

Rethinking Brout-Englert-Higgs Physics

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Belgium



NAWI Graz
Natural Sciences

FWF

Der Wissenschaftsfonds

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 - Gauge-invariant perturbation theory
 - Checking its validity

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- Review: 1712.04721

Why it is not obvious that the Higgs and W/Z are physical particles

Or: What states can be gauge-invariant

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- Coupling g and some numbers f^{abc}



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

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- Local SU(2) gauge symmetry

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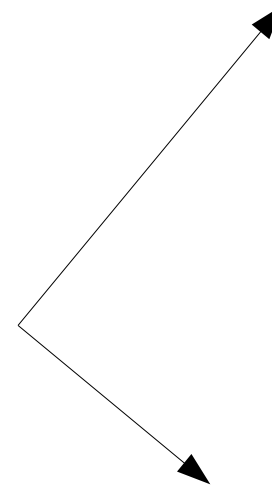
Gauge symmetry - a reminder

- A gauge symmetry allows to choose a coordinate system for the symmetry



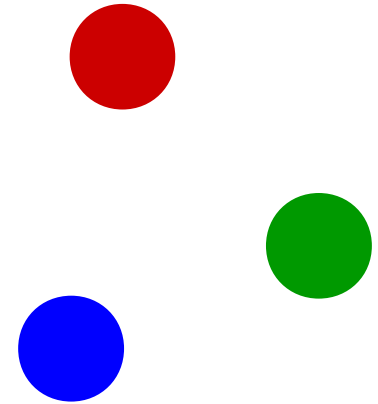
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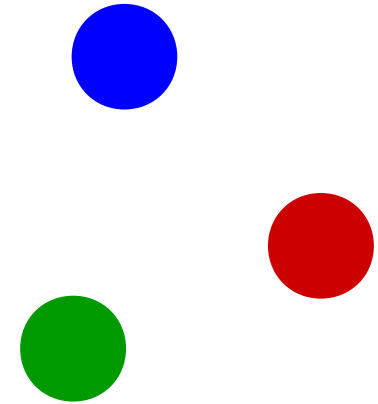
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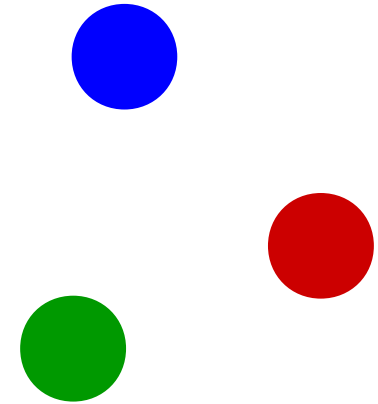
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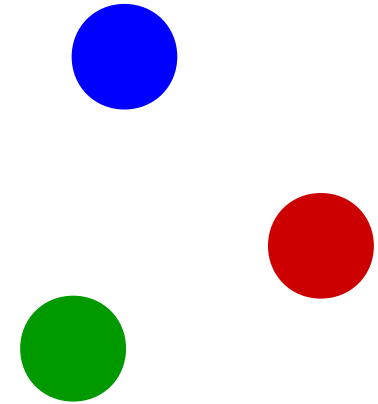
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- Human choice



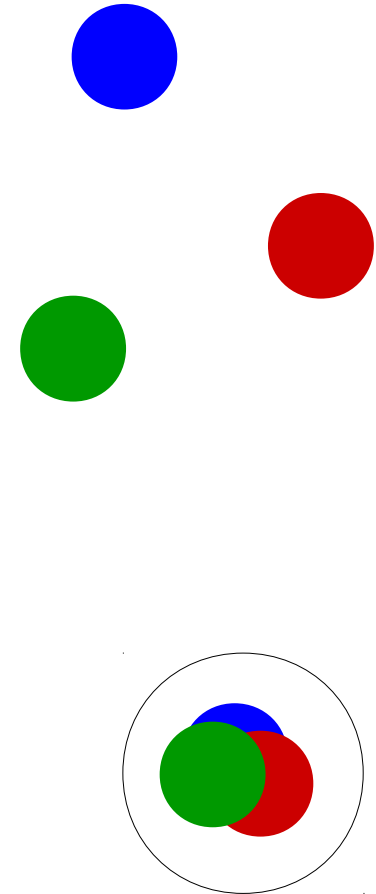
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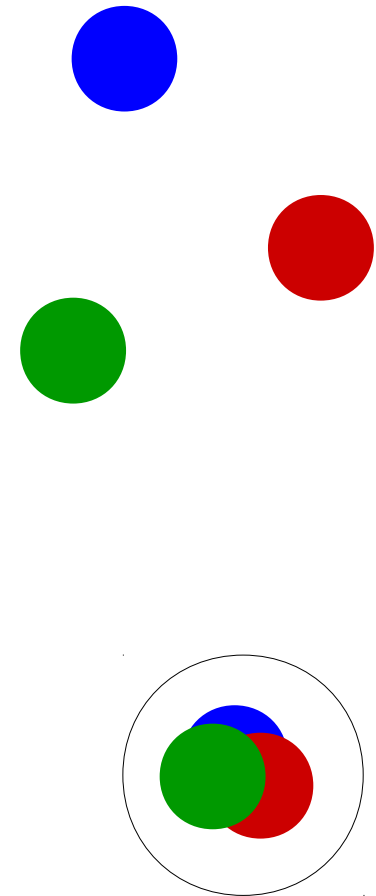
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- E.g. in QCD: Choose what is red, green, and blue at every point differently
- Human choice: Physics cannot depend on it – only what is independent of the choice is physical
- Field theory: Cannot be prohibited/broken [Elitzur'74]



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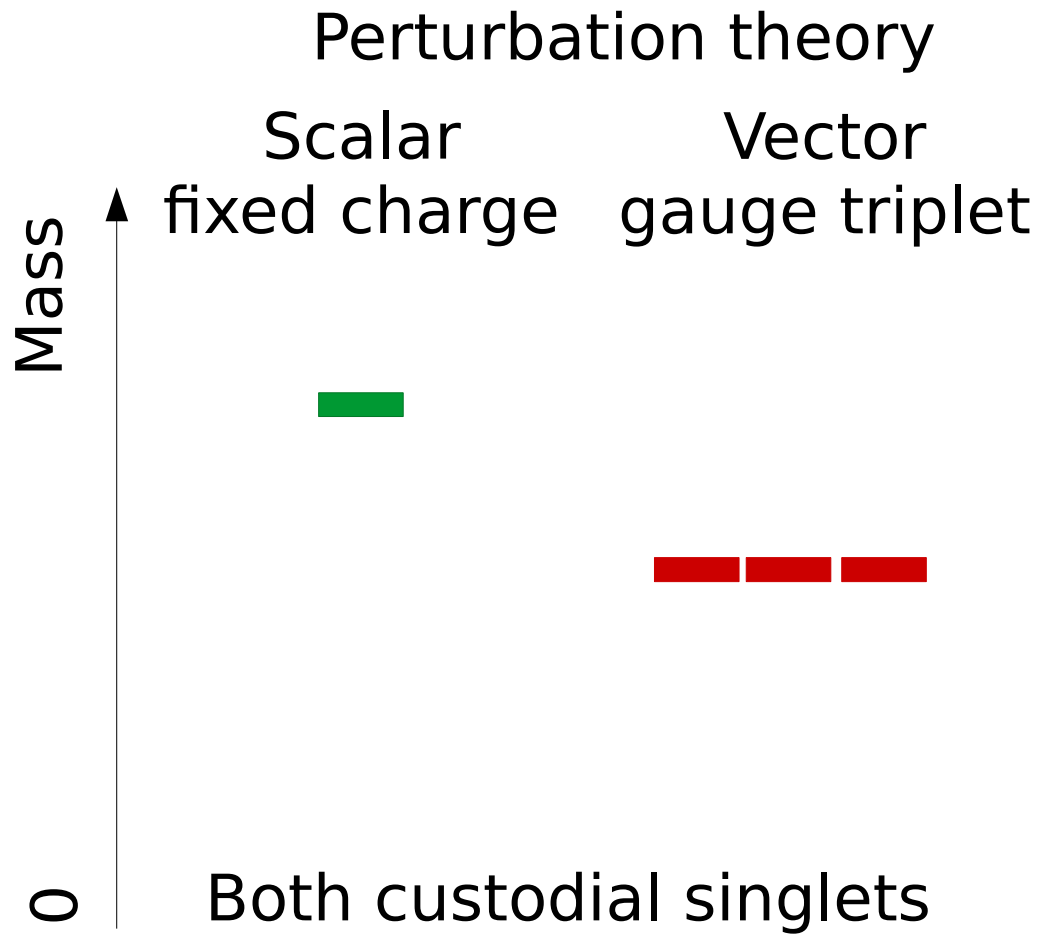
$$W_\mu^a \rightarrow W_\mu^a + (\delta_b^a \partial_\mu - g f_{bc}^a W_\mu^c) \phi^b \qquad h_i \rightarrow h_i + g t_a^{ij} \phi^a h_j$$

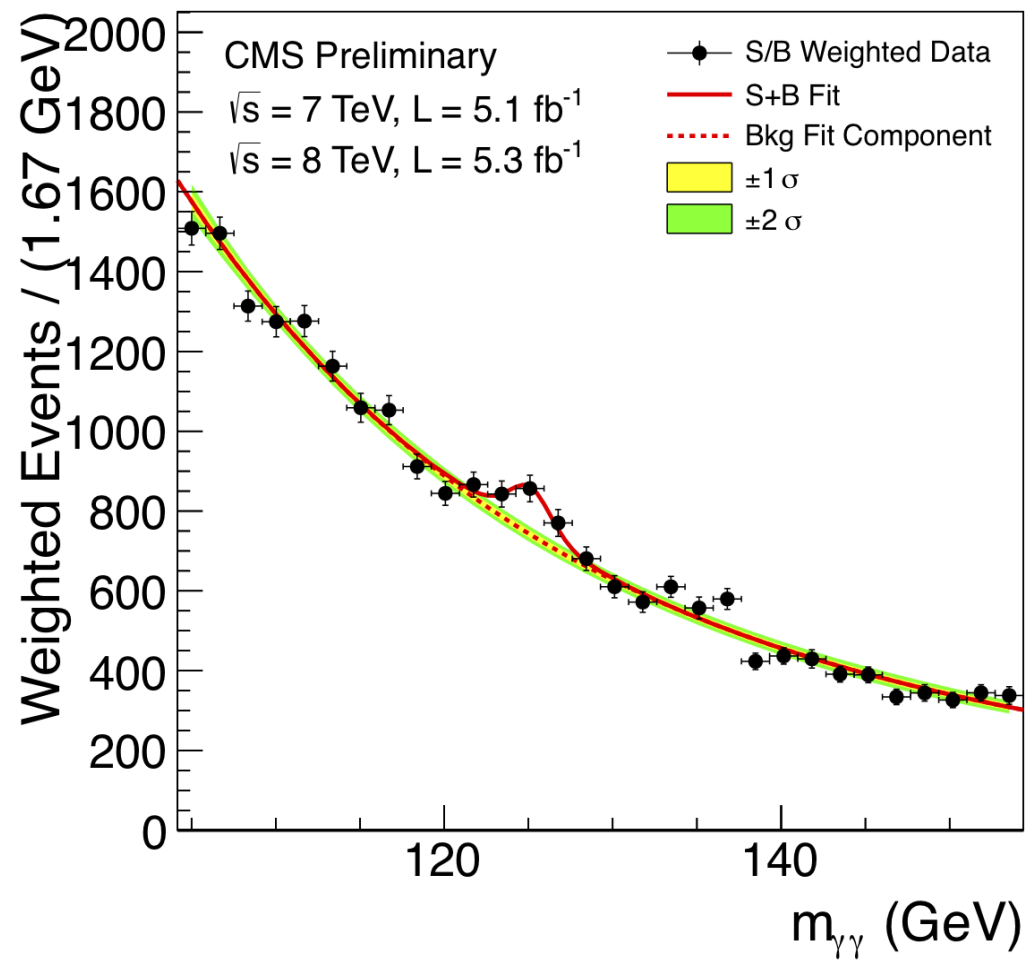
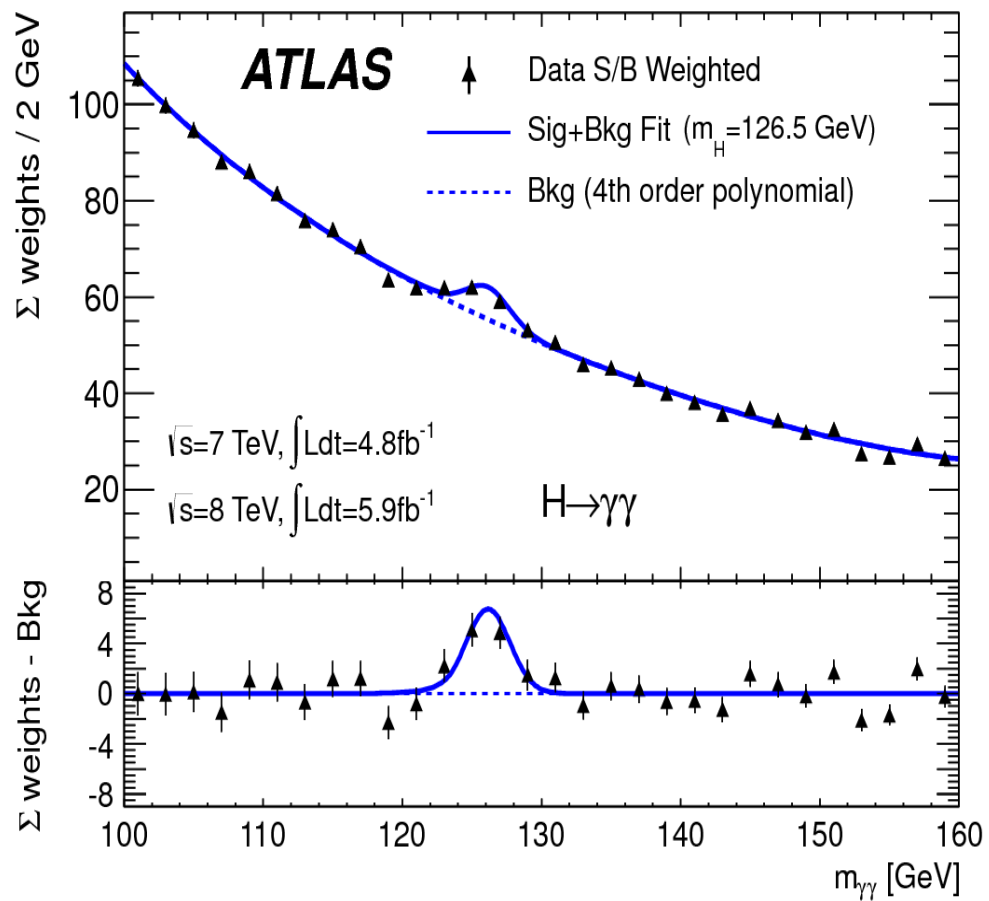
- Global SU(2) Higgs custodial (flavor) symmetry

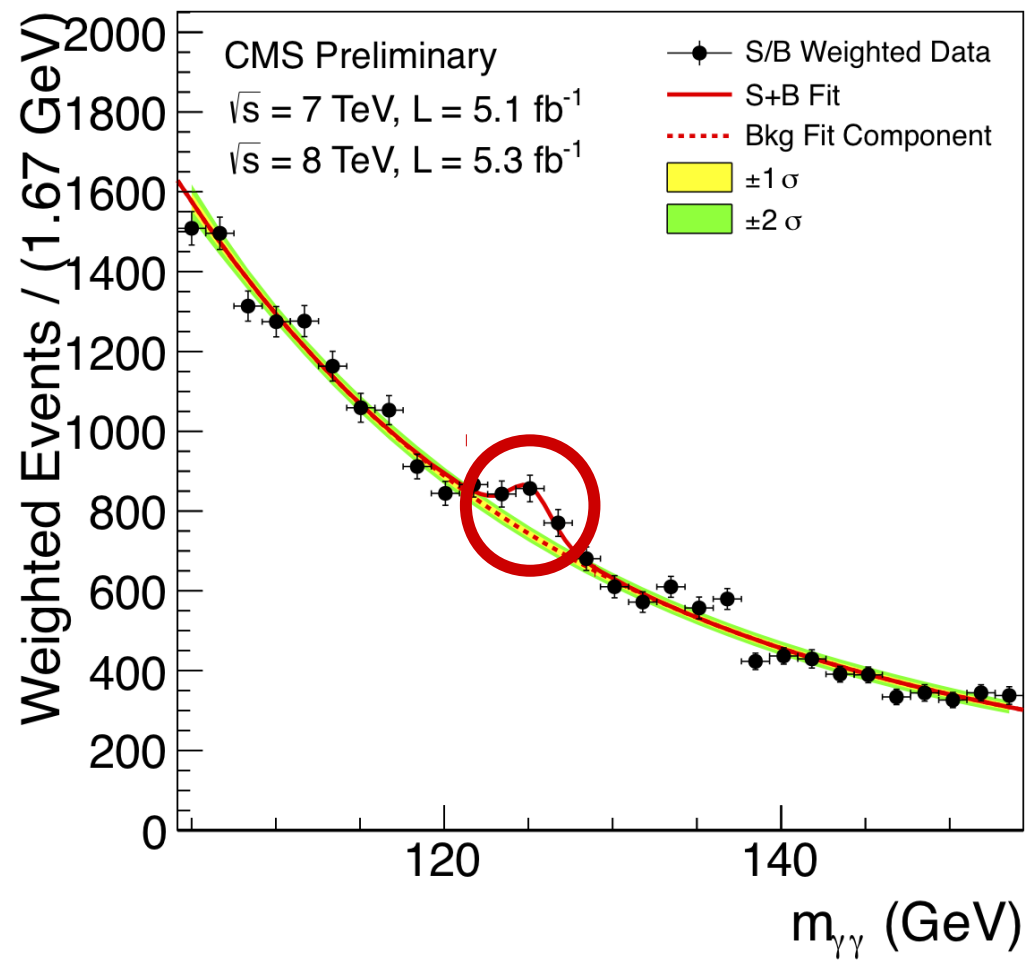
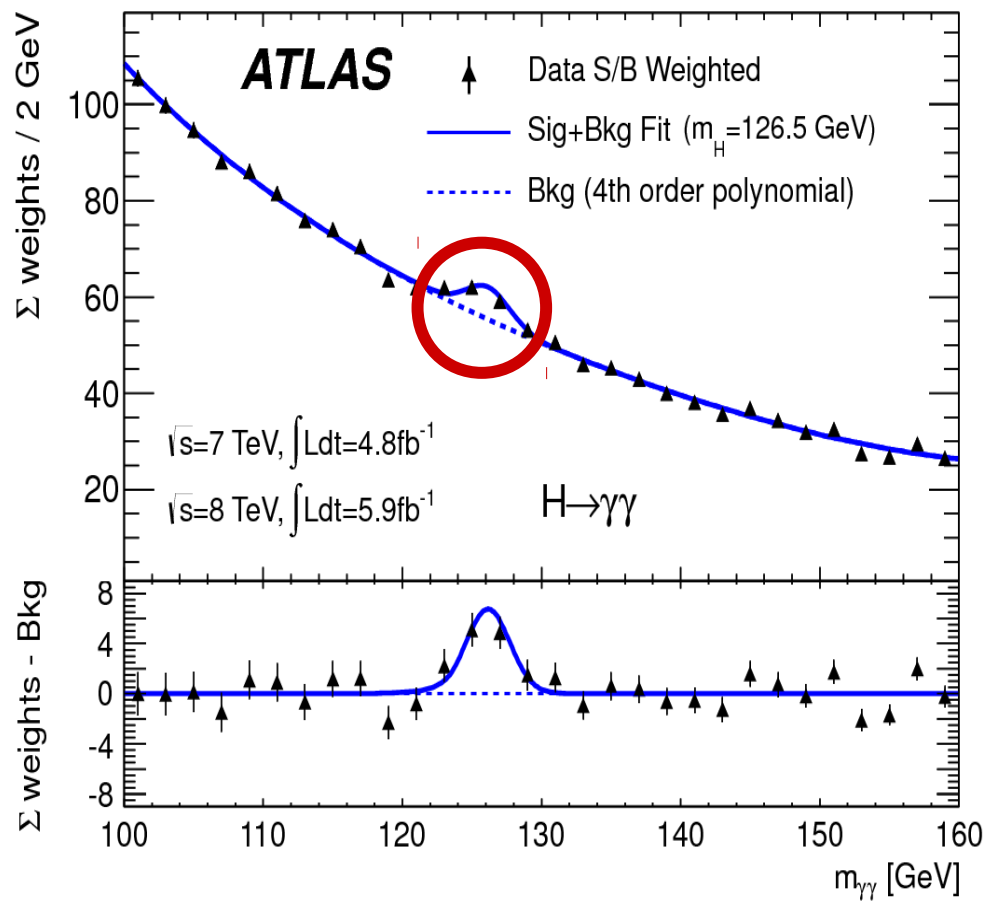
- Acts as (right-)transformation on the Higgs field only

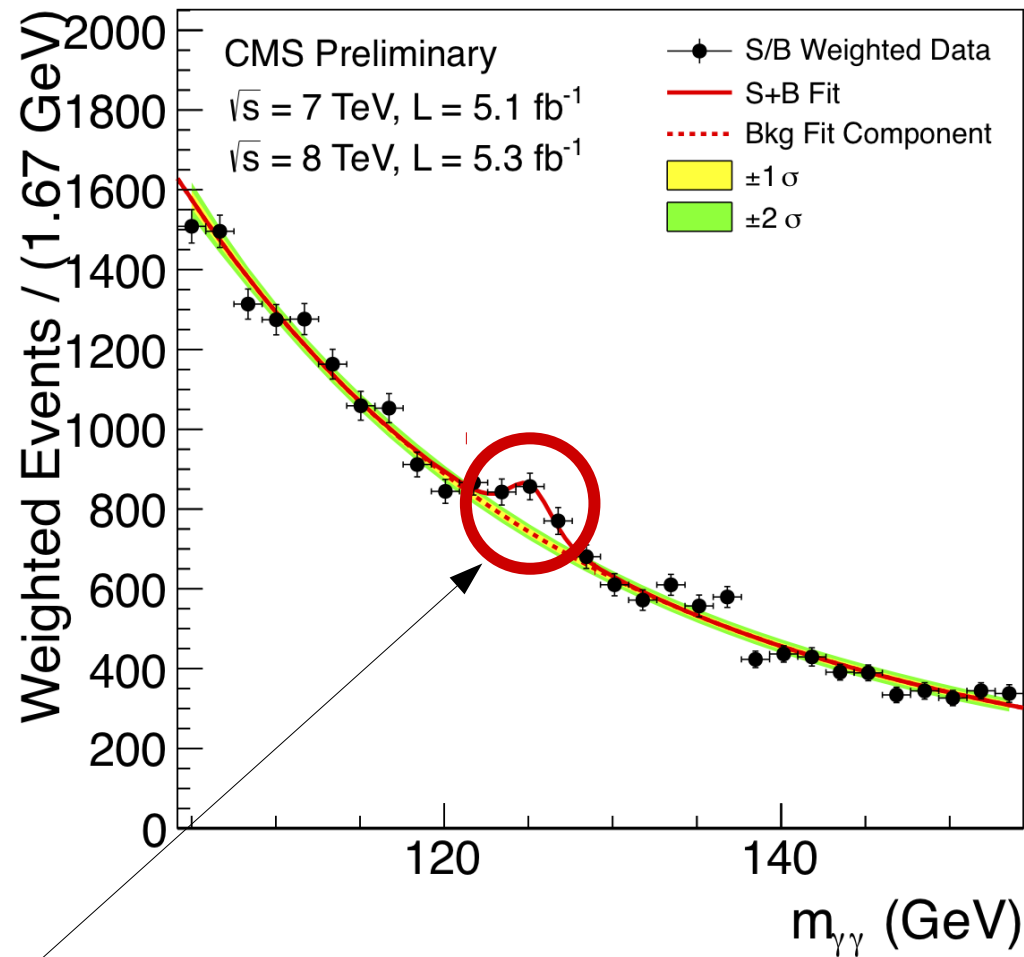
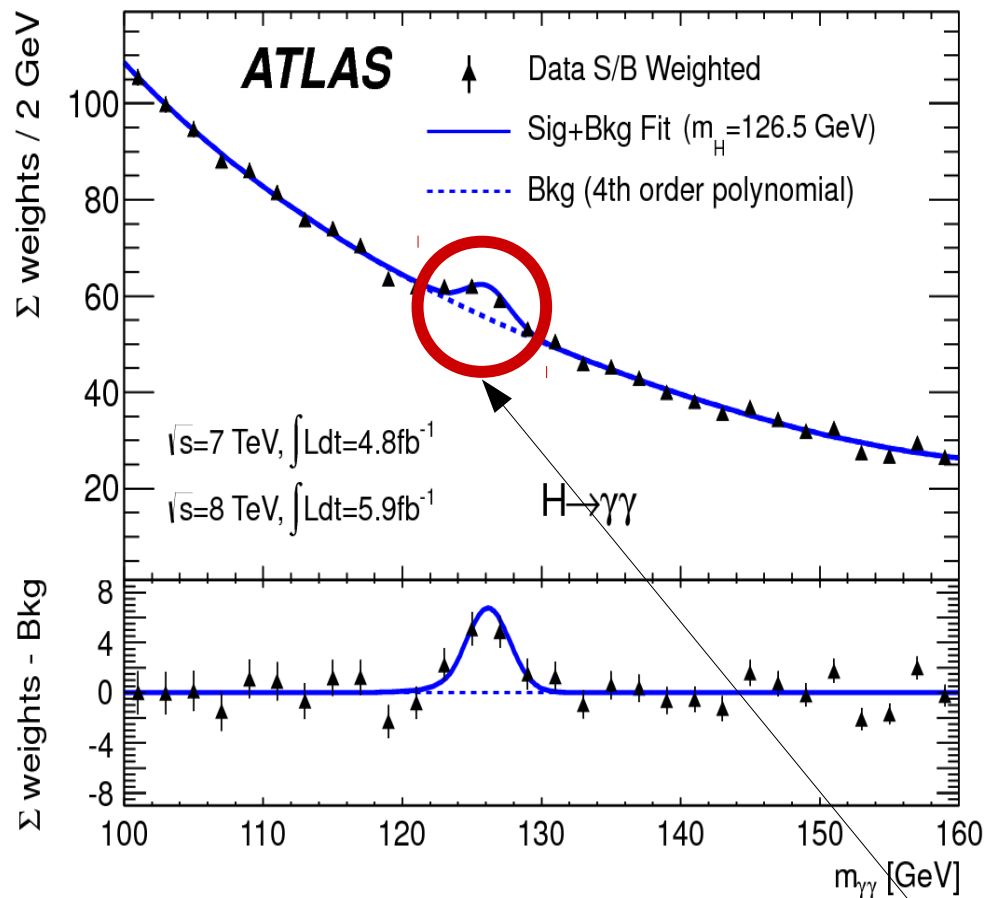
$$W_\mu^a \rightarrow W_\mu^a \qquad h_i \rightarrow h_i + a^{ij} h_j + b^{ij} h_j^*$$

Physical spectrum



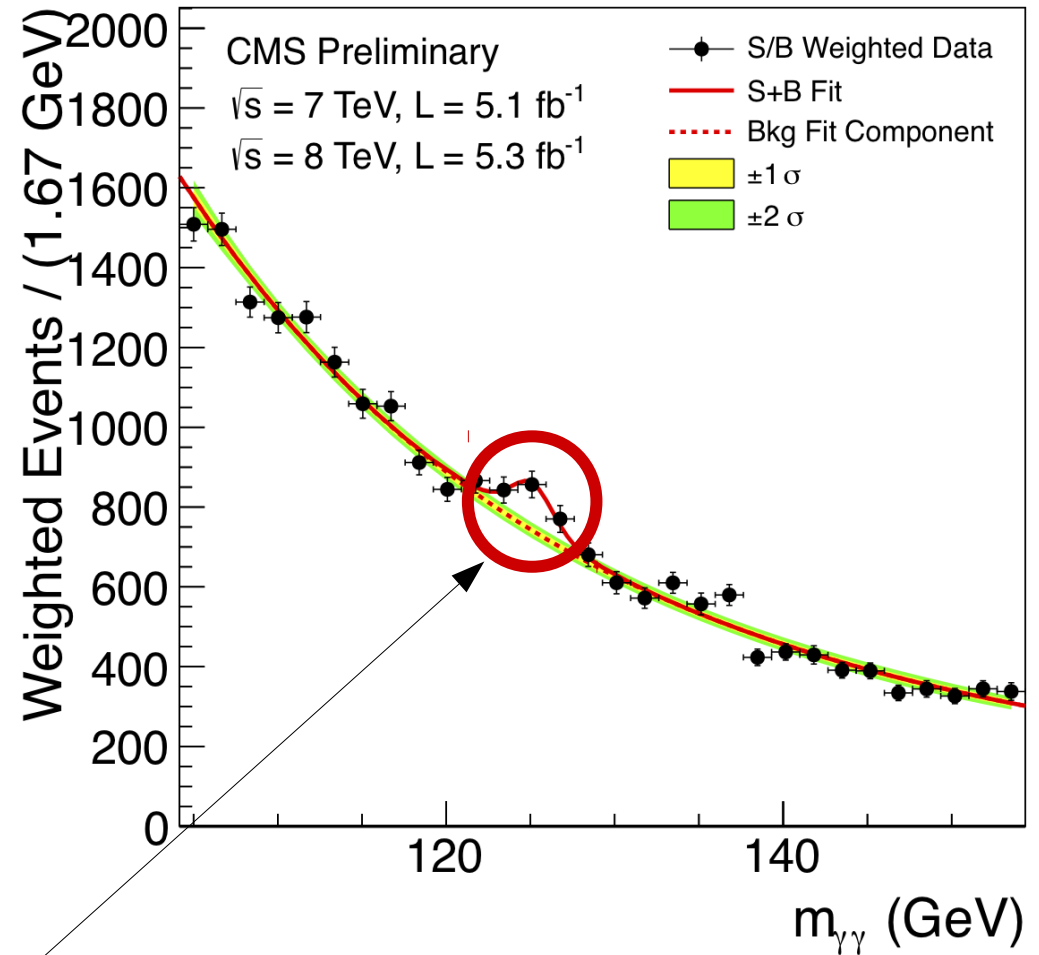
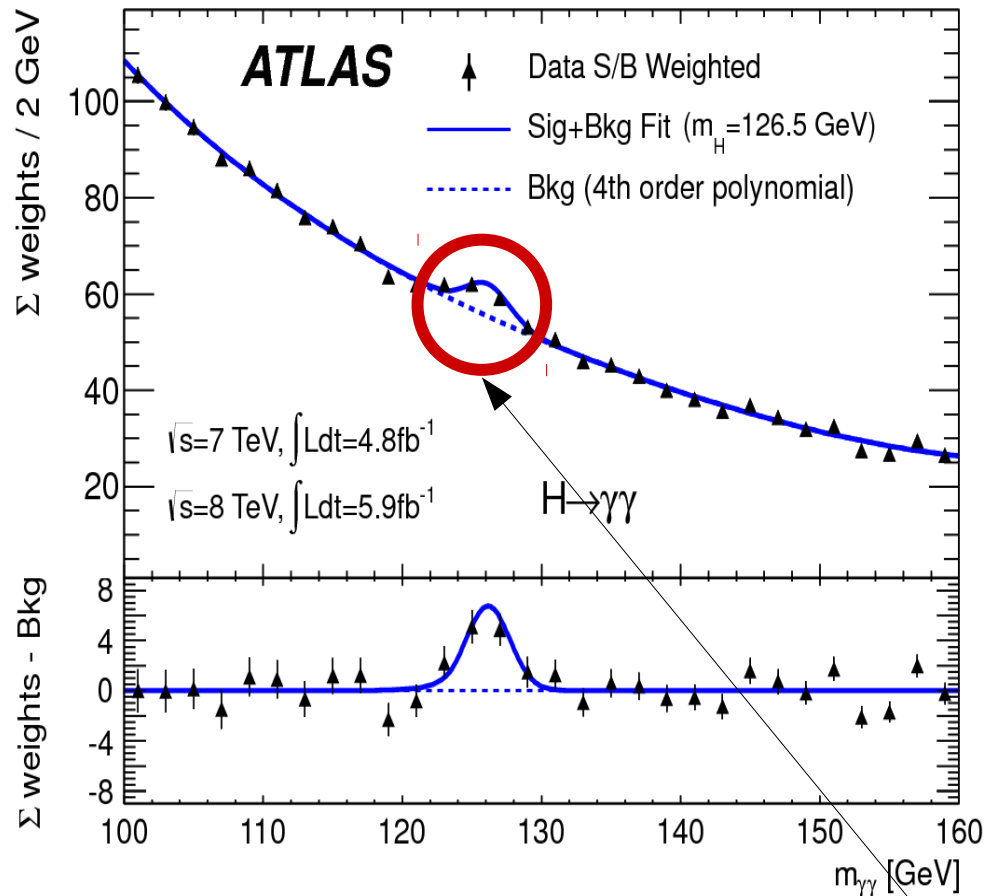






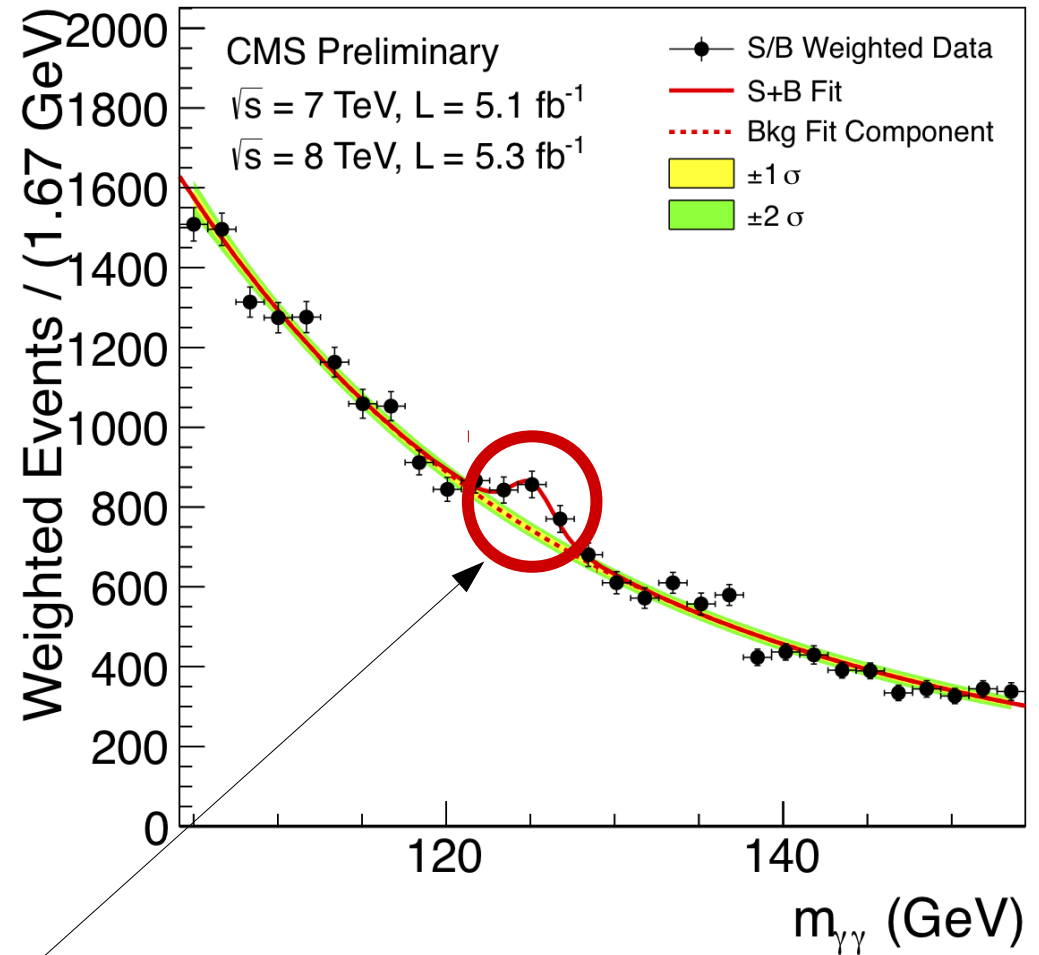
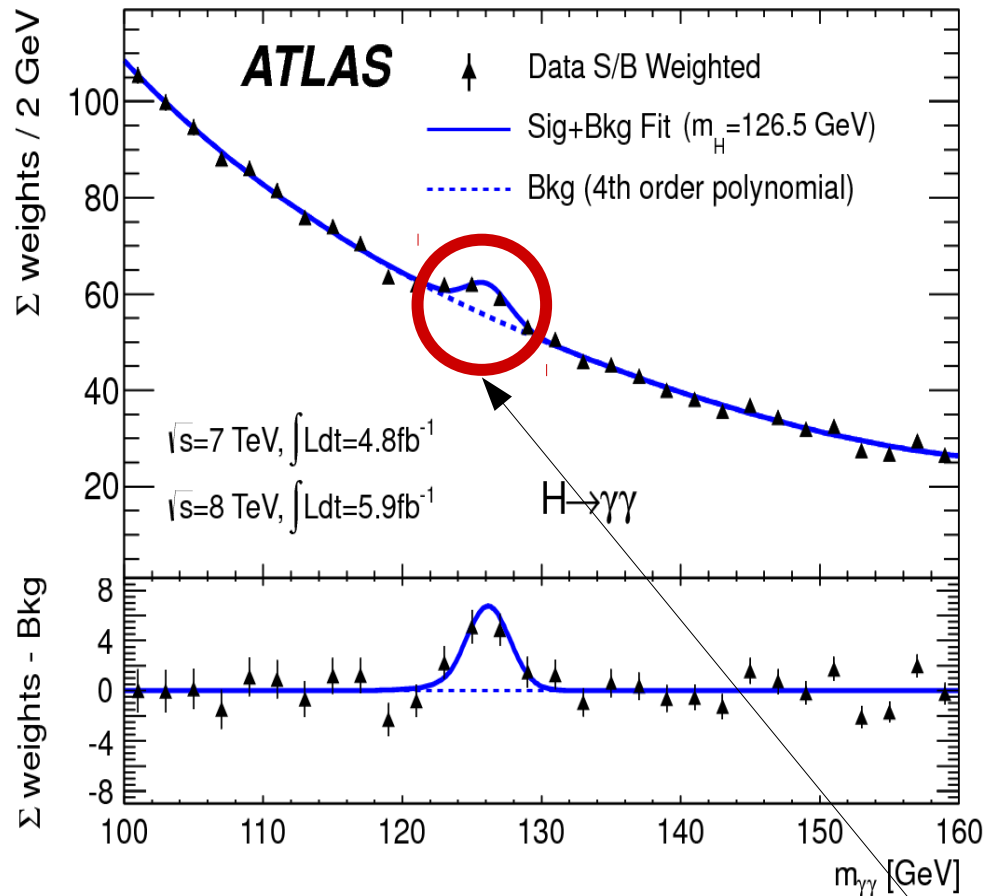
What did we see here?

What is seen in experiment?



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Is this **really** the Higgs?

What is seen in experiment?



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Is this **really** the Higgs?

Higgs depends on the gauge choice!

Physical states

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

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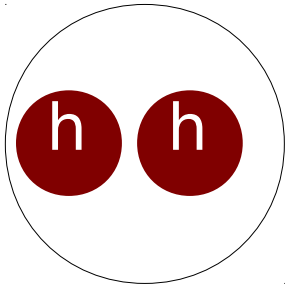
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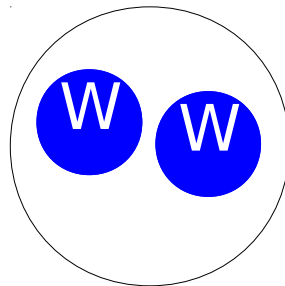
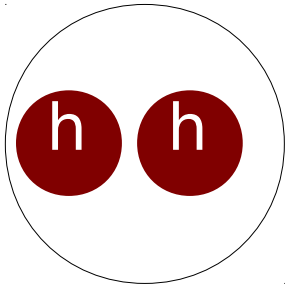
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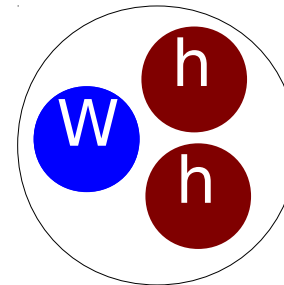
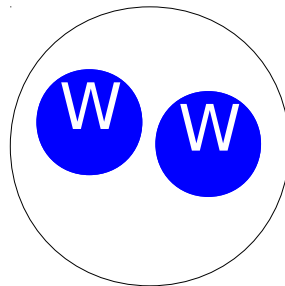
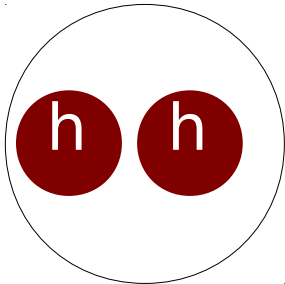
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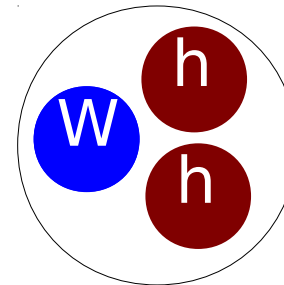
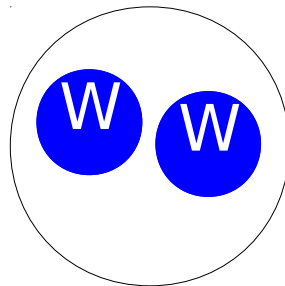
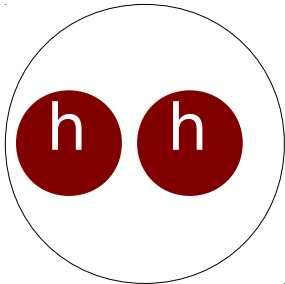
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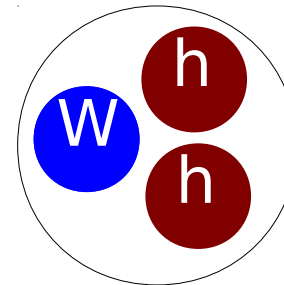
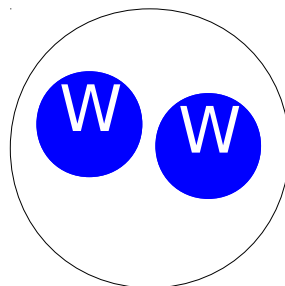
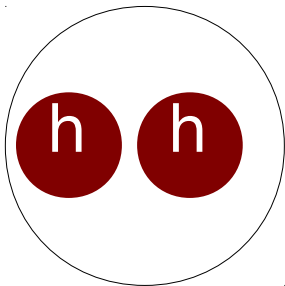


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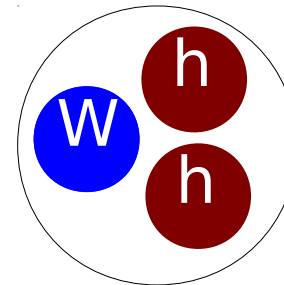
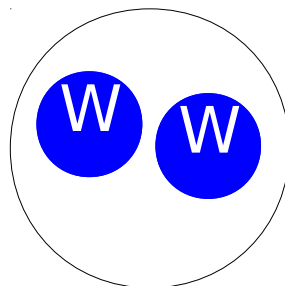
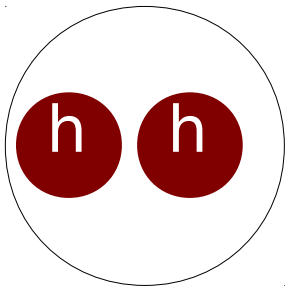


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- Can this matter?

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The full answer requires a full solution: Lattice

Why it does (almost) not matter in the standard model

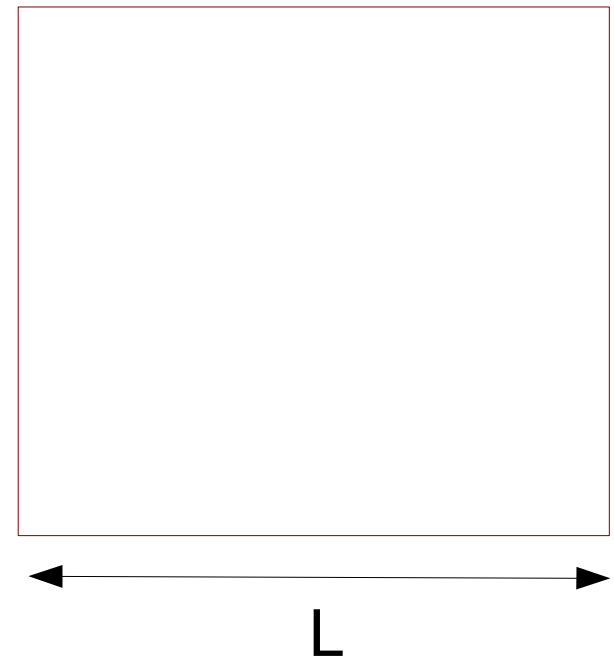
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But can be simplified afterwards:

Introducing gauge-invariant perturbation theory

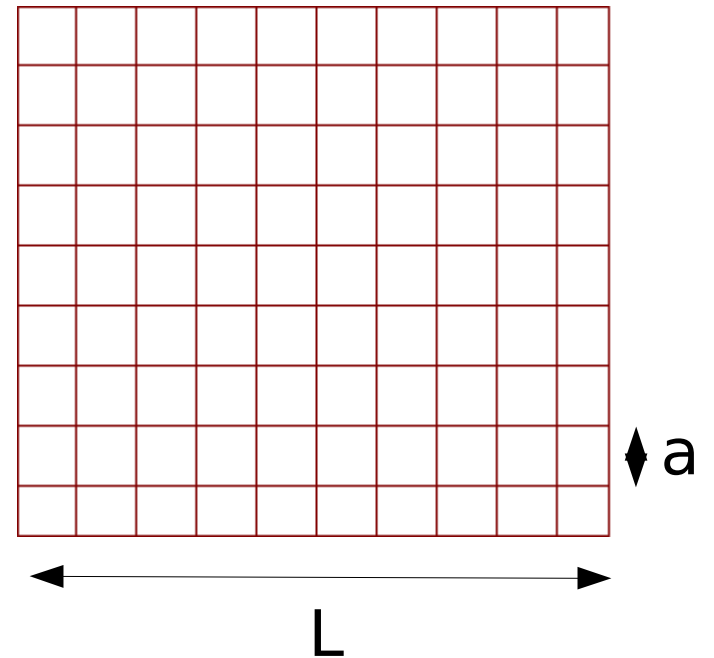
Lattice calculations

- Take a **finite volume** - usually a hypercube



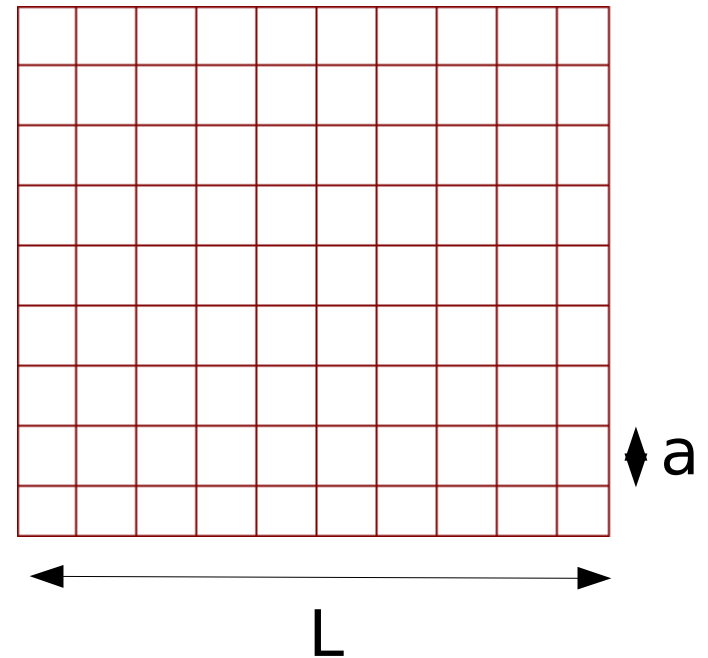
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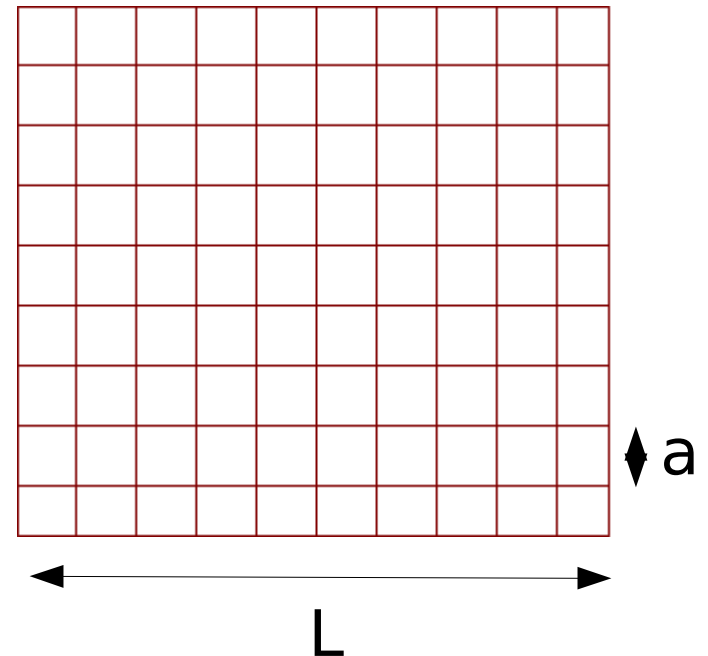
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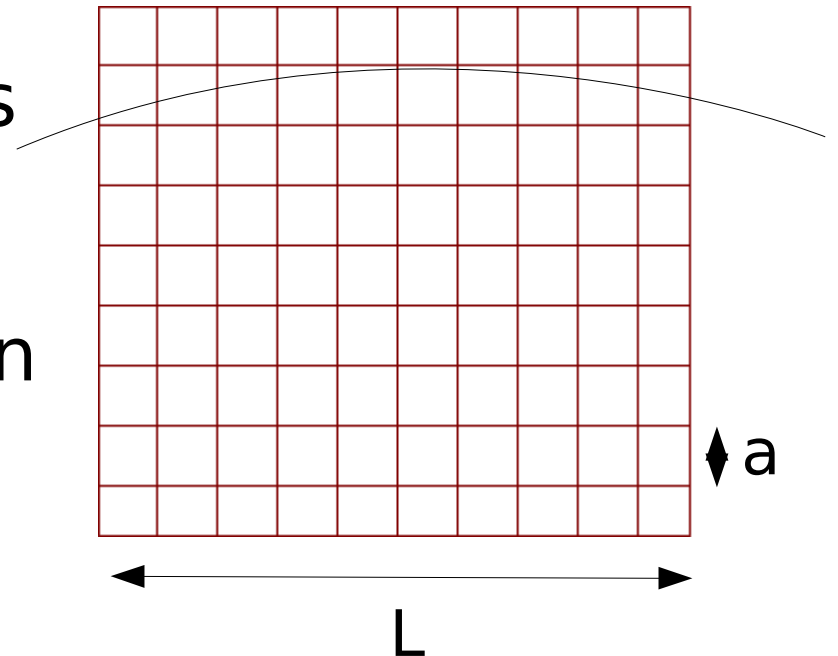
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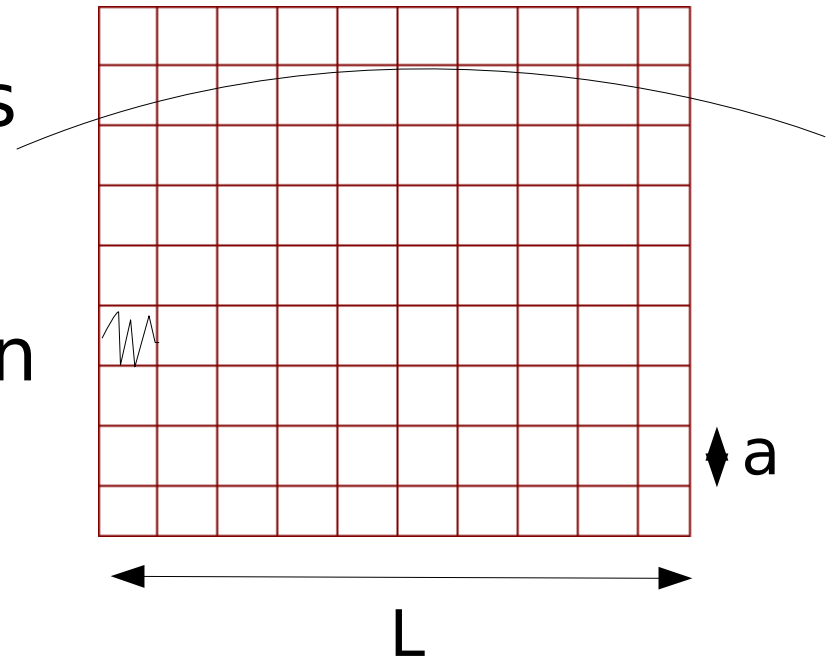
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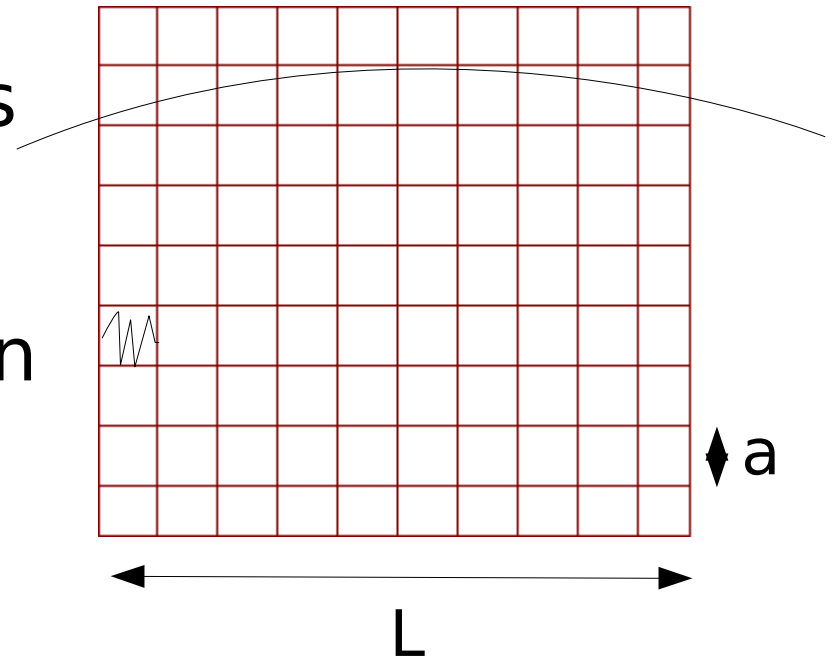
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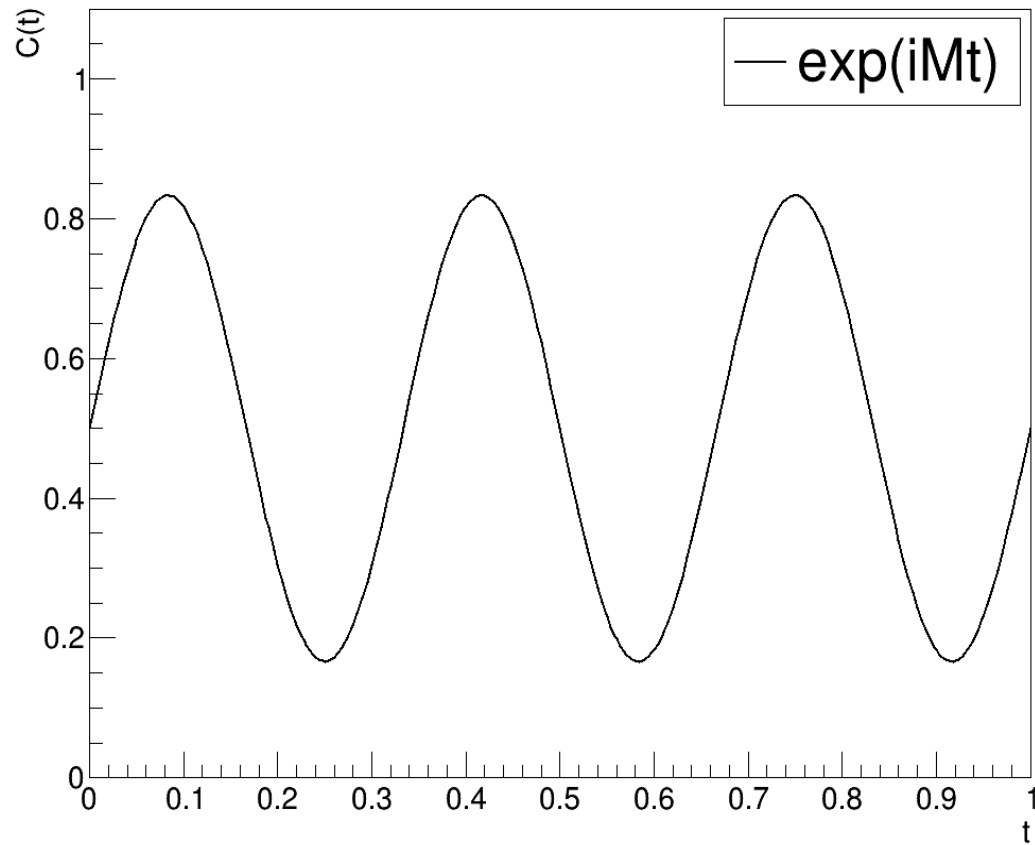
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 - Euclidean formulation



Masses from the lattice

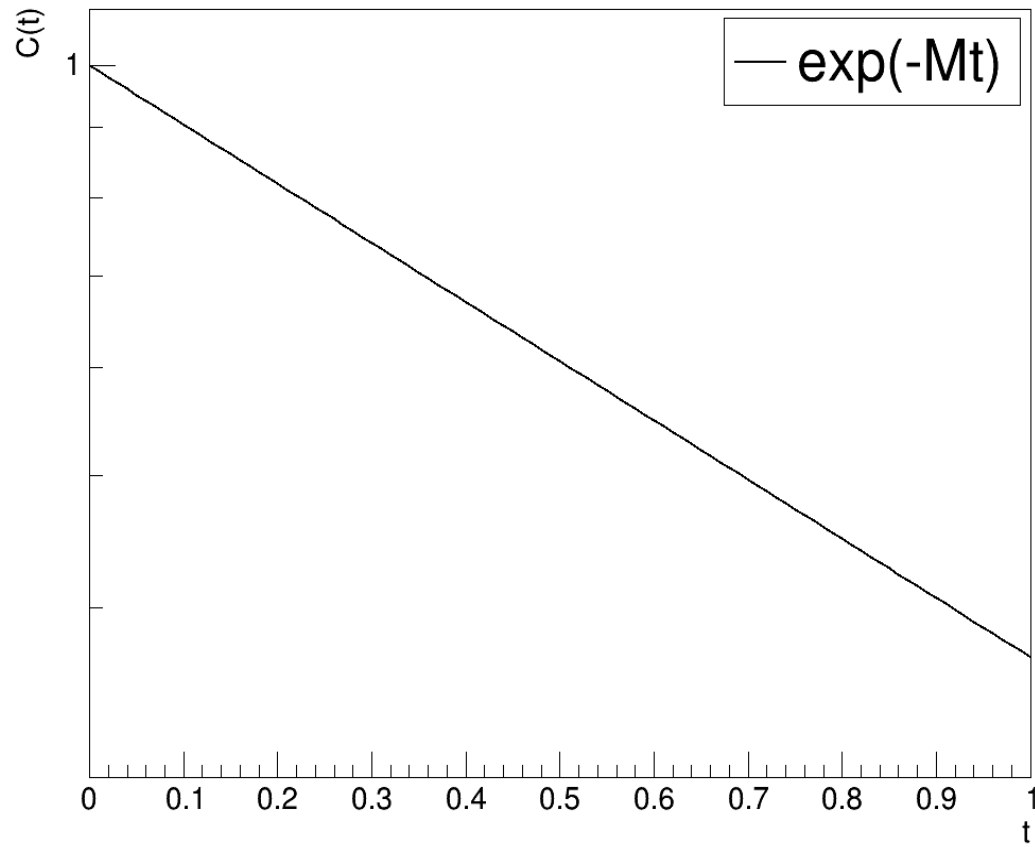
Wave-function - Minkowski



- Masses from 'wave-functions'

Masses from the lattice

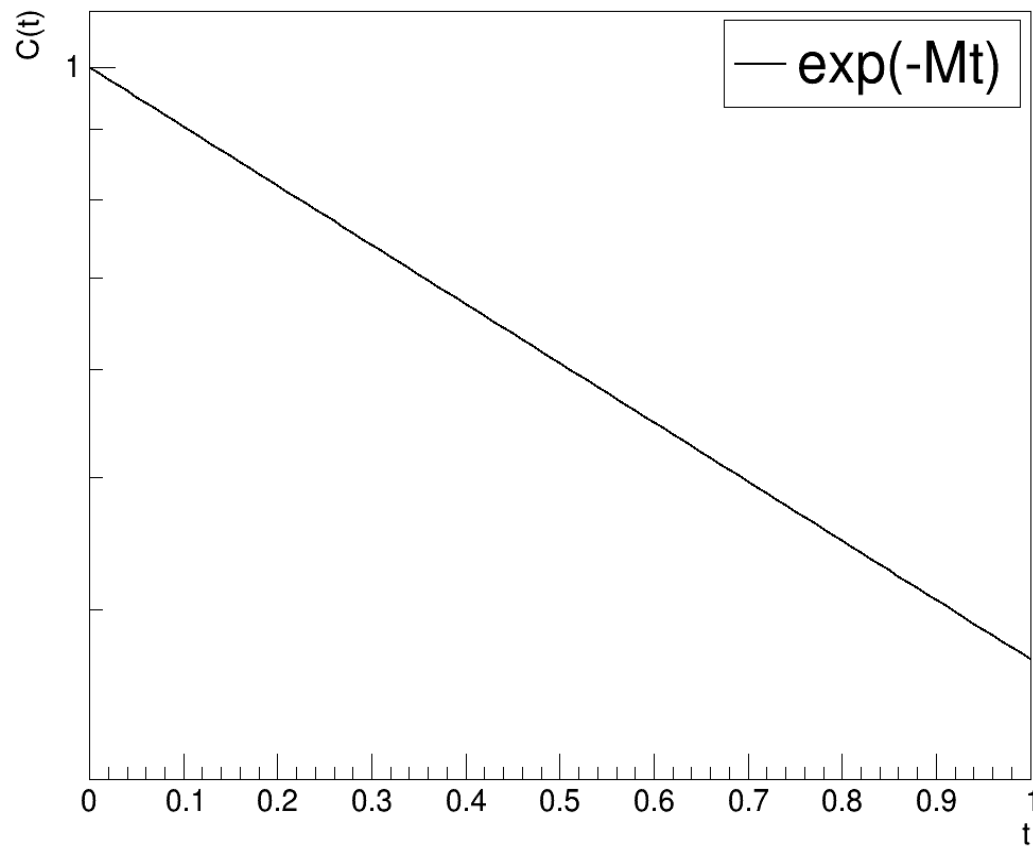
Wave-function - Euclidean



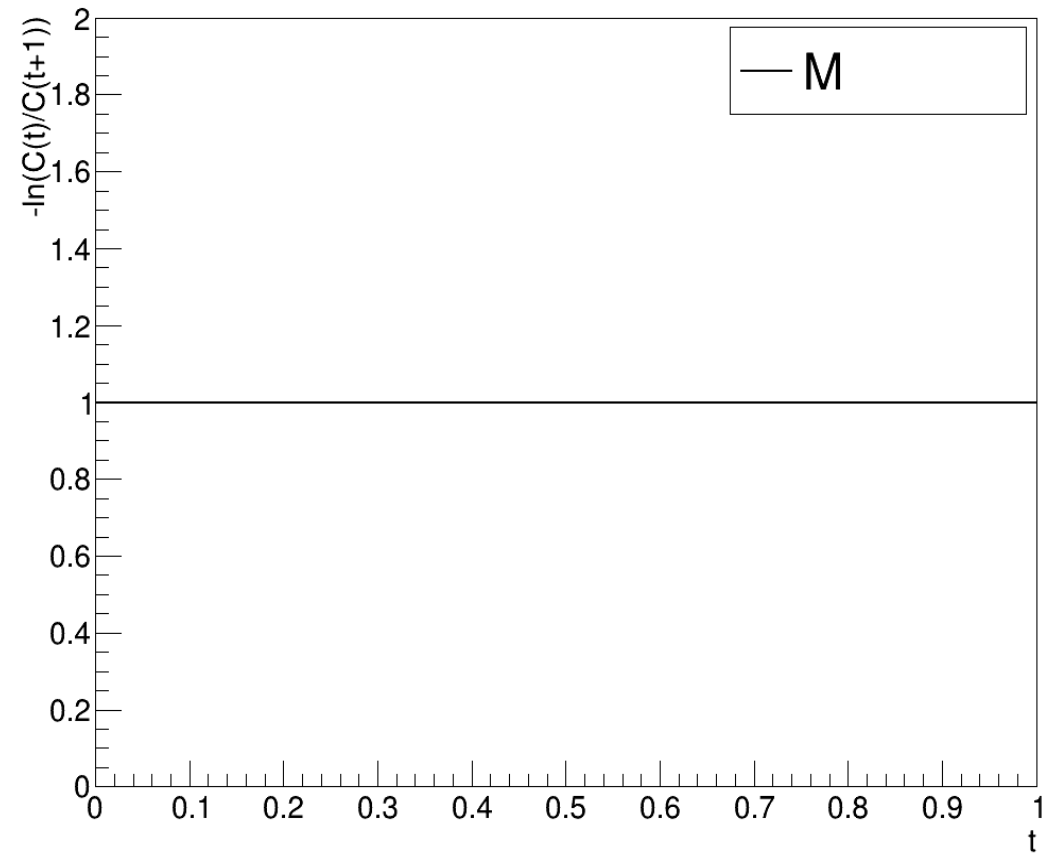
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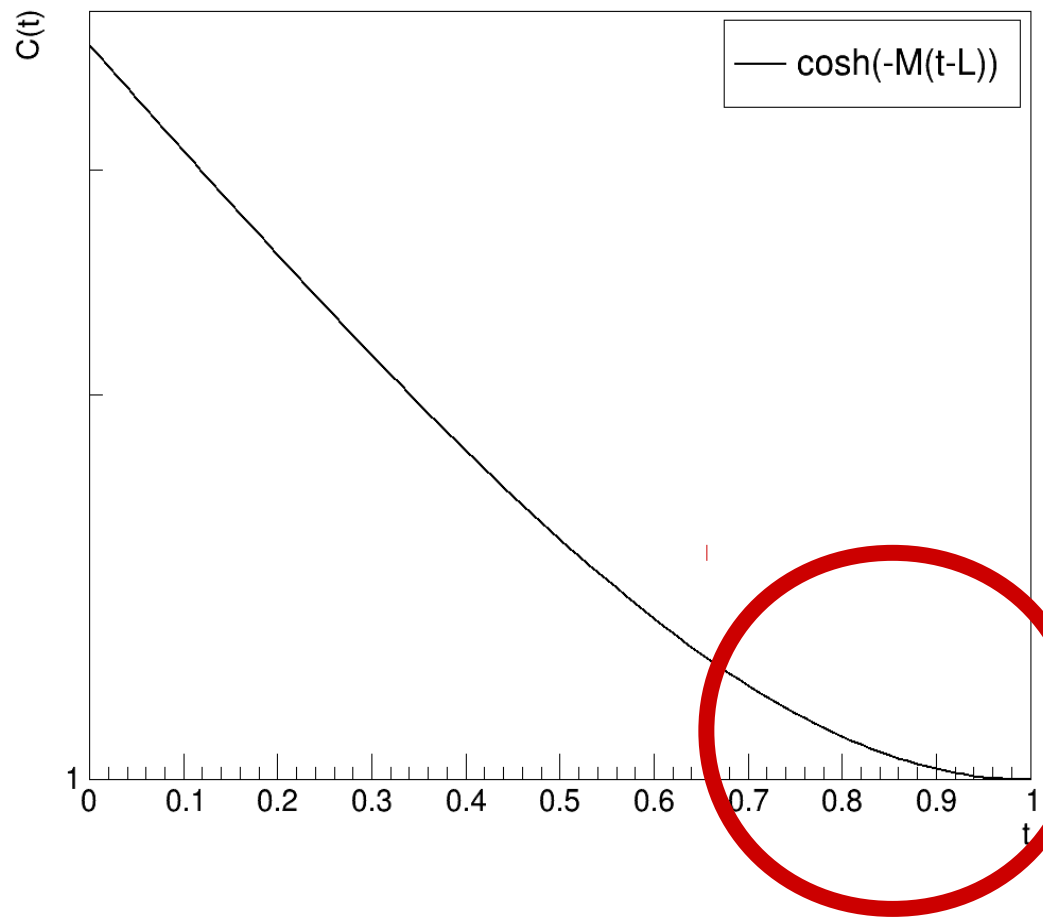
Effective mass



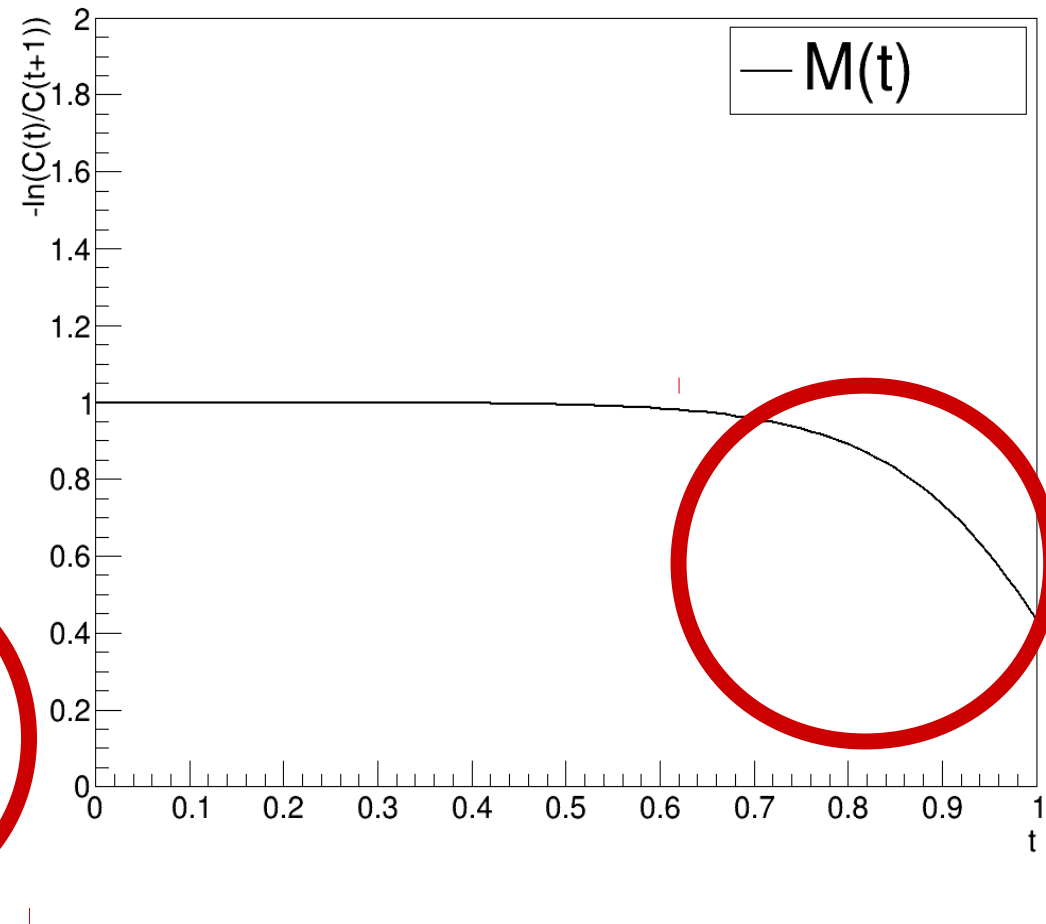
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Masses from the lattice

Wave-function - Euclidean and finite volume



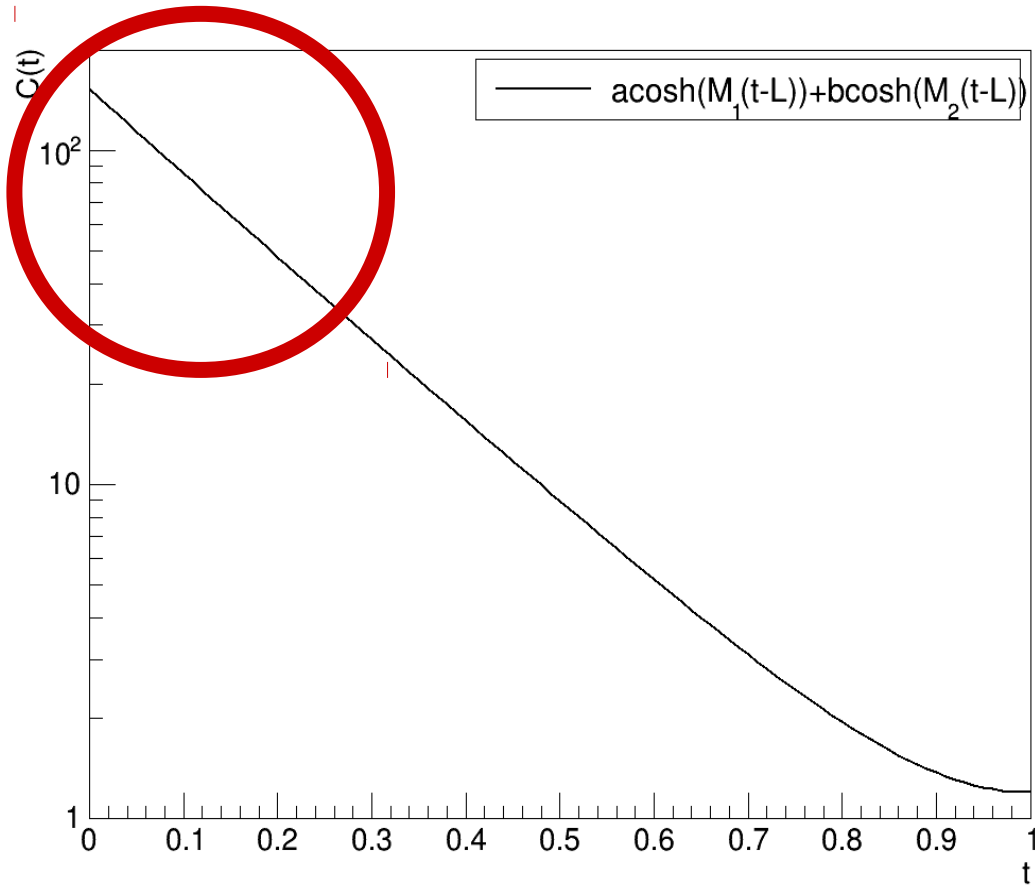
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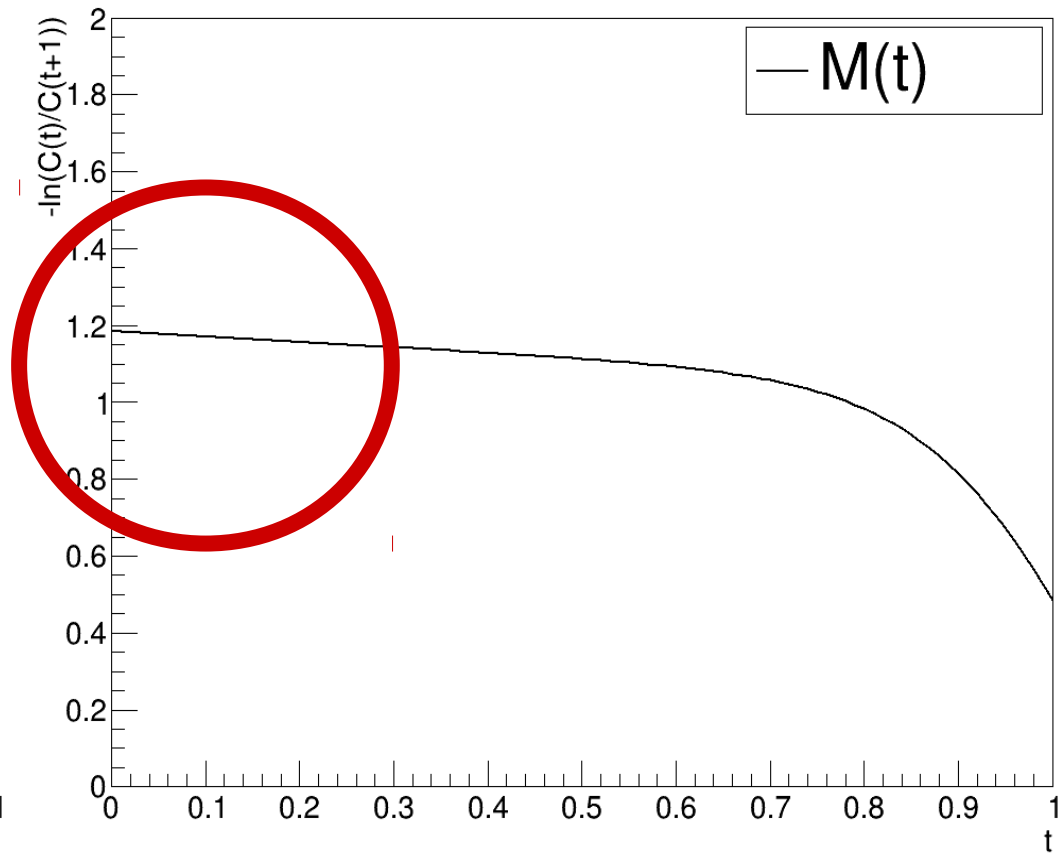
- Masses from 'wave-functions'
 - Affected by finite volume

Masses from the lattice

Wave-function - Euclidean in a finite volume and contamination

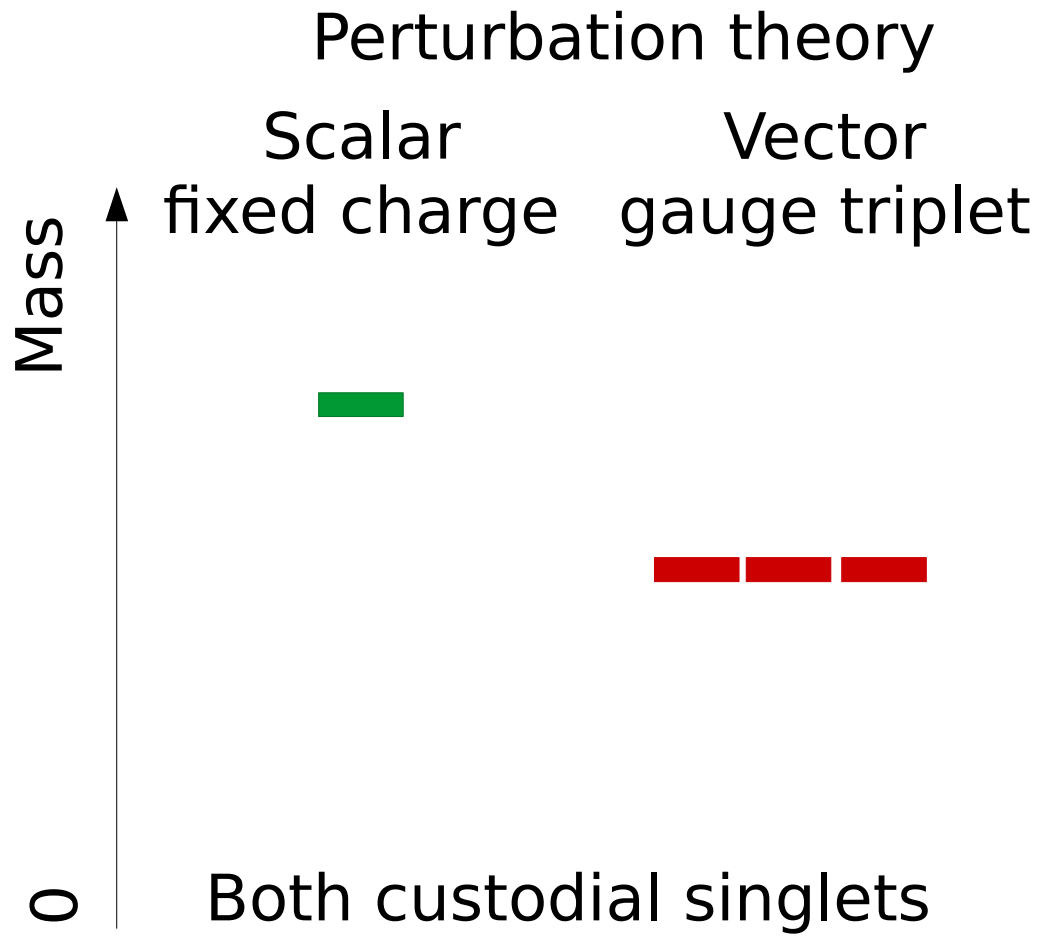


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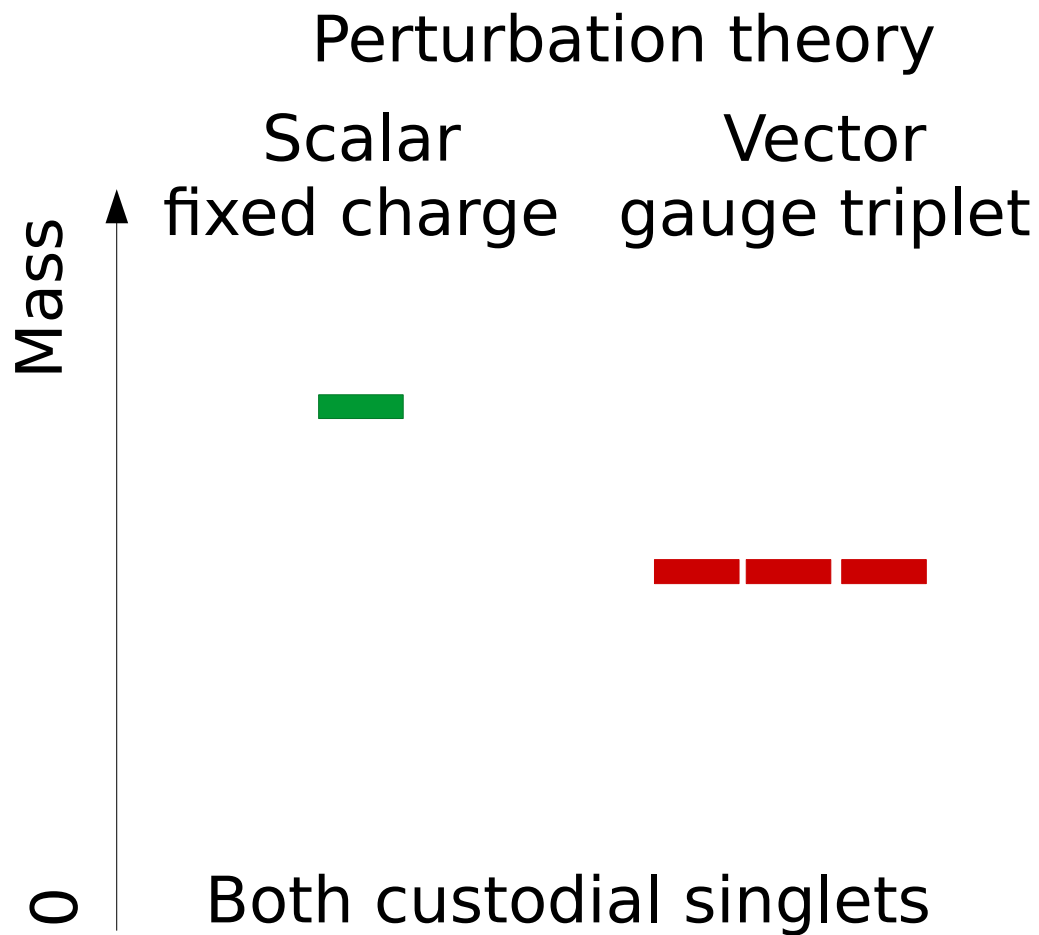


- Masses from 'wave-functions'
 - Affected by finite volume and contamination
 - Needs to be analyzed and extracted

Physical spectrum



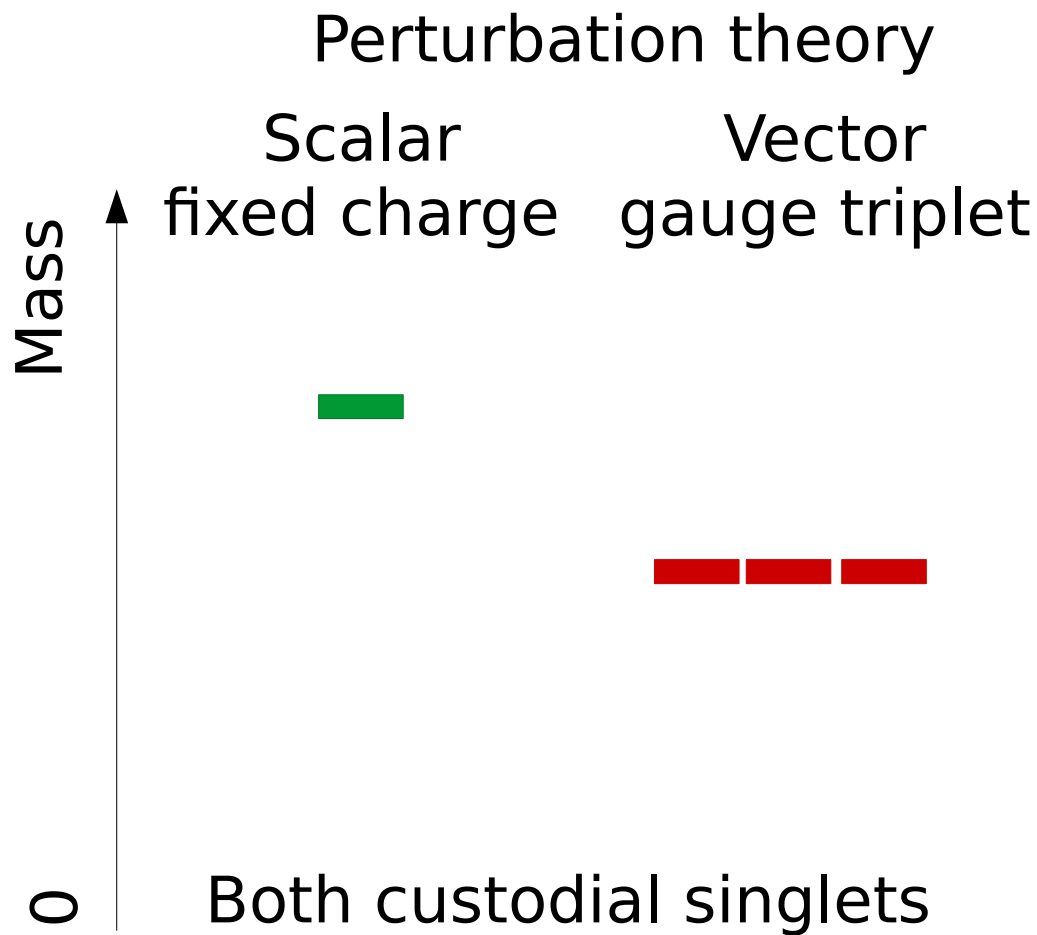
Physical spectrum



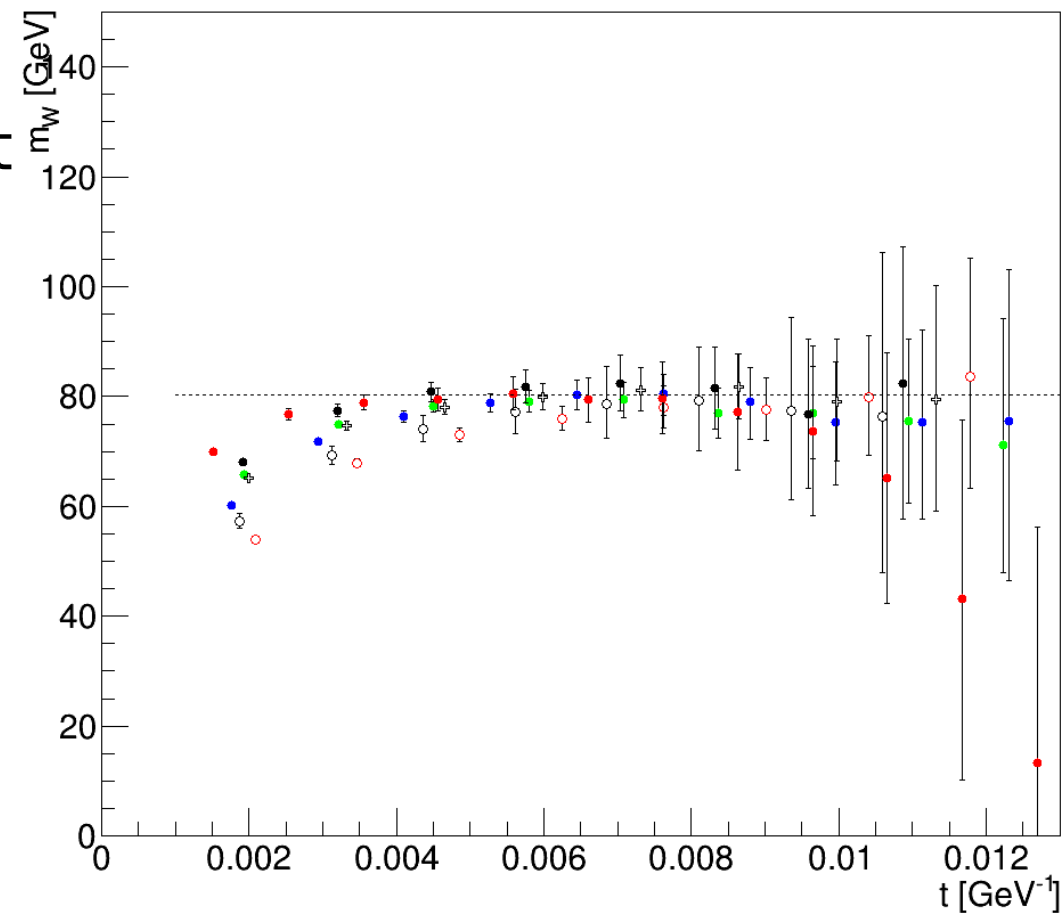
W mass for
different lattice parameters

Physical spectrum

[Maas'12, Maas & Mufti'13]

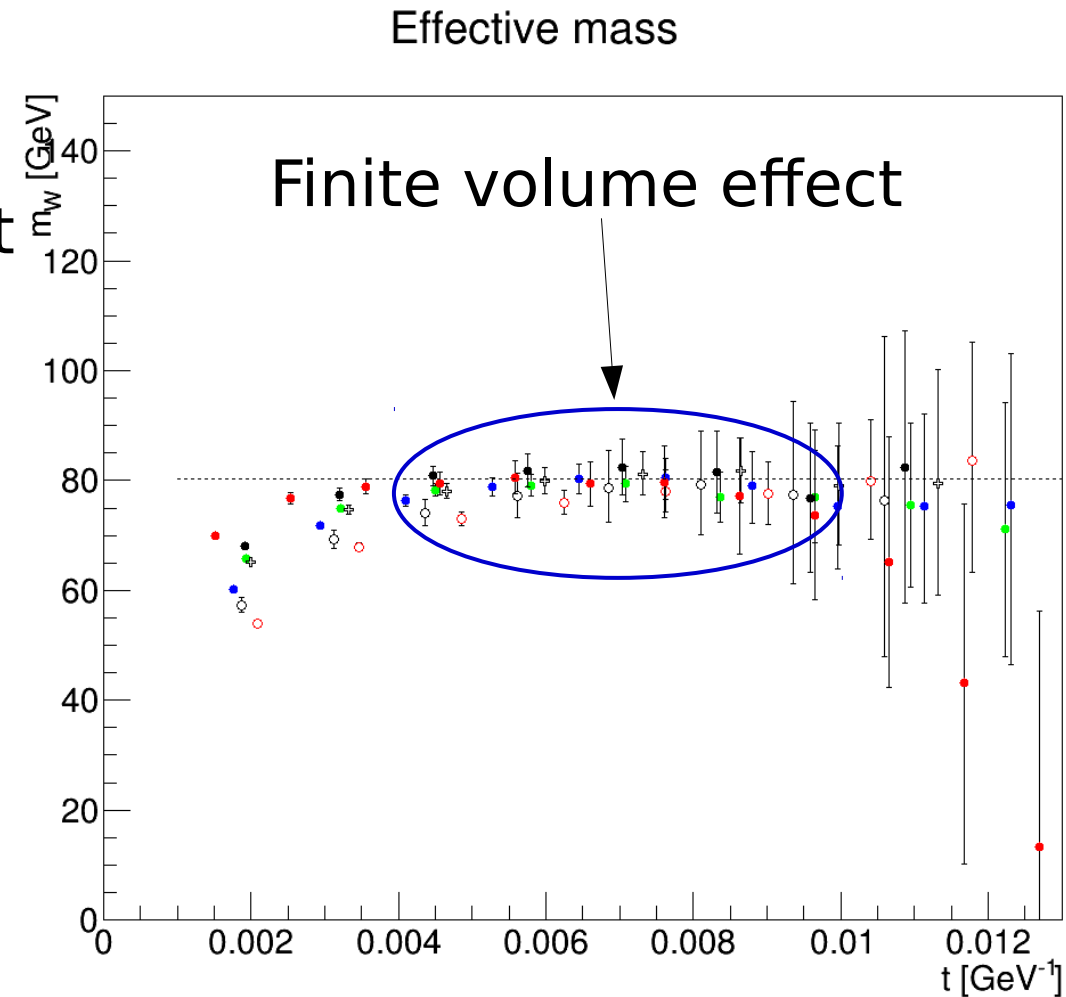
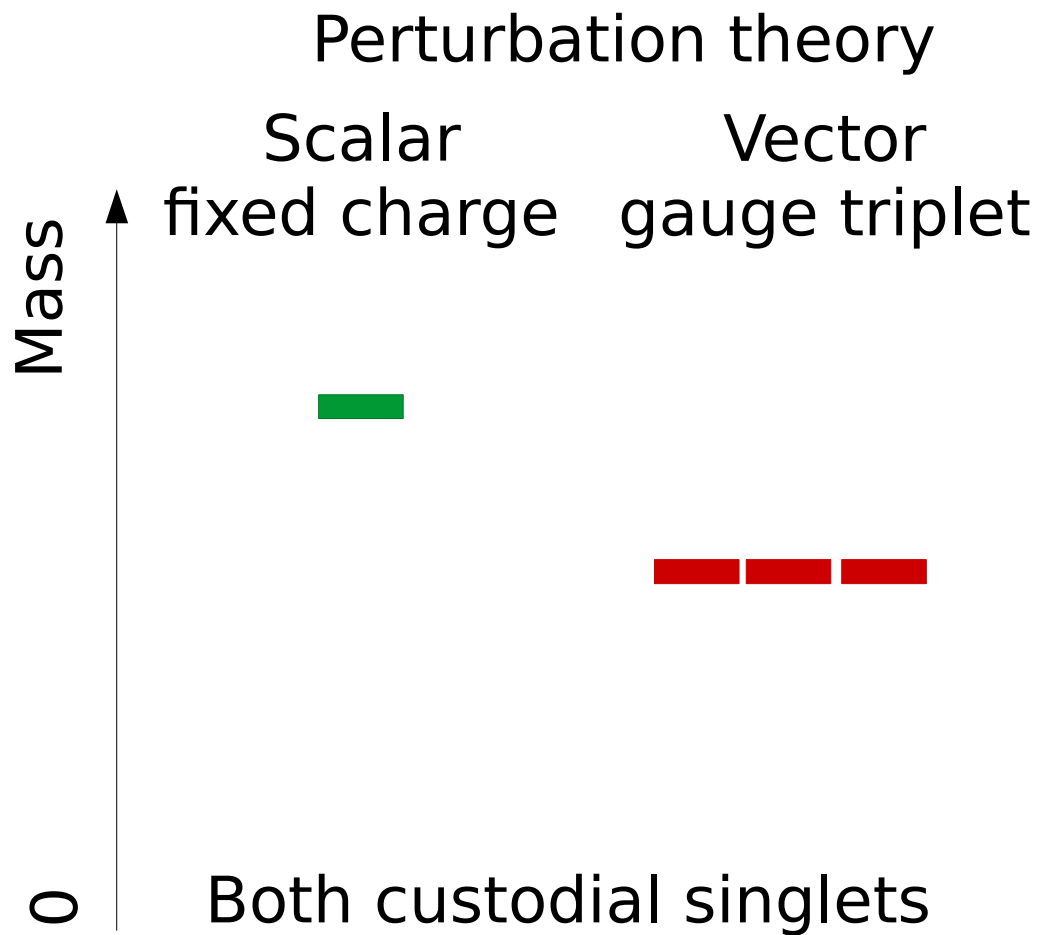


Effective mass



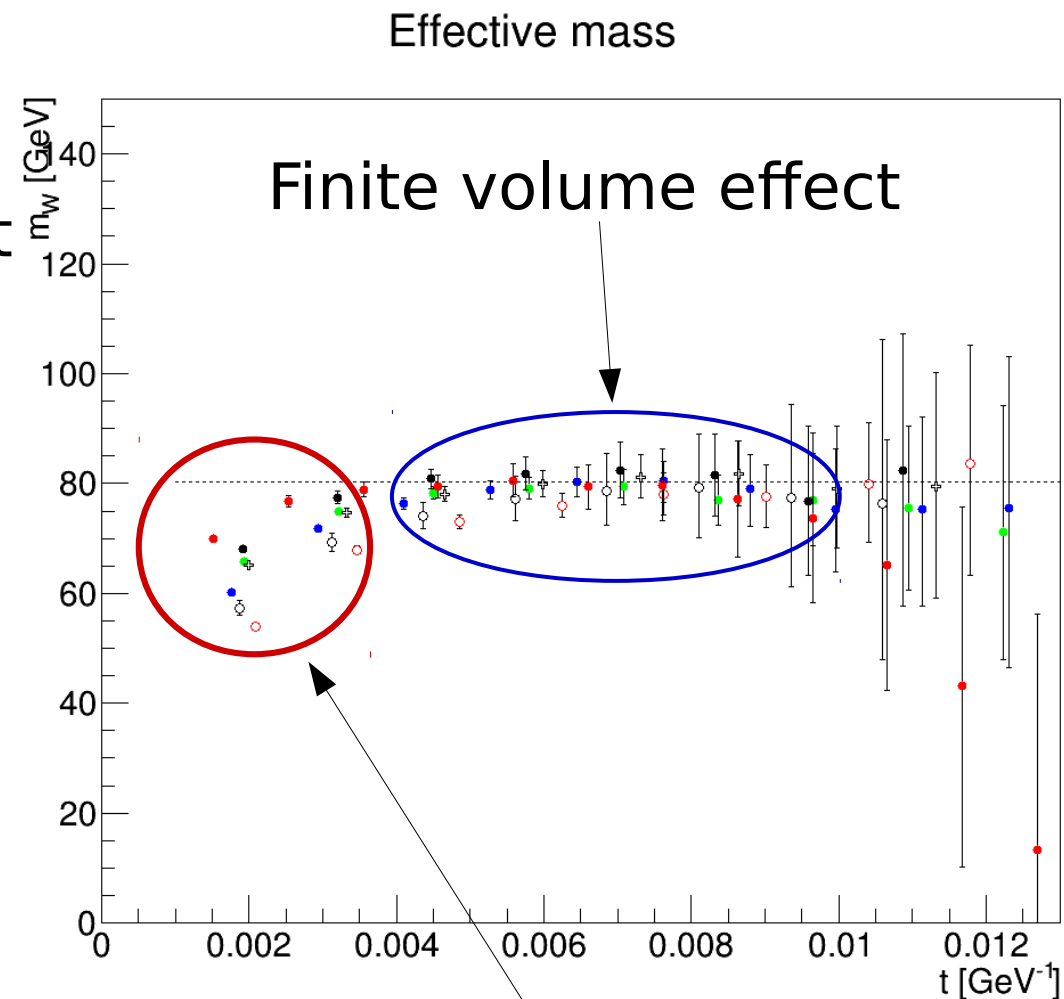
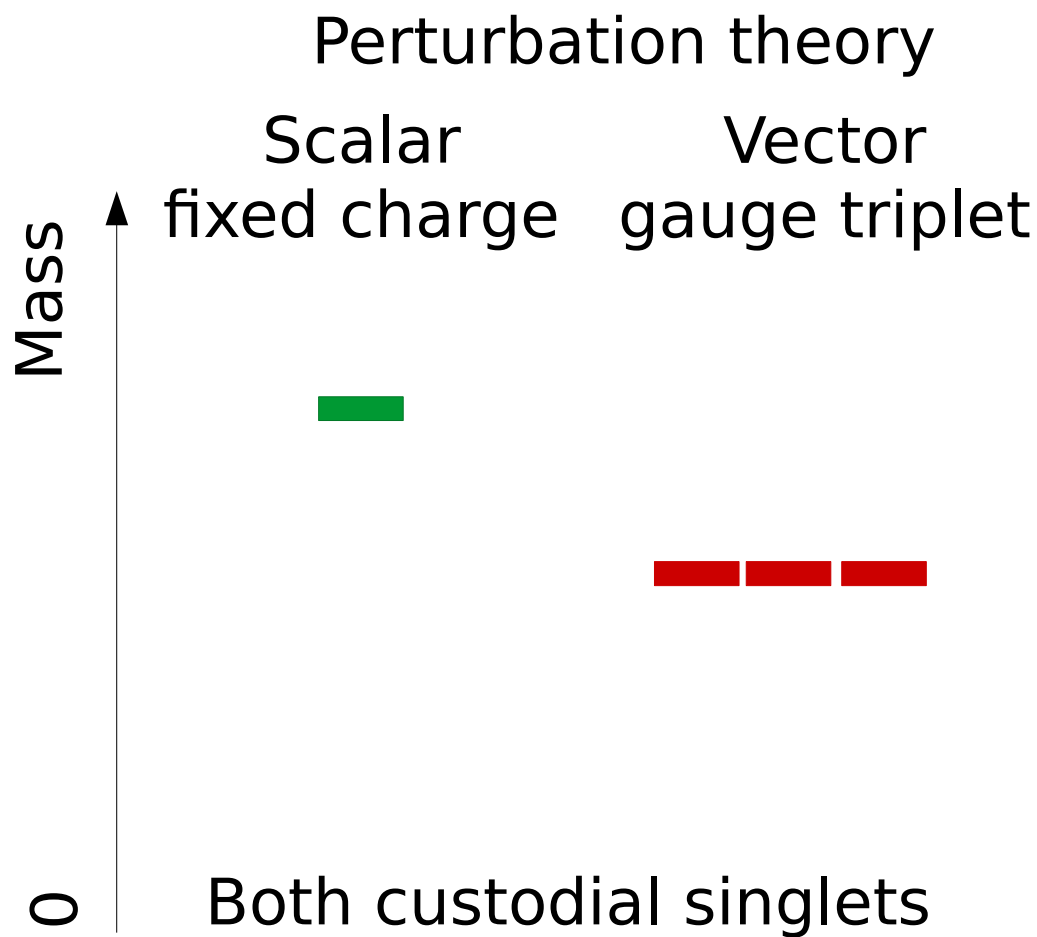
W mass for different lattice parameters

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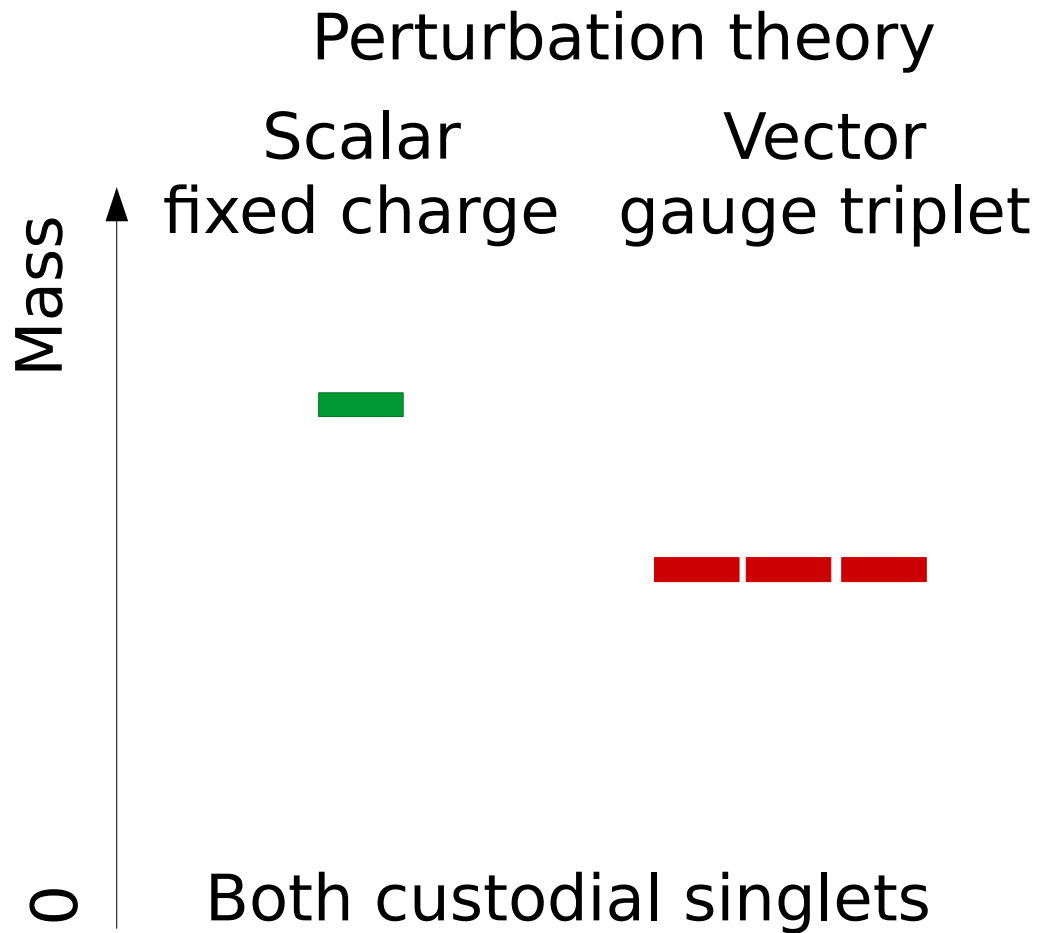
Physical spectrum



Perturbative effect
(Oehme-Zimmermann)

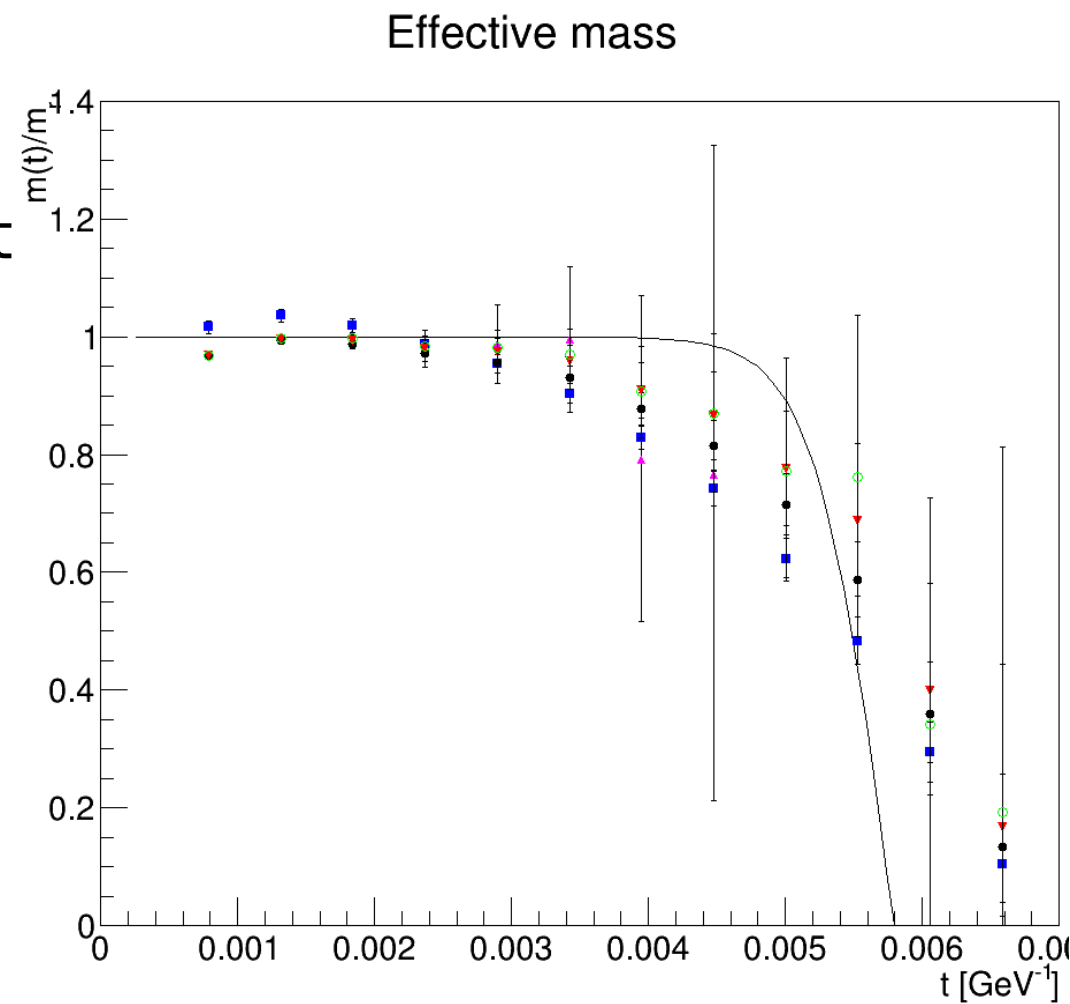
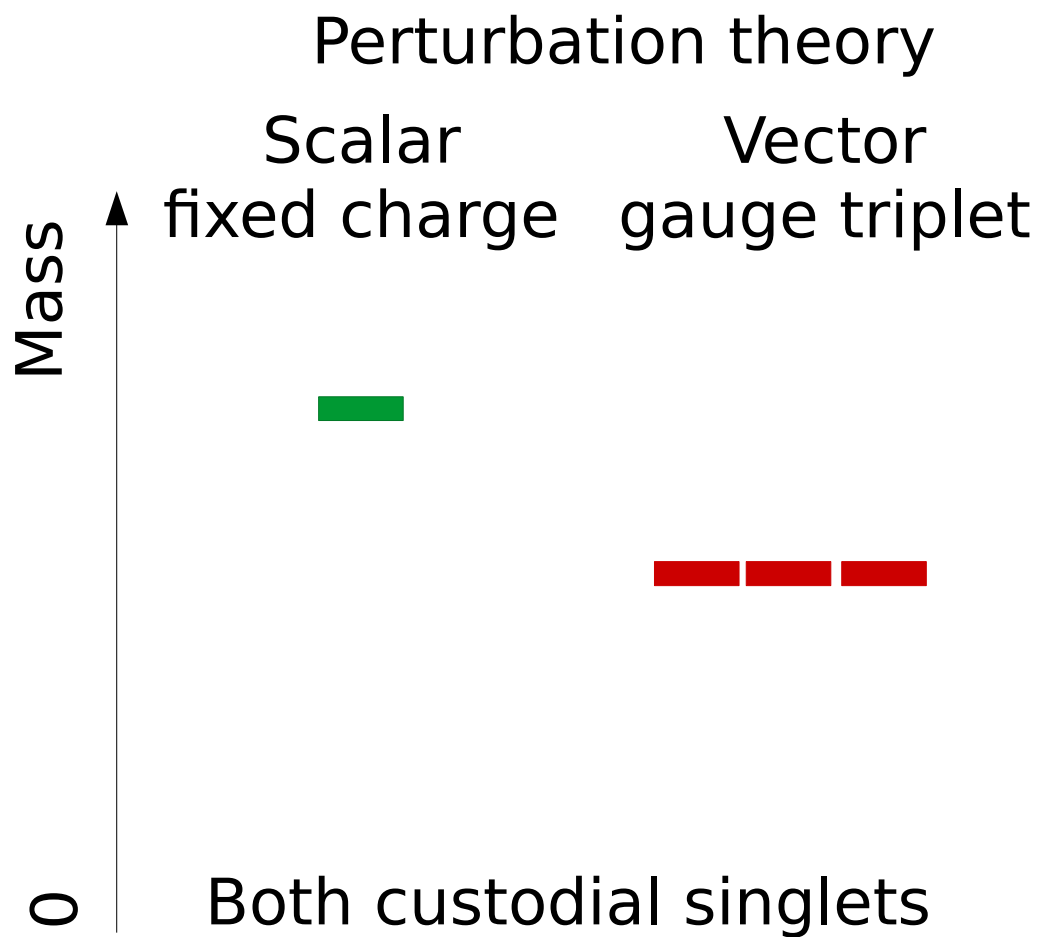
W mass for
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Physical spectrum



Higgs for
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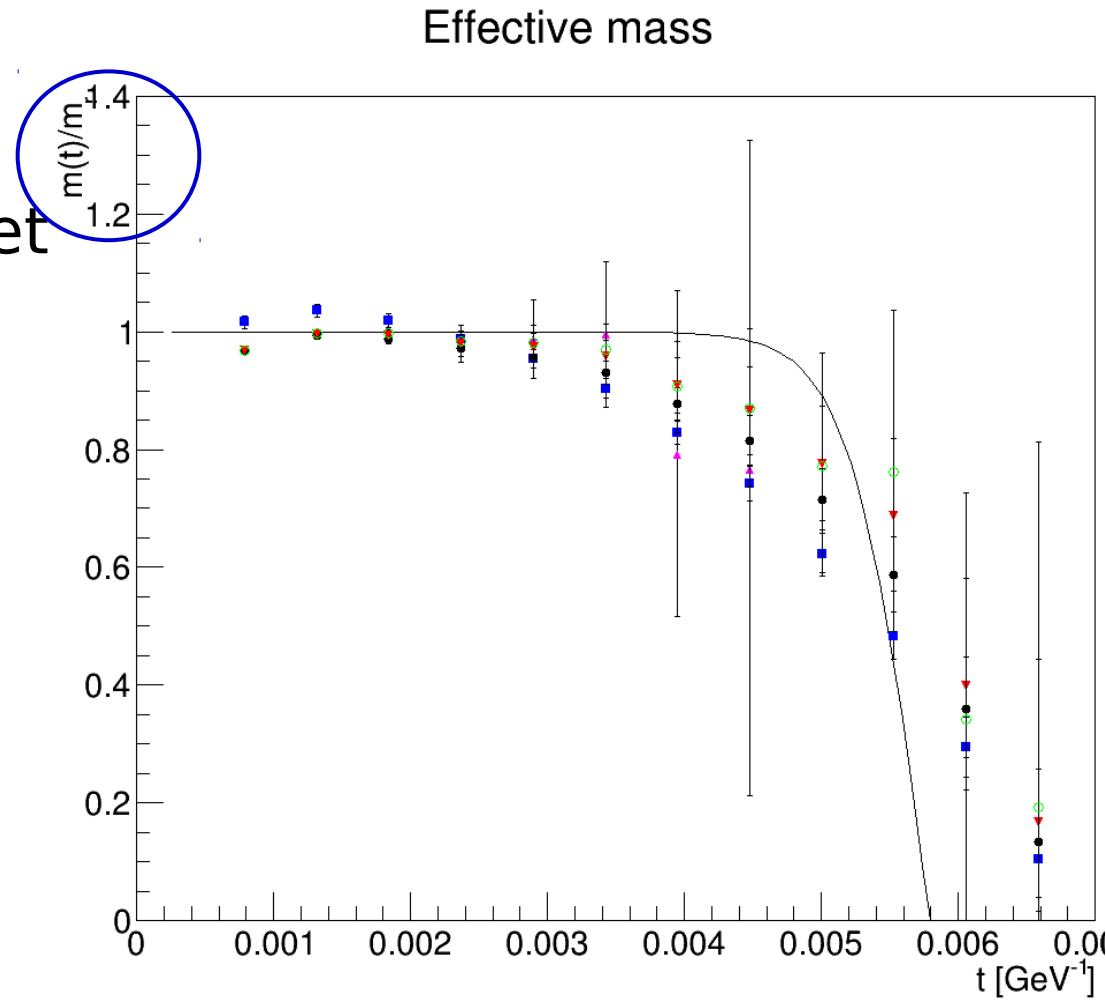
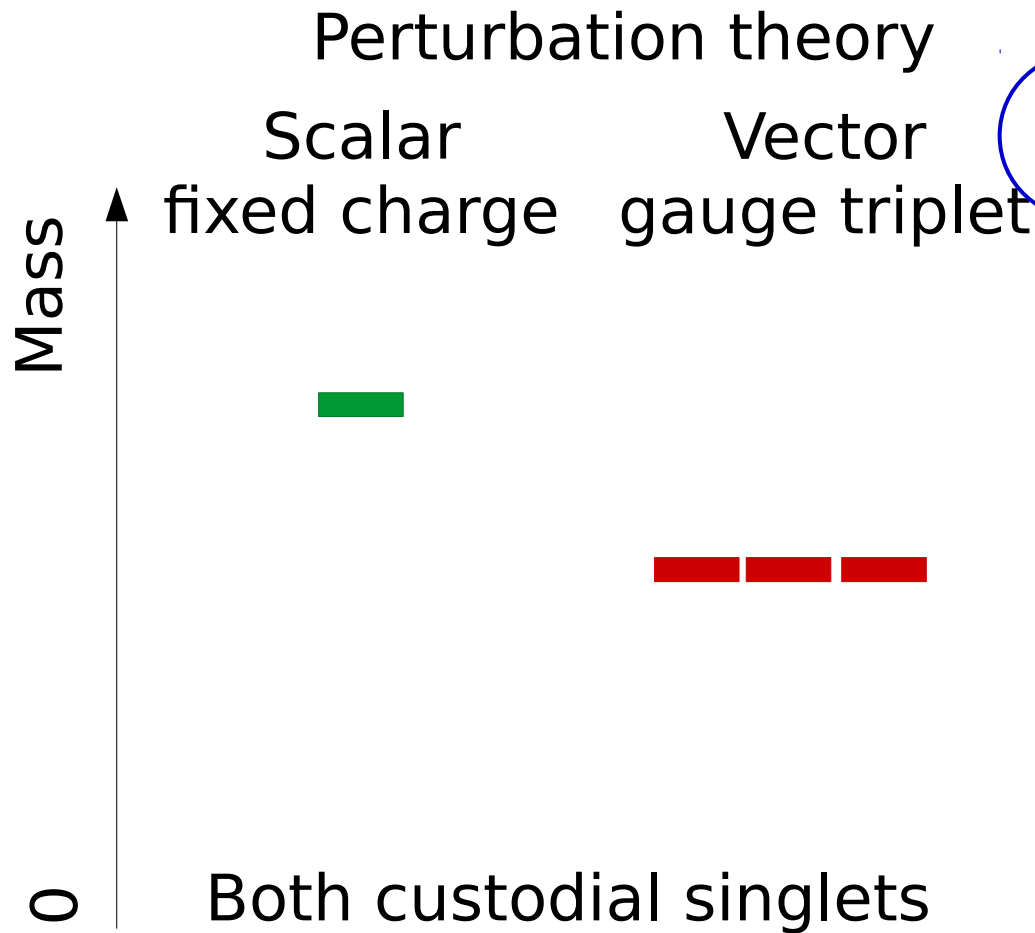
Physical spectrum



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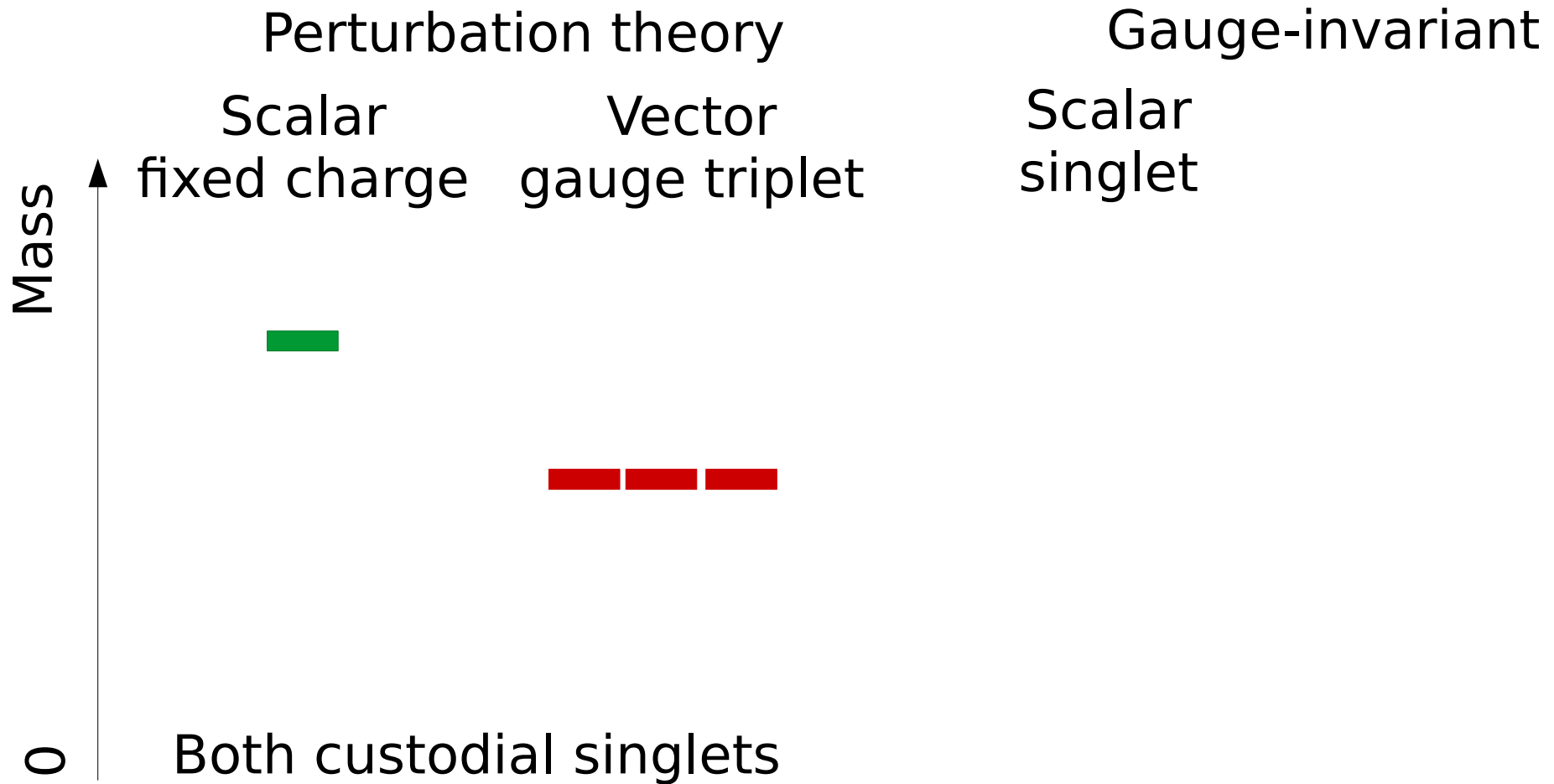
[Maas'12, Maas & Mufti'13]



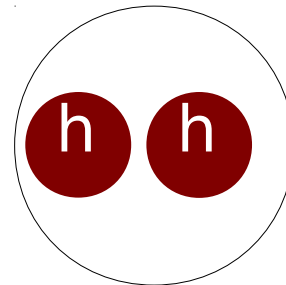
Higgs for different lattice parameters

Higgs mass requires renormalization

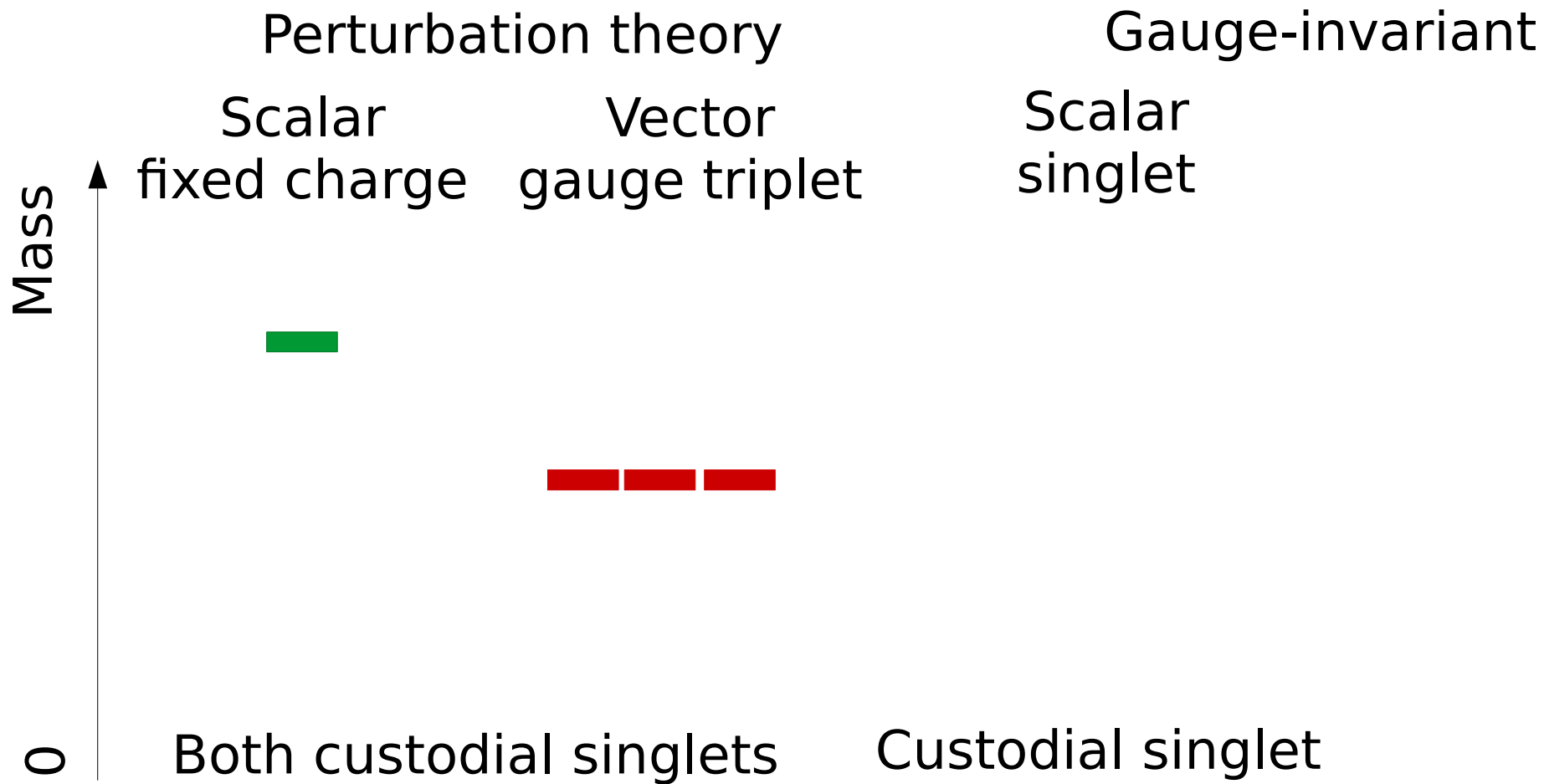
Physical spectrum



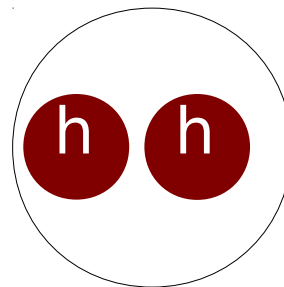
$$h(x)^+ h(x)$$



Physical spectrum

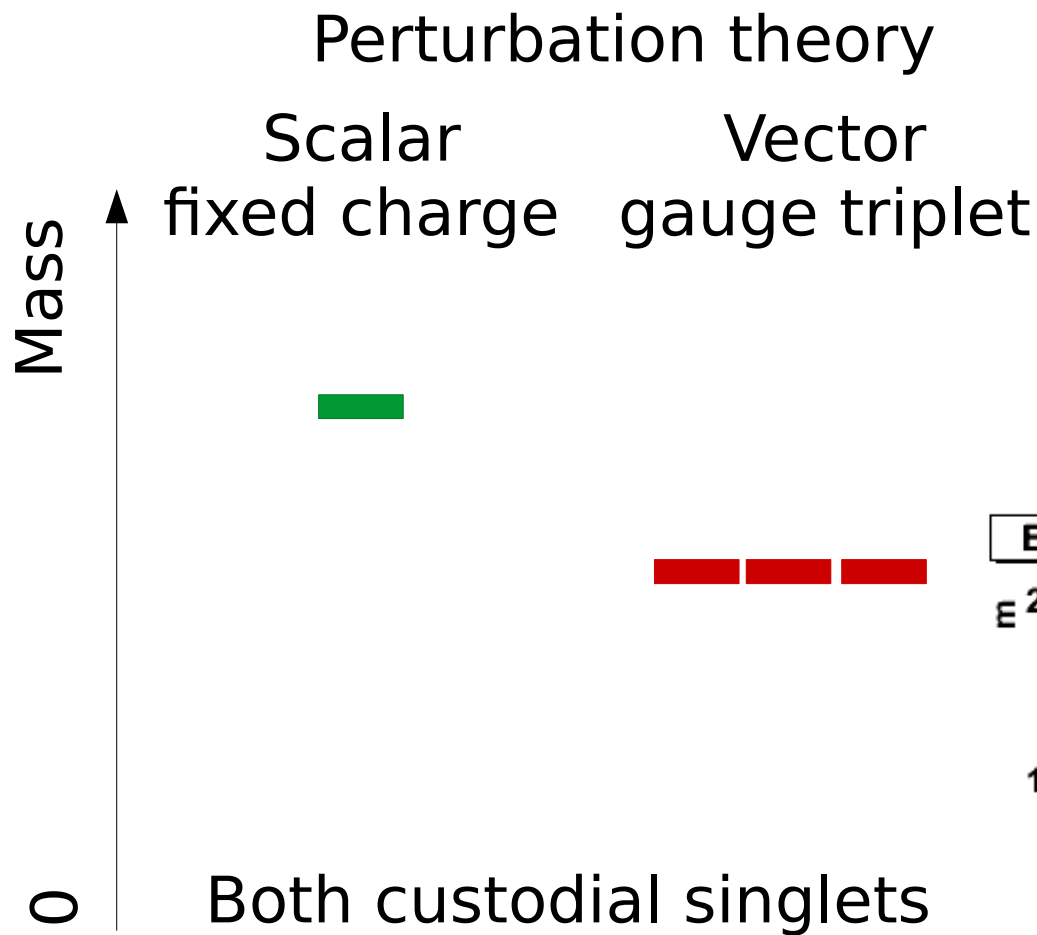


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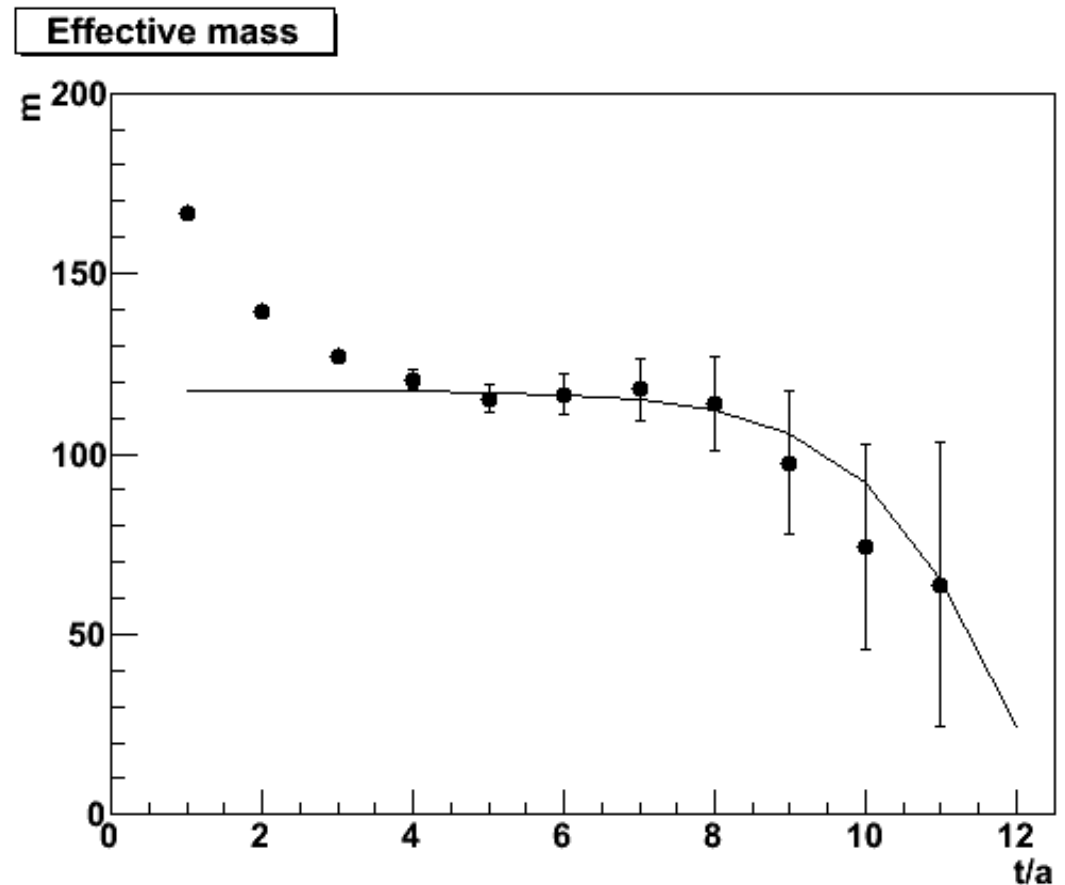
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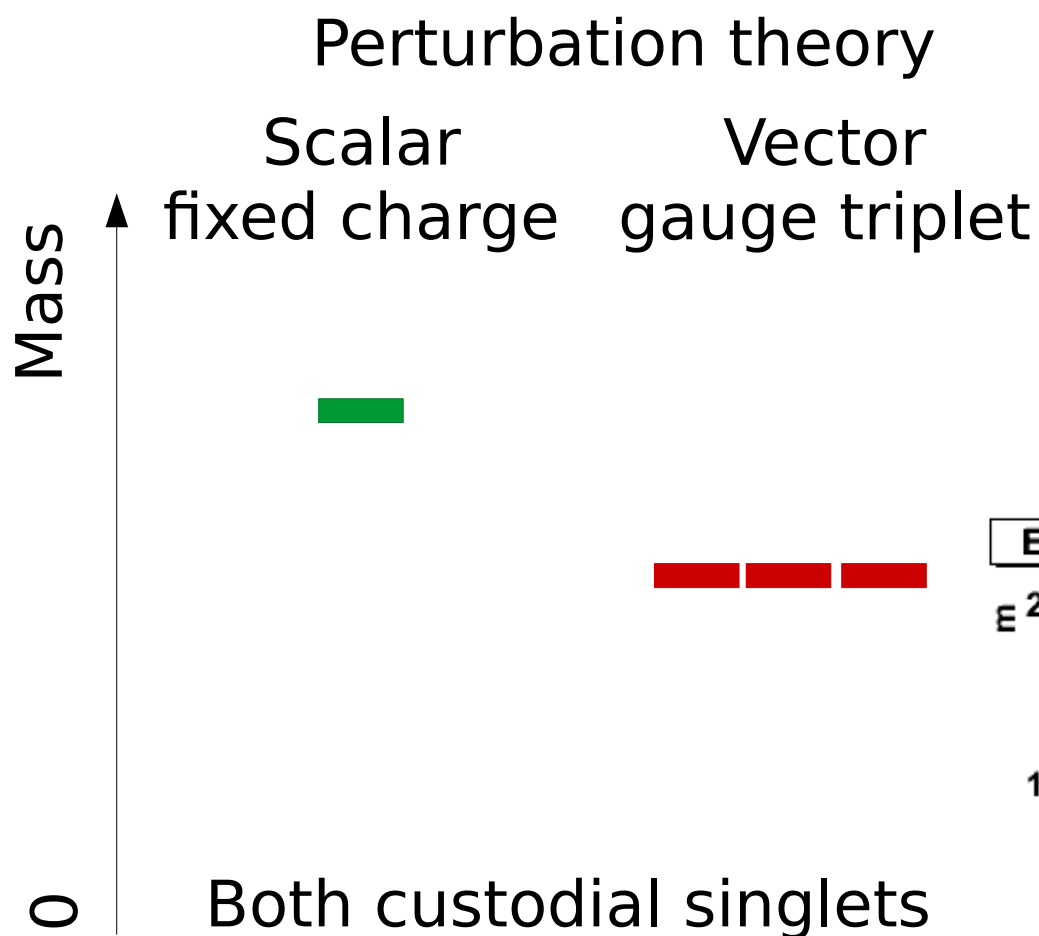


Gauge-invariant

Scalar singlet

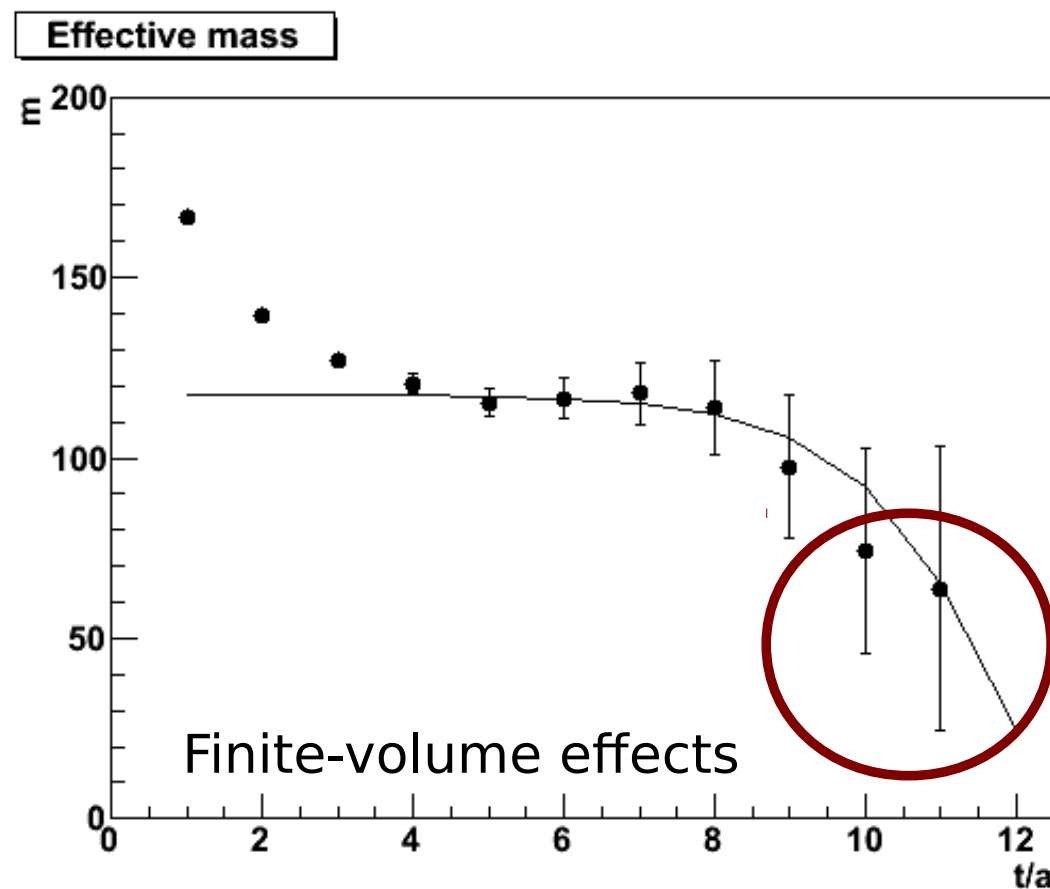


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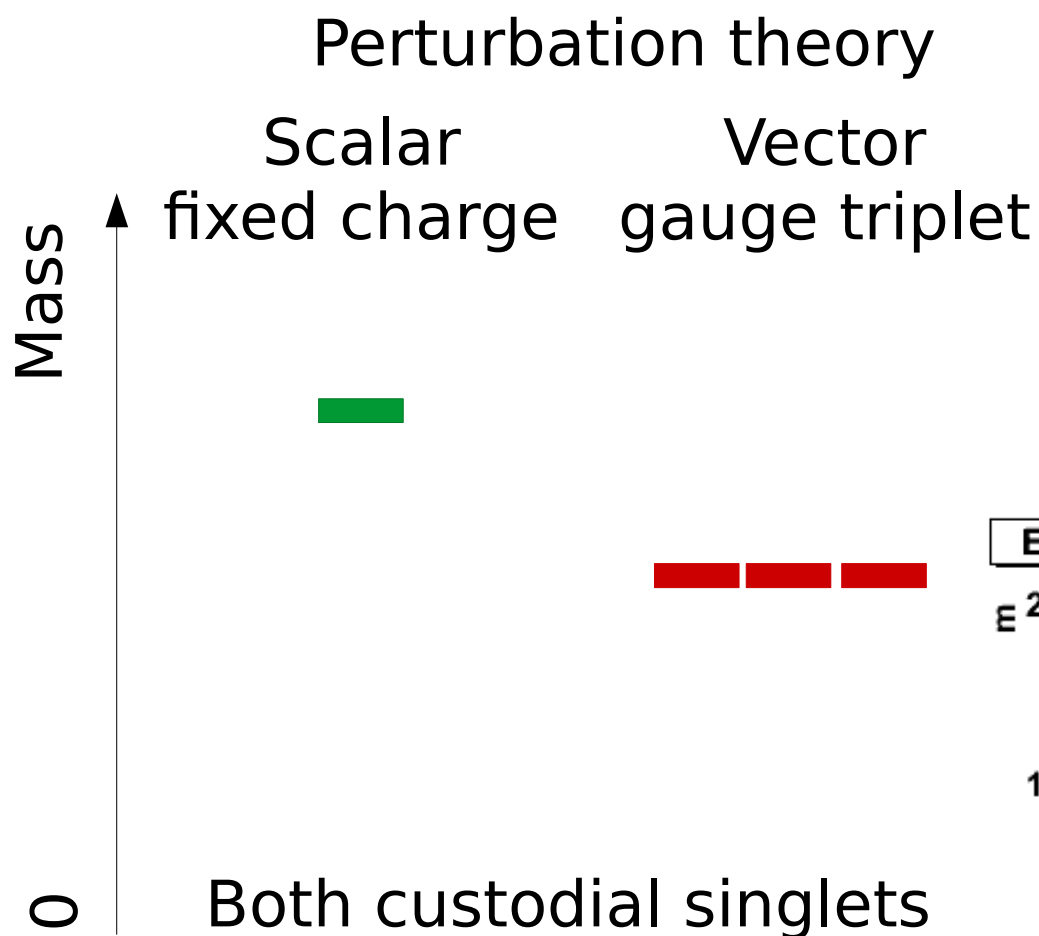


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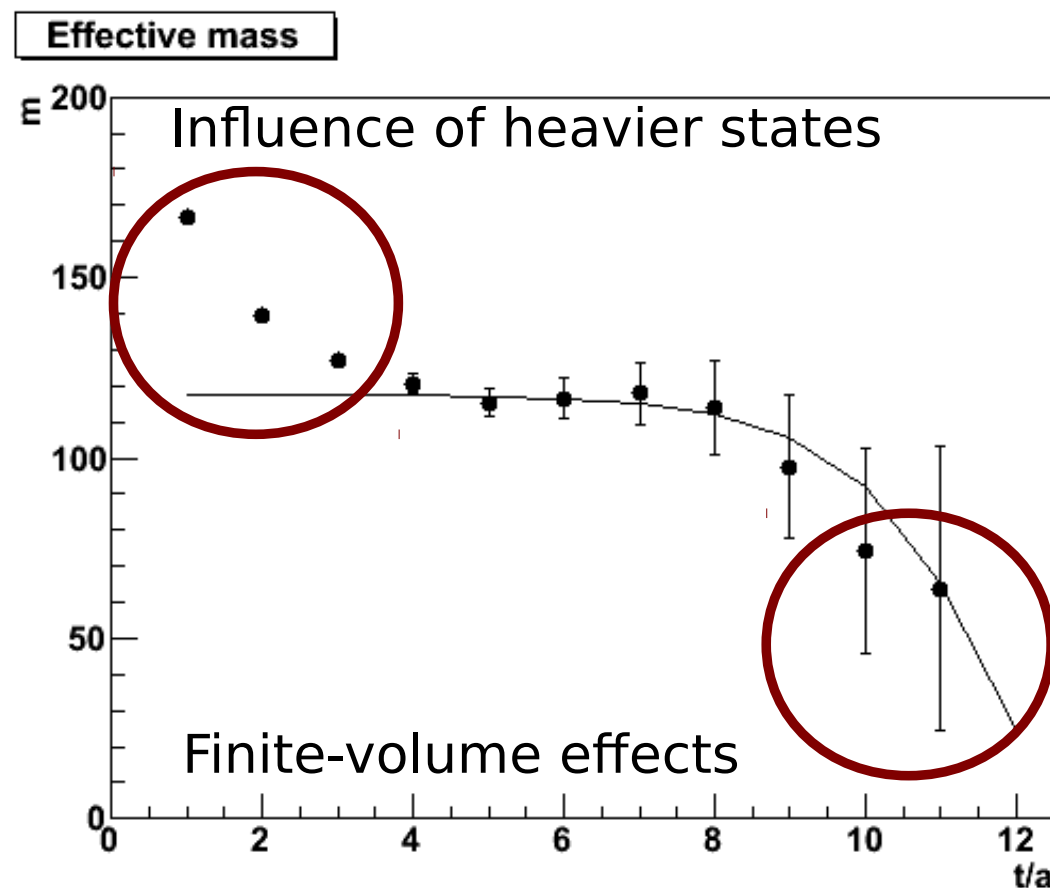


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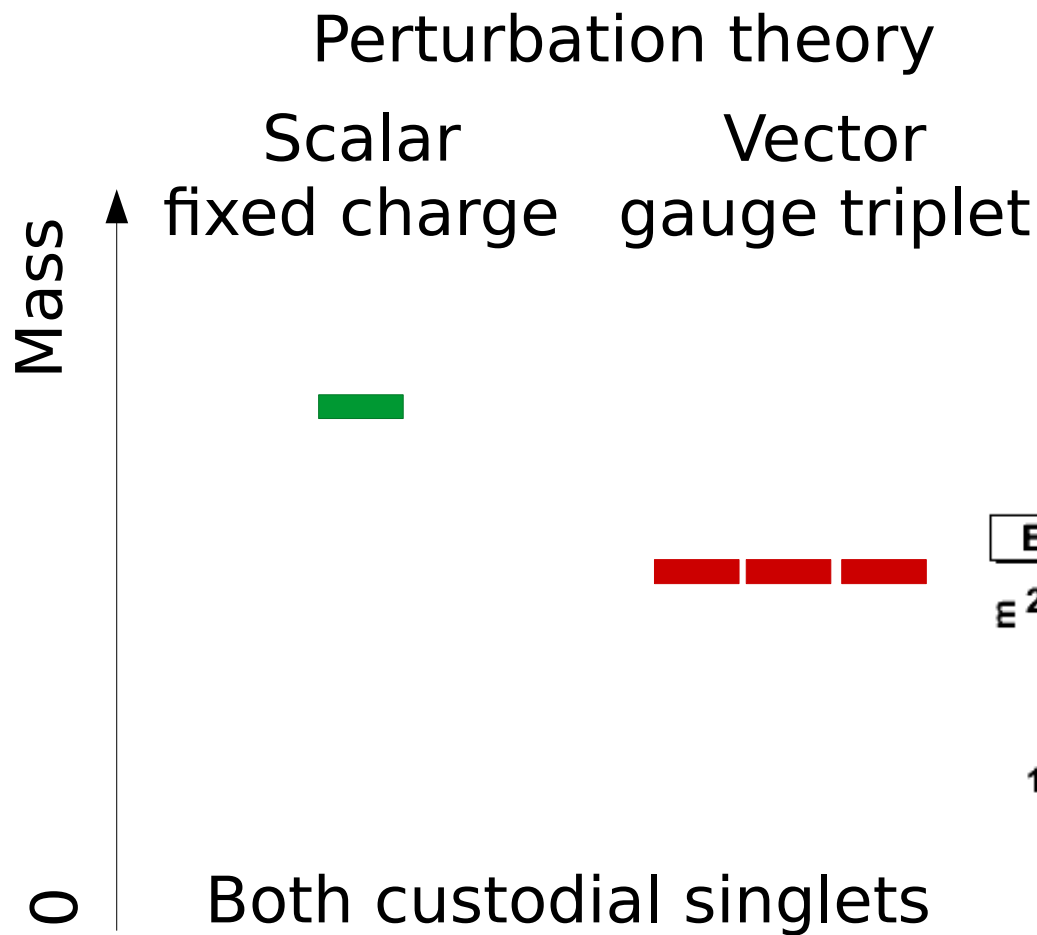


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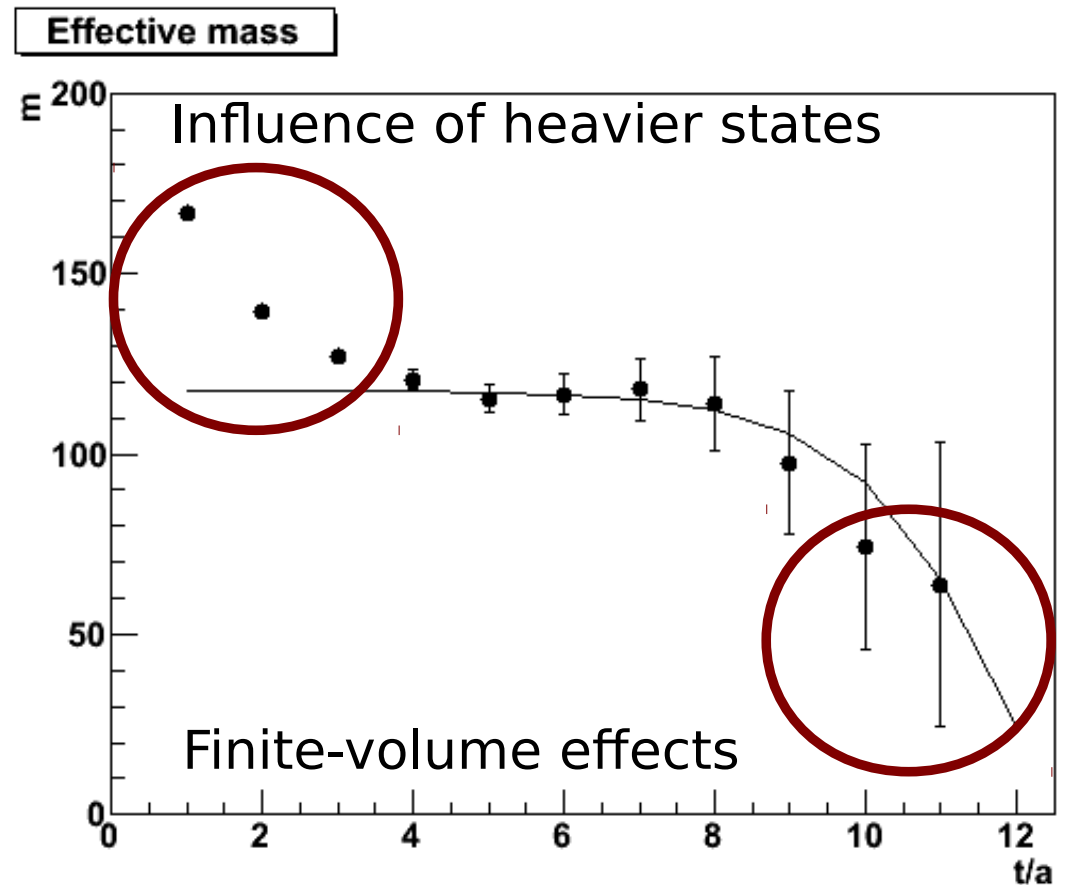


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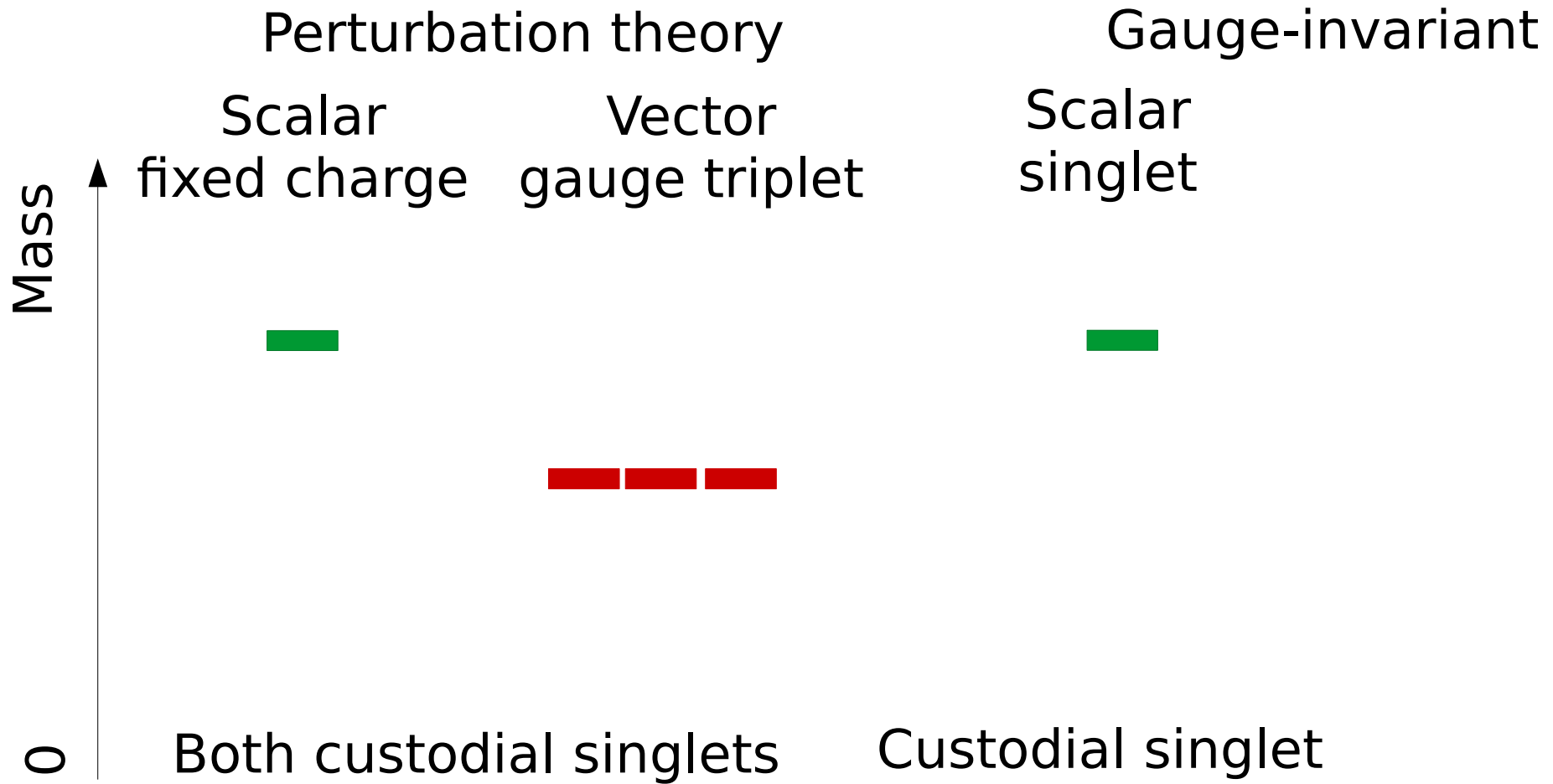


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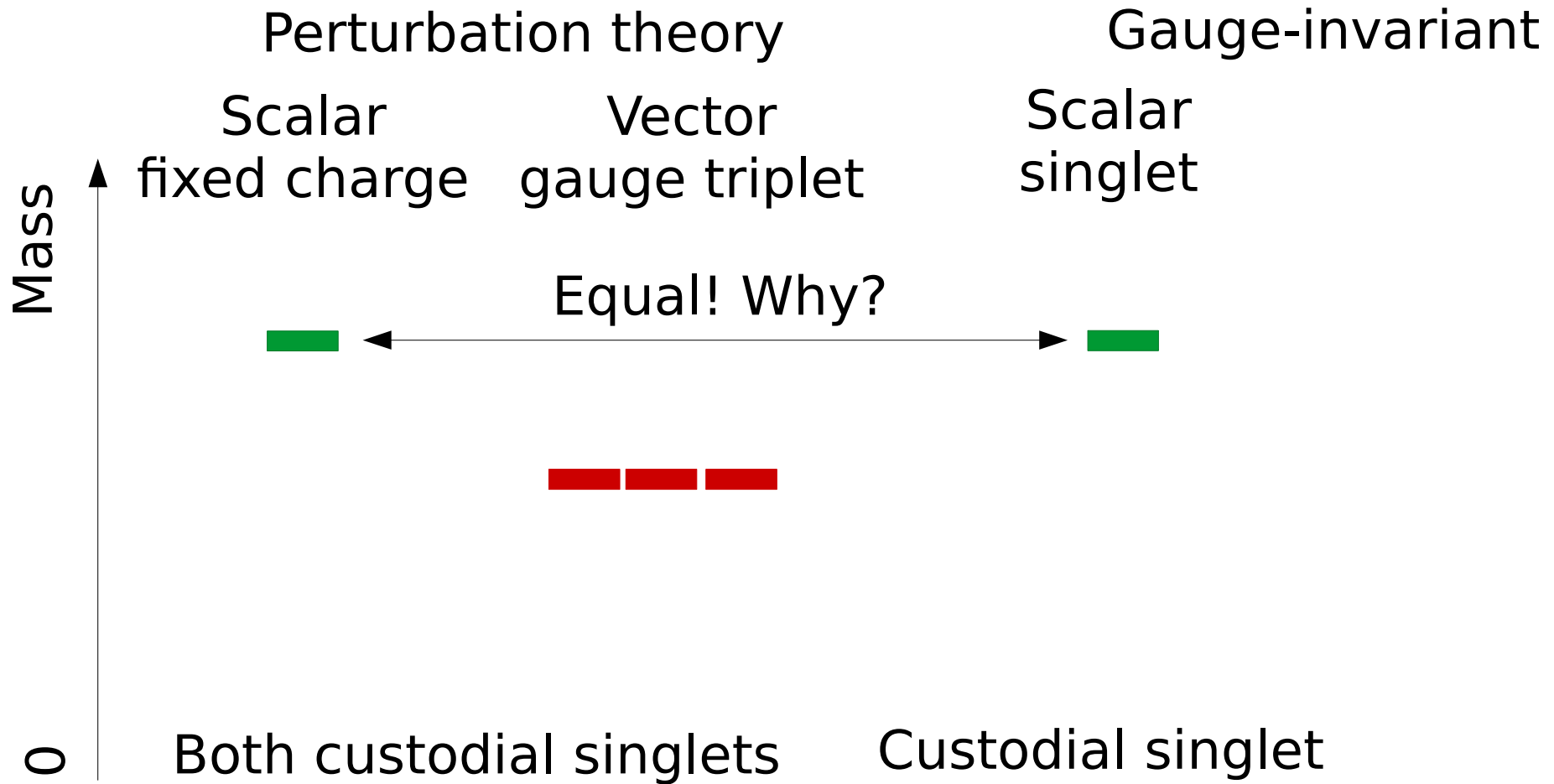
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Physical spectrum



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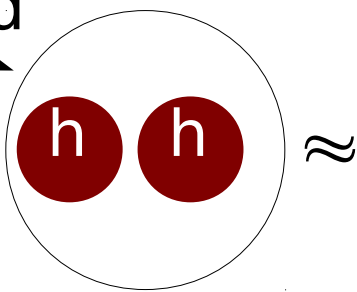
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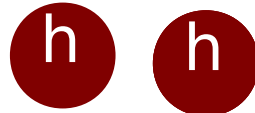
Bound
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mass



\approx



+



+ something small

Higgs
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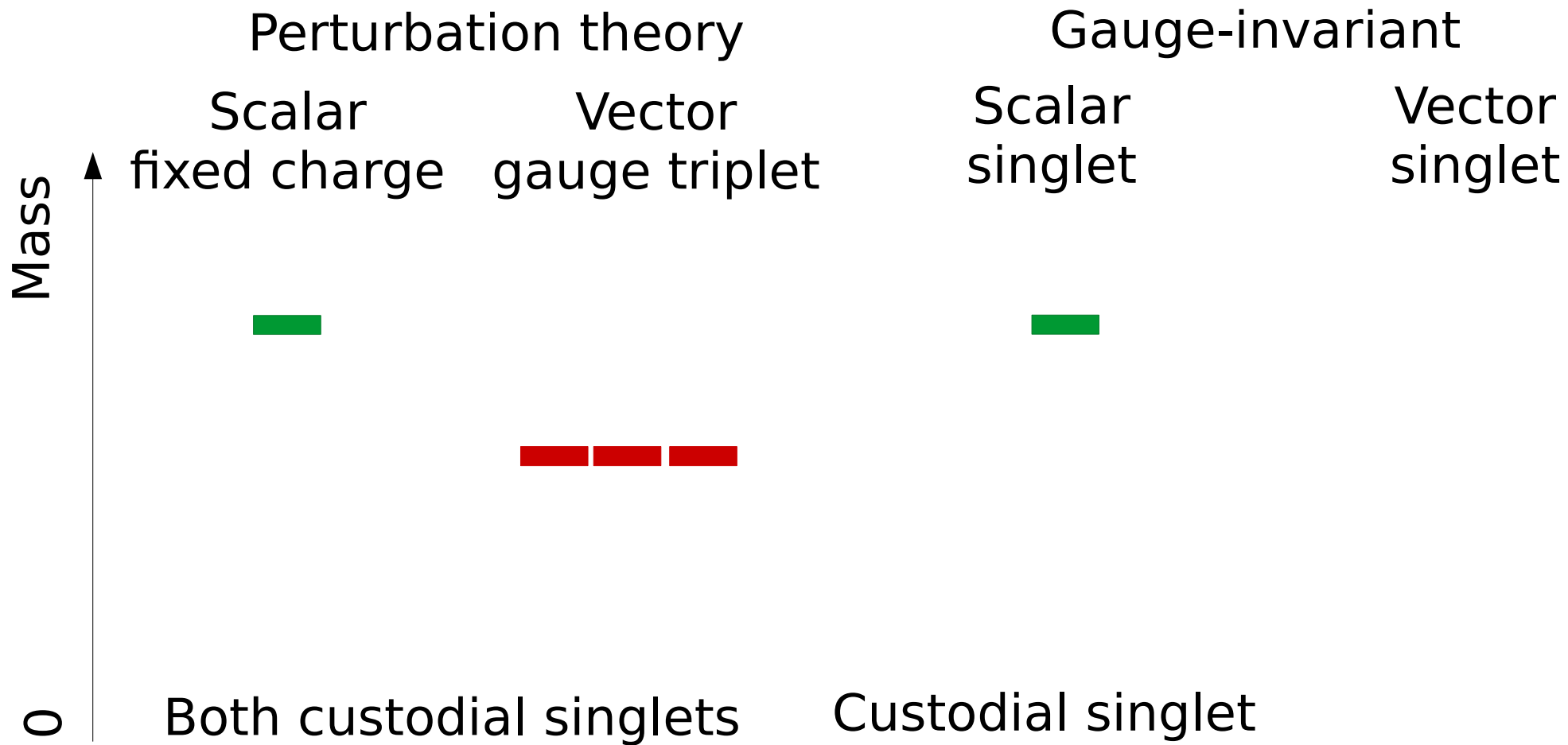
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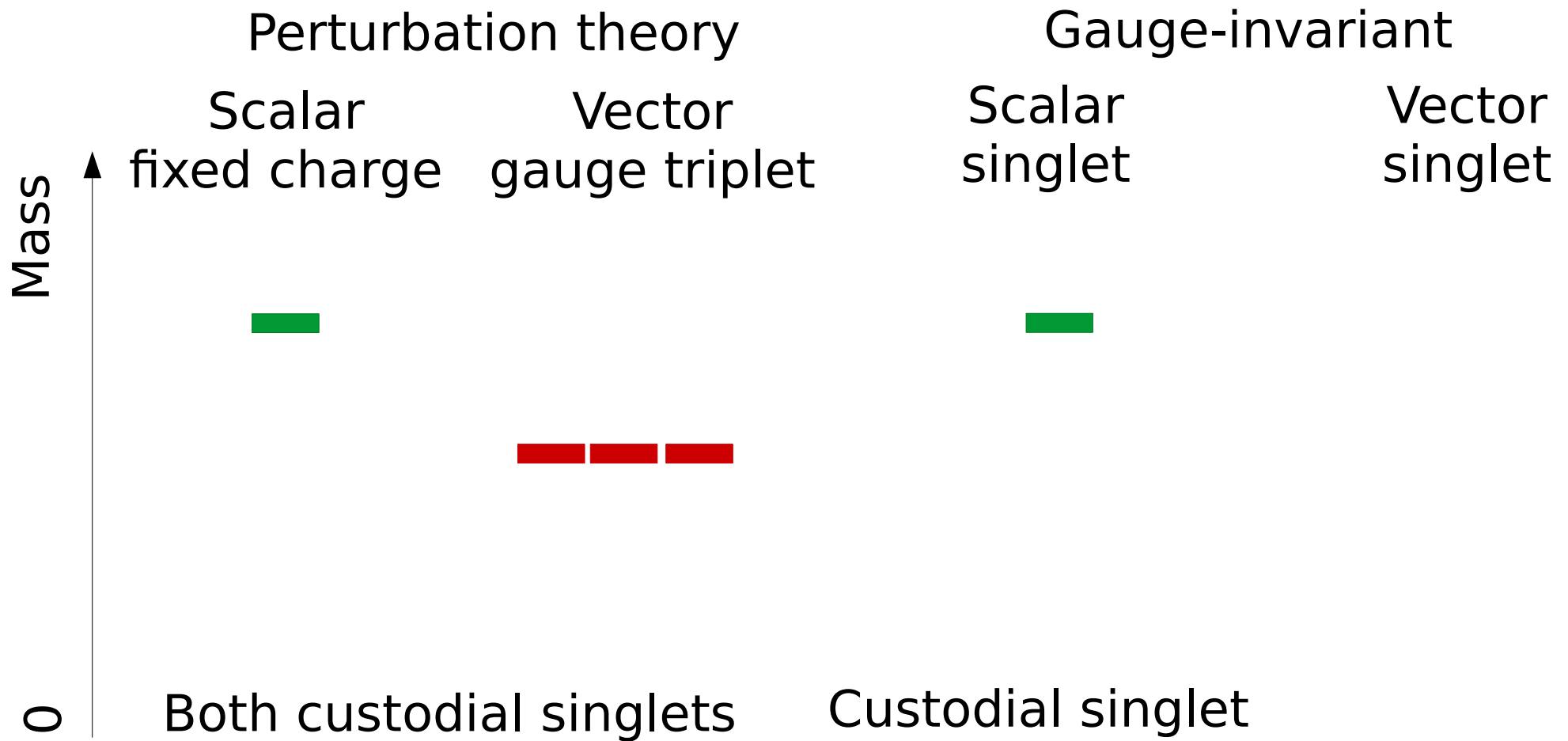
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- Deeply-bound relativistic state
 - Mass defect \sim constituent mass
 - Cannot describe with quantum mechanics
 - Very different from QCD bound states

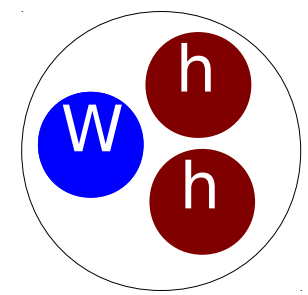
Physical spectrum



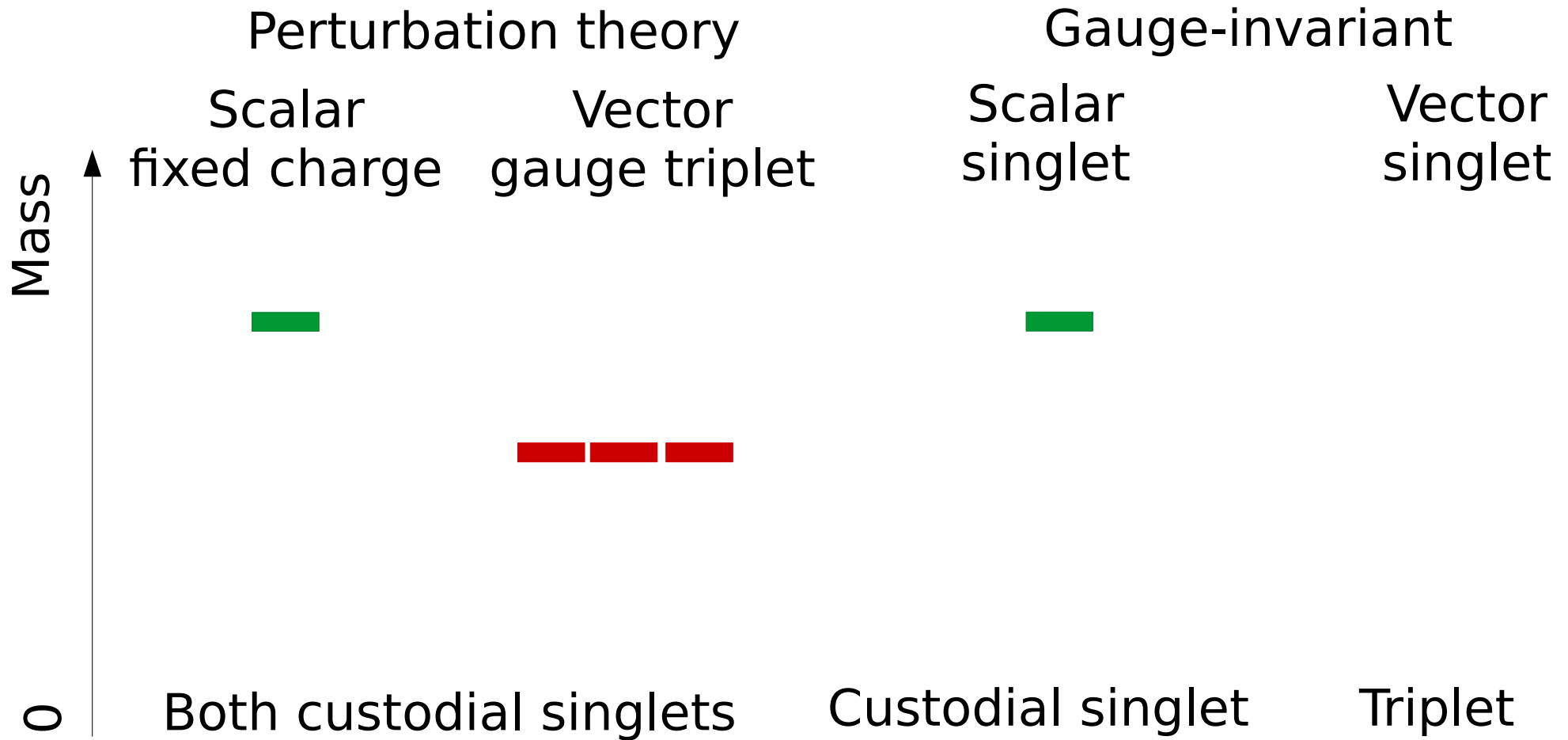
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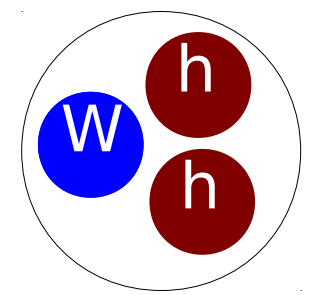
$$\text{tr } t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$$



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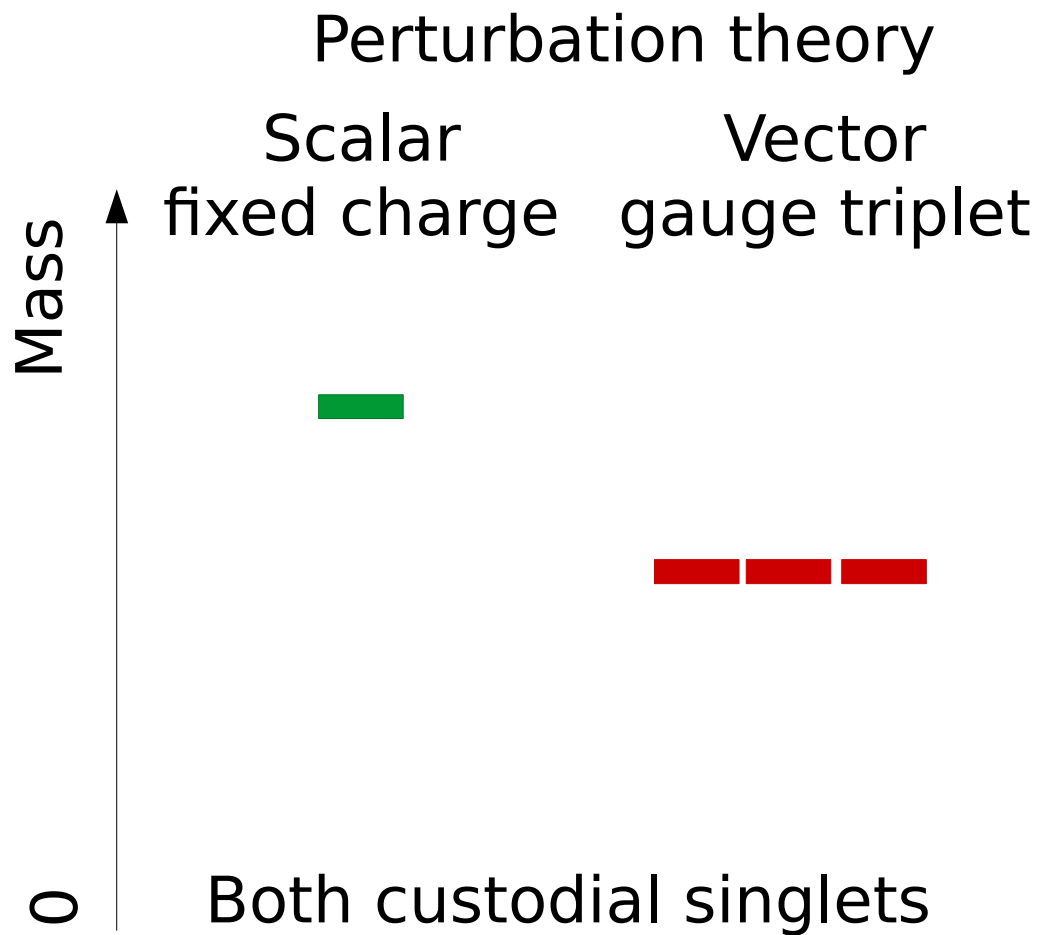


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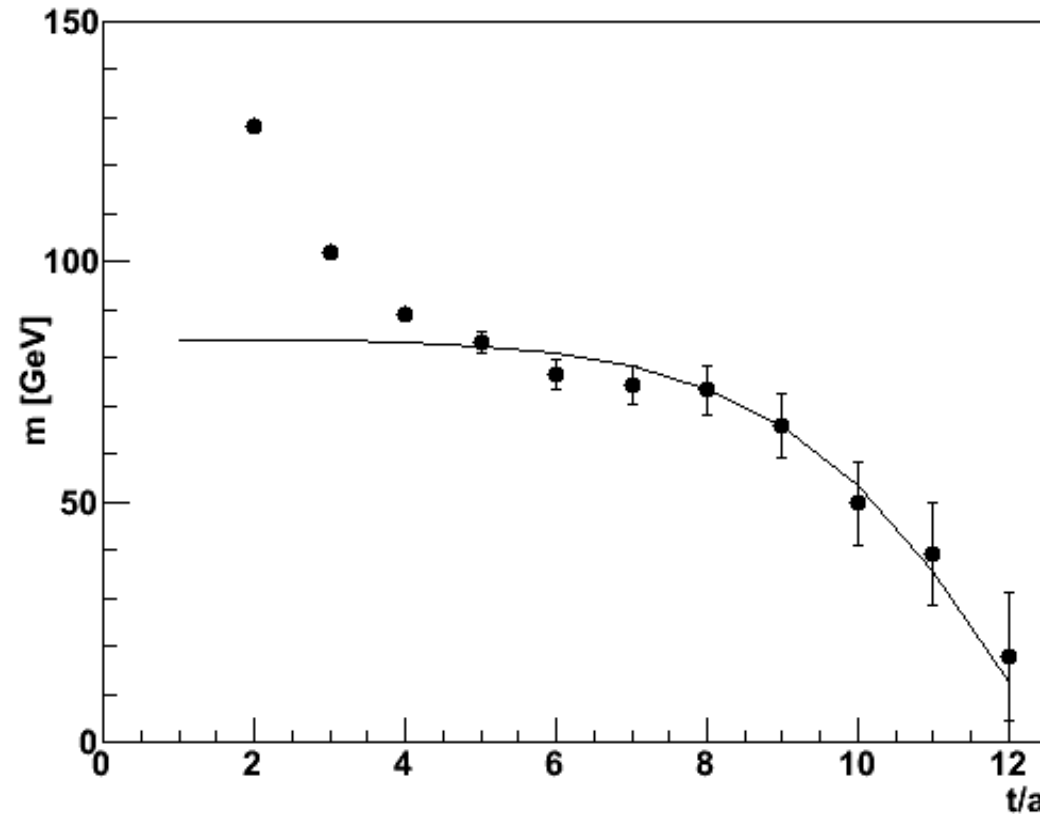
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Gauge-invariant

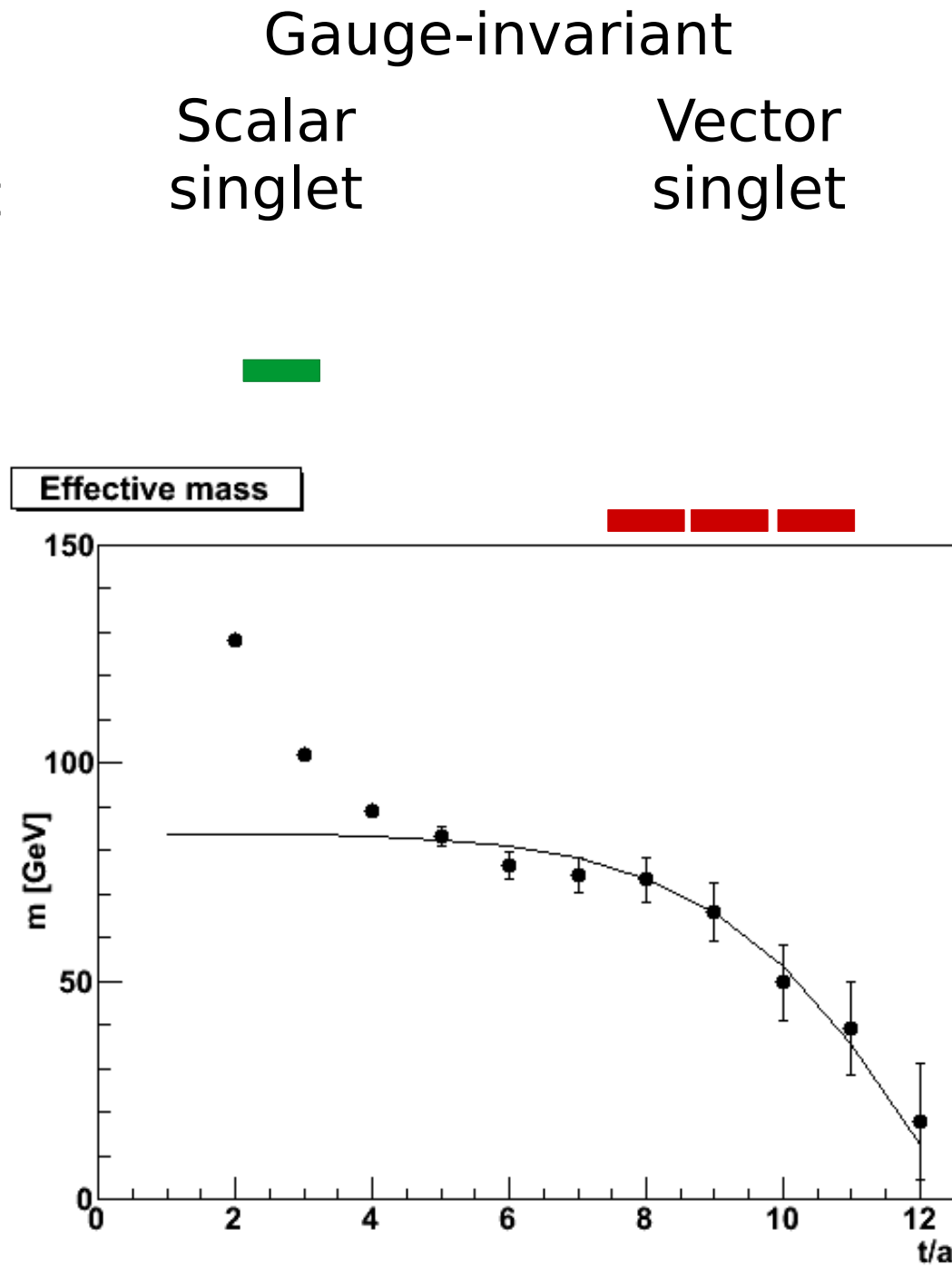
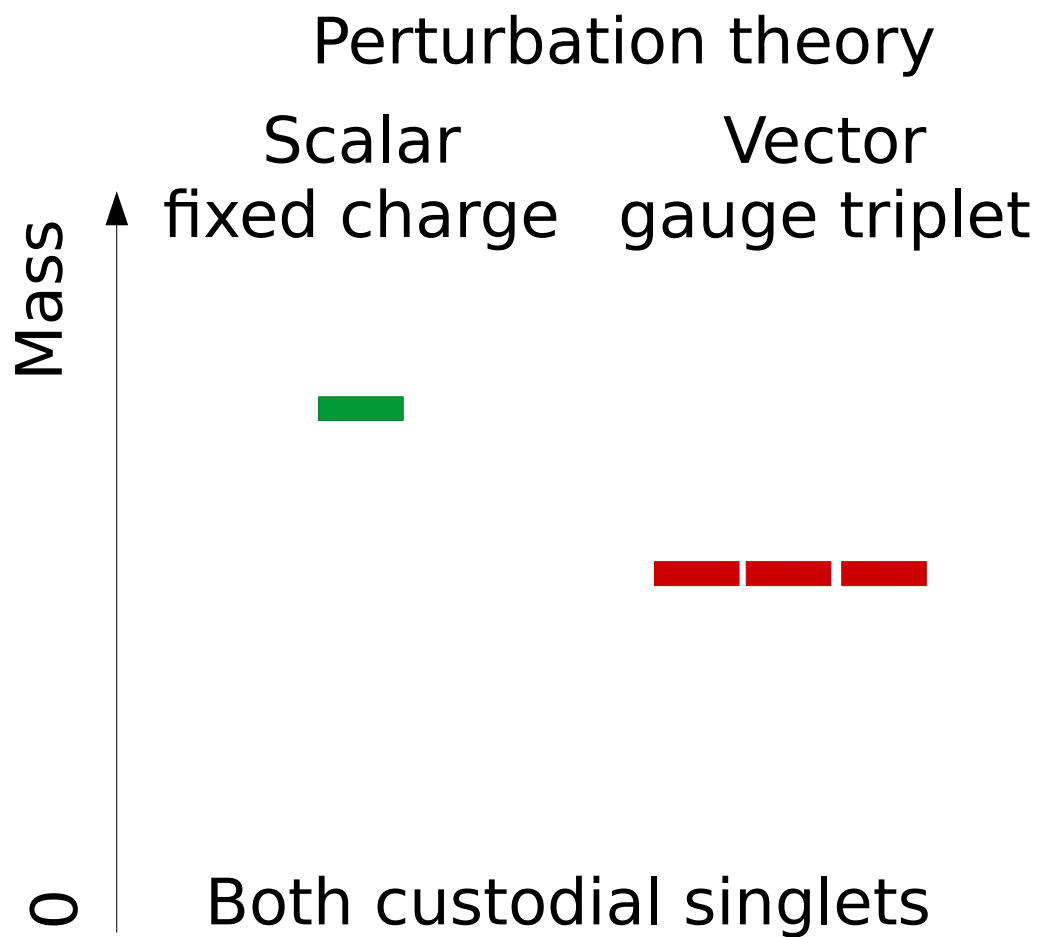
Scalar singlet Vector singlet

Effective mass

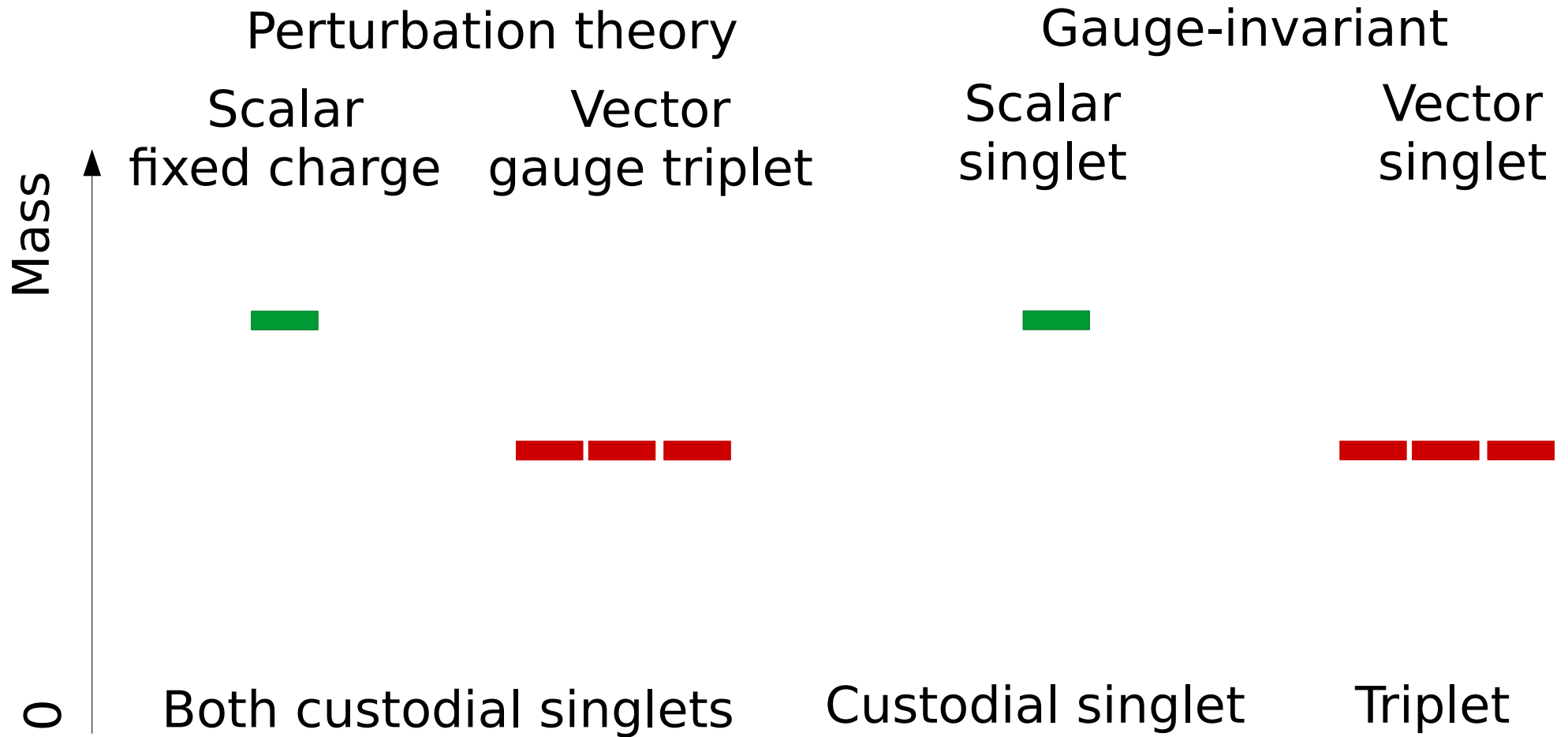


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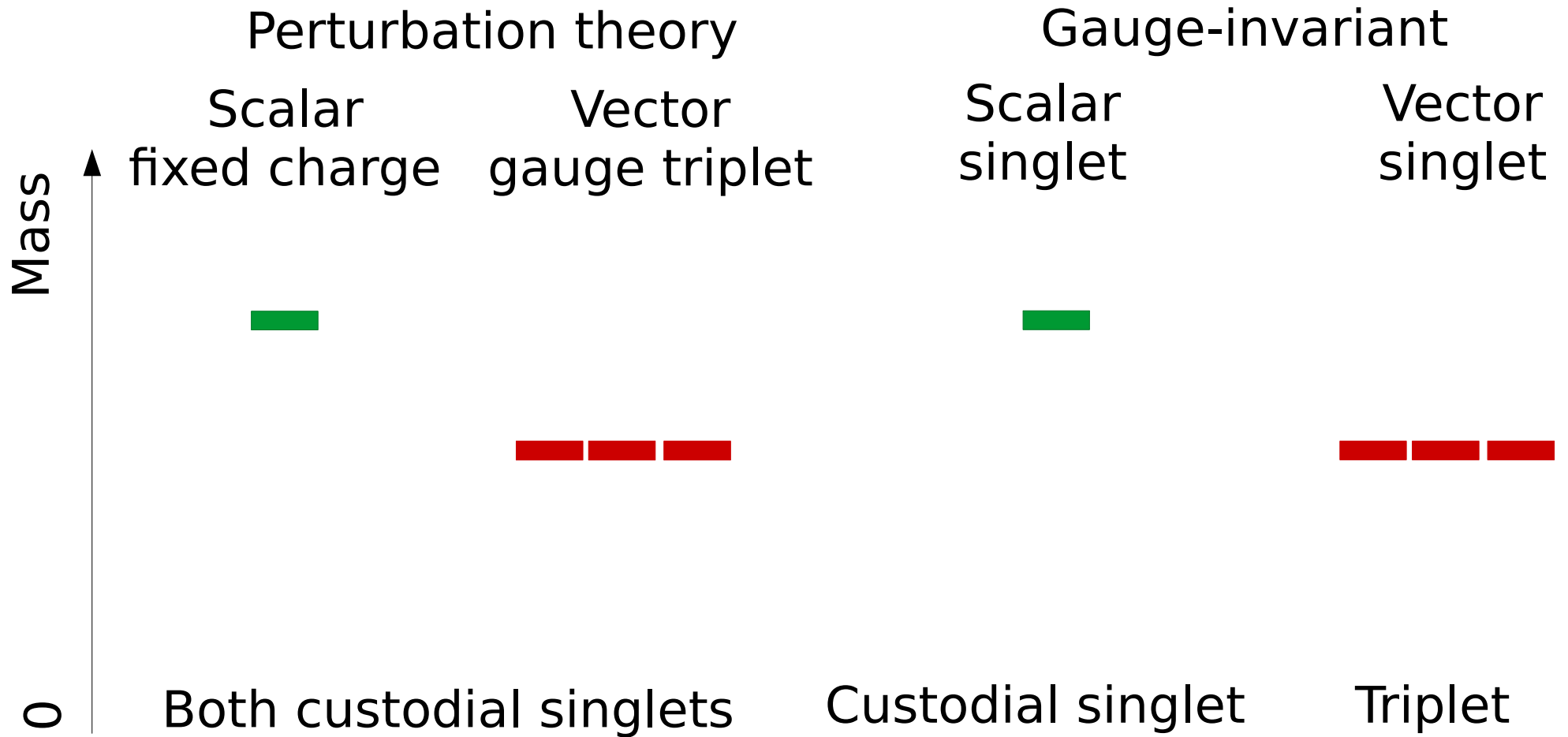
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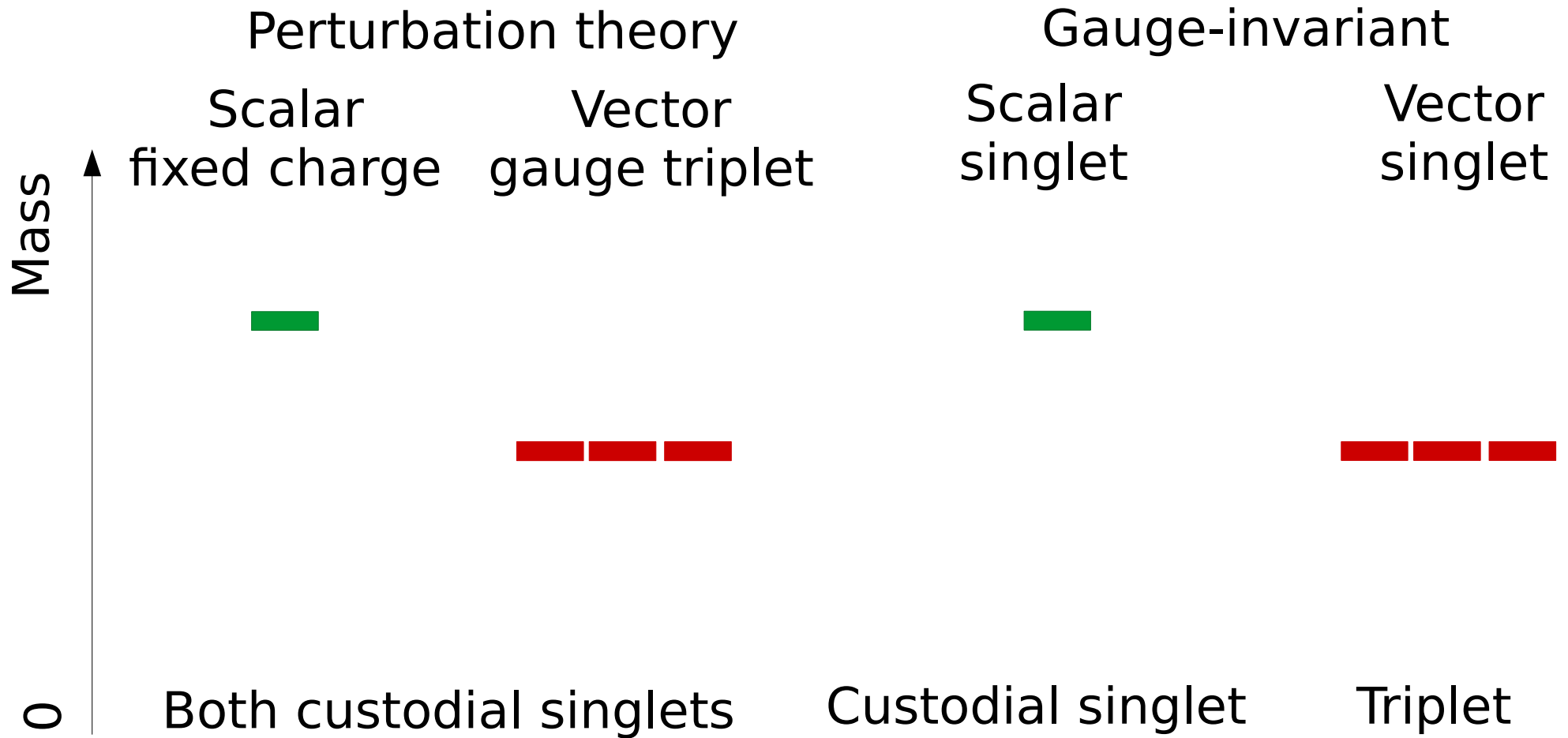
- Same poles at leading order
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 - Exchanges a gauge for a custodial triplet

Physical spectrum



- Quantitatively equivalent spectrum

Physical spectrum



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- Special to this case? Standard model?
 - Lattice also for $SU(2) \times U(1)$ [Shrock et al. 85-88]

Flavor

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

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

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

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Flavor of hadrons

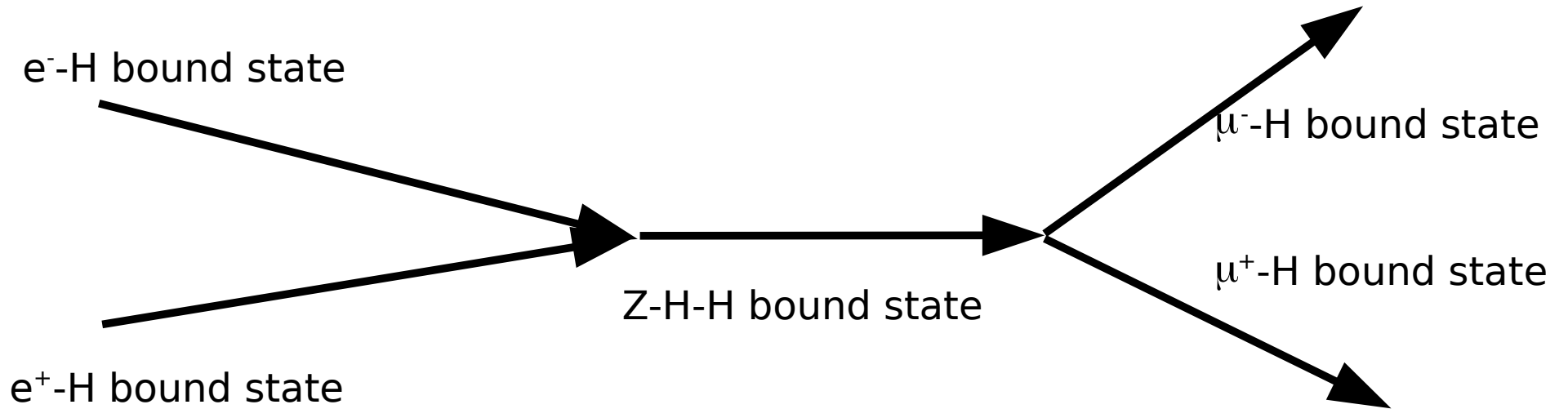
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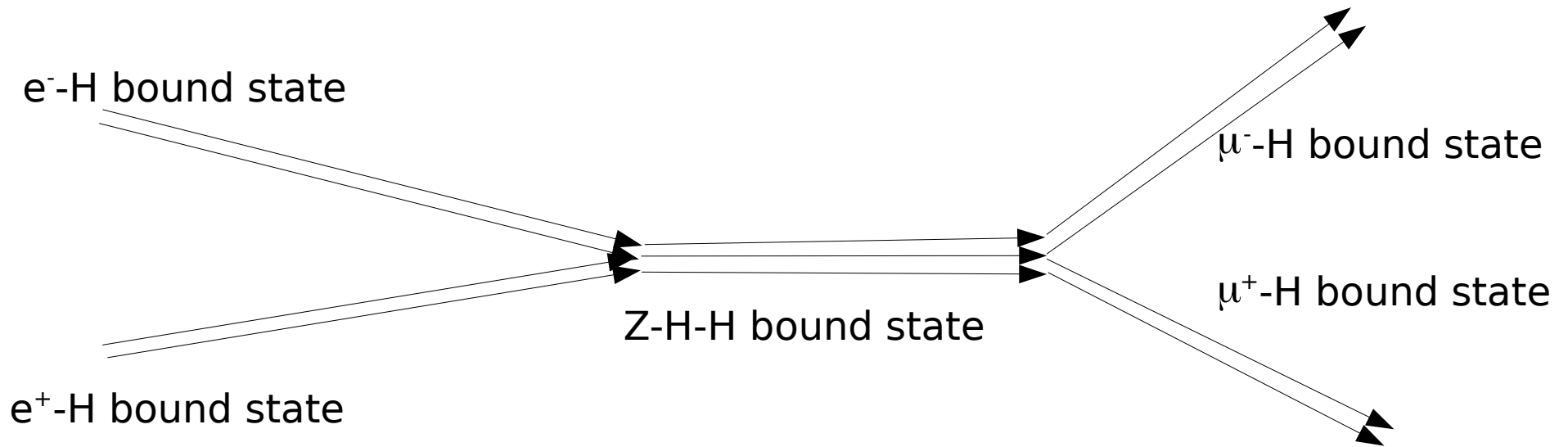
[Maas'12]



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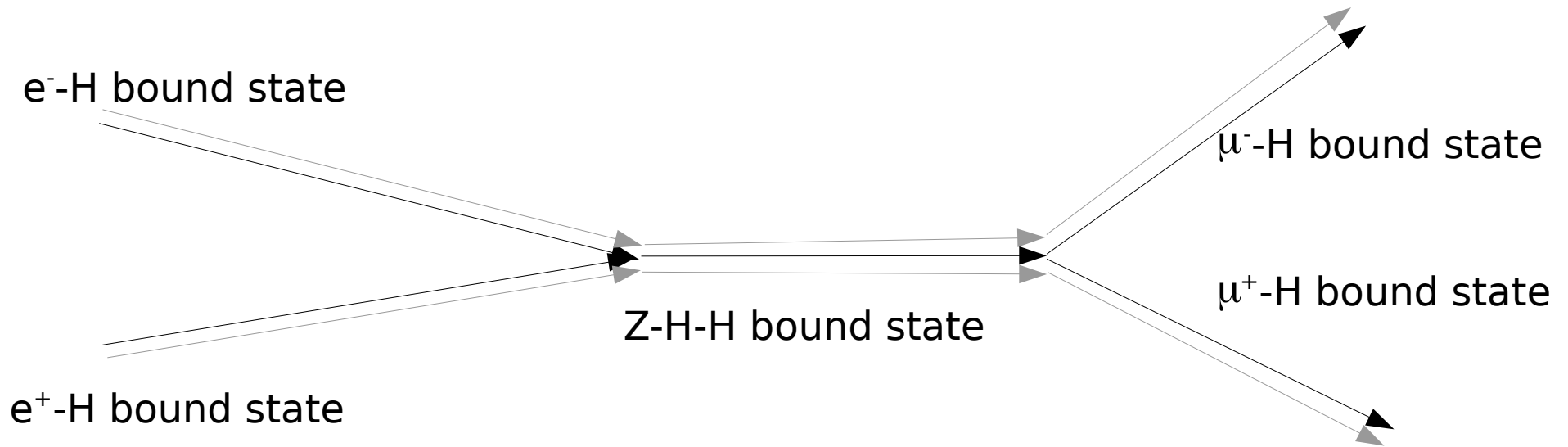
[Maas'12]



- Collision of bound states - 'constituent' particles

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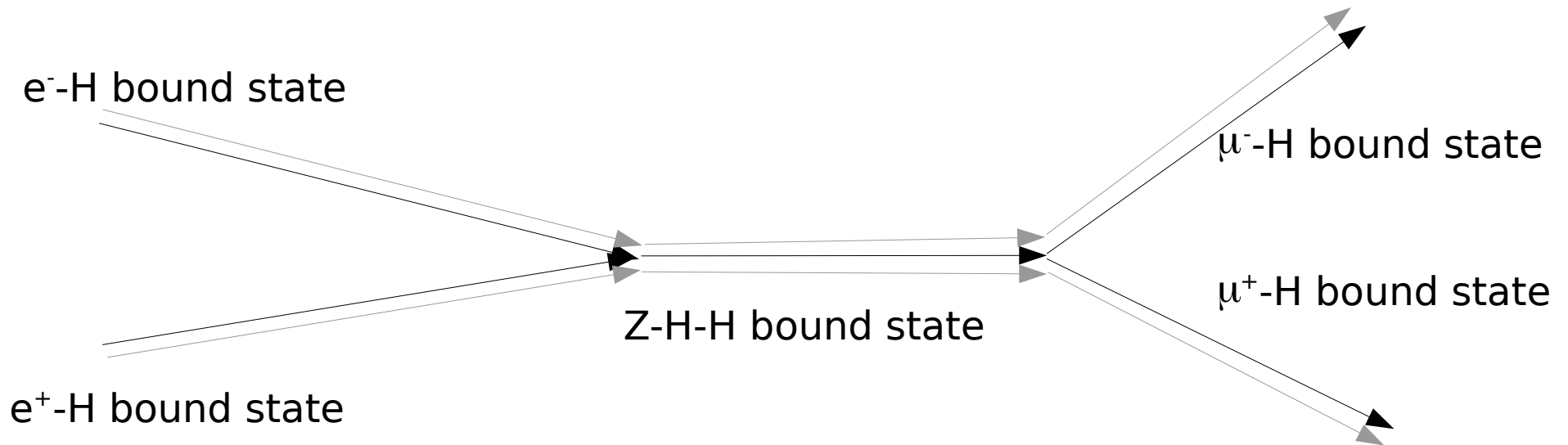
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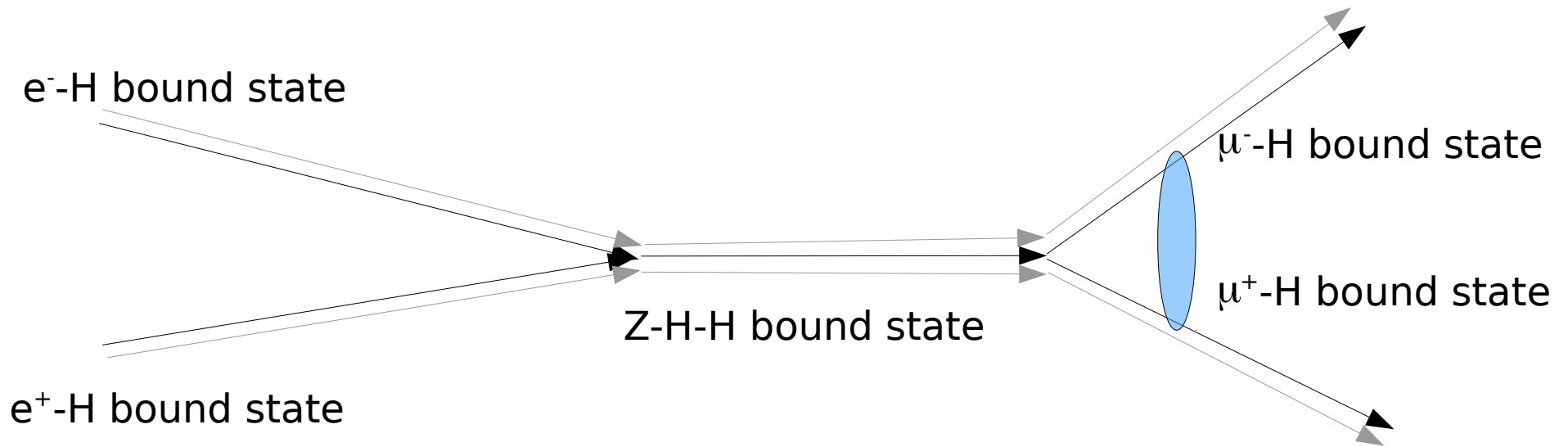
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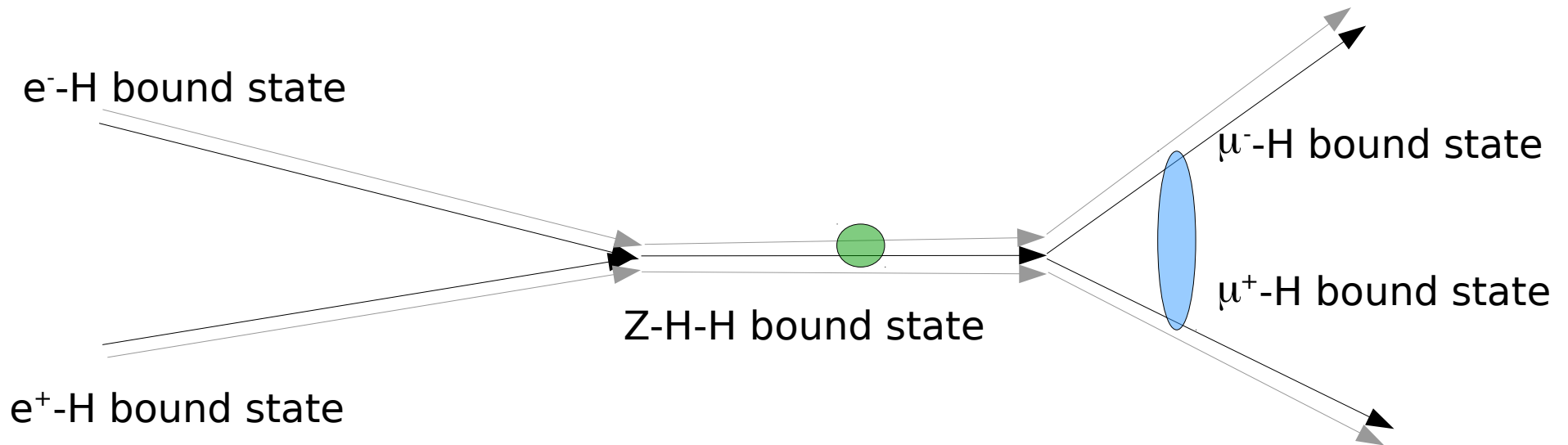
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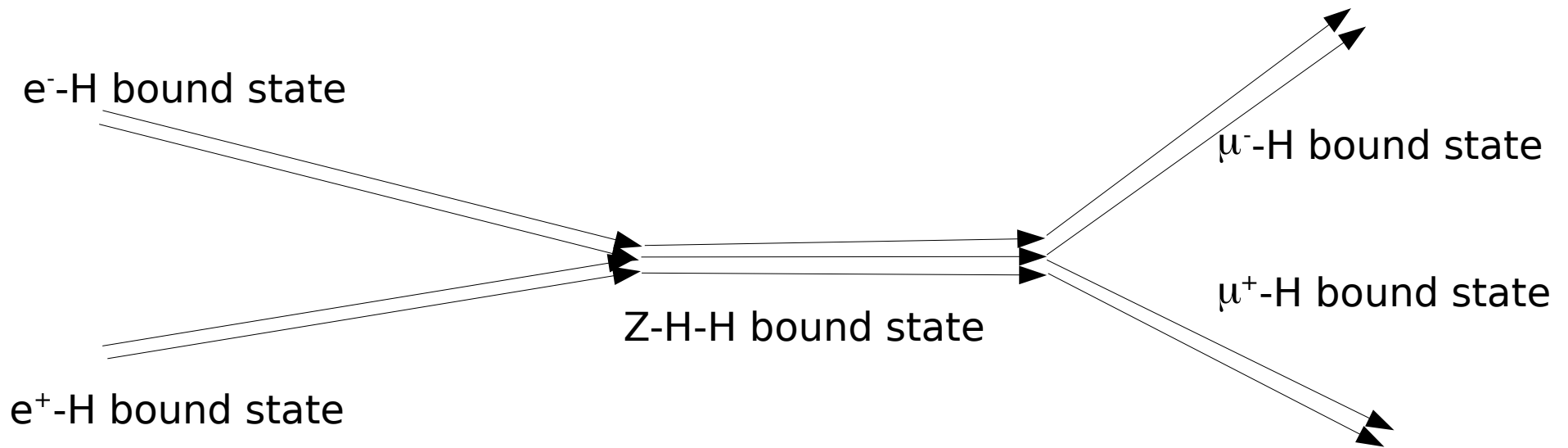
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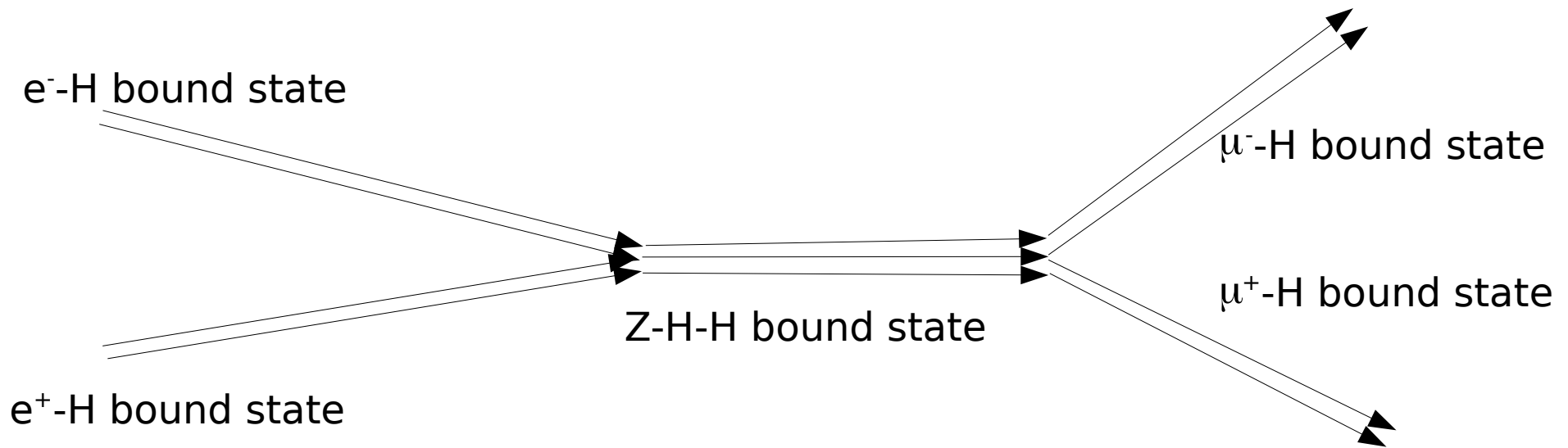
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- Description of impact?

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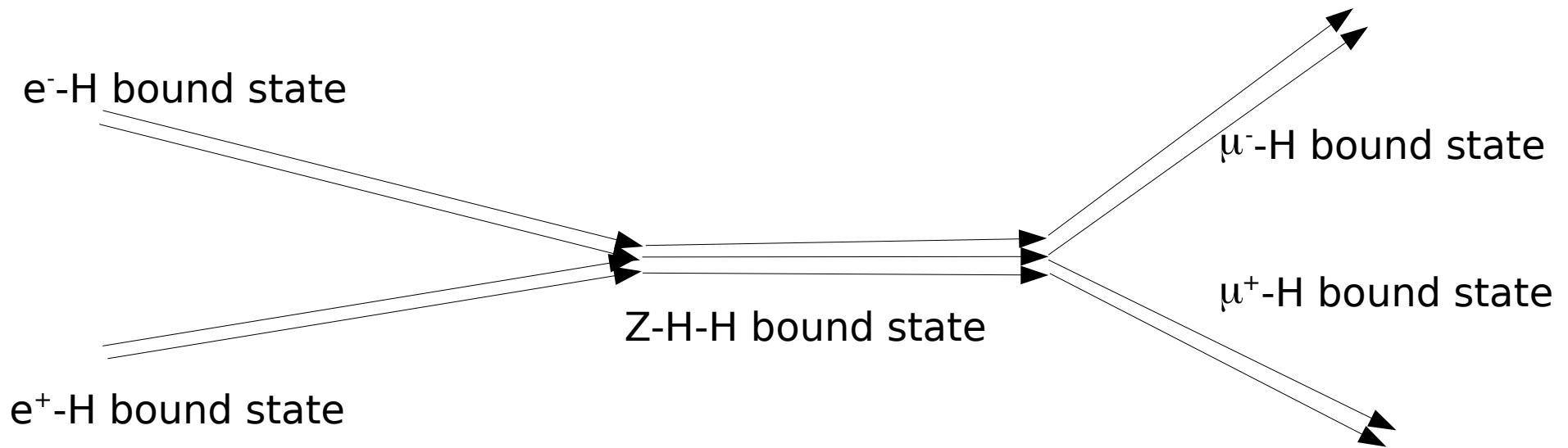
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- Description of impact? Gauge-invariant perturbation theory!

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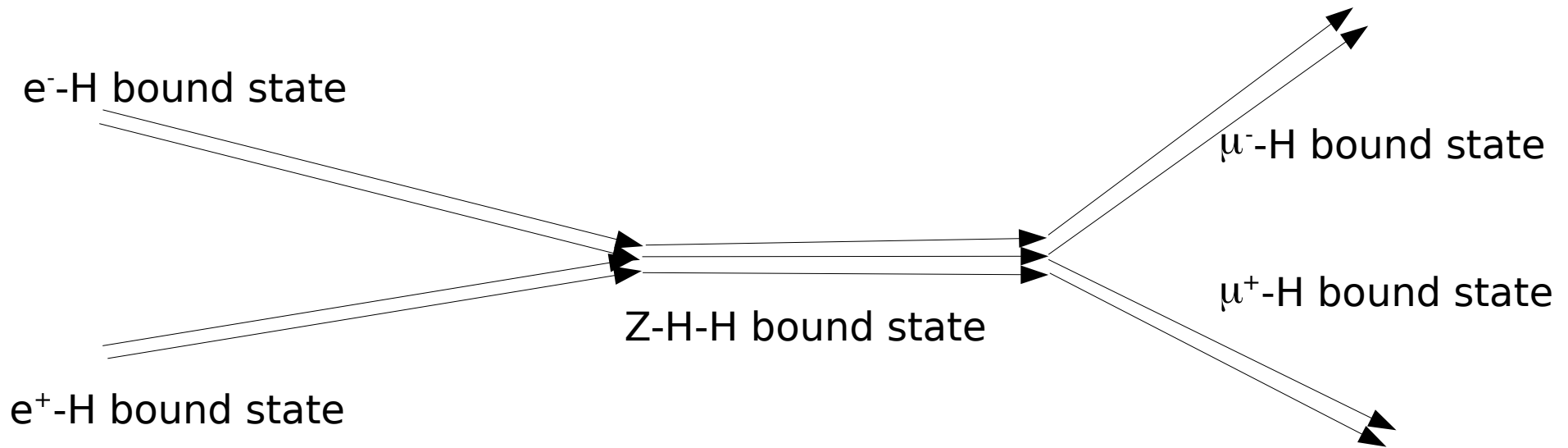


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$$\langle hehe | h\mu h\mu \rangle$$

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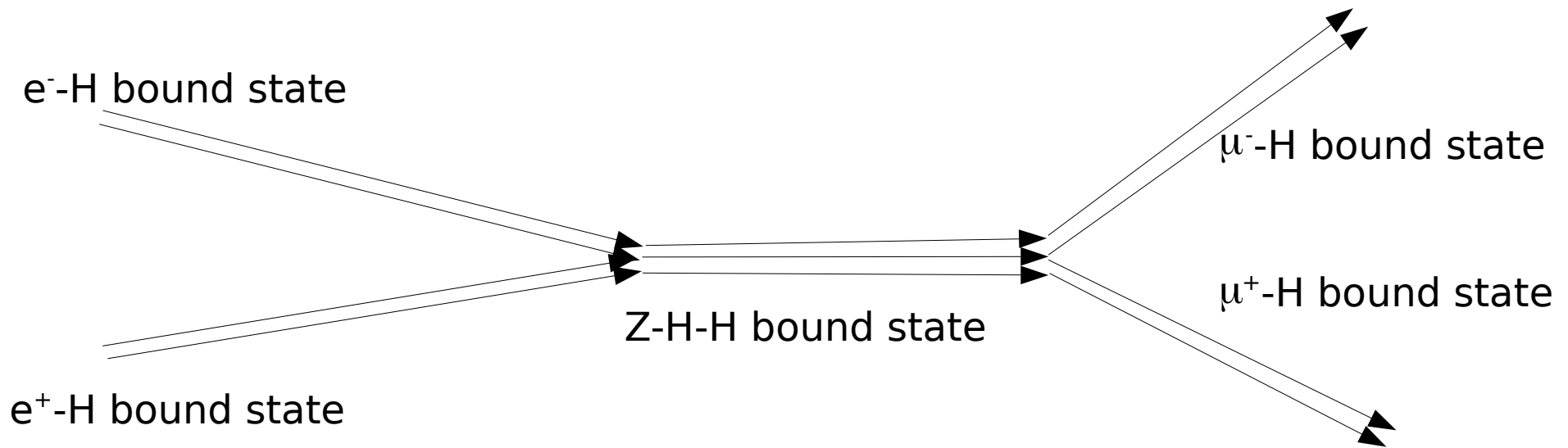
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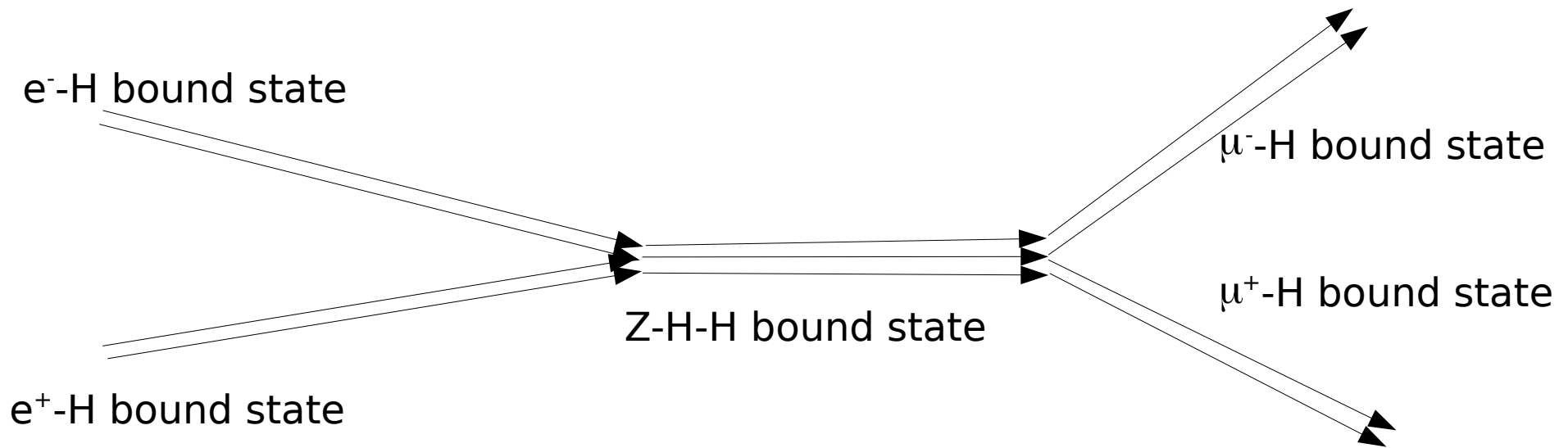
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- Modification of ordinary contribution

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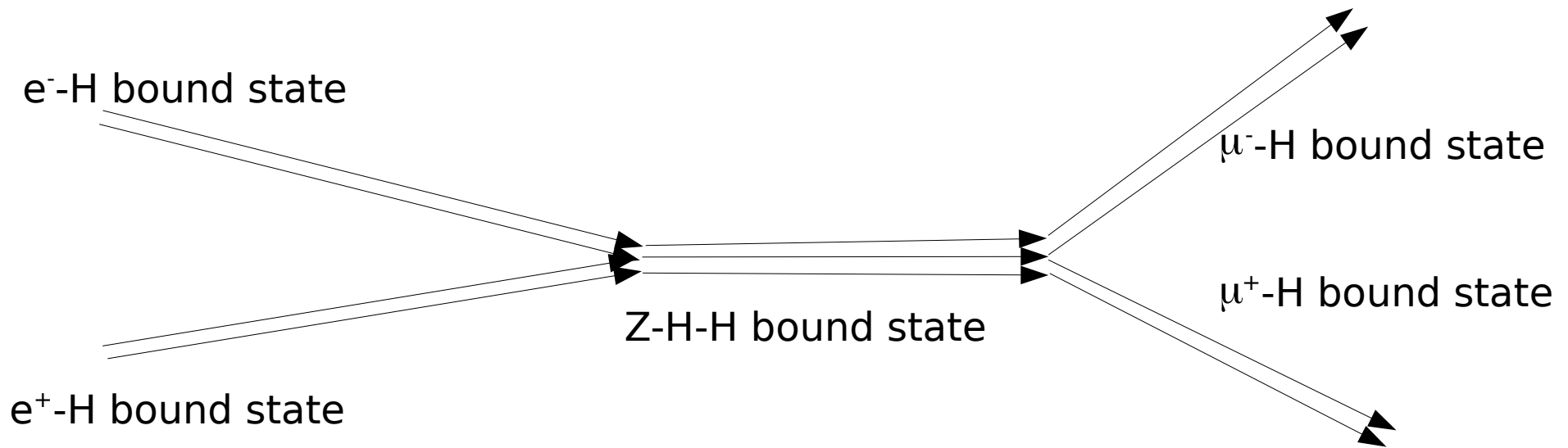
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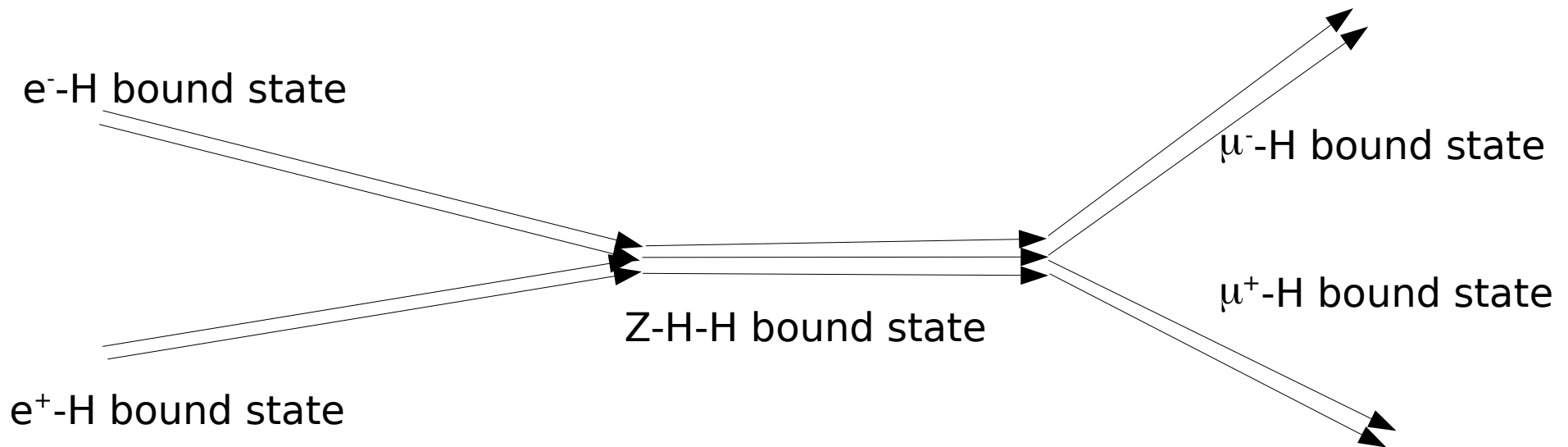
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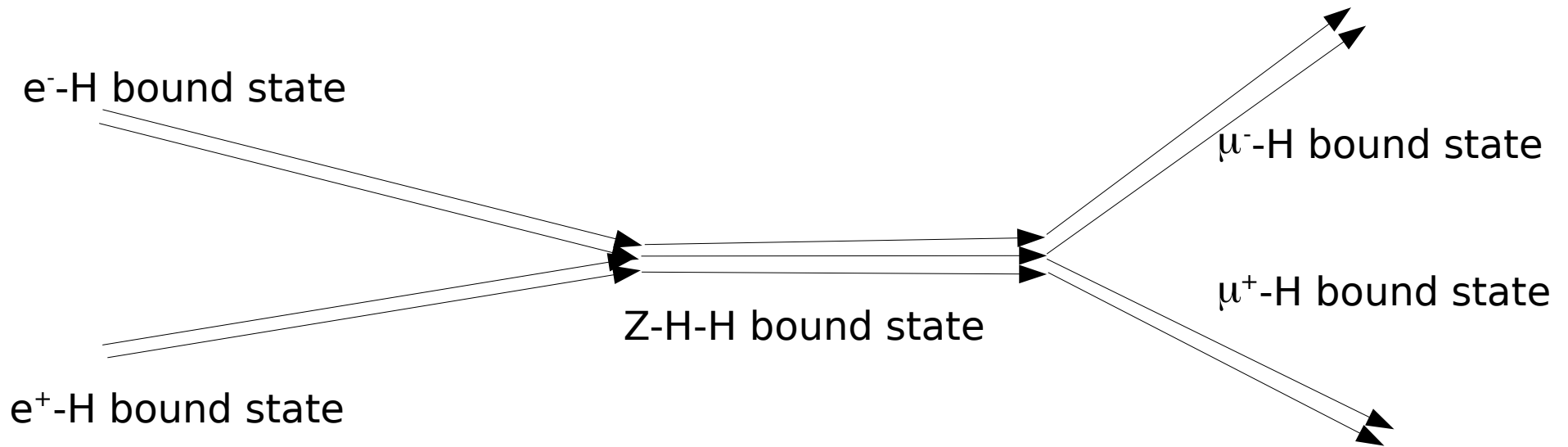
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- Modification of ordinary contribution
- Higgs as initial state
- More contributions...complicated

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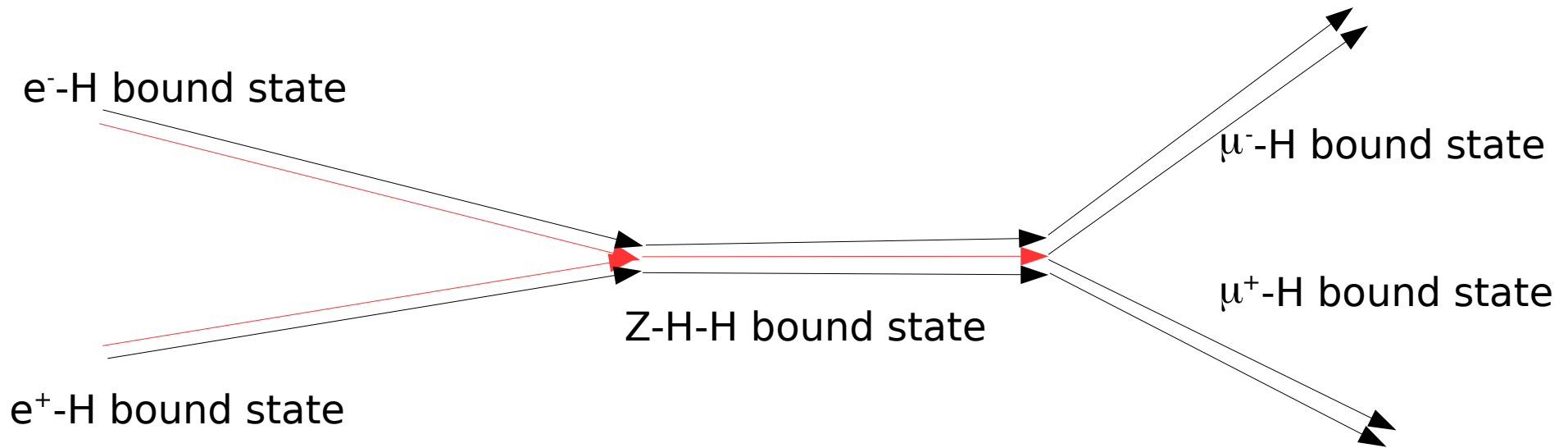
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- Description of impact? PDF-type language!

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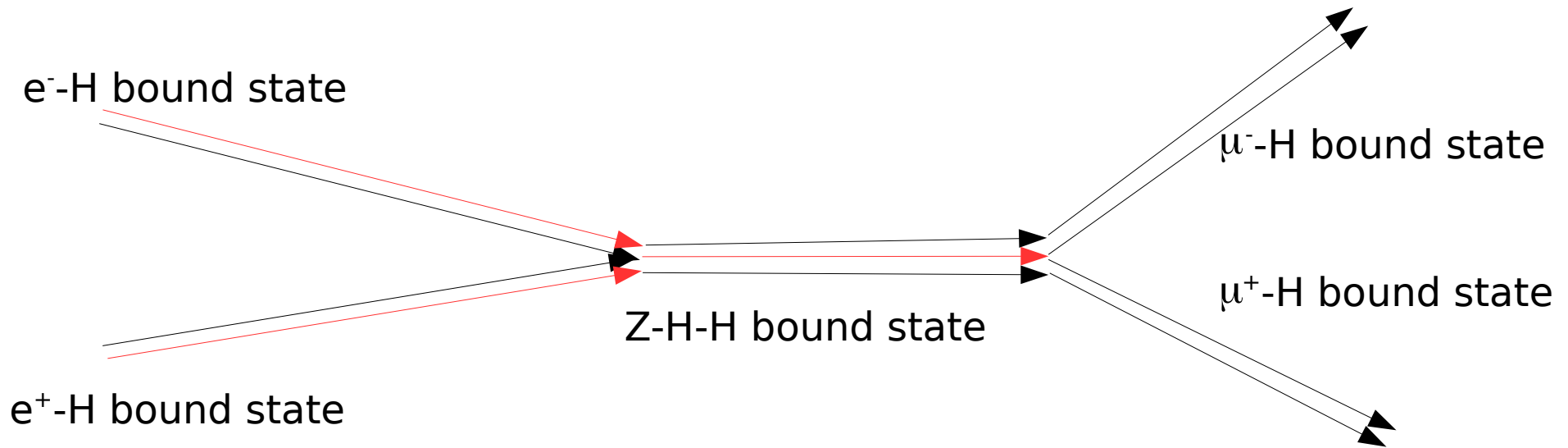
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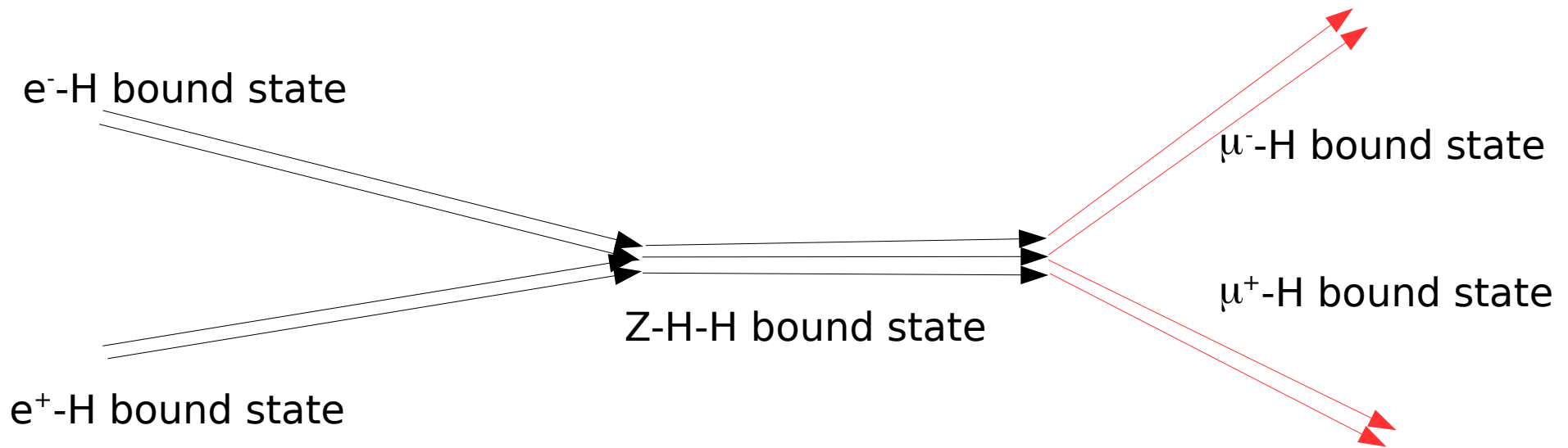
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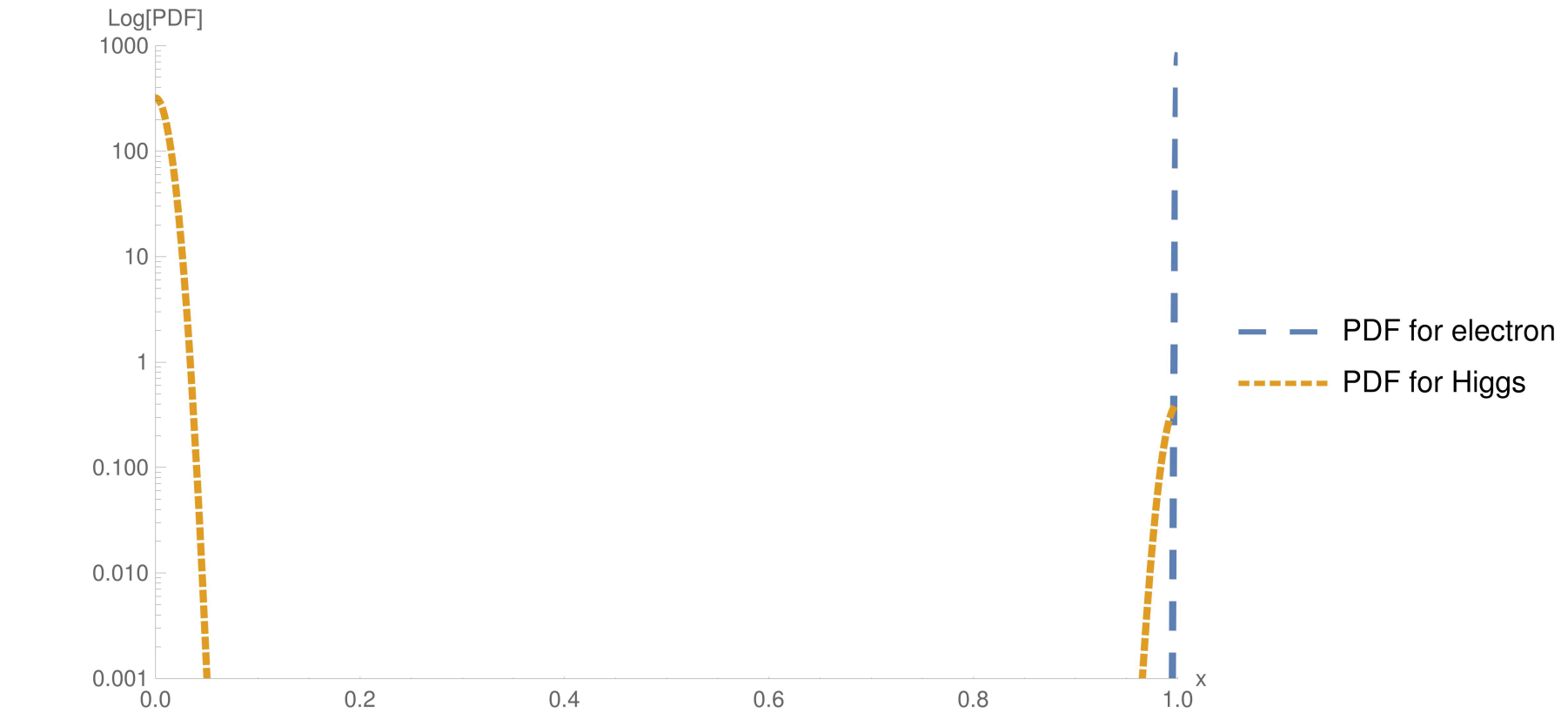
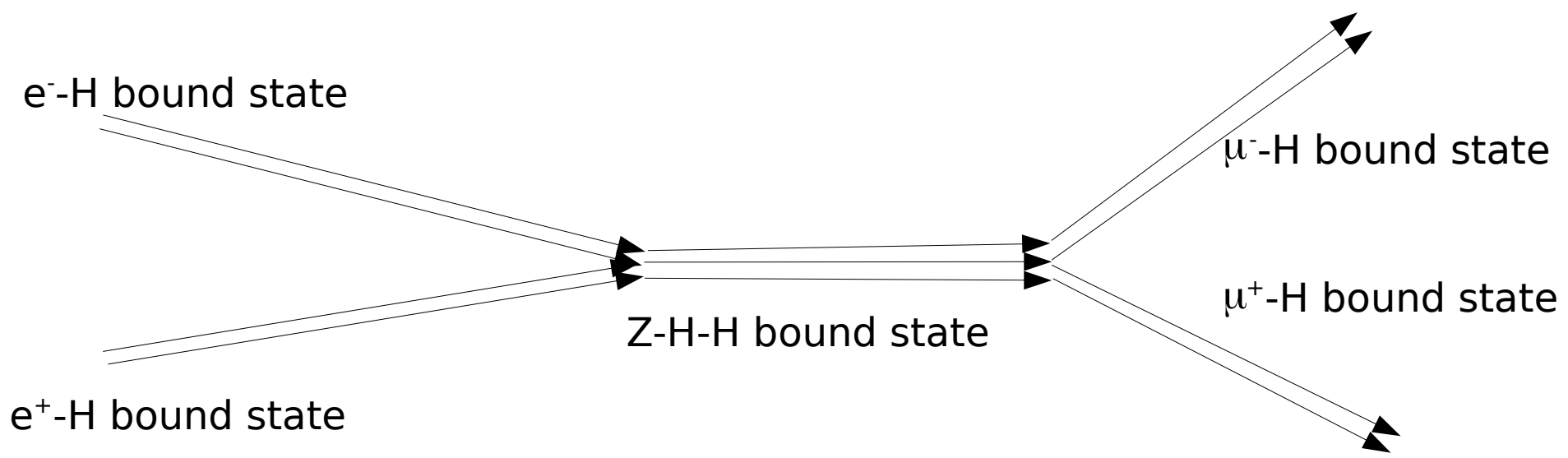
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- Description of impact? PDF-type language!
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- Fragmentation 100% efficient - like for quarks

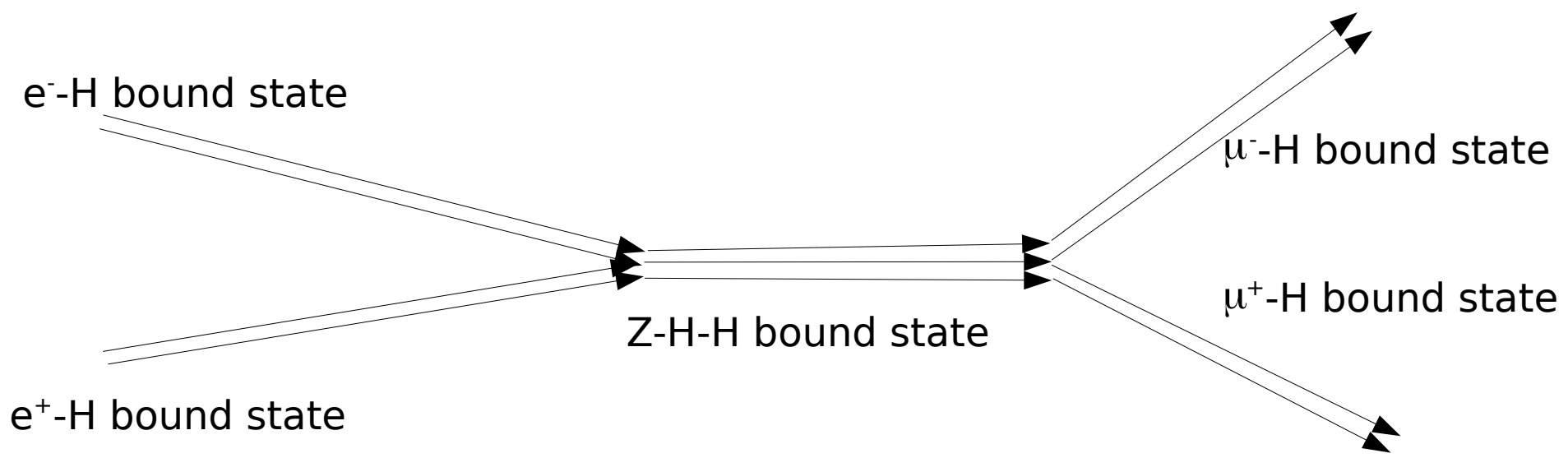
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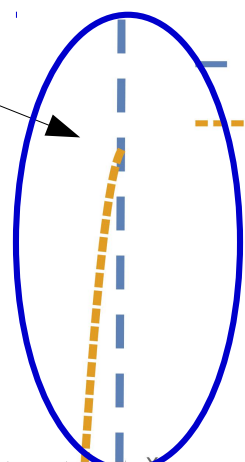
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Log[PDF]

1000
100
10
1
0.100
0.010
0.001

- Strong constraints from sumrules
 - Only electron carries charge!
 - Will change if W etc. included

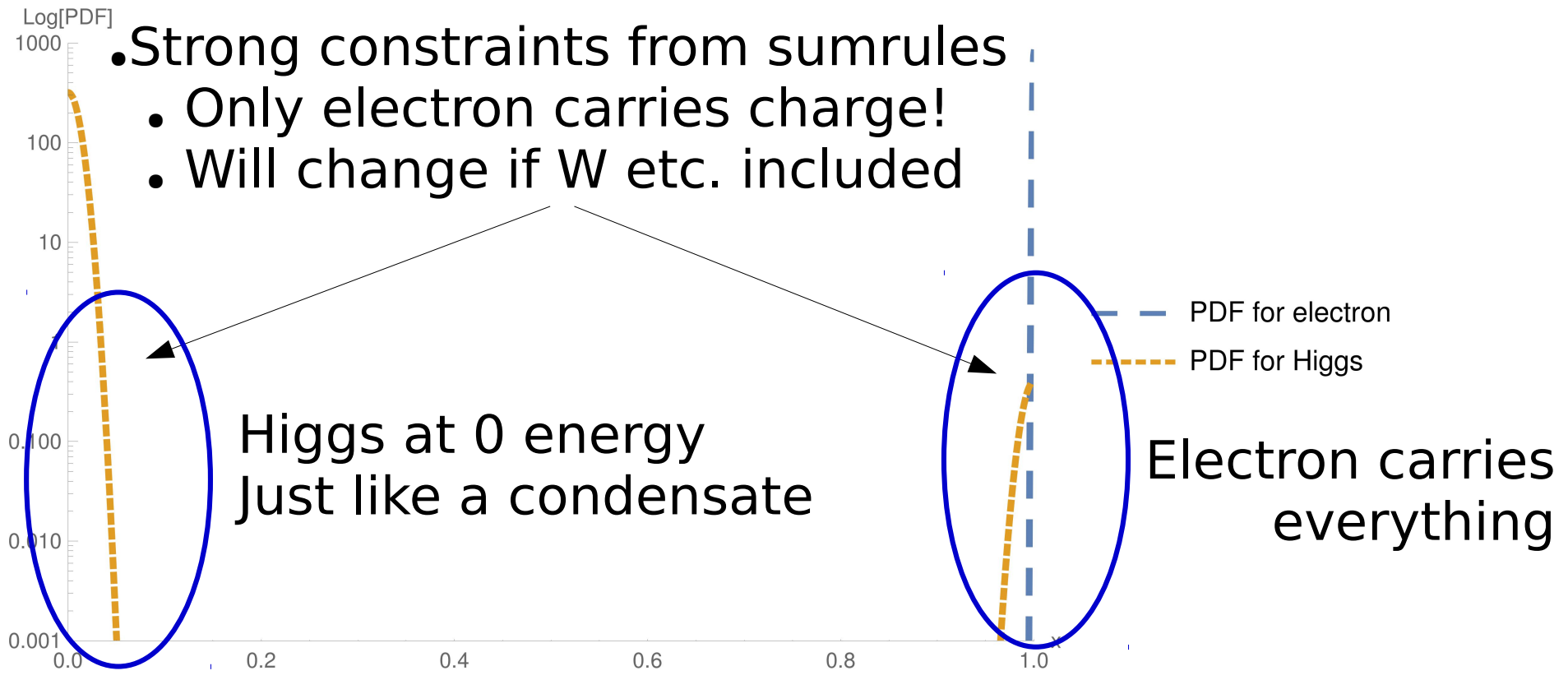
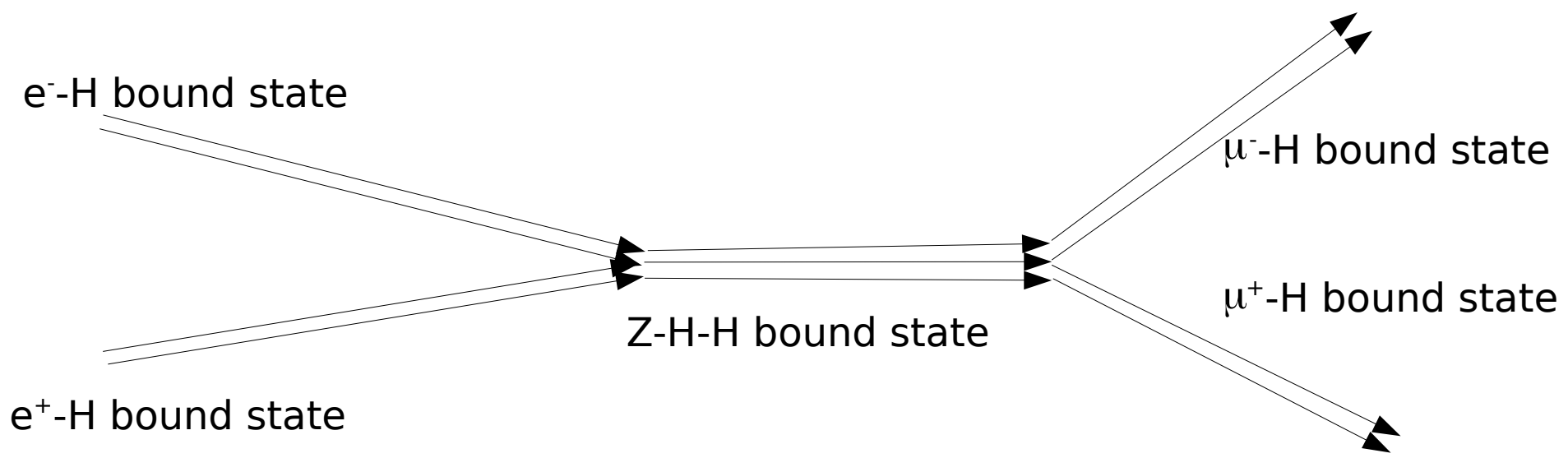


— PDF for electron
- - - PDF for Higgs

Electron carries everything

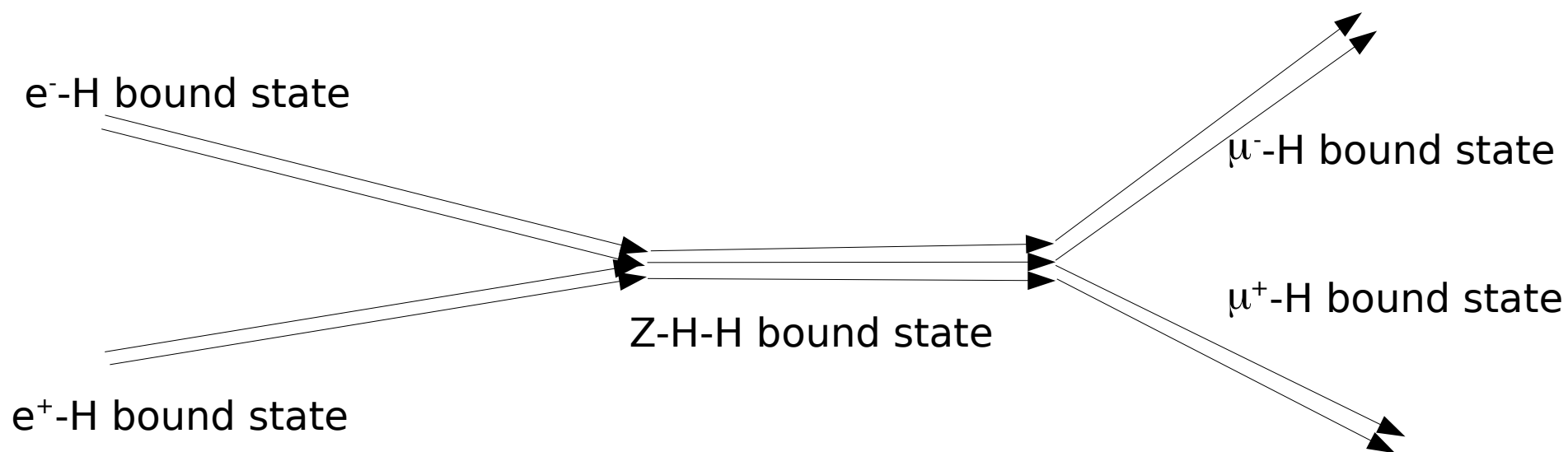
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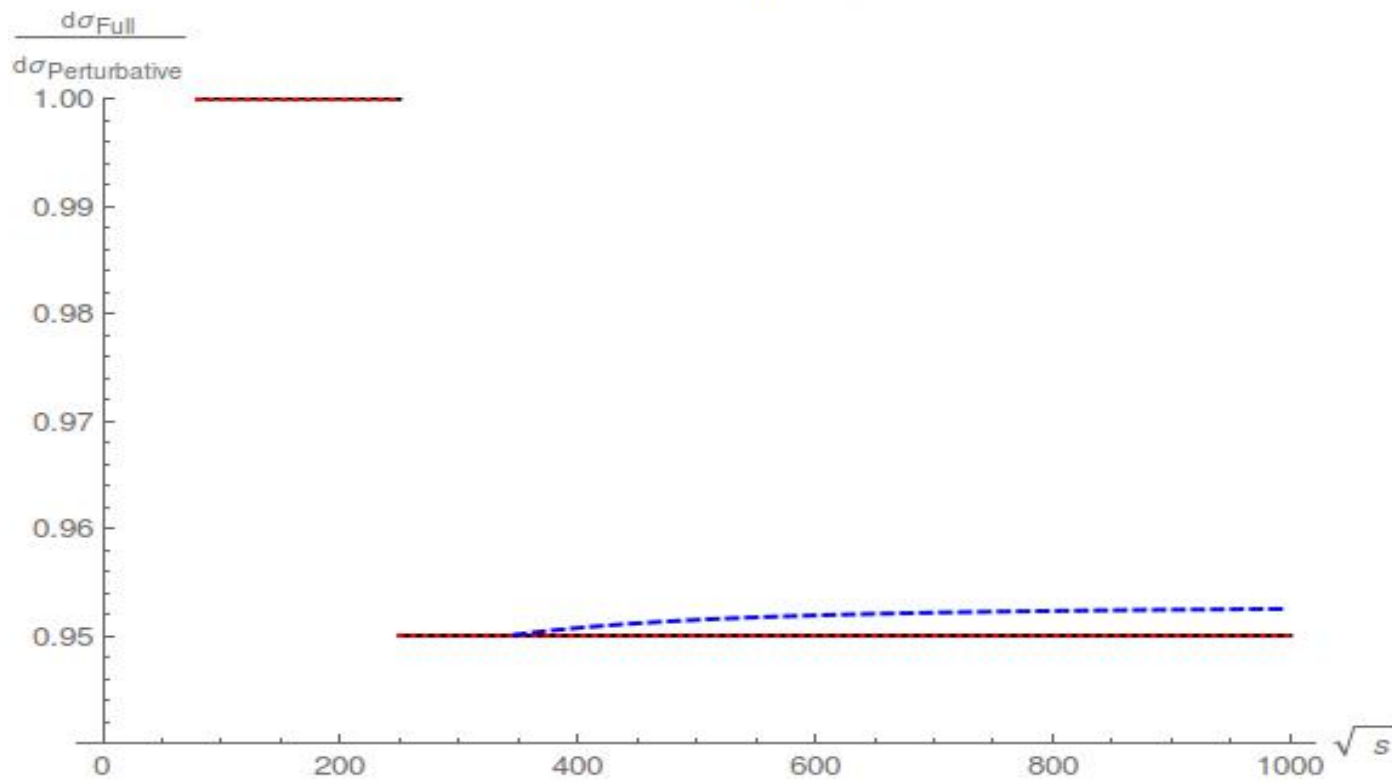


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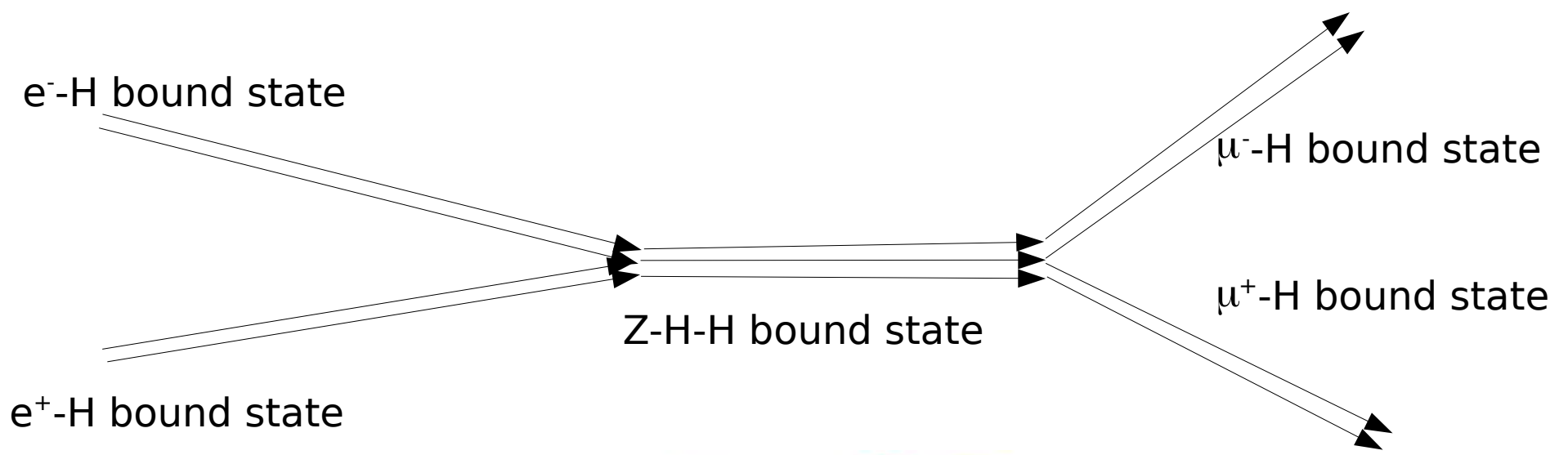


Final state — μ — b — t

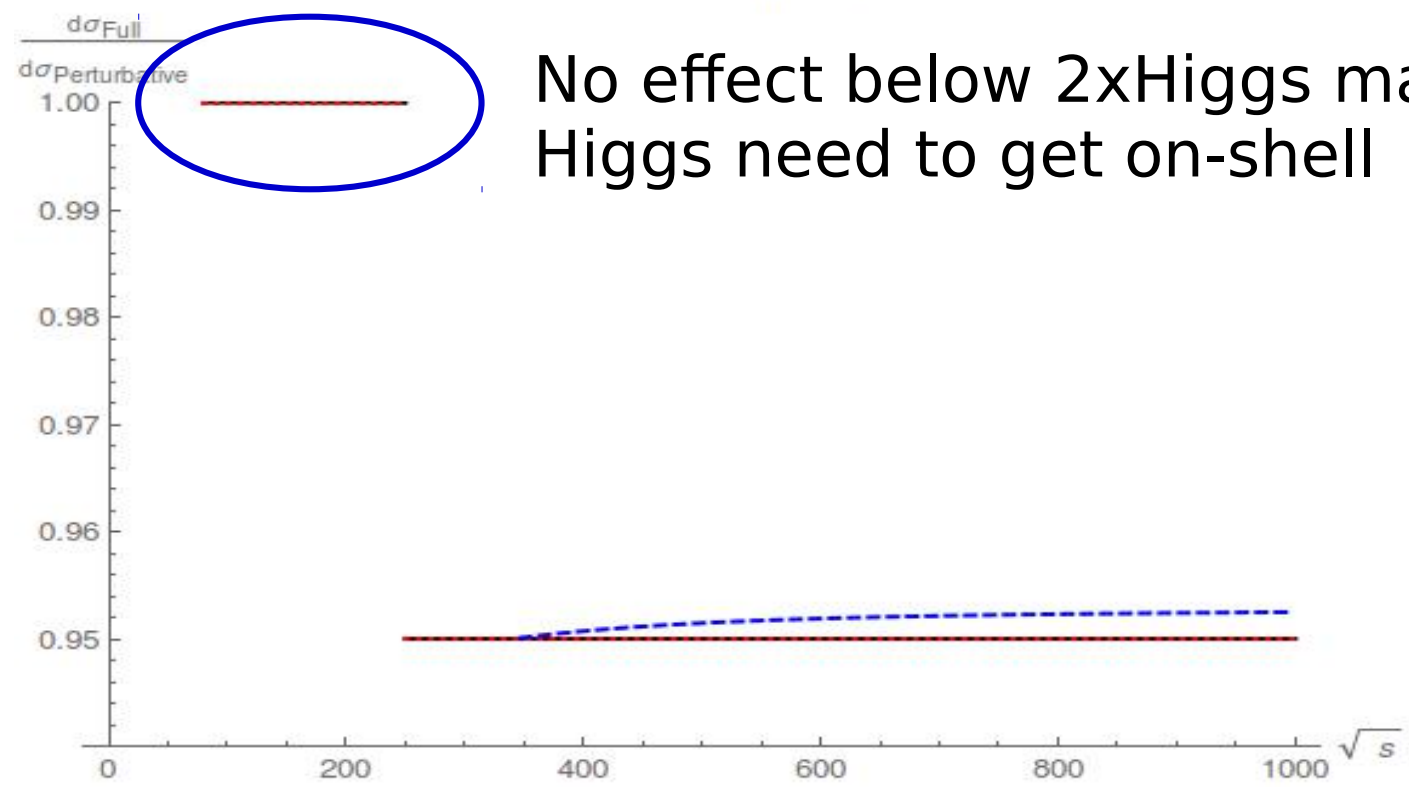


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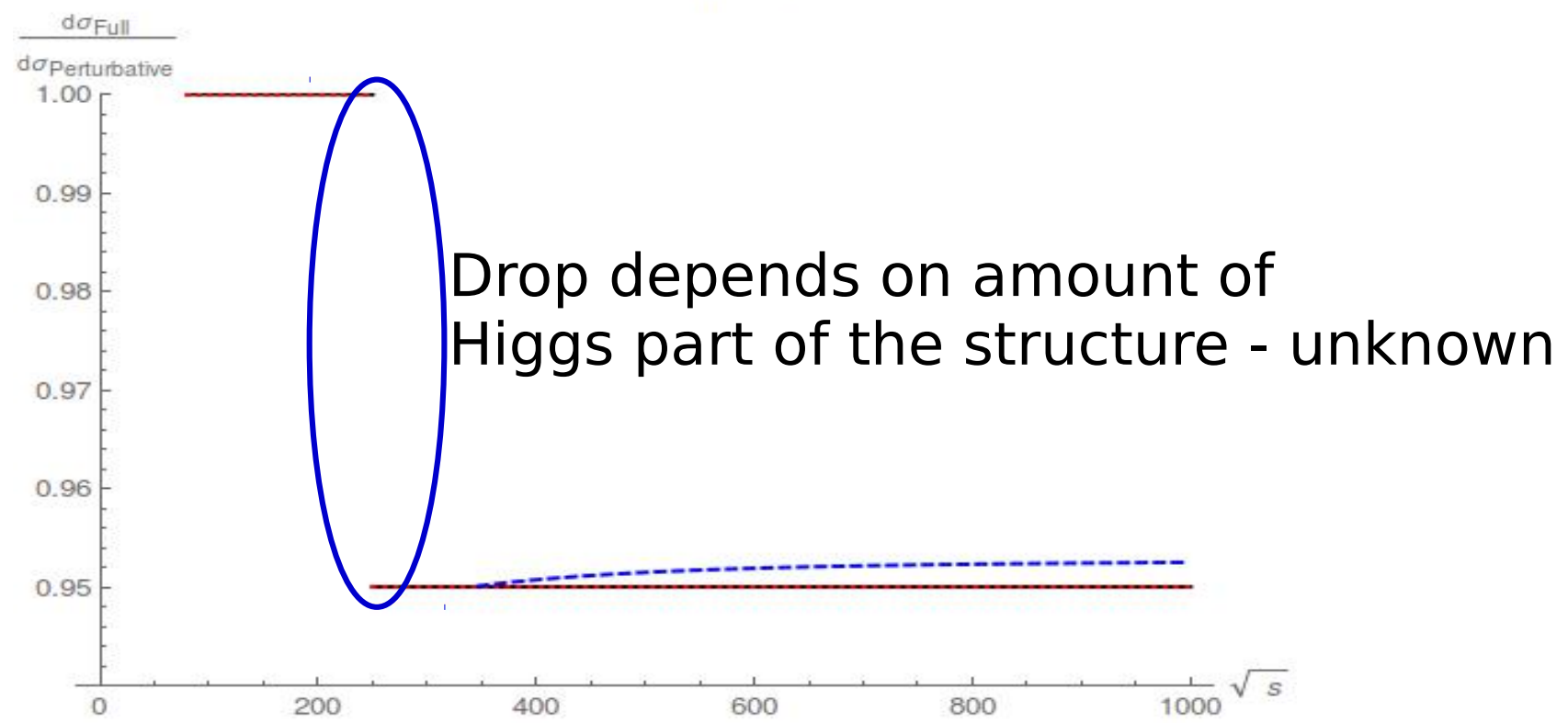
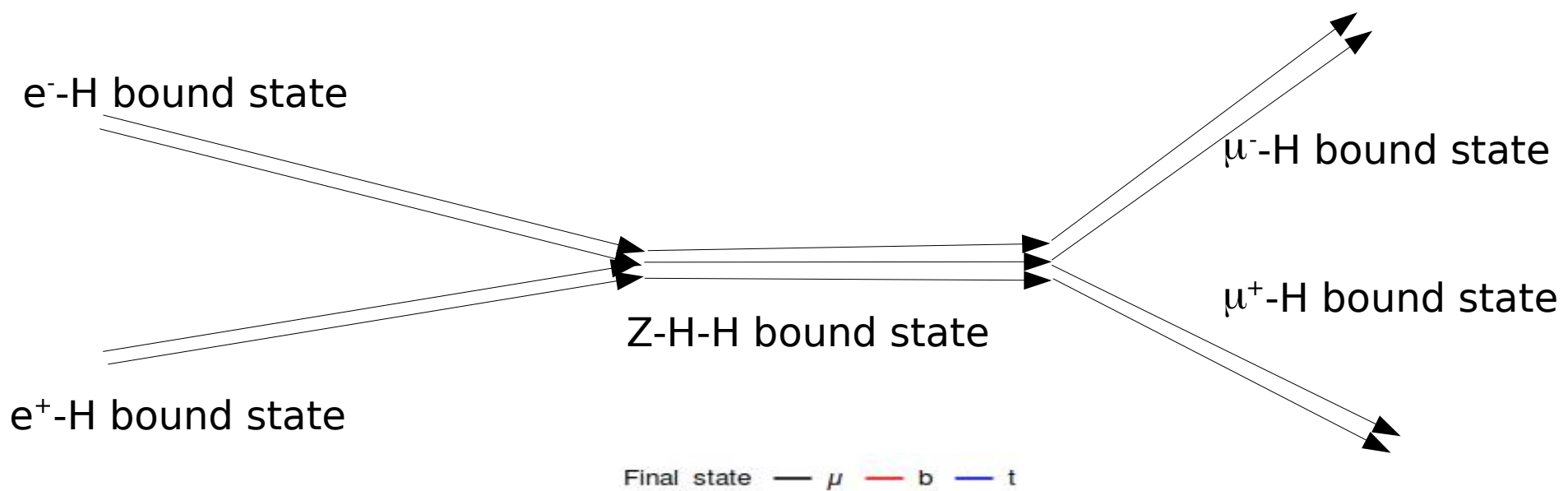
Final state — μ — b — t



No effect below $2 \times m_H$ mass
Higgs need to get on-shell

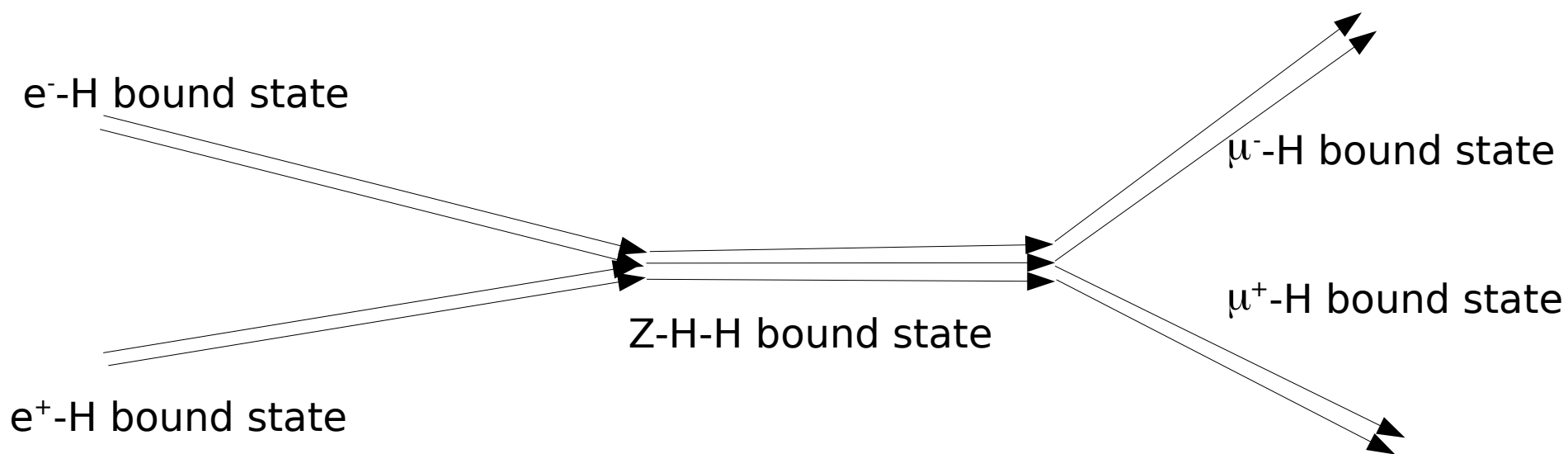
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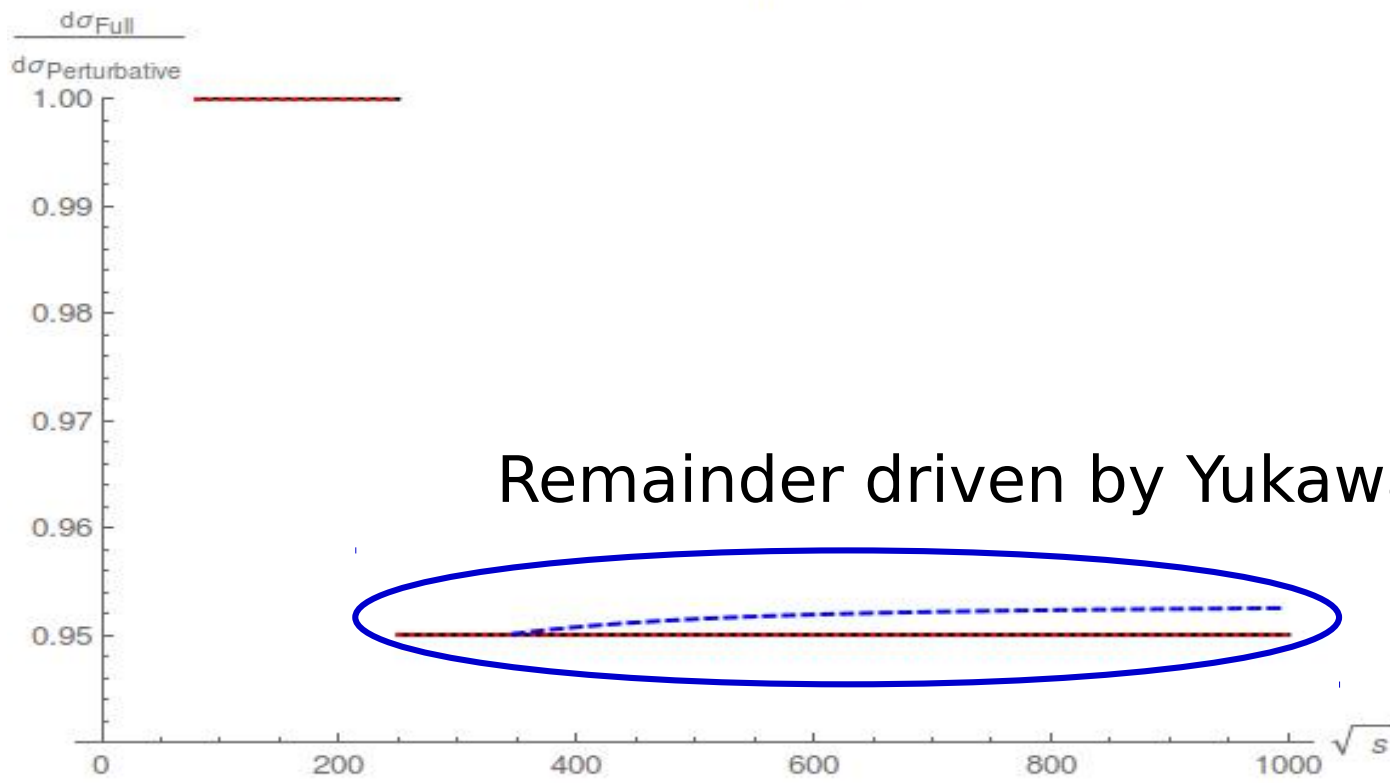


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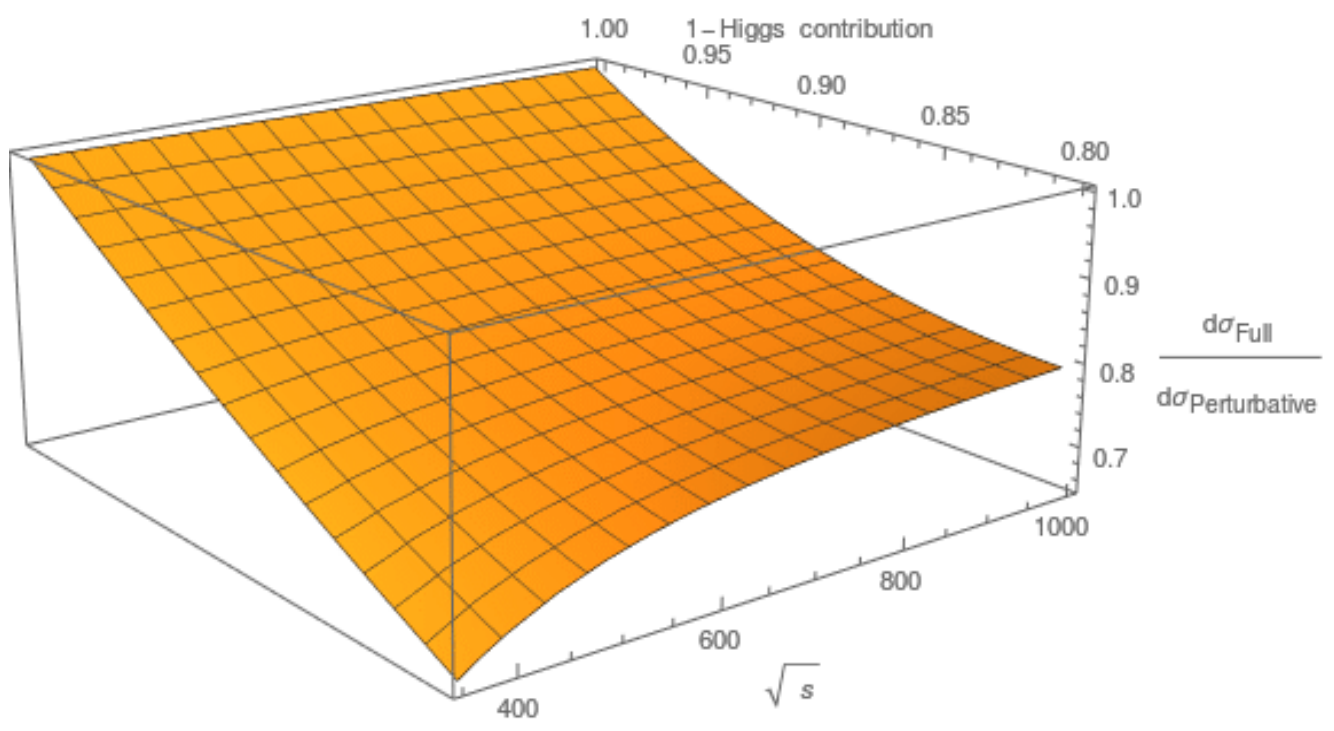
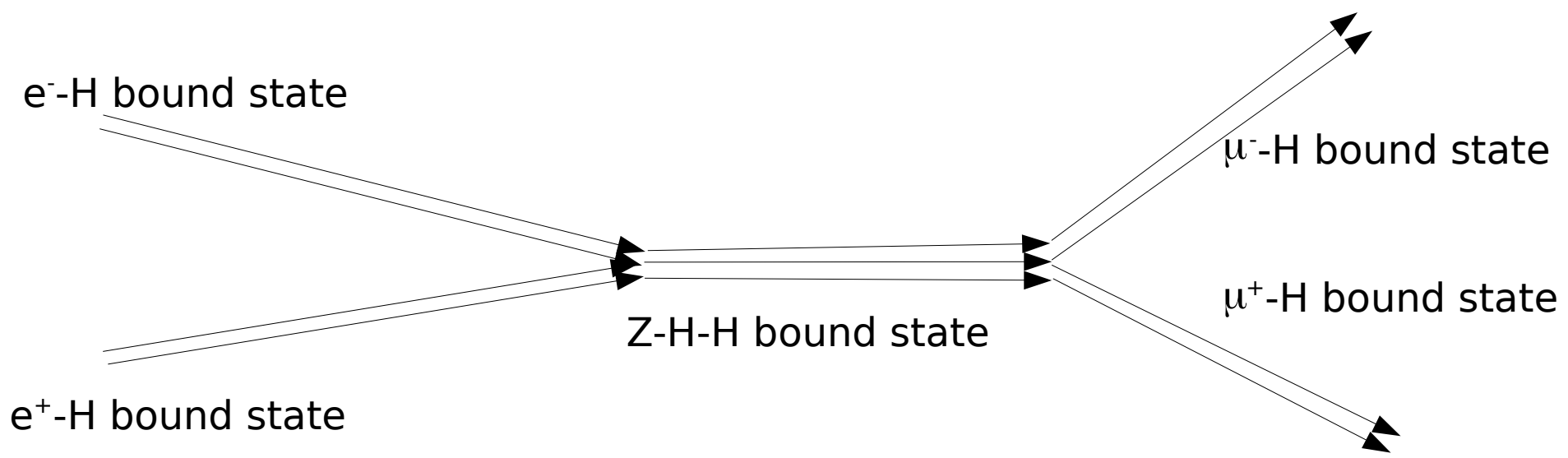


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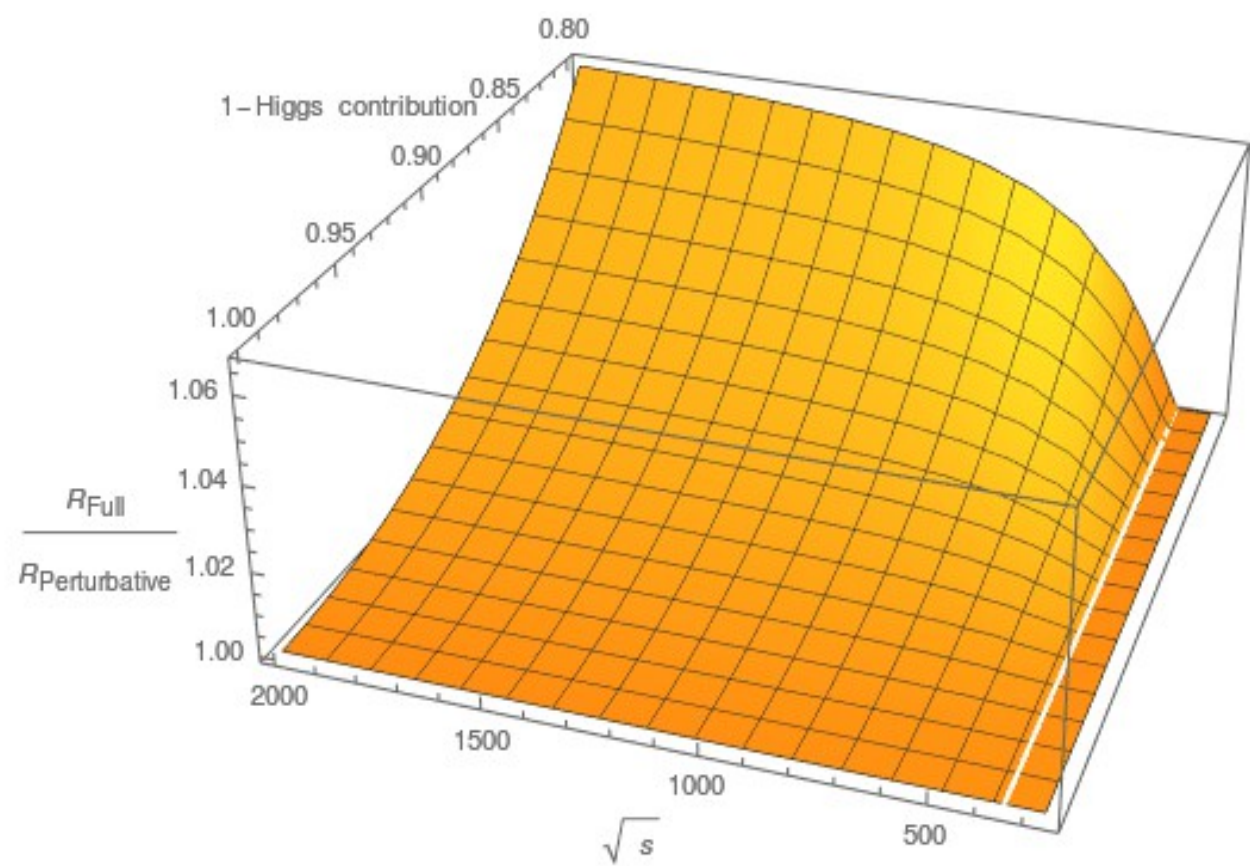
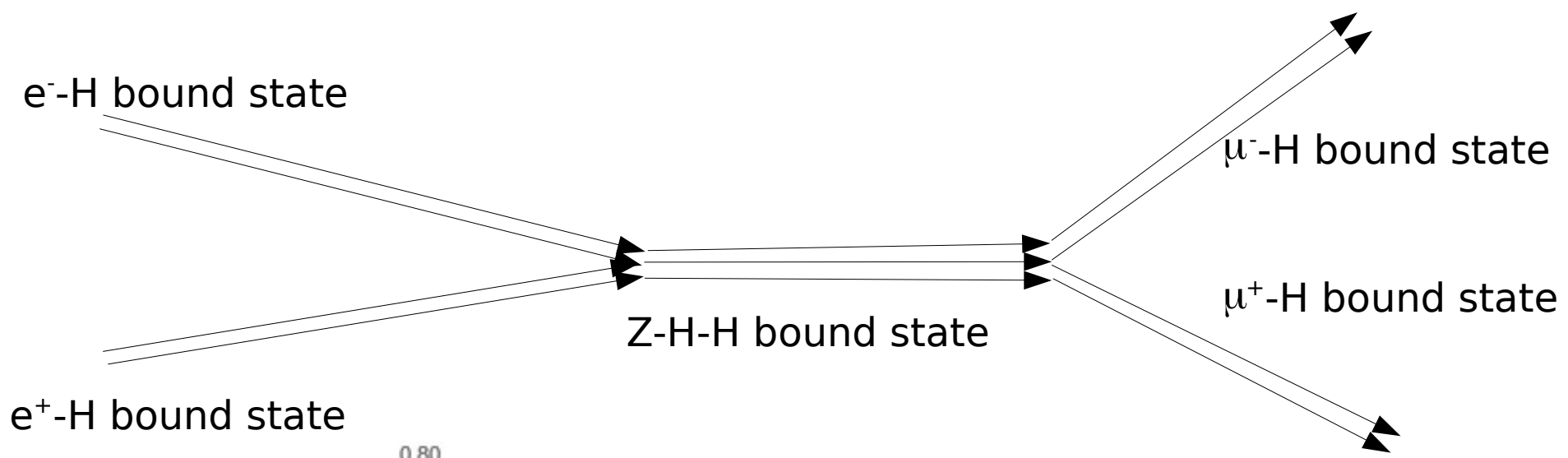
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Top case:
Strong dependence
on the amount of
Higgs and energy

How events looks like (LEP/ILC)

[Maas'12, Egger et al.'17]



Not all quantities are equally influenced

Why it can matter beyond the standard model

And when this can be dealt with using gauge-invariant perturbation theory

Status of the standard model

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 - Observed in experiment
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Other cases looked at: 2HDM, generic single-Higgs theories, compositeness → 1712.04721

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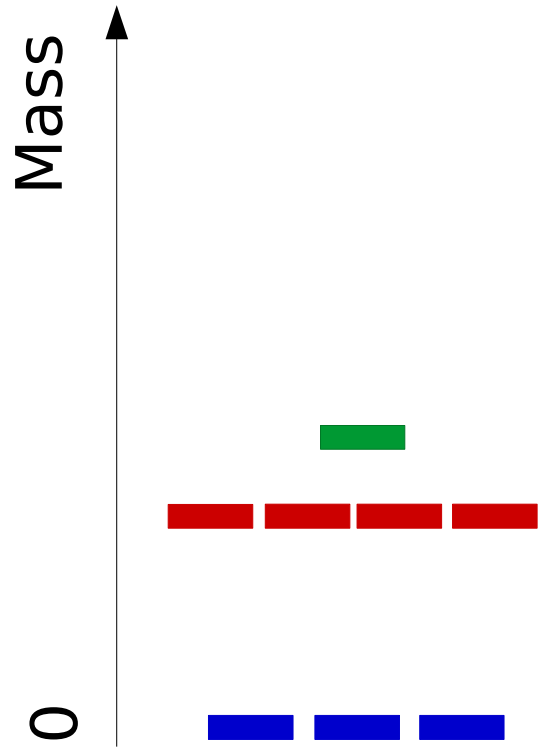
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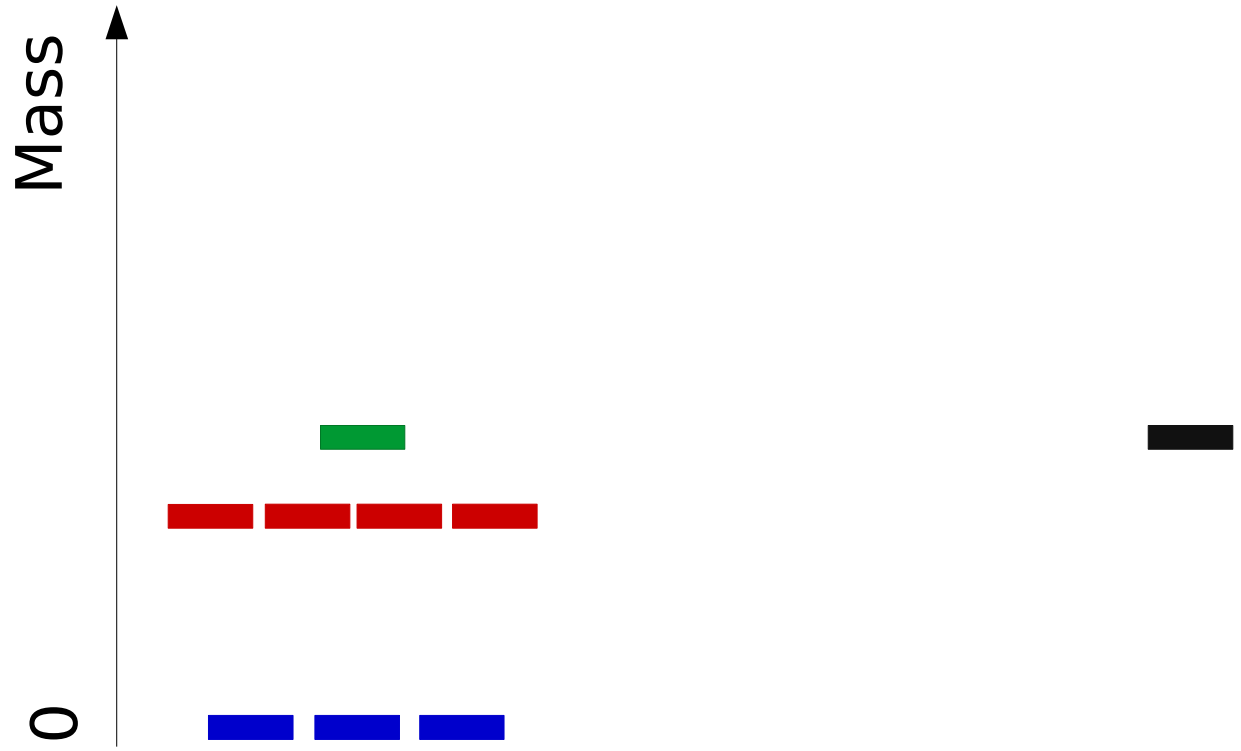


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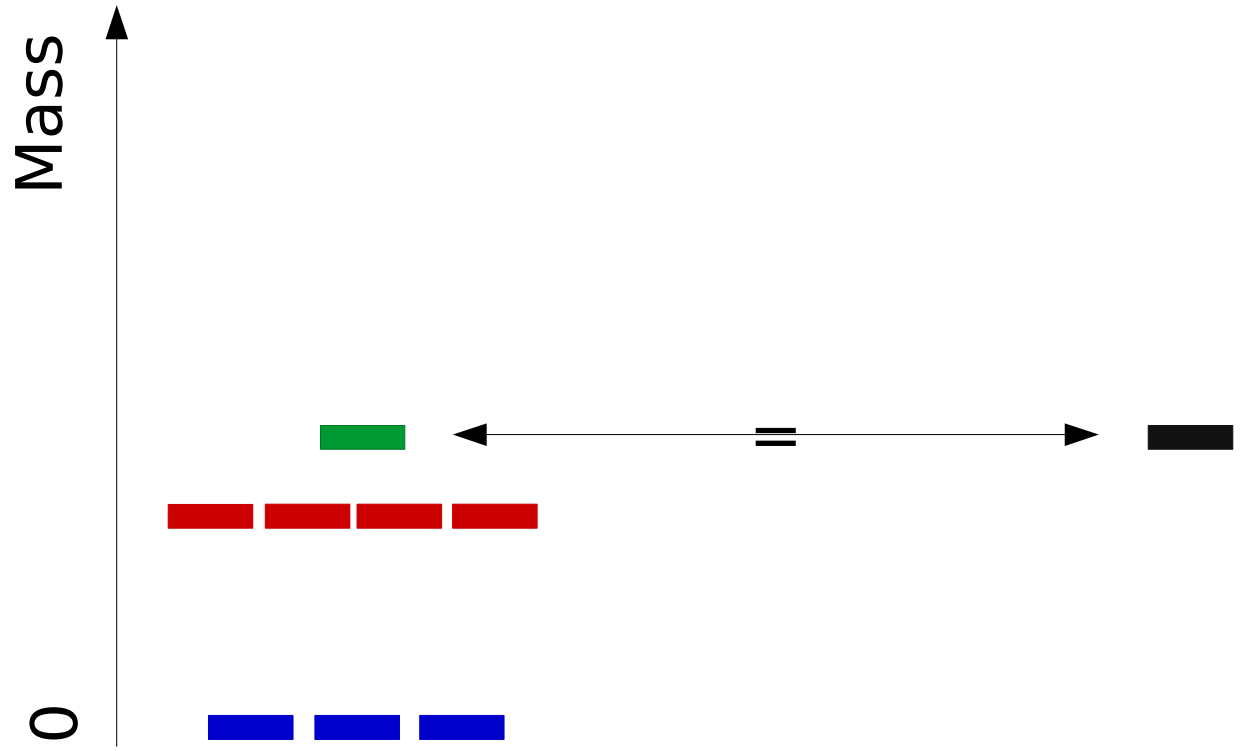
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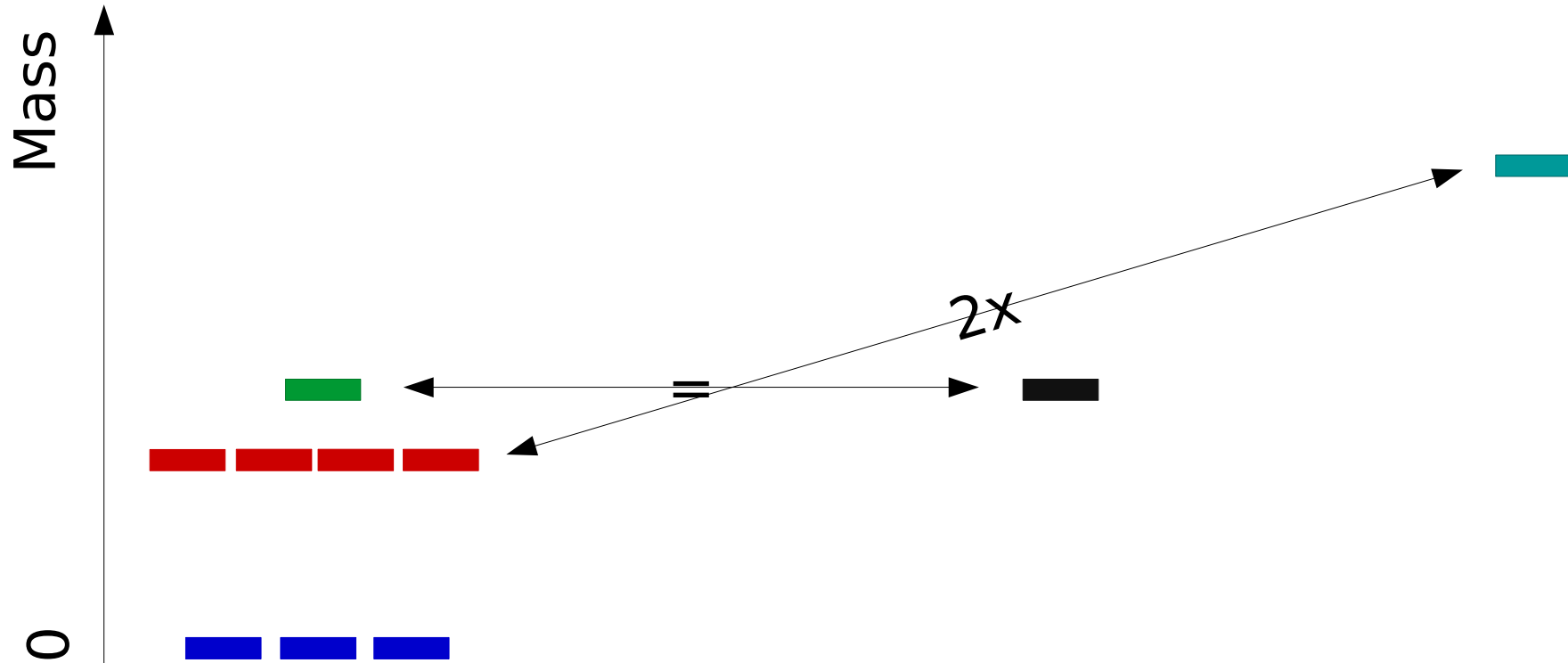
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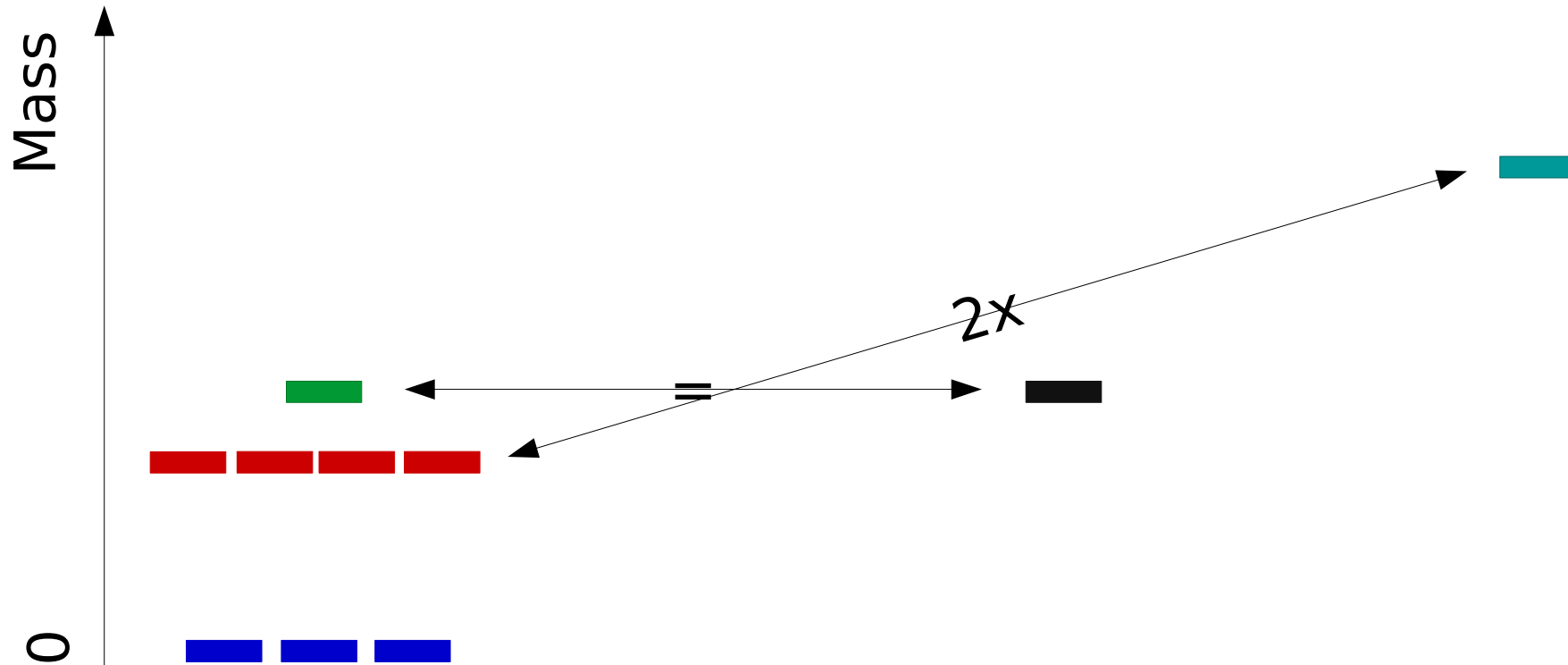
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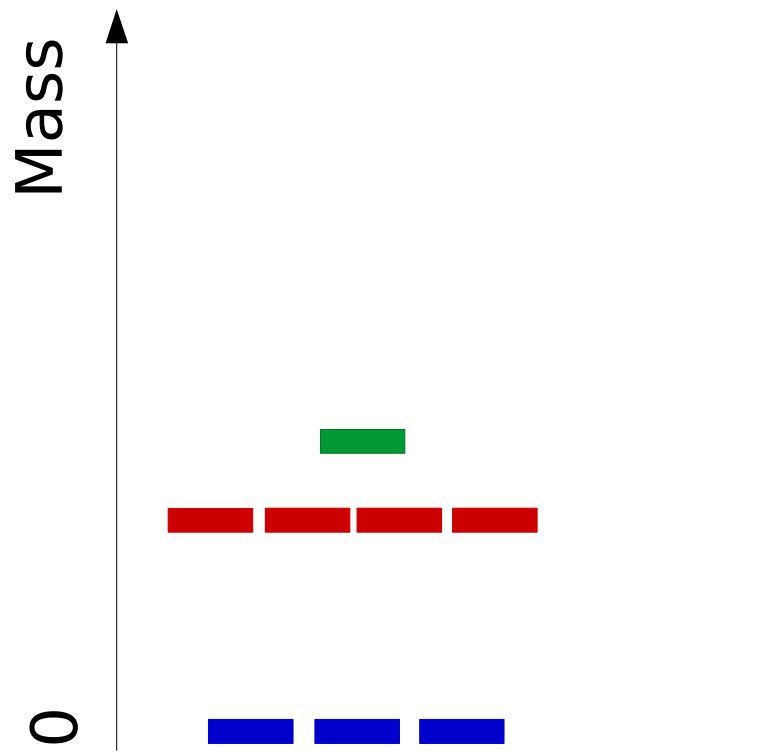


- Qualitatively different spectrum
 - Scalars similar but no confirmation yet (statistics!)

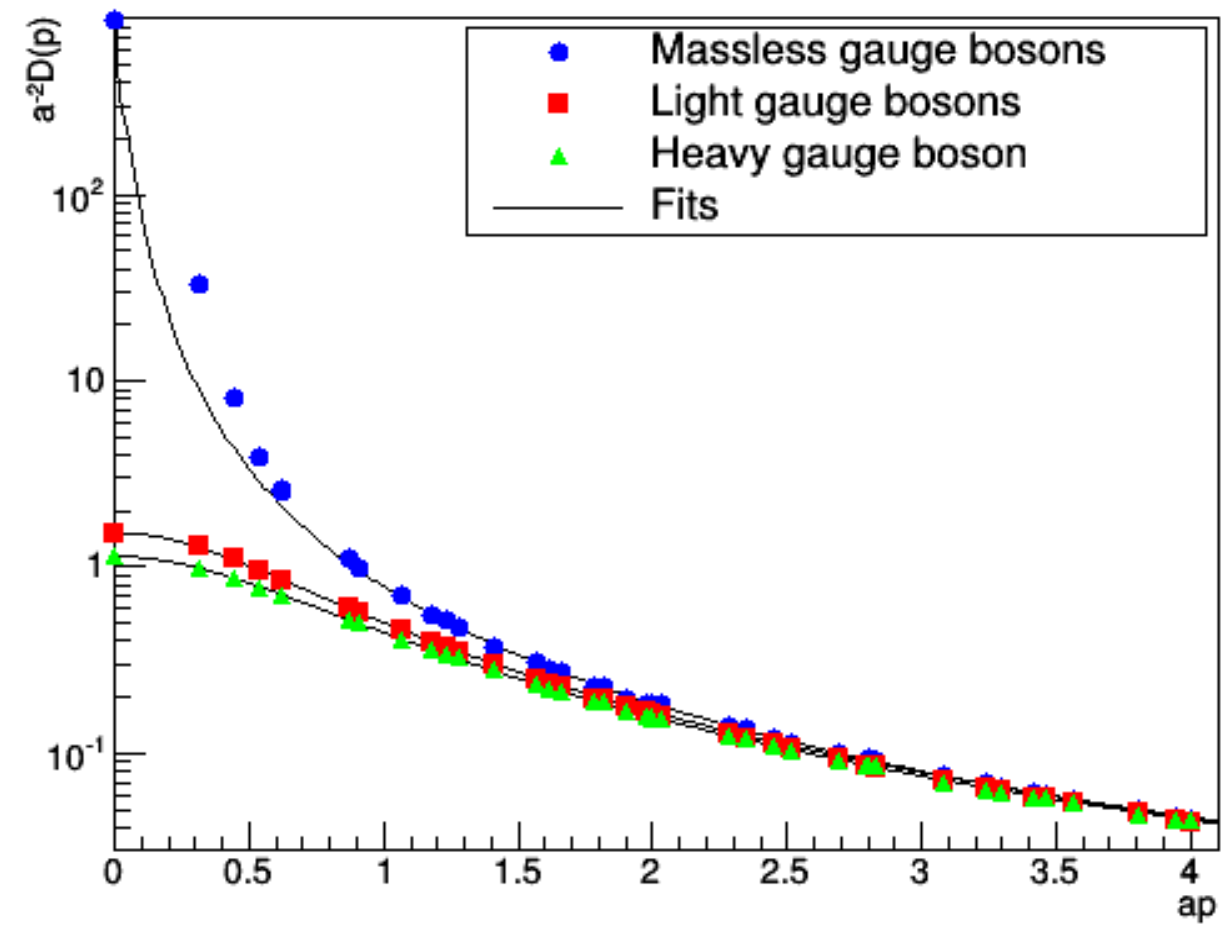
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Gauge boson propagator



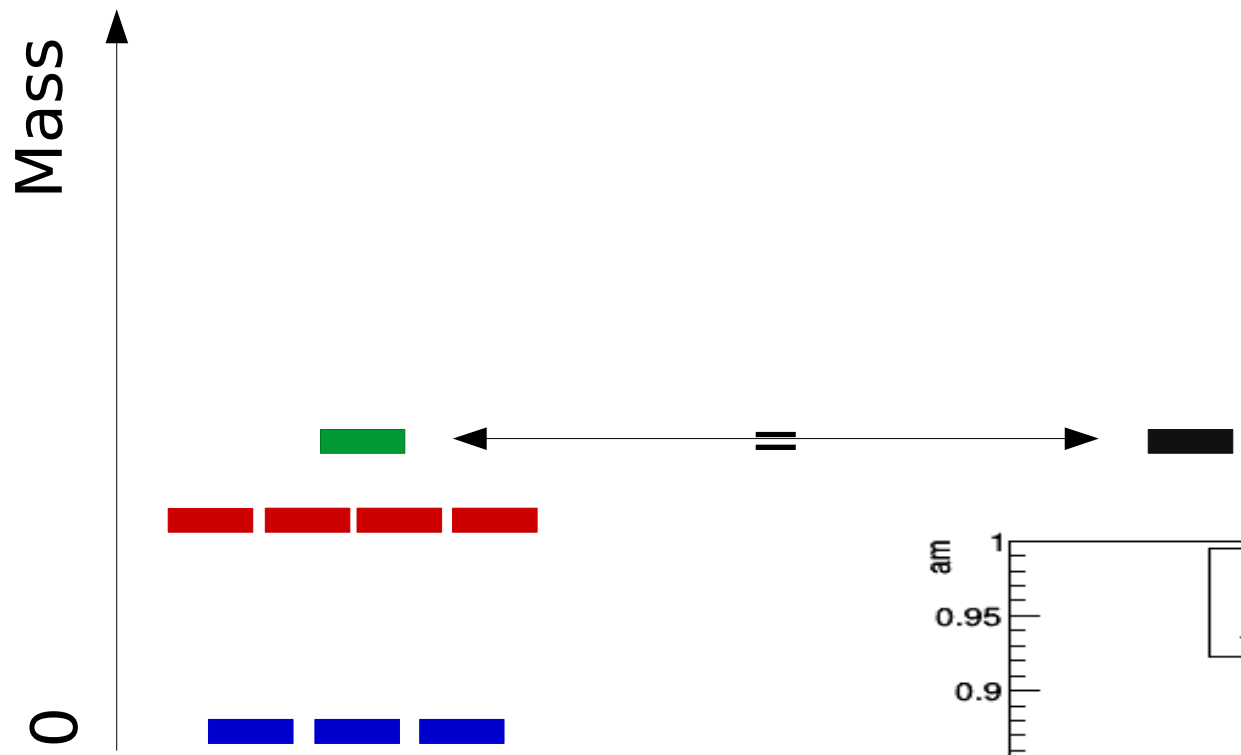
- Theory weakly interacting

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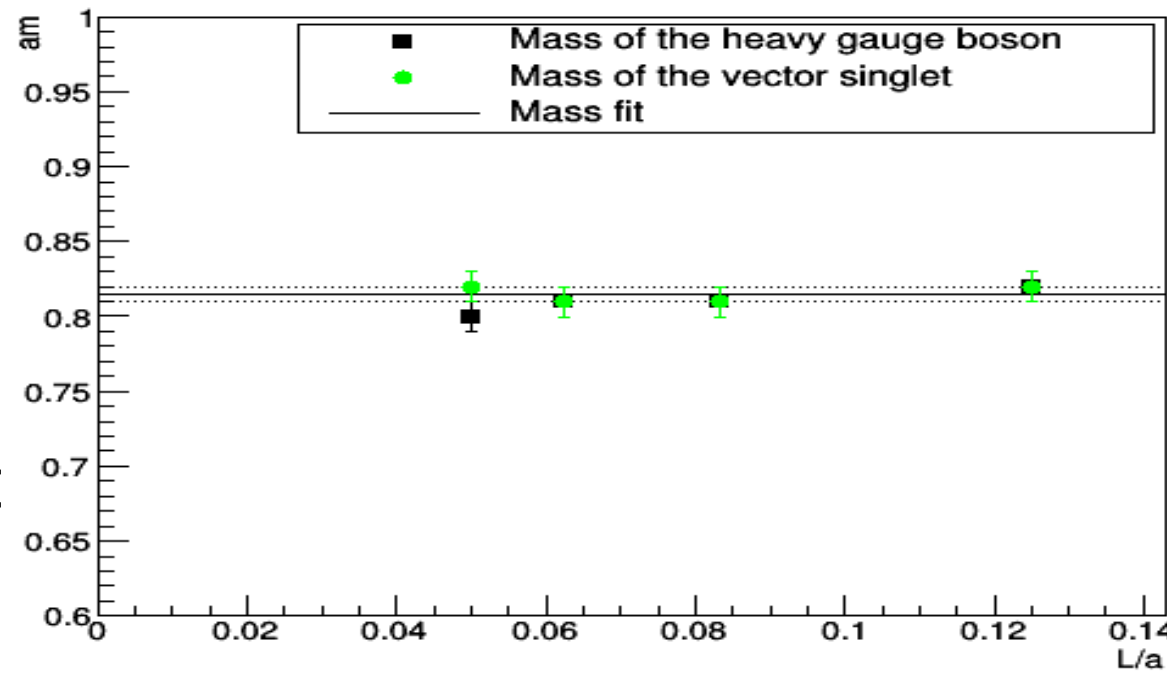
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Check of prediction



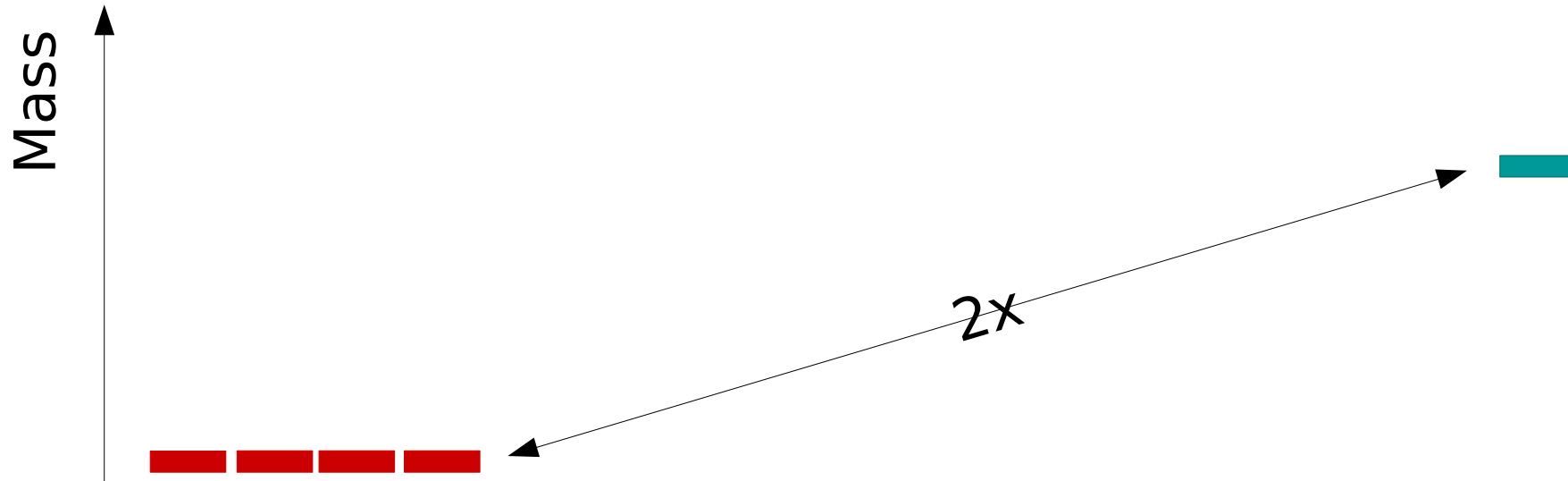
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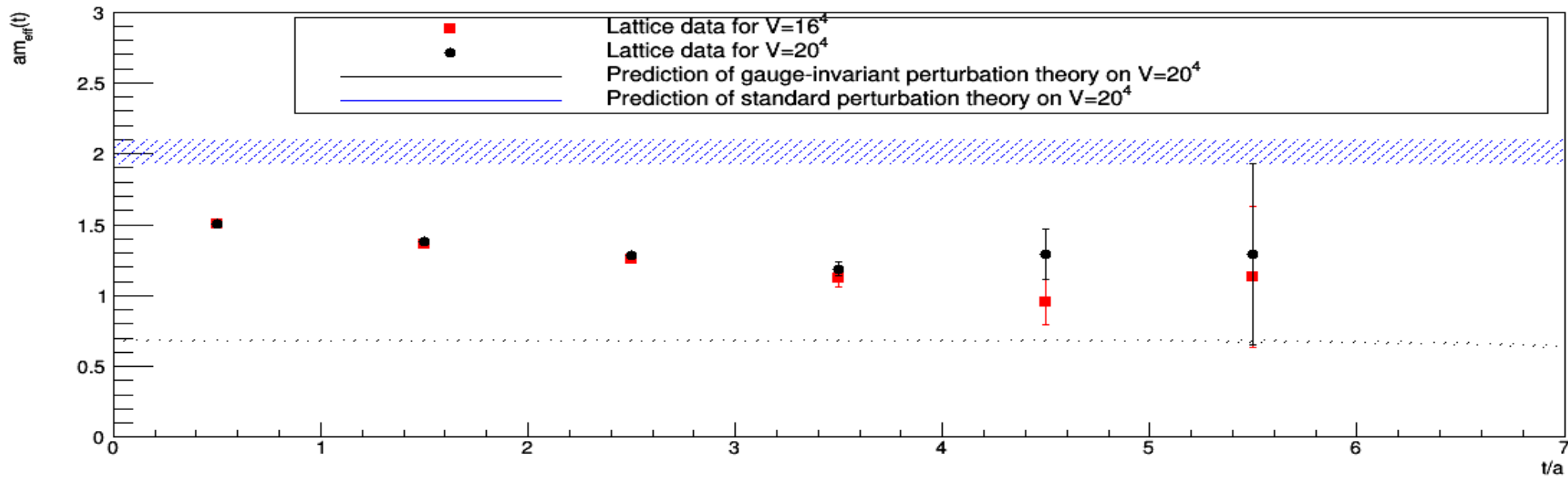
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Check of prediction for the open U(1) vector



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- Disagreement generic [Maas, Sondenheimer & Törek'17]
 - Some lattice support for one adjoint Higgs

[Lee & Shigimetsu'85]

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Outlook

Review: 1712.04721

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 - Size of 'W' bound state
 - Anomalous gauge couplings
 - Quantitative prediction for ILC
 - HERWIG version with Higgs components
 - Tops at the LHC