What is physical?
Local vs. Global Symmetries

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Vienna
Austria

NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

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Review: 1712.04721

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- How this matters (eg) in BSM theories

Review: 1712.04721

A toy model

- Consider an SU(3) with a single fundamental Higgs

A toy model

- Consider an SU(3) with a single fundamental scalar
- Looks very similar to the standard model Higgs

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

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

$$W^a_\mu \to W^a_\mu \qquad h \to \exp\left(ia\right) h$$

Textbook approach

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

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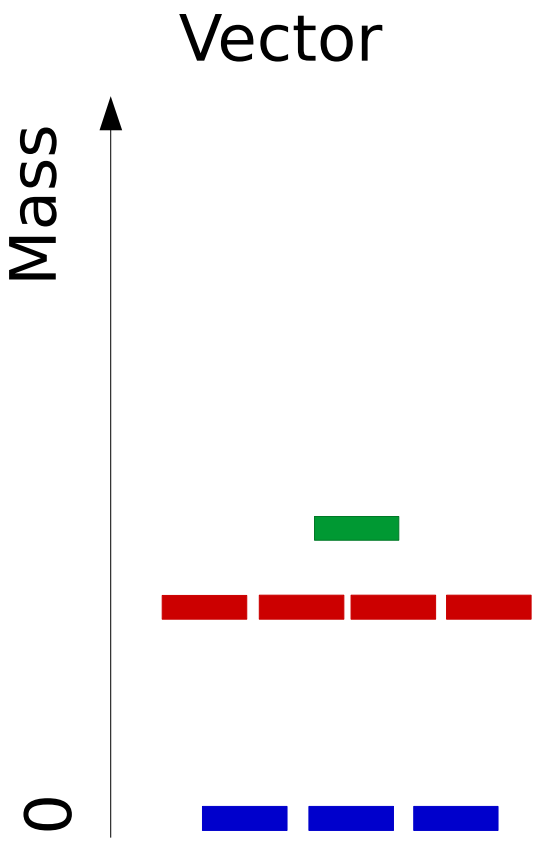

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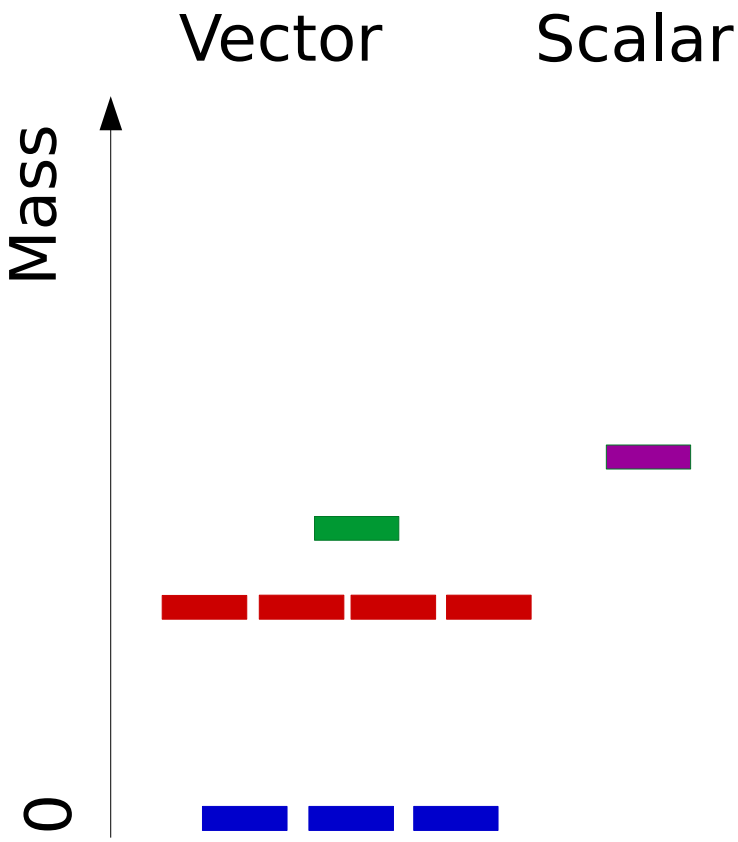

The origin of the problem

[Fröhlich et al.'80, Banks et al.'79]

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

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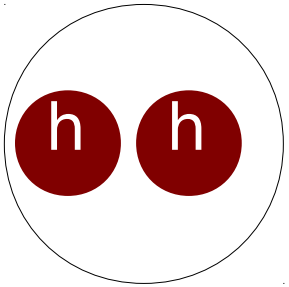

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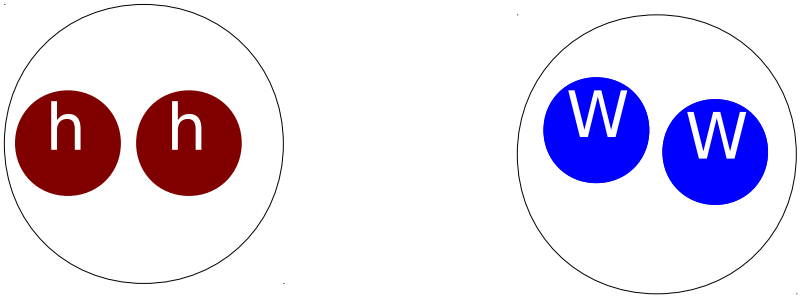

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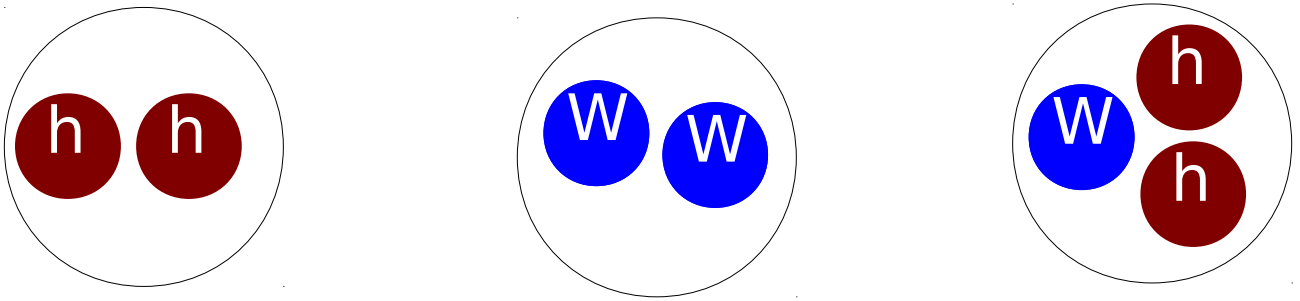

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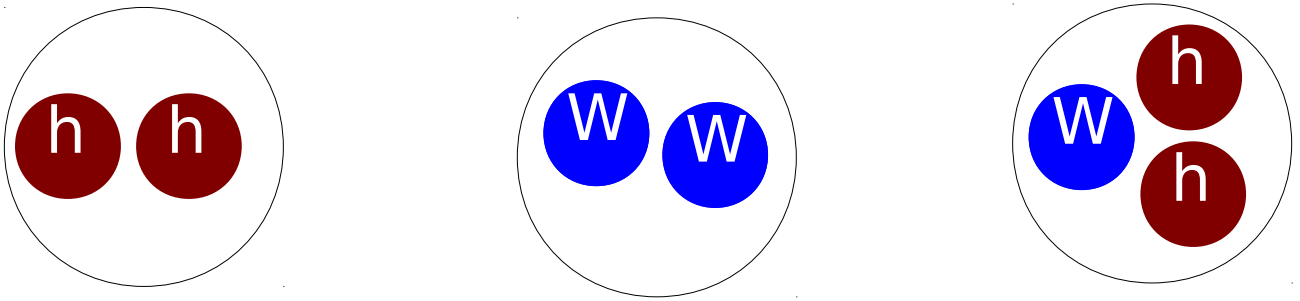

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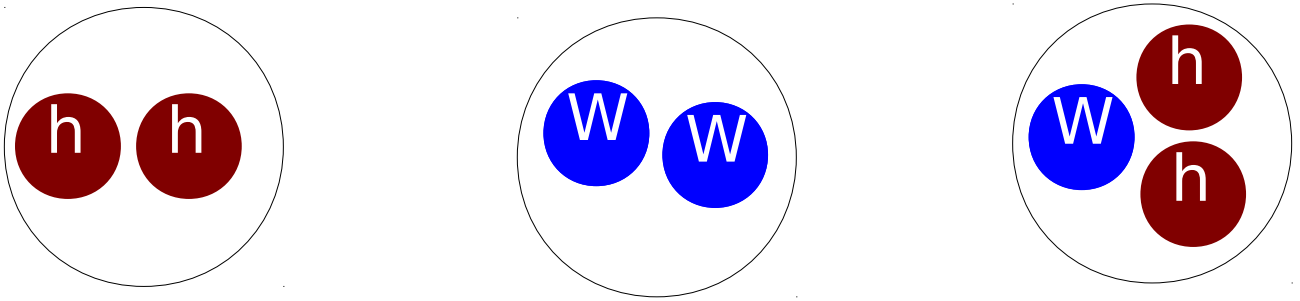

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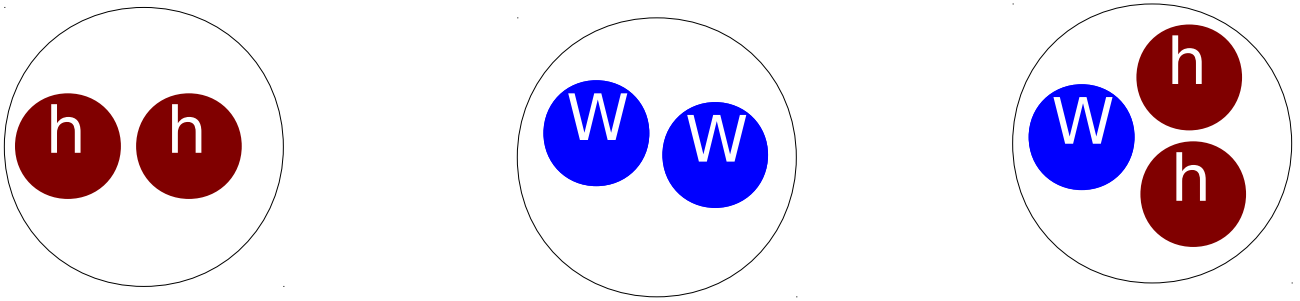

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- Can this matter?

How to make predictions

[Fröhlich et al.'80,'81,
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Spectrum

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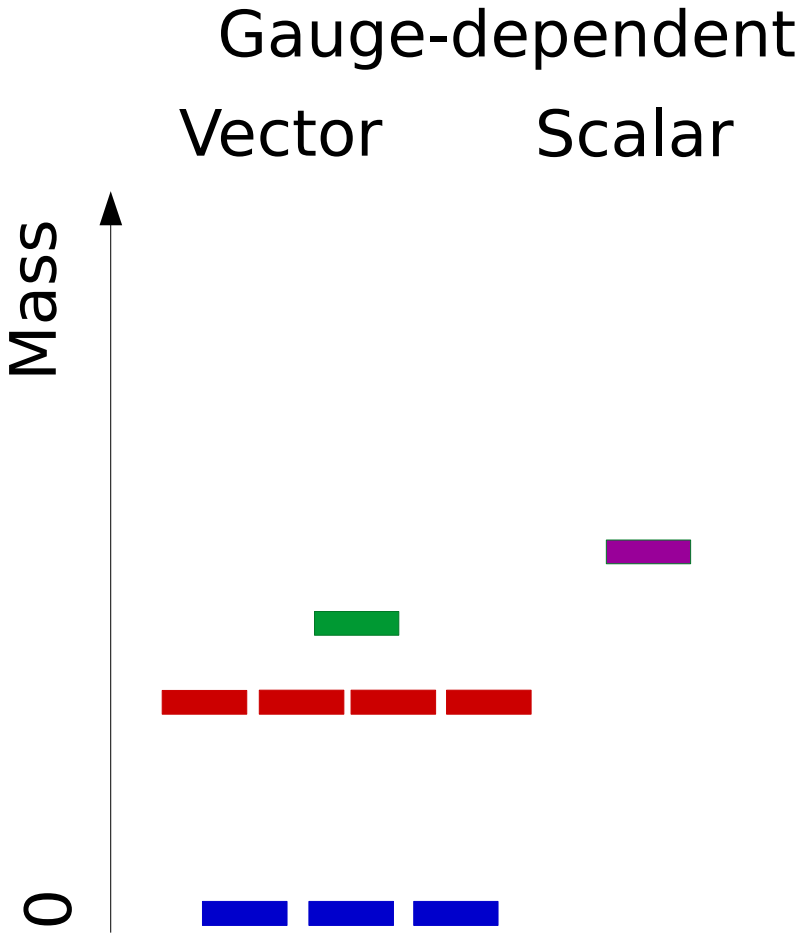

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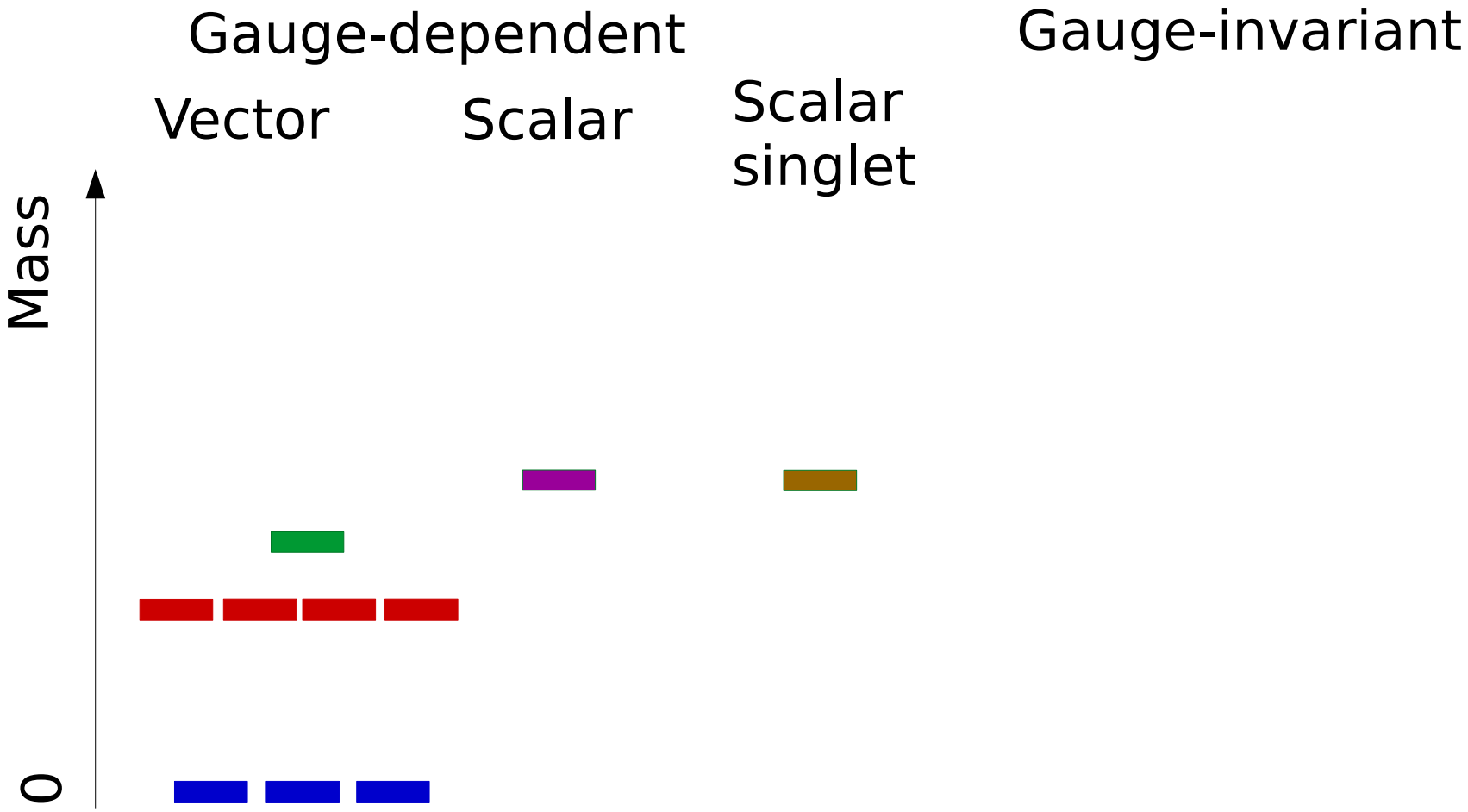

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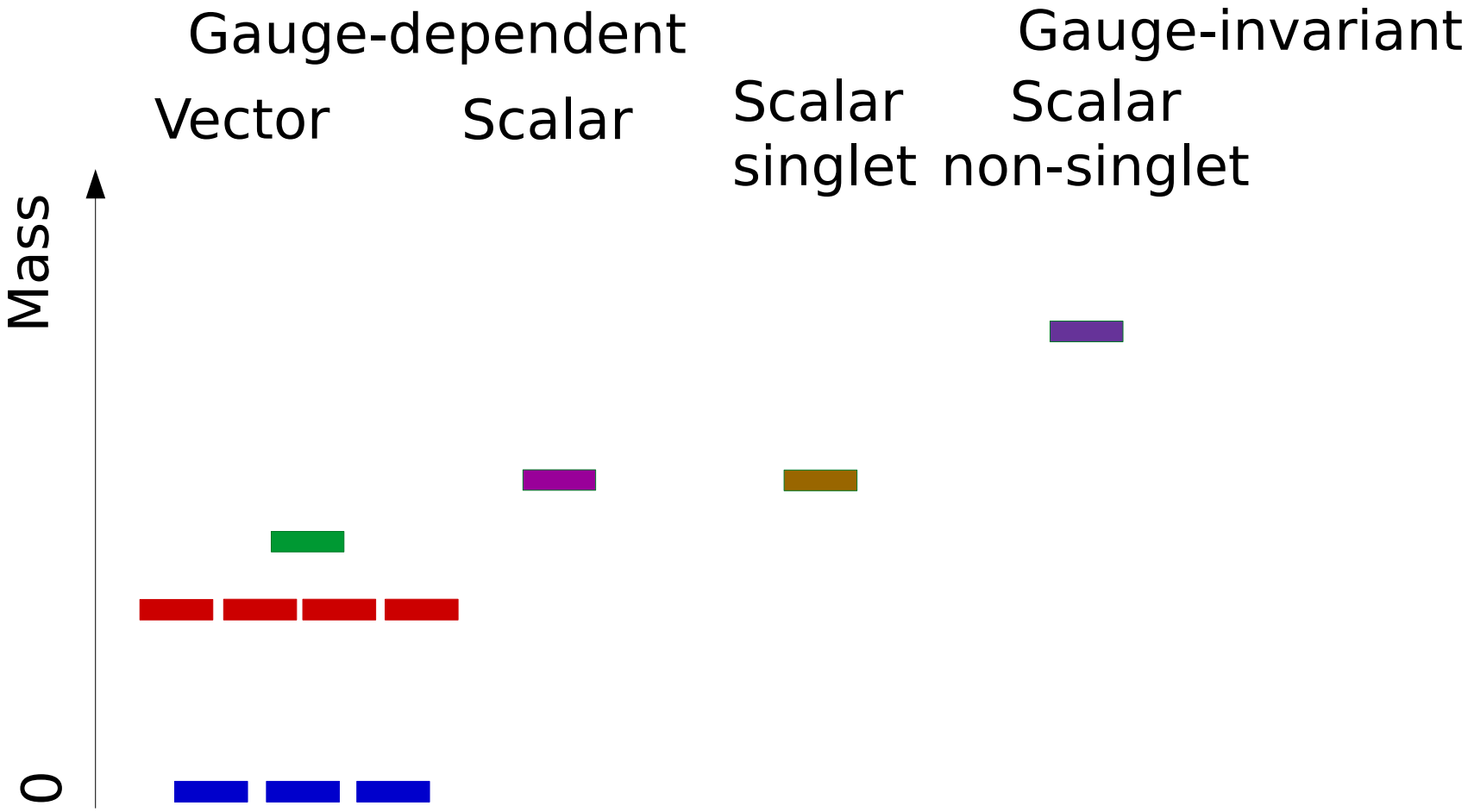

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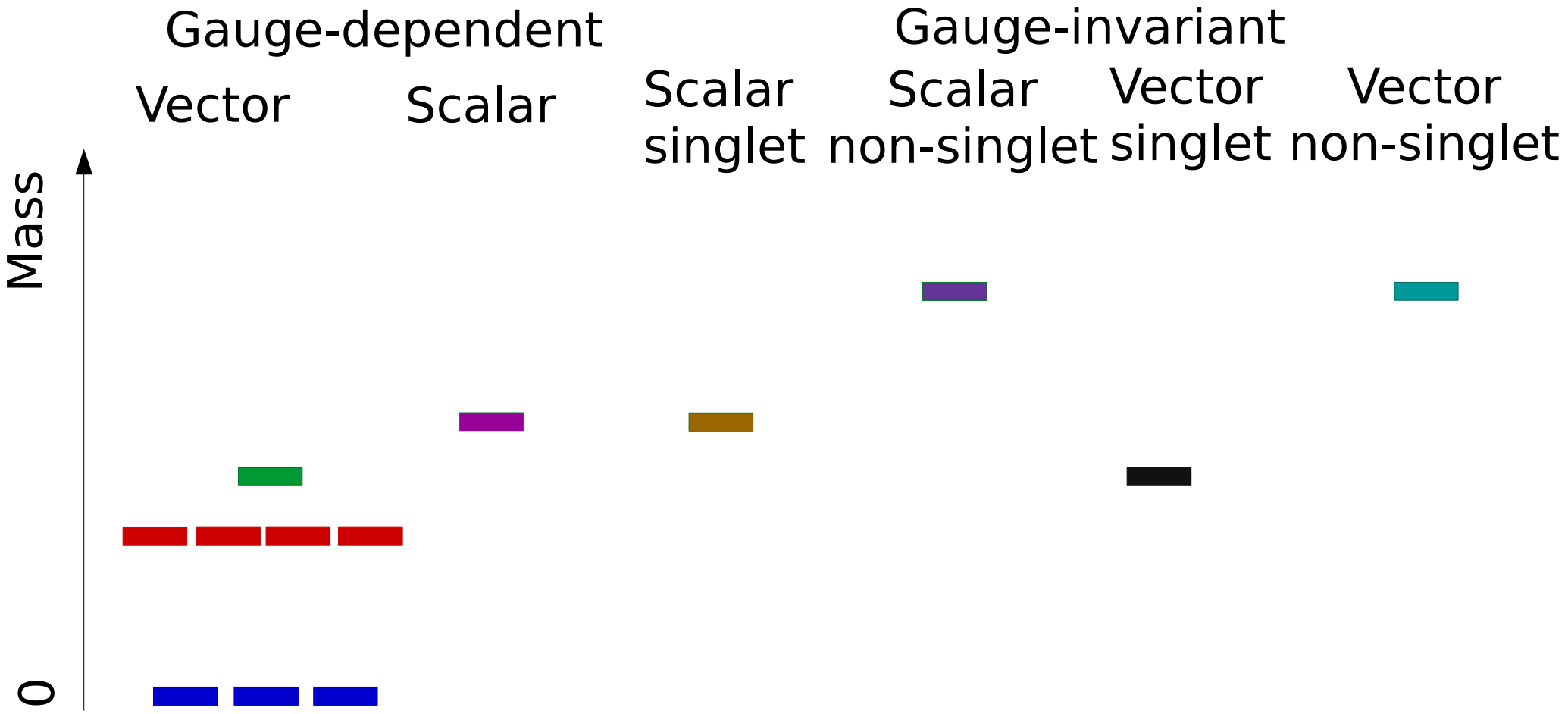

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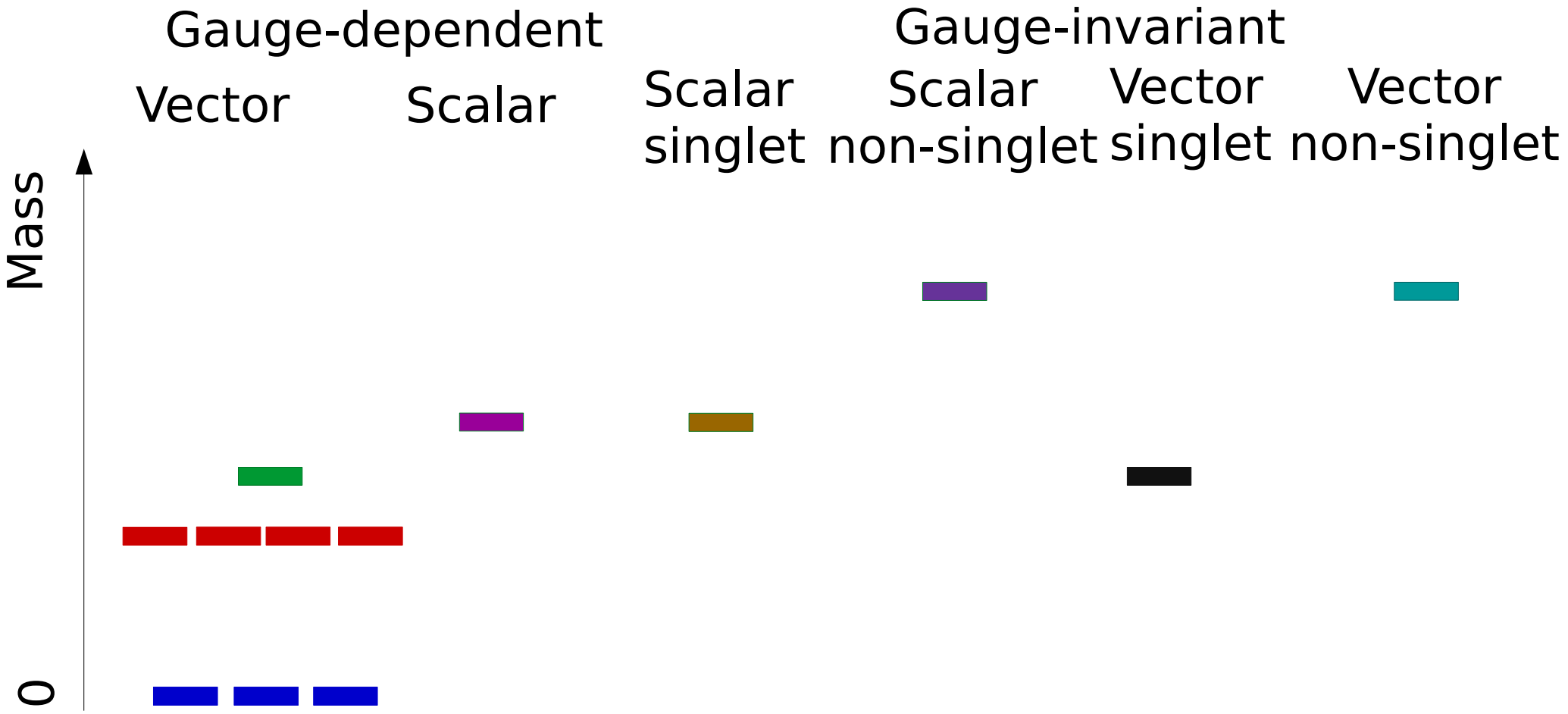

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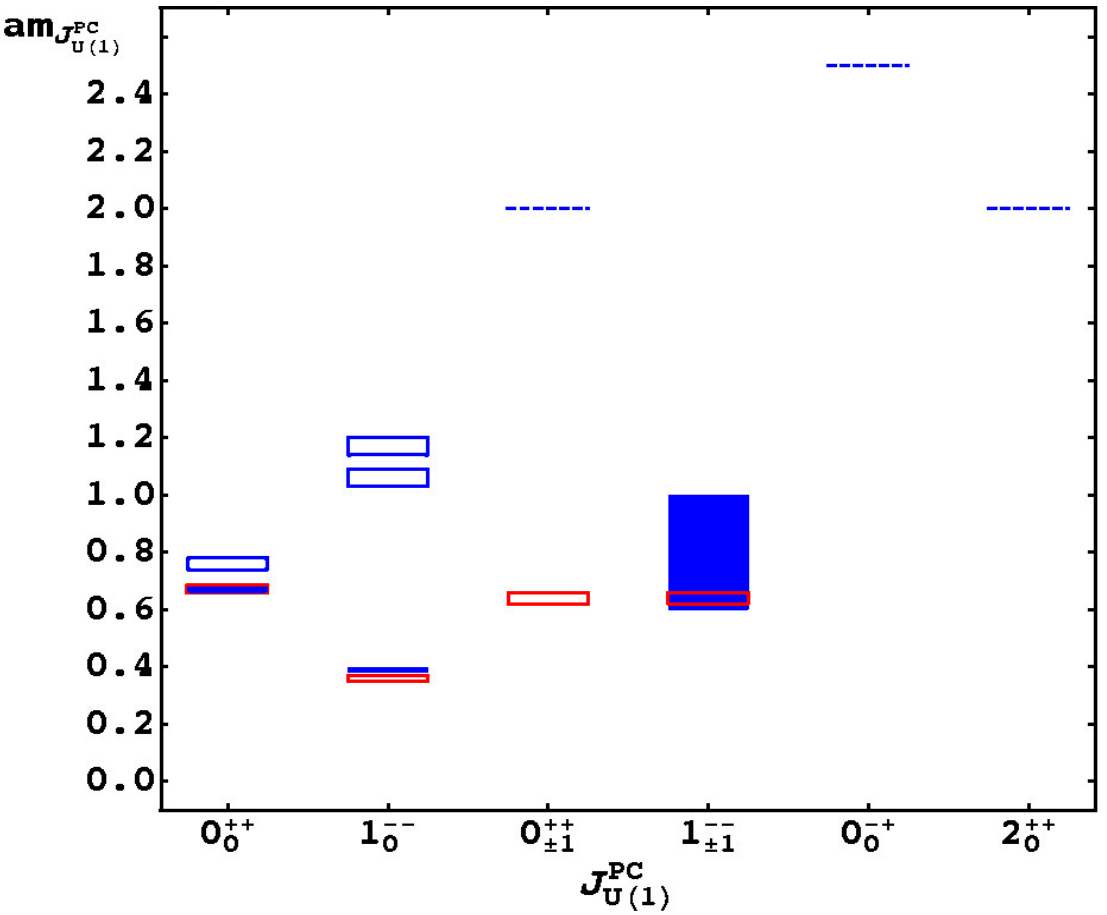
Gauge-invariant

Scalar singlet	Scalar non-singlet	Vector singlet	Vector non-singlet



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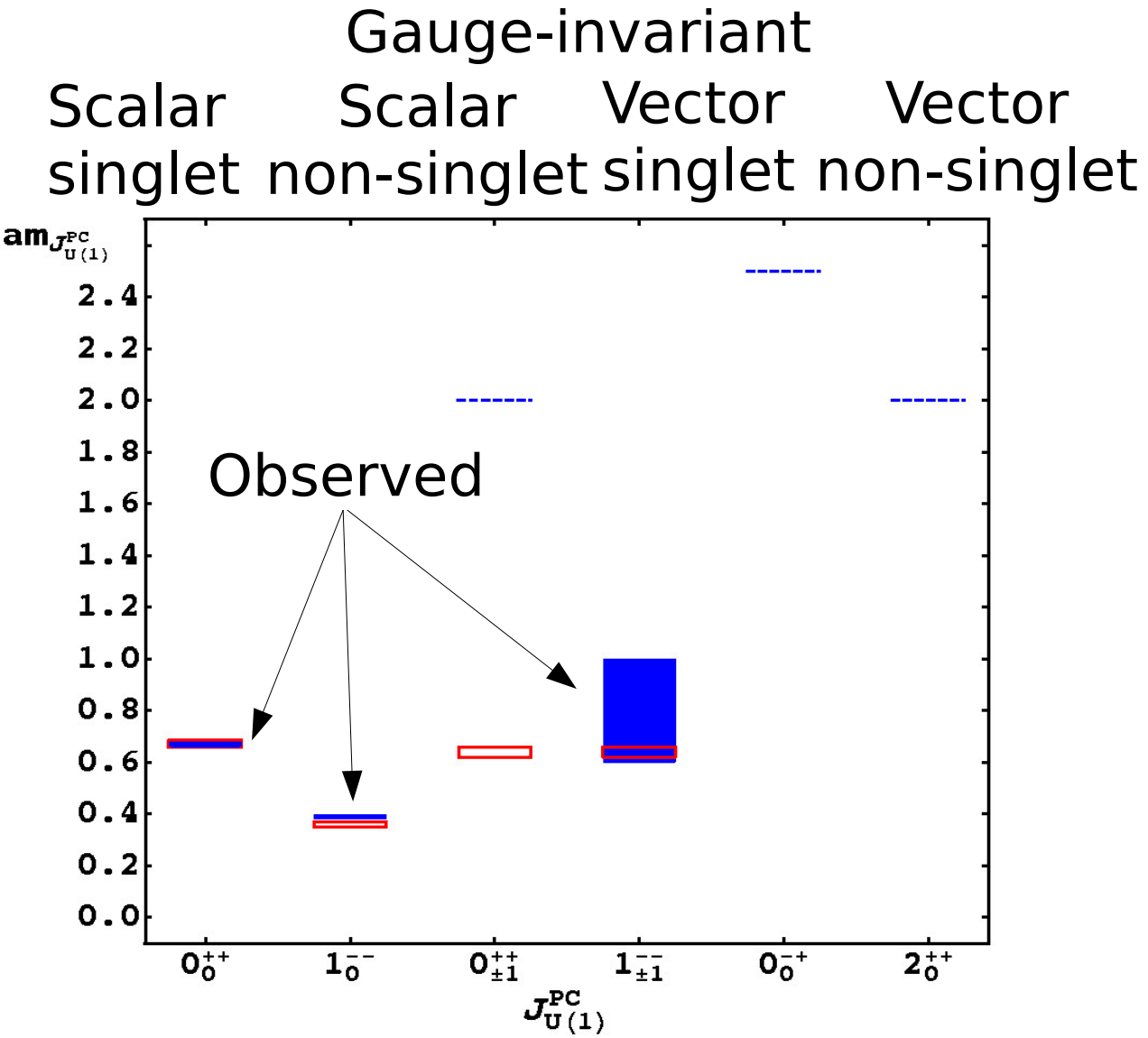

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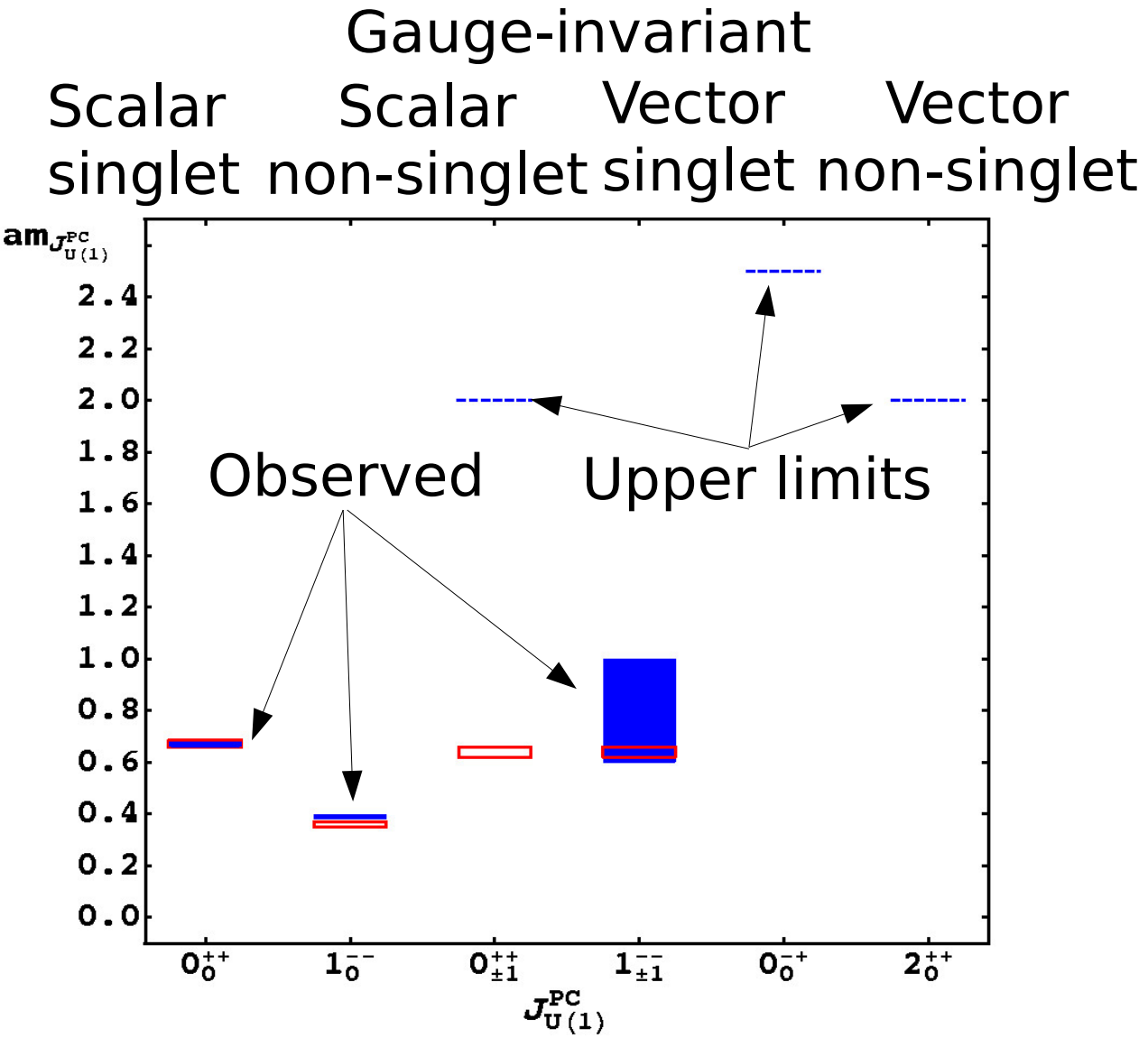

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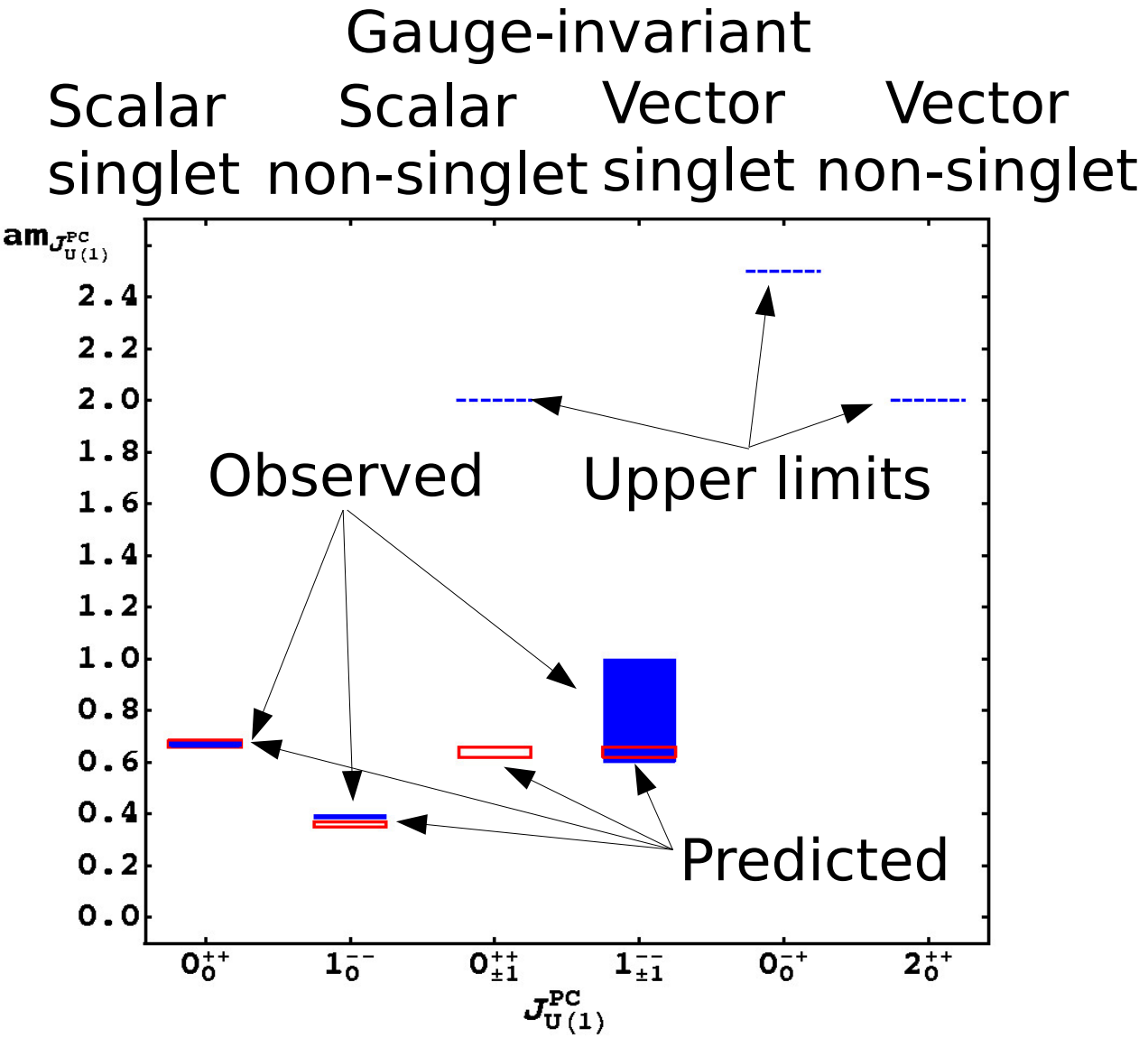

- Qualitatively different spectrum
- Results in agreement with analytic predictions

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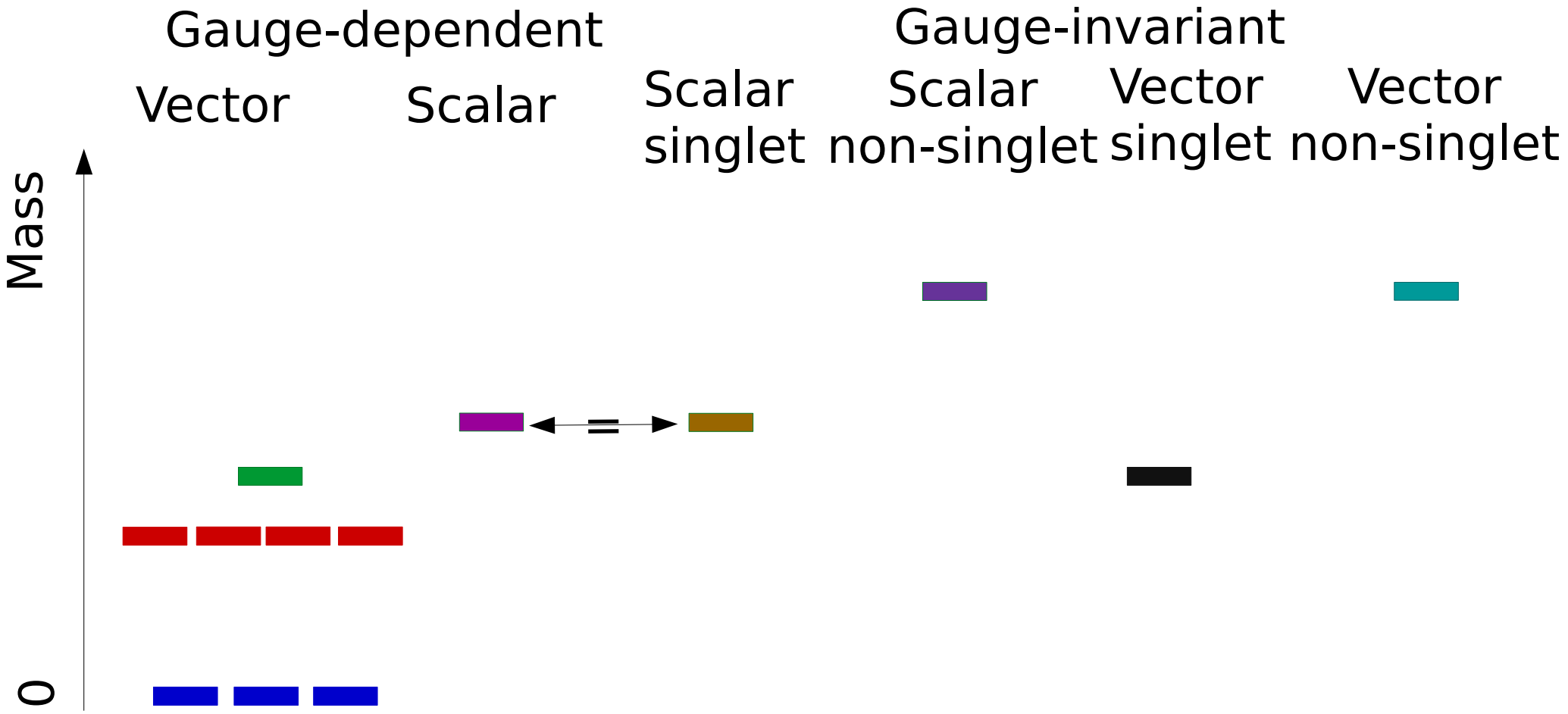

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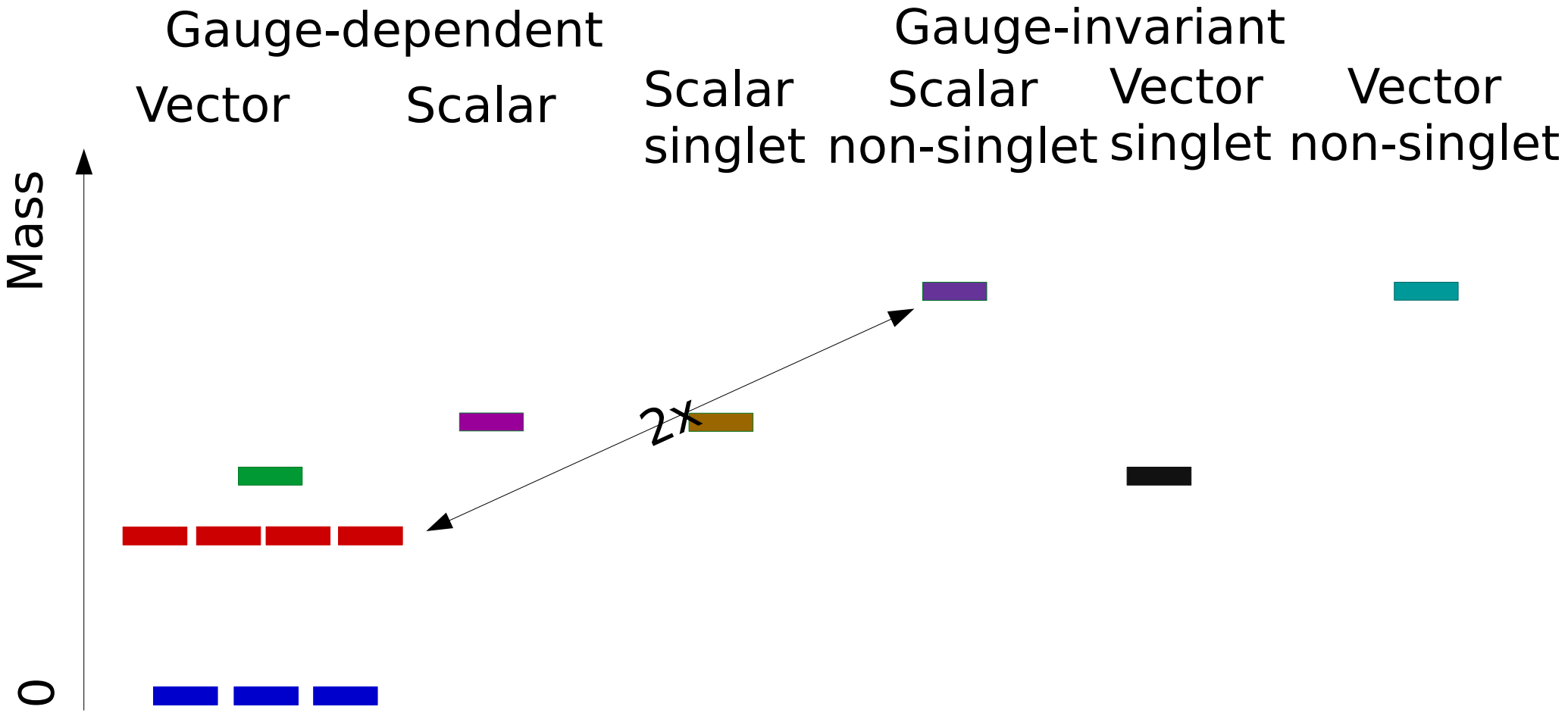

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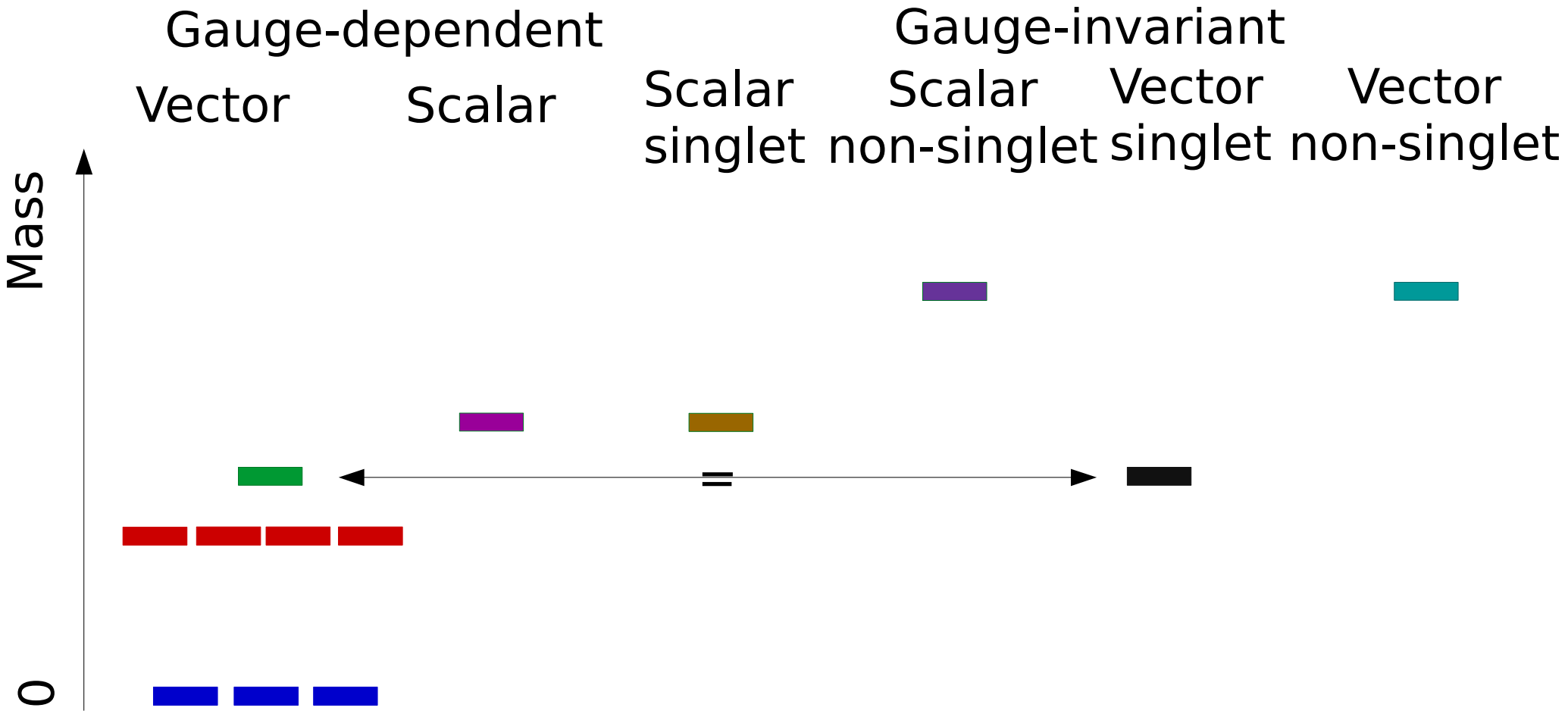

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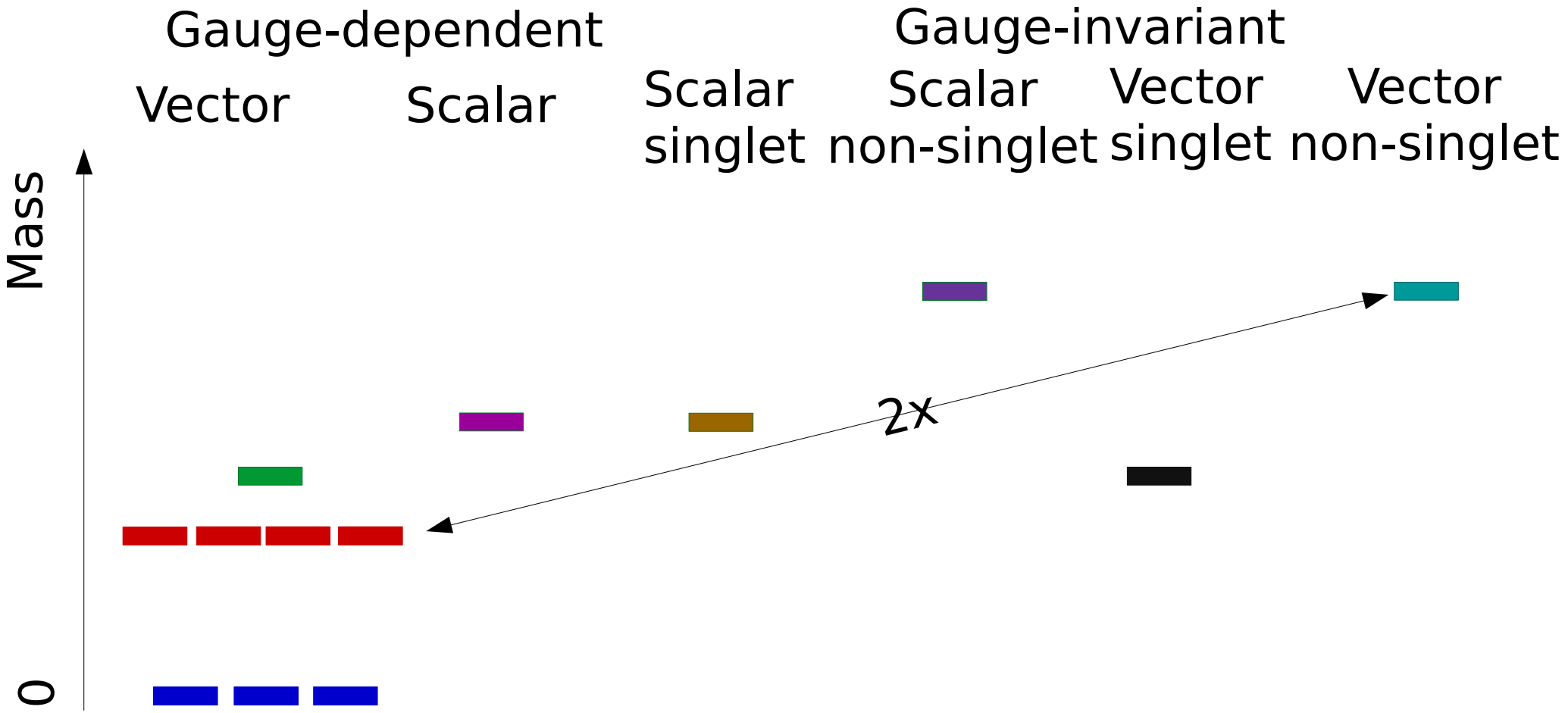

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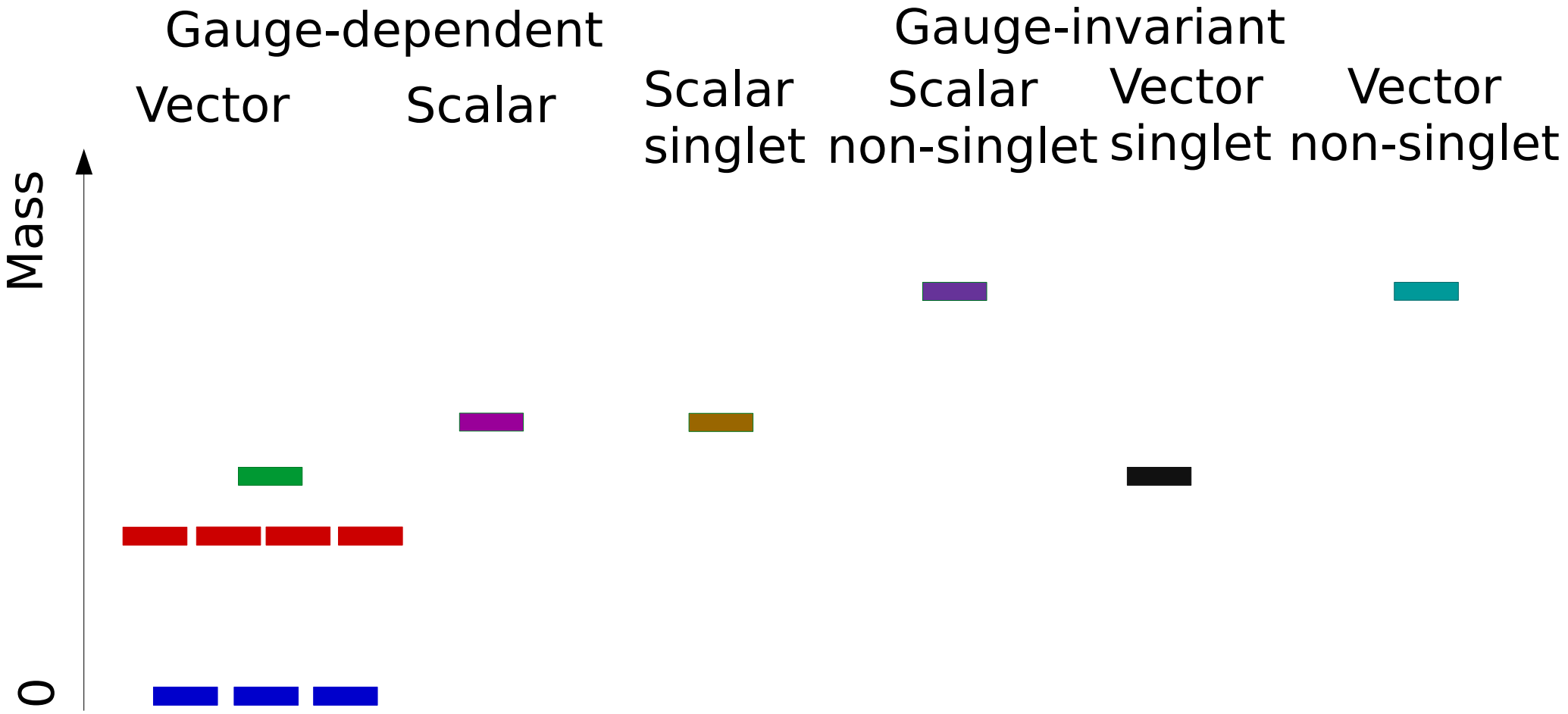

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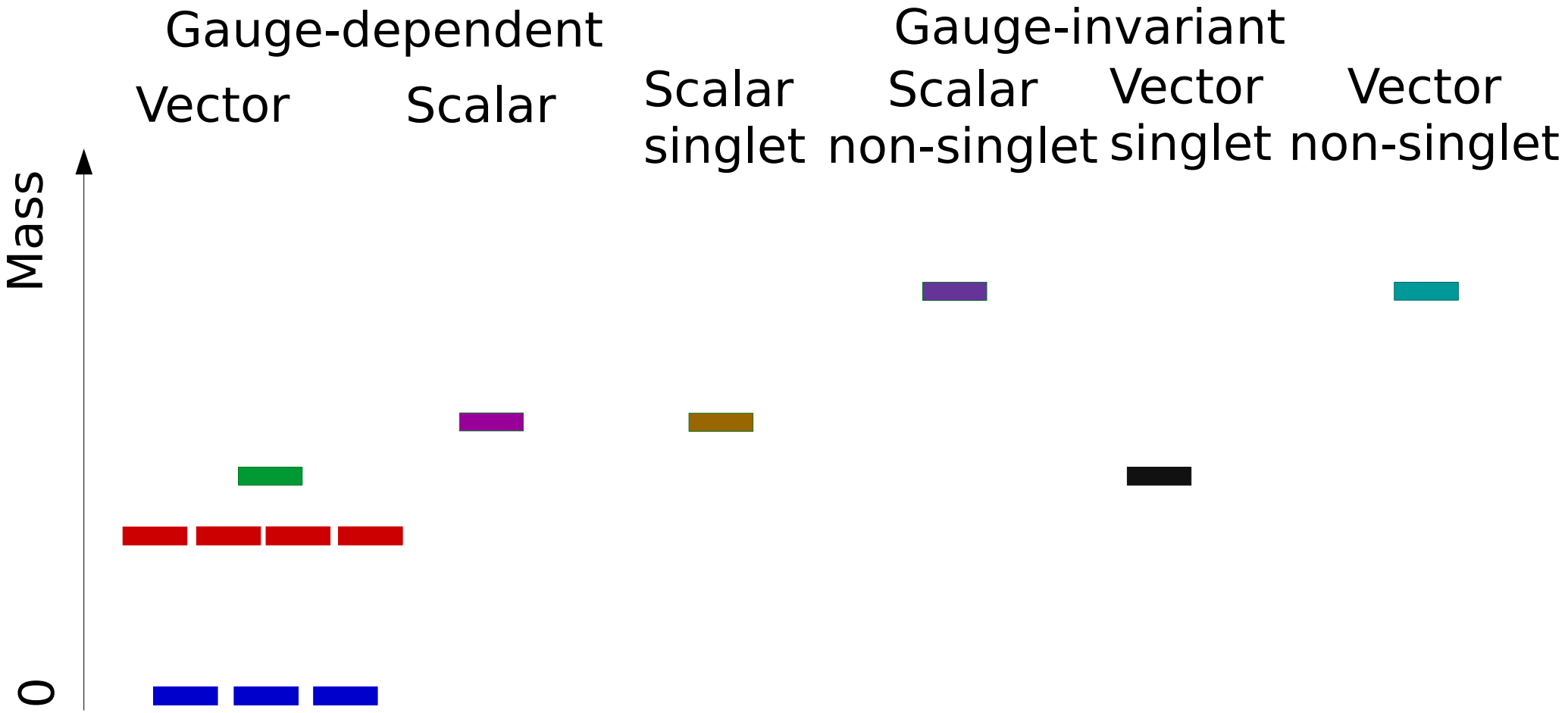

- Qualitatively different spectrum
- No mass gap! - But can be there: Adjoint Higgs

[Maas, Sondenheimer & Törek'17, Shigemitsu & Lee'85]

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- 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
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  - But coupling is still weak and there is a BEH

How to make predictions

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  - Perform double expansion [Fröhlich et al.'80, Maas'12]
    - Vacuum expectation value (FMS mechanism)
    - Standard expansion in couplings
    - Together: Gauge-invariant perturbation theory

Gauge-invariant perturbation theory

[Fröhlich et al.’80,’81
Maas'12,’17]

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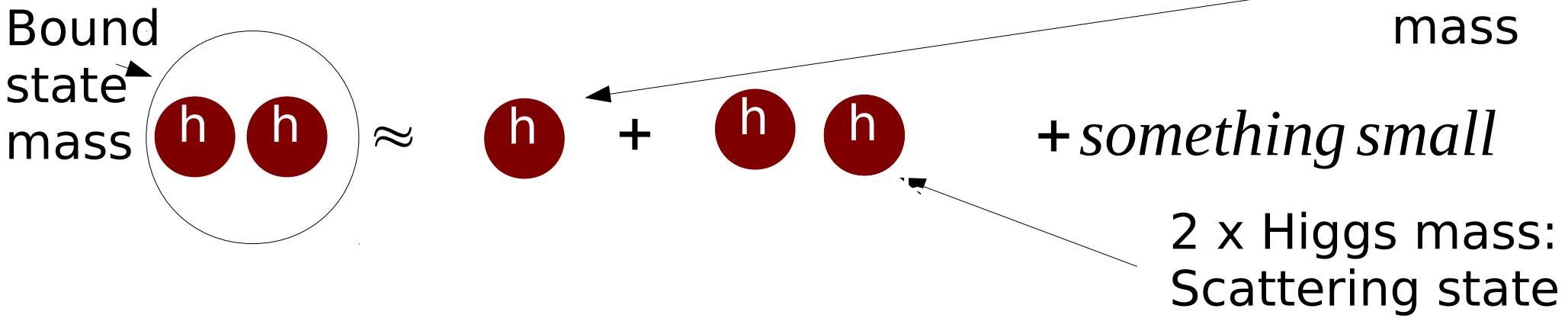

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Only one state remains in the spectrum at mass of gauge boson 8 (heavy singlet)

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- Ws W^a_μ 

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- No QED: Ws and Zs are degenerate
- Couplings g, v, λ and some numbers f^{abc} and t^{ij}_a

Symmetries of the system

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- Local SU(2) gauge symmetry

$$W^a_\mu \to W^a_\mu + (\delta^a_b \partial_\mu - g f^a_{bc} W^c_\mu)\Phi^b \qquad h_i \to h_i + g\, t^{ij}_a \Phi^a h_j$$

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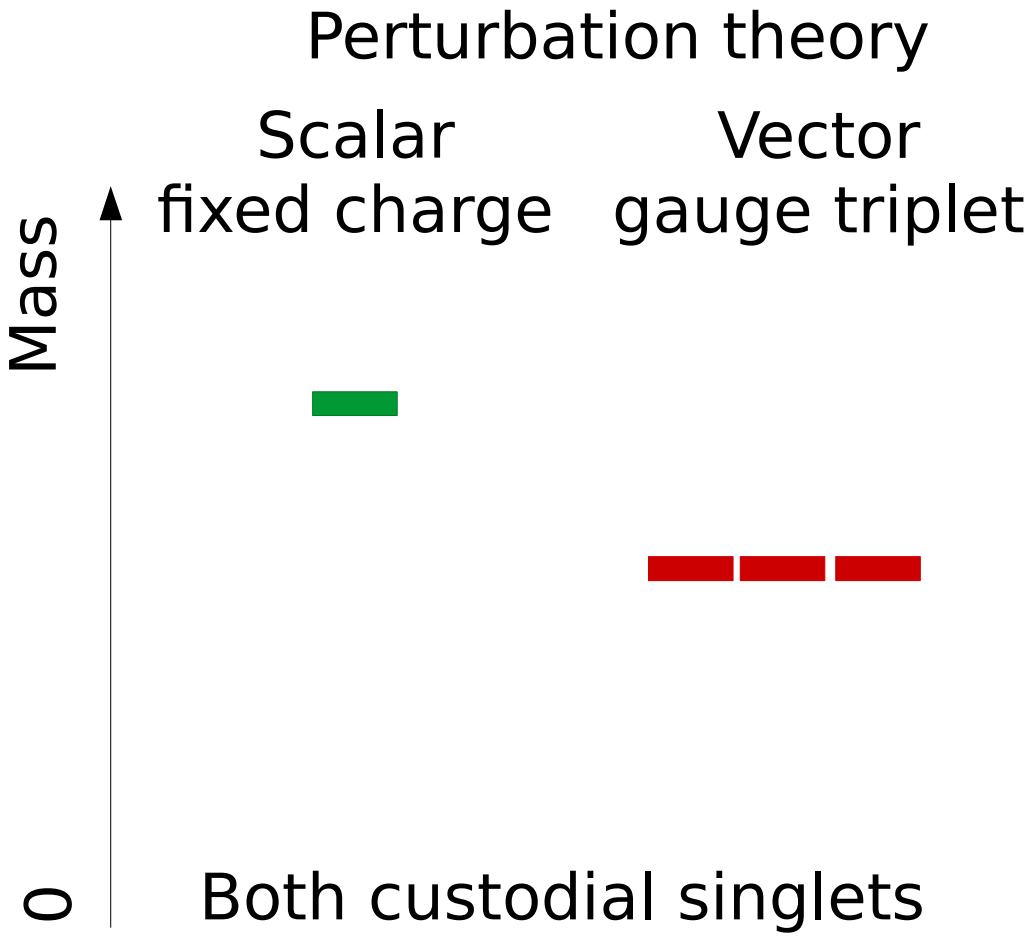
- Global SU(2) Higgs custodial (flavor) symmetry
  - Acts as (right-)transformation on the Higgs field only

$$W^{a}_{\mu}\rightarrow W^{a}_{\mu} \qquad h_{i}\rightarrow h_{i}+a^{ij}h_{j}+b^{ij}h_{j}^{*}$$

Physical spectrum



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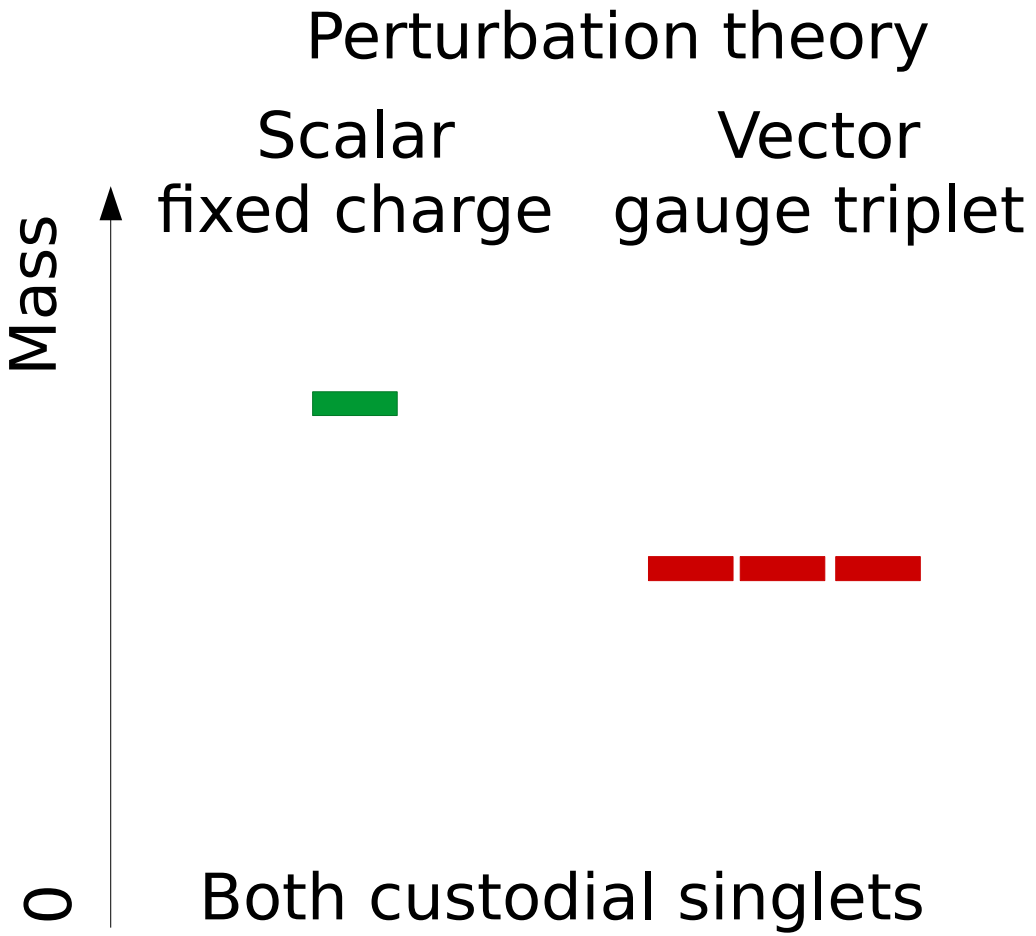

Experiment tells that somehow the left is correct

Physical spectrum

Perturbation theory

Scalar fixed charge

Vector gauge triplet

Mass

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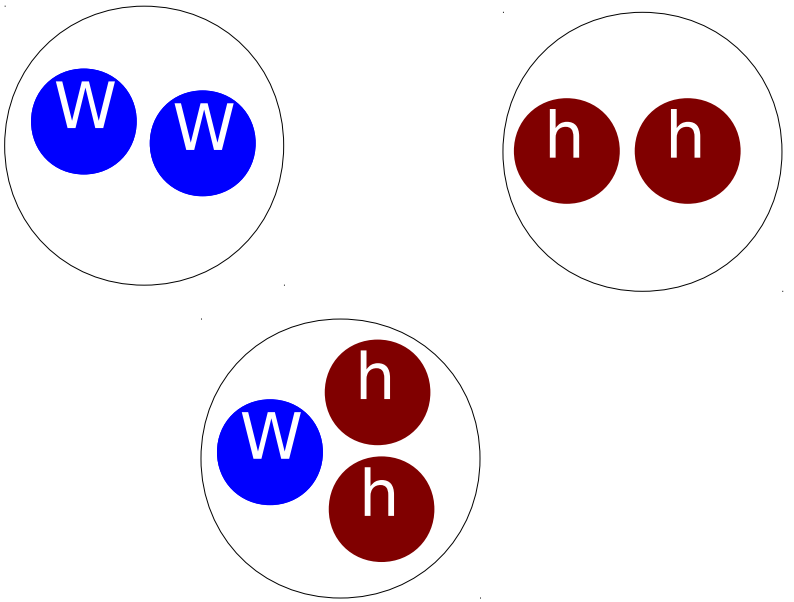
Both custodial singlets

Composite (bound) states



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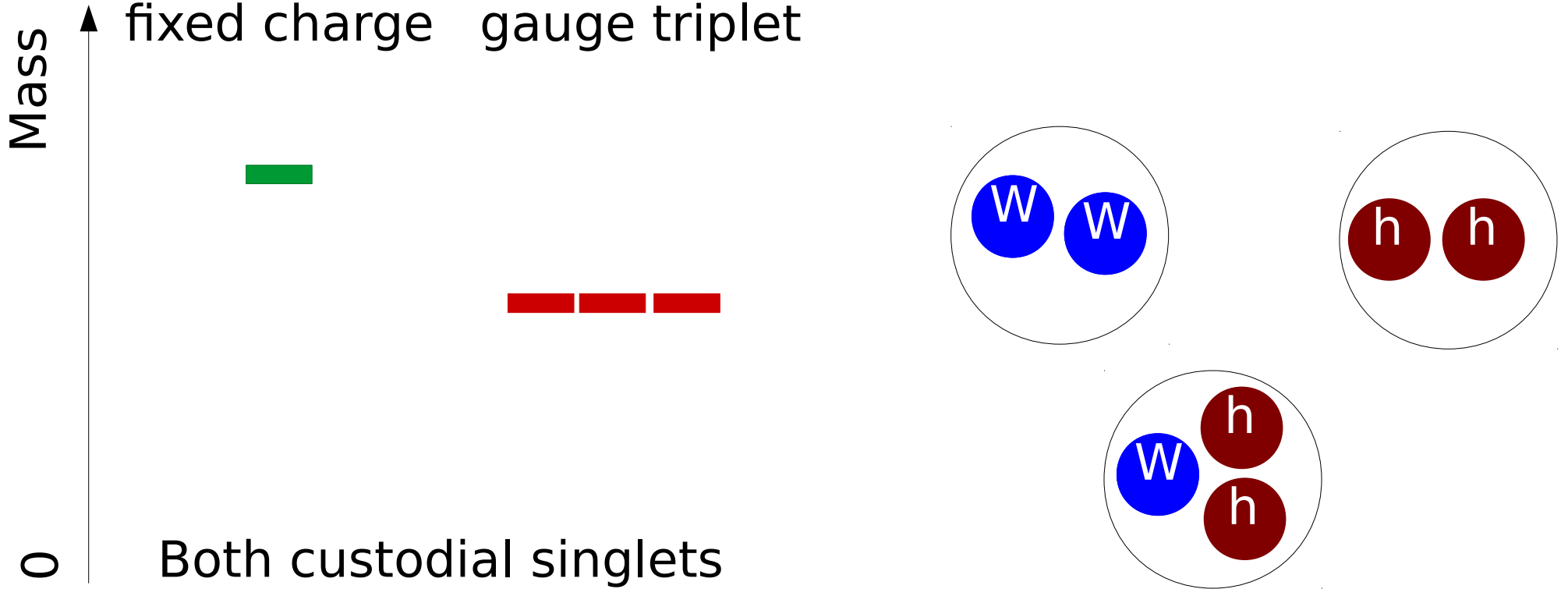

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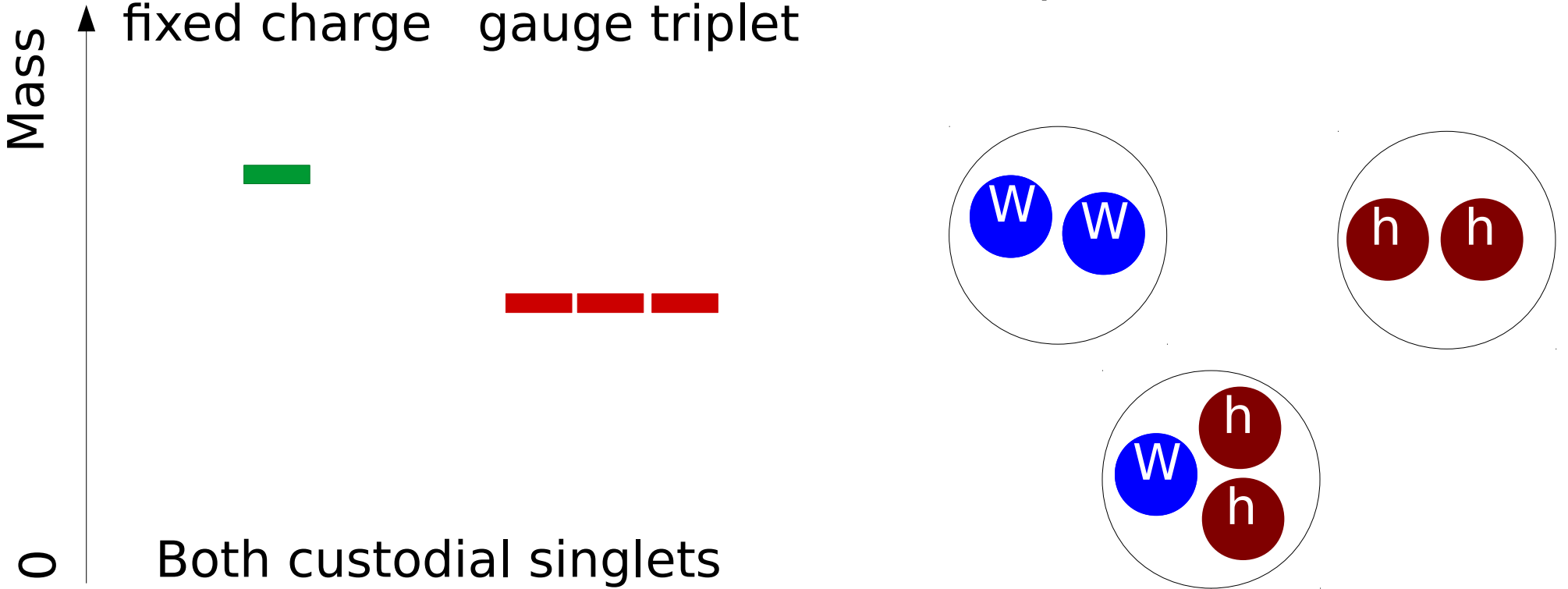

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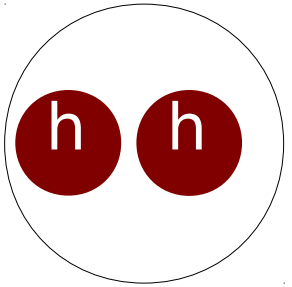

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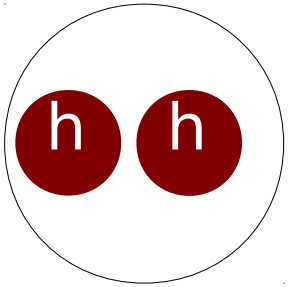

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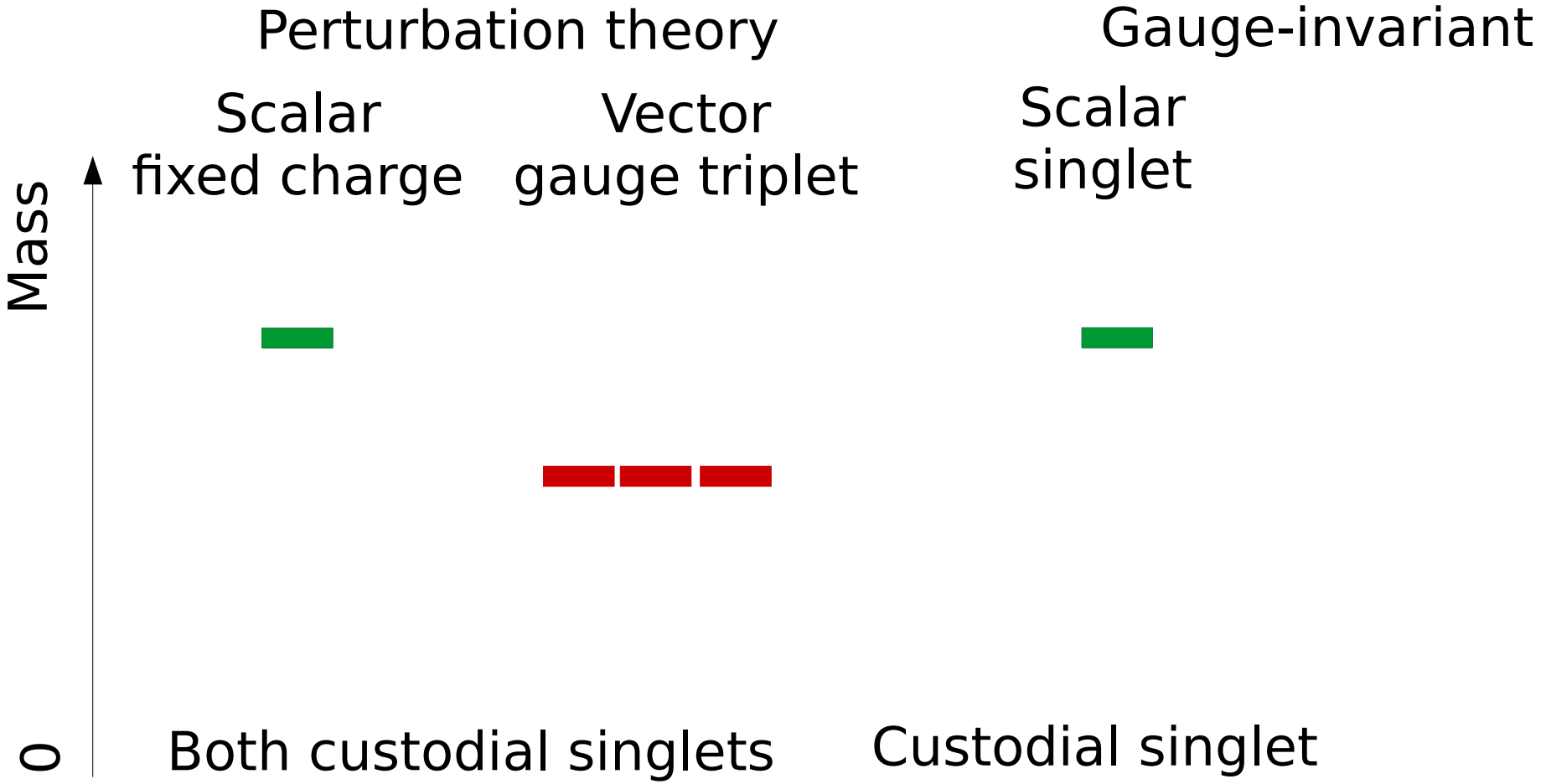

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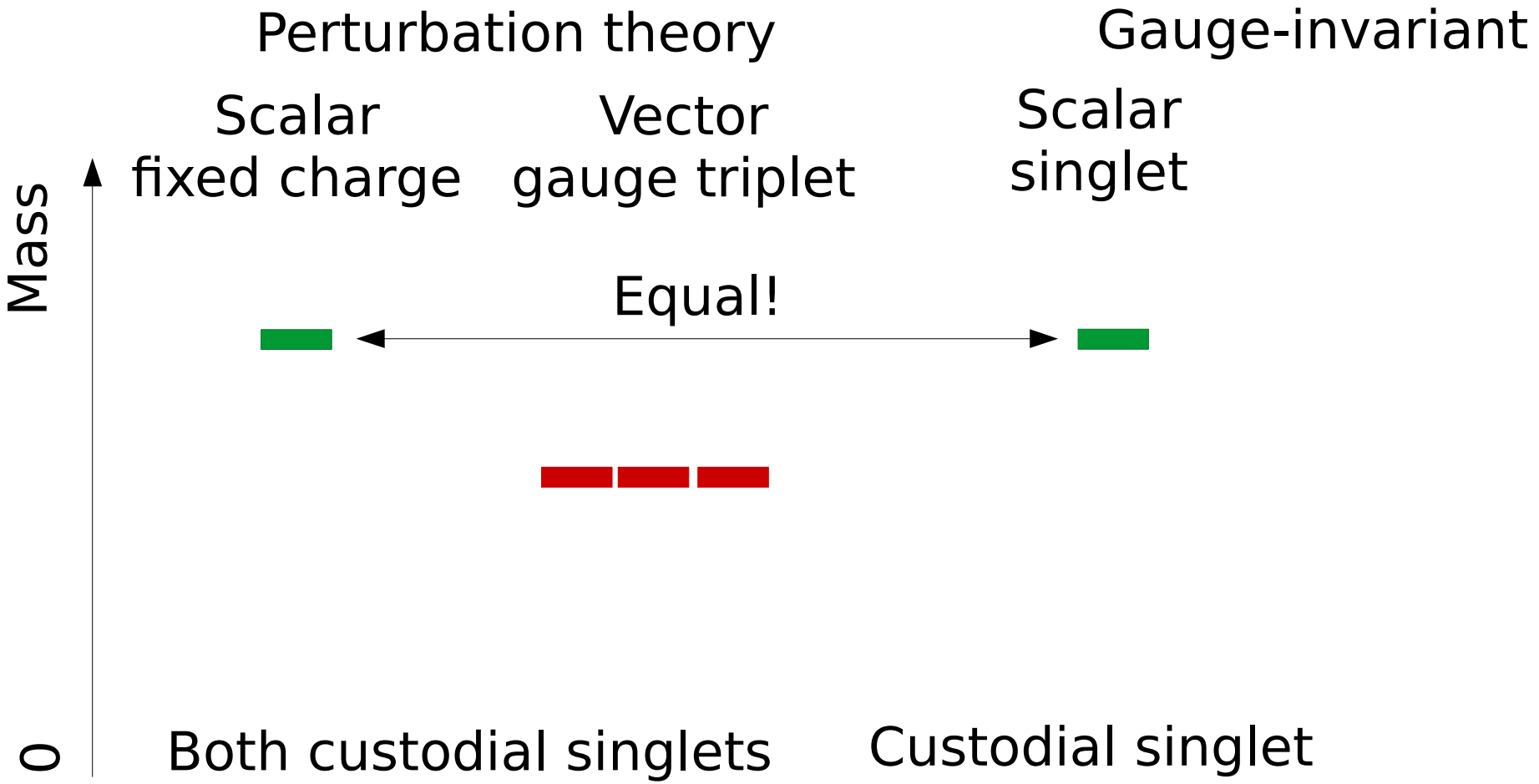

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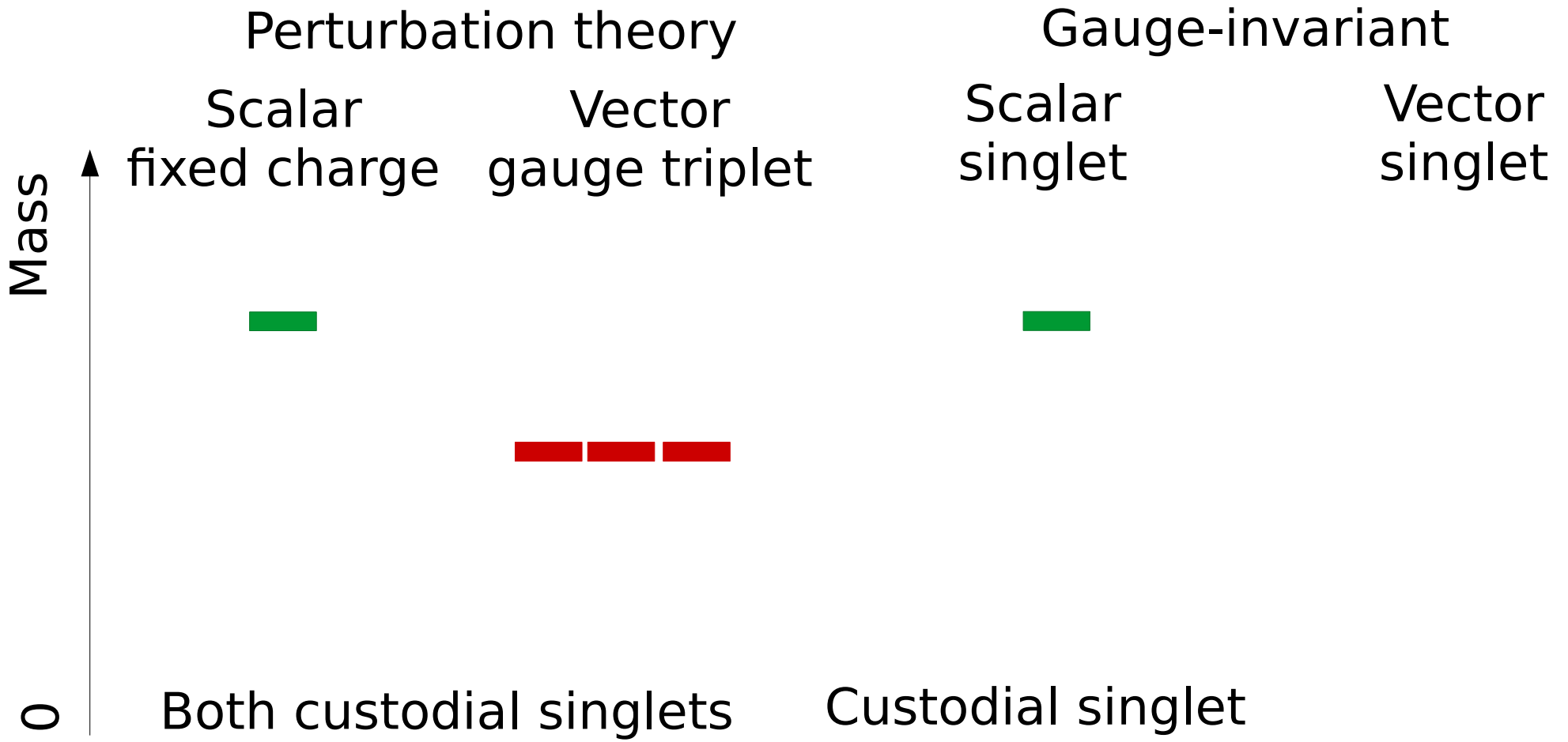

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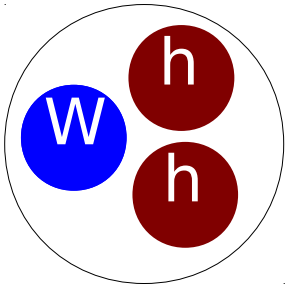

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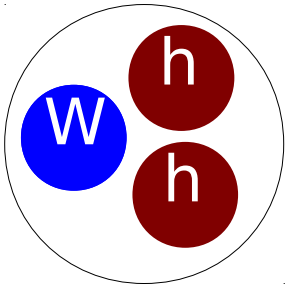

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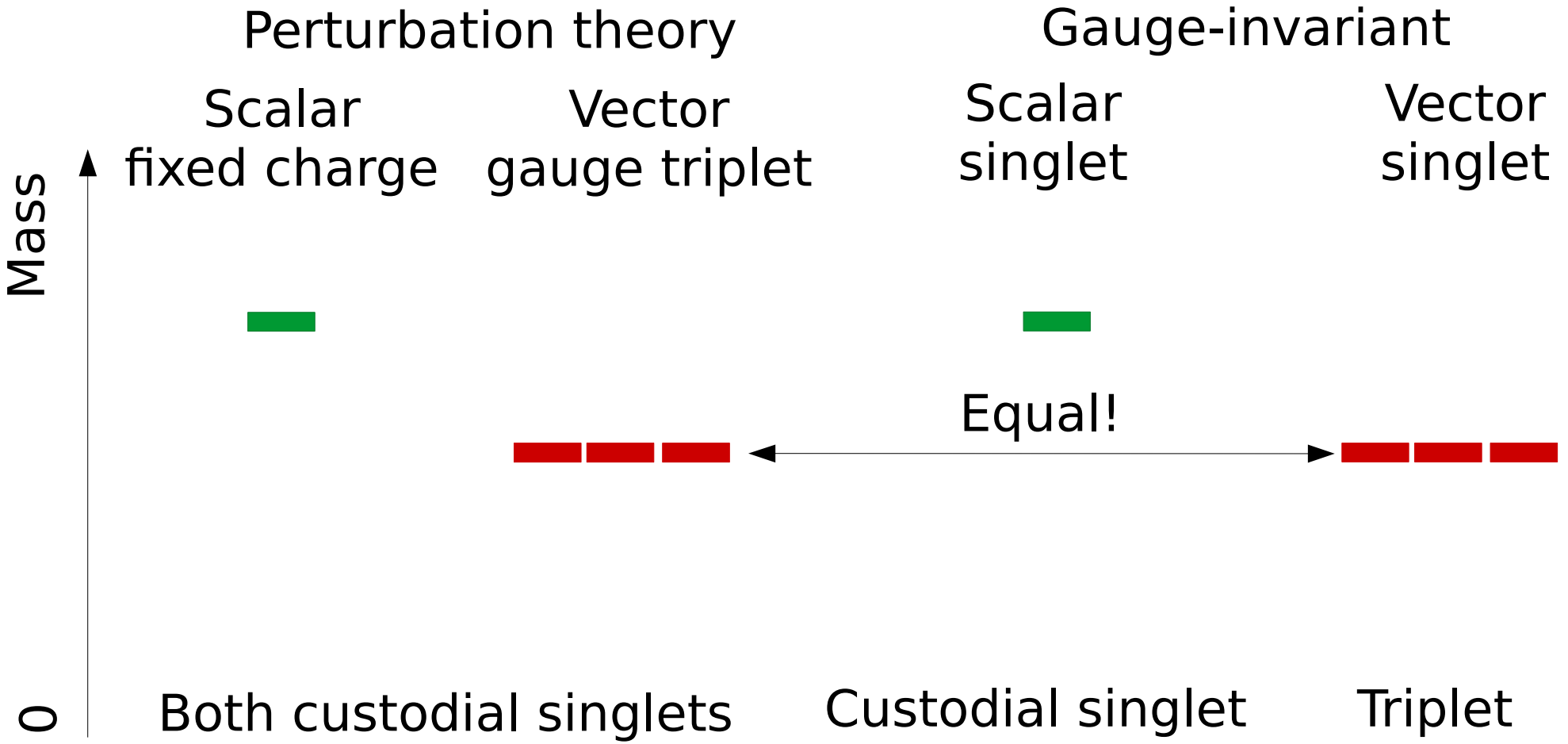

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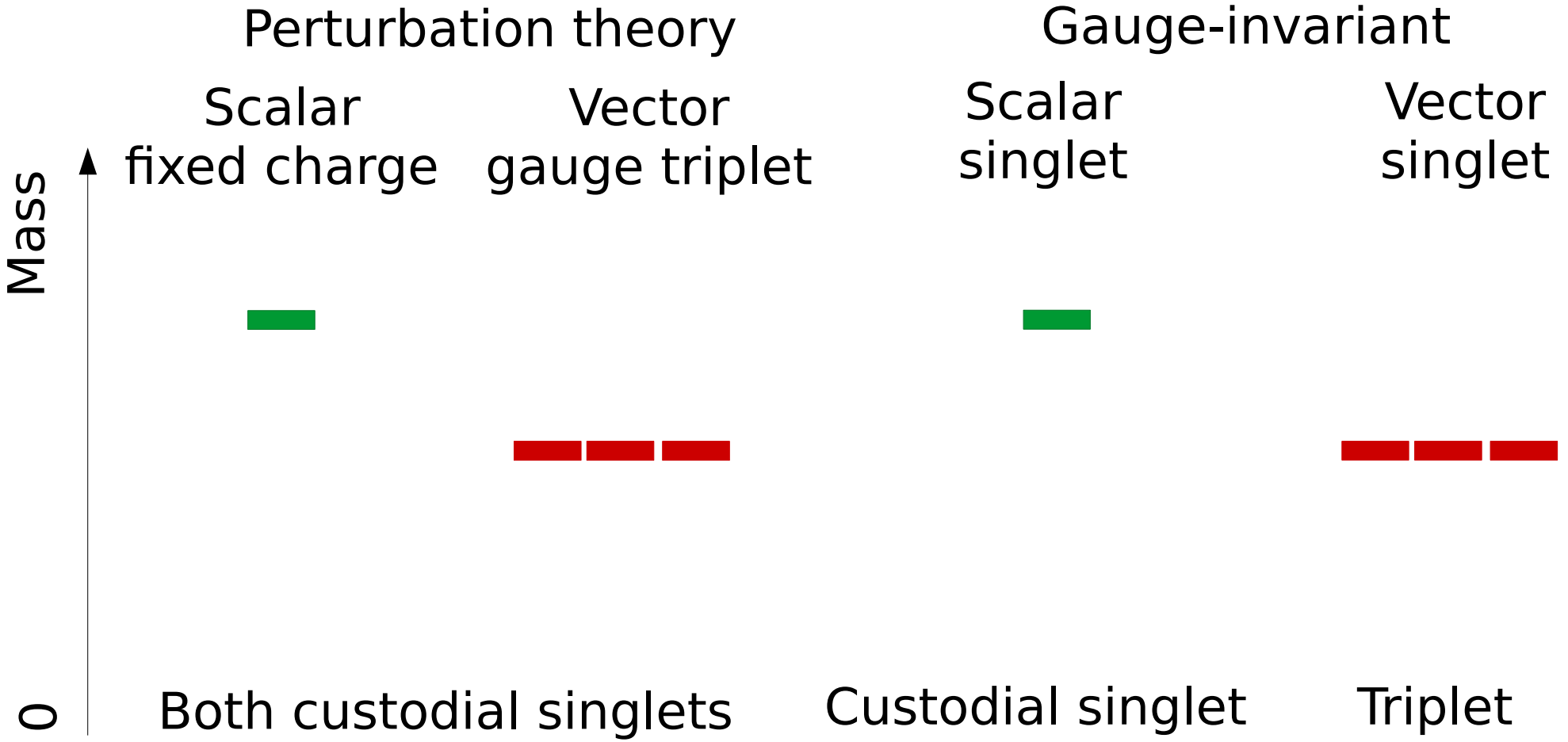

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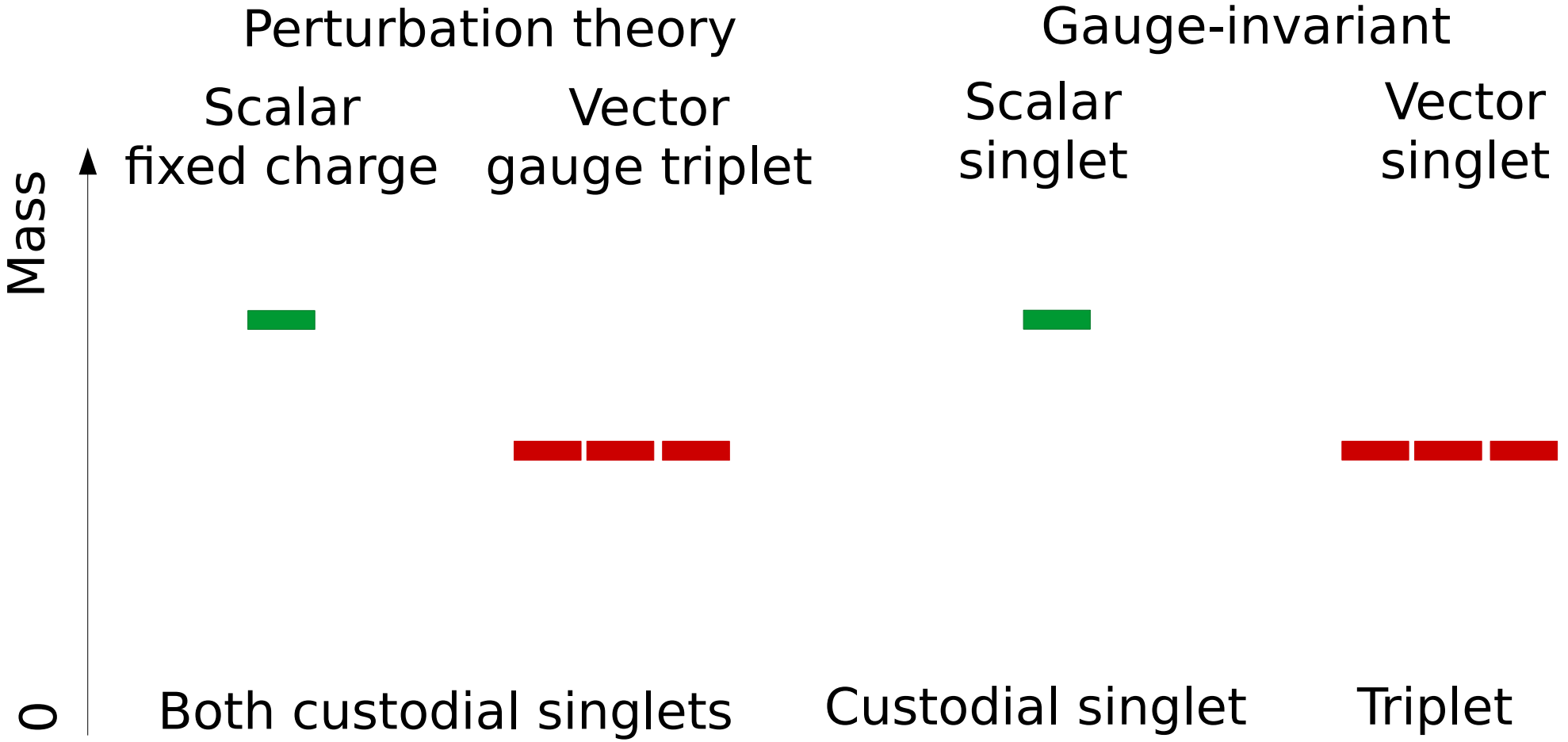

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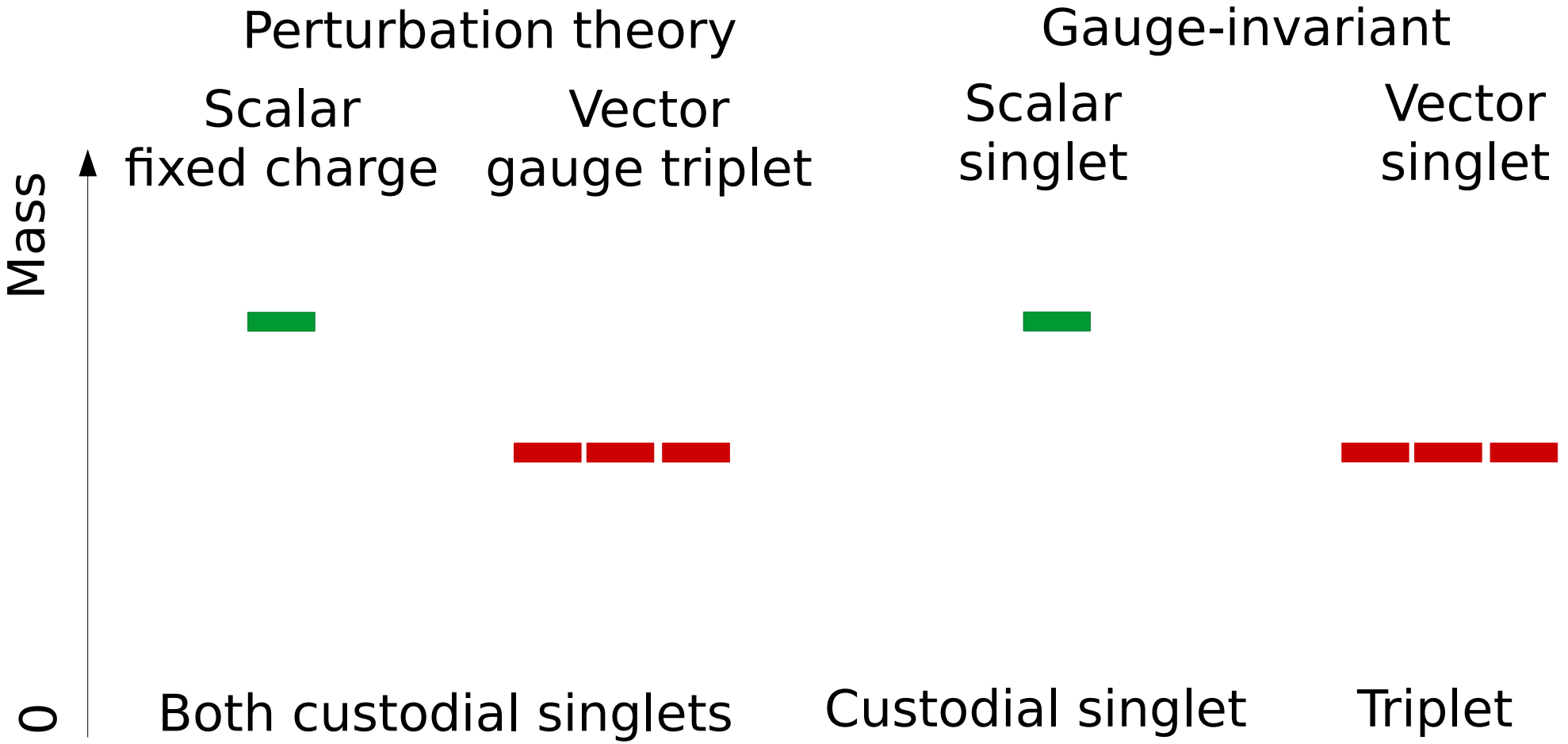

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[Fröhlich et al.'80,
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- Yukawa terms break custodial symmetry
  - Different masses for doublet members

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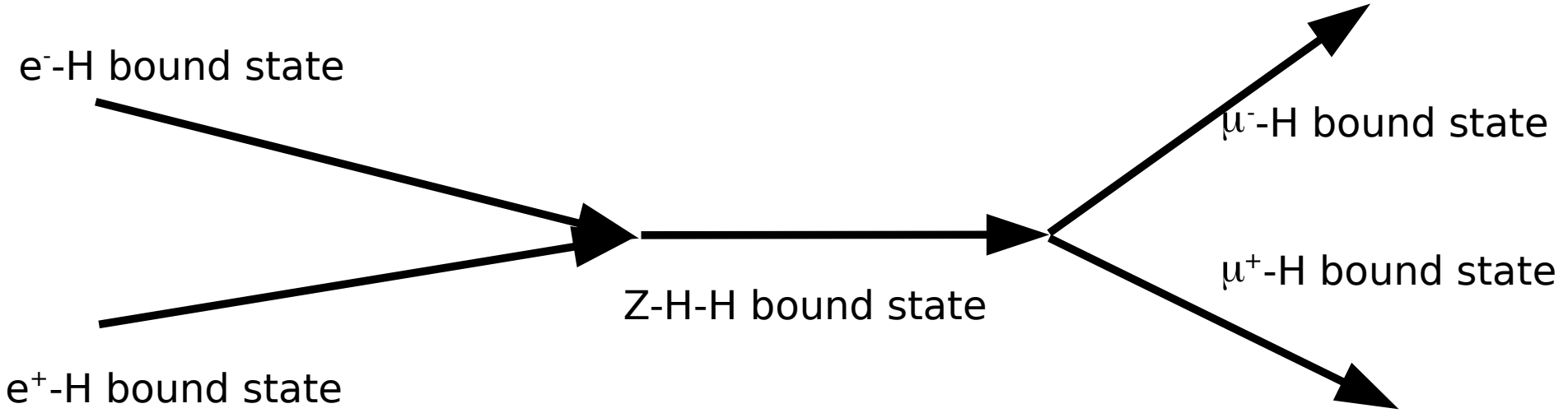
$$\langle (h_i^+ f_a)(x)^+ (h_{ib}^+ f_b)(y)\rangle \overset{h=v+\eta}{\approx} \langle f_a^+(x) f_a(y)\rangle + O(\eta)$$

- Gauge-invariant state, but custodial doublet
- Yukawa terms break custodial symmetry
  - Different masses for doublet members
- Implications for experiment?

How events looks like (LEP/ILC)

[Maas'12]



- Collision of bound states

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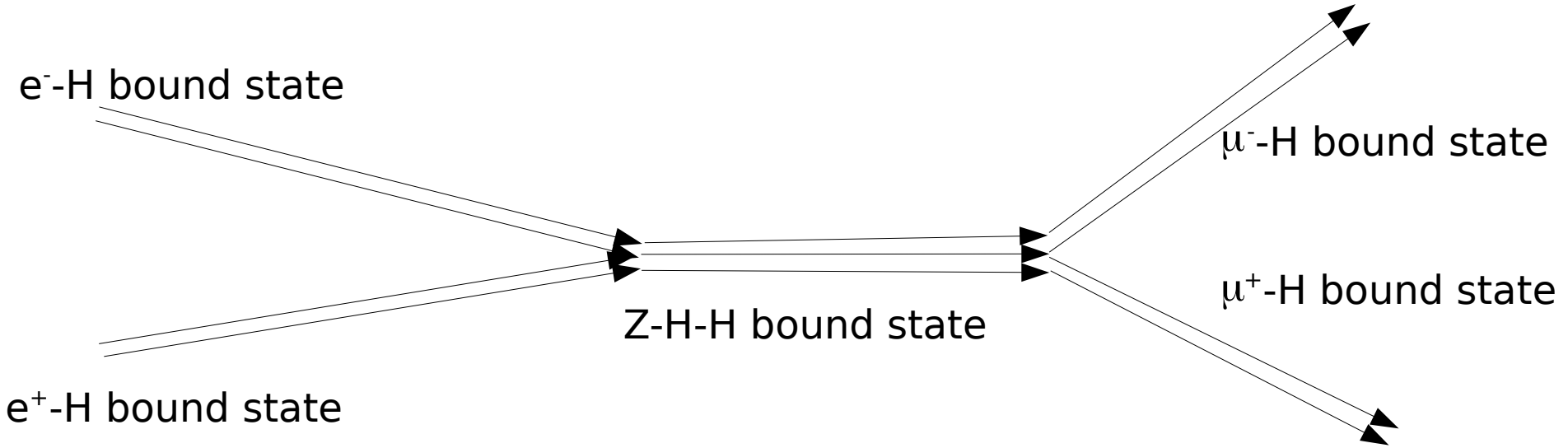

- Collision of bound states - 'constituent' particles

How events looks like (LEP/ILC)

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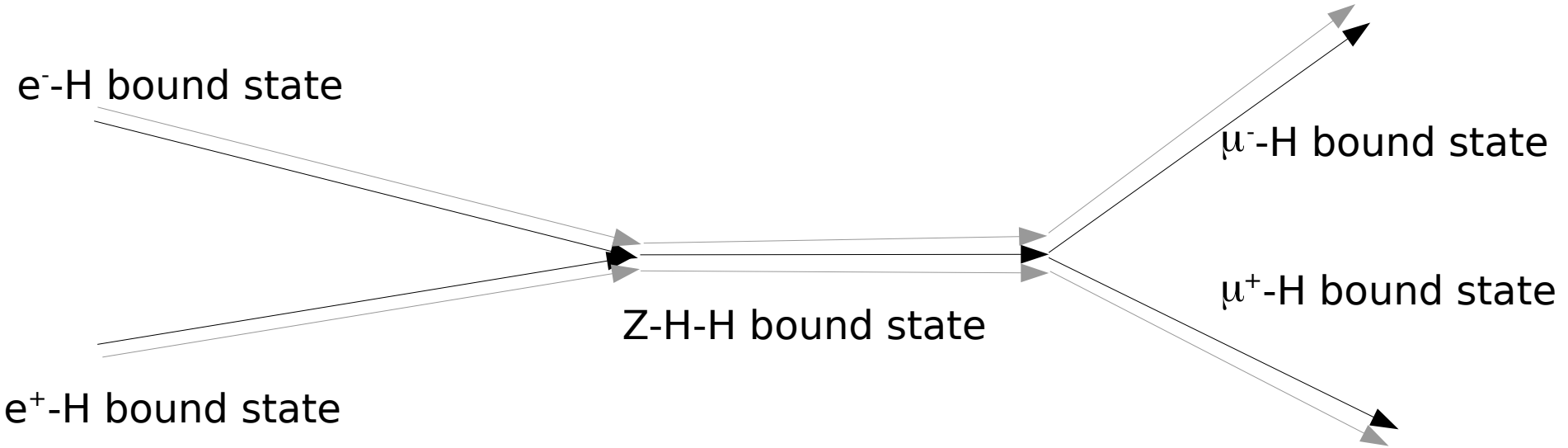

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- Higgs partners just spectators
  - Similar to pp collisions

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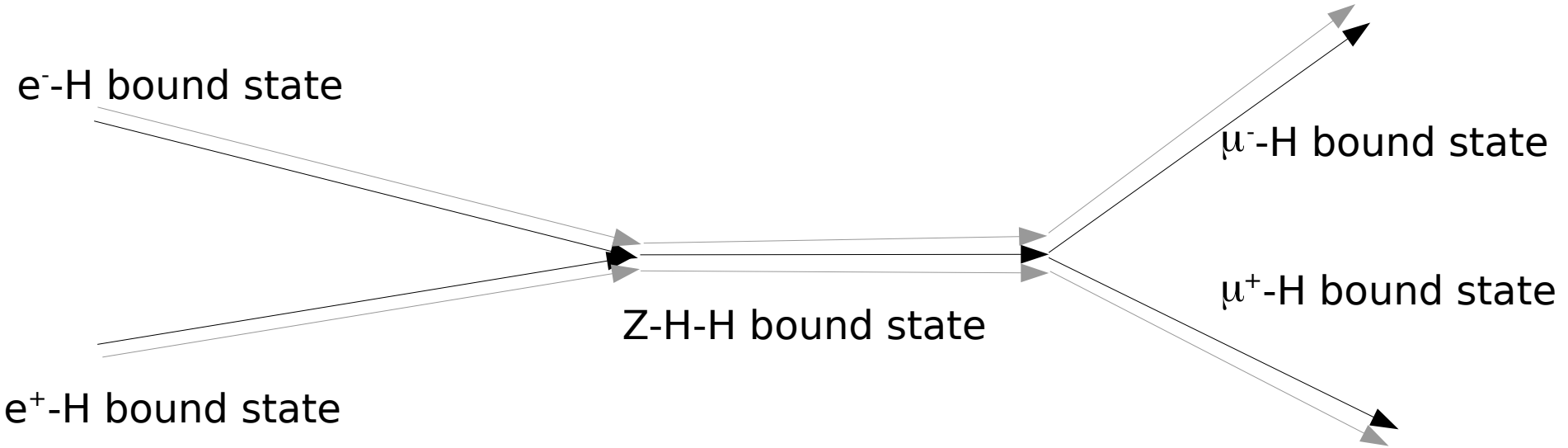

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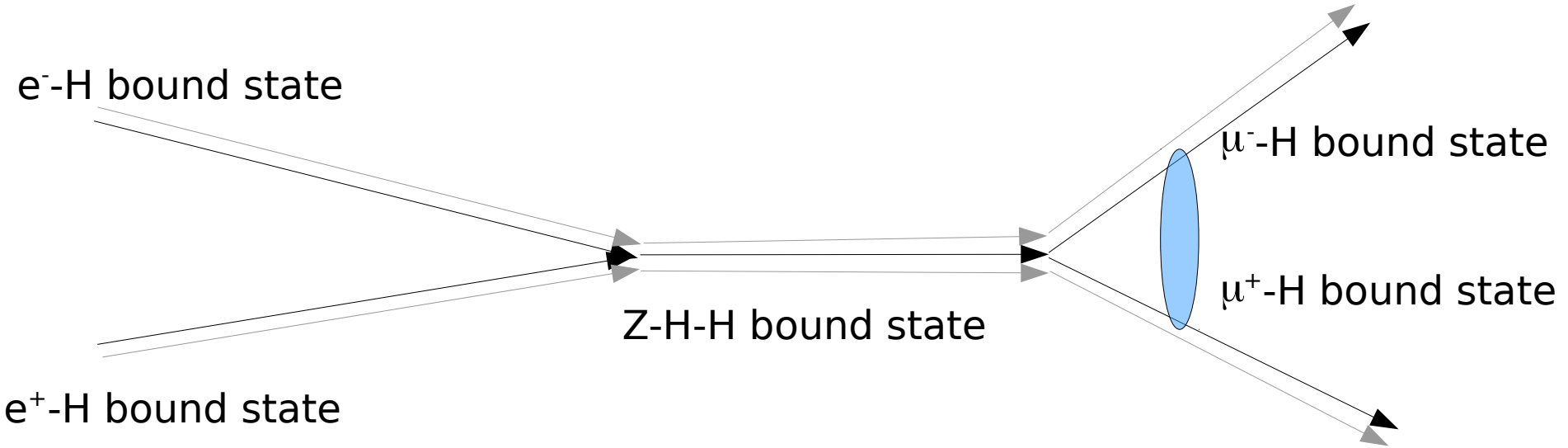

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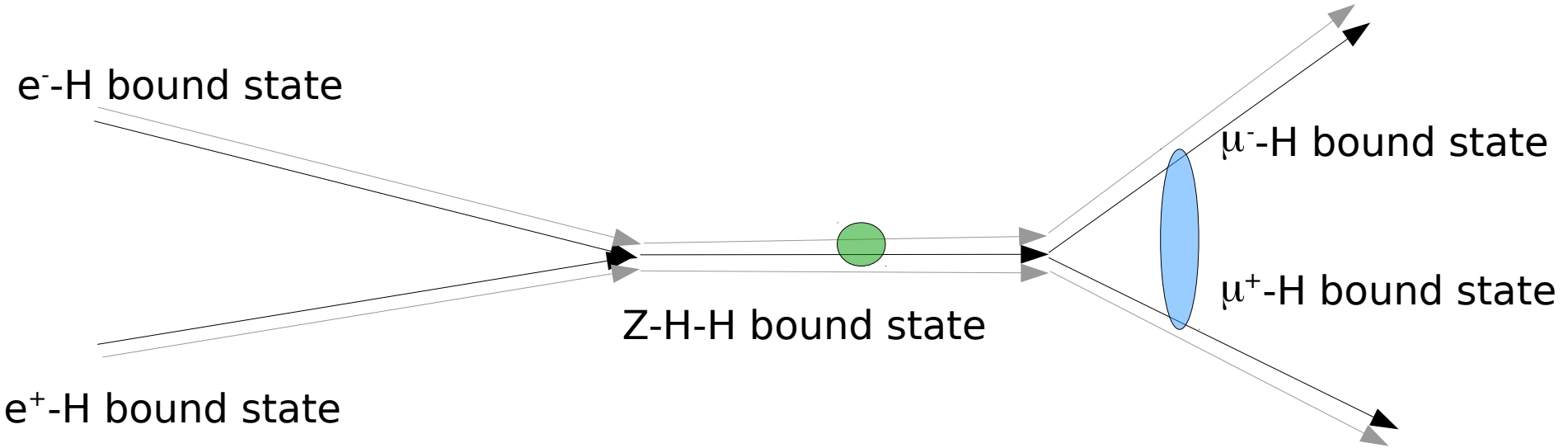

- Collision of bound states - 'constituent' particles
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  - Similar to pp collisions
- Sub-leading contributions
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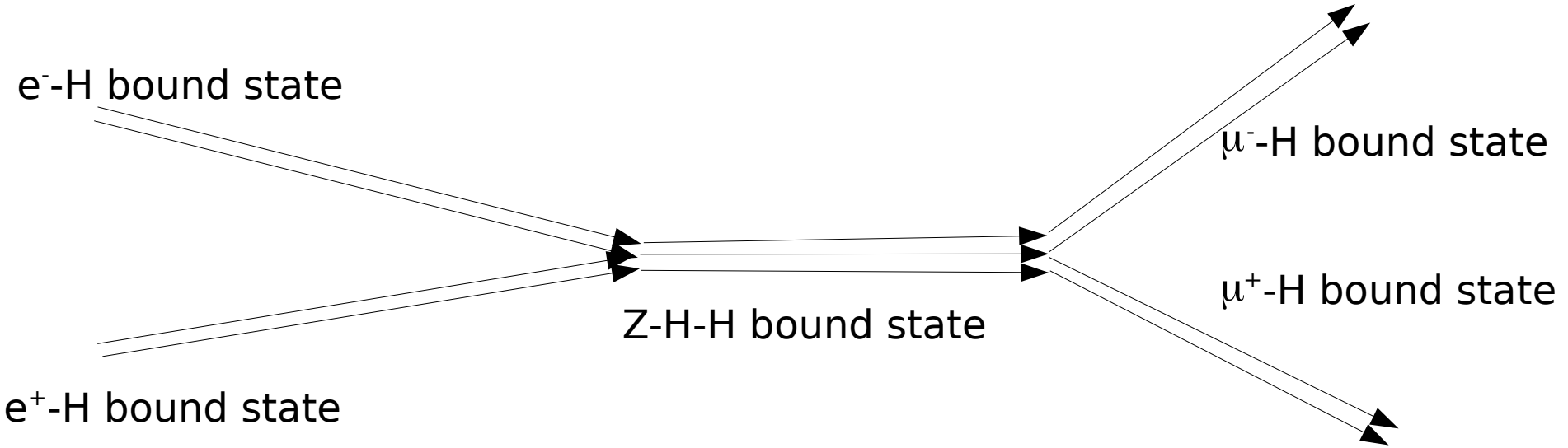
  - New ones: Small, require more sensitivity

How events looks like (LEP/ILC)

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



- Description of impact?

How events looks like (LEP/ILC)

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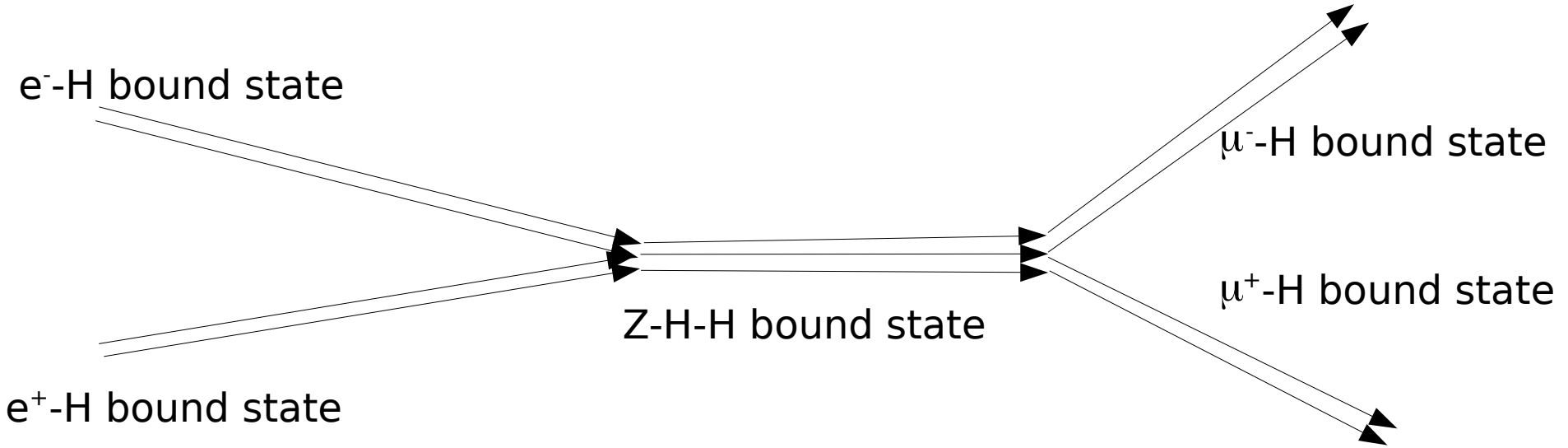

- Description of impact? Gauge-invariant perturbation theory!

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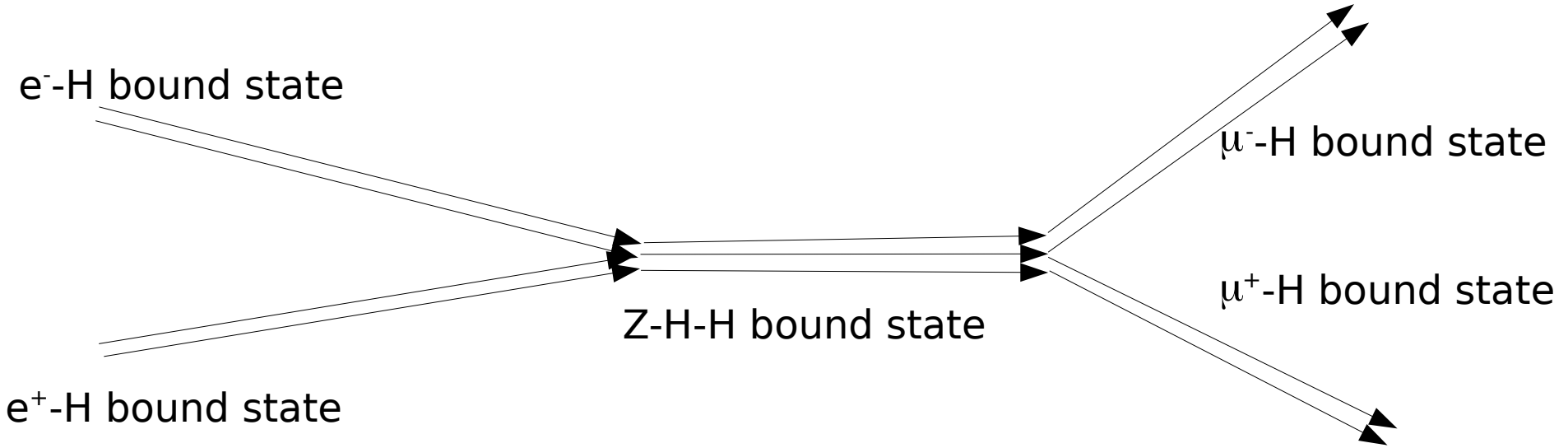

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$$\langle hehe | h\mu\, h\mu \rangle$$

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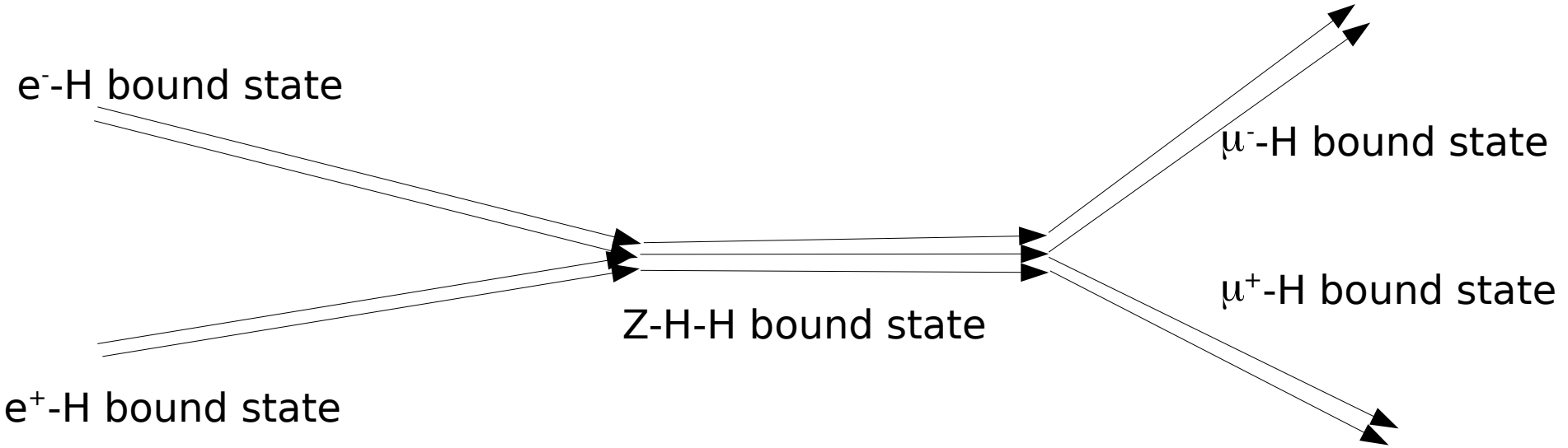

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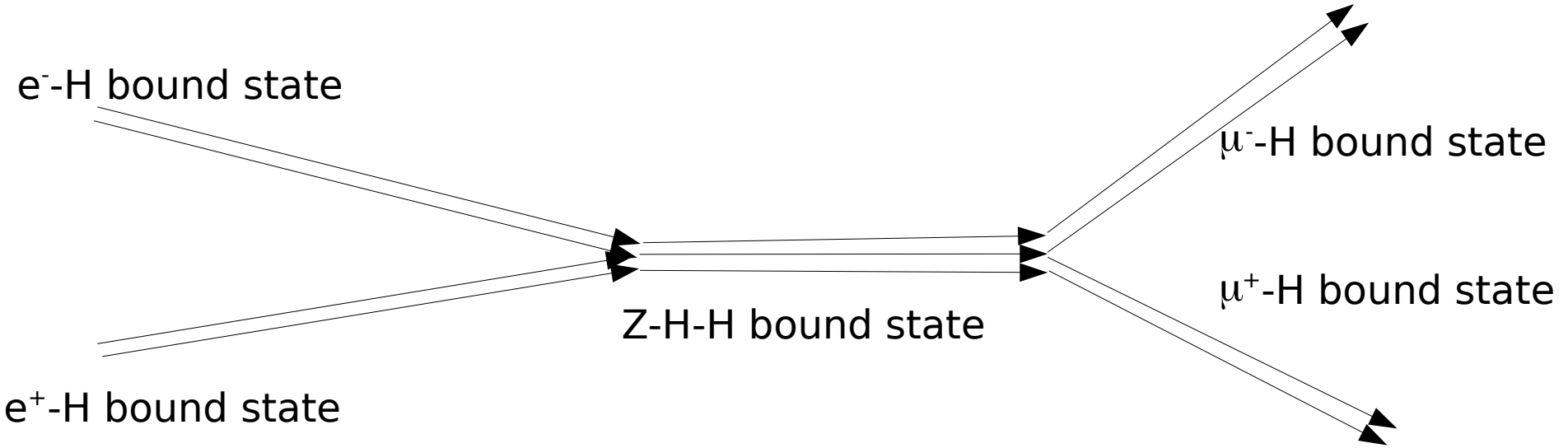

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$$\langle hehe | h\mu\, h\mu \rangle = \langle ee | \mu\mu \rangle + \langle \eta\eta \rangle \langle ee | \mu\mu \rangle$$

  - Ordinary contribution
  - Modification of ordinary contribution

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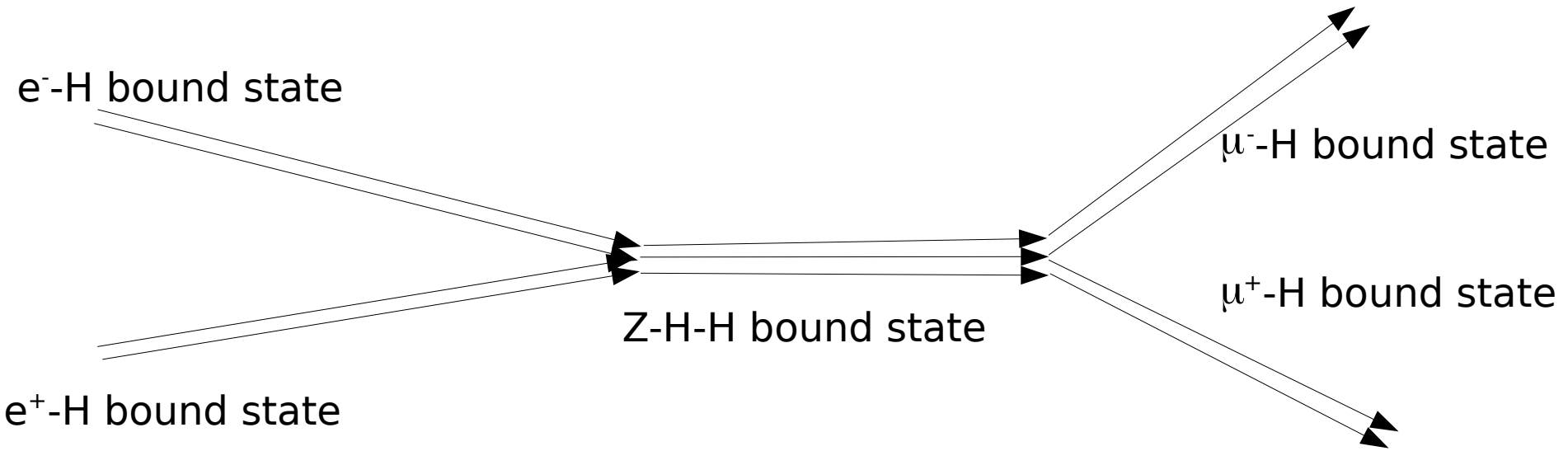

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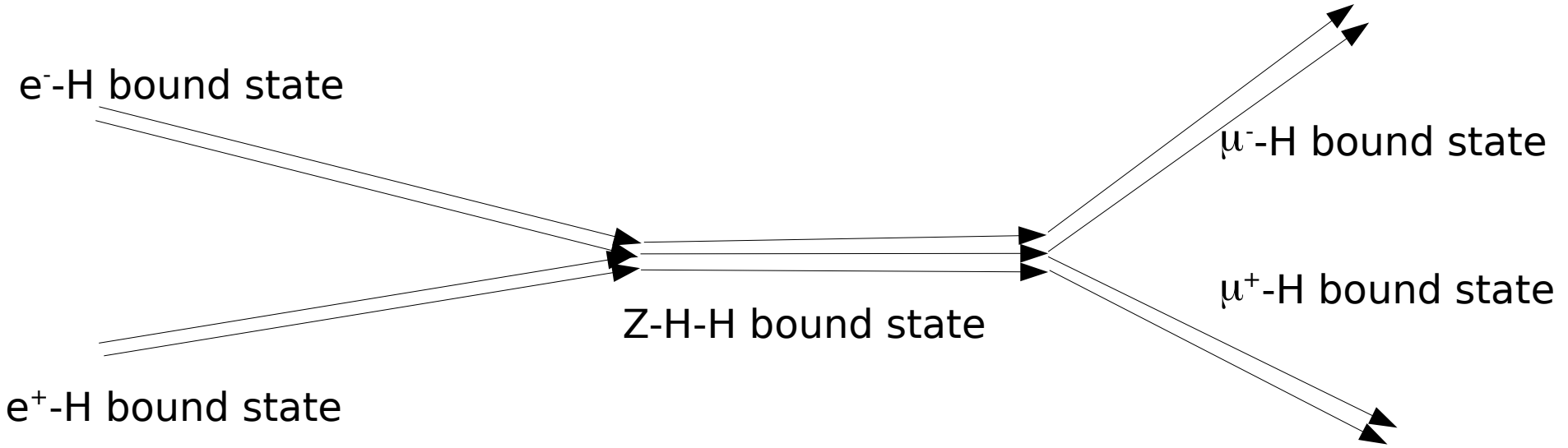

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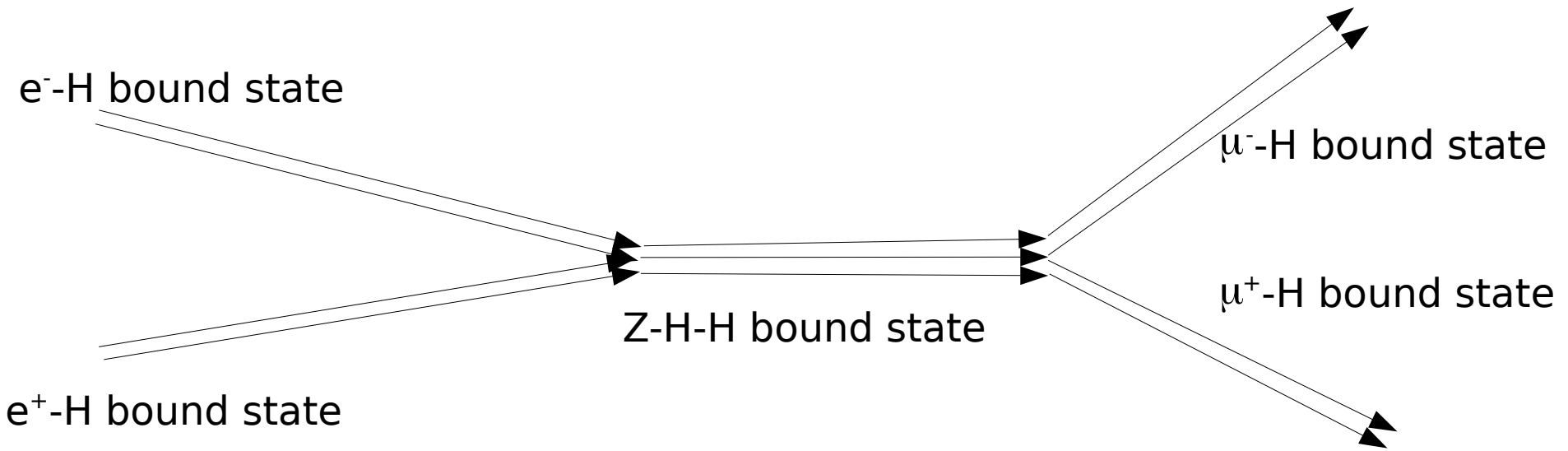

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  - More contributions...complicated

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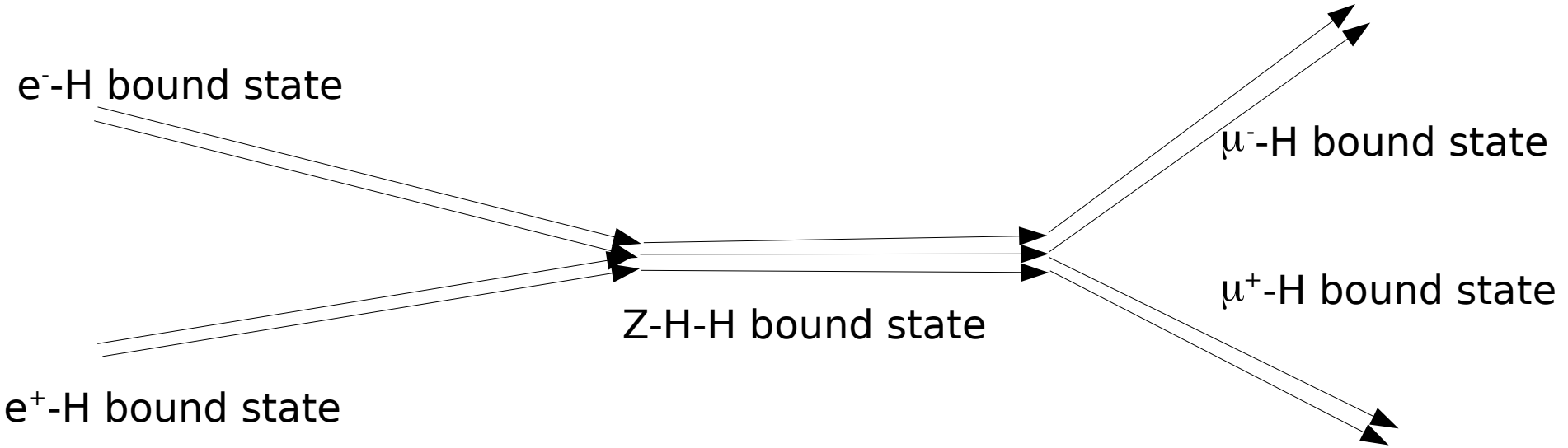

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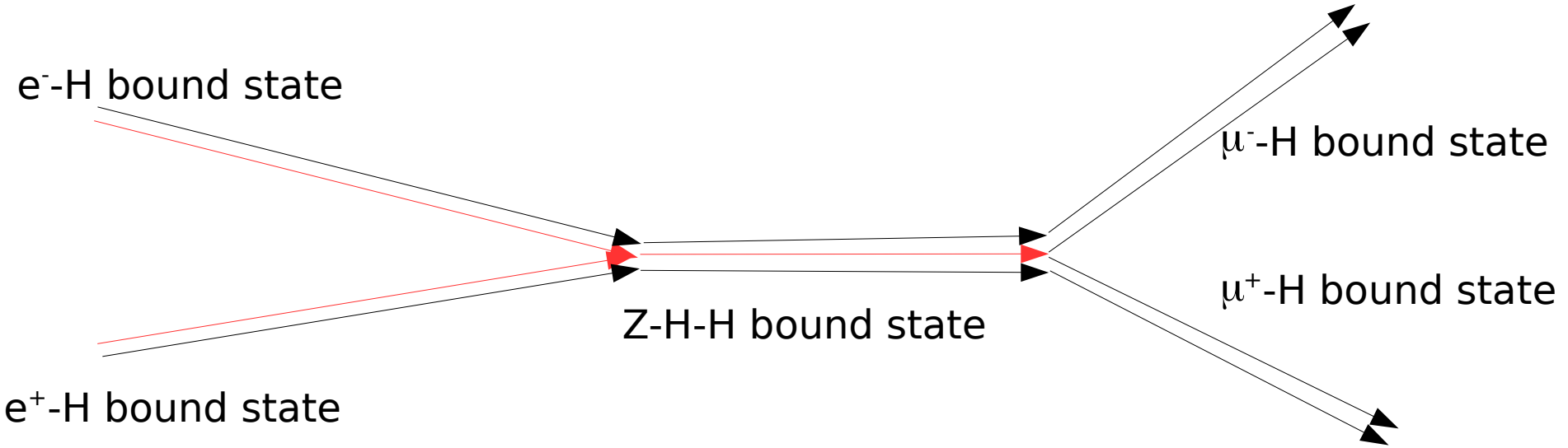

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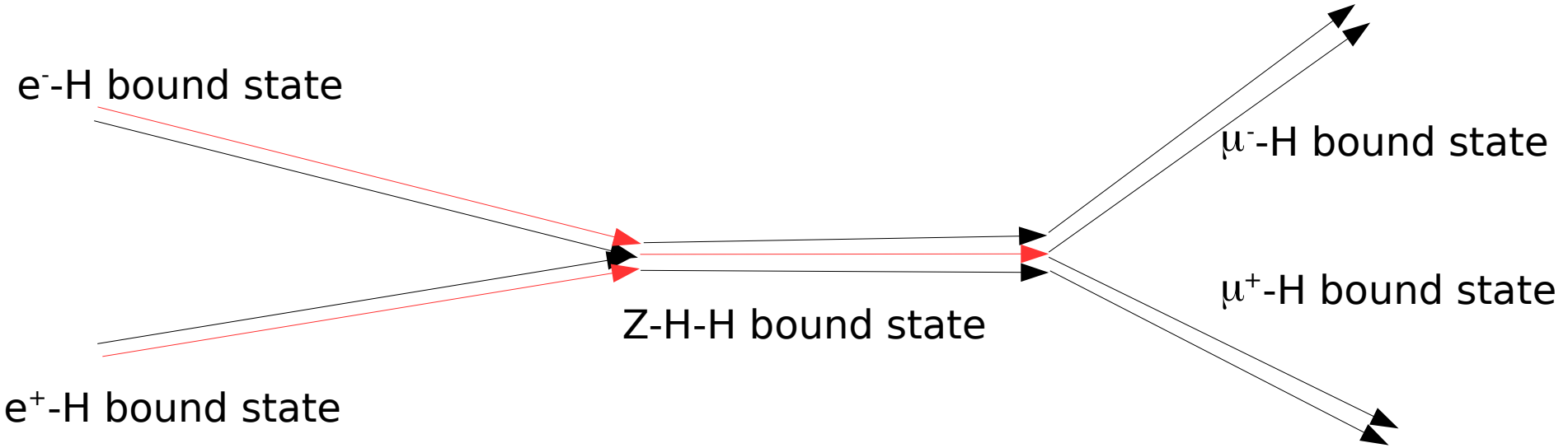

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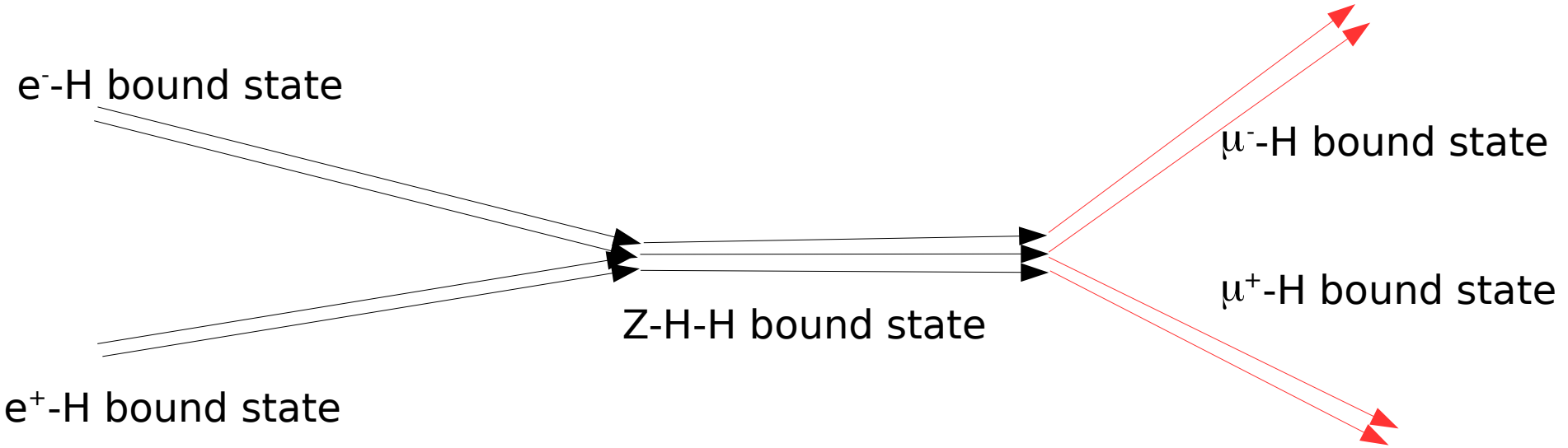

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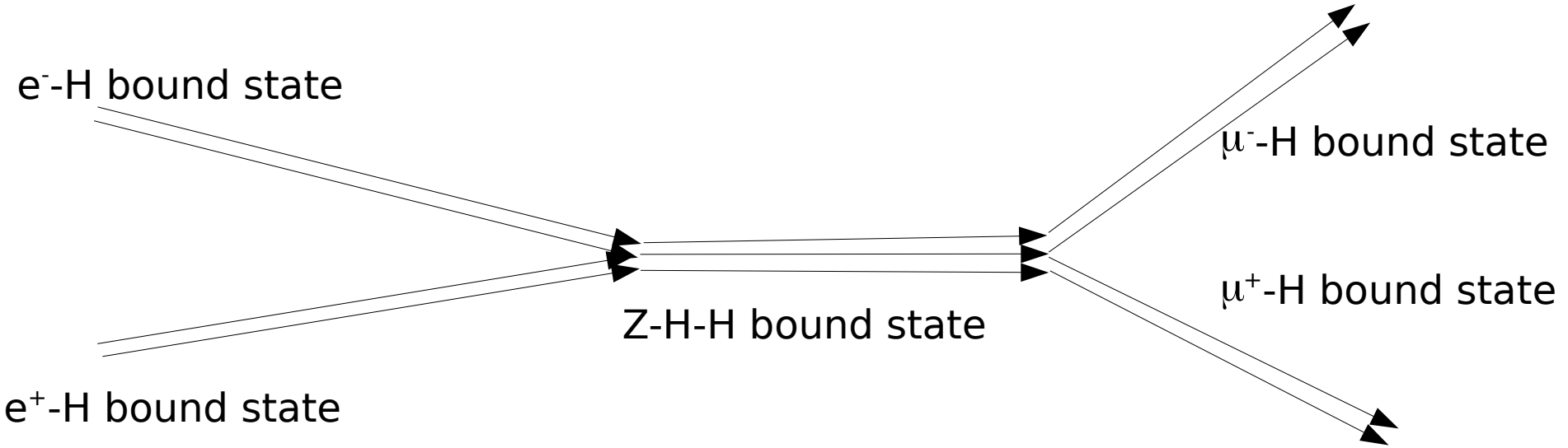

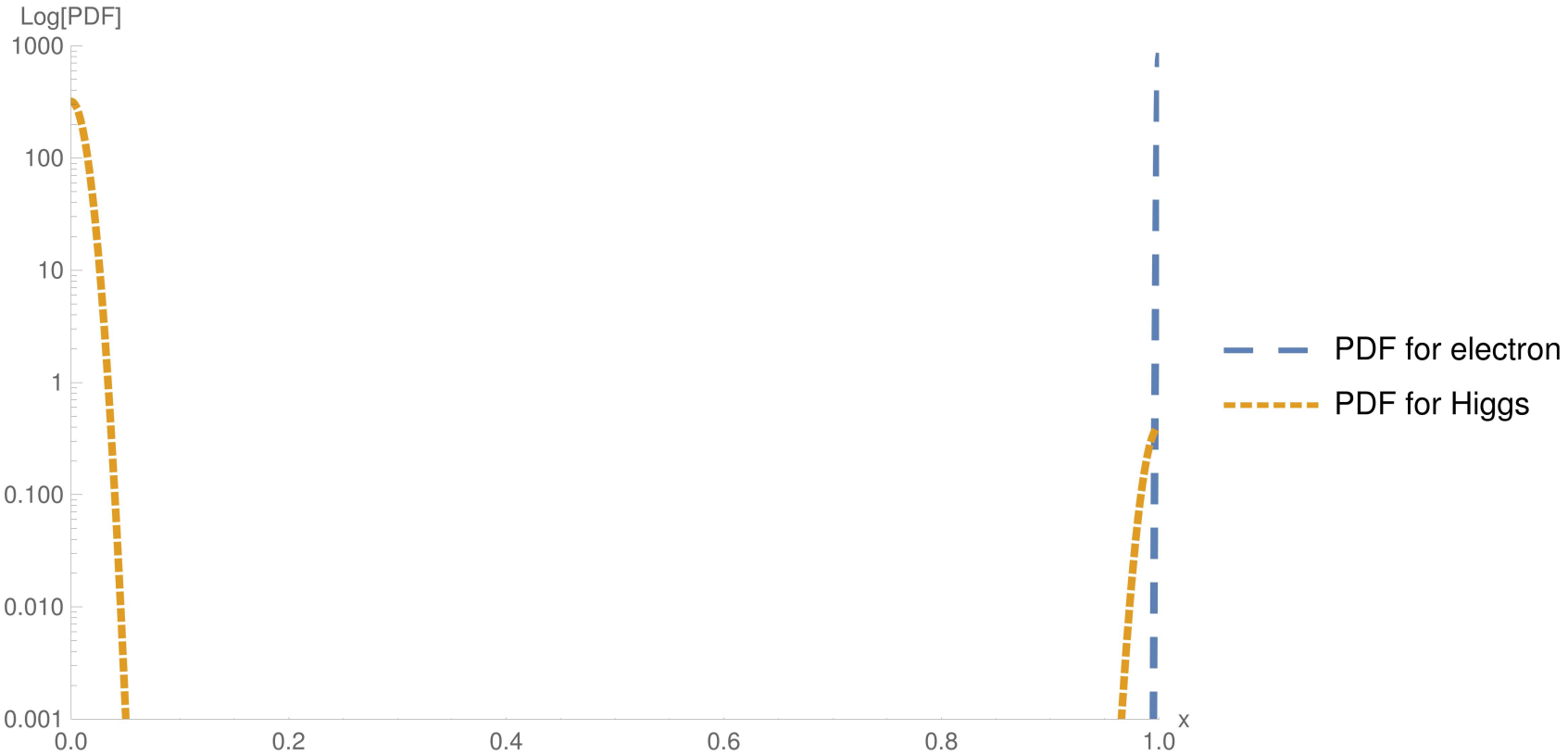

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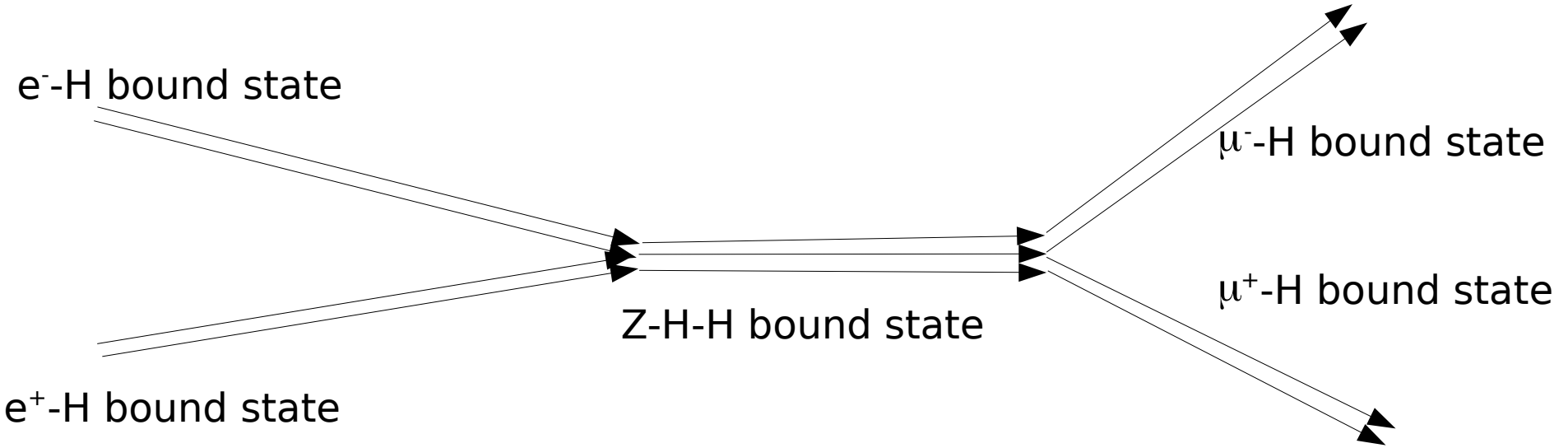
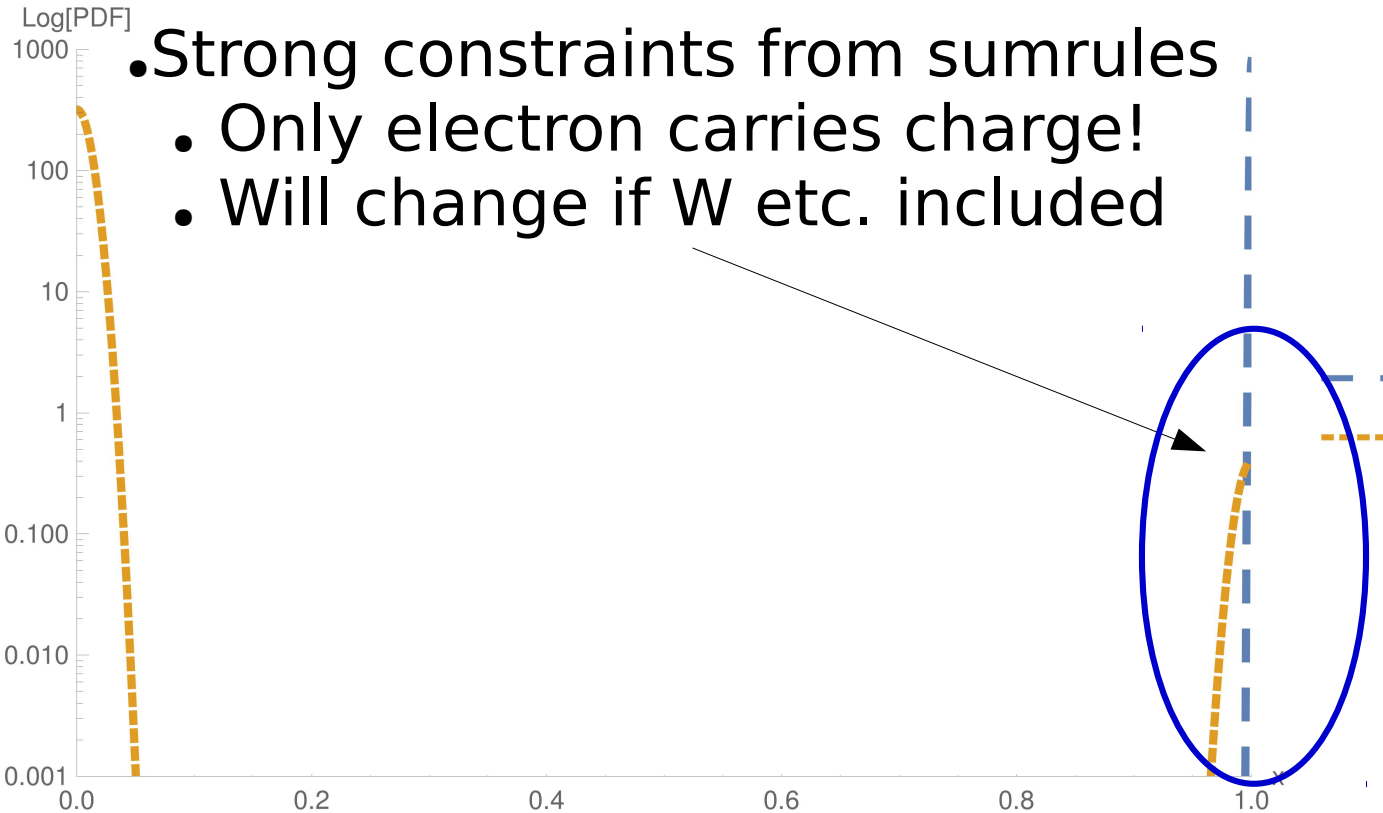


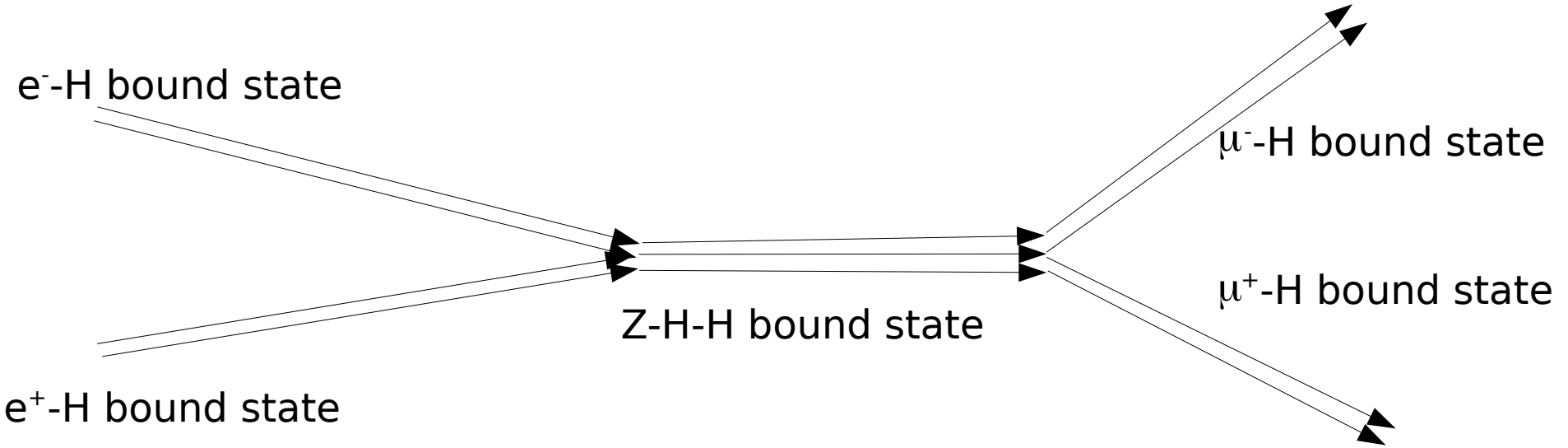
- Strong constraints from sumrules
  - Only electron carries charge!
  - Will change if W etc. included



Electron carries everything

How events looks like (LEP/ILC)

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



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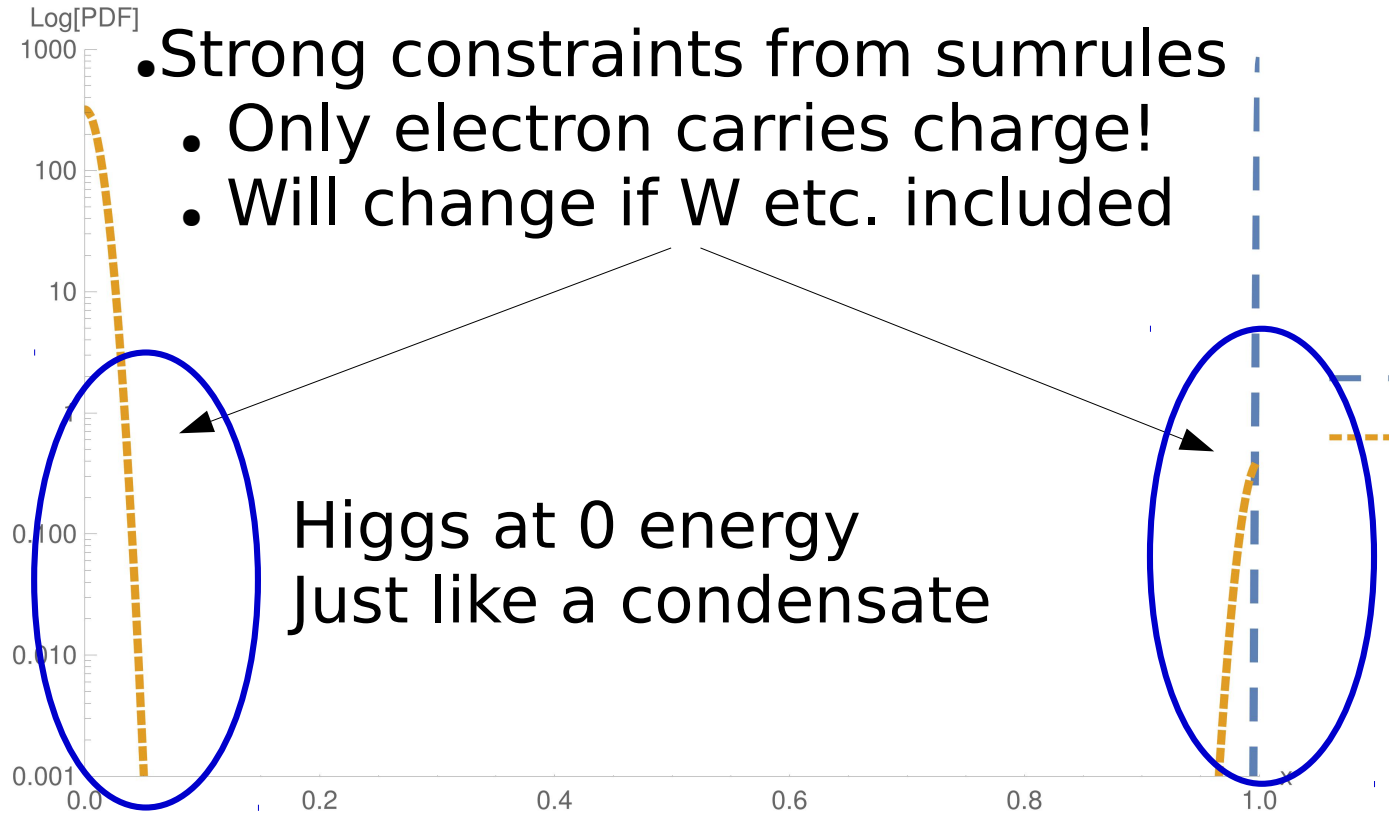

Higgs at 0 energy
Just like a condensate

Electron carries everything

How events looks like (LEP/ILC)

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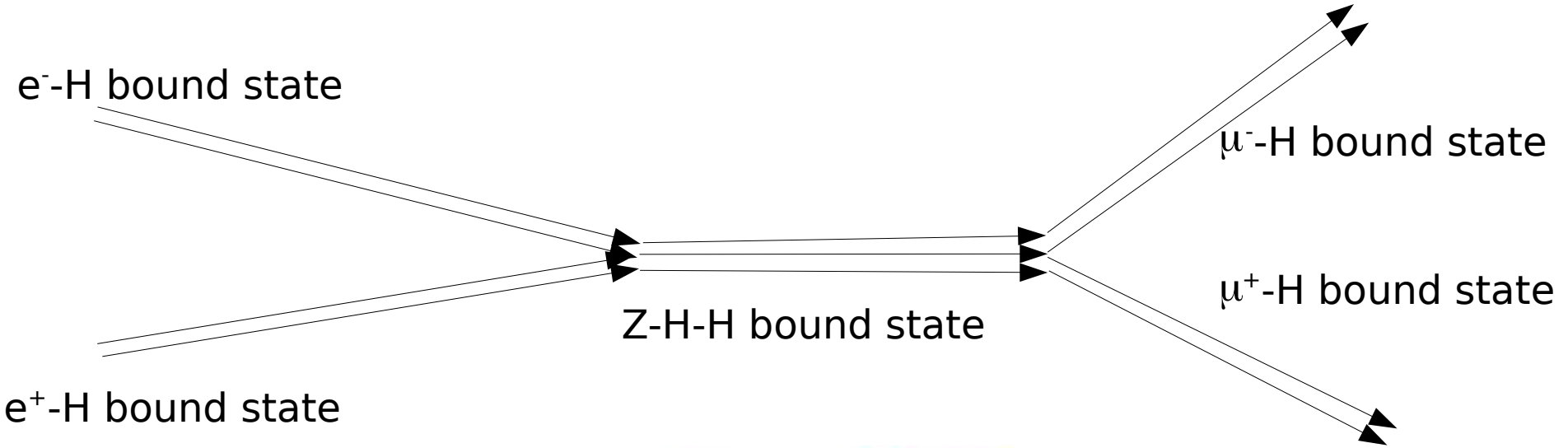

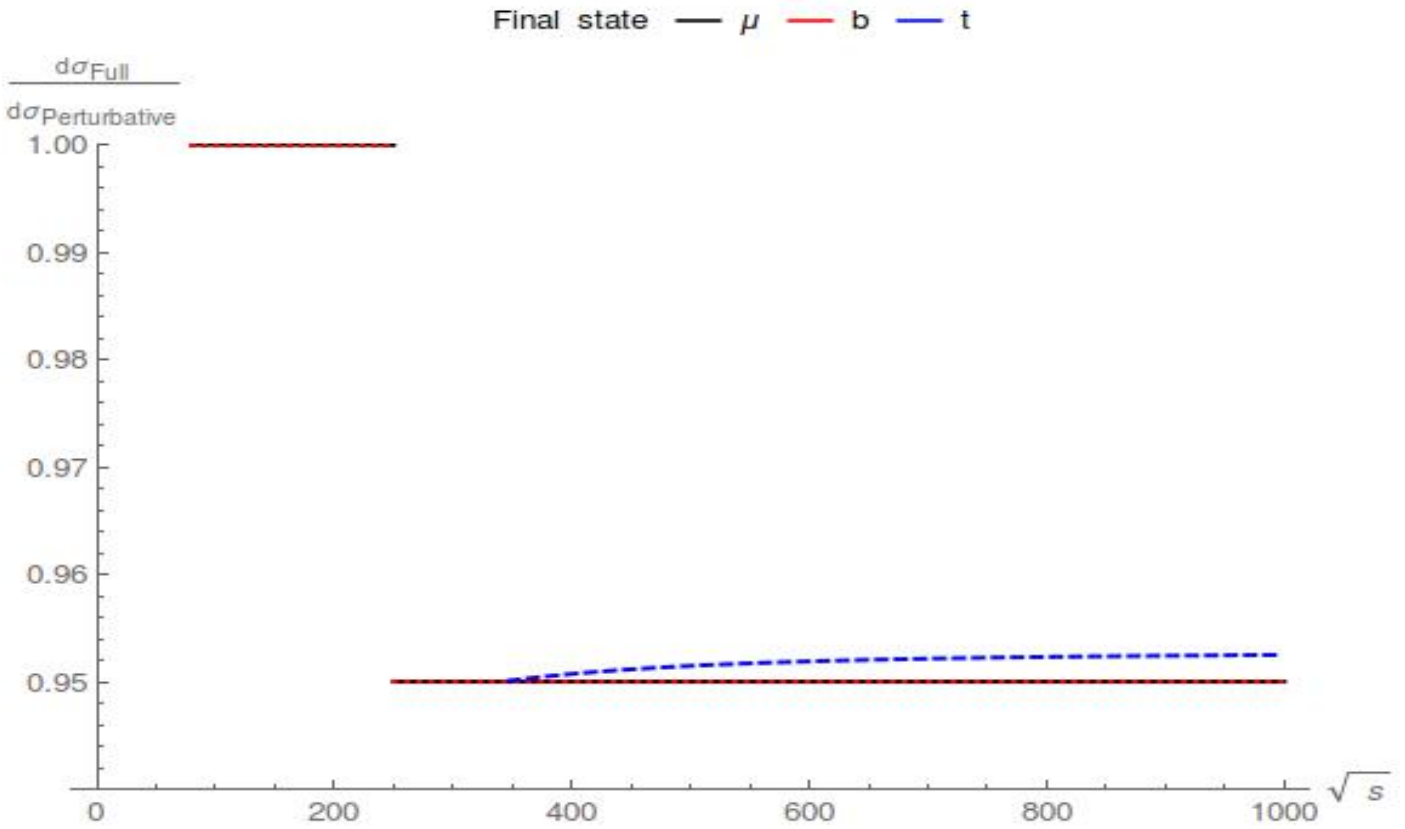

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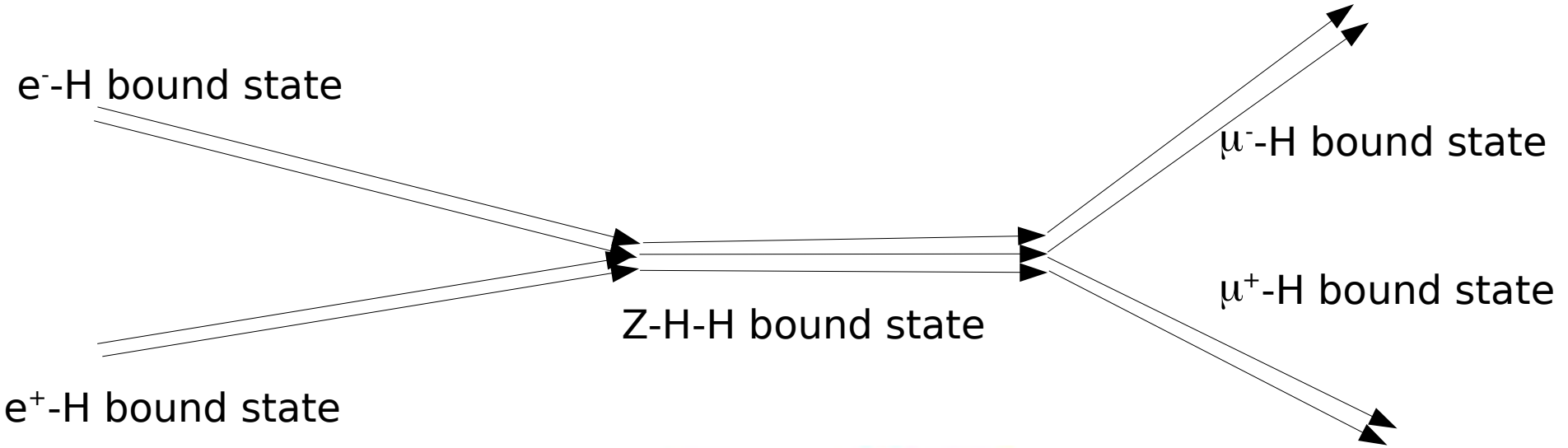

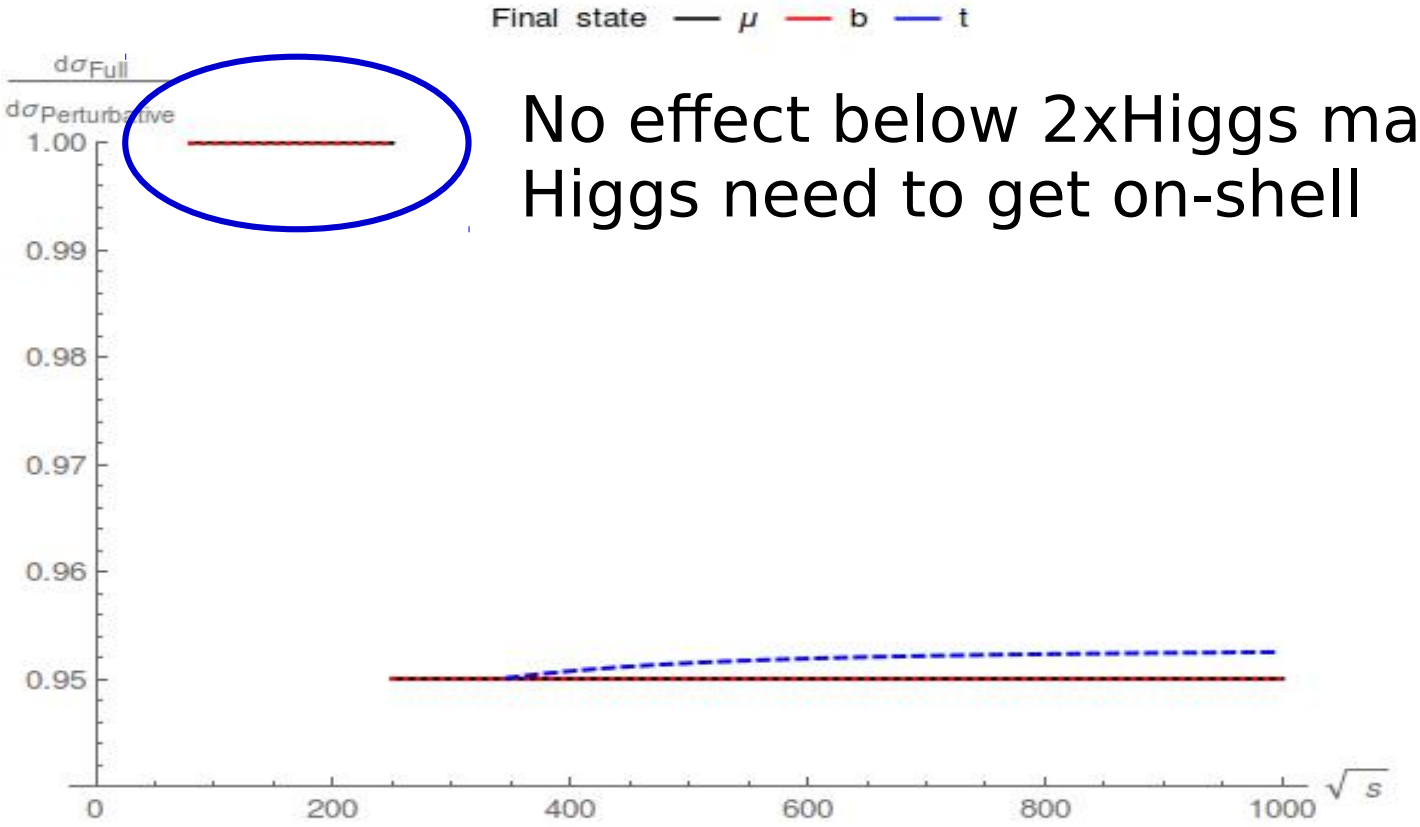

No effect below 2xHiggs mass
Higgs need to get on-shell

How events looks like (LEP/ILC)

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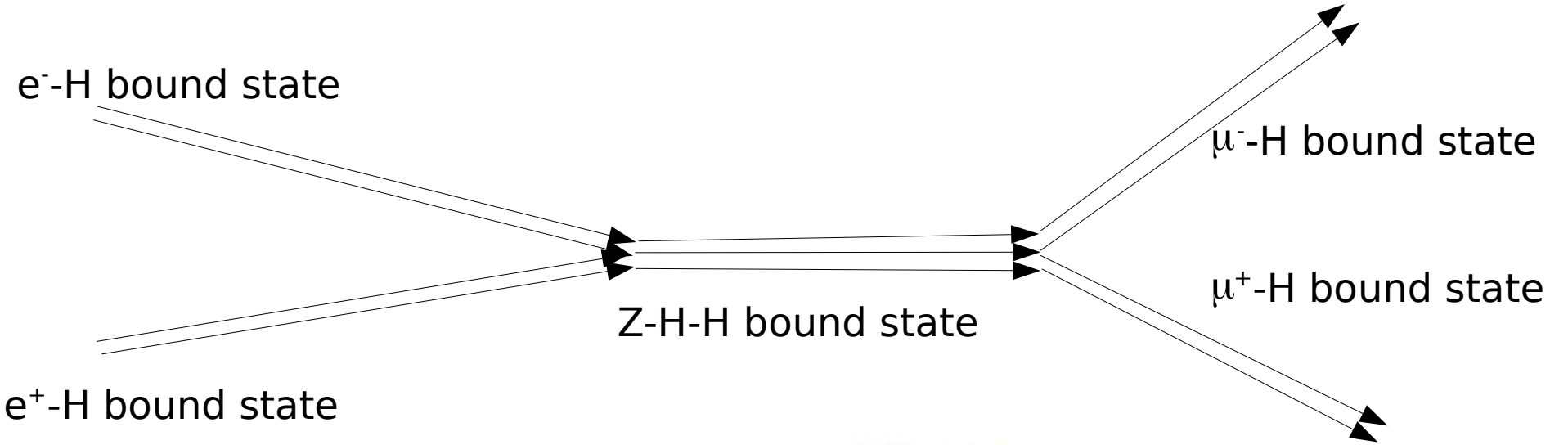

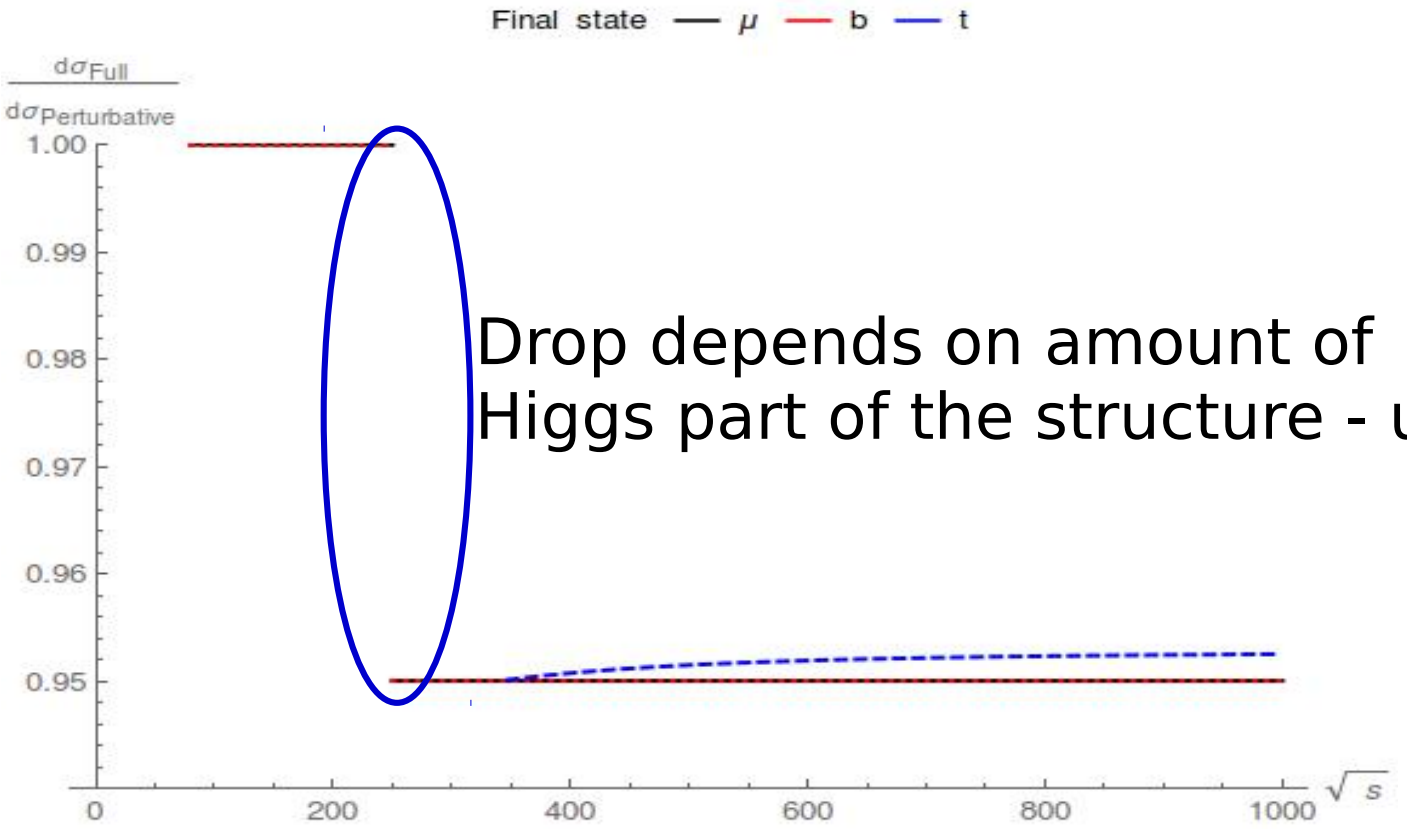

Drop depends on amount of Higgs part of the structure - unknown

How events looks like (LEP/ILC)

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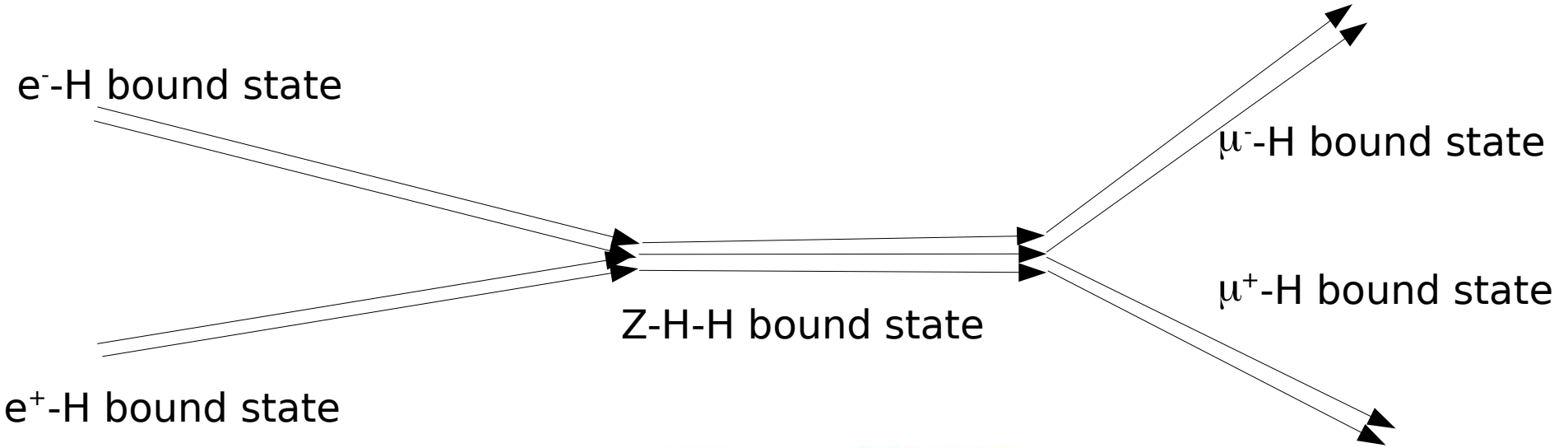

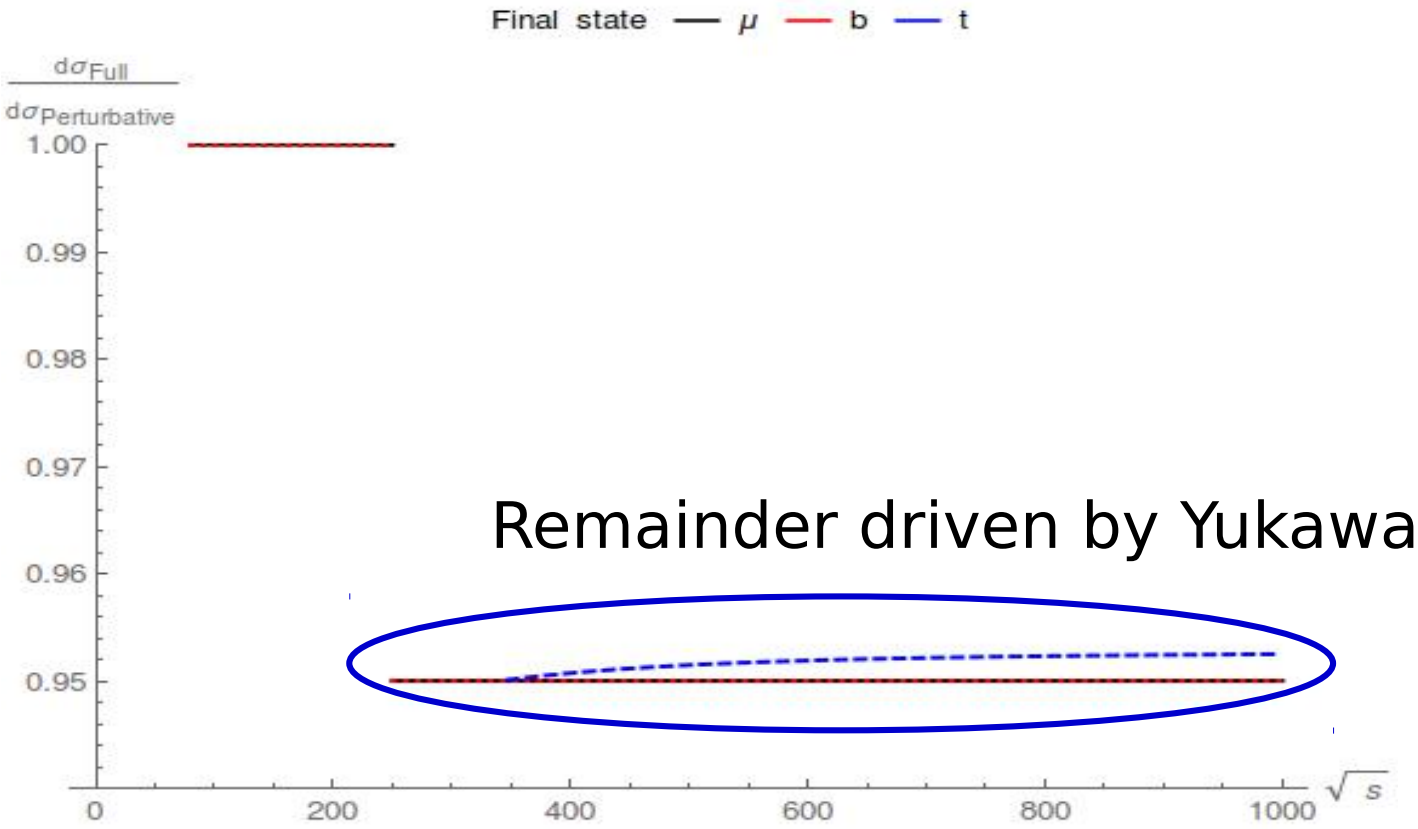

Remainder driven by Yukawa coupling

How events looks like (LEP/ILC)

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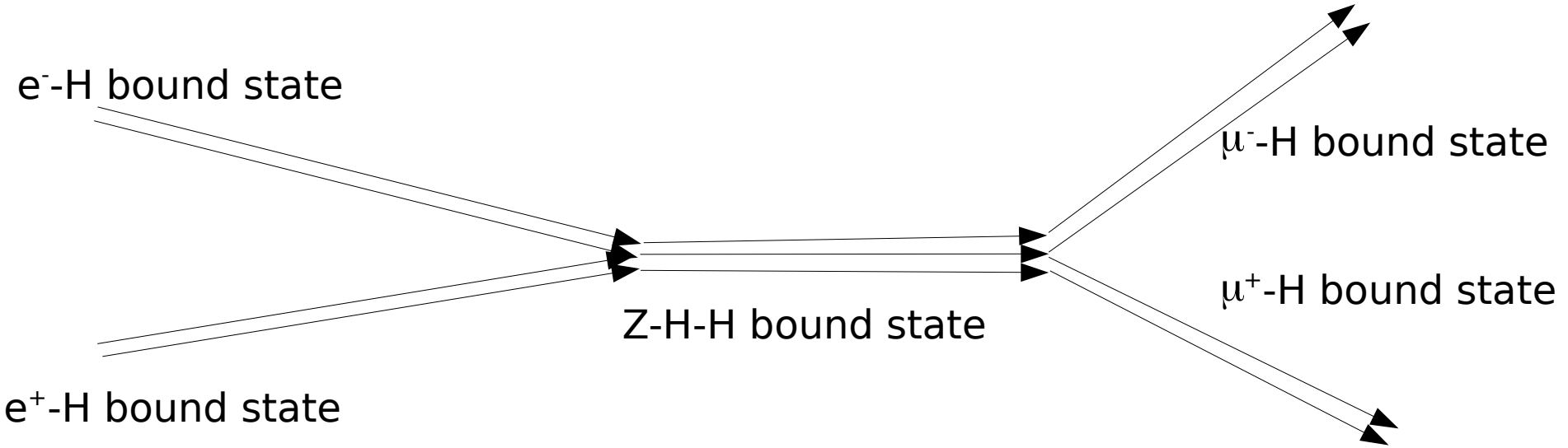

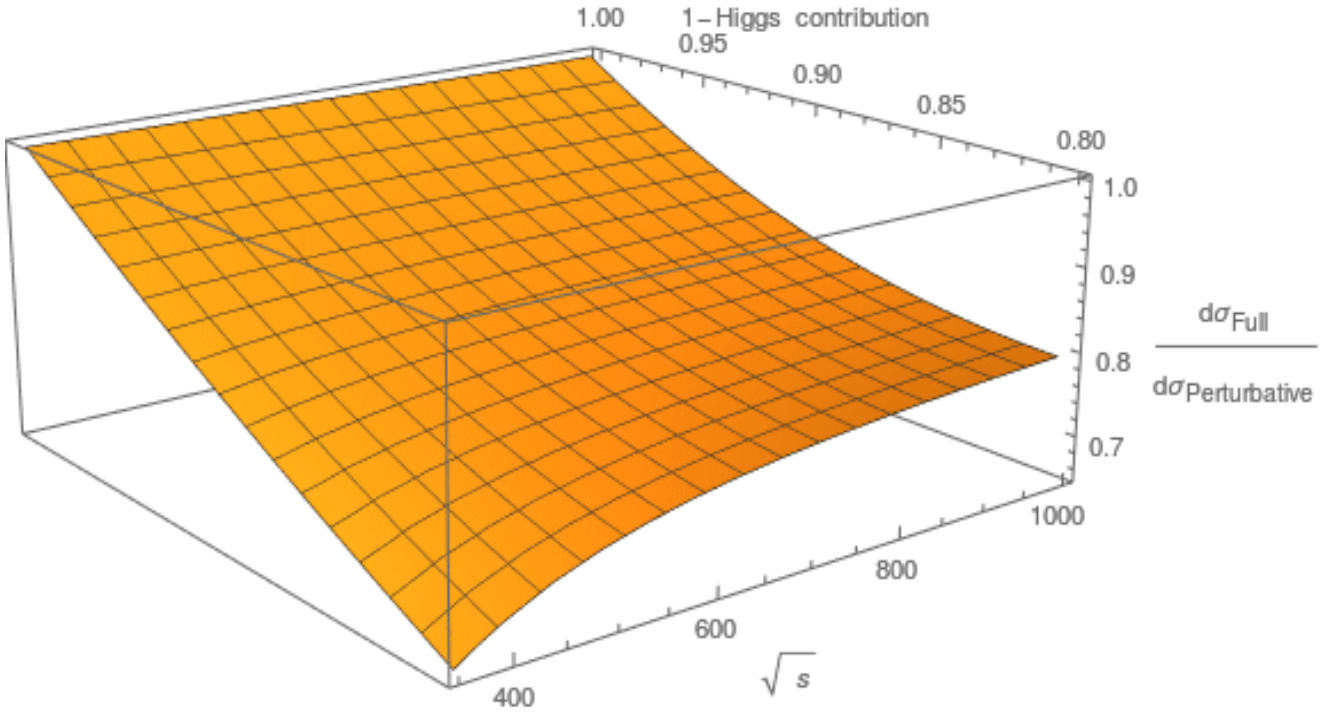

Top case:
Strong dependence on the amount of Higgs and energy

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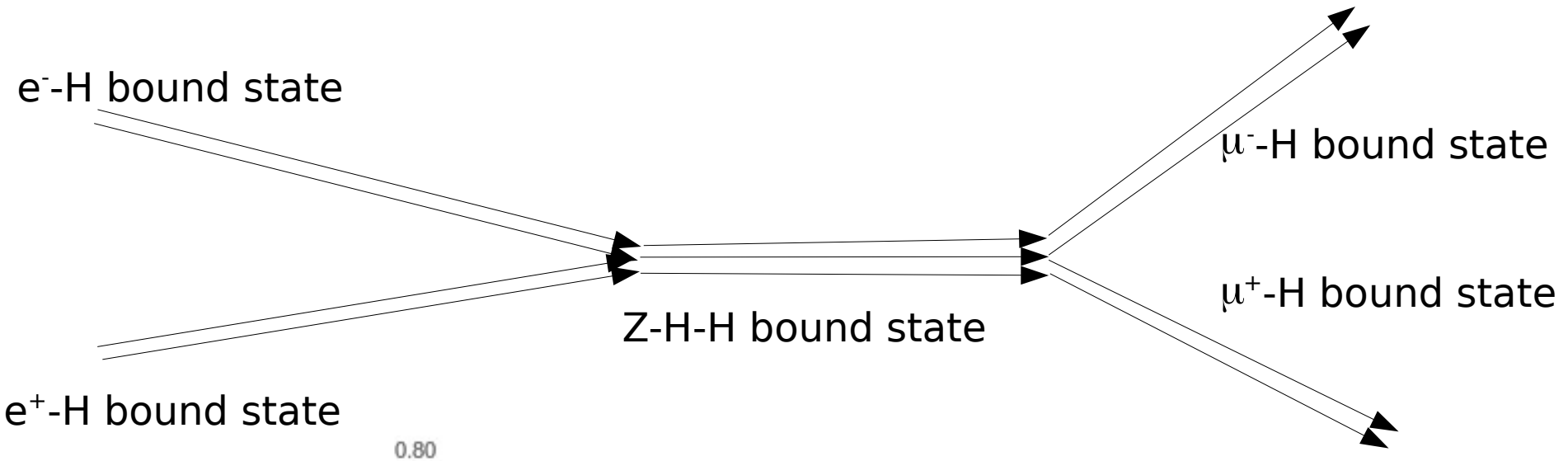

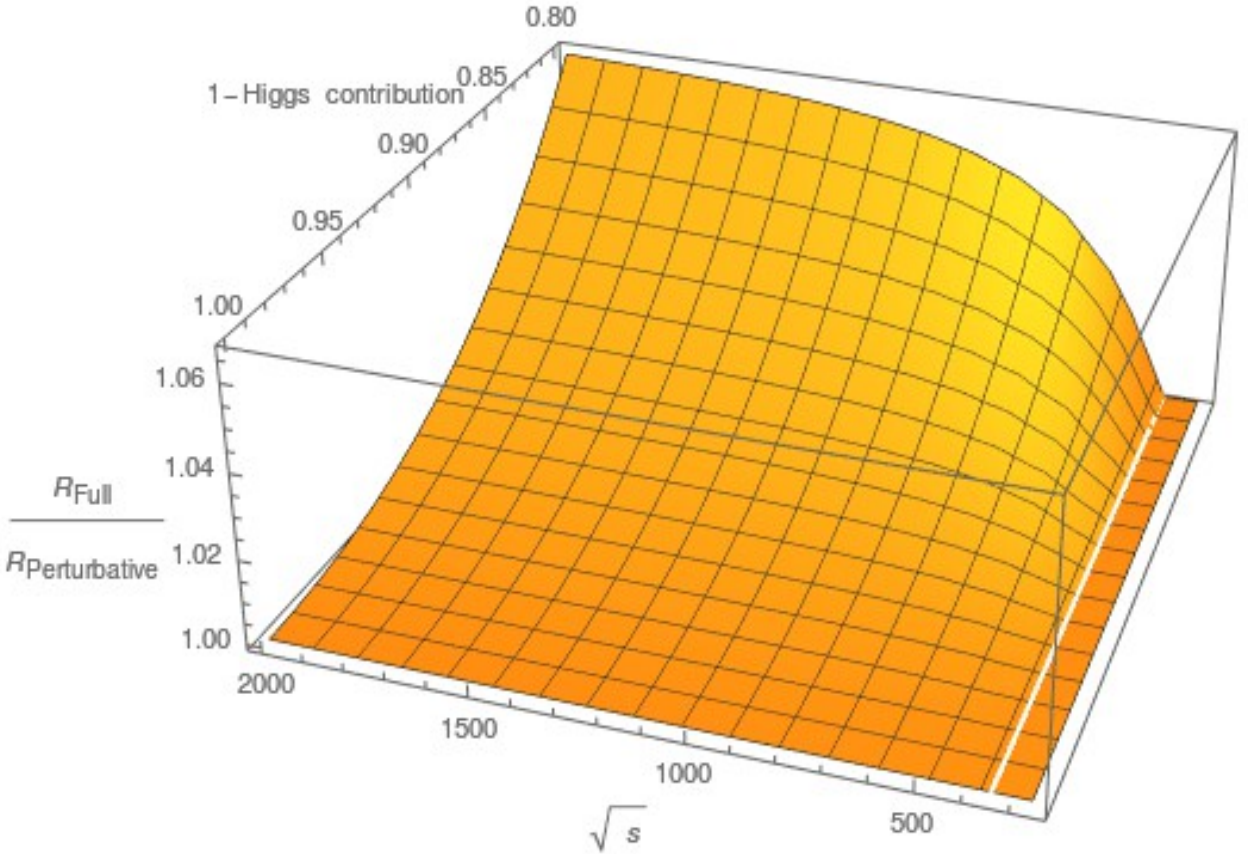

Not all quantities are equally influenced

How events looks like (LEP/ILC)

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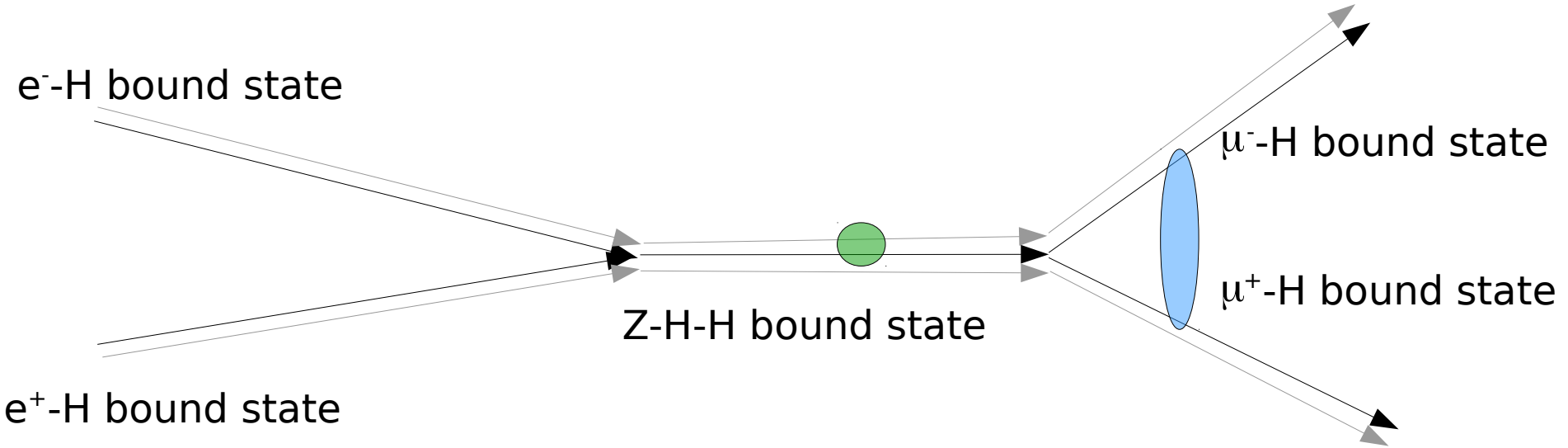

- Picture consistent with PDG

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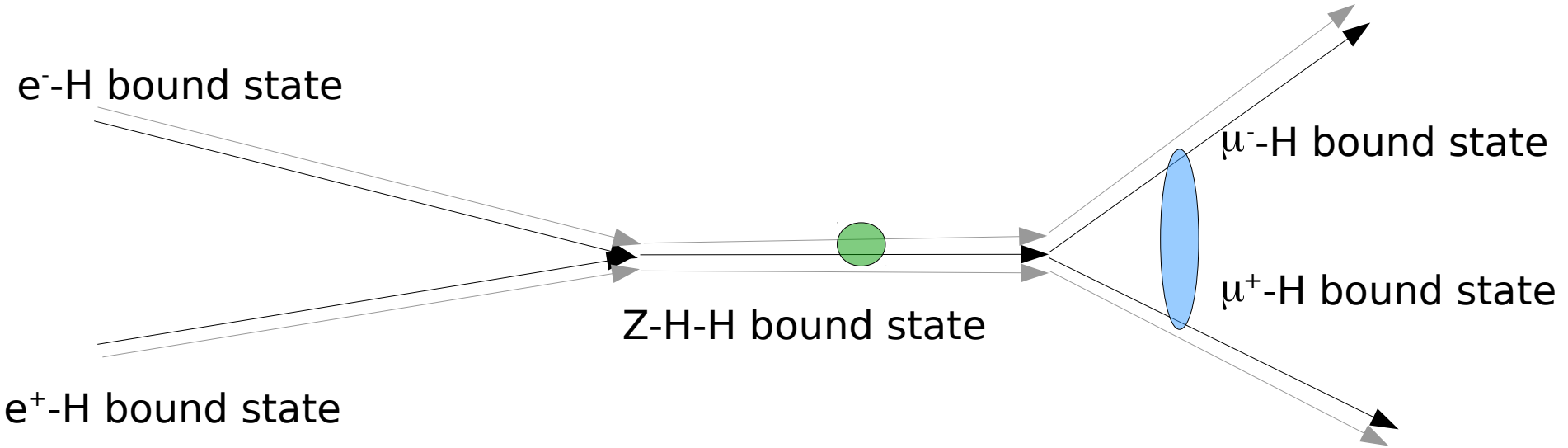

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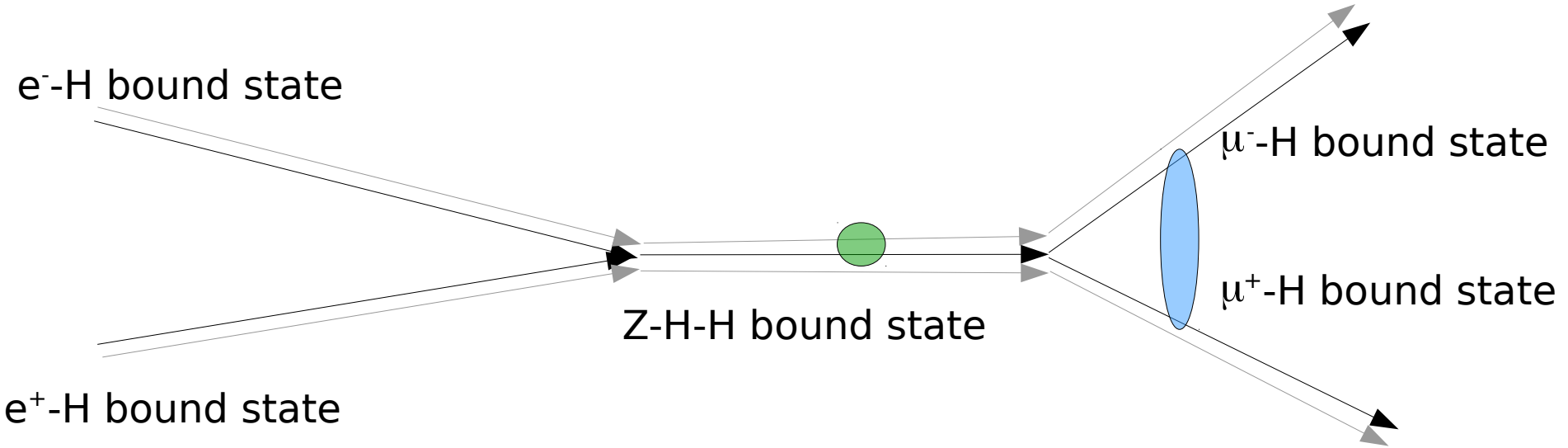

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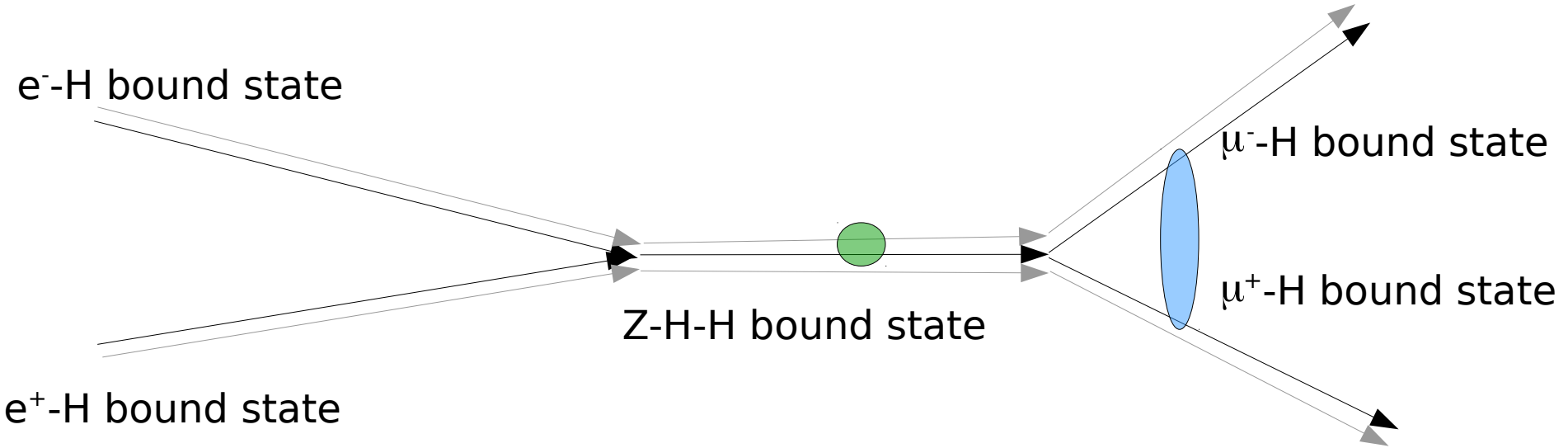

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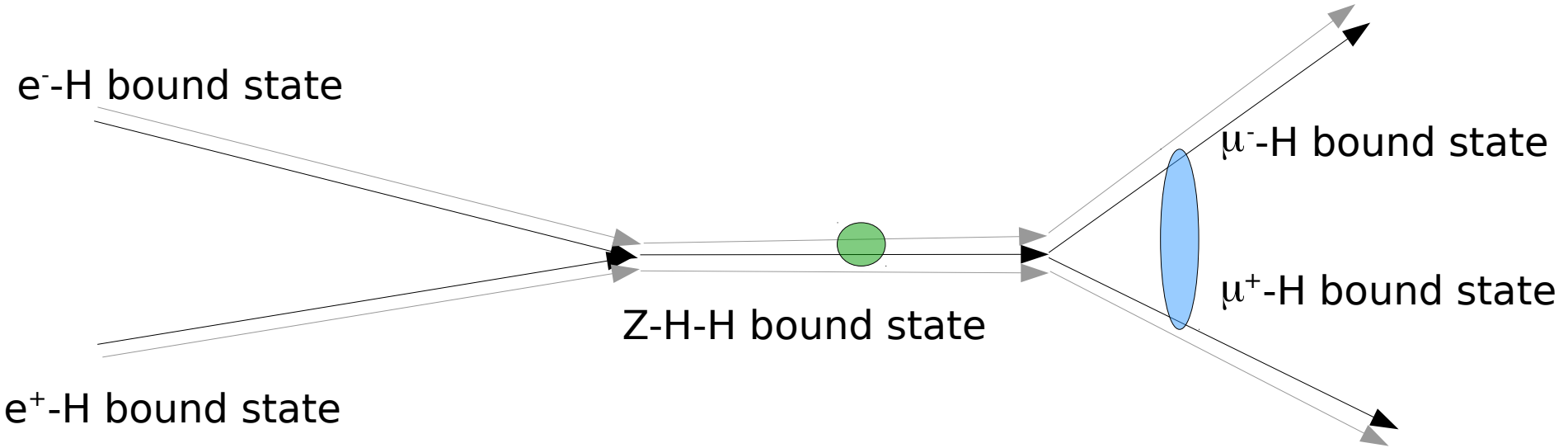

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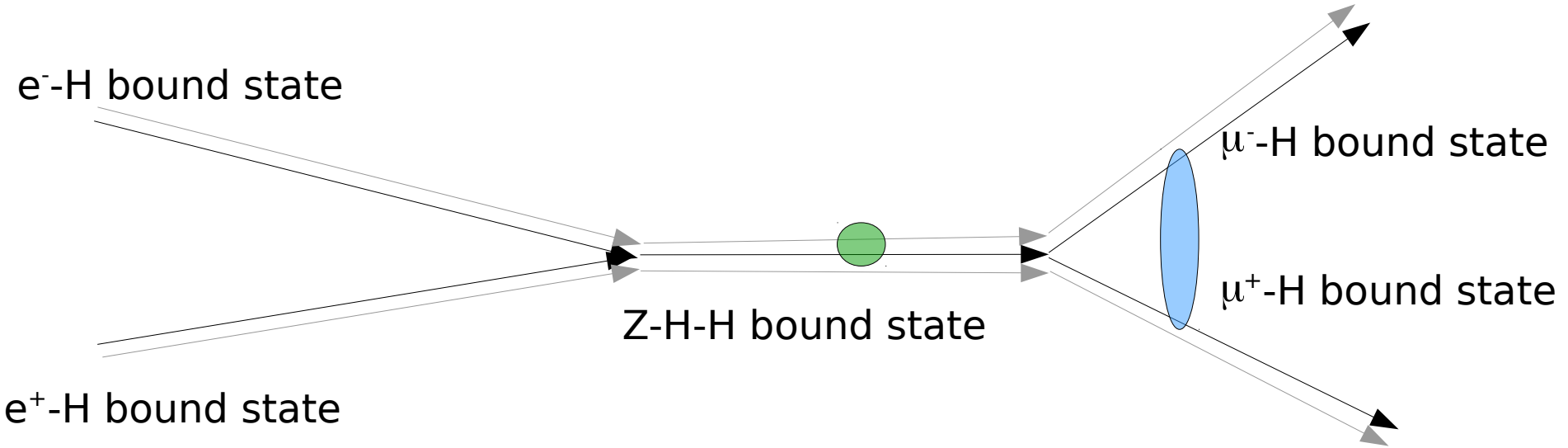

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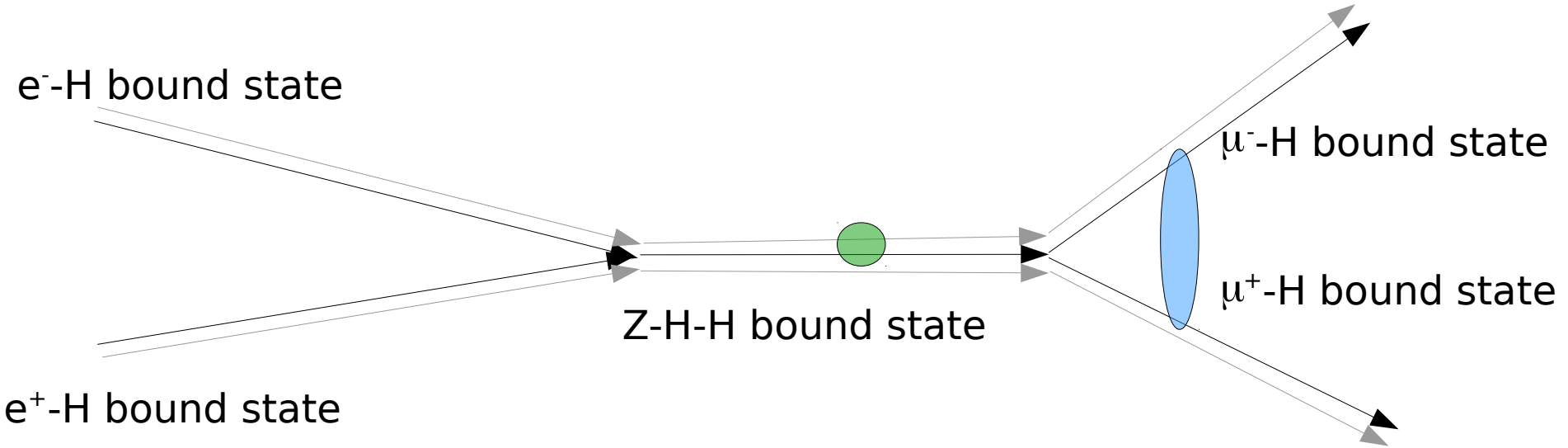

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- What about LHC? What about protons?

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

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- Straightforward for leptons
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  - Consider nucleon
  - qqq open flavor, cannot be gauge invariant
    - Impossible to build a gauge-invariant 3-quark state

Flavor of hadrons

[Egger, Maas, Sondenheimer'17]

- Flavor is replaced by custodial symmetry
- Straightforward for leptons
- Implications for hadrons?
- Open flavor must be replaced by custodial symmetry
- Requires Higgs component
  - Consider nucleon
  - qqq open flavor, cannot be gauge invariant
    - Impossible to build a gauge-invariant 3-quark state
  - Replacement: qqq**h**

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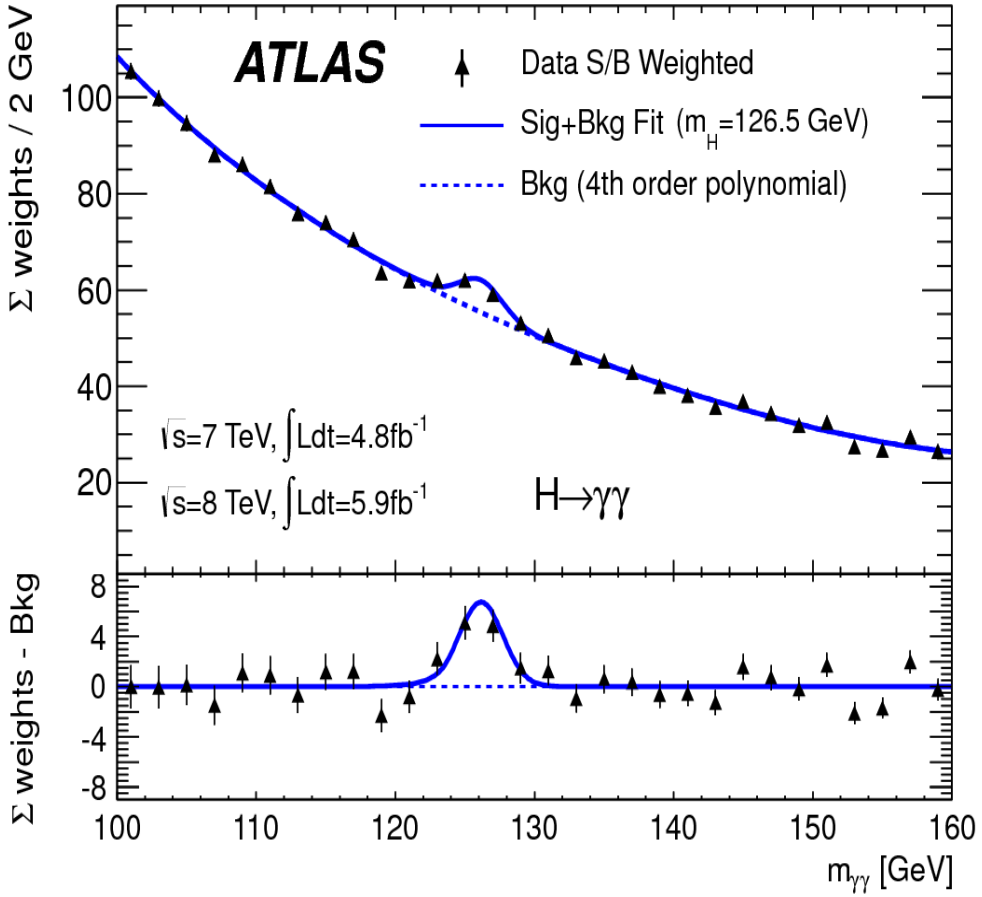
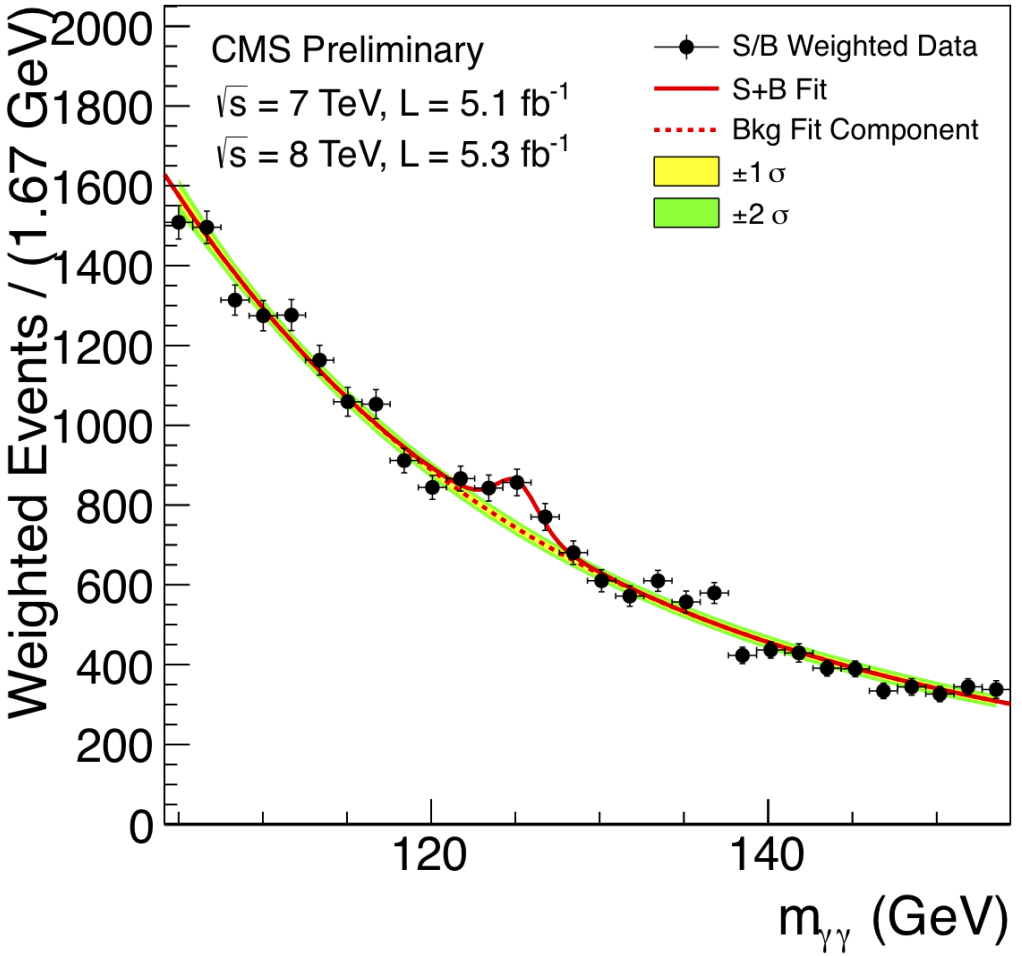
- Detectable at LHC? $pp \to \bar{t}tX$ using PDFs under investigation...

This is physical





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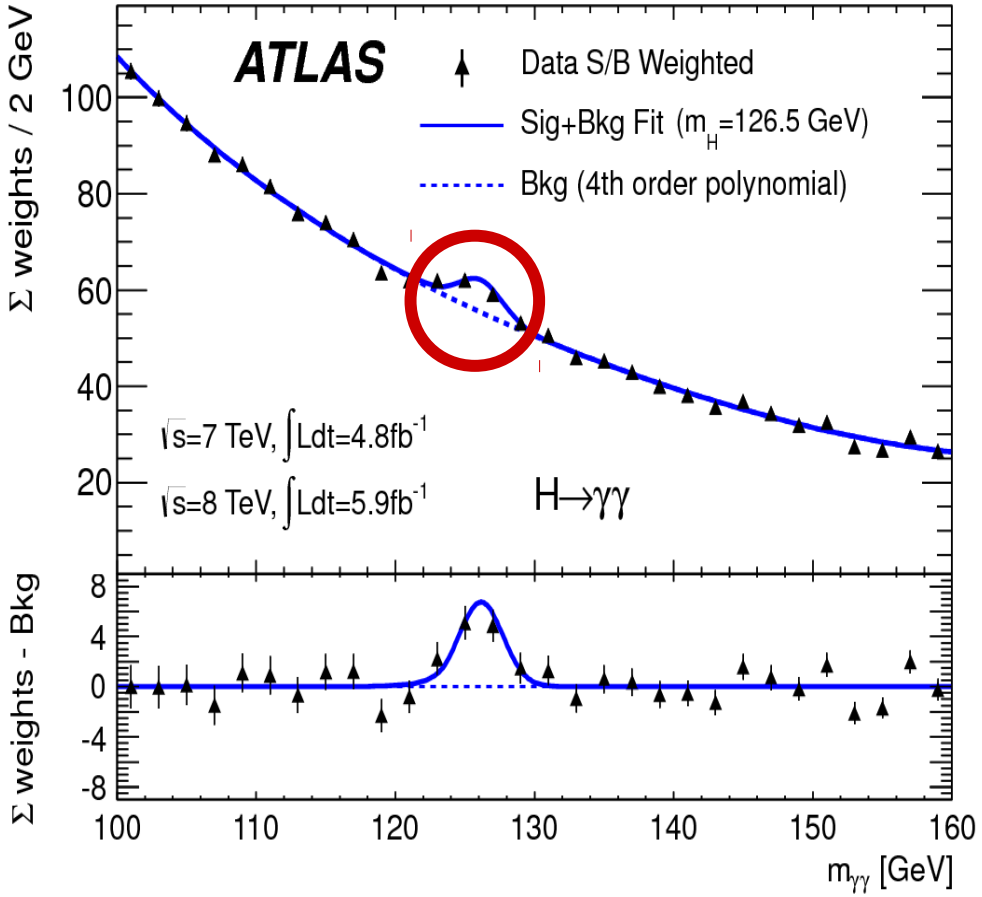

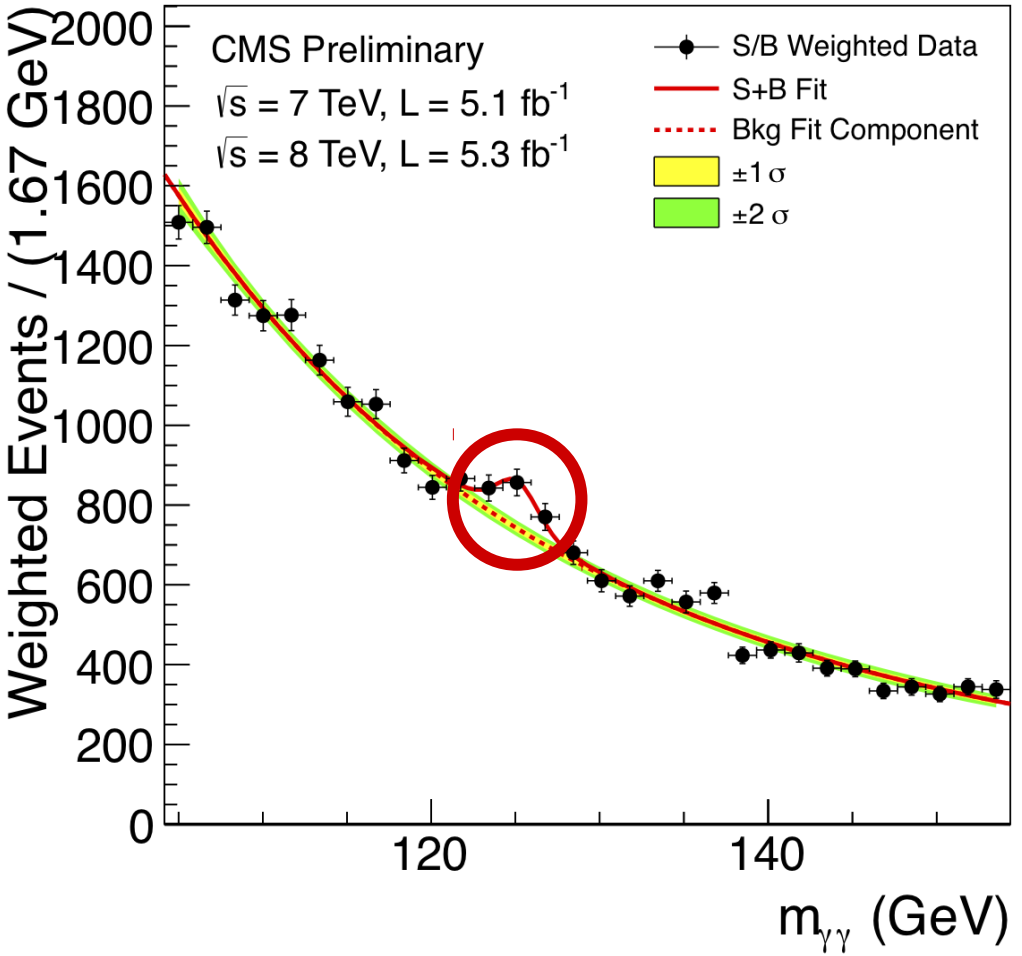

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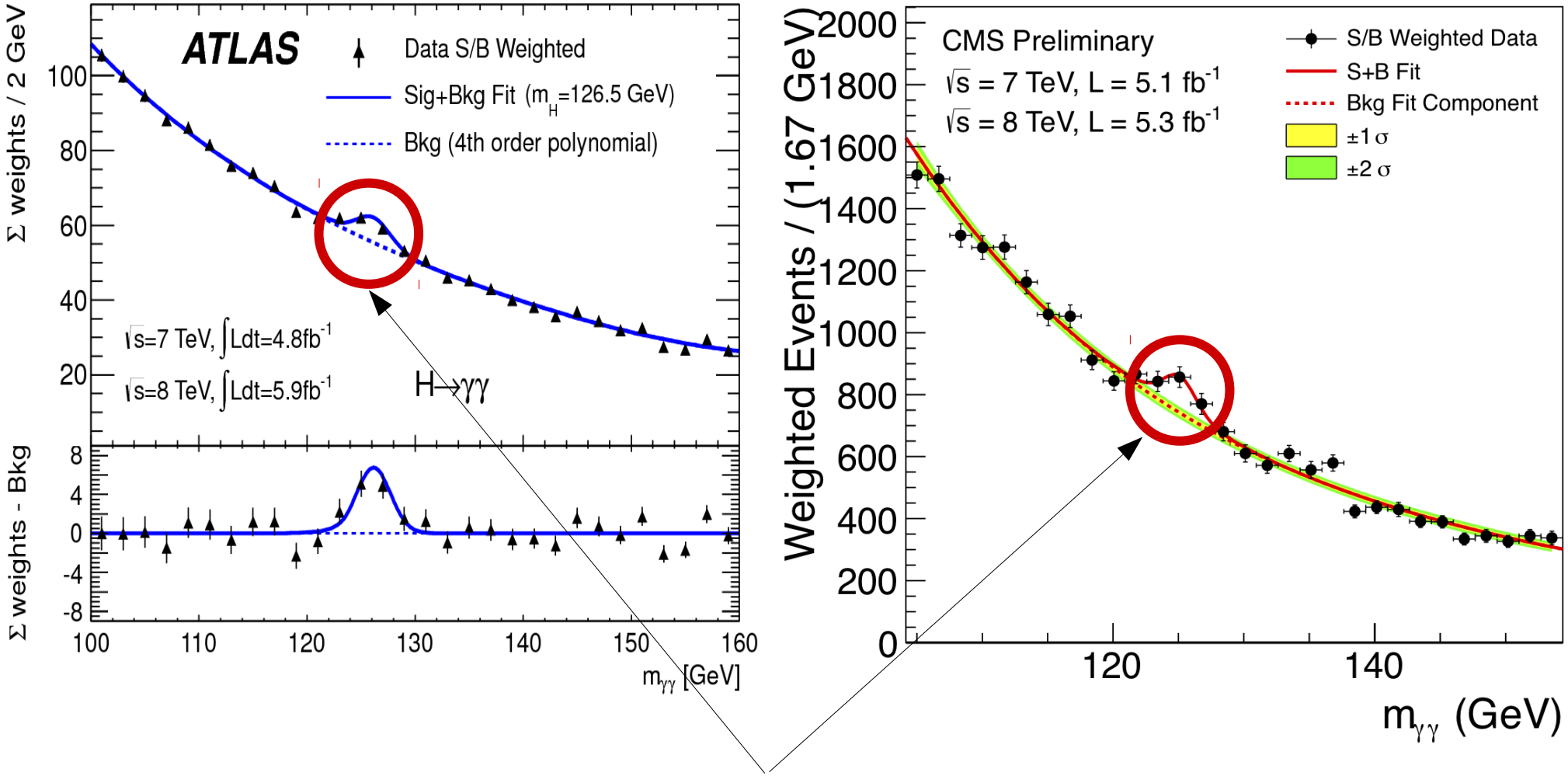

Bound state

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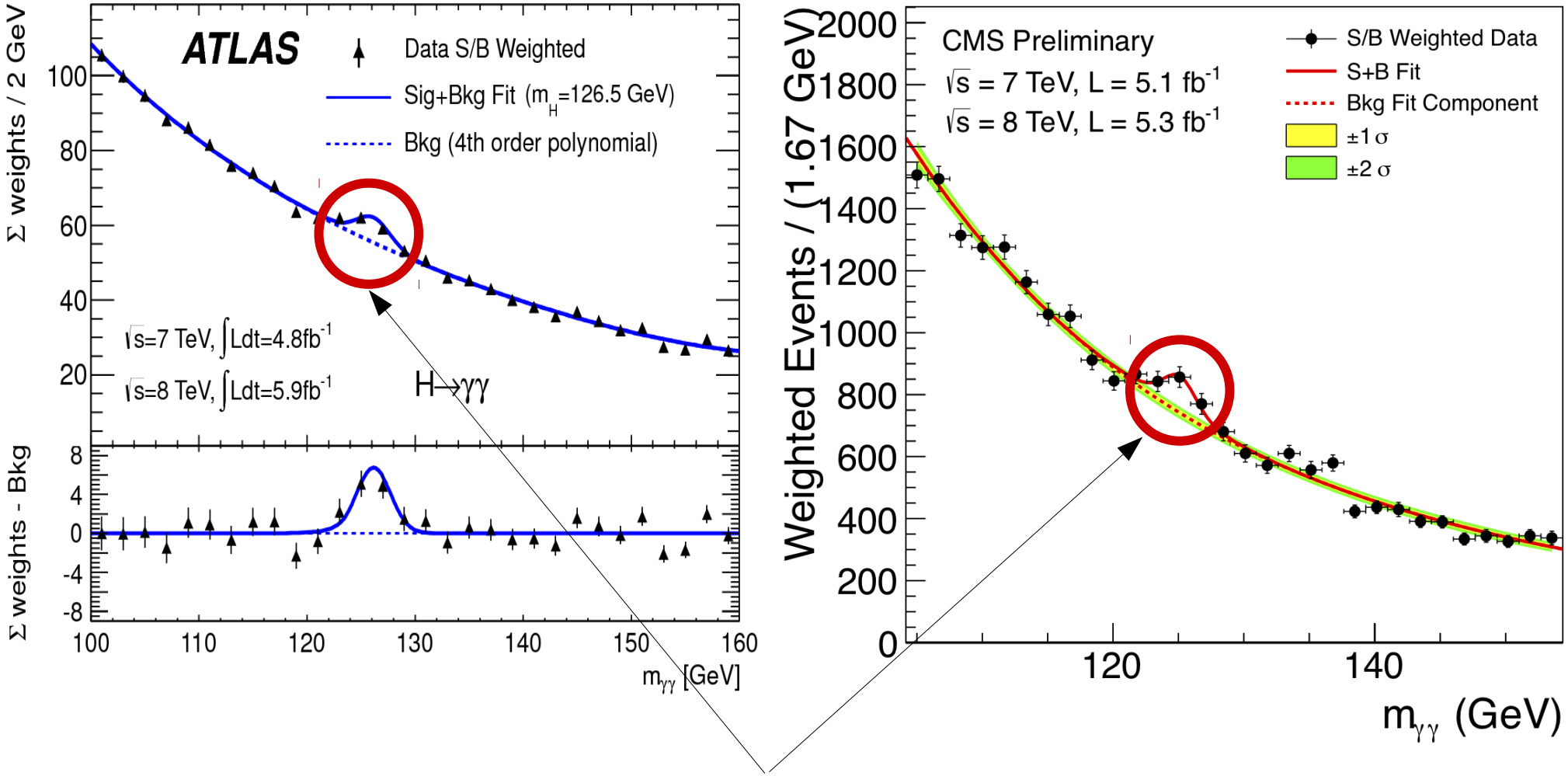

Bound state

Manifestly invariant under local symmetries

Classified by global symmetries

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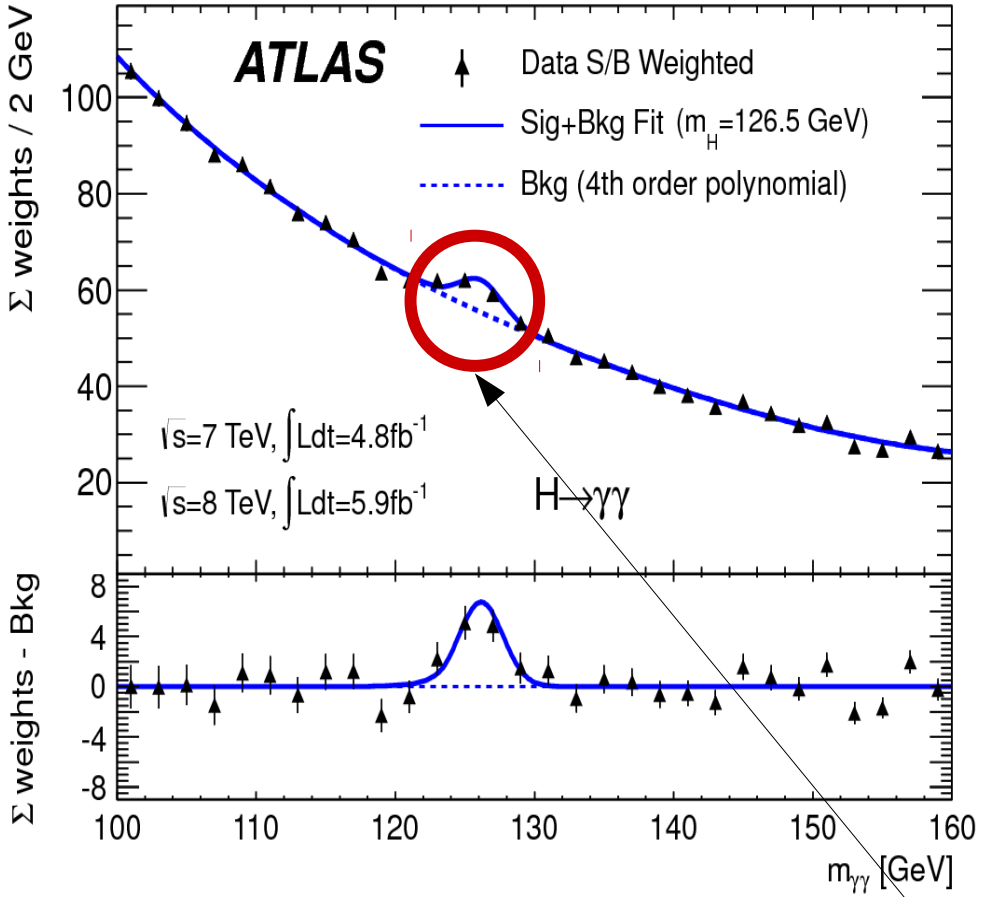

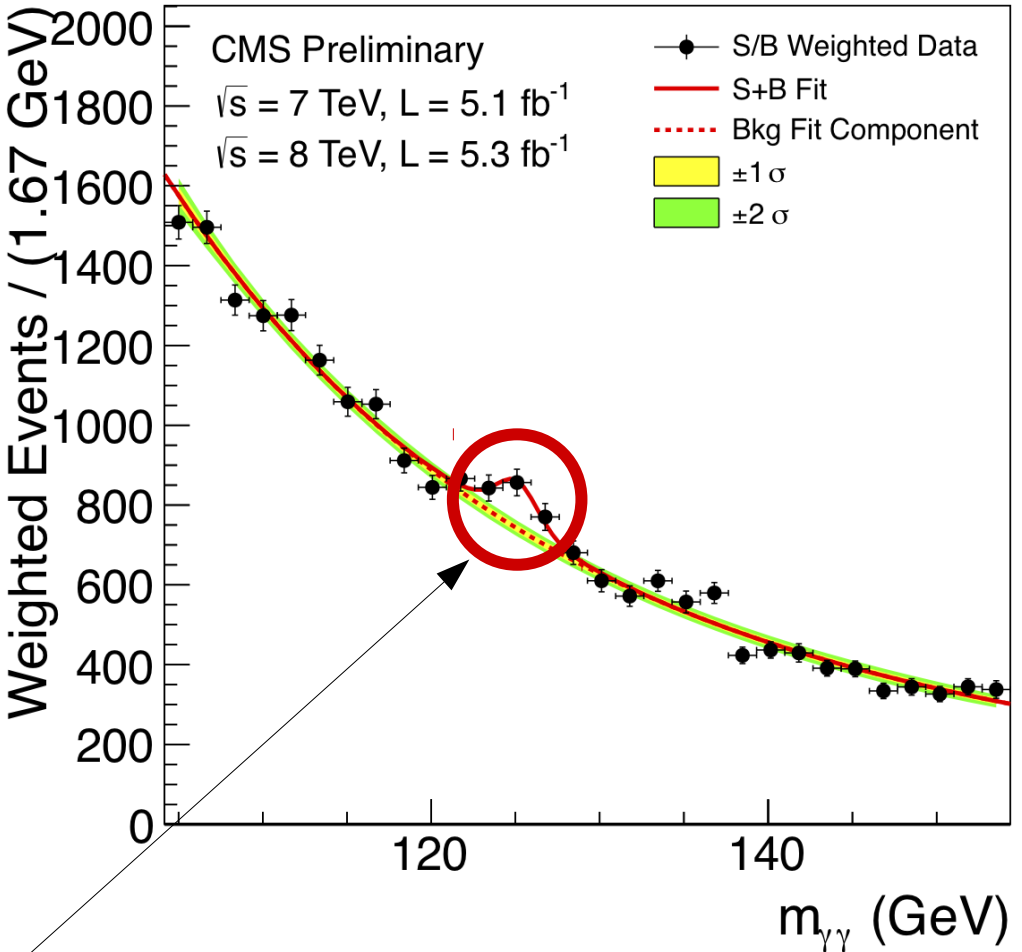

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Needs to be taken into account for BSM signals

Summary

- Physics determined by manifest gauge-invariant, composite objects

Review: 1712.04721

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- Yields unexpected patterns...but can be controlled analytically
- Interesting consequences for both new physics and standard model physics

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