Gauge invariance and Observables in Particle Physics

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Zurich
Switzerland

What is this talk about?

- Why an invariant formulation?
  - Path integral formulation and symmetries

Review: 1712.04721 Update: 2305.01960

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- Brout-Englert-Higgs Physics

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    - Experimental signatures

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  - Standard Model
    - Experimental signatures
  - Beyond the Standard Model
    - Qualitative changes
  - Quantum (super)gravity

Review: 1712.04721 Update: 2305.01960

What’s the deal?
-
Gauge symmetry

Path integral

$$Z = \int_{\Omega} D\phi \, e^{iS[\phi]}$$

Path integral

Integral over all space-time
histories of the universe

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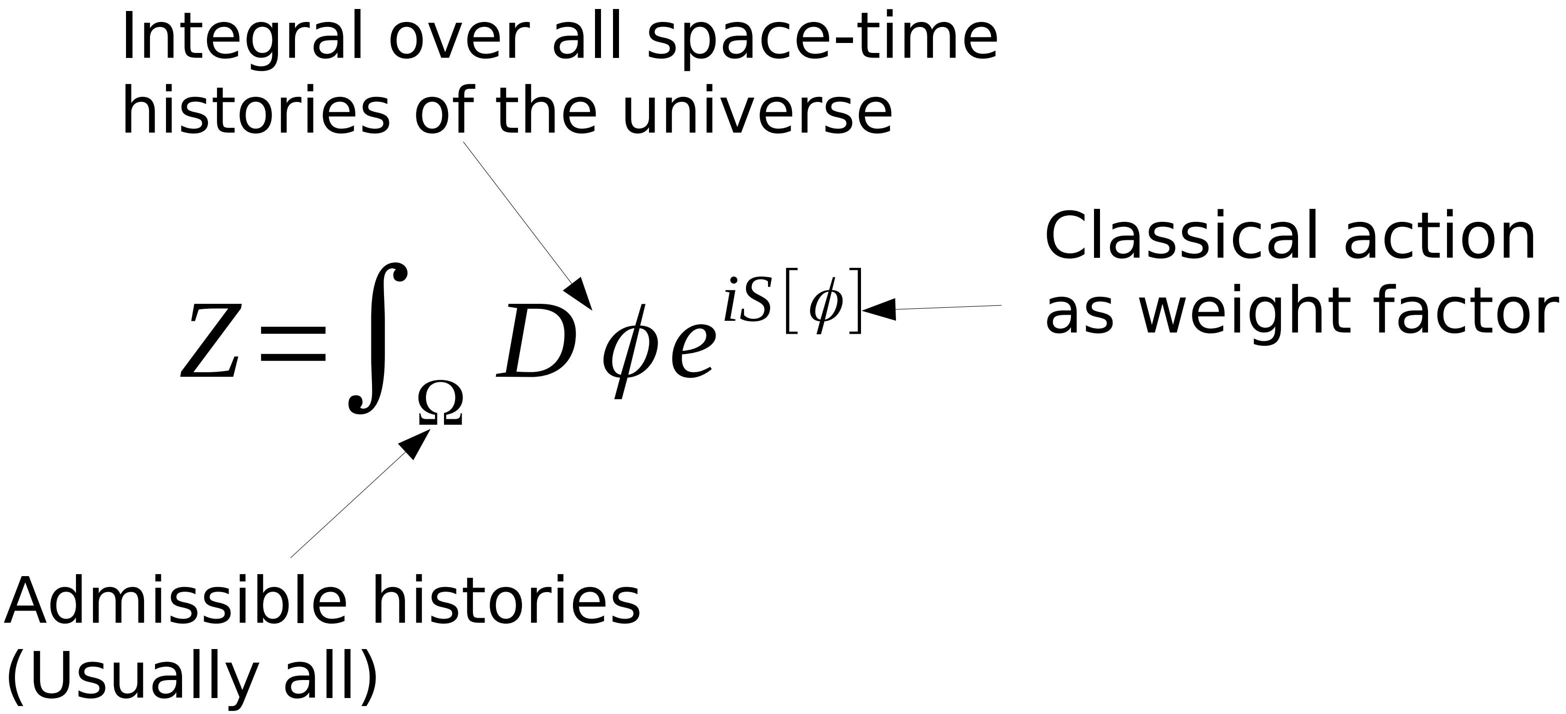

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Classical action as weight factor

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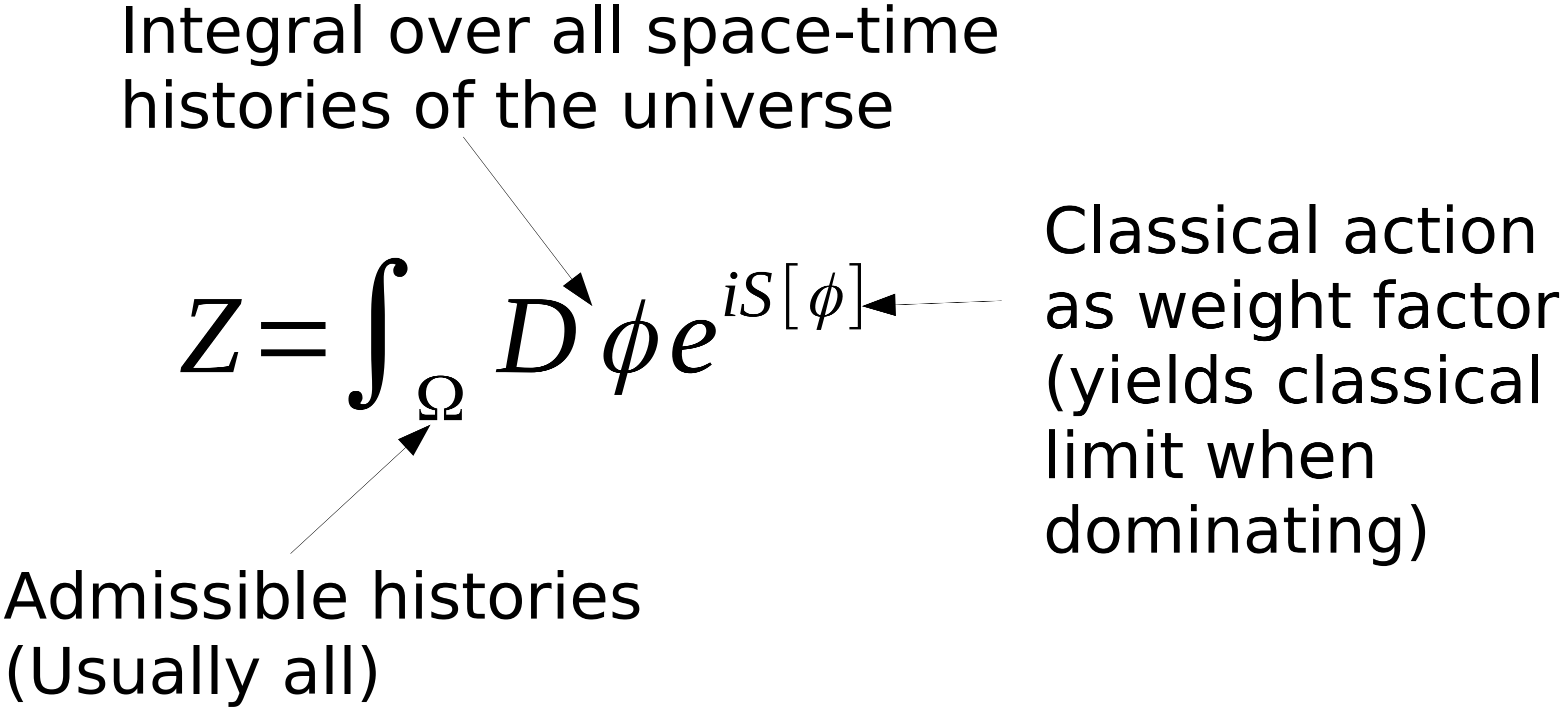

Integral over all space-time
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Classical action
as weight factor
(yields classical
limit when
dominating)

Admissible histories
(Usually all)

Path integral

$$\langle \phi(x) \ldots \phi(z) \rangle = \int_{\Omega} D\phi \, \phi(x) \ldots \phi(z) \, e^{iS[\phi]}$$

Expectation values are weighted averages
over space-time histories

Path integral

Dependencies on special events
is only due to external choices

$$\langle \phi(x)\dots\phi(z)\rangle = \int_{\Omega} D\phi\,\phi(x)\dots\phi(z)\,e^{iS[\phi]}$$

Expectation values are weighted averages
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Path integral and global symmetries

[Review: Maas'17]

$$Z=\int_{\Omega} D\phi^{a}\, e^{iS[\phi]}$$

Path integral and global symmetries

[Review: Maas’17]

Field – transforms linearly under a group $\phi^a \rightarrow G^{ab}\,\phi^b$

$$Z=\int_\Omega D\phi^a e^{iS[\phi]}$$

Path integral and global symmetries

[Review: Maas'17]

Measure is invariant
- no anomalies

$$Z=\int_\Omega D\phi^a e^{iS[\phi]}$$

Action is invariant

$$S[\phi]=S[G\phi]$$

Path integral and global symmetries

[Review: Maas'17]

$$Z=\int_{\enclose{circle}{\Omega}} D\phi^a e^{iS[\phi]}$$

Integration range

- contains all orbits $G\phi$

Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a e^{iS[\phi]} \phi^b(x)$$

Path integral and global symmetries

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$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a e^{iS[\phi]} \phi^b(x)$$

- There is no preferred point on the group orbit
  - There is no absolute orientation/frame in the internal space
  - Does not change when averaging over position
  - There is no absolute charge

Path integral and global symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \rangle = \int_\Omega D\phi^a e^{iS[\phi]} \phi^b(x) = 0$$

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Path integral and global symmetries

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$$\langle \phi^b(x)\phi^c(y)\rangle = \int_\Omega D\phi^a e^{iS[\phi]}\phi^b(x)\phi^c(y)$$

- Relative charge measurement averaged over all possible starting points

Path integral and global symmetries

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- Relative charge measurement averaged over all possible starting point
  - Vanishes because no preferred absolute starting point

Path integral and global symmetries

[Review: Maas'17]

$$\langle \delta_{bc} \phi^b(x) \phi^c(y) \rangle$$

$$= \int_\Omega D\phi^a e^{iS[\phi]} \delta_{bc} \phi^b(x) \phi^c(y)$$

- Group-invariant quantity
  - Measures relative orientation
  - Created from an invariant tensor δ_{ab}

Path integral and global symmetries

[Review: Maas'17]

$$\langle \delta_{bc}\phi^b(x)\phi^c(y)\rangle$$

$$=\int_\Omega D\phi^a e^{iS[\phi]}\delta_{bc}\phi^b(x)\phi^c(y)\neq 0$$

- Group-invariant quantity
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Path integral and local symmetries

[Review: Maas’17]

$$Z=\int_{\Omega} D\phi^a e^{iS[\phi]}$$

Path integral and local symmetries

[Review: Maas'17]

Field – transforms locally under a group $\phi^a(x) \rightarrow G^{ab}(x)\phi^b(x)$

$$Z = \int_{\Omega} D\phi^a e^{iS[\phi]}$$

Path integral and local symmetries

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Path integral and local symmetries

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$$= \int_\Omega D\phi^a e^{iS[\phi]} \delta_{bc} \phi^b(x) \phi^c(y) = 0$$

- No longer invariant under gauge transformations
  - Vanishes just as any other non-invariant quantity

Path integral and local symmetries

[Review: Maas'17]

$$\langle \phi^b(x) \overset{\text{Transporter}}{\boxed{U^{bc}(x,y)}} \phi^c(y) \rangle$$

$$= \int_\Omega D\phi^a DU e^{iS[\phi]} \phi^b(x) U^{bc}(x,y) \phi^c(y)$$

- Transporter compensates gauge transformations
  - Implemented by gauge fields

Path integral and local symmetries

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Path integral and local symmetries

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Reduced integration range

$$\langle \phi^b(x)\phi^c(y)\rangle$$

$$=\int_{\Omega_c} D\phi^a DU\, W(U,\phi) e^{iS[\phi]} \phi^b(x)\phi^c(y) \neq 0$$

- Reduction of integration region by gauge fixing
  - Arbitrary choice of coordinates
  - Weight factor to keep gauge-invariant quantities the same

Brout-Englert-Higgs Physics
-
The Standard Model

A toy model

A toy model: Higgs sector of the SM

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- Consider an SU(2) with a fundamental scalar

A toy model: Higgs sector of the SM

- Consider an SU(2) with a fundamental scalar
- Essentially the standard model Higgs

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

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

- Ws W_{μ}^{a} W

- Coupling g and some numbers f^{abc}

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- Higgs h_i h
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A toy model: Higgs sector of the SM

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

$$W^{a}_{\mu\nu} = \partial_{\mu} W^{a}_{\nu} - \partial_{\nu} W^{a}_{\mu} + g f^{a}_{bc} W^{b}_{\mu} W^{c}_{\nu}$$

$$D^{ij}_{\mu} = \delta^{ij} \partial_{\mu} - i g W^{a}_{\mu} t^{ij}_{a}$$

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- Ws W_{μ}^{a} W
- Higgs h_i h
- 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

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

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

$W^a_\mu\rightarrow W^a_\mu$ $\qquad h\rightarrow h\Omega$

Textbook approach

- Choose parameters to get a Brout-Englert-Higgs effect

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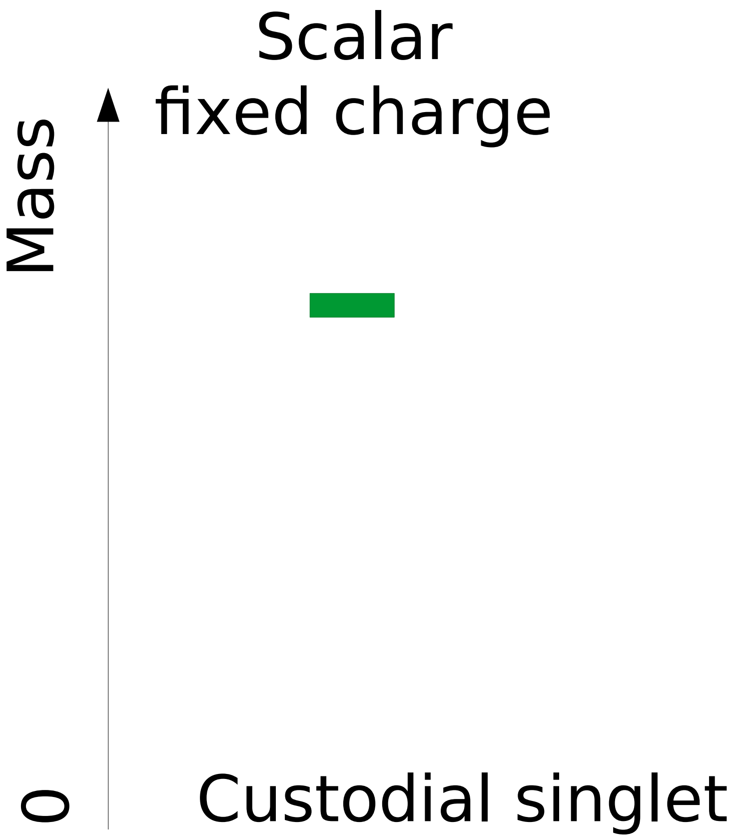
- Choose a suitable gauge and obtain ‘spontaenous gauge symmetry breaking’: SU(2) → 1
- Get masses and degeneracies at tree-level
- Perform perturbation theory

Physical spectrum

Perturbation theory

Physical spectrum

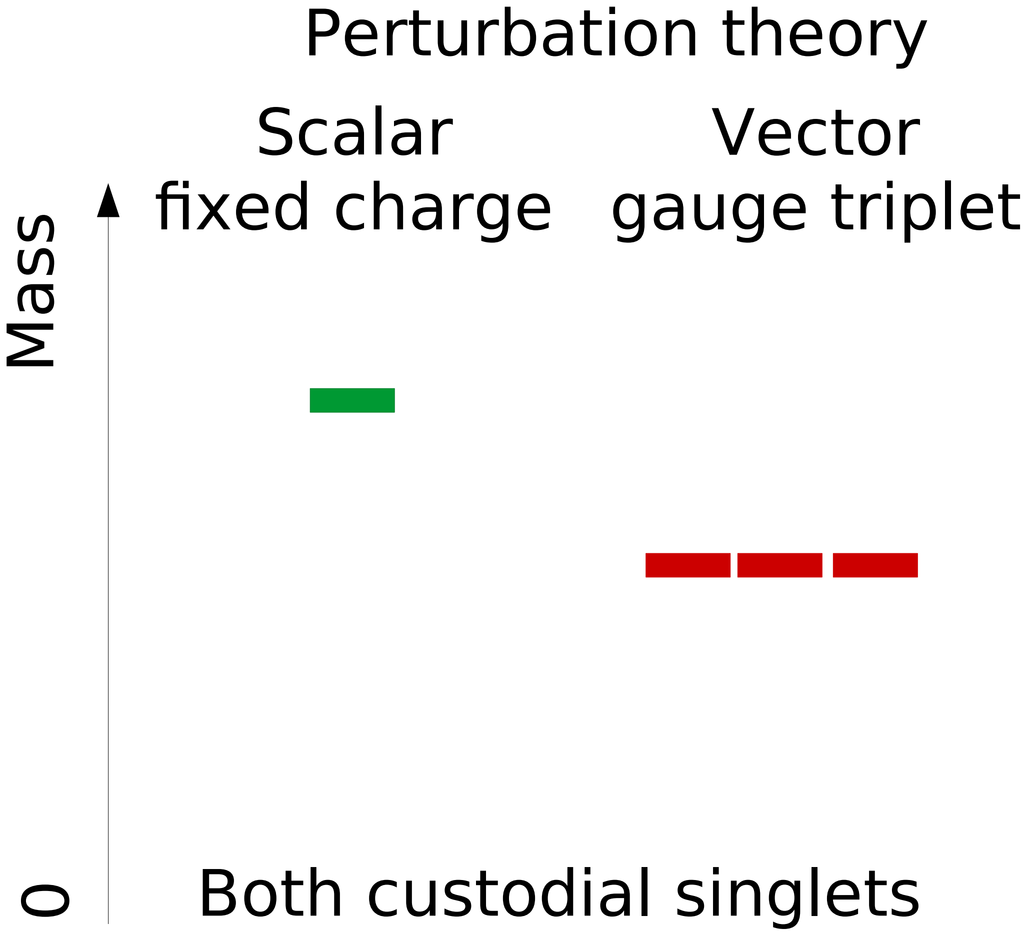
Perturbation theory



Scalar
fixed charge

Custodial singlet

Physical spectrum



Perturbation theory

Scalar
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Vector
gauge triplet

Both custodial singlets

The origin of the problem

[Fröhlich et al.'80,
Banks et al.'79]

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    - ...and gauge-symmetry breaking is not there

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- Physics has to be expressed in terms of manifestly gauge-invariant quantities
  - And this includes non-perturbative aspects...
  - ...even at weak coupling [Gribov’78,Singer’78,Fujikawa’82]

Physical states

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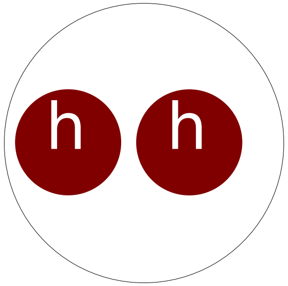

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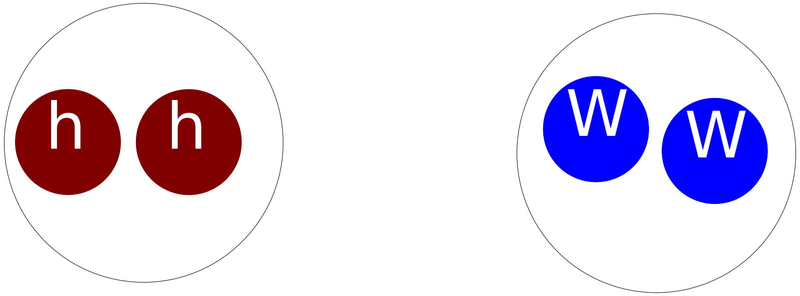

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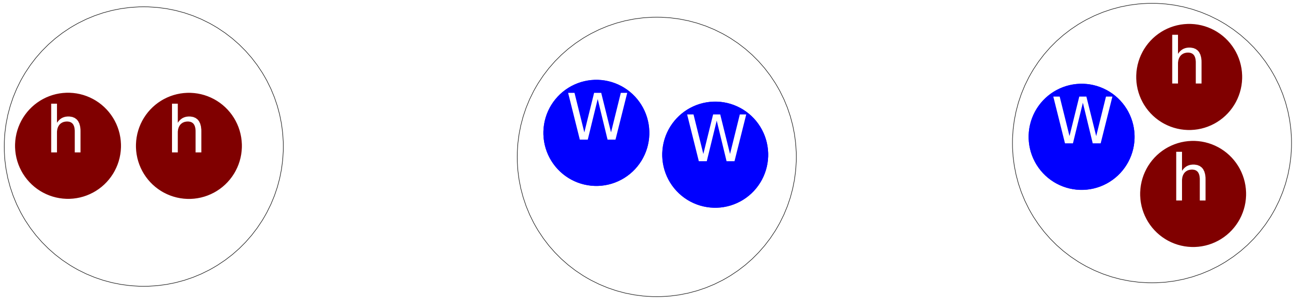

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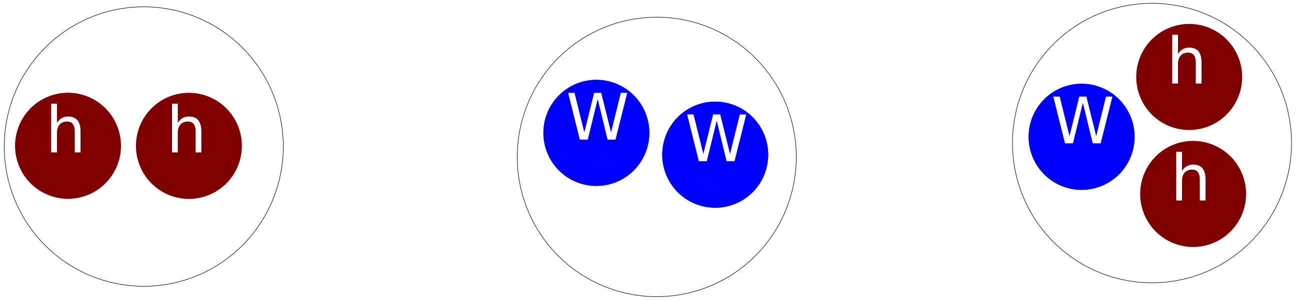

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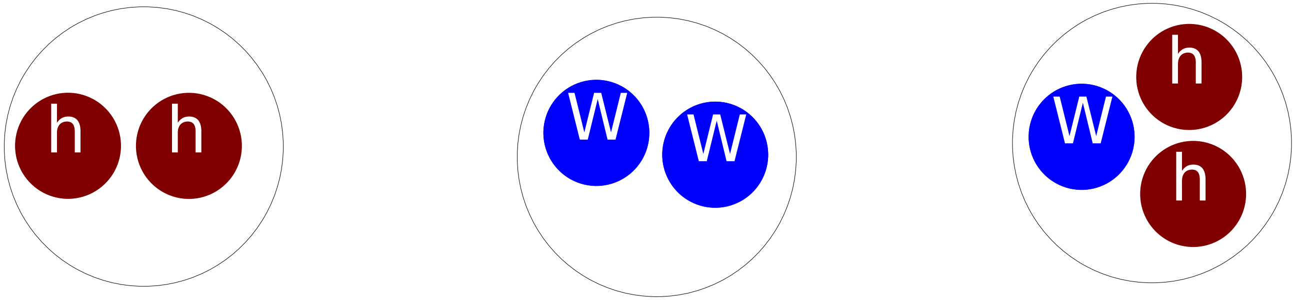

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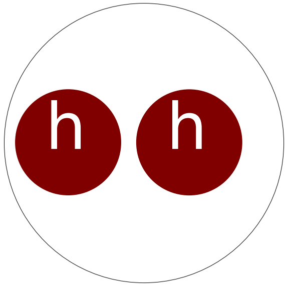

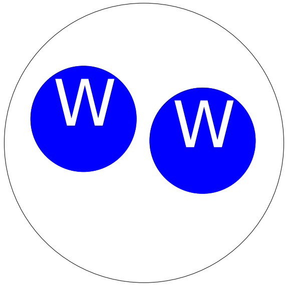

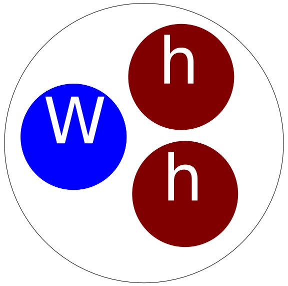

- Has nothing to do with weak coupling
  - Think QED (hydrogen atom!)
- Can this matter?

How to make predictions

[Fröhlich et al.’80,’81,
Maas & Törek'16,’18,
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- J^{PC} and custodial charge only quantum numbers

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  - Bound state structure

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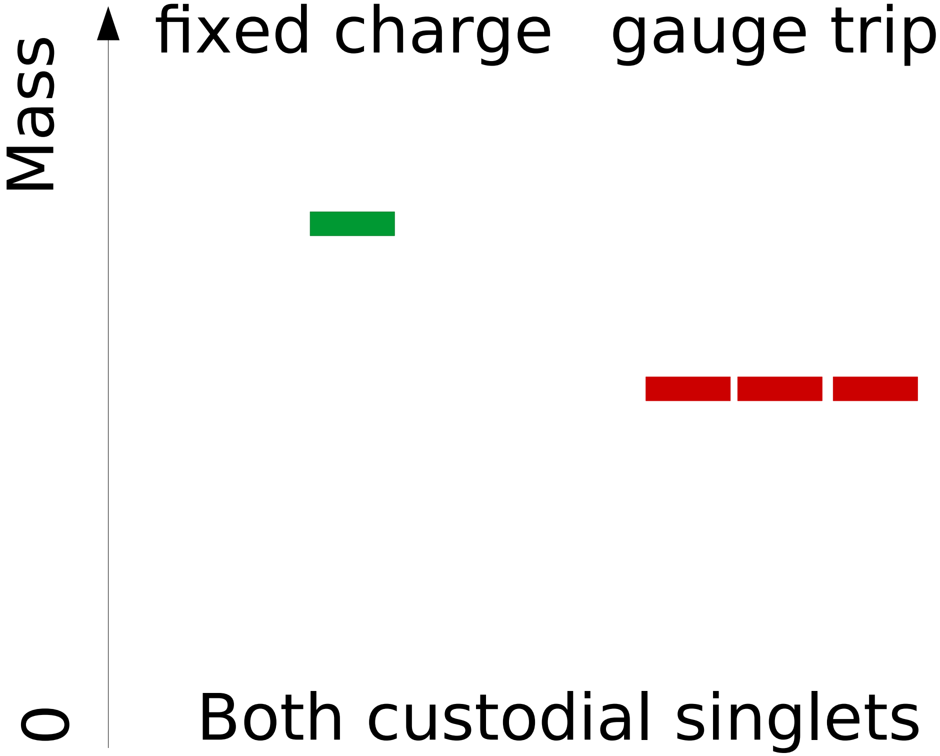
- Formulate gauge-invariant, composite operators
  - Bound state structure – non-perturbative methods! - Lattice

Physical spectrum

Perturbation theory

Scalar
fixed charge

Vector
gauge triplet



Both custodial singlets

Experiment tells that somehow the left is correct

Physical spectrum

Perturbation theory

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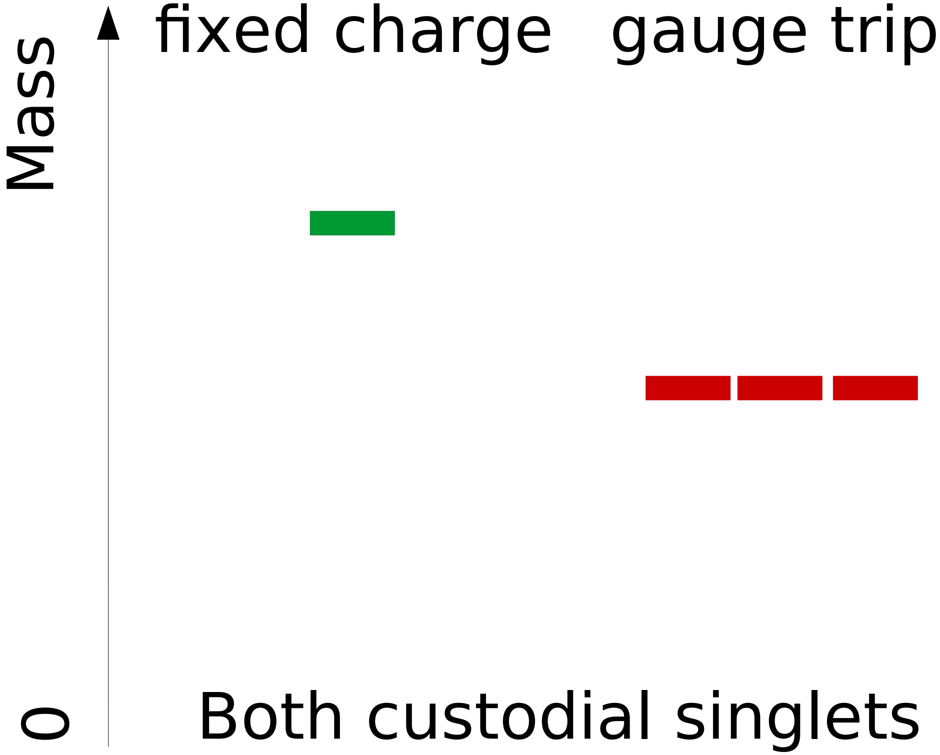
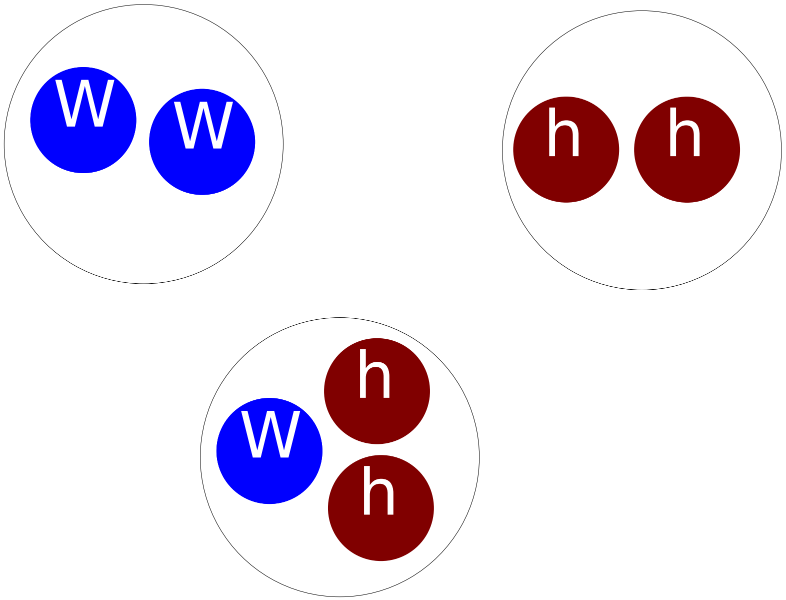
fixed charge

Vector
gauge triplet



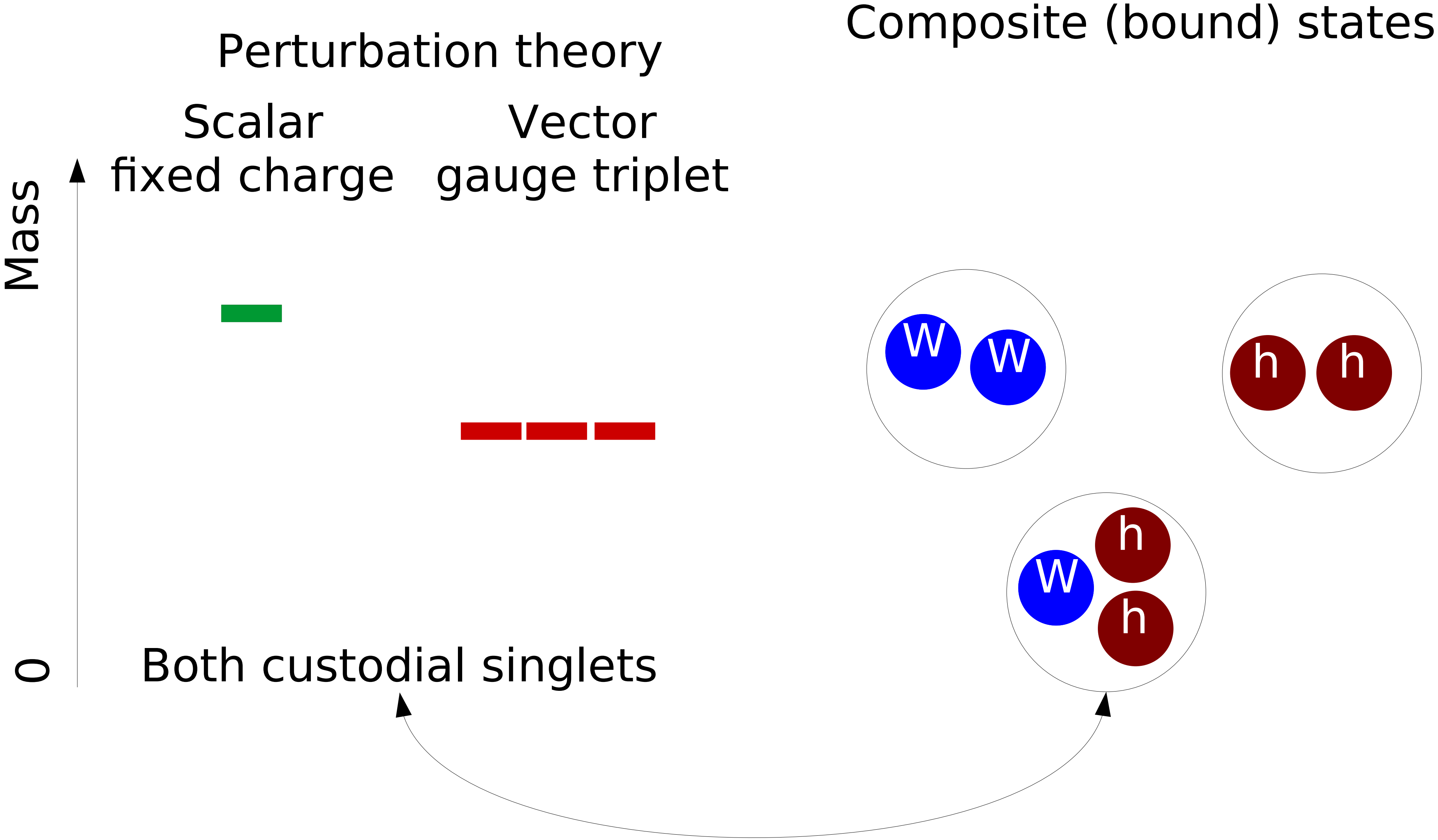
Both custodial singlets

Composite (bound) states



Experiment tells that somehow the left is correct
Theory say the right is correct

Physical spectrum



Perturbation theory

Composite (bound) states

Scalar
fixed charge

Vector
gauge triplet

Both custodial singlets

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]

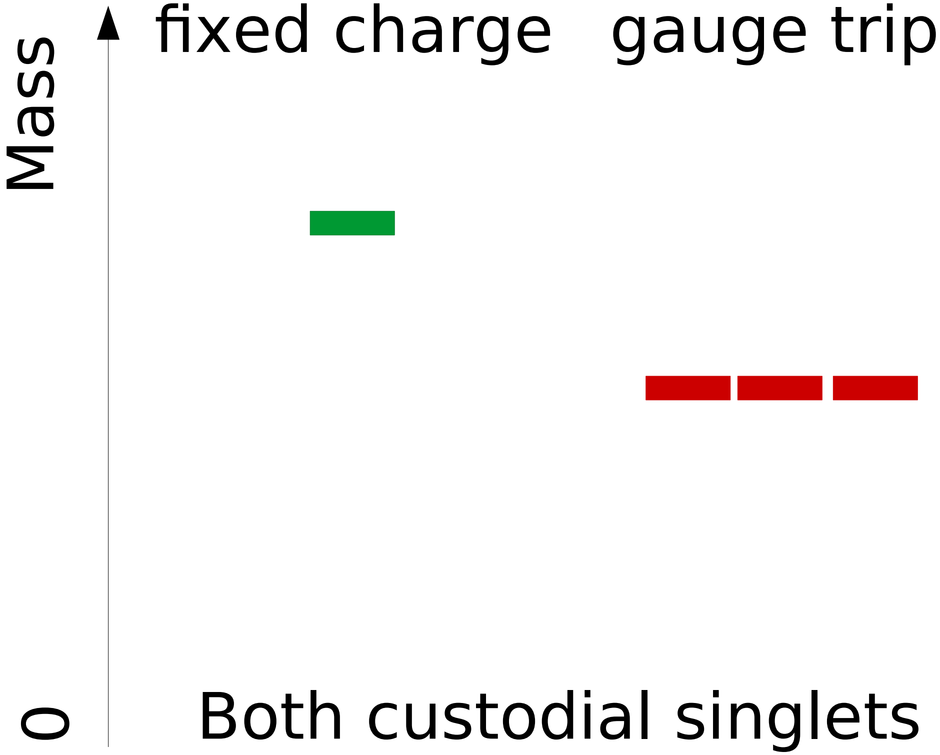
Perturbation theory

Gauge-invariant

Scalar
fixed charge

Vector
gauge triplet

Scalar
singlet



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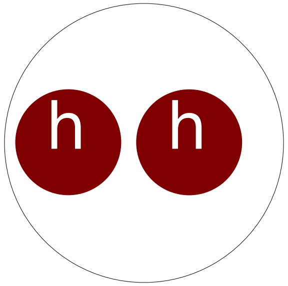
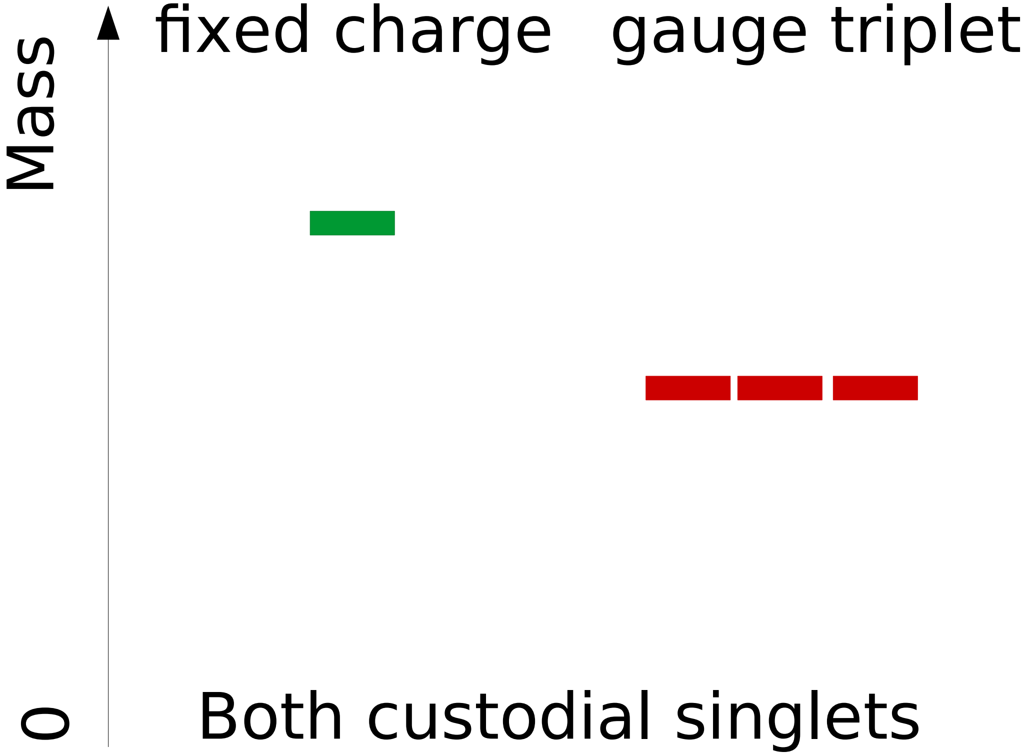
$$h(x)^{+}\,h(x)$$



Physical spectrum

[Maas'12, Maas & Mufti'14]



Perturbation theory

Scalar
fixed charge

Vector
gauge triplet

Both custodial singlets

Gauge-invariant

Scalar
singlet

Custodial singlet

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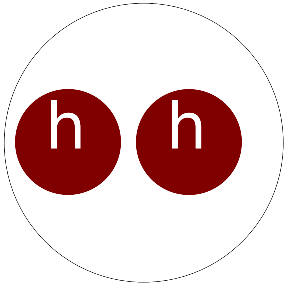

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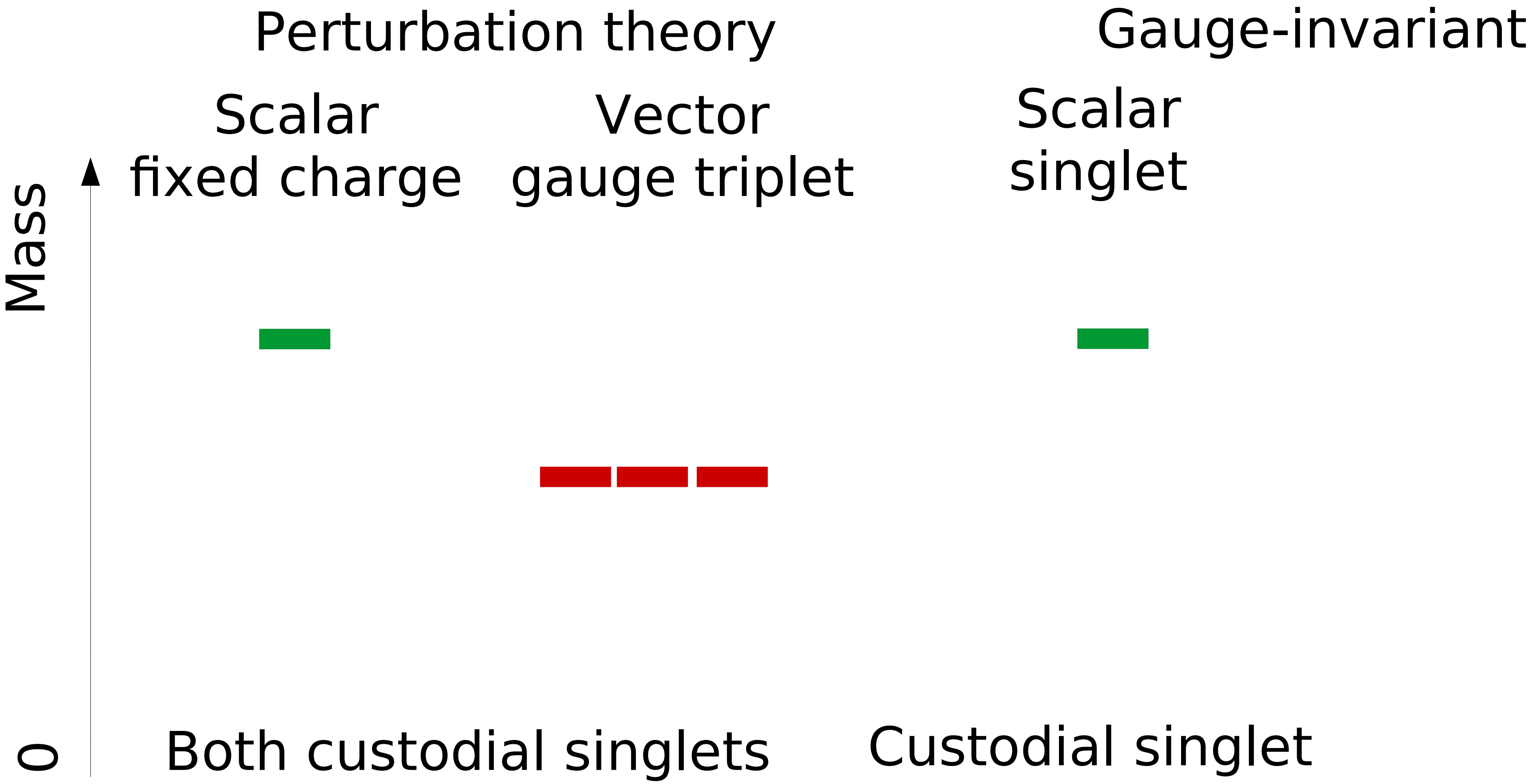

Perturbation theory

Scalar
fixed charge

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Physical spectrum

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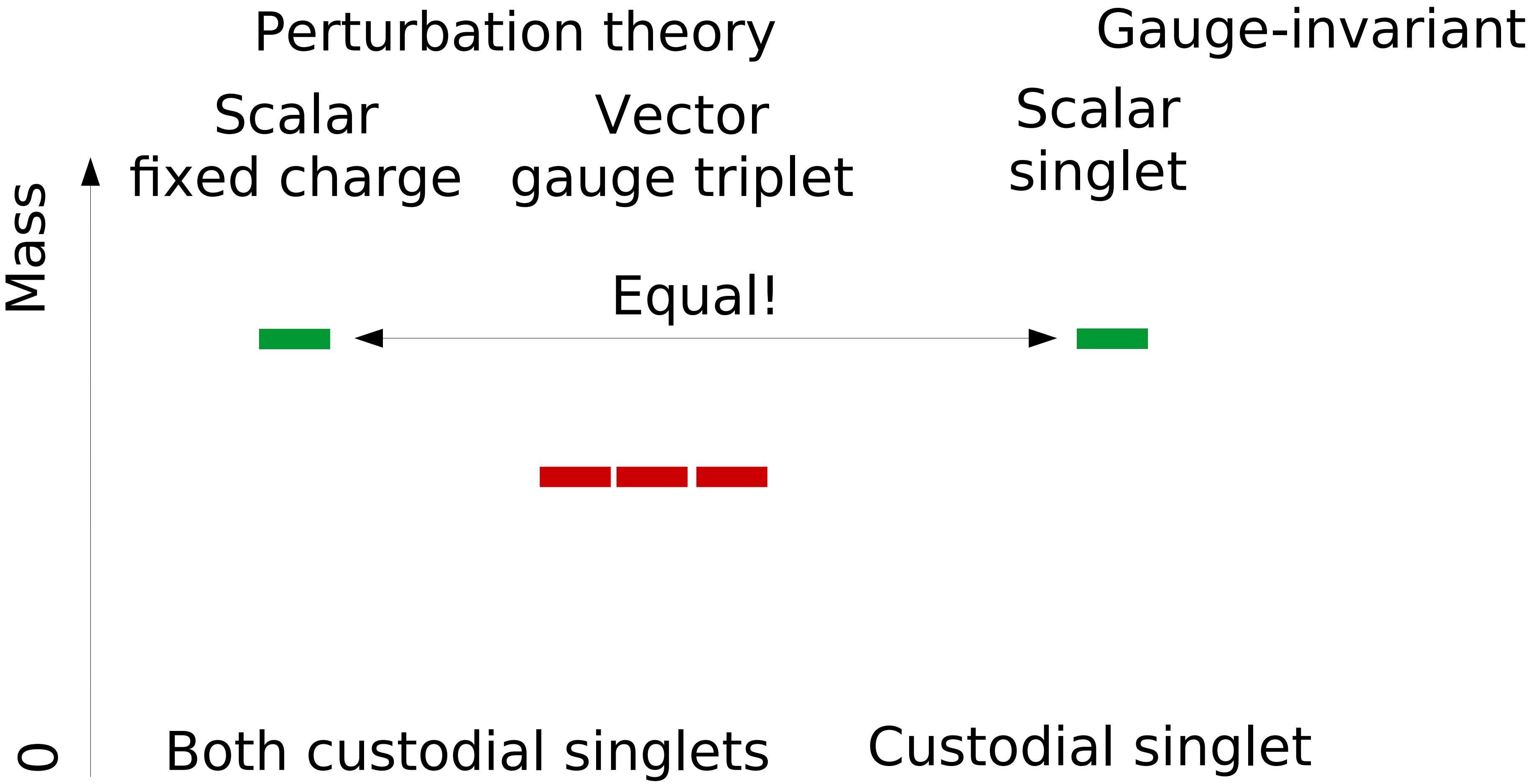


Perturbation theory

Gauge-invariant

Scalar
fixed charge

Vector
gauge triplet

Scalar
singlet

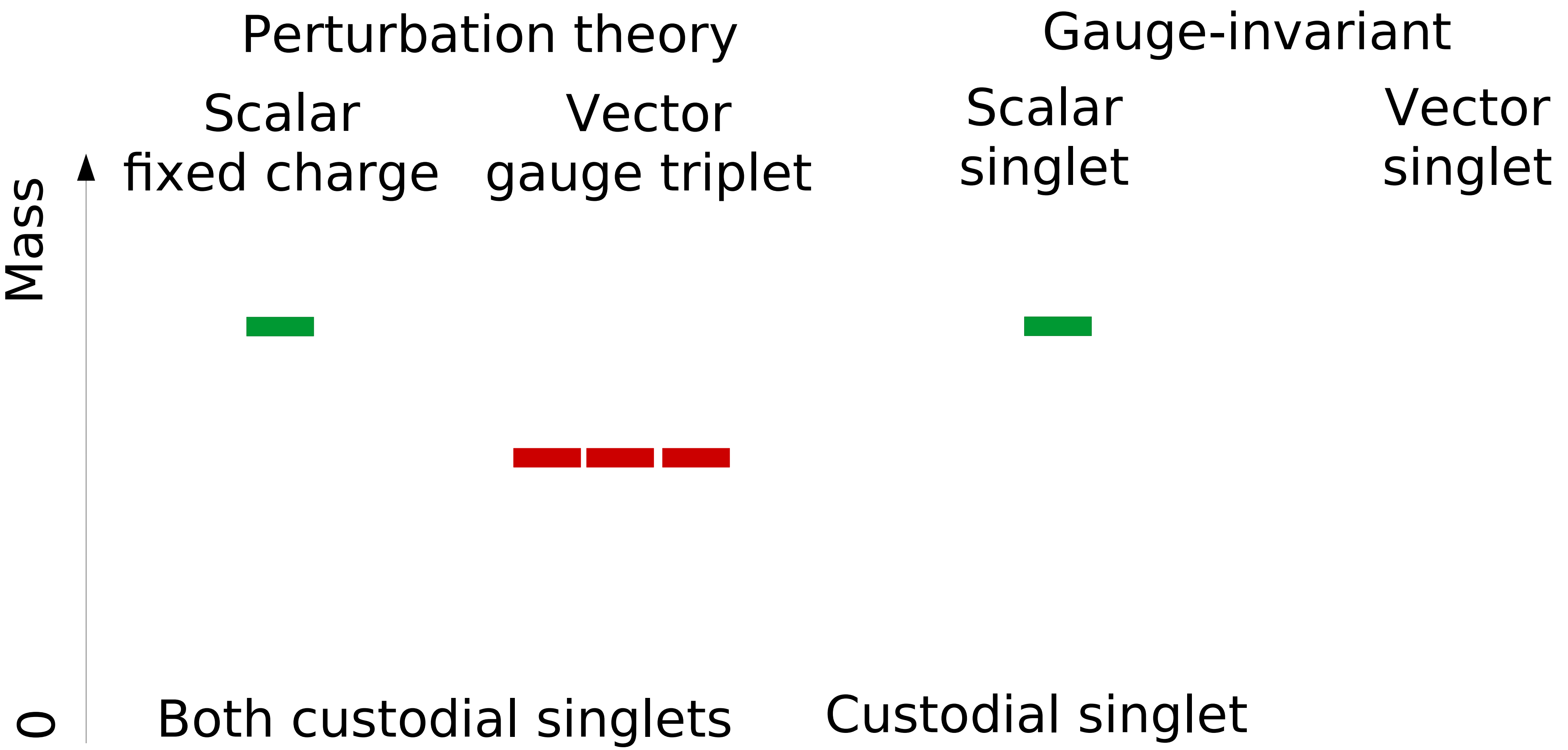
Equal!

Both custodial singlets

Custodial singlet

Physical spectrum

[Maas'12, Maas & Mufti'14]



Perturbation theory

Scalar
fixed charge

Vector
gauge triplet

Both custodial singlets

Gauge-invariant

Scalar
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Vector
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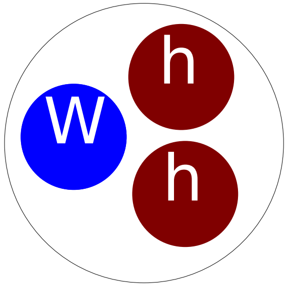
Custodial singlet

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



Physical spectrum

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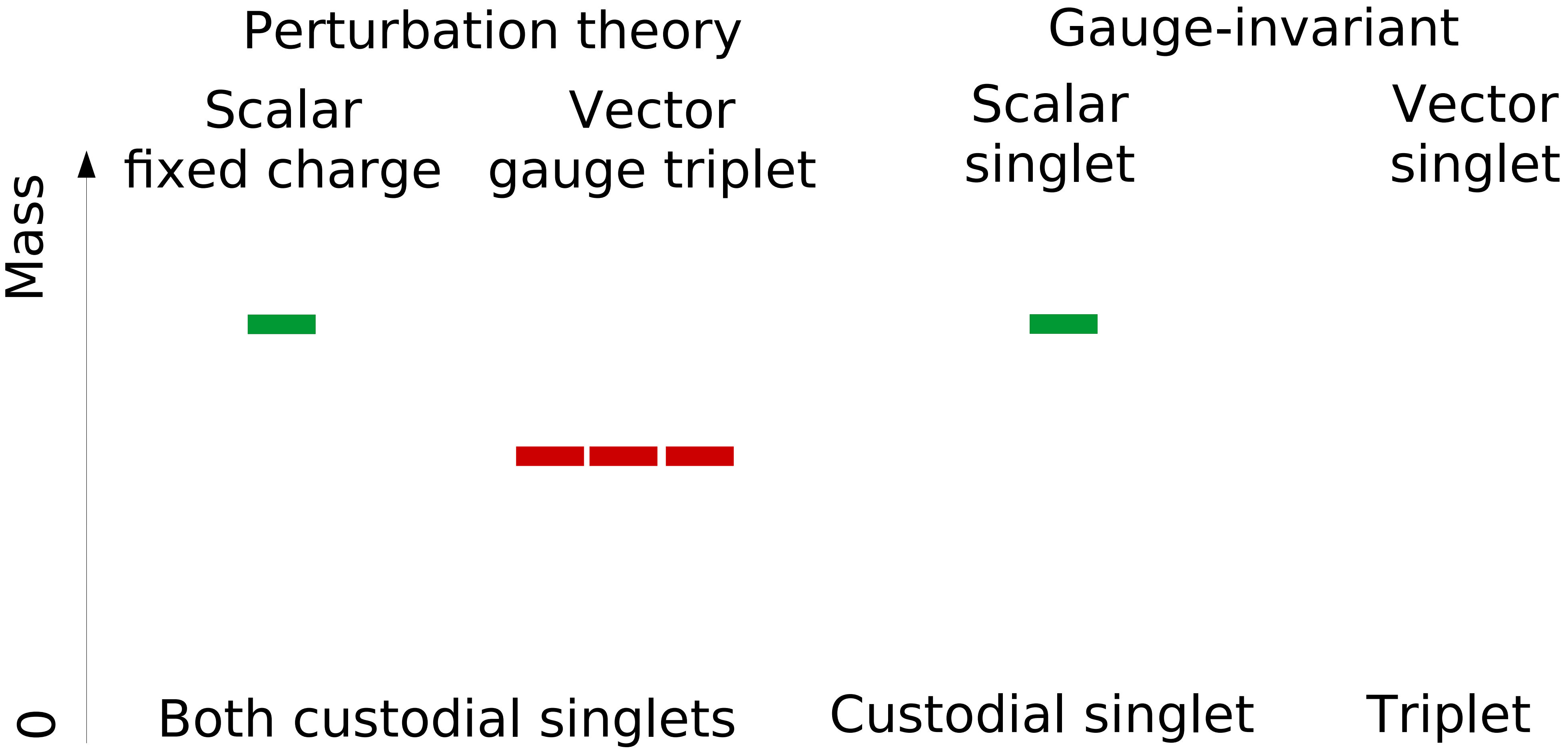

Perturbation theory

Scalar
fixed charge

Vector
gauge triplet

Gauge-invariant

Scalar
singlet

Vector
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Both custodial singlets

Custodial singlet

Triplet

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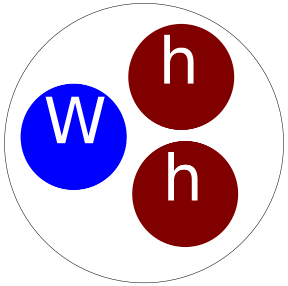

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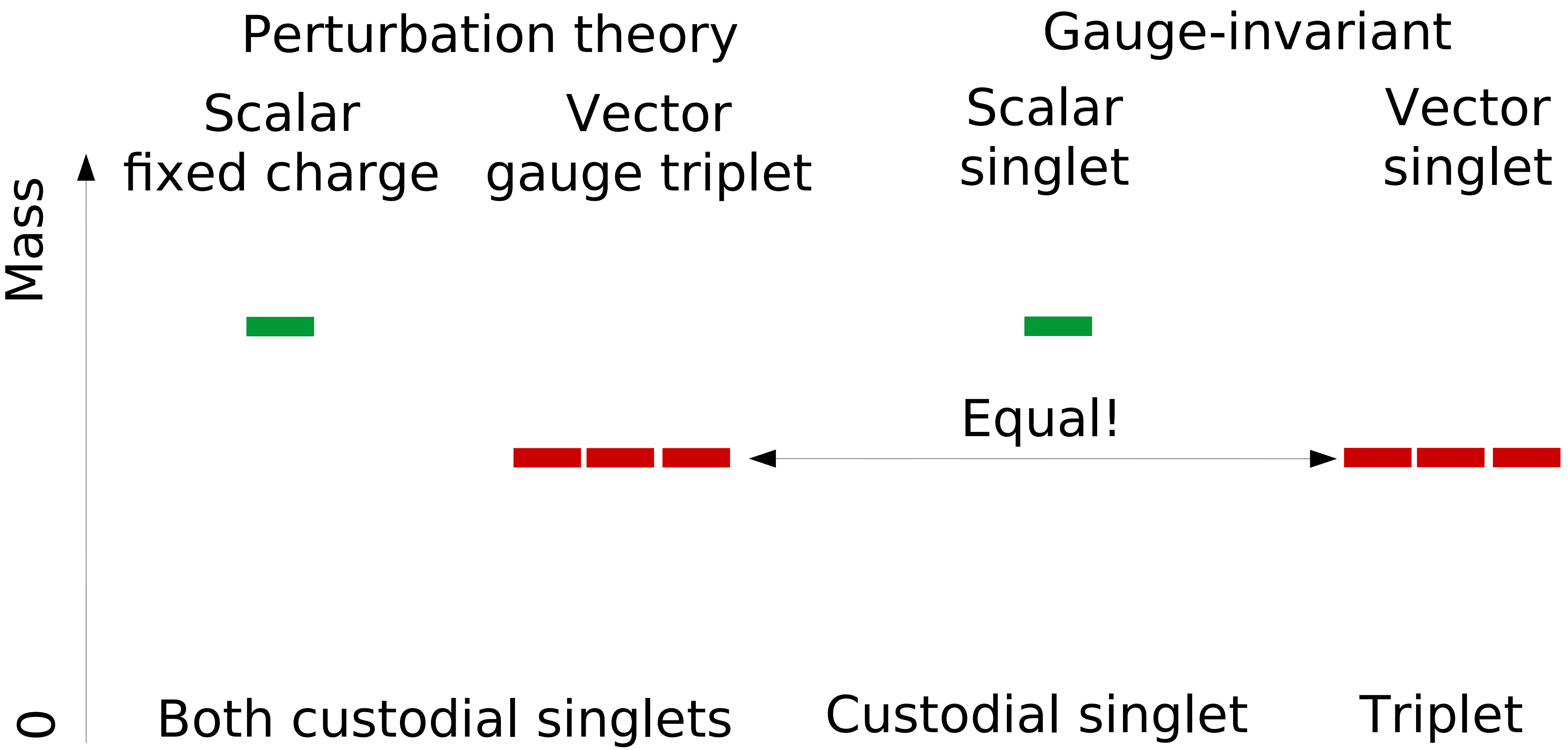

Perturbation theory

Scalar
fixed charge

Vector
gauge triplet

Gauge-invariant

Scalar
singlet

Vector
singlet

Mass

0

Equal!

Both custodial singlets

Custodial singlet

Triplet

A microscopic origin
-
Fröhlich-Morchio-Strocchi mechanism

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

[Fröhlich et al.’80,’81
Maas'12,’17]

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Higgs field

Augmented perturbation theory

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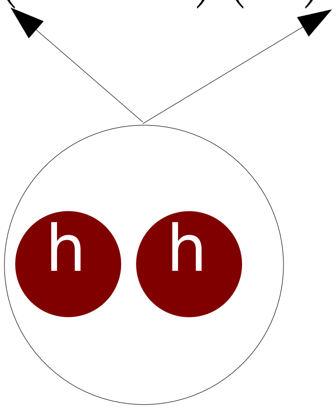

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Trivial two-particle state

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3) Standard perturbation theory

Bound state mass

Higgs mass

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Standard Perturbation Theory

Bound state mass

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What about this?

3) Standard perturbation theory

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Consequences: The Higgs

[Maas'12,’17
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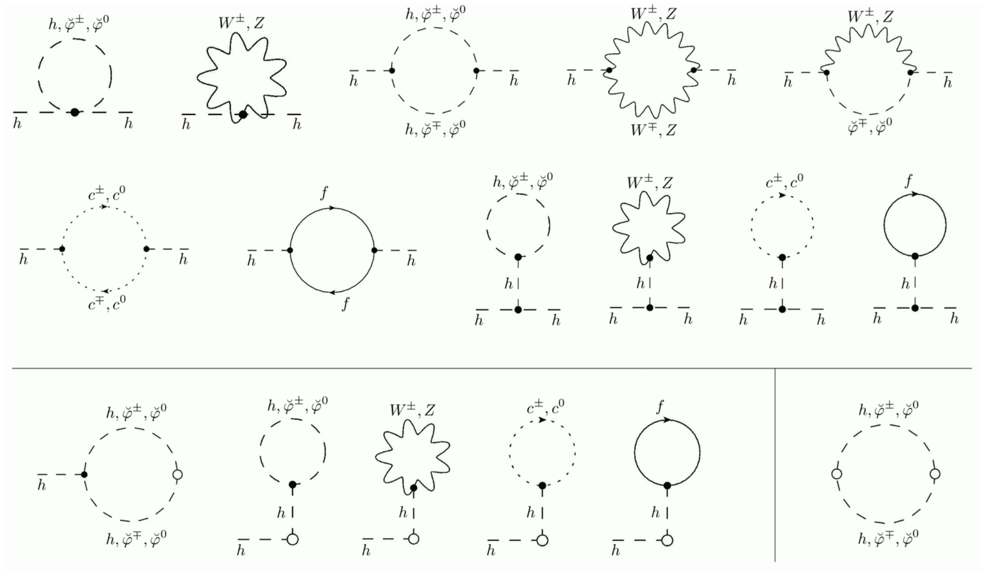

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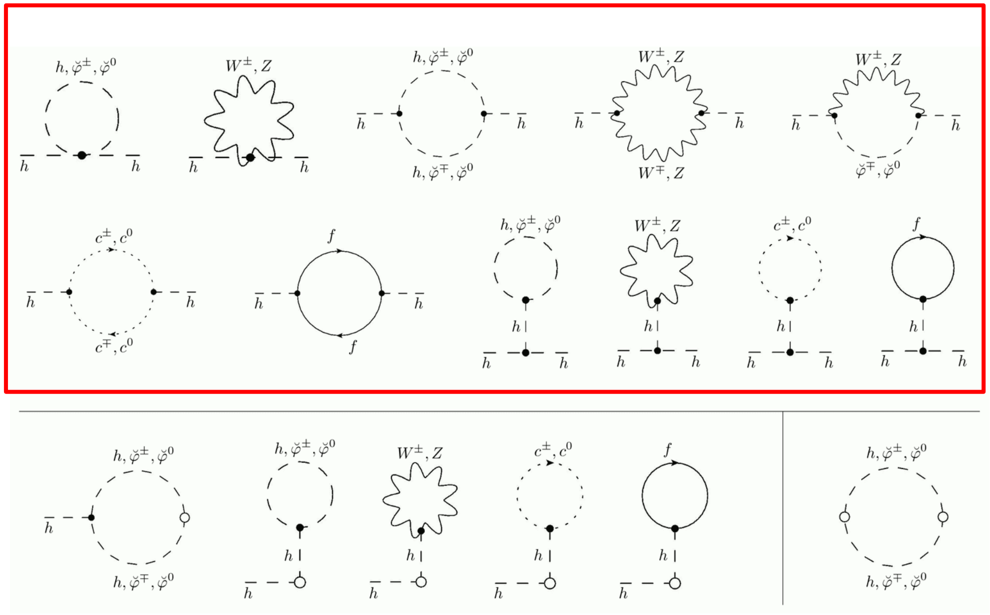

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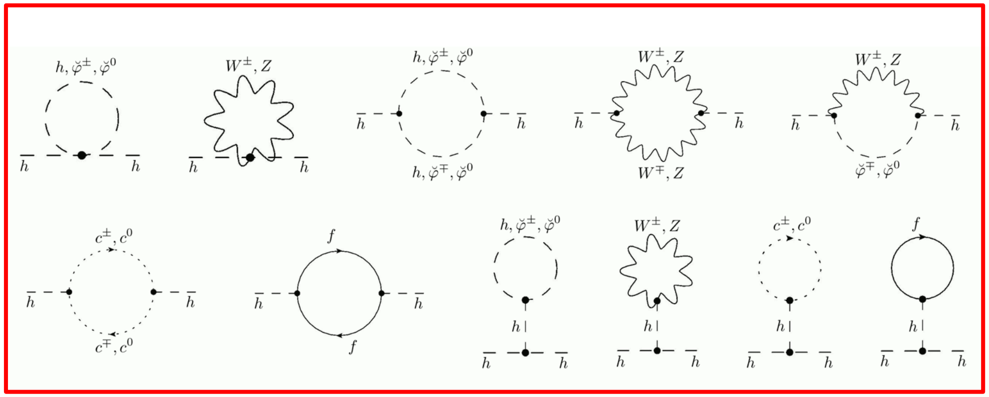

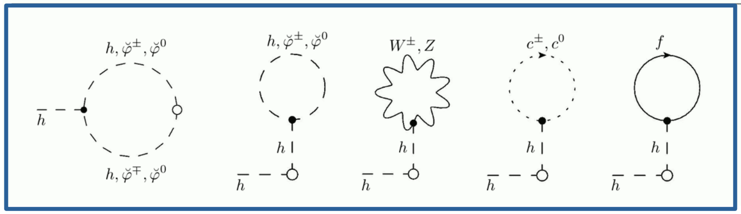

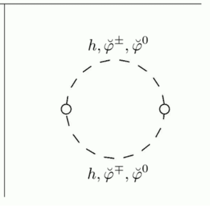

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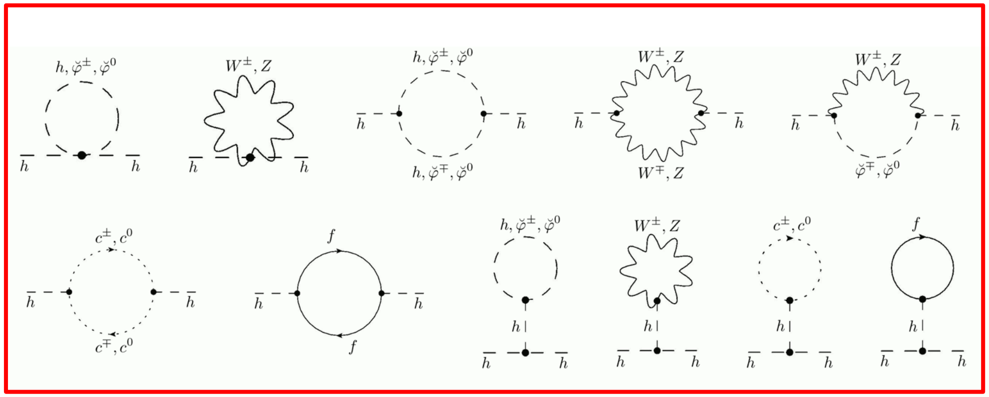

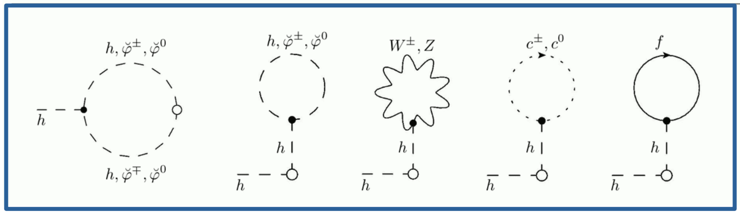

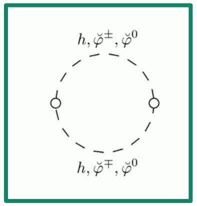

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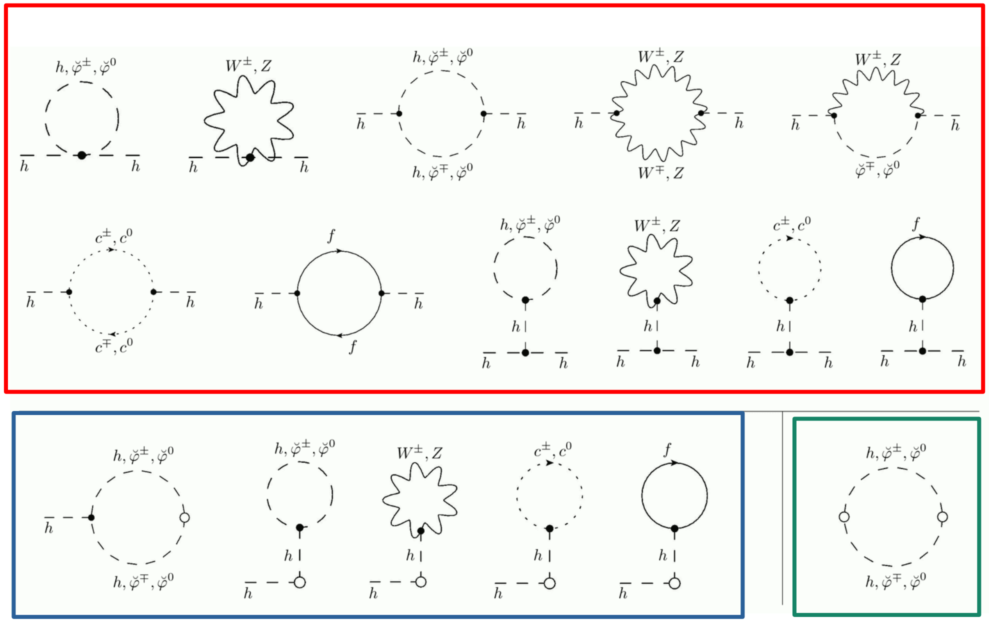

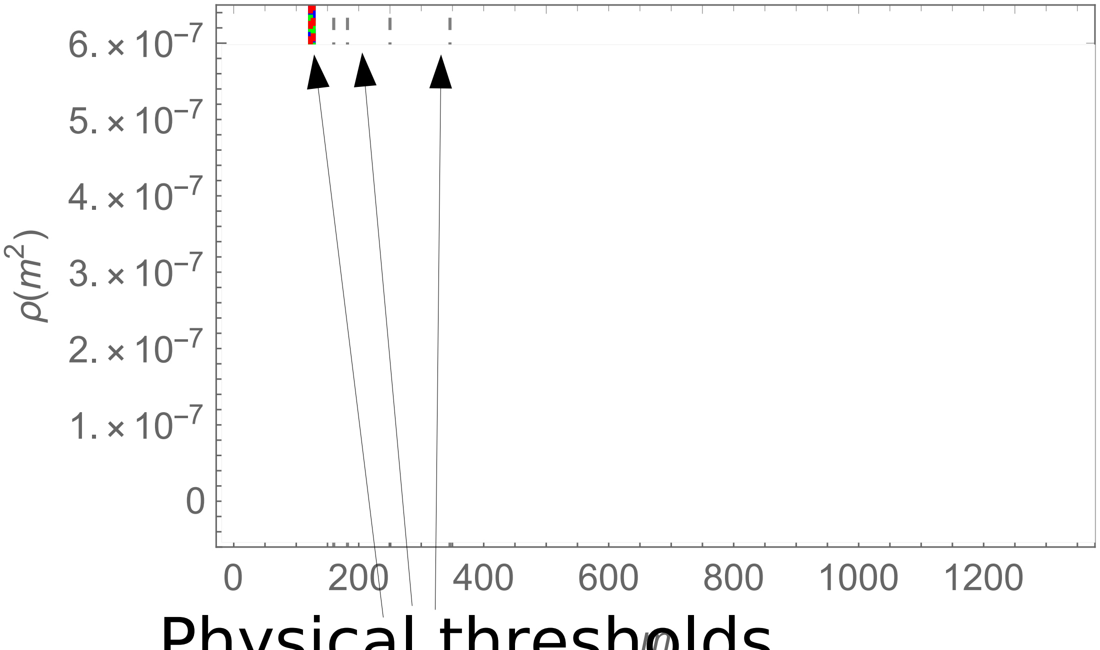

Physical thresholds

Consequences: The Higgs

[Maas'12,'17
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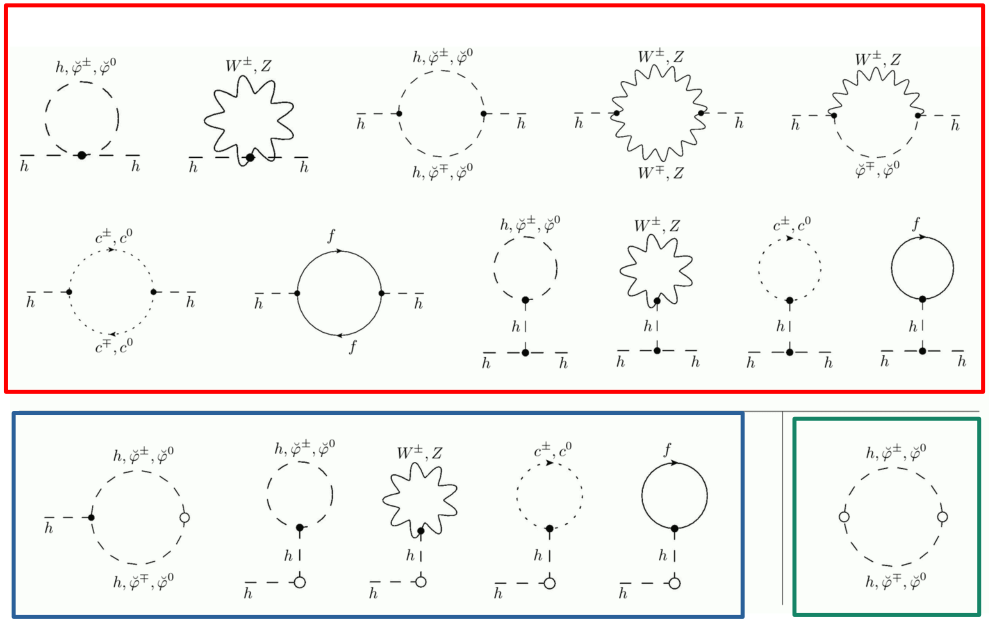

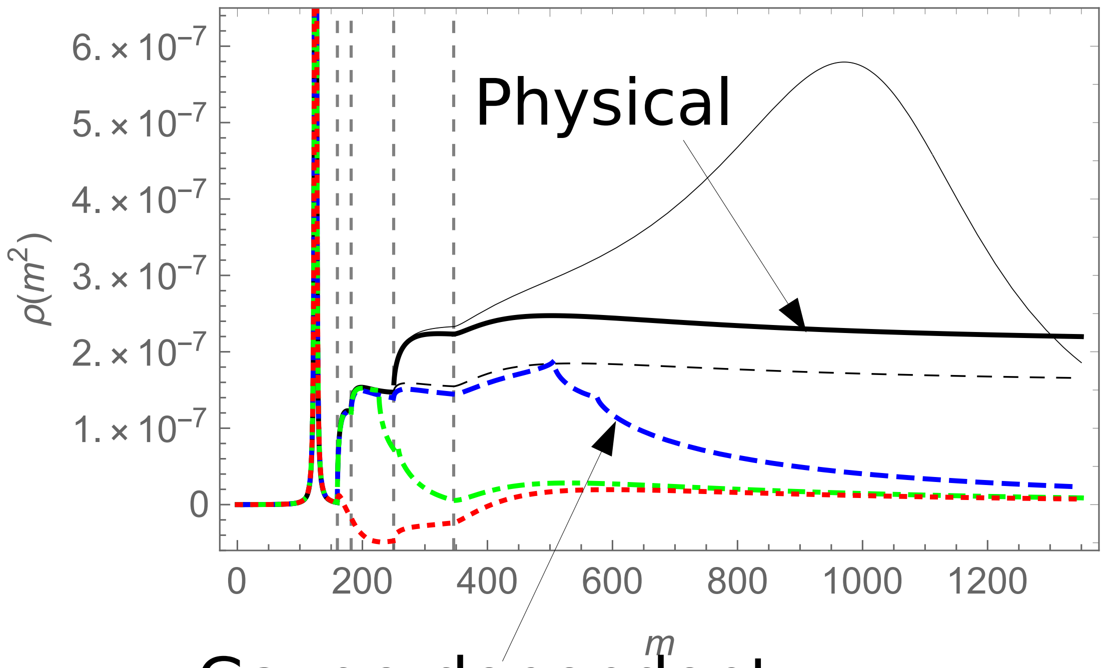

Physical

Gauge-dependent

Consequences: The Higgs

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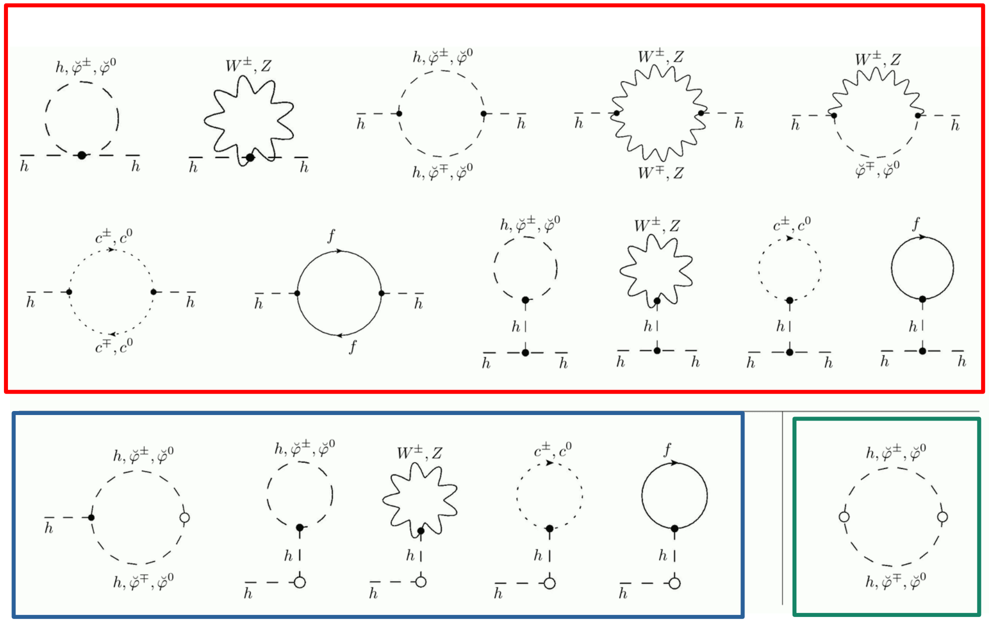

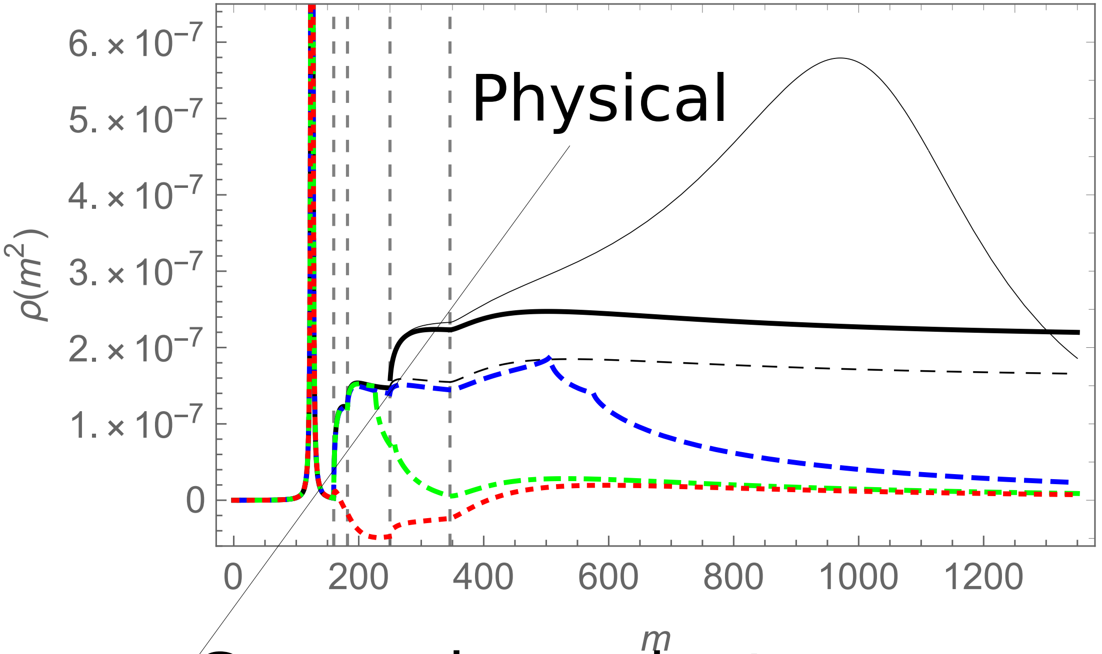

Physical

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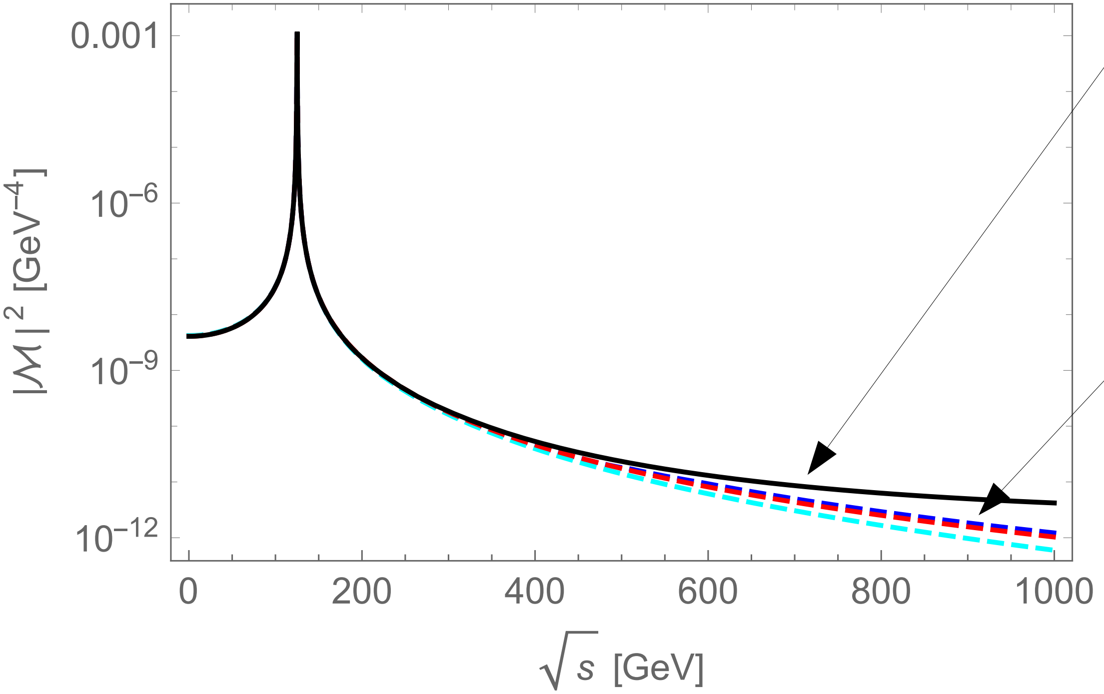

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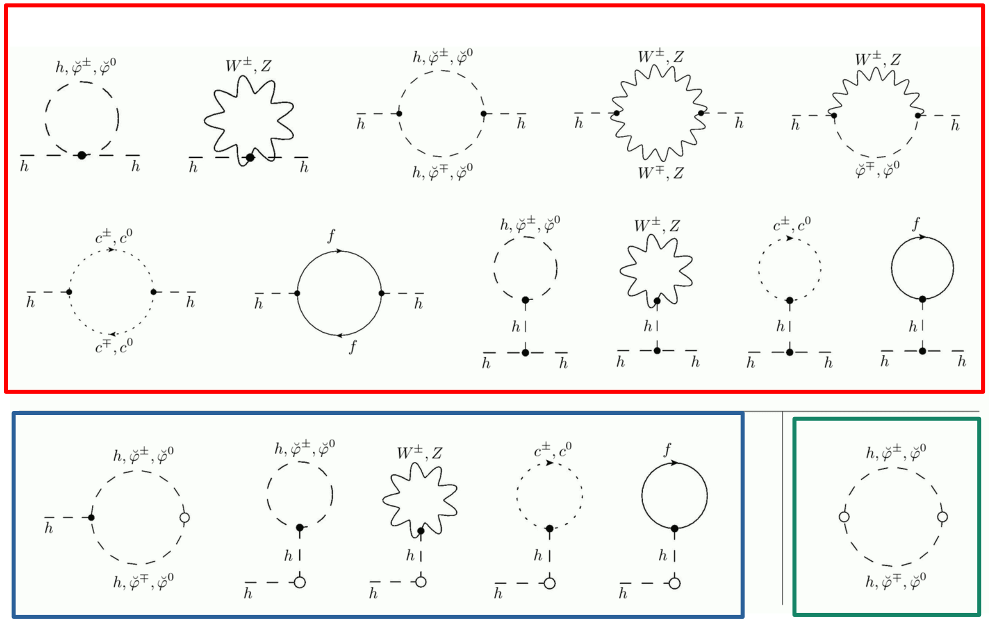

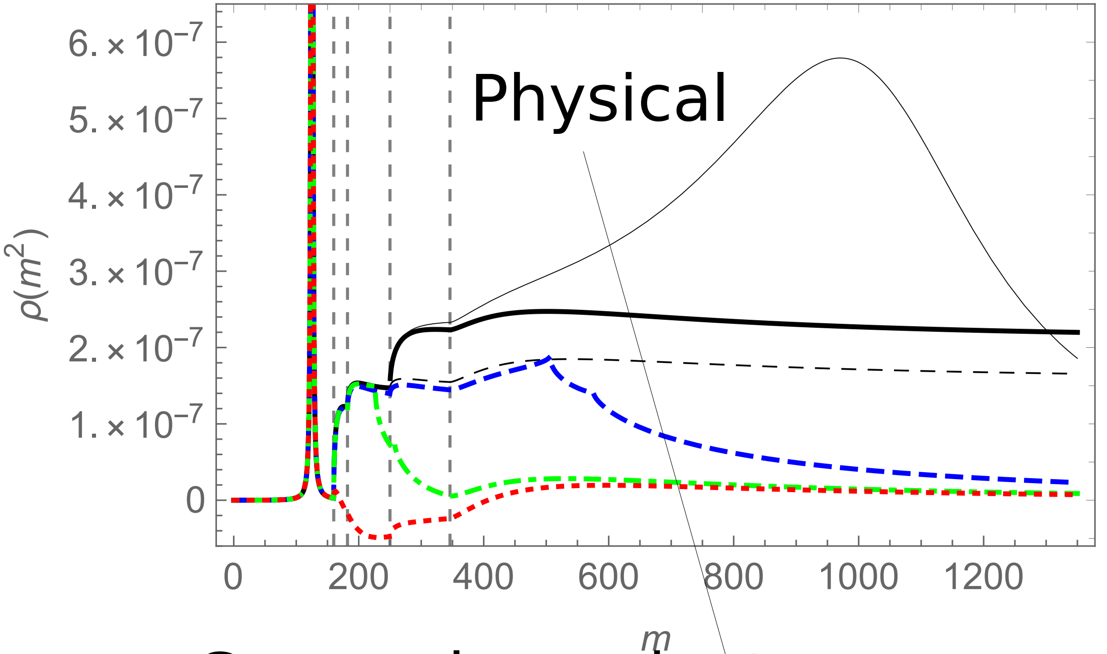

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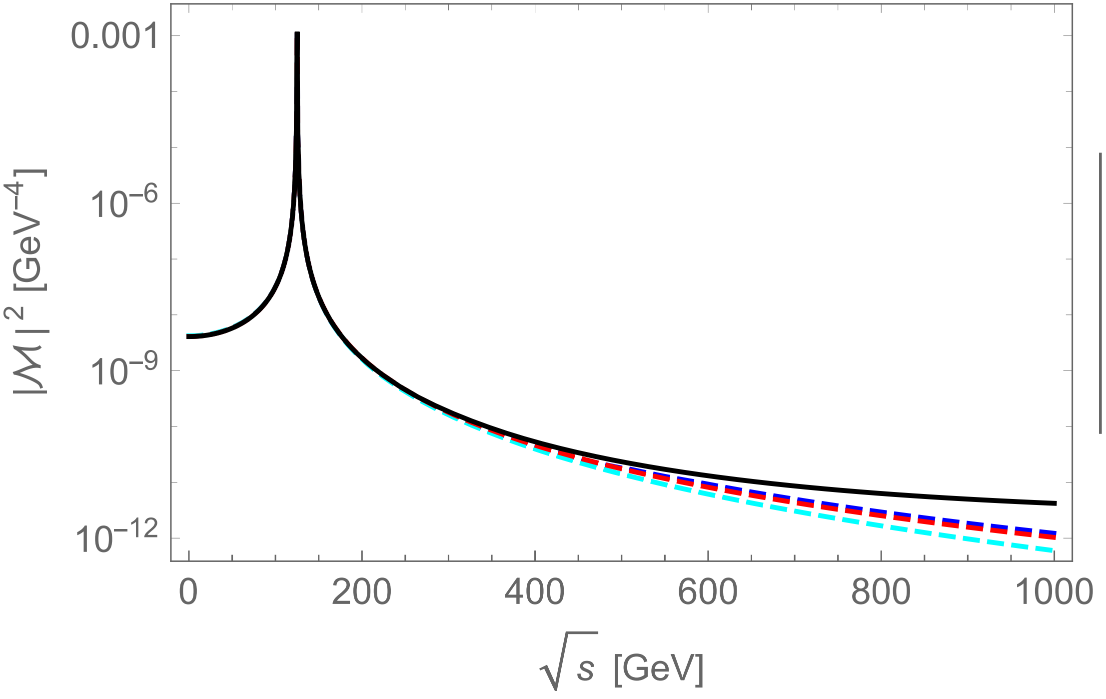
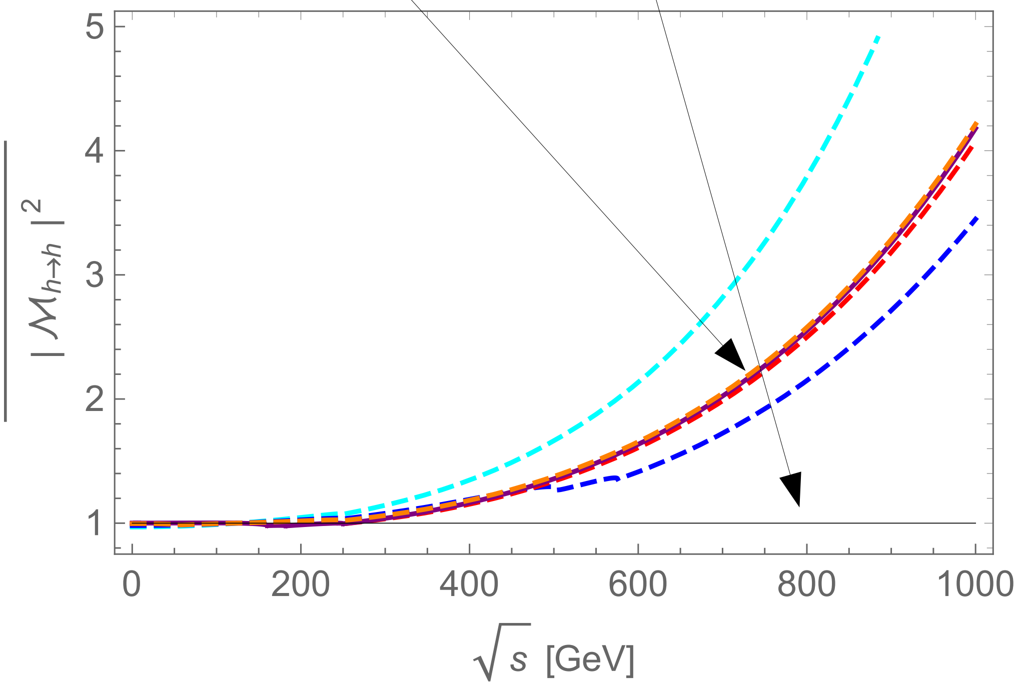
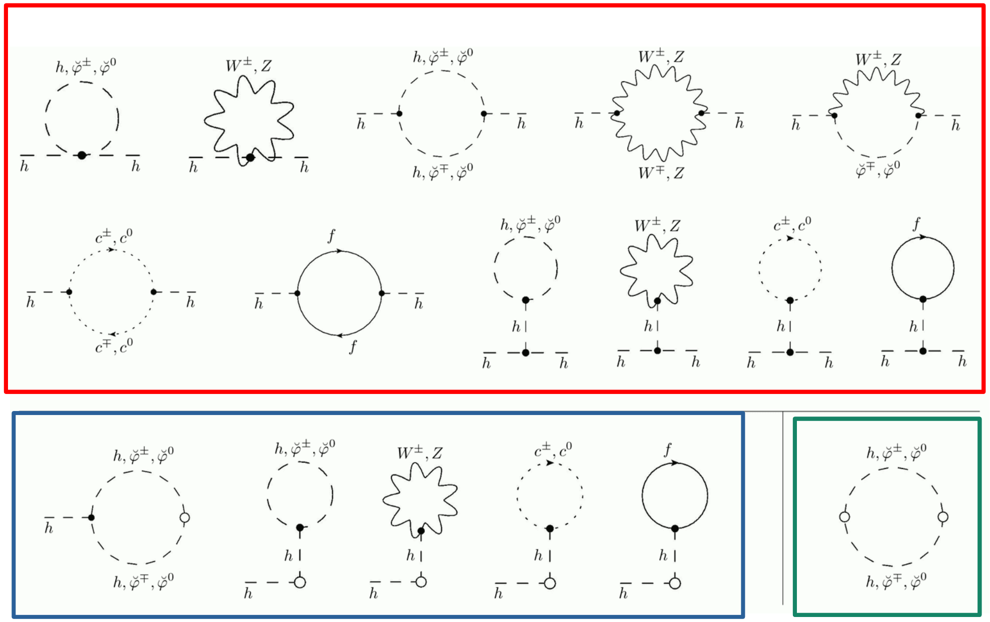


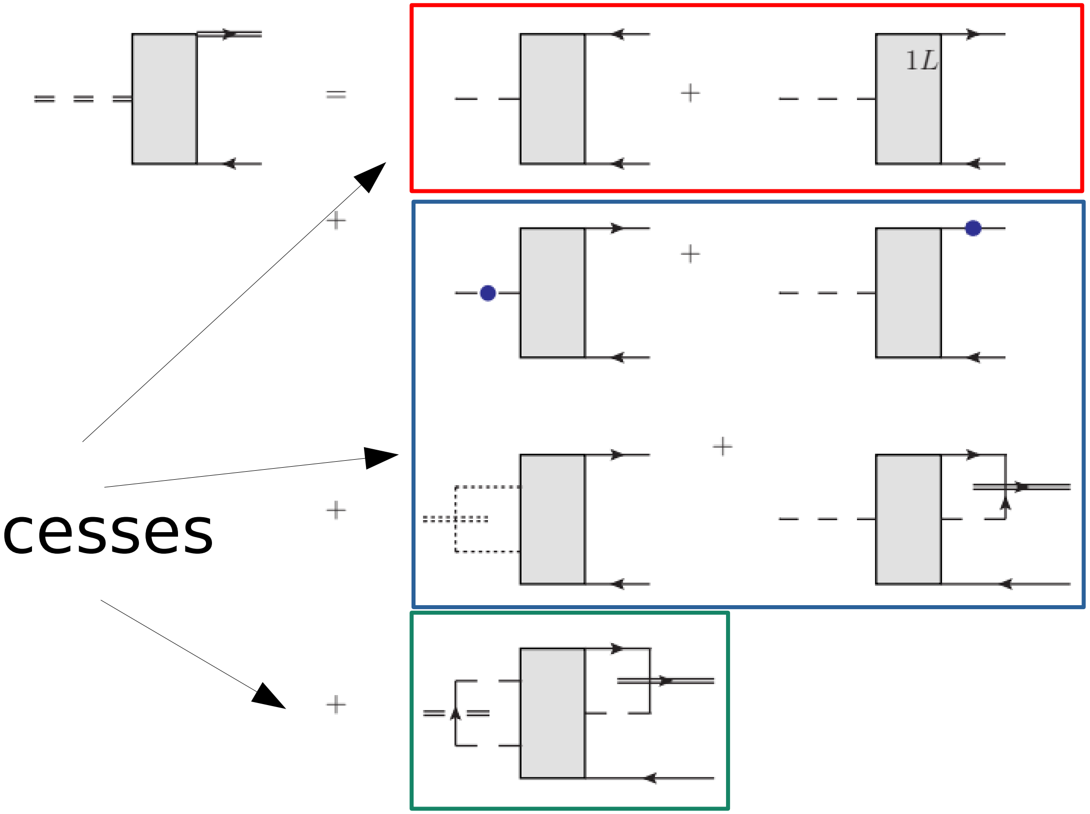


Consequences: The Higgs

[Maas'12,'17
Maas & Sondenheimer'20,
Maas et al. unpublished]



Same structure repeats itself
For decays and scattering processes



What about the vector?

[Fröhlich et al.’80,’81
Maas'12]

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1^- triplet: $\langle(\tau^i h^+ D_\mu h)(x)(\tau^j h^+ D_\mu h)(y)\rangle$

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c projects custodial states to gauge states

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Matrix from group structure

c projects custodial states to gauge states

Exactly one gauge boson for every physical state

Phenomenological Implications

-

Can we measure this?

Bound states as extended objects

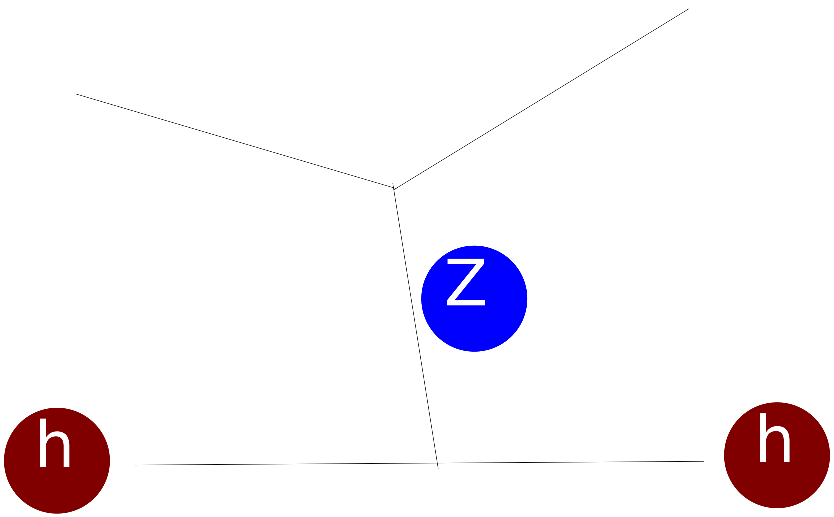
Bound states as extended objects

- Two possibilities to measure extension

Bound states as extended objects

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

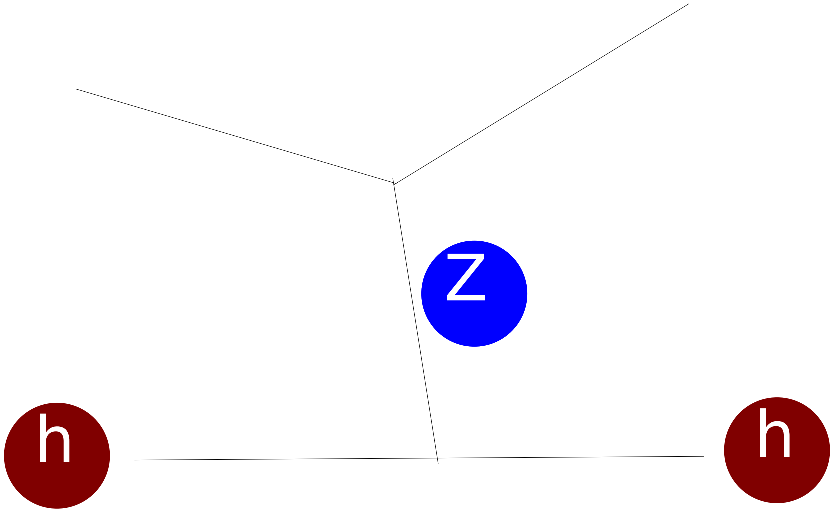
[Maas, Raubitzek, Törek'18]

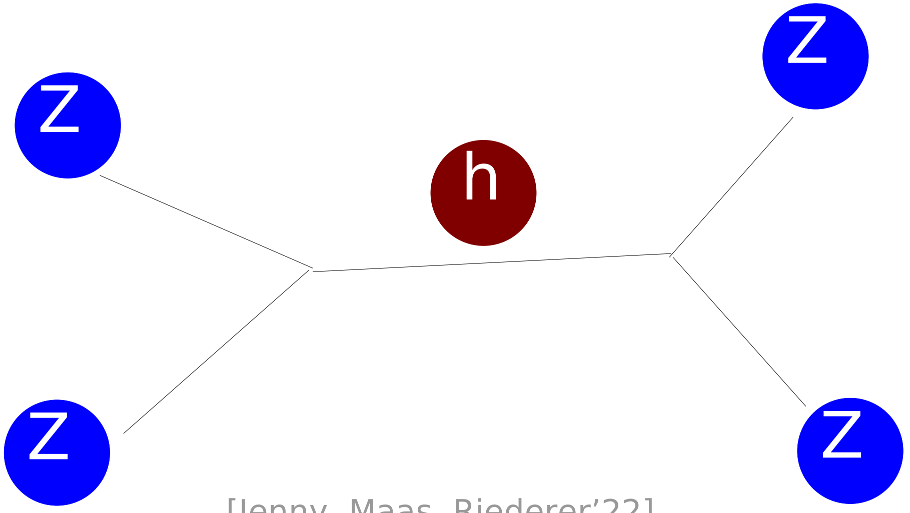


Bound states as extended objects

- Two possibilities to measure extension
  - 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: $160/180\,GeV \leqslant \sqrt{s} \leqslant 250\,GeV$
  - *s* is the CMS energy in the initial/final ZZ/WW system

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Cross section

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Matrix element

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Matrix element

$$M(s,\Omega) = 16\pi \sum_J (2J+1) f_J(s) P_J(\cos\theta)$$

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Legendre polynom

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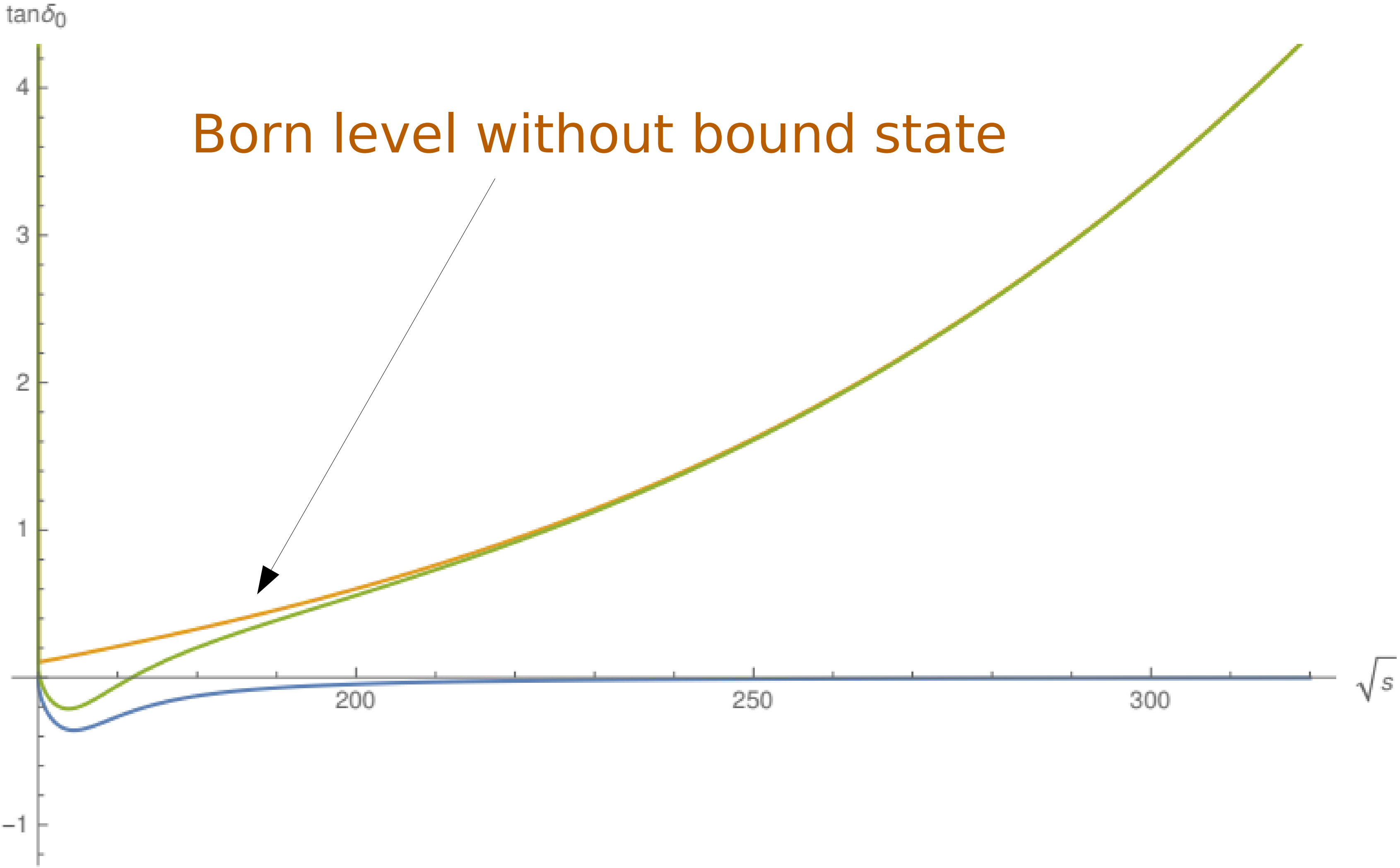
Scattering length~"size"

Phase shift

Impact of a finite size of the Higgs

- Consider the Higgs: $J=0$

Impact of a finite size of the Higgs



Born level without bound state

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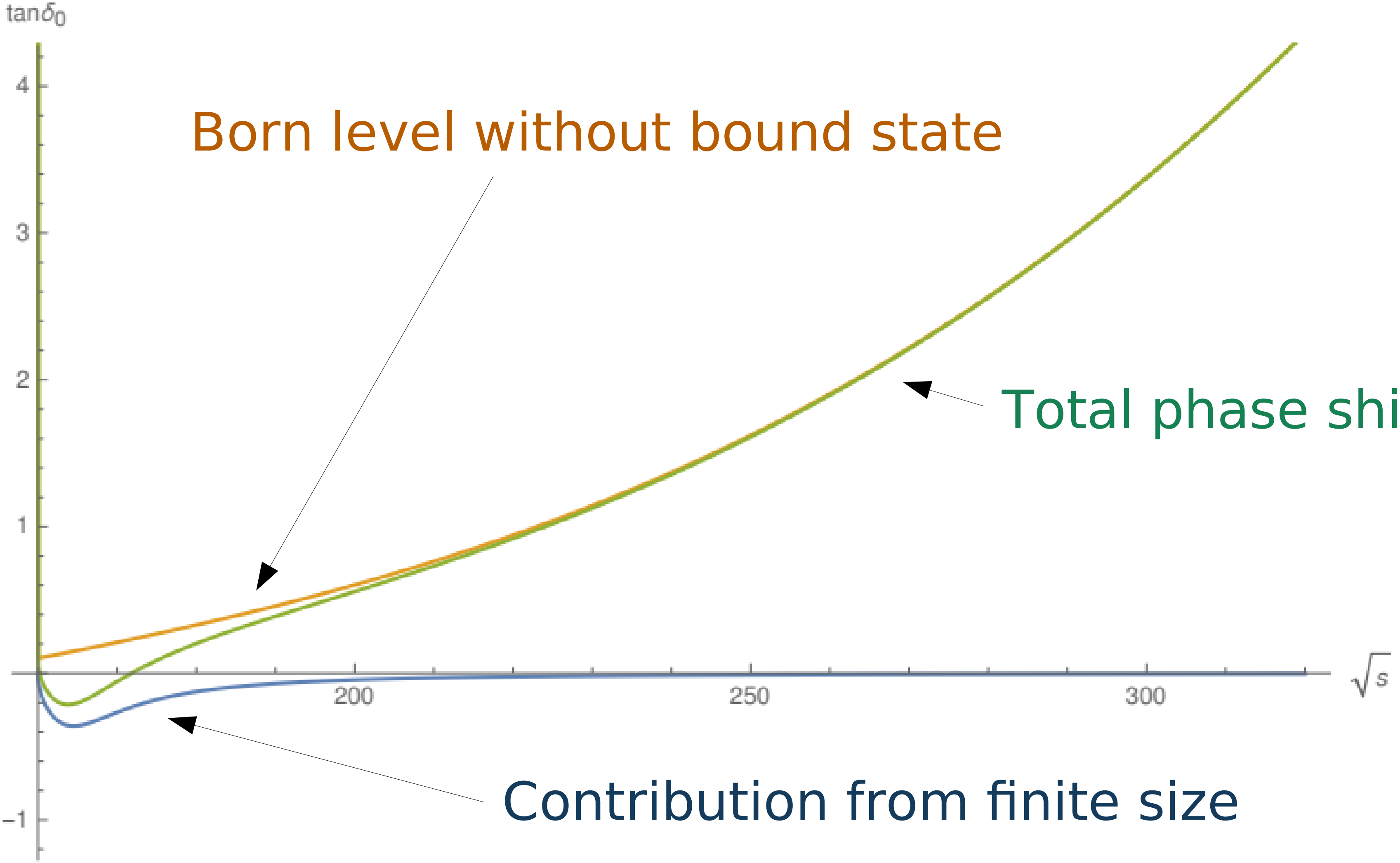


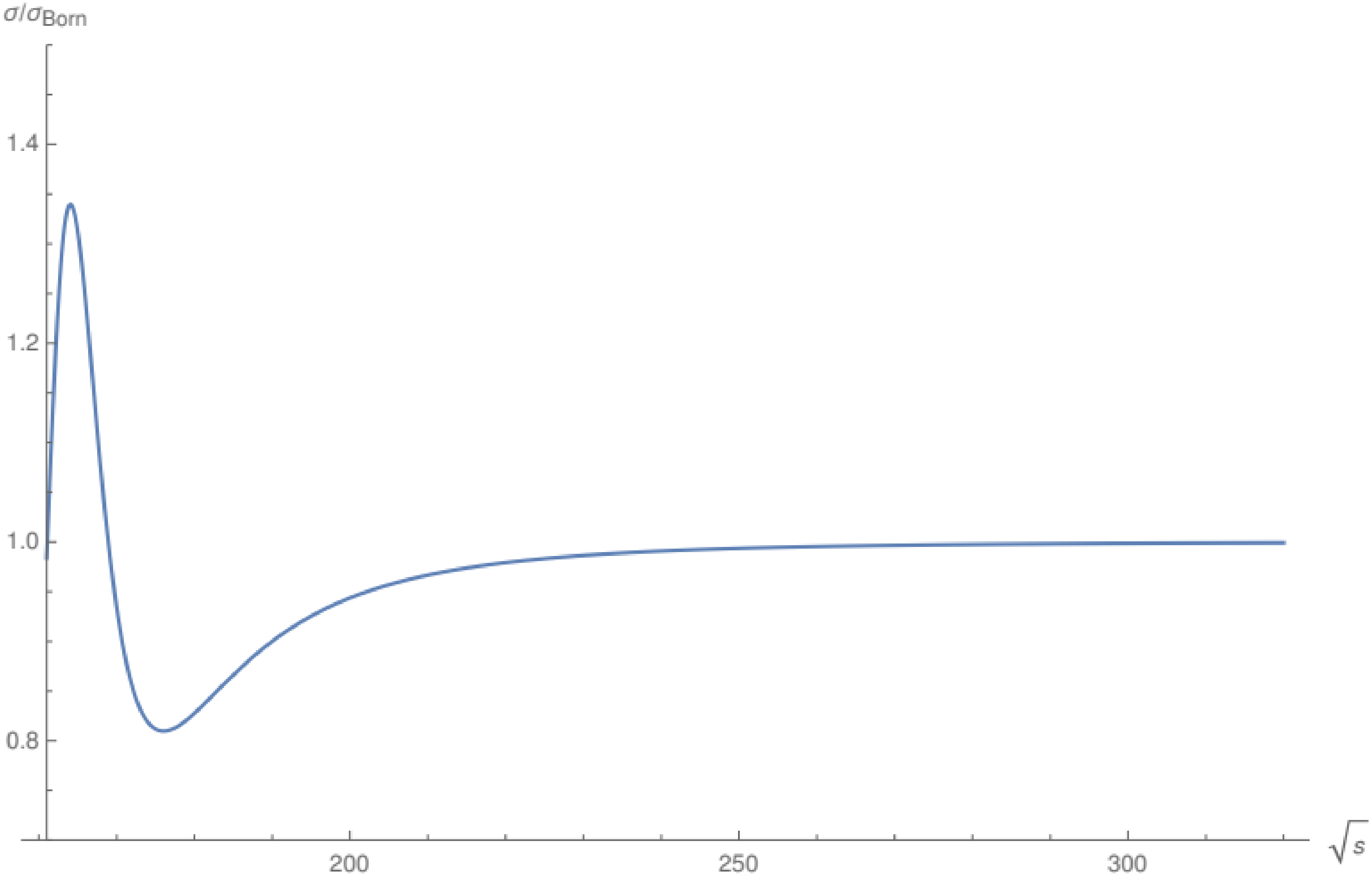
Born level without bound state

Total phase shift

Contribution from finite size

- Consider the Higgs: *J=0*
- Mock-up effect
  - Scattering length 1/(40 GeV)

Impact of a finite size of the Higgs



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Impact on the radius of the Higgs

- Reduced SM: Only W/Z and the Higgs
  - Parameters slightly different
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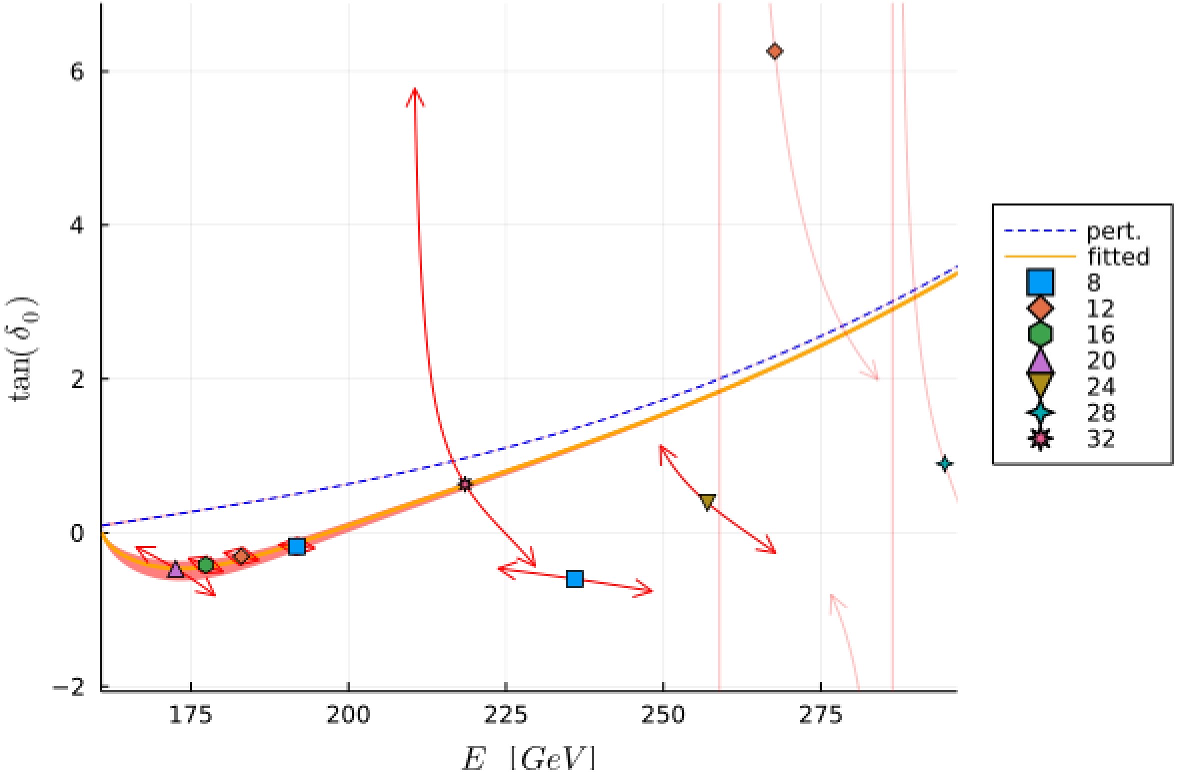

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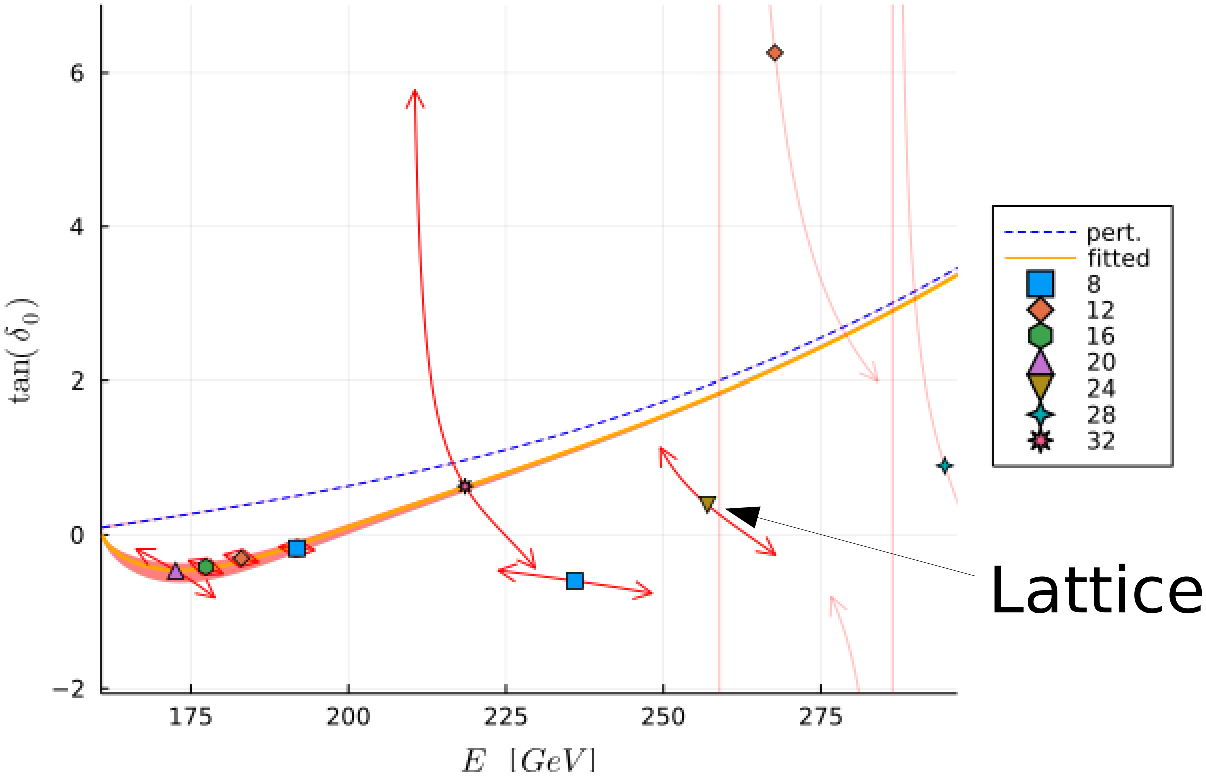

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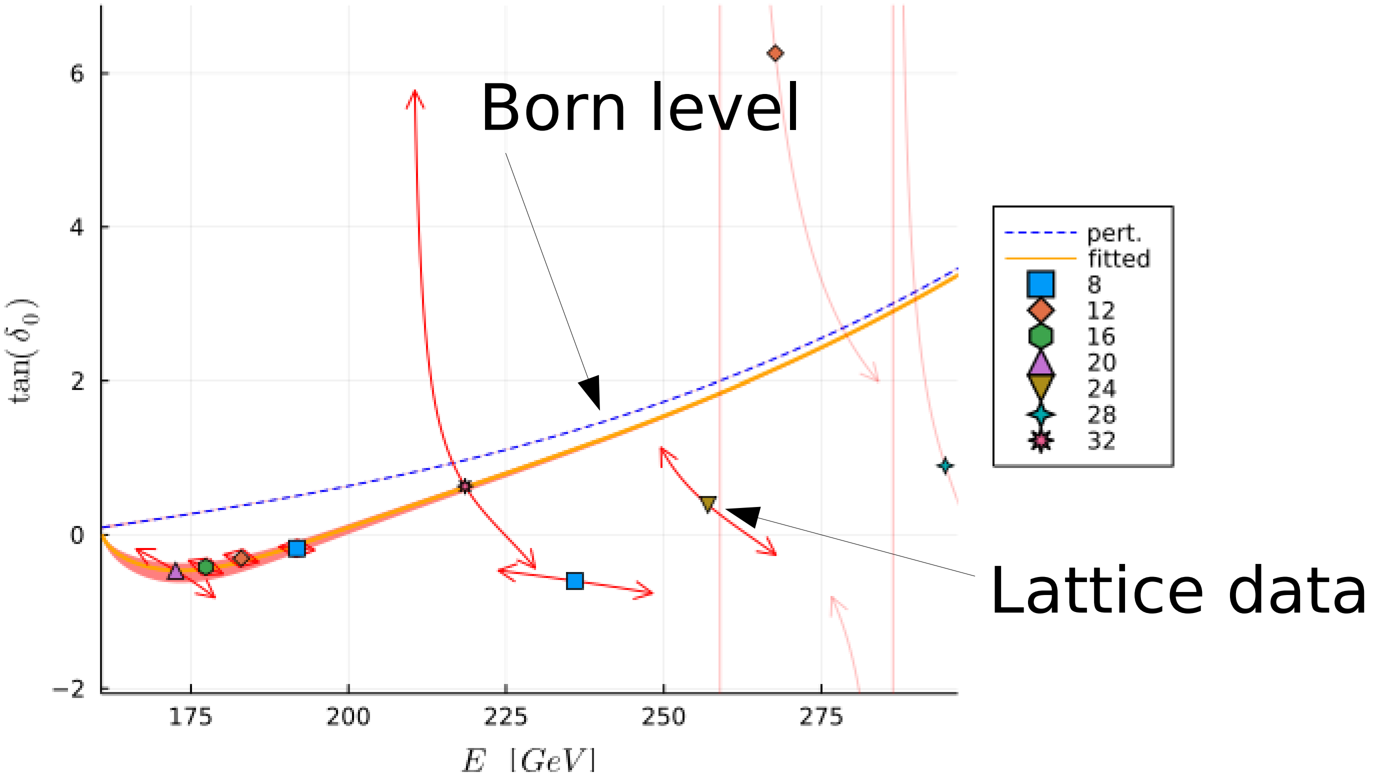

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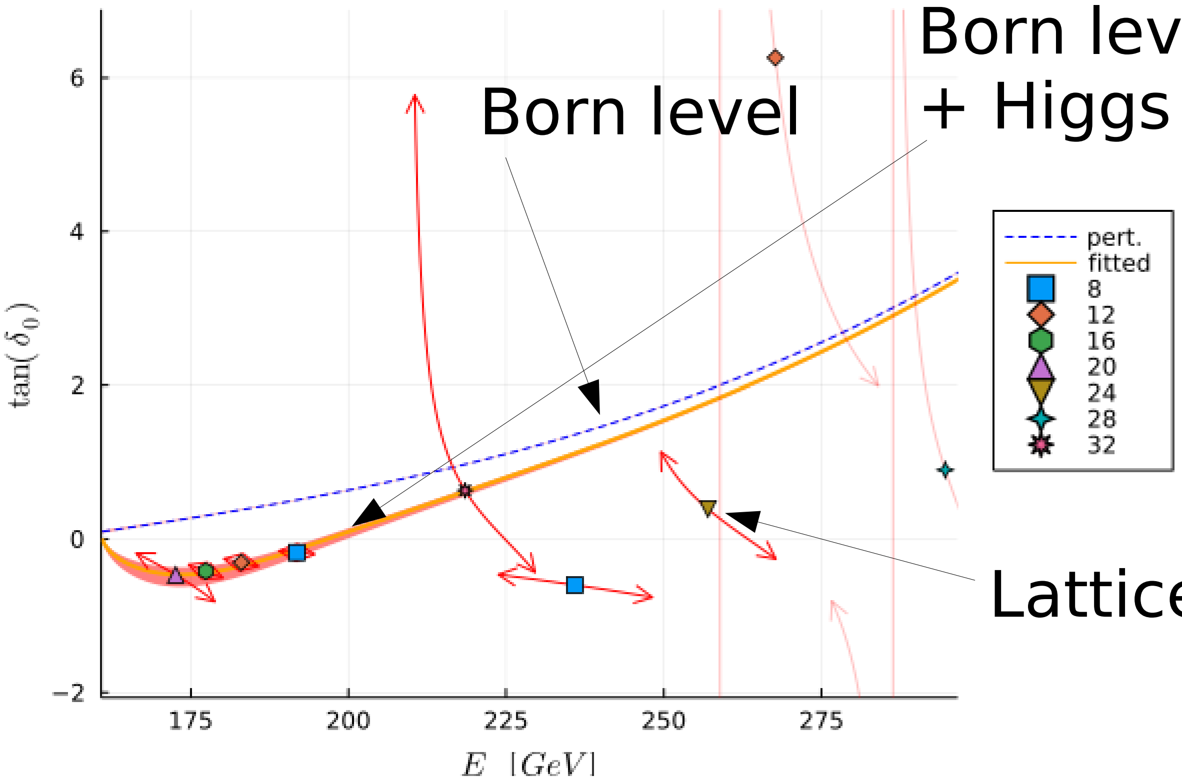

Born level

Born level FMS
+ Higgs size of (40 Gev)$^{-1}$

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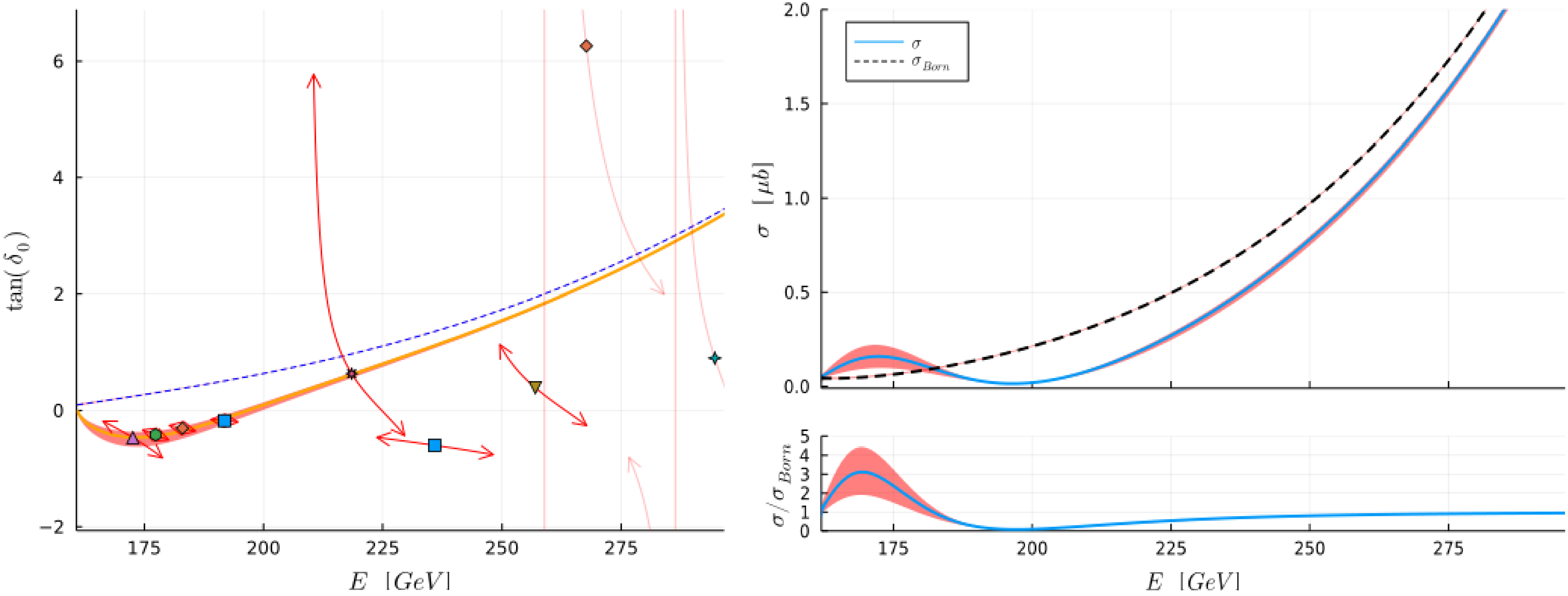

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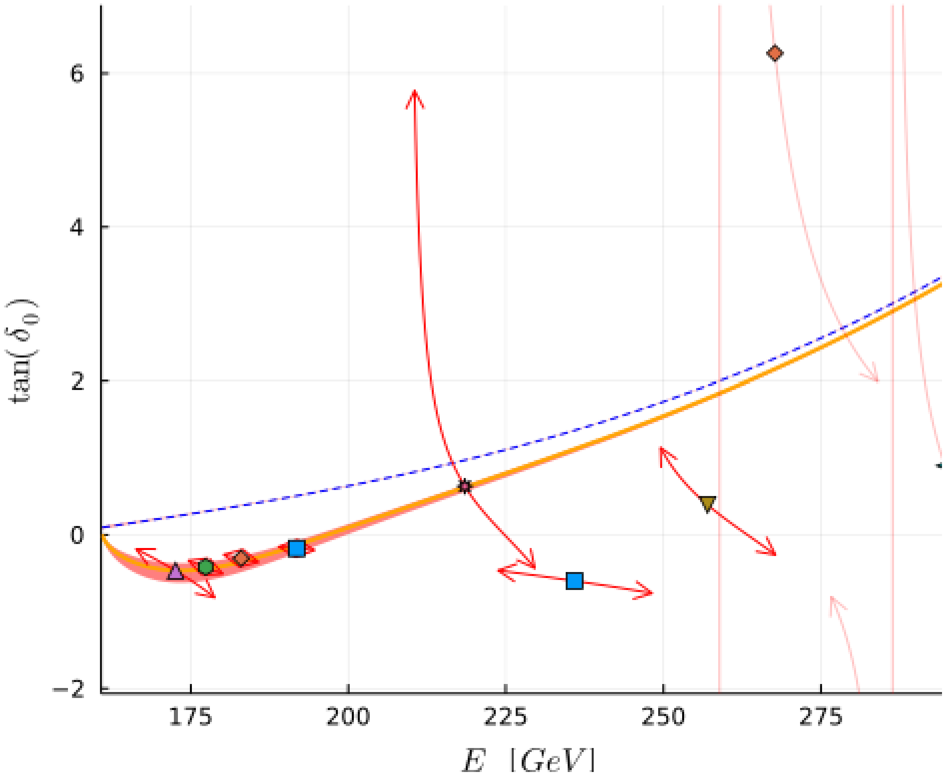
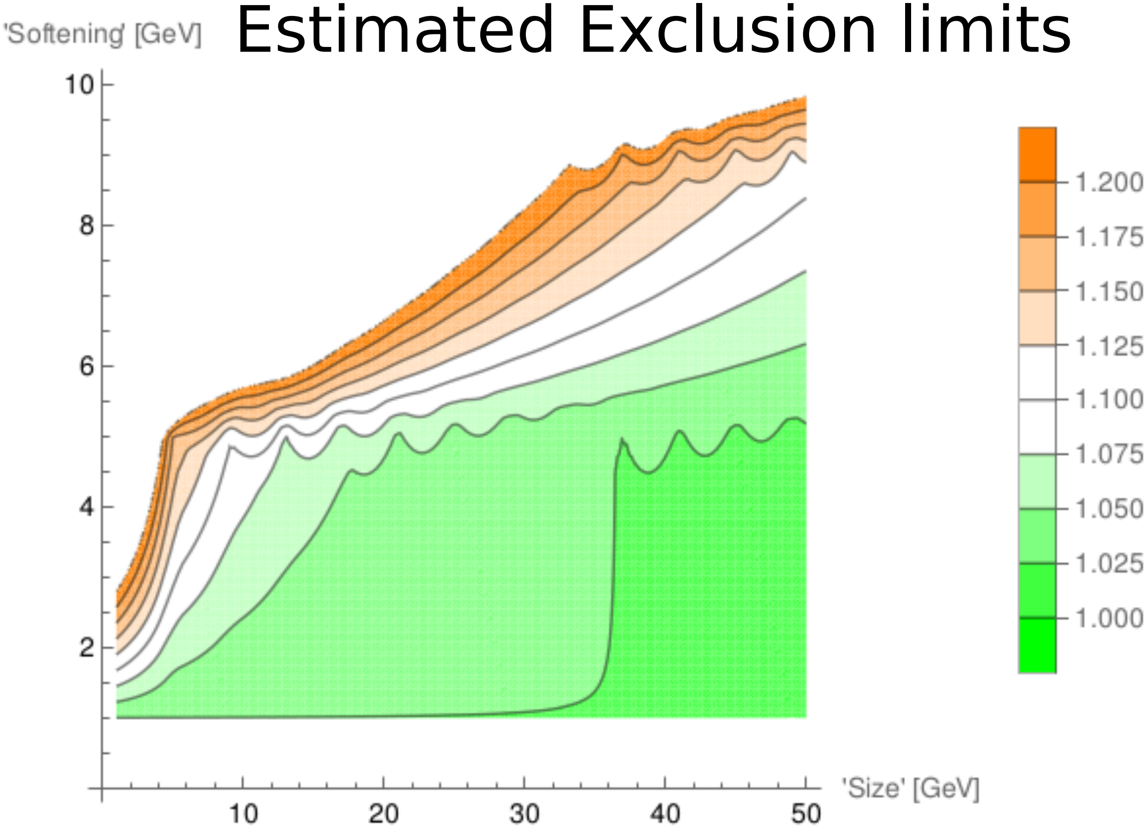


Estimated Exclusion limits



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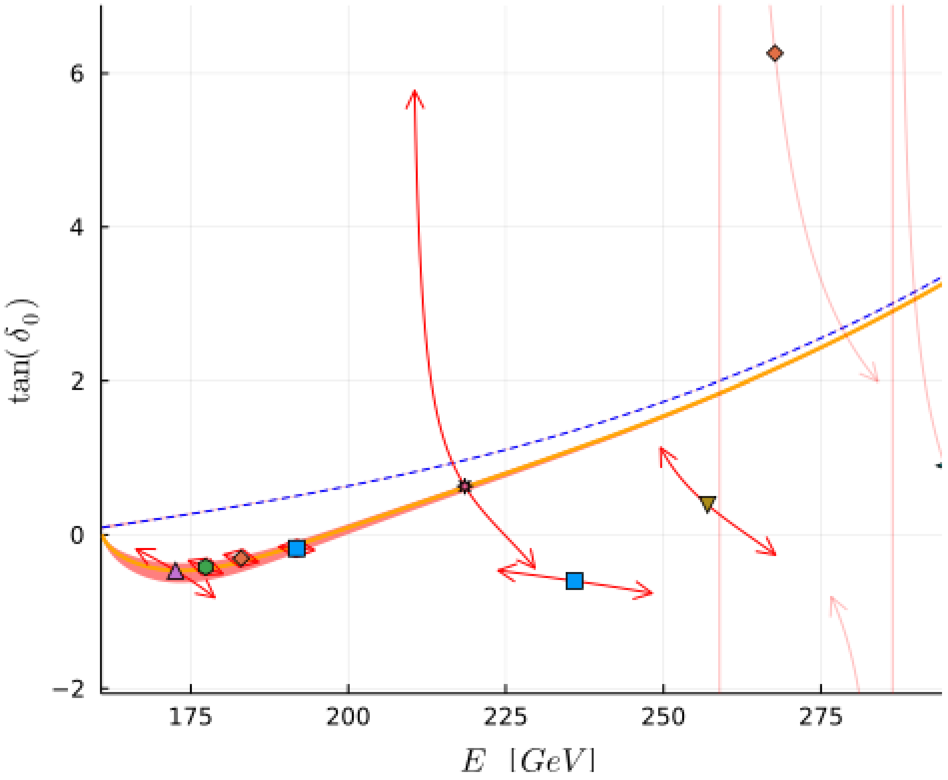

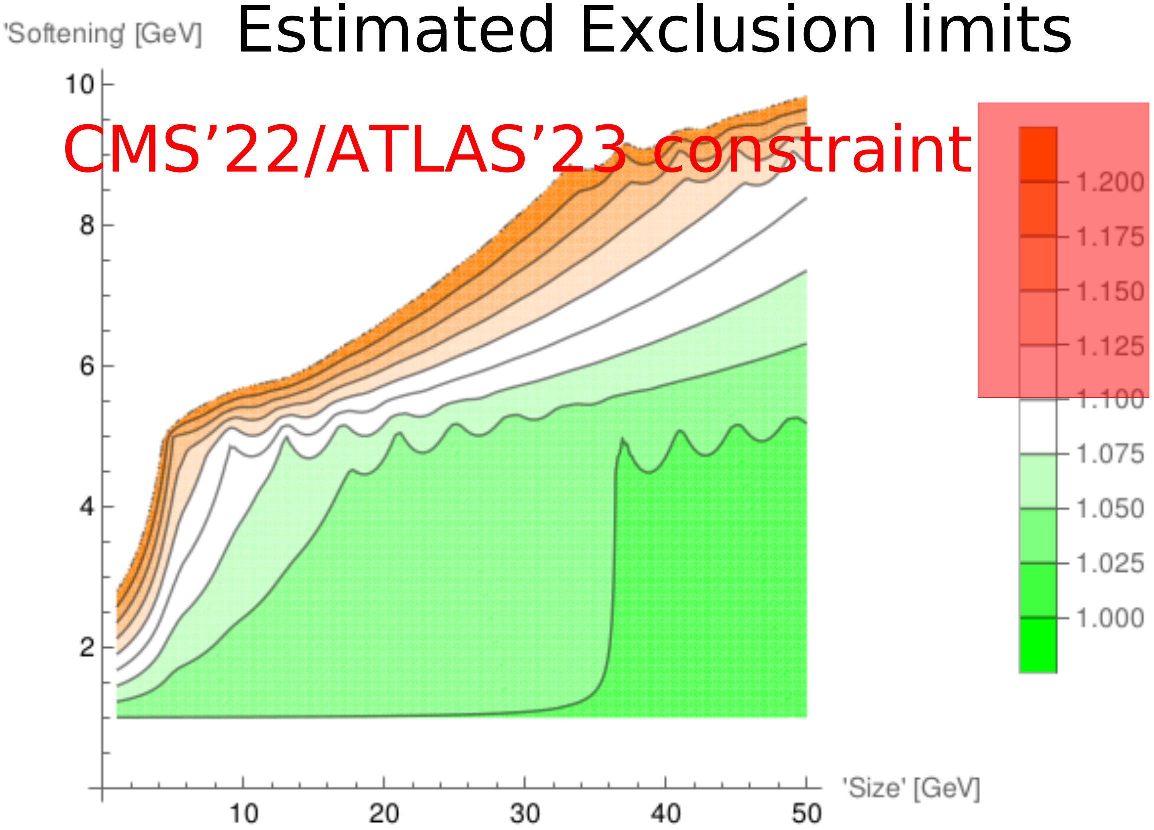

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CMS’22/ATLAS’23 constraint

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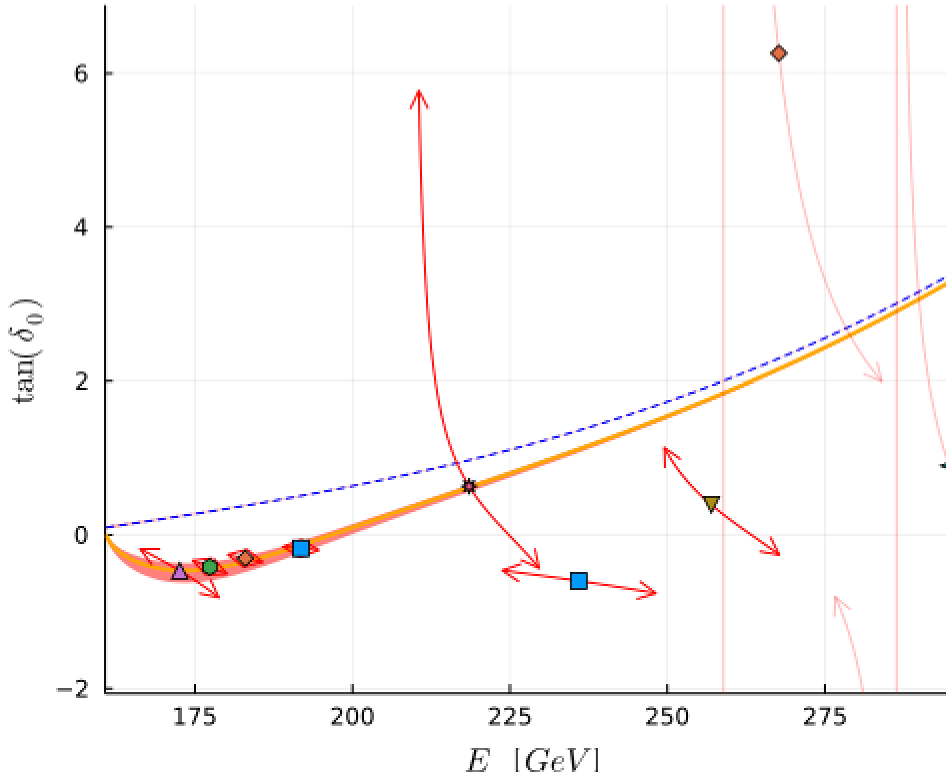

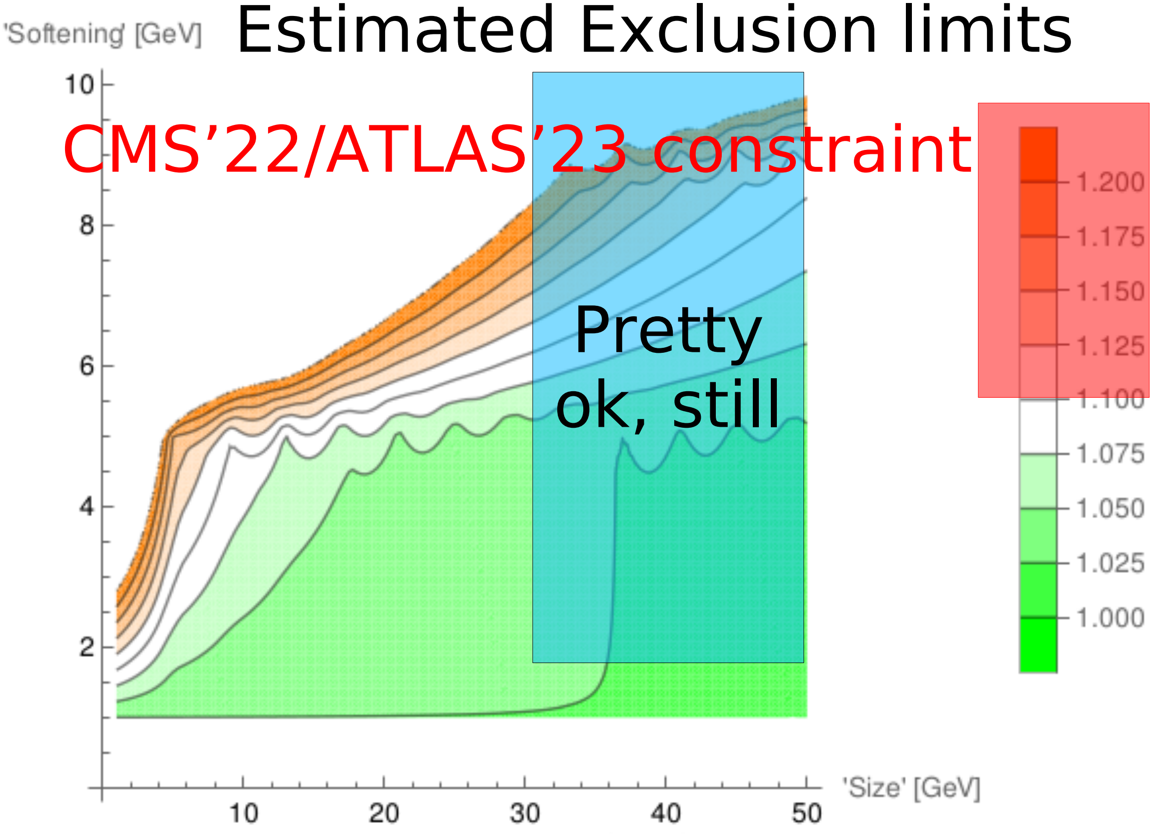

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Pretty ok, still

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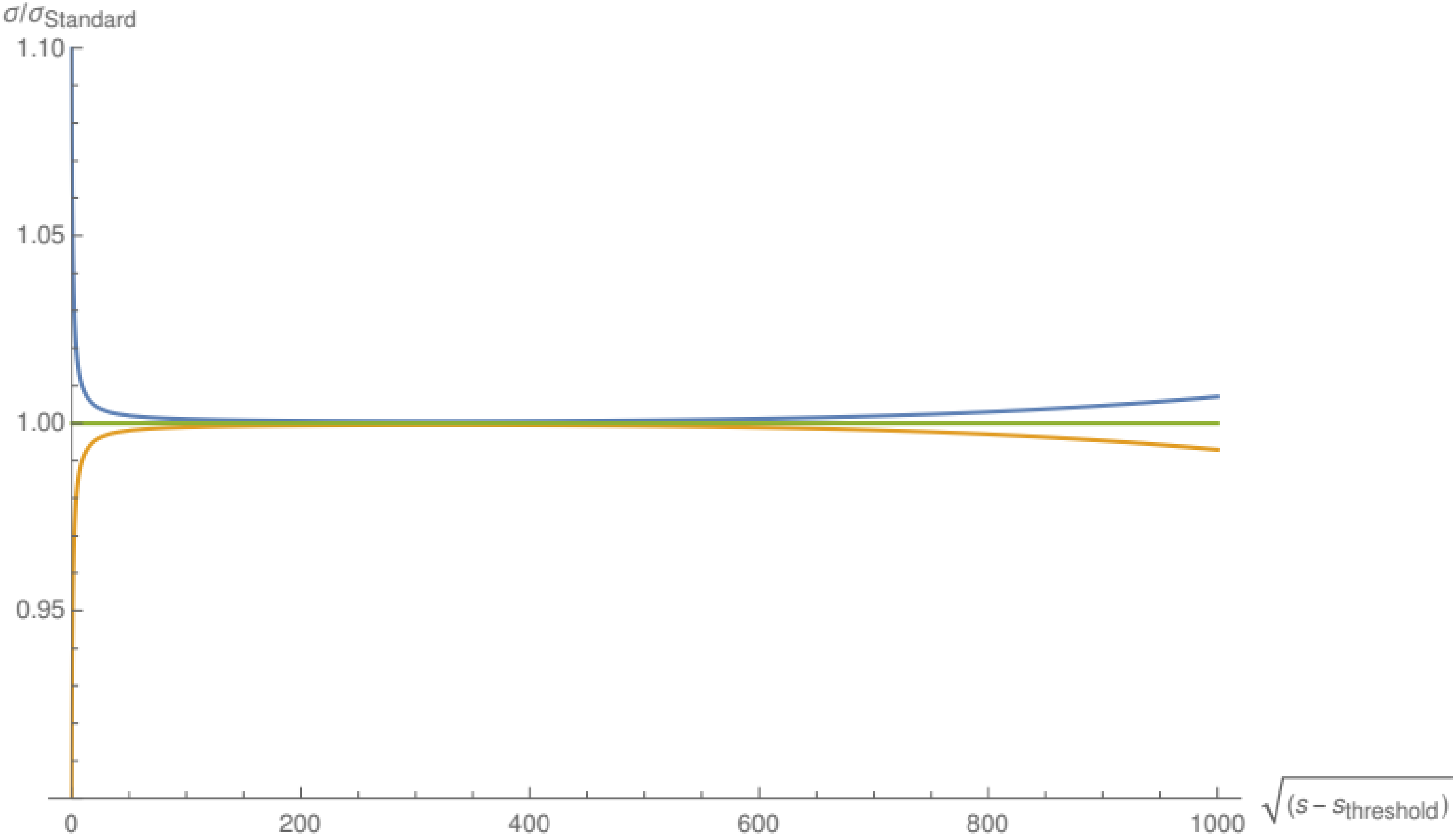
Generic behavior: DIS-like



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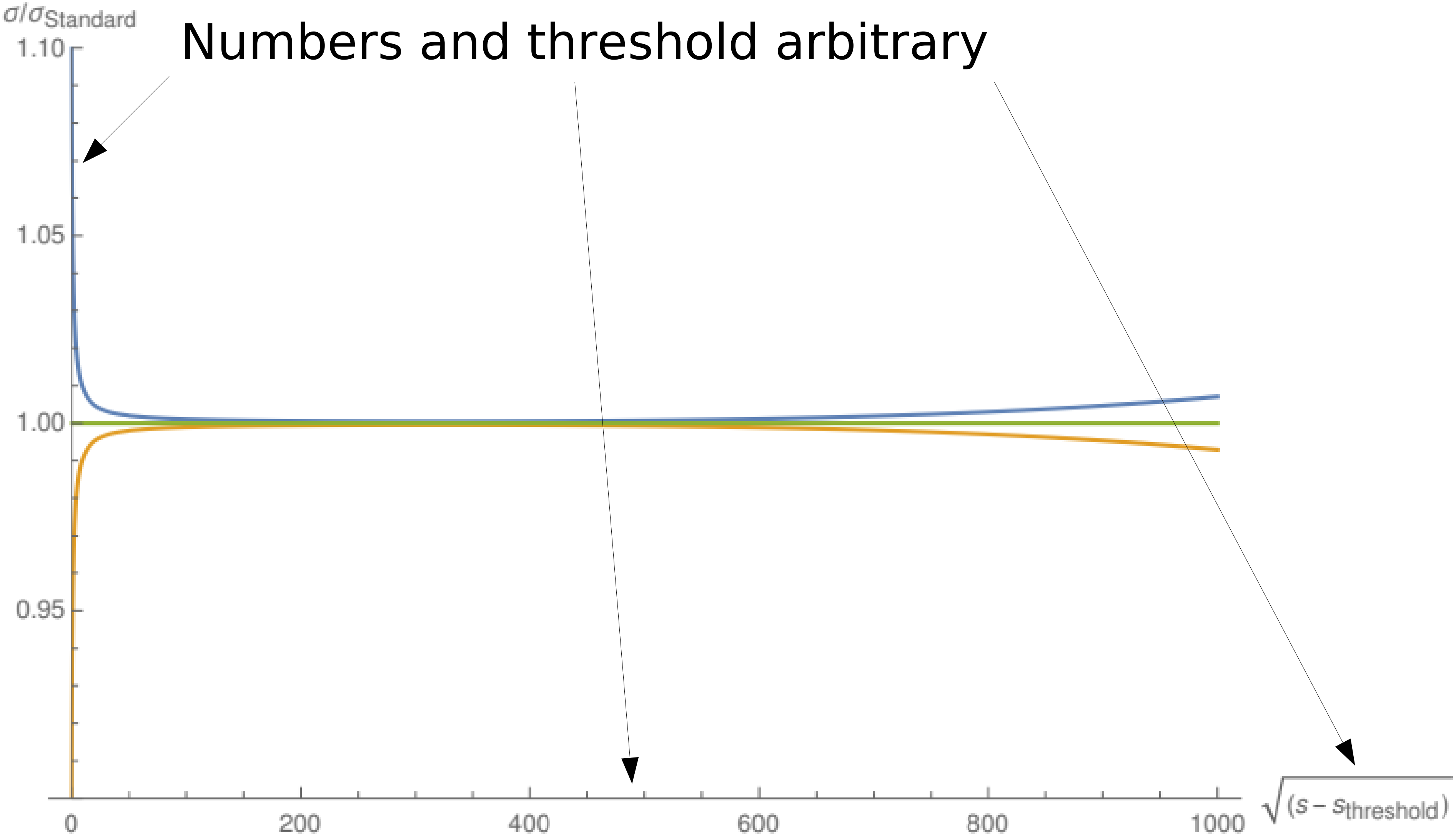

Numbers and threshold arbitrary

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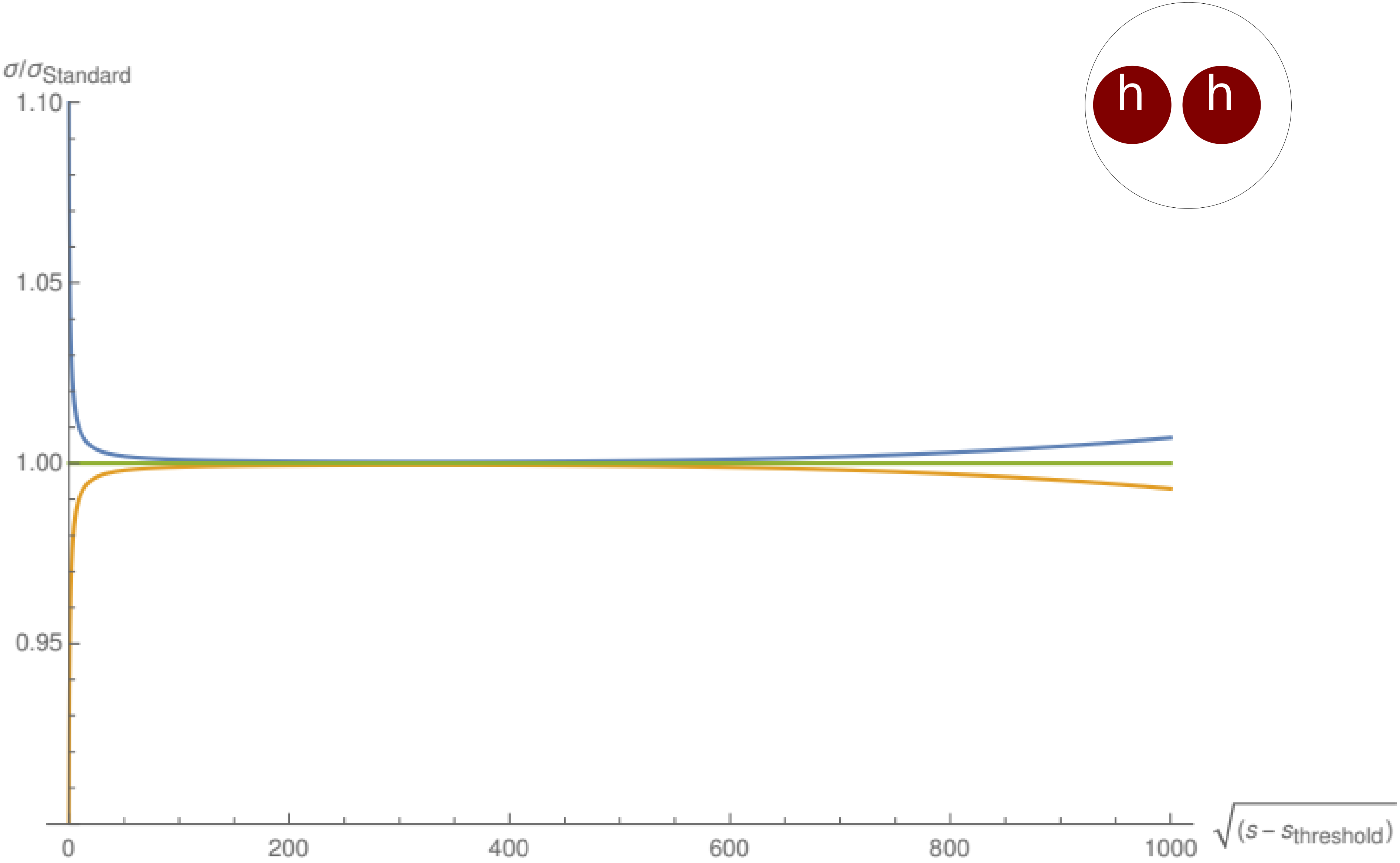

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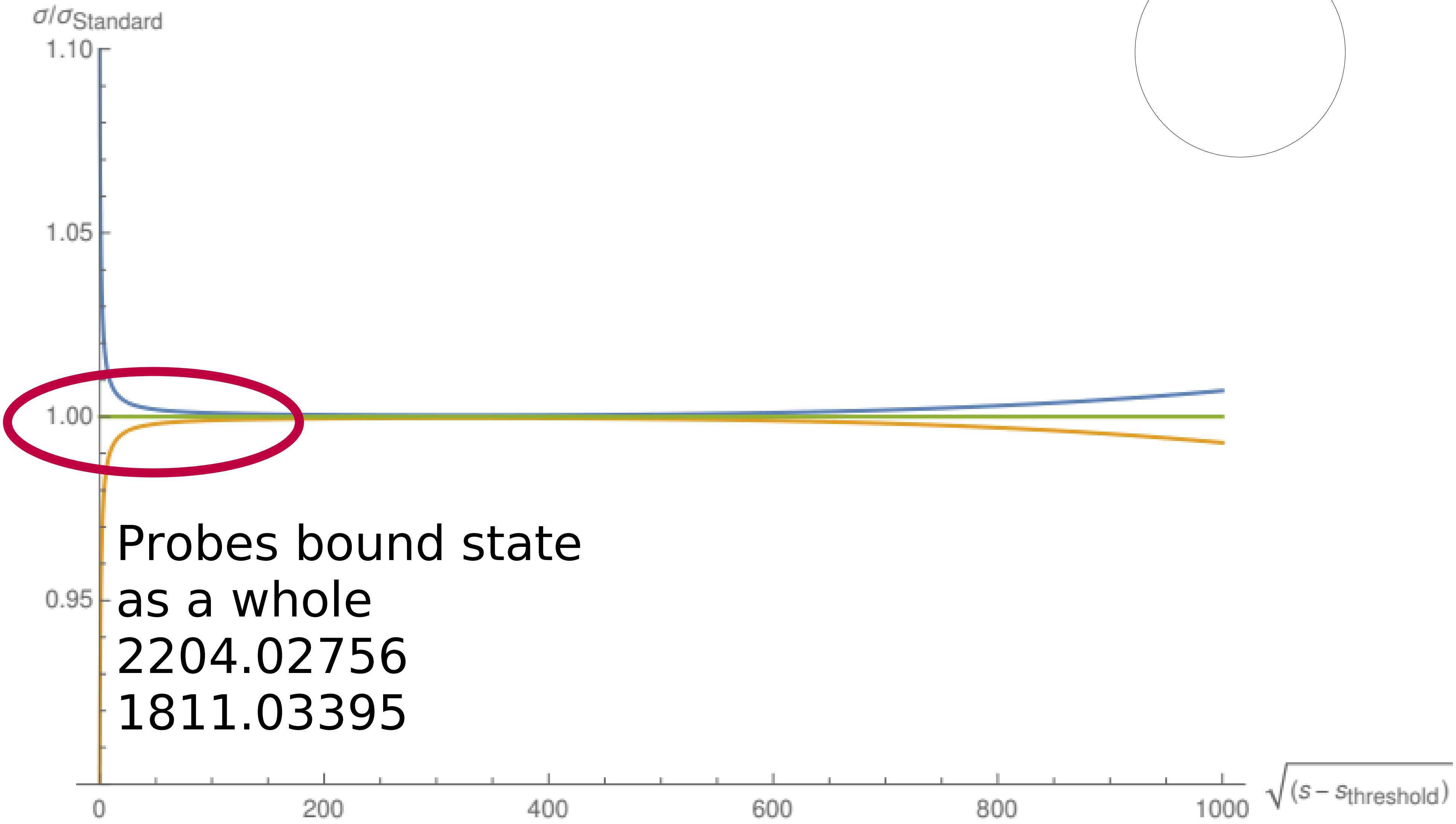
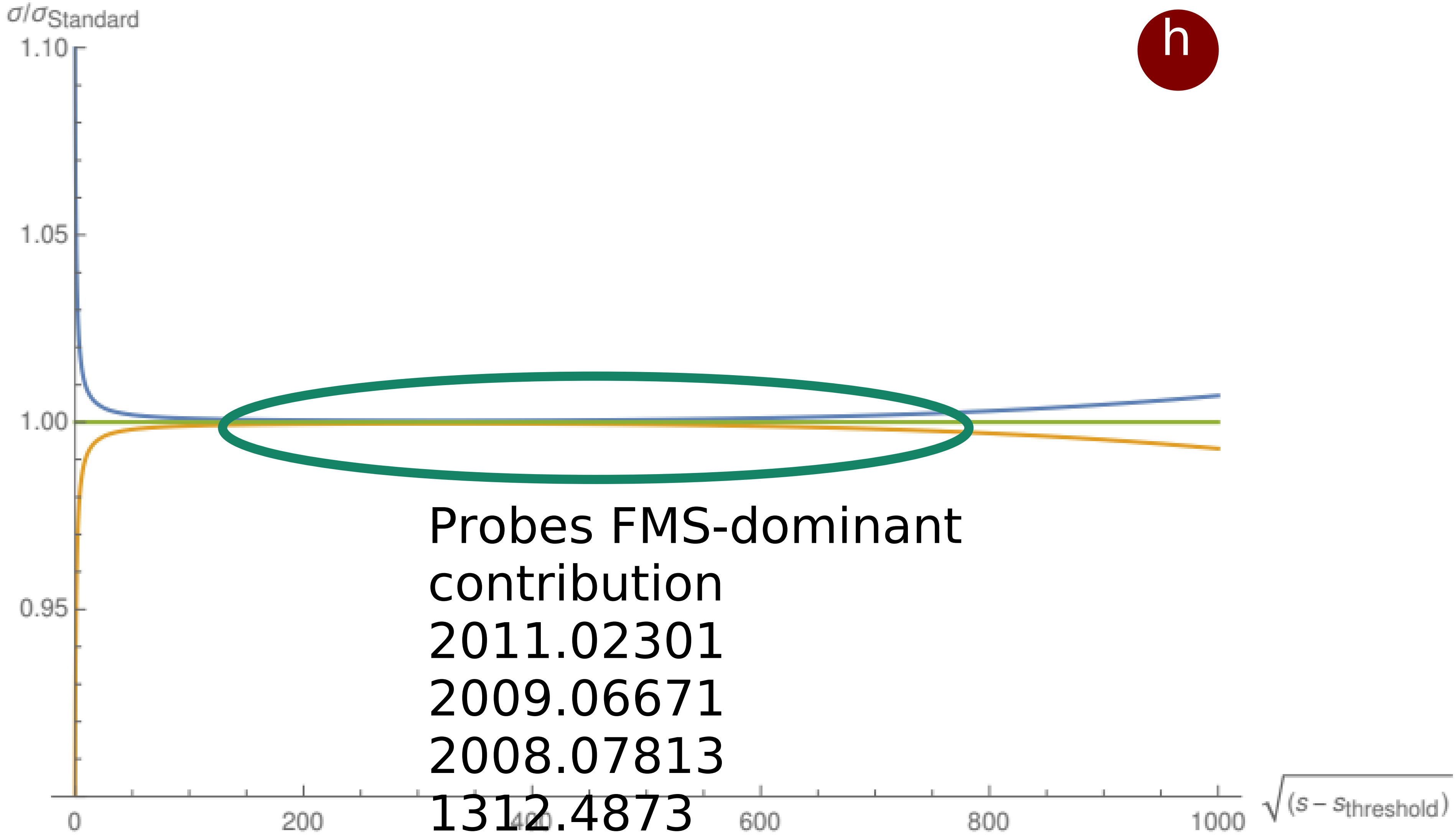


Probes bound state
as a whole
2204.02756
1811.03395

Generic behavior: DIS-like



Probes FMS-dominant contribution

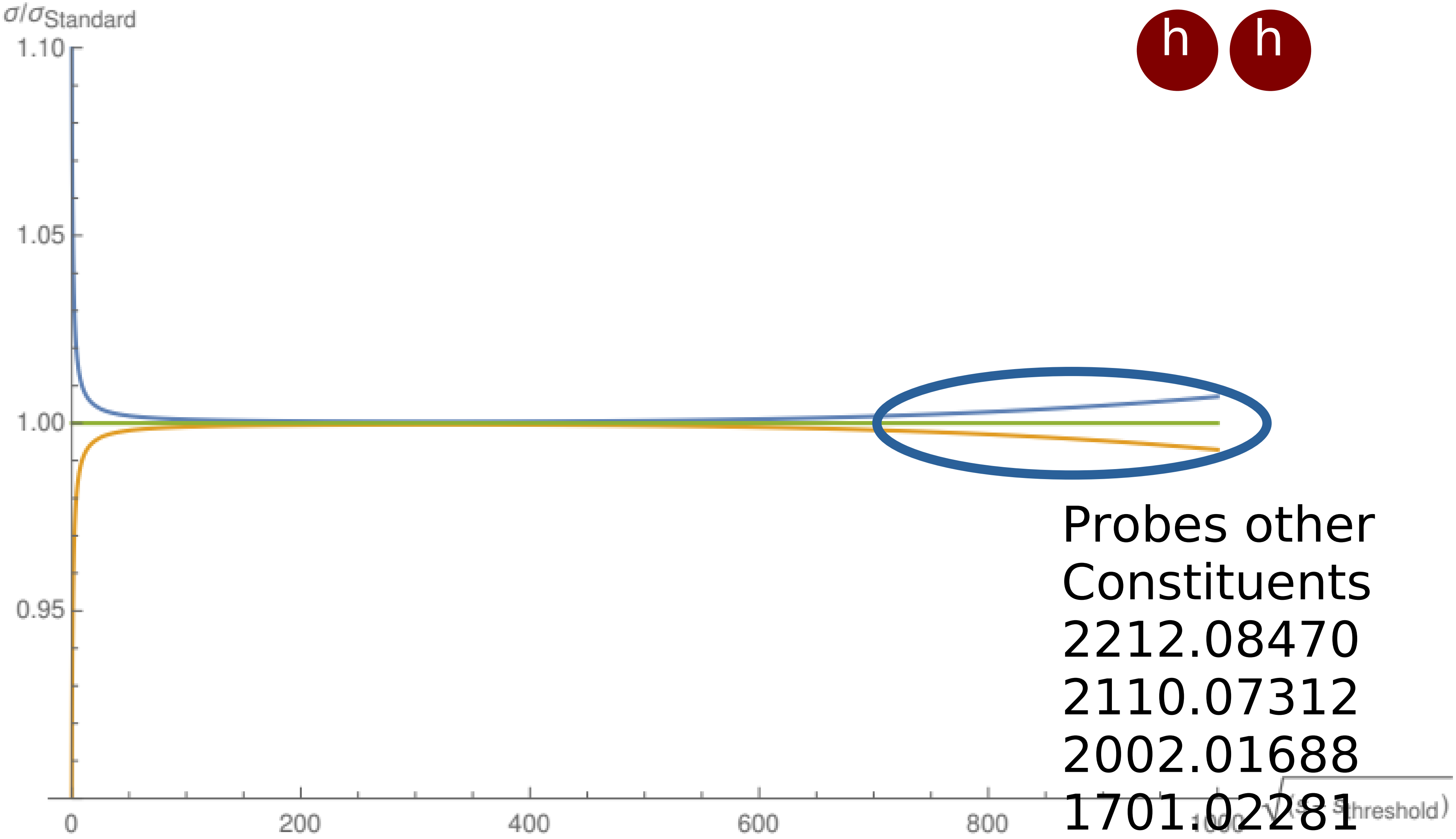
2011.02301

2009.06671

2008.07813

1312.4873

Generic behavior: DIS-like

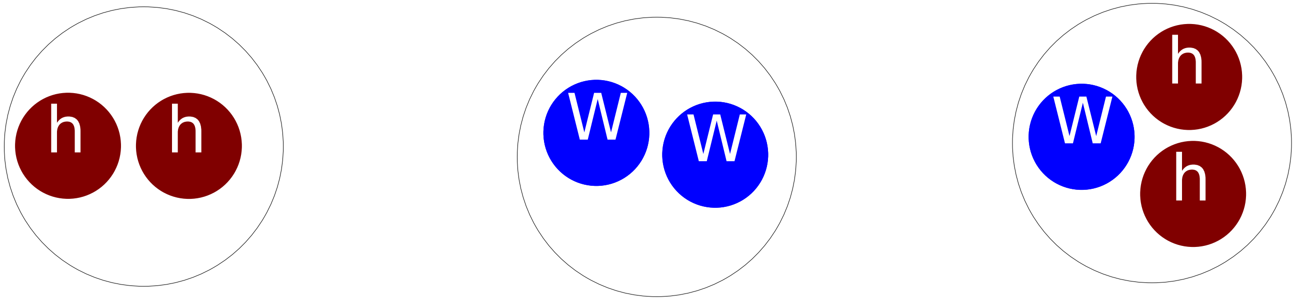


Probes other
Constituents
2212.08470
2110.07312
2002.01688
1701.02281

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.



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  - Think QED (hydrogen atom!)
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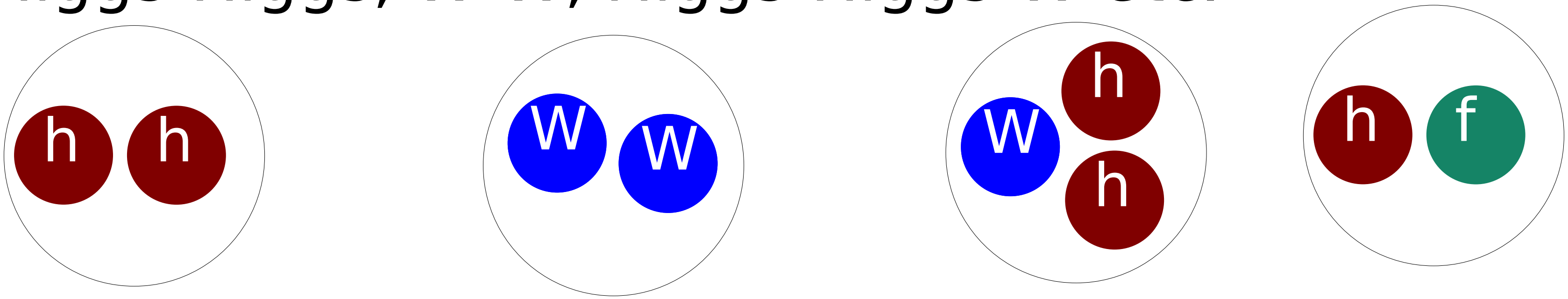

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Flavor

[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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- Yukawa terms break custodial symmetry
  - Different masses for doublet members
- 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
    - Quenched

Flavor on the lattice

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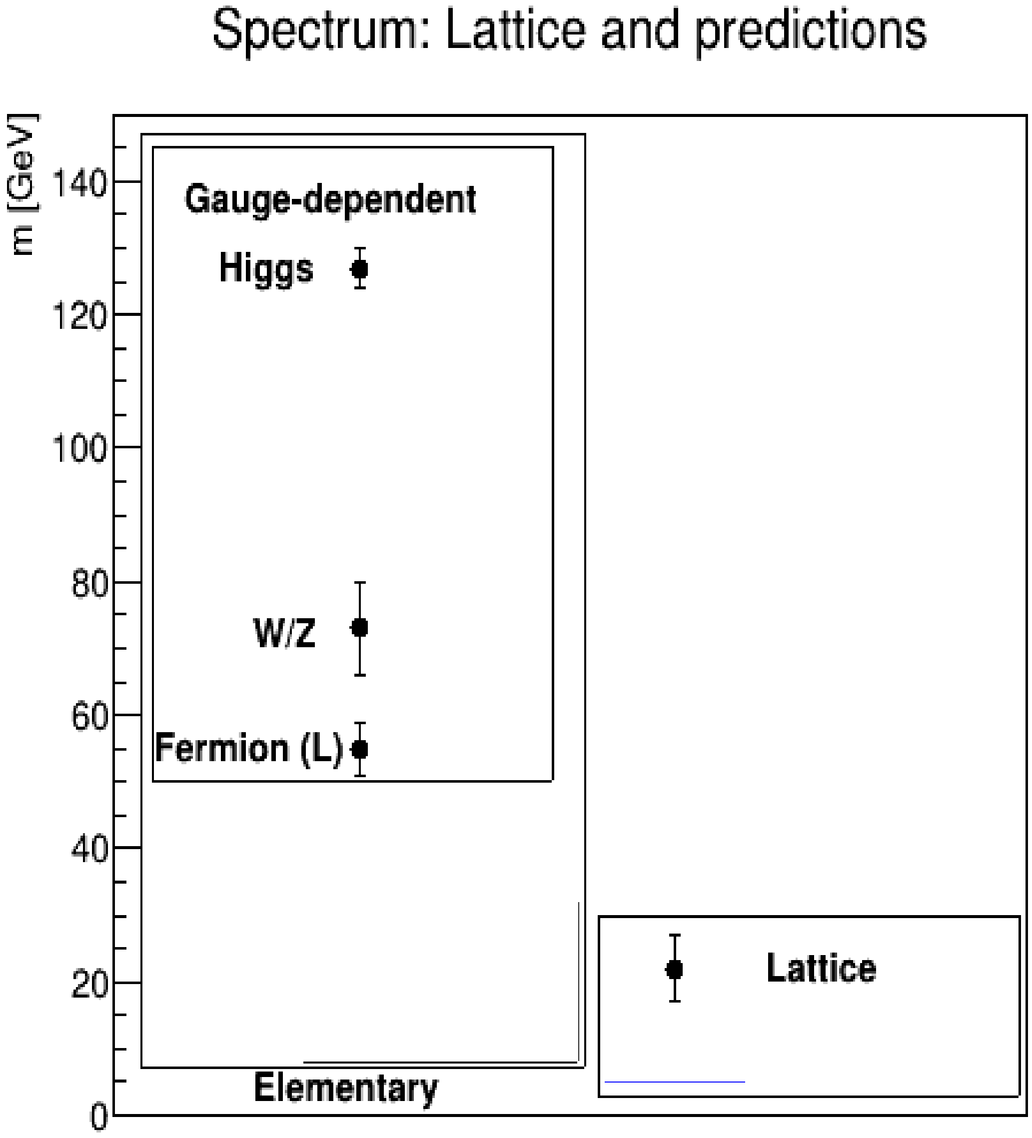

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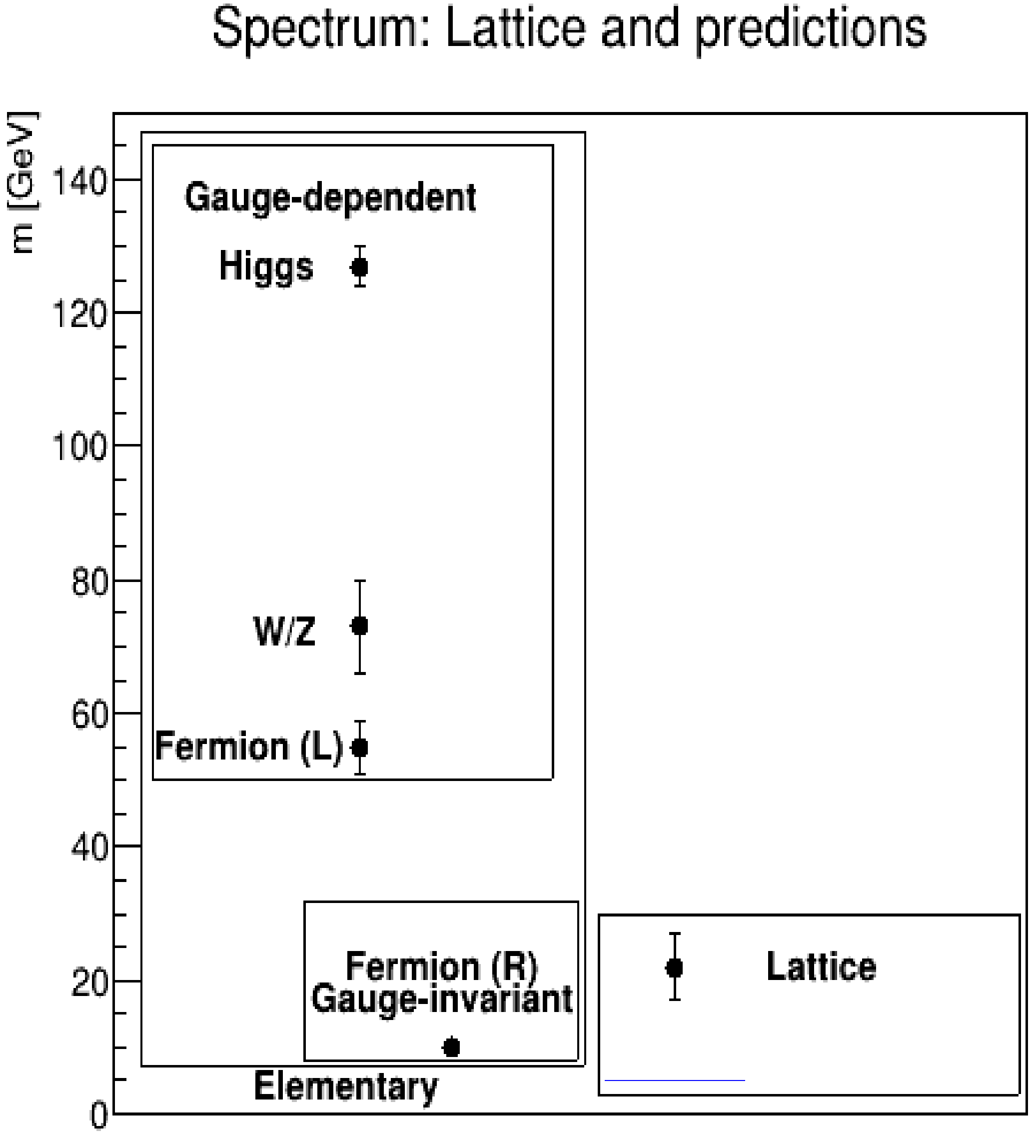

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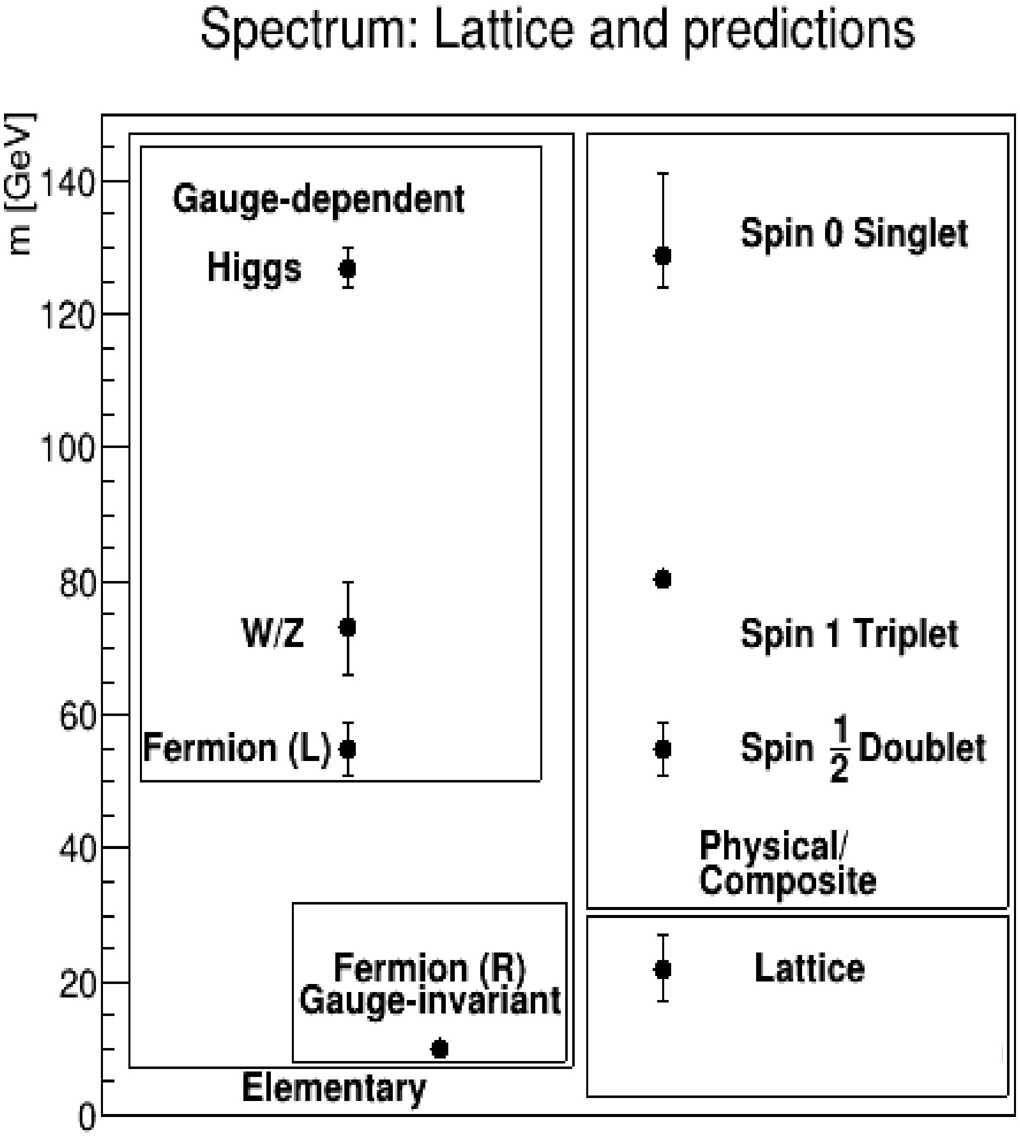

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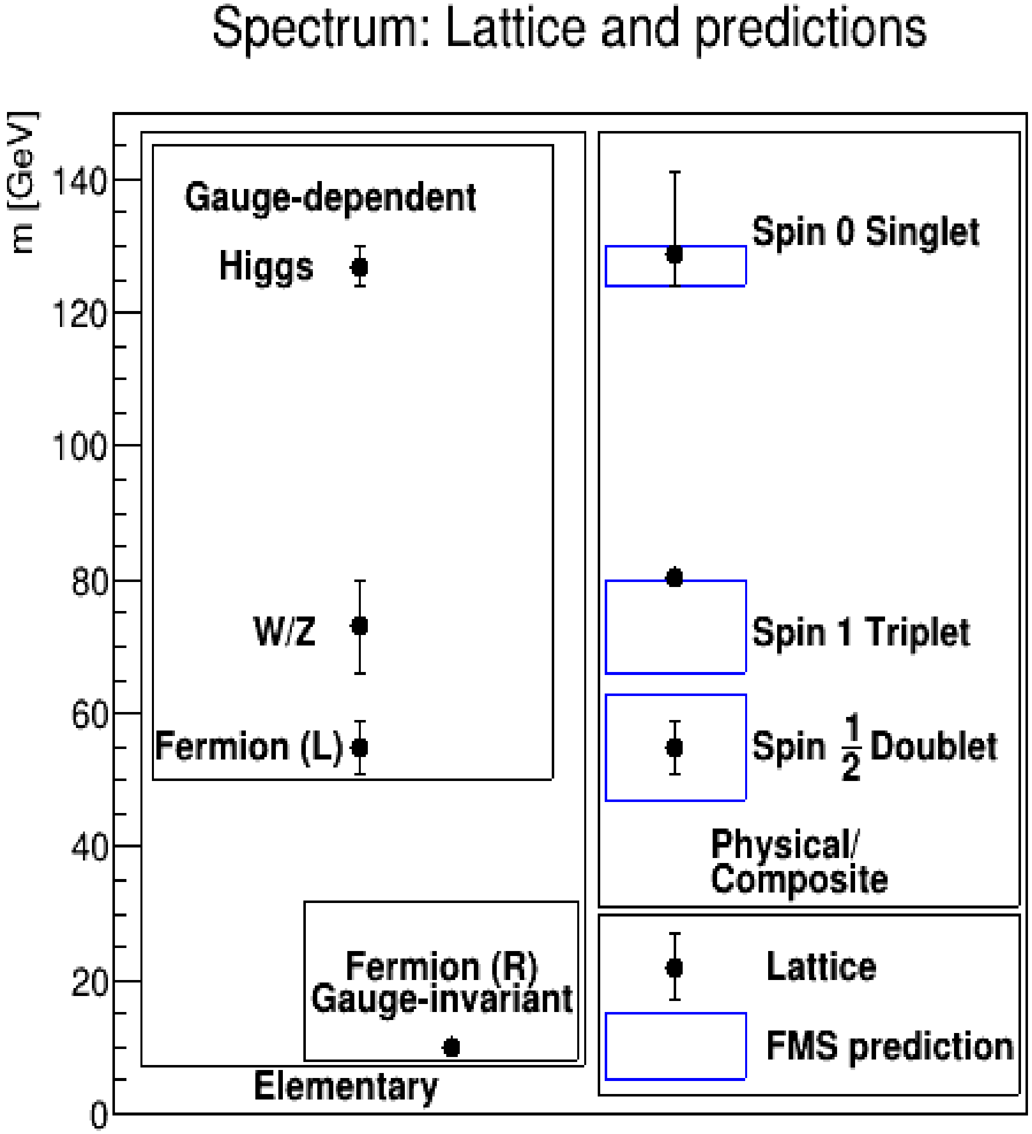

New physics
-
Qualitative changes

Beyond the standard model

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

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A toy model for unification

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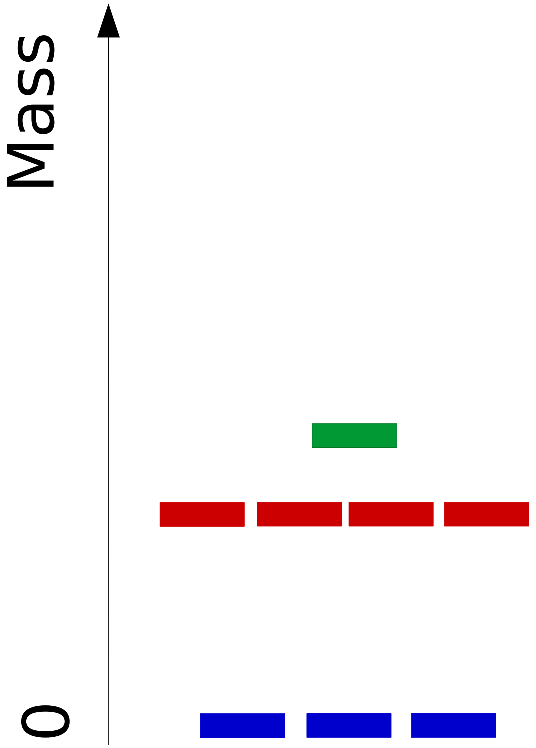
- Global U(1) custodial (flavor) symmetry
  - Acts as (right-)transformation on the scalar field only

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a} \qquad h\rightarrow\exp\left(ia\right)h$$

Spectrum

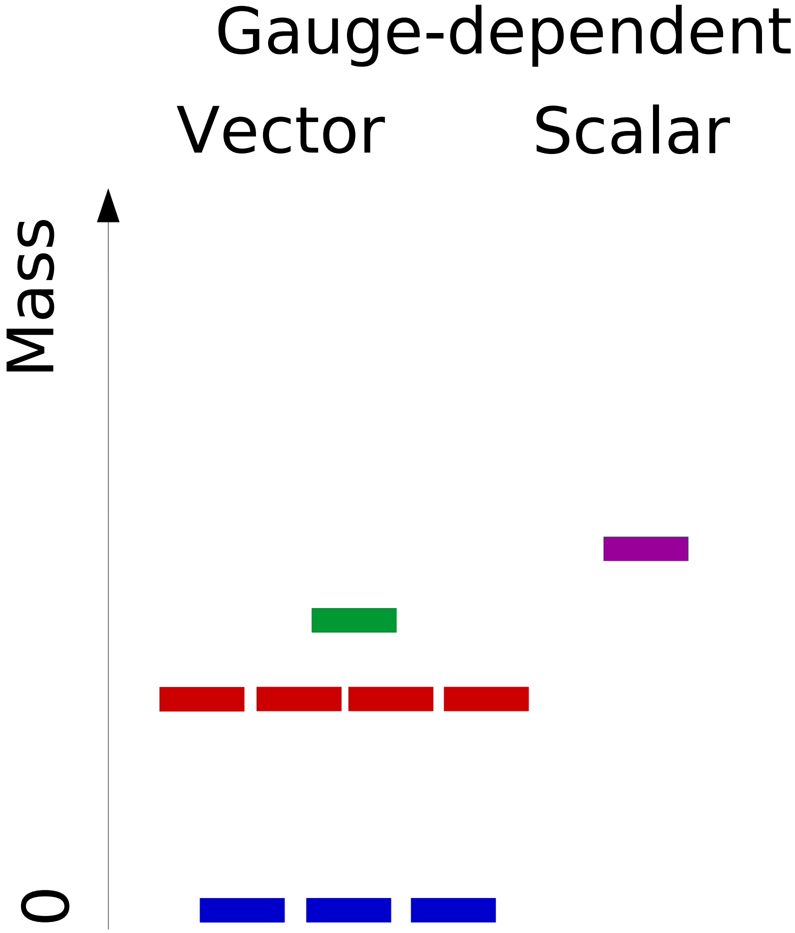
Gauge-dependent

Vector



‘SU(3)→ SU(2)’

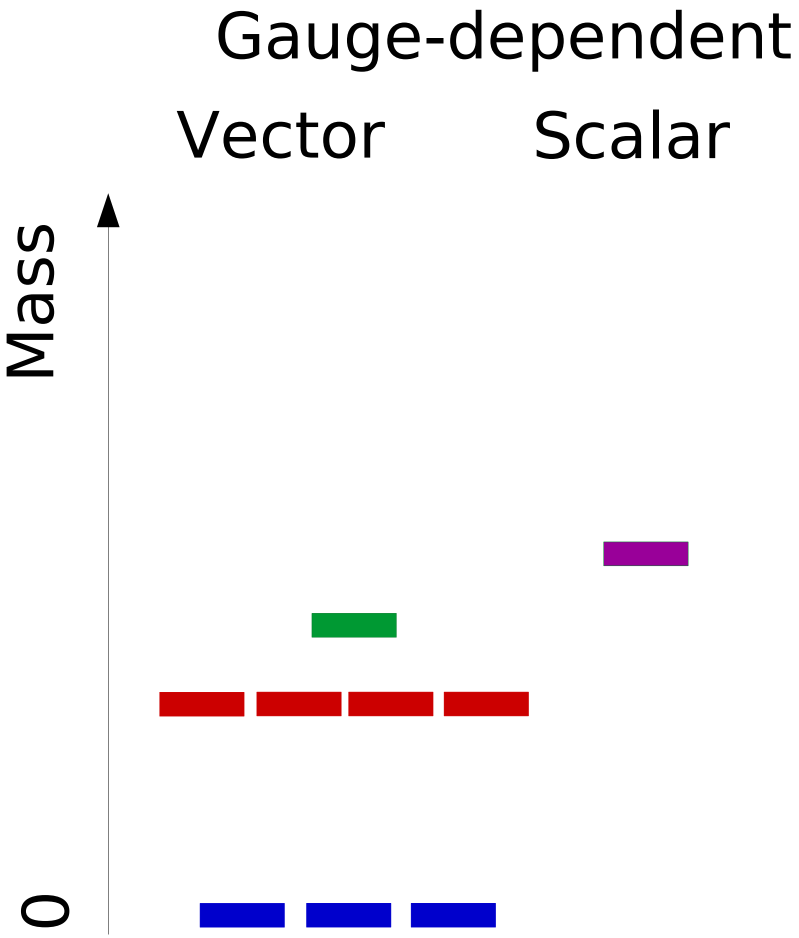
Spectrum



Gauge-dependent

Vector Scalar

Spectrum



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

Spectrum

[Maas & Törek’16,'18
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Gauge-dependent

Gauge-invariant

Vector

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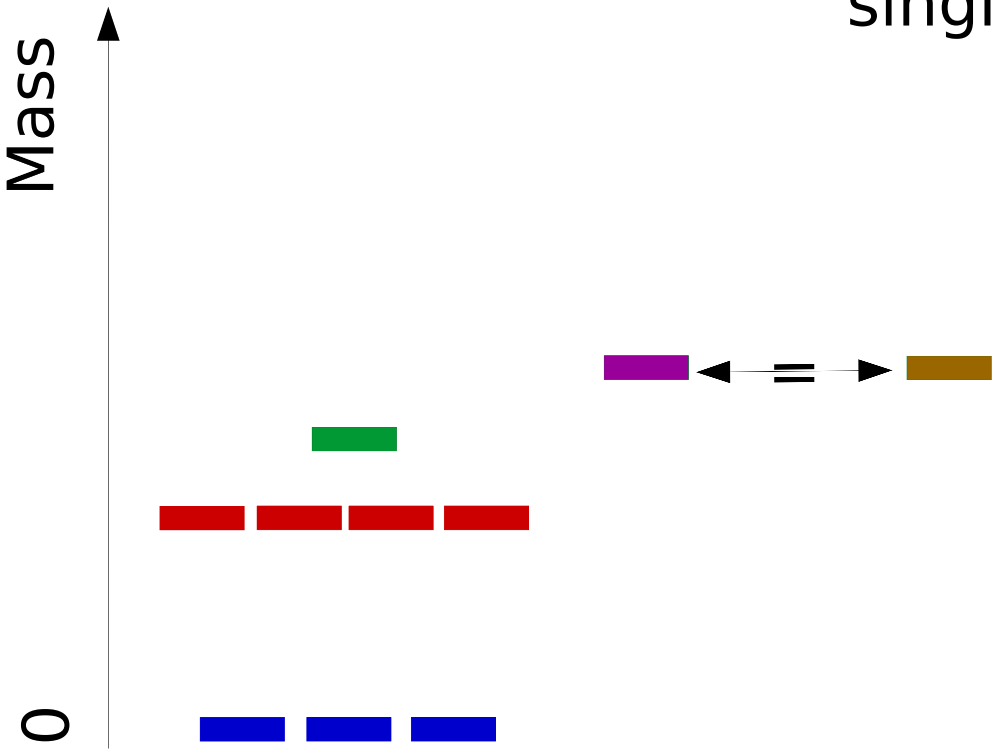

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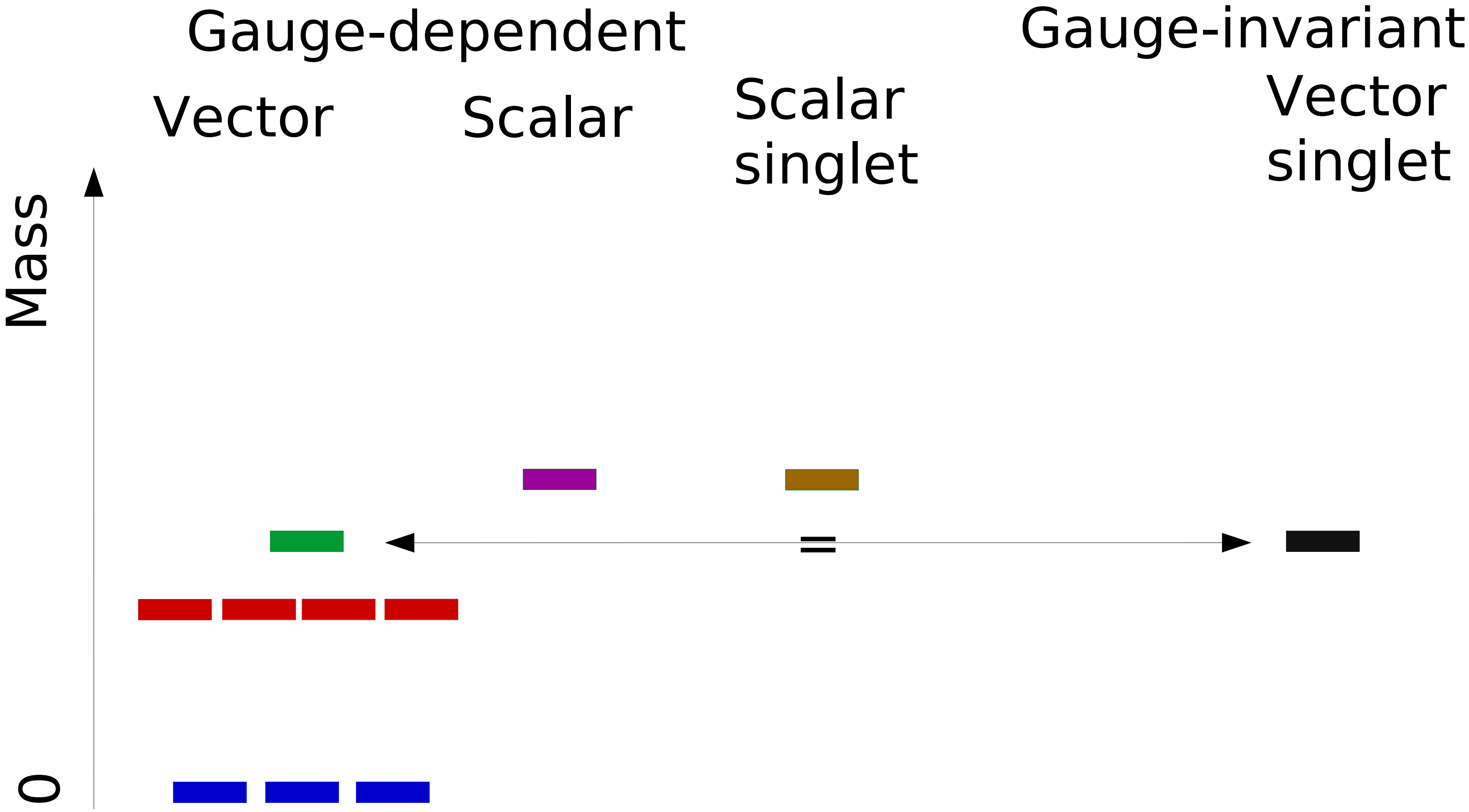

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Vector

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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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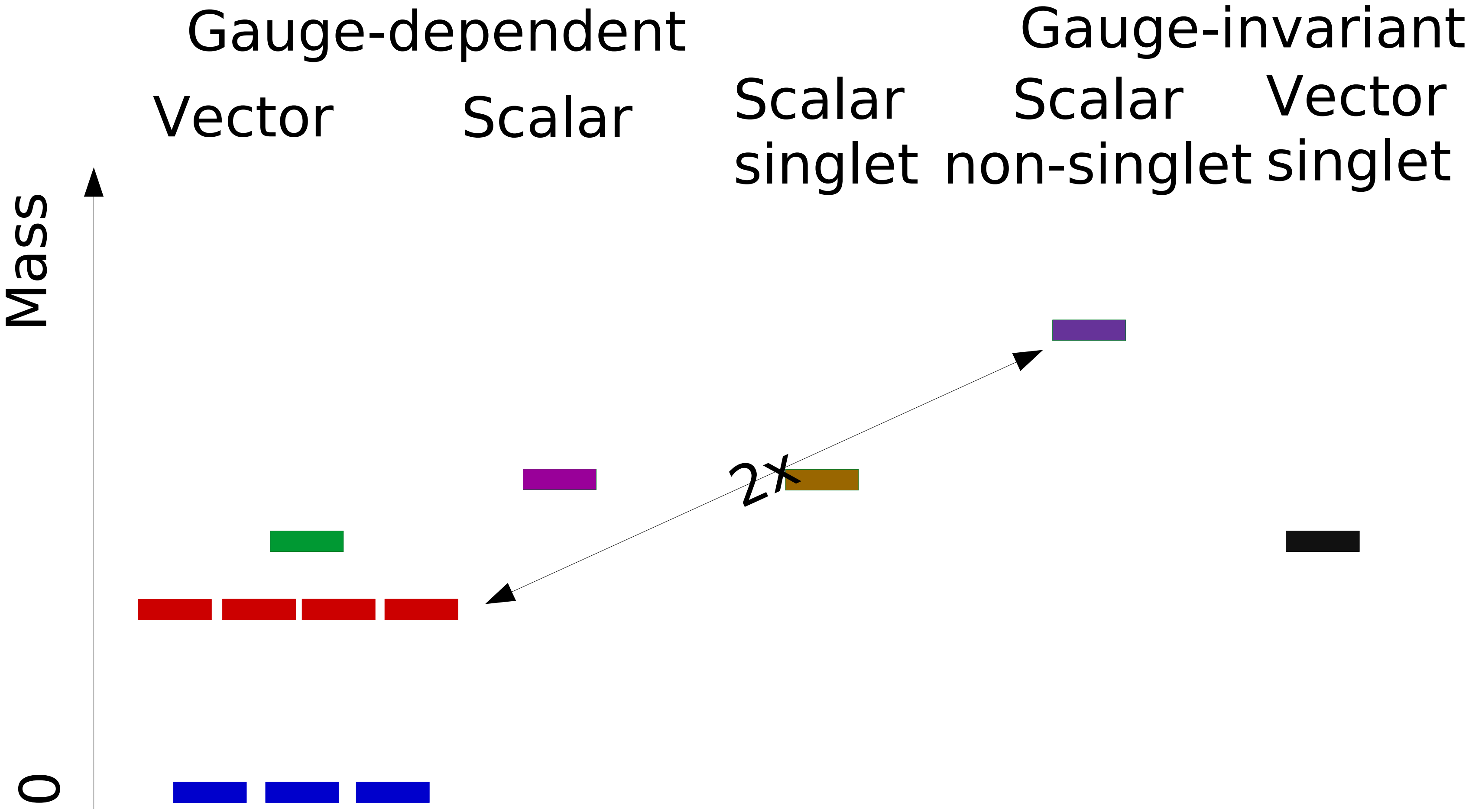

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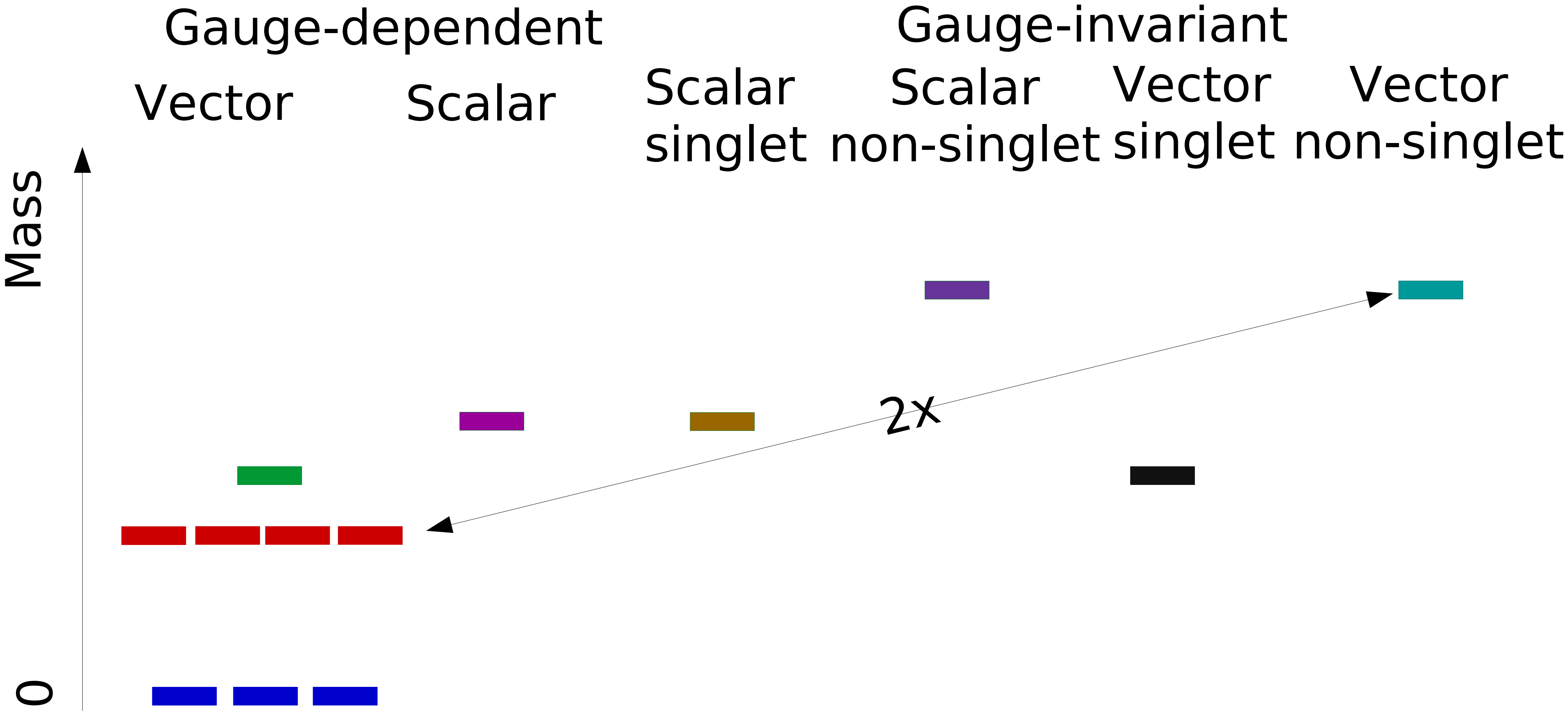

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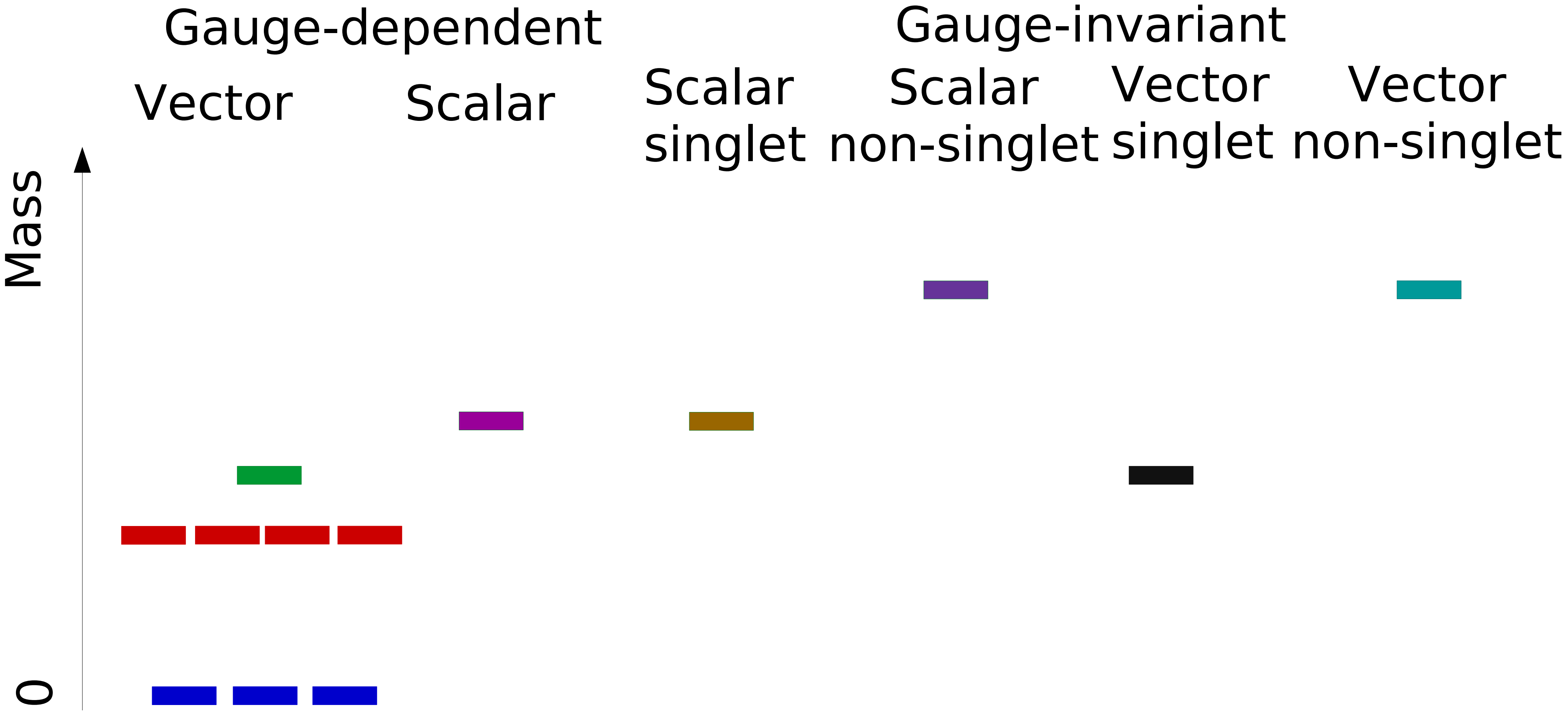

- Qualitatively different spectrum
- No mass gap!

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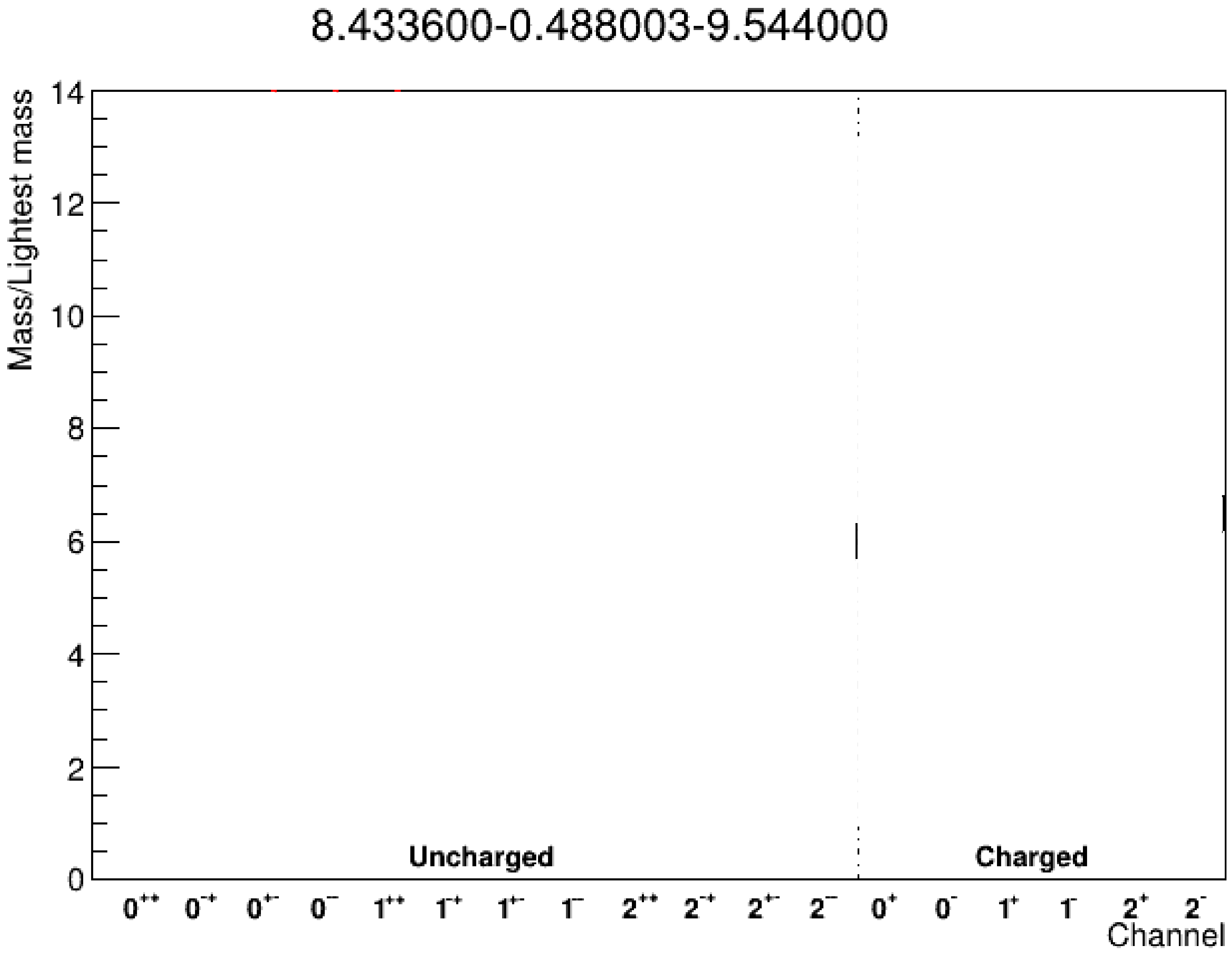
  - Lattice calulations
  - All channels: J<3
  - Aim: Ground state for each channel
    - Characterization through scattering states

Spectrum

PRELIMINARY

[Dobson et al.’21]



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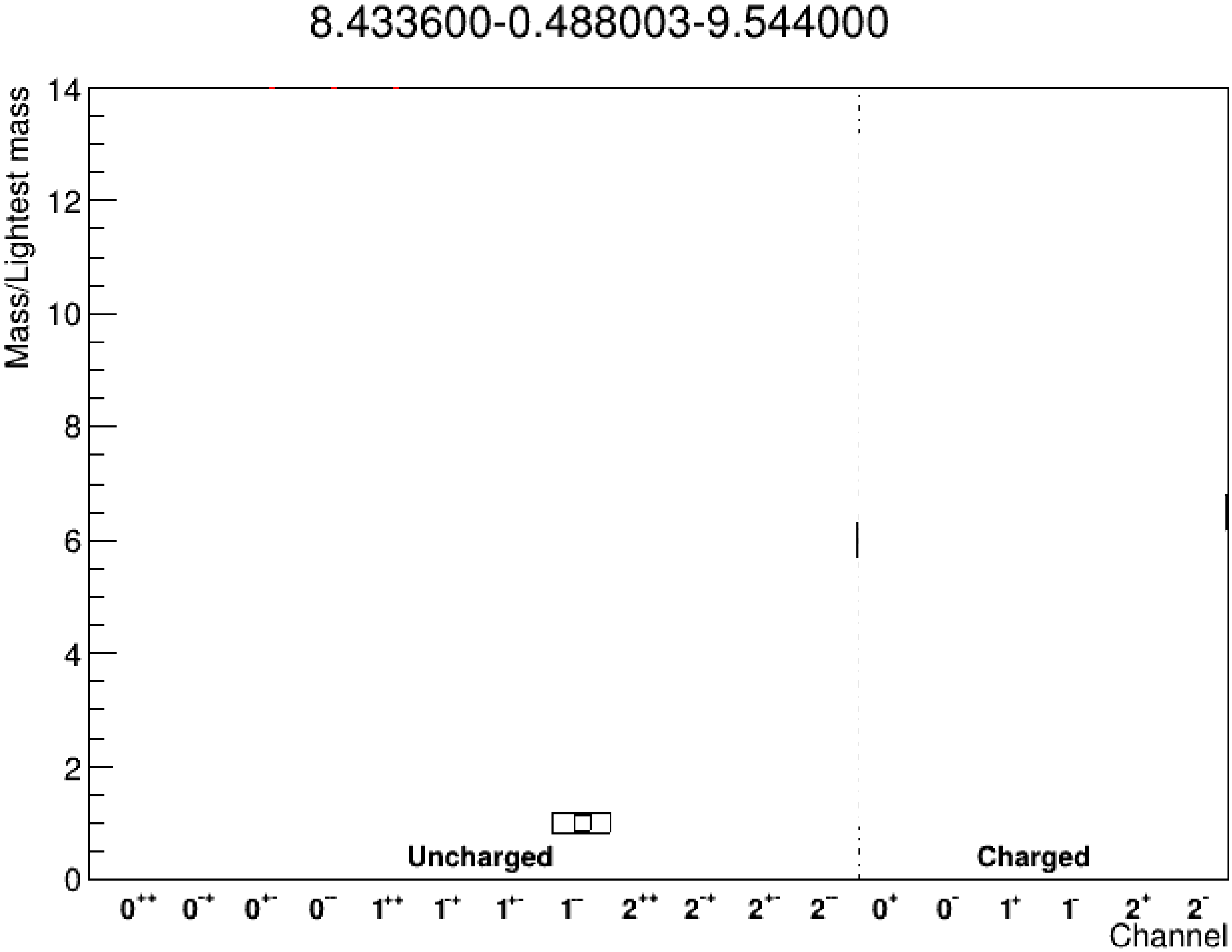

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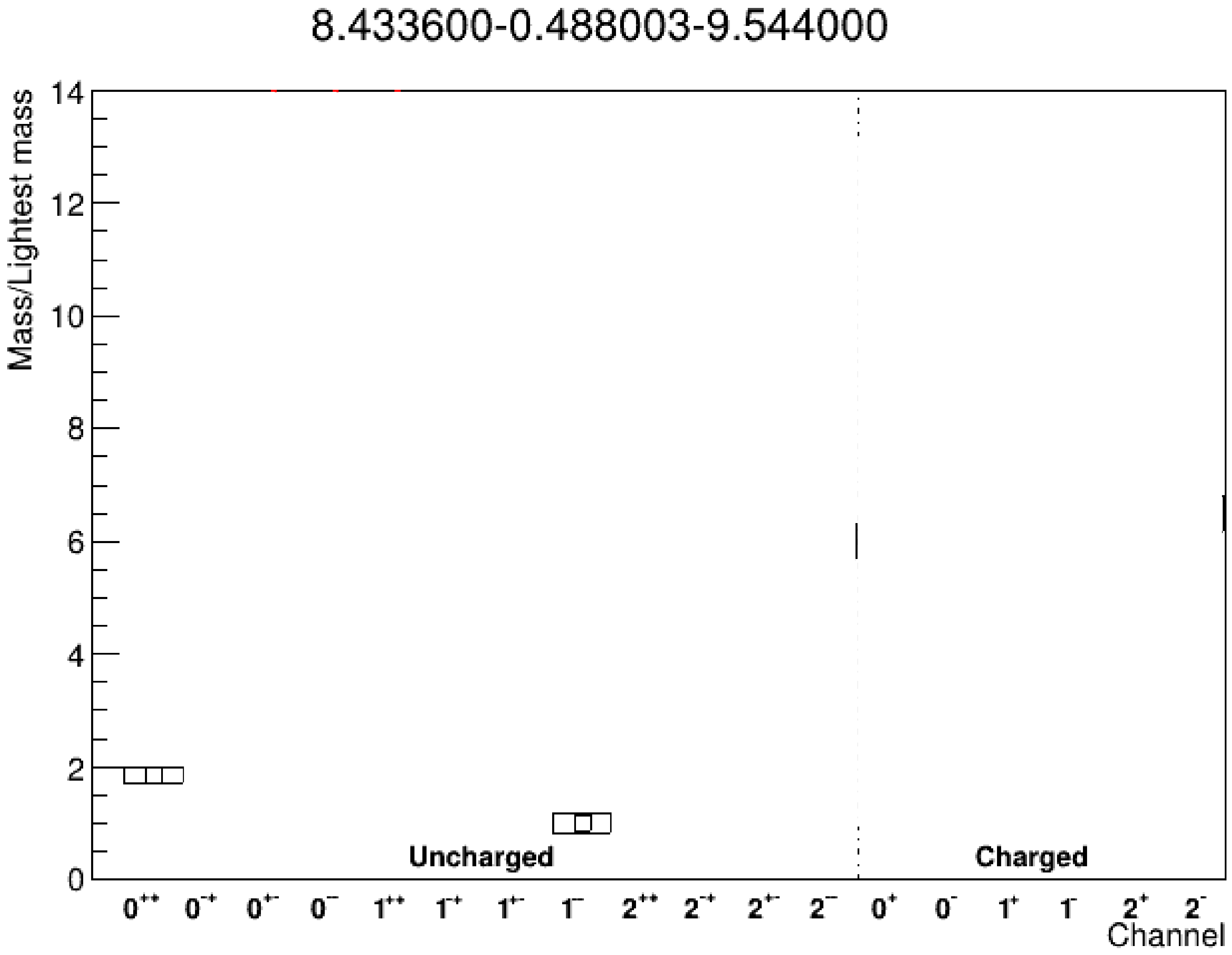

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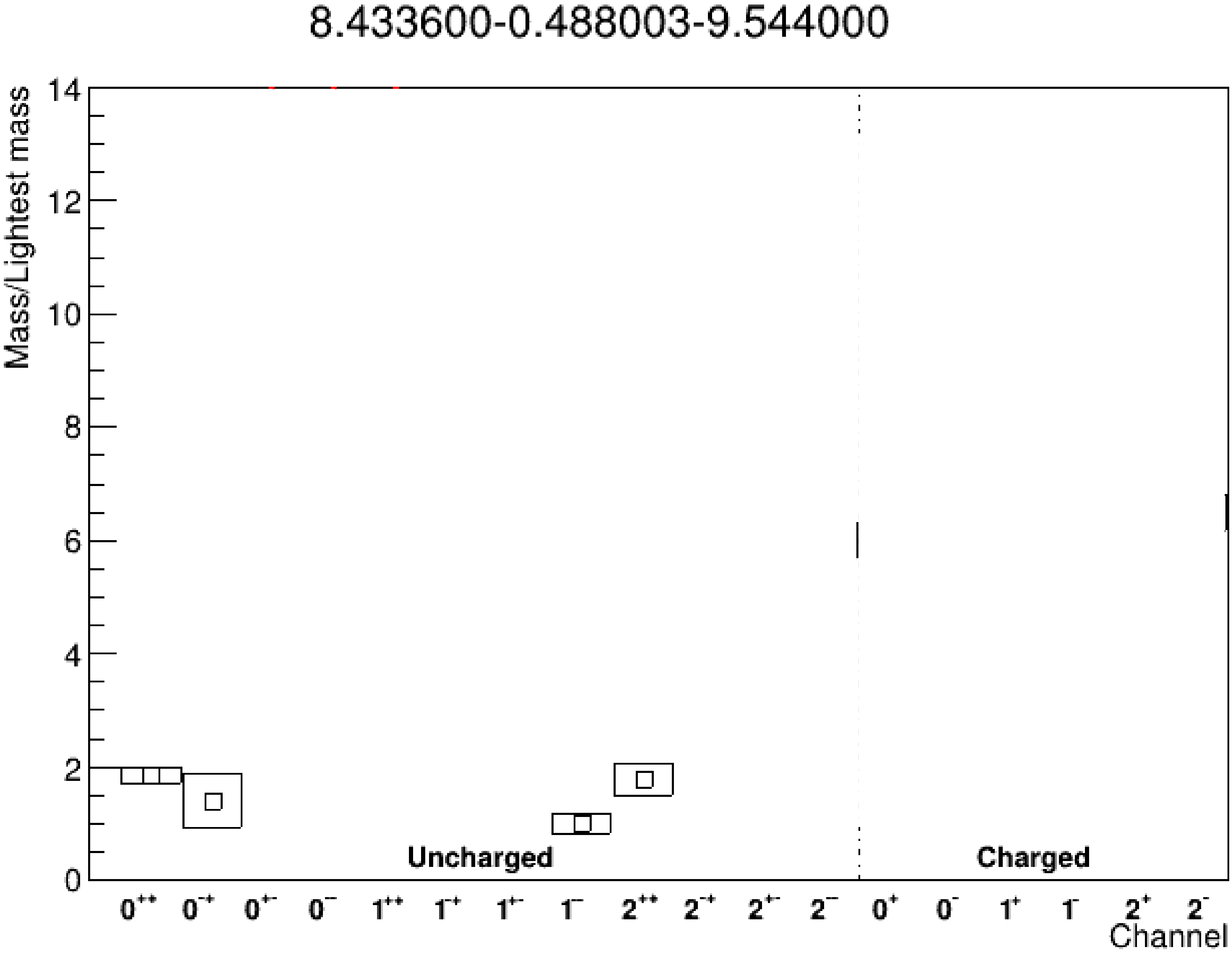

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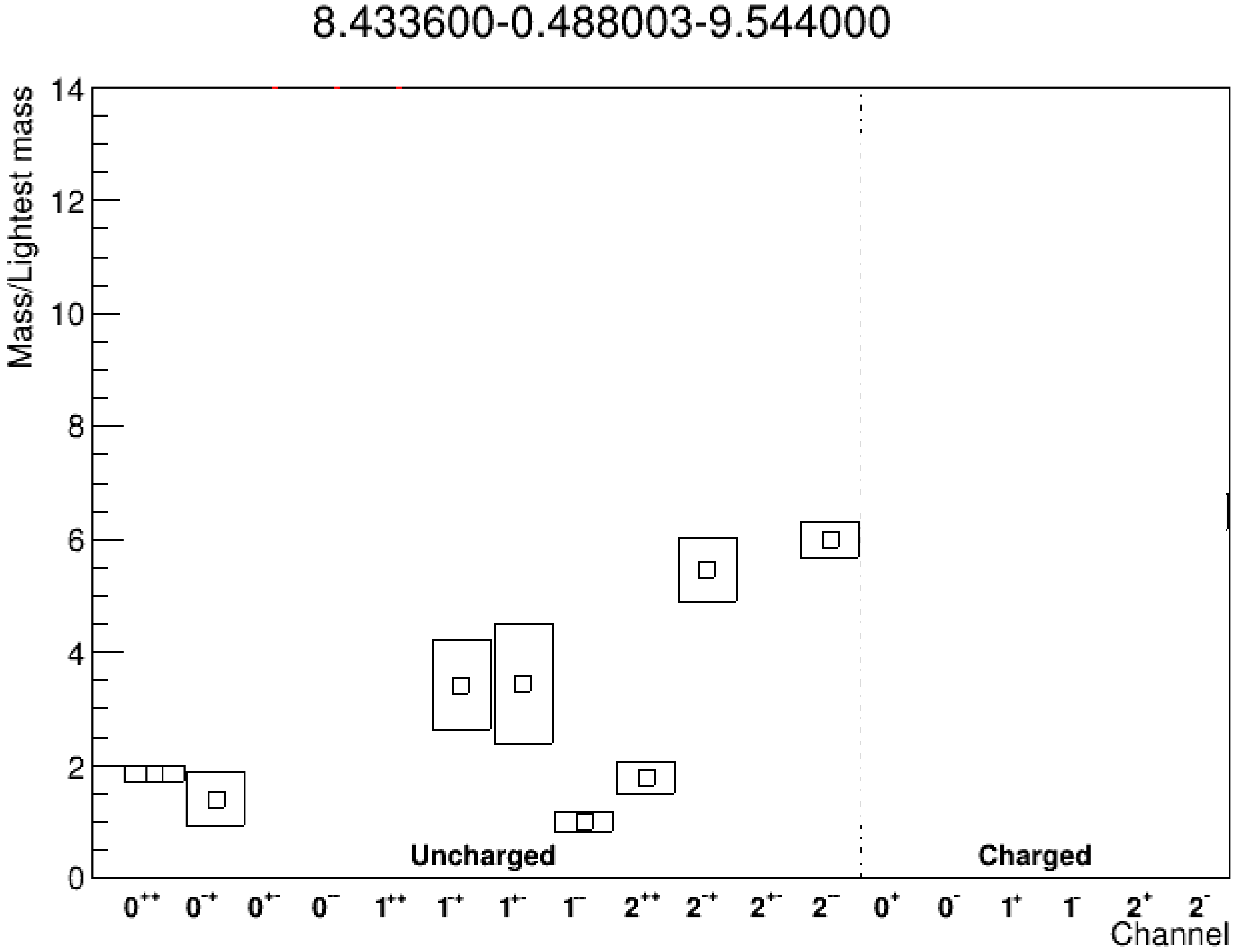

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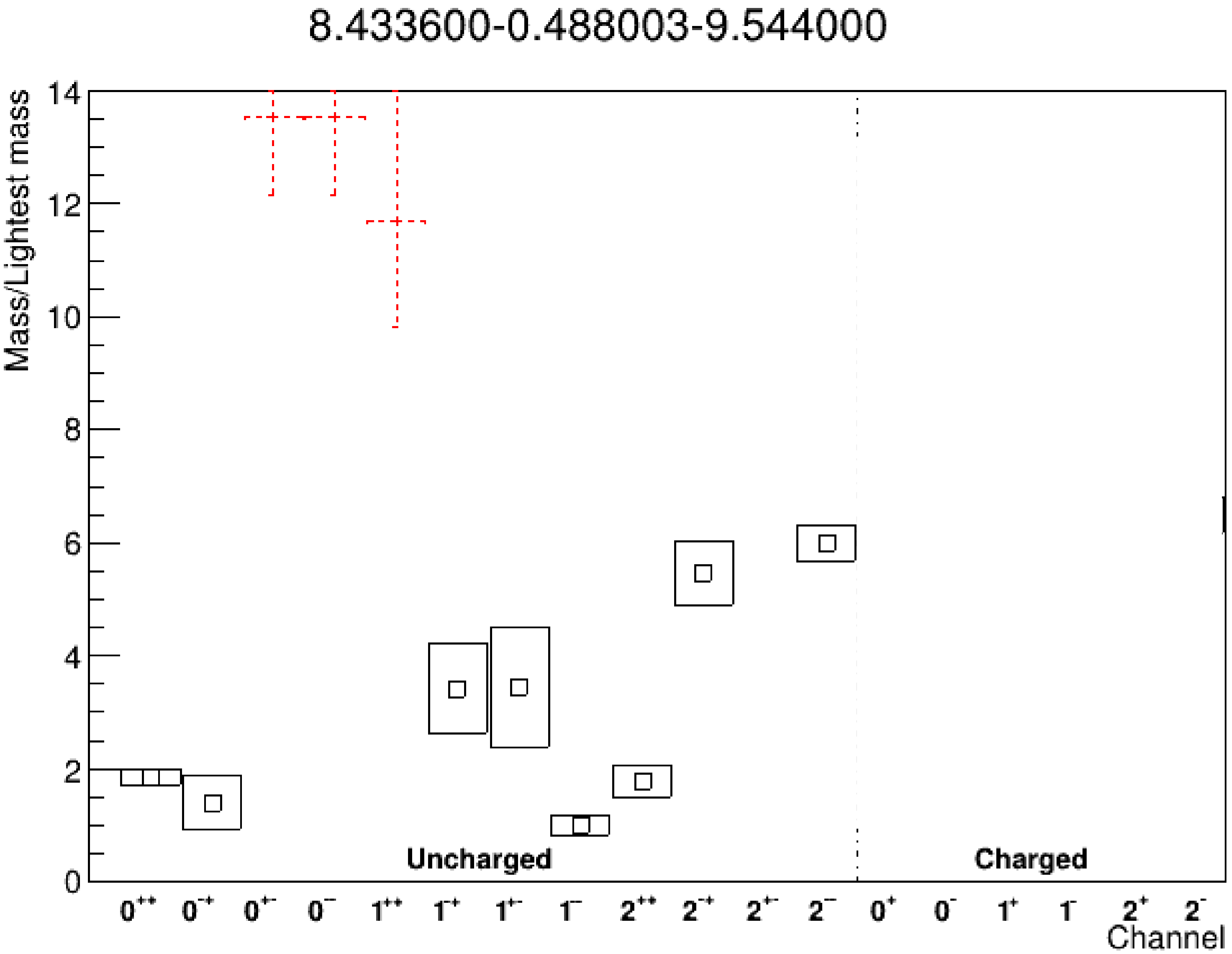

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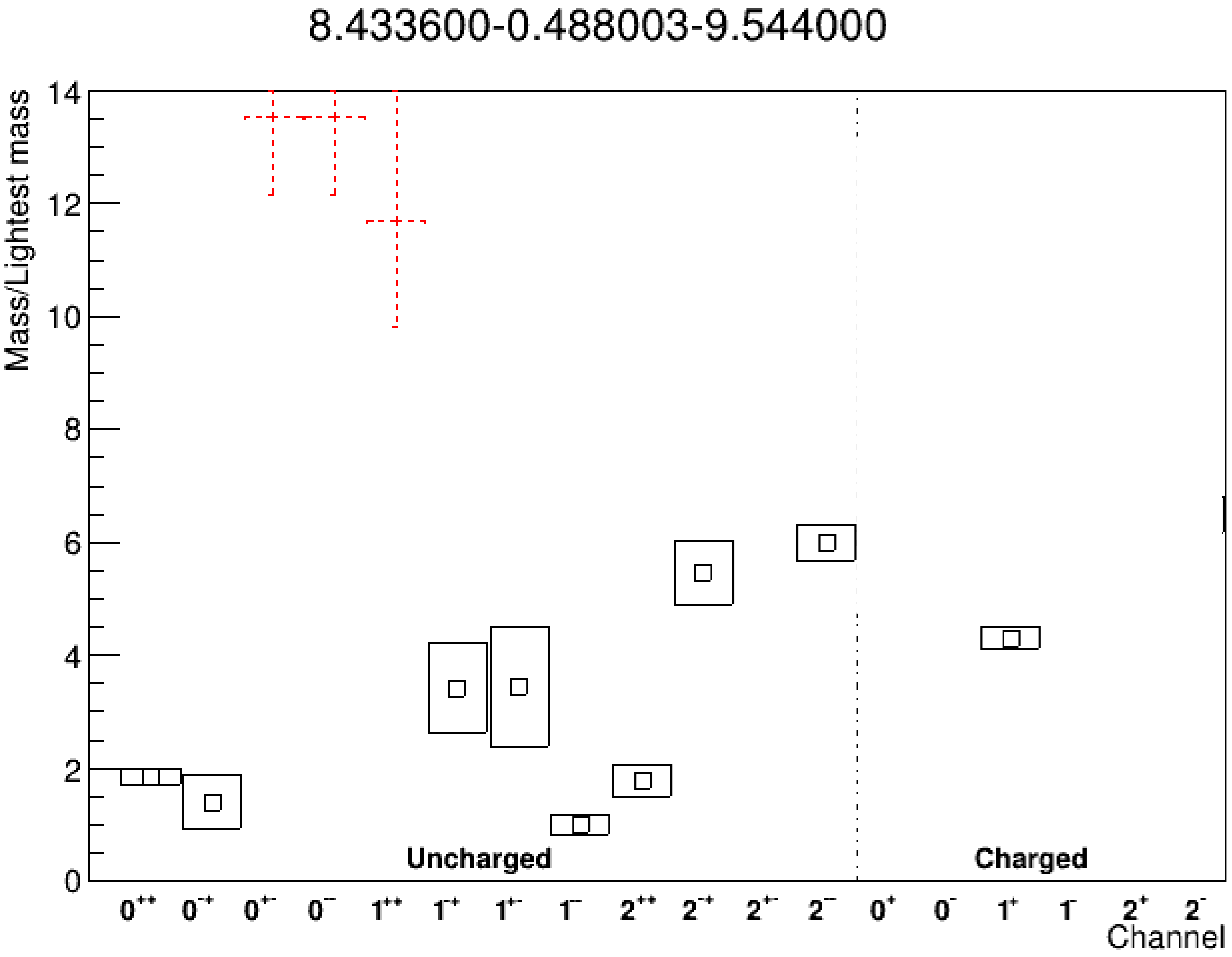

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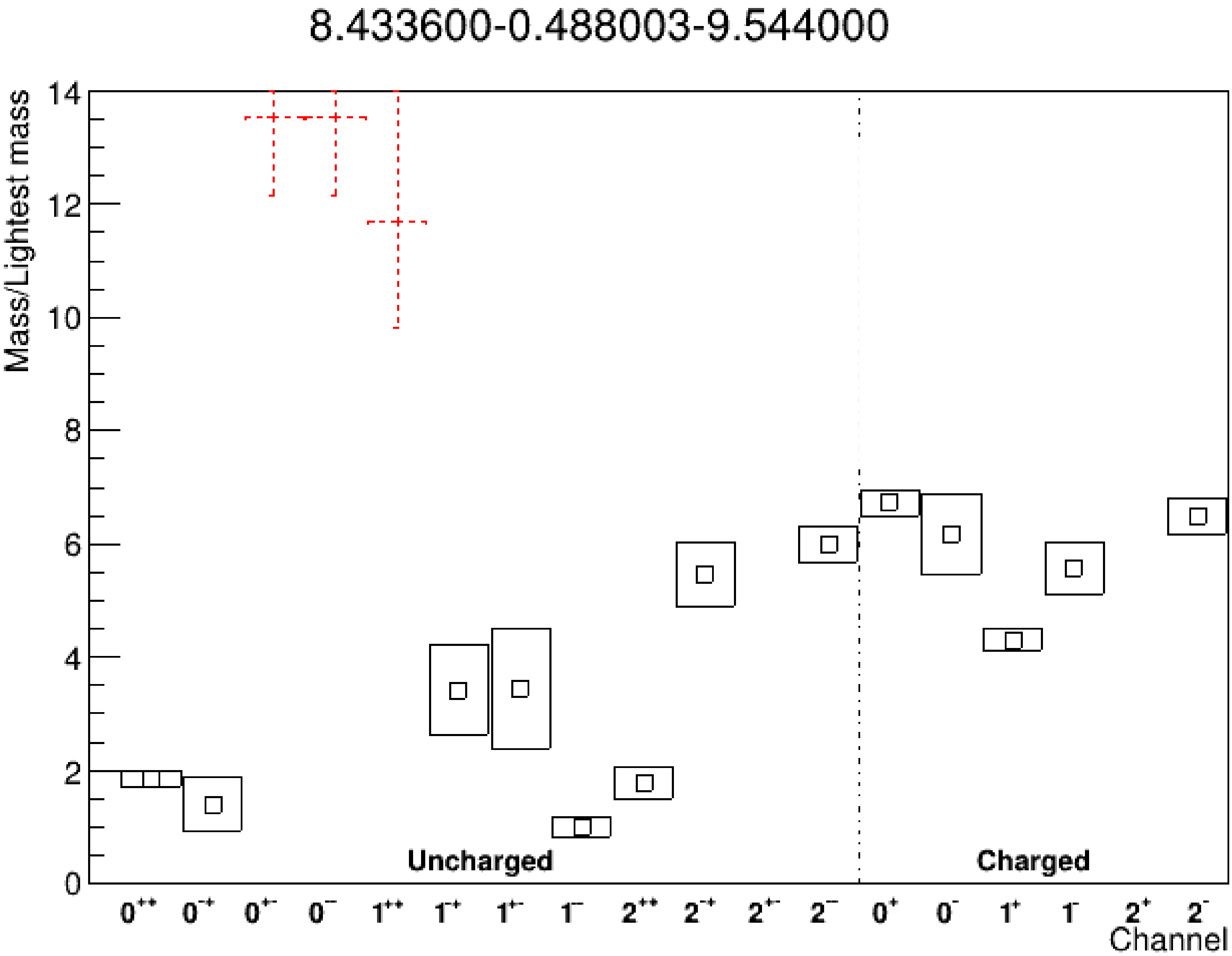

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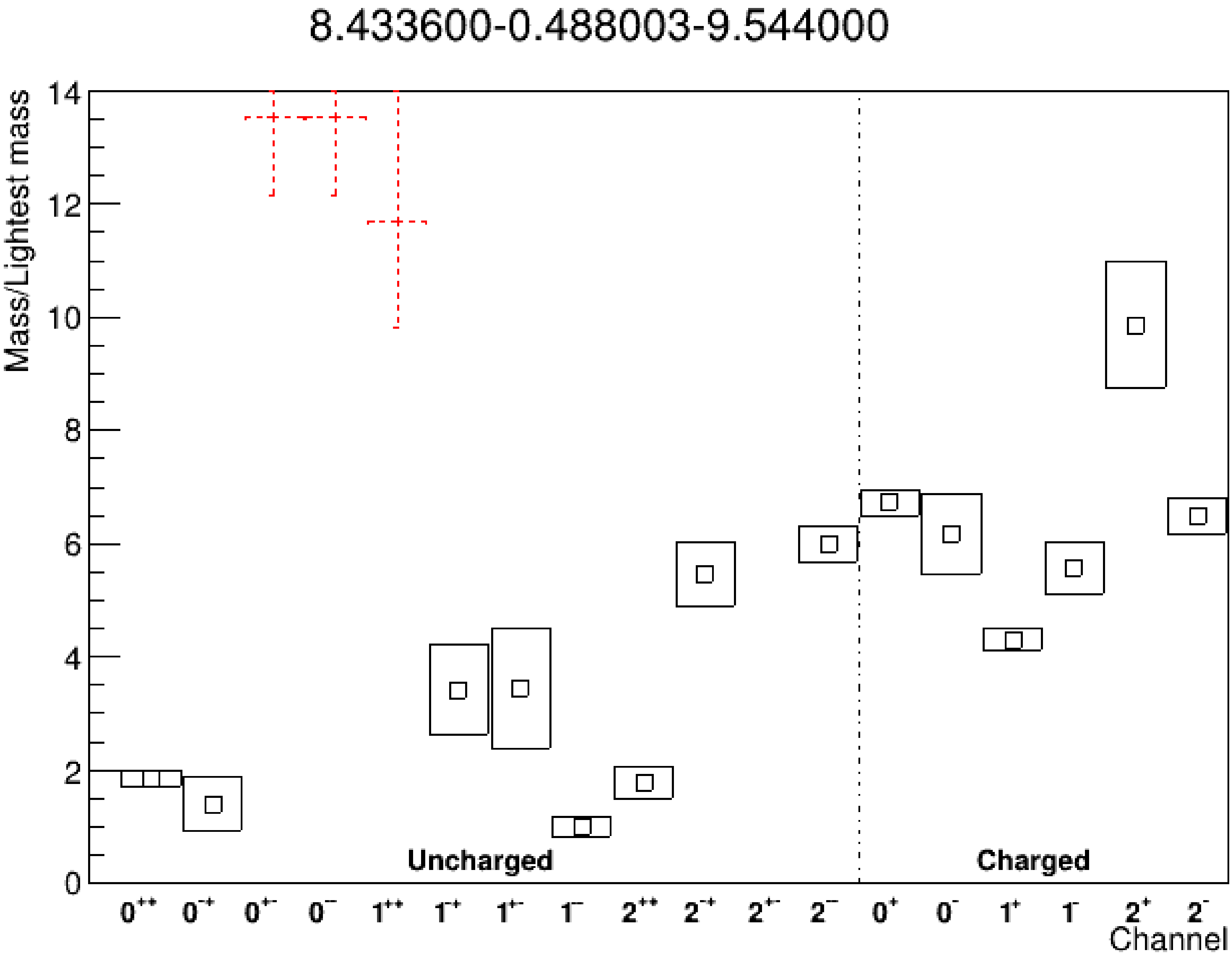

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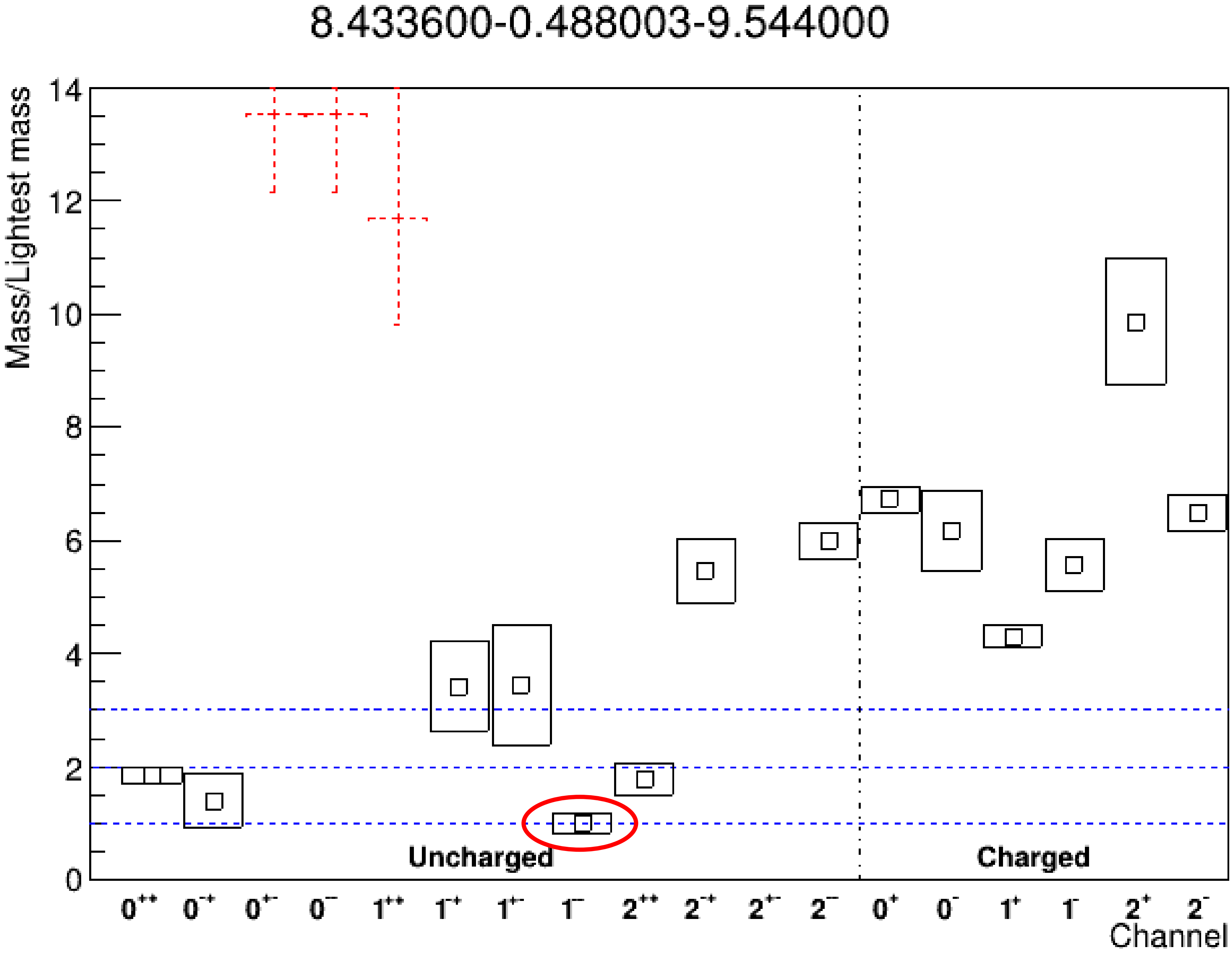

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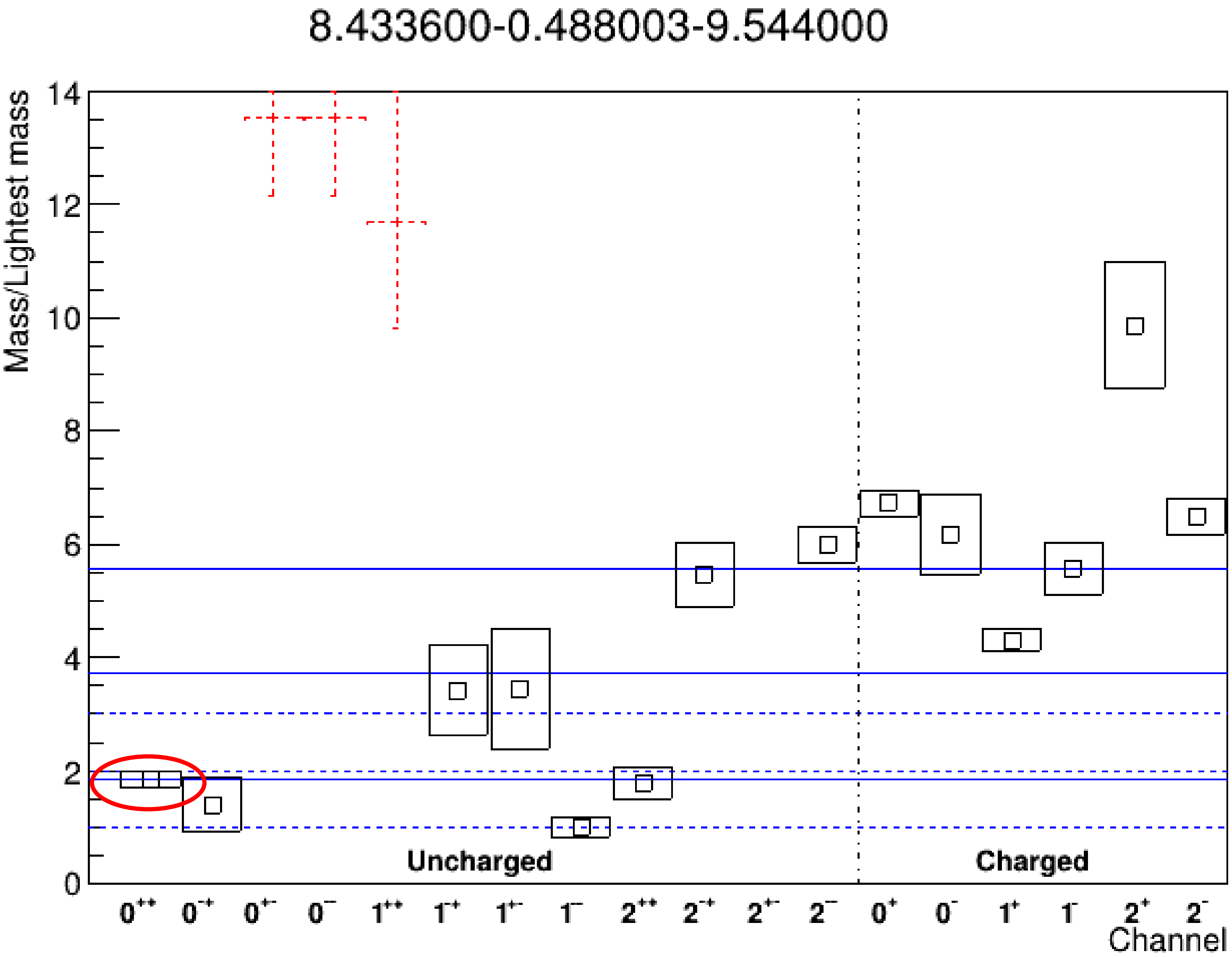

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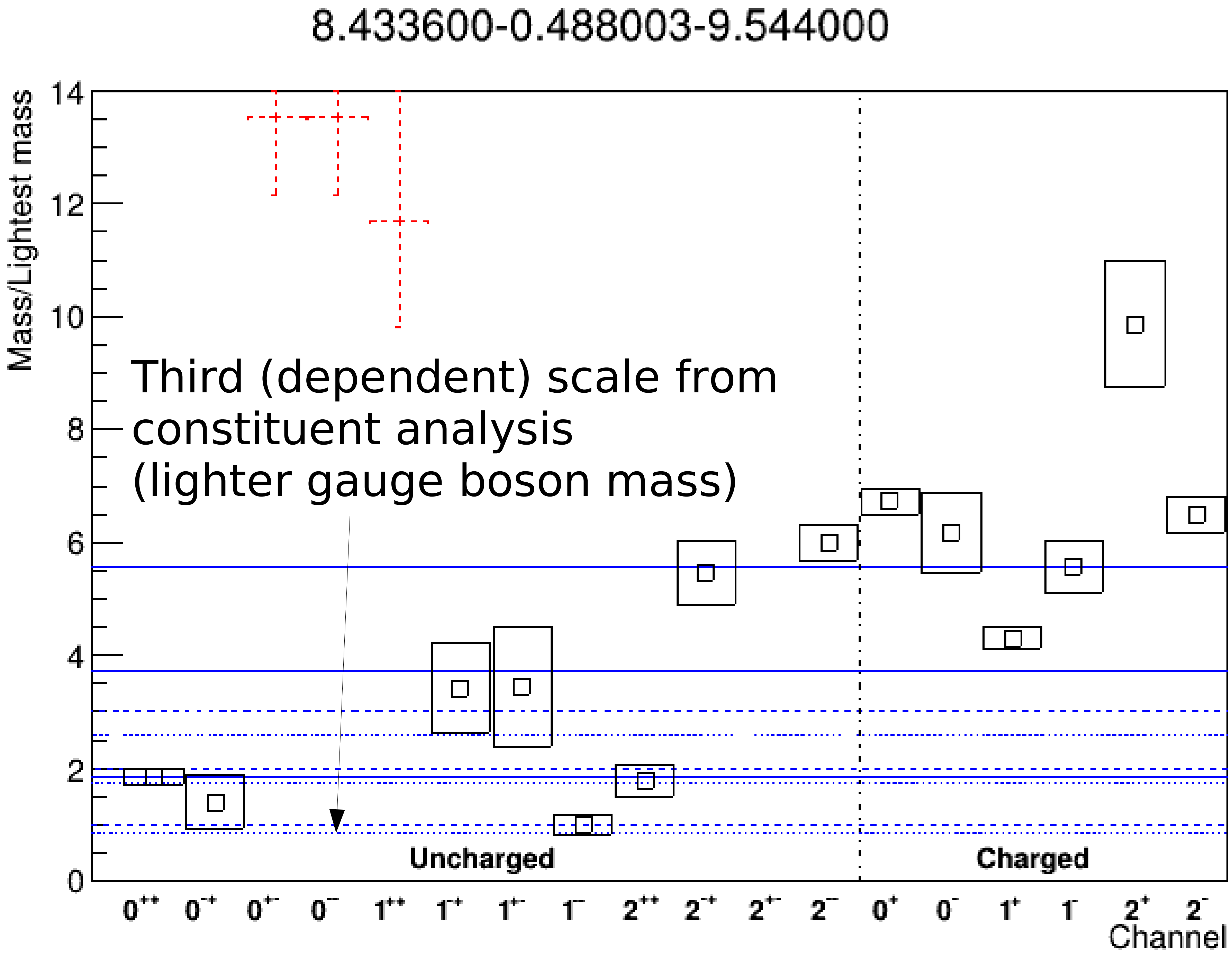

Third (dependent) scale from constituent analysis (lighter gauge boson mass)

Experimental consequences

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[Maas & Török'18
Maas'17]

- Add fundamental fermions

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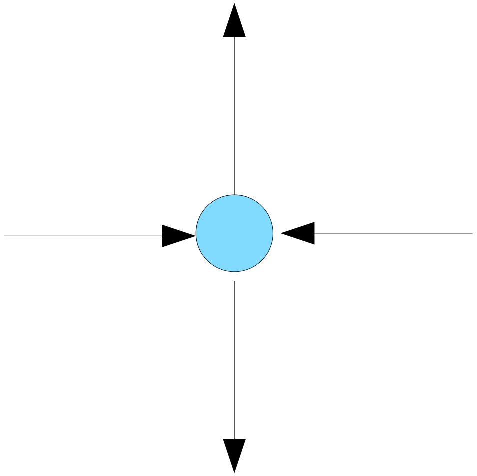

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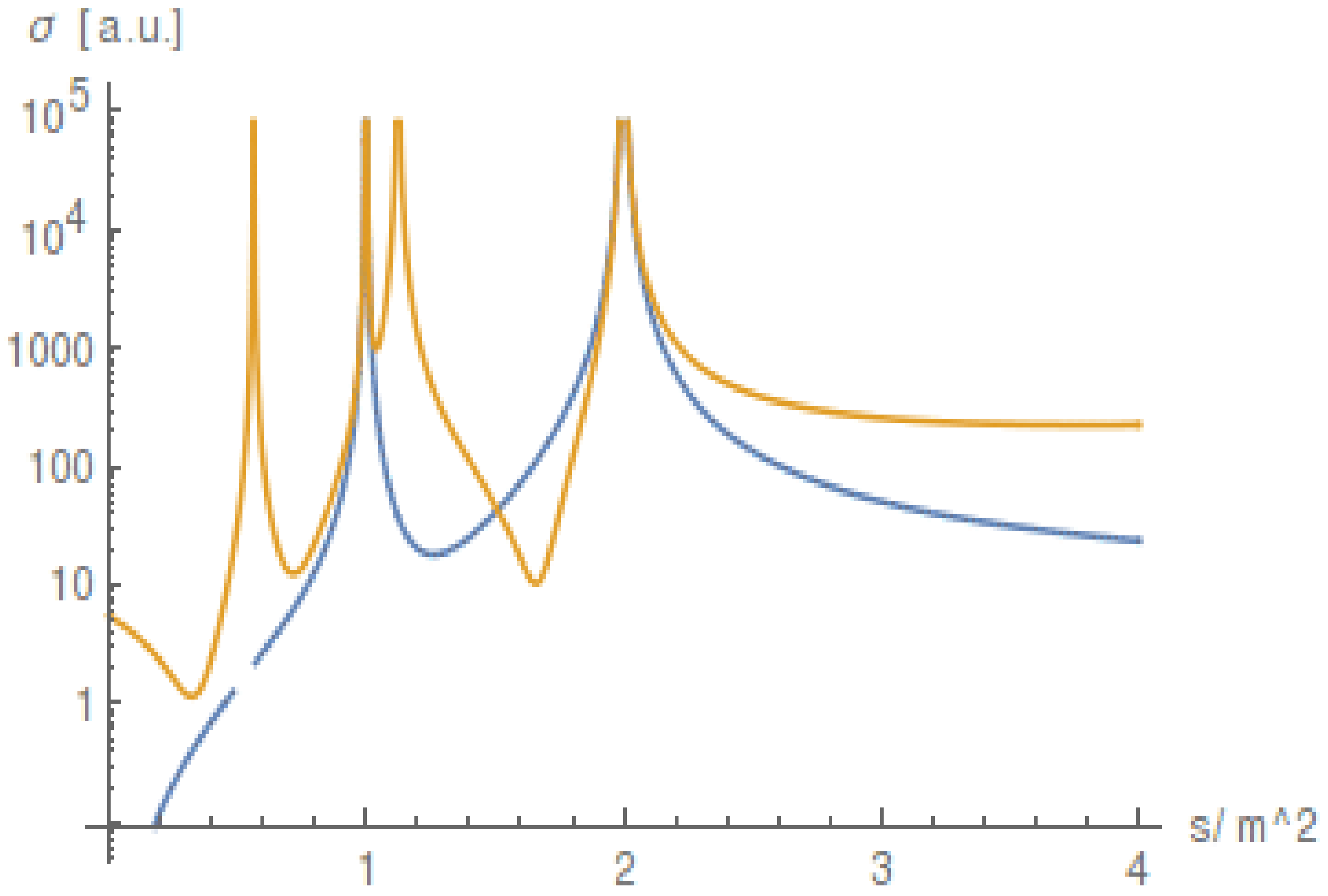

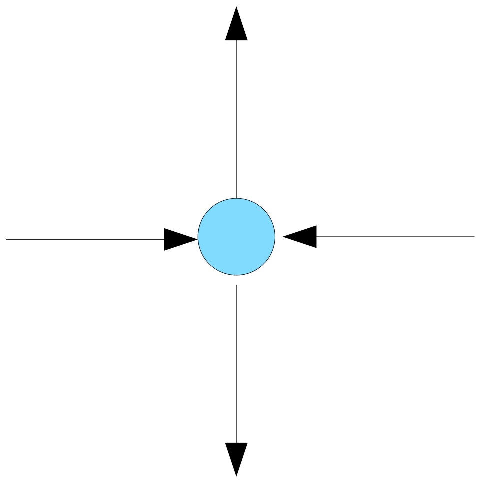

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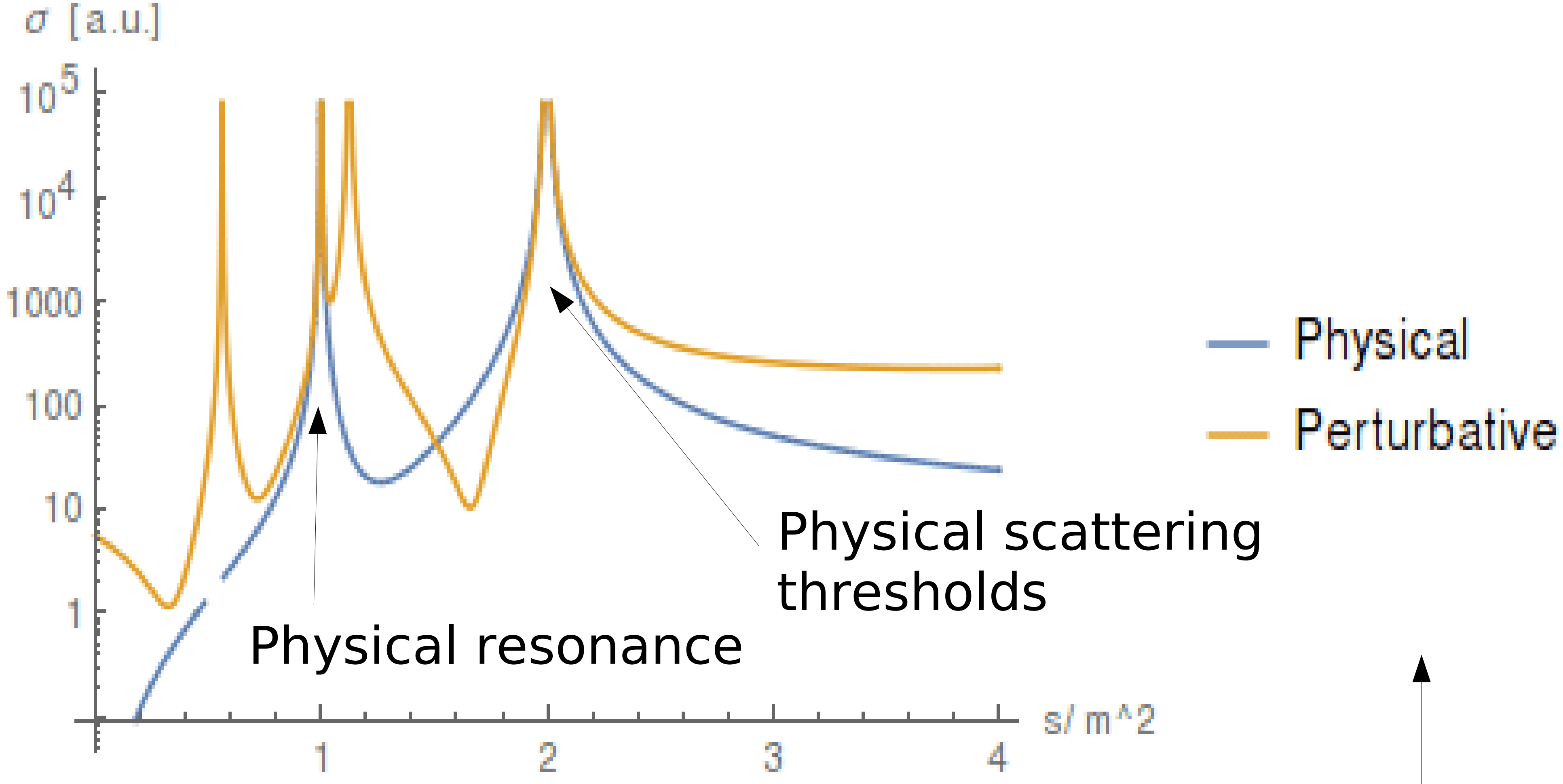
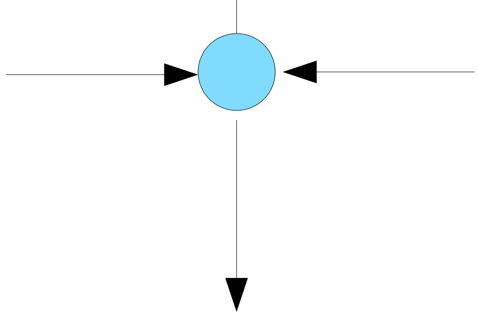


Physical scattering thresholds

Physical resonance



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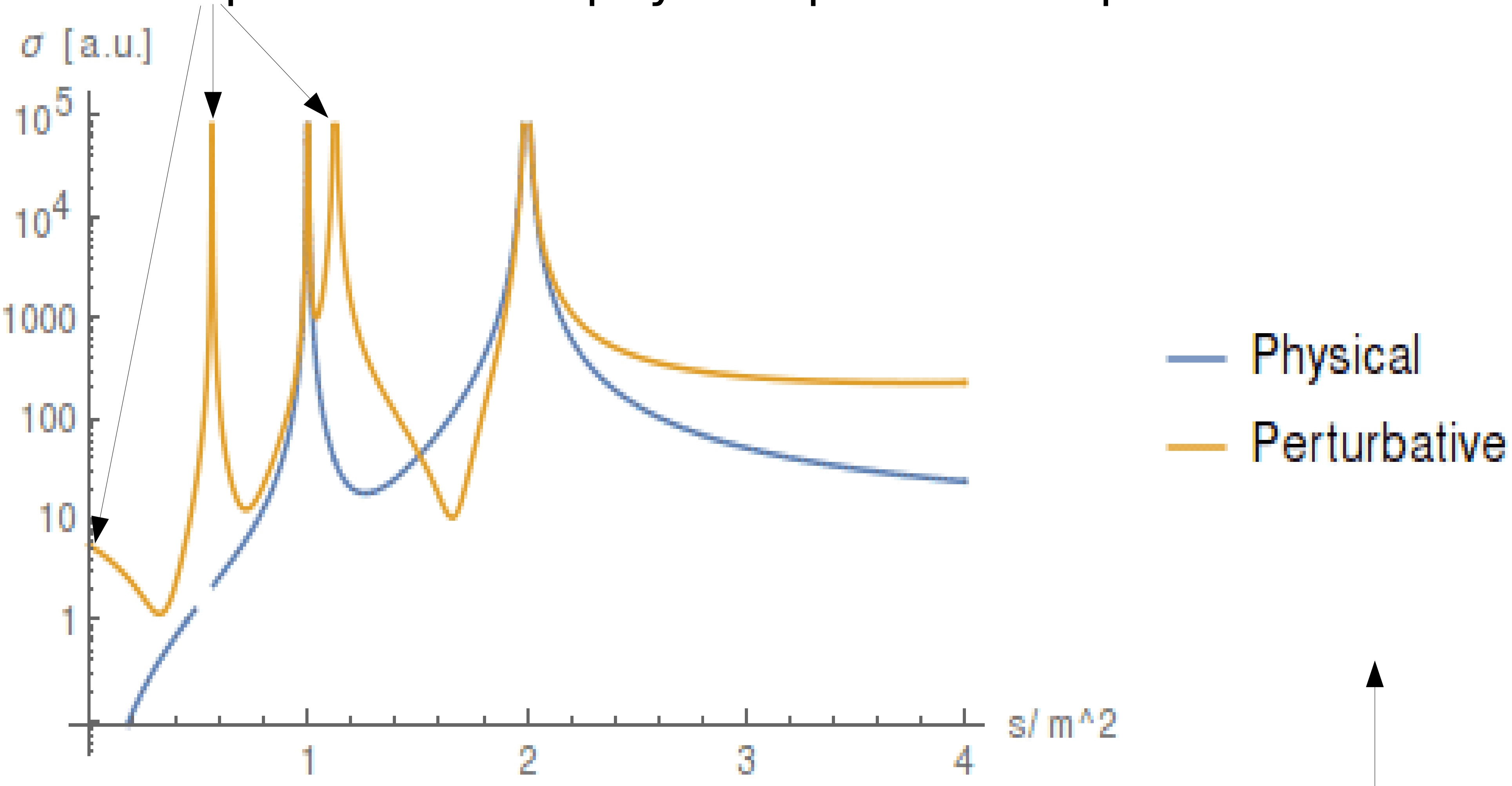
Maas'17]

Ghost peaks from unphysical particles in perturbation theory



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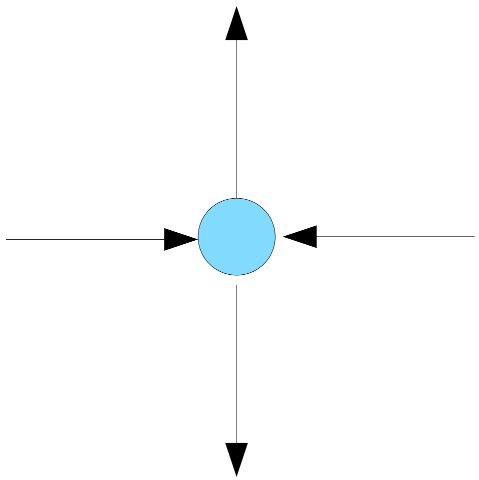
- Bhabha scattering



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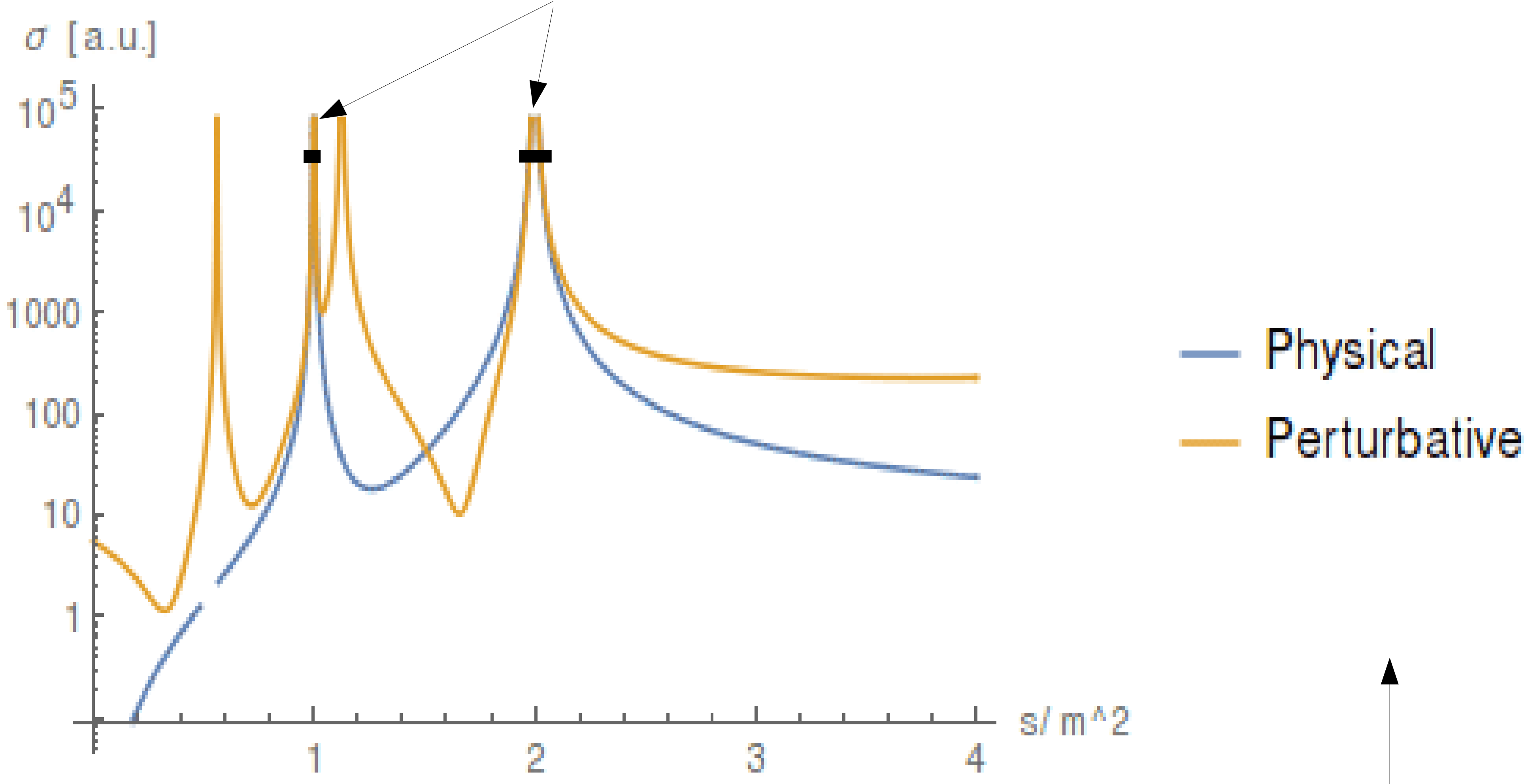
Close to true structures identical!



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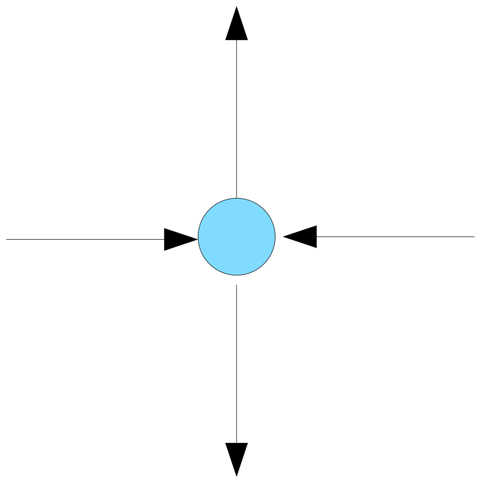

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Quantum gravity

[Maas'19,
Maas, Markl, Müller'22]

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  - Diffeomorphism and local Lorentz
- FMS mechanism applicable
  - A 'BEH effect' for gravity
  - Technically much more involved
  - First predictions agree with dynamical triangulation results [Dai et al.'21]

Supergravity

[Maas'23]

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- FMS mechanism as applicable as to quantum gravity

Summary

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Review: 1712.04721 Update: 2305.01960

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Summary

- Full invariance necessary for physical observables in path integrals
- FMS mechanism allows estimates of quantum effects in a systematic expansion
- Gives a new perspective on particle physics and quantum gravity

Philosophy of physics perspective: 2110.00616
Review: 1712.04721 Update: 2305.01960

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