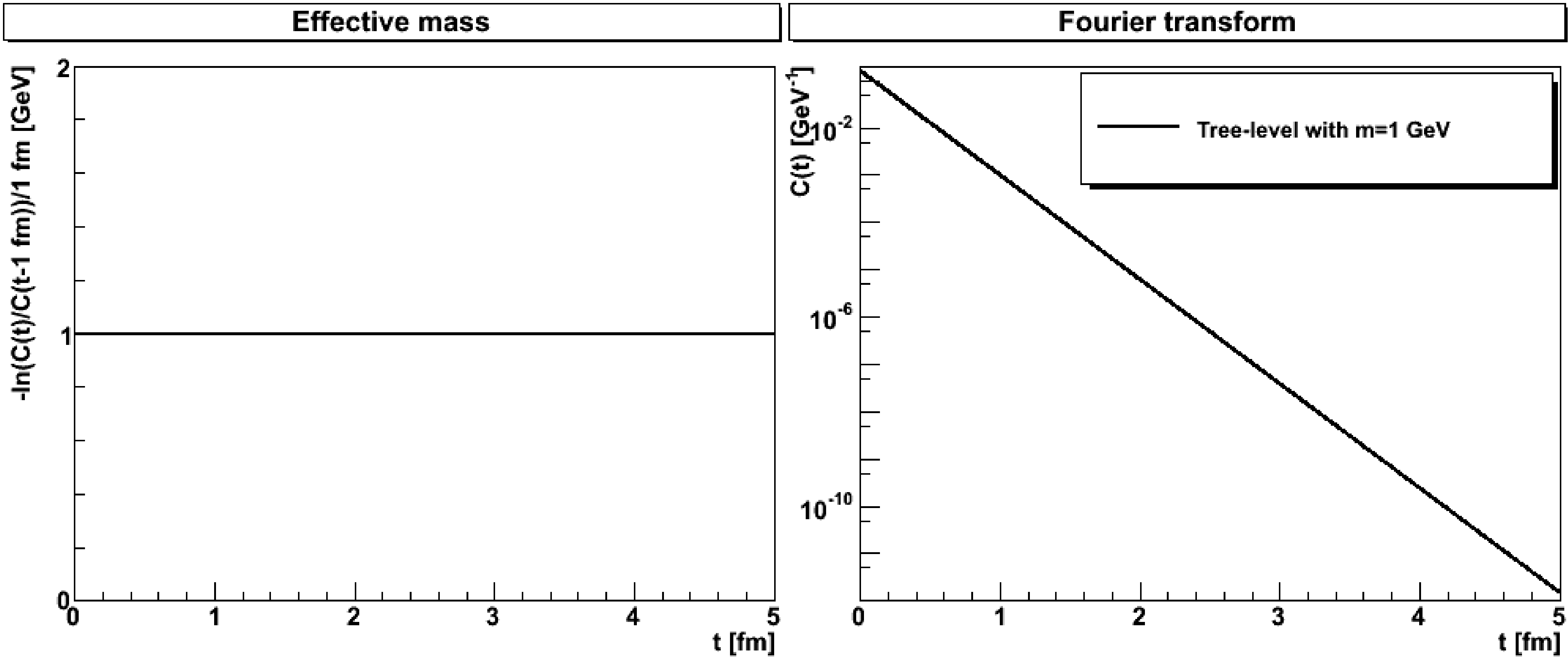

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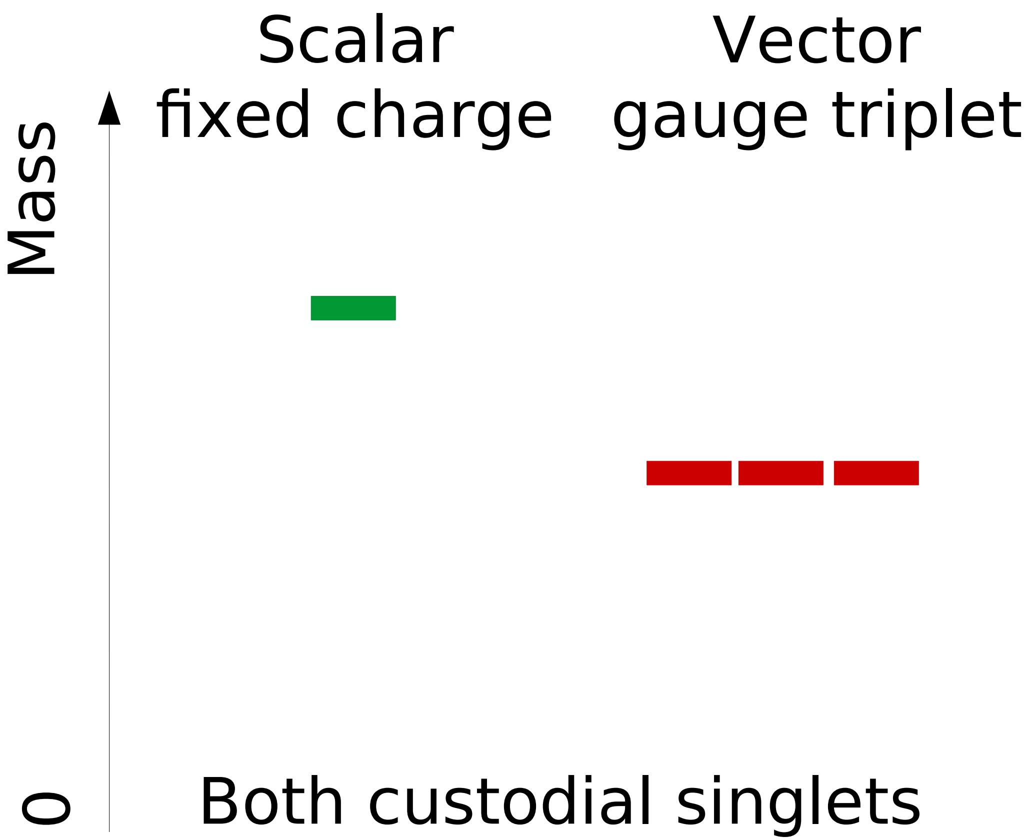
Physical spectrum

Perturbation theory



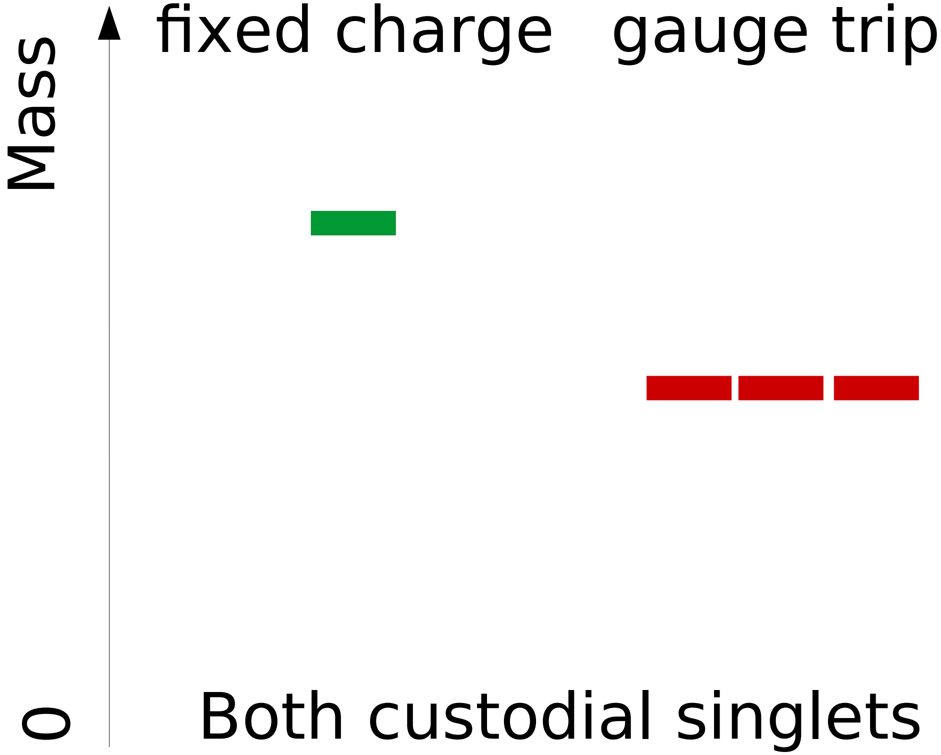
Experiment tells that somehow the left is correct

Physical spectrum

Perturbation theory

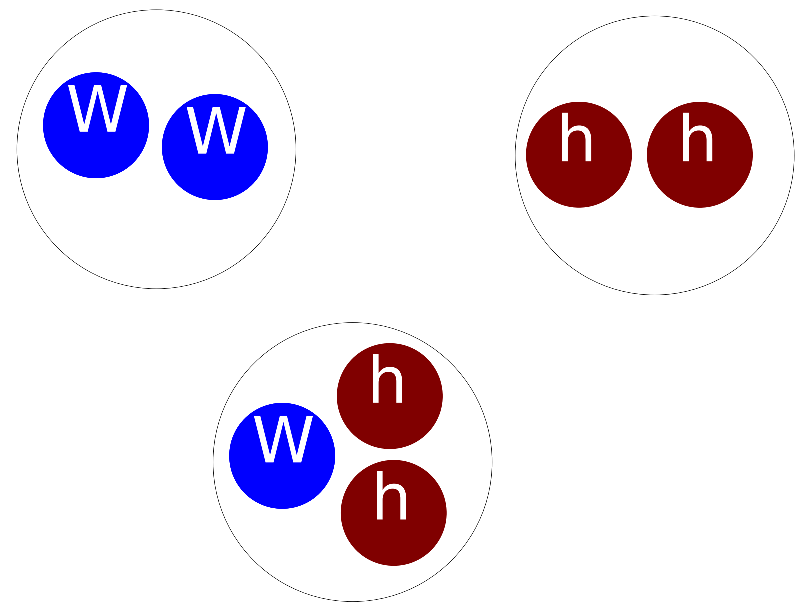
Scalar
fixed charge

Vector
gauge triplet



Both custodial singlets

Composite (bound) states



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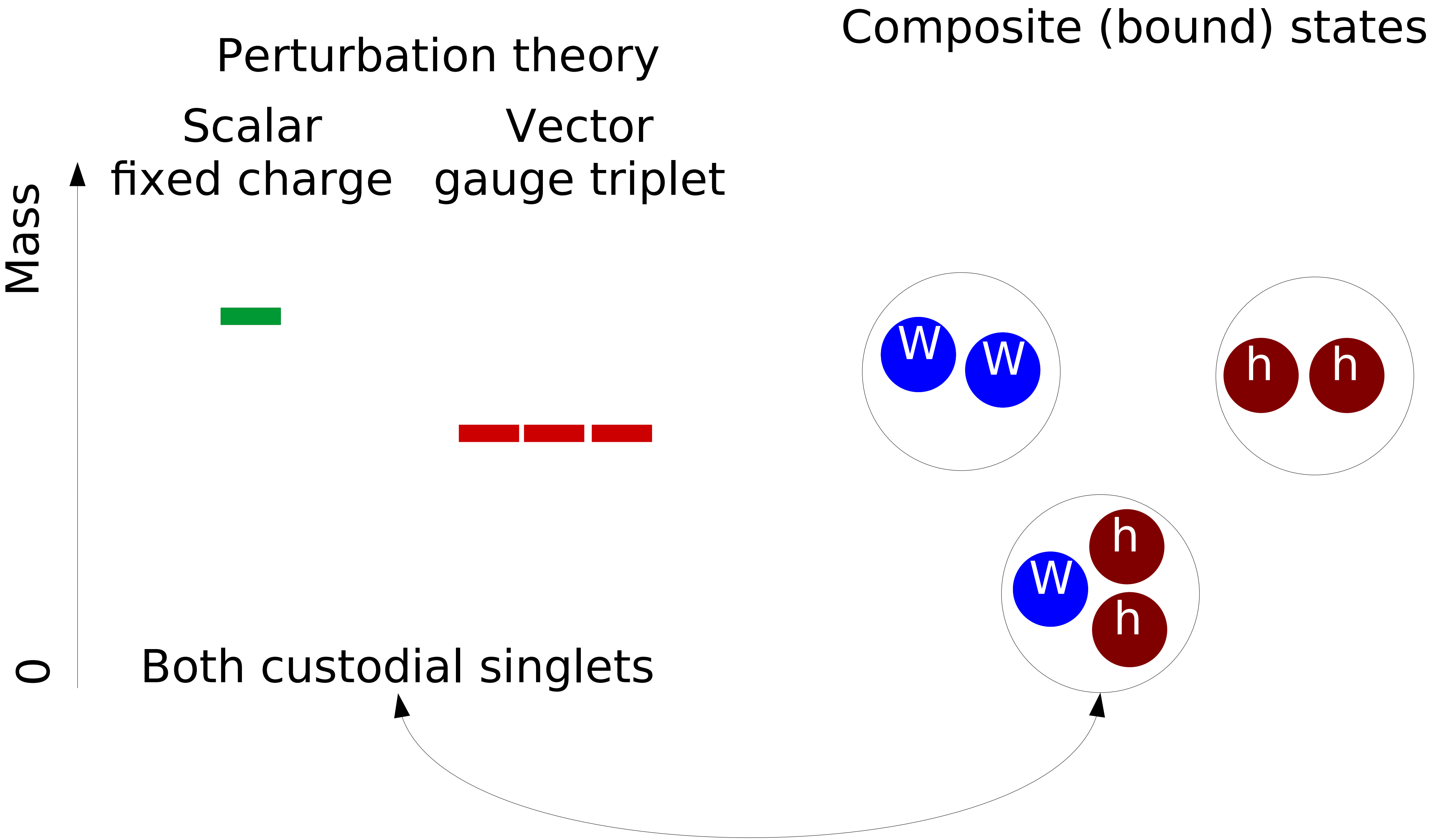
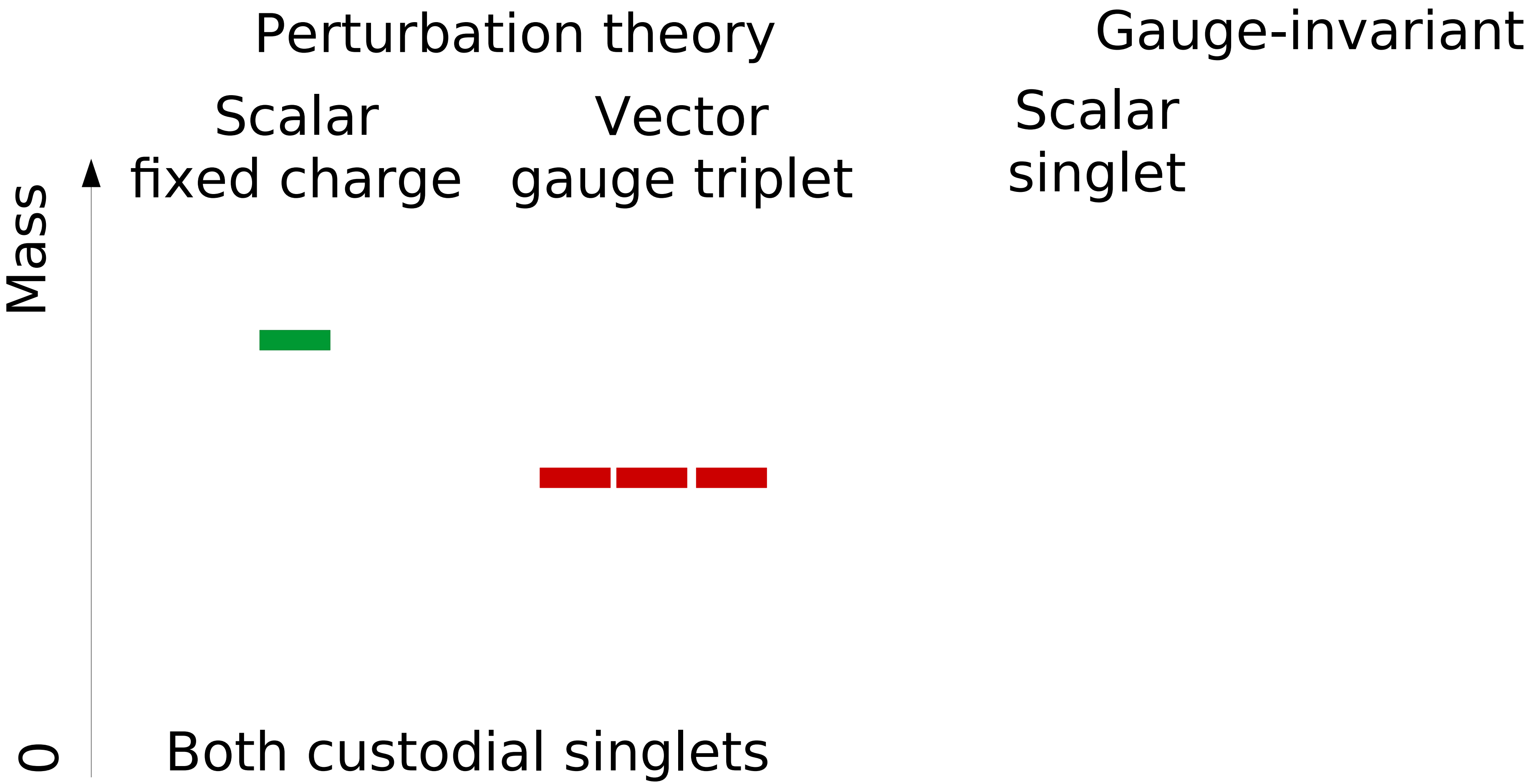
Physical spectrum



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

Physical spectrum

[Maas'12, Maas & Mufti'14]



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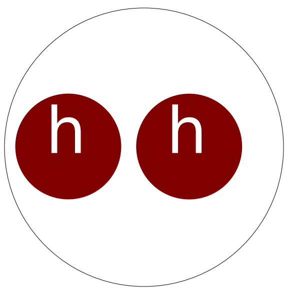

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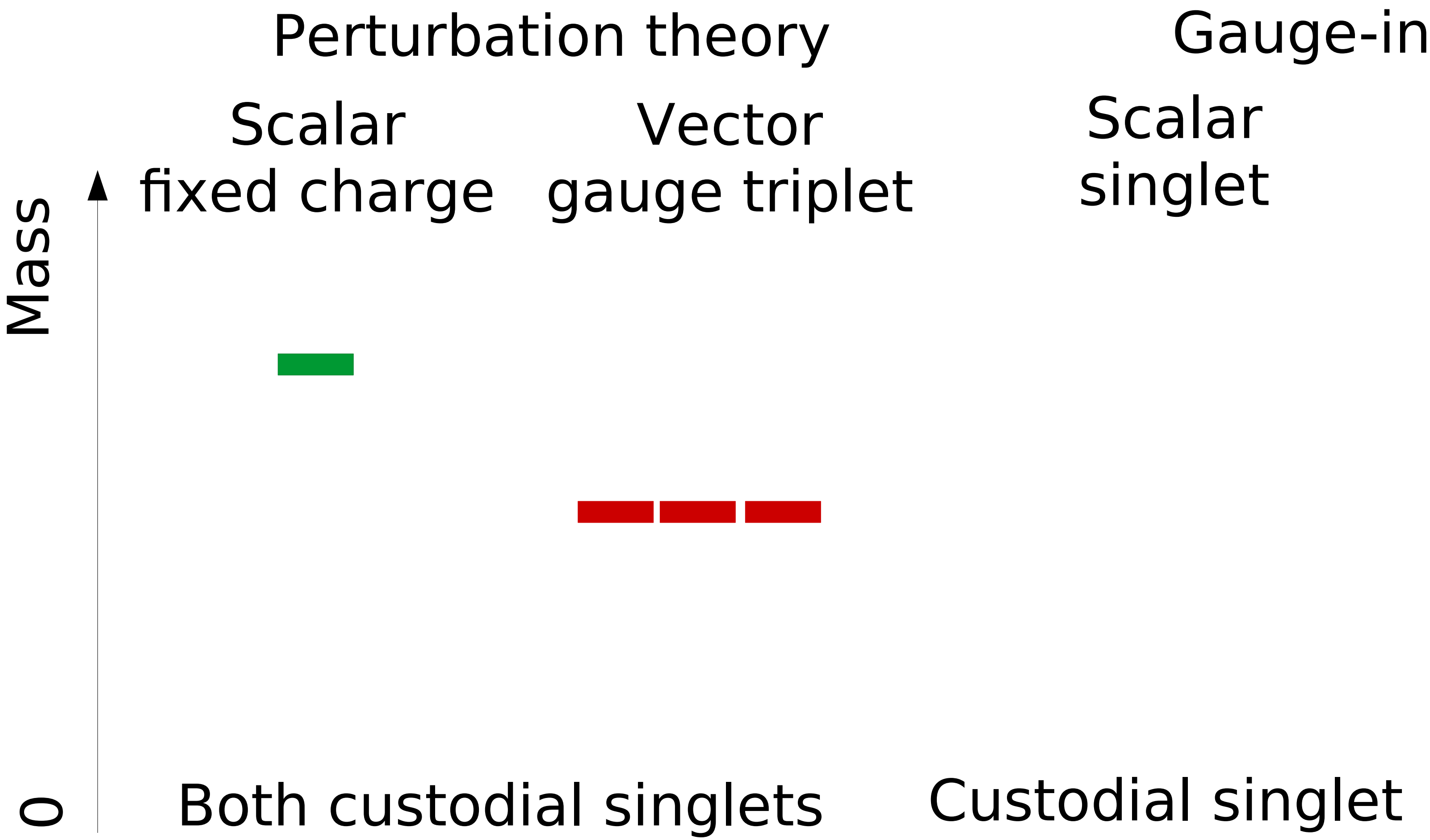

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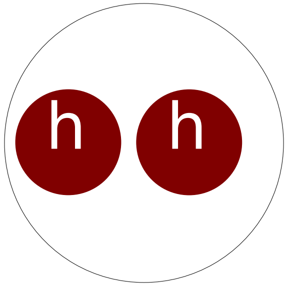
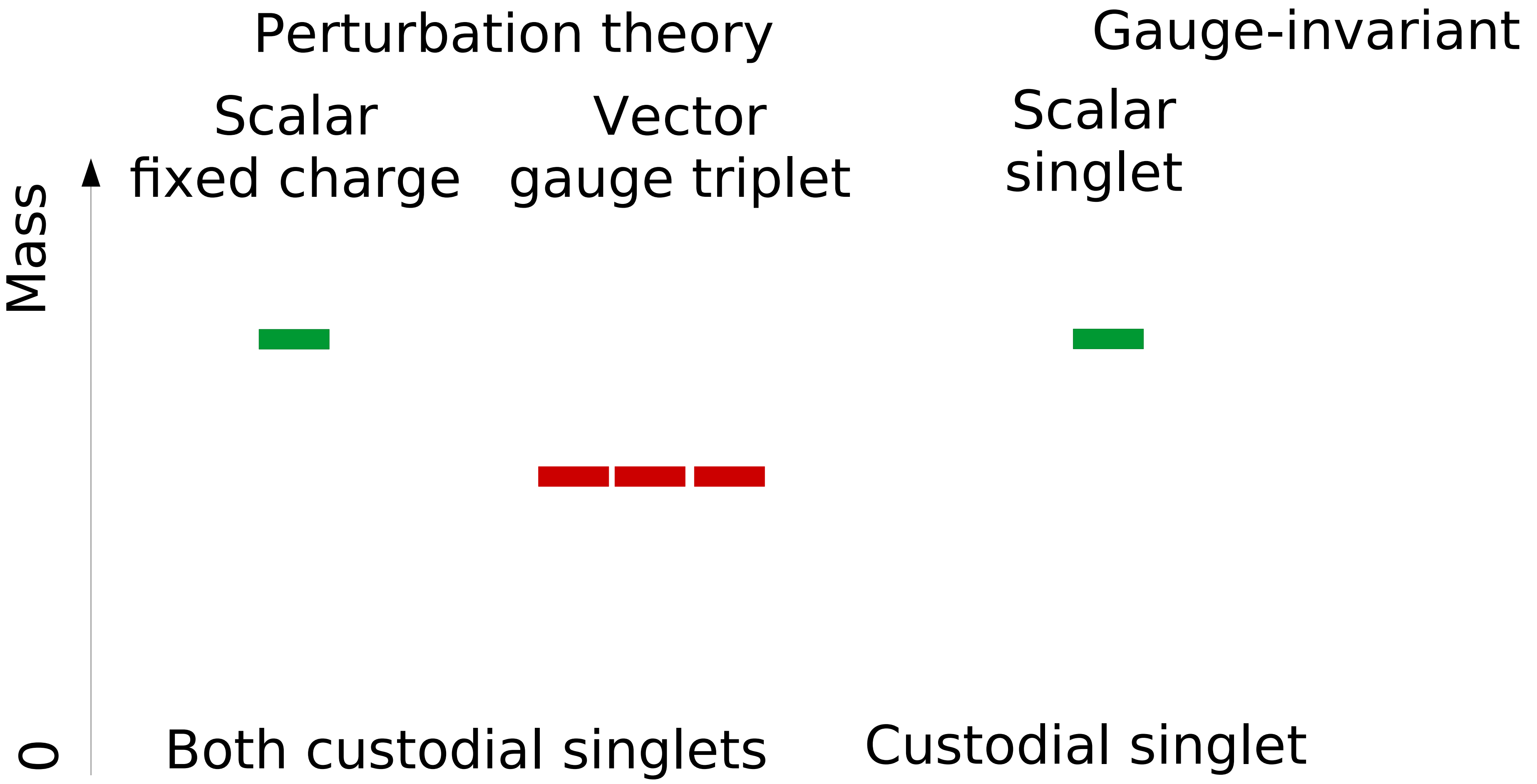


Physical spectrum

[Maas'12, Maas & Mufti'14]



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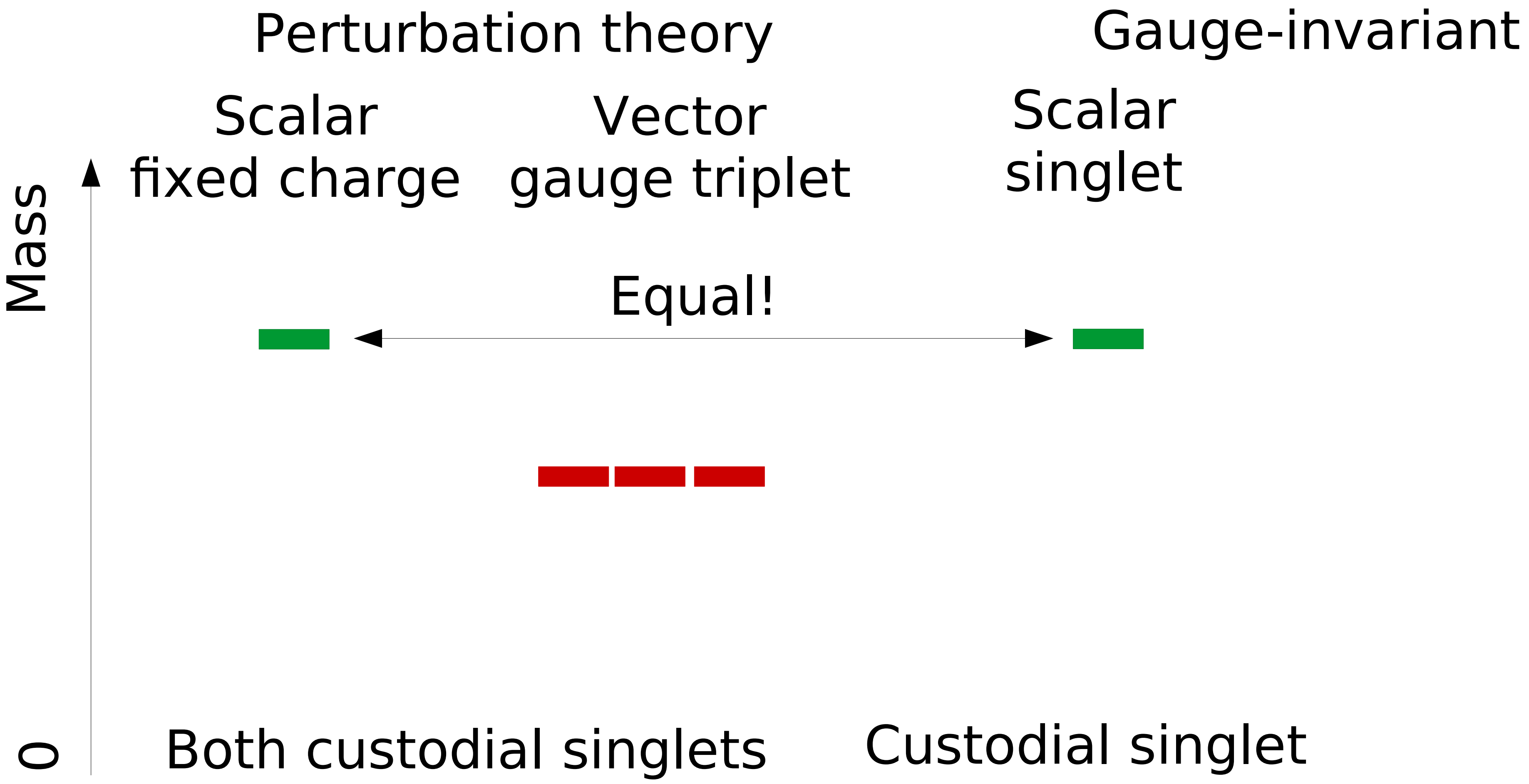
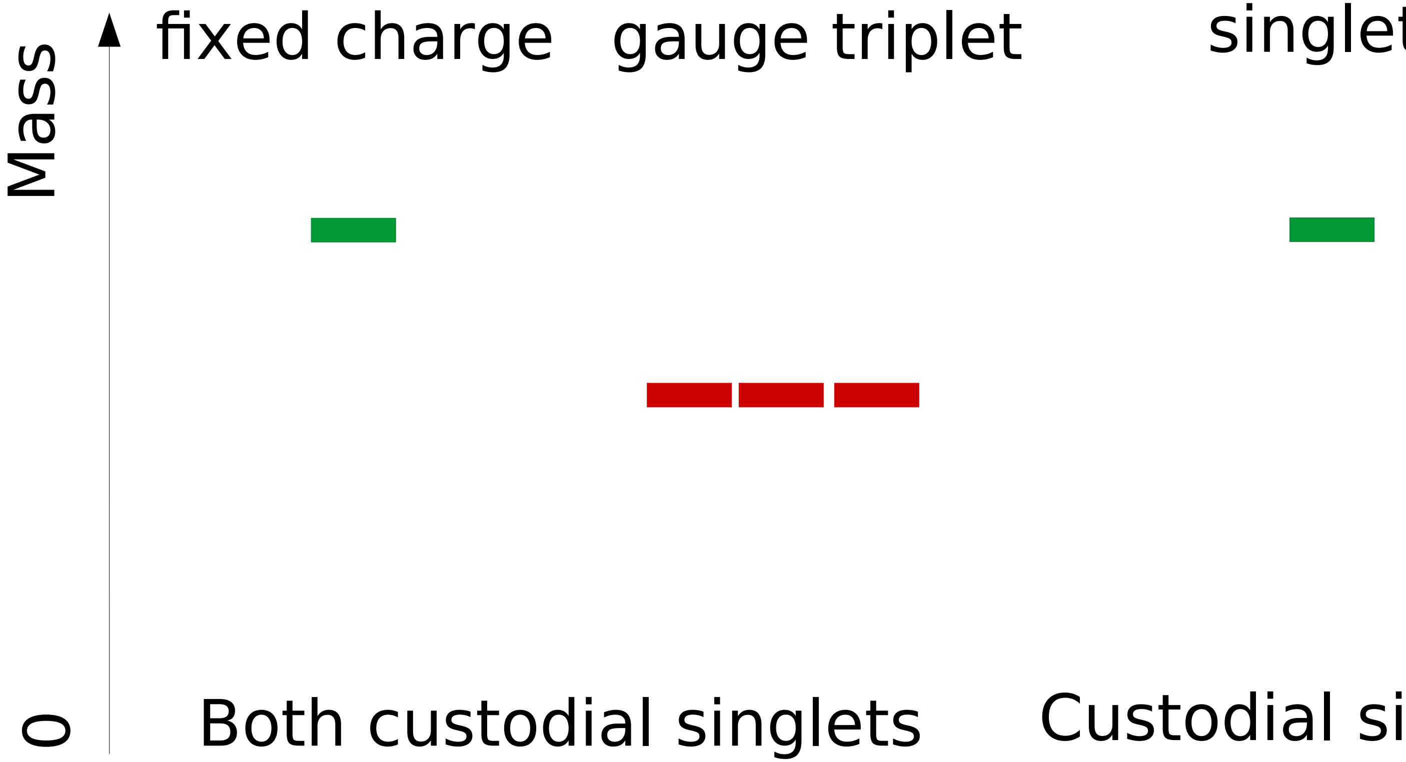


Physical spectrum

[Maas'12, Maas & Mufti'14]

Perturbation theory | Gauge-invariant

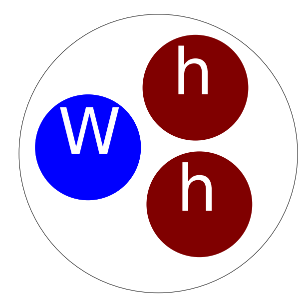
Scalar fixed charge | Vector gauge triplet | Scalar singlet | Vector singlet



Both custodial singlets

Custodial singlet

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



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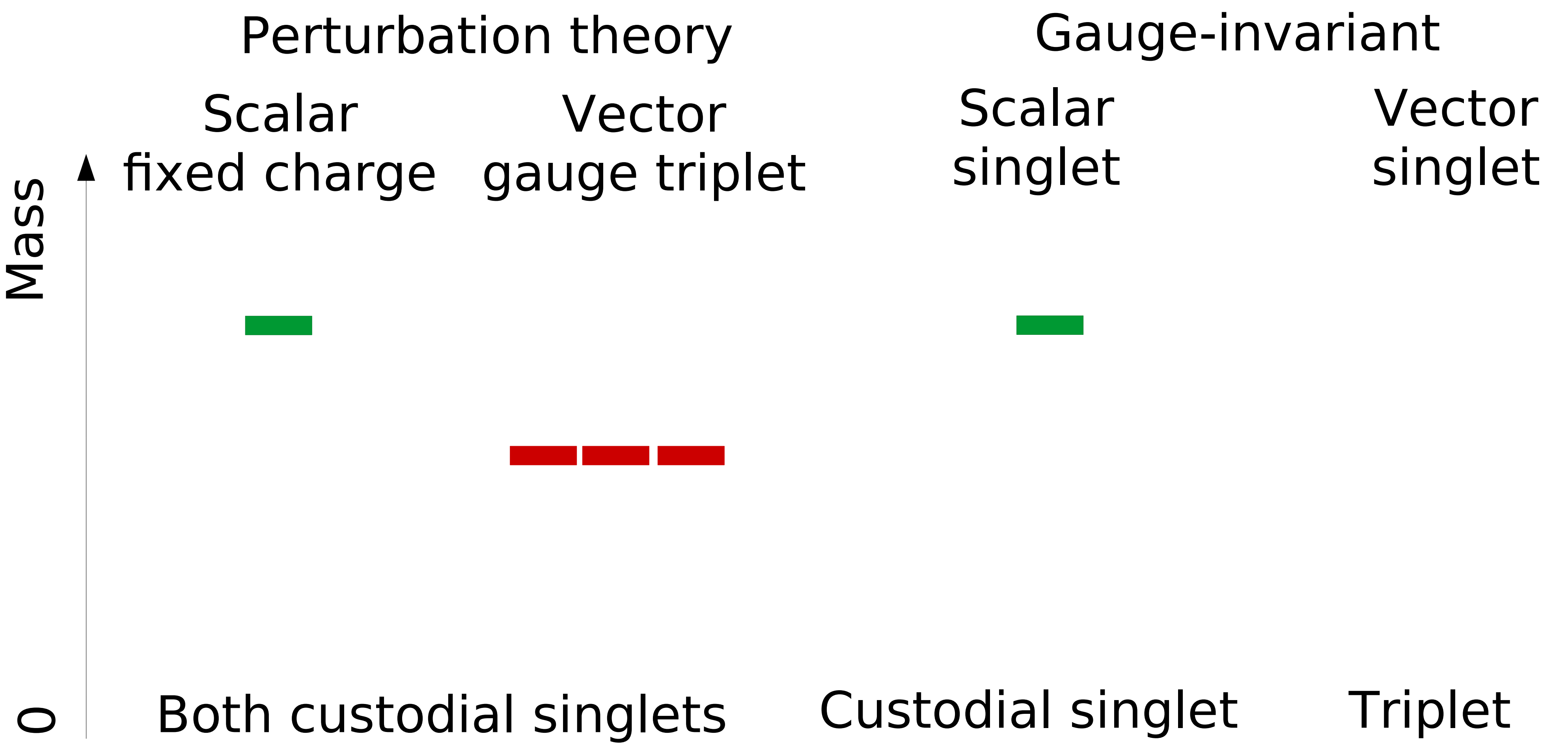

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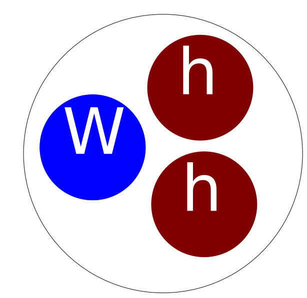

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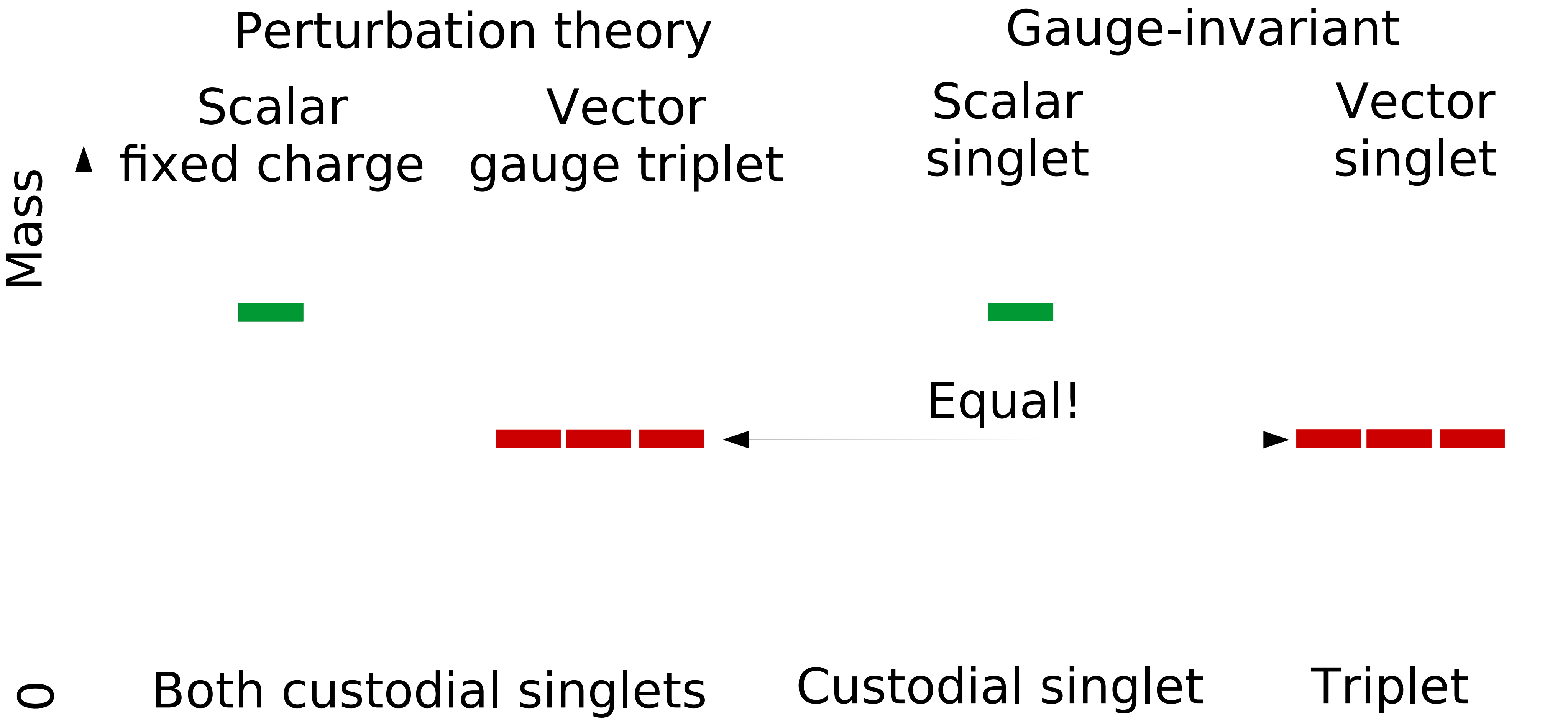

A microscopic mechanism
-
Why on-shell is important

How to make predictions

[Fröhlich et al.'80,'81,
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?

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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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Higgs field

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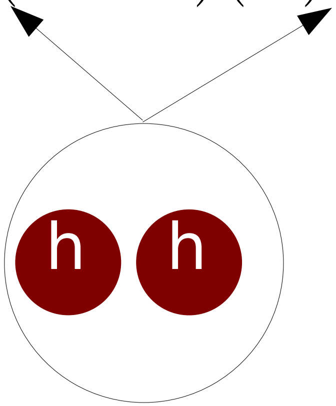

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Trivial two-particle state

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What about this?

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Consequences: The Higgs

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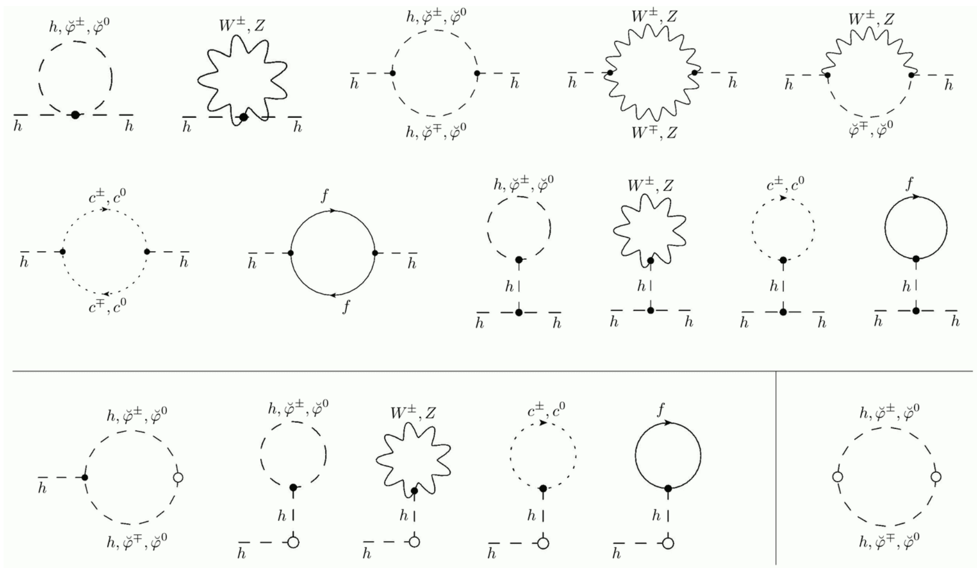

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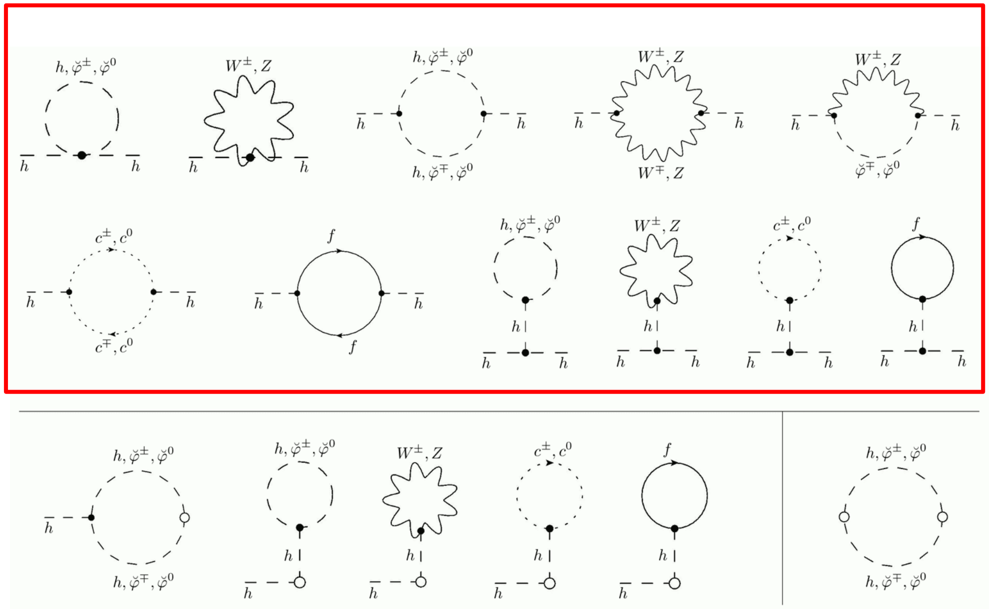

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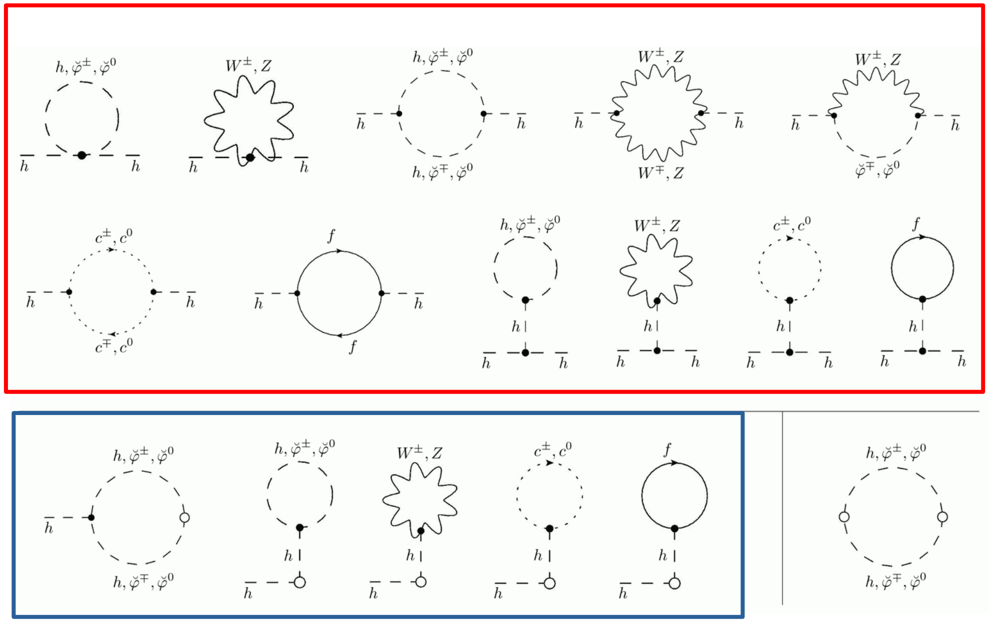

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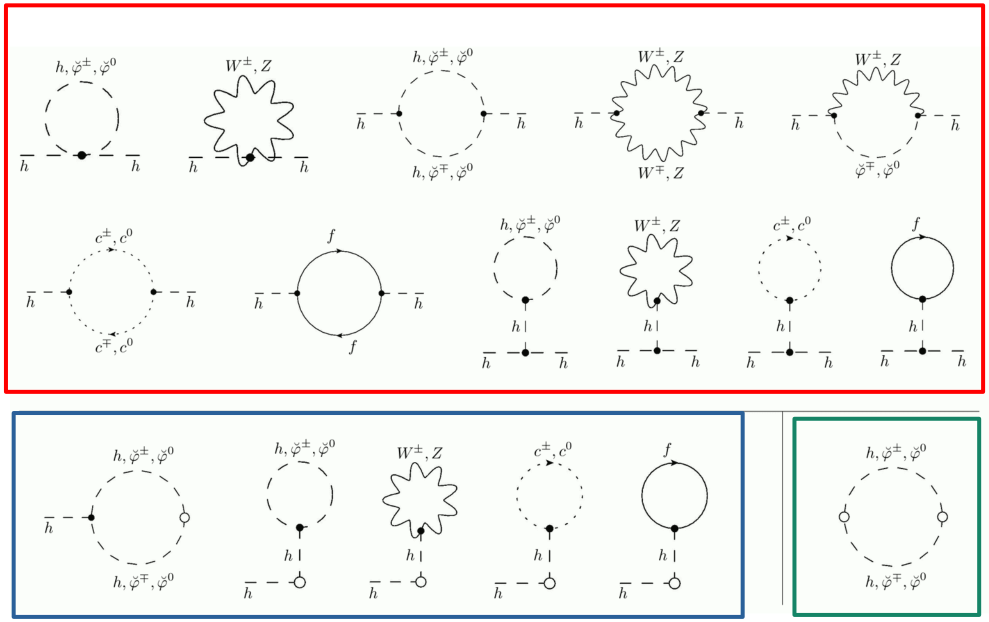

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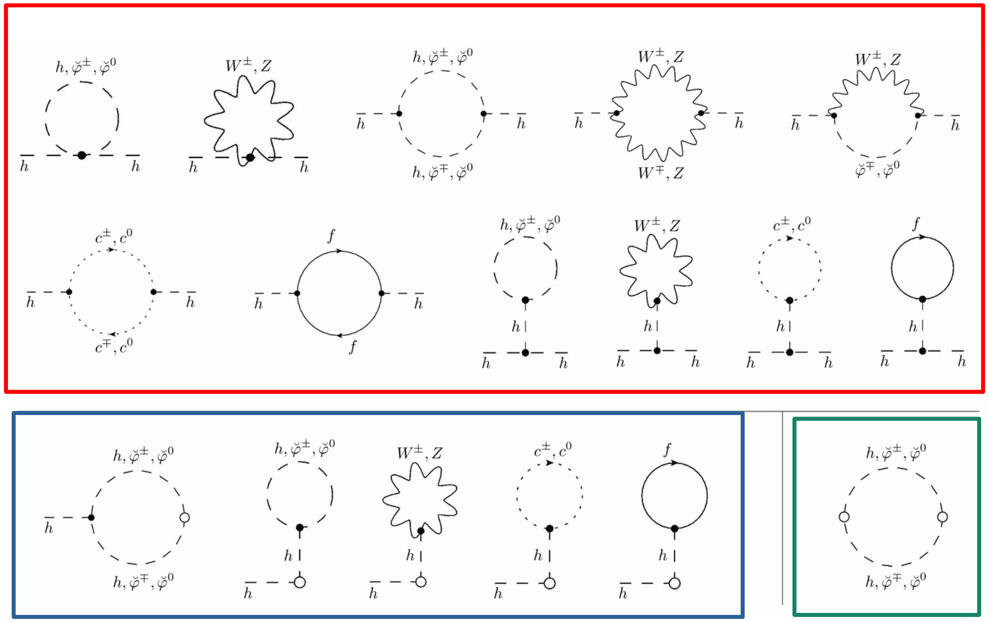

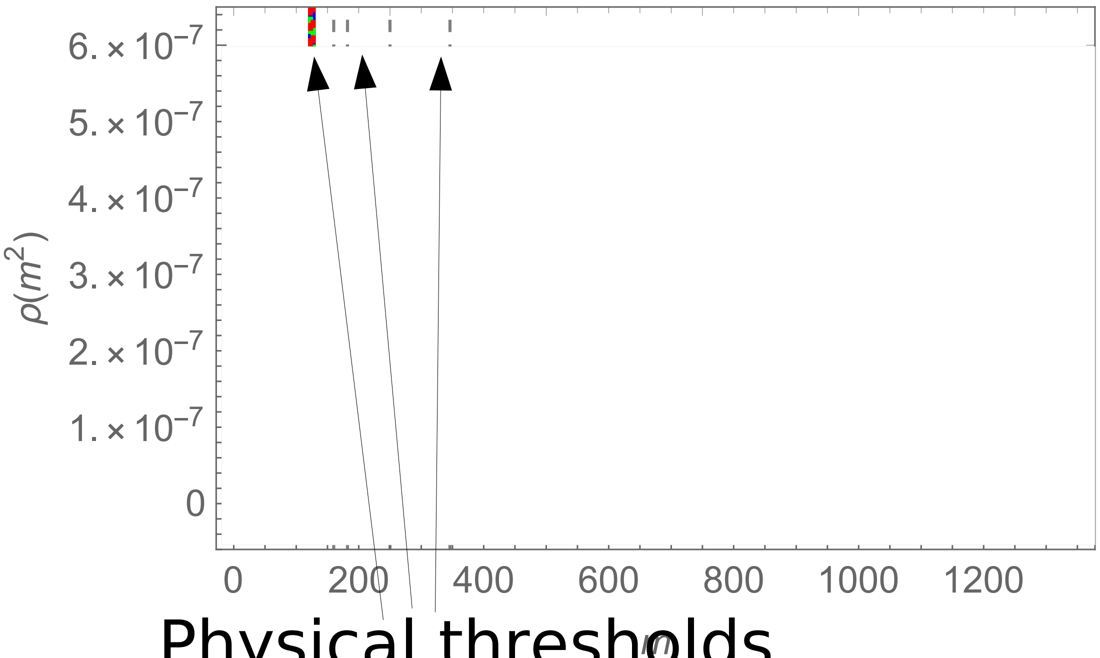

Physical thresholds

Consequences: The Higgs

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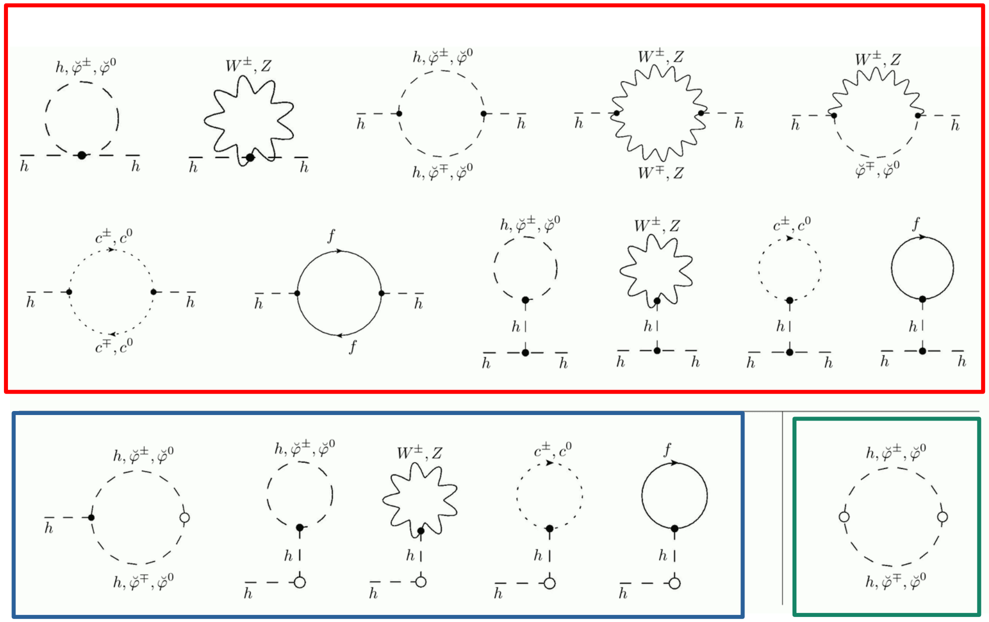

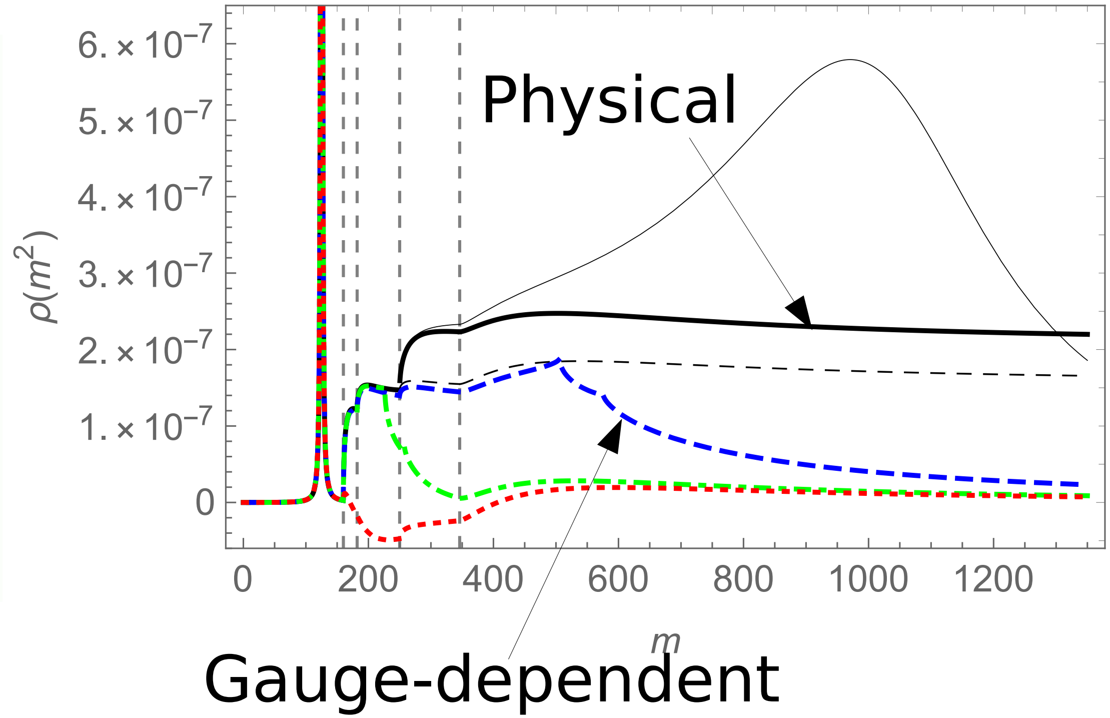

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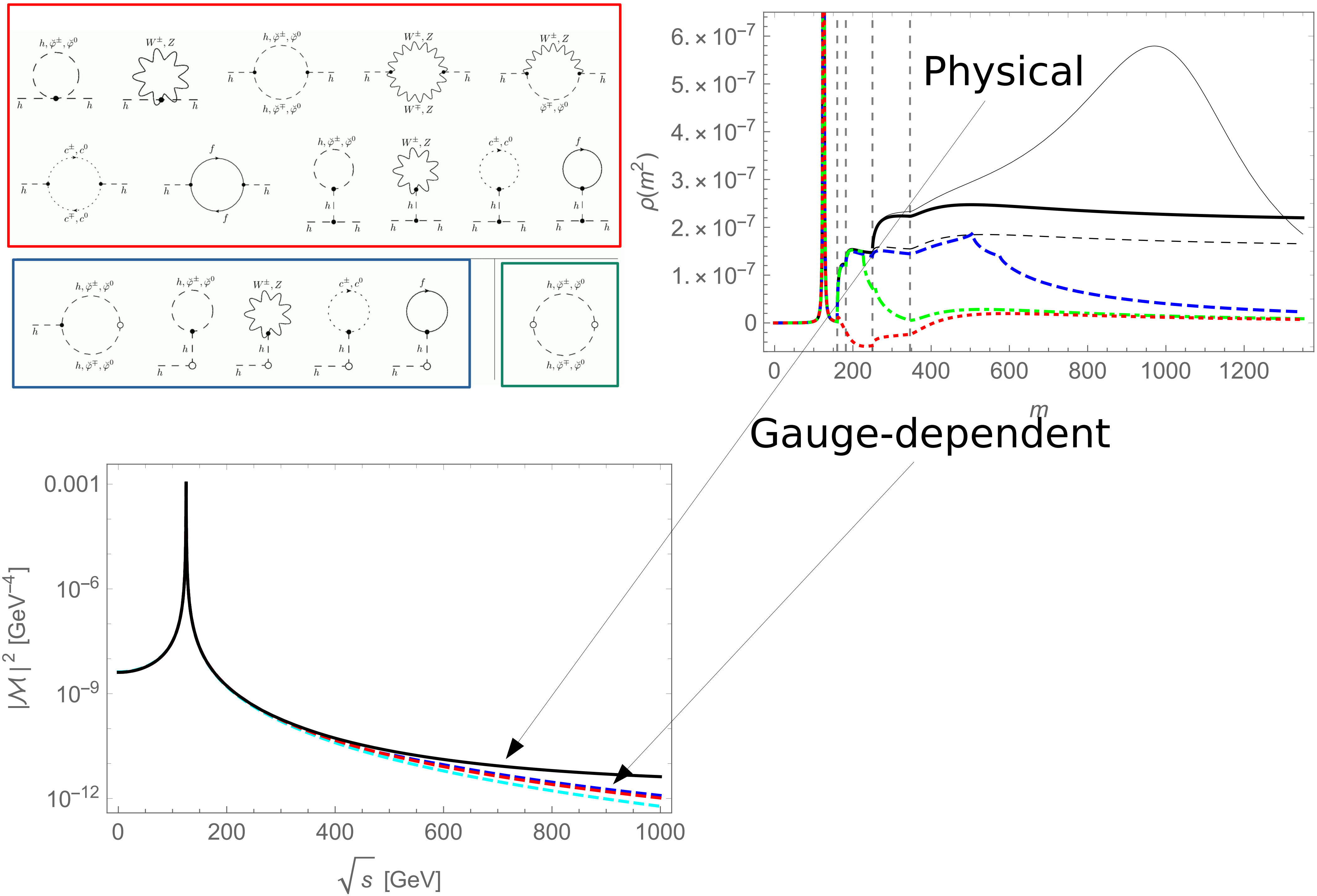

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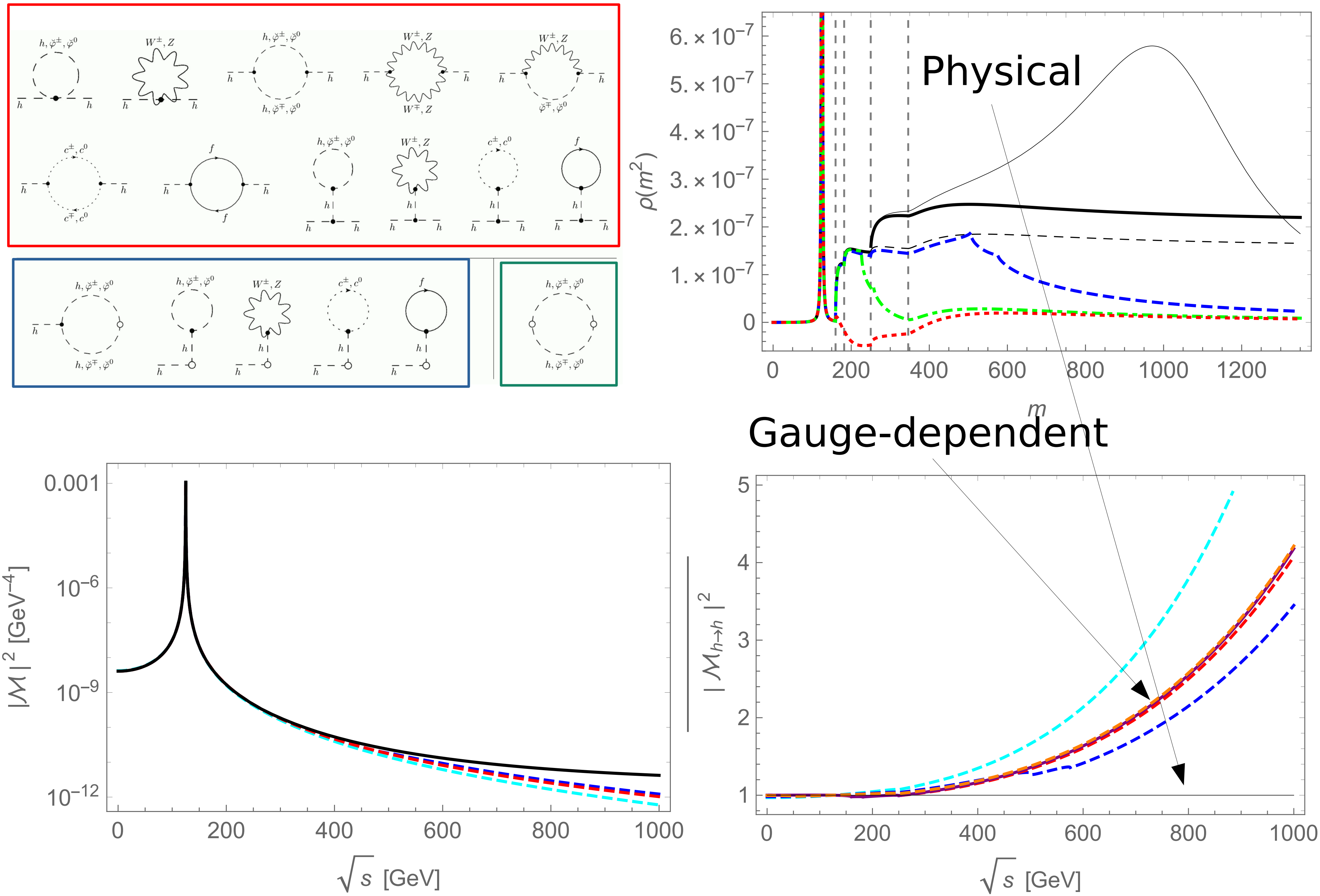

What about the vector?

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

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c projects custodial states to gauge states

Exactly one gauge boson for every physical state

Matrix from group structure

Phenomenological Implications
-
Can we measure this?

Bound states as extended objects

- Bound states have an extension
  - Can it be measured?

Bound states as extended objects

[Maas,Raubitzke,Törek'18]

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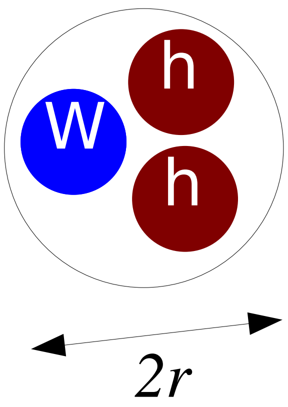
  - Example: Vector



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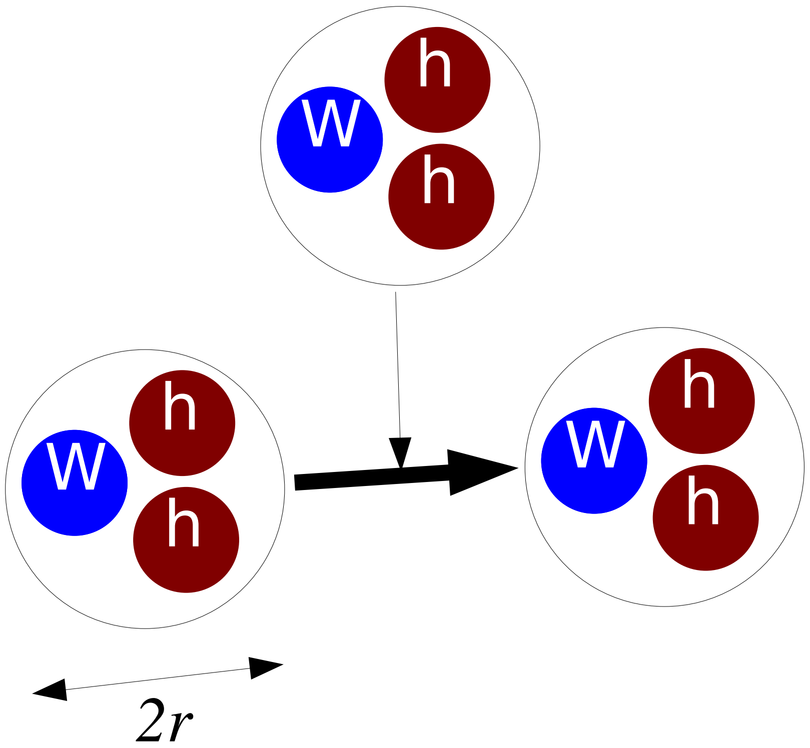
  - Measure the form factor



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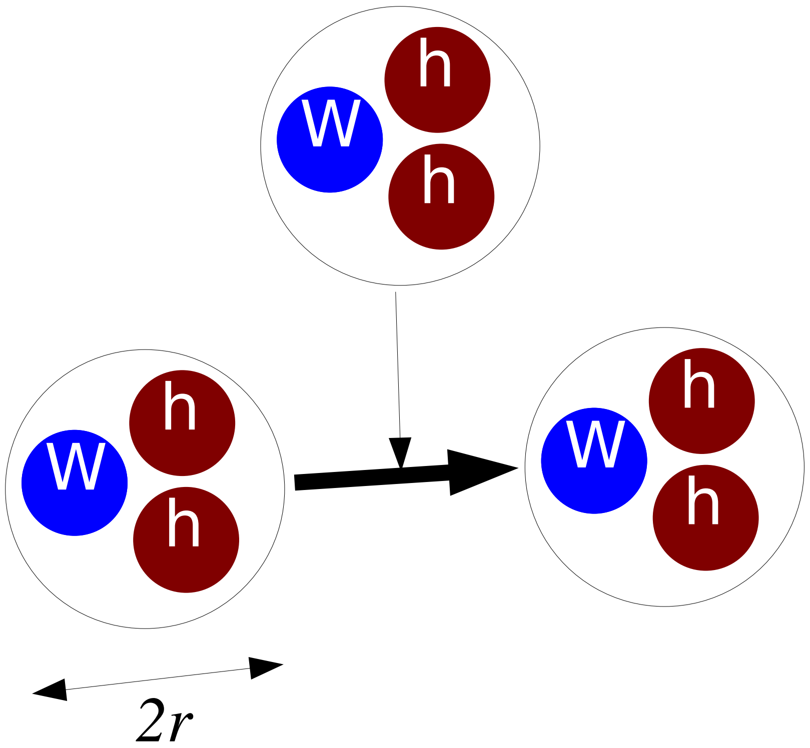
    $F\left(q^2,q^2,q^2\right)$



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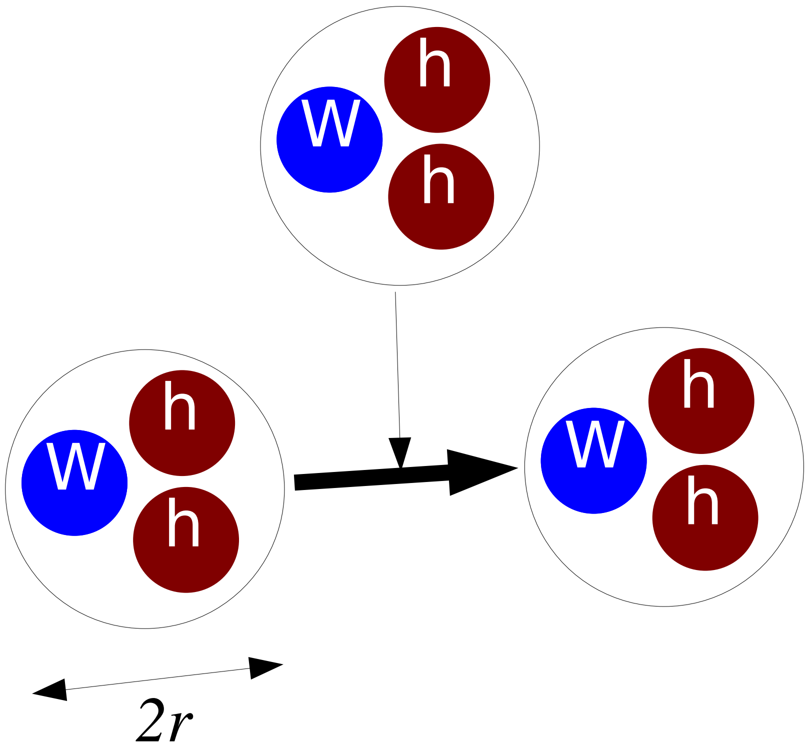
$$F(q^2,q^2,q^2)=1-\frac{q^2\langle r^2\rangle}{6}+\dots$$



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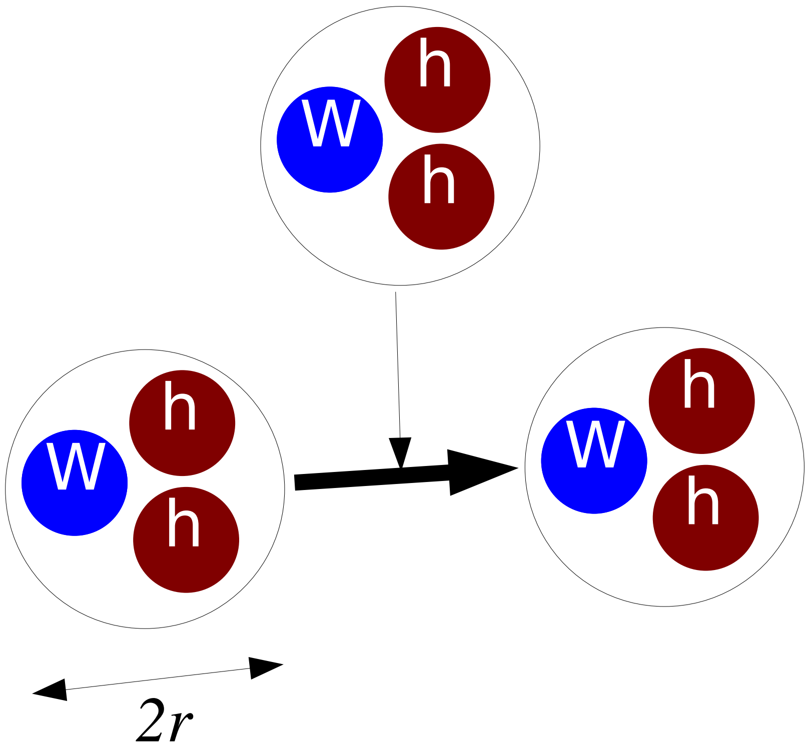

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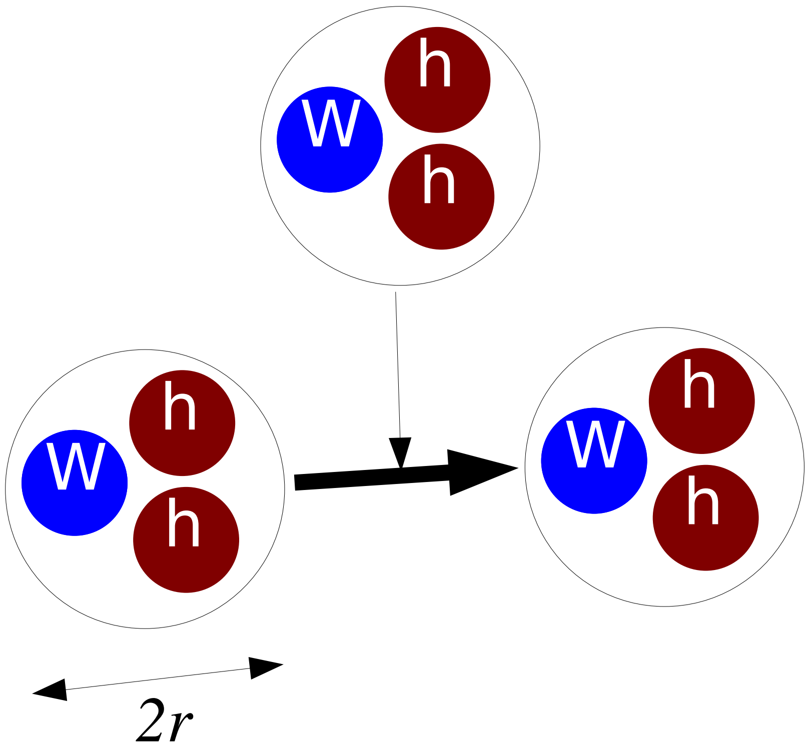

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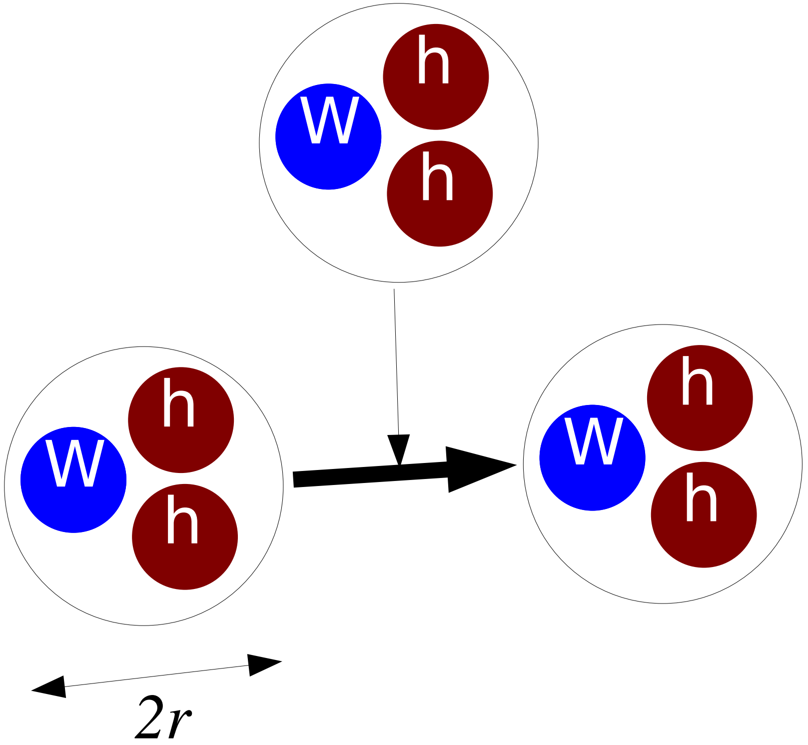

- Comparison proton: $mr\sim 5$

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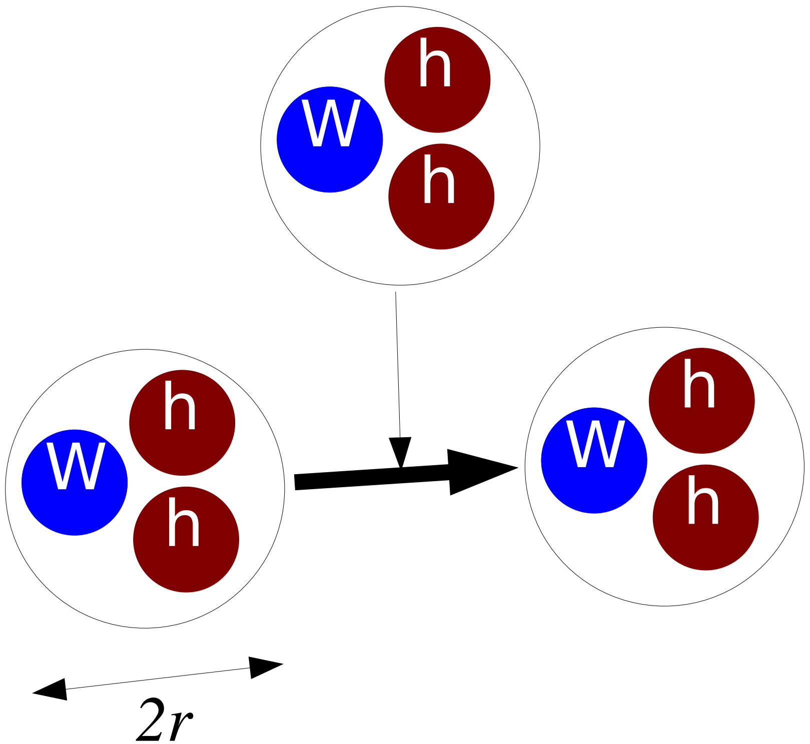


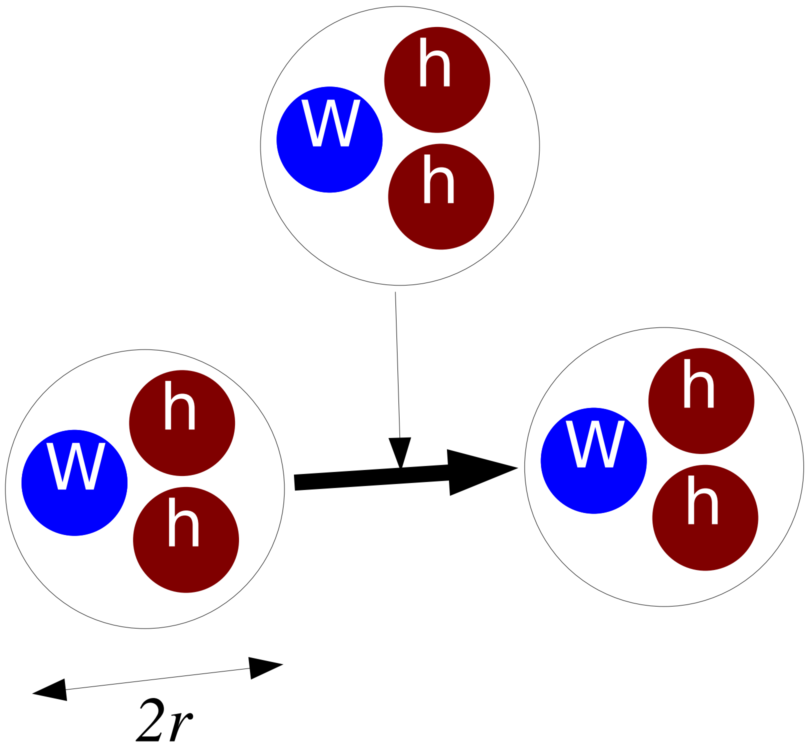
- Comparison proton: $mr\sim5$ – Here: Lattice

Bound states as extended objects

[Maas,Raubitzke,Törek'18]

- Bound states have an extension
  - Can it be measured?
  - Example: Vector
  - Measure the form factor

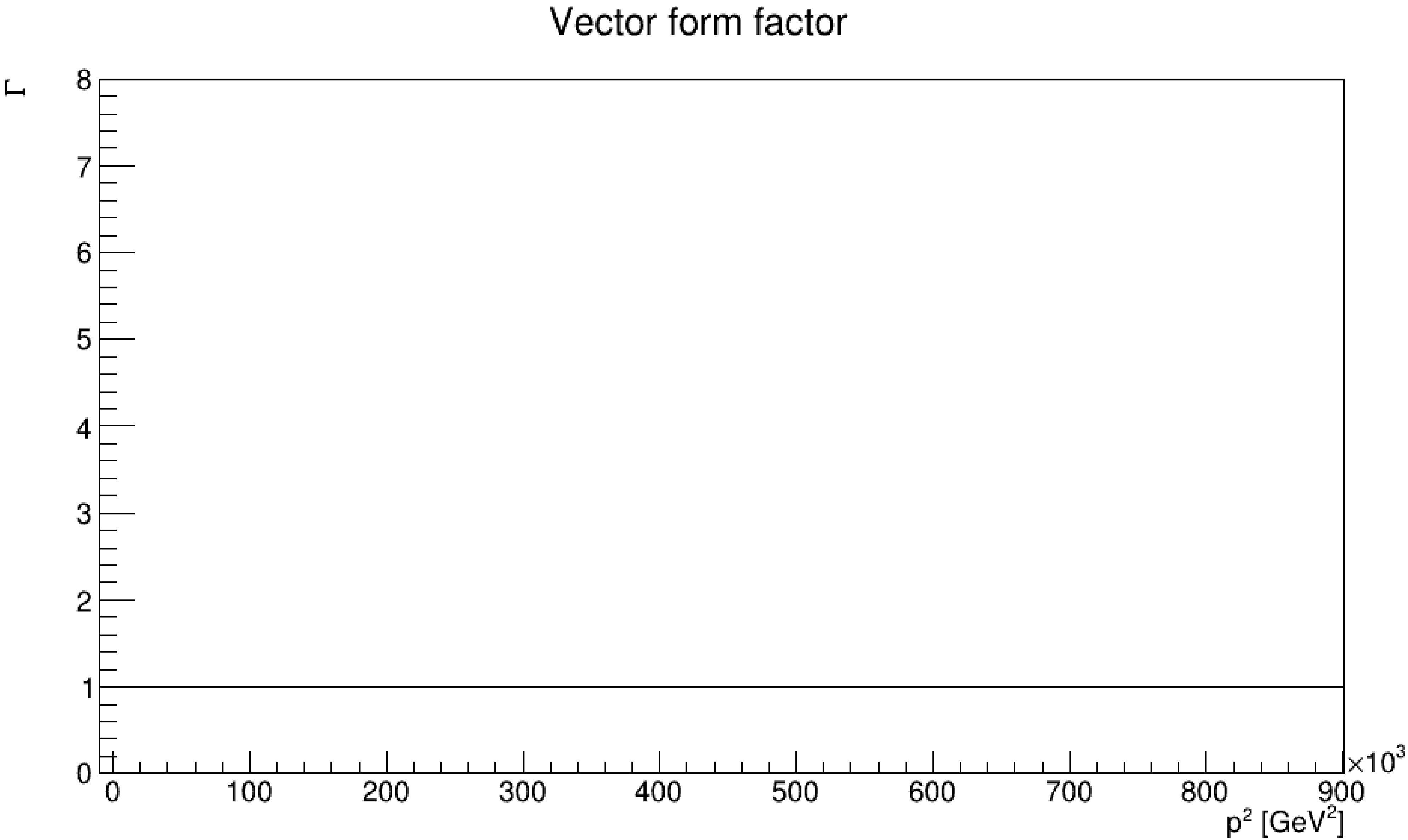
$$F(q^2,q^2,q^2) = 1 - \frac{q^2\langle r^2\rangle}{6} + \ldots$$
$$= F_{WWW}(q^2,q^2,q^2) + \ldots$$
$$= \frac{1}{q^2 - m^2} + \ldots$$



- Comparison proton: $mr \sim 5$ – Here: Lattice
  - Experimentally hard, but possible

Bound states as extended objects

[Maas,Raubitzke,Törek'18]



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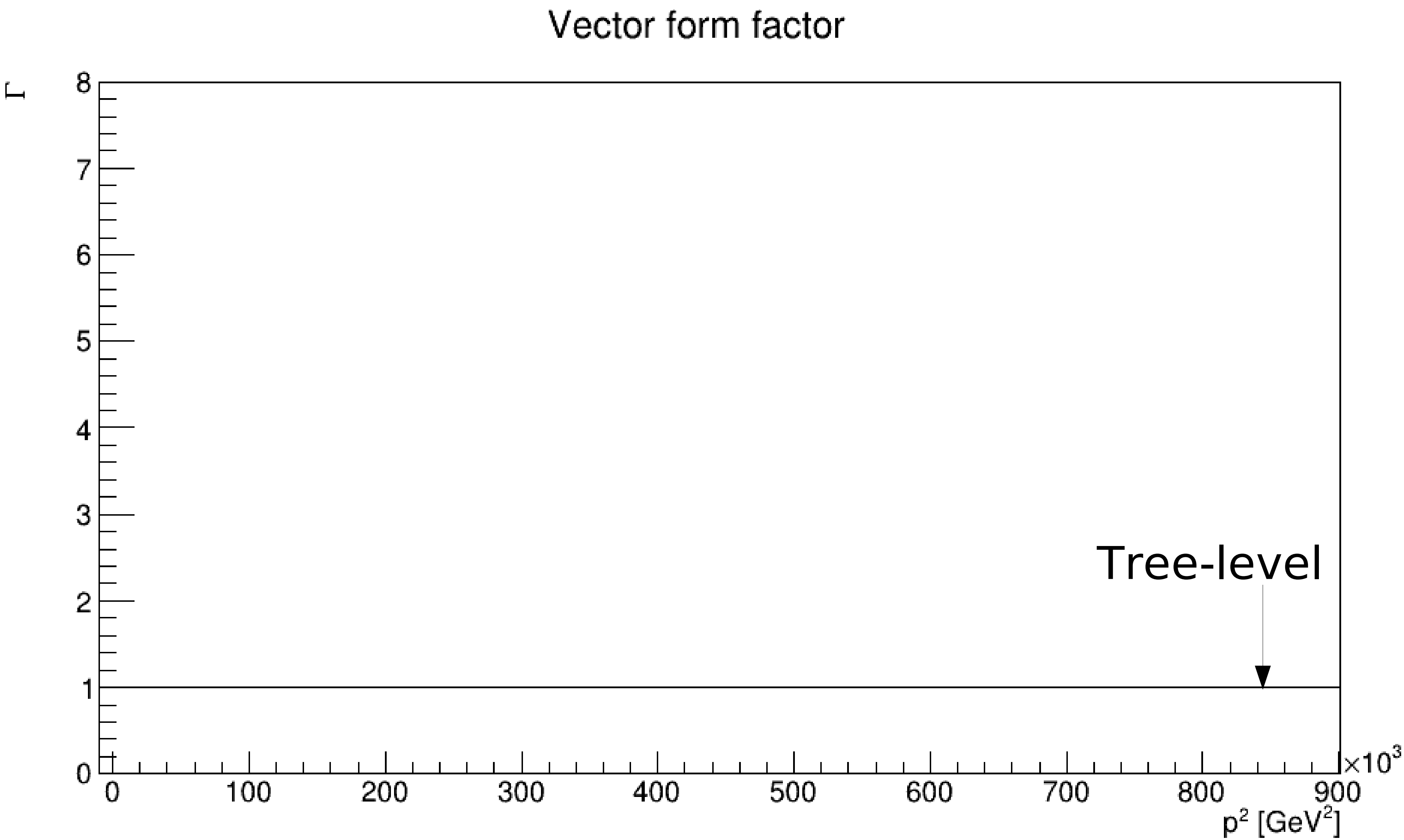

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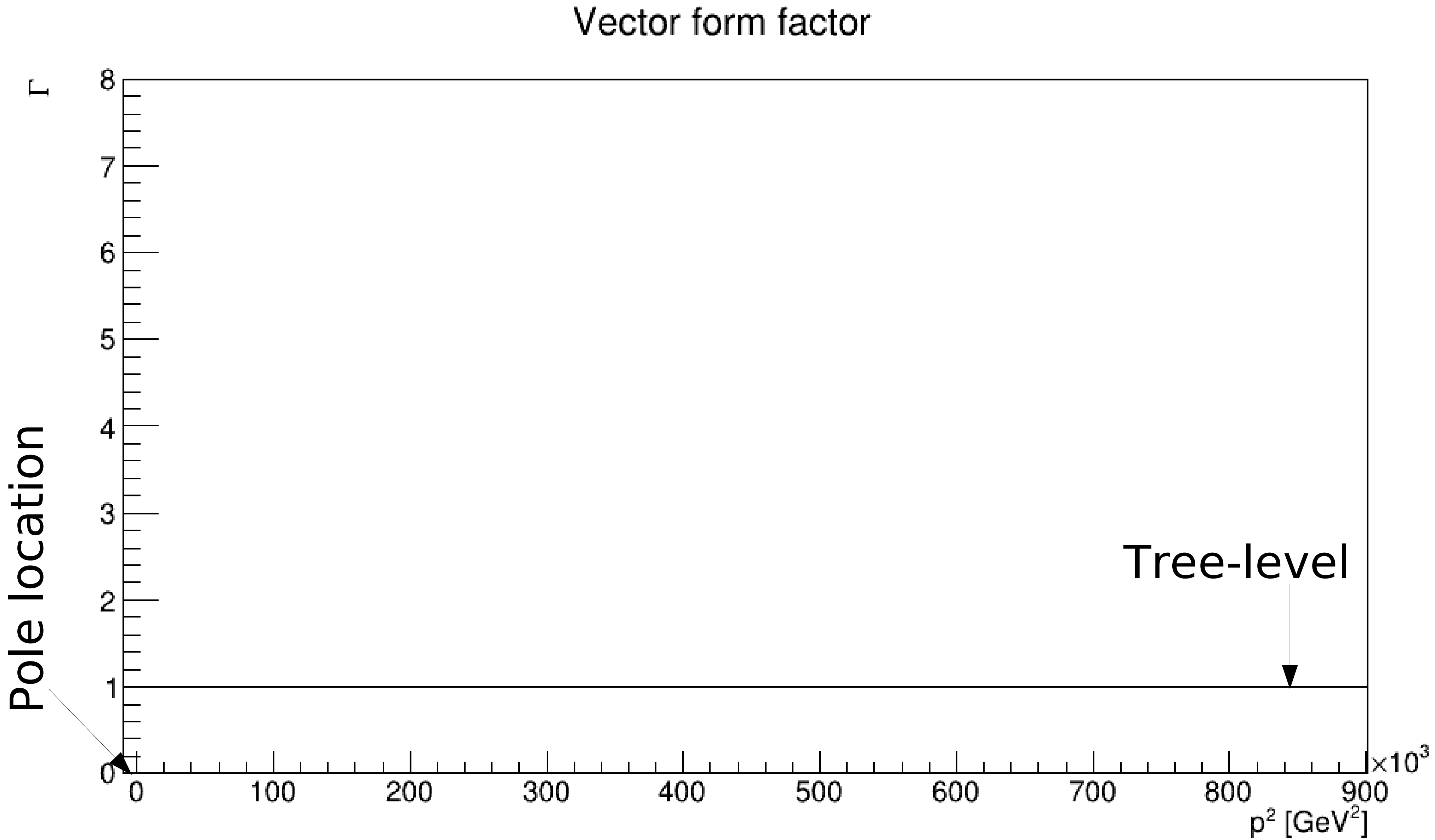

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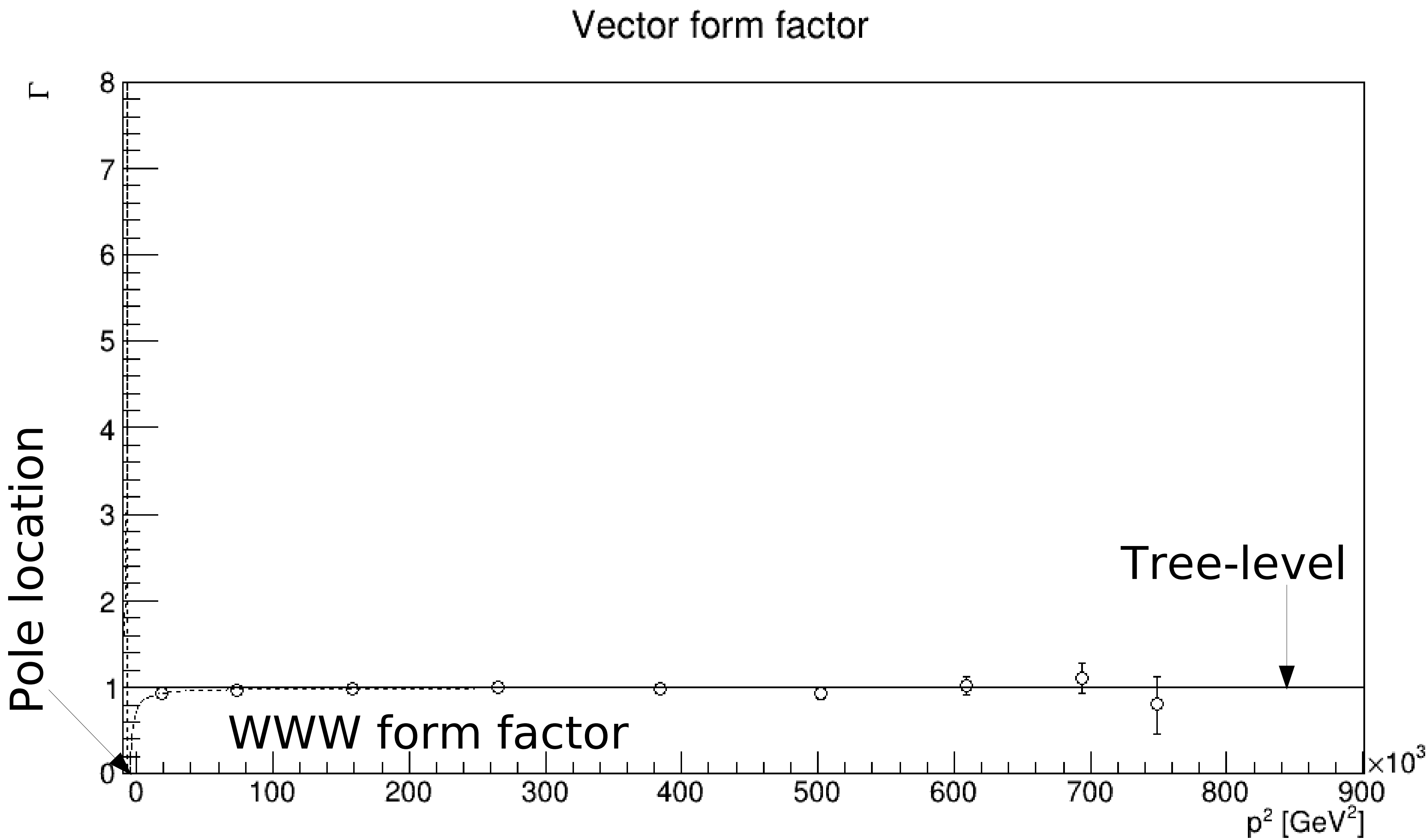

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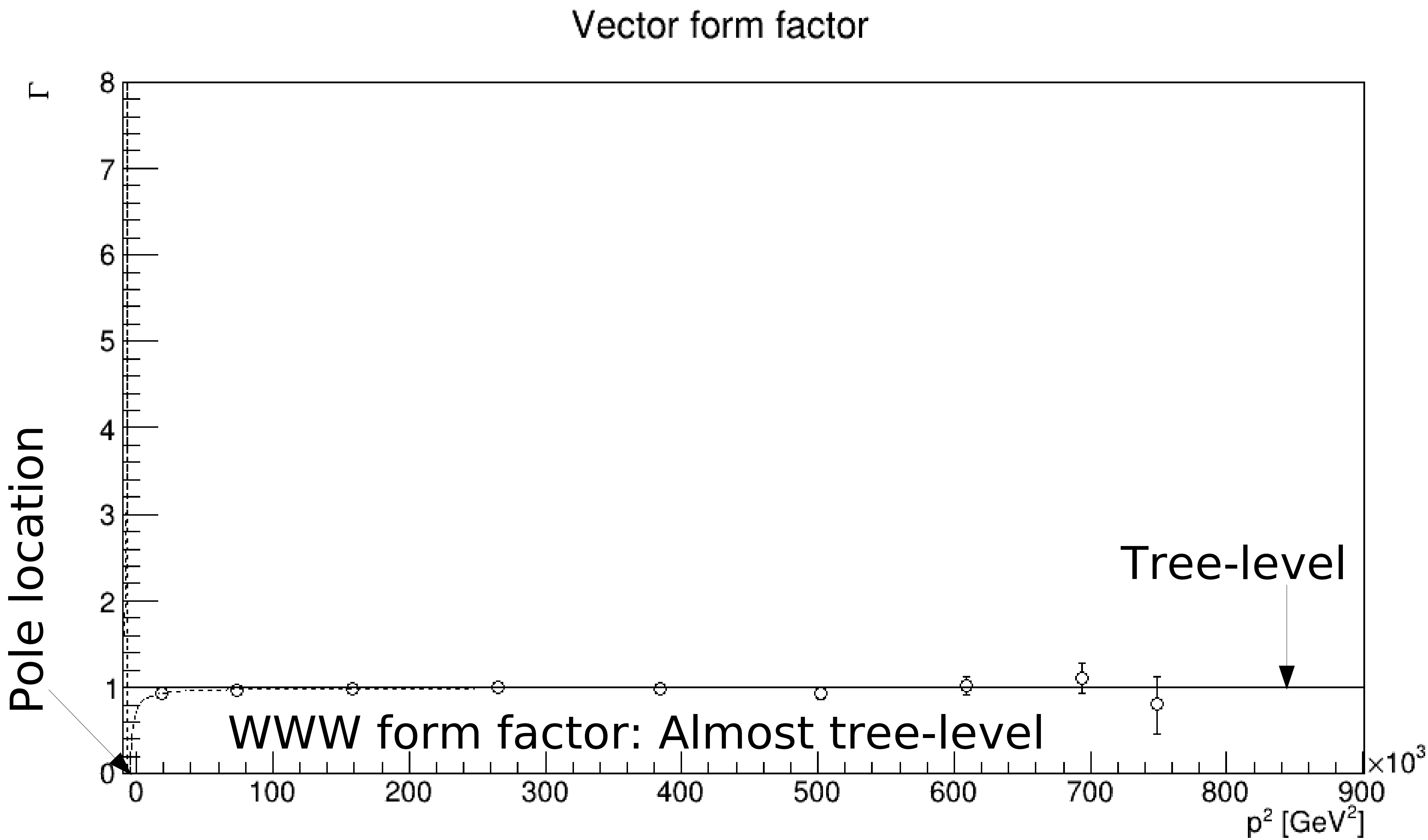

- Gauge-dependent W has *mr~0.5i*

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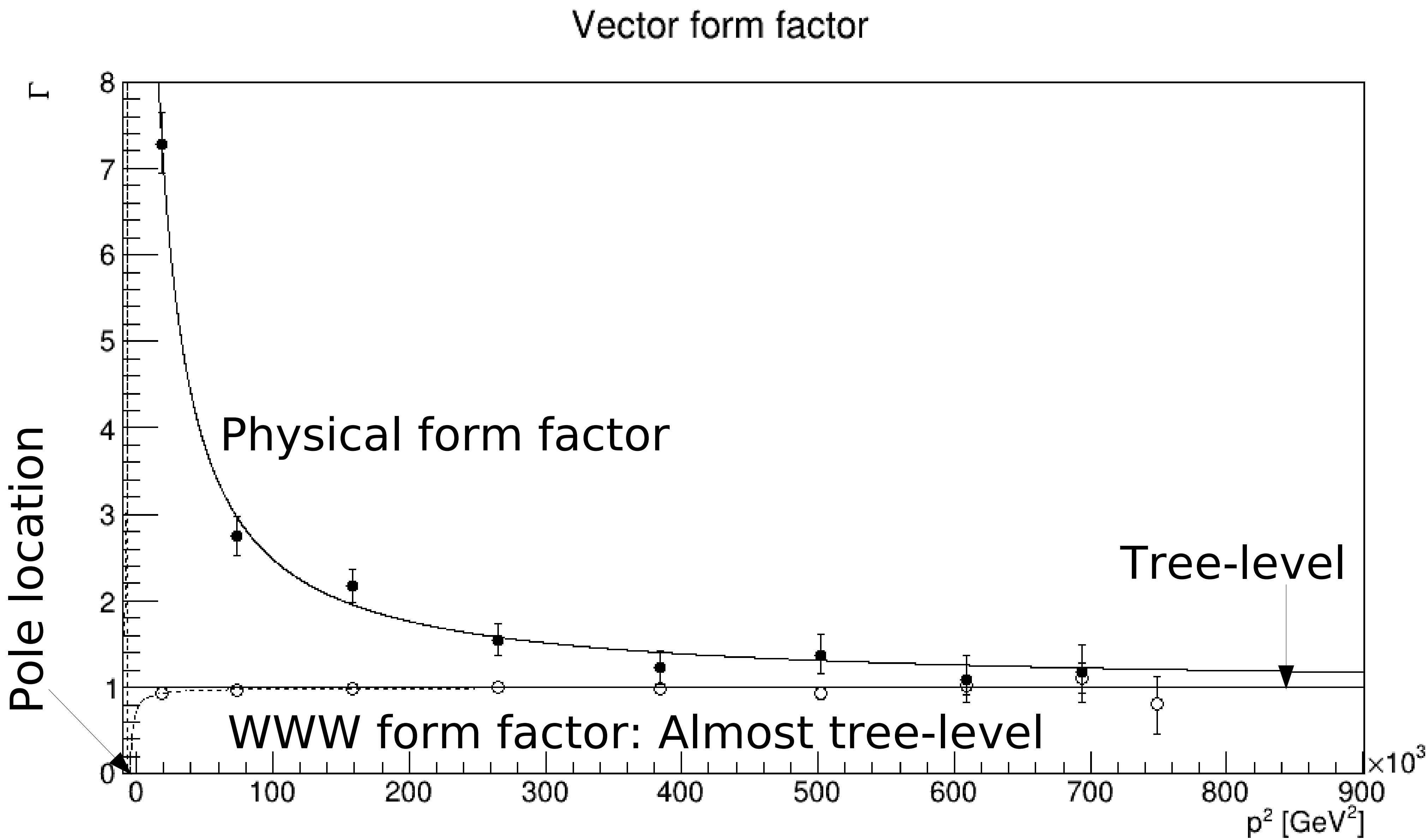
[Maas,Raubitzke,Törek'18]



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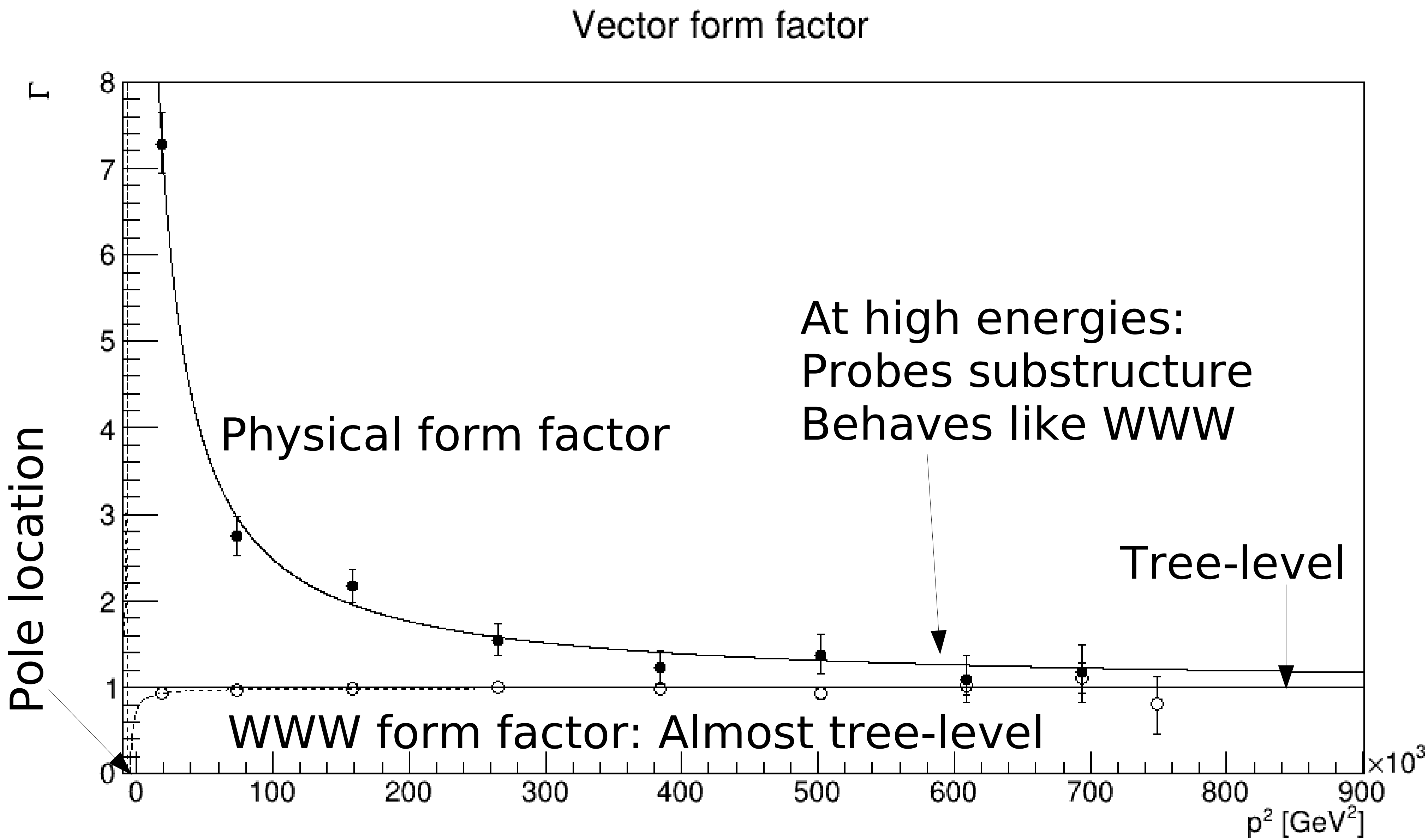

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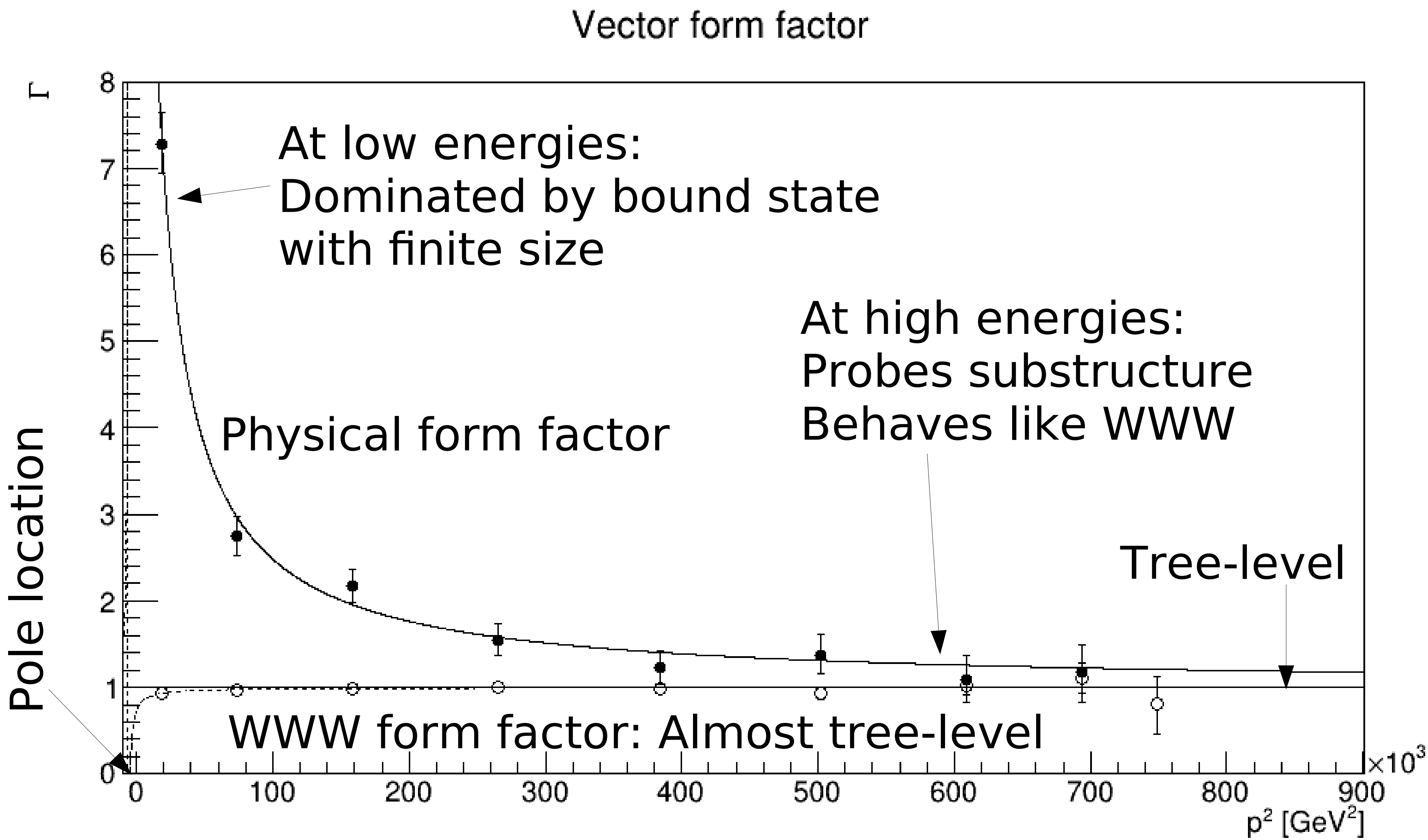

- Physical *mr~2* while gauge-dependent W has *mr~0.5i*

Measuring the radius

- Two standard possibilities

Measuring the radius

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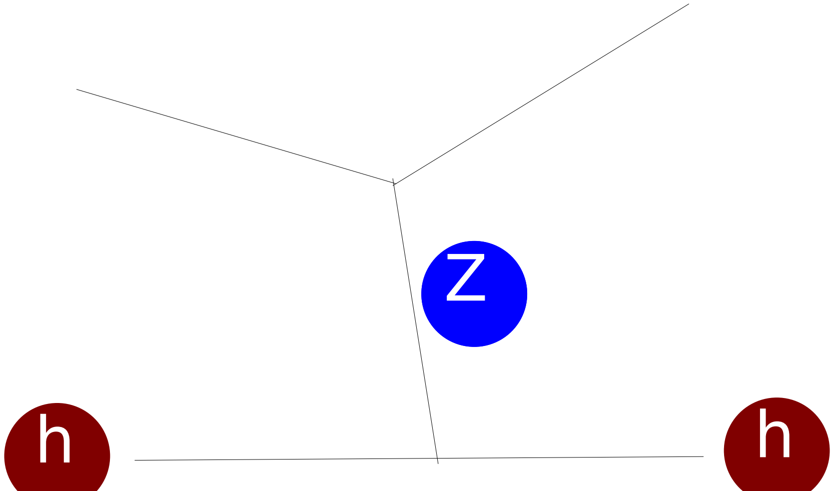
  - Form factor
    - Difficult
      - Higgs and Z need to be both produced in the same process

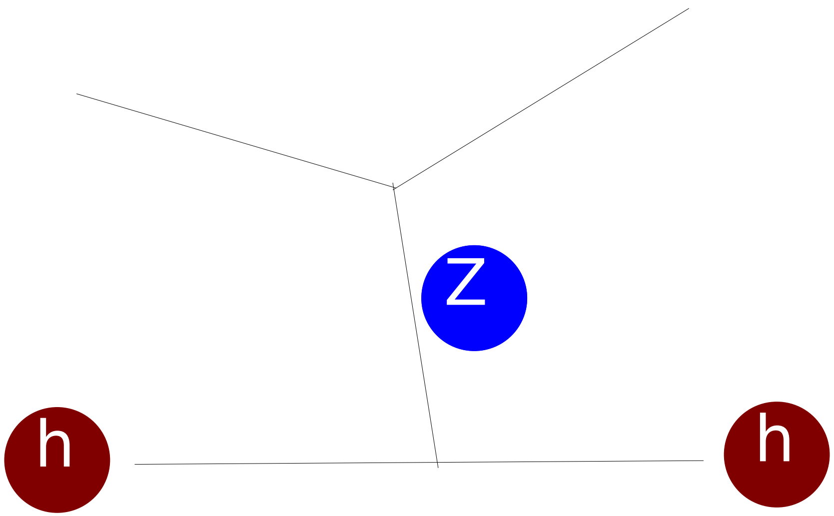
[Maas, Raubitzek, Törek'18]

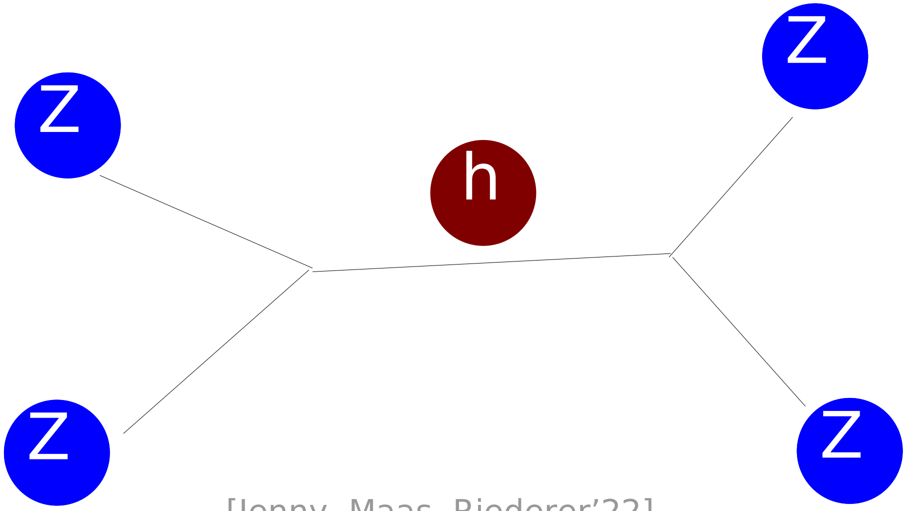


Measuring the radius

- Two standard possibilities
  - Form factor
    - Difficult
      - Higgs and Z need to be both produced in the same process
  - Elastic scattering
    - Standard vector boson scattering process at low energies
    - Use this one

[Maas, Raubitzek, Törek’18]





[Jenny, Maas, Riederer’22]

Radius from elastic scattering in VBS

- Elastic region: $160/180\, GeV \leqslant \sqrt{s} \leqslant 250\, GeV$
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Cross section

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Matrix element

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Legendre polynom

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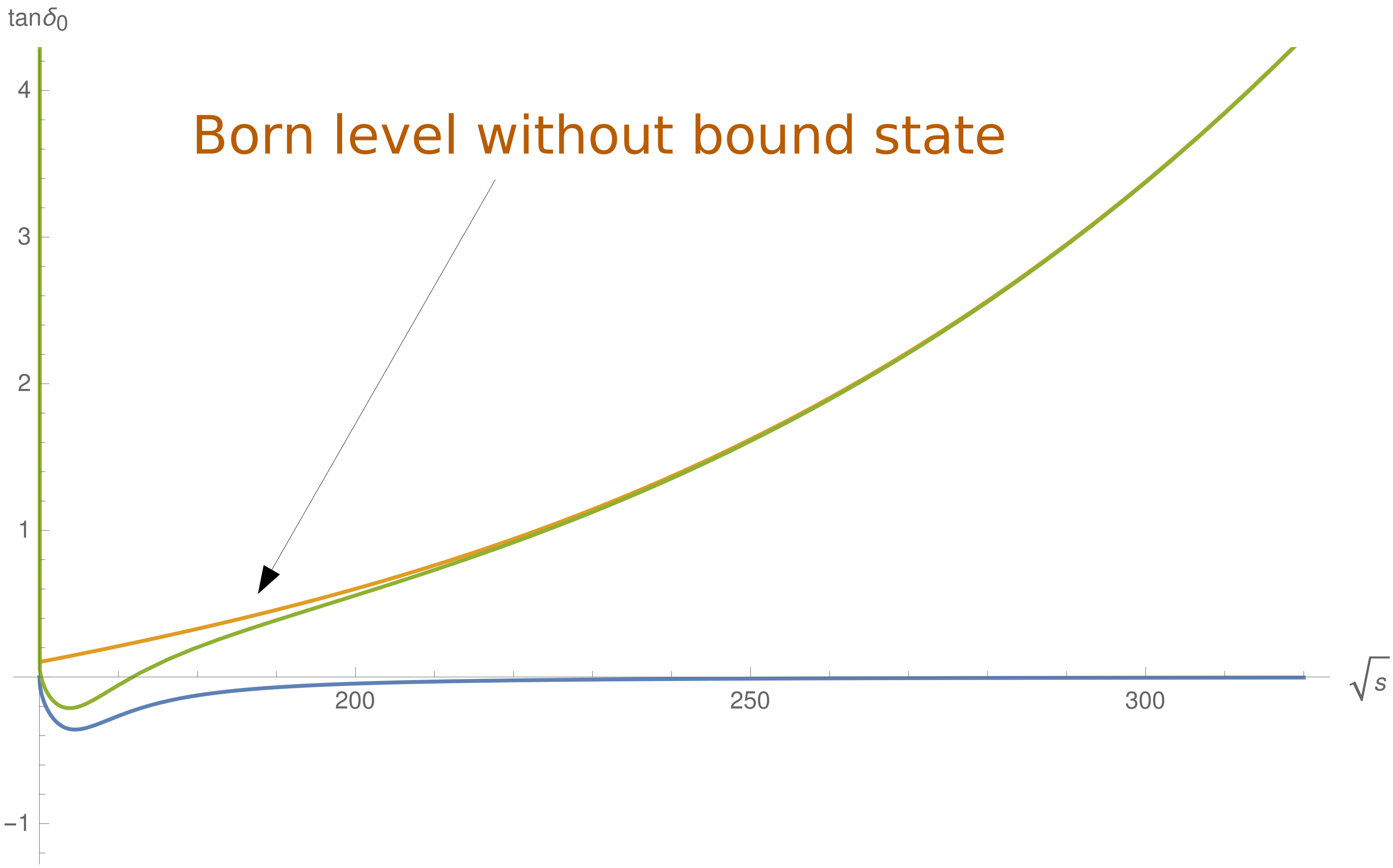
Scattering length~"size"

Phase shift

Impact of a finite size of the Higgs

- Consider the Higgs: $J=0$

Impact of a finite size of the Higgs



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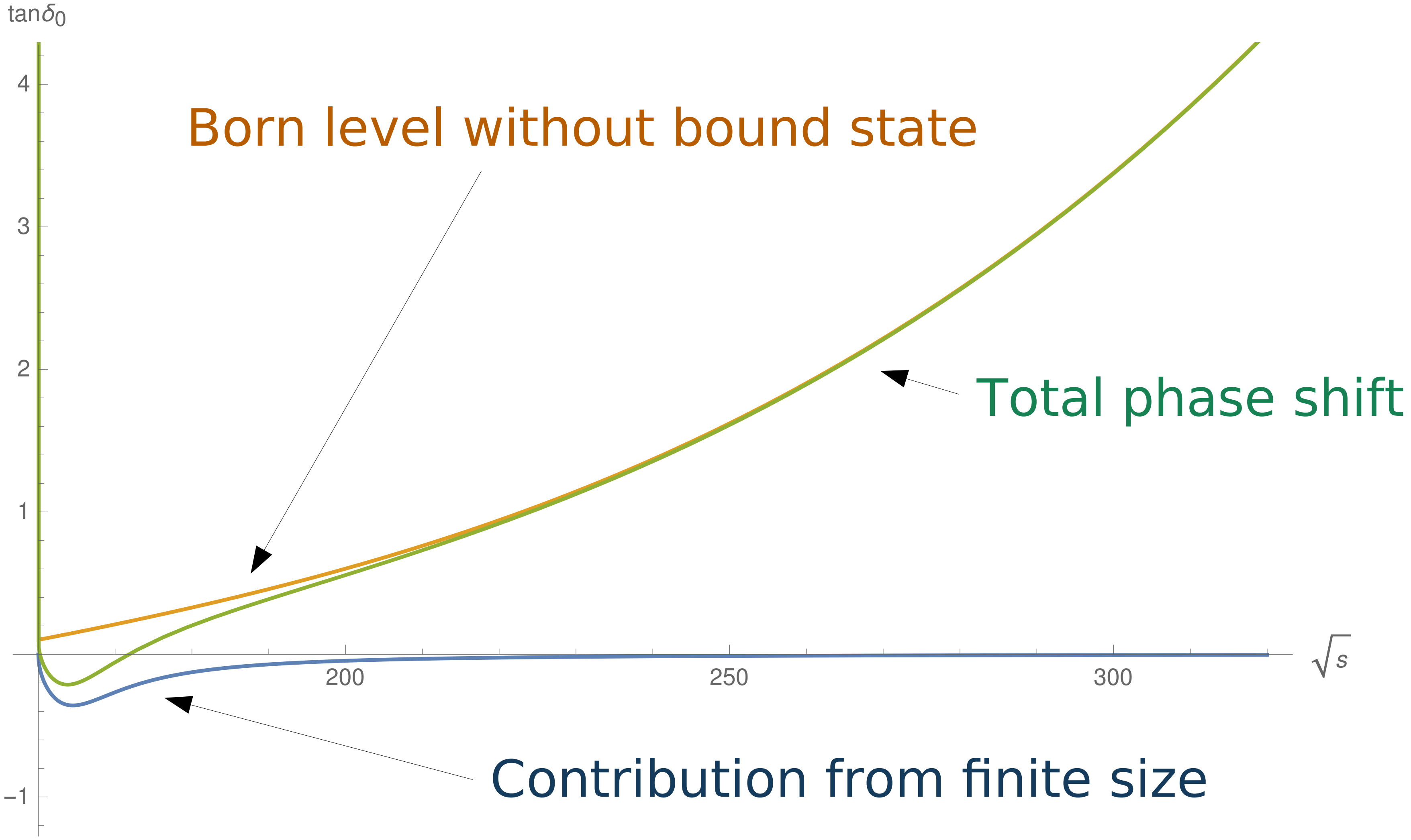

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- Mock-up effect
    - Scattering length 1/(40 GeV)

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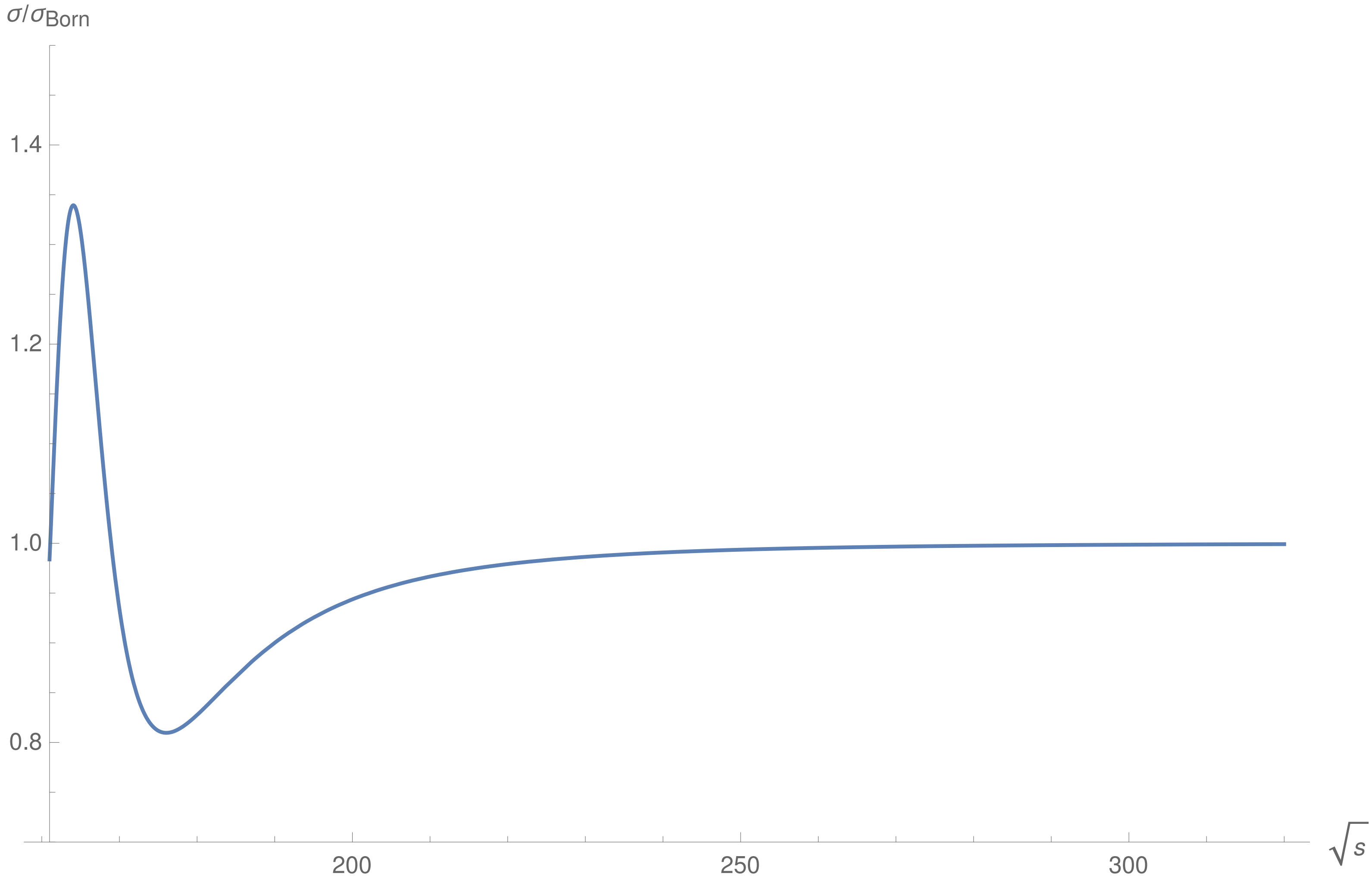

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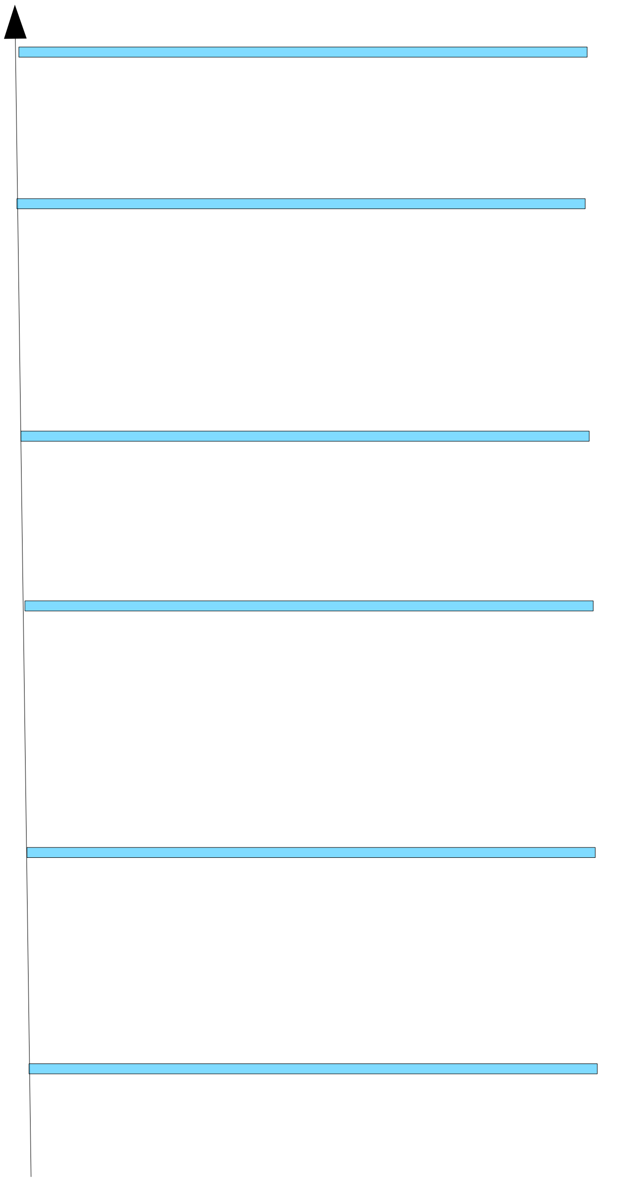
Excited states on the lattice

- Each quantum number channel has a spectrum
  - Discreet in a finite volume



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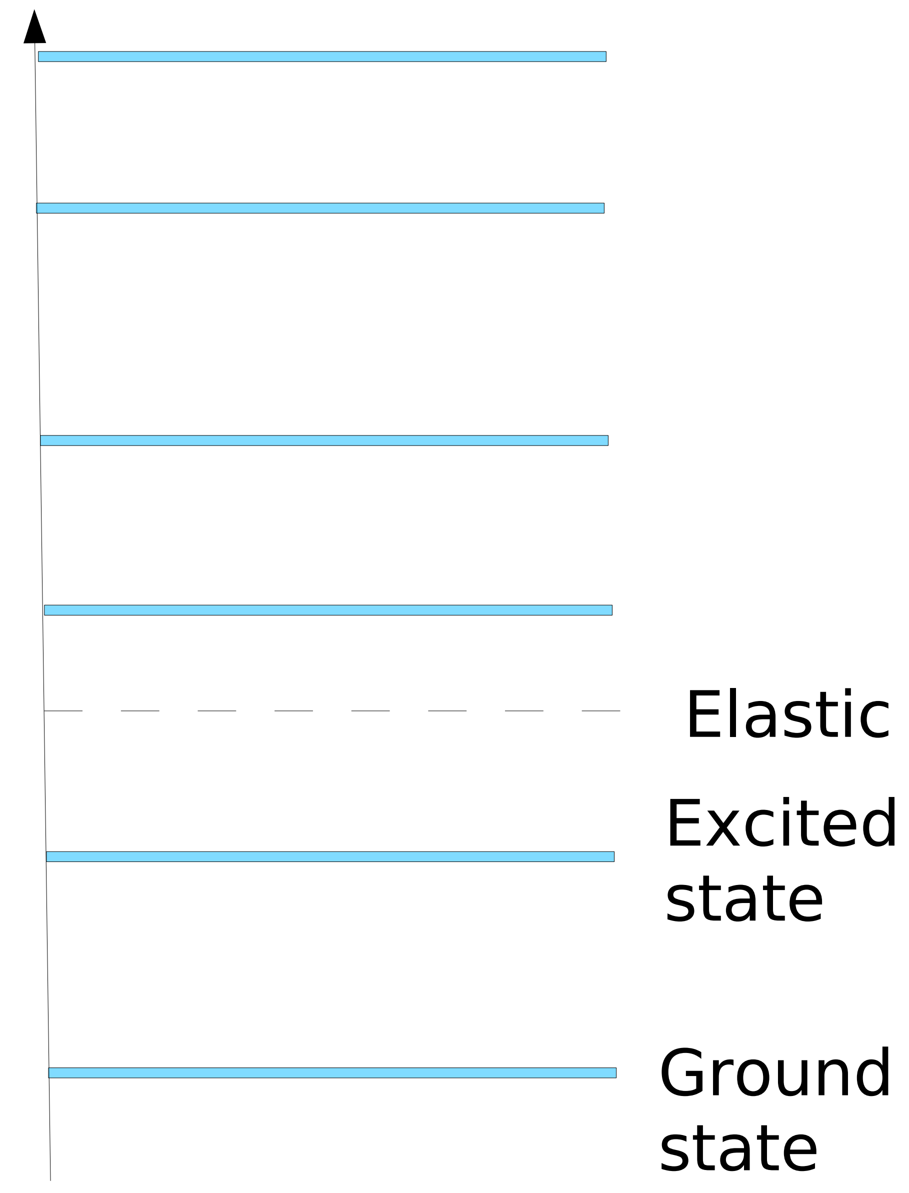

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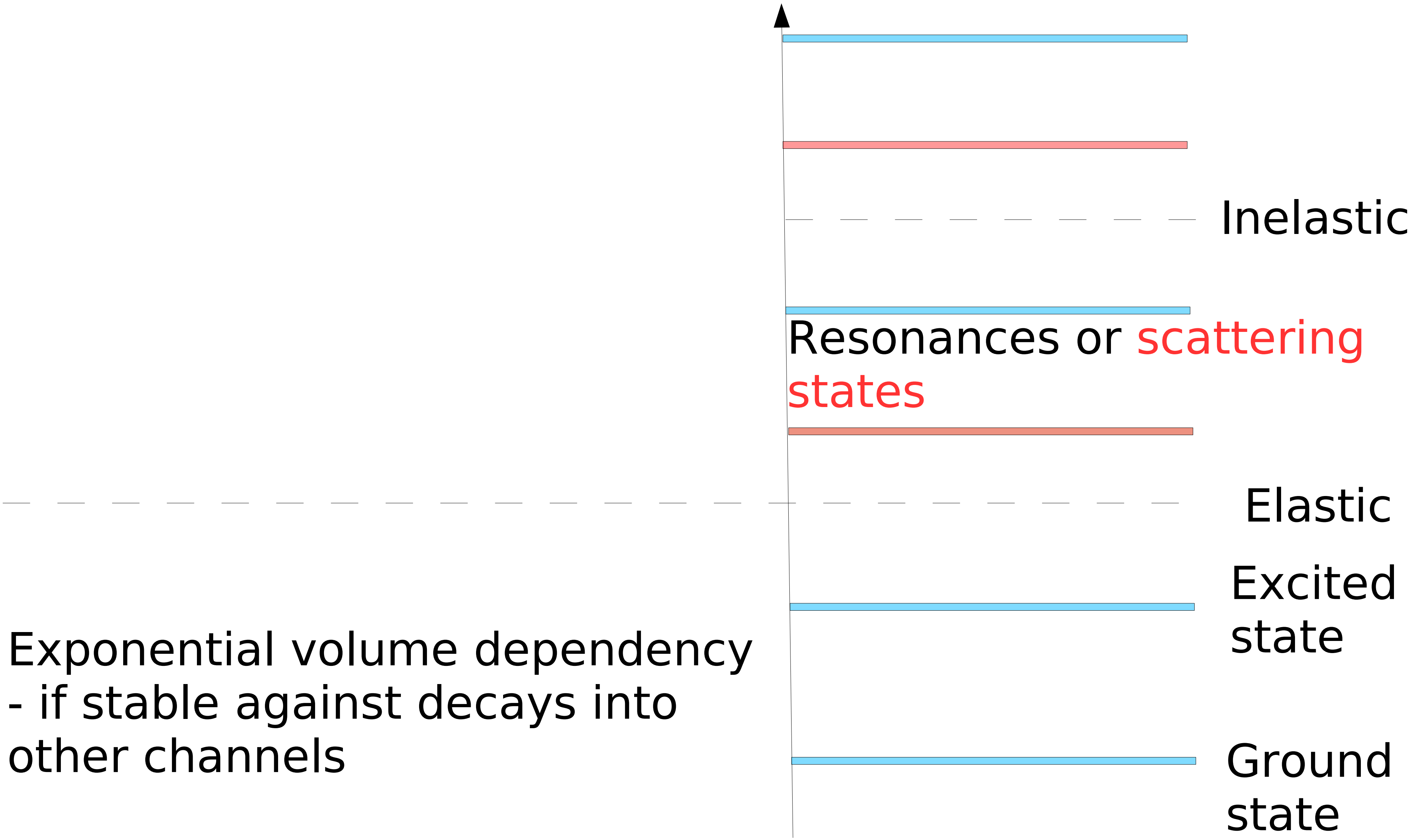
Excited states on the lattice

[Luescher'85,'86,'90,'91]



Exponential volume dependency
- if stable against decays into other channels

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- Width and nature from phase shifts below the inelastic threshold

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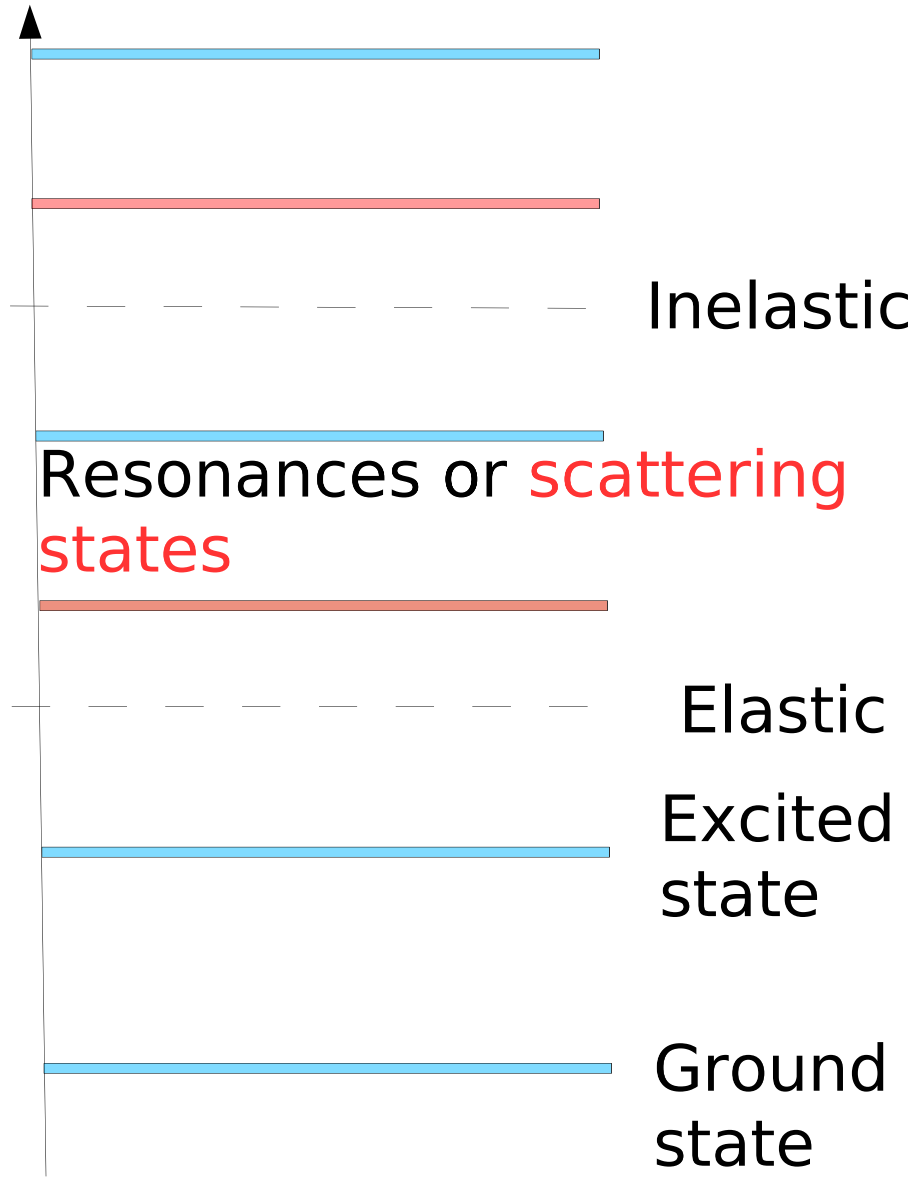

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Above inelastic threshold still complicated

- Polynominal (inverse) volume dependence
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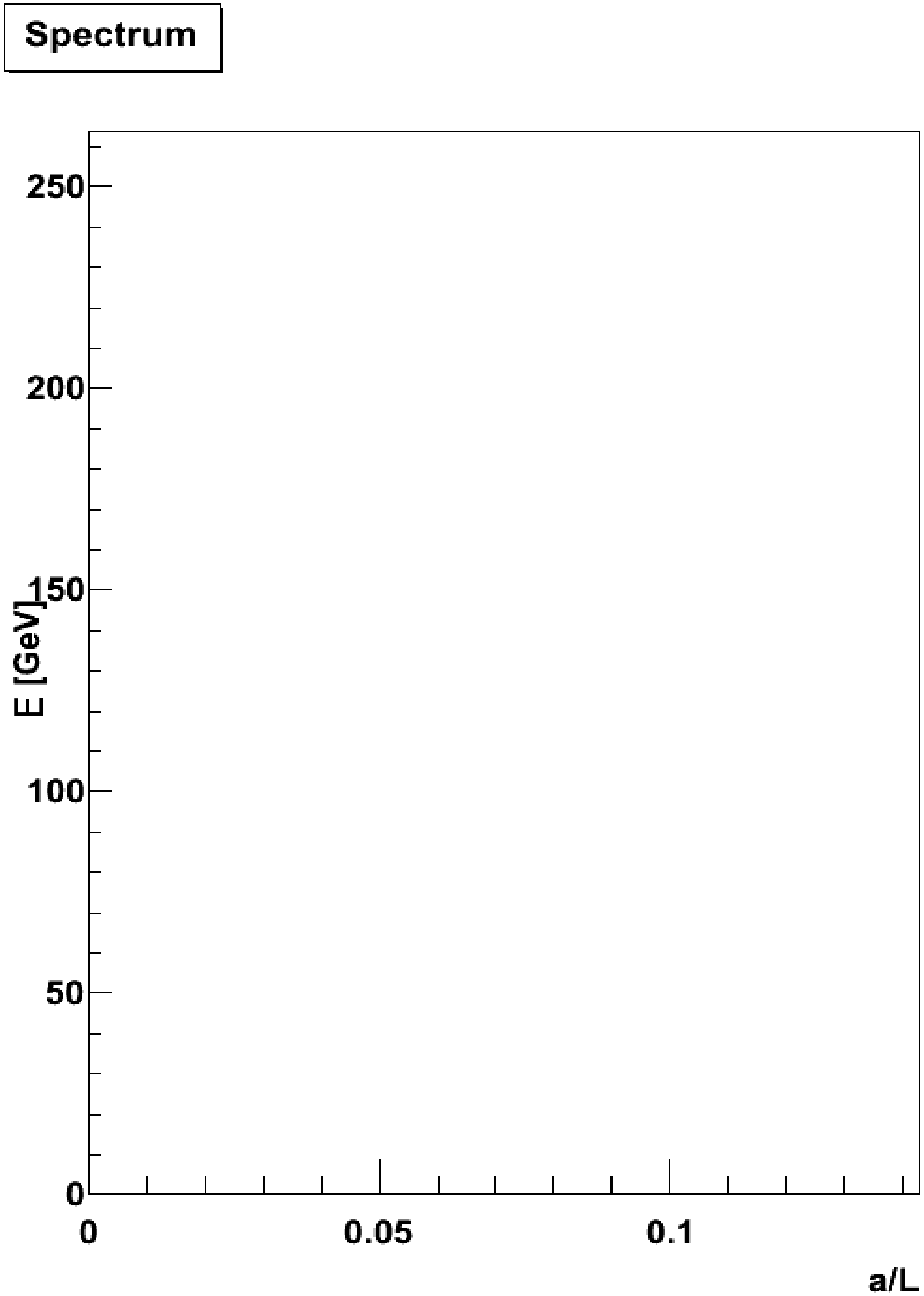

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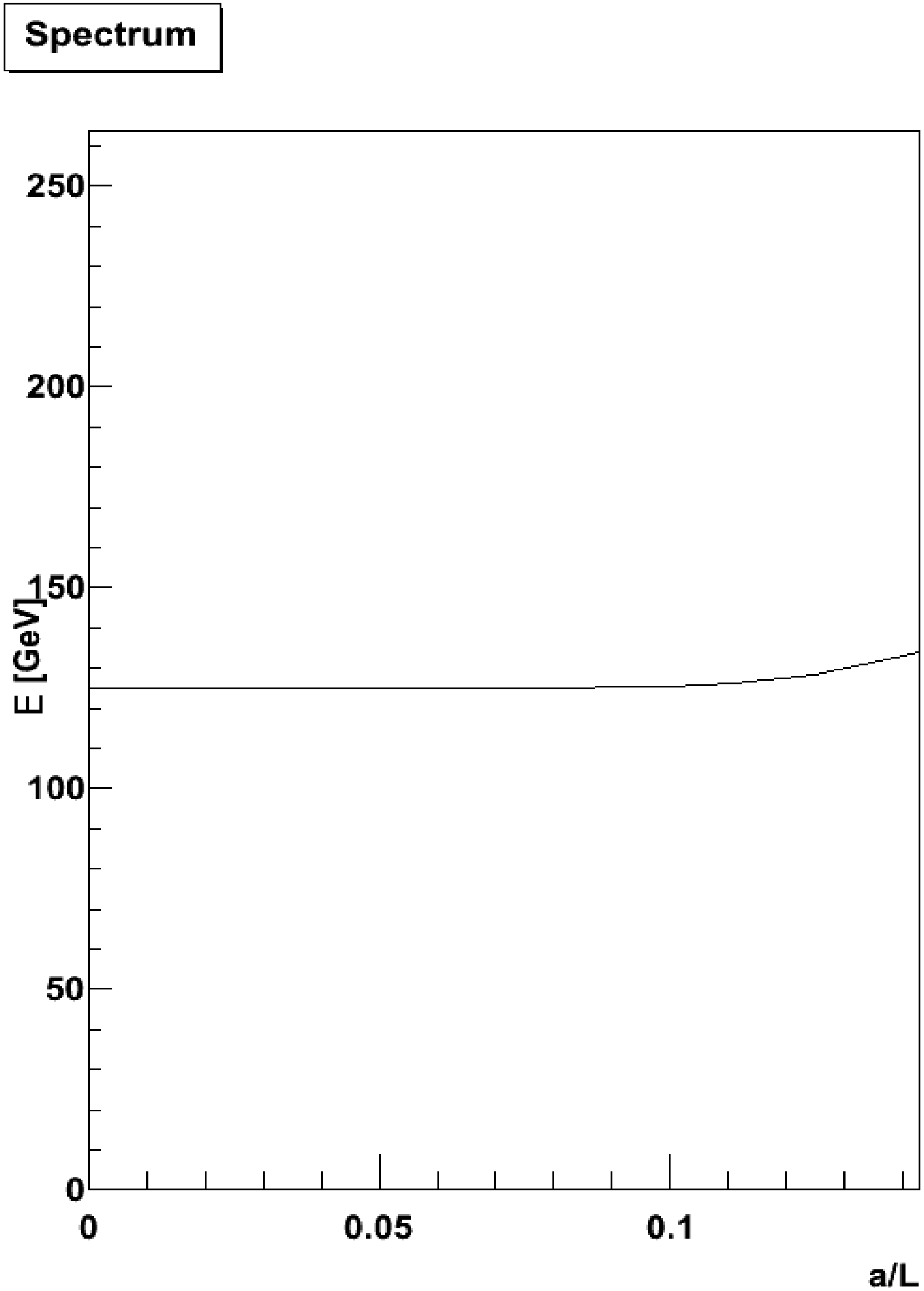

Ground state

Excited states on the lattice

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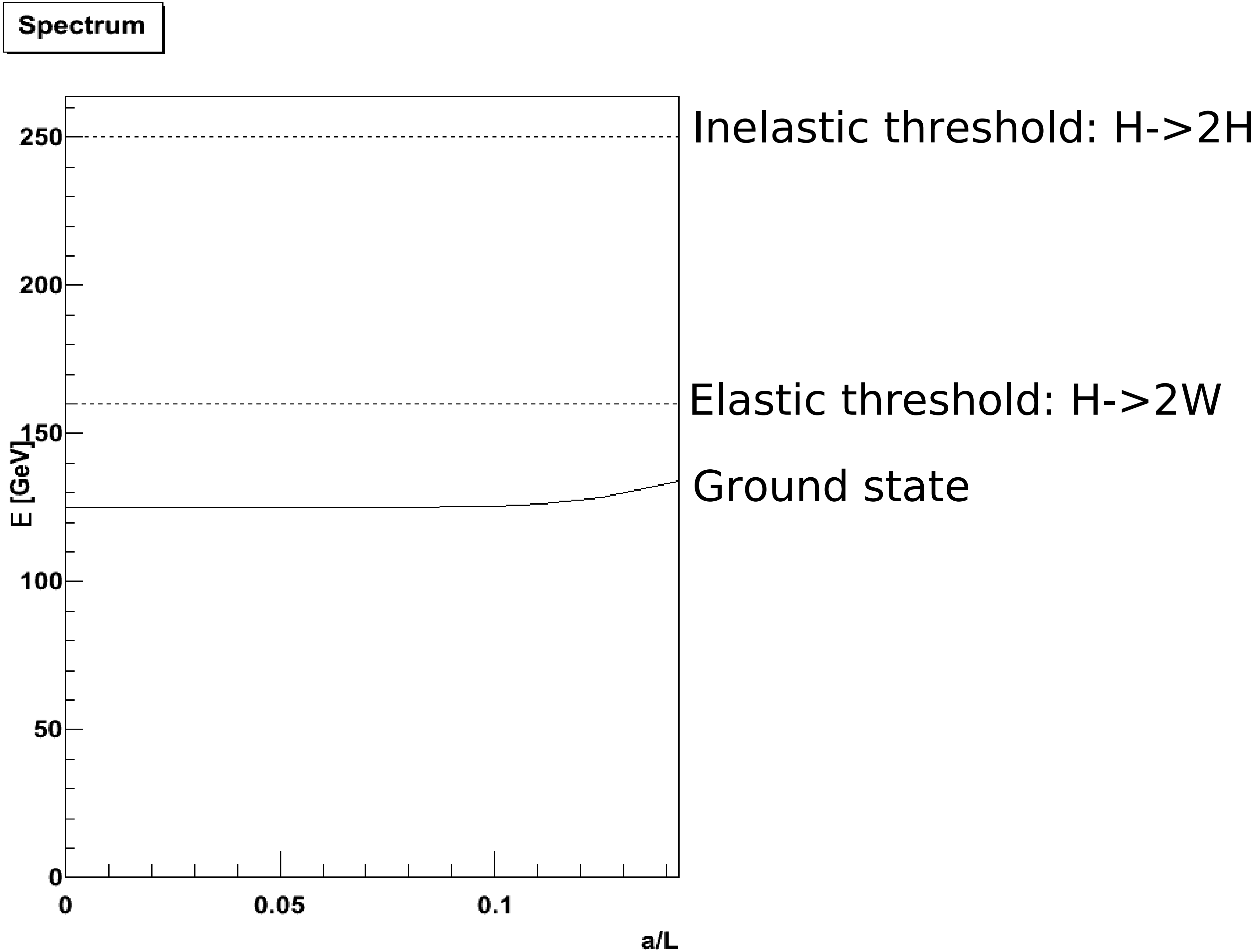

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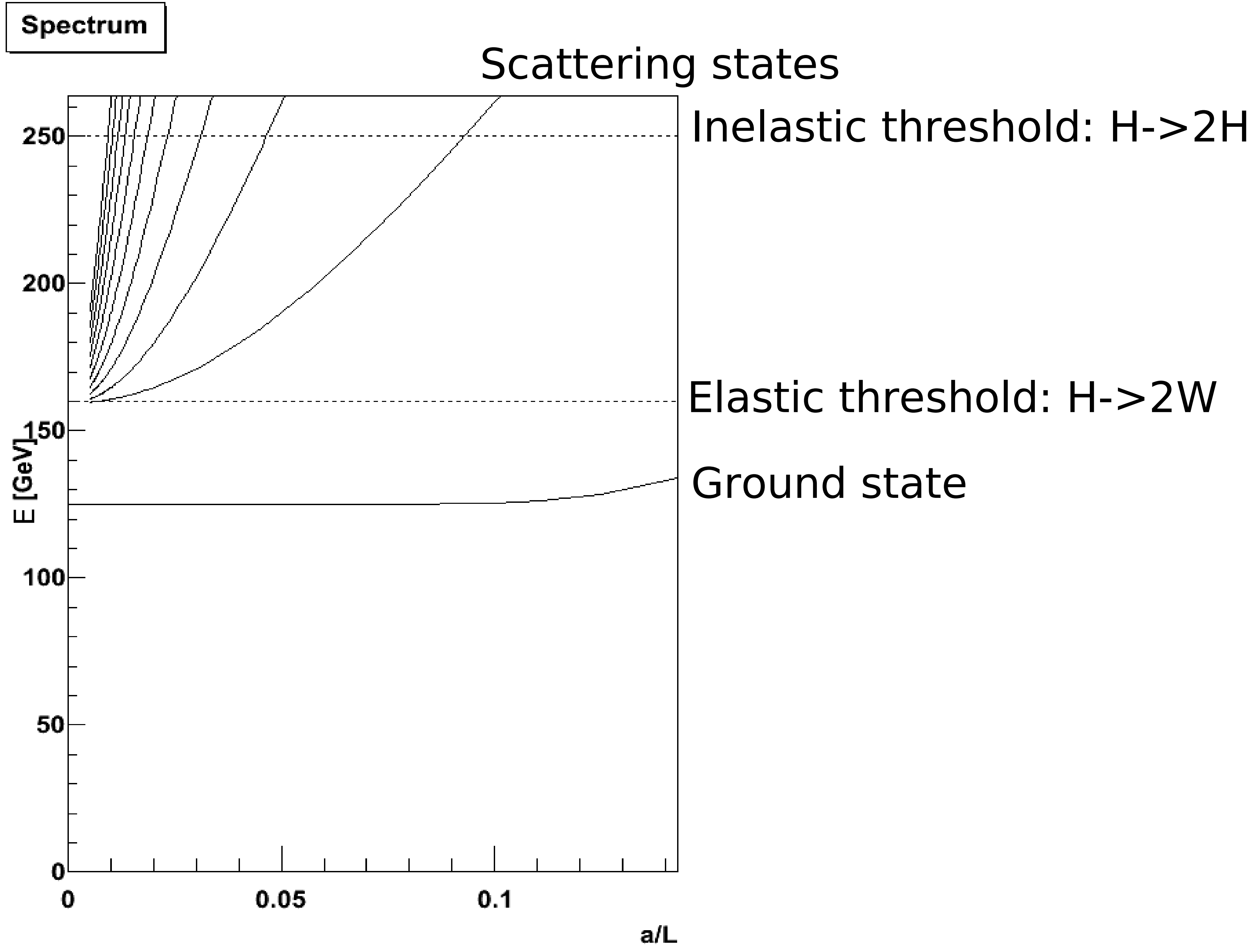

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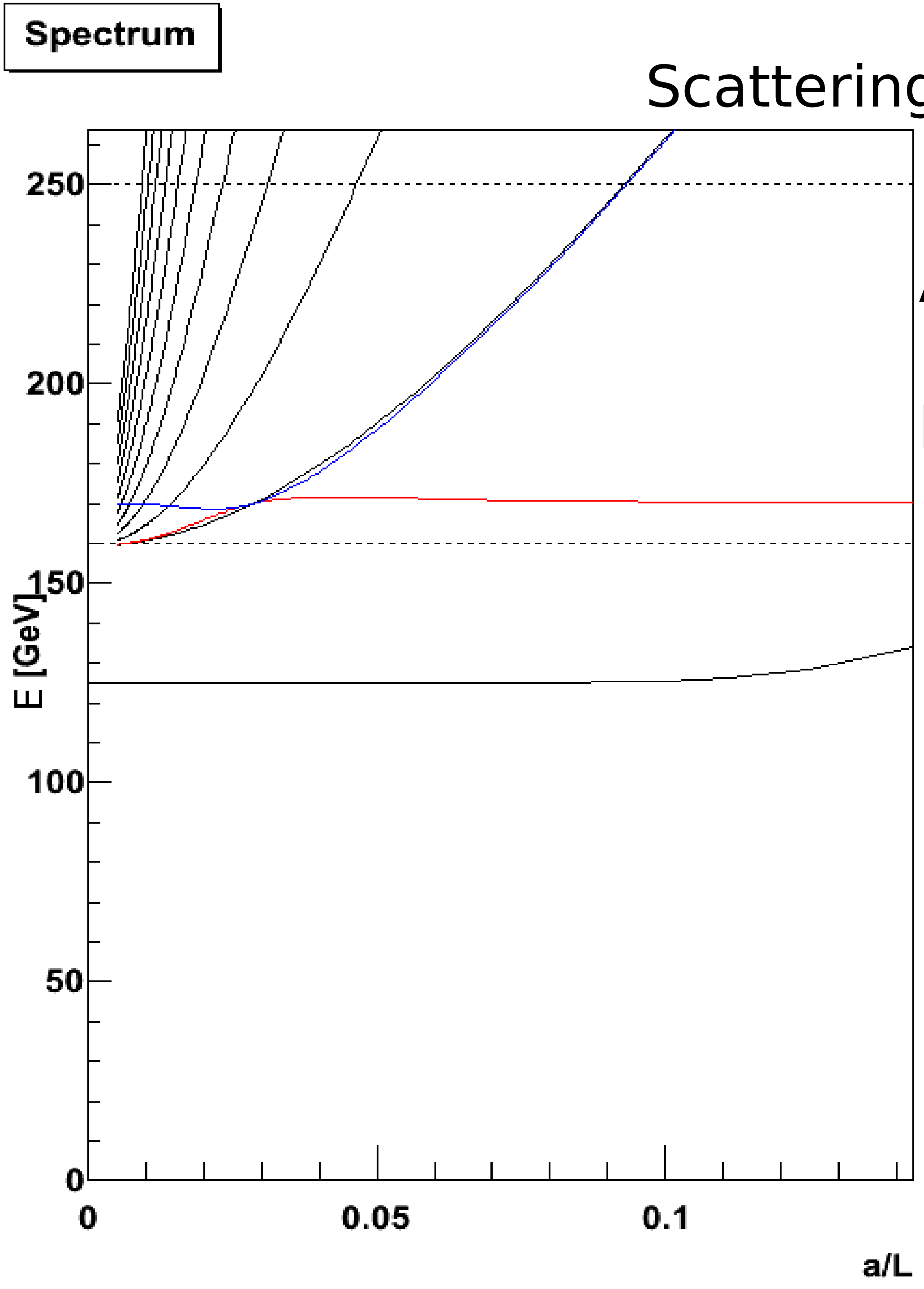

Scattering states

Inelastic threshold: H->2H

Avoided level crossing
Identification and widths from phase shifts

Elastic threshold: H->2W

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Measuring these levels as a function of volume allows the extraction of the phase shift in each quantum number channel

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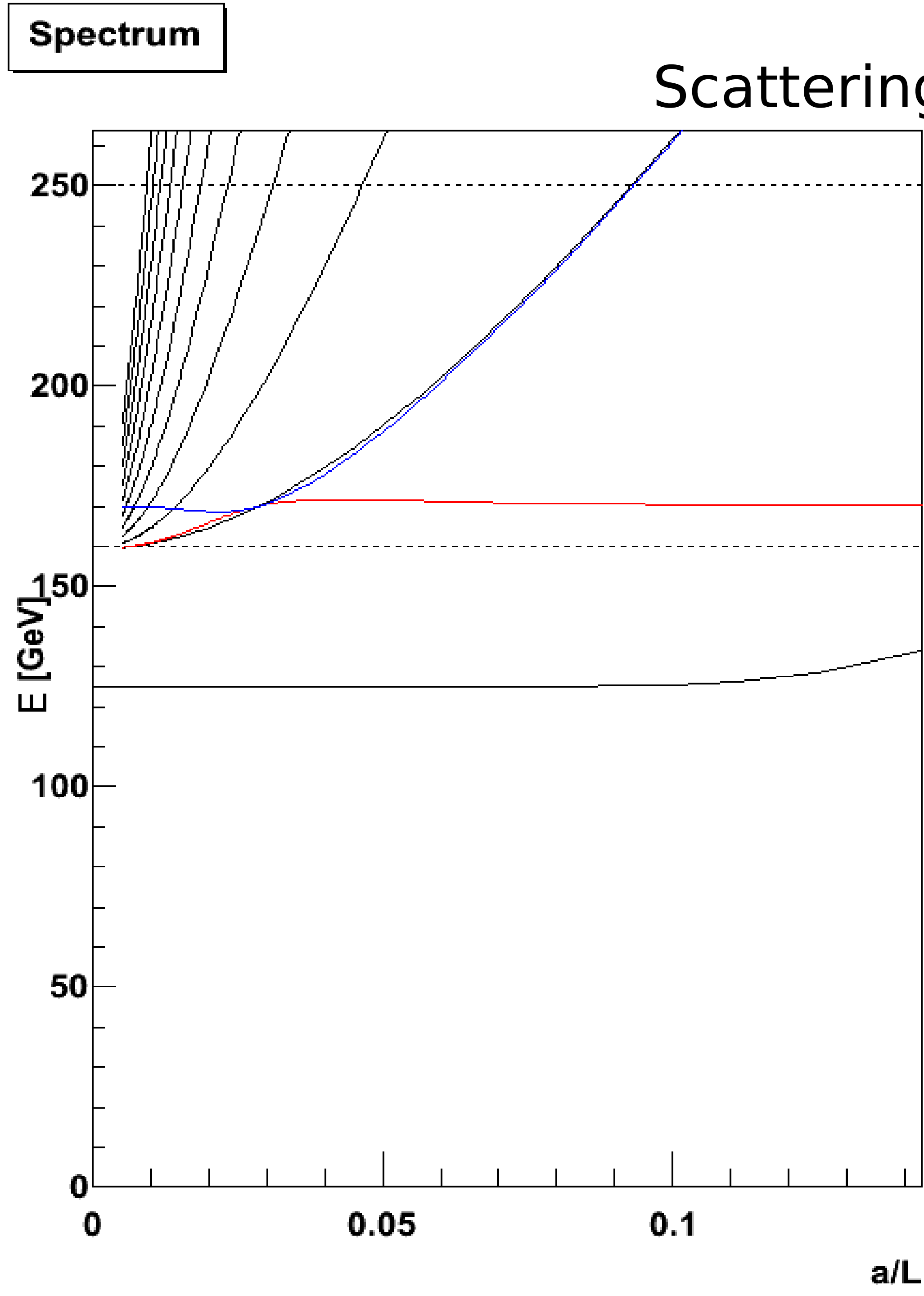

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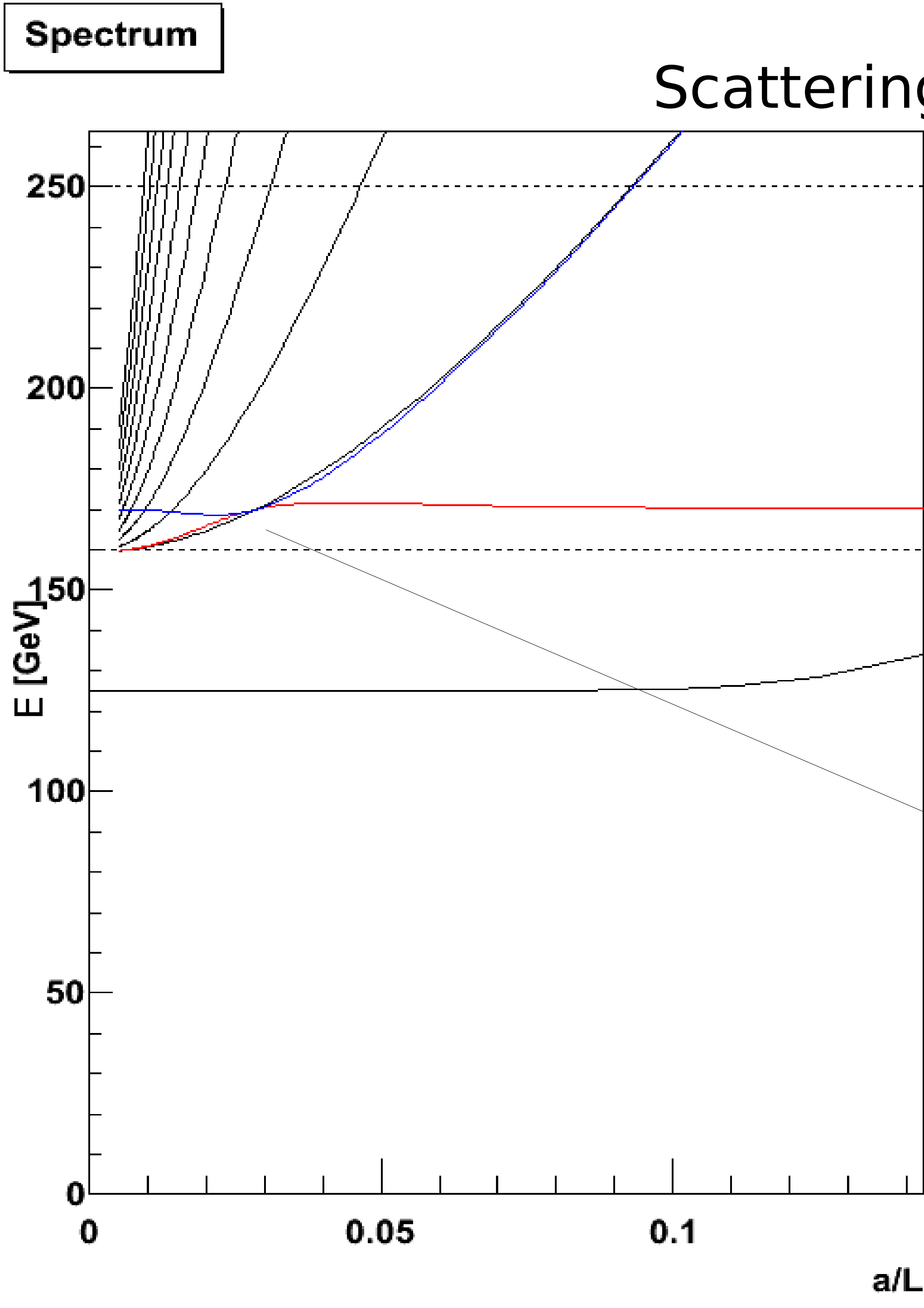

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Geometry

Impact on the radius of the Higgs

- Reduced SM: Only W/Z and the Higgs
  - Parameters slightly different
    - Higgs too heavy (145 GeV) and too strong weak coupling
  - Qualitatively but not quantitatively

[Jenny, Maas, Riederer'22]

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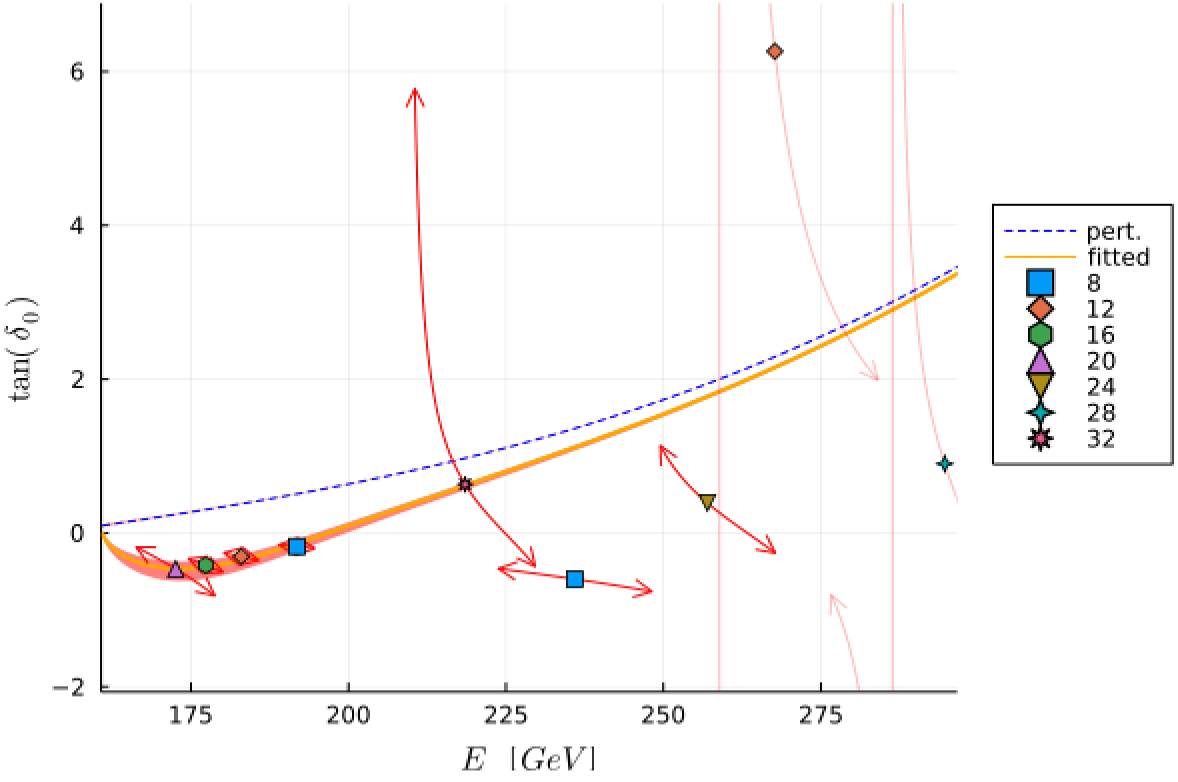

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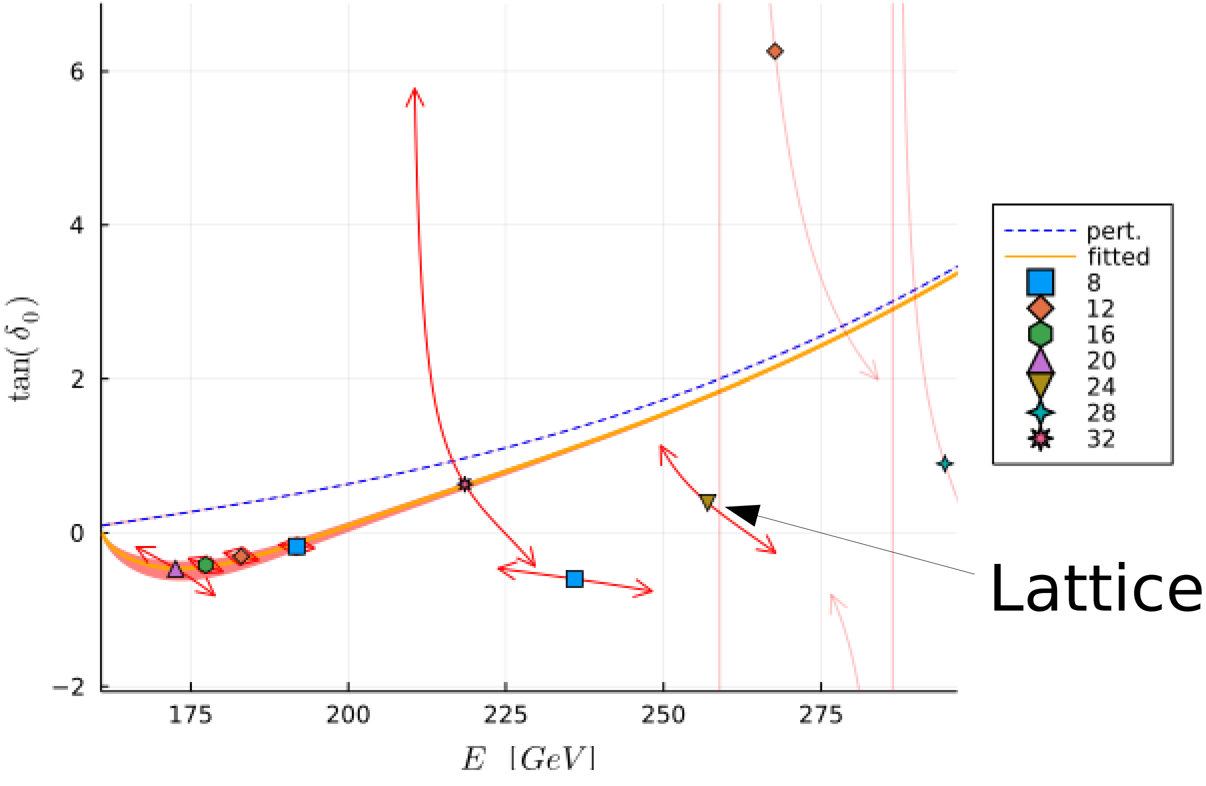

Lattice data

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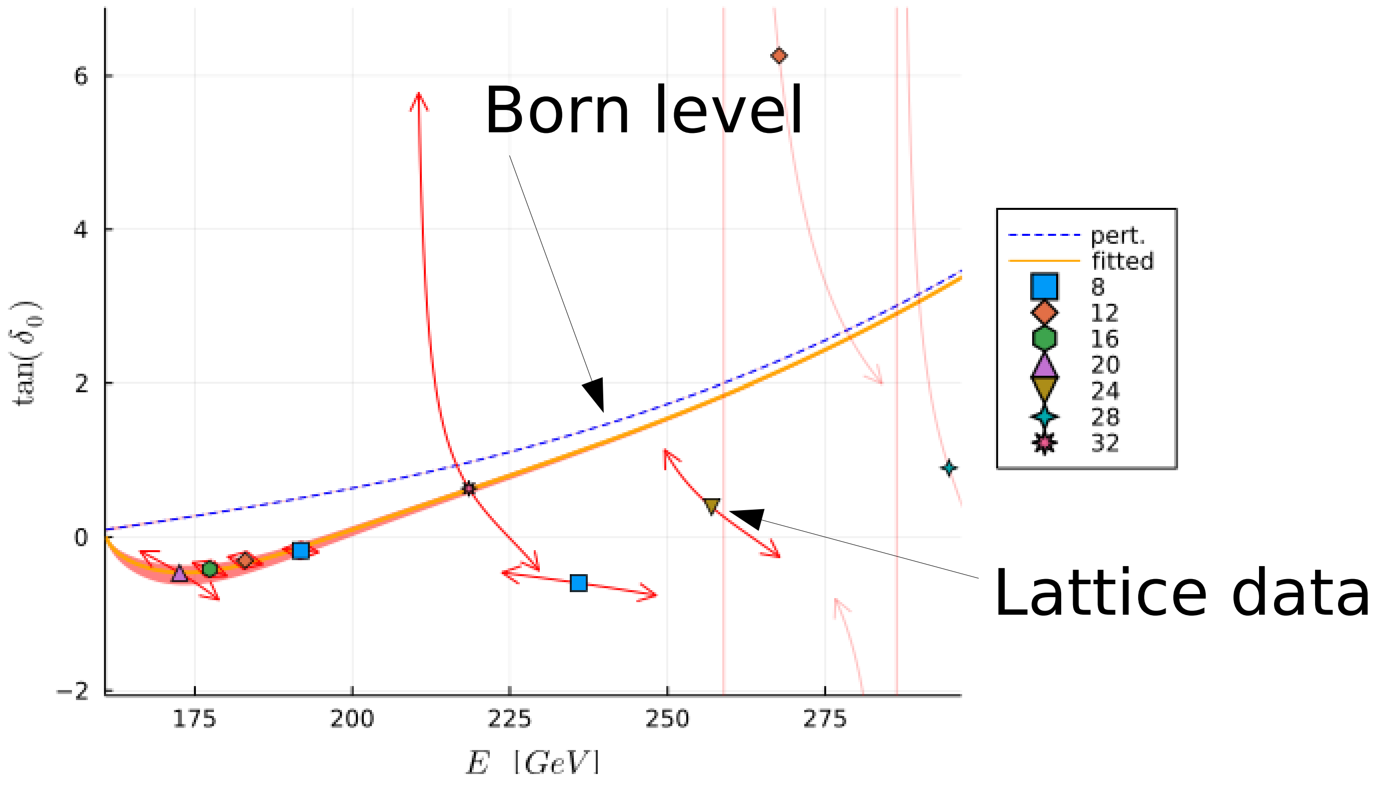

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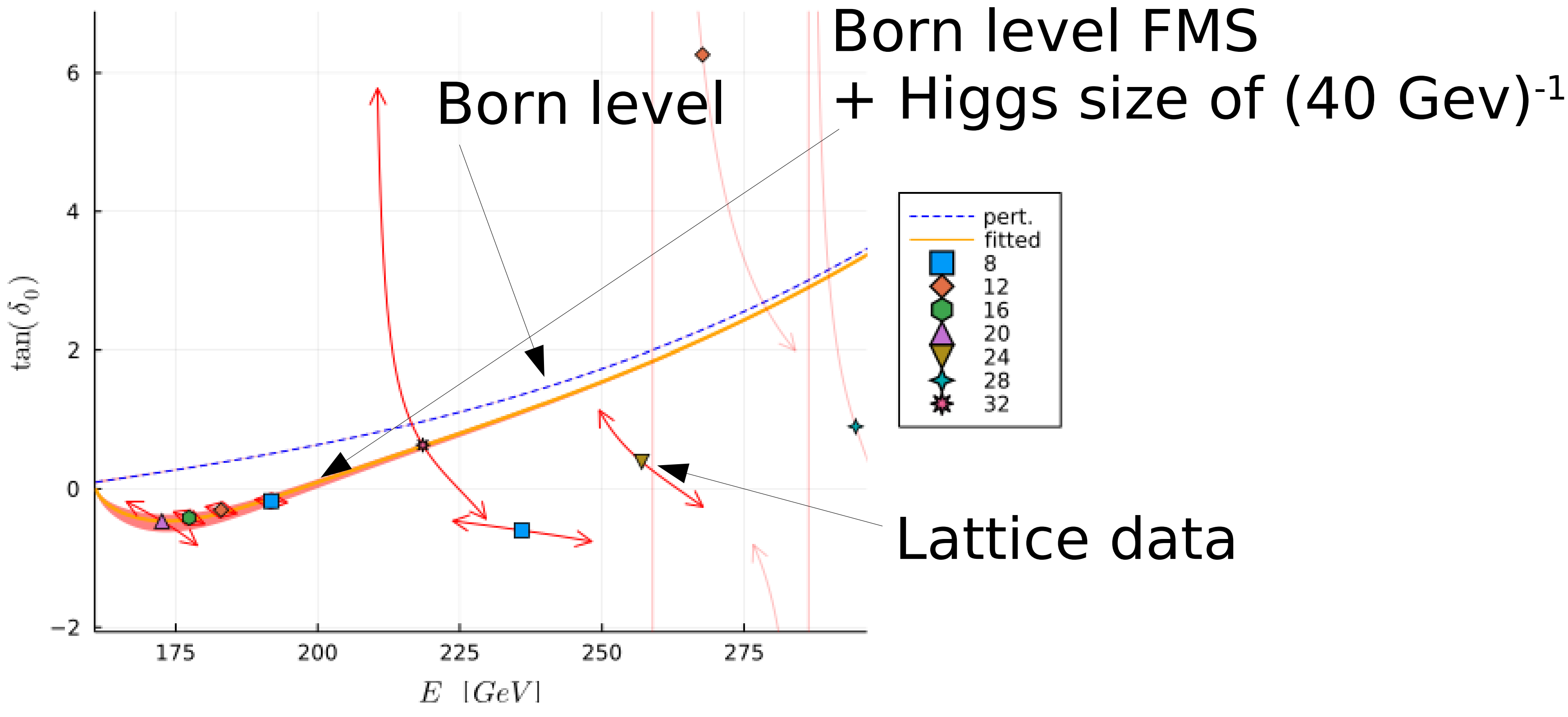

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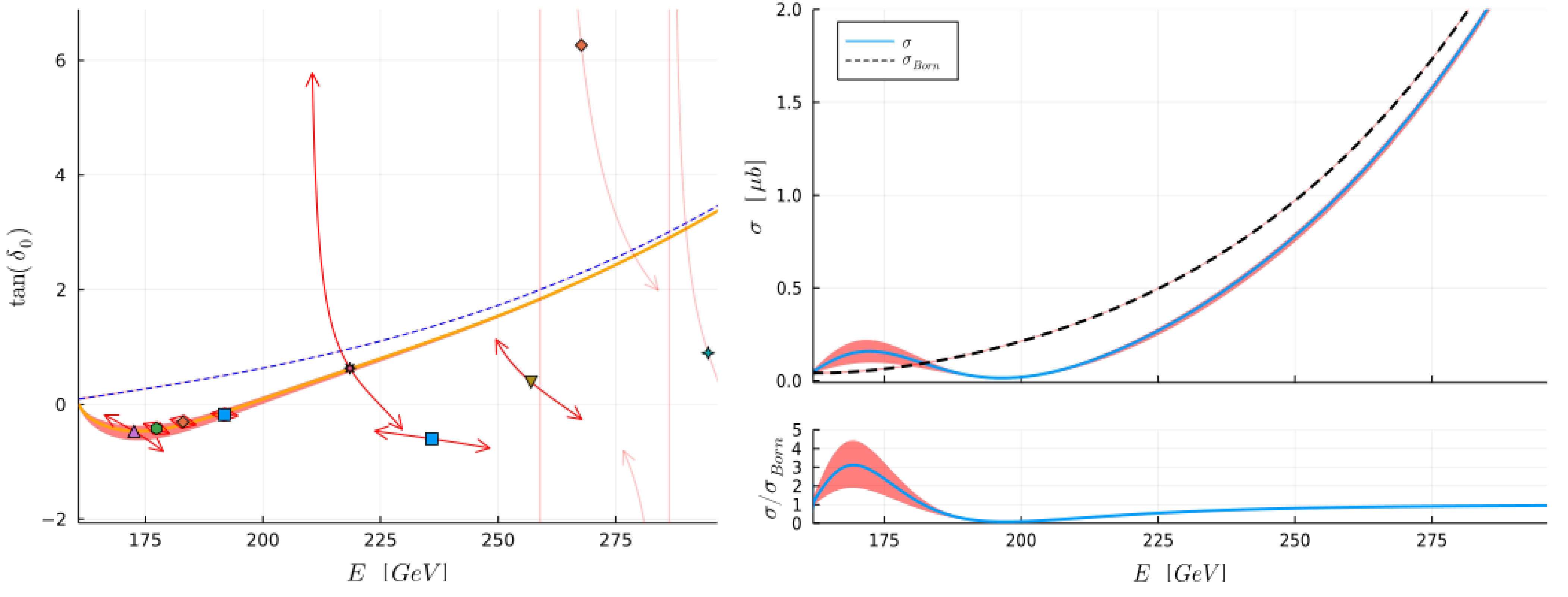

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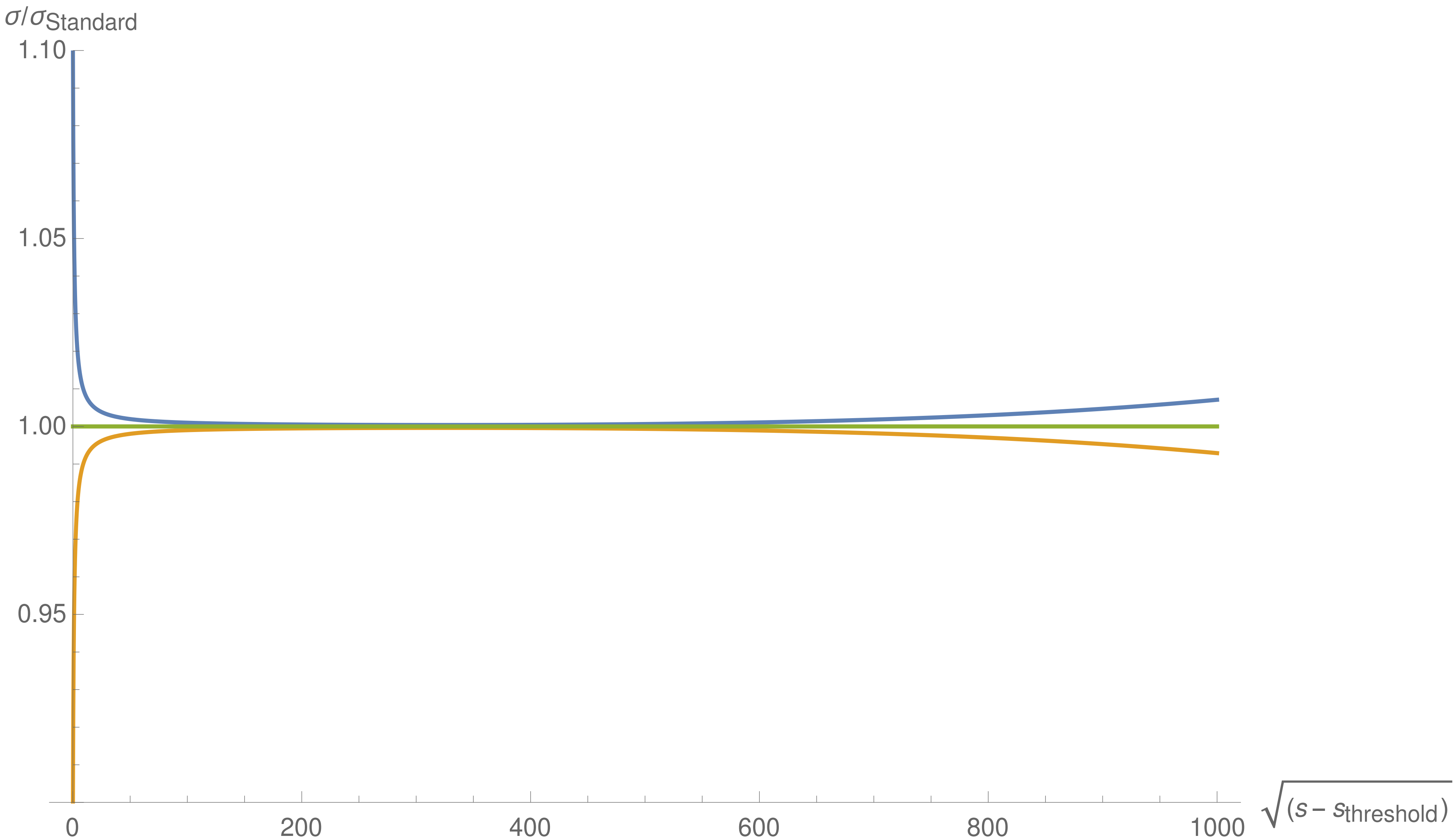

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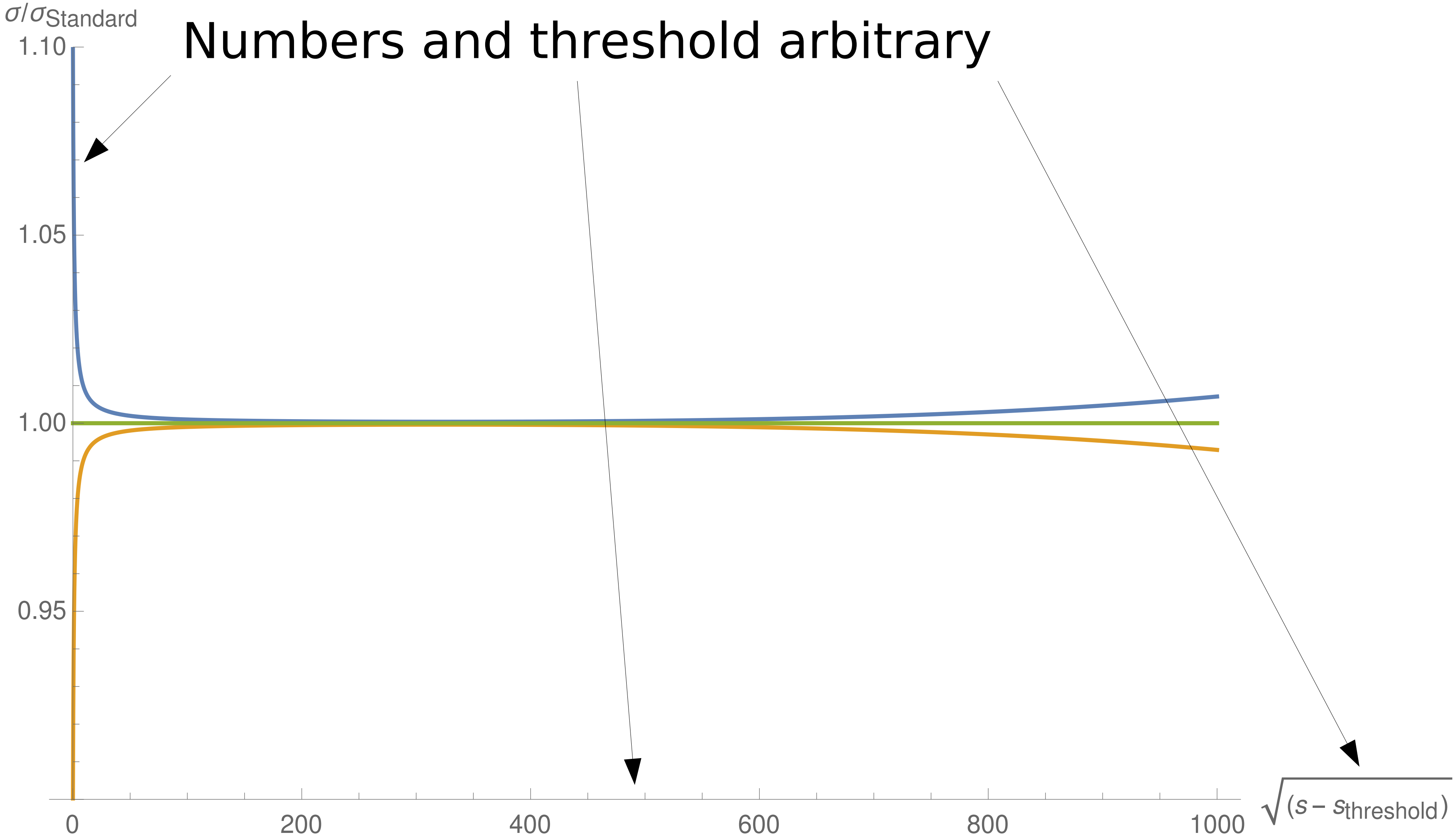

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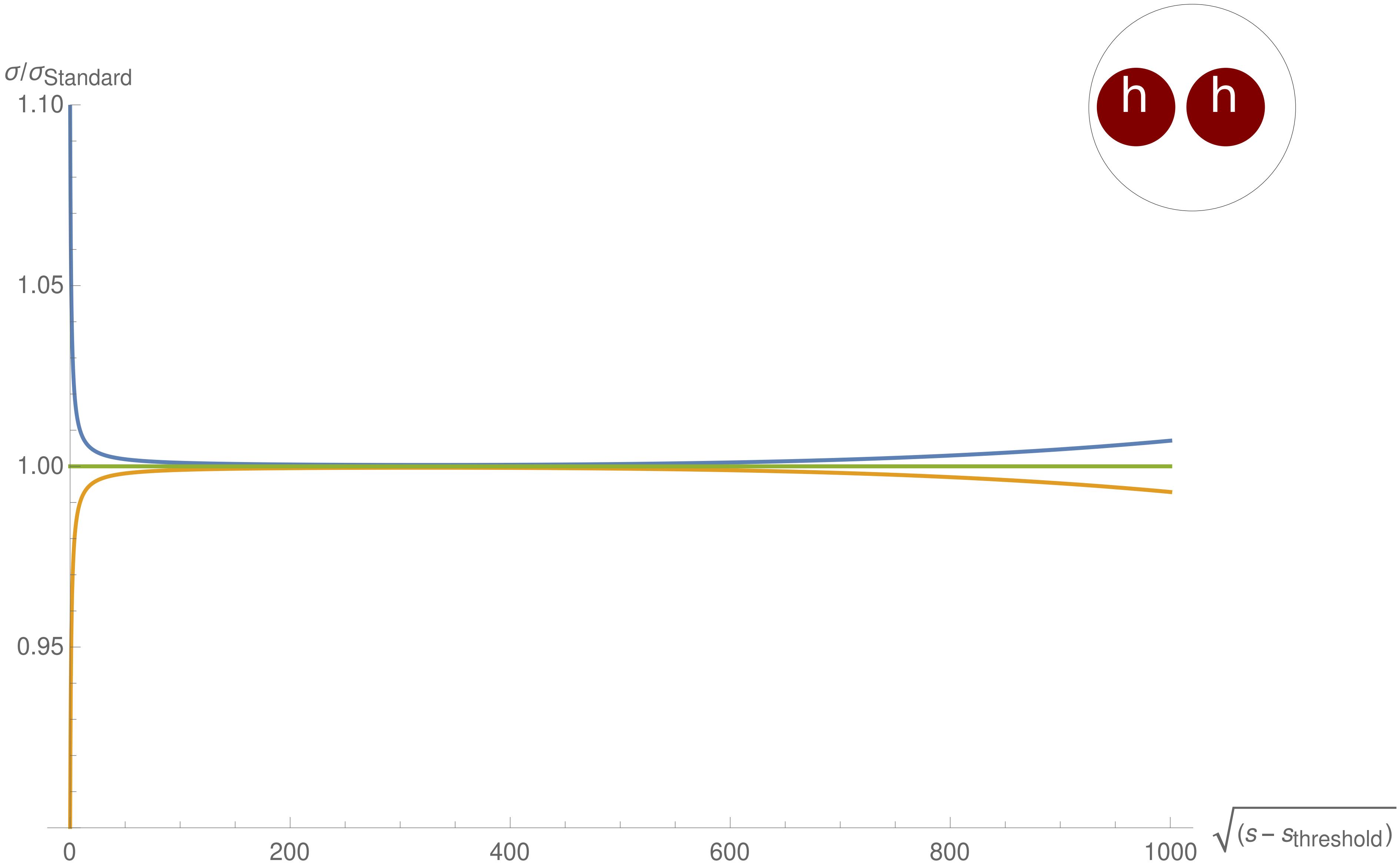

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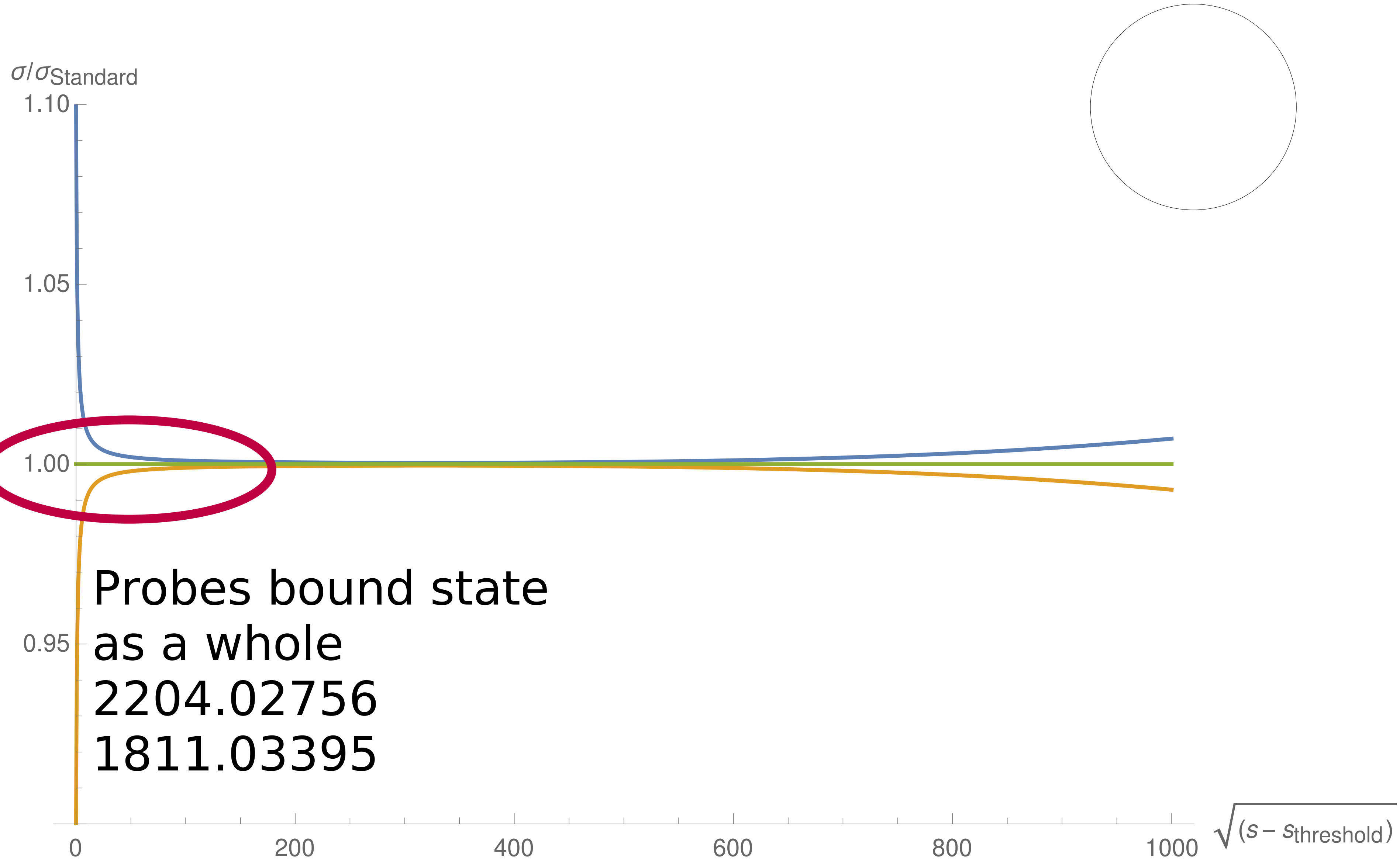
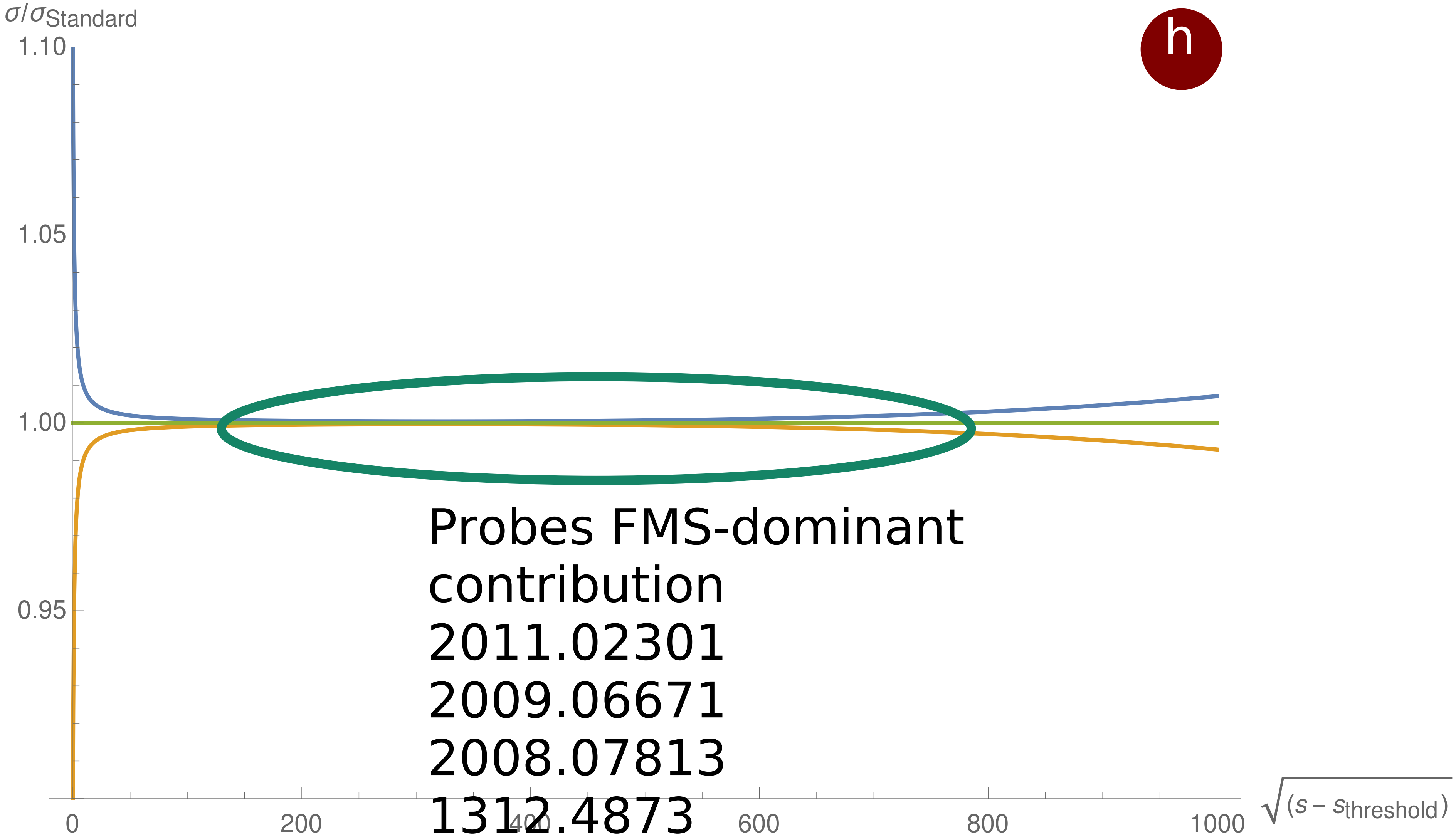


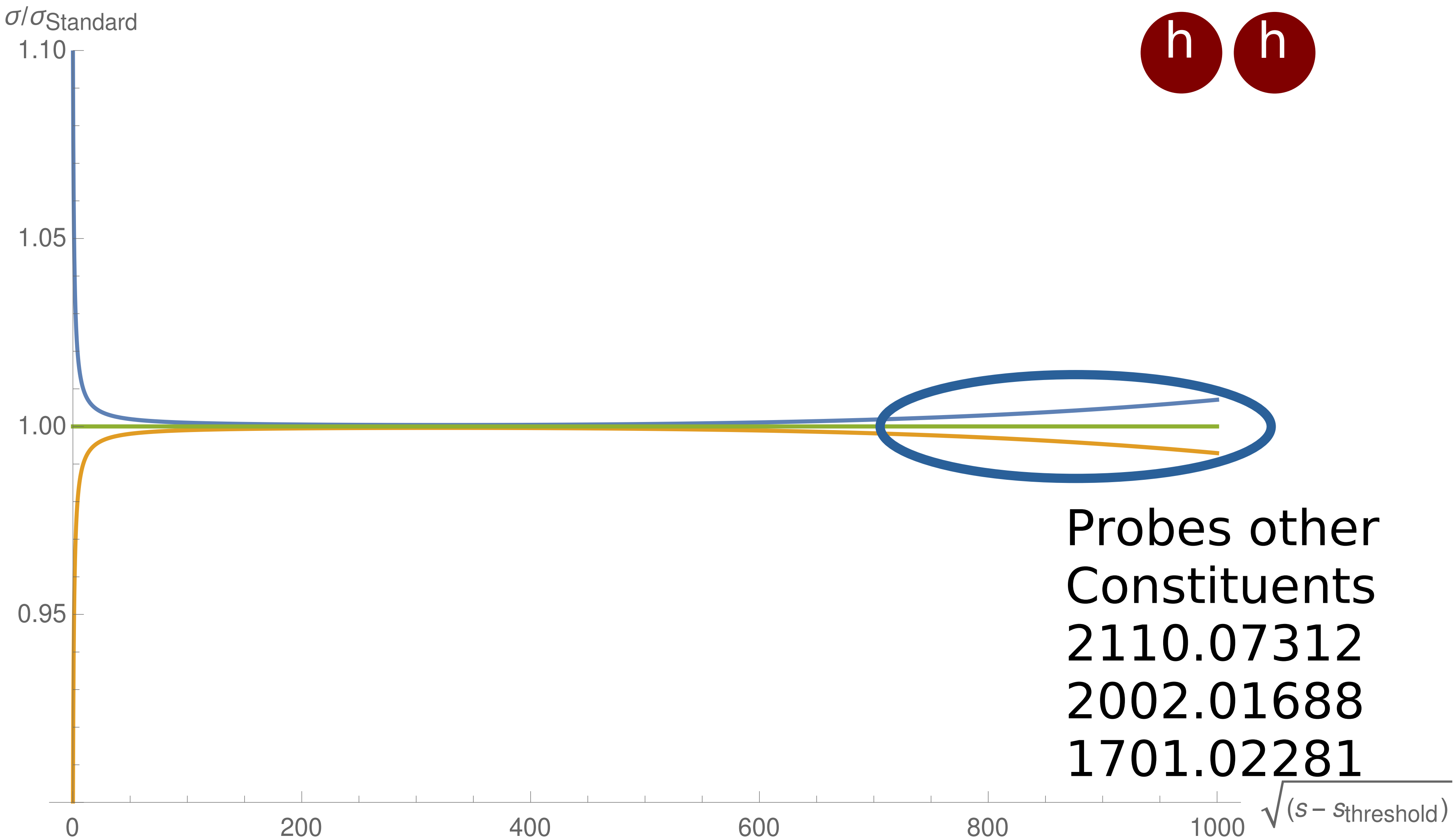
Probes bound state
as a whole
2204.02756
1811.03395

Generic behavior: DIS-like



Probes FMS-dominant contribution
2011.02301
2009.06671
2008.07813
1312.4873

Generic behavior: DIS-like



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Review: 1712.04721

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- FMS applicable to many theories
  - MSSM, Quantum gravity, supergravity,...