Non-perturbative Brout-Englert-Higgs Physics

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Natural Sciences

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- Investigations on the lattice
  - Group theory
  - Symmetry “breaking” on the lattice

Overview

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  - Observables, phase structure,...

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- Review article upcoming
- O'Raifeartaigh: Group structure of gauge theories

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- Are there (relevant) non-perturbative effects in the weak interactions and the Higgs?
  - How could there be not?

A precursor:
Global symmetry breaking revisited

A path integral perspective

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  - Does not depend on the parameters: Always
  - Symmetry is always manifest

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  the theory experiences SSB
  - Goldstone’s theorem only at $j\to 0$, not at 0

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  - Theory is part of a system
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- No other possibilities

Metastability

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  - No Goldstone bosons, full degeneracy pattern

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    - Measures relative orientation, but invariant
    - Note: $\left\langle \varphi^2 \right\rangle$ does not work

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- A split like $\varphi \rightarrow \psi + \nu$ does not break a symmetry
  - Only hides it
  - Symmetry is realized in a non-trivial way

The Higgs sector of the standard model

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$$L = -\frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu}$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g f^a_{bc} W^b_\mu W^c_\nu$$

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- Coupling g and some numbers f^{abc}

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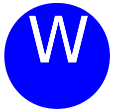
- Ws W_{μ}^{a} 

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

Symmetries

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- Local SU(2) gauge symmetry

$$W_{\mu}^{a}\rightarrow W_{\mu}^{a}+\left(\delta_{b}^{a}\partial_{\mu}-g f_{bc}^{a}W_{\mu}^{c}\right)\phi^{b} \qquad h_{i}\rightarrow h_{i}+g\, t_{a}^{ij}\phi^{a}h_{j}$$

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

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

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$$X = \begin{pmatrix} h_{1} & -h_{2}^{+} \\ h_{2} & h_{1}^{+} \end{pmatrix} \Rightarrow X' = G_{gauge} X G_{custodial}$$

Classical analysis

[Bohm et al. 2001]

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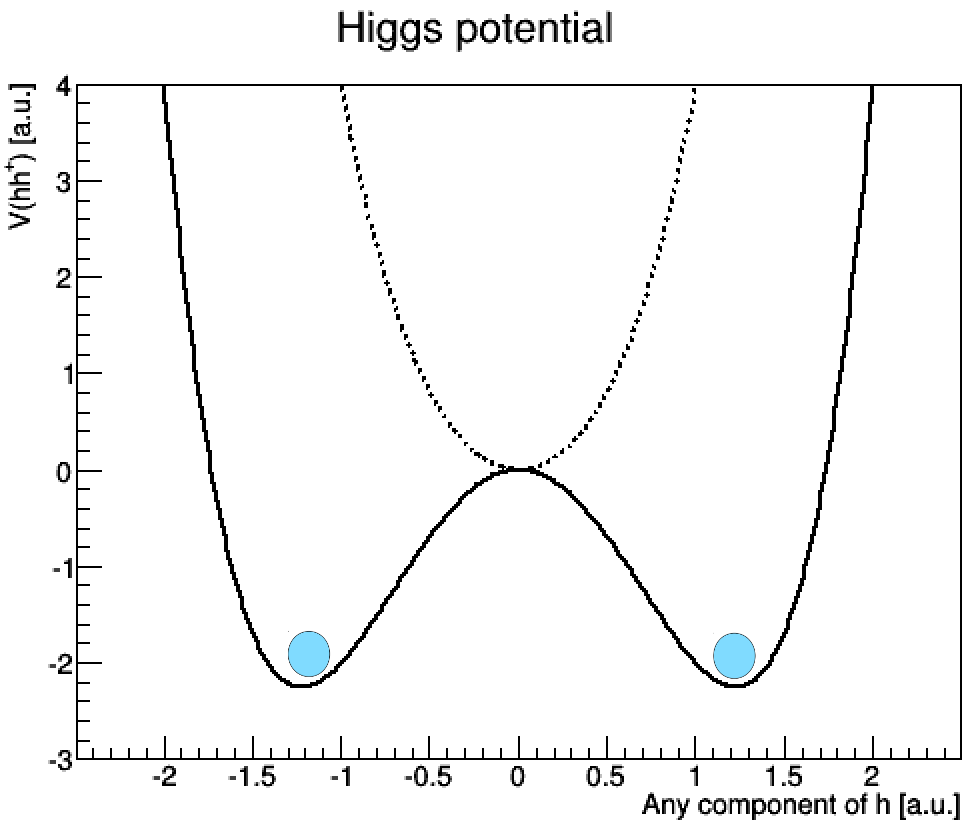

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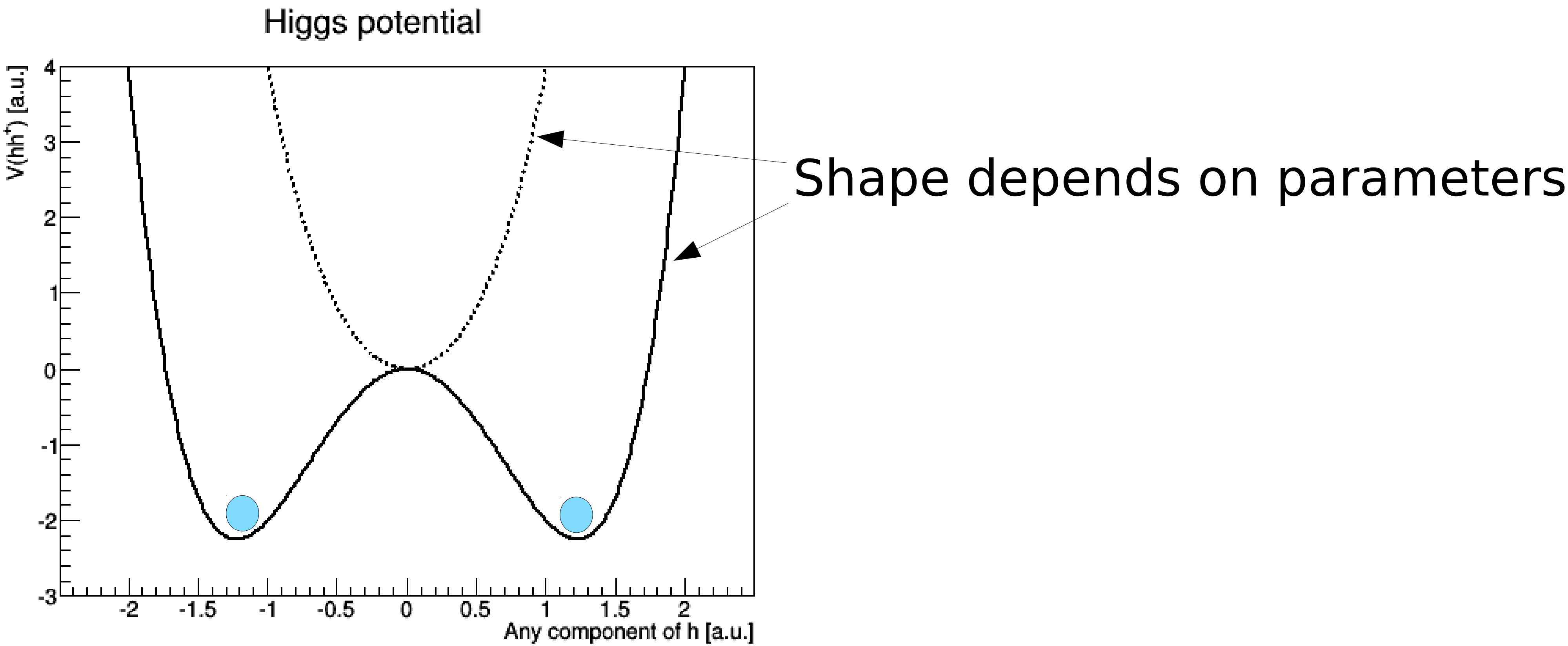

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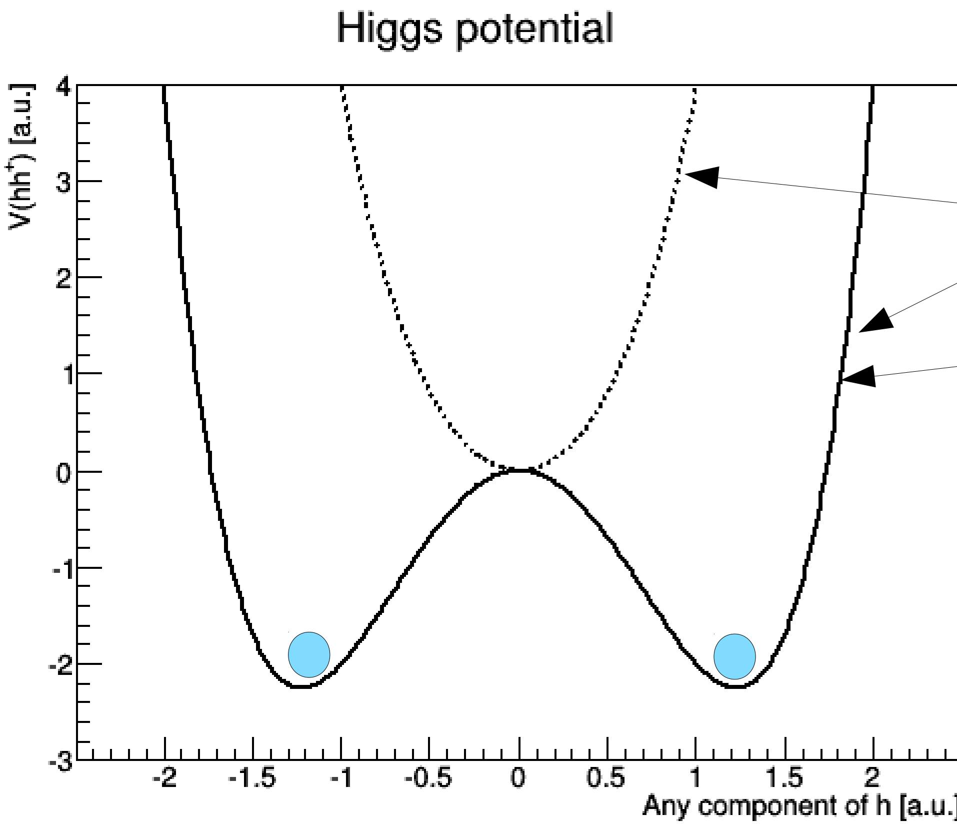

Shape depends on parameters

Experiments decides
- Higgs mass is tachyonic

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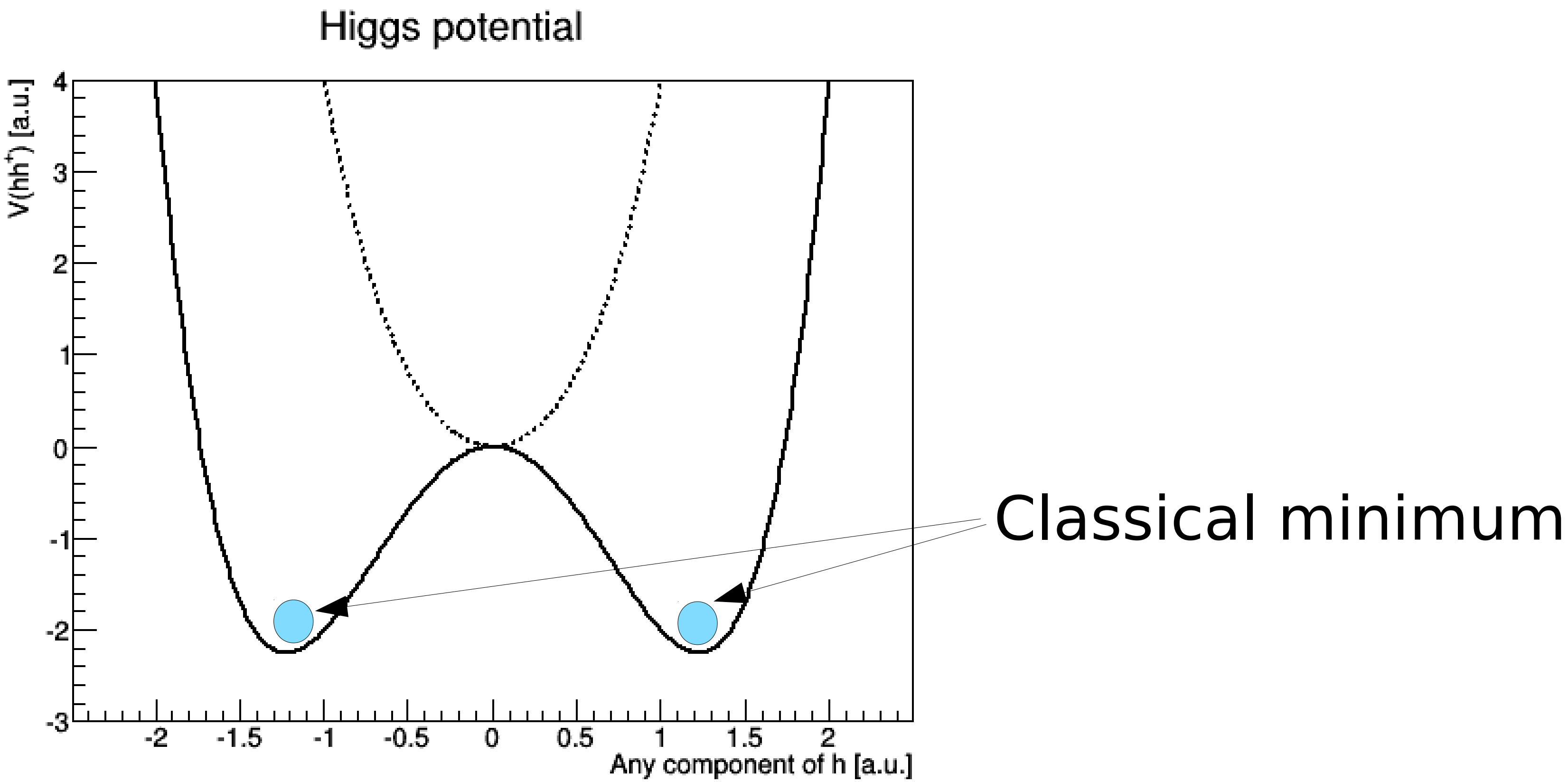

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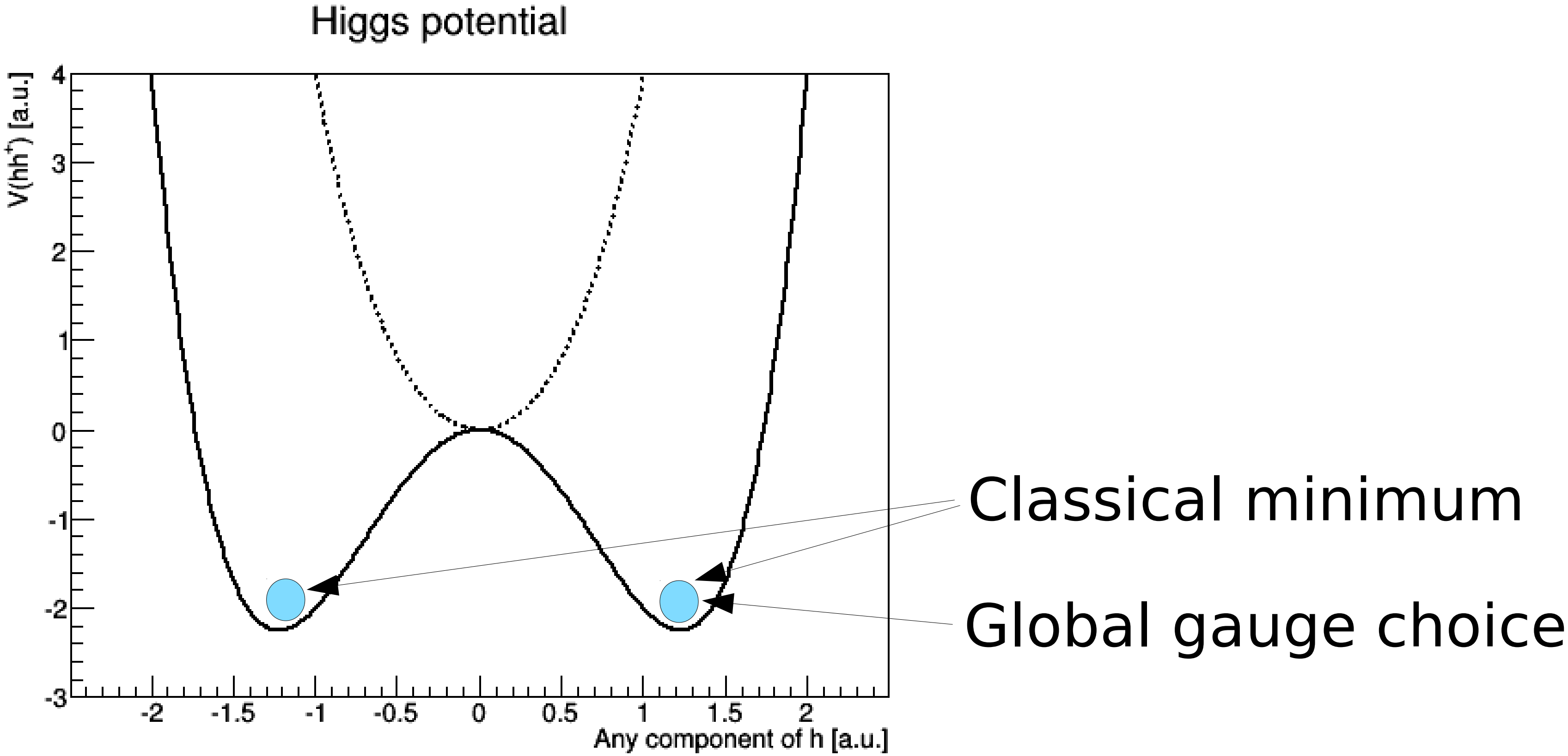

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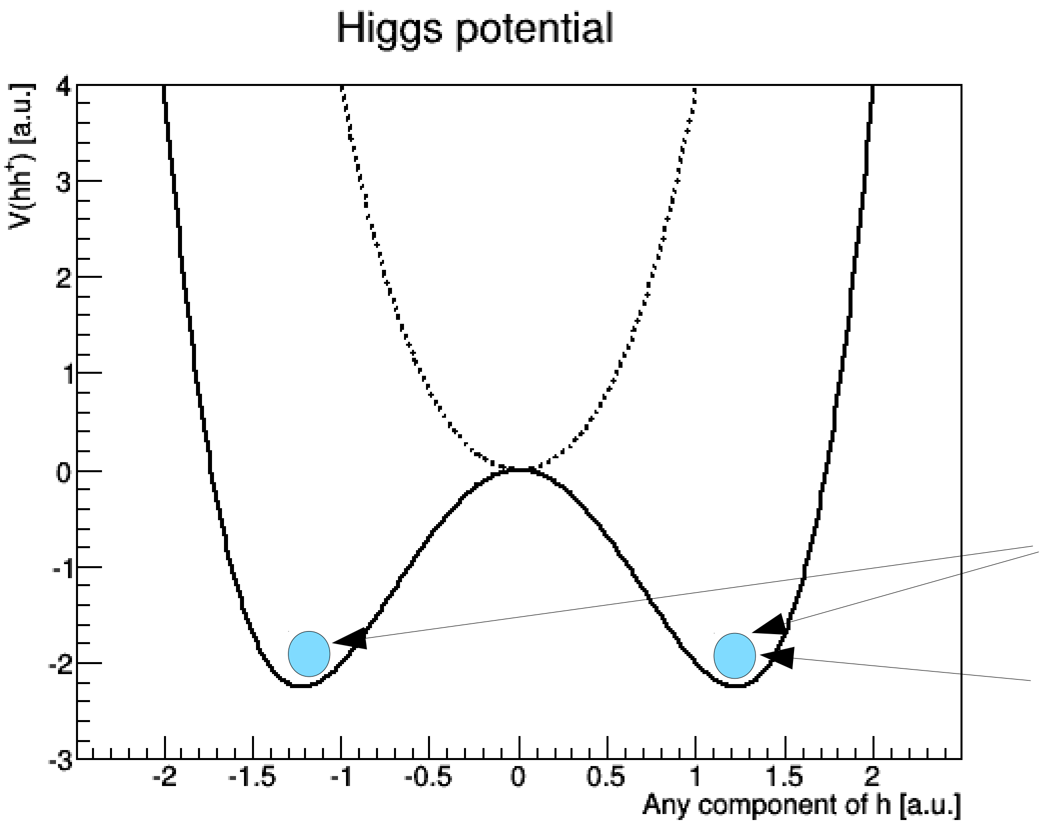
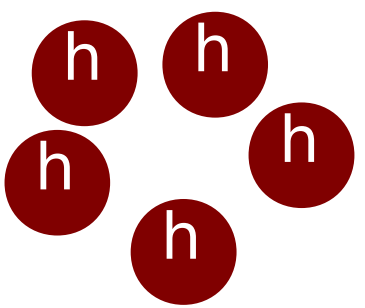


Classical minimum

Global gauge choice



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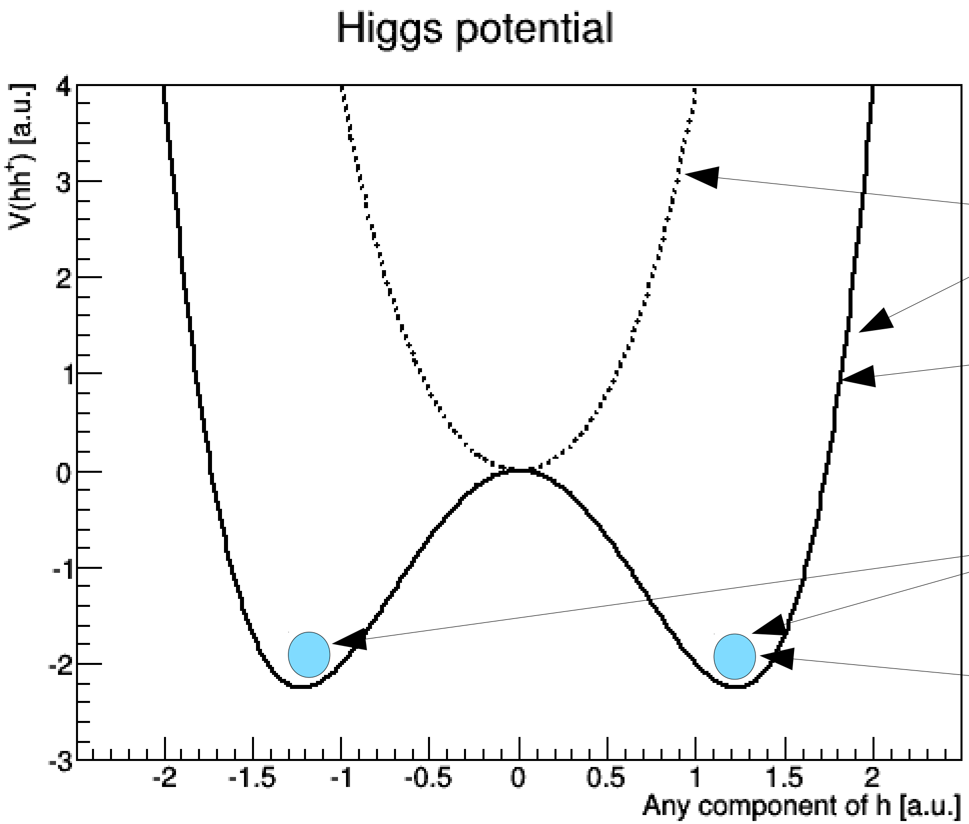

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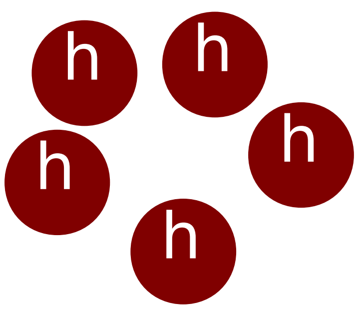

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- Perform perturbative expansion around the classical vacuum

Standard approach

[Bohm et al. 2001]

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  - Yields $hh^{+} = v^{2}$ - Higgs vev

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  - Perform perturbation theory

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  - Otherwise W/Z massless to all orders

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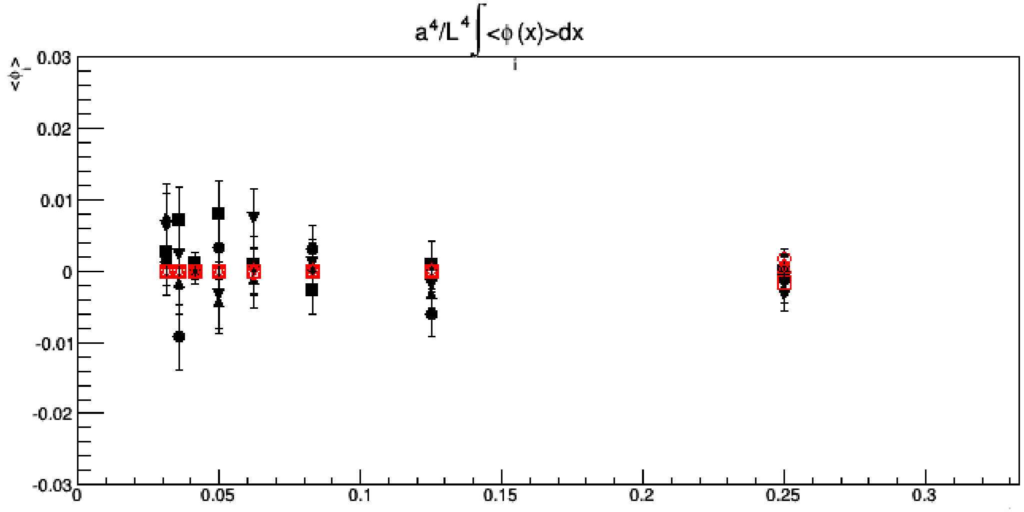

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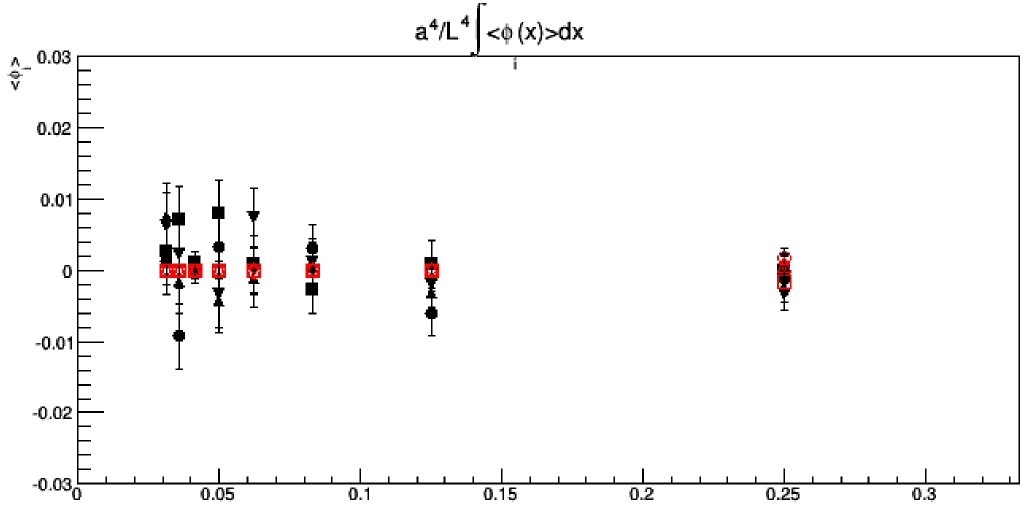
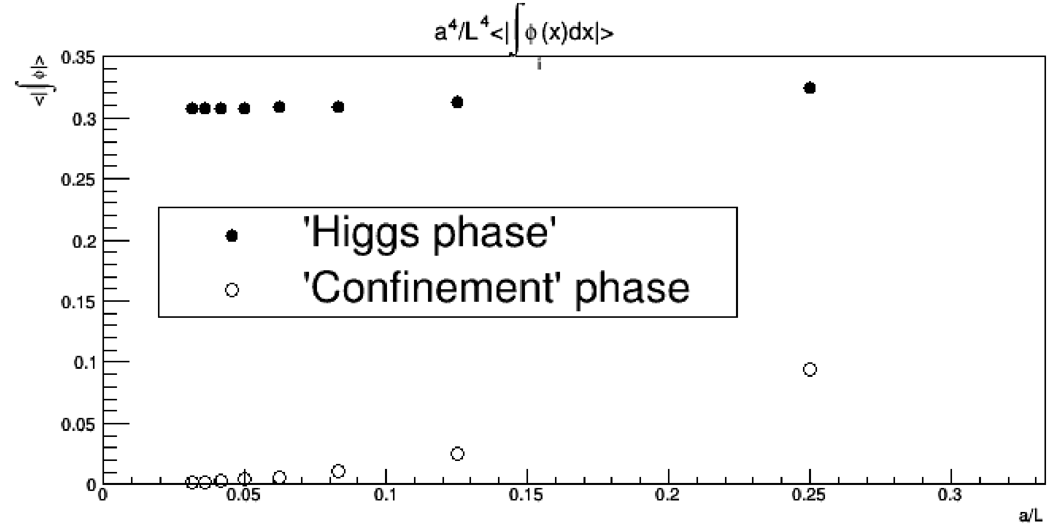
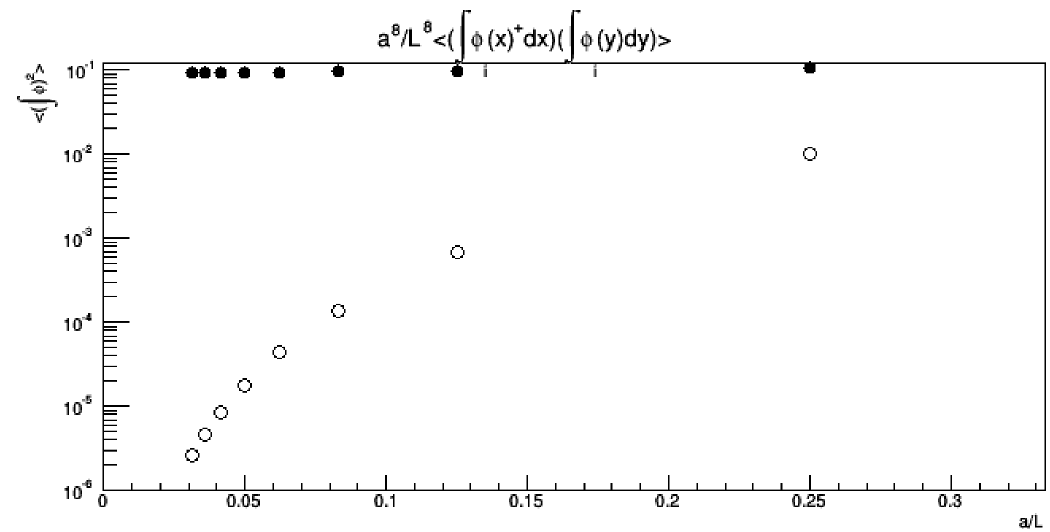
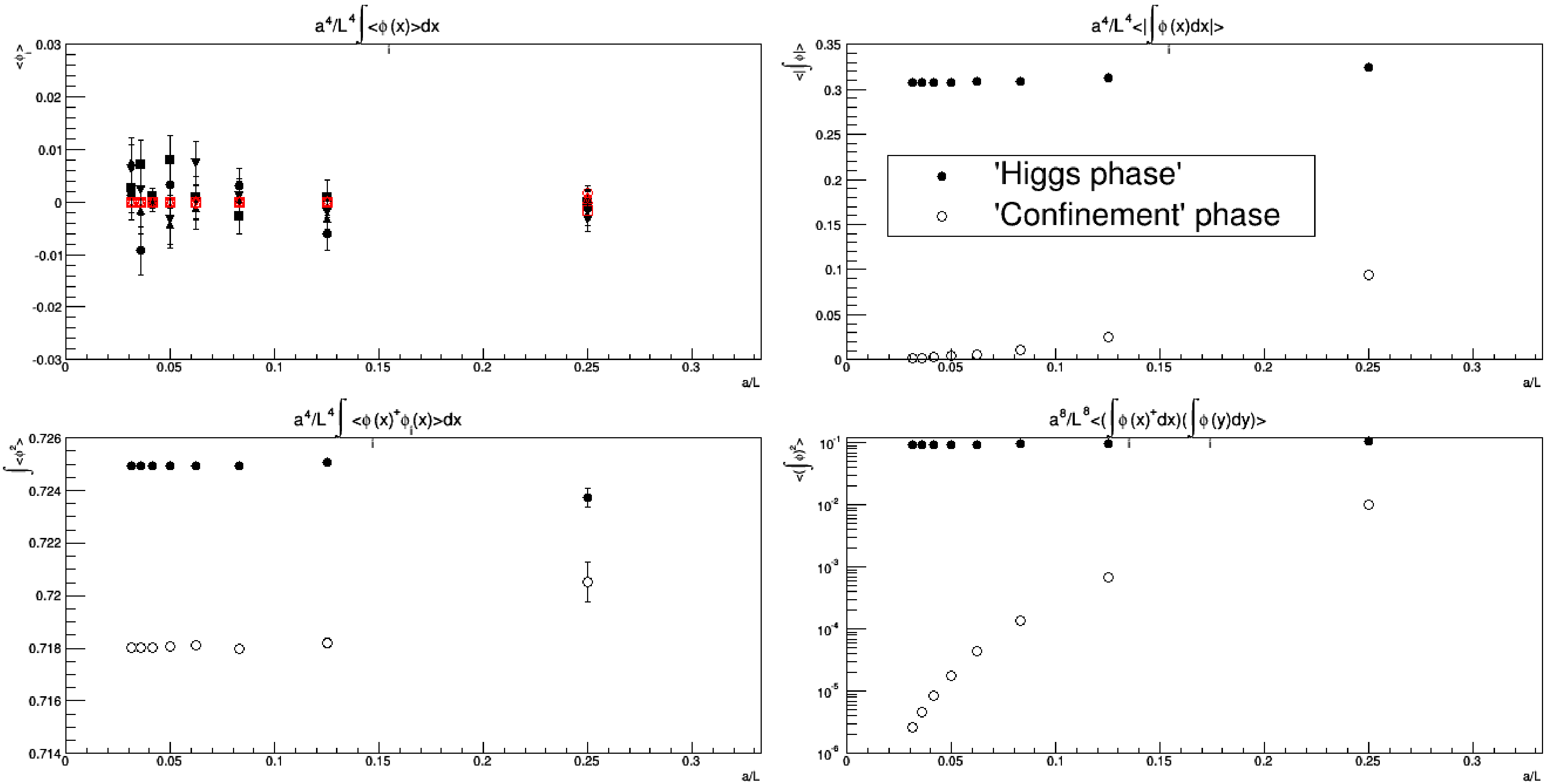






- Possible to have gauges without vev [Maas'13]
    - Do not select a global direction

Alternative gauges



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The physics of the Higgs sector

a: The phase diagram

Lines of constant physics

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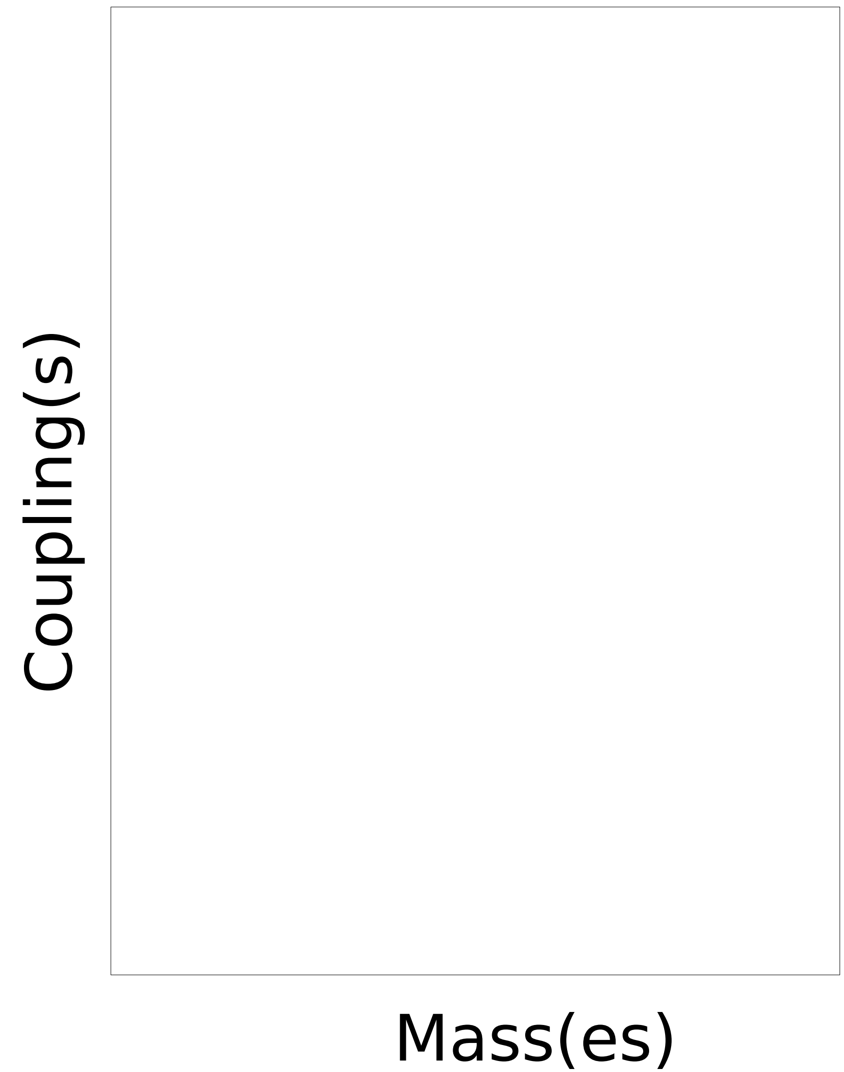

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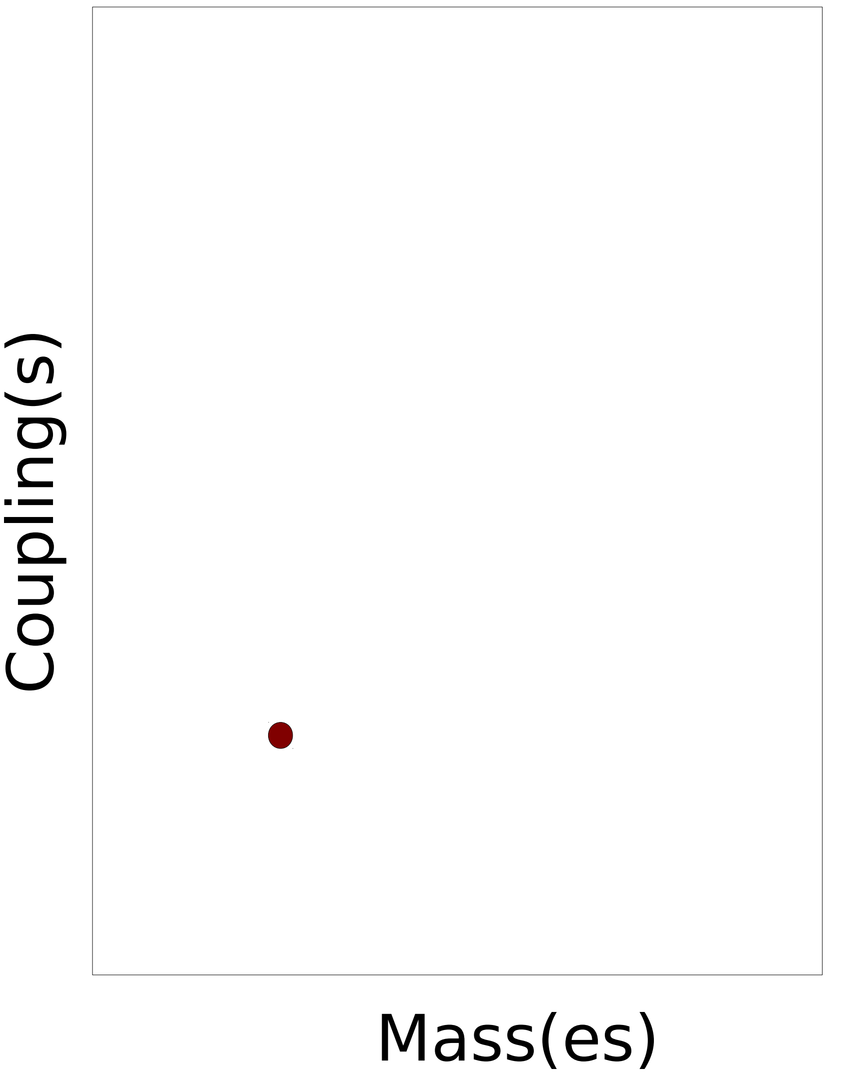

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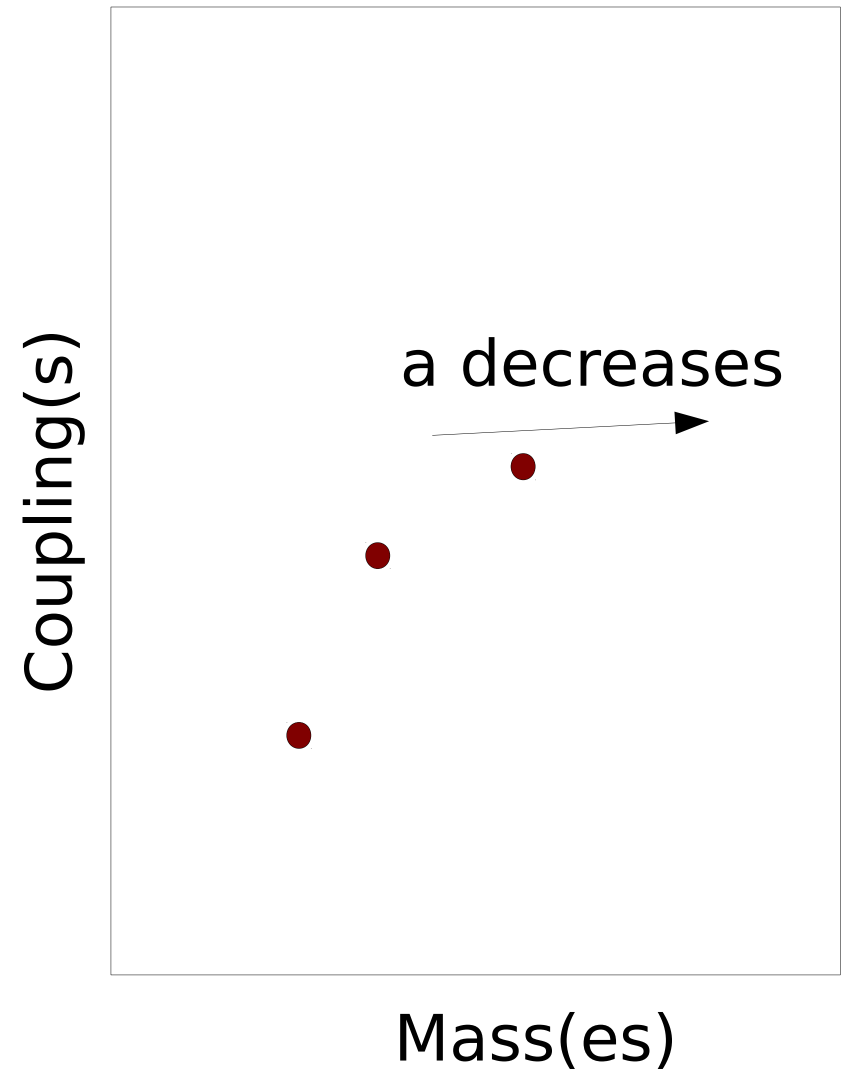

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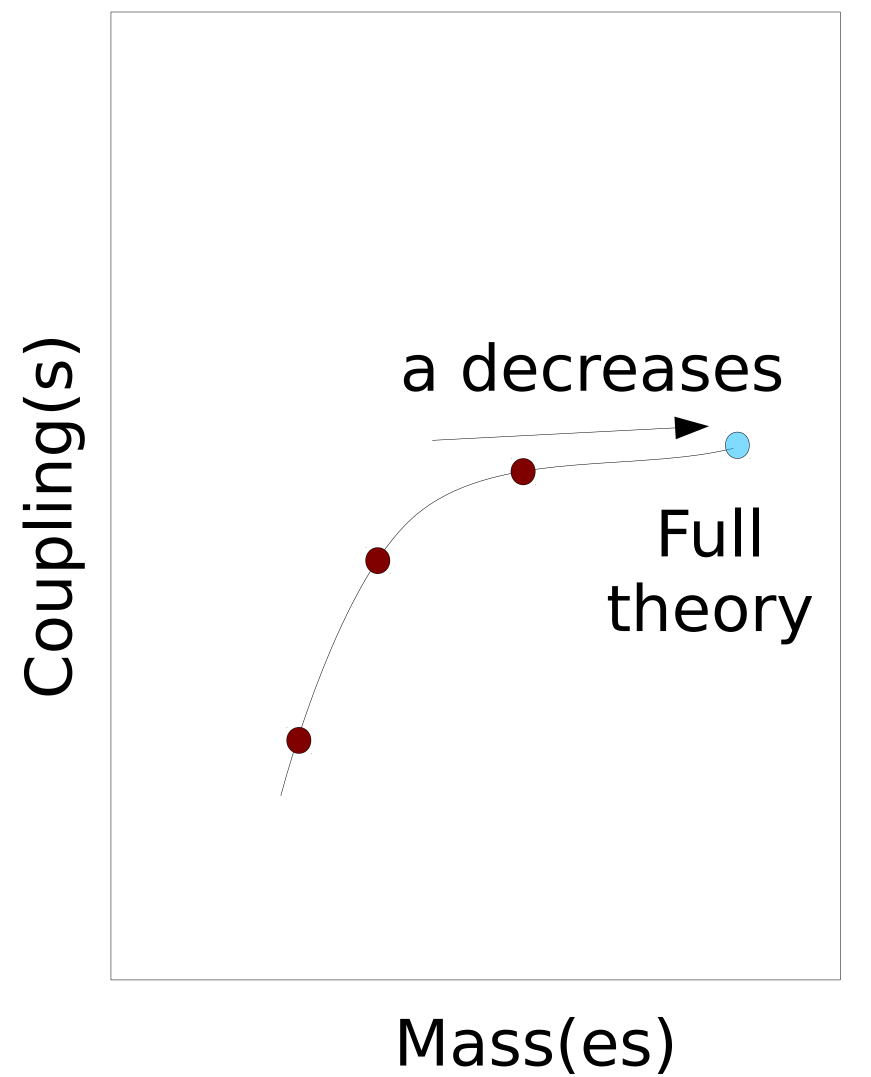

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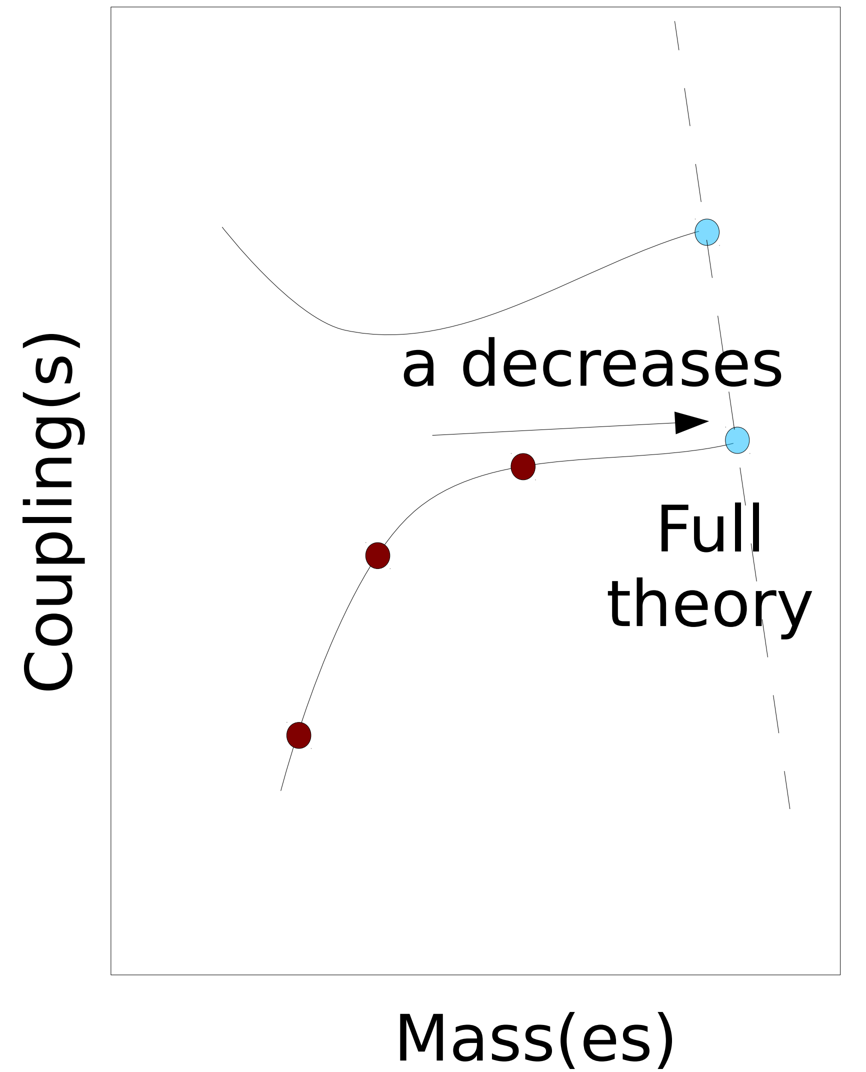
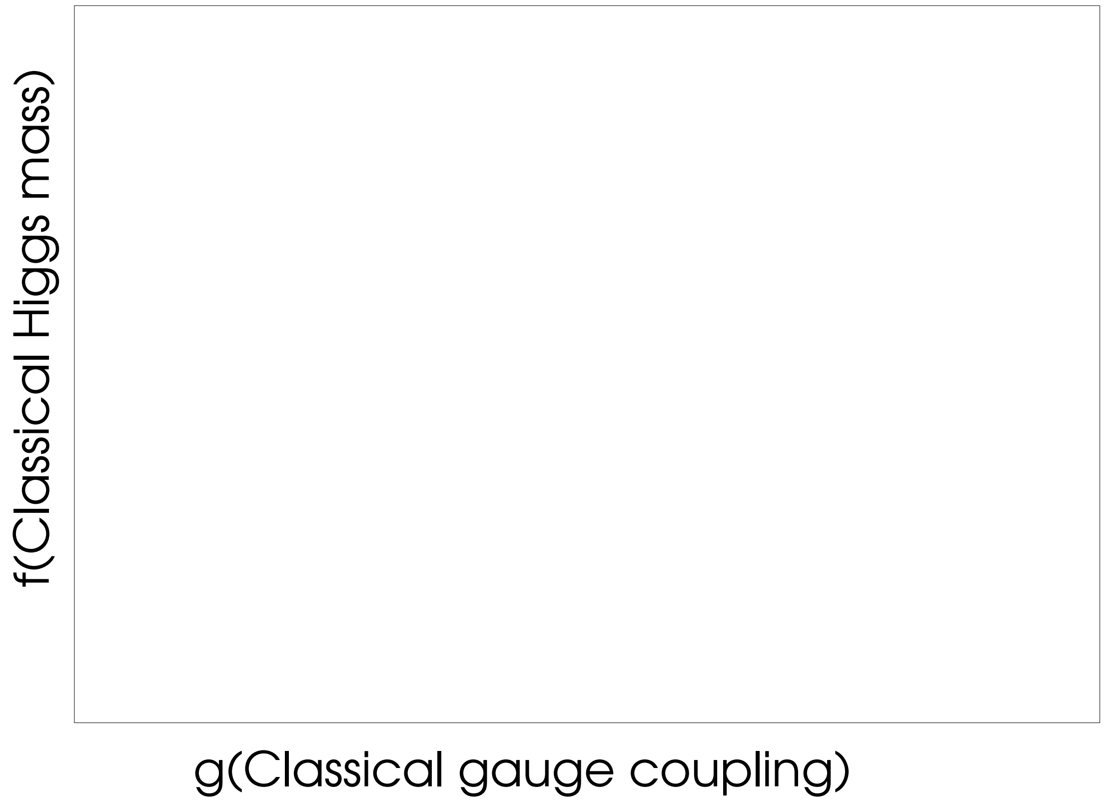
  - Different starting points yield different physics



Phase diagram

[Osterwalder et al.'78, Fradkin et al.'79
Caudy et al.'07]

- (Lattice-regularized) phase diagram



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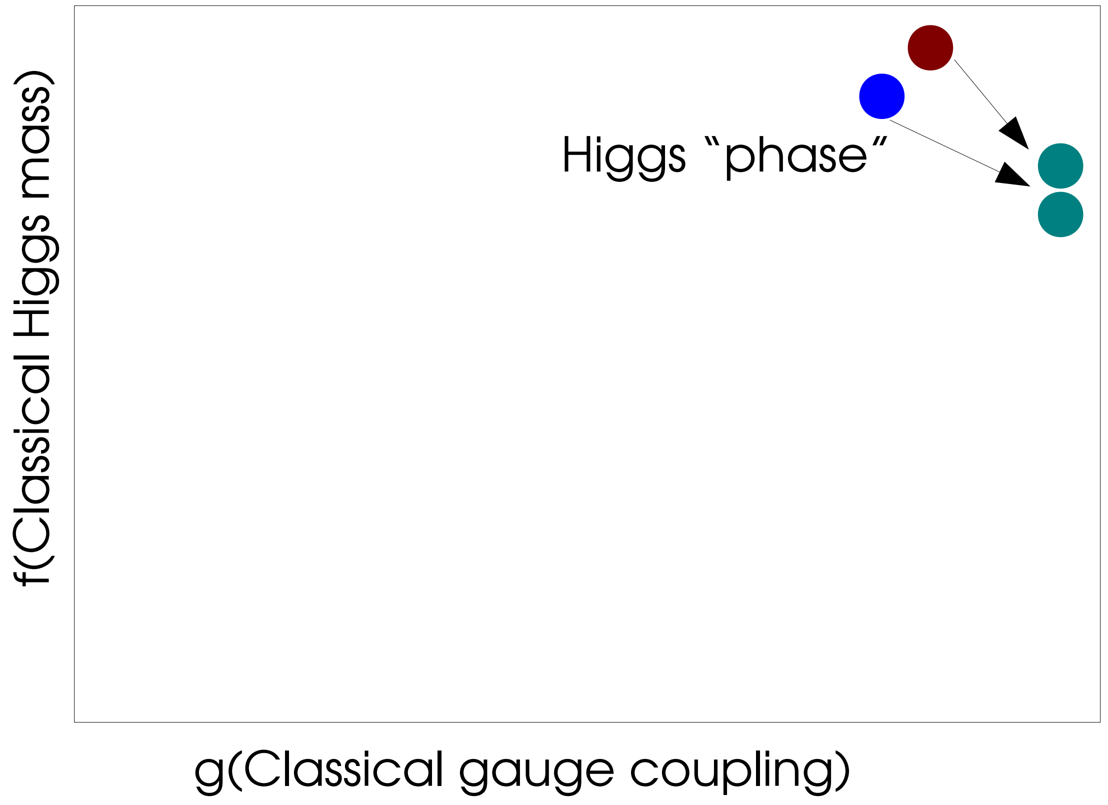

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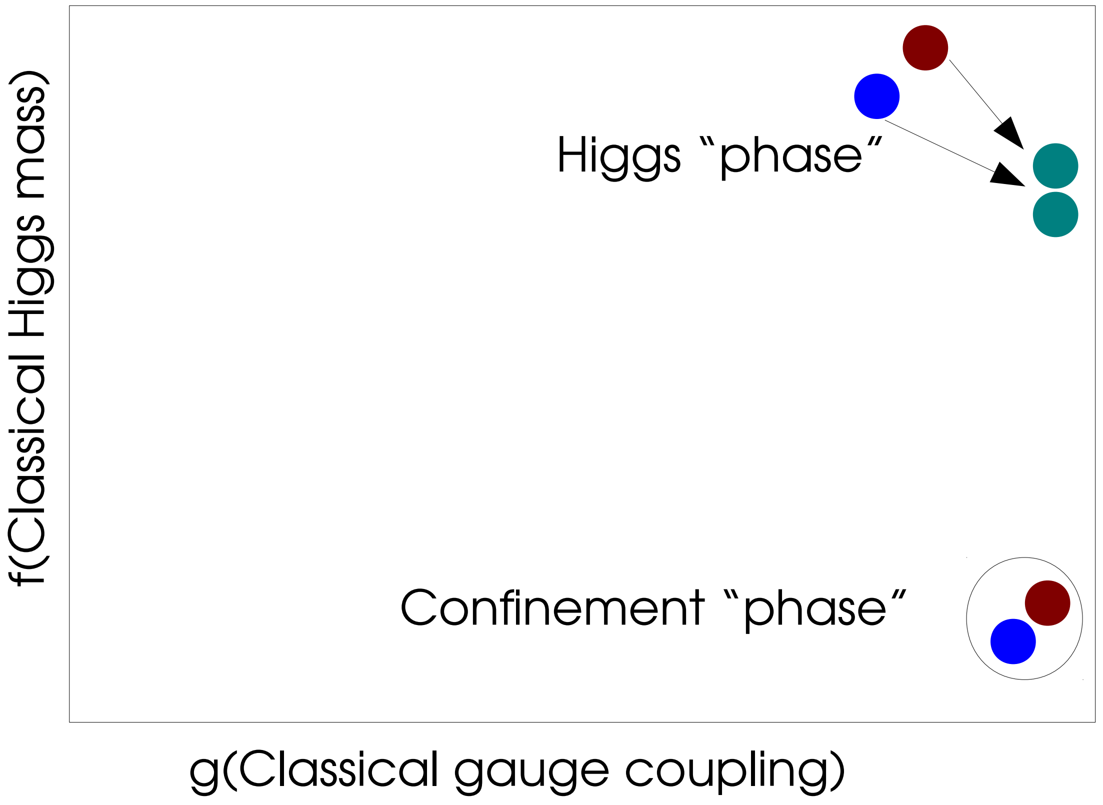

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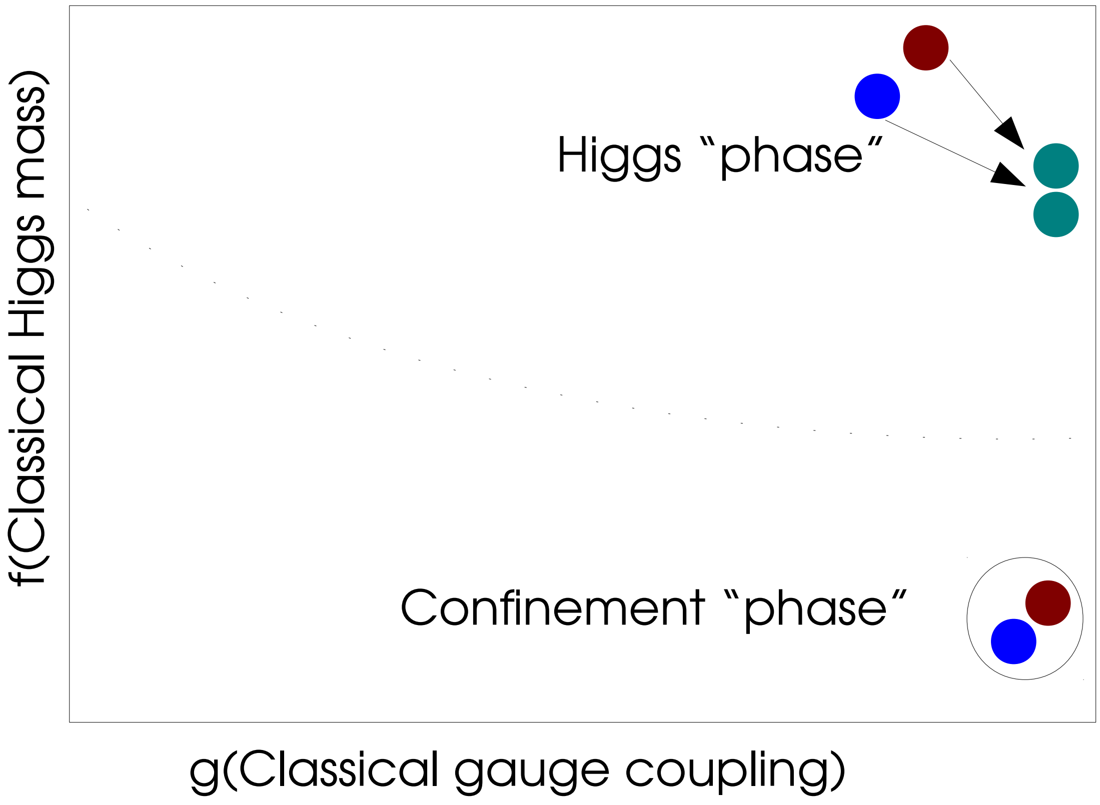

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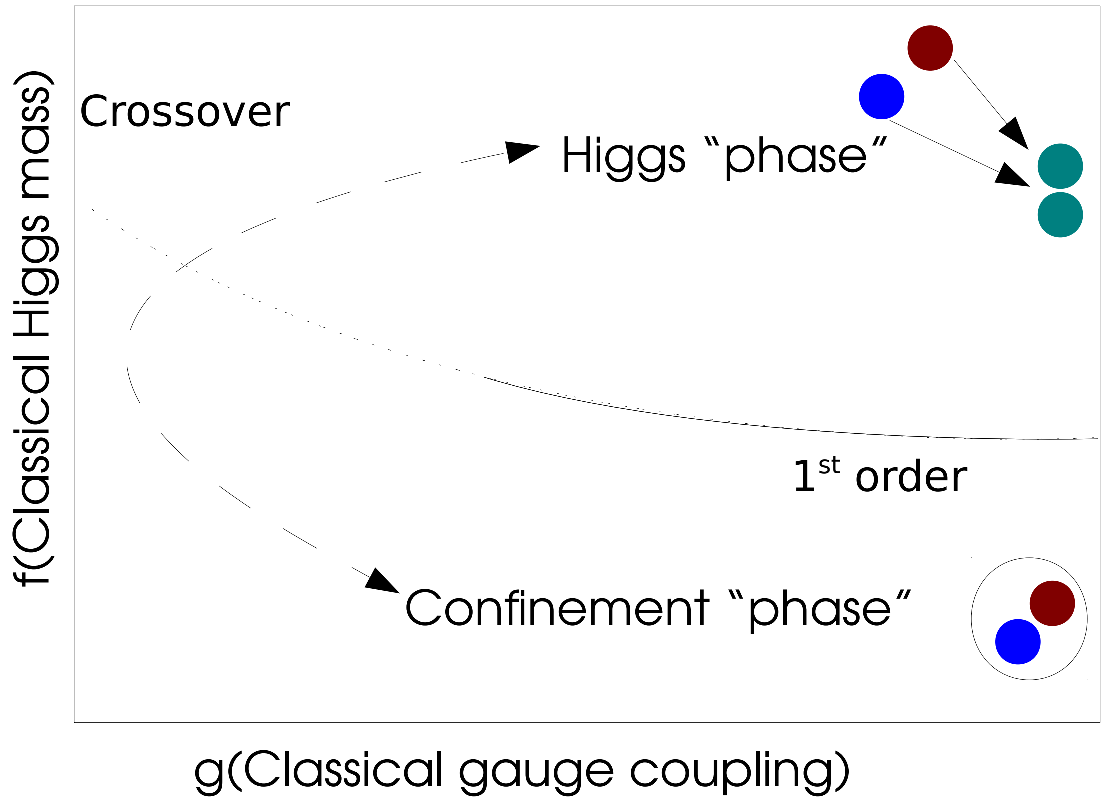
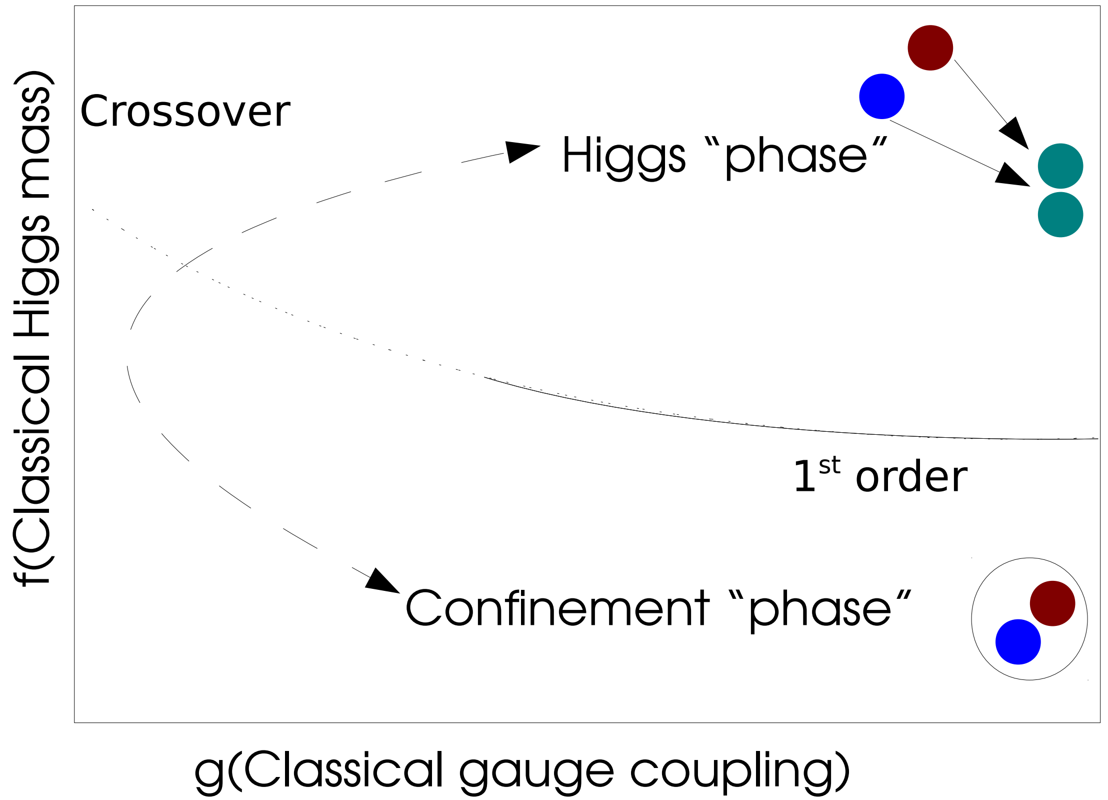


Phase diagram

[Osterwalder et al.'78, Fradkin et al.'79
Caudy et al.'07]

- (Lattice-regularized) phase diagram continuous
  - Free energy can be shown to be analytic
    - On a finite lattice
      - Continuum limit
      - Validity for unregularized theory?
    - Works (likely) only for the standard-model case
    - Osterwalder-Seiler/Fradkin-Shenker construction



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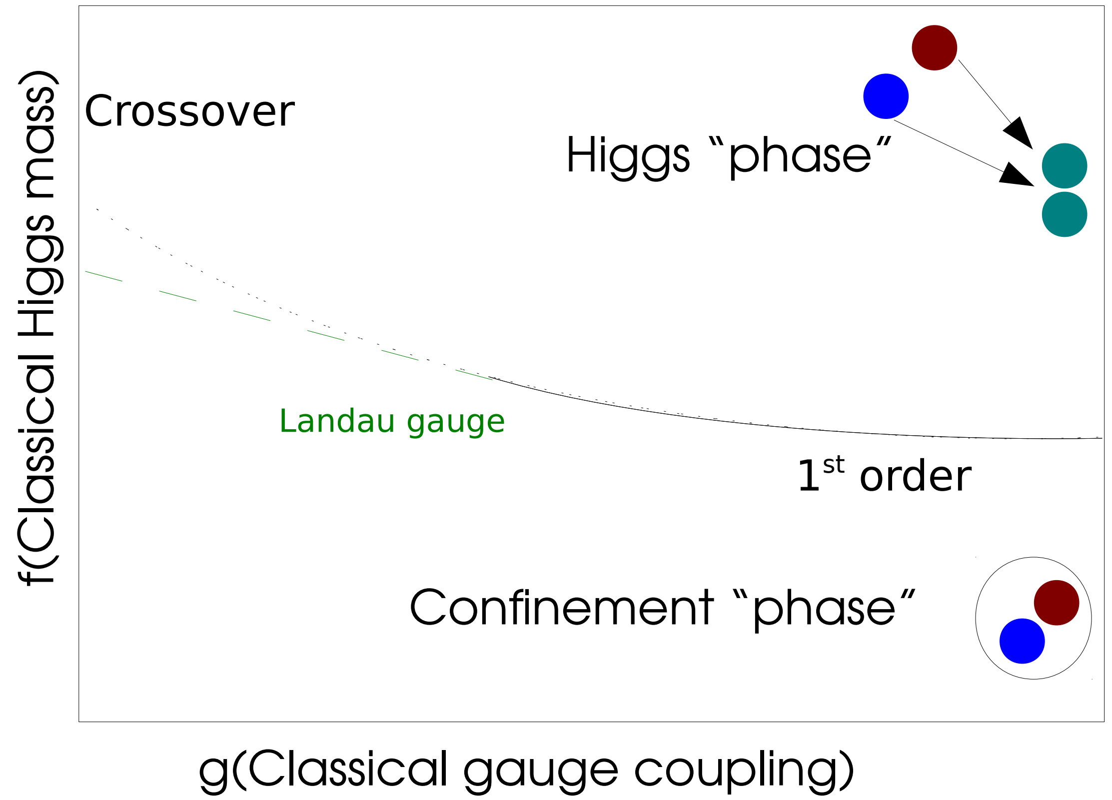

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[Osterwalder et al.'78, Fradkin et al.'79
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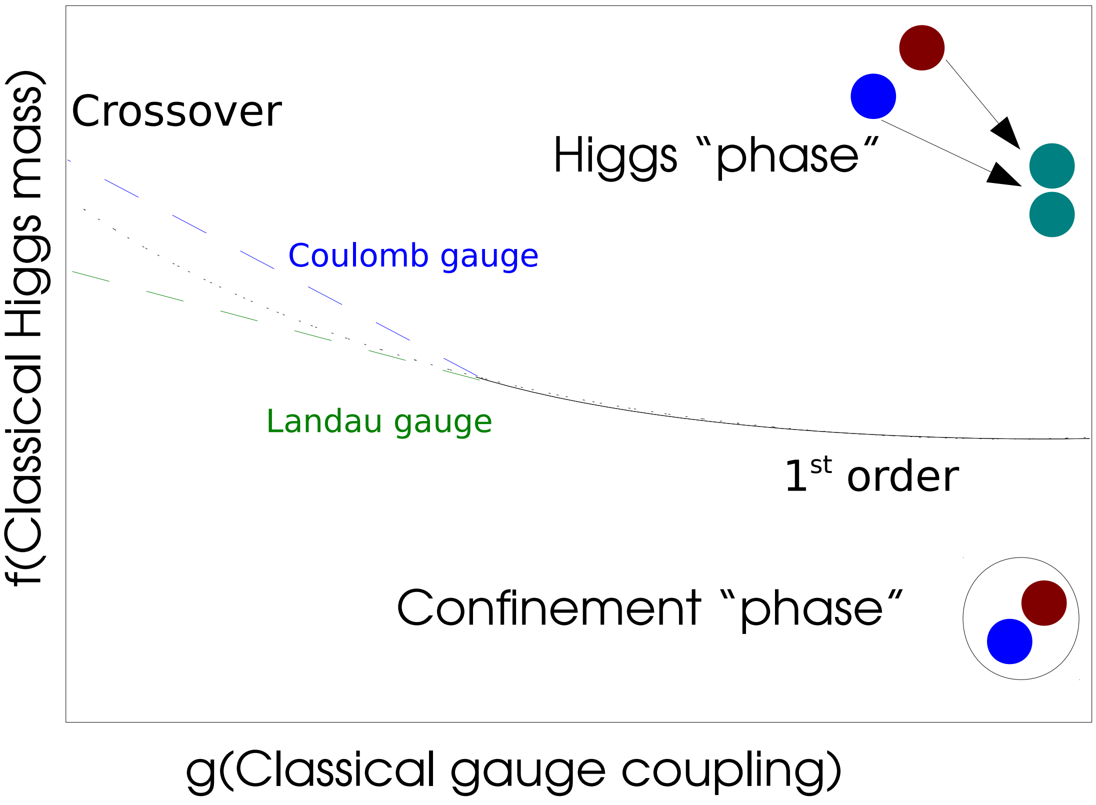
  - Separation only in fixed gauges
  - But different in different in different gauges!



Phase diagram

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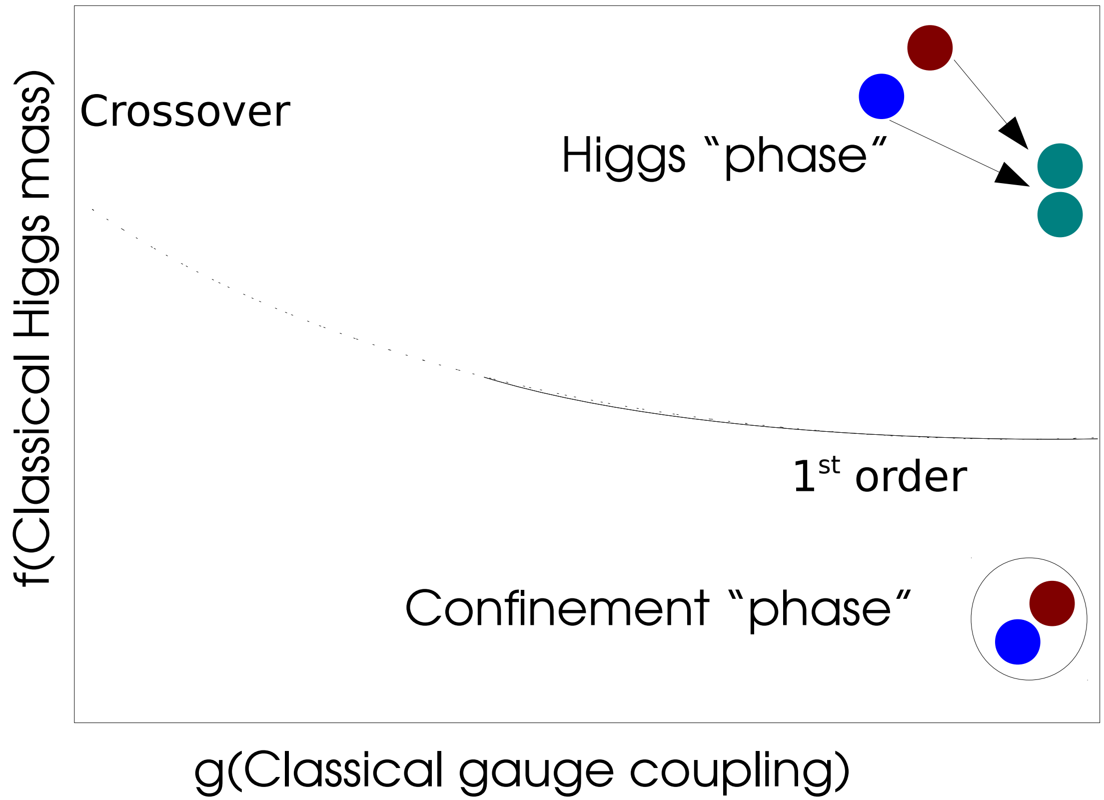
- Same asymptotic states in confinement and Higgs pseudo-phases



- Same asymptotic states irrespective of coupling strengths

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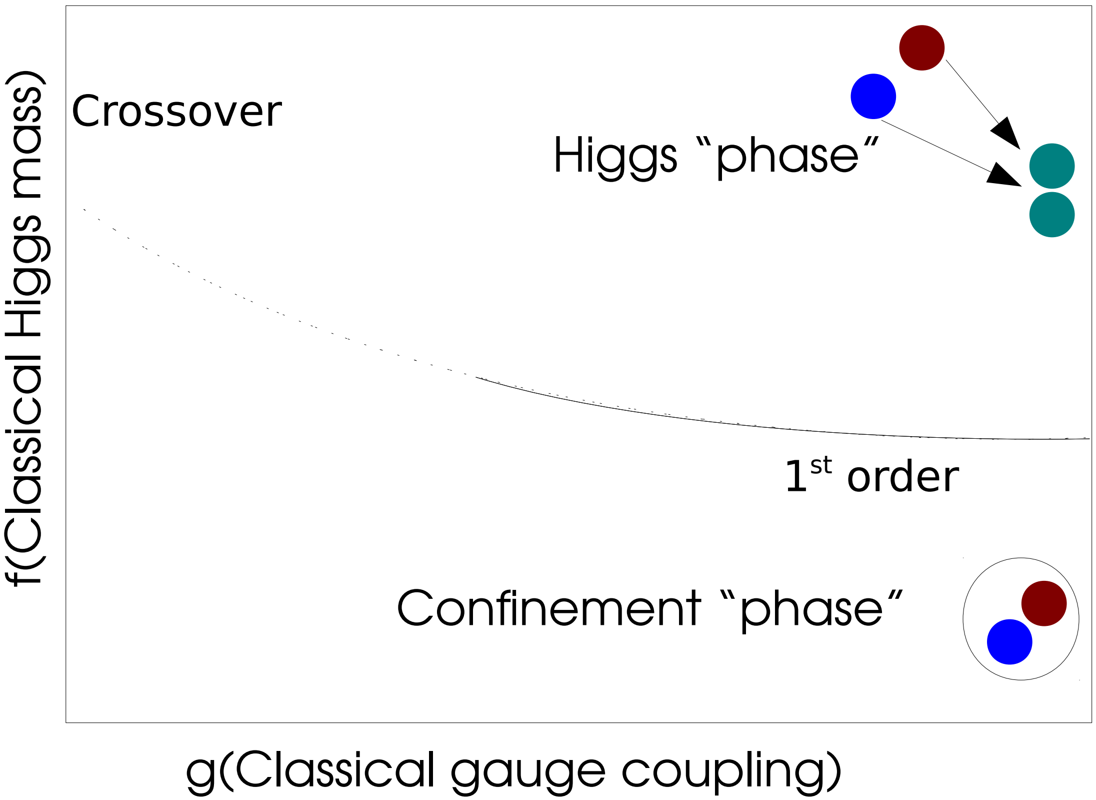
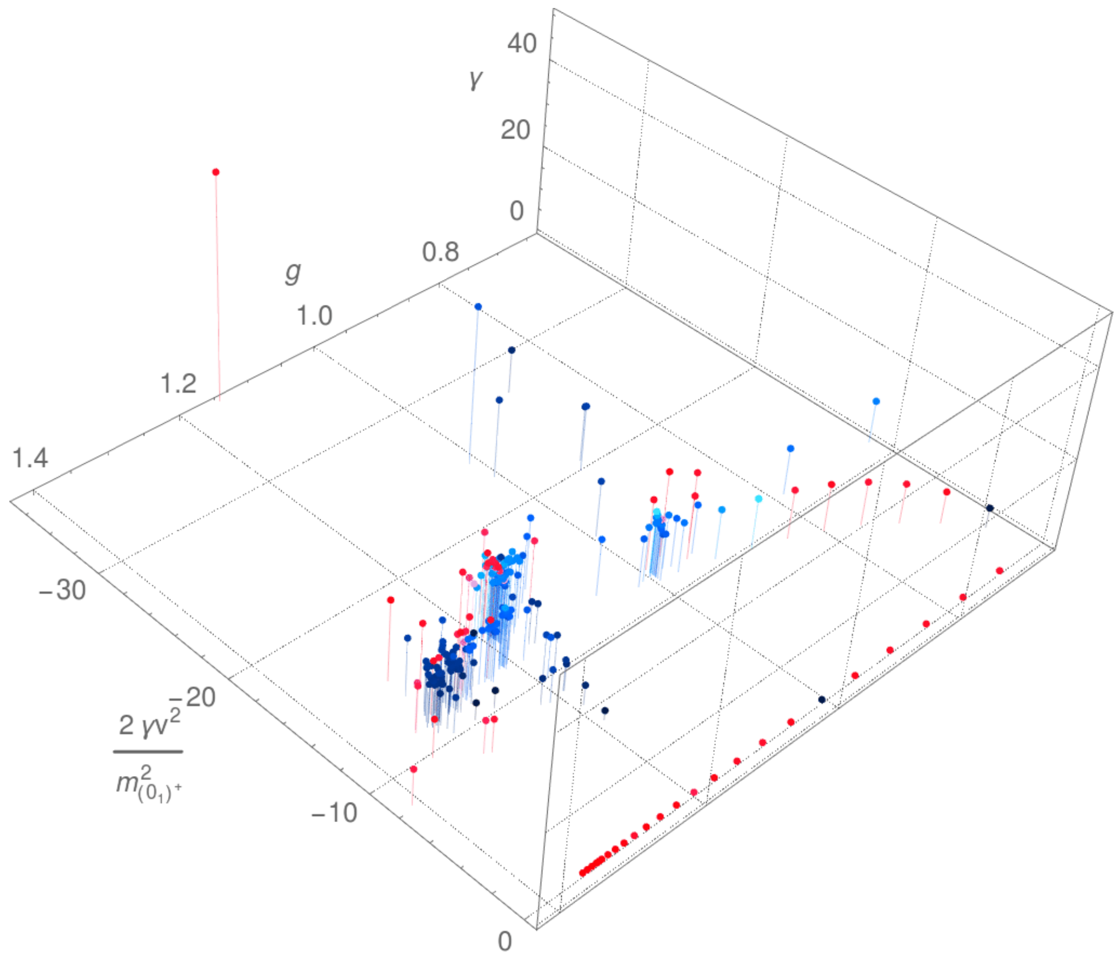
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges
- Same asymptotic states in confinement and Higgs pseudo-phases
- Same asymptotic states irrespective of coupling strengths
- Other states than 'Higgs' and 'W'?



Phase diagram

[Maas & Mufti'15]



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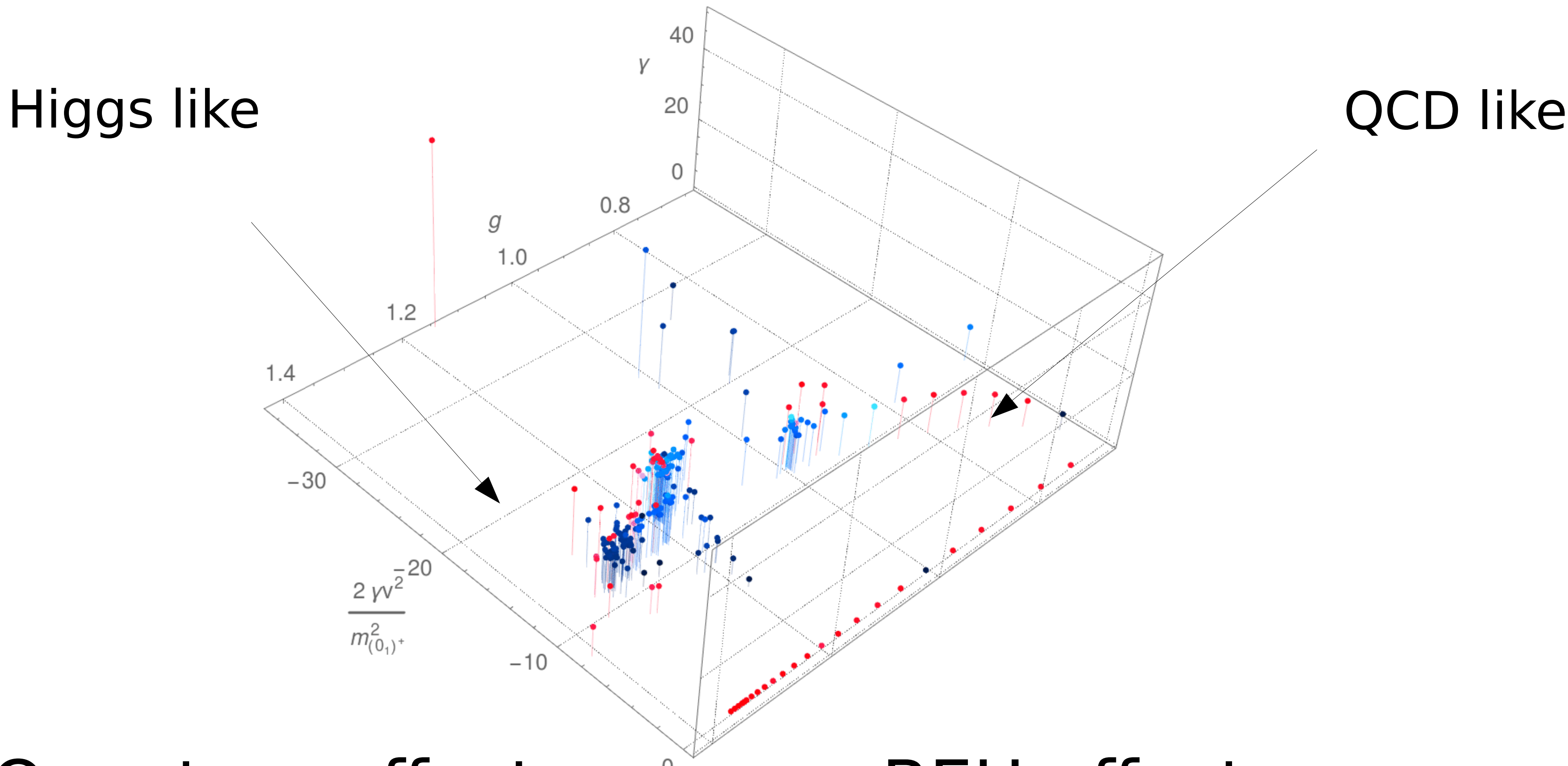

- Quantum effects remove BEH effect
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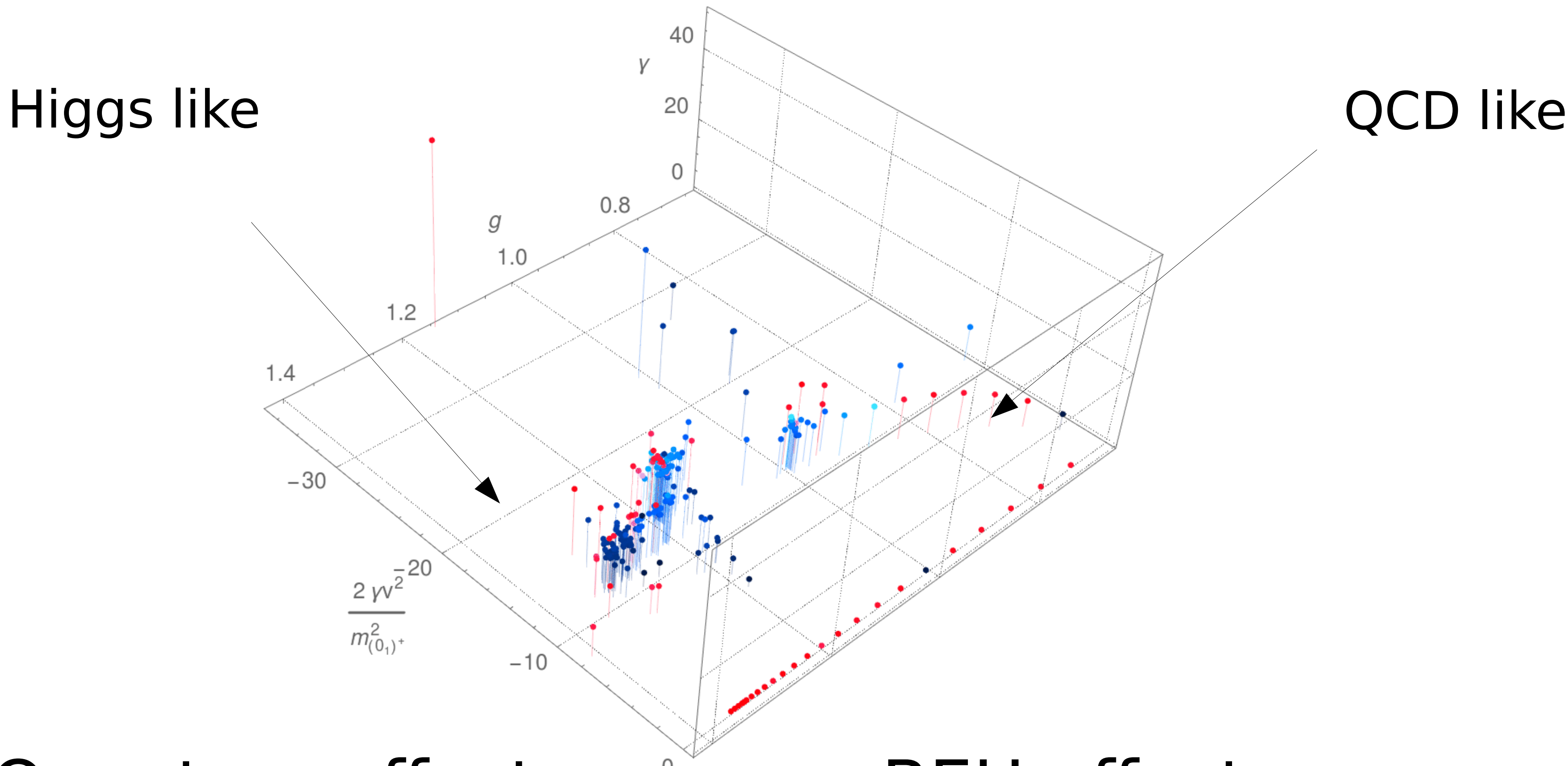

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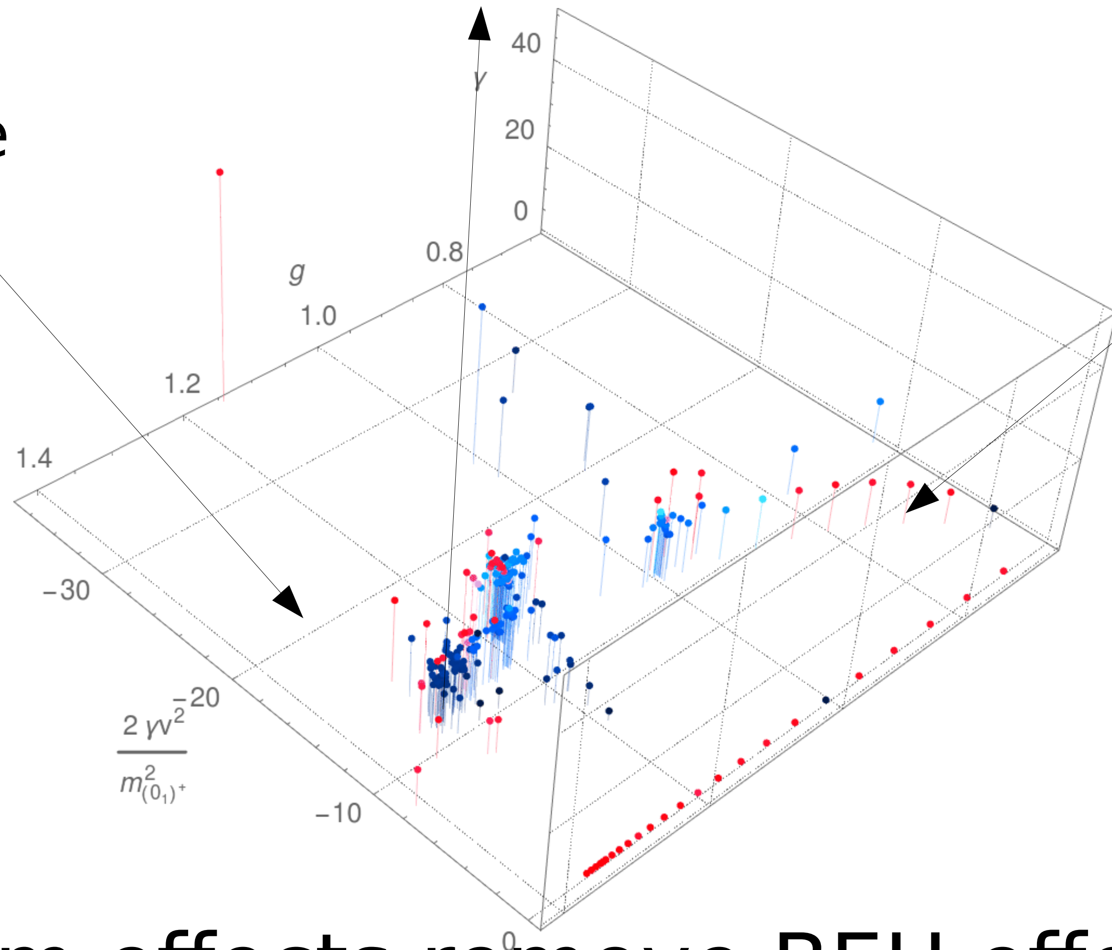
Phase diagram

[Maas & Mufti'15]

Critical end-line? [Bonati et al.'10]

Higgs like

QCD like



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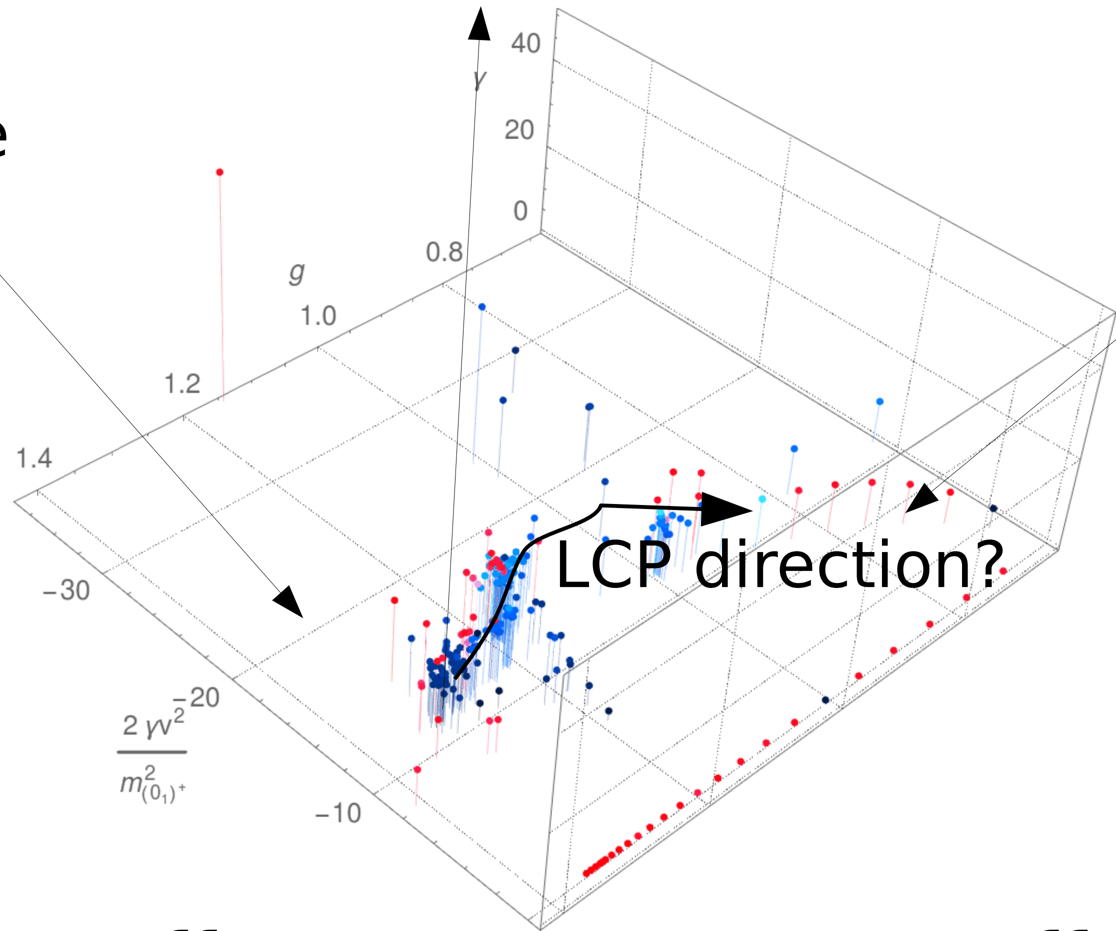

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  - LCP: 0^+, 1^- mass, $\alpha\left(200\,GeV\right)$ (miniMOM scheme)

Ultraviolet structure

- Selection criterion for candidate new physics

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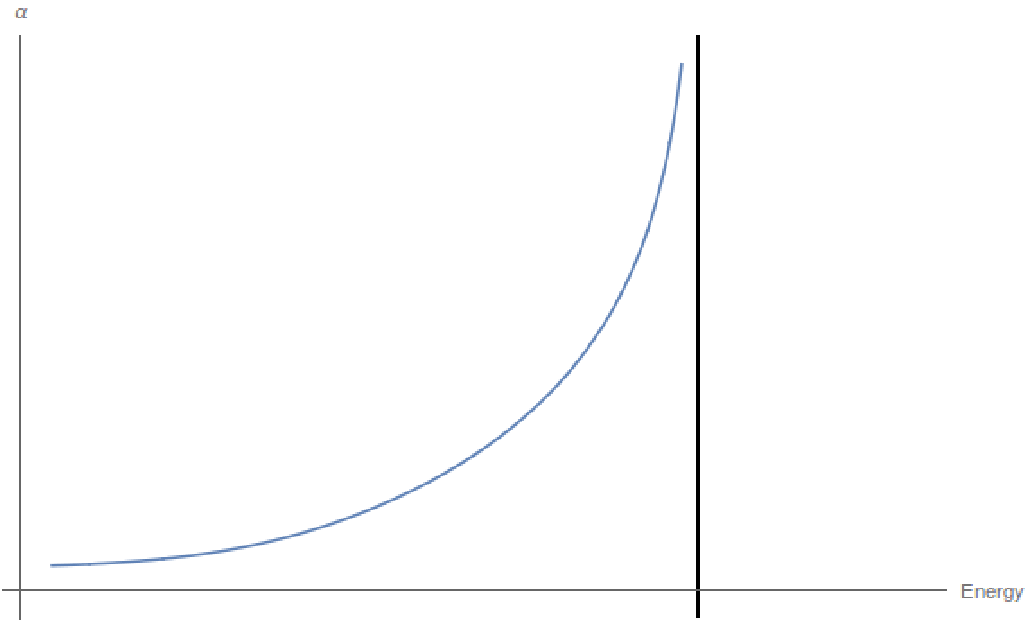

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    (1) No Landau poles (small coupling)

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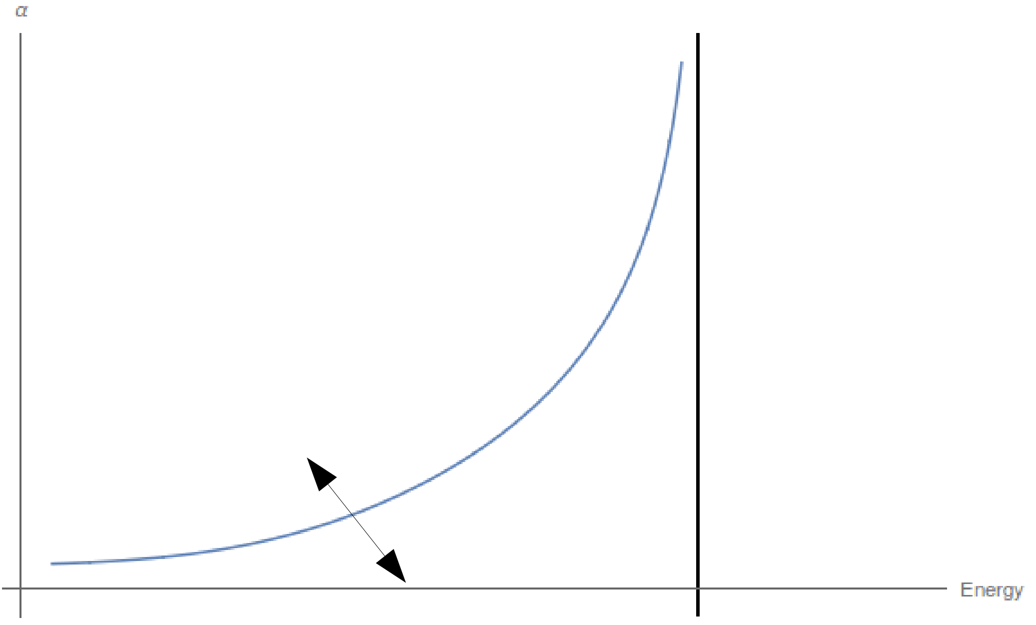

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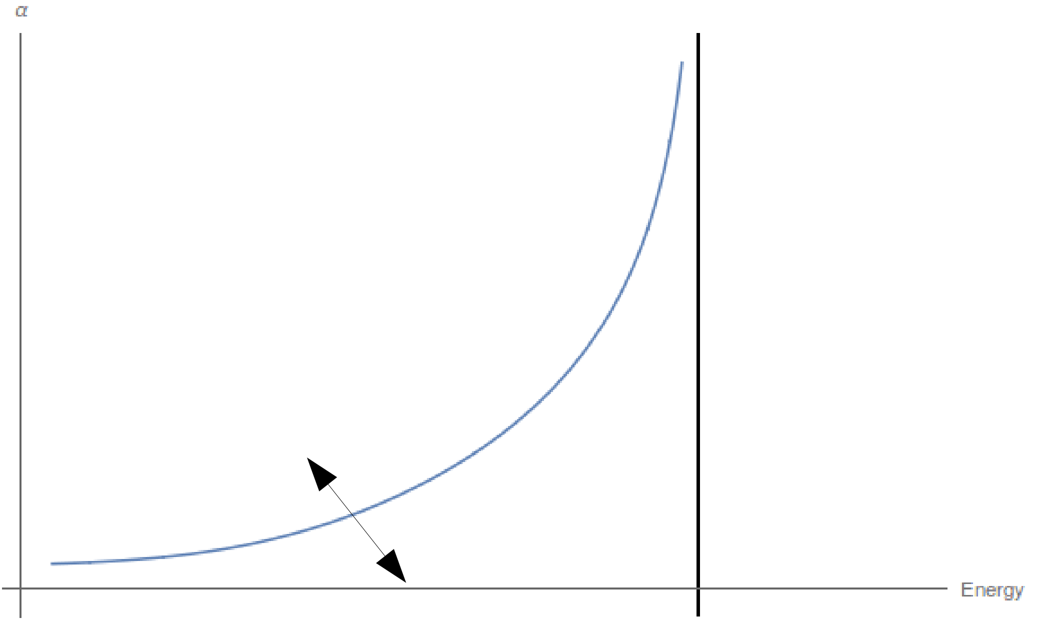

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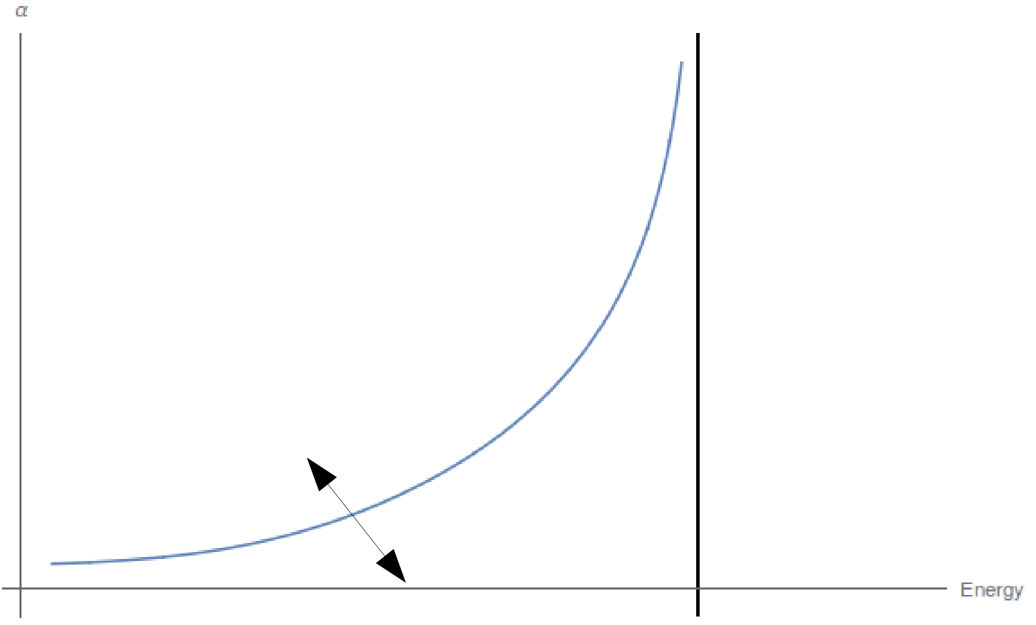

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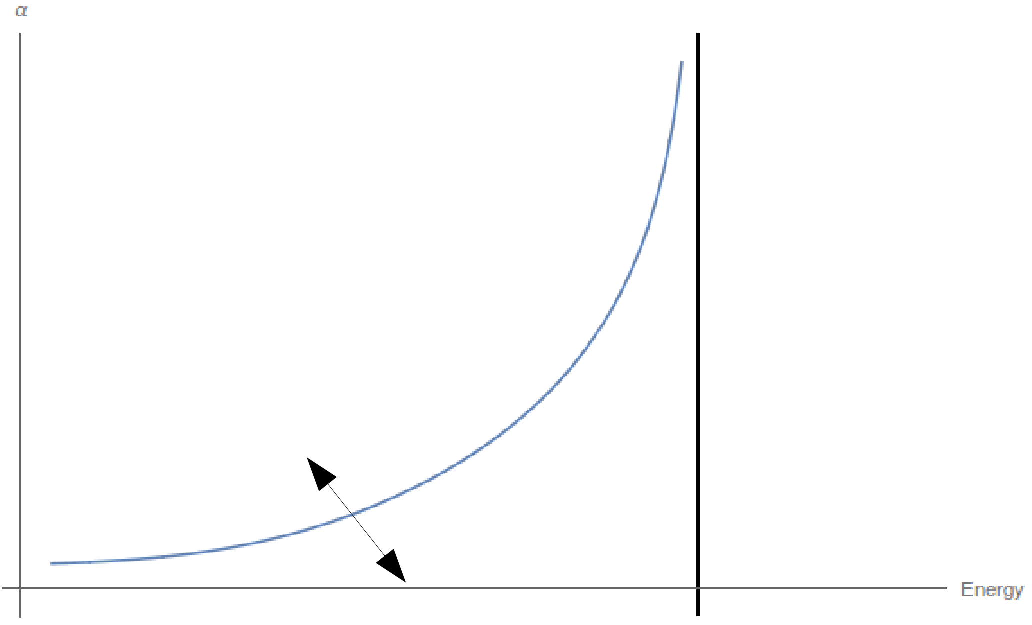

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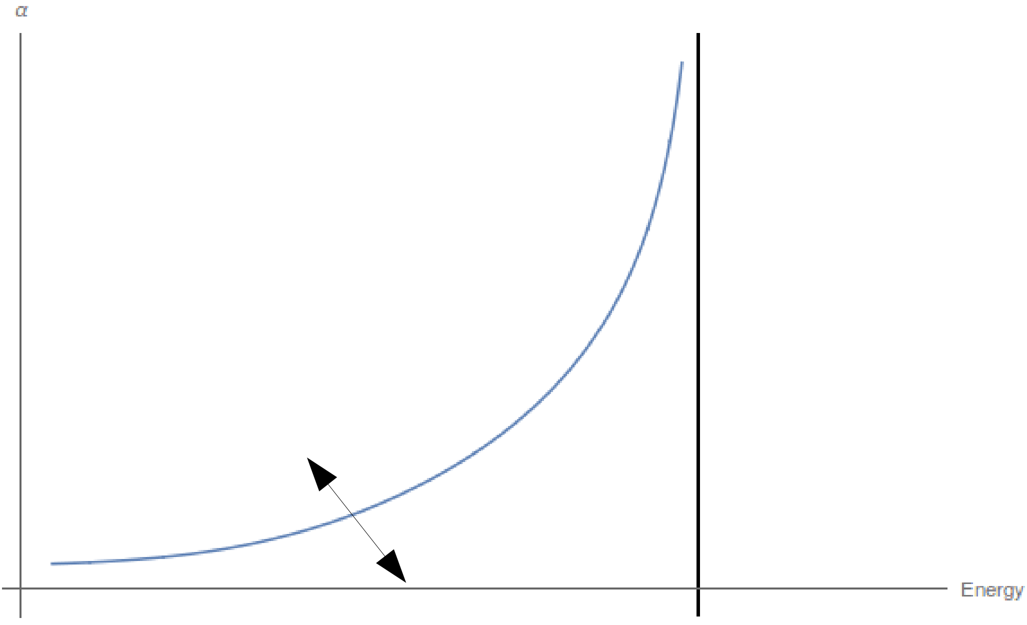
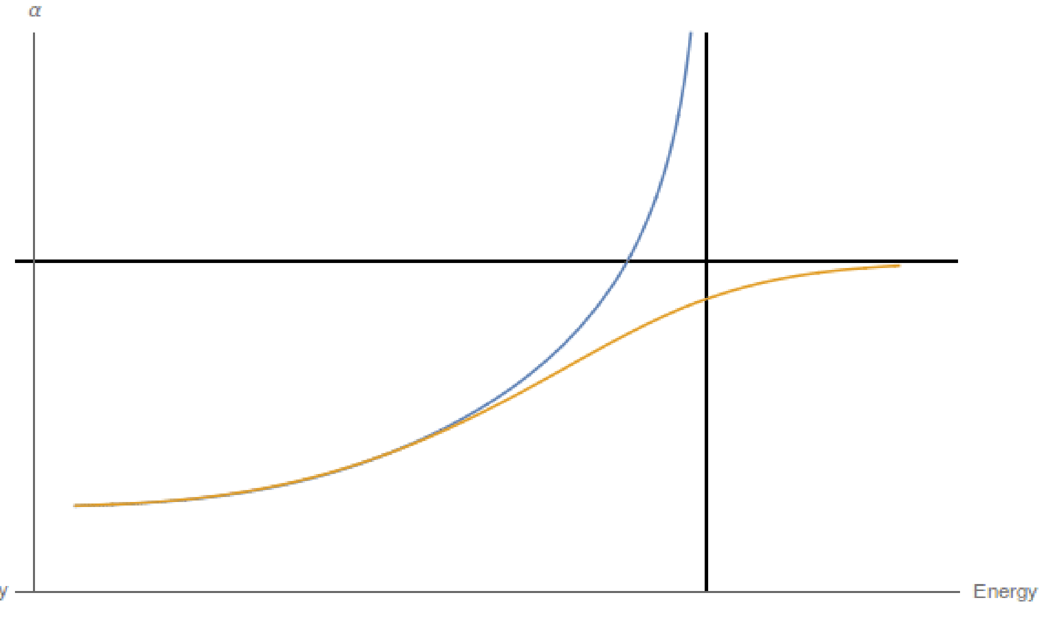
Possible scenarios





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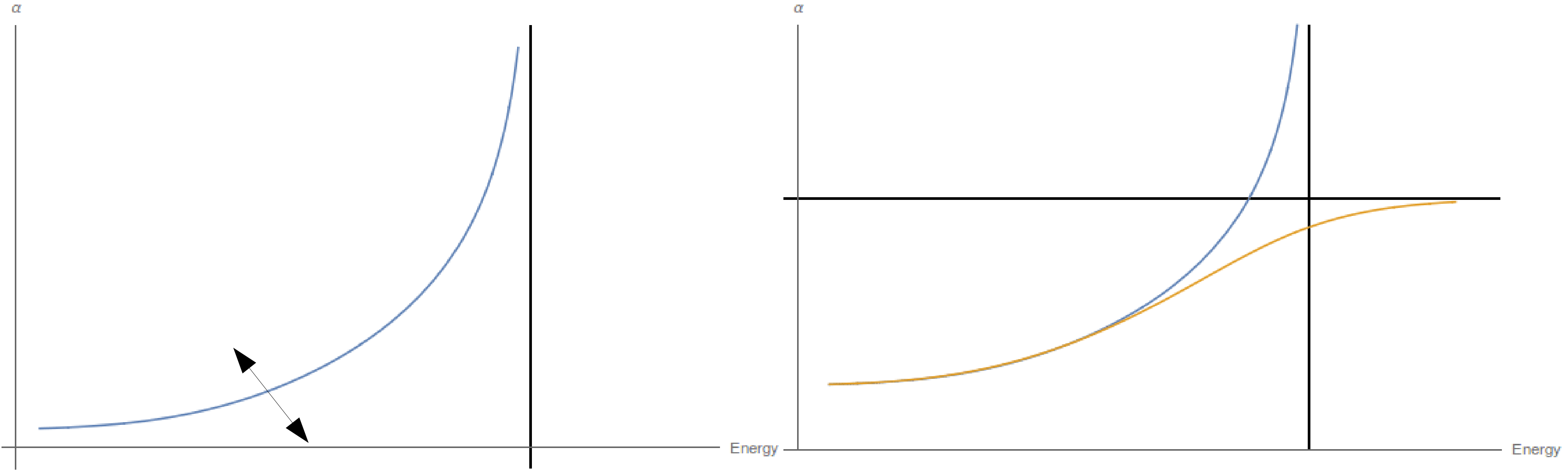

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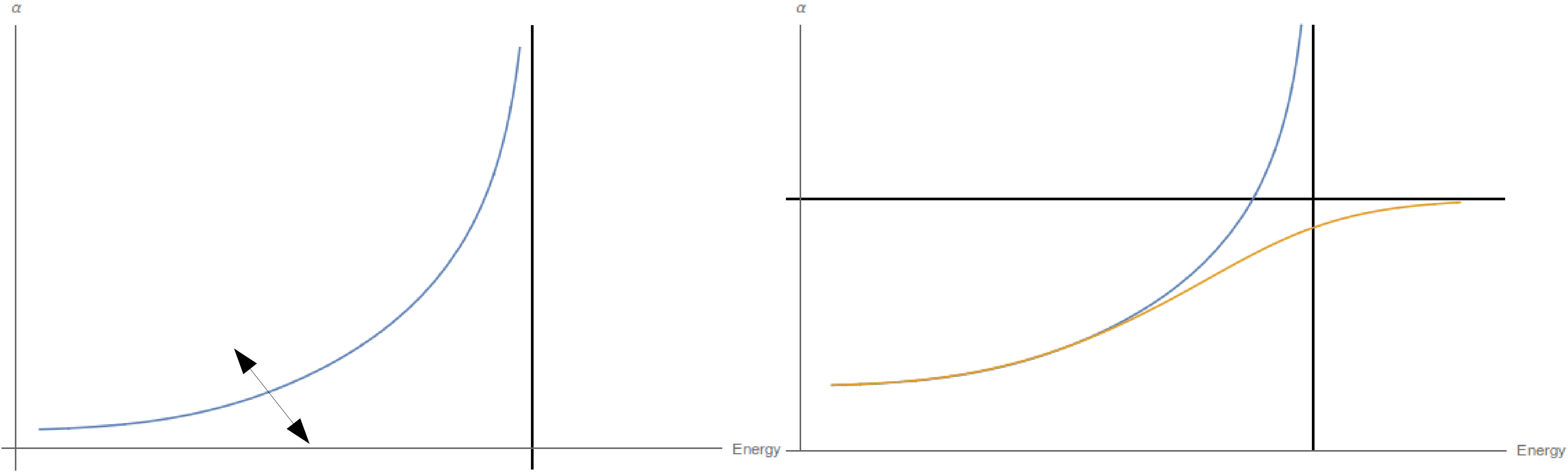

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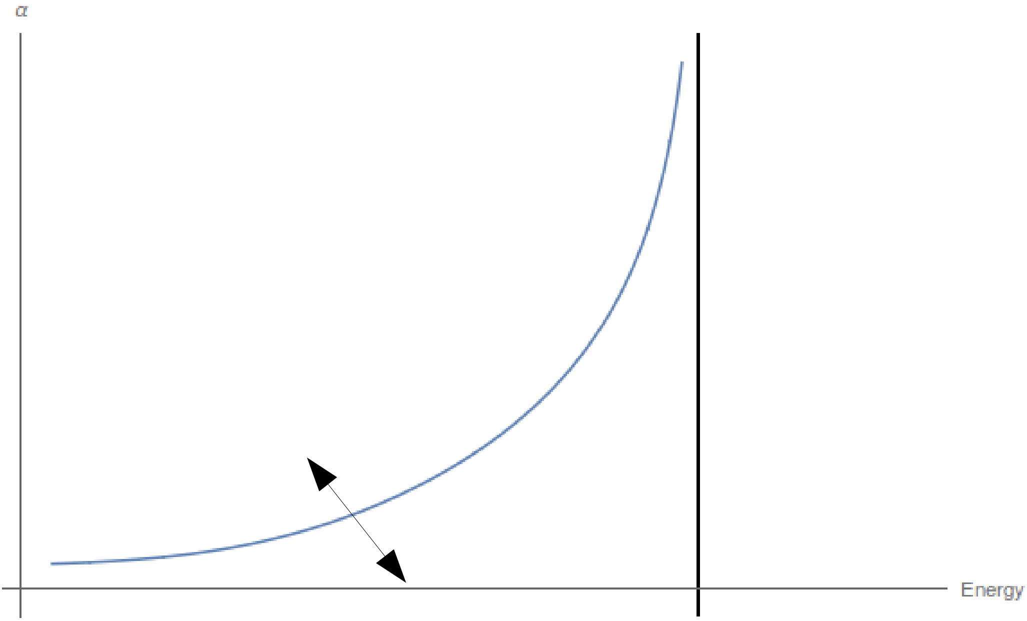

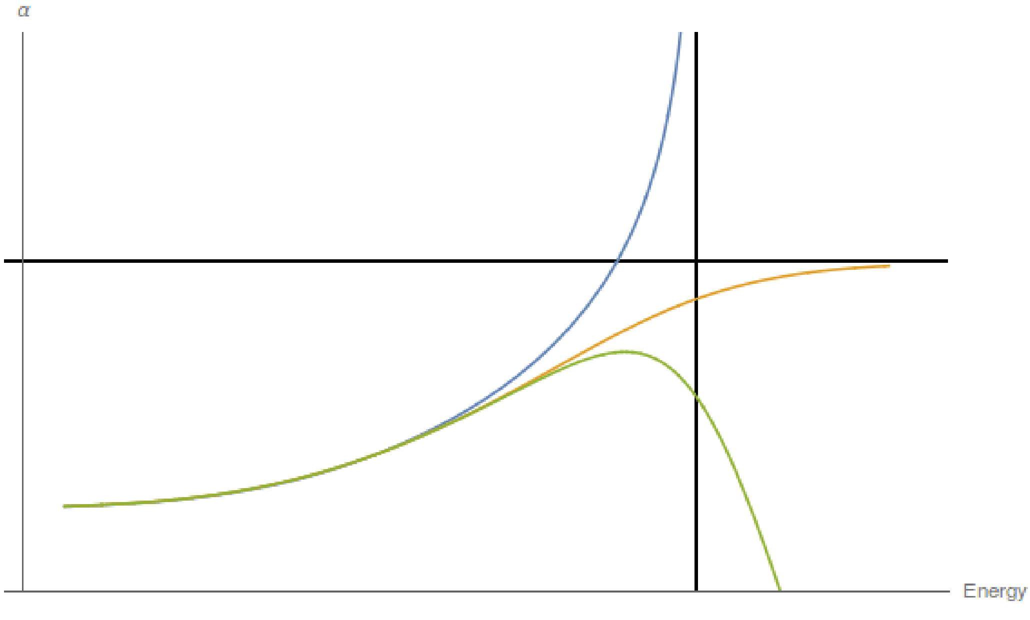

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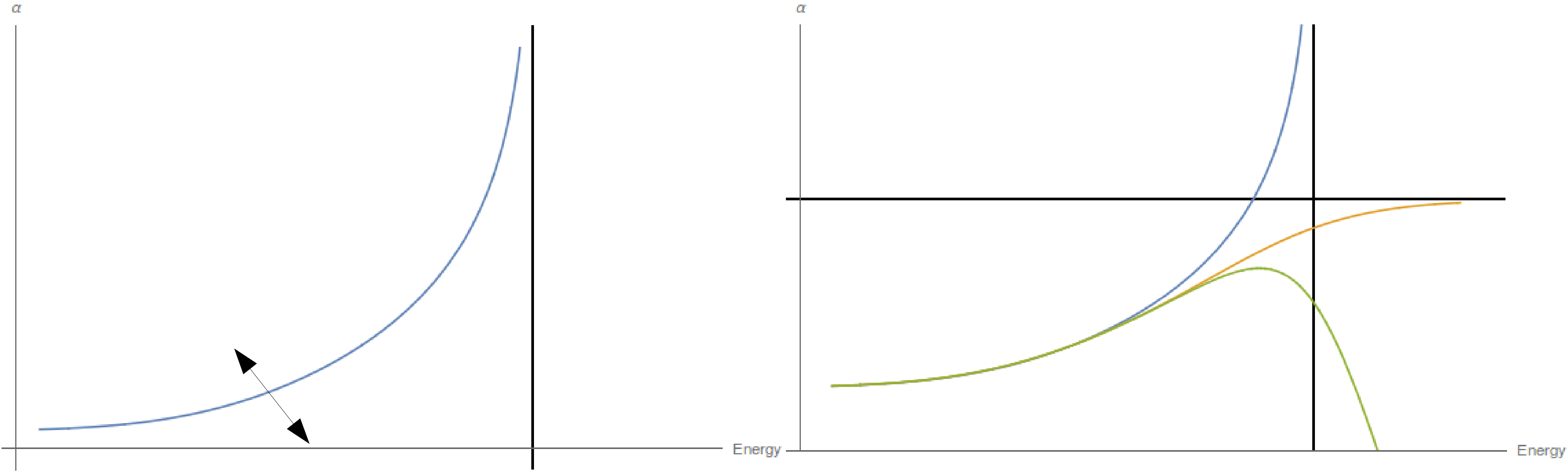
Where to look for it



- Experimentally hard to find
  - Energy-dependence of running couplings
    - Tiny deviations at accessible energies: Precision tests

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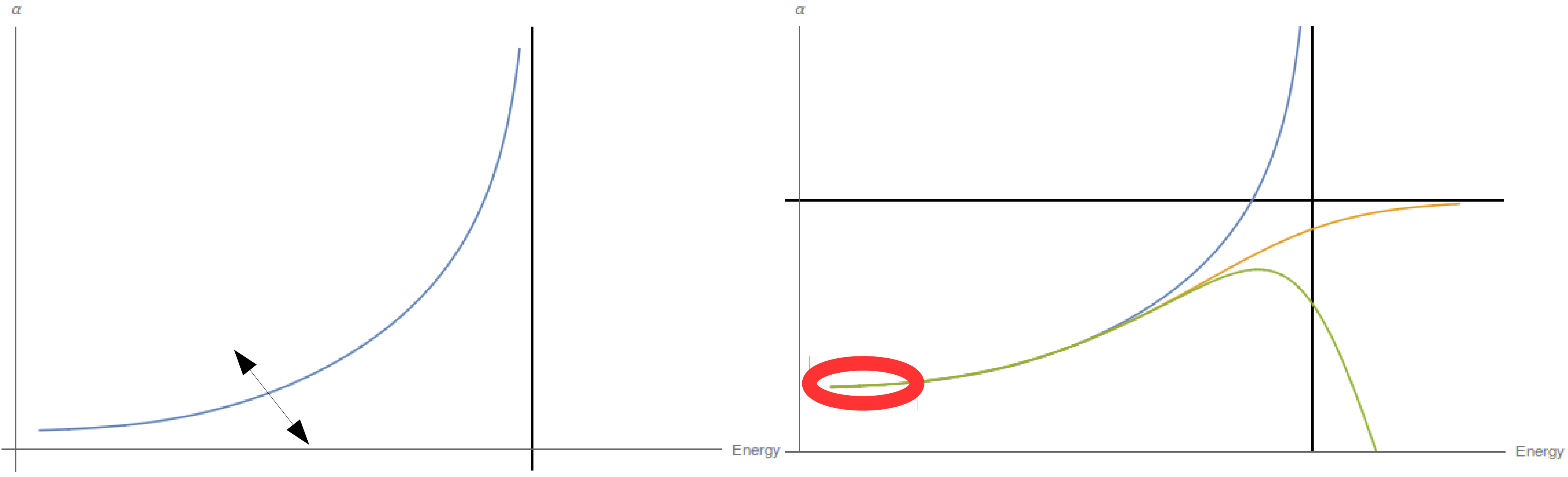

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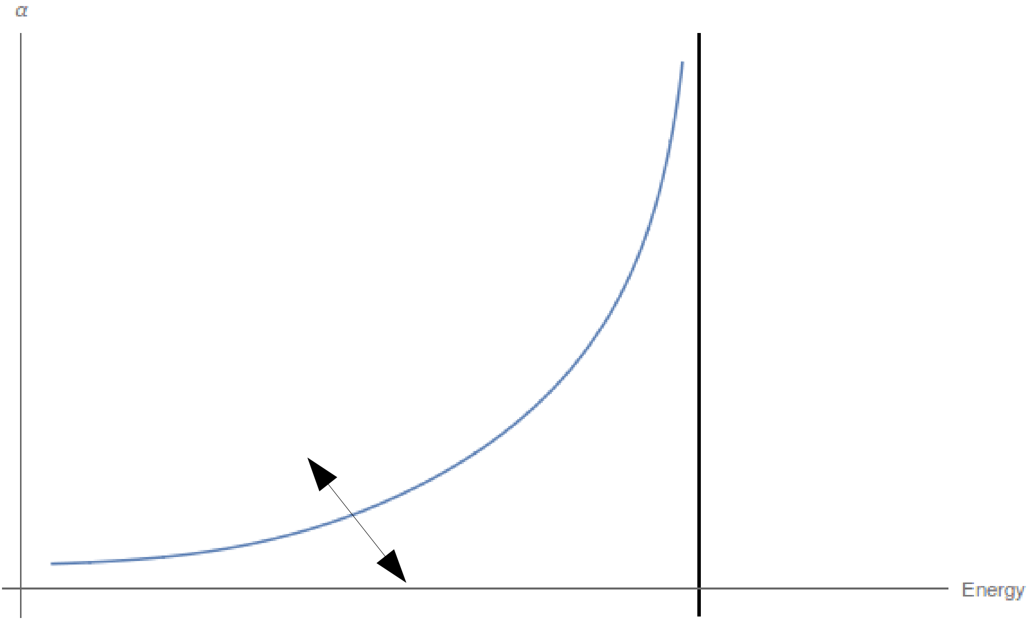

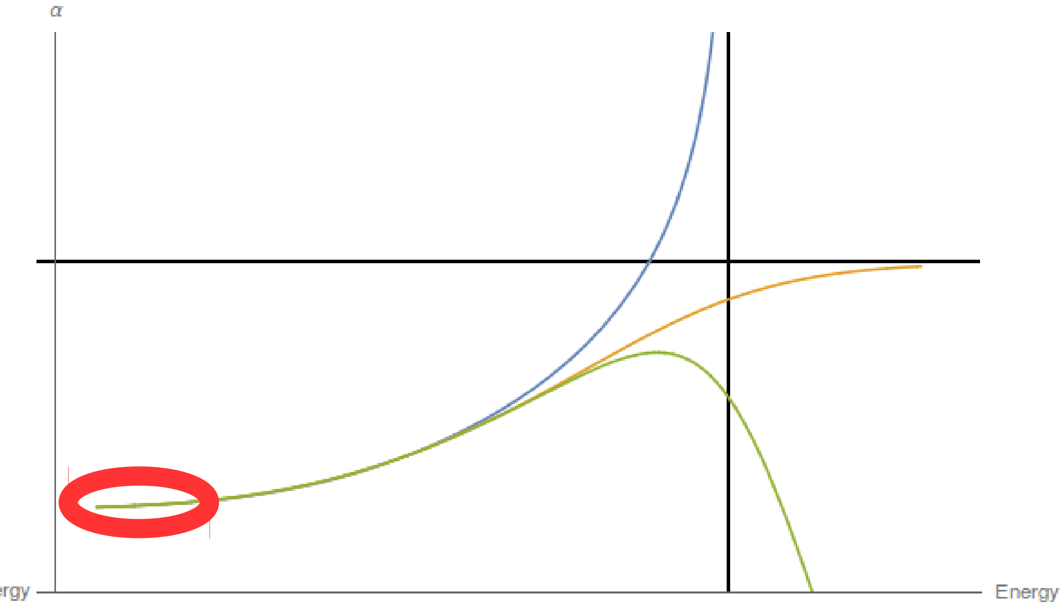

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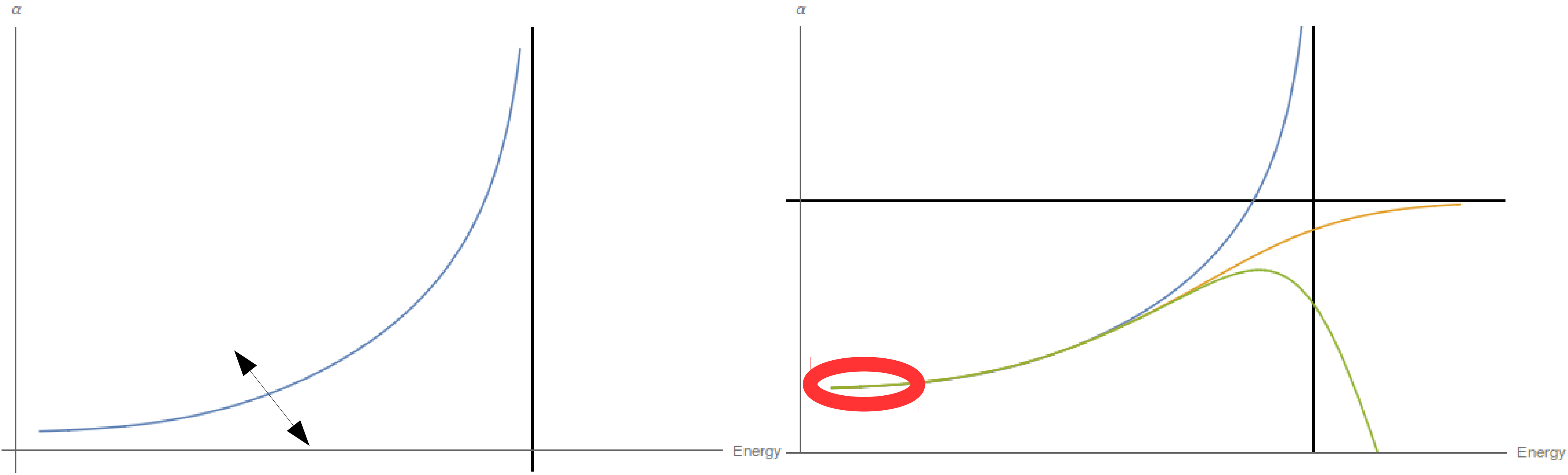
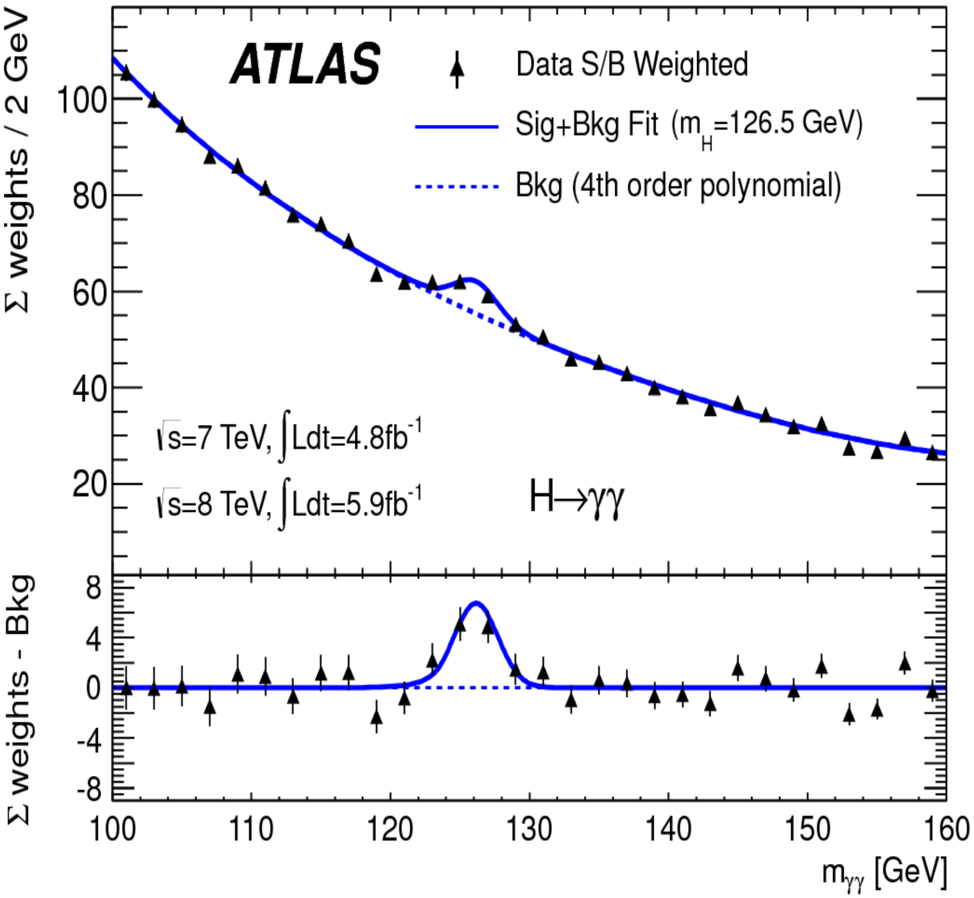
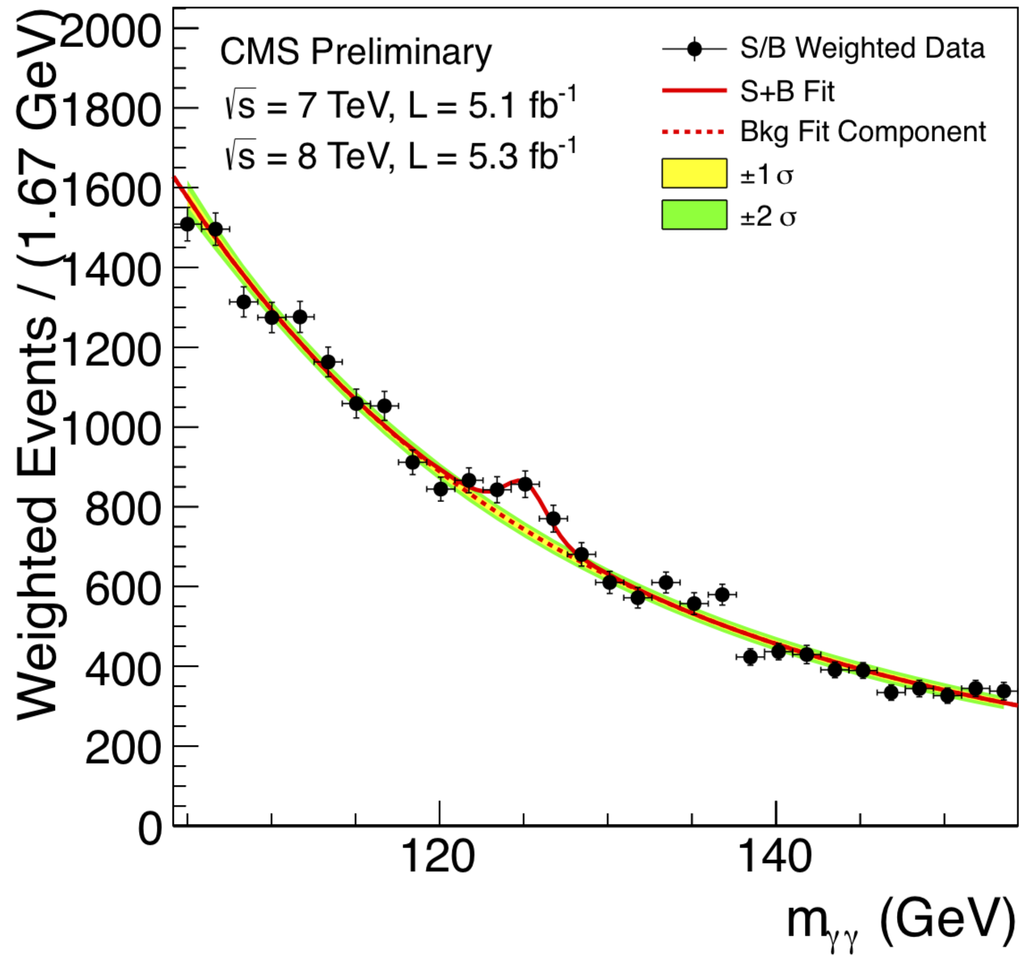


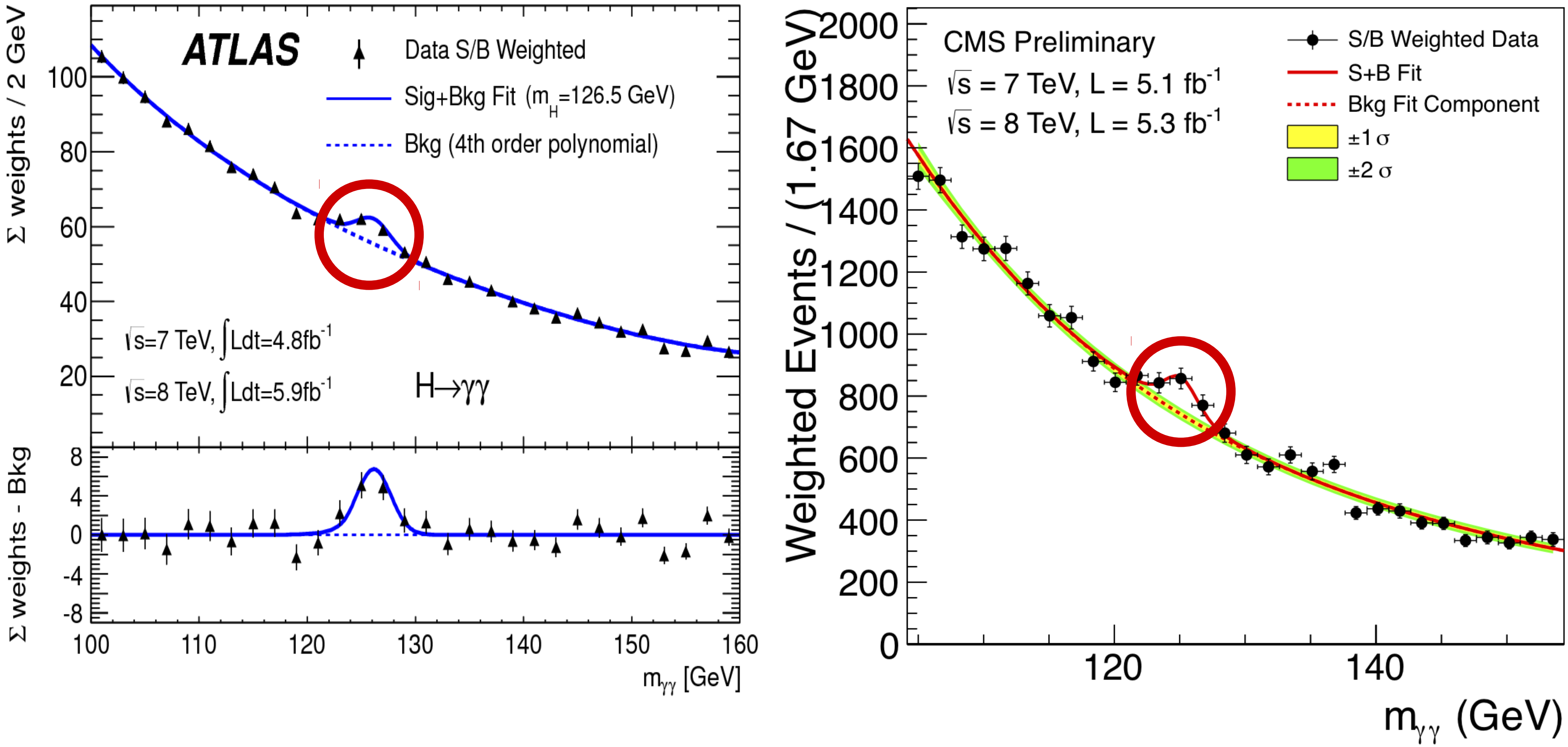
- Experimentally hard to find
  - Energy-dependence of running couplings
    - Tiny deviations at accessible energies: Precision tests
  - Particle content constrained
- Quantum gravity has implications for cosmology
  - Cosmological constant becomes running
  - Tests against astrophysical data

The physics of the Higgs sector

b: Observable particles

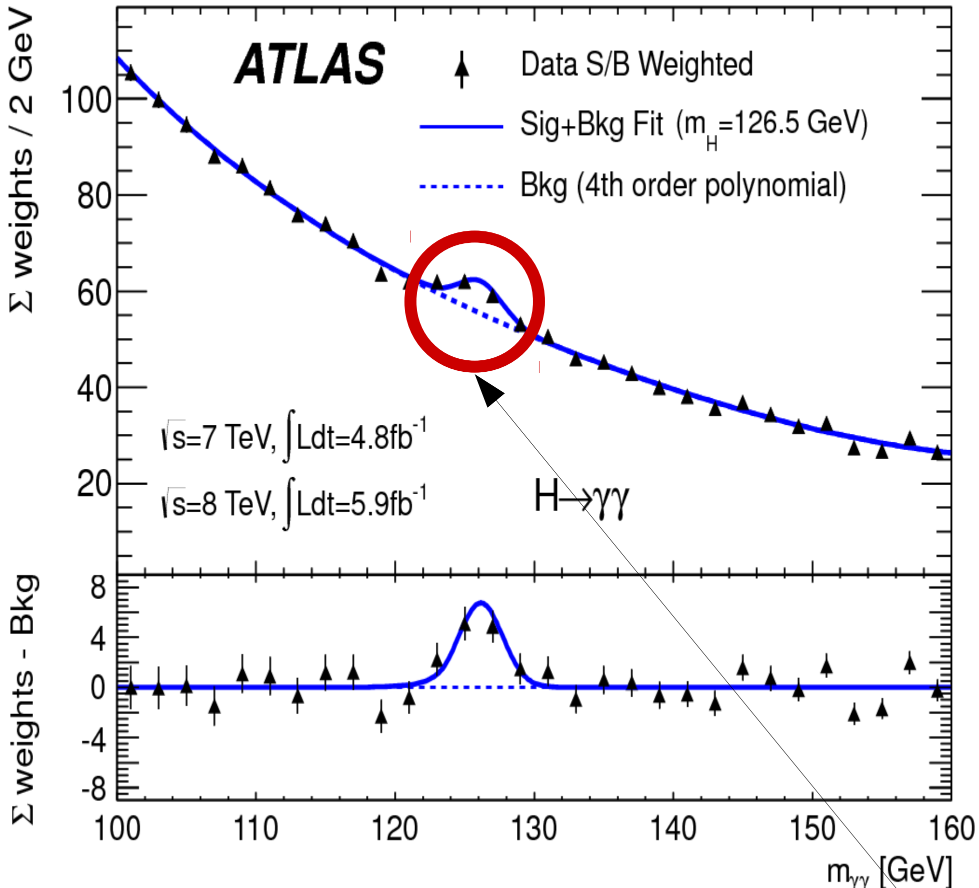

ATLAS
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
$H\rightarrow\gamma\gamma$
Σ weights / 2 GeV
Σ weights - Bkg
$m_{\gamma\gamma}$ [GeV]

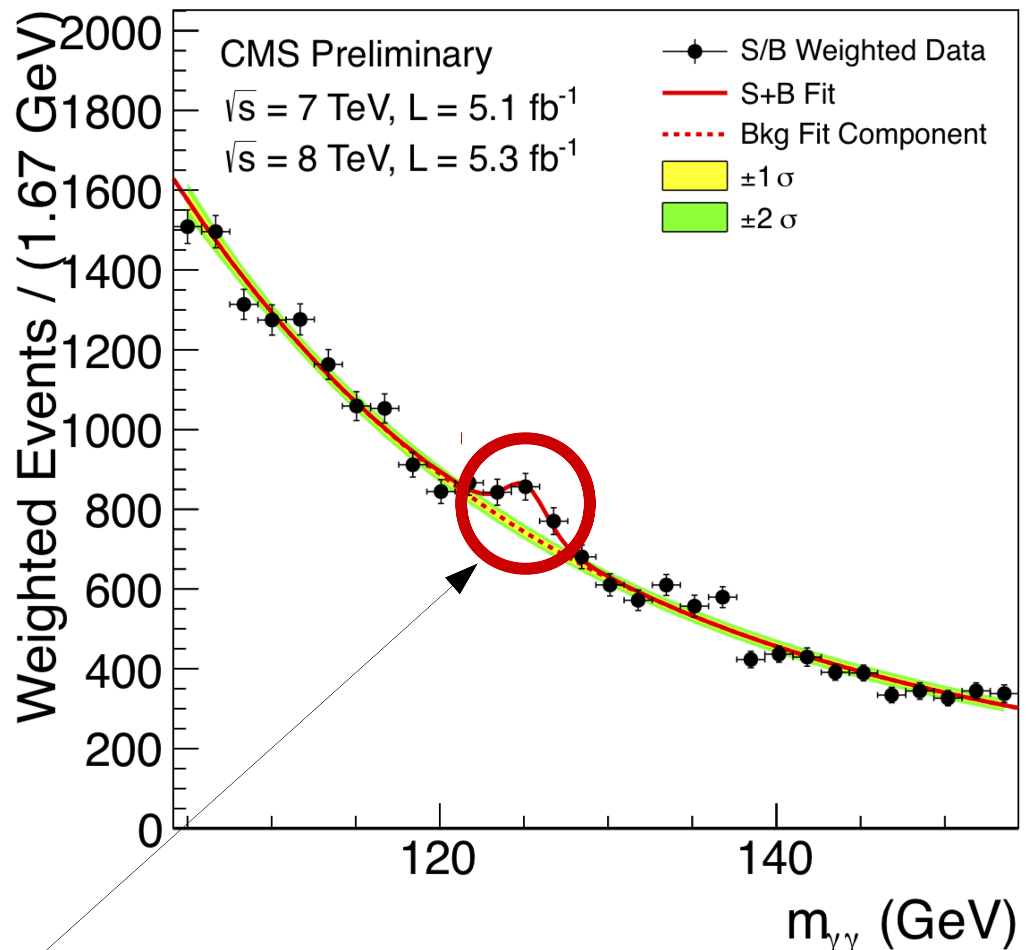

CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
S/B Weighted Data
S+B Fit
Bkg Fit Component
$\pm1\,\sigma$
$\pm2\,\sigma$
Weighted Events / (1.67 GeV)
$m_{\gamma\gamma}$ (GeV)



ATLAS
Data S/B Weighted
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb⁻¹
√s=8 TeV, ∫Ldt=5.9fb⁻¹
H→γγ
Σ weights / 2 GeV
Σ weights - Bkg
$m_{\gamma\gamma}$ [GeV]
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
$m_{\gamma\gamma}$ (GeV)

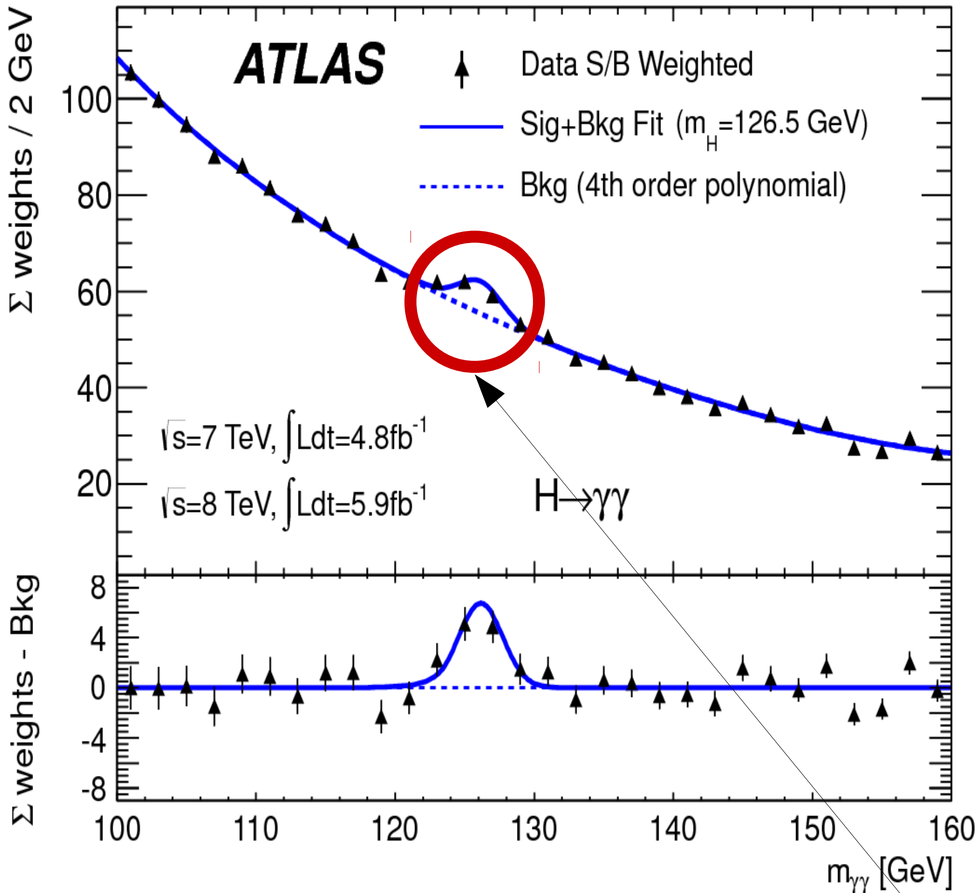
What is seen in experiment?

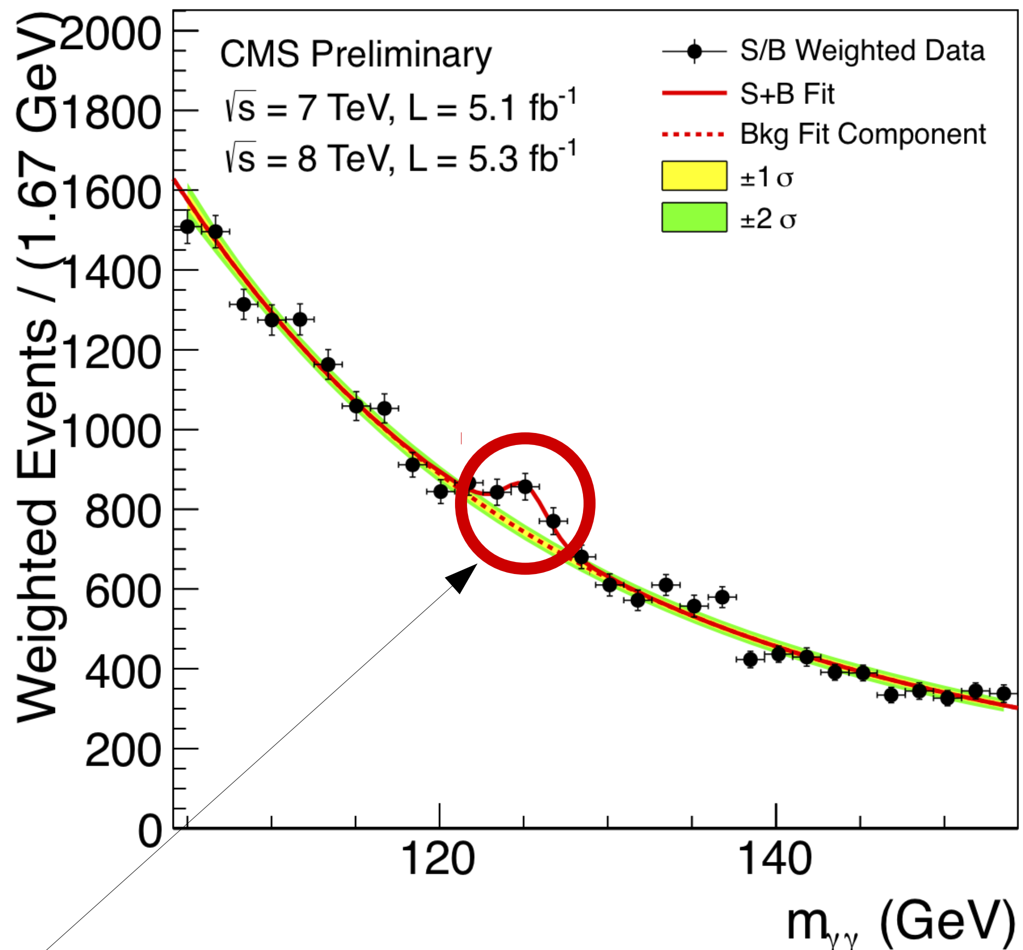




What did we see here?

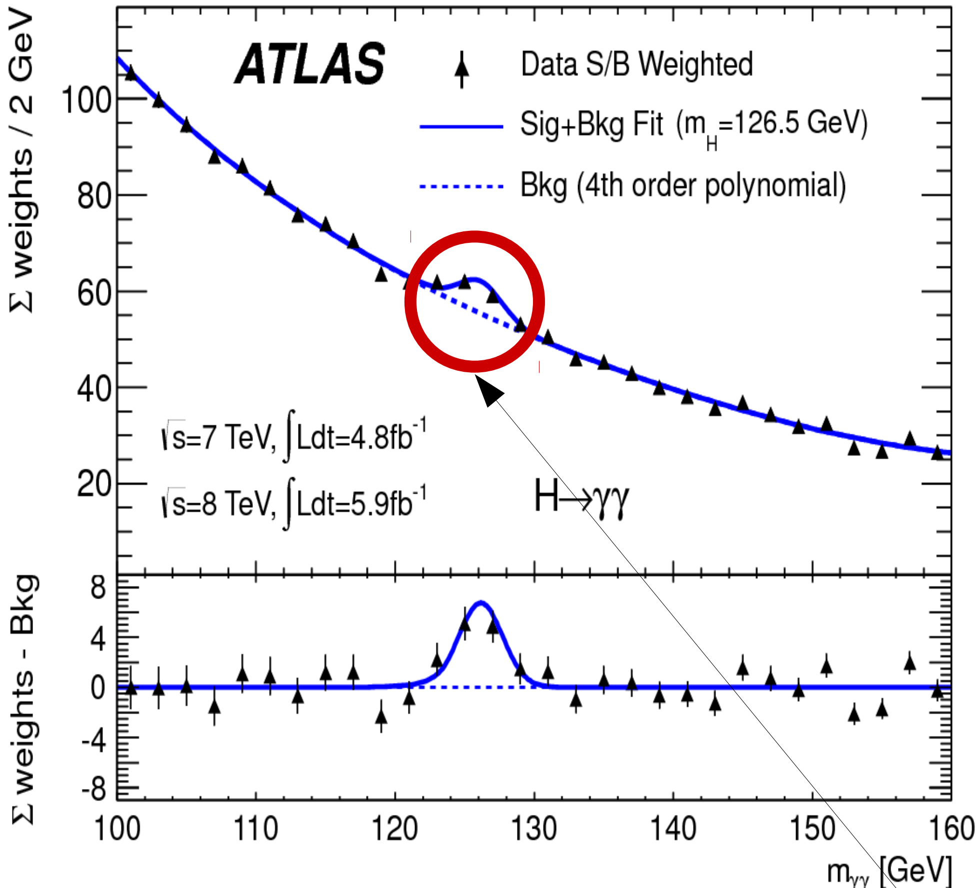
What is seen in experiment?

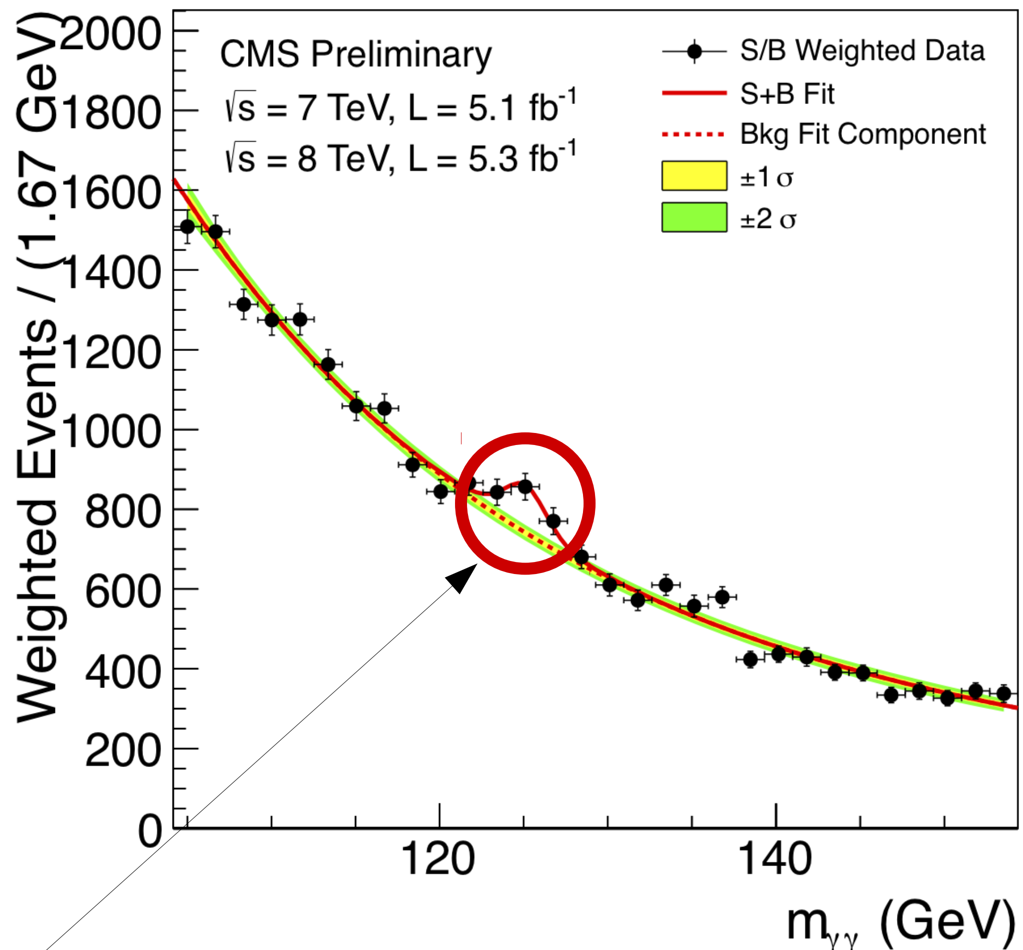




What did we see here?
Is this **really** the Higgs?

What is seen in experiment?





What did we see here?
Is this **really** the Higgs?
And what do we mean by Higgs, anyway?

Physical states

[Fröhlich et al.'80,
't Hooft'80,
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- Physical spectrum: Observable particles
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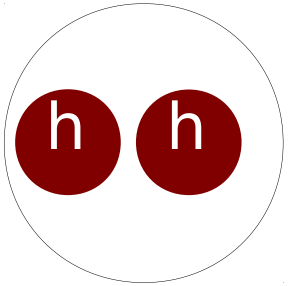

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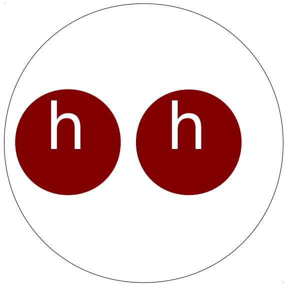

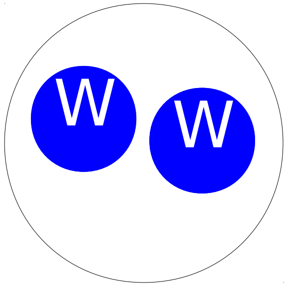

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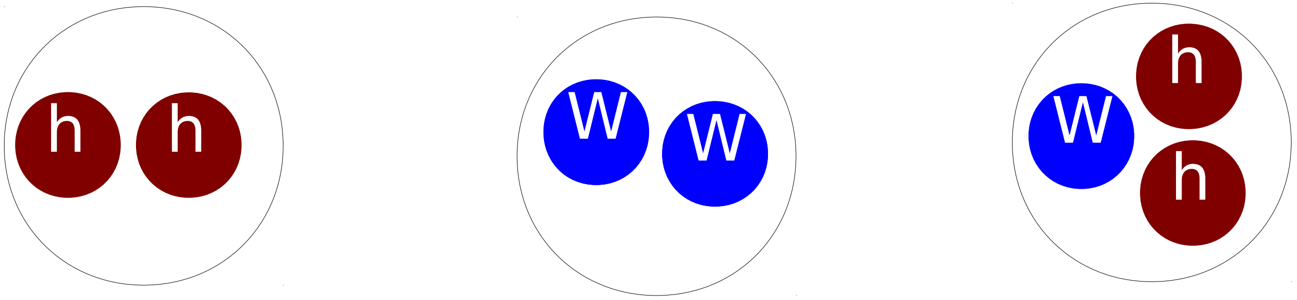

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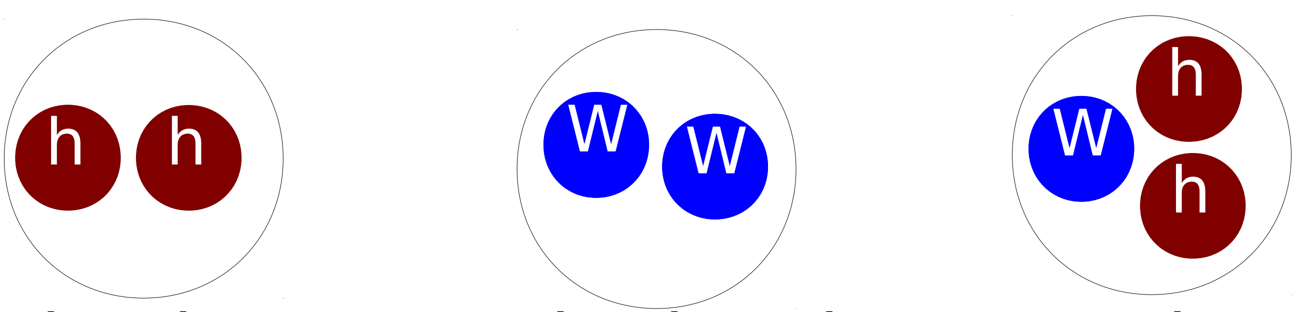

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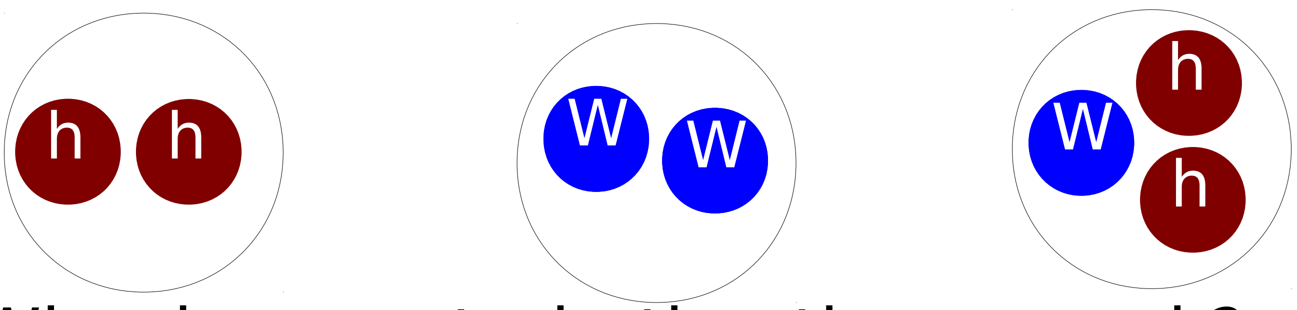

  - Why does perturbation theory work?
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Why it does not matter in the standard model

Introducing gauge-invariant perturbation theory

Masses of the Higgs and the W/Z

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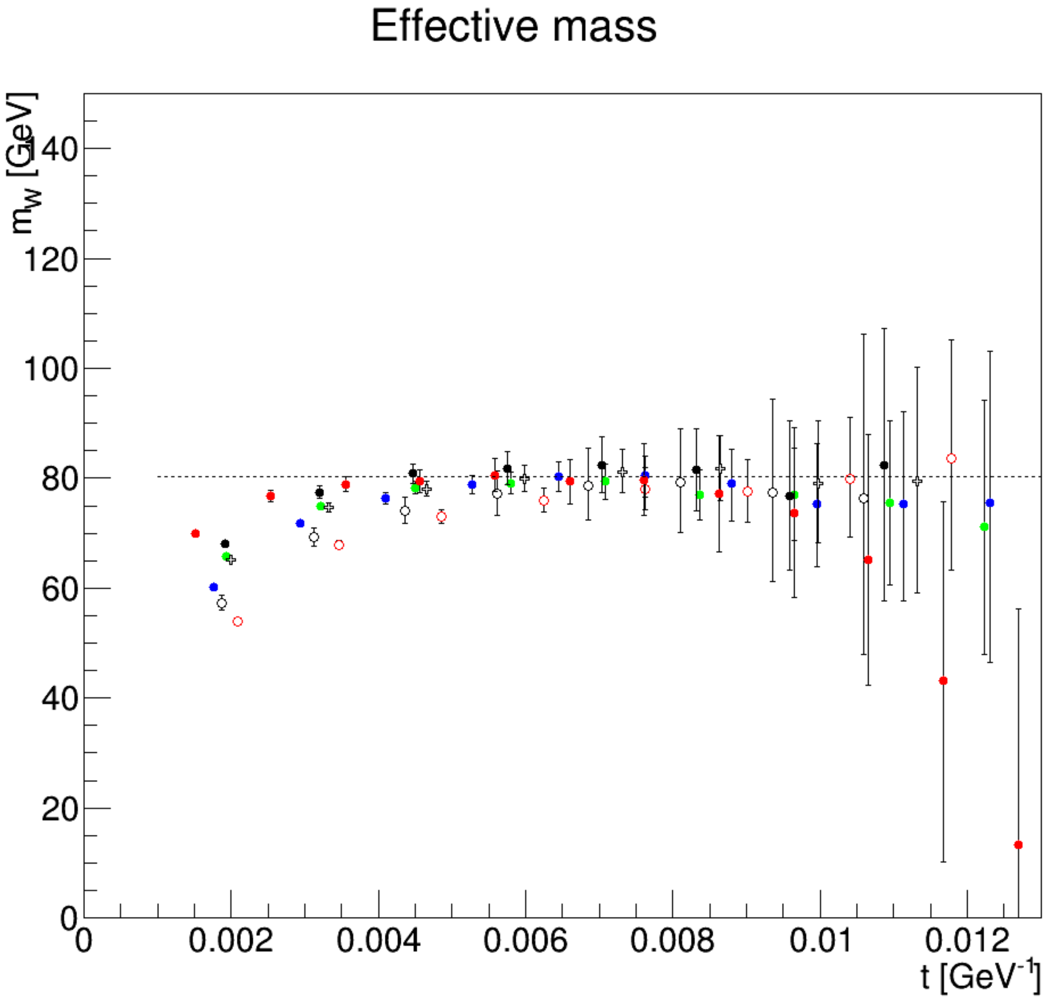

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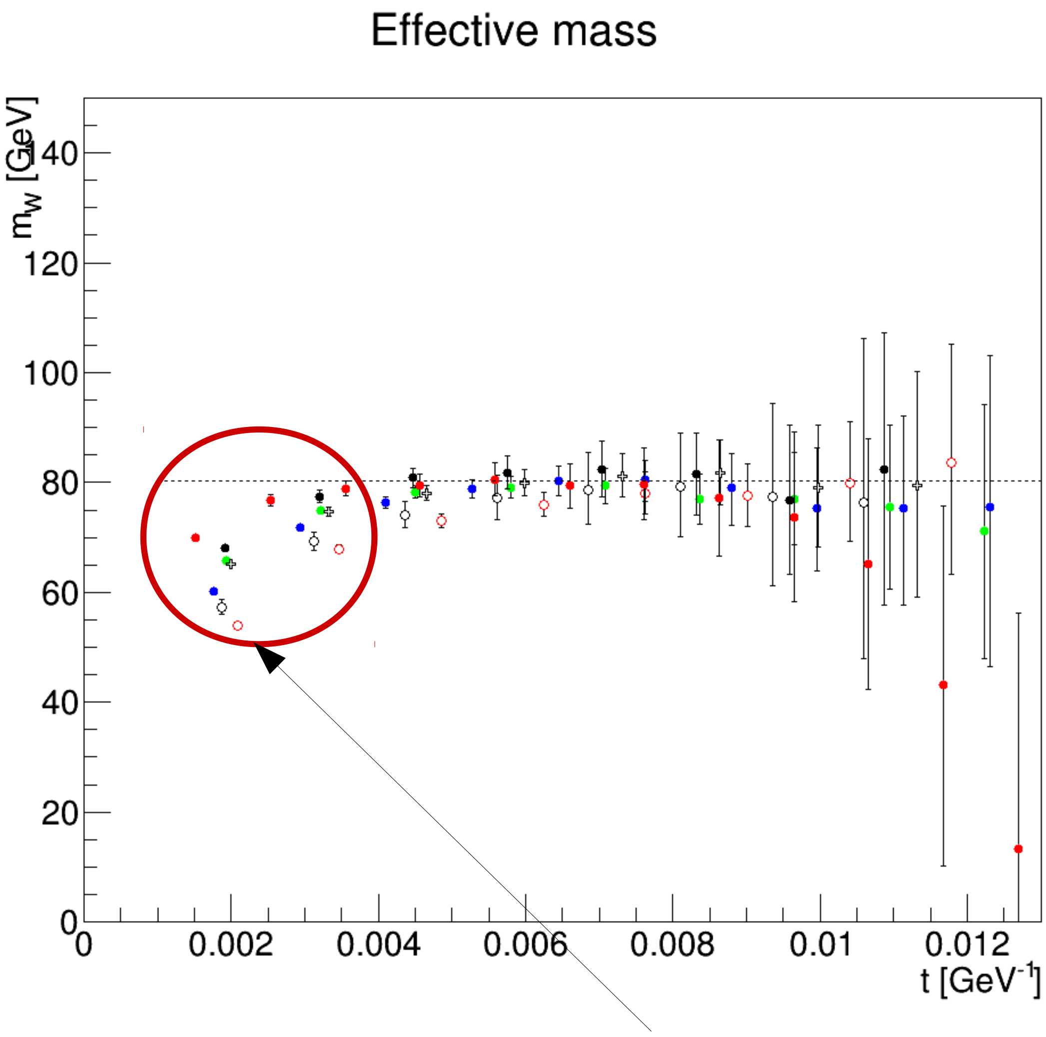

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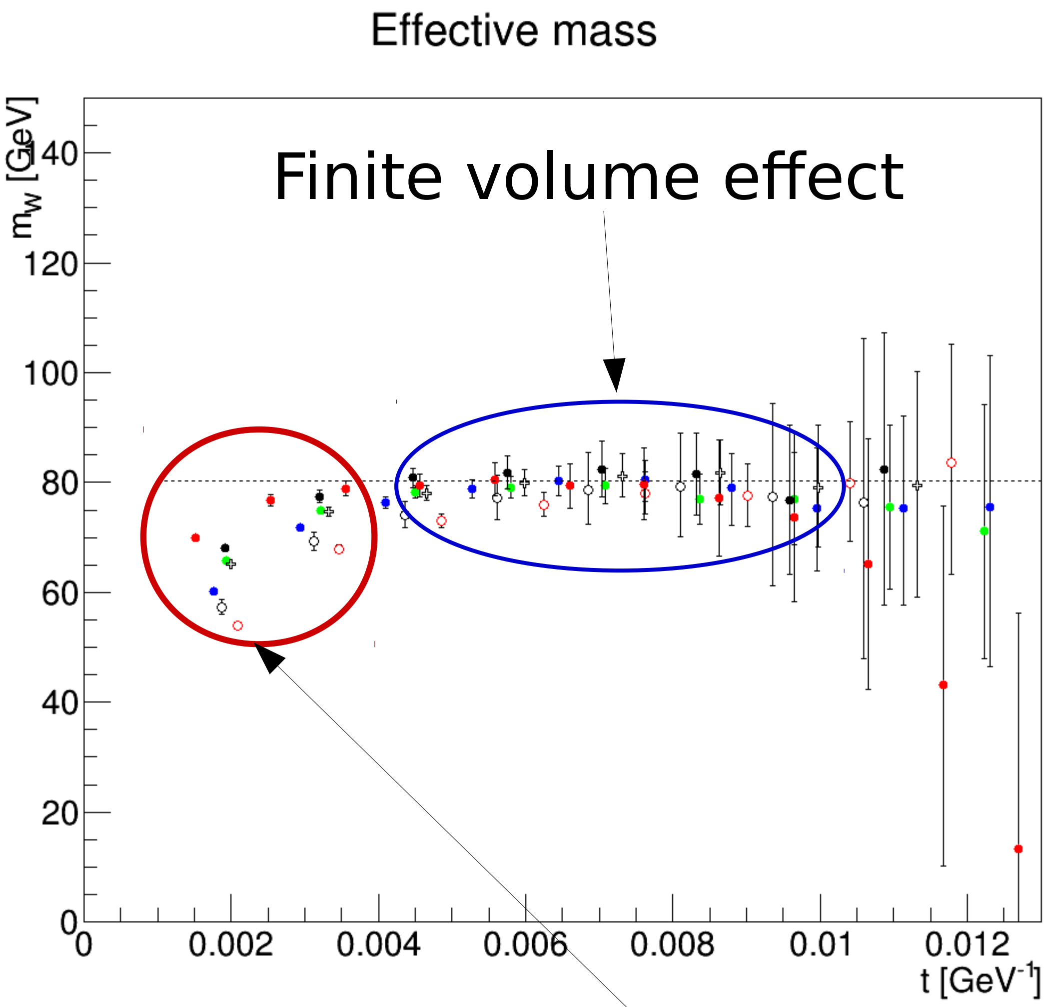

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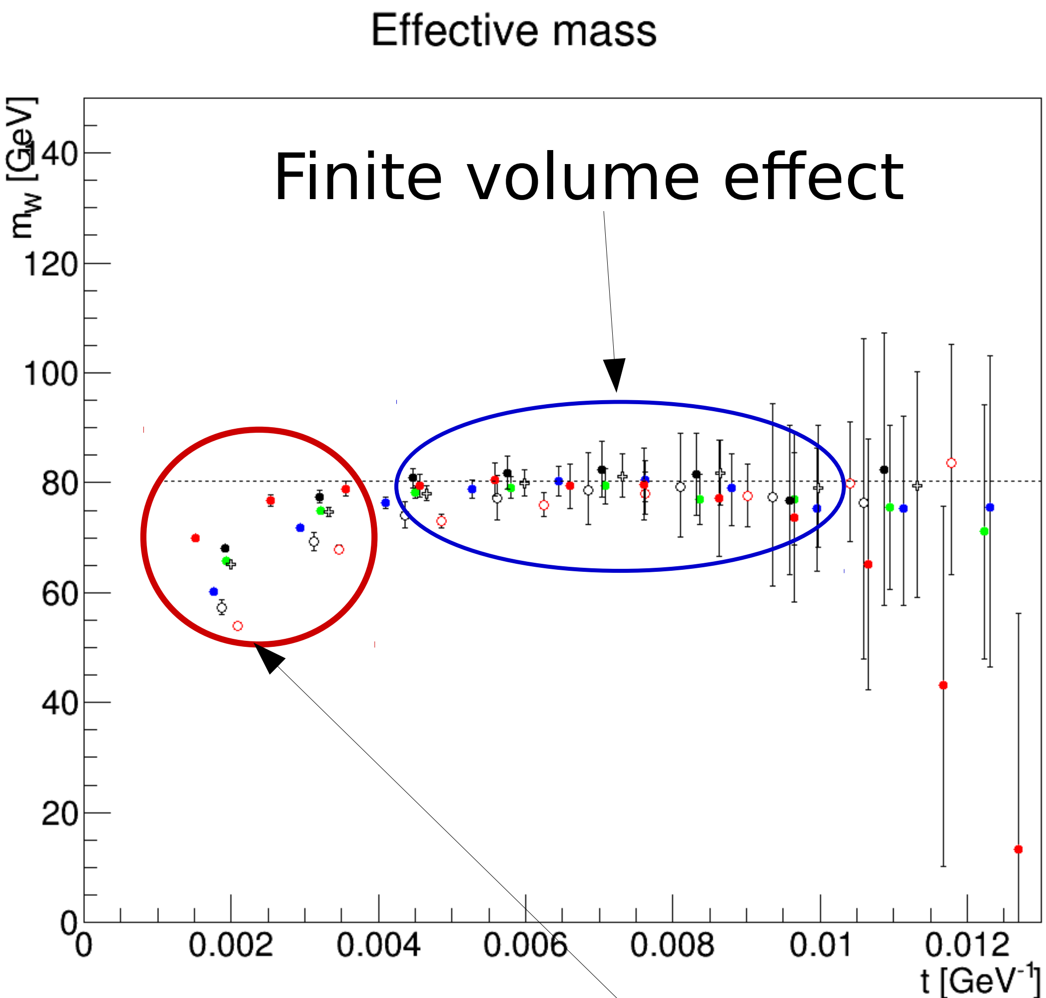

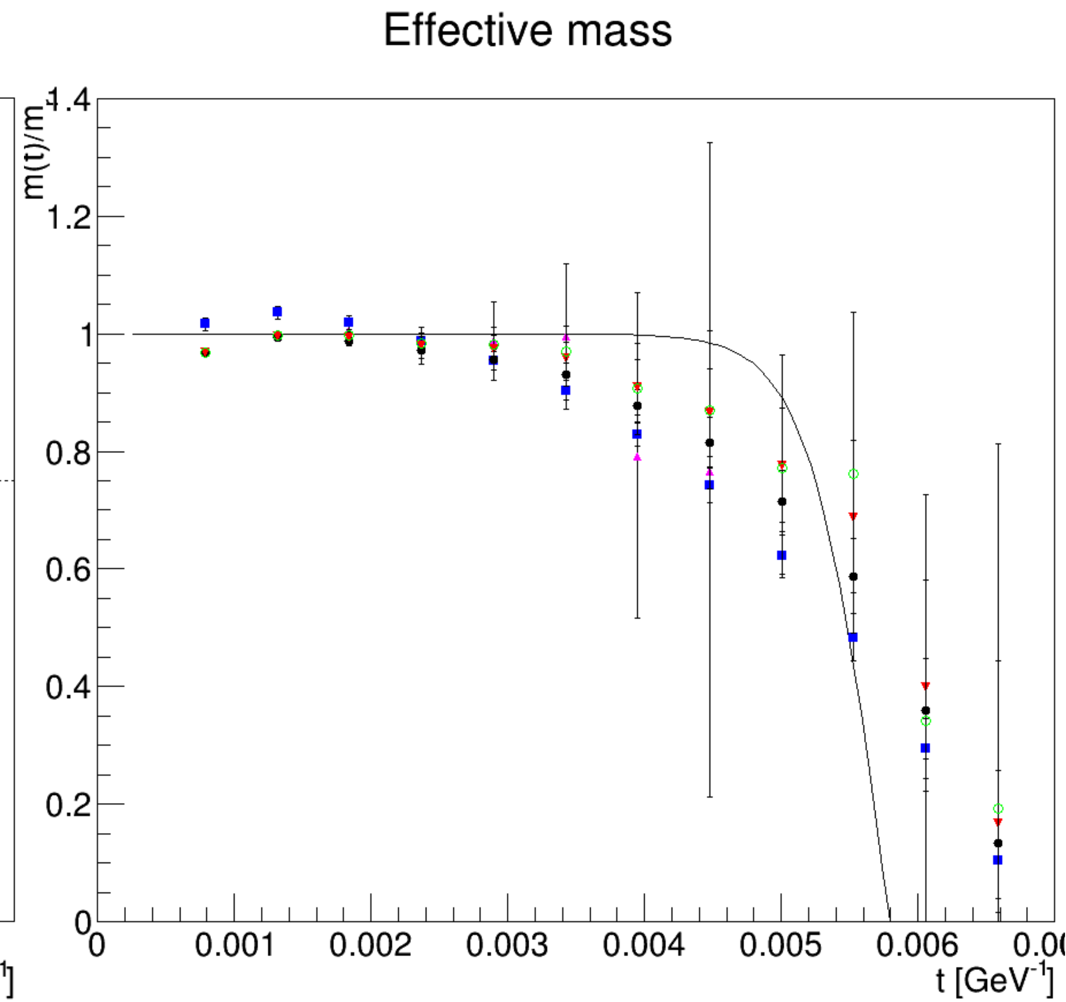

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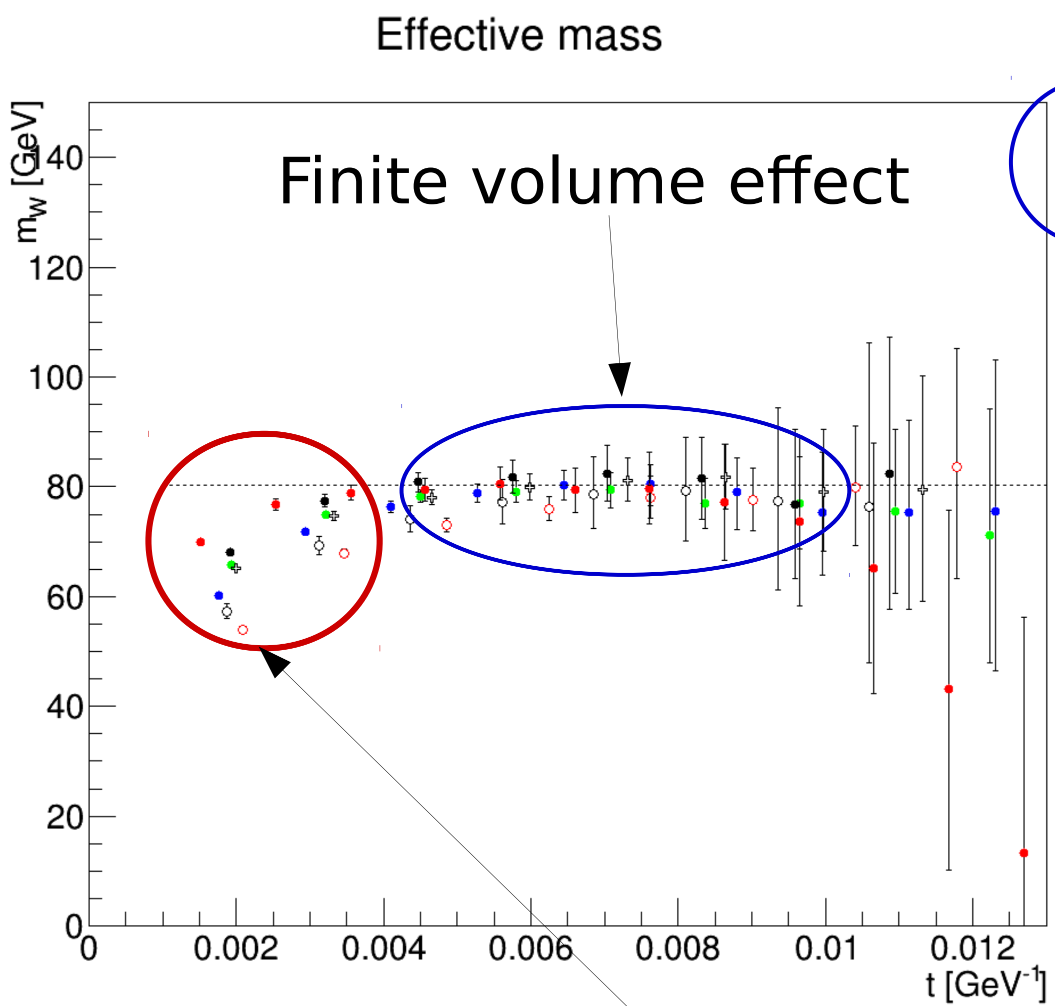

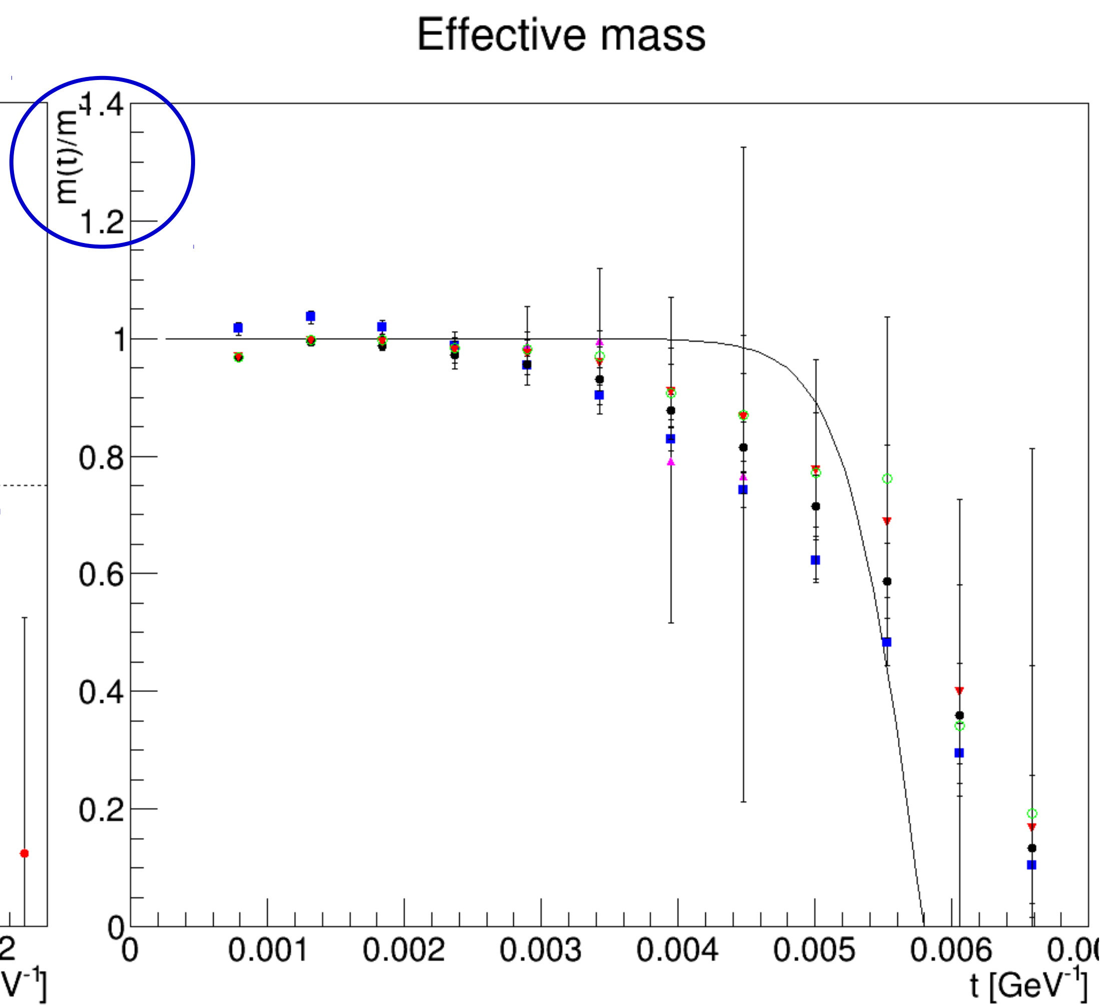

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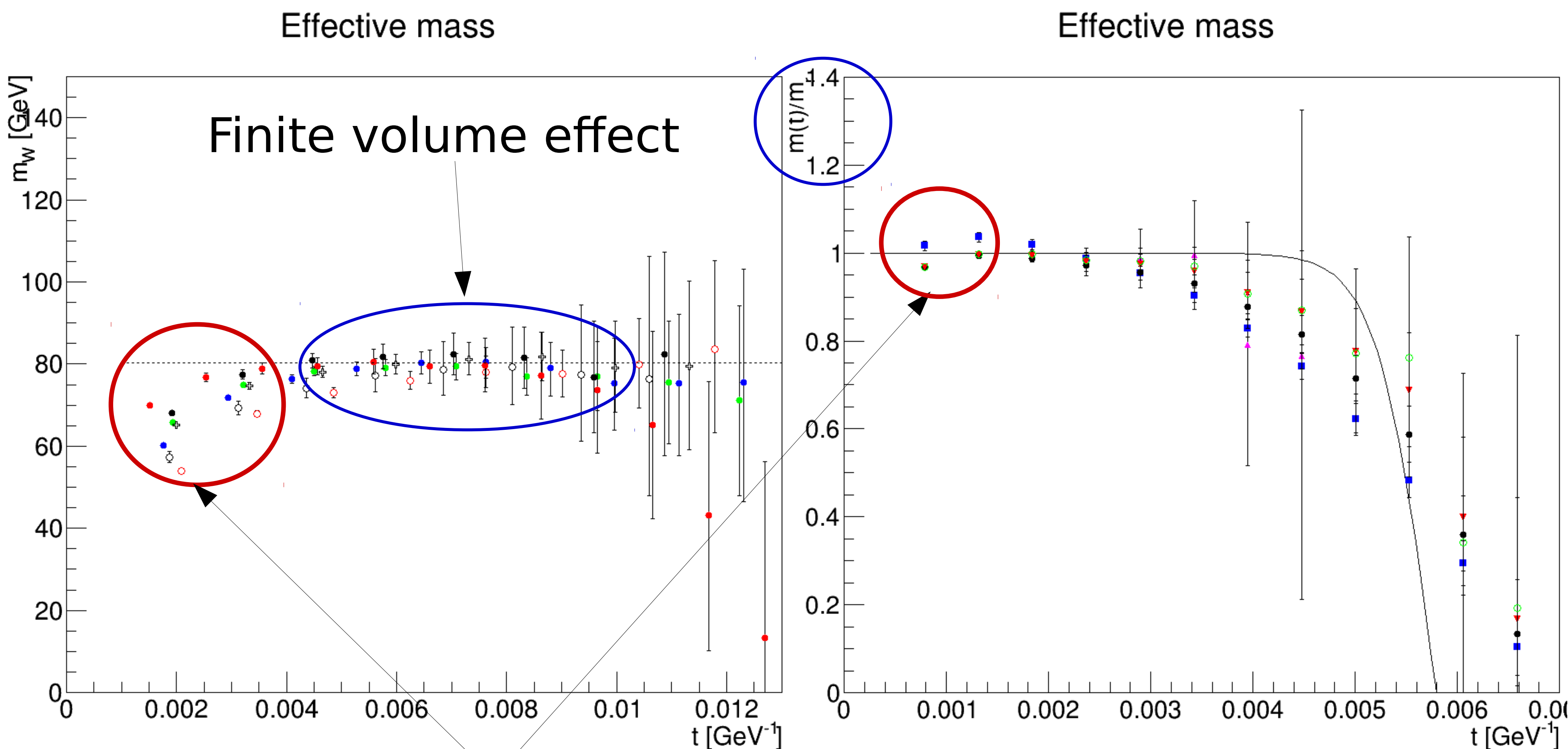

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Intermission

The W mass and QCD

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Contribution to the W/Z mass

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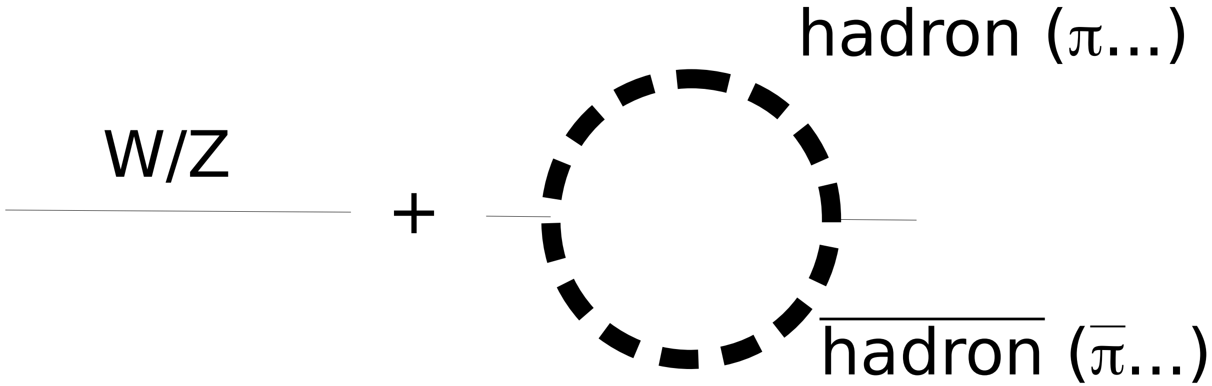

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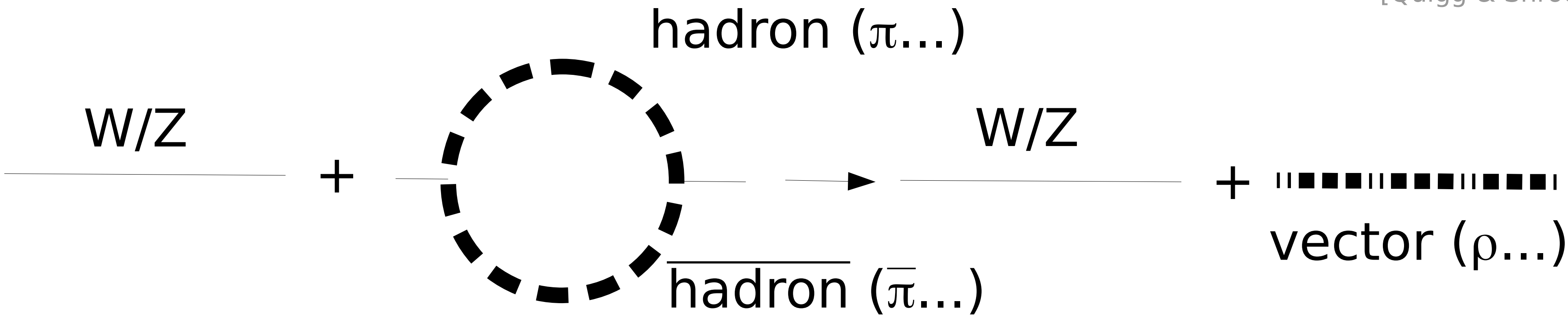

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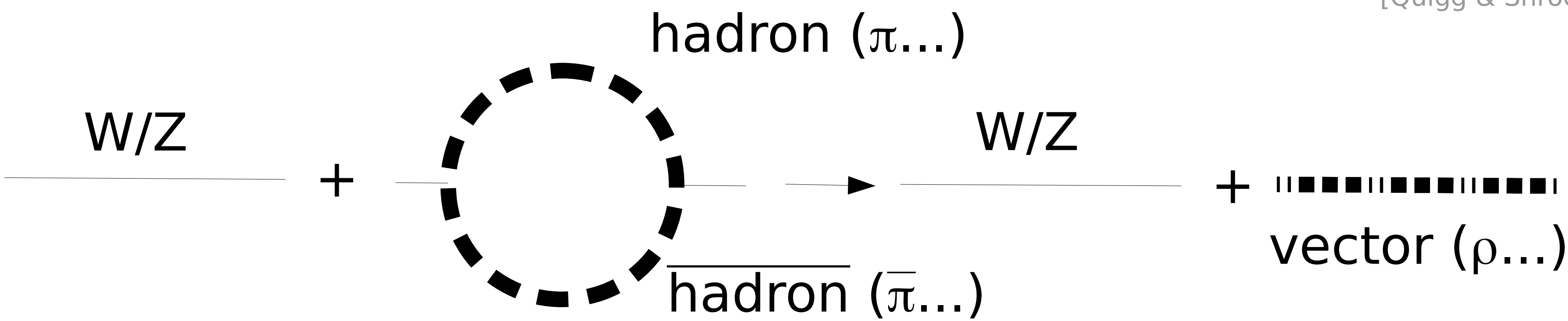

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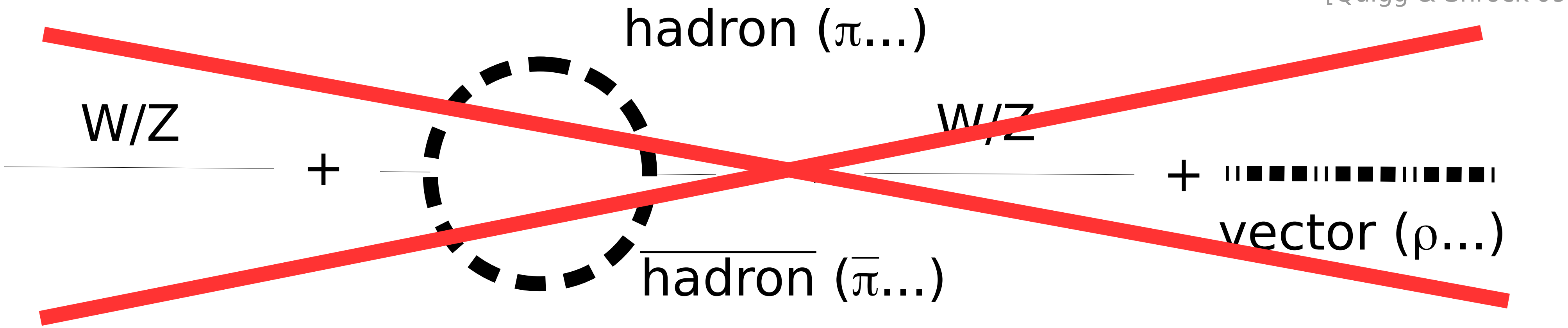

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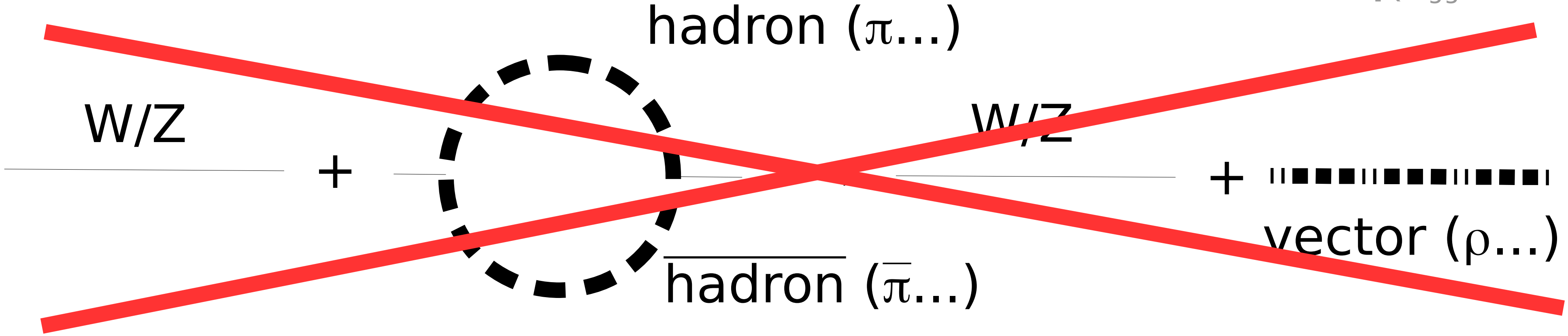

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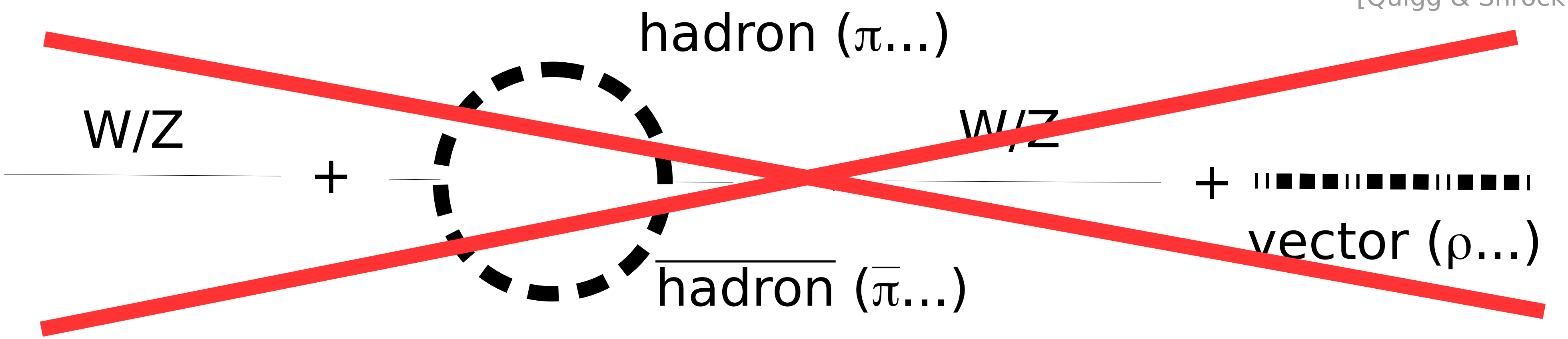

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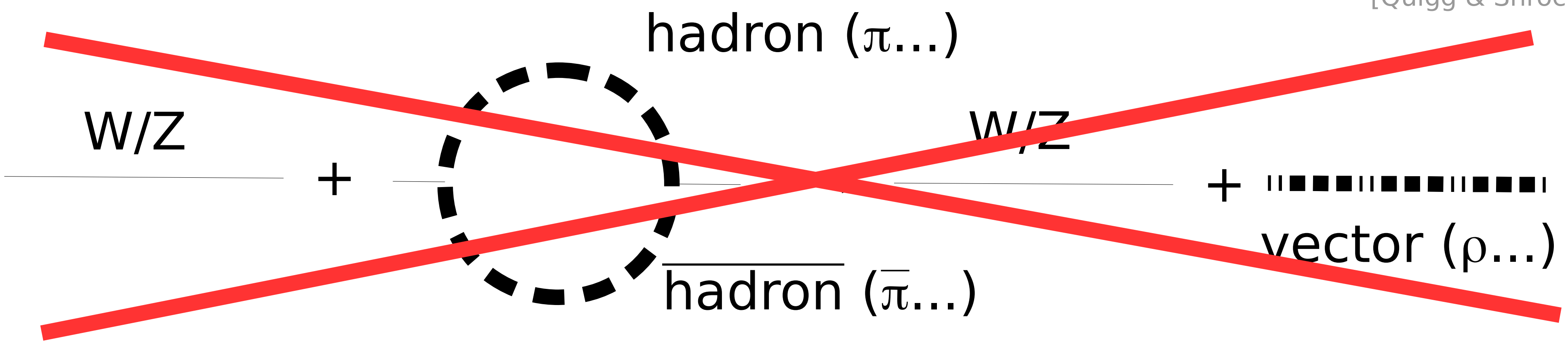

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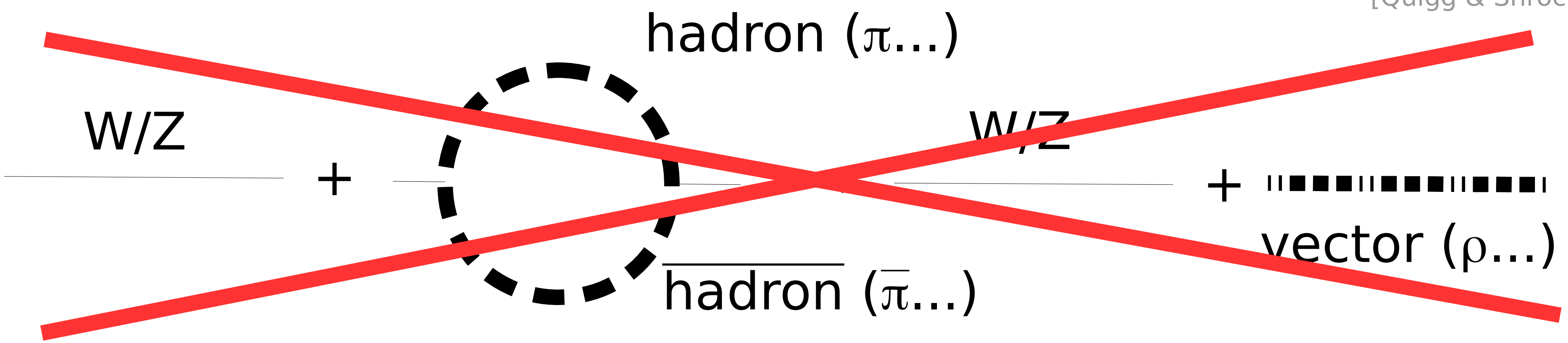

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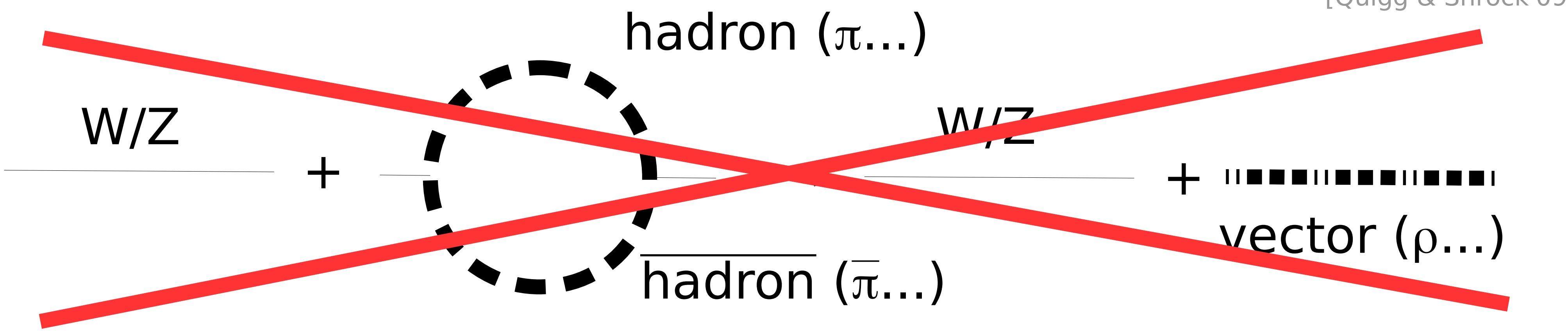

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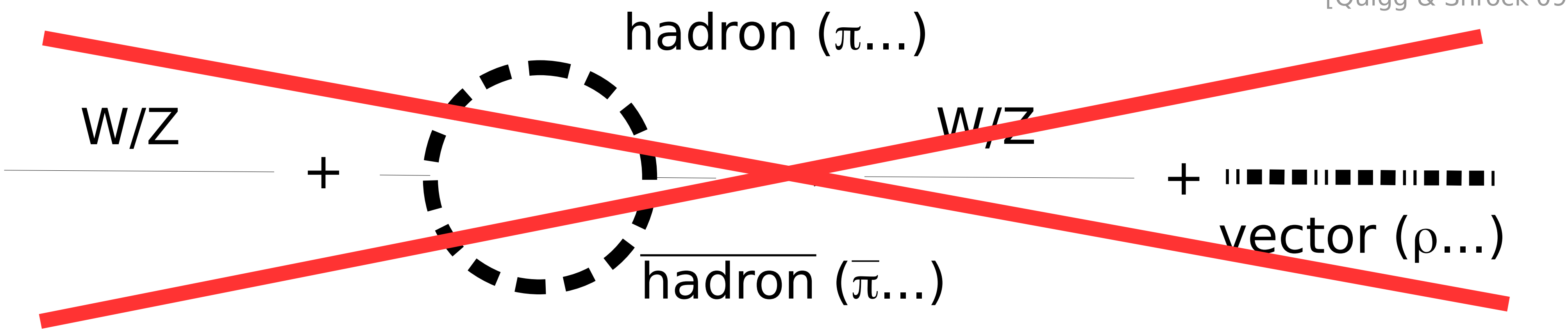

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Back on track

Physical Mass Spectrum

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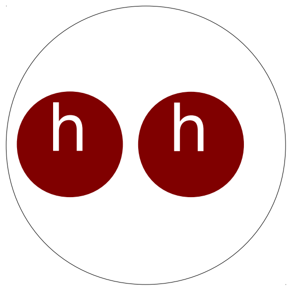

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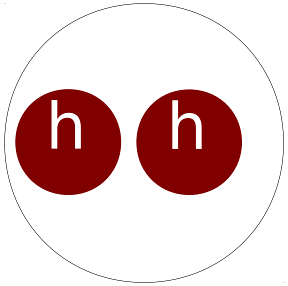

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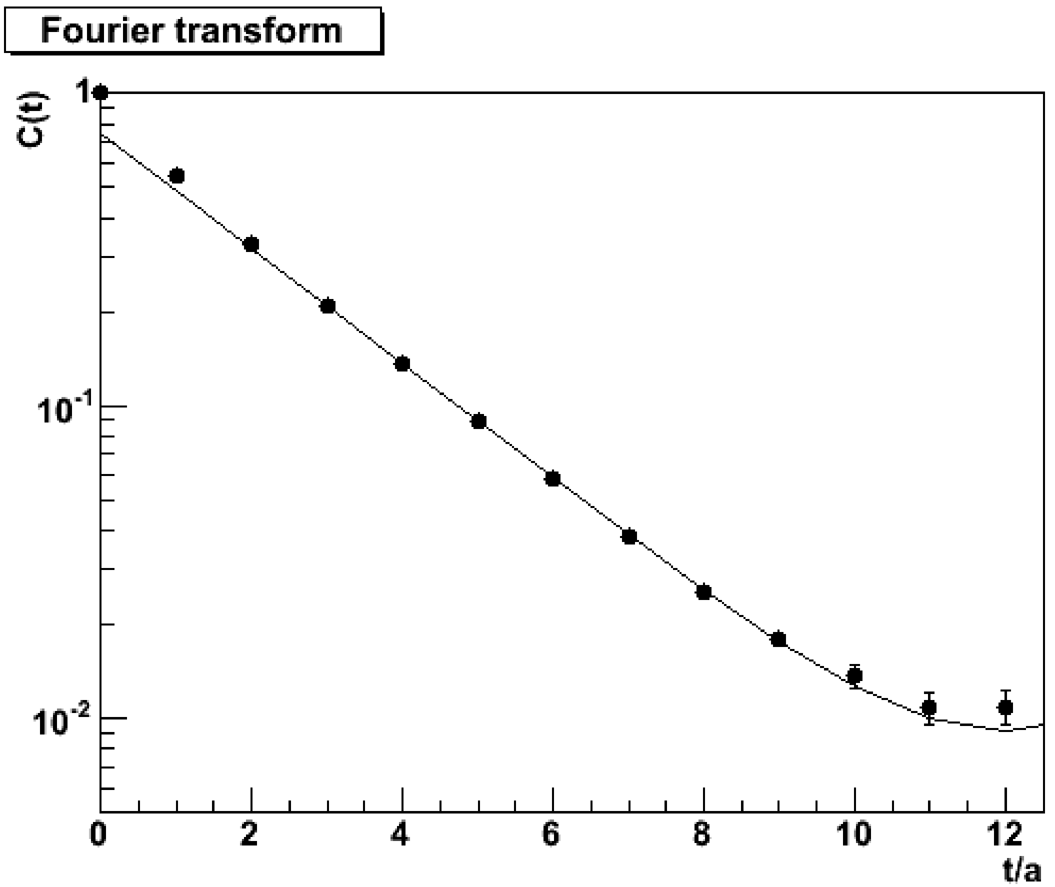

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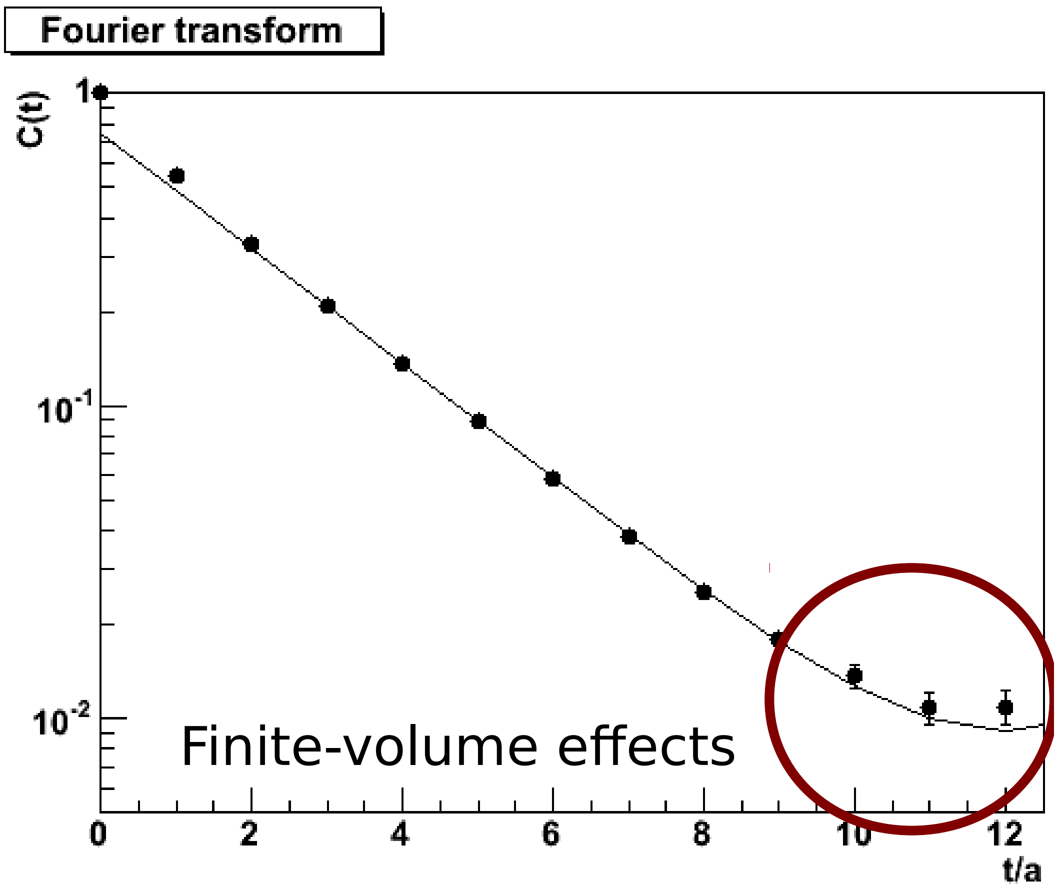

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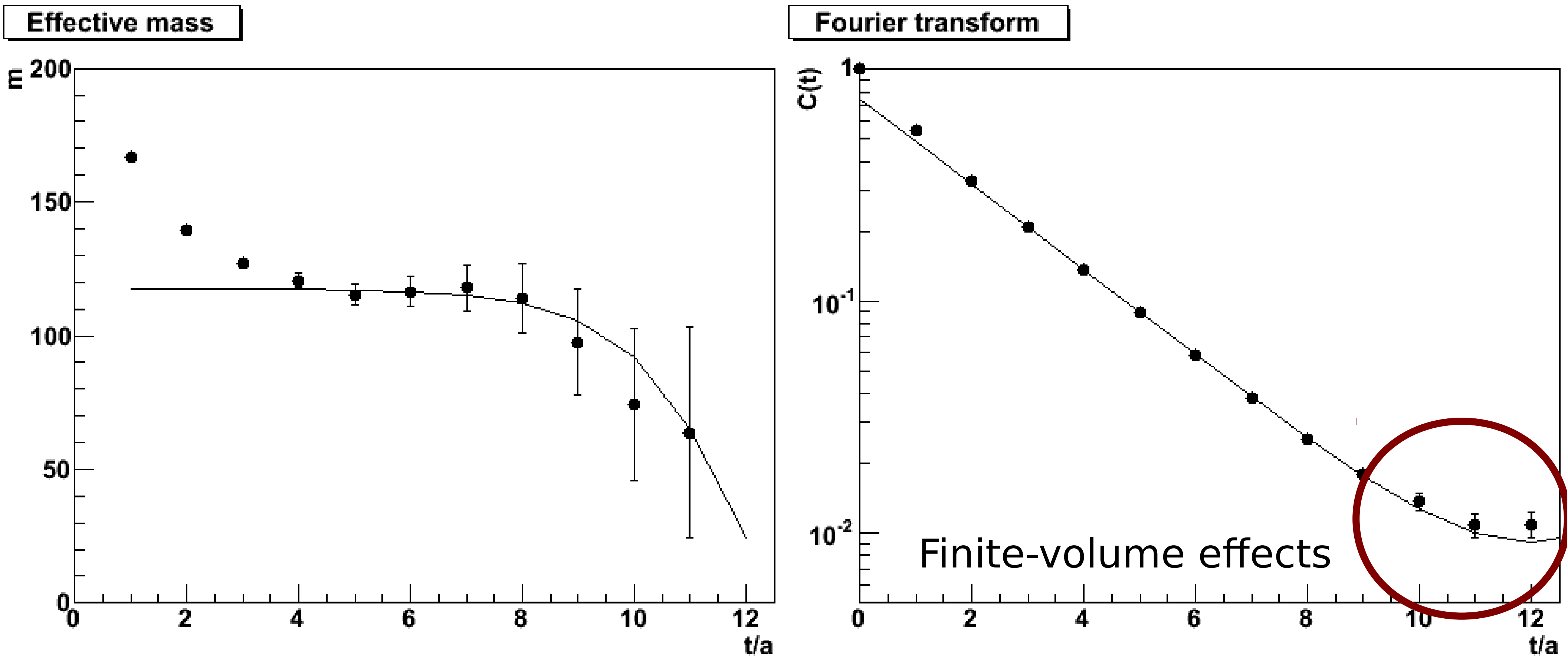

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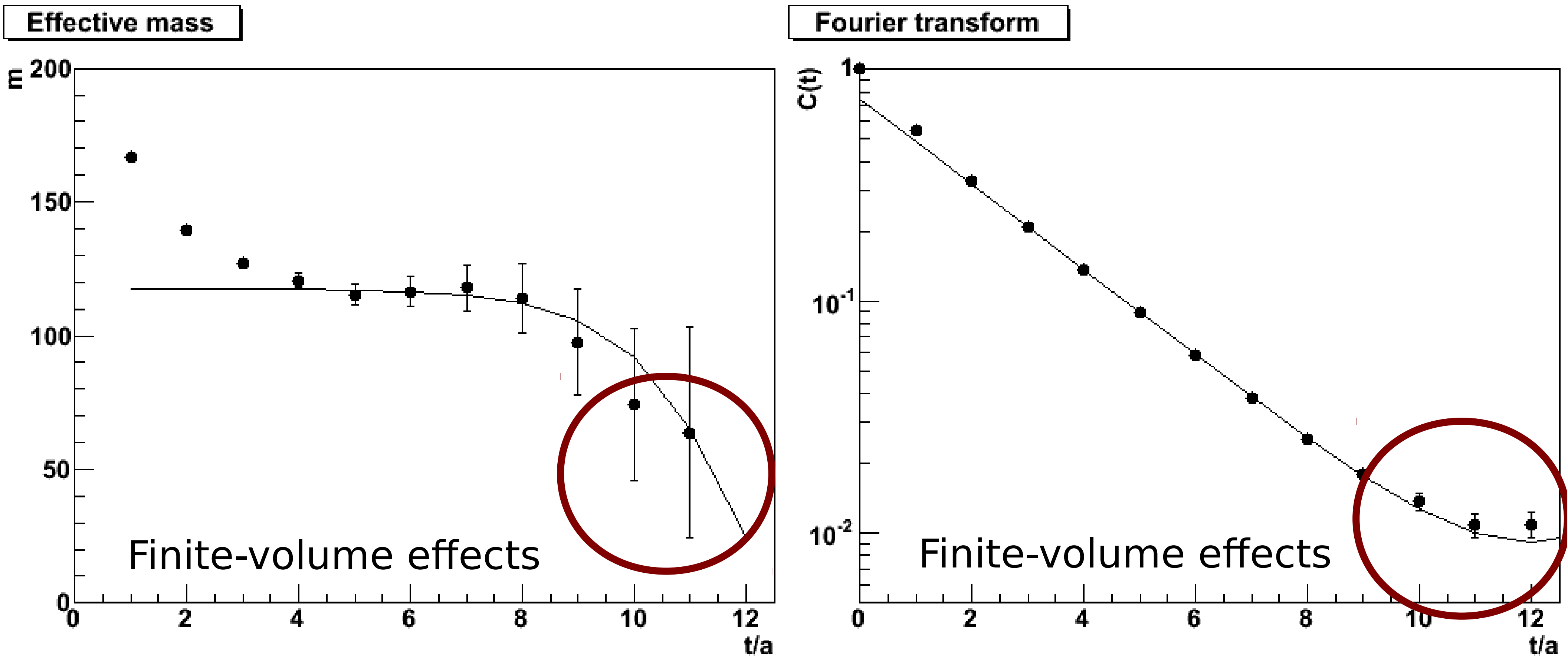

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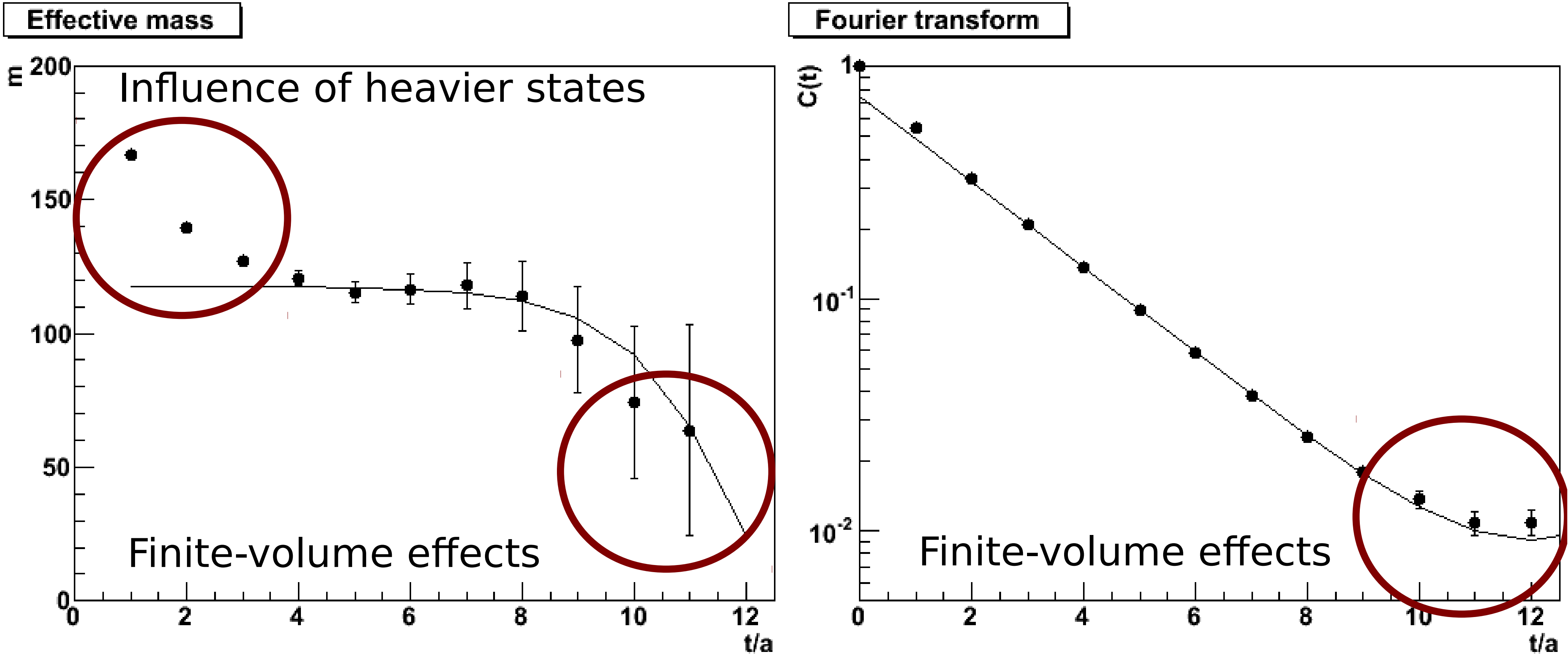

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Mass relation - Higgs

[Fröhlich et al.'80
Maas'12, Maas & Mufti'13]

- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
- Coincidence? No.
  - Duality between elementary states and bound states
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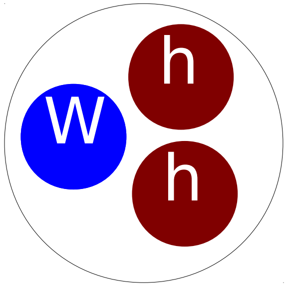
- Fröhlich-Morchio-Strocchi (FMS) mechanism
- Deeply-bound relativistic state
  - Mass defect~constituent mass
  - Cannot describe with quantum mechanics
  - Very different from QCD bound states

Isovector-vector state



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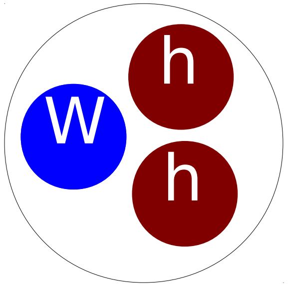

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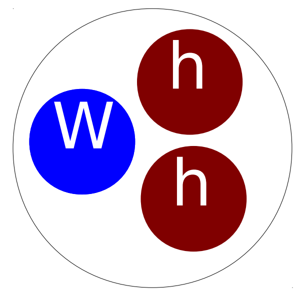

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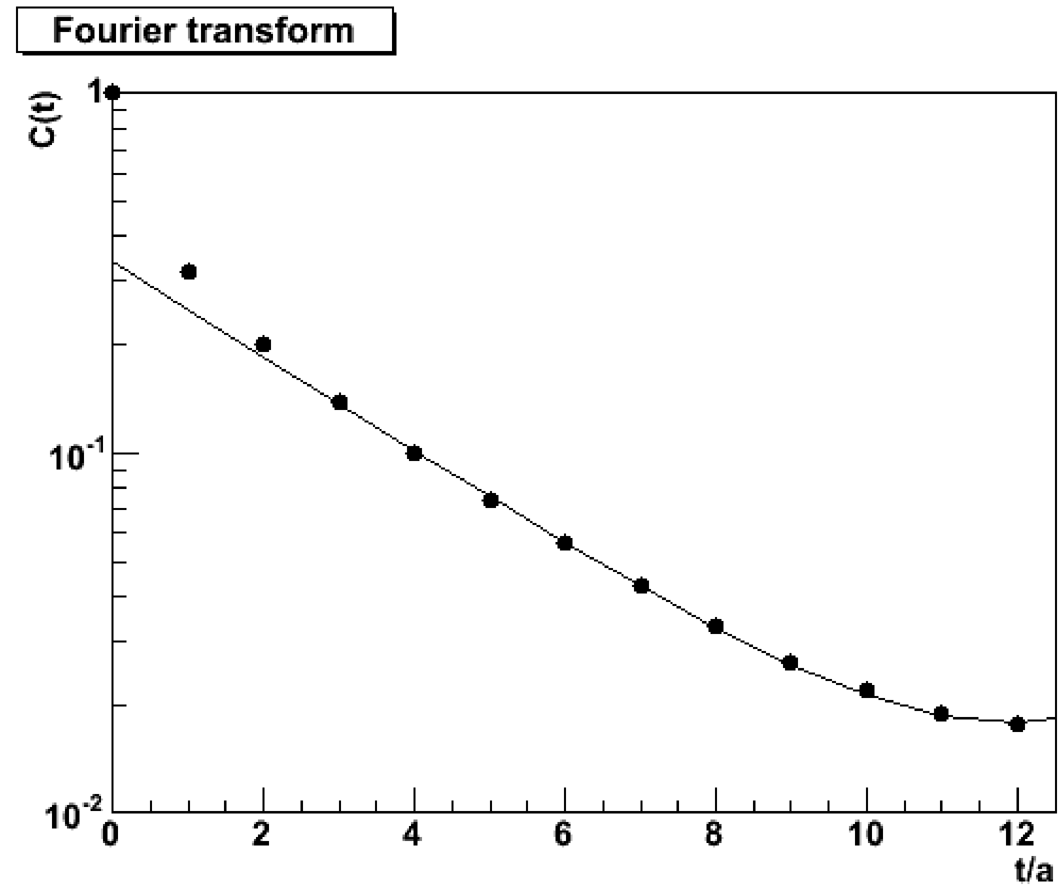

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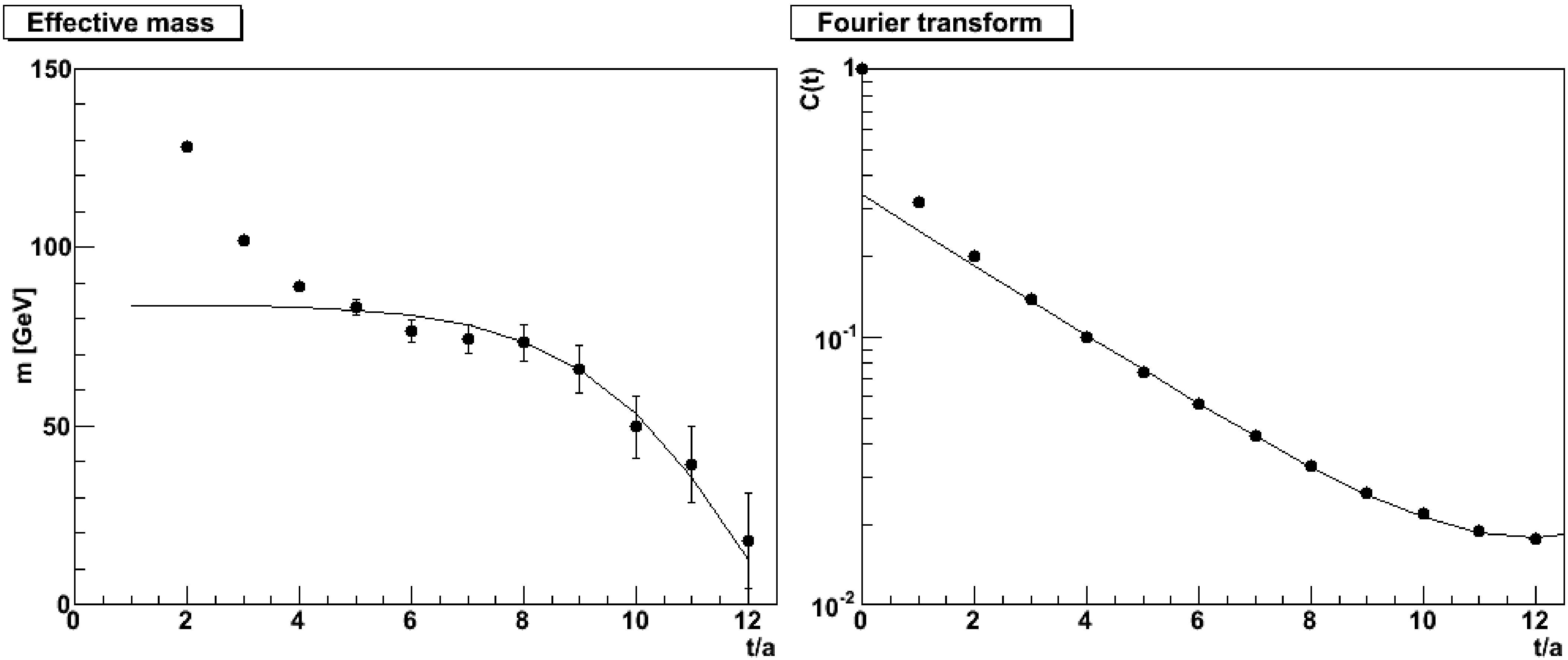

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  - Mass about 80 GeV

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$$h = v + \eta$$

$$\approx \quad const. + \langle W_\mu(x) W_\mu(y)\rangle + O(\eta^3)$$

$$\partial v = 0$$

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  - Exchanges a gauge for a custodial triplet

The remainder of the standard model

Is there an experimental lever to see all this?

What about the rest?

[Fröhlich et al.'80,
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- QED
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- Leptons
  - Flavor is actually weak gauge interaction

Flavor

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  - Global SU(3) generation
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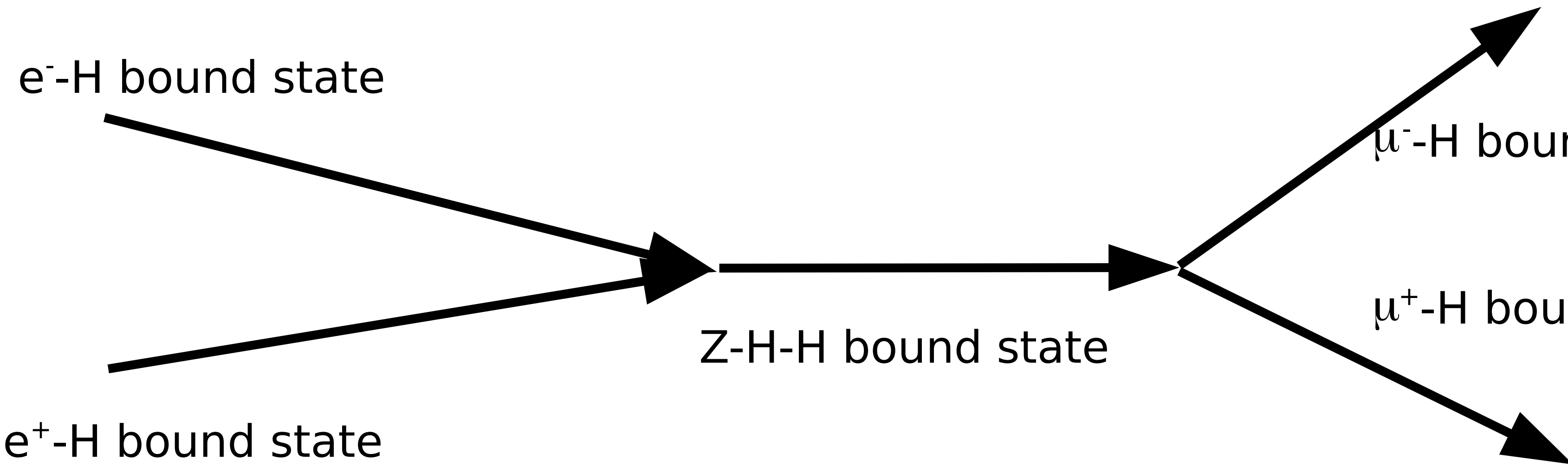
How events looks like (LEP/ILC)

[Maas'12]



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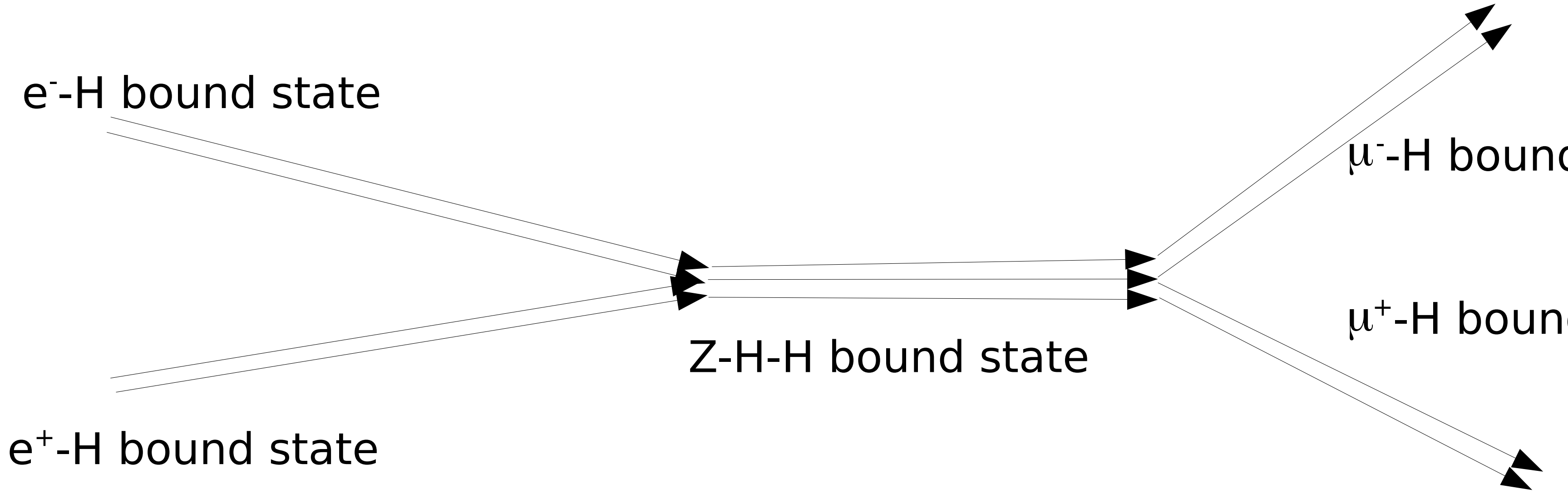

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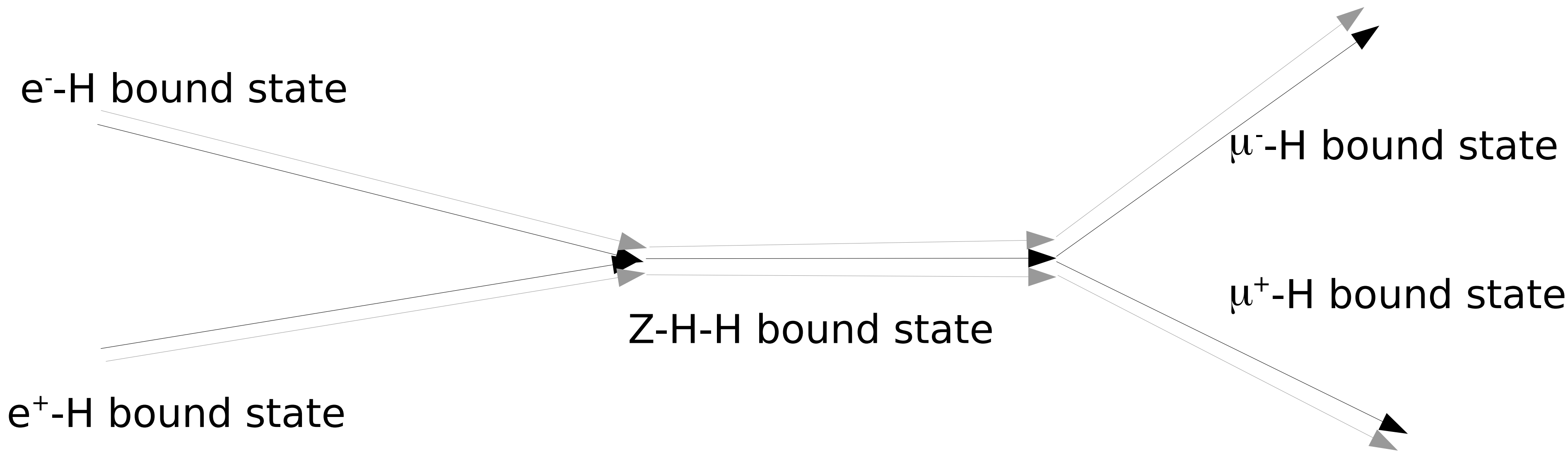

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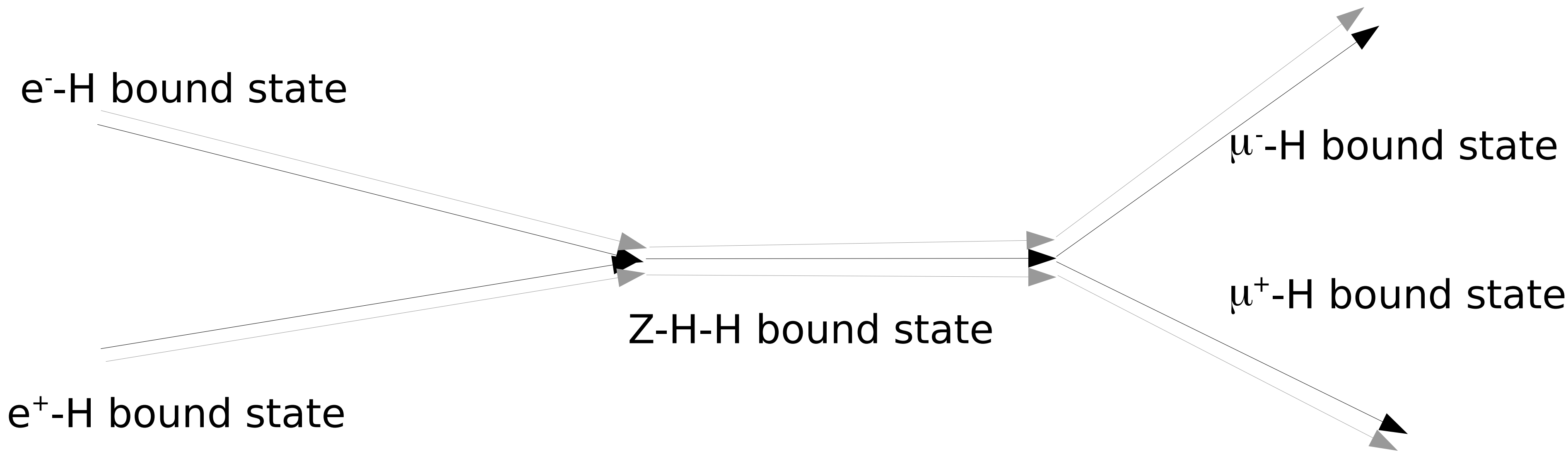

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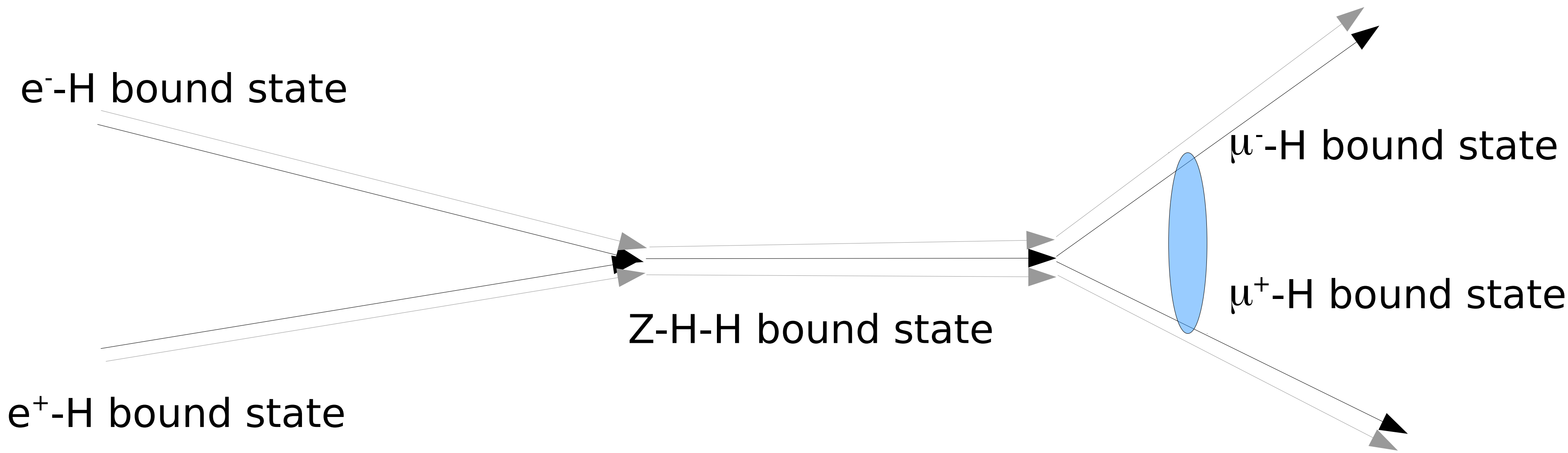

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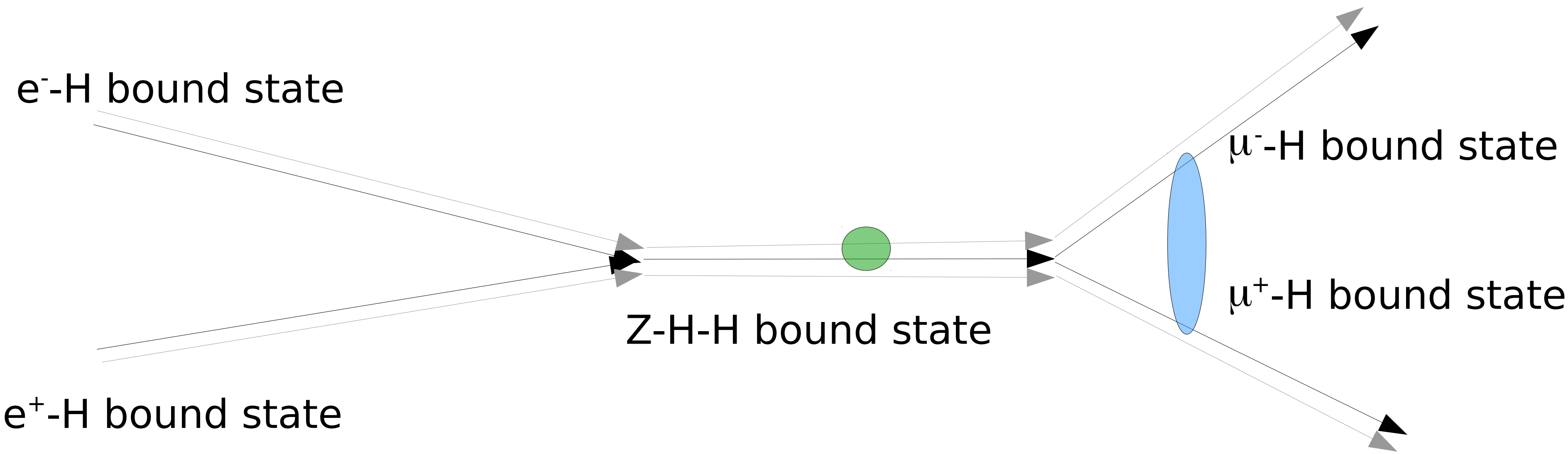

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  - New ones: Small, require more sensitivity

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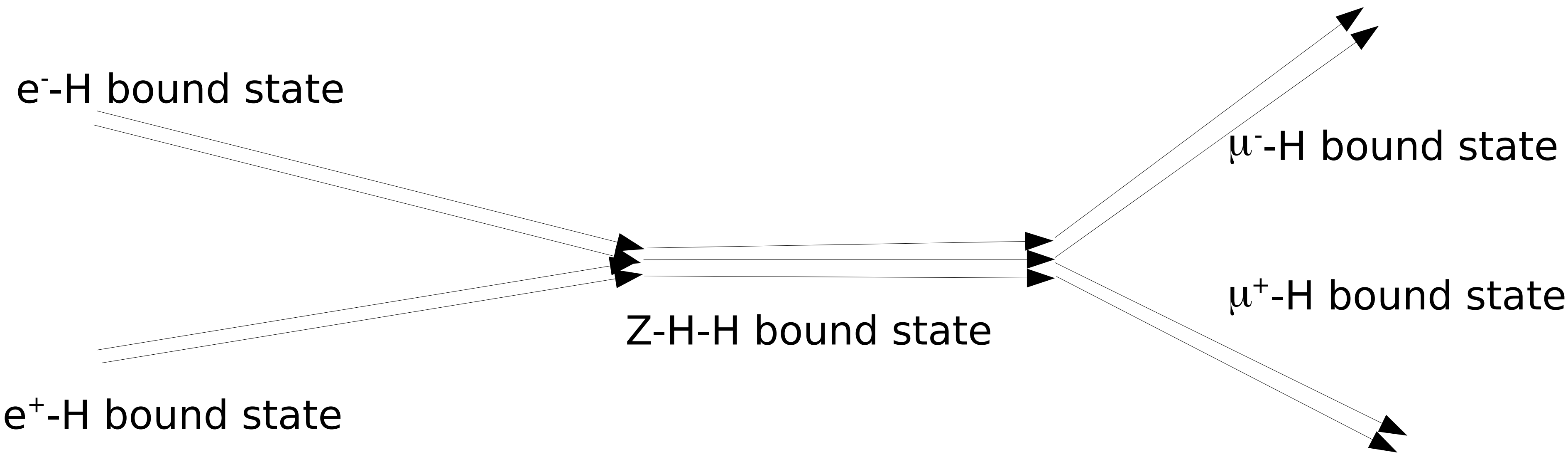

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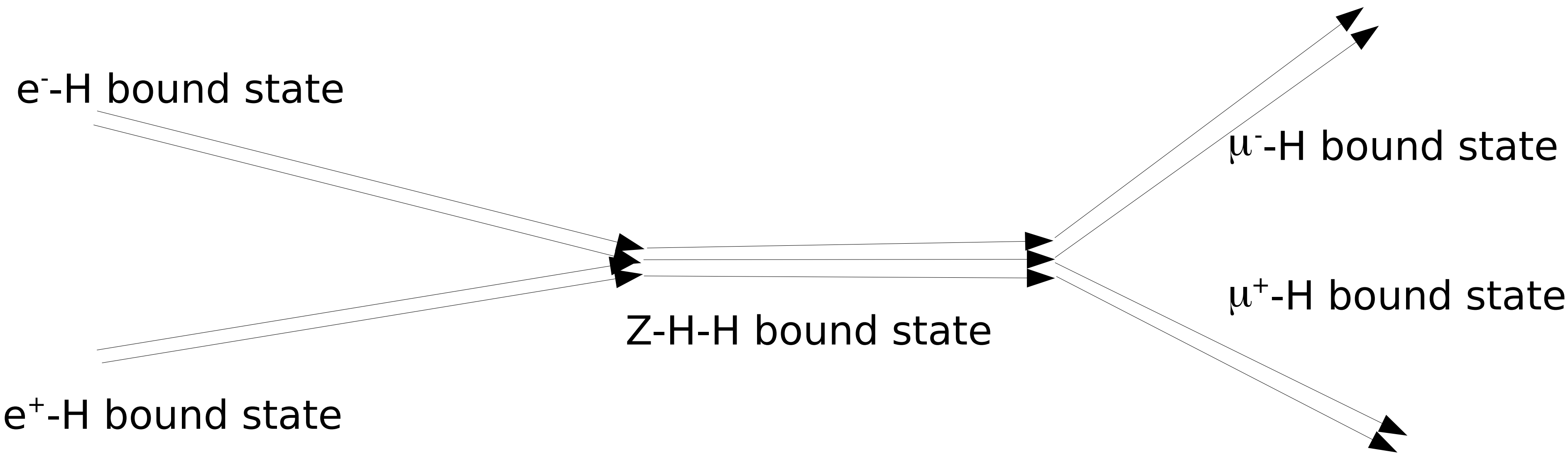

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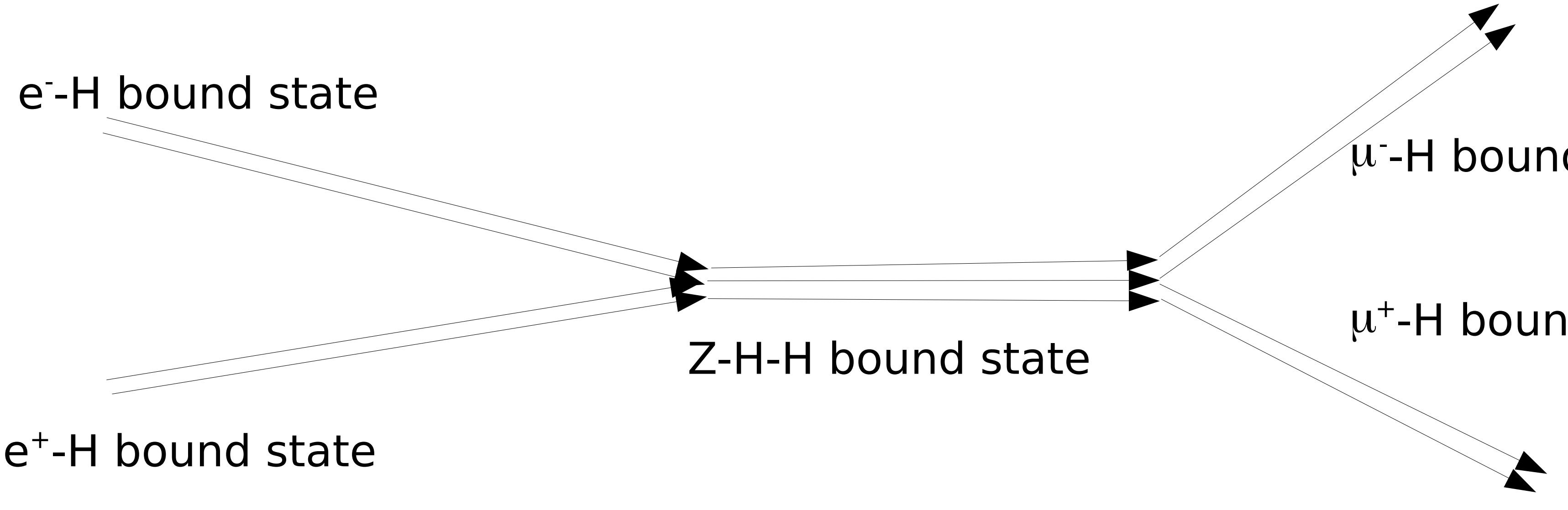

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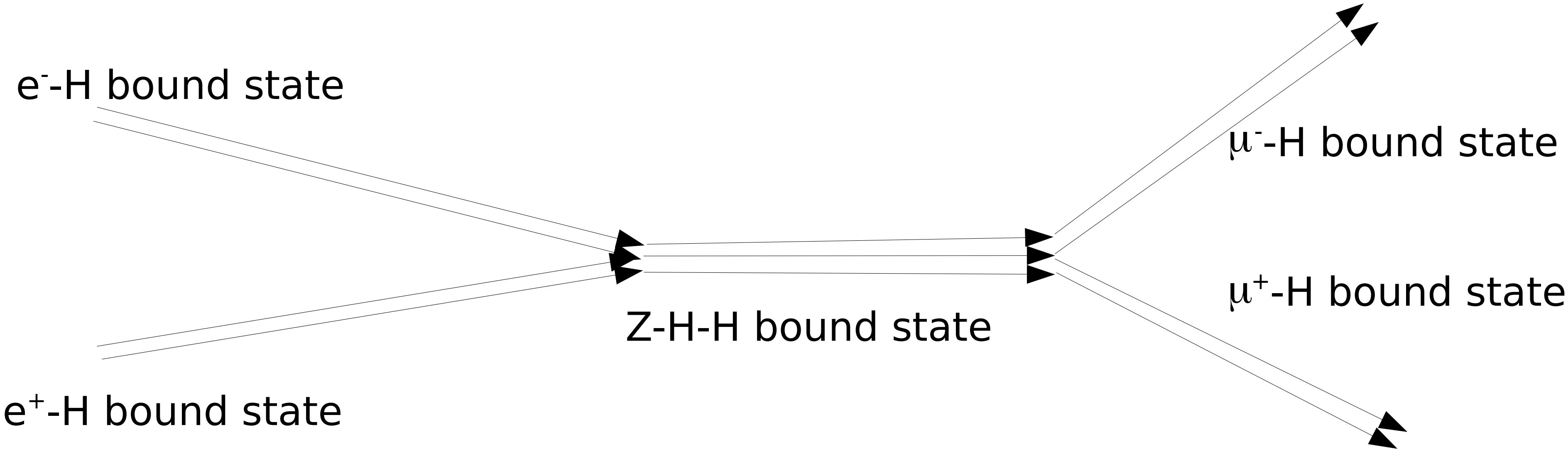

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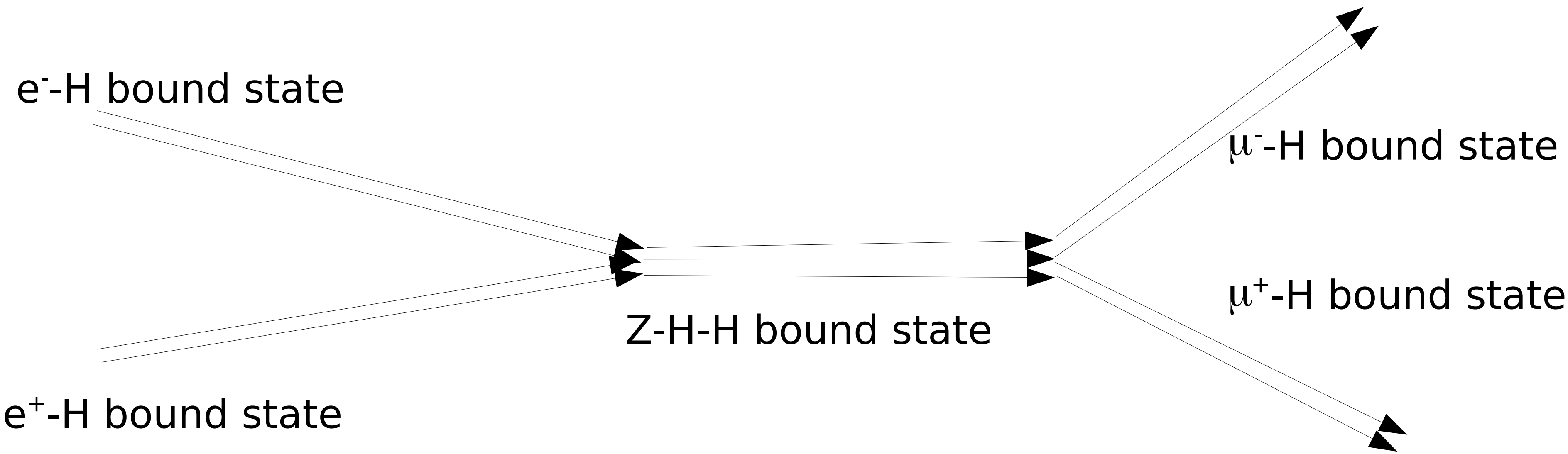

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  - Modification of ordinary contribution

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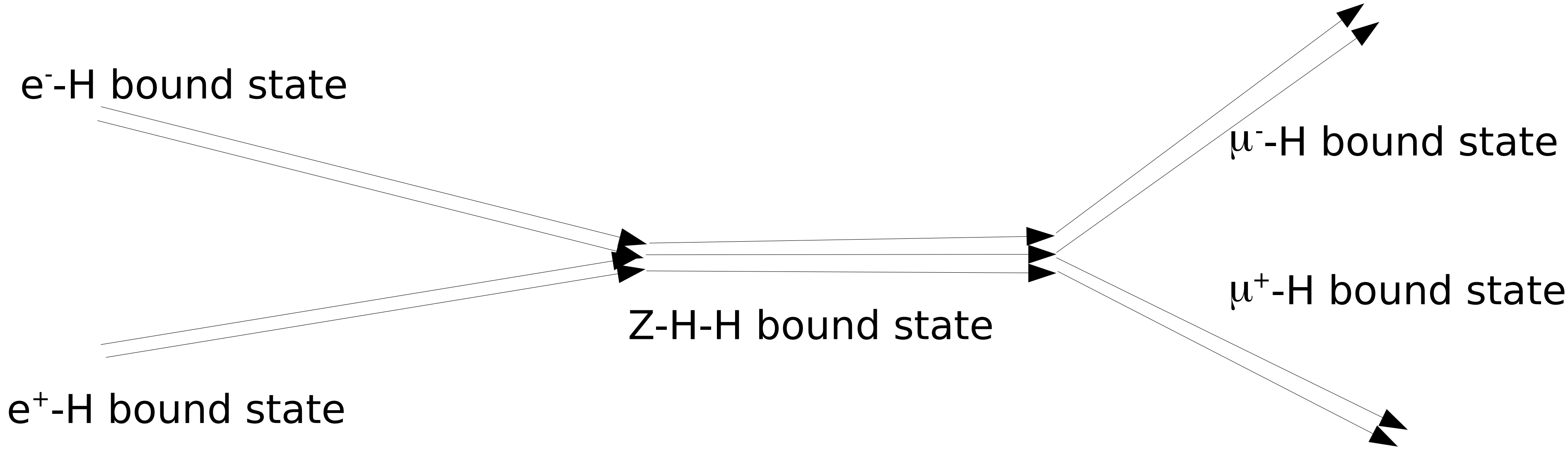

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  - Higgs as initial state

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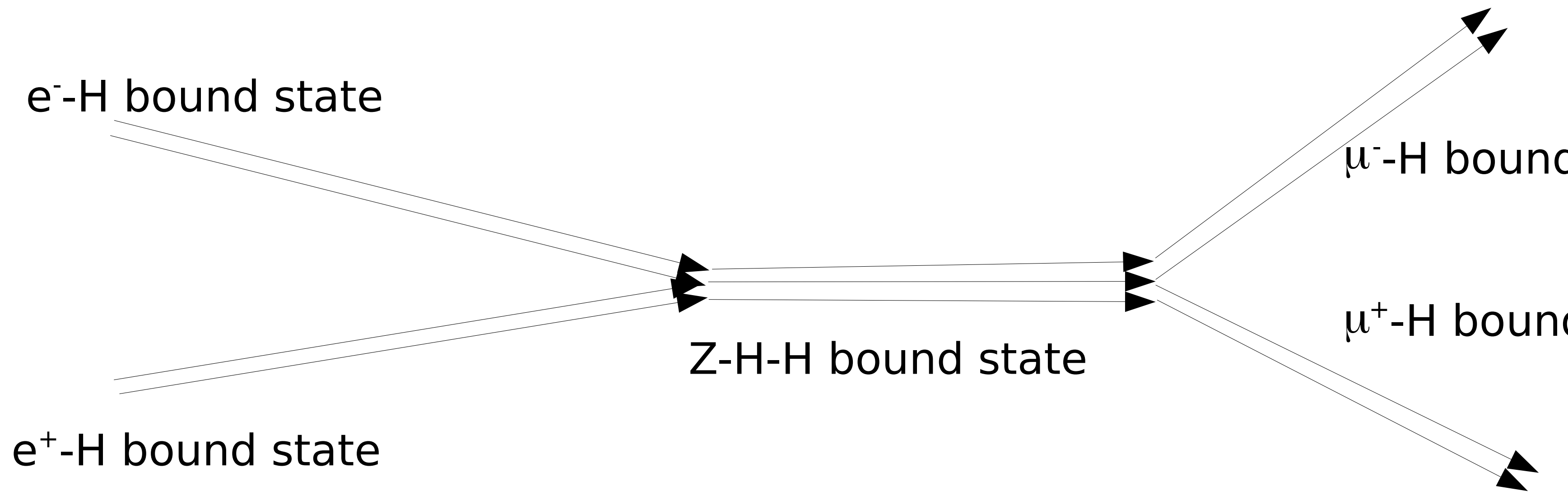

- Description of impact? Gauge-invariant perturbation theory!

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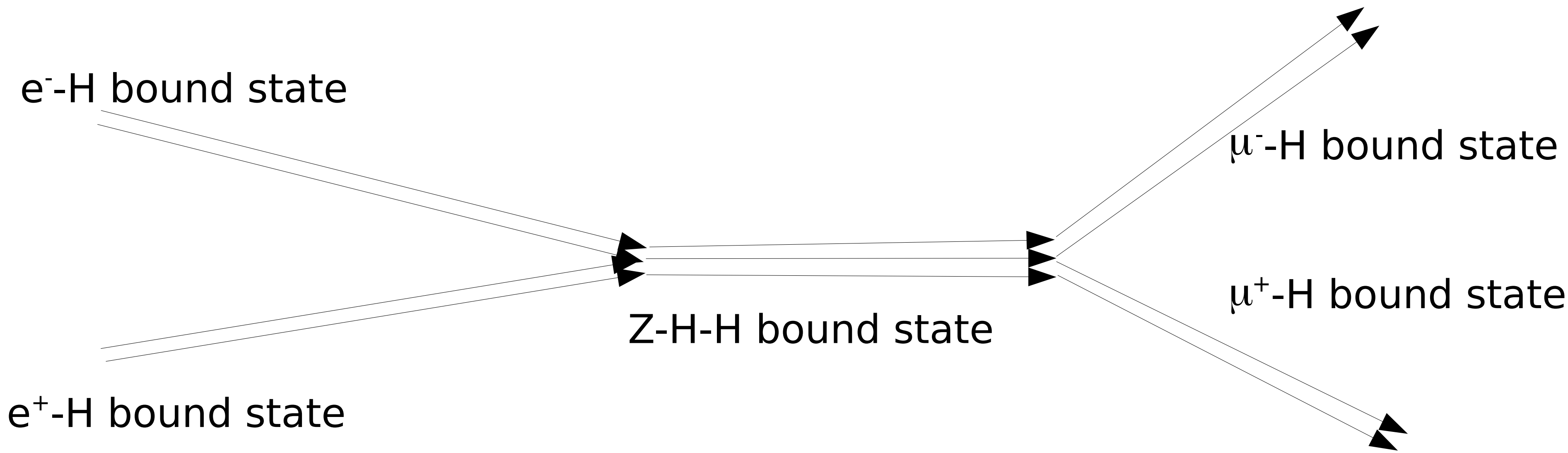

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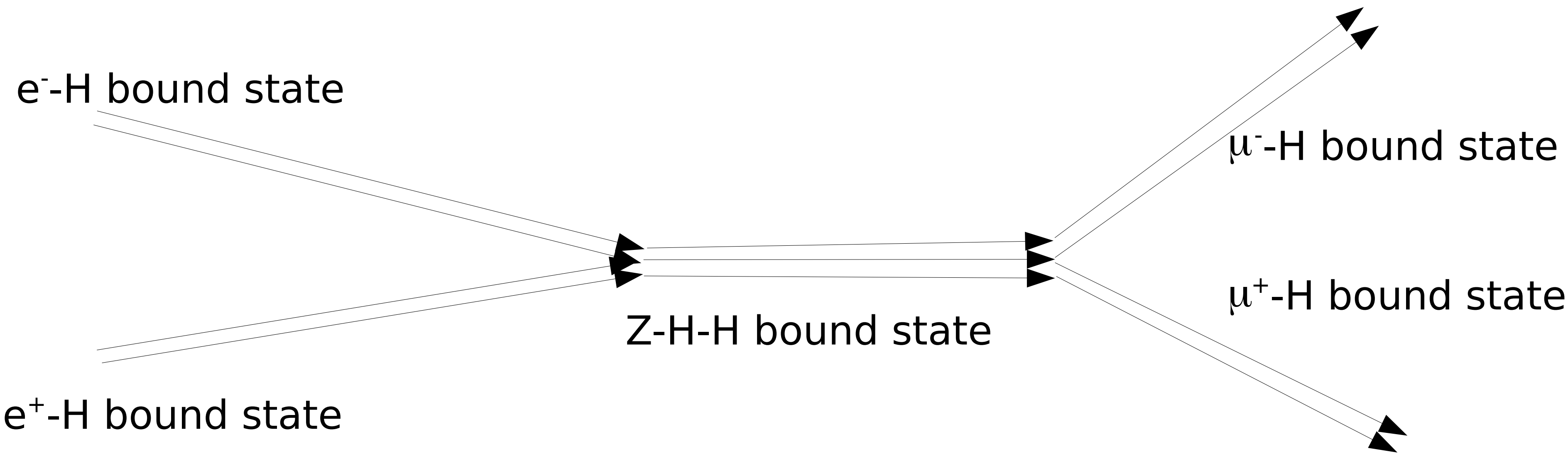

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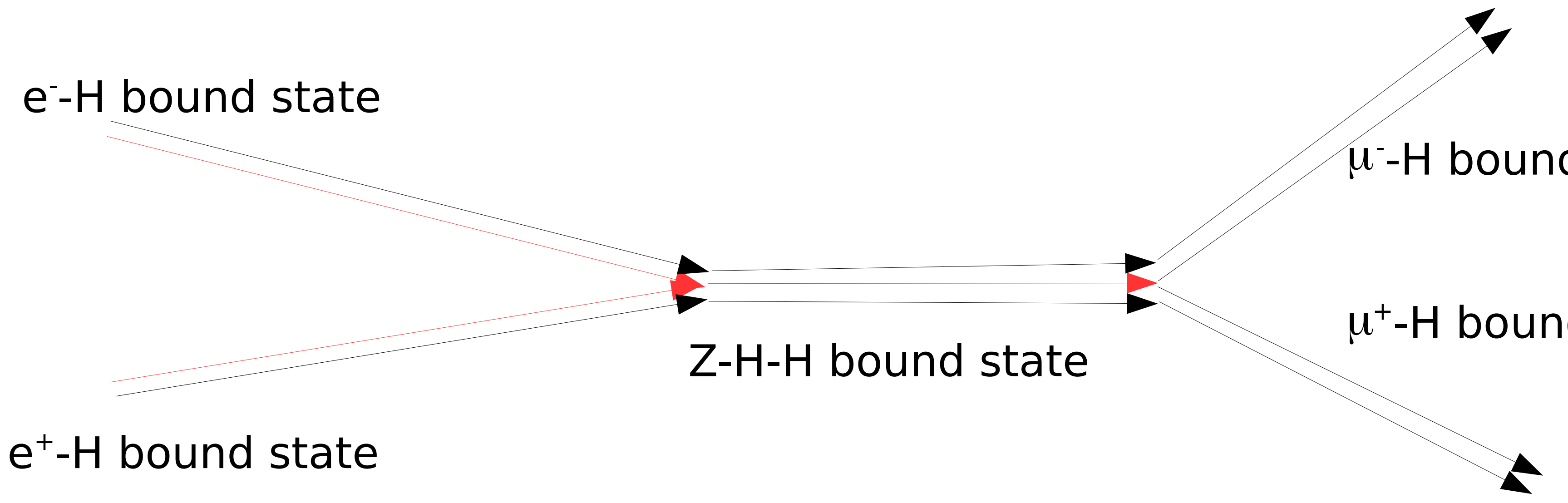

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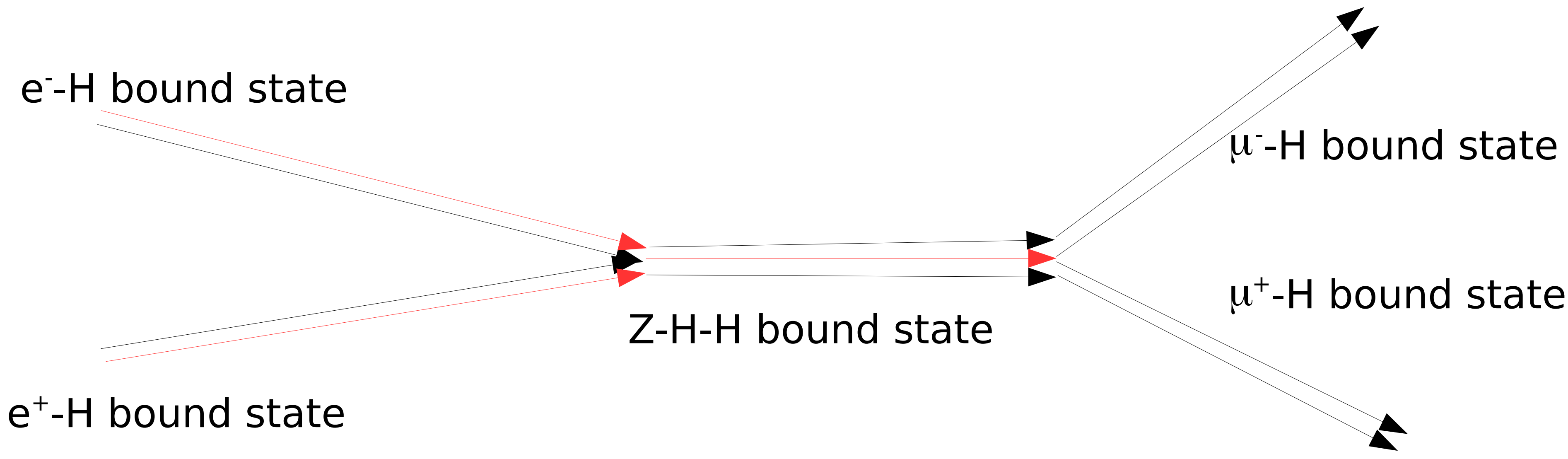

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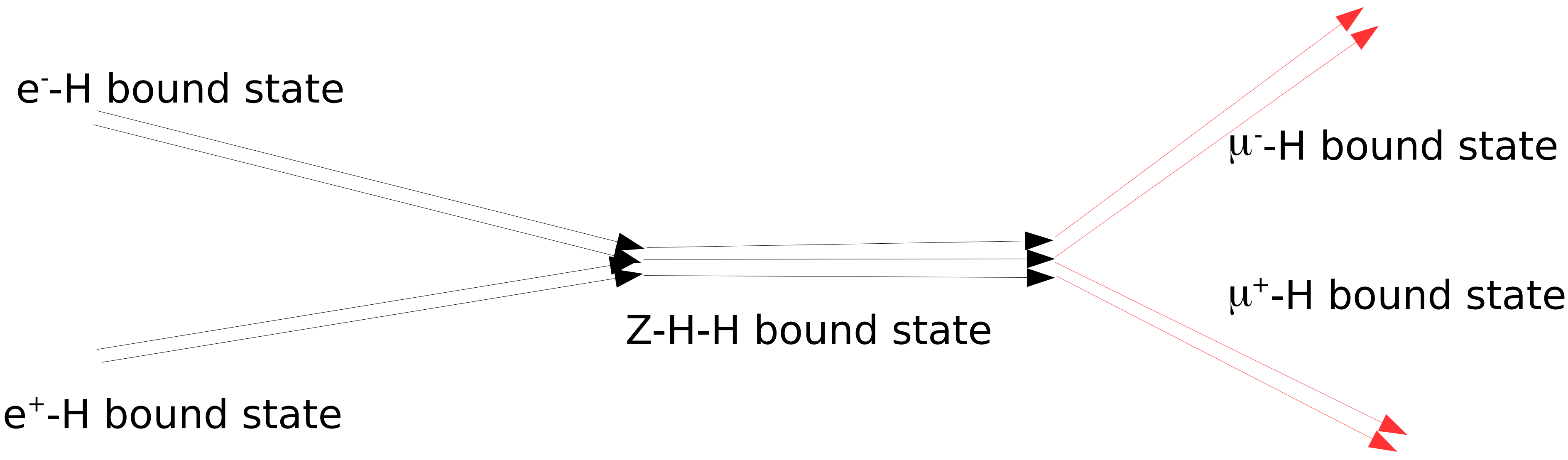

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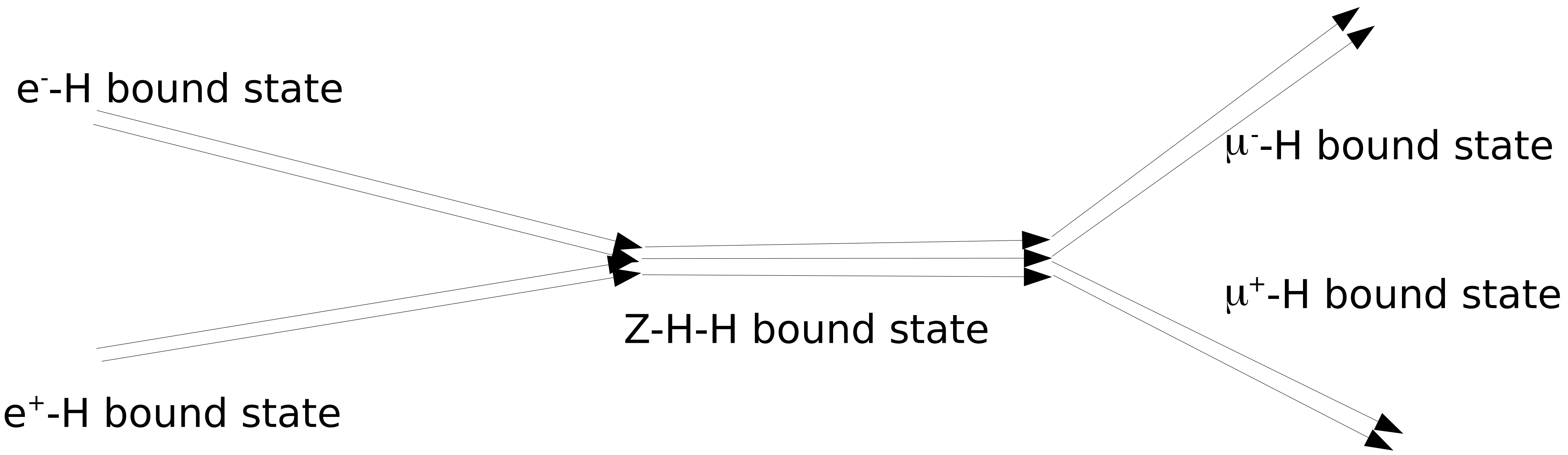

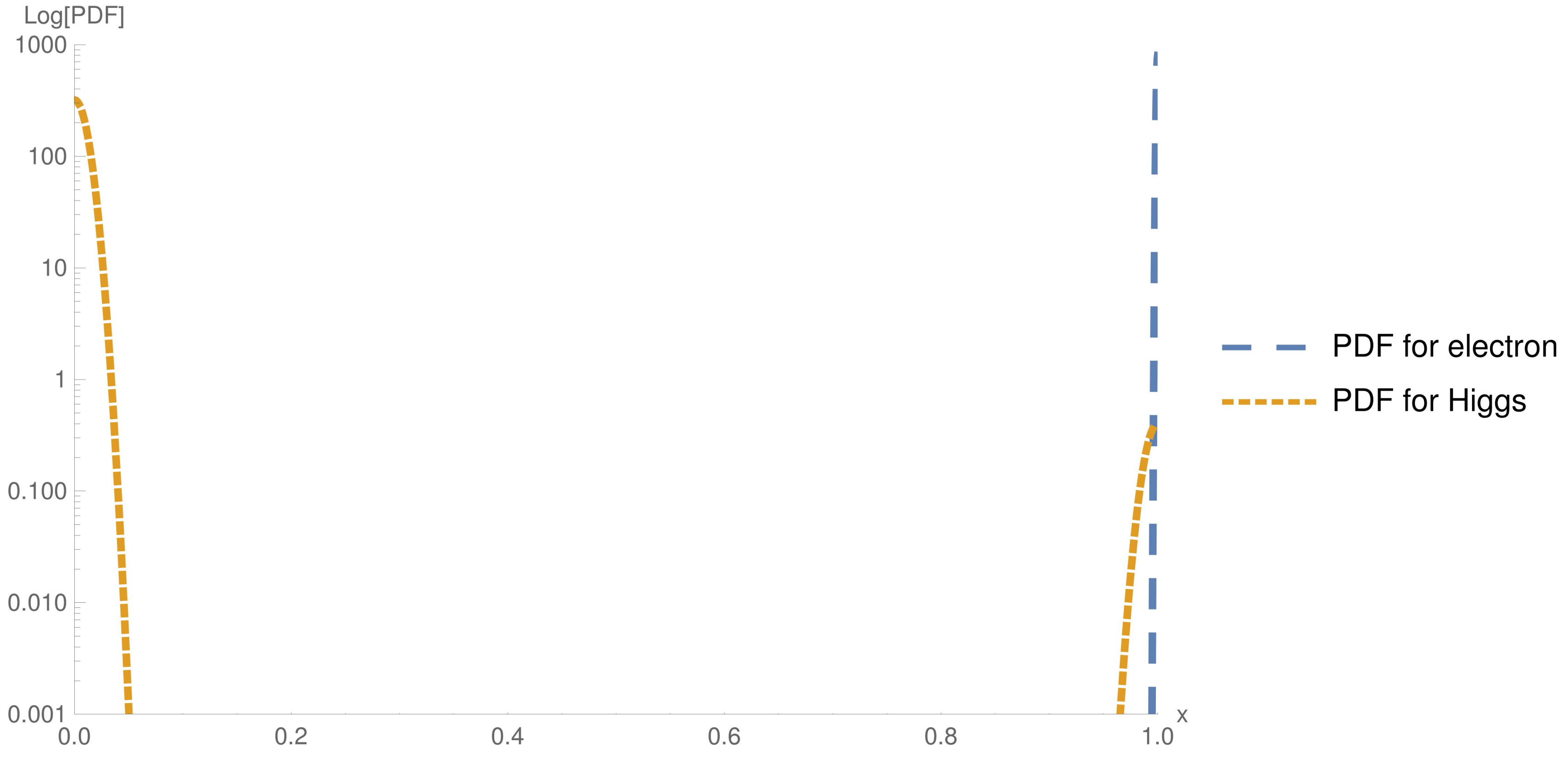

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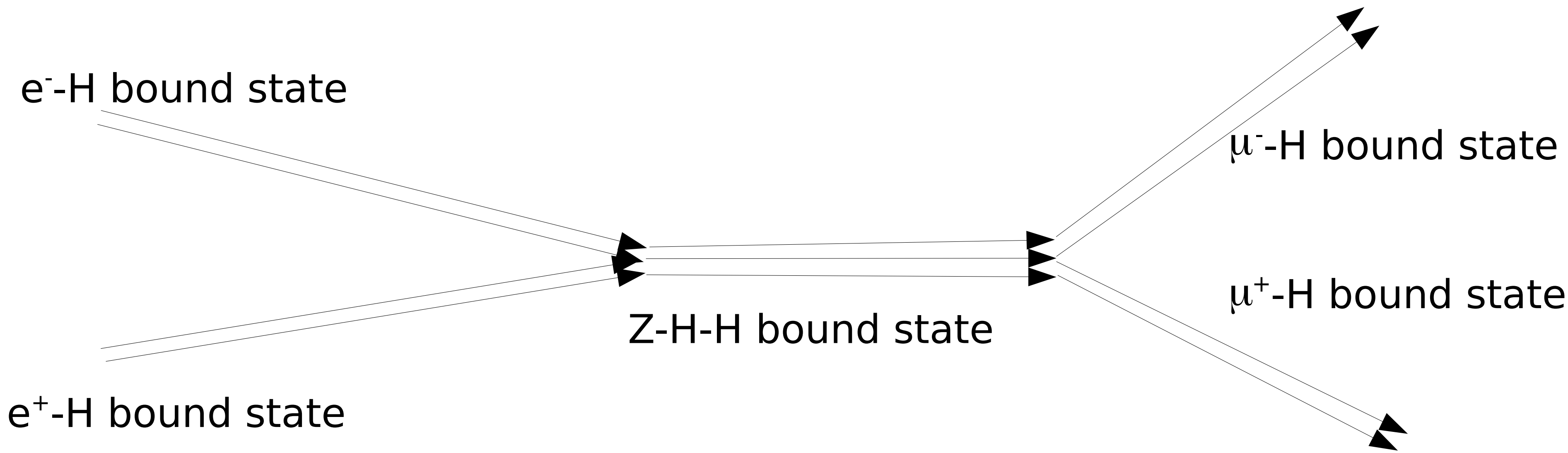

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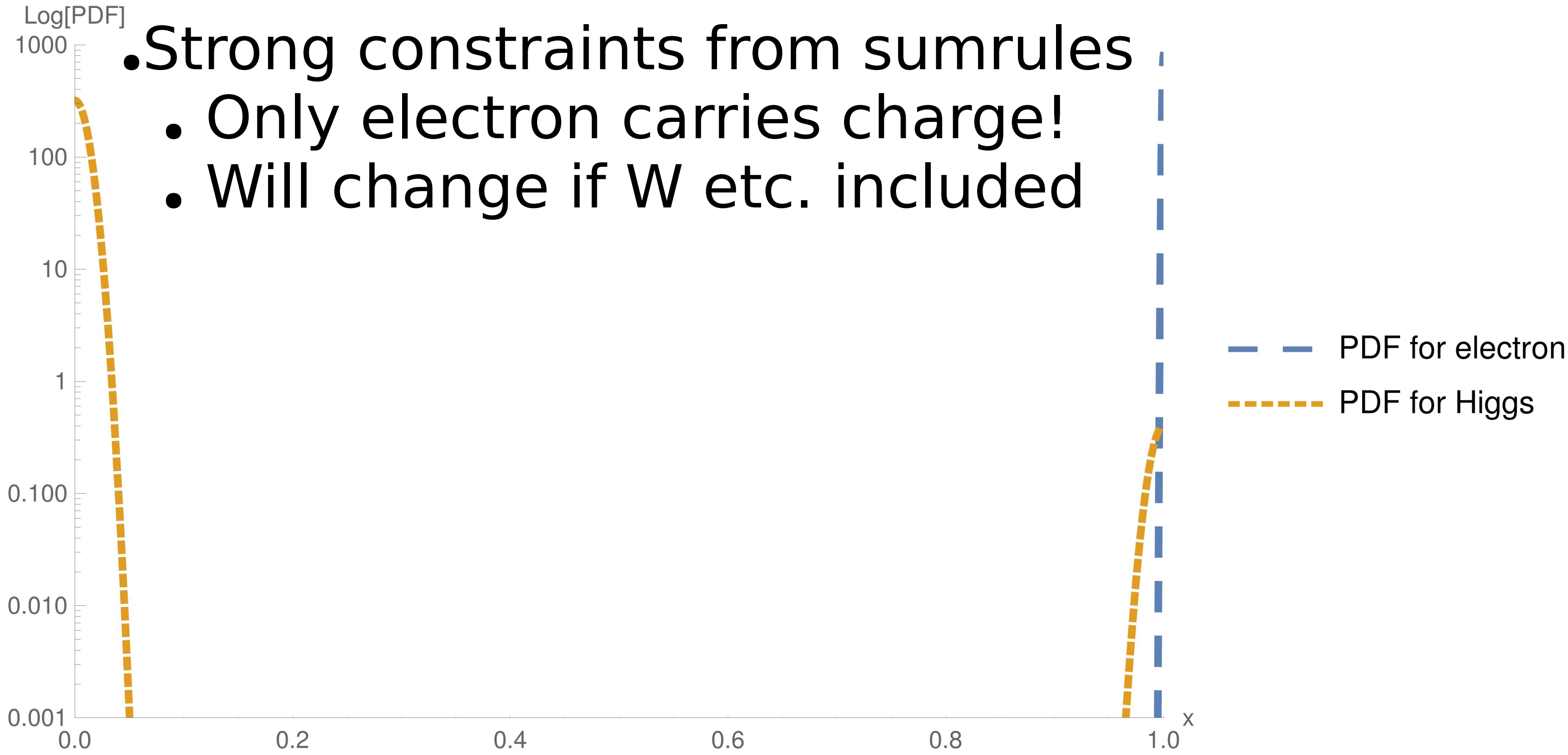

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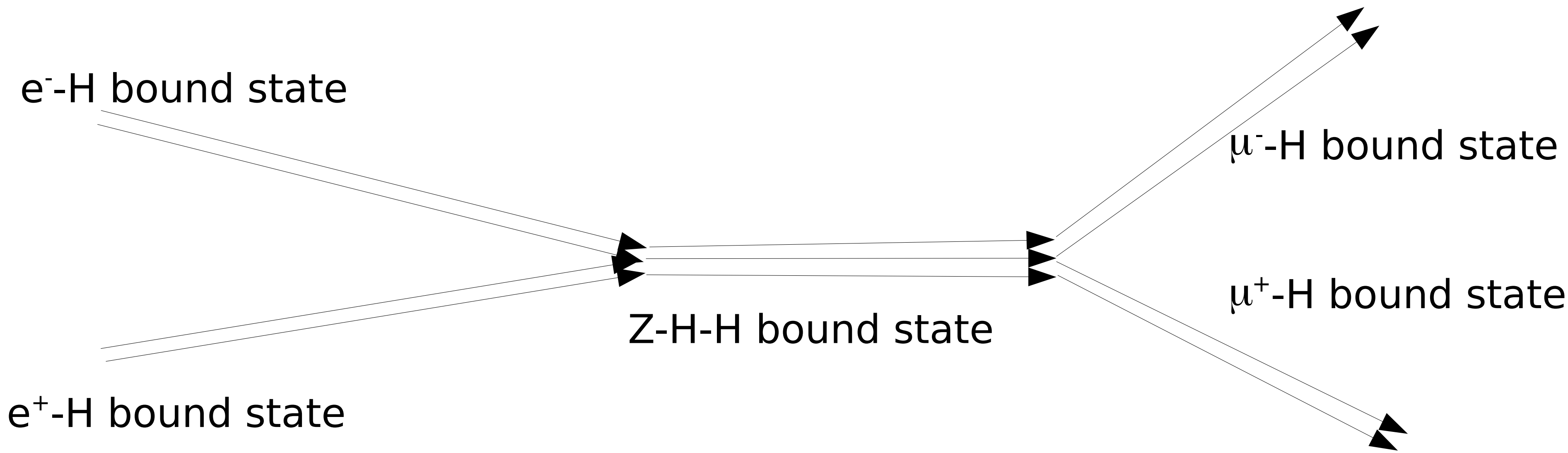

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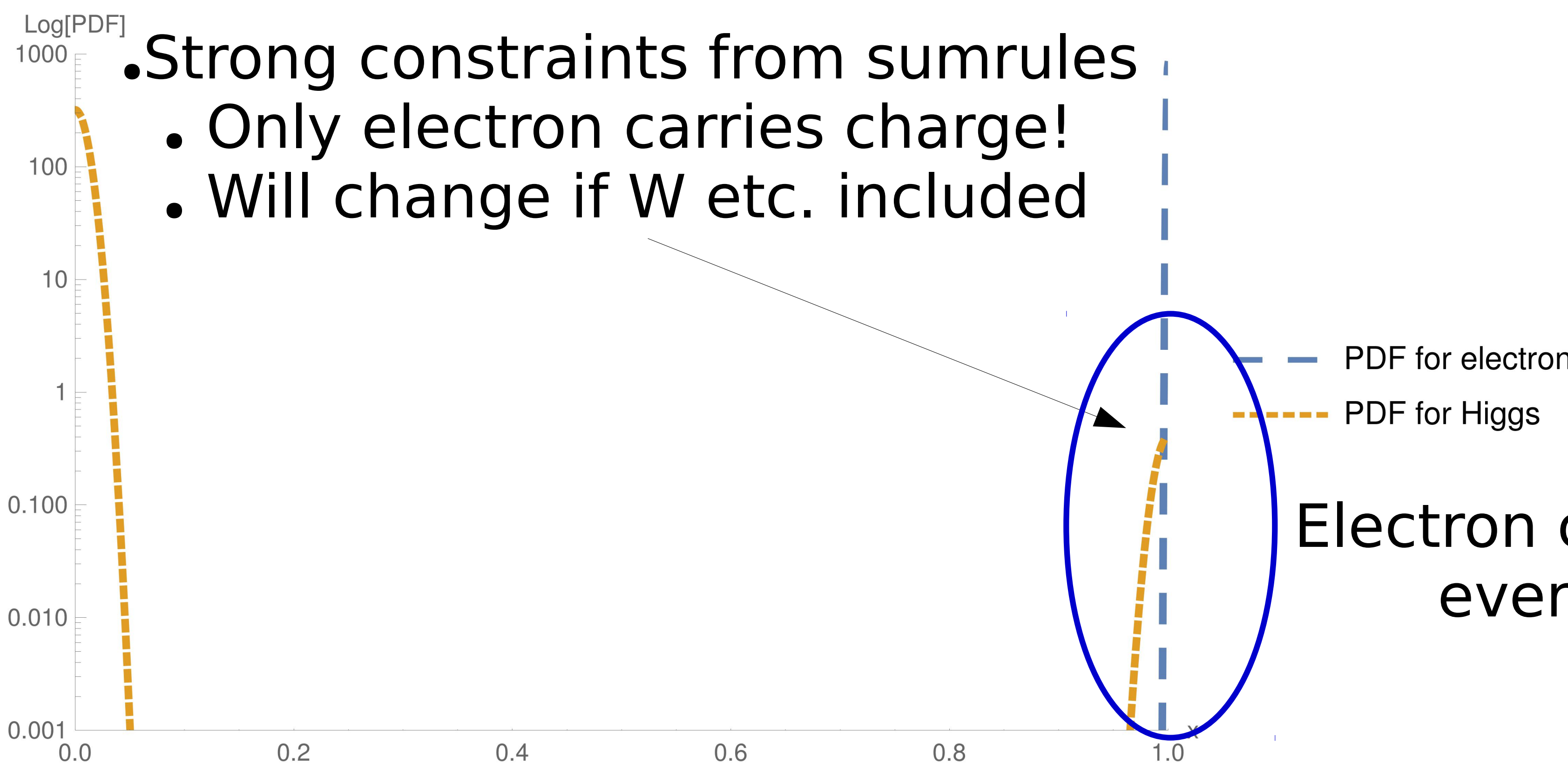

Electron carries everything

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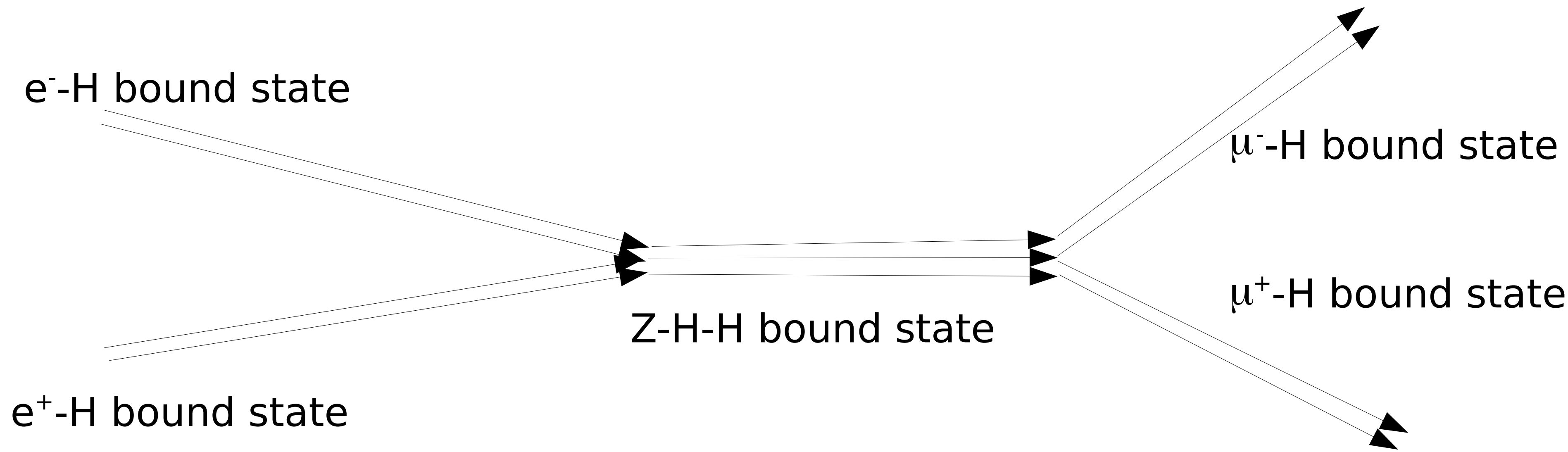

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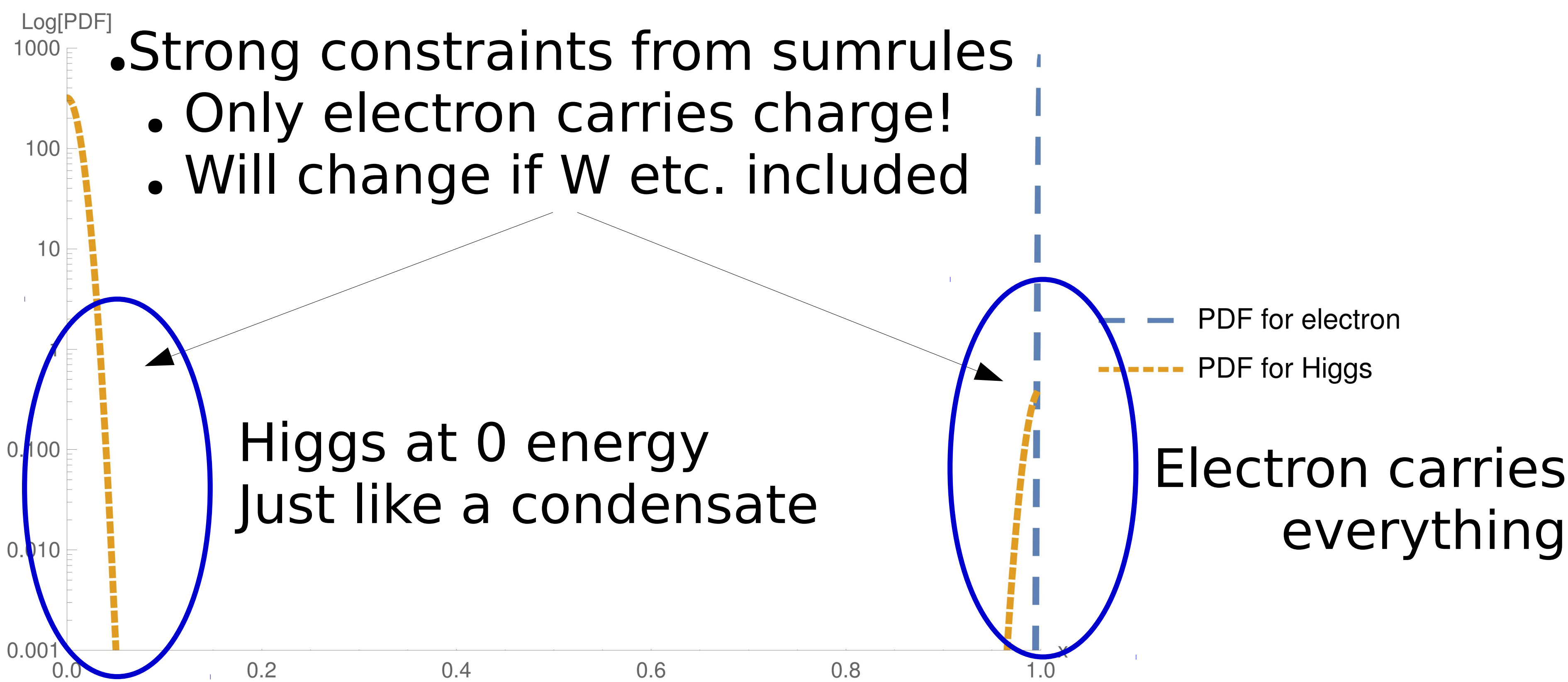

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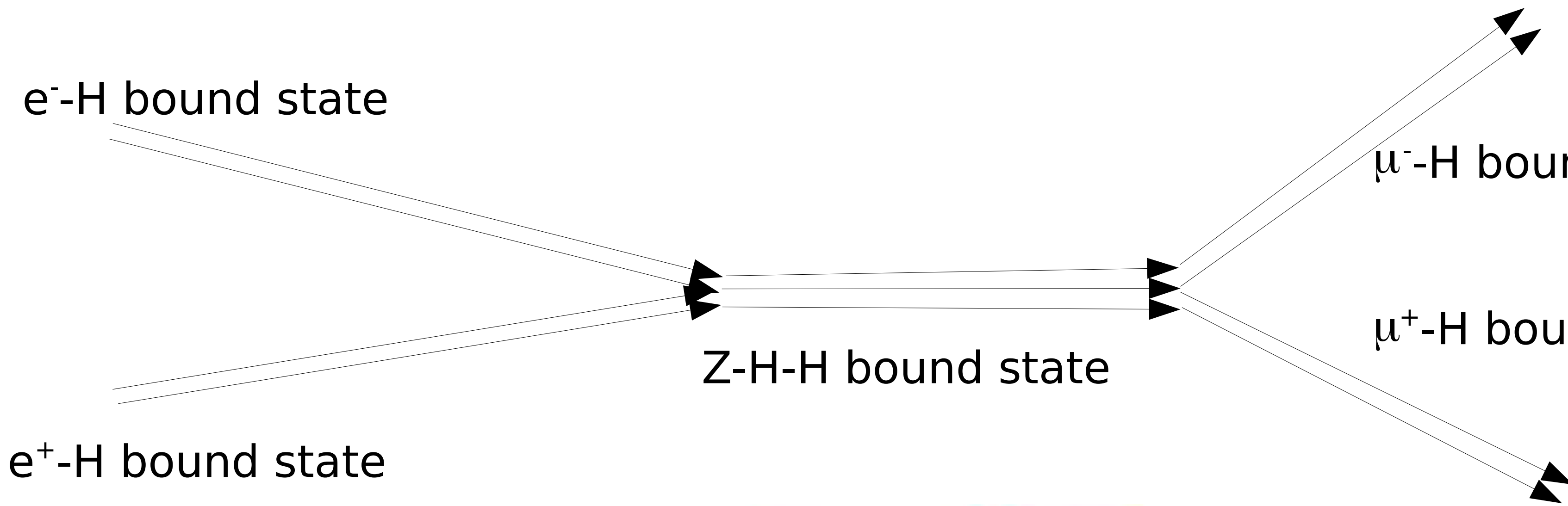

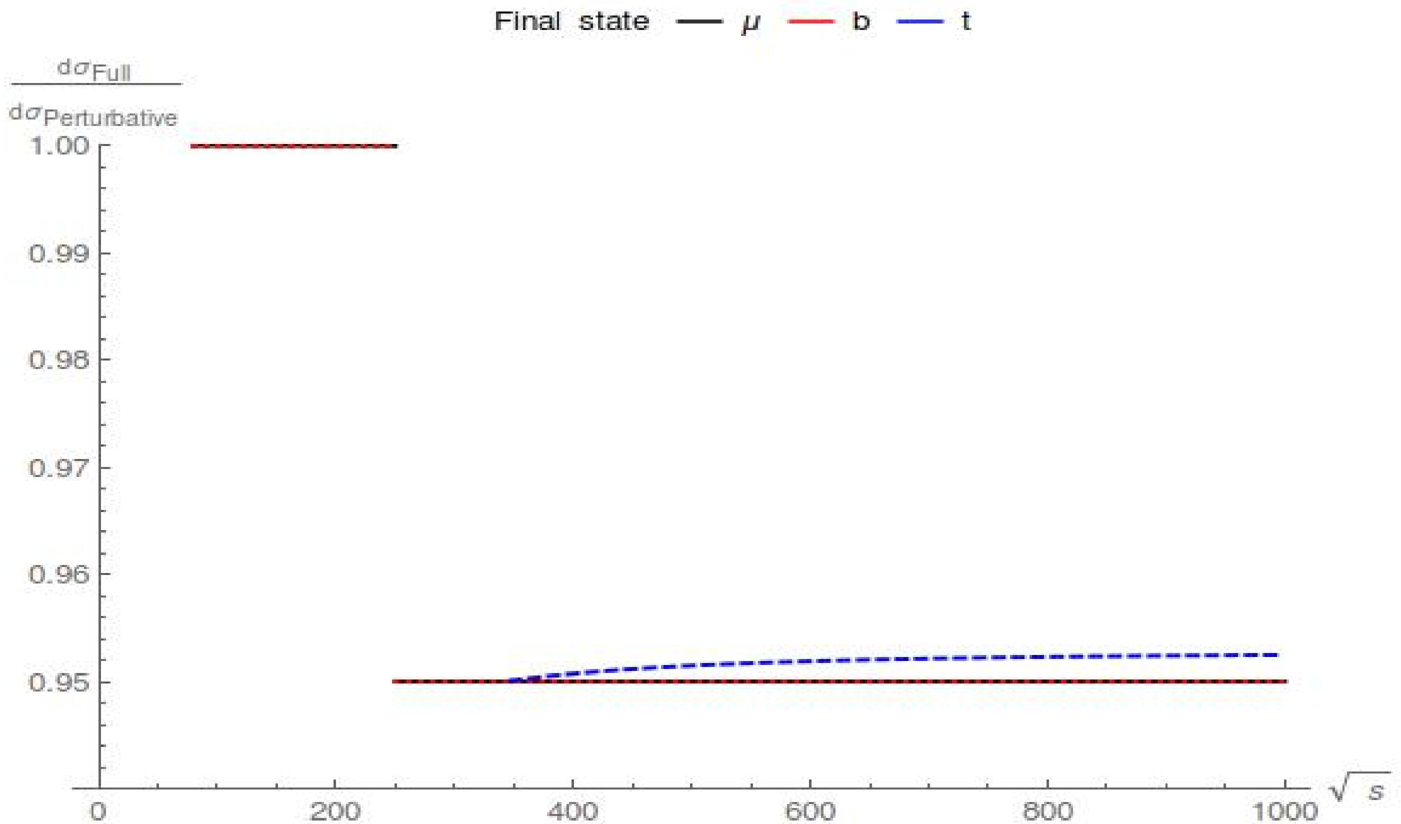

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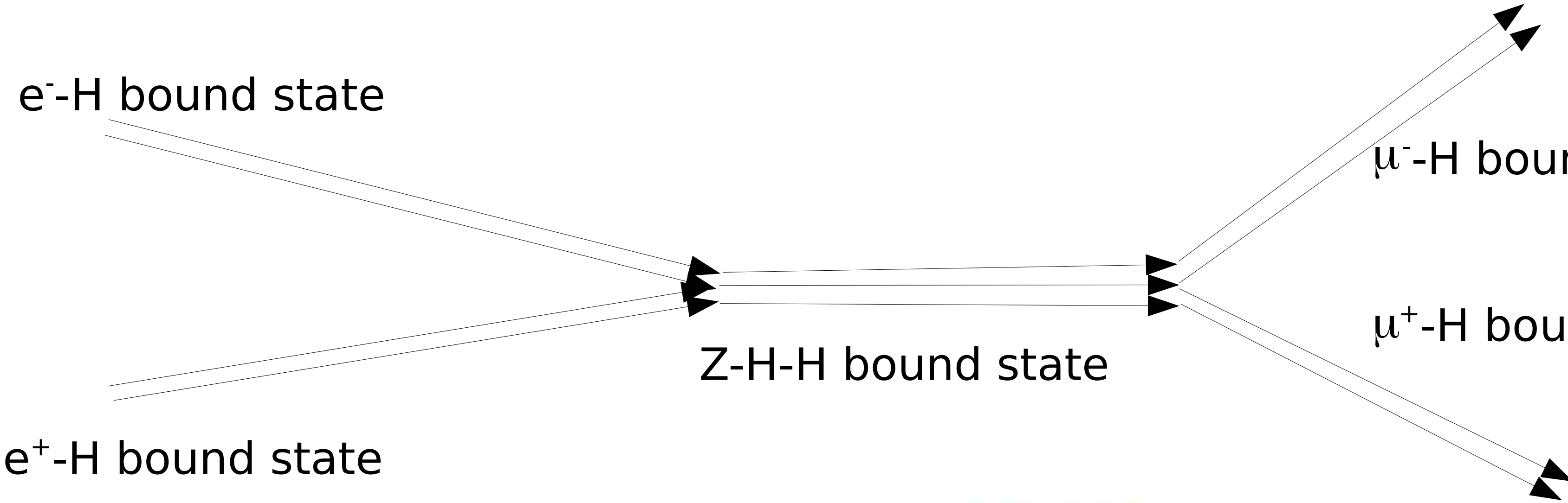

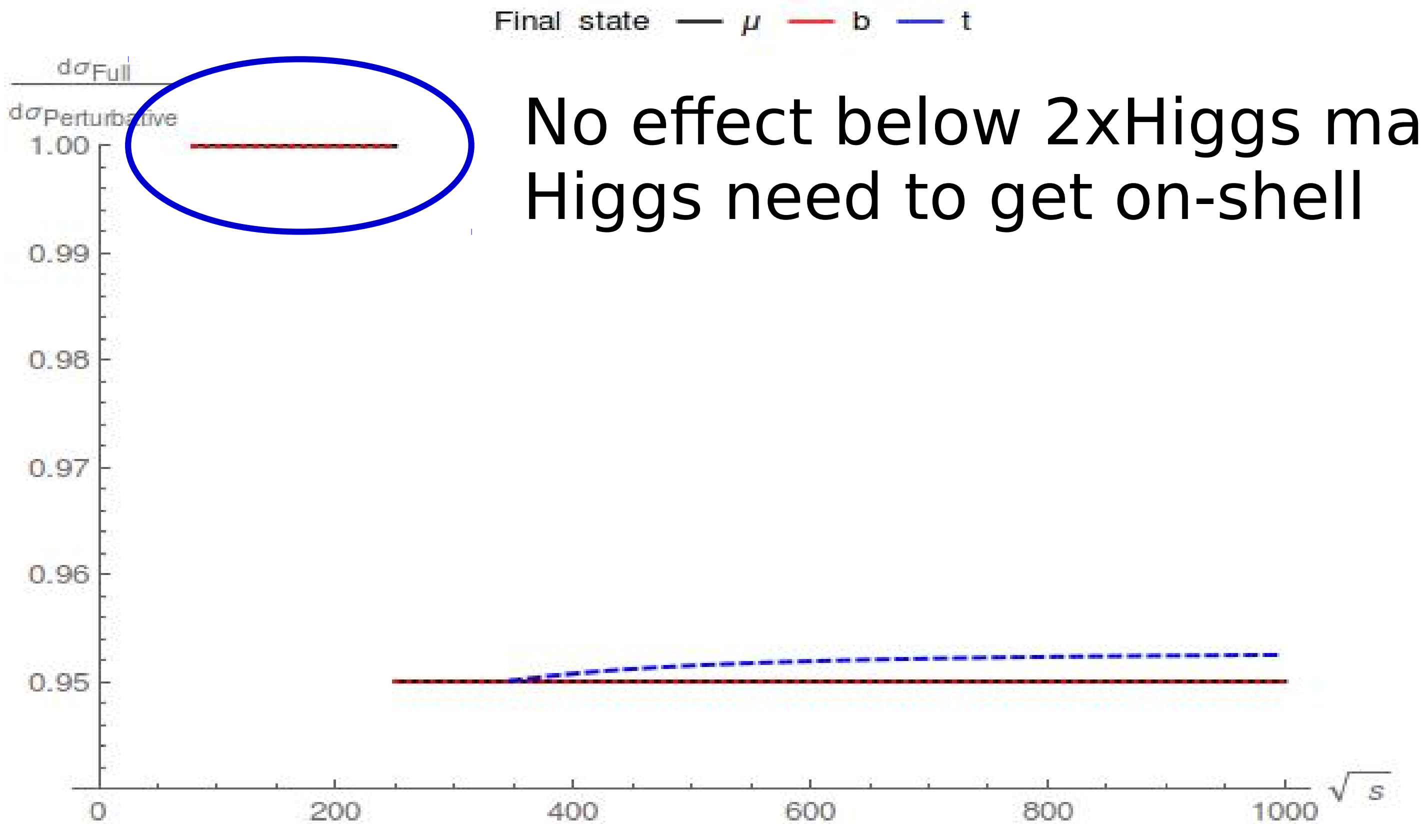

No effect below 2xHiggs mass
Higgs need to get on-shell

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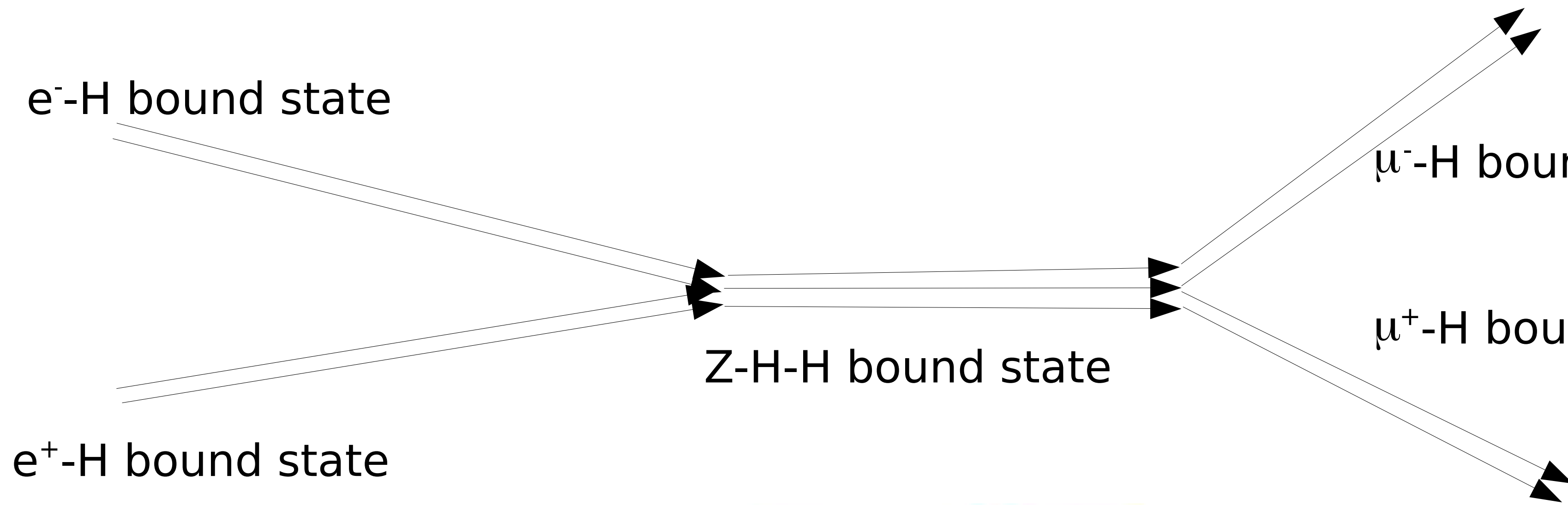

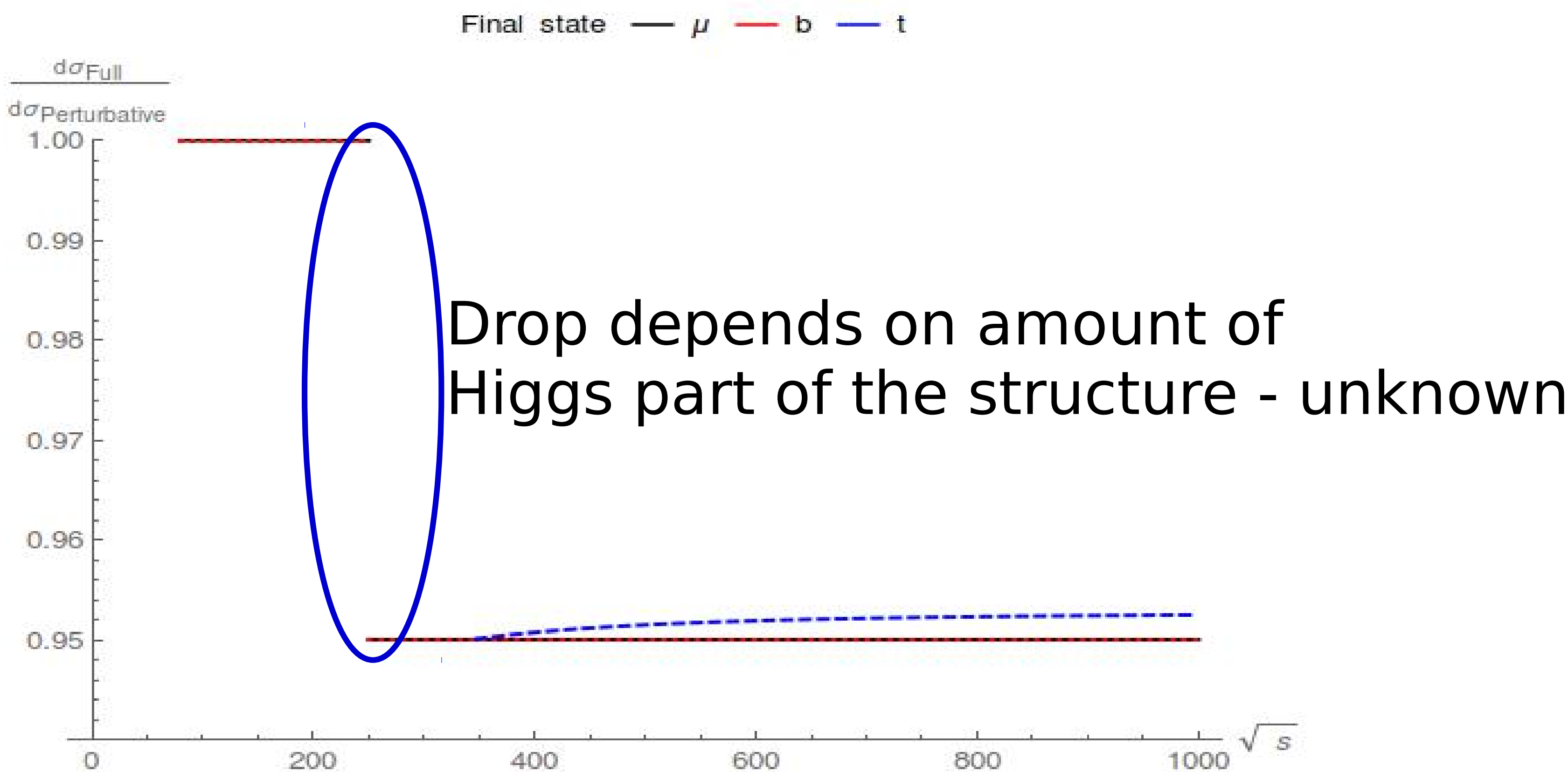

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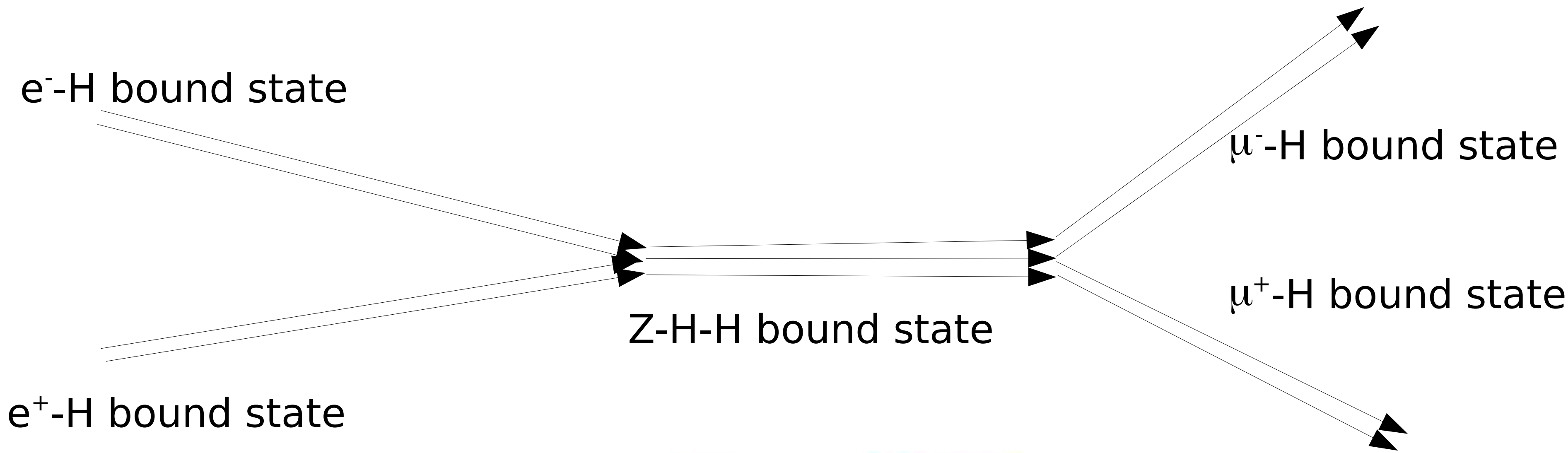

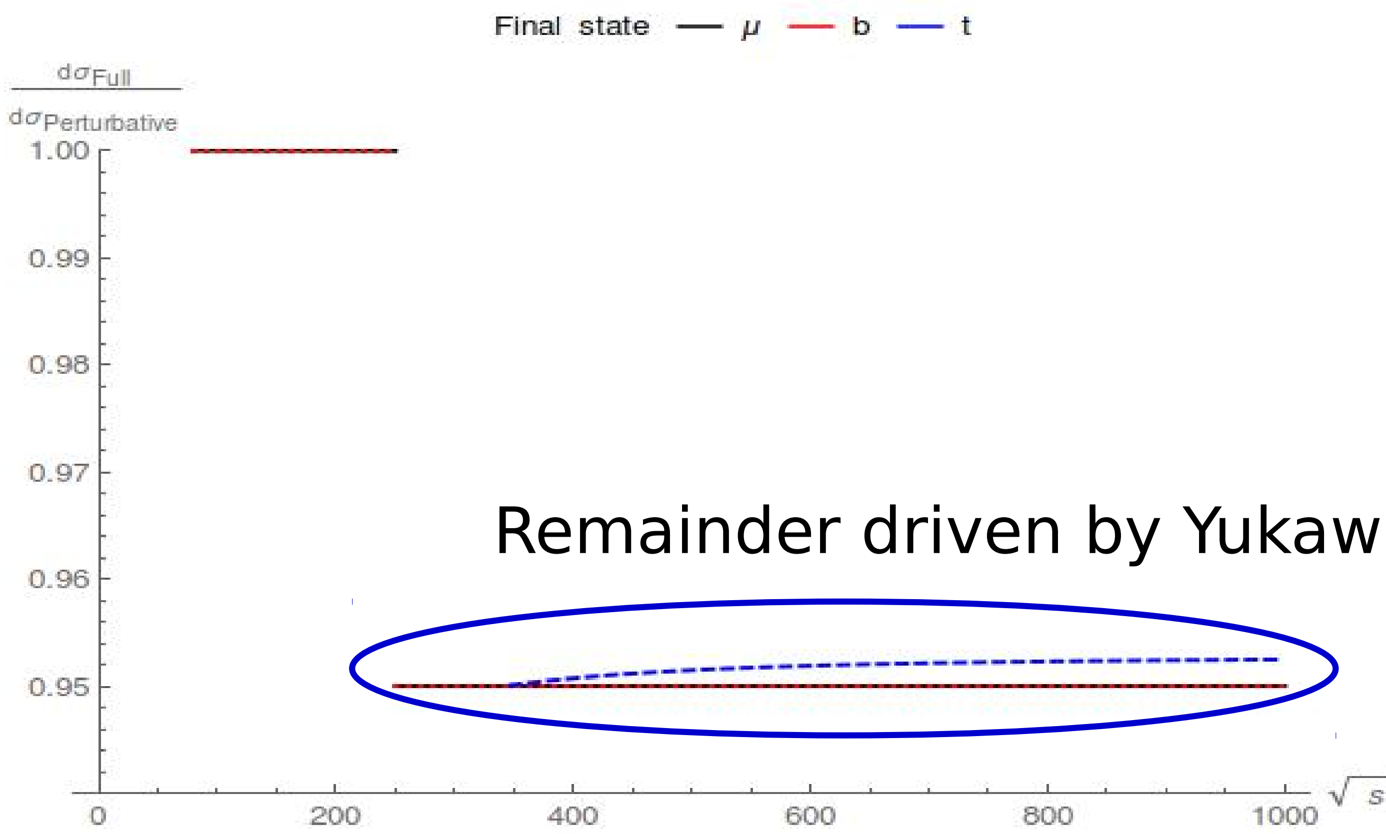

Remainder driven by Yukawa coupling

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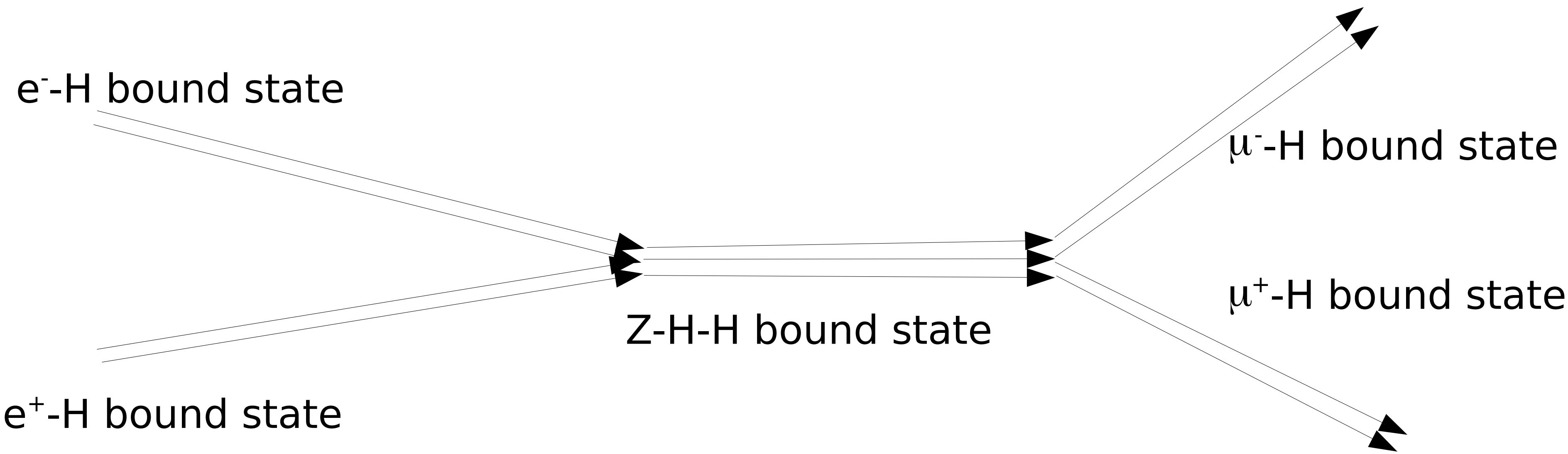

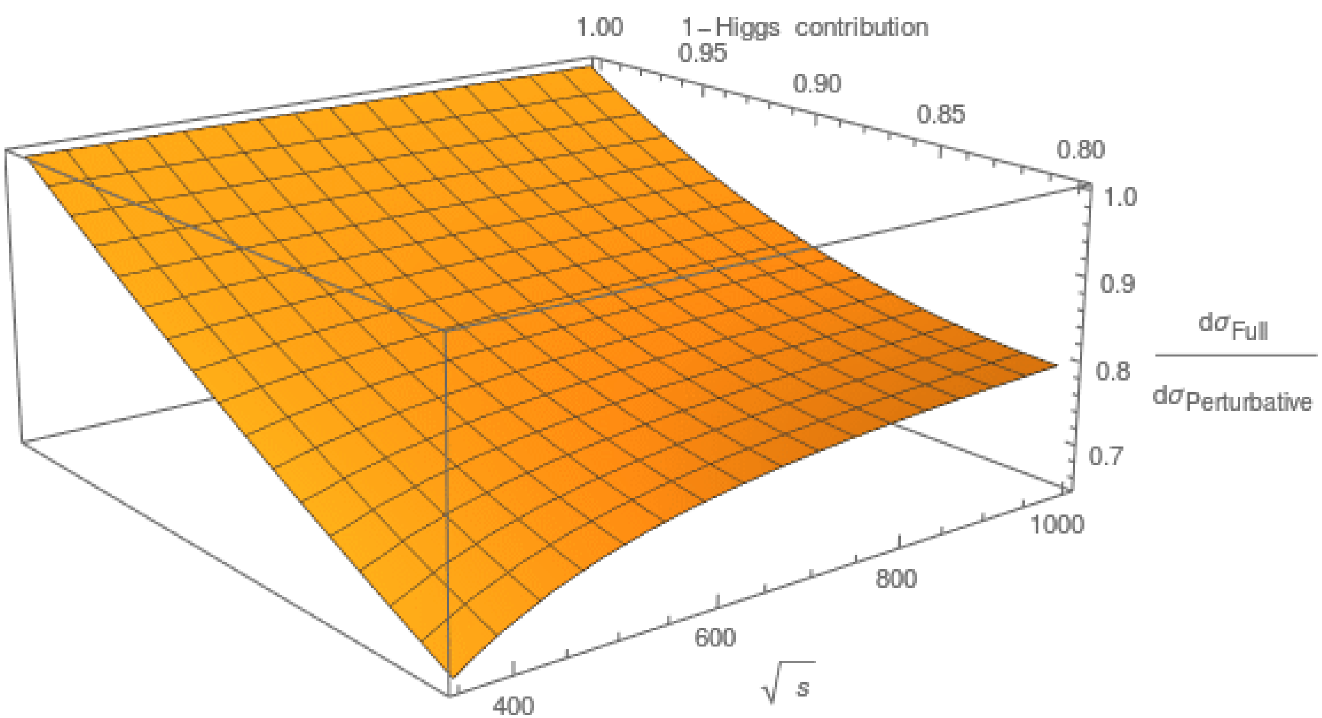

Top case:
Strong dependence on the amount of Higgs and energy

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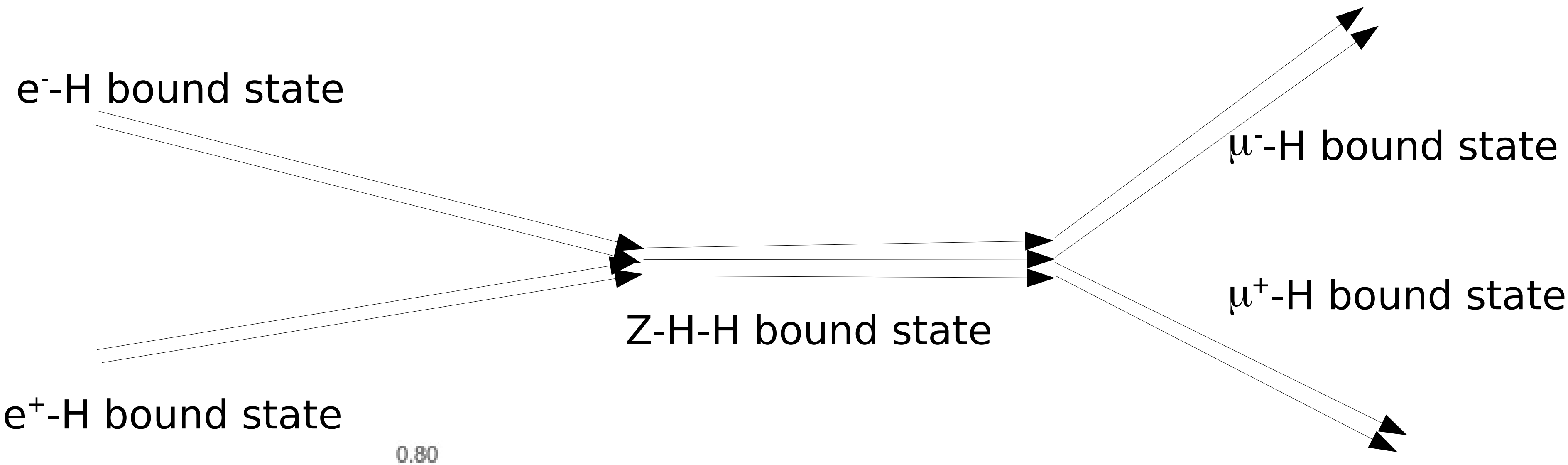

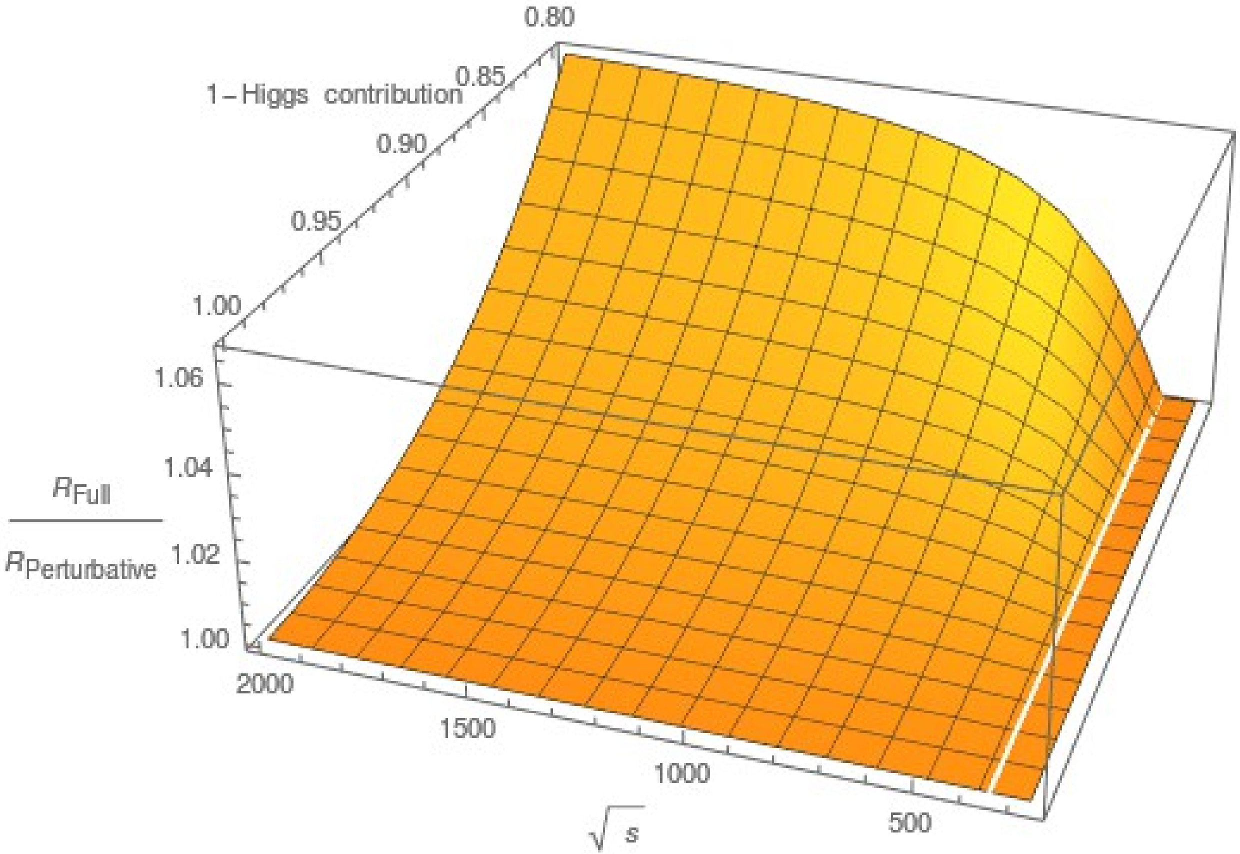

Not all quantities are equally influenced

Highly speculative consequences

[Egger et al.'17]

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  - Almost impossible to check with current methods

Why it can matter beyond the standard model

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

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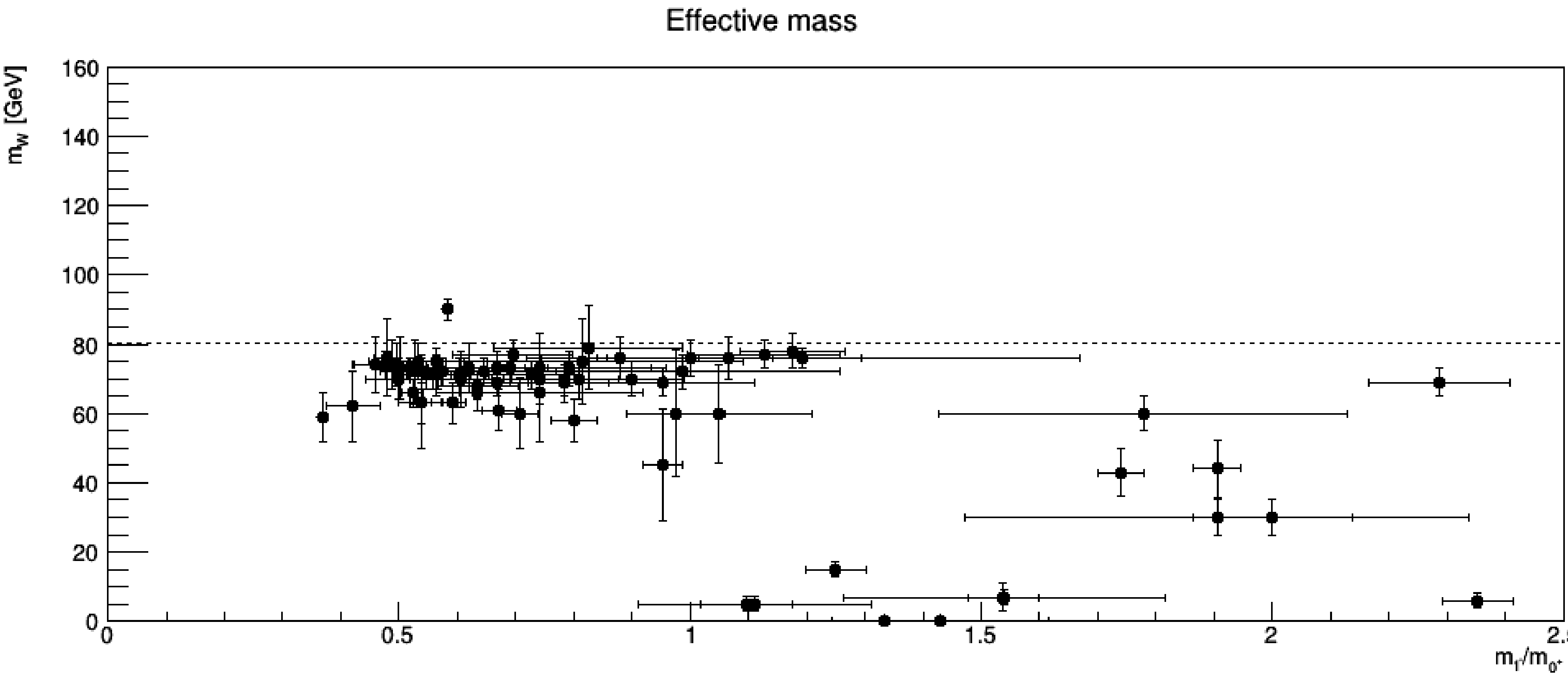
[Maas & Mufti'14]



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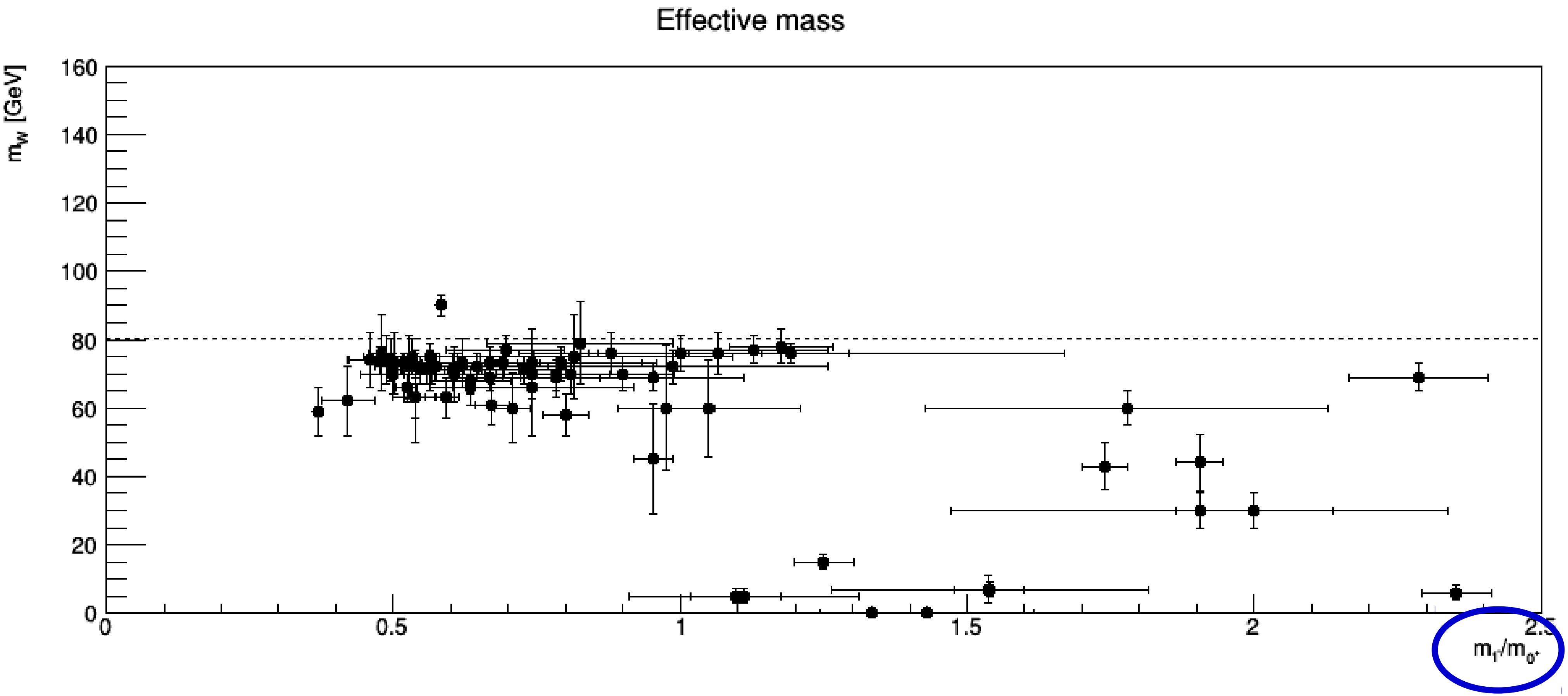
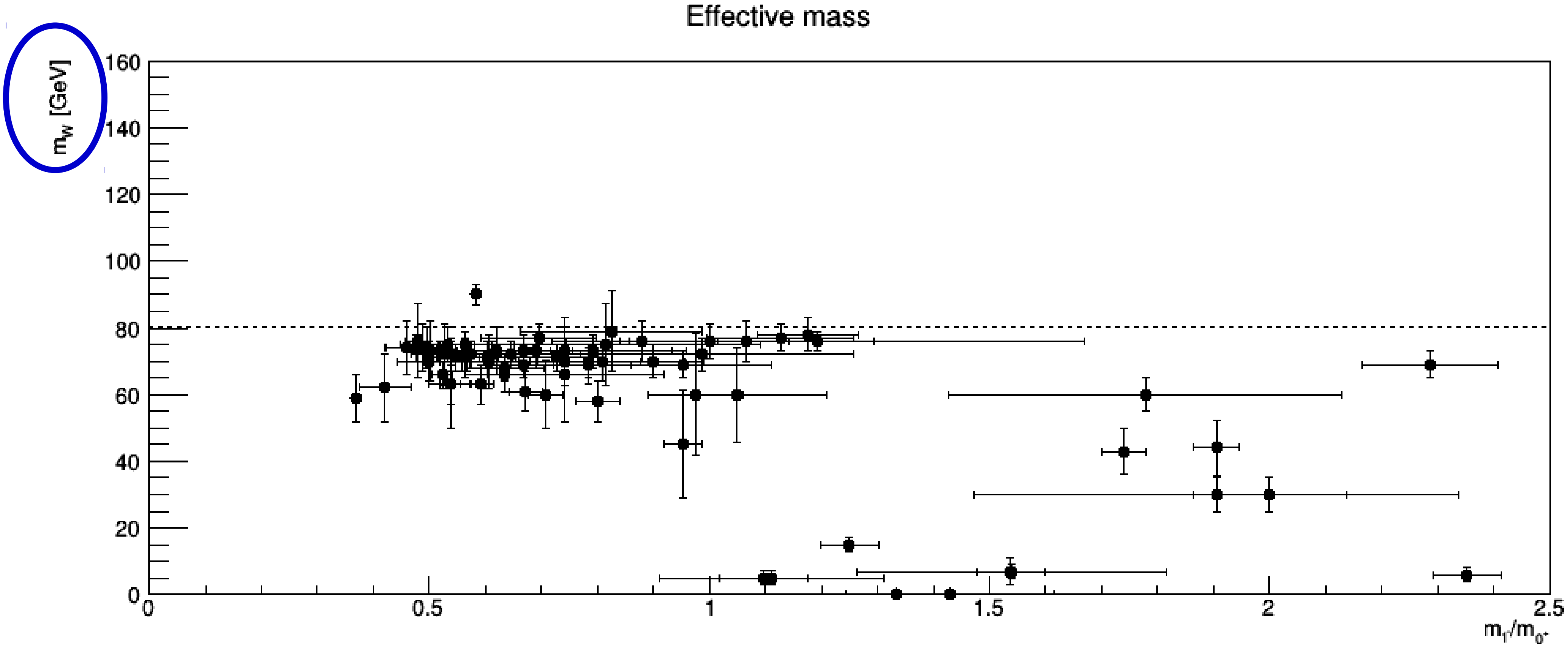


Ratio of physical observables

Limits

[Maas & Mufti'14]

Gauge-dependent quantity



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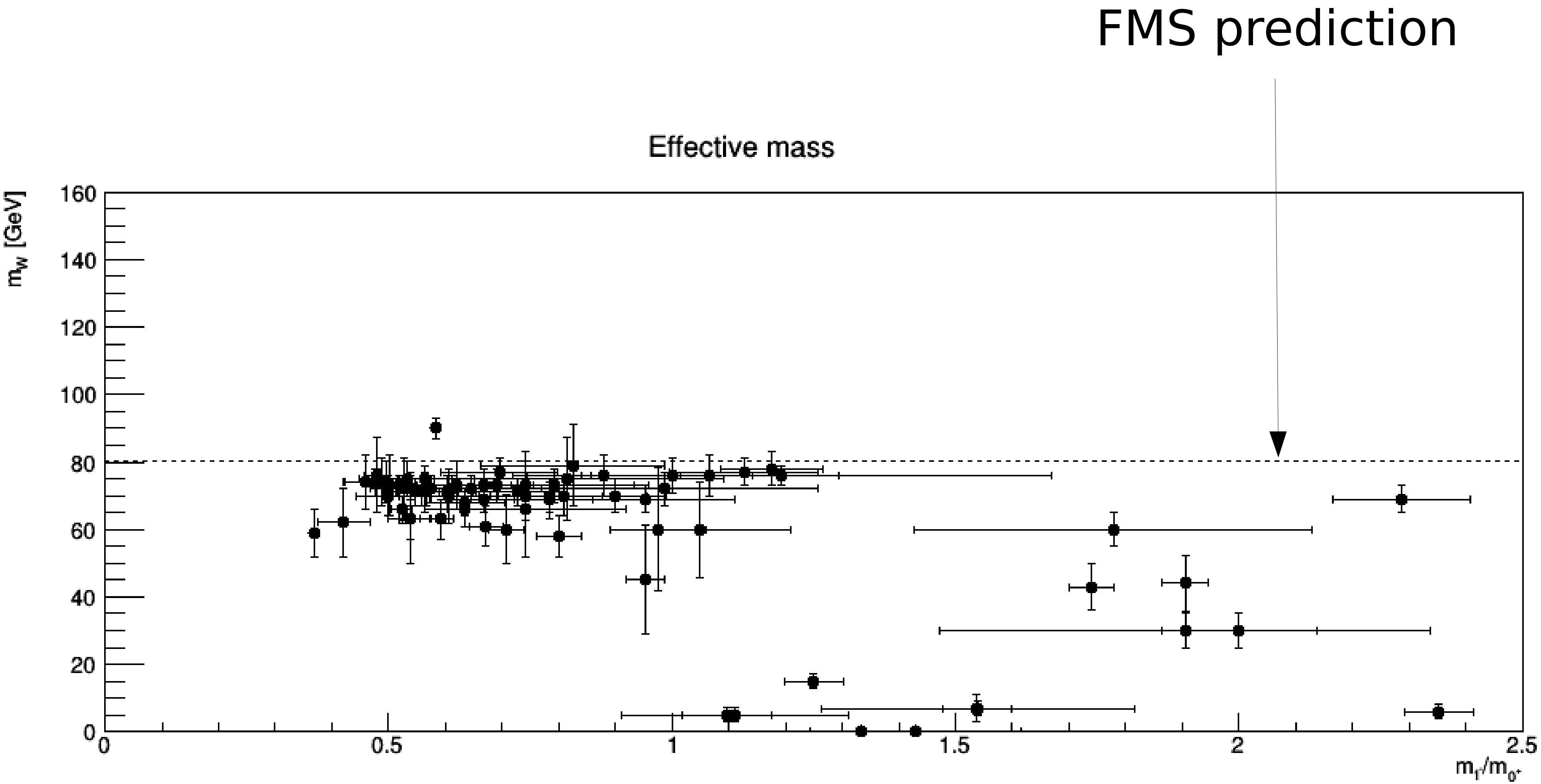

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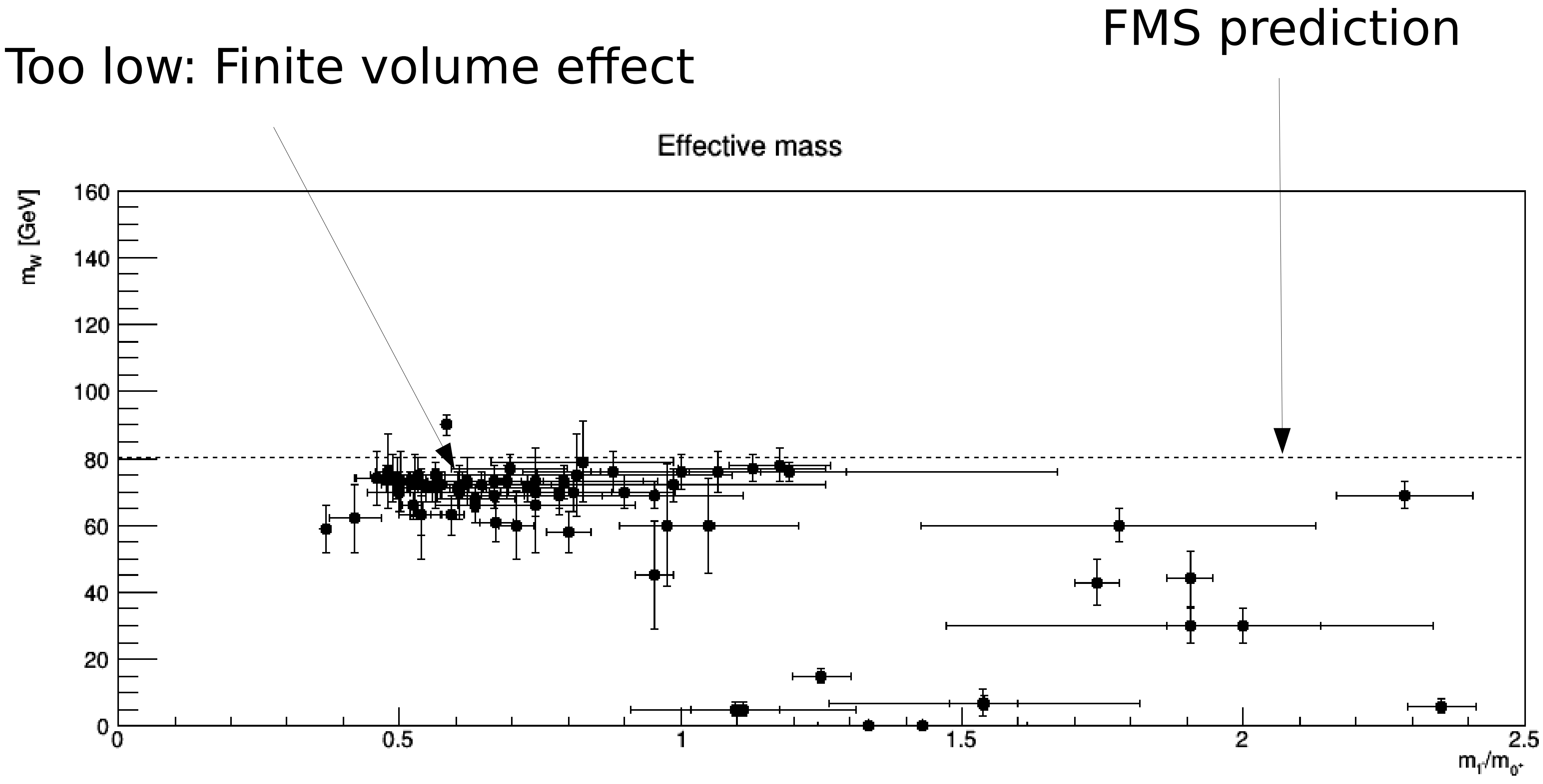

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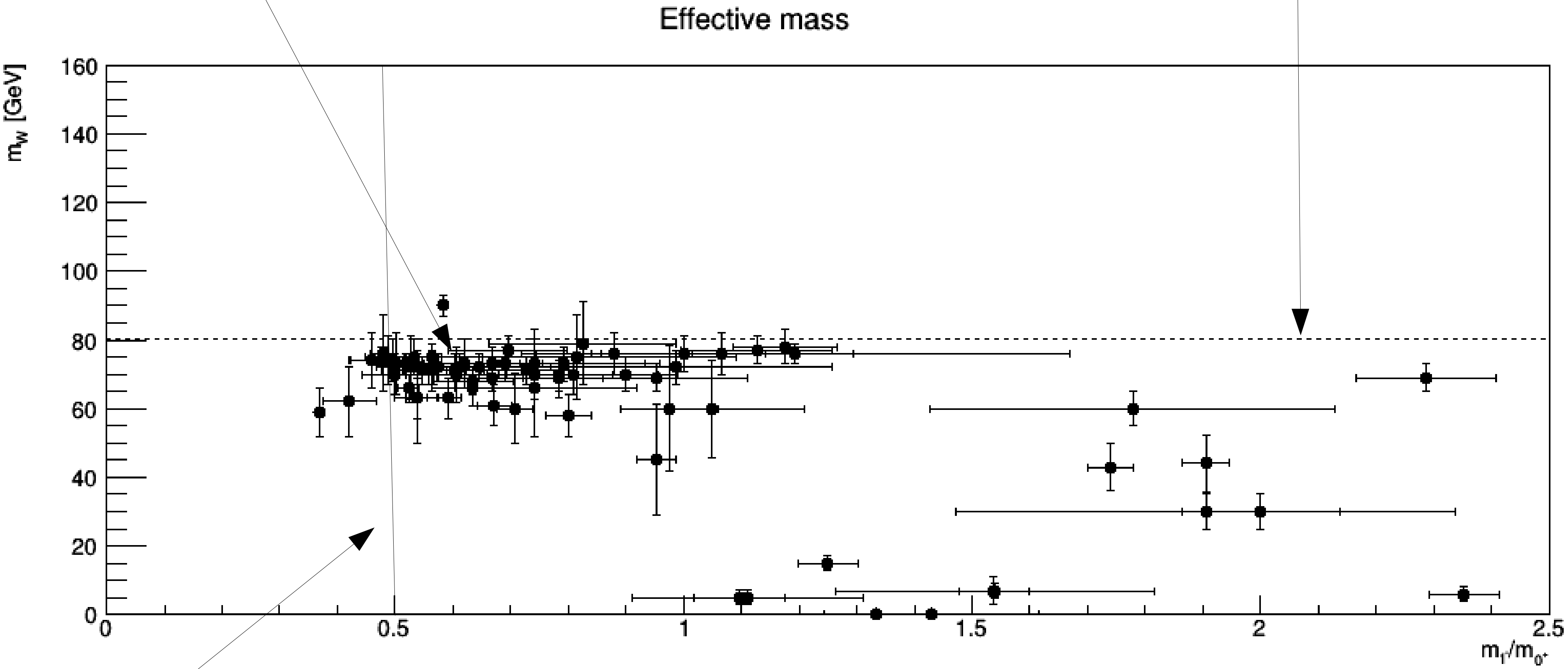
FMS prediction

Too low: Finite volume effect



Elastic decay threshold
Higgs as resonance
Expensive, signal very bad

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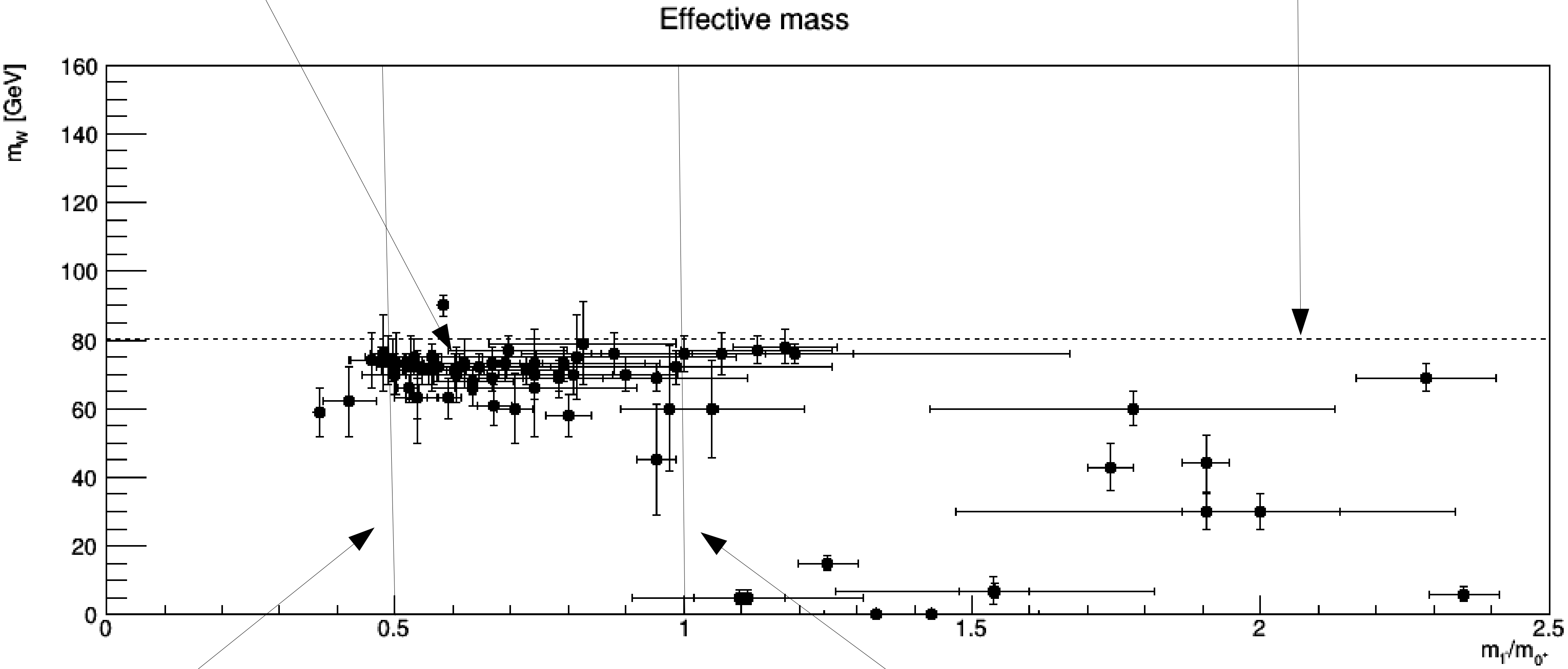

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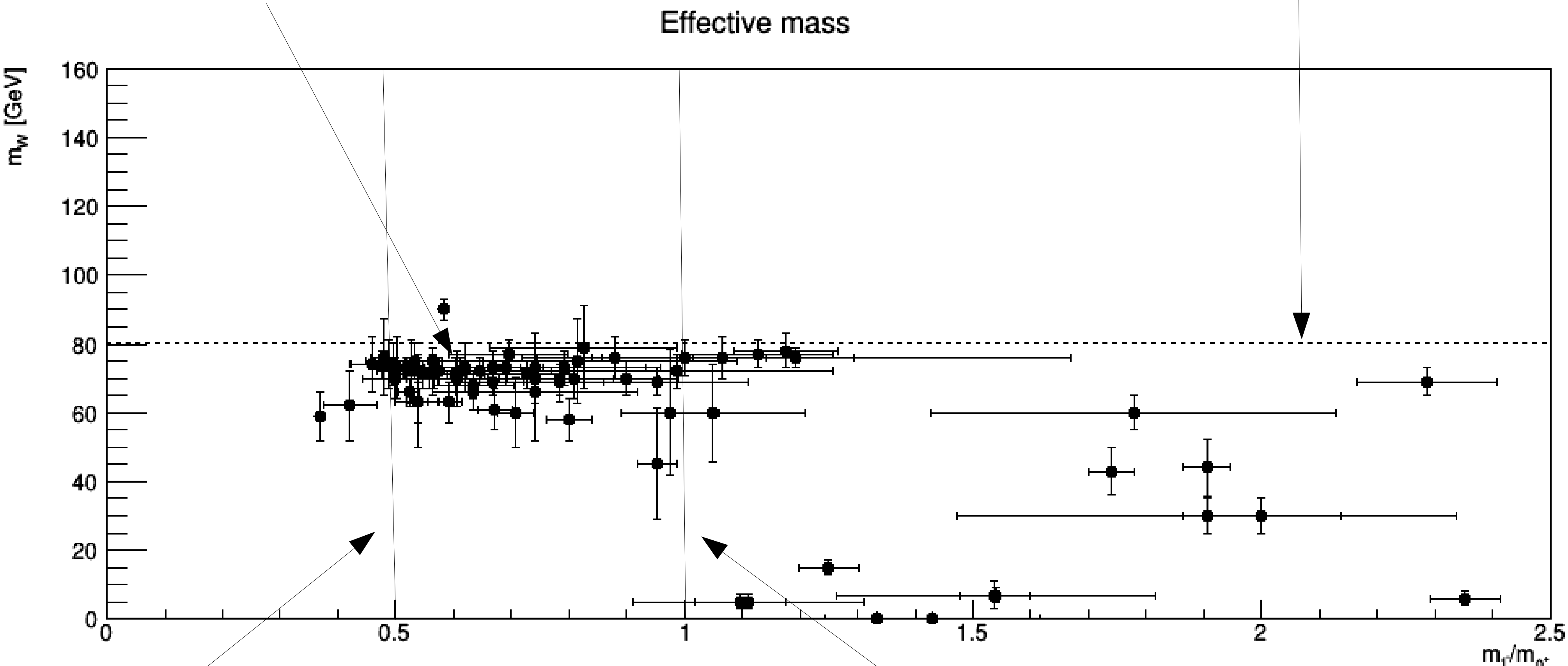

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So does Brout-Englert-Higgs!

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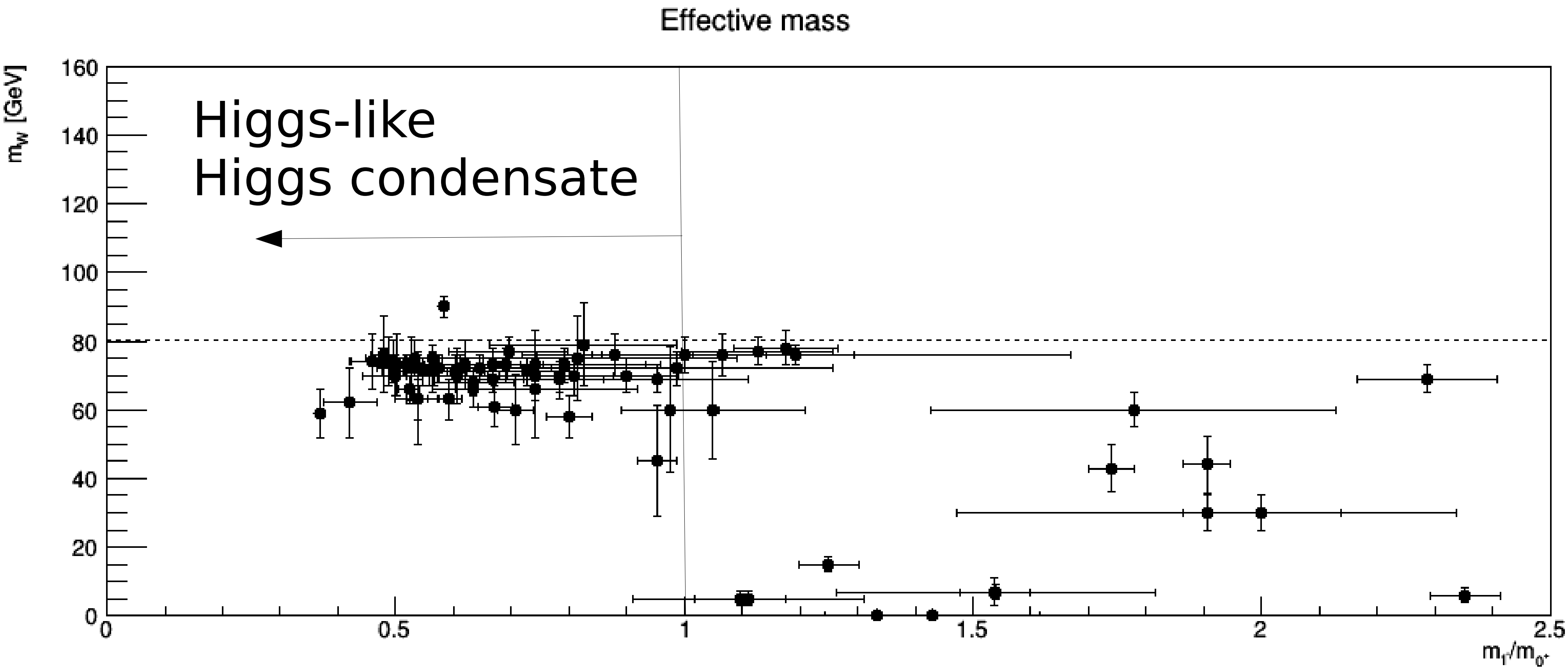

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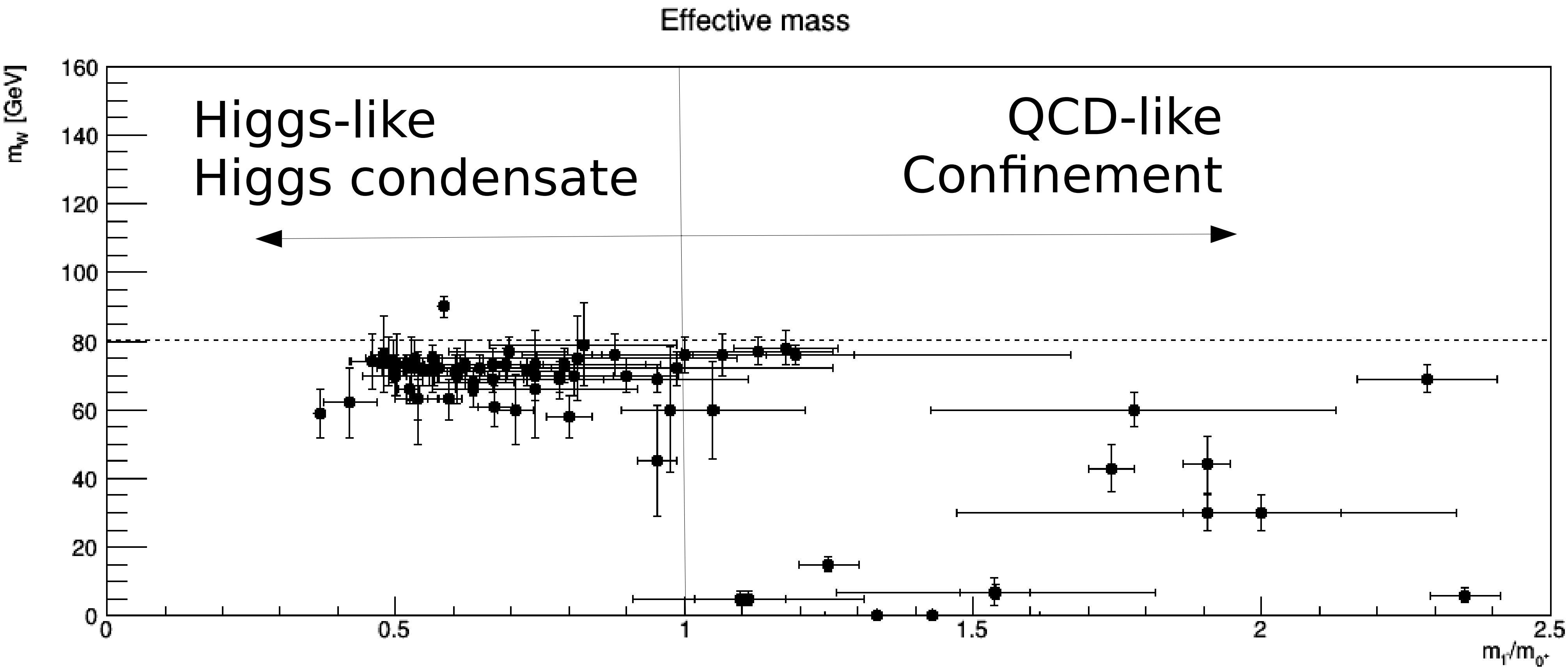

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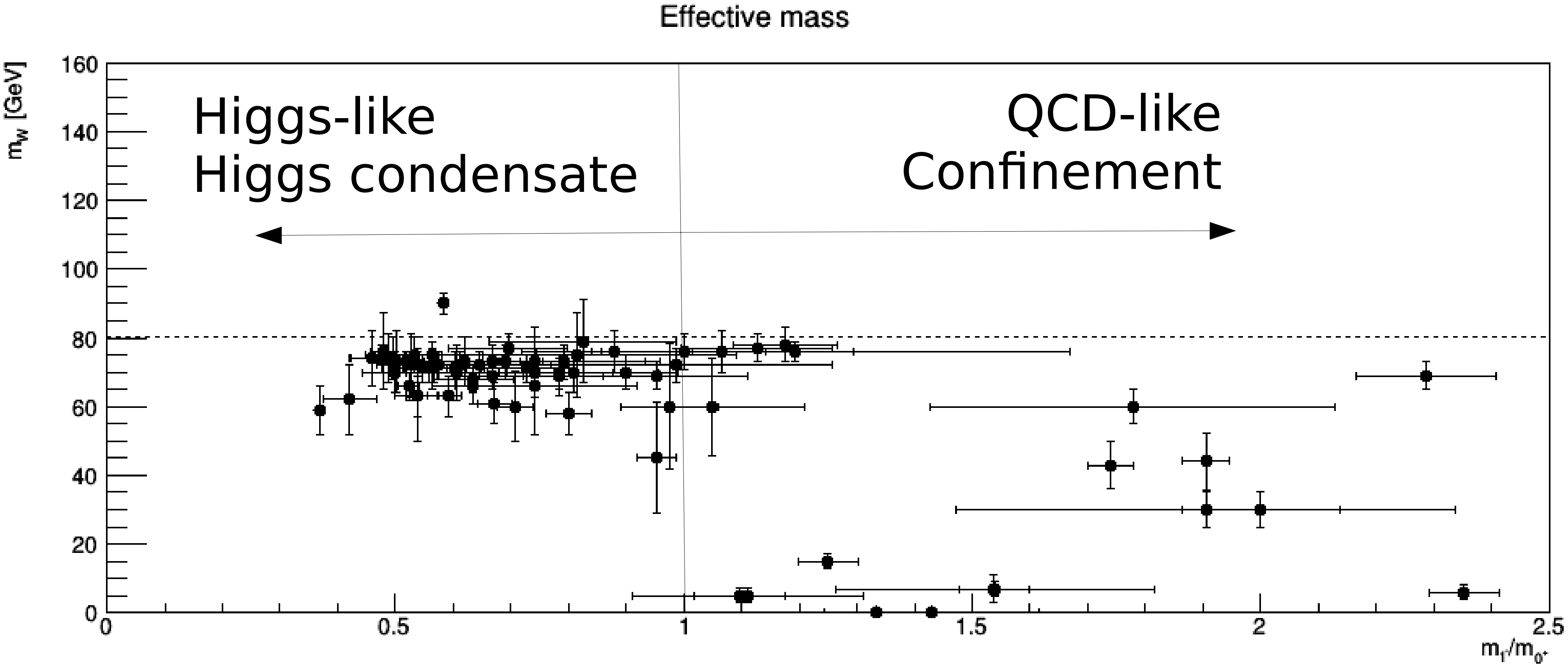

Does not coincide with weak/strong coupling transitions!

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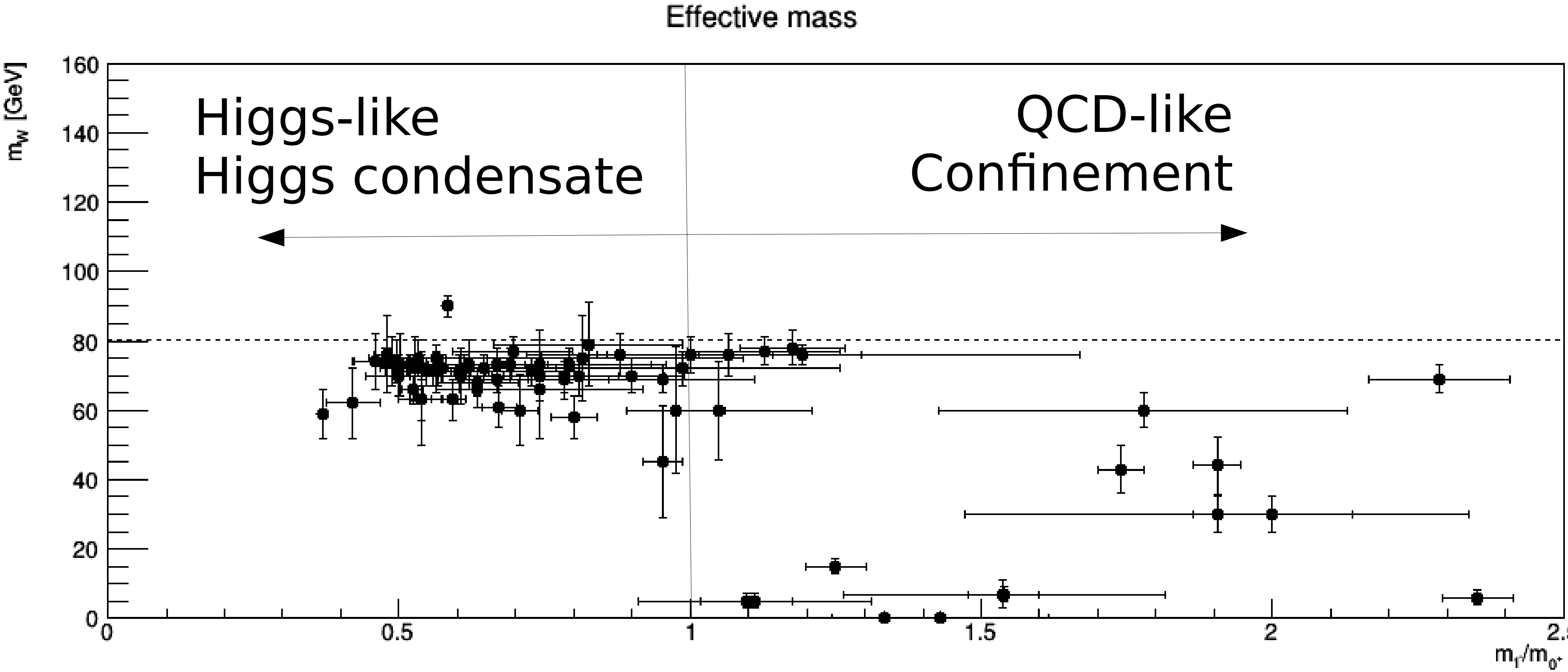

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Why?

Higgs mass

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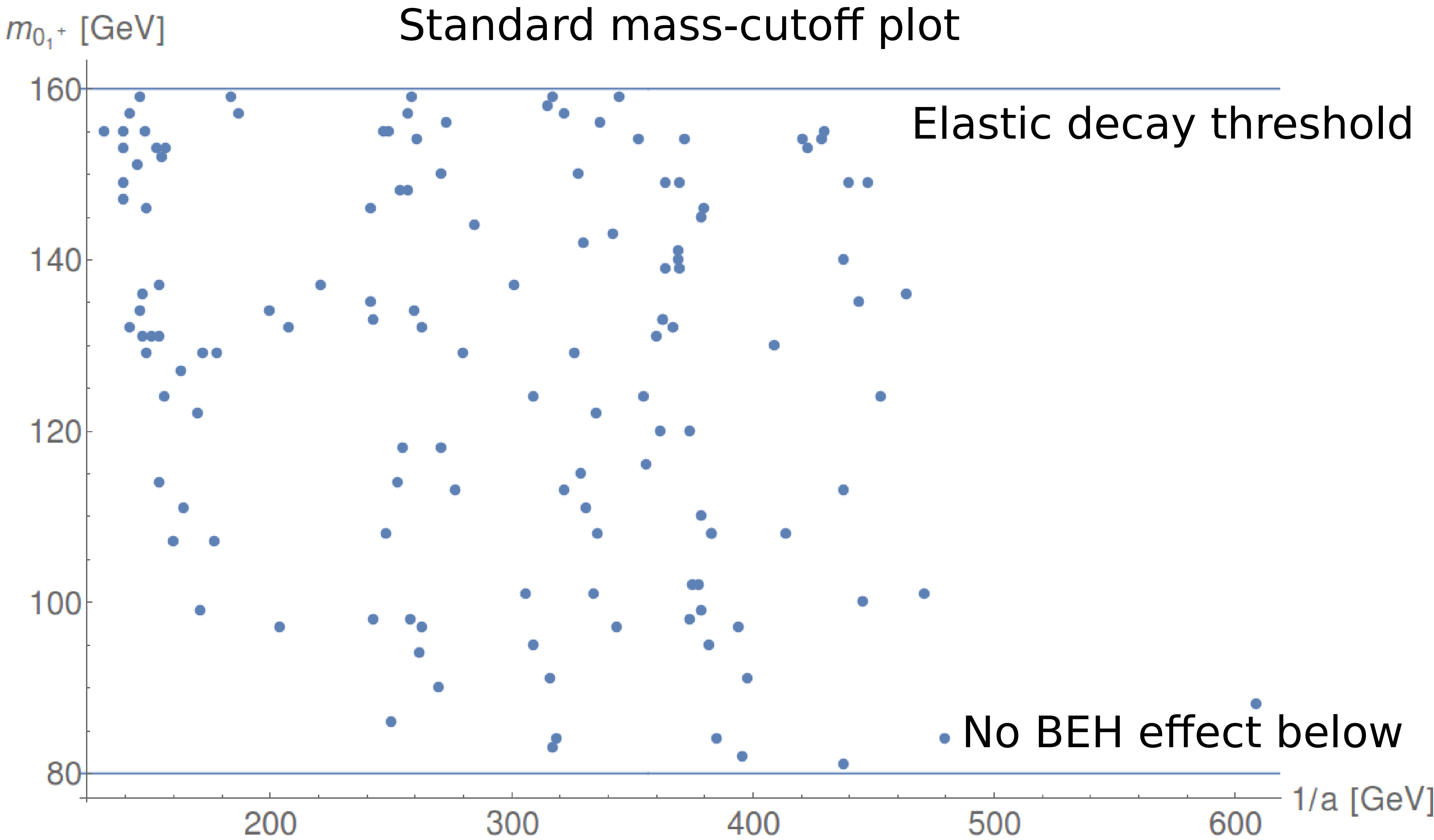
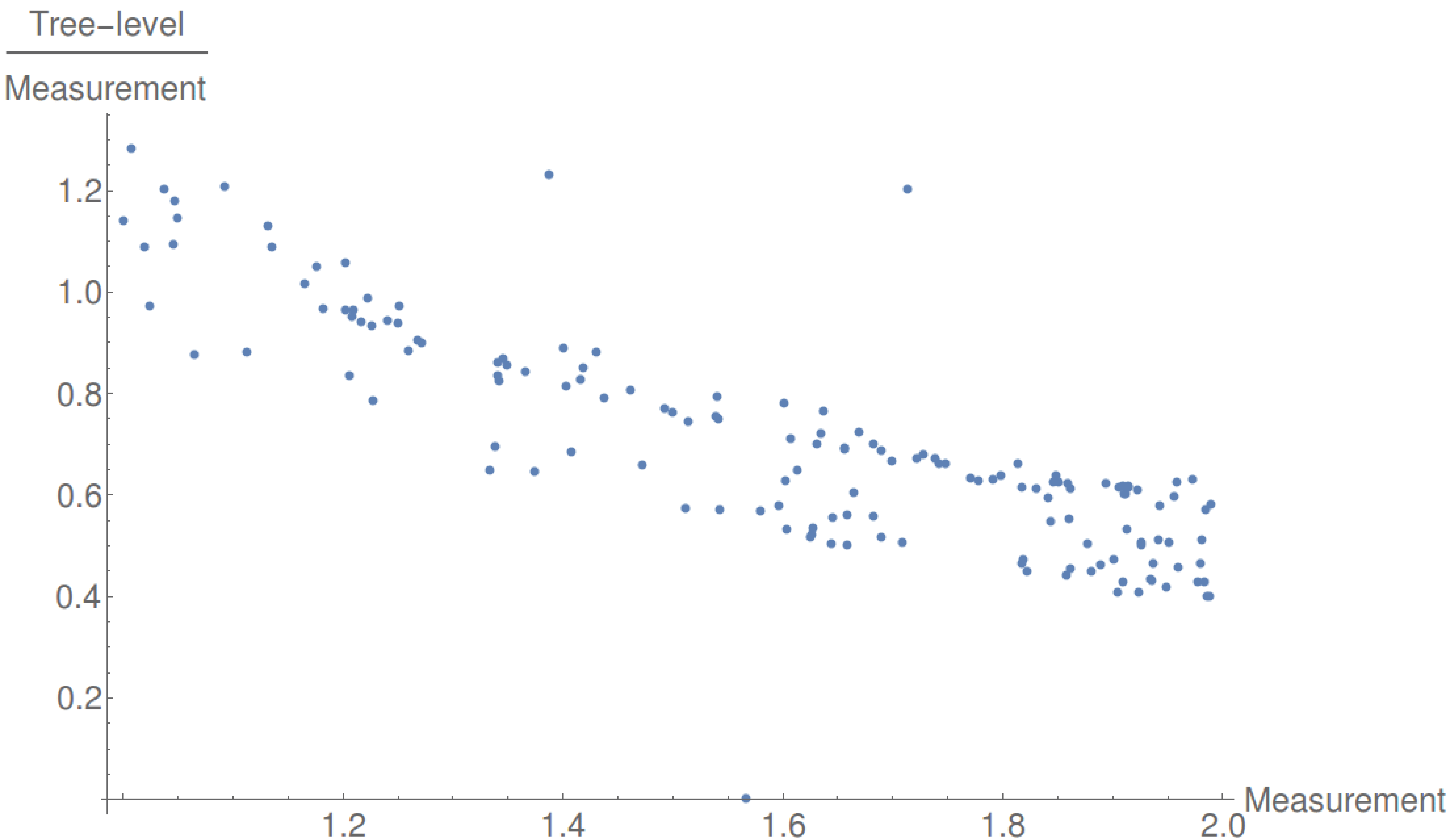


No strong dependence of mass range on cutoff - expected

Perturbative predictivity: Mass ratios



$0^+/1^-$ mass ratio

[Maas, unpublished]

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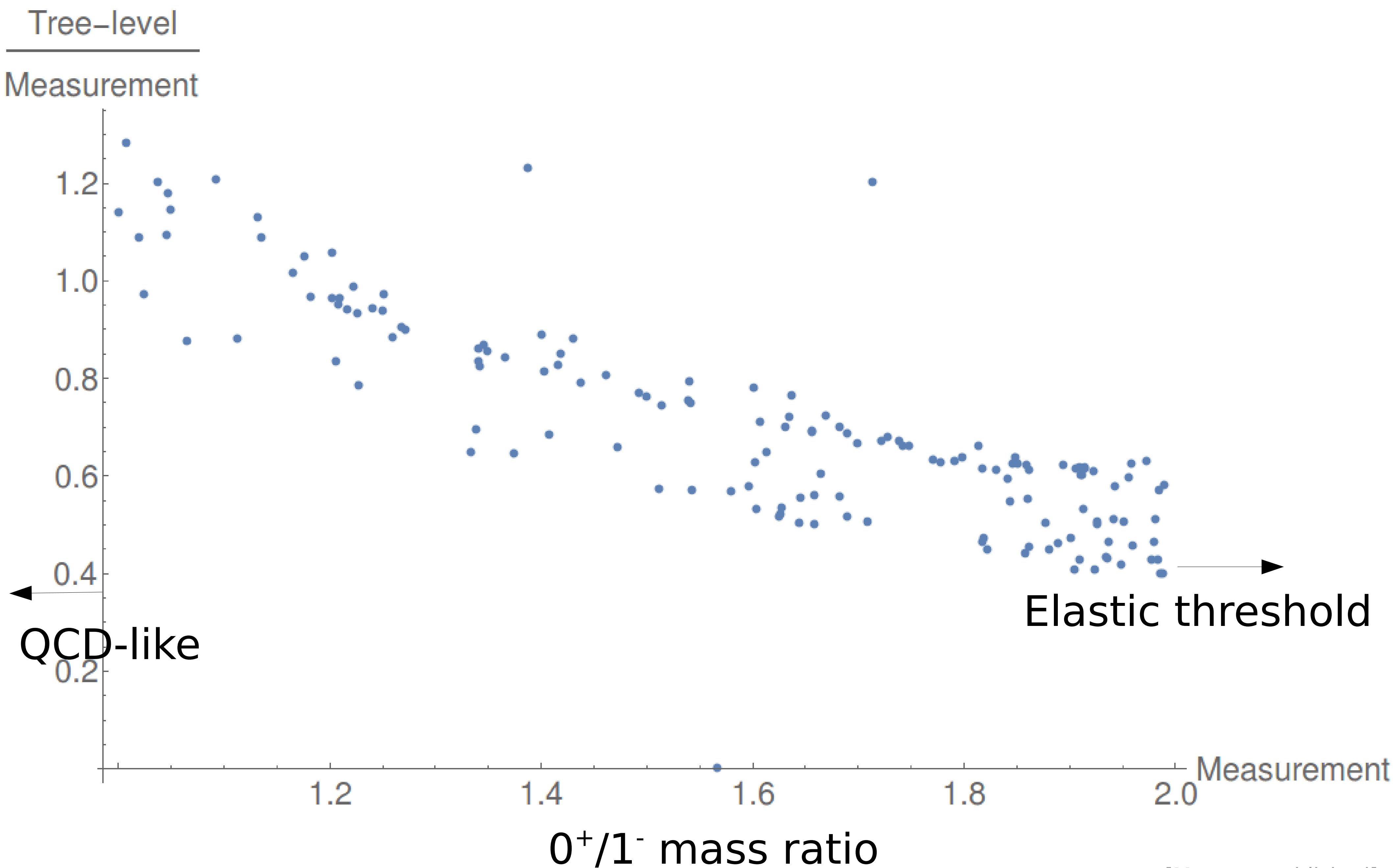

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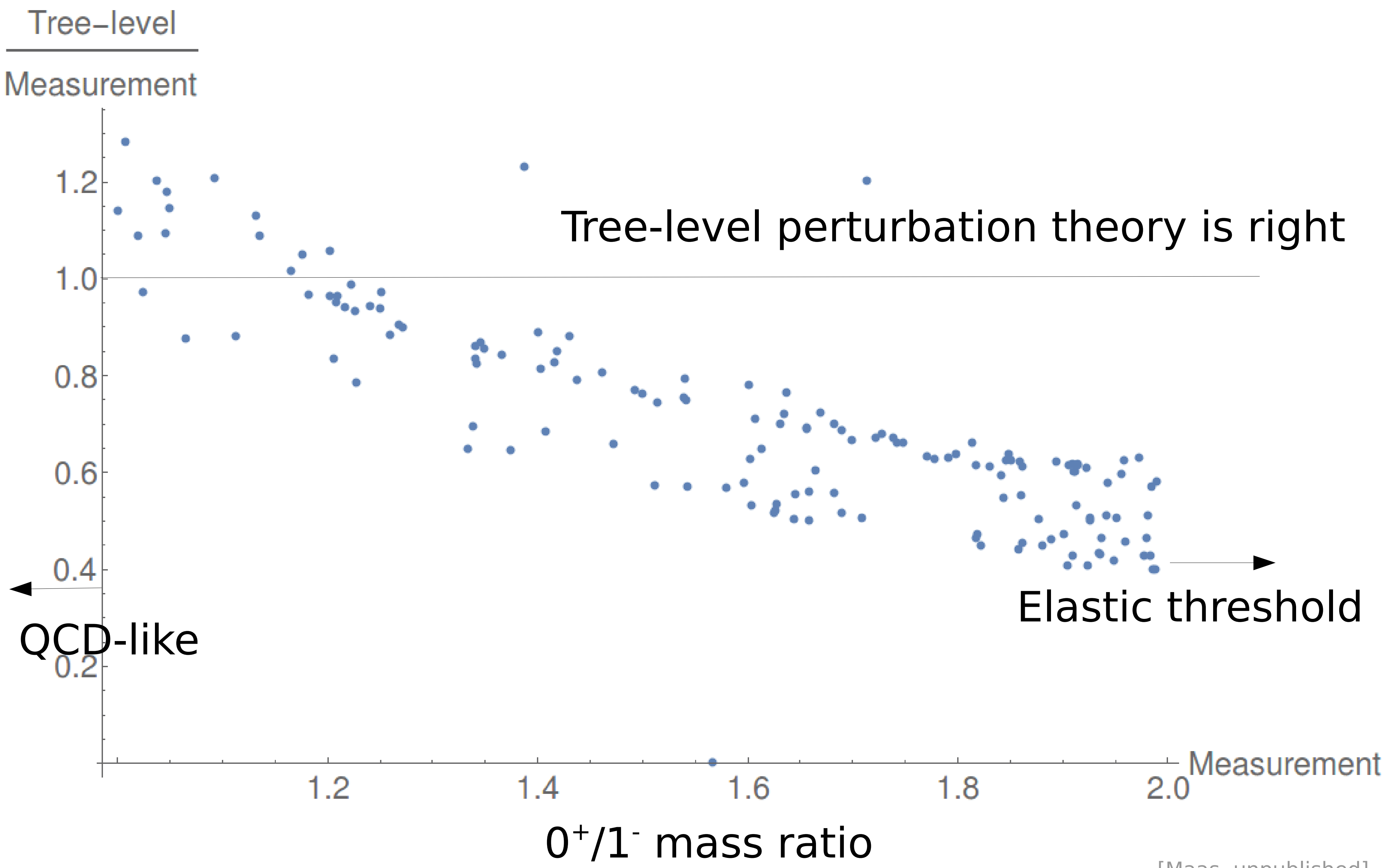

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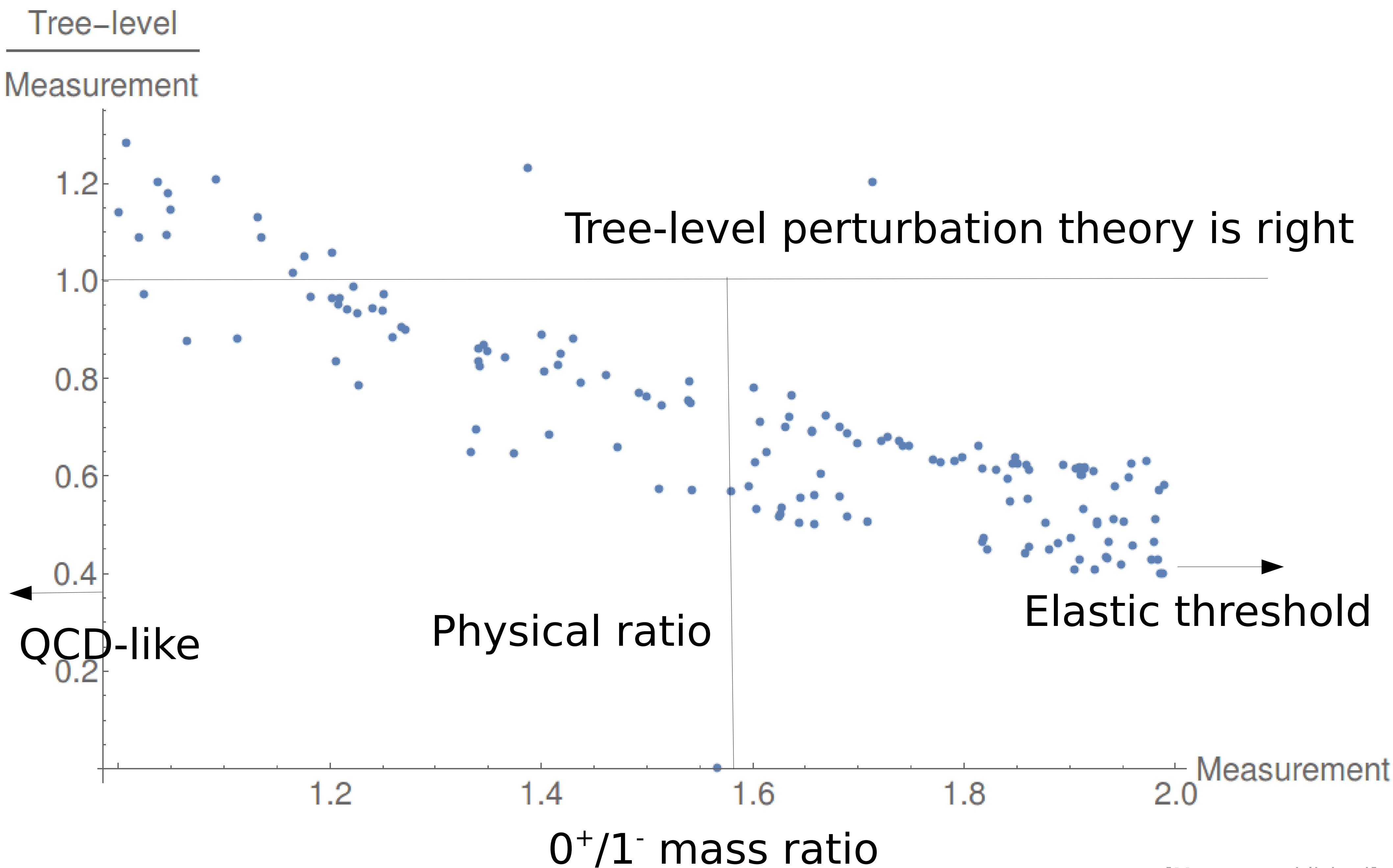

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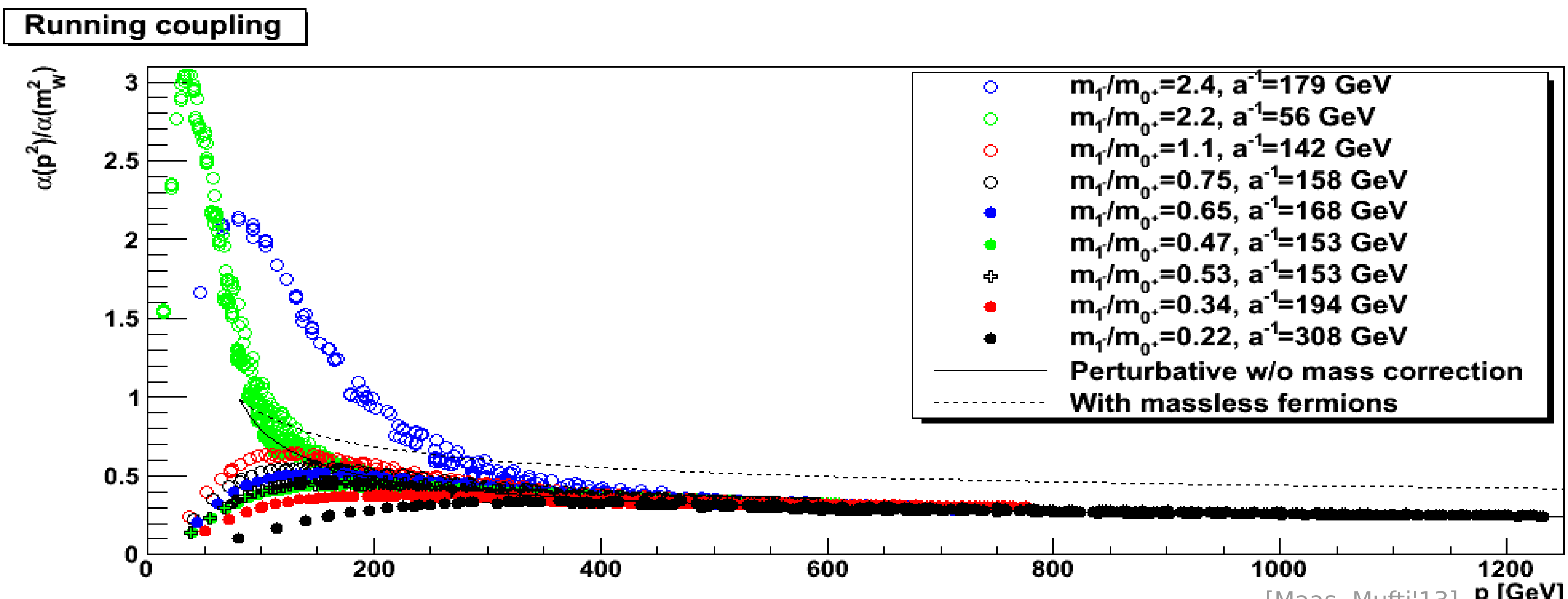
  - Couplings run differently – proceed with caution



[Maas, Mufti'13]

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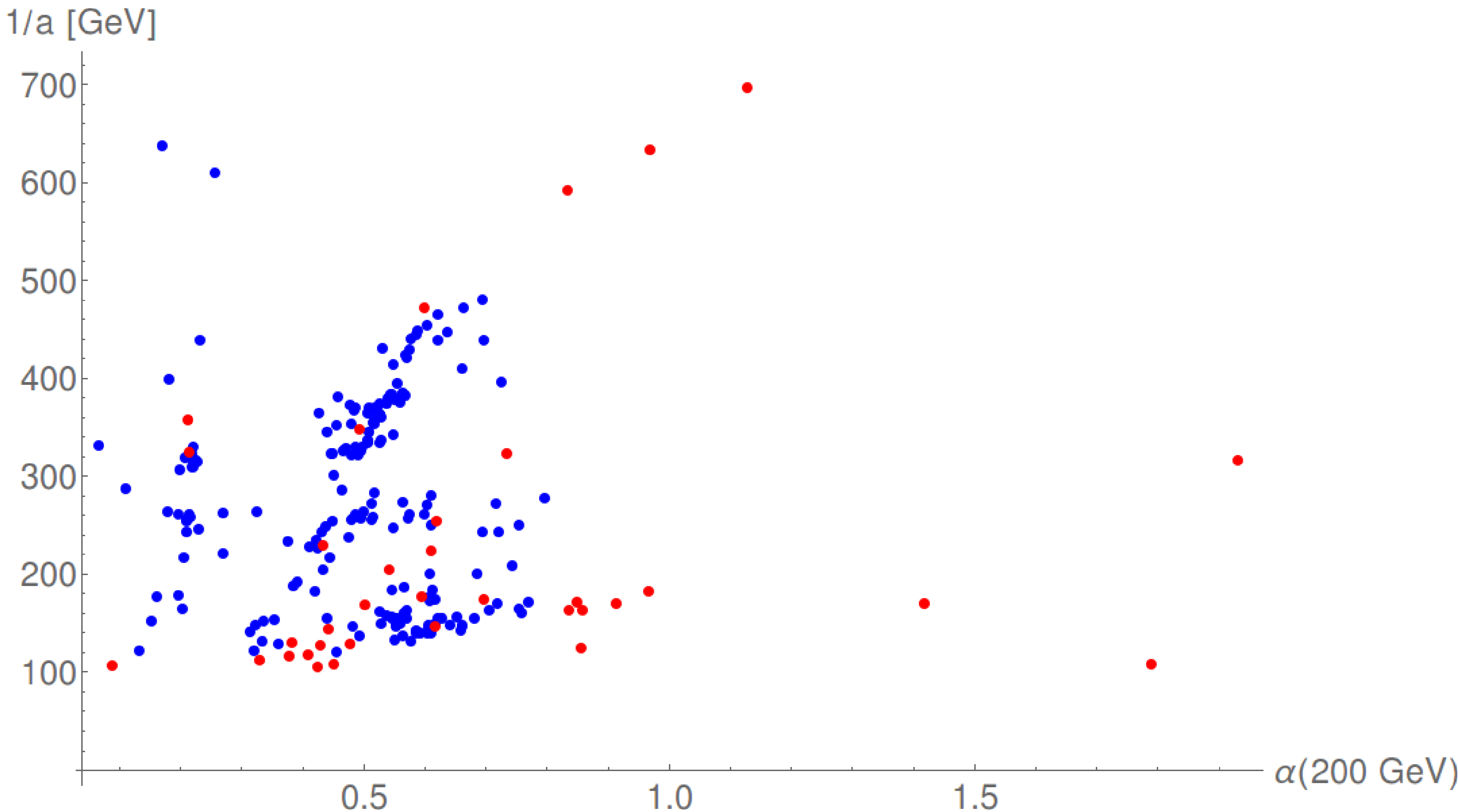

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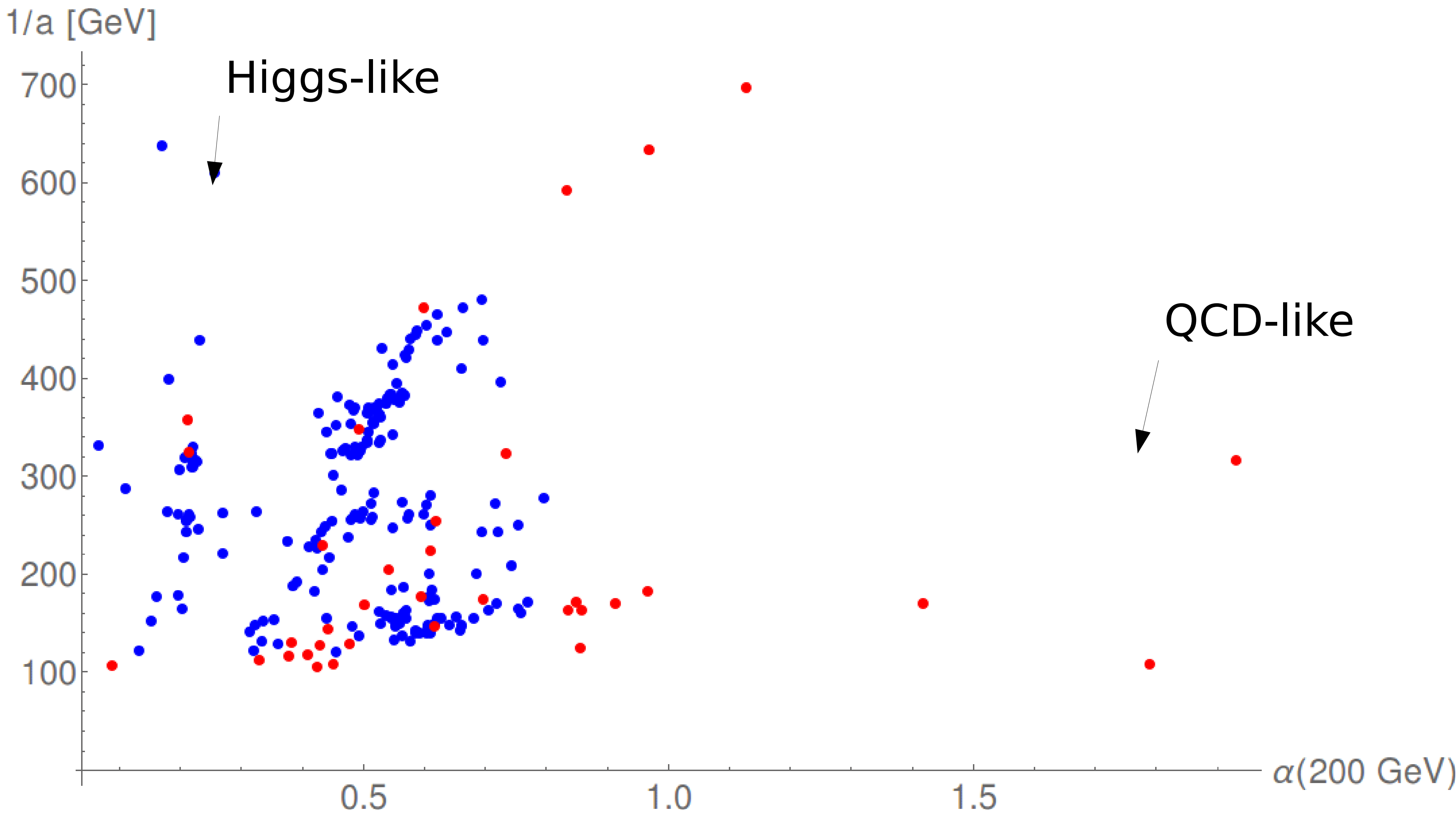

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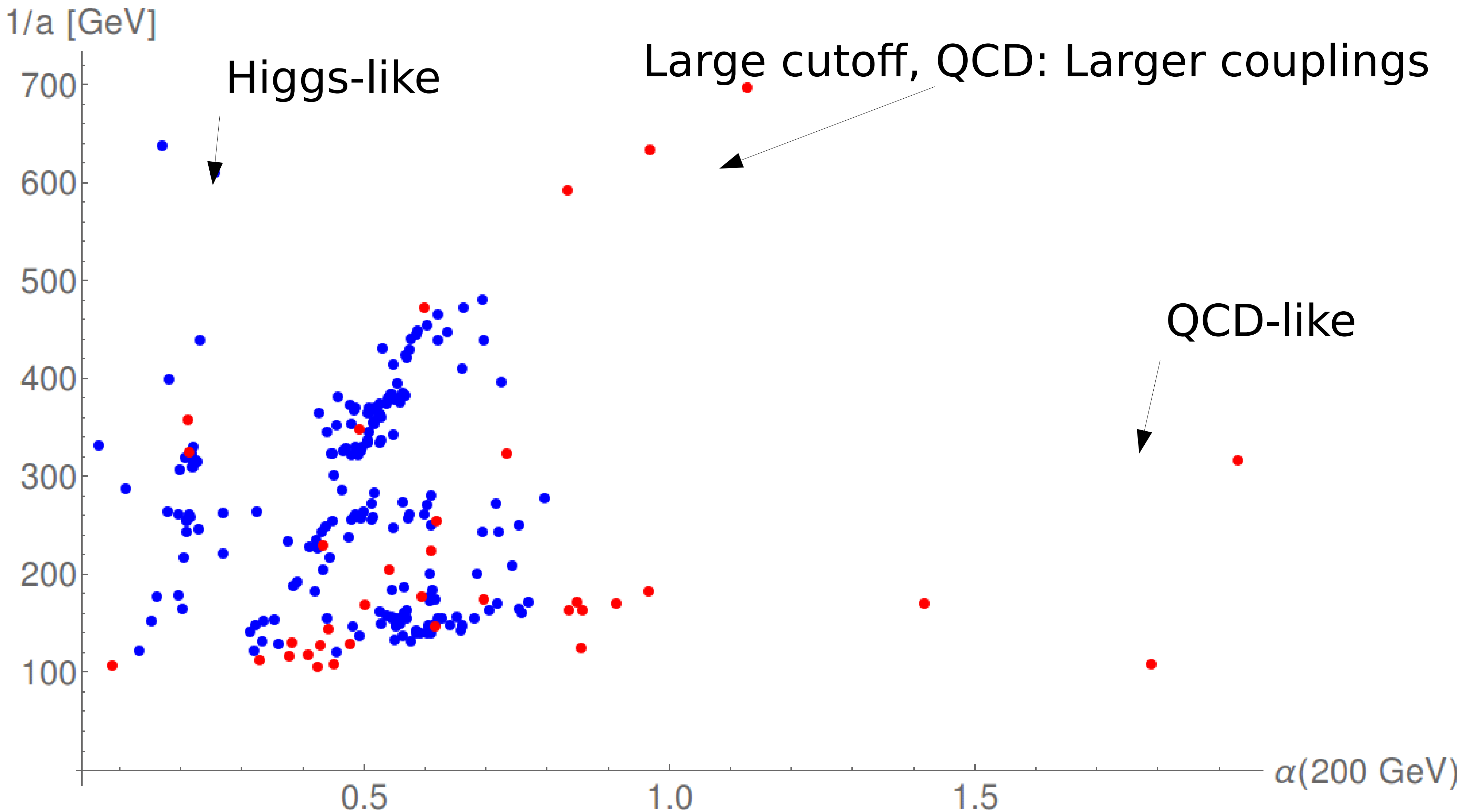

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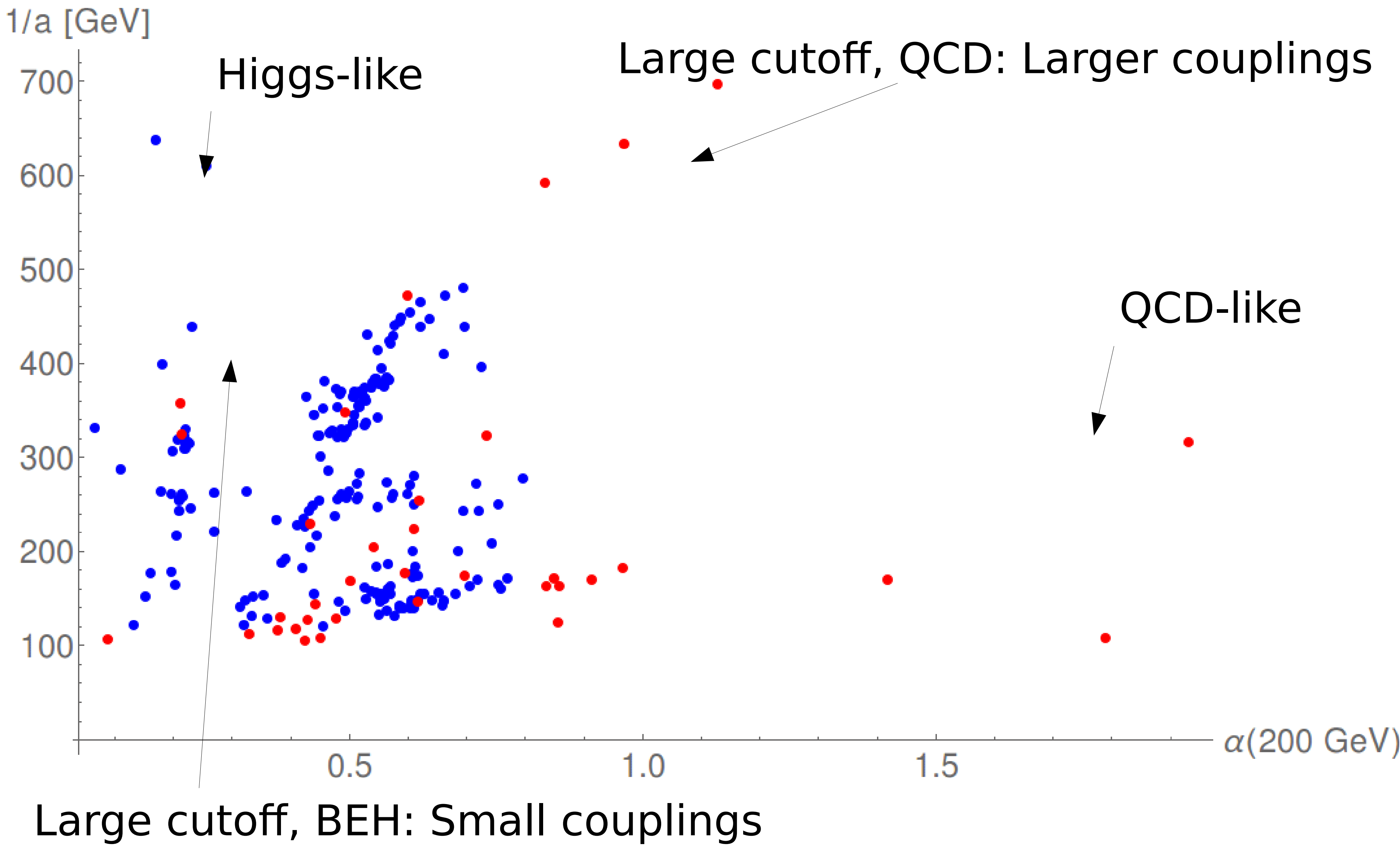

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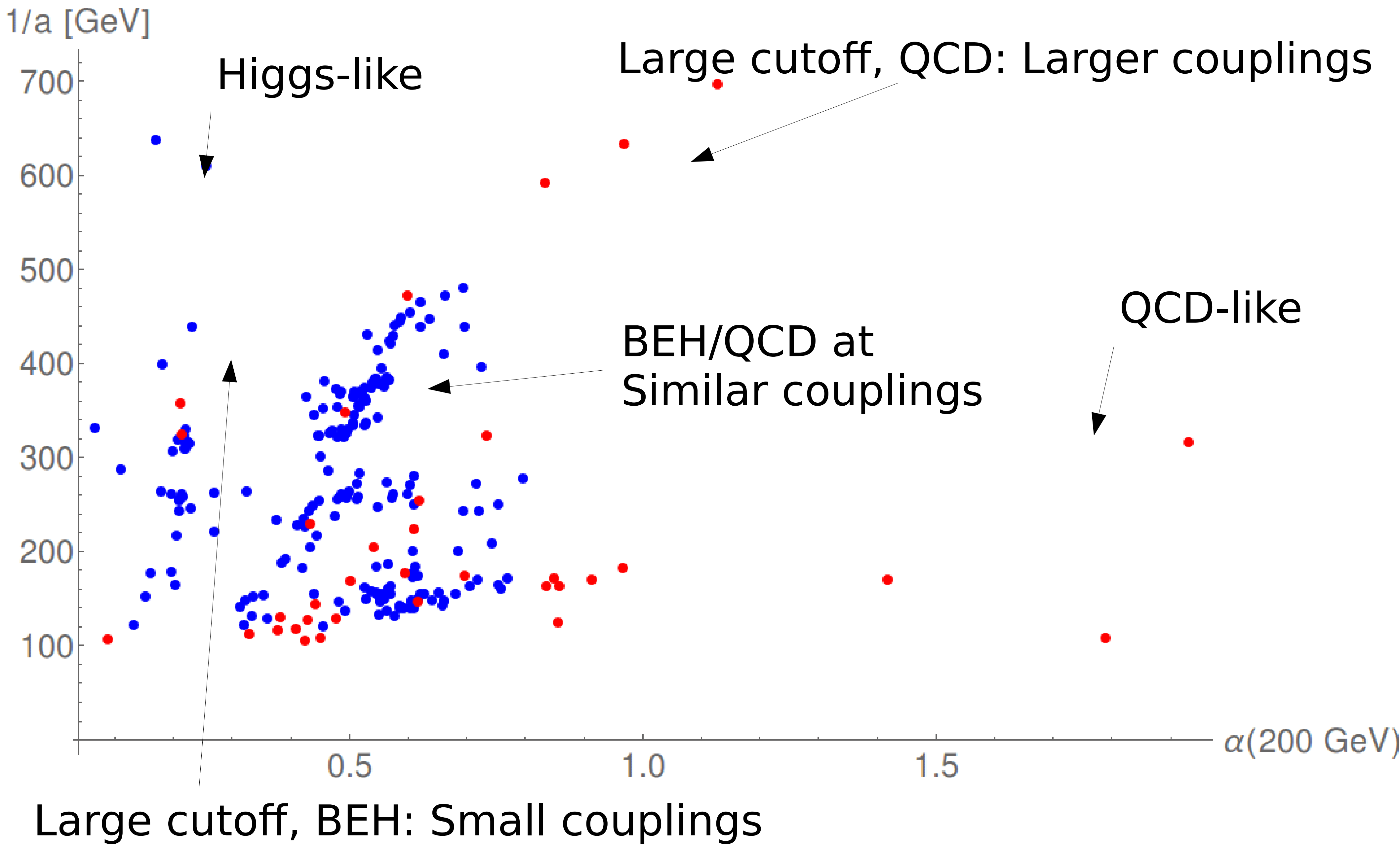

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Impact on quartic gauge coupling

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[Maas et al. Unpublished]

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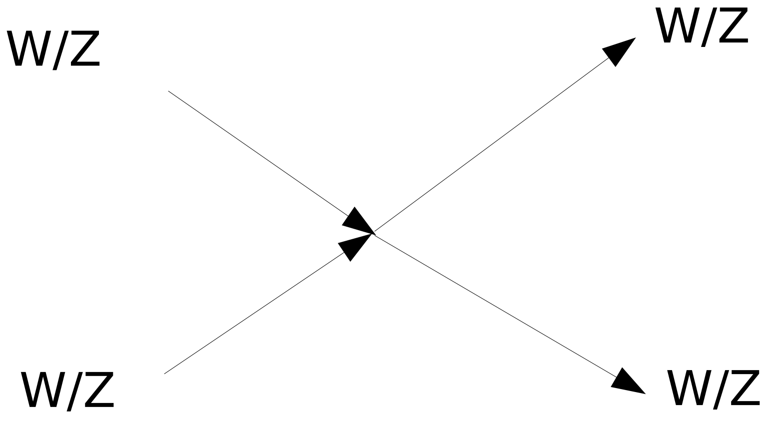

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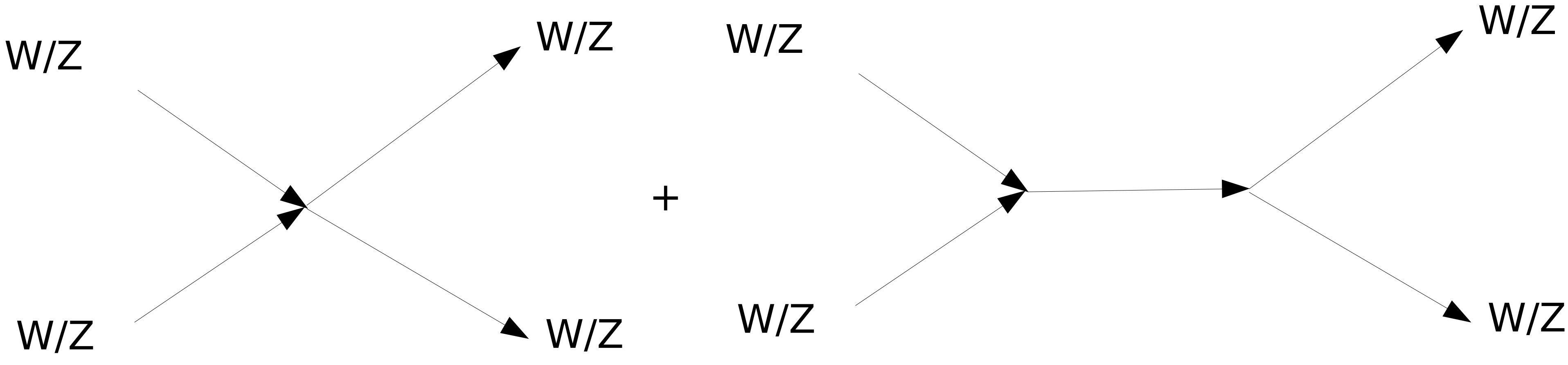

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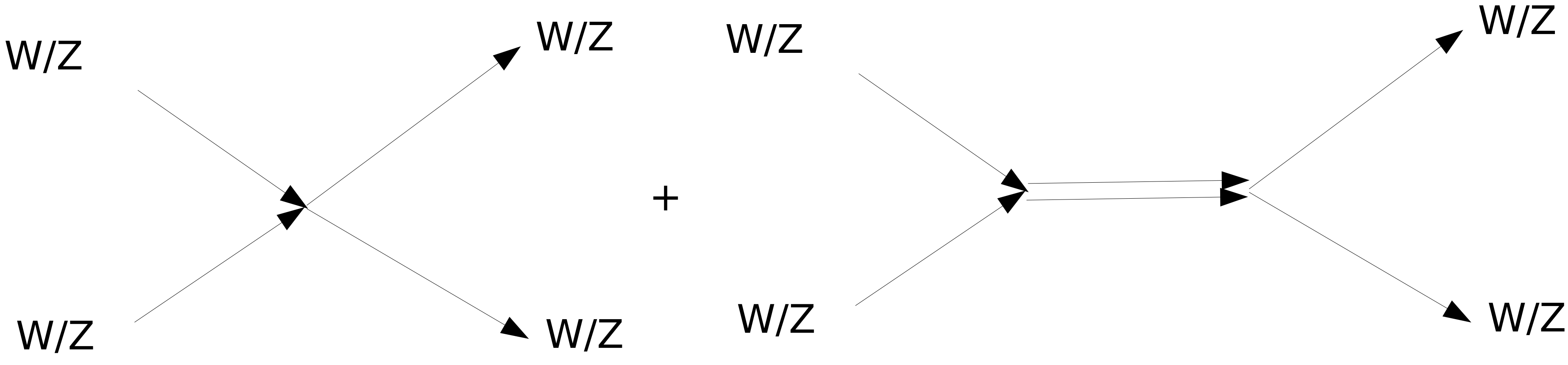

Impact on quartic gauge coupling

[Maas et al. Unpublished]

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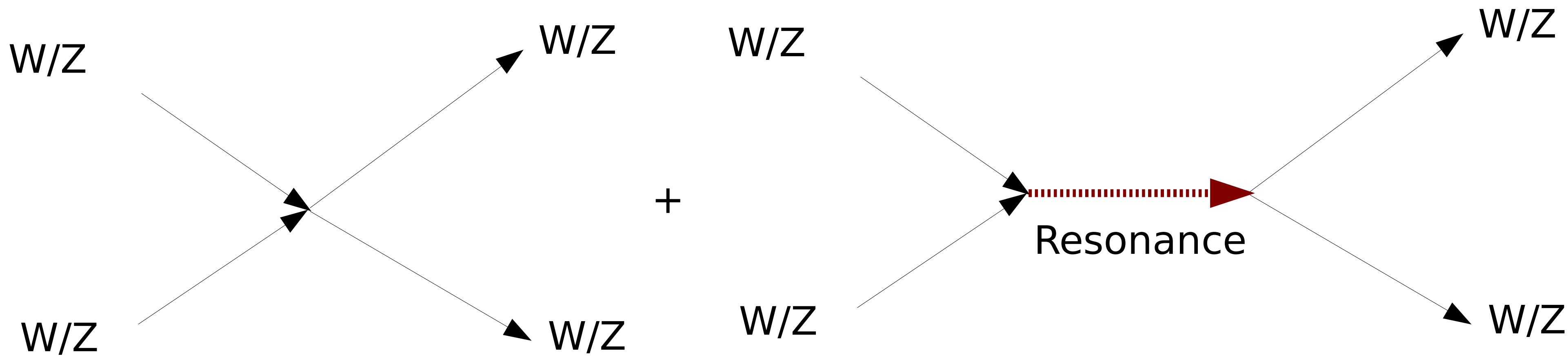
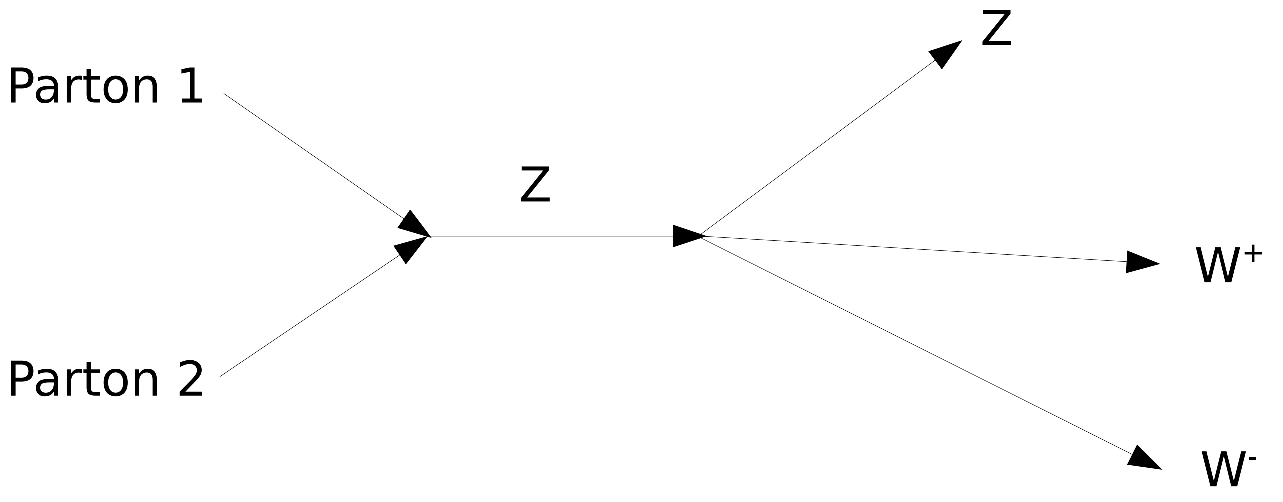


- Resonance peak in final state invariant mass?

Experimental accessibility

[Maas et al. Unpublished]



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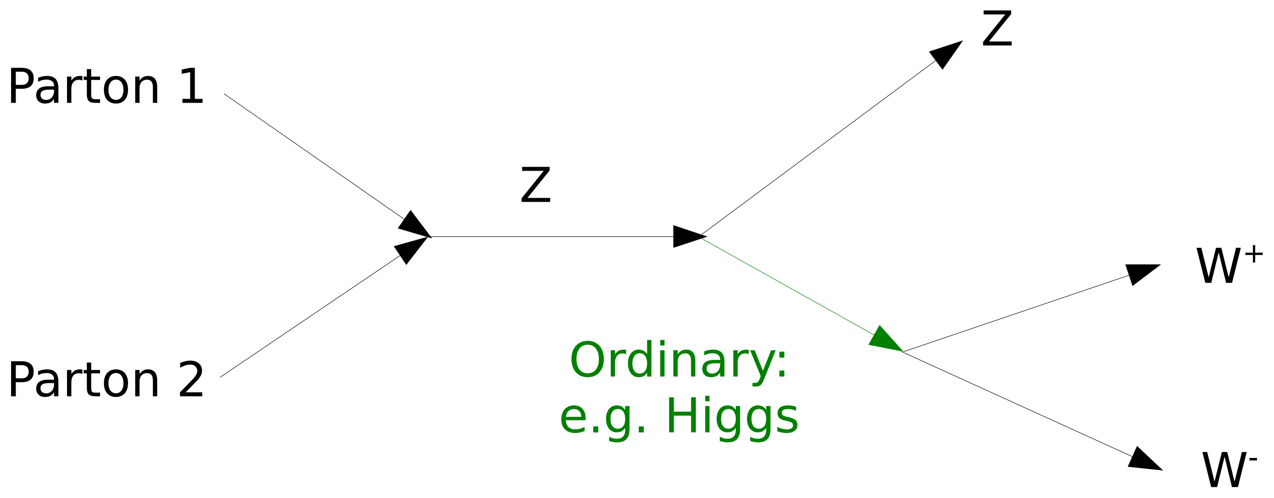

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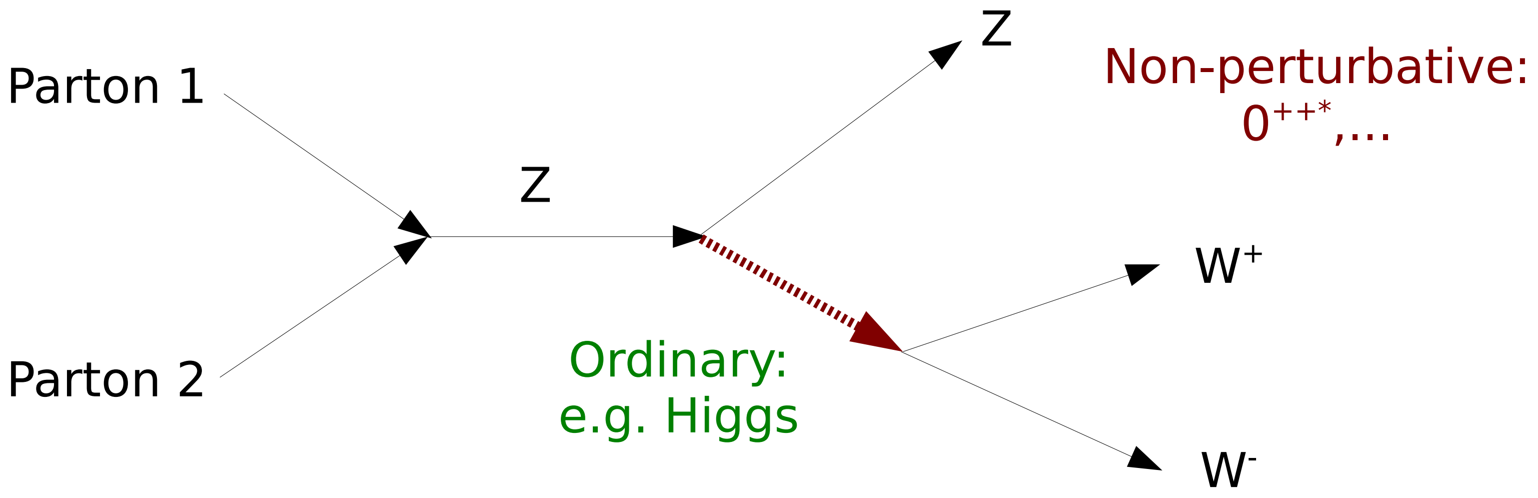
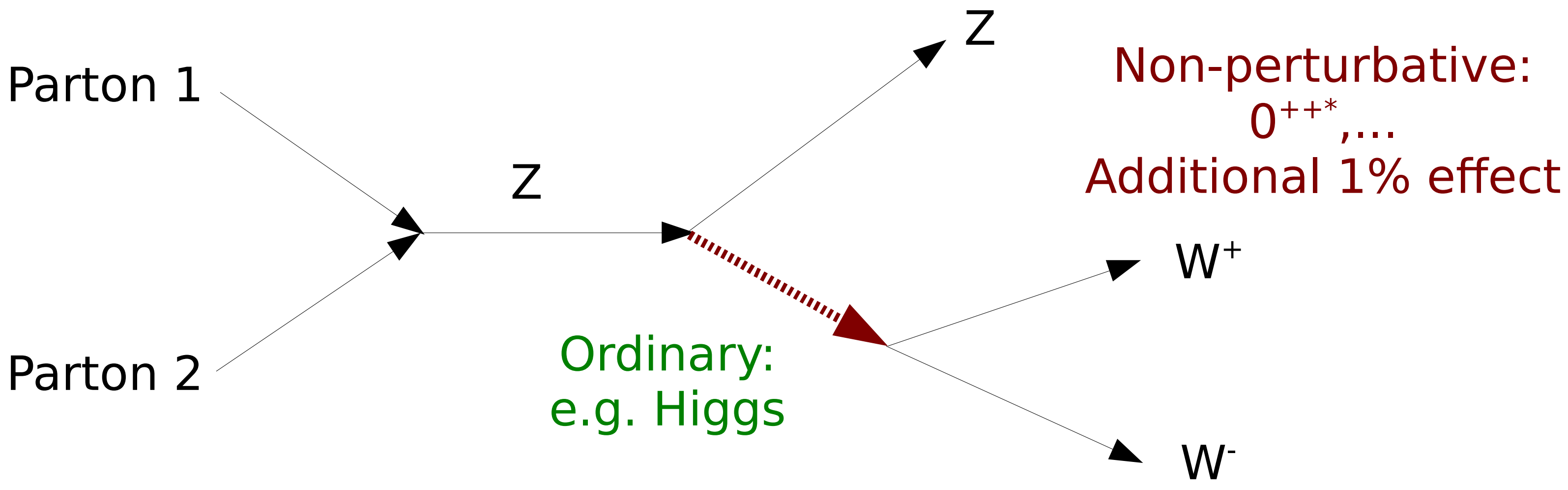


- E.g. excited Higgs: Decay channel: 2W

Experimental accessibility

[Maas et al. Unpublished]



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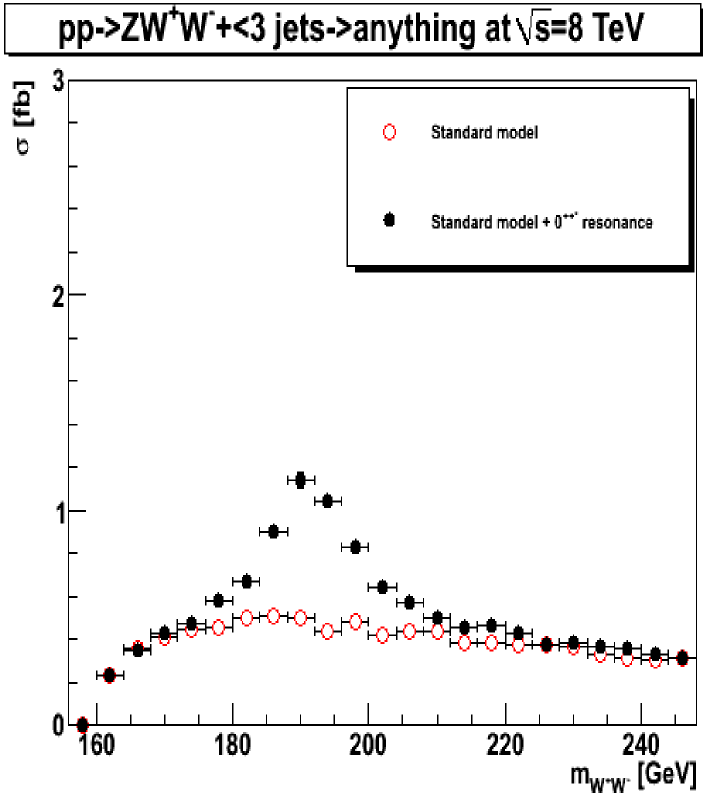
SPECULATIVE



[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

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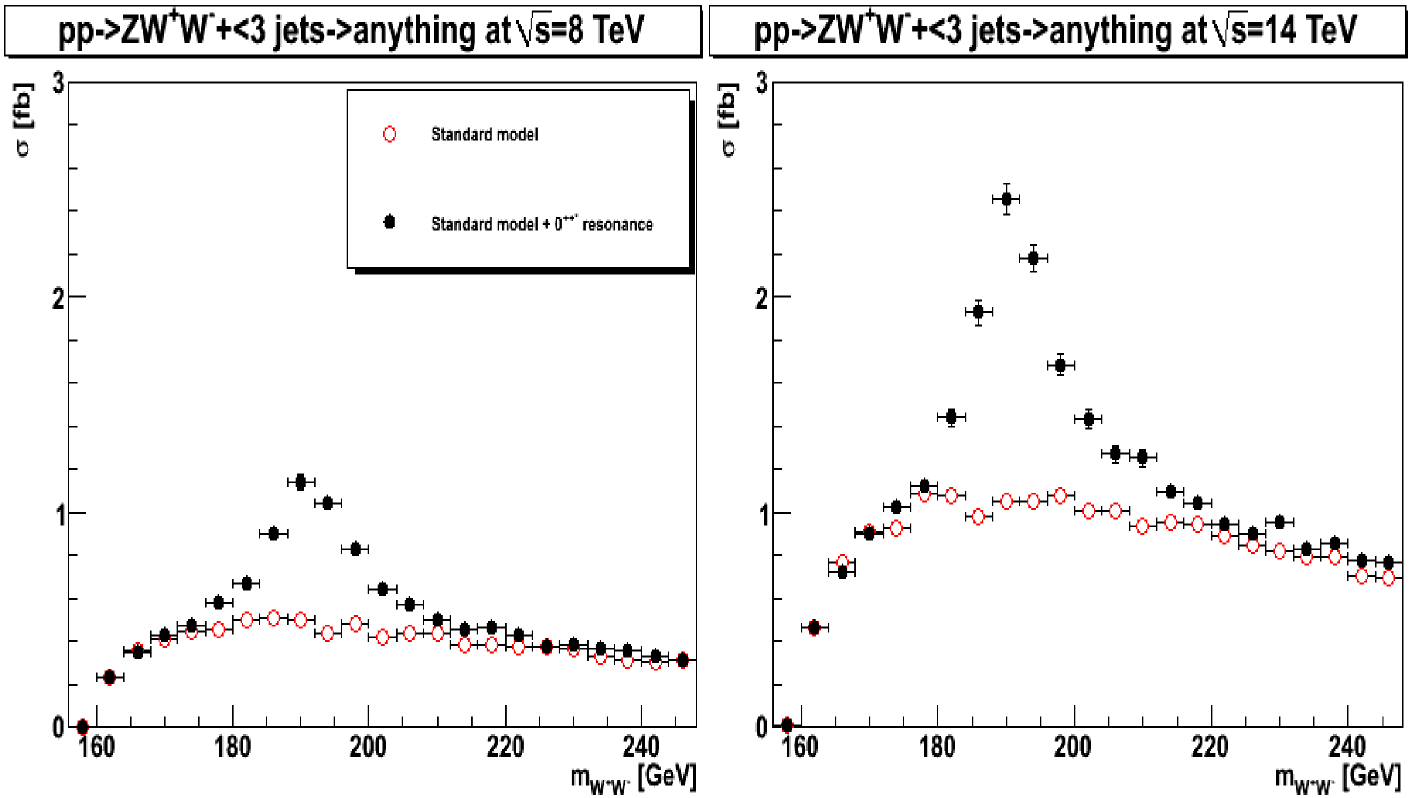

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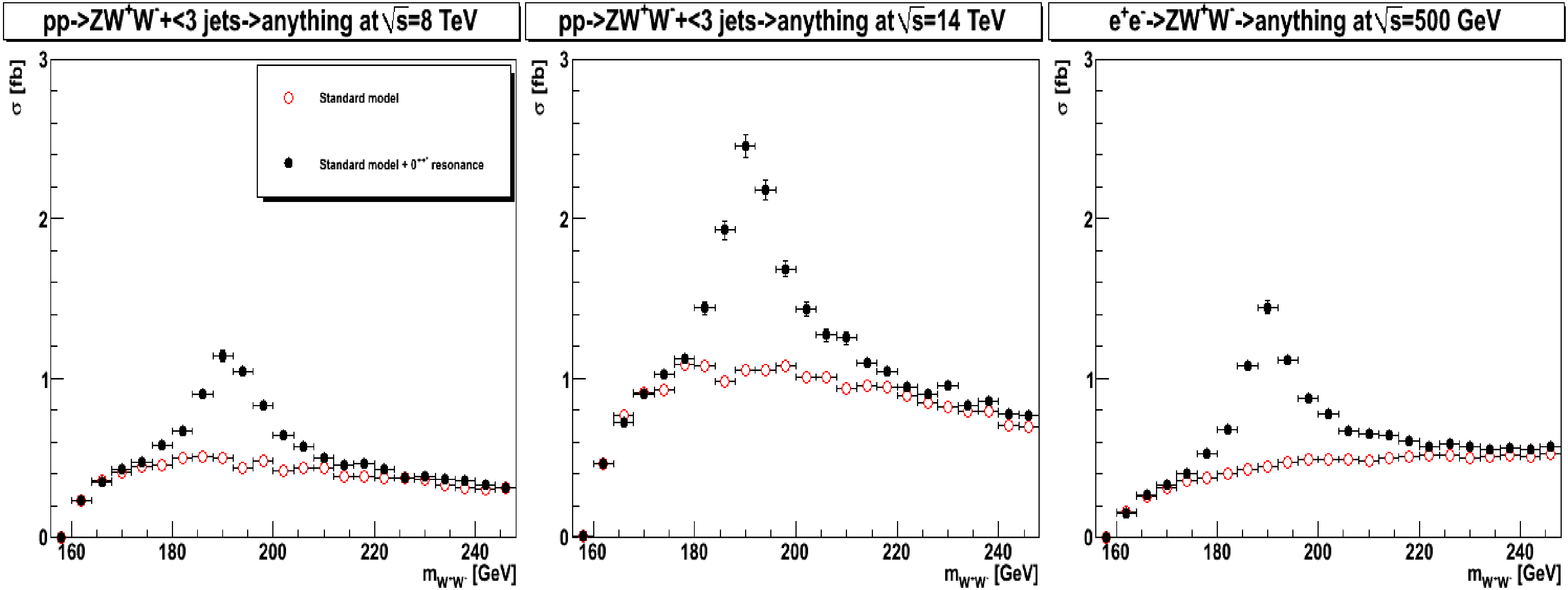

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Experimental accessibility

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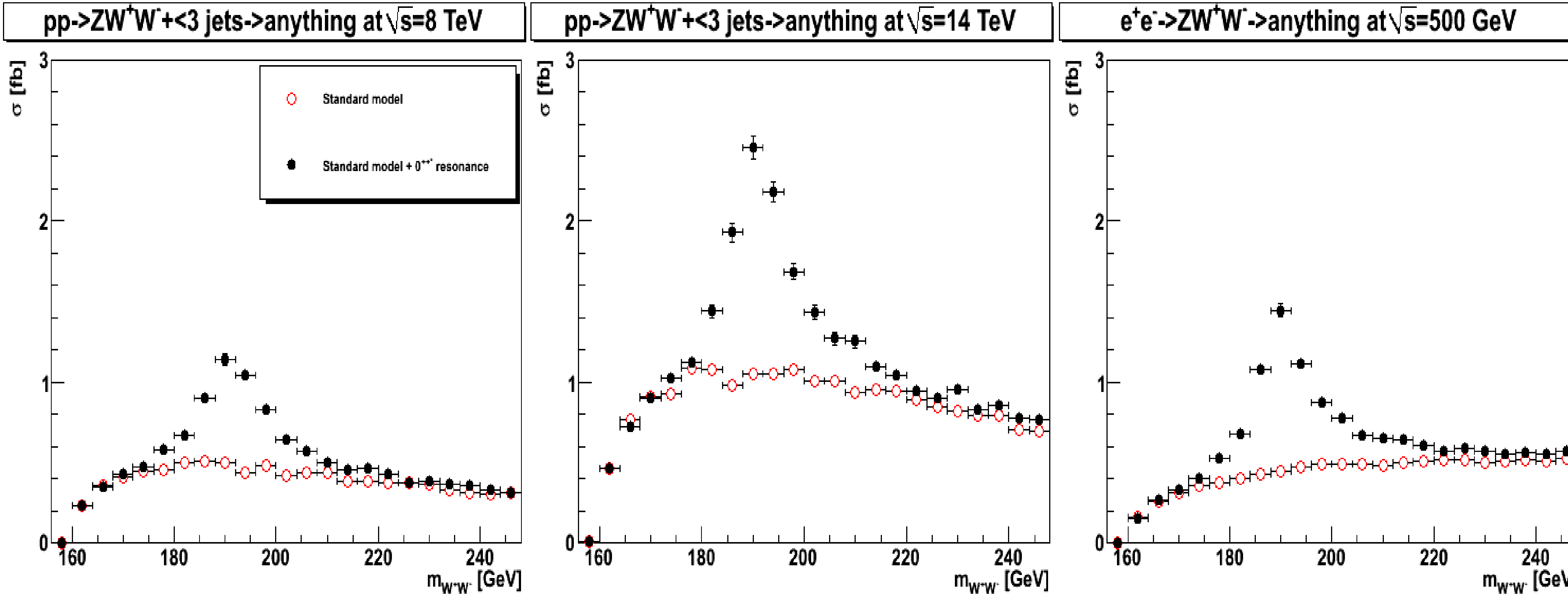

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- If yes, this would fake new physics!

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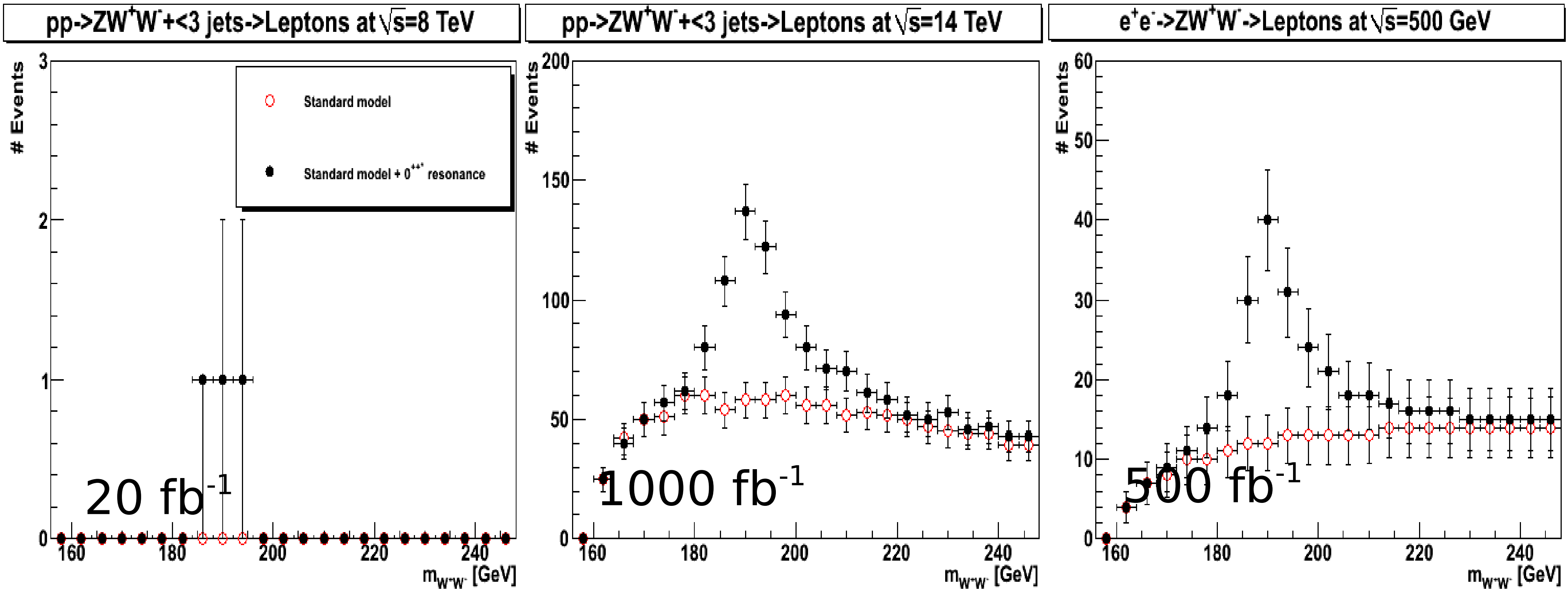
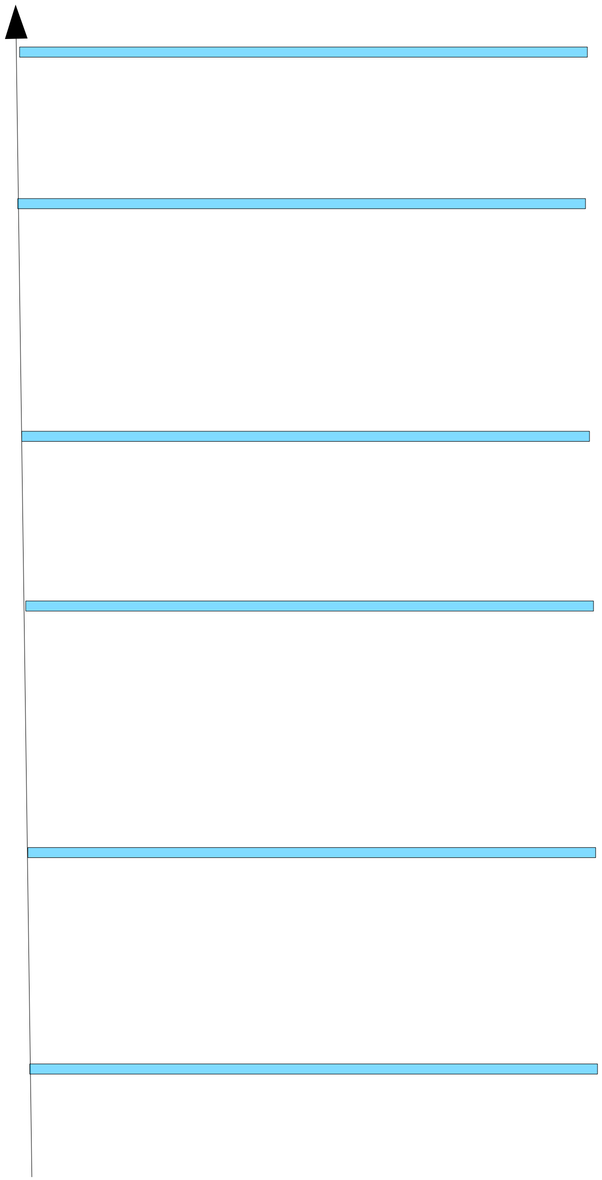


[Low-energy effective Lagrangian, MC by Sherpa 1.4.2]

- E.g. excited Higgs: Decay channel: 2W
- Does it happen in the standard model?
- If yes, this would fake new physics!
  - And would be hard to detect

Excited states on the lattice

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



Excited states on the lattice

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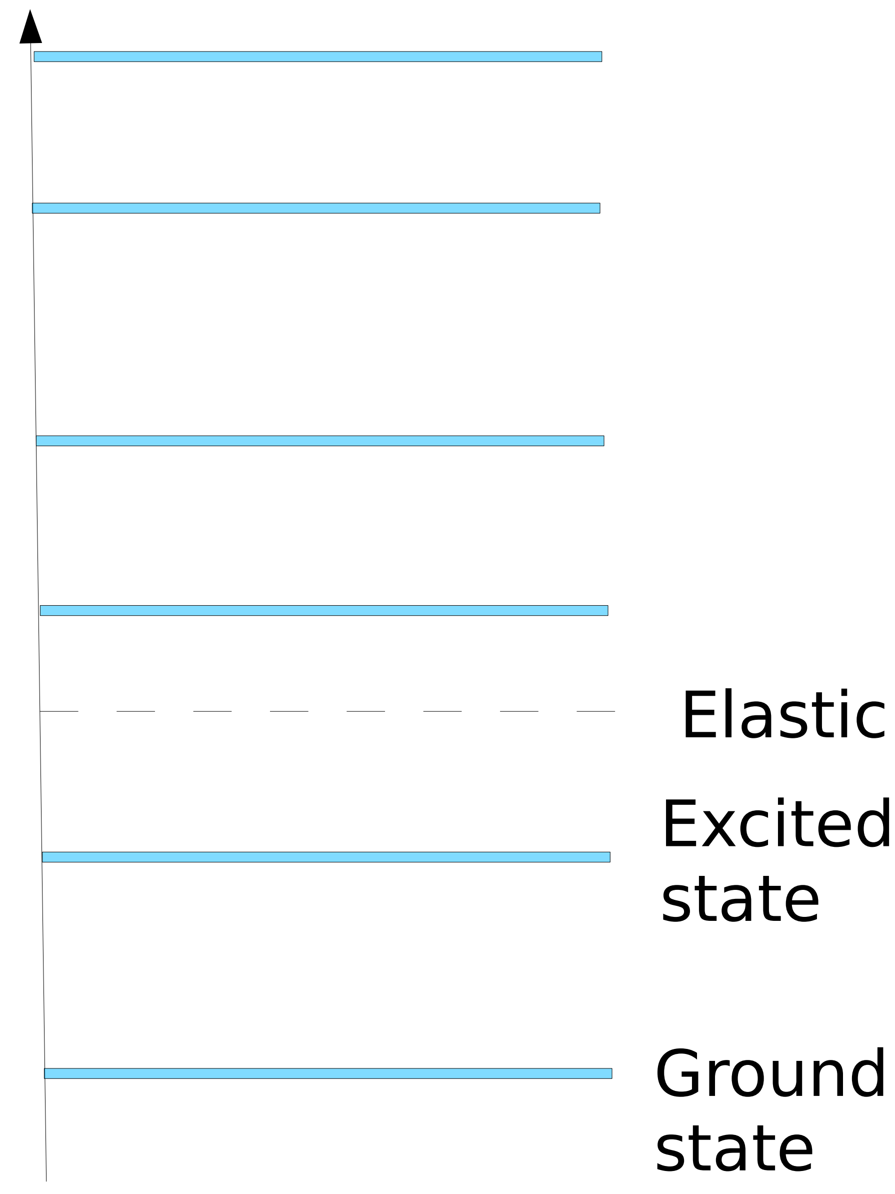

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Excited states on the lattice

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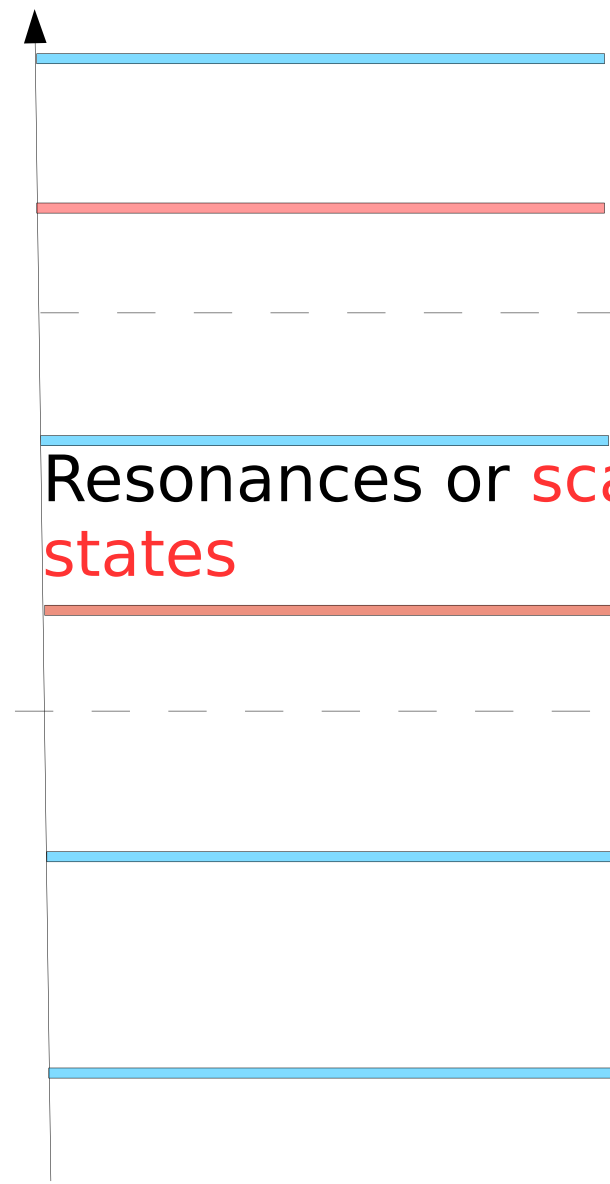
Excited states on the lattice

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



Exponential volume dependency
- if stable against decays into
other channels

Excited states on the lattice

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

- Polynominal (inverse) volume dependence
- Width and nature from phase shifts below the inelastic threshold

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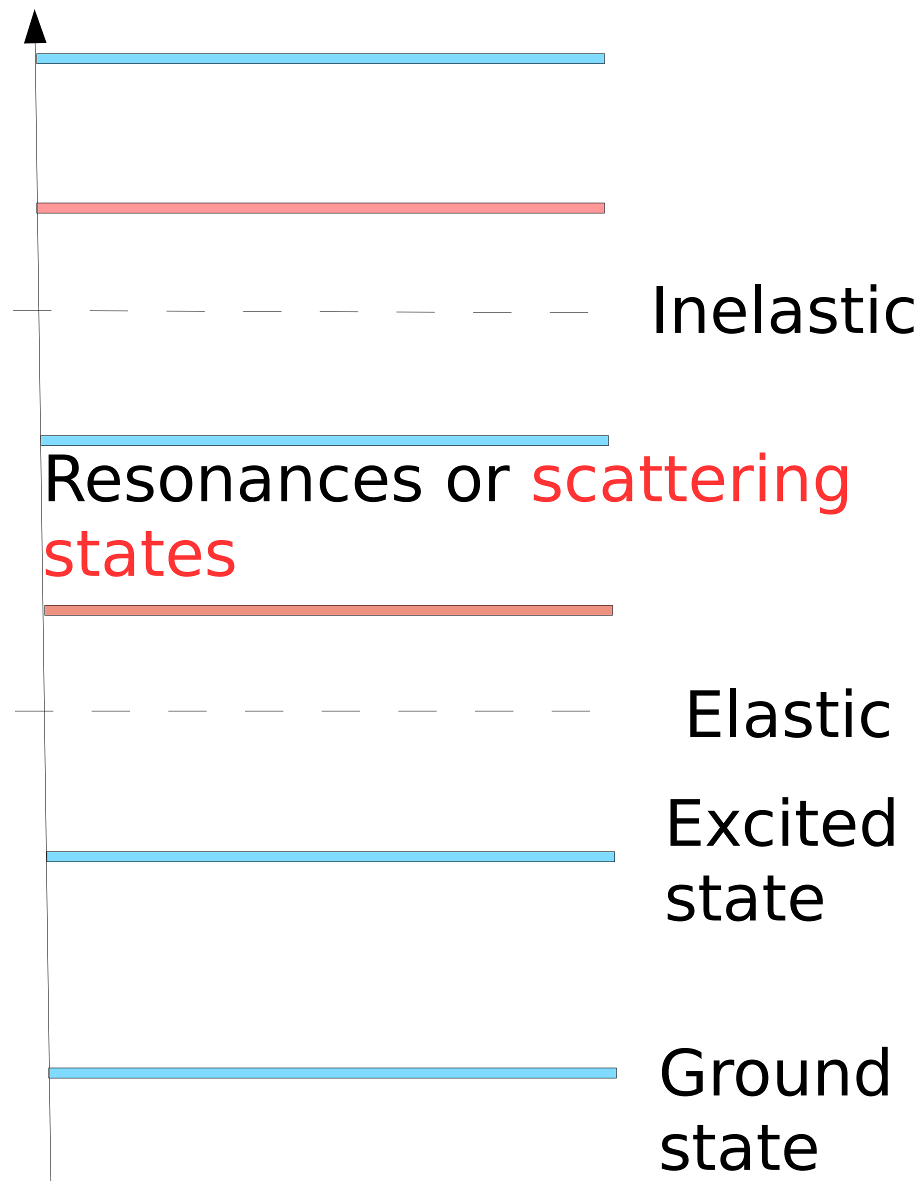


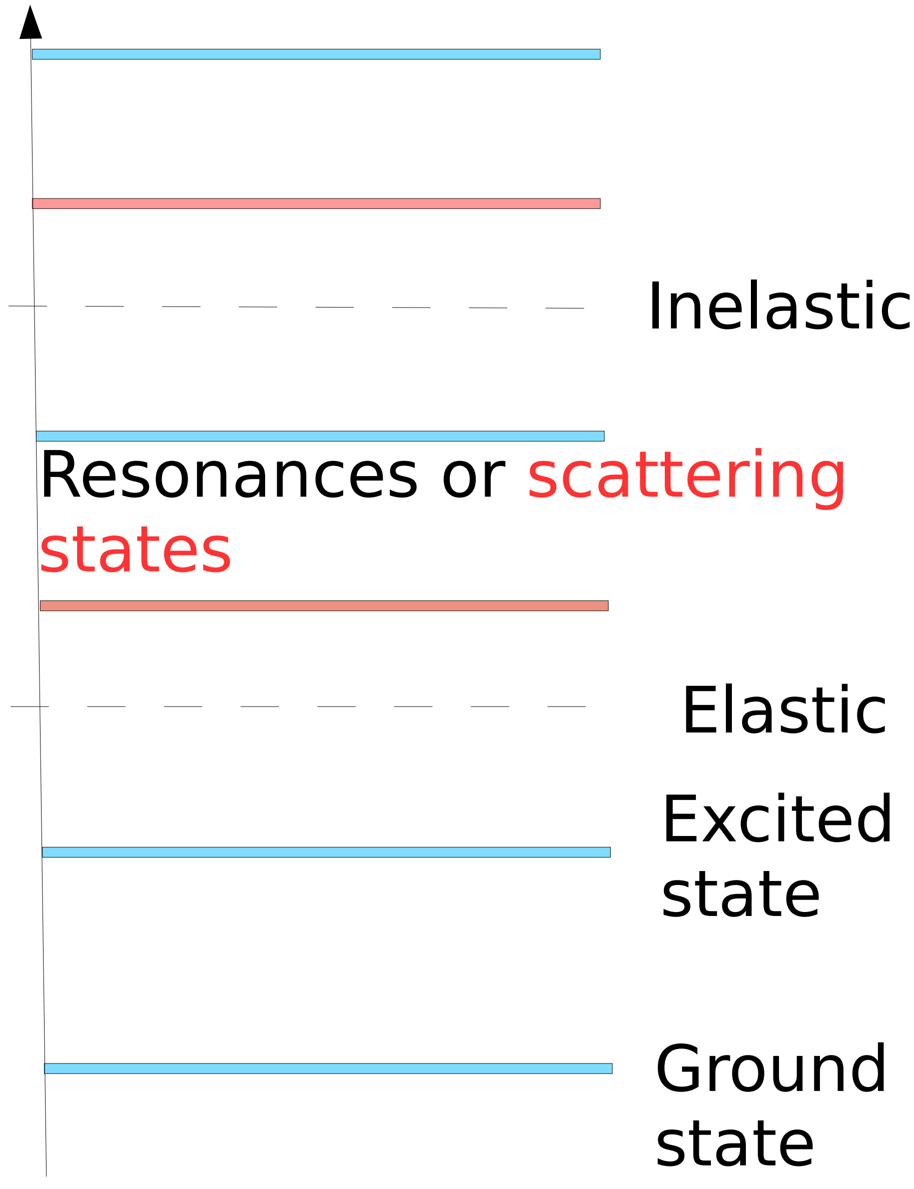
Excited states on the lattice

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

Above inelastic threshold still complicated

- Polynominal (inverse) volume dependence
- Width and nature from phase shifts below the inelastic threshold

Exponential volume dependency - if stable against decays into other channels



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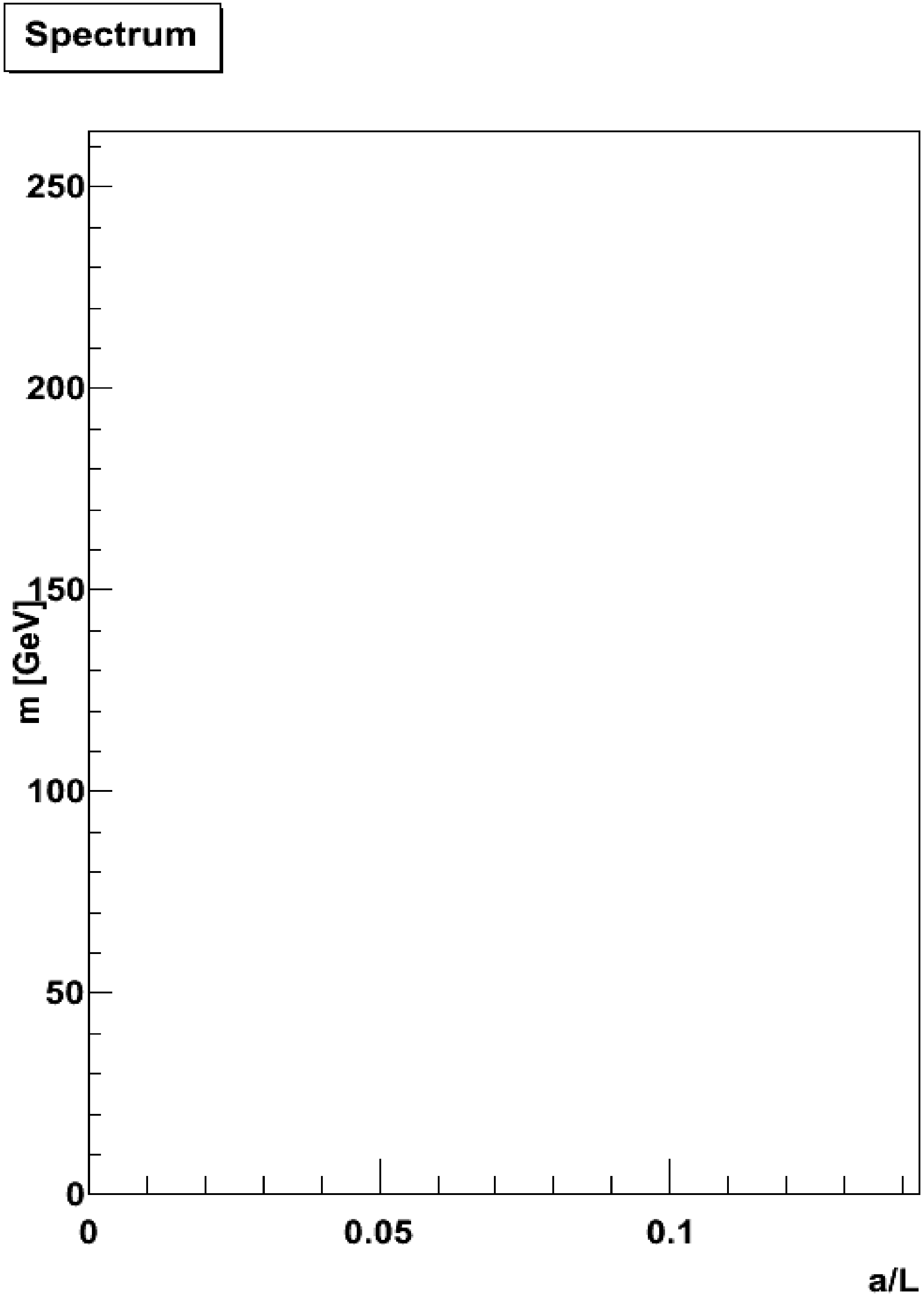

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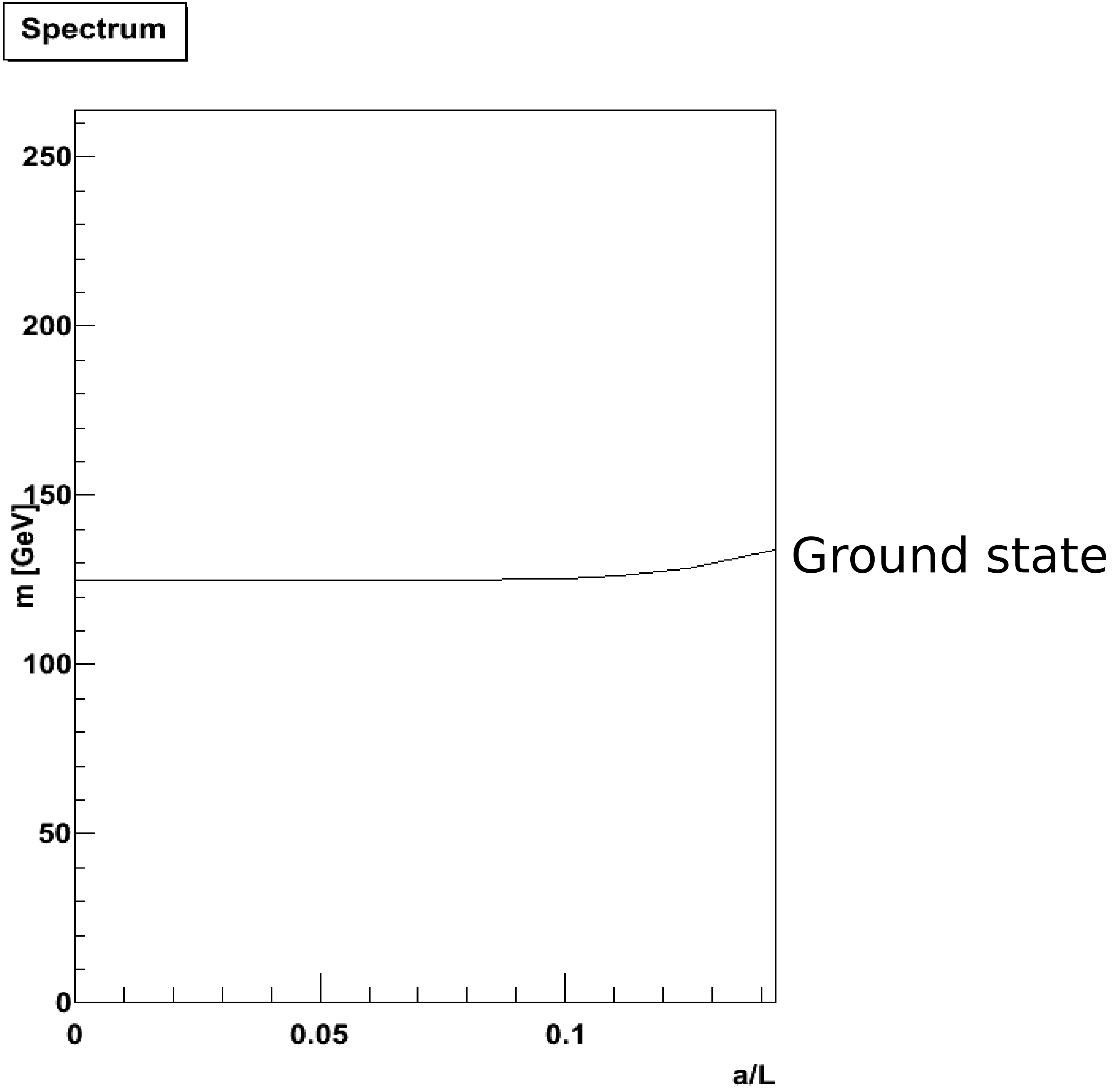

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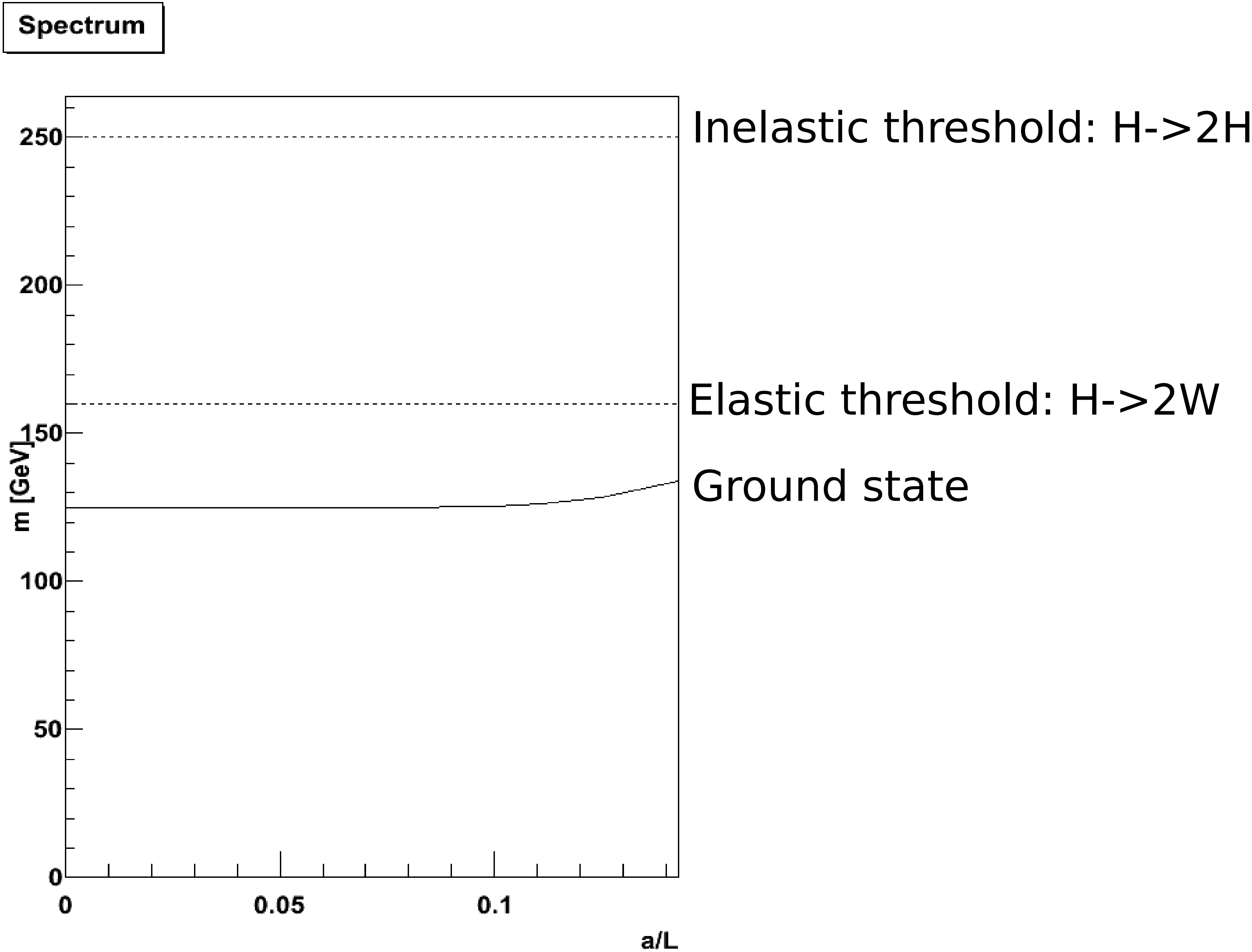

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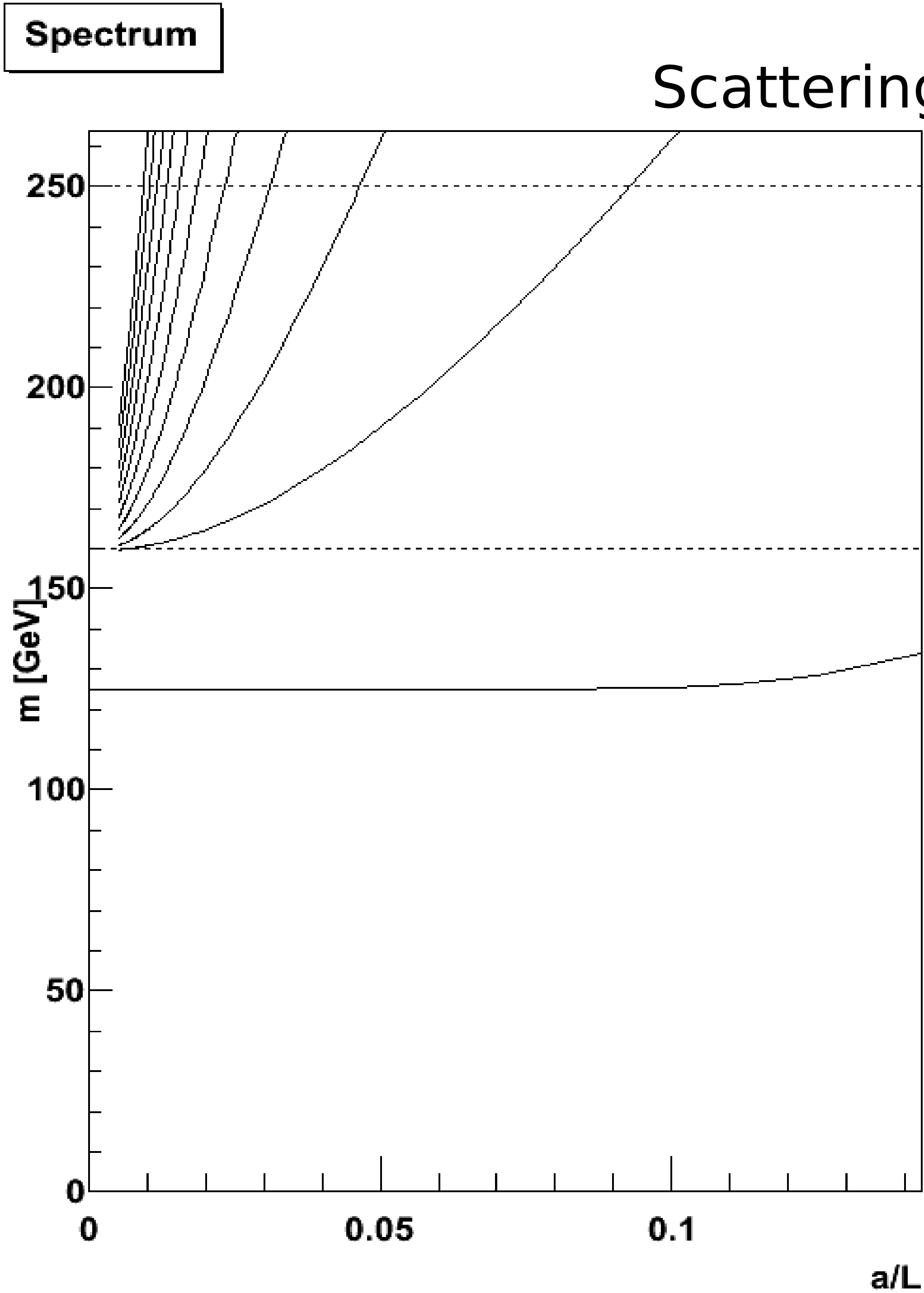

Inelastic threshold: H->2H

Elastic threshold: H->2W

Ground state

Excited states on the lattice

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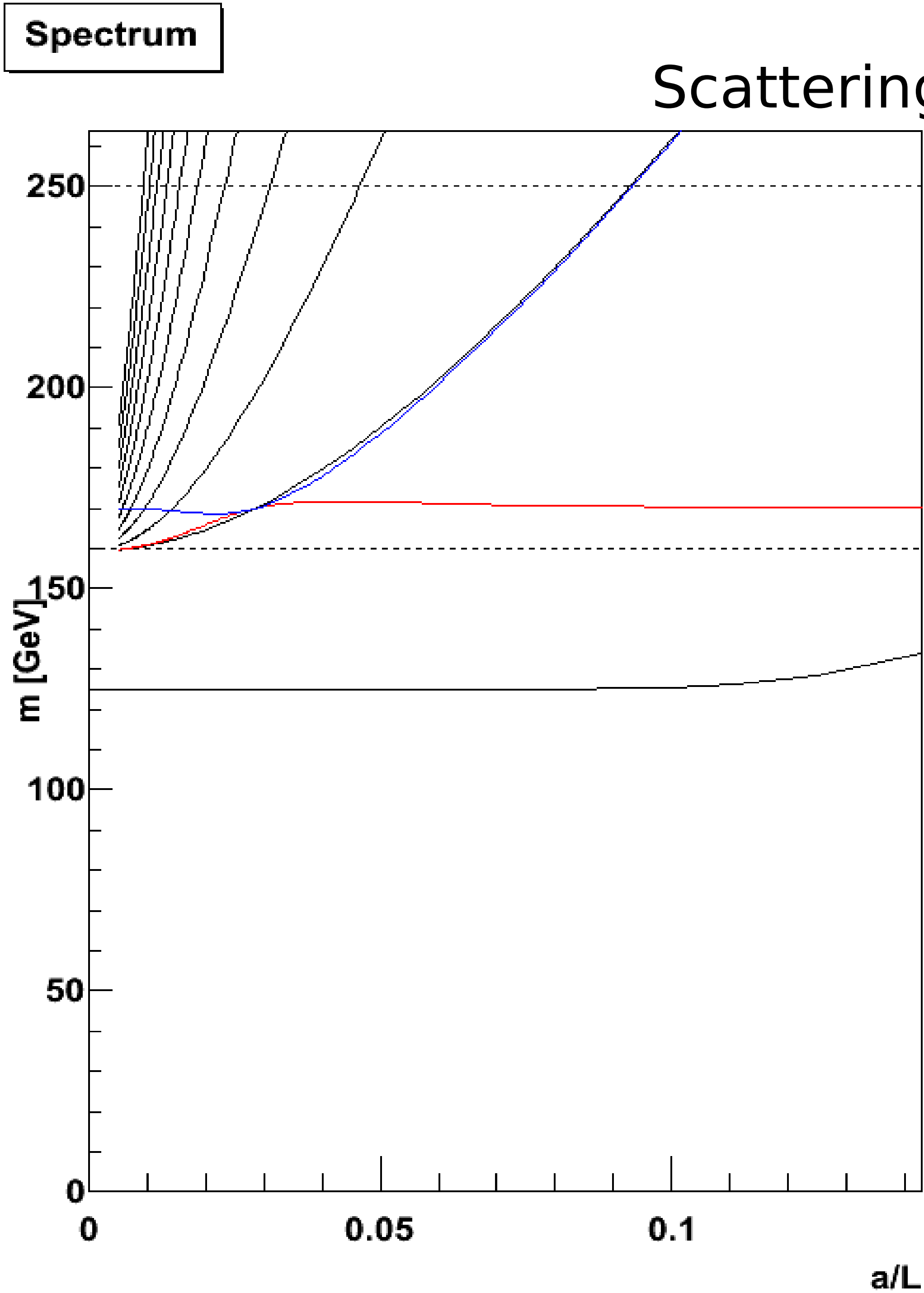


Scattering states

Inelastic threshold: H->2H

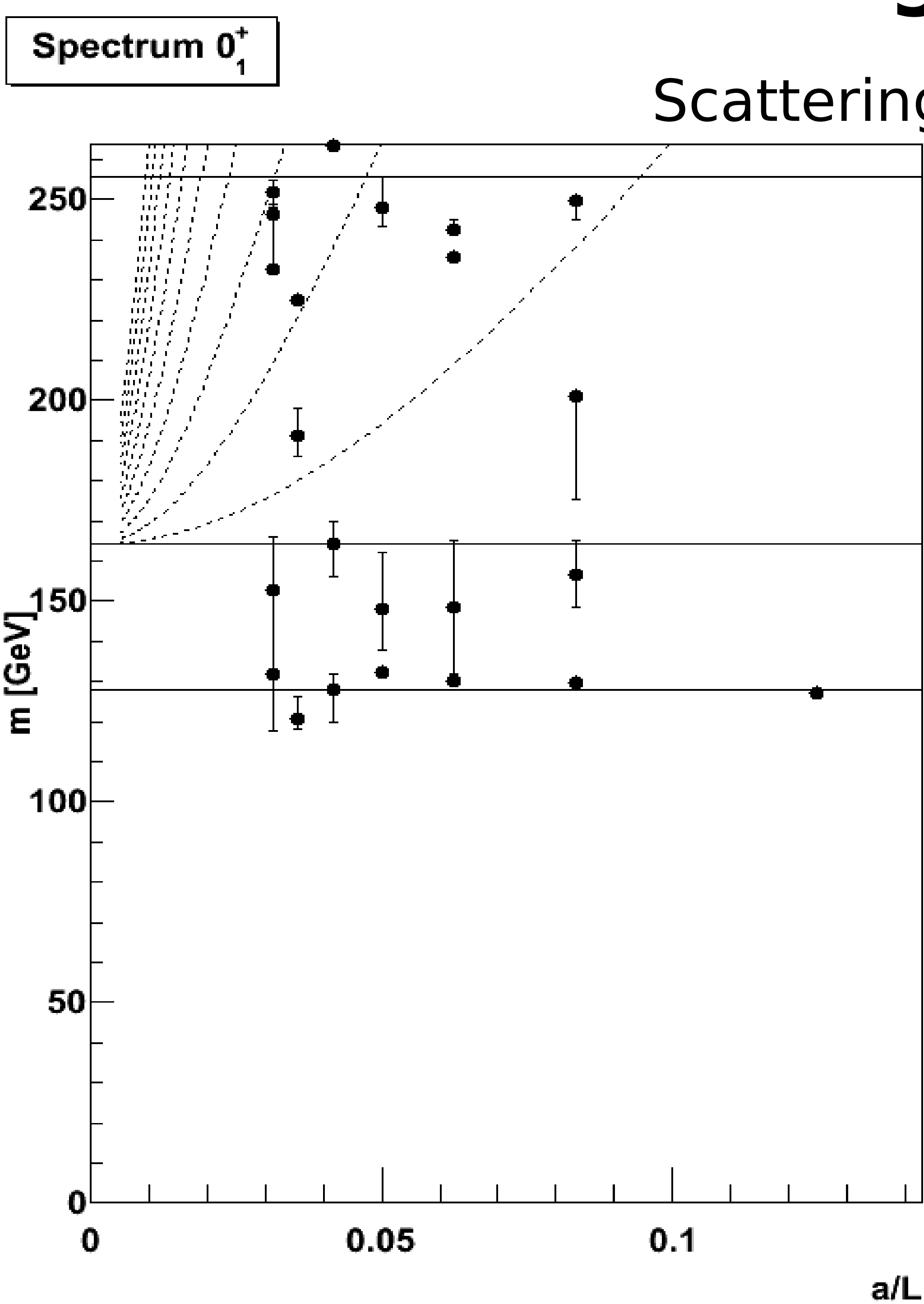
Avoided level crossing
Identification and widths from phase shifts

Elastic threshold: H->2W

Ground state

Search: Excited Higgs

[Maas et al.'14]



Scattering states

Inelastic threshold

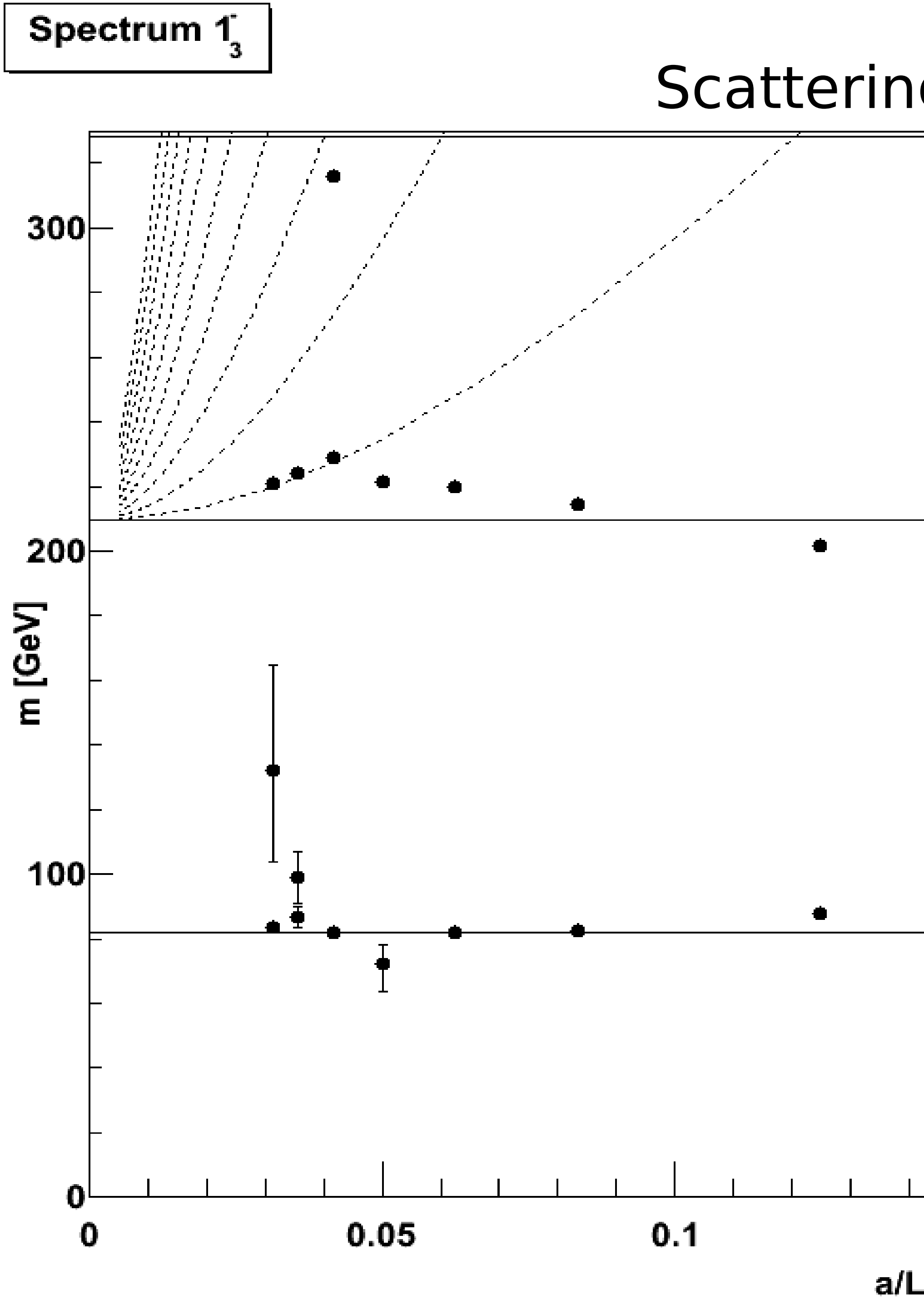
Elastic threshold

Ground state

NB: weakly coupled

Search: Z'

[Maas et al.'14]



Scattering states

Inelastic threshold

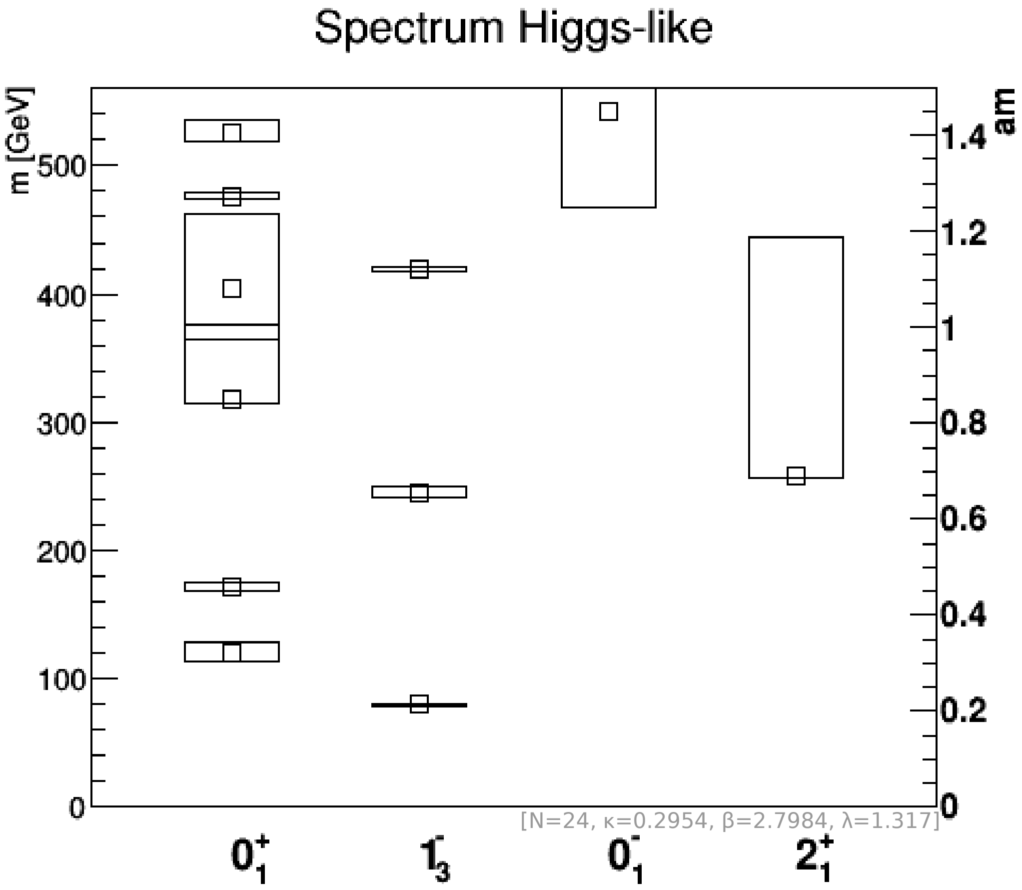
Elastic threshold

Ground state

NB: weakly coupled

[Maas, Mufti '13,'14,
Evertz et al.'86, Langguth et al.'85,'86]

Typical spectra



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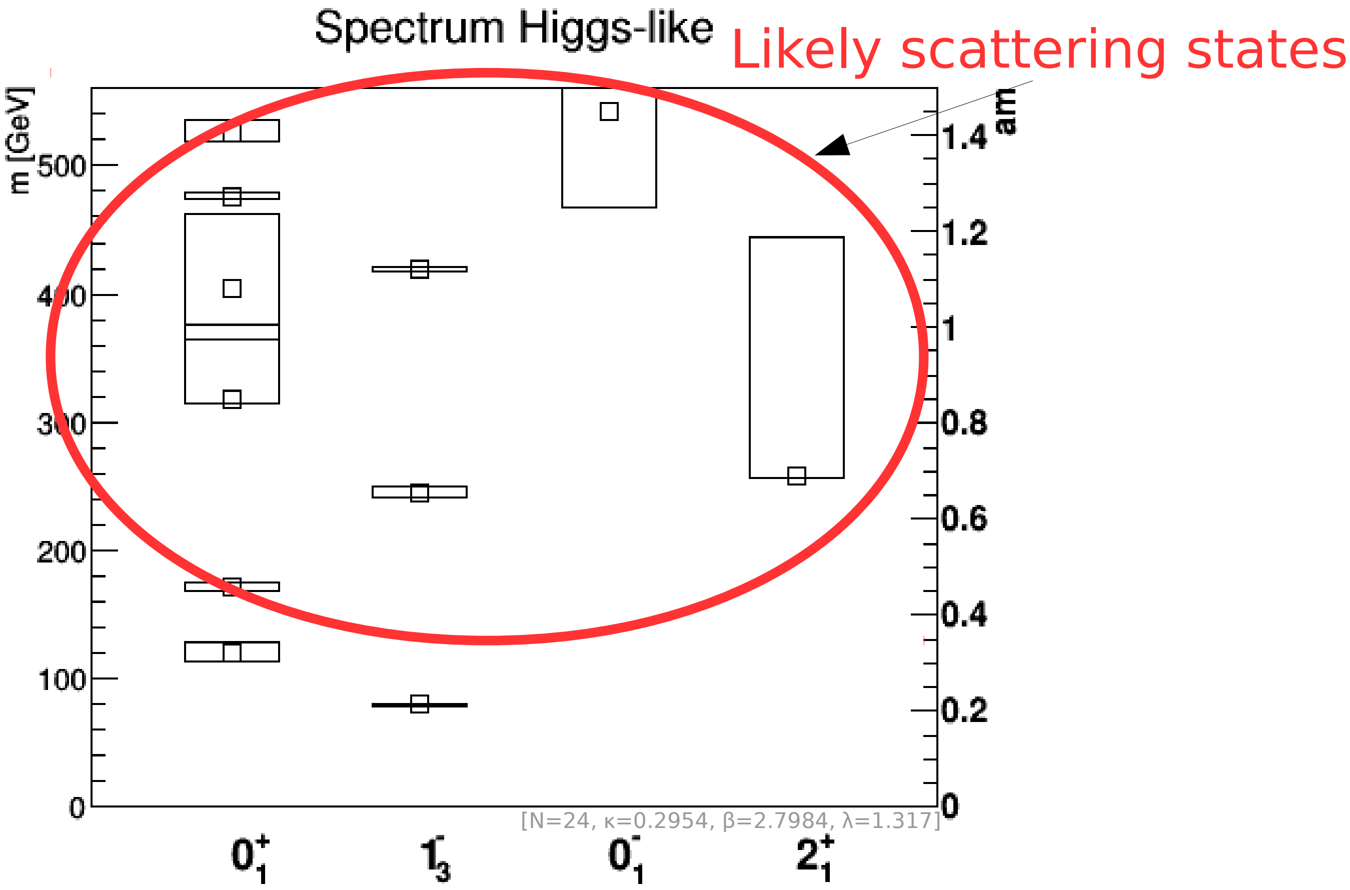

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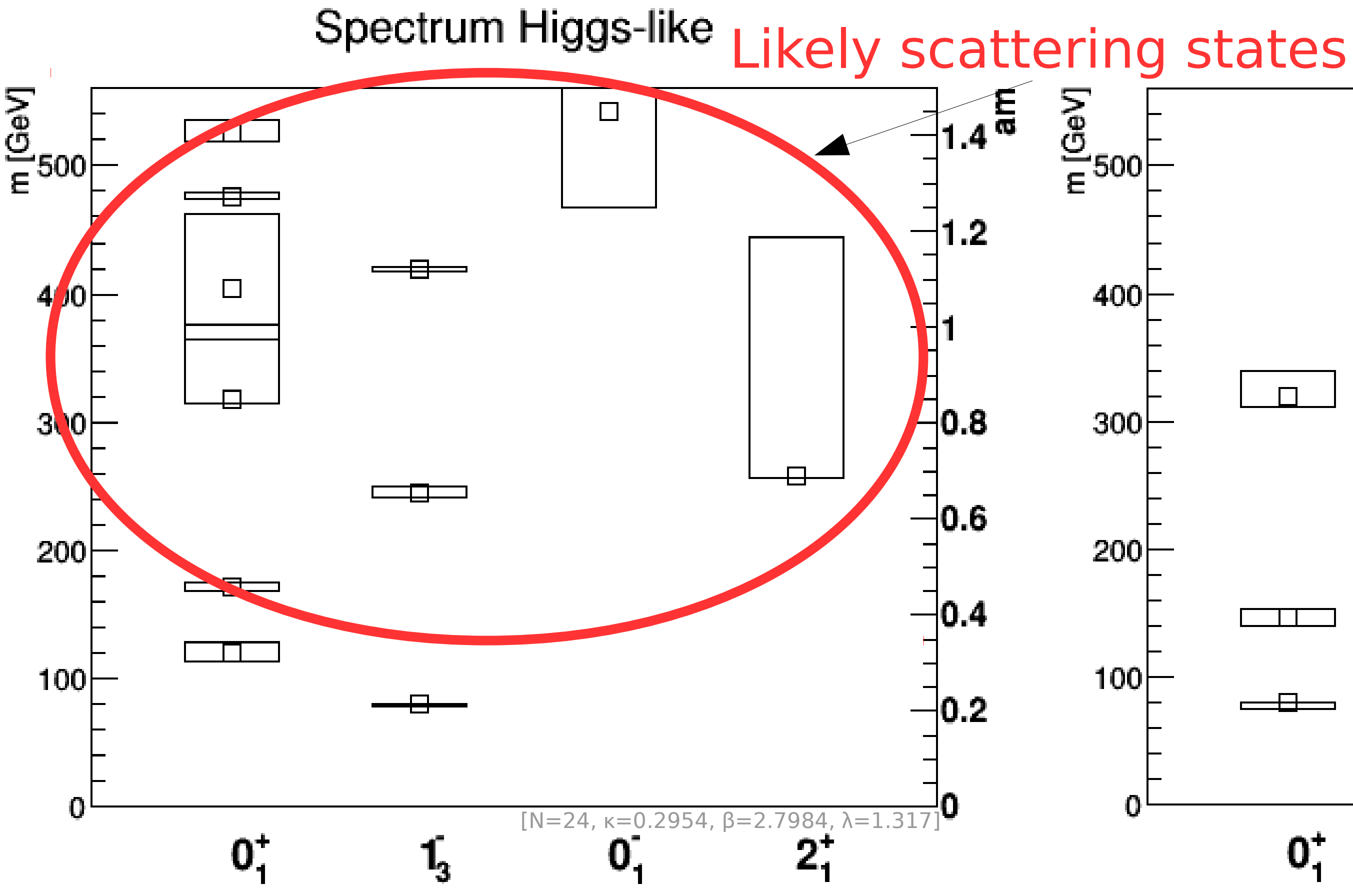

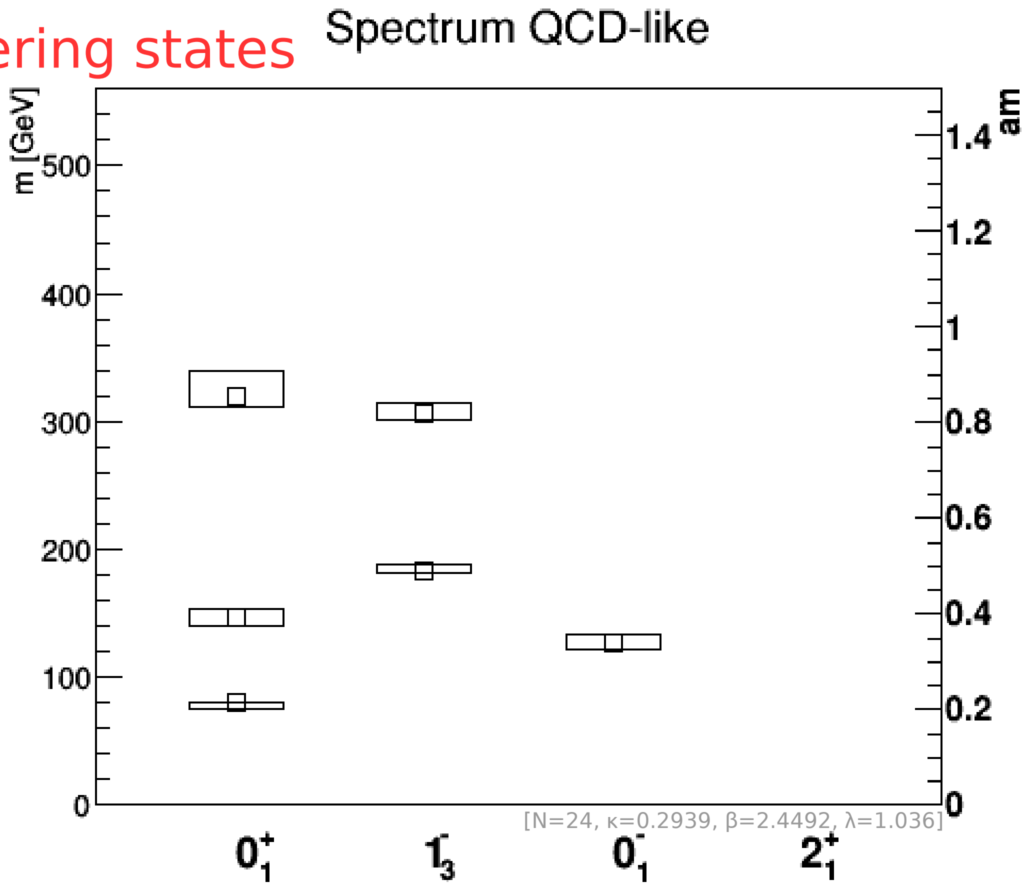

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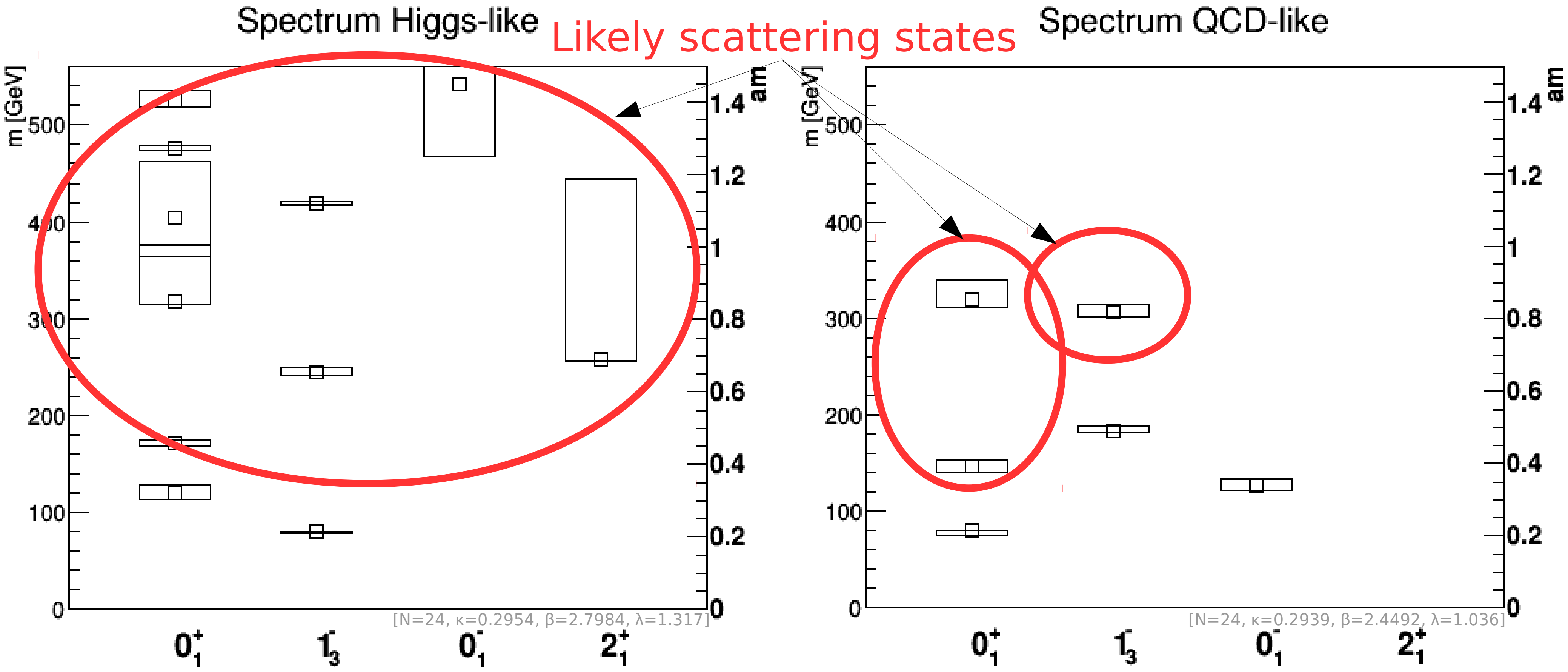

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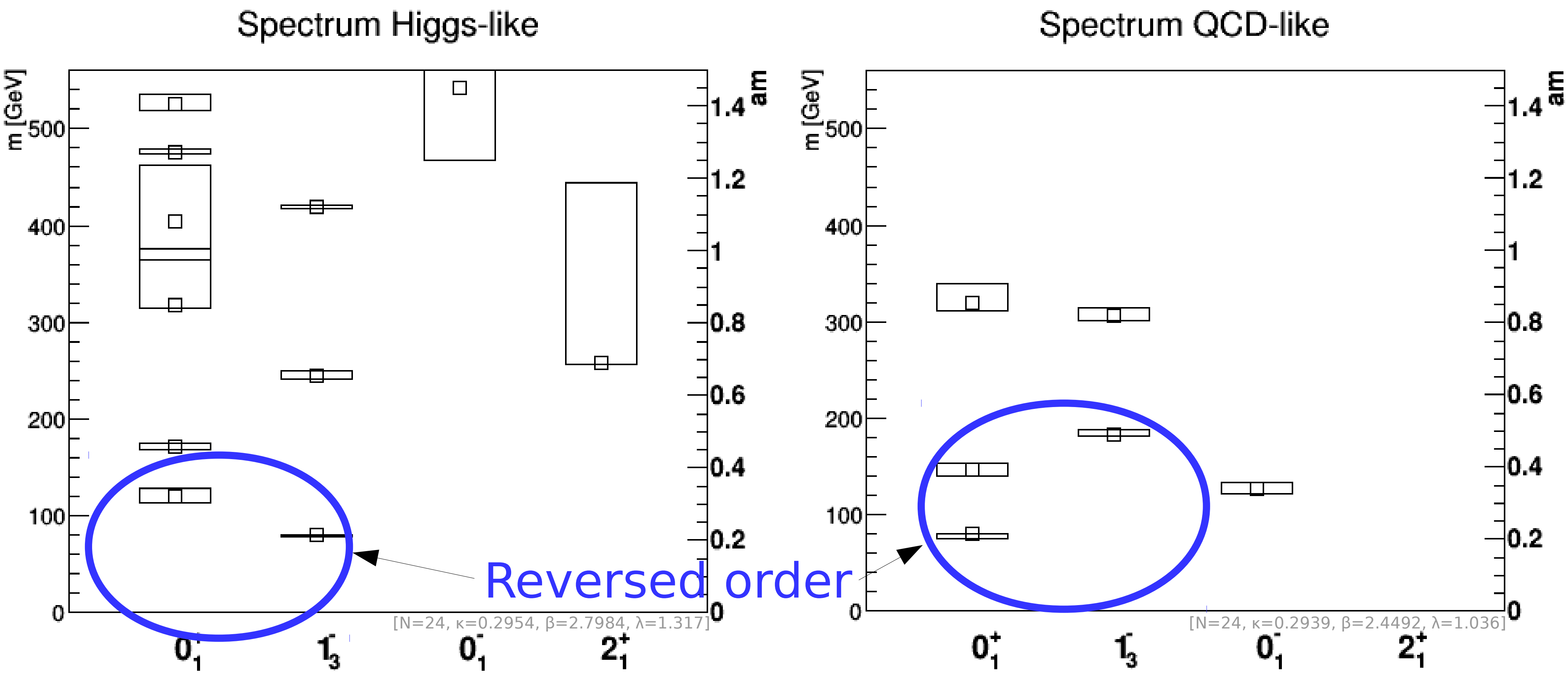

- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
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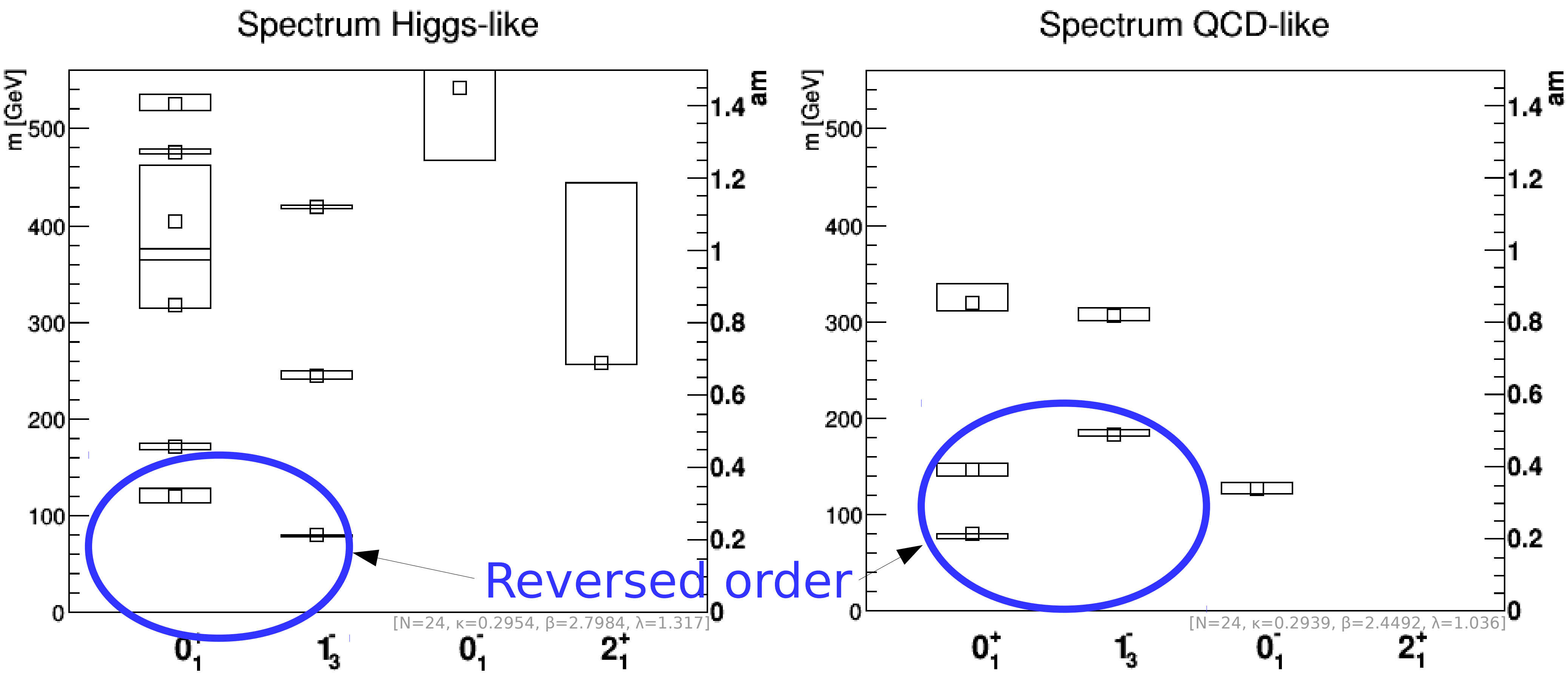

- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
  - 1^- lighter in Higgs-like region
- Coincides with gauge-dependent definitions

Status of the standard model

- Physical states are bound states
  - Observed in experiment
  - Described using gauge-invariant perturbation theory based on the FMS mechanism
  - Mostly the same as ordinary perturbation theory
- Is this always true? No. [Maas'15, Maas & Mufti'14]
  - Fluctuations can invalidate it
- So what could happen? Probably nothing.

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- So what could happen? Probably nothing.
- What happens for a different structure
  - Different gauge group or more Higgs

Example 1: 2HDM

Like the standard model
Gauge-invariant and ordinary perturbation theory coincide

Implications for 2HDM

[Maas'15, Maas & Pedro'16]

- Additional Higgs doublet
- Enlarged custodial group

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Implications for 2HDM

[Maas'15, Maas & Pedro'16]

- FMS states for maximal custodial group:
  - Scalar sector Singlet

$$\langle (h^+ h)(x)(h^+ h)(y)\rangle \approx const. + \langle \eta_h^+(x)\eta_h(y)\rangle + O(\eta_h^3)$$

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- Discrete factor groups could yield doubling

Implications for 2HDM

[Maas'15,
Maas & Pedro'16]

- Additional Higgs doublet
- Enlarged custodial group
- BEH Effect - FMS mechanism applicable
  - In a suitable basis, all condensates contained in a single doublet
  - Yields again perturbative spectrum
    - Discrete factor groups may be a problem
- Key: Global multiplet structure diverse

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- Key: Global multiplet structure diverse
- Size of fluctuations needs to be checked non-perturbatively!

Example 2: GUT-like structure

Gauge-invariant perturbation theory correct
and
different from ordinary perturbation theory

Implications for GUTs

[Maas'15
Törek & Maas '15, '16]

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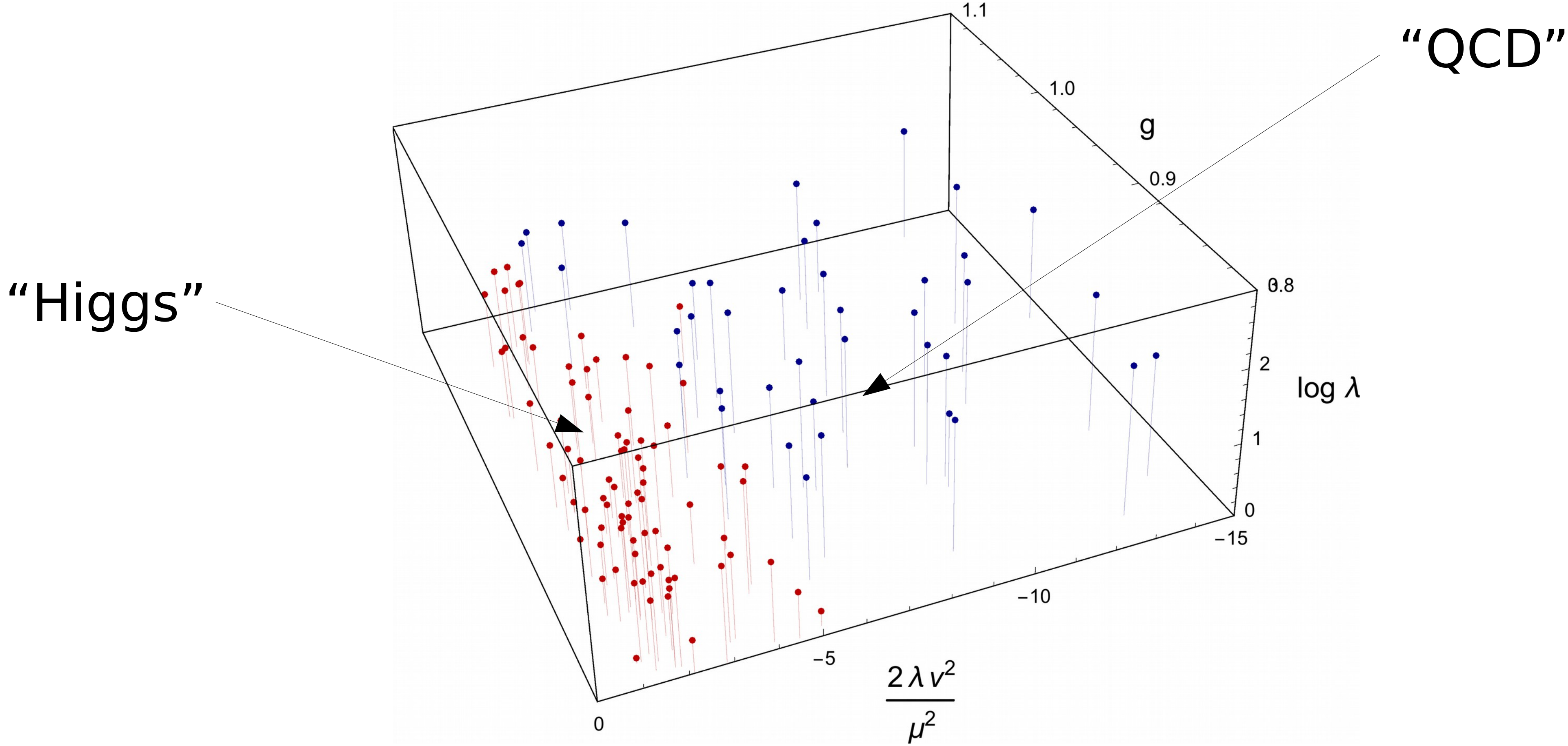
- Toy-GUT: SU(3) broken to SU(2)

Test for GUTs

[Maas & Törek'16]



- Separation into Higgs-like and QCD-like

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    - 1 massive Higgs, 3 massless and
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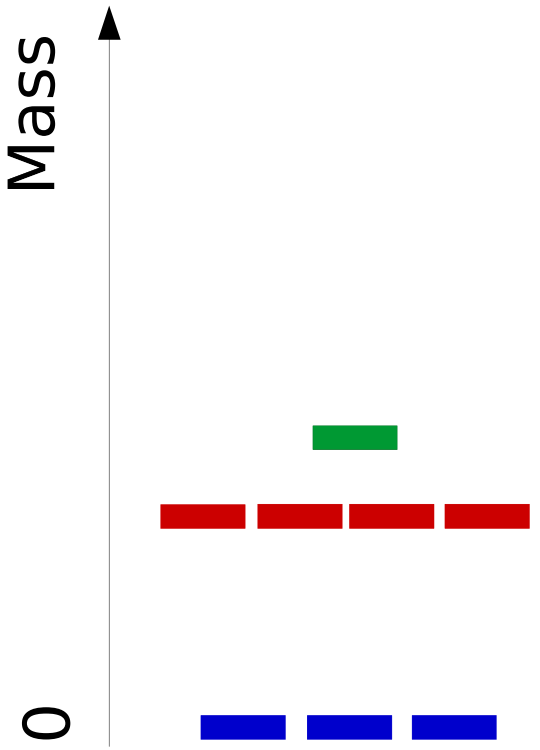
  - ...or something else?

Toy-GUT: Vectors

[Maas & Török'16
Maas, Sondenheimer & Török'17]

Perturbation theory

Gauge-dependent



Toy-GUT: Vectors

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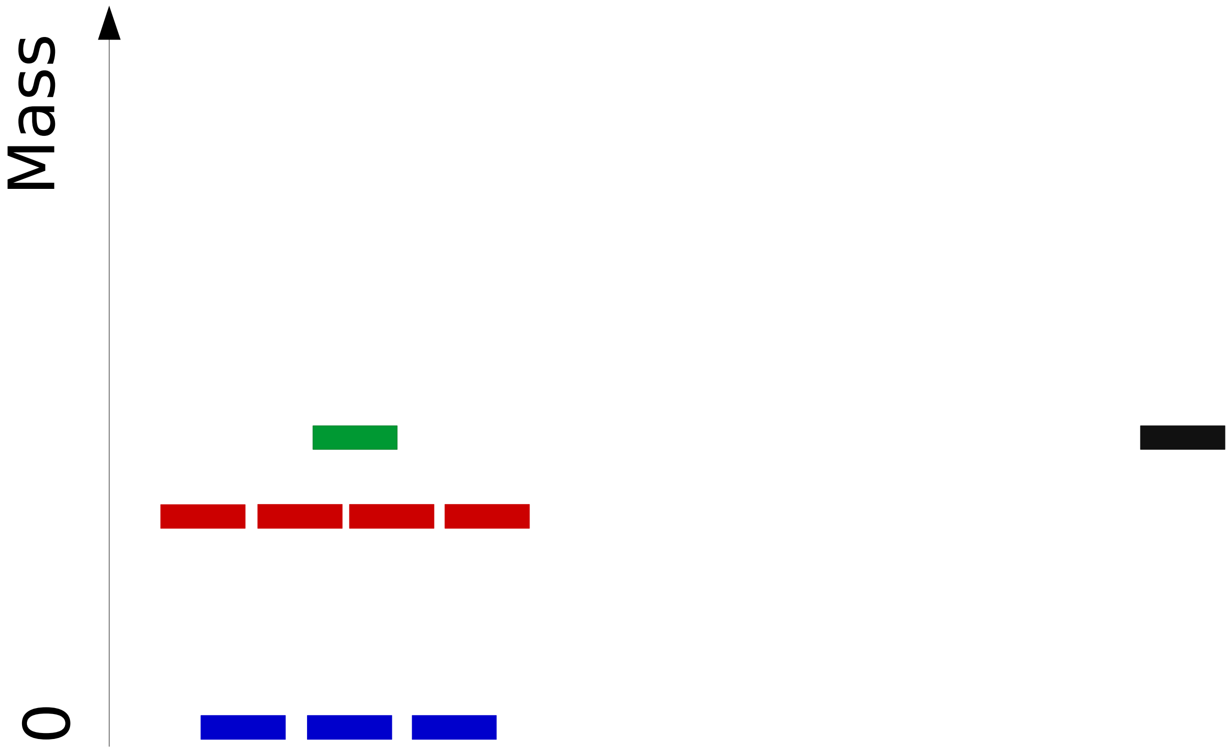
Perturbation theory

Gauge-dependent

FMS expansion

U(1) singlets



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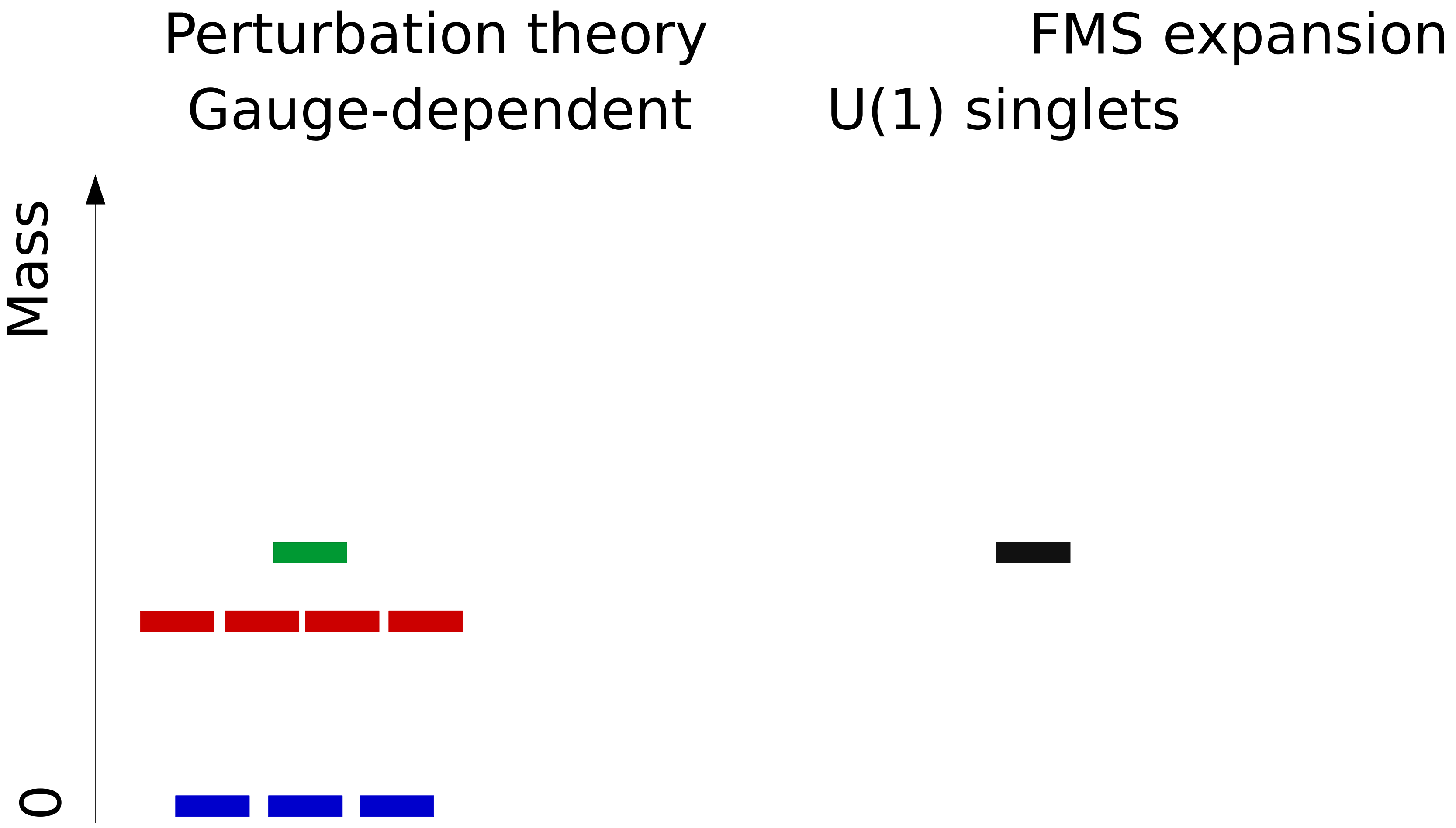

- Qualitatively different spectrum

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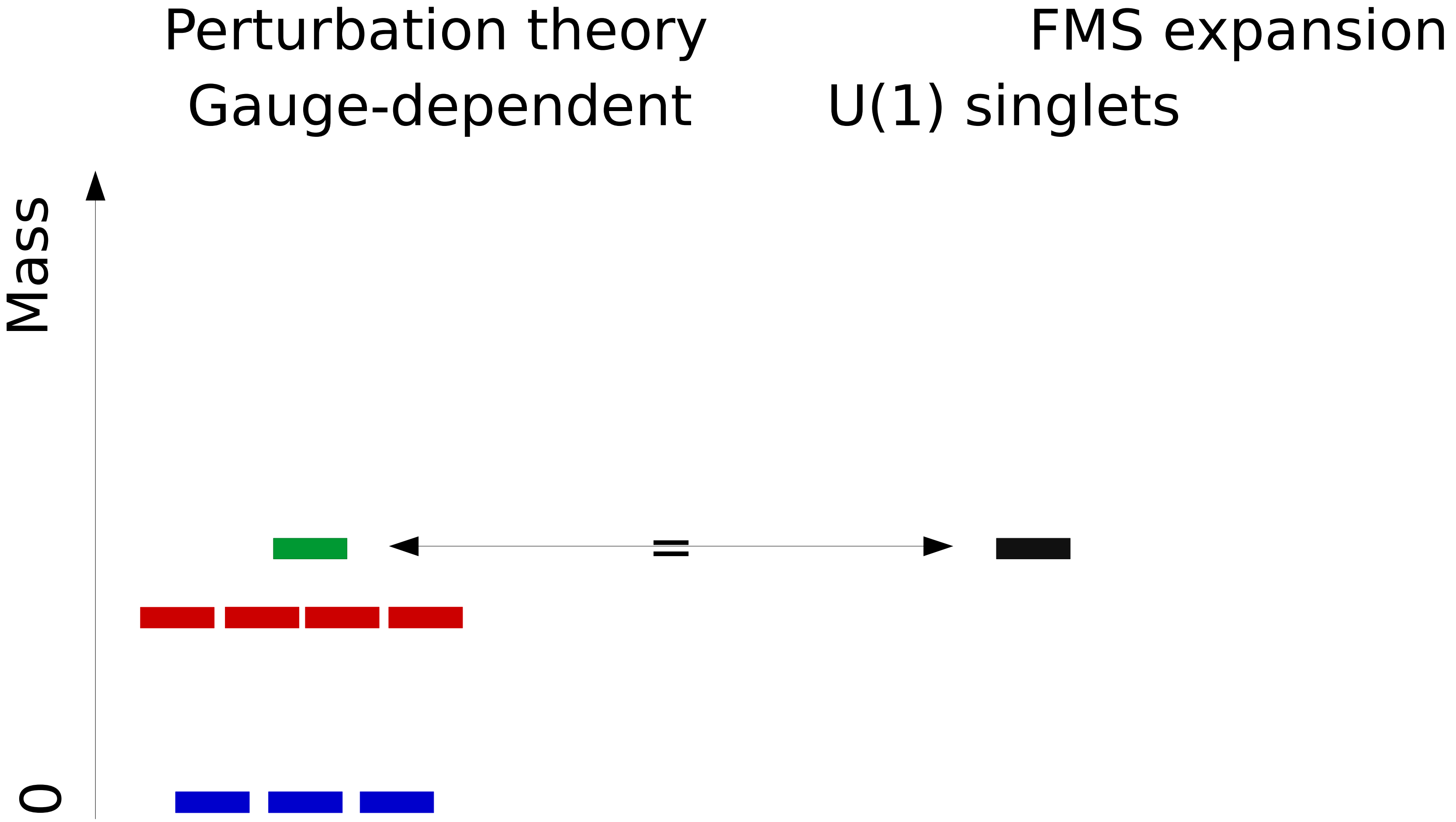

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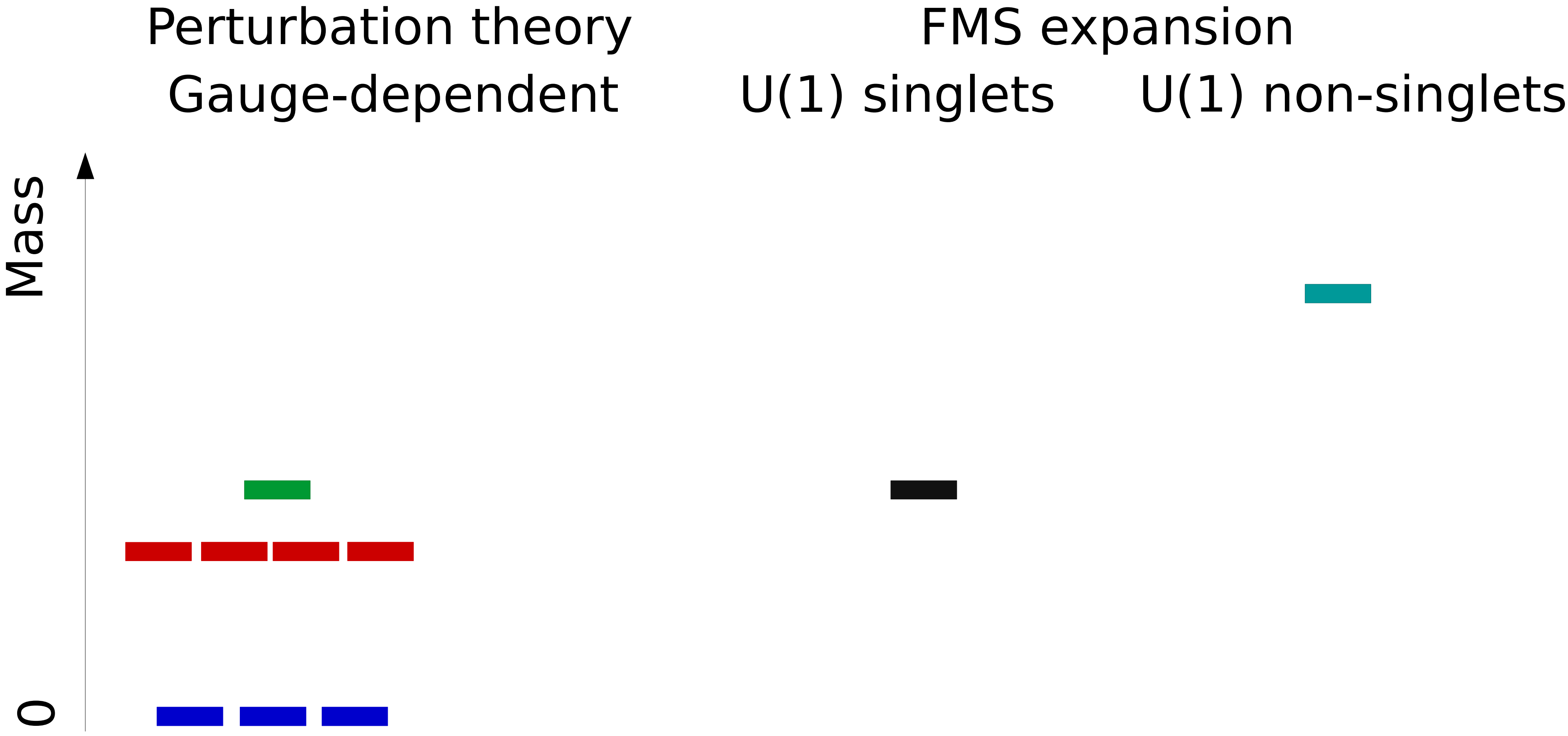

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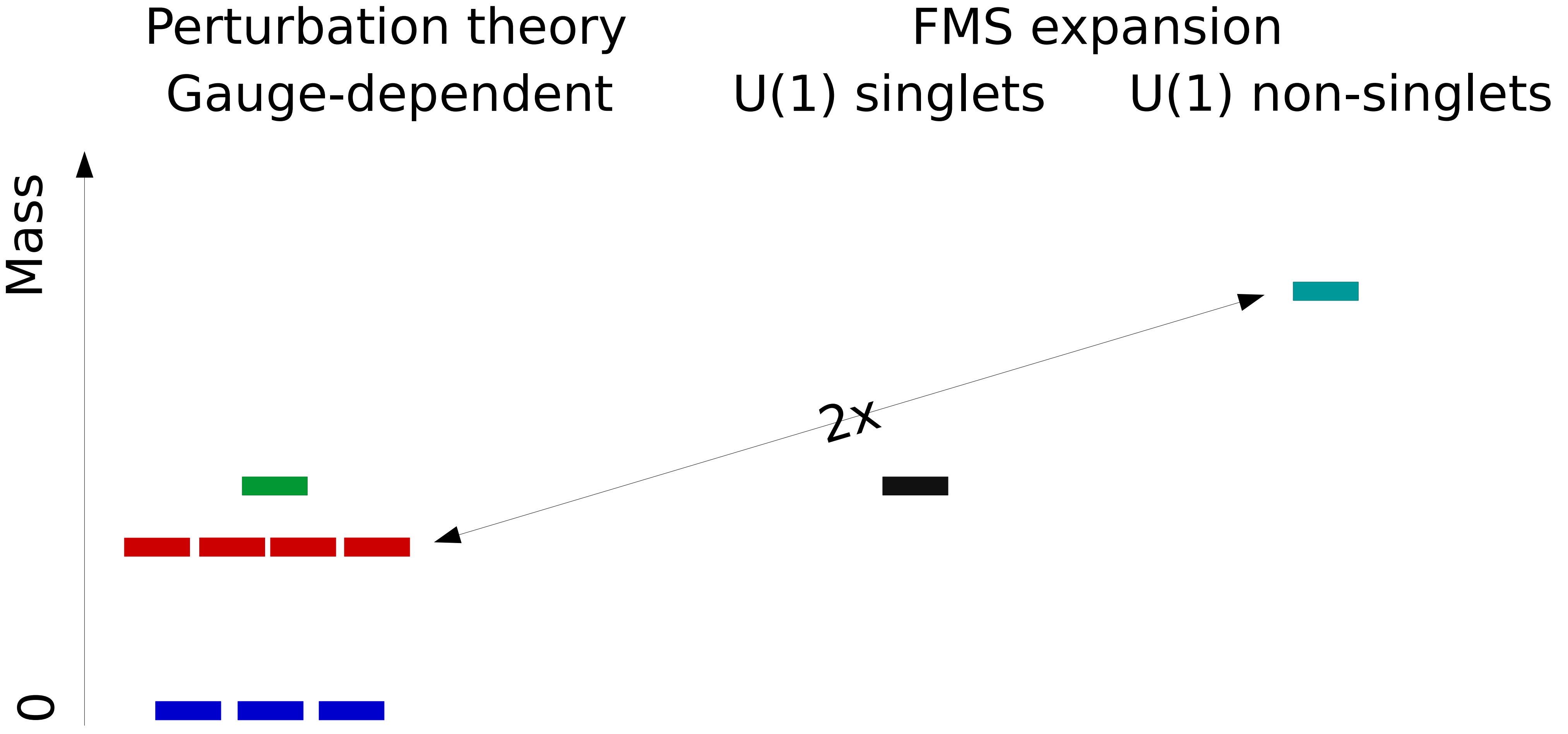

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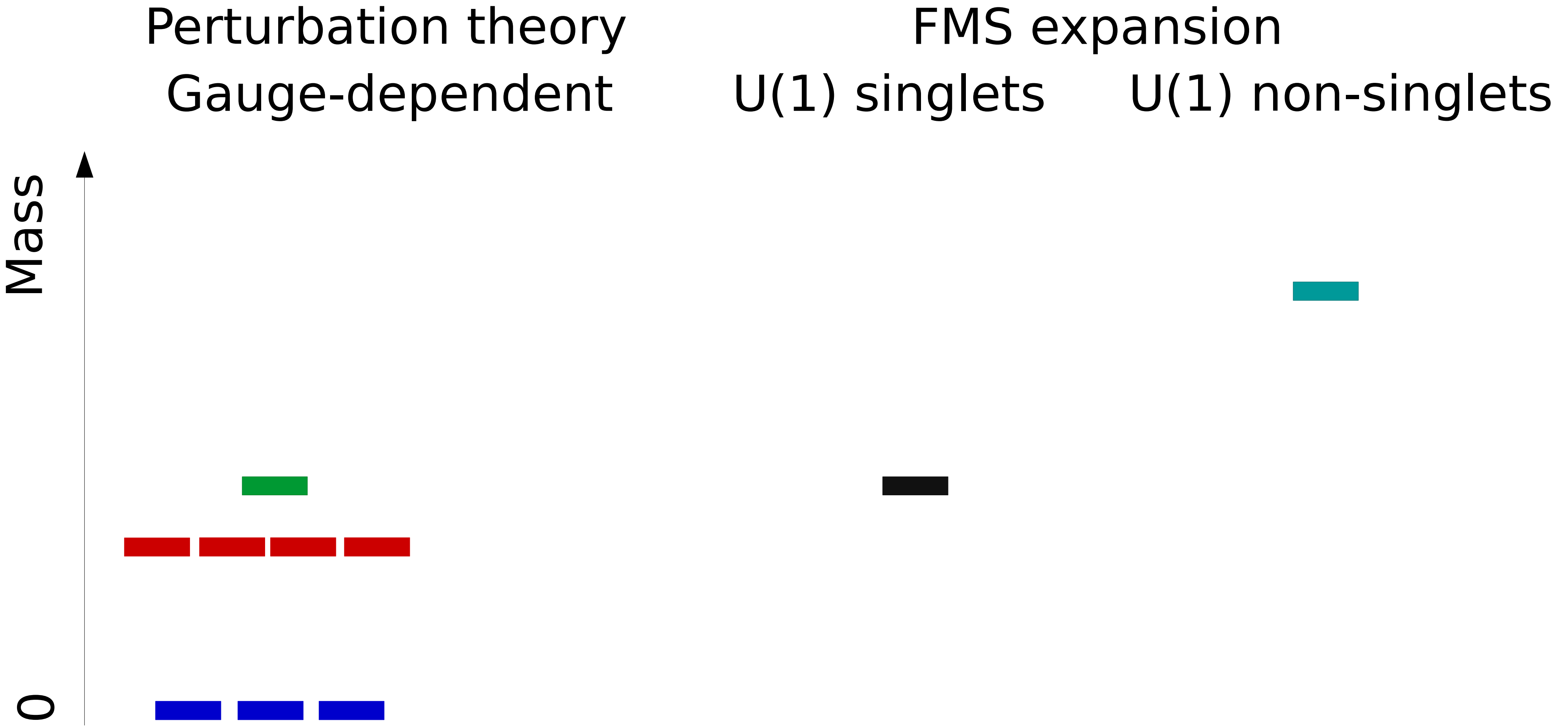

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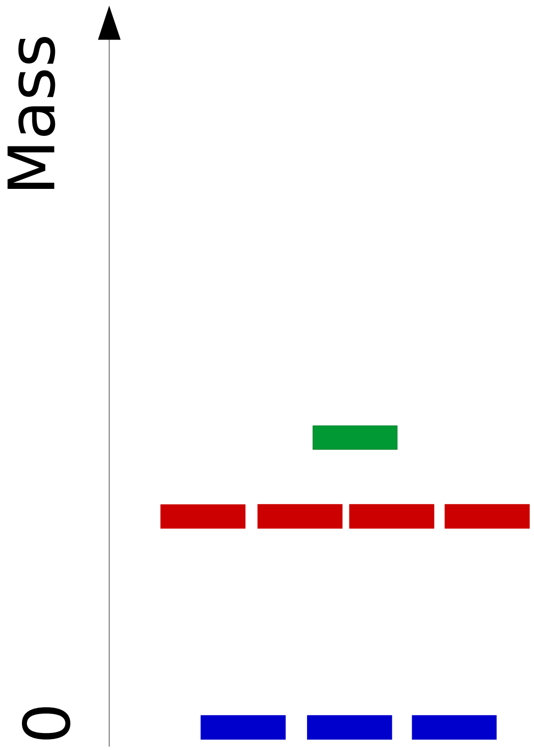
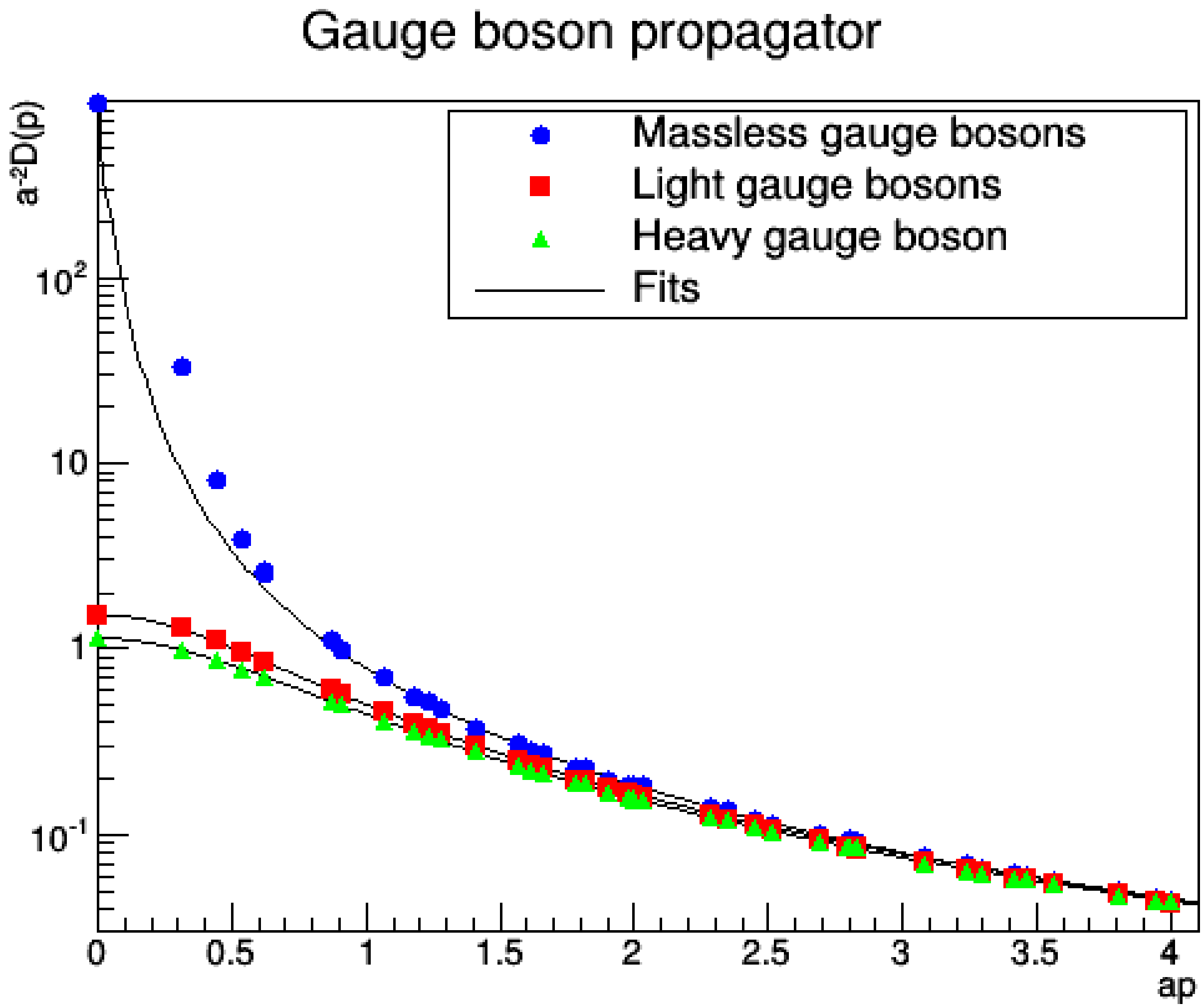
  - Scalars similar but no confirmation yet (statistics!)

Toy-GUT: Vectors

[Maas & Török'16+unpublished
Maas, Sondenheimer & Török'17]

Perturbation theory
Gauge-dependent





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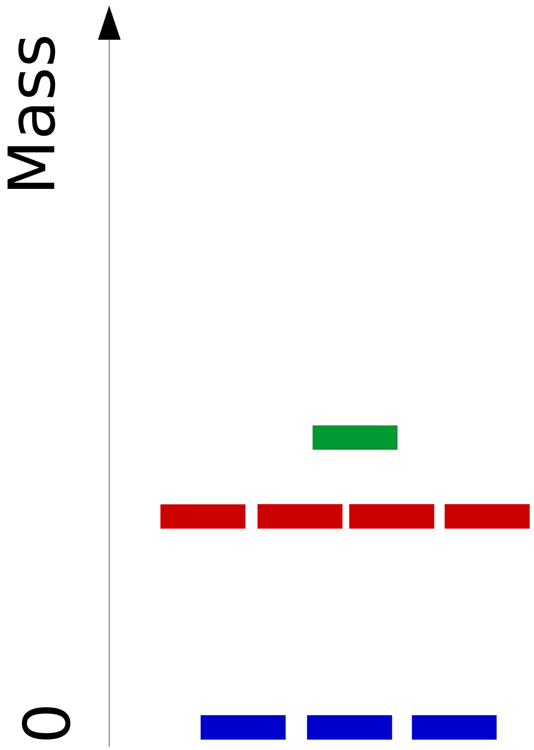

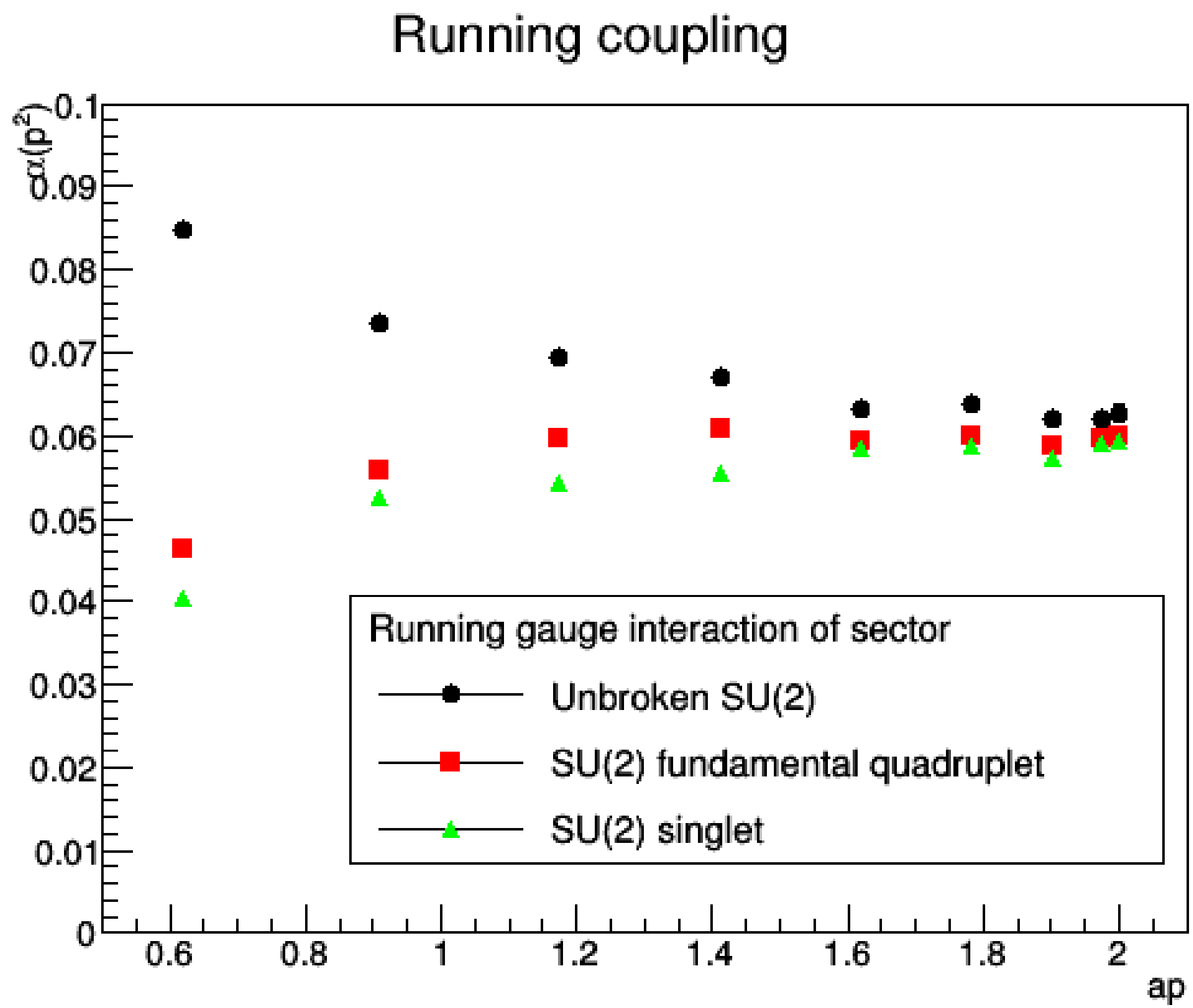

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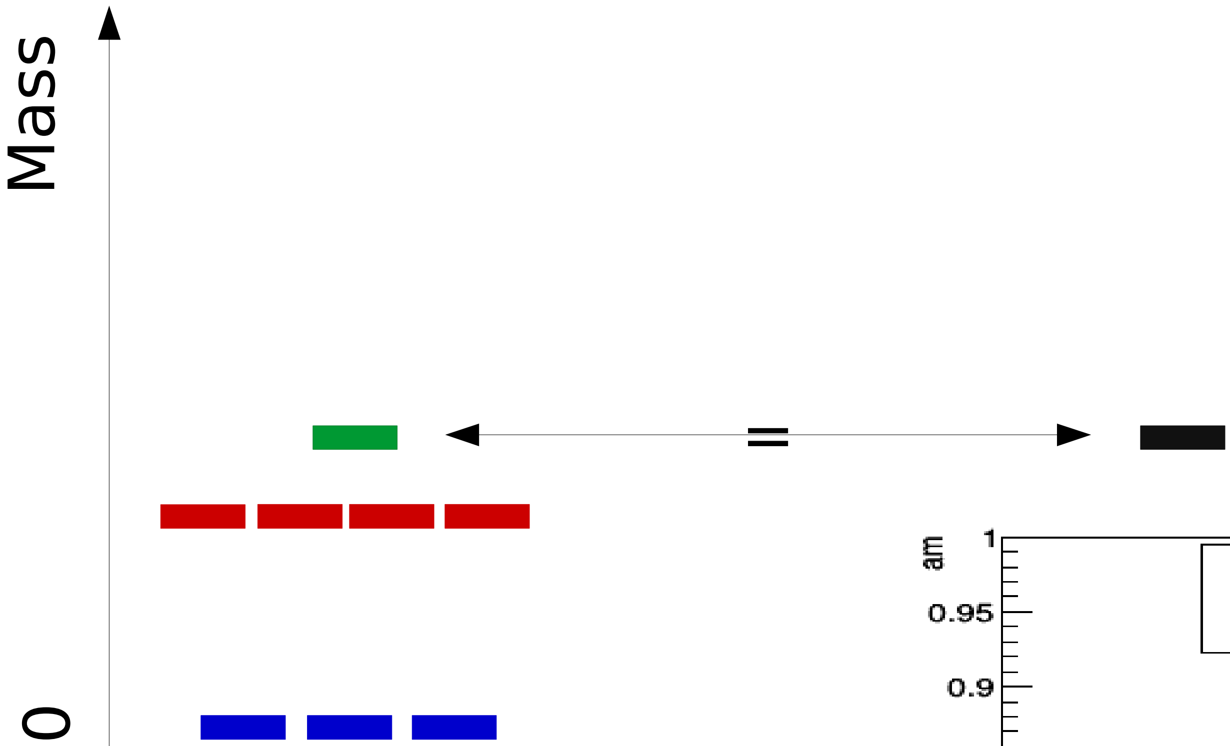
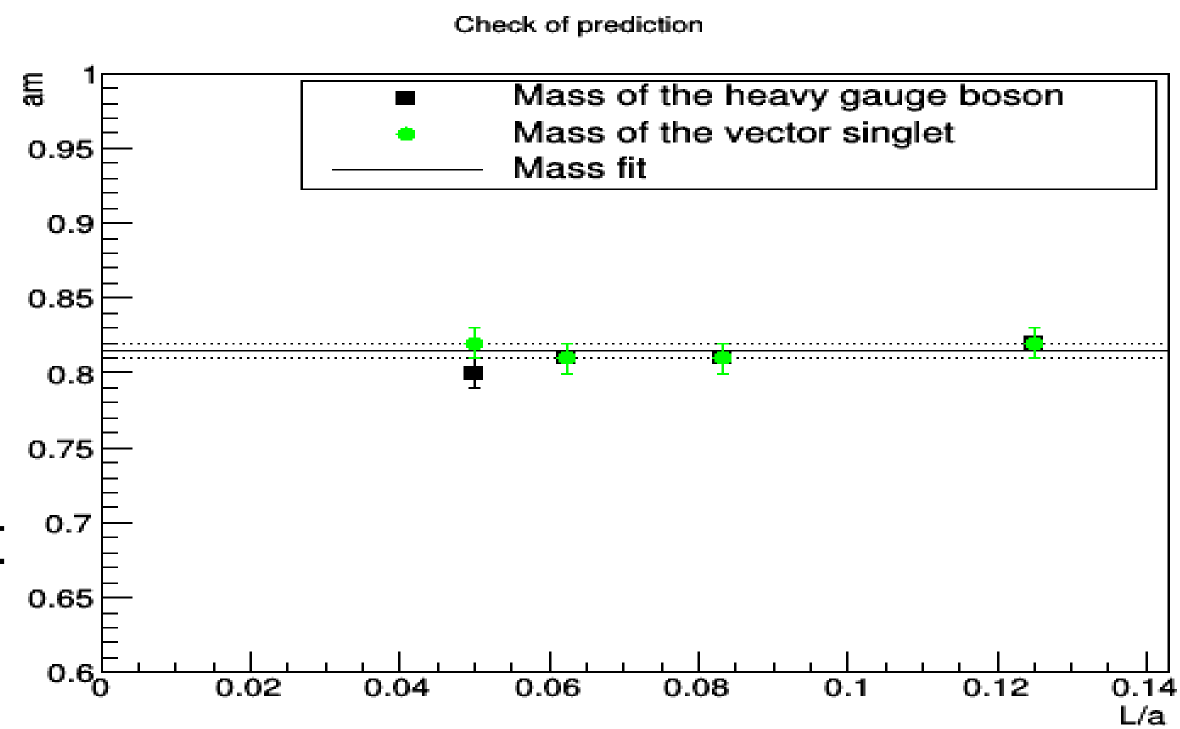
Perturbation theory FMS expansion

Gauge-dependent U(1) singlets





- Quantitative agreement

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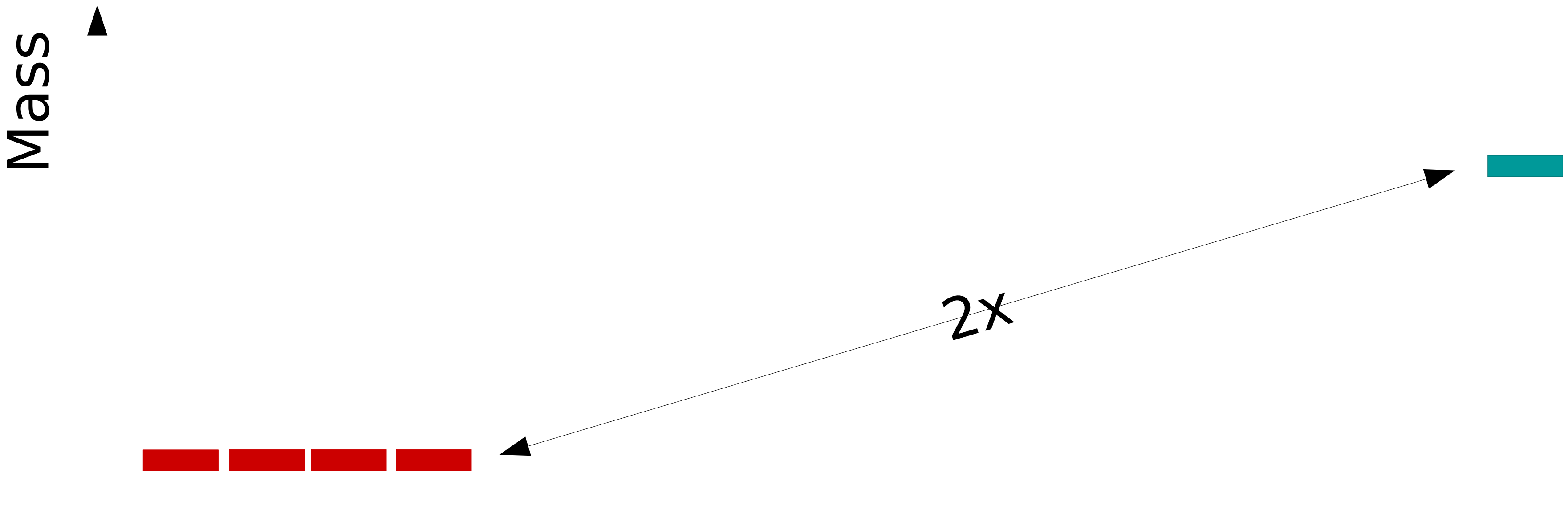
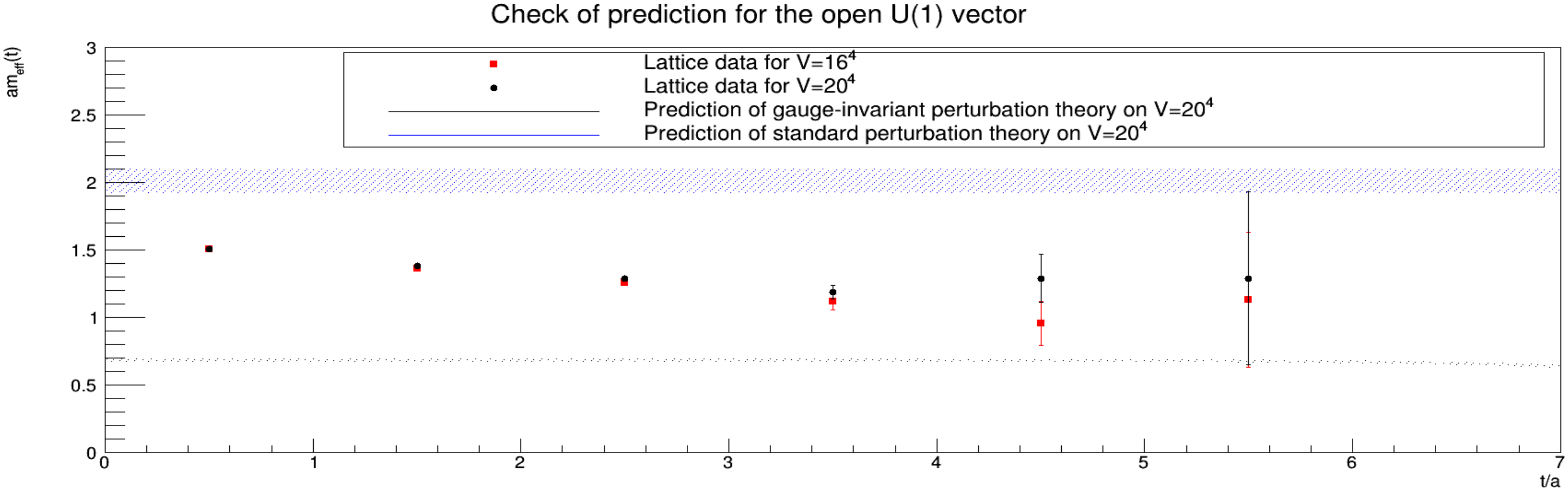
Perturbation theory
Gauge-dependent

FMS expansion
U(1) non-singlets





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- Note: Predicts vector lighter than scalar!

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- SU(N) with adjoint Higgs

Other scenarios: Group theory

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  - Spectrum still different in every pattern
    - Too many massless states, too few massive

Example 3: Technicolor

No gauge-invariant perturbation theory
but
interesting implications

Implications for Technicolor

[Maas,'15]

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- Observable states must still be gauge-invariant
  - Needs to create Higgs and W/Z(!) signals by (new) bound states
  - Vectors must be lighter
    - Behavior not yet seen for strong interactions
    - Usually: Scalars and pseudoscalars

Summary

- Observable (particles) must be gauge-invariant

Summary

UPCOMING REVIEW IN MID DECEMBER

Brief introduction: Törek & Maas'16

- Observable (particles) must be gauge-invariant
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  - Often at odds with standard phenomenology

Advertisment

Bound States in Strongly Coupled Systems

A Galileo Galilei Workshop

12th-16th of March 2018

Firenze, Italy

https://www.ggi.infn.it/showevent.pl?id=286

Alps 2018

An Alpine Physics Summit

15th-20th of April 2018

Obergurgl, Austria

alps2018.hephy.at