Brout-Englert-Higgs physics: From foundations to phenomenology

Axel Maas
with
Larissa Egger, Leonardo Pedro, and Pascal Törek

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Vienna
Austria

UNI GRAZ
NAWI Graz Natural Sciences
FWF Der Wissenschaftsfonds.

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- Why it can matter beyond the standard model
- How this can be treated
  - Introducing gauge-invariant perturbation theory
  - Checking its validity

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  - Bound states, phase transitions,...
- Are there (relevant) non-perturbative effects in the weak interactions and the Higgs?

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

Or: What states can be gauge-invariant

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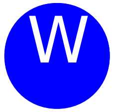
- Ws W^a_μ 

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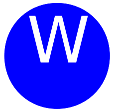
- Ws W^a_μ 

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

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

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[Bohm et al. 2001]

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- Consequence: Symmetry in charge space not manifest (hidden)
  - Symmetry expressed in STIs/WTIs

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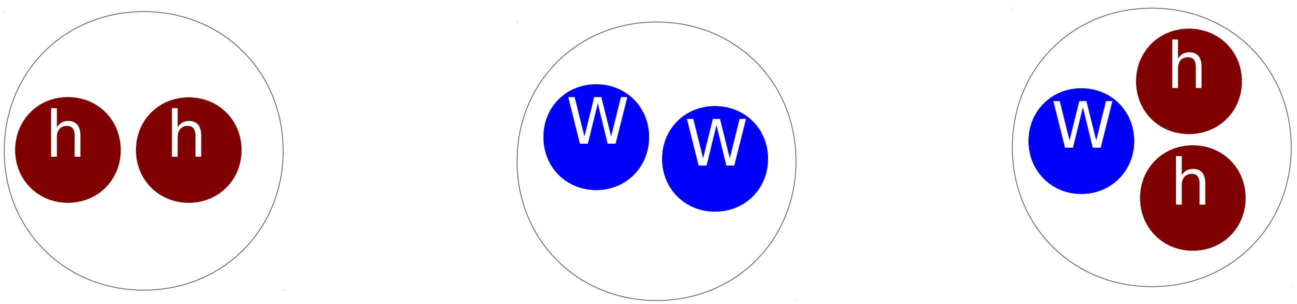

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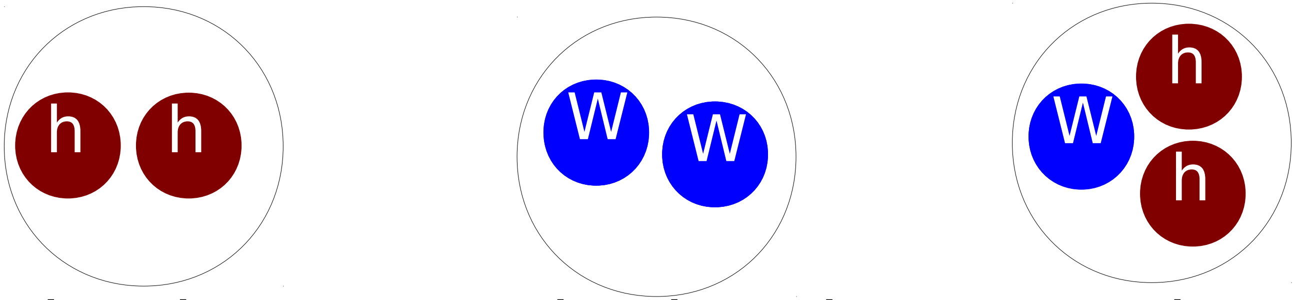

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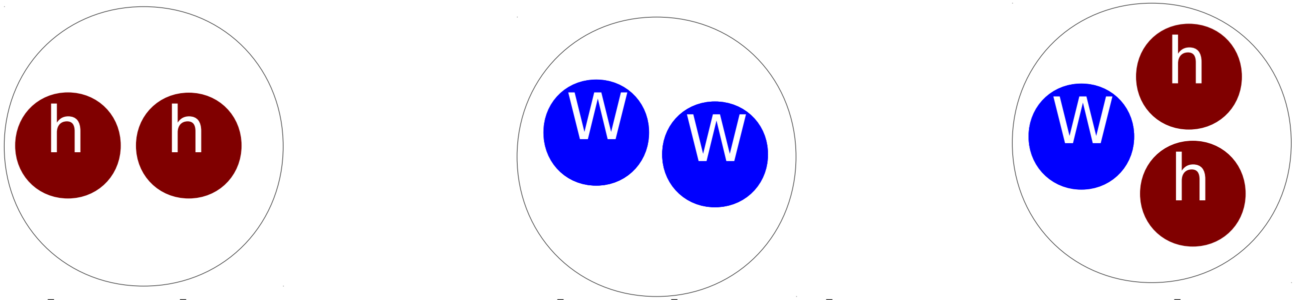

  - Why does perturbation theory work?
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Why it does not matter in the standard model

Introducing gauge-invariant perturbation theory

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- Gauge-invariant: Non-perturbative method

Lattice calculations

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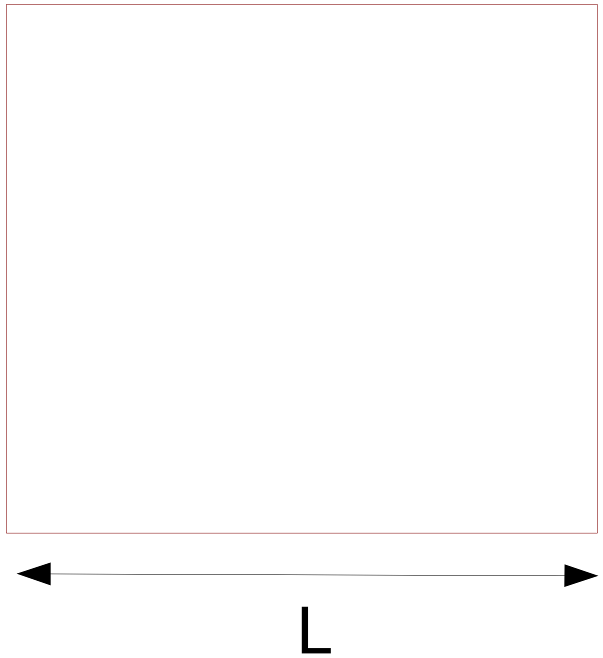

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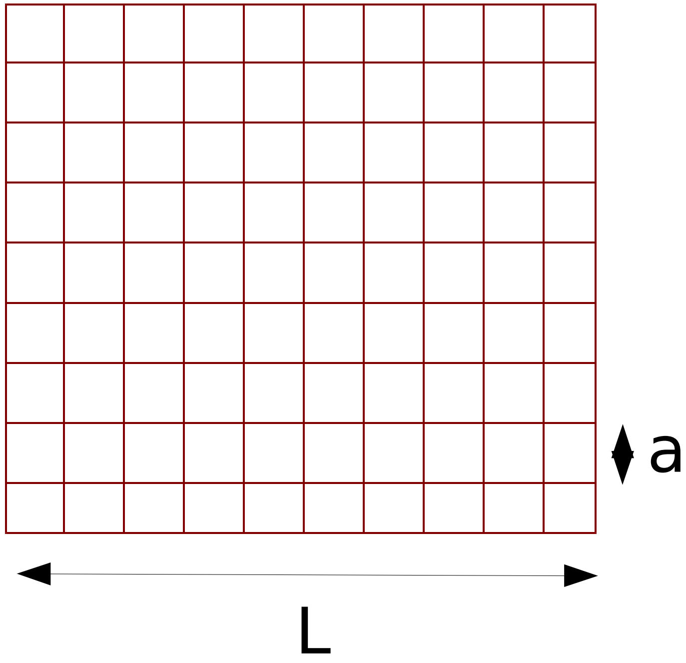

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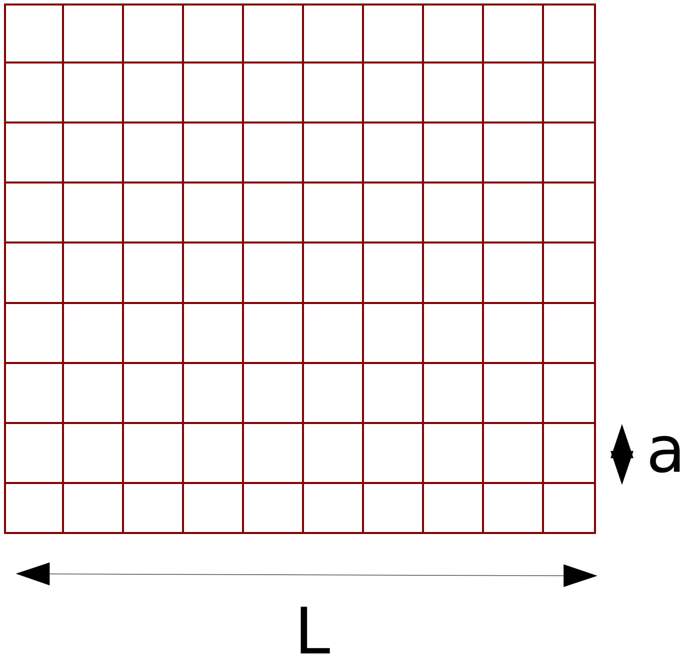

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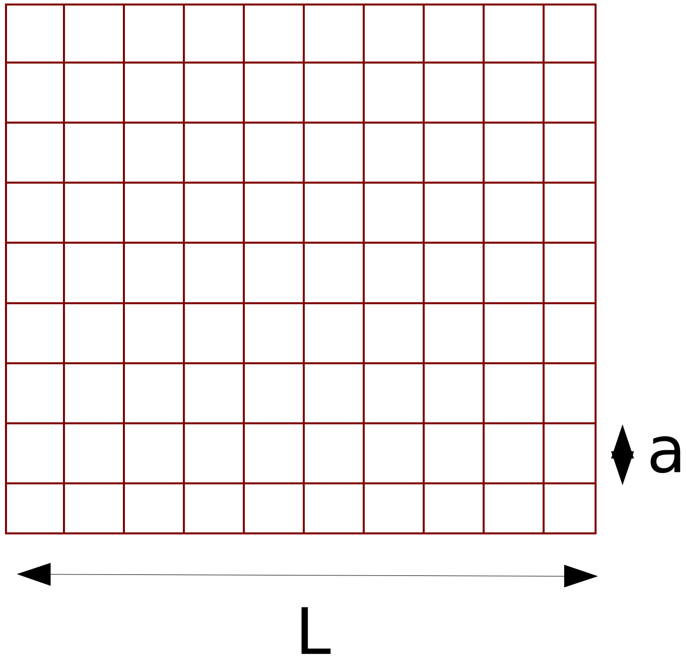

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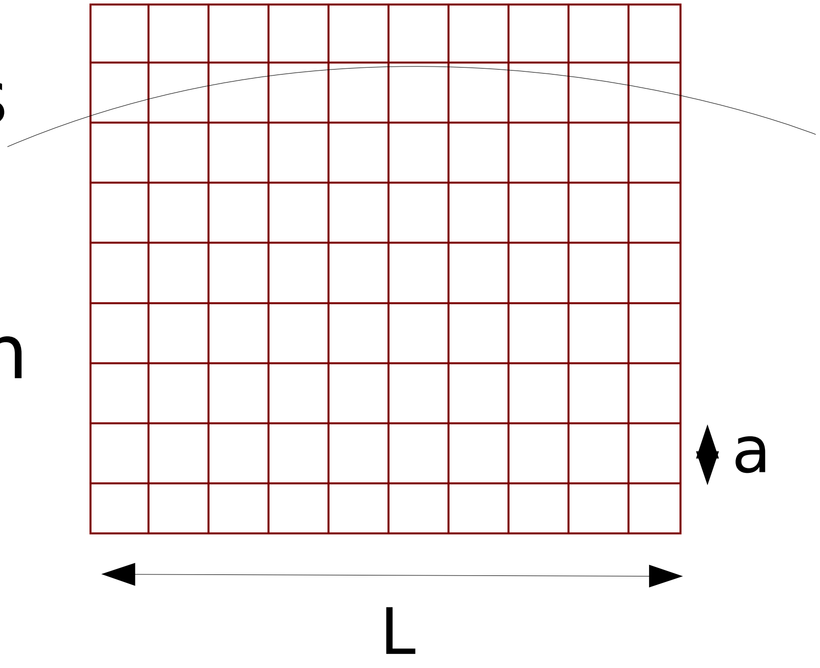

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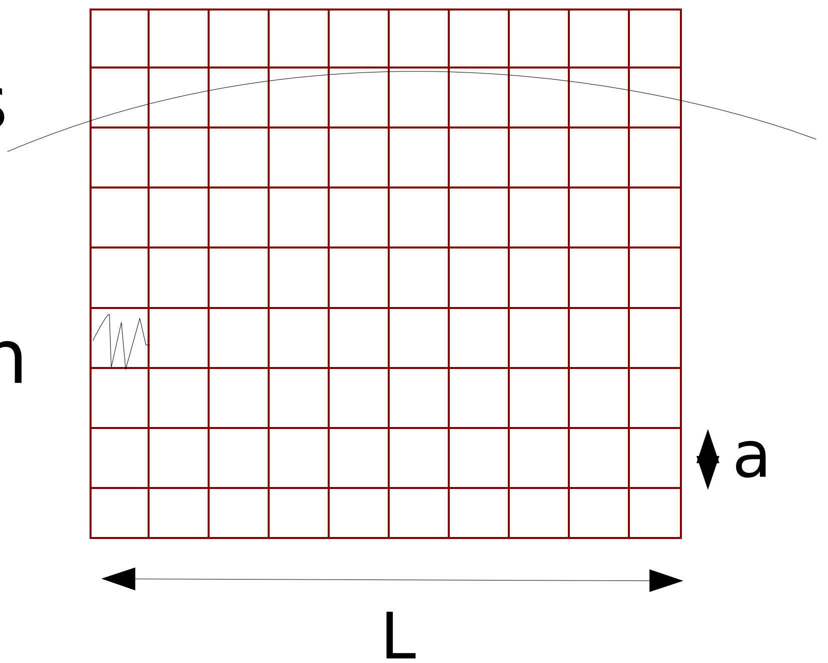

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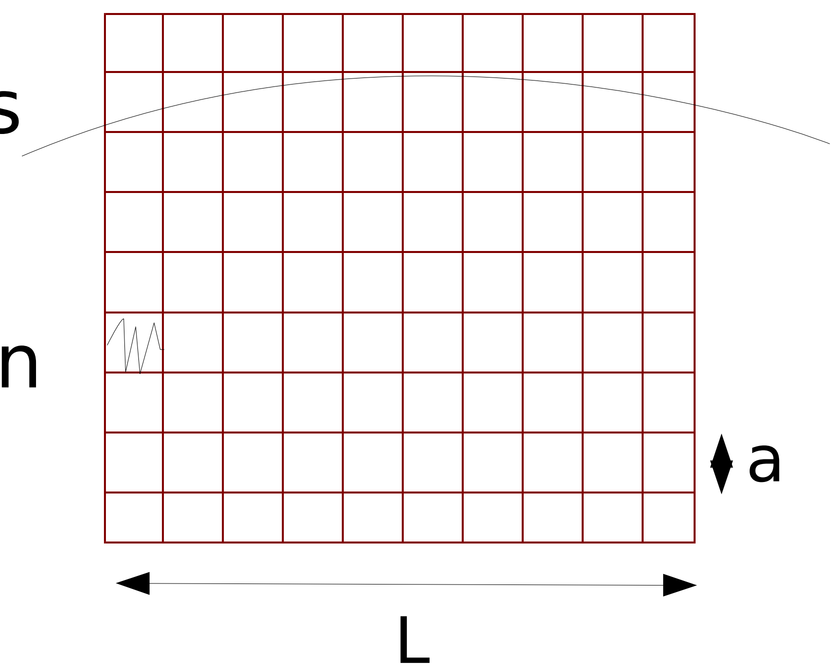

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$$\sum a_i=1 \wedge m_0 < m_1 < \dots$$

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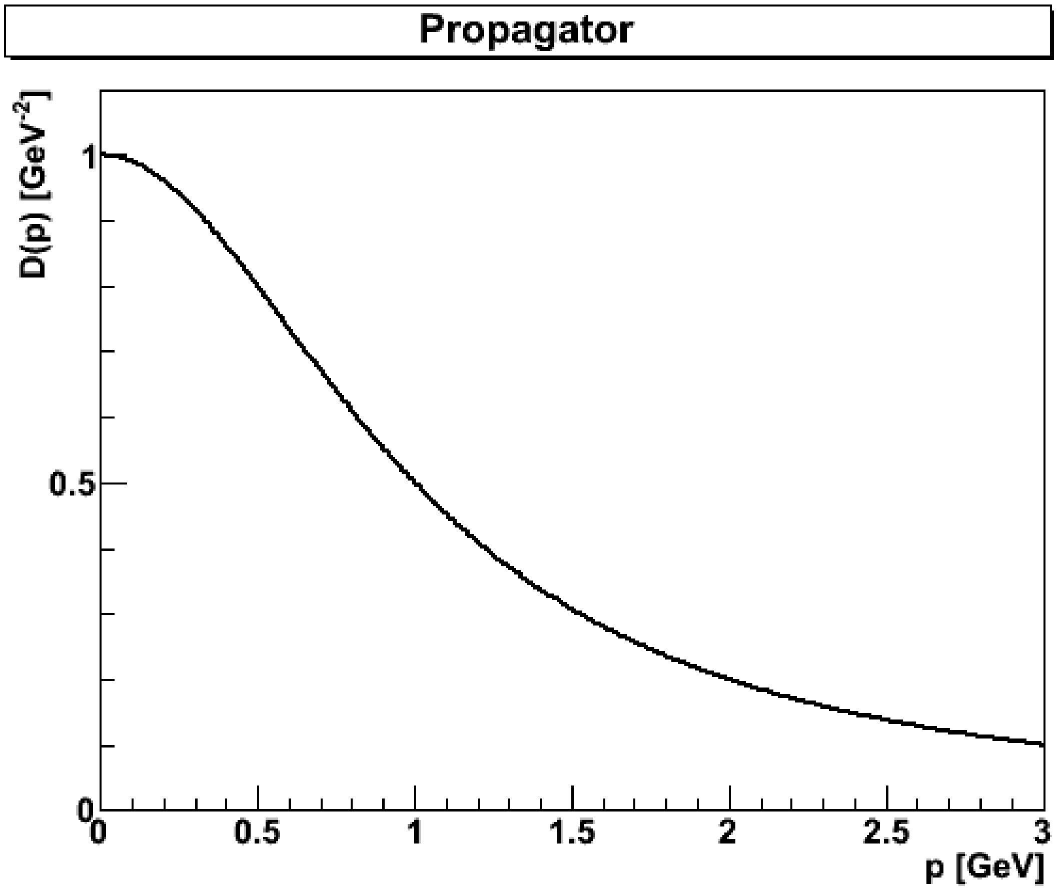

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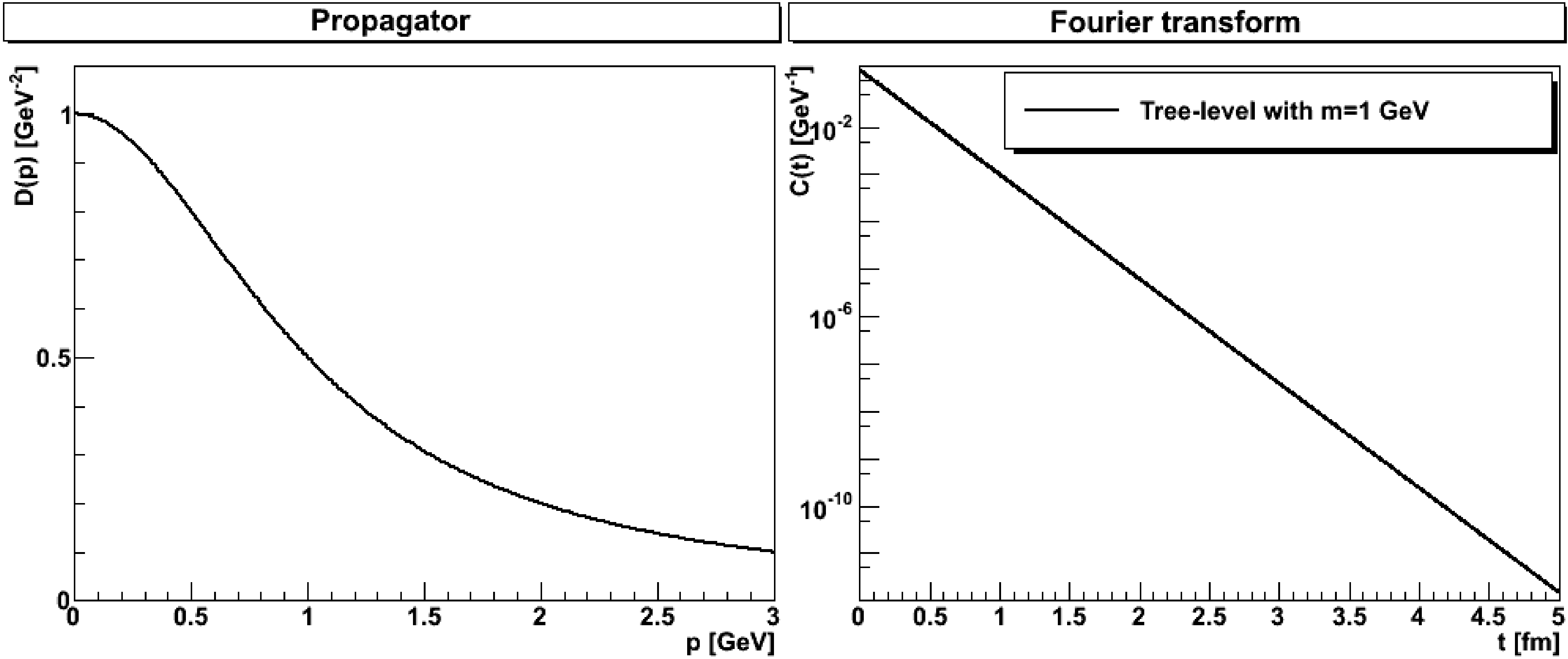

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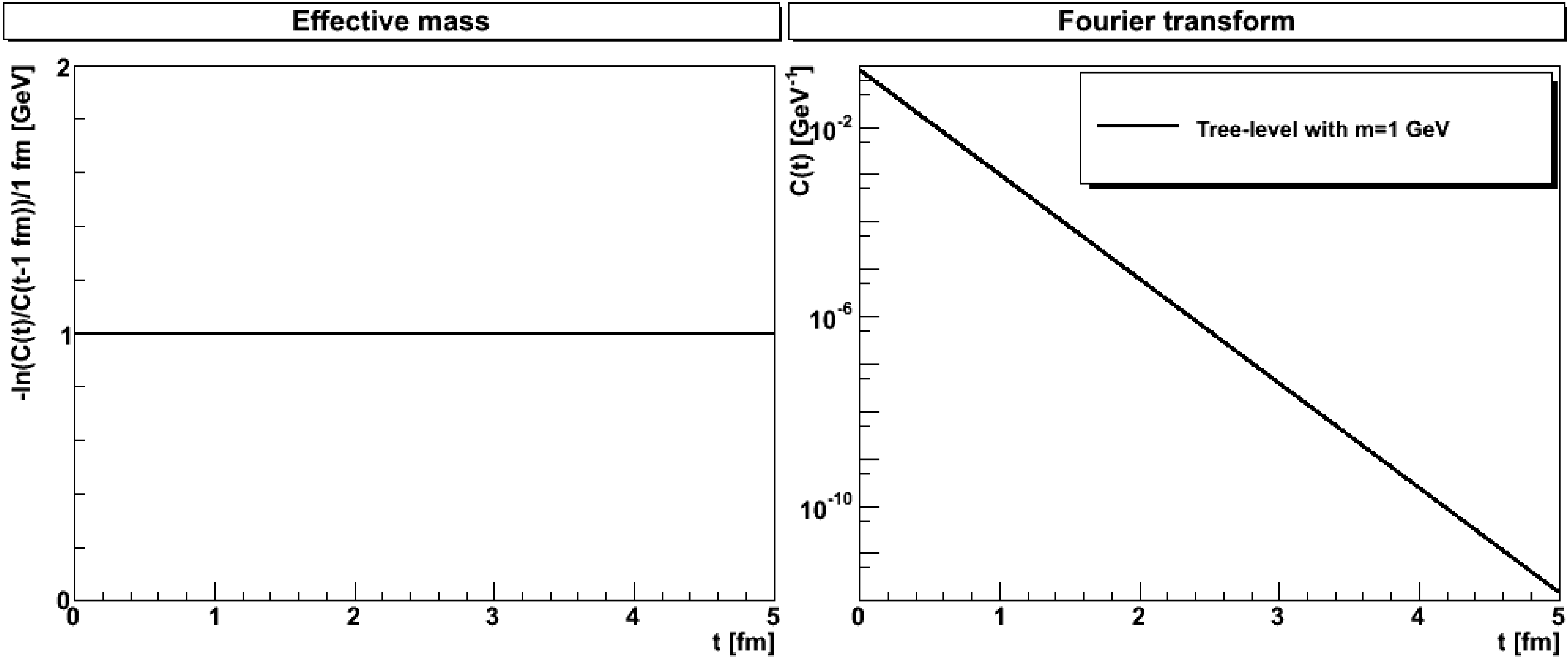

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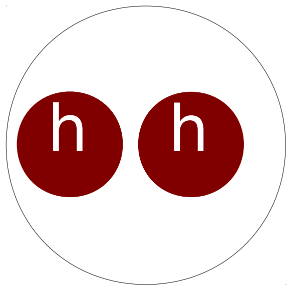

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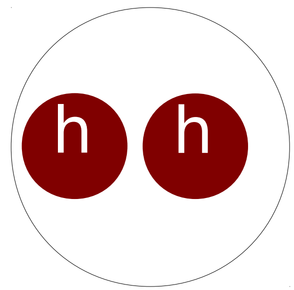

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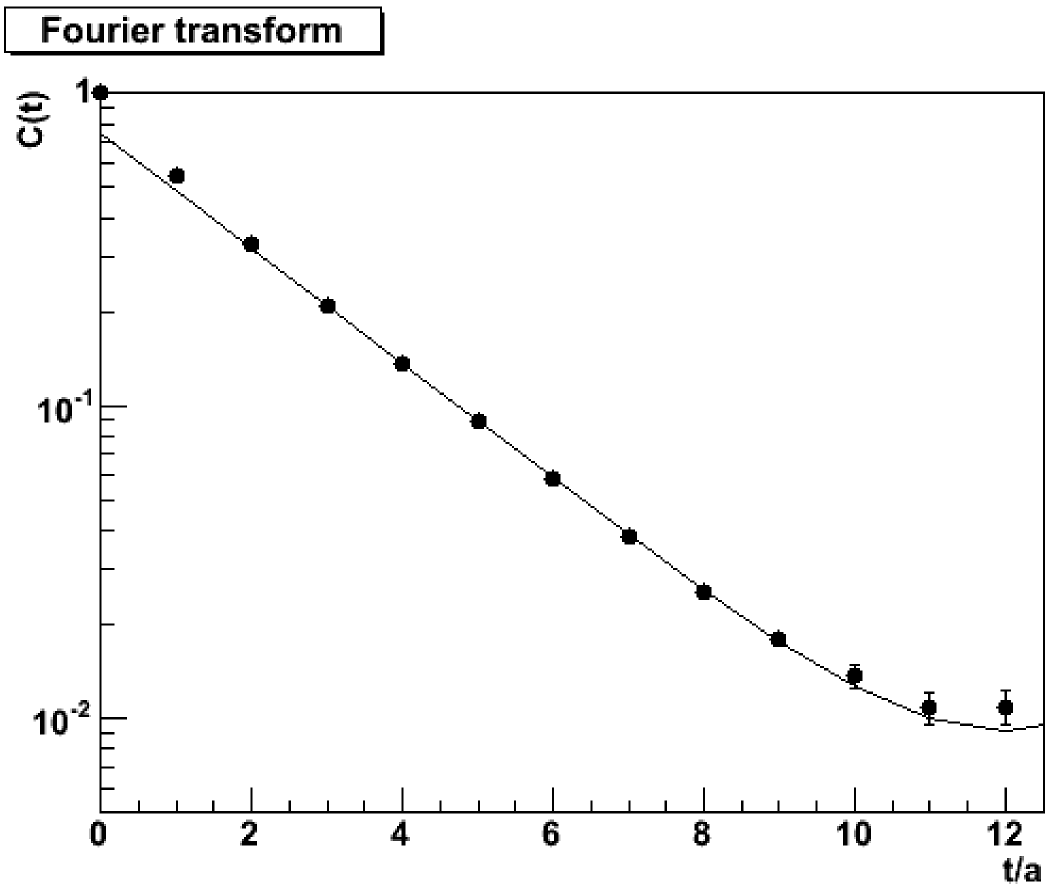

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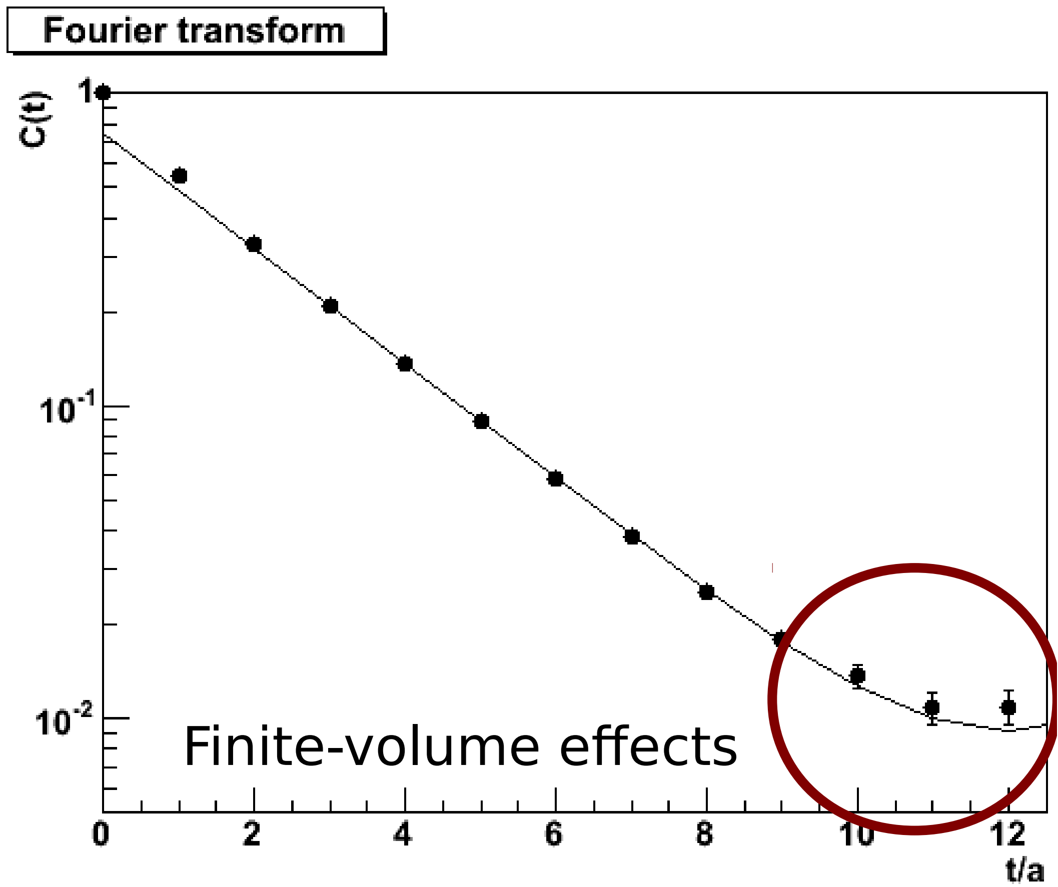

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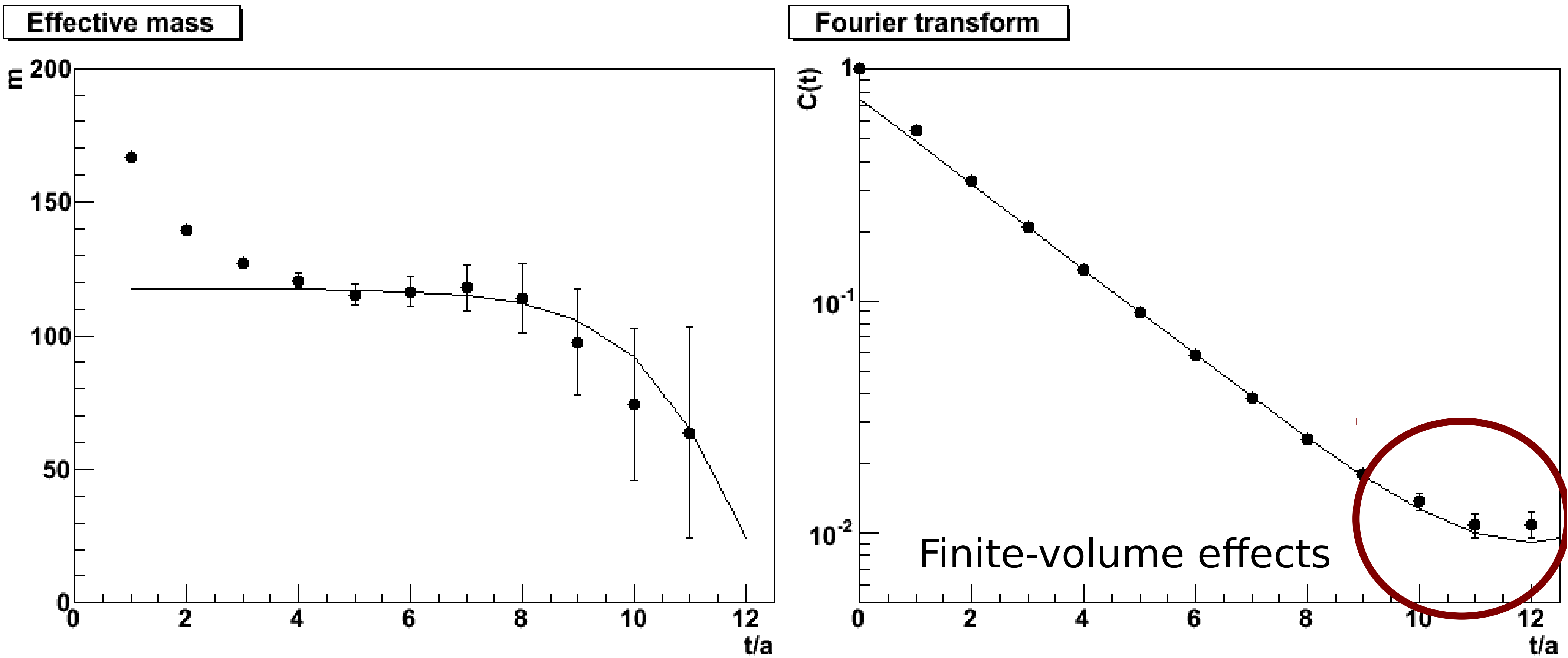

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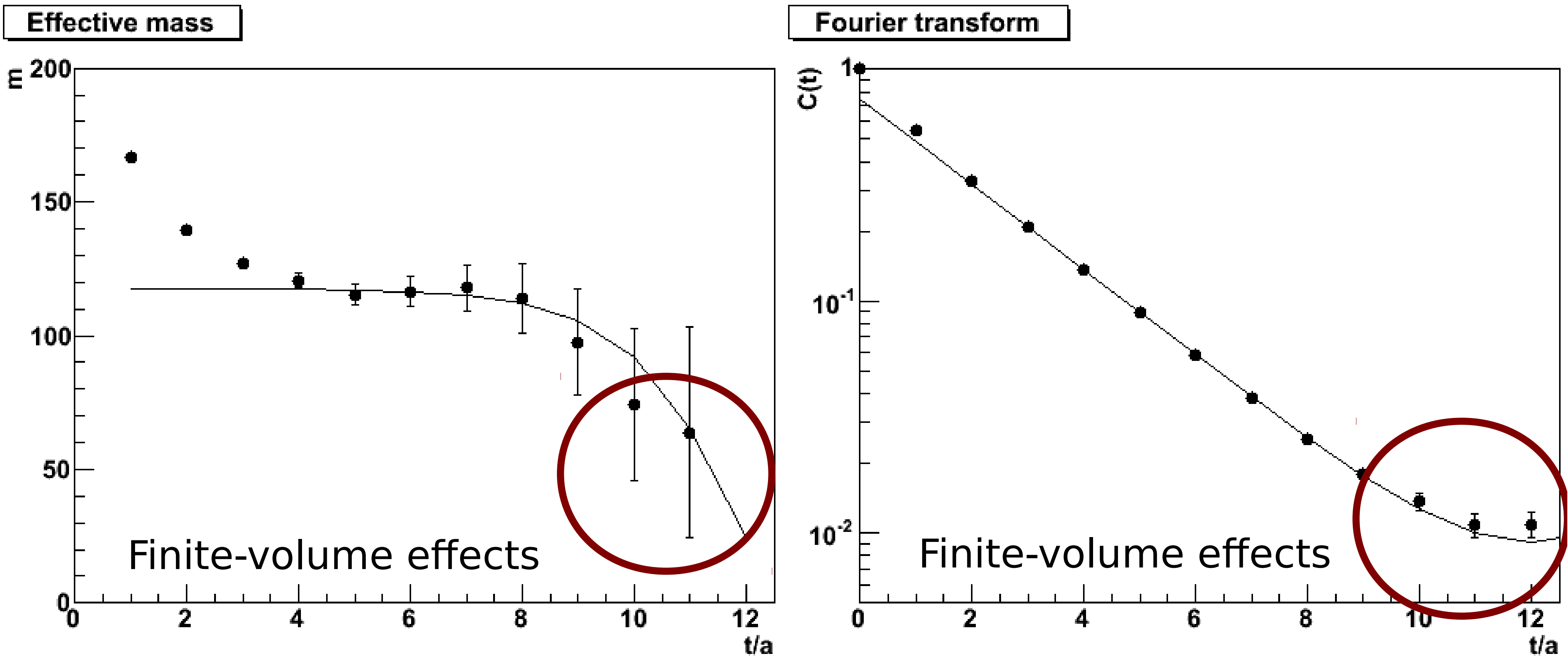

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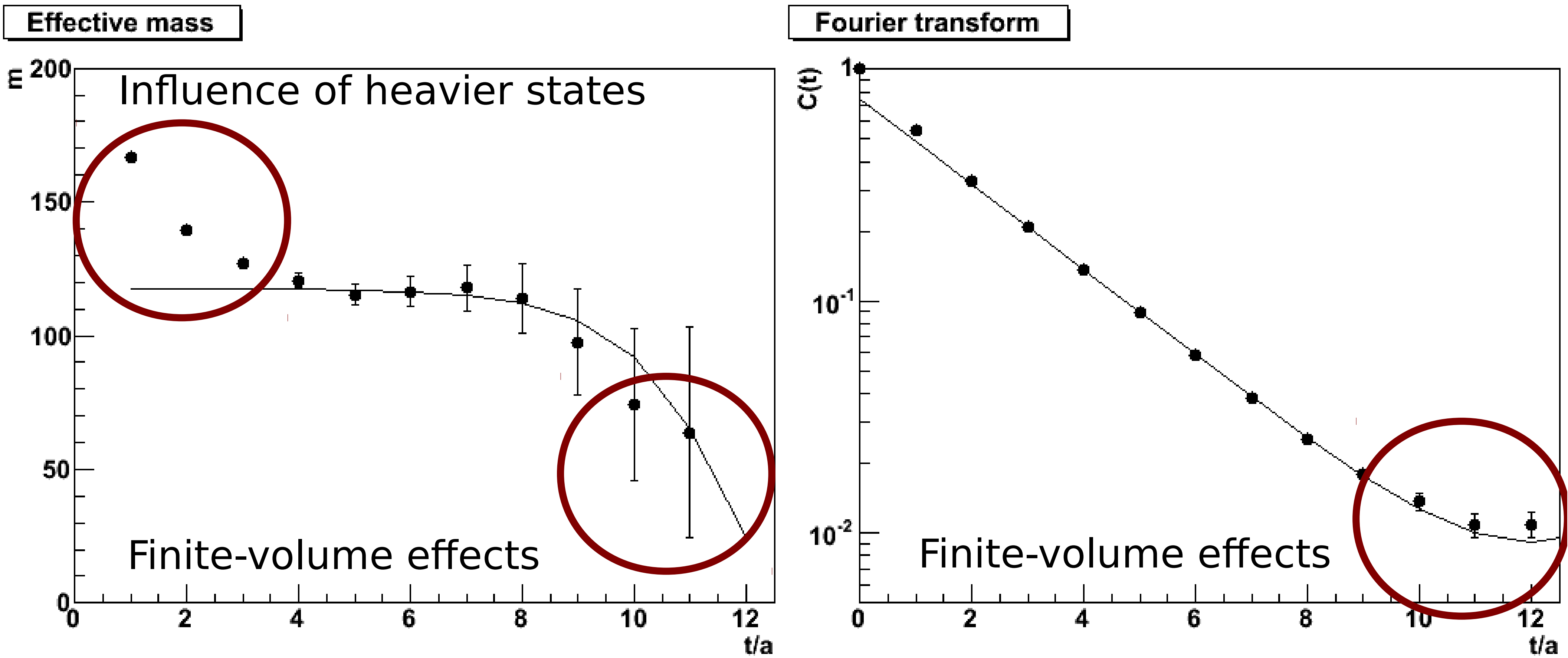

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3) Standard perturbation theory

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$$+ \langle \eta^+(x)\eta(y)\rangle\langle \eta^+(x)\eta(y)\rangle + O(g,\lambda)$$

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- Higgsonium: 120 GeV, Higgs at tree-level: 120 GeV
  - Scheme exists to shift Higgs mass always to 120 GeV
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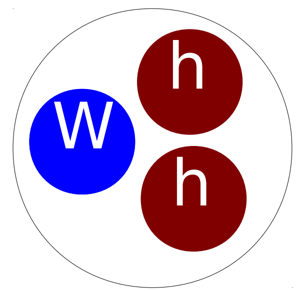
- Deeply-bound relativistic state
  - Mass defect~constituent mass
  - Cannot describe with quantum mechanics
  - Very different from QCD bound states

Isovector-vector state



- Vector state 1^- with operator $tr\, t^a \frac{h^+}{\sqrt{h^+ h}} D_\mu \frac{h}{\sqrt{h^+ h}}$
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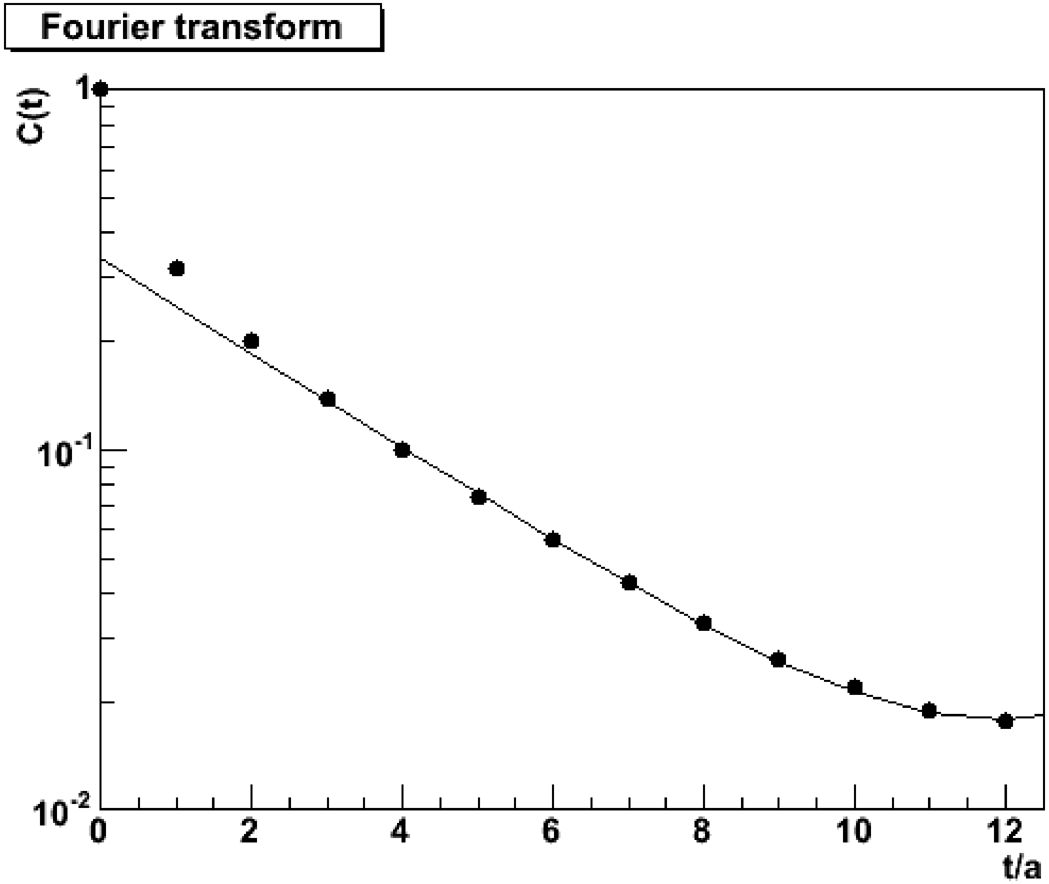

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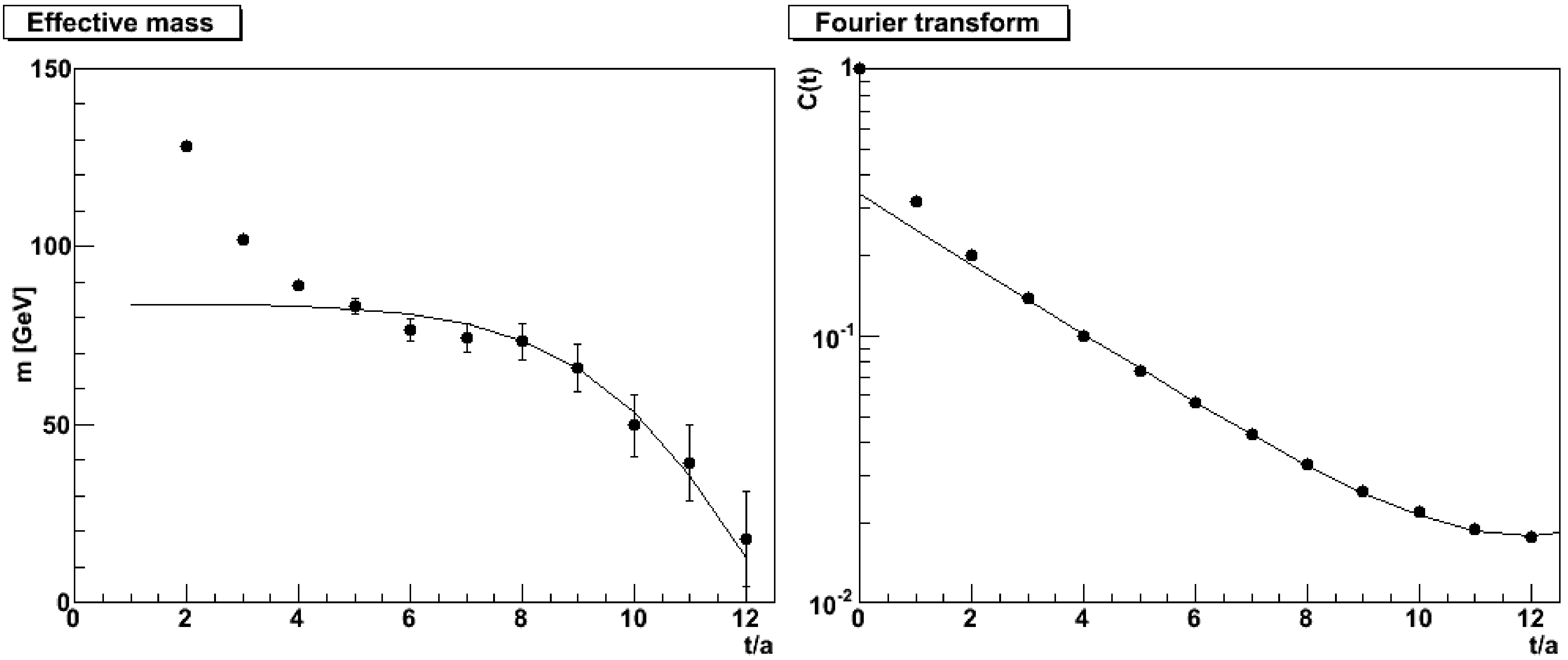

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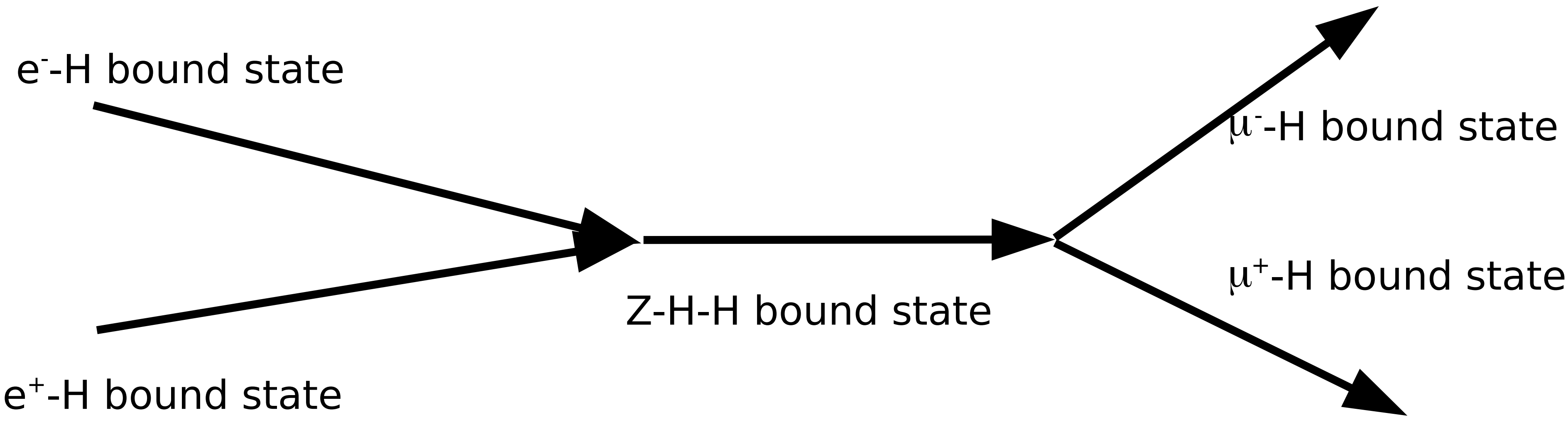
- Photons
  - QED similar but simpler

How events looks like (LEP/ILC)

[Maas'12]



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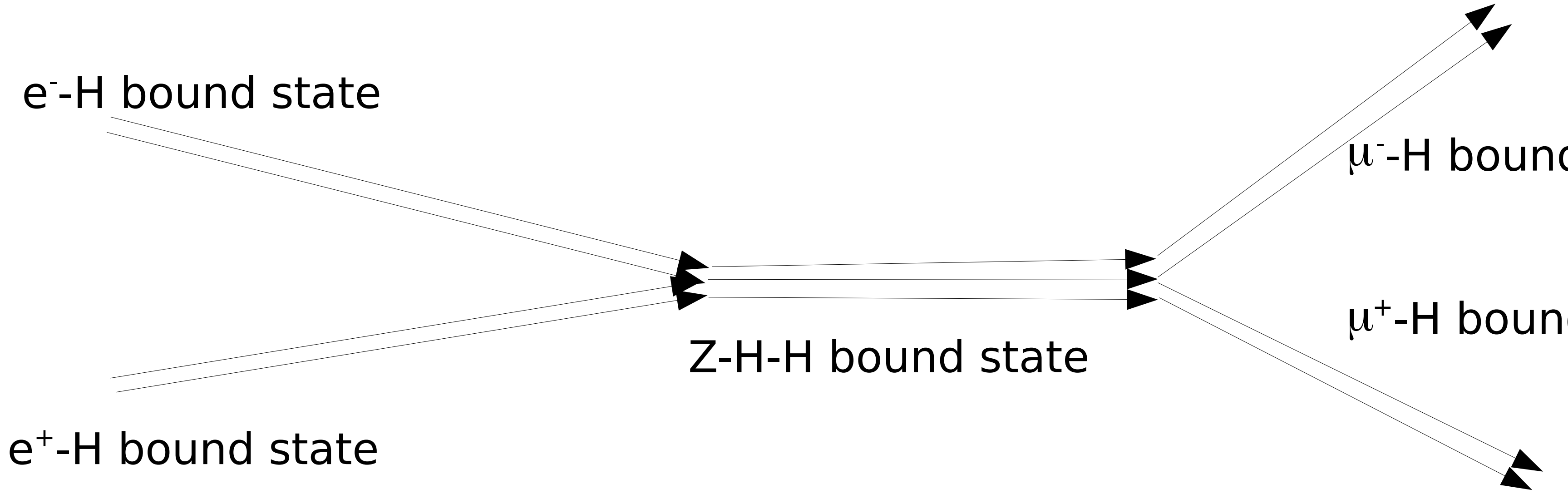

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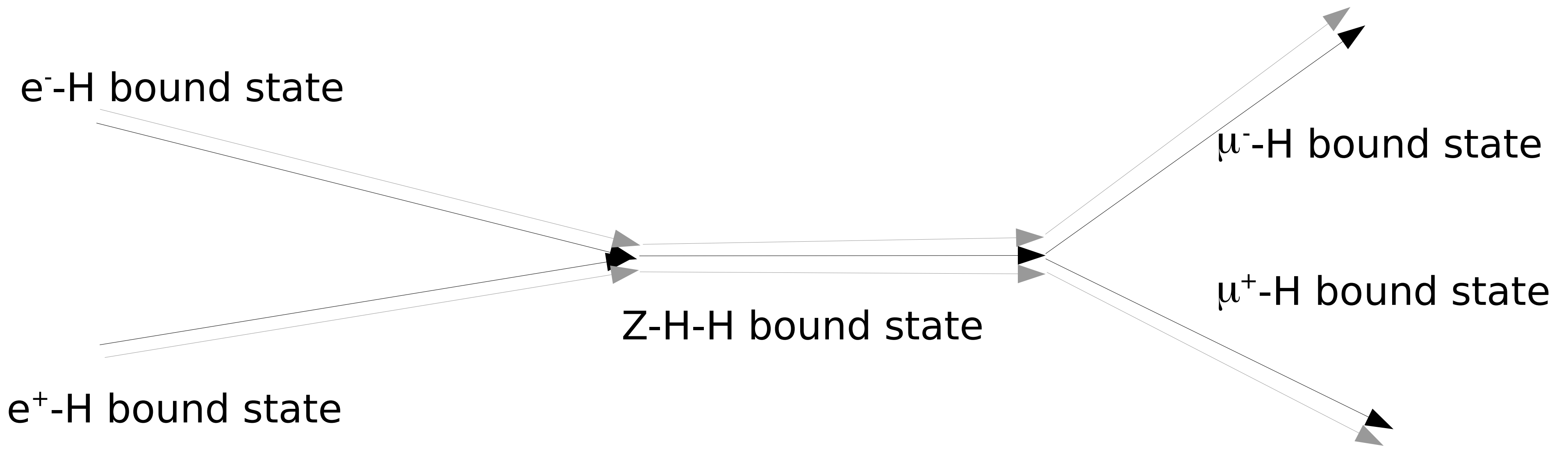

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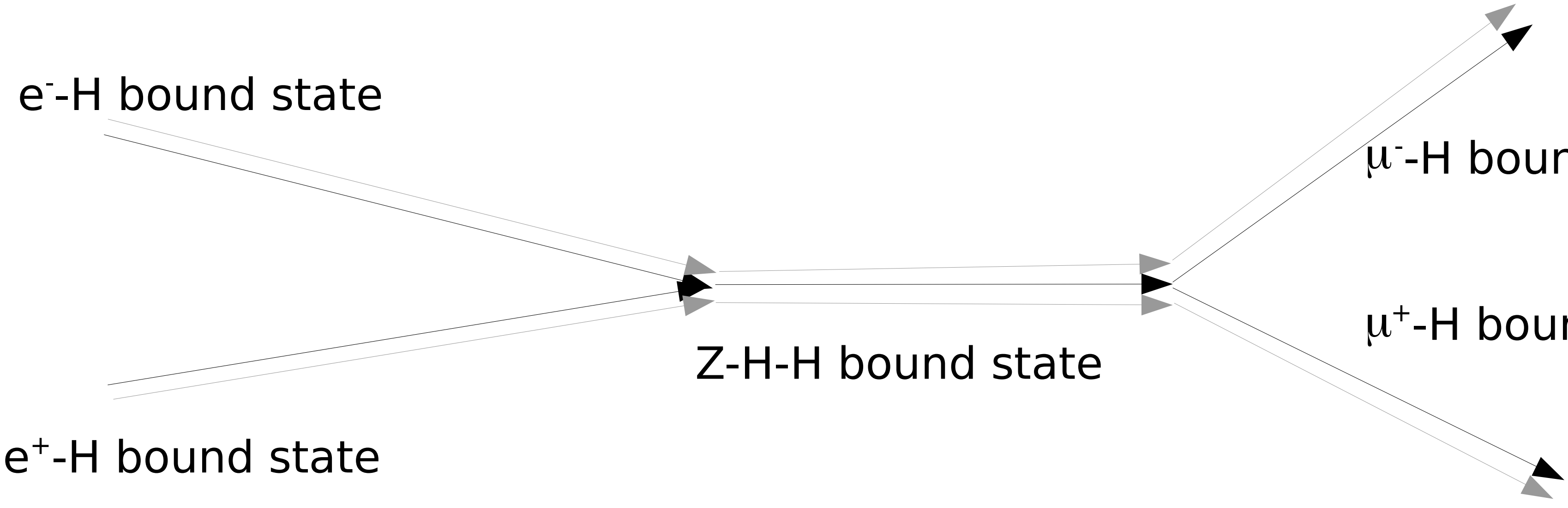

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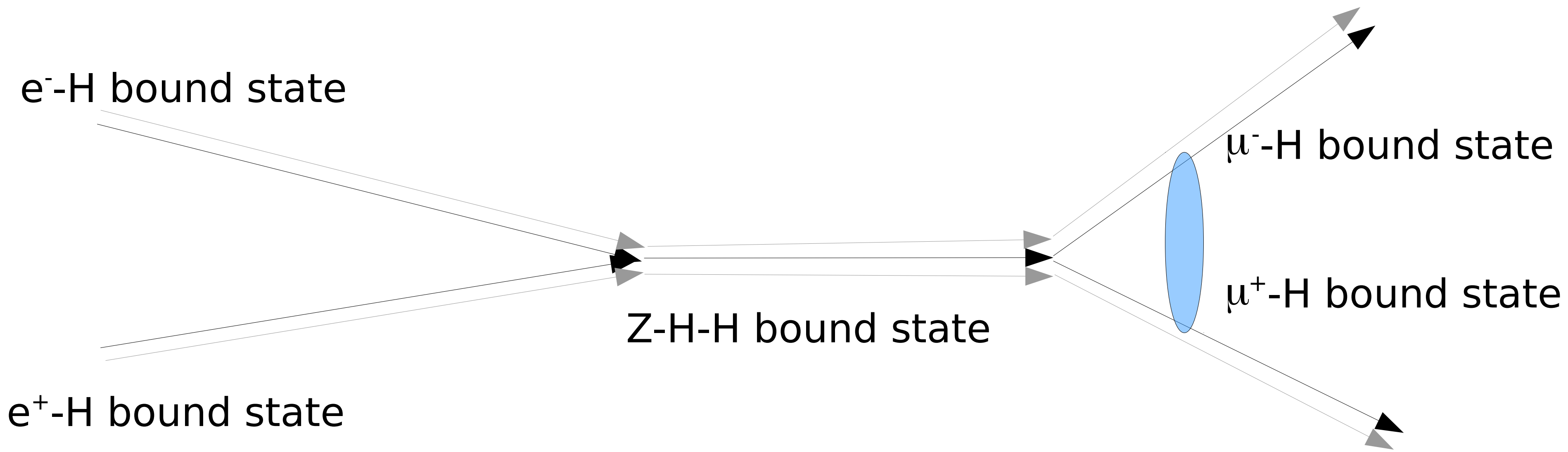

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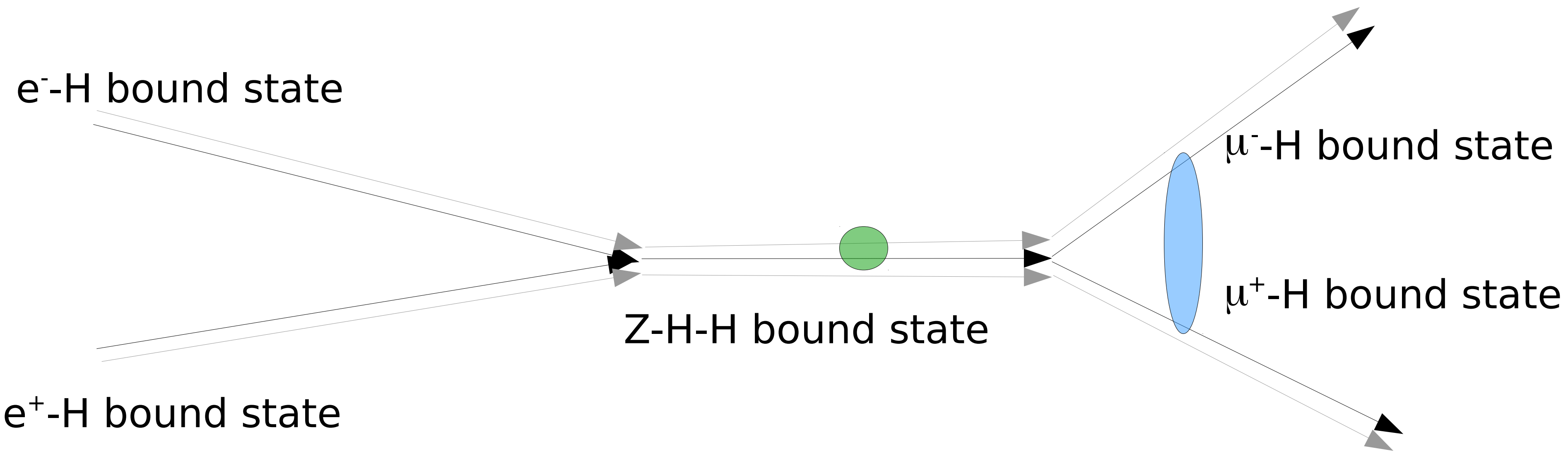

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  - New ones: Small, require more sensitivity

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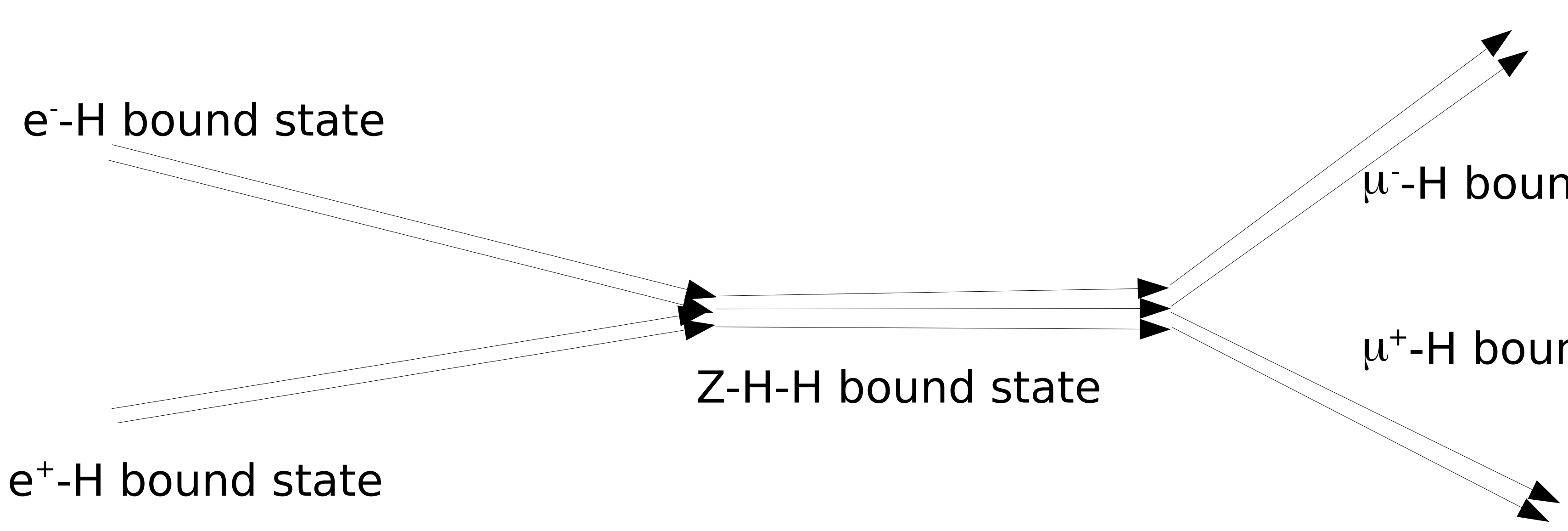

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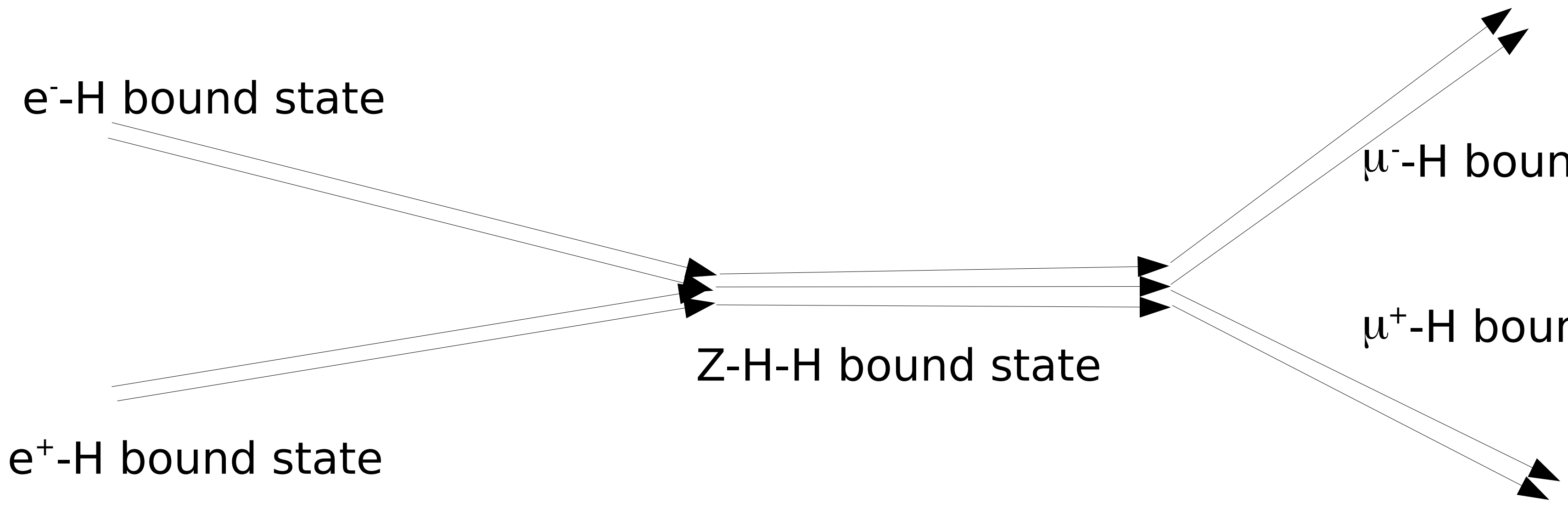

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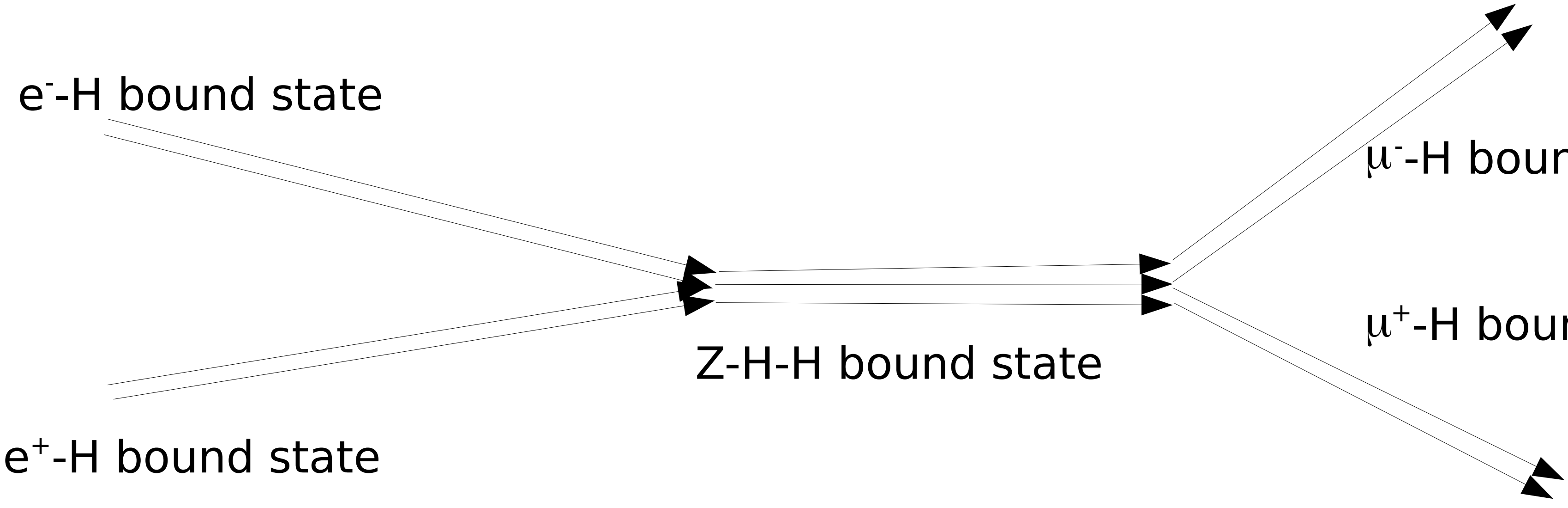

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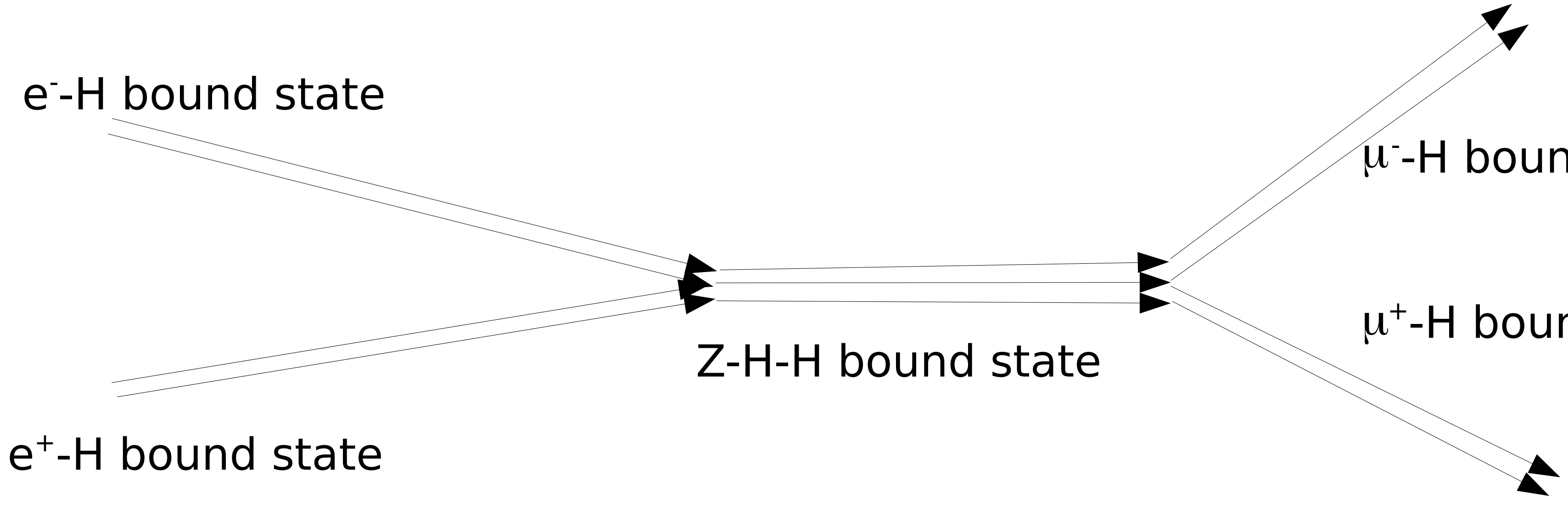

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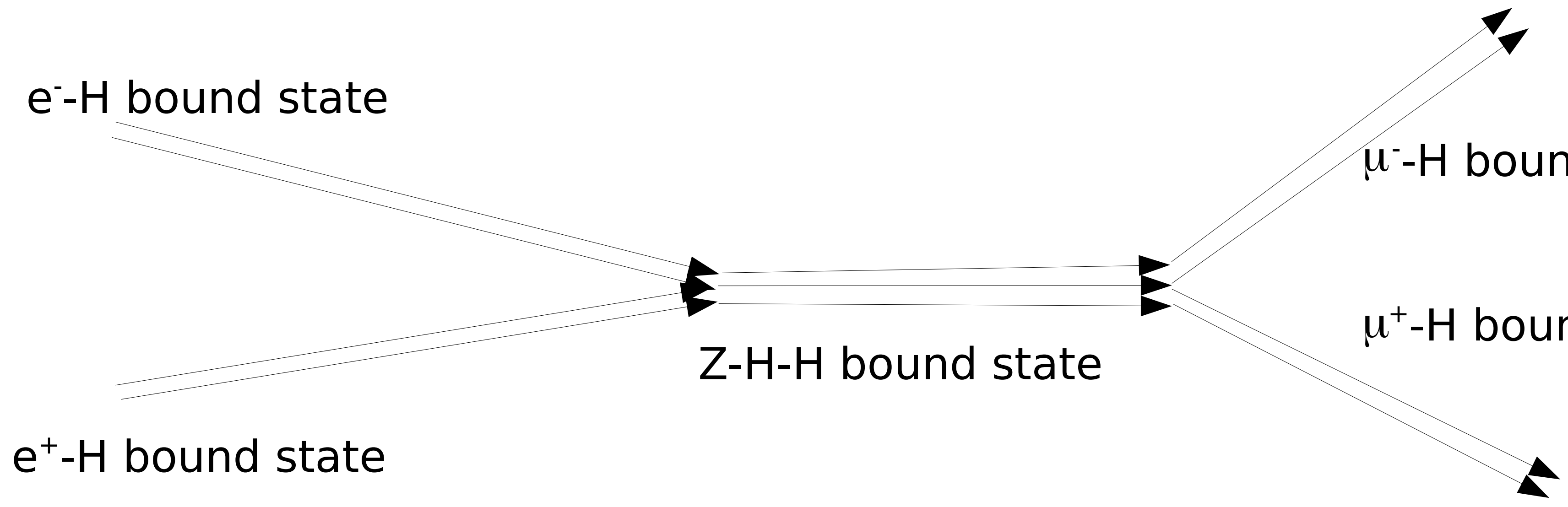

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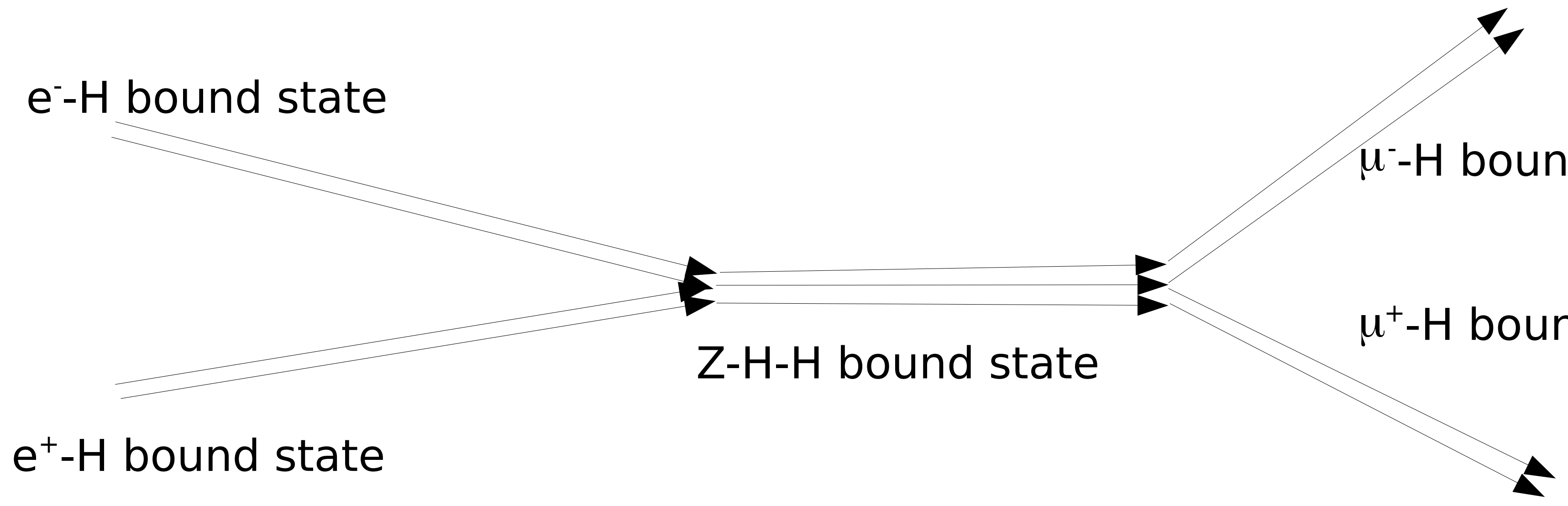

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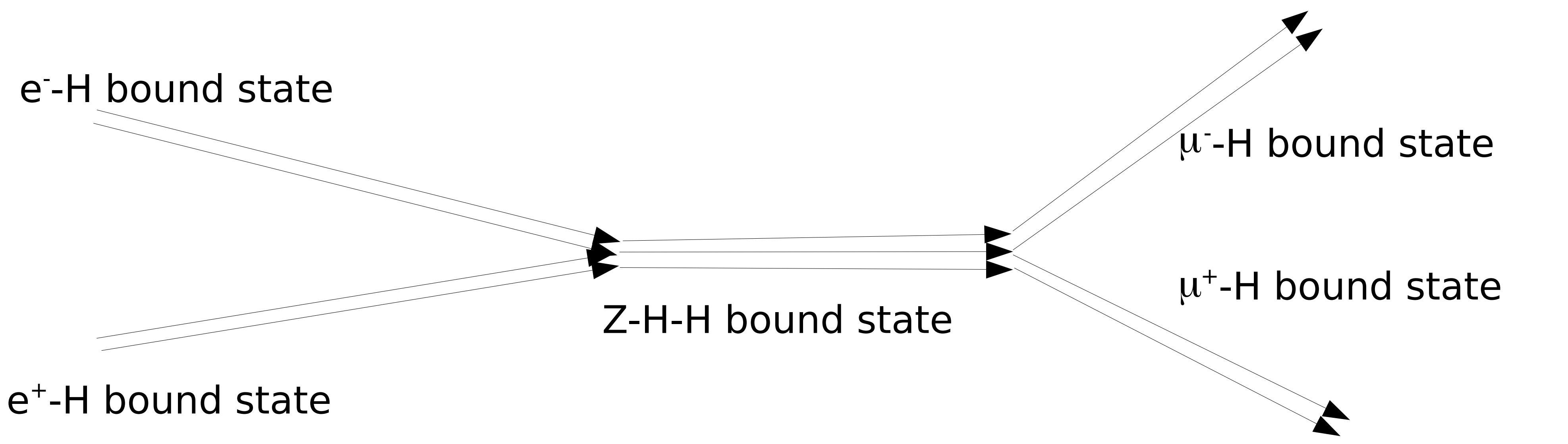

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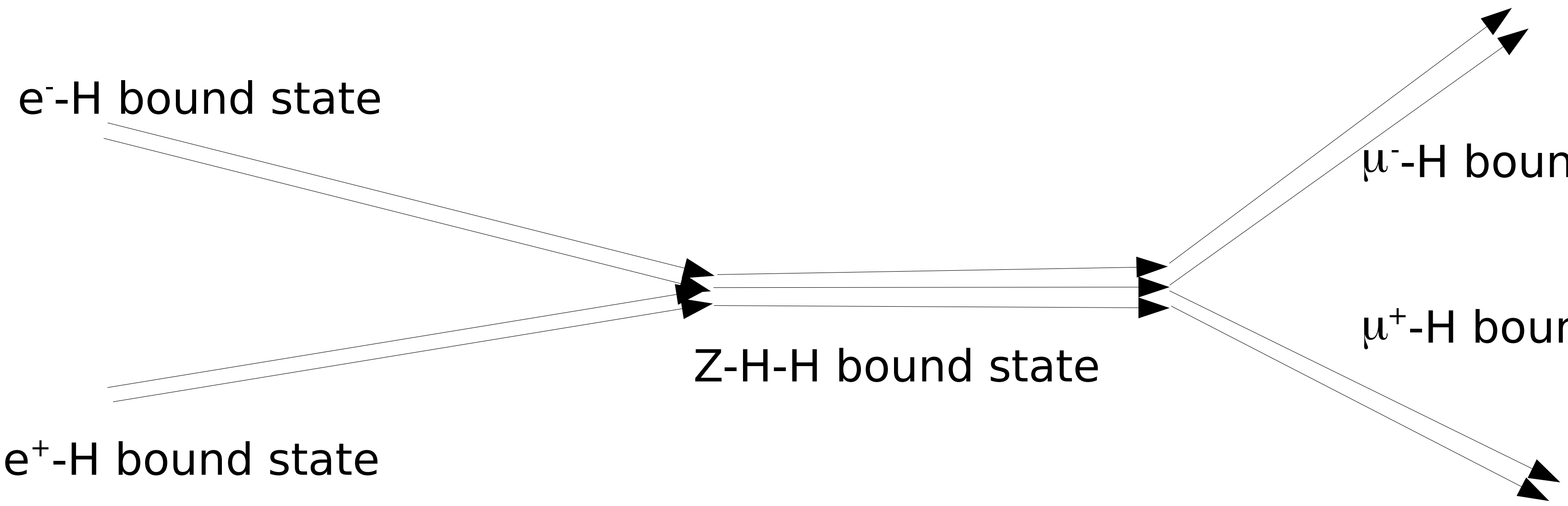

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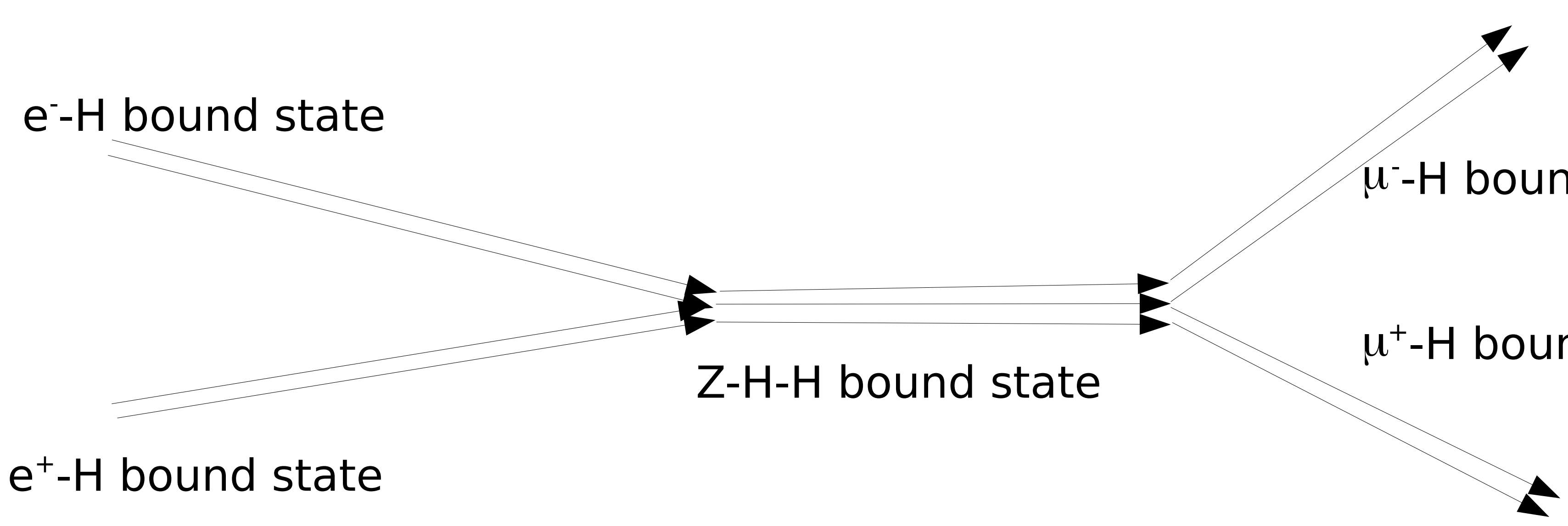

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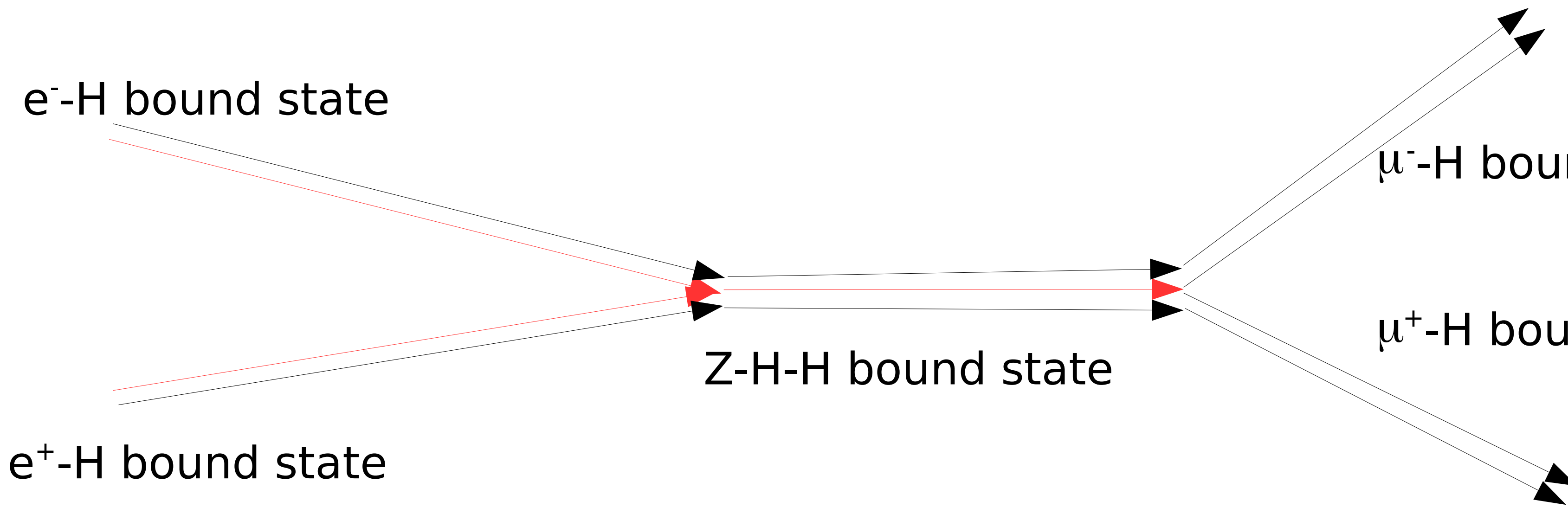

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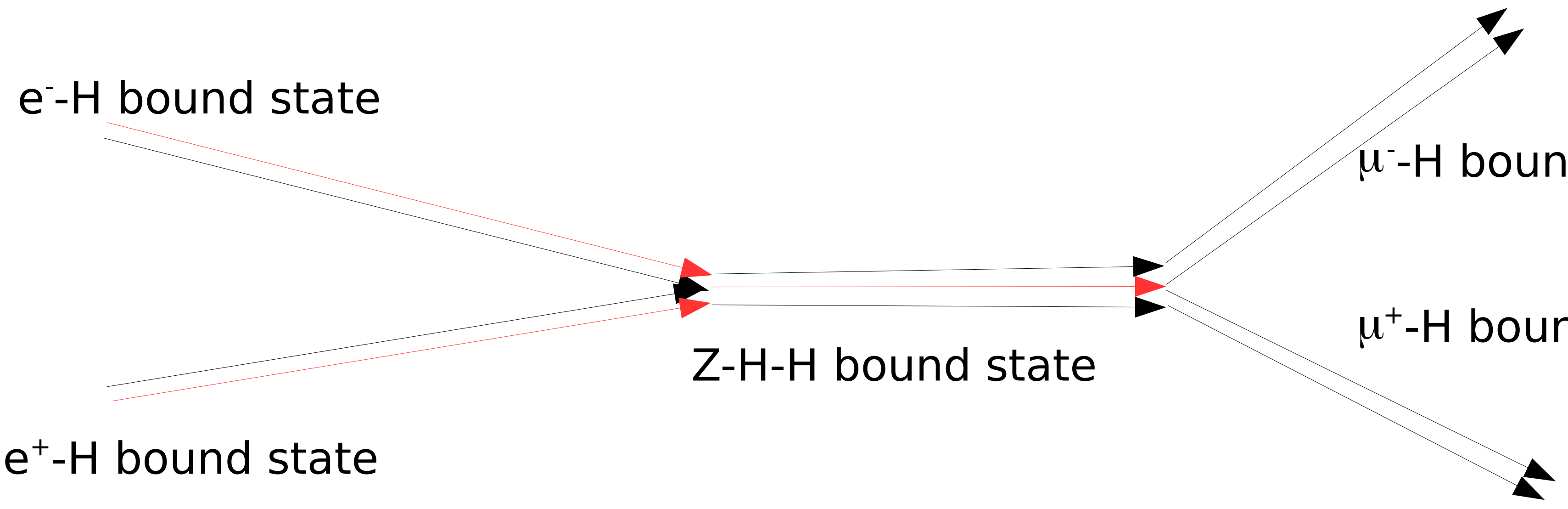

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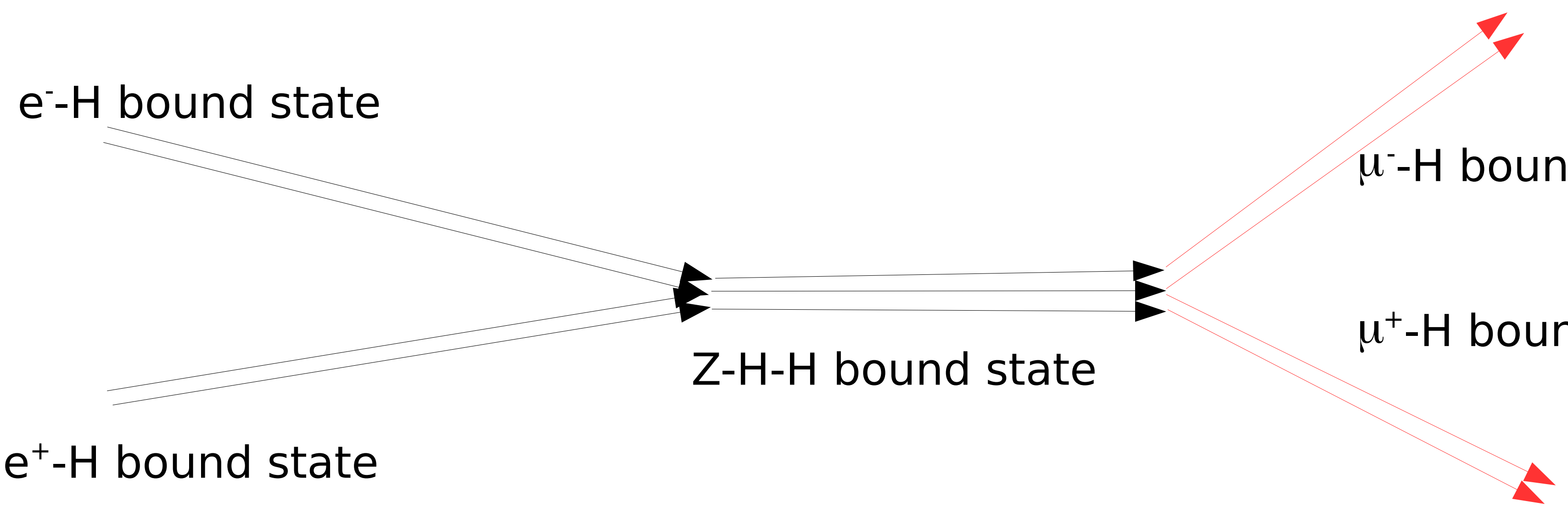

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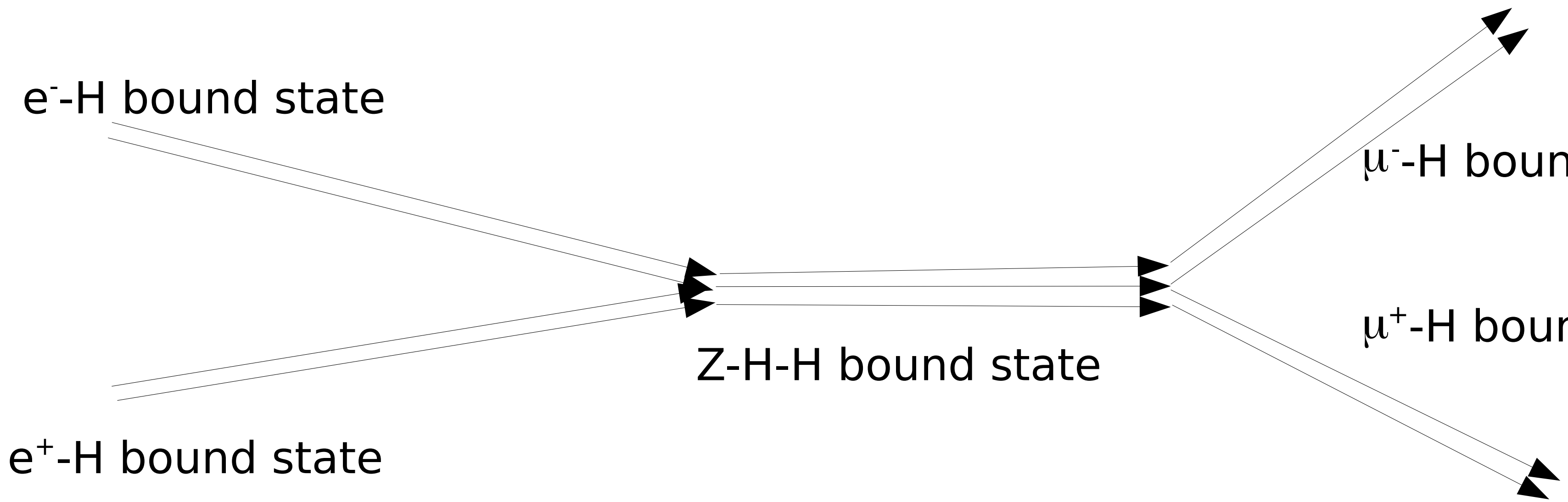

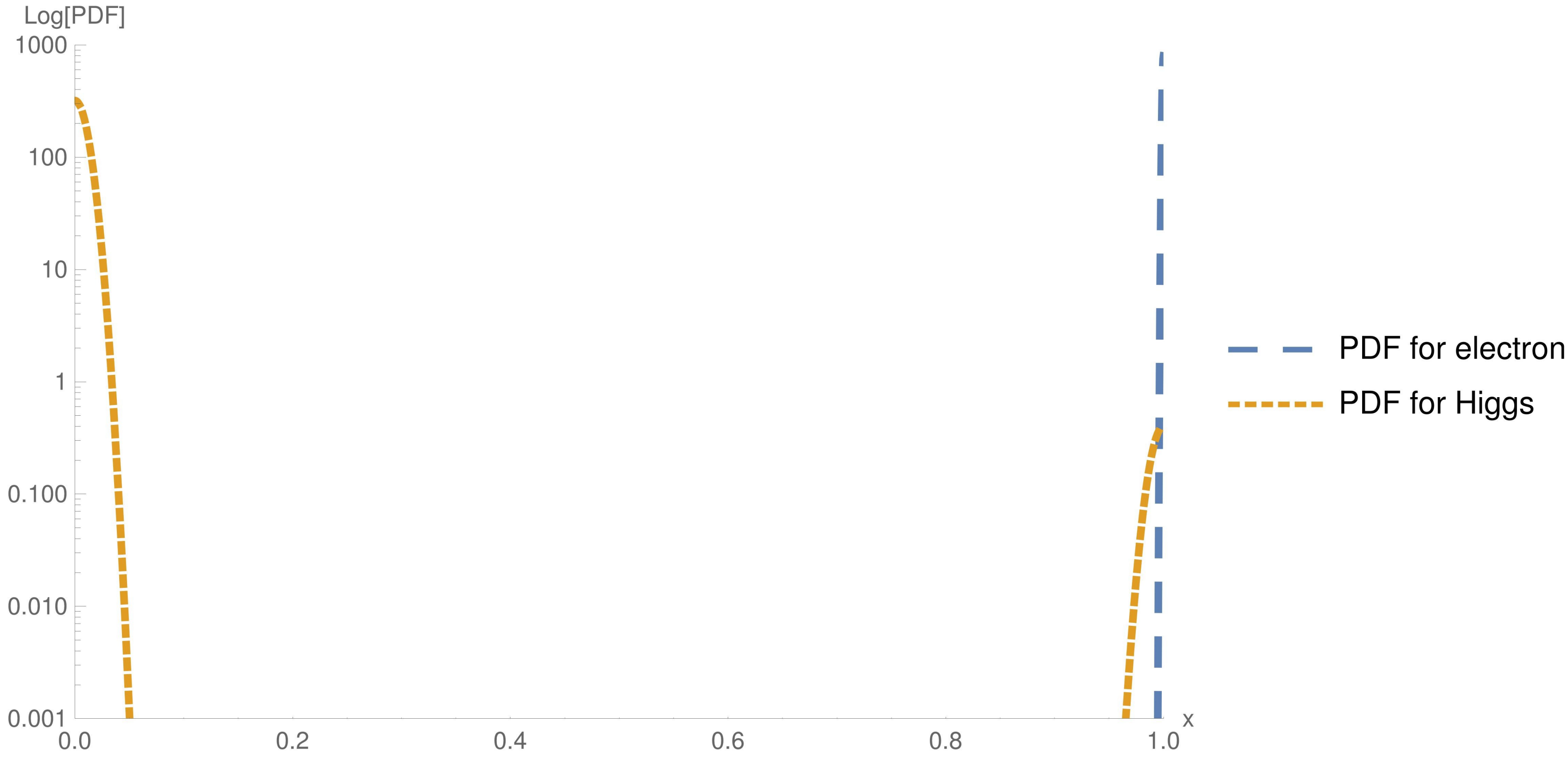

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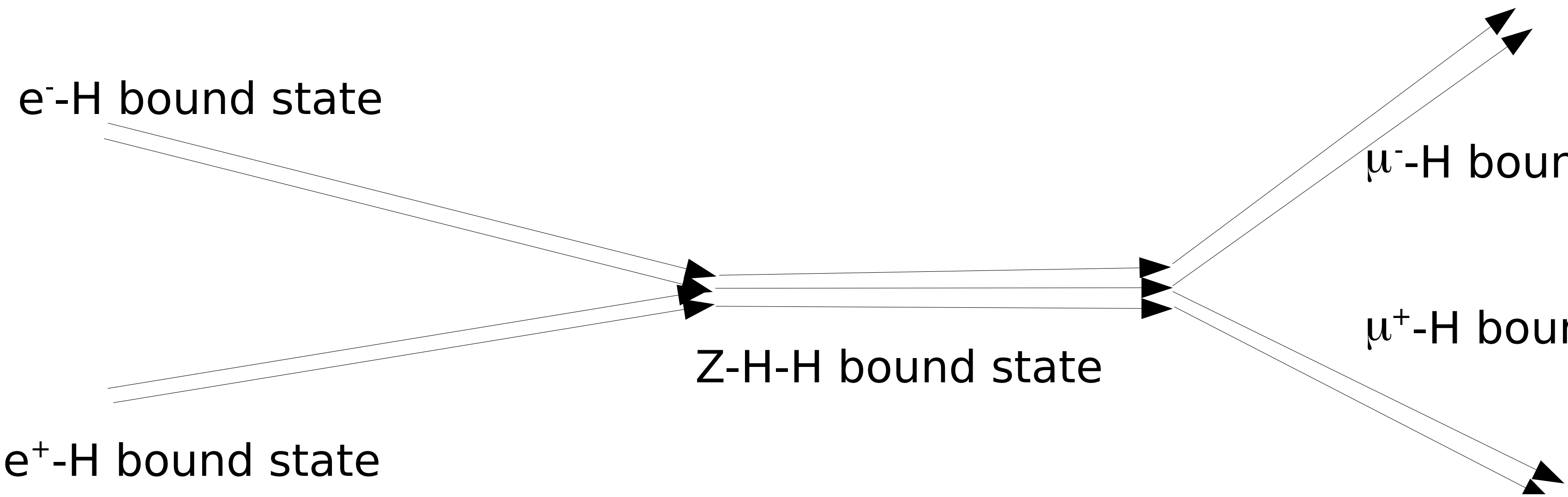

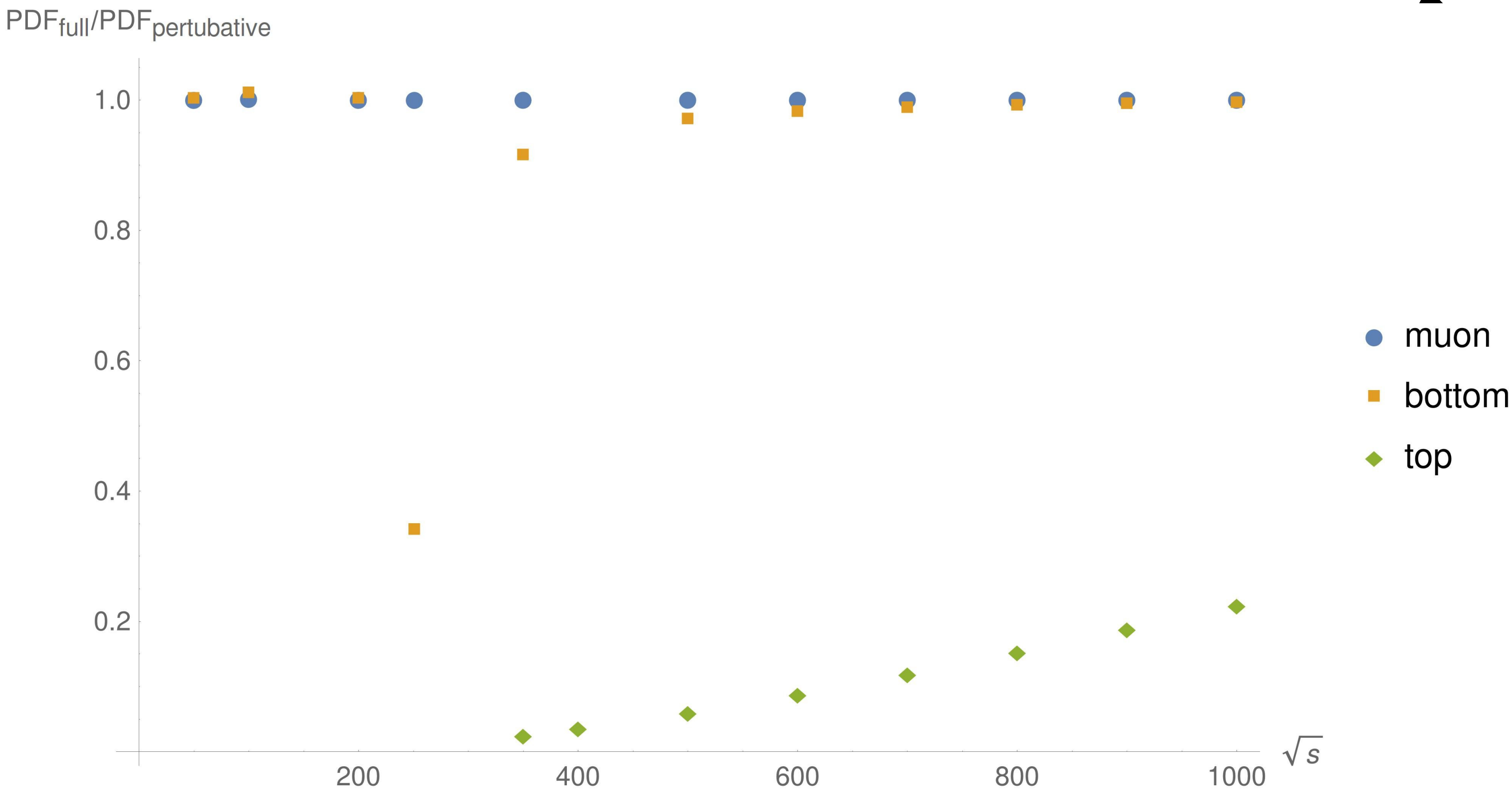

Why it can matter beyond the standard model

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

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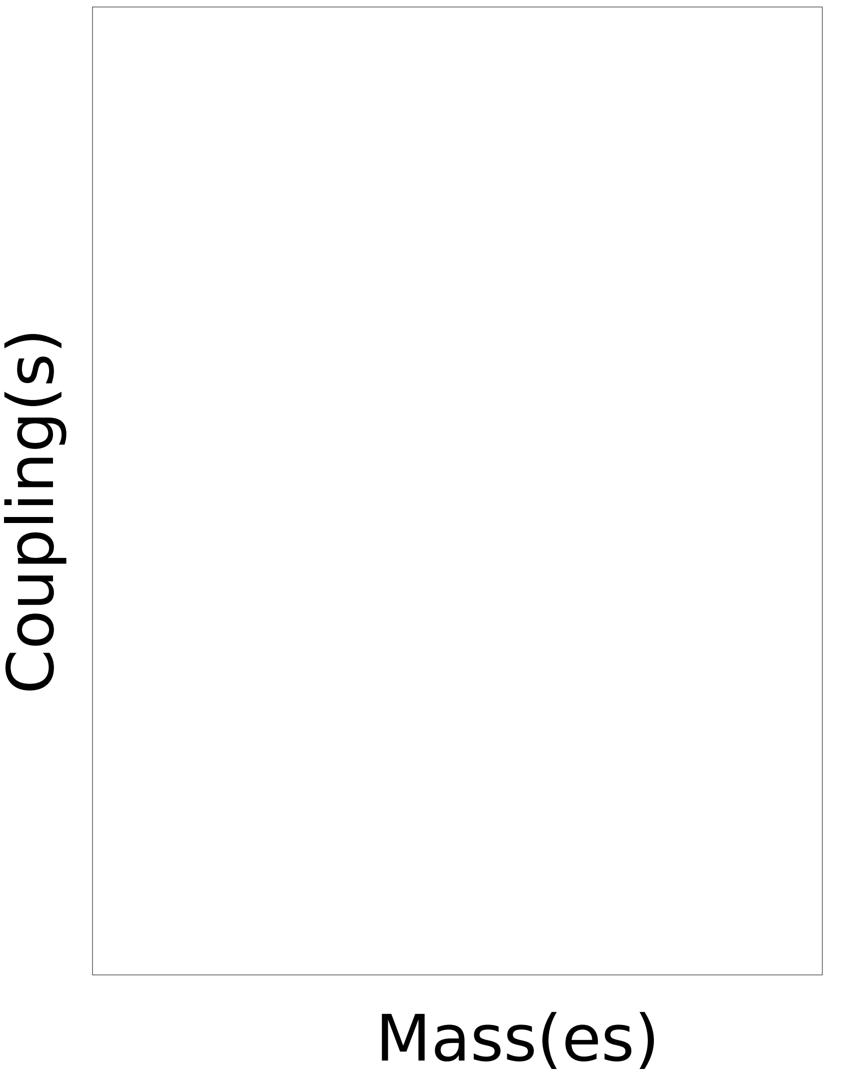

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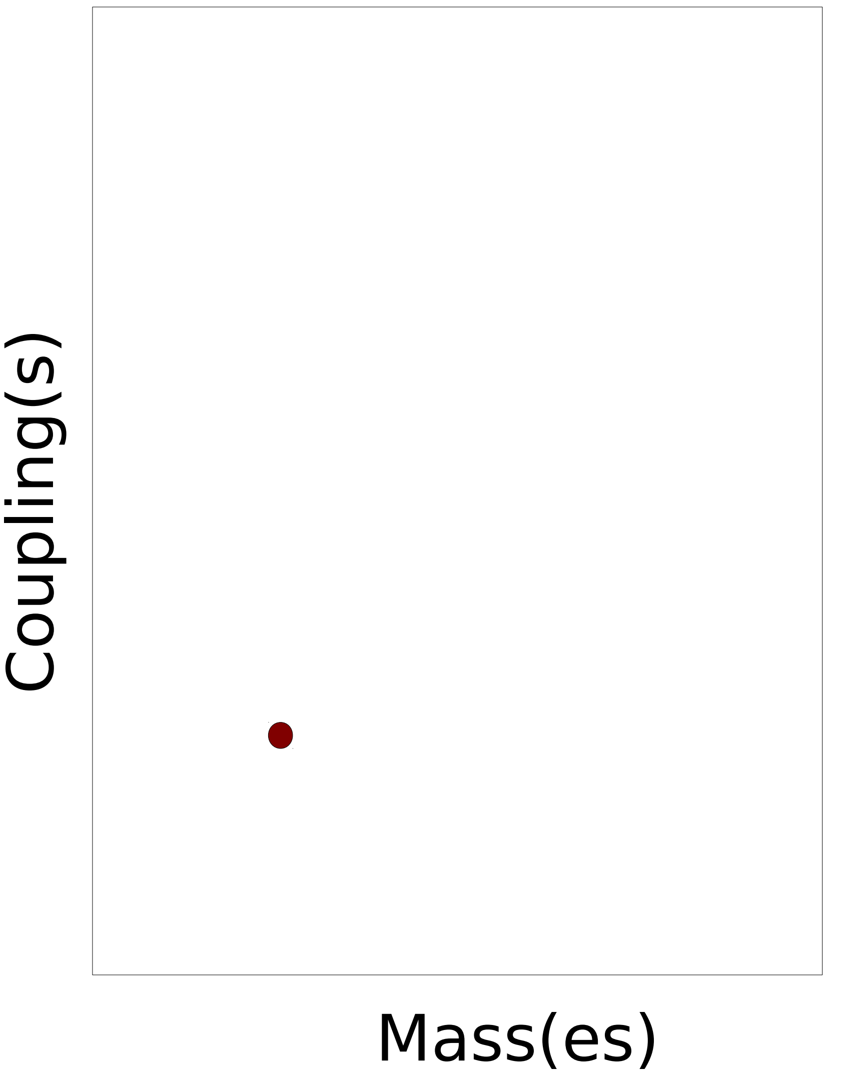

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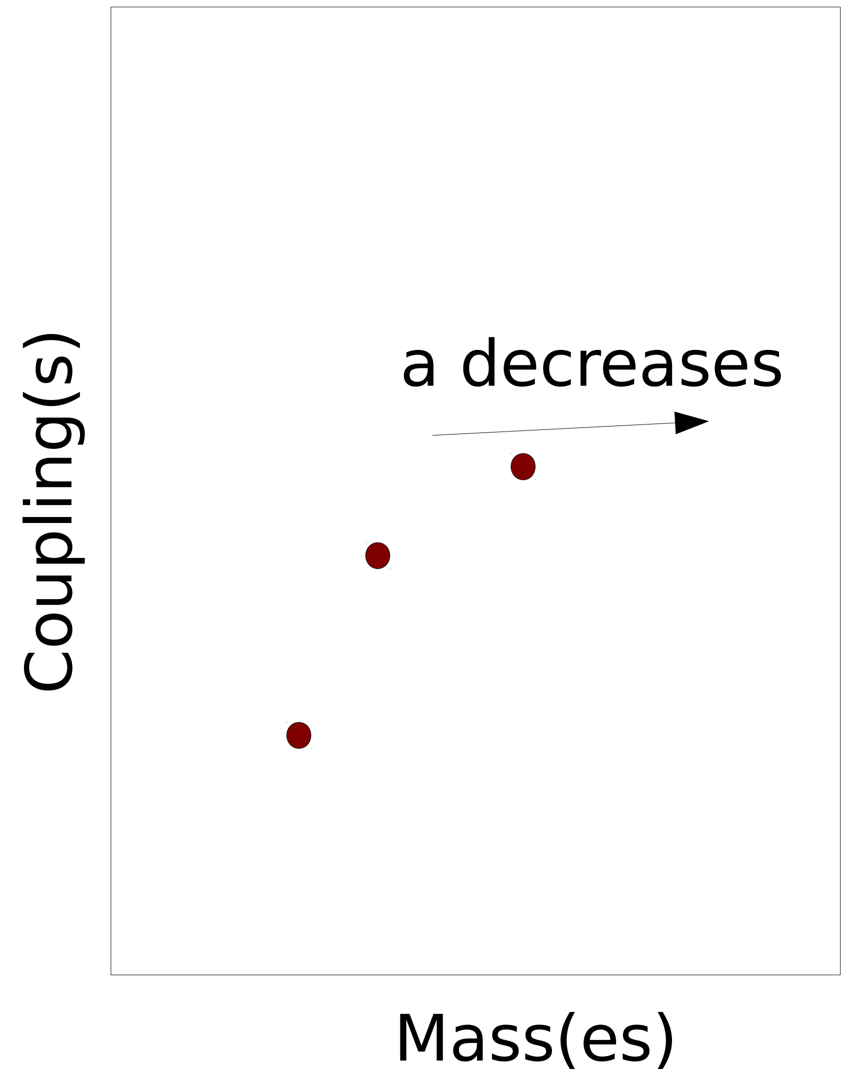

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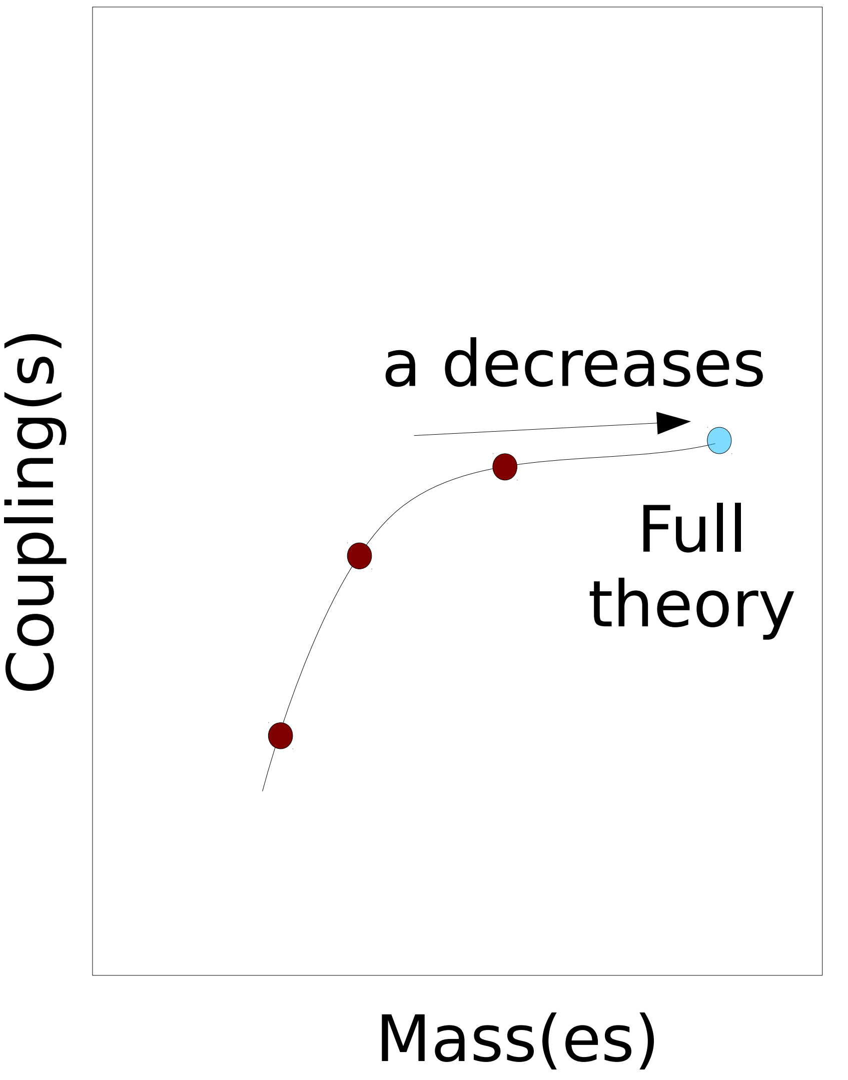

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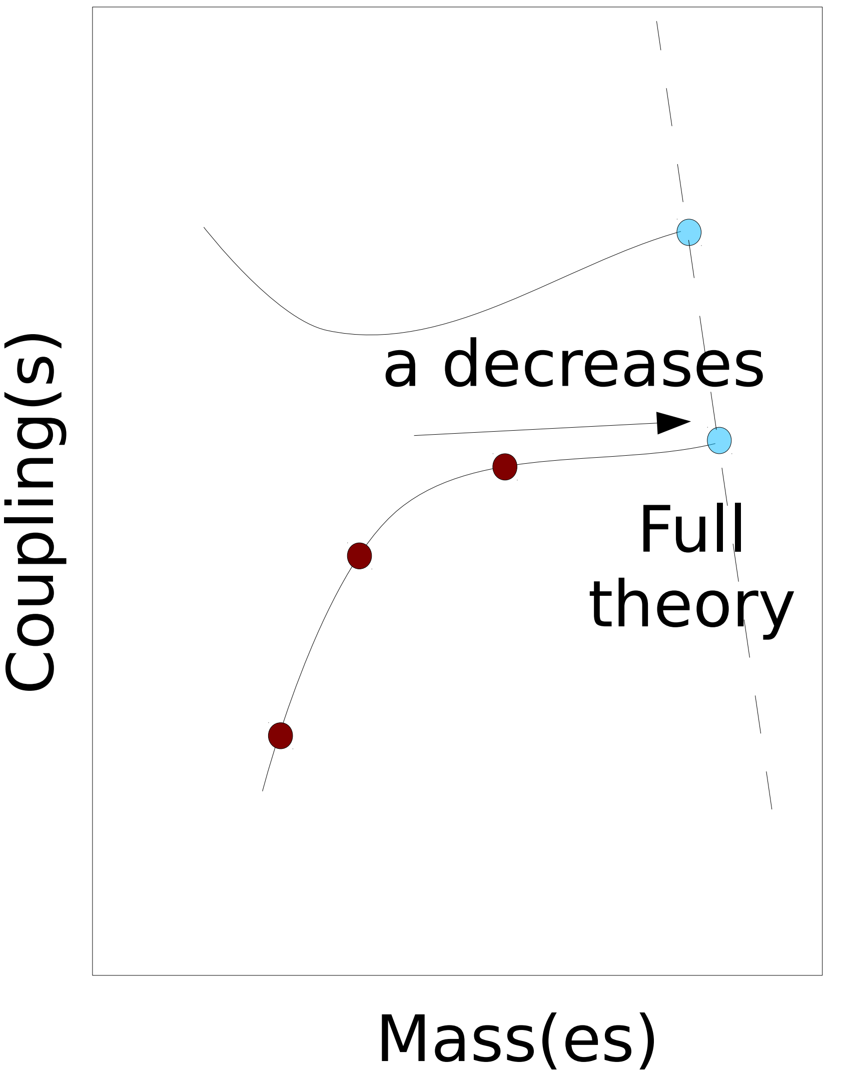
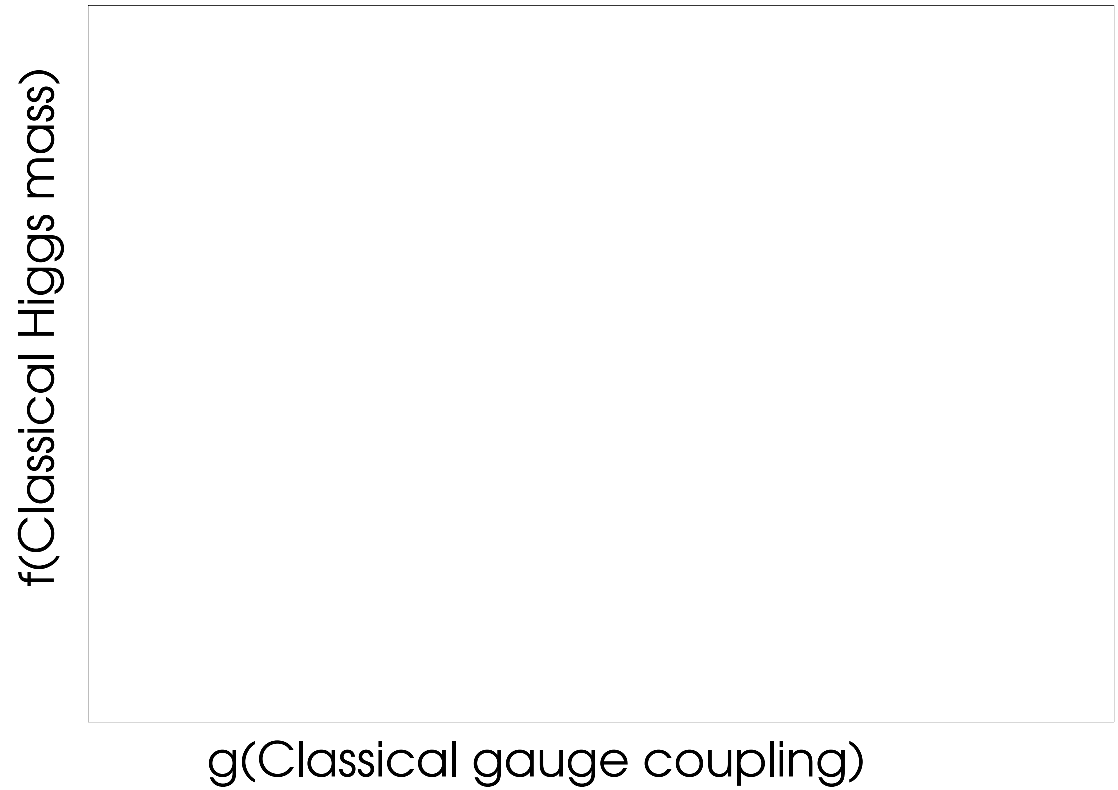
  - Different starting points yield different physics



Phase diagram

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

- (Lattice-regularized) phase diagram



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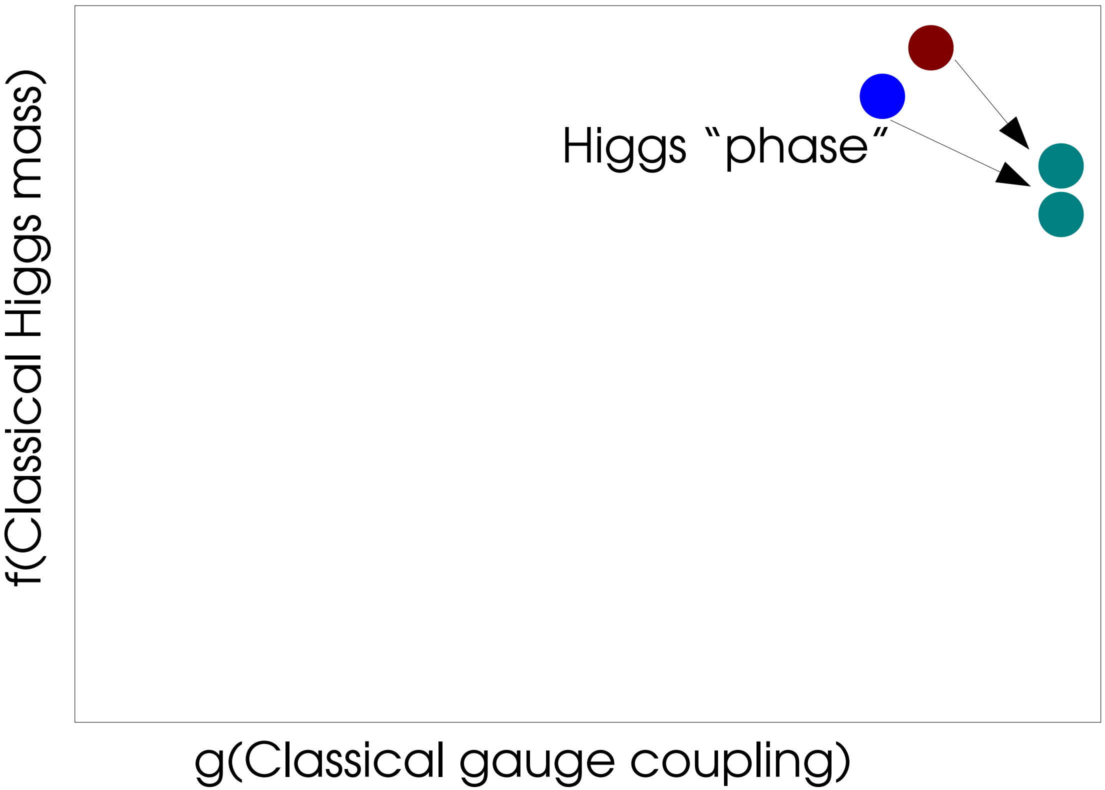

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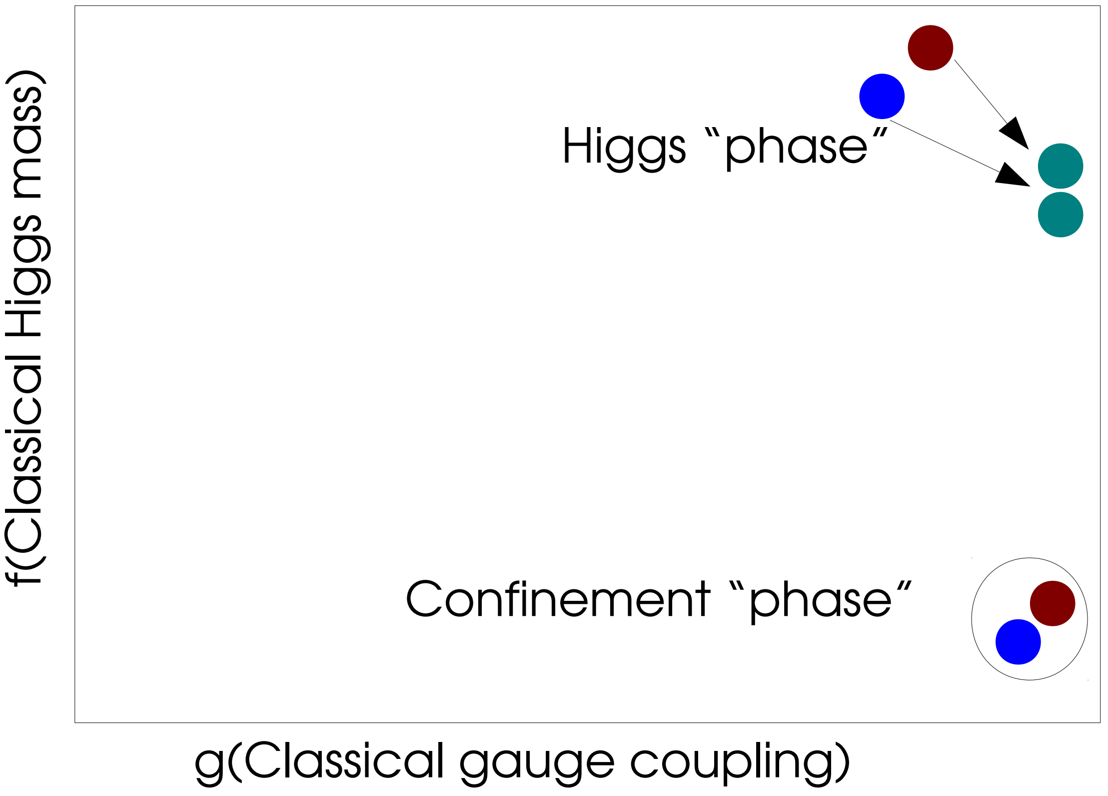

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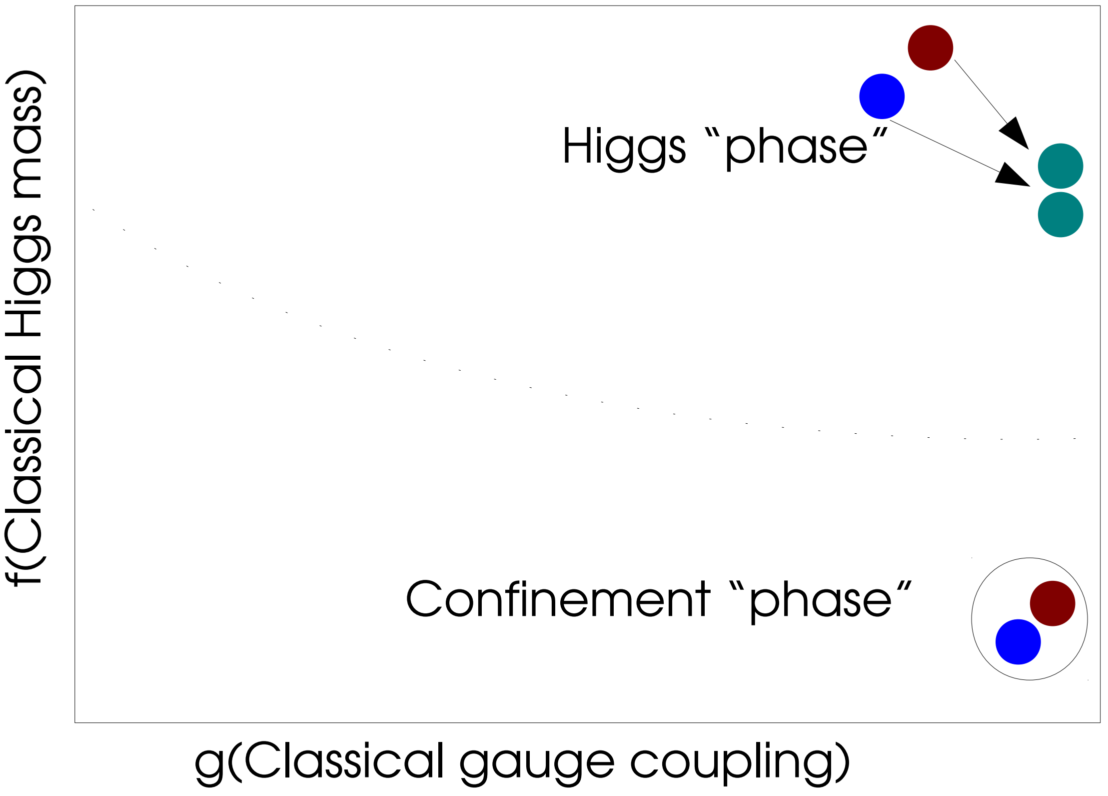

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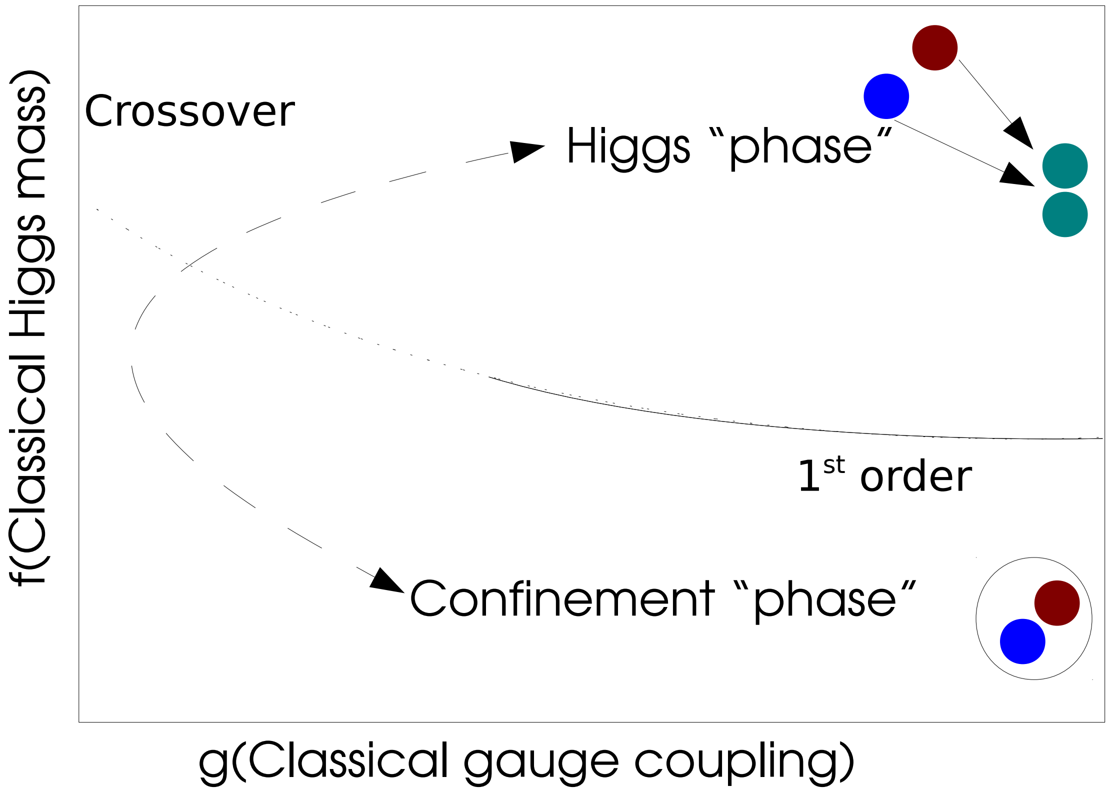

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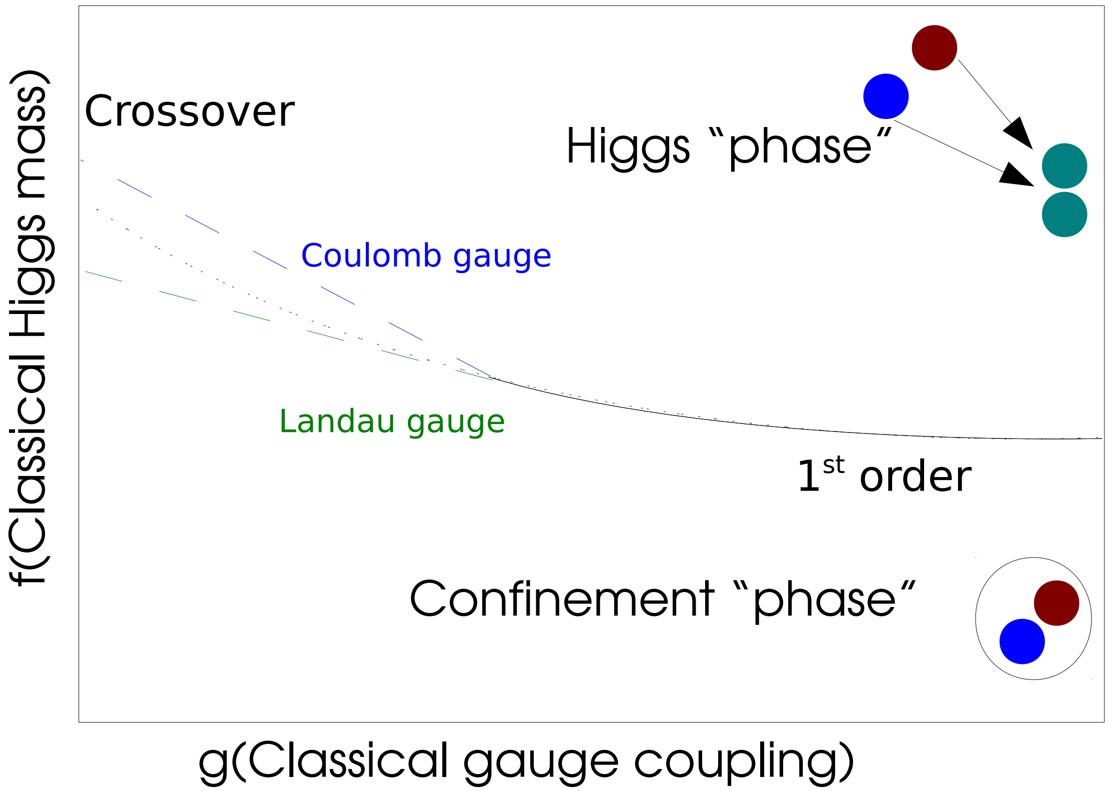
  - Separation only in fixed gauges



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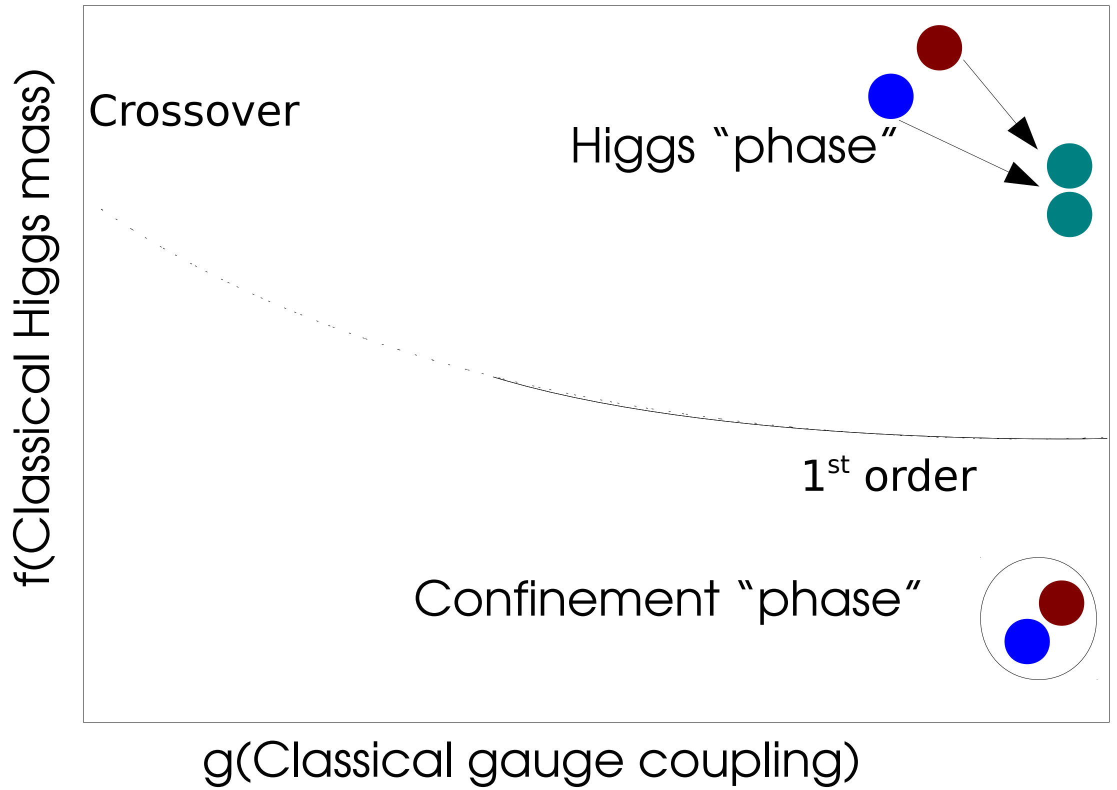

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- Same asymptotic states in confinement and Higgs pseudo-phases
- Same asymptotic states irrespective of coupling strengths

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[Osterwalder et al.'78, Fradkin et al.'79
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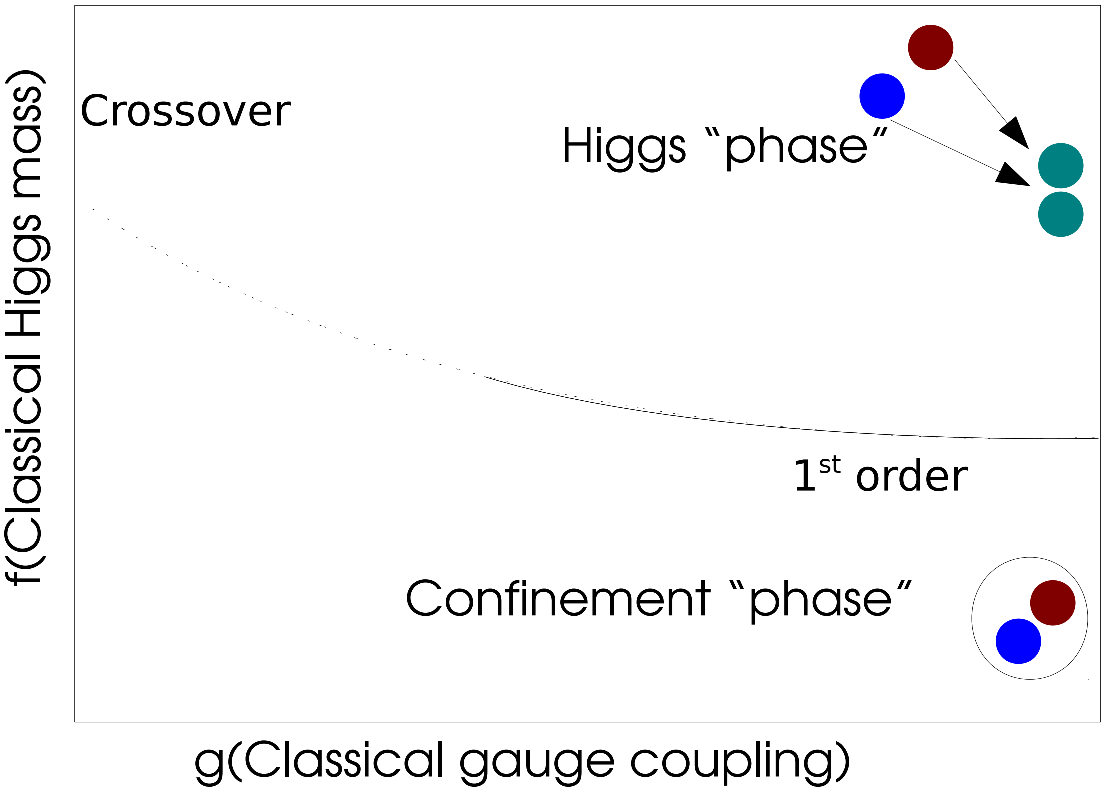
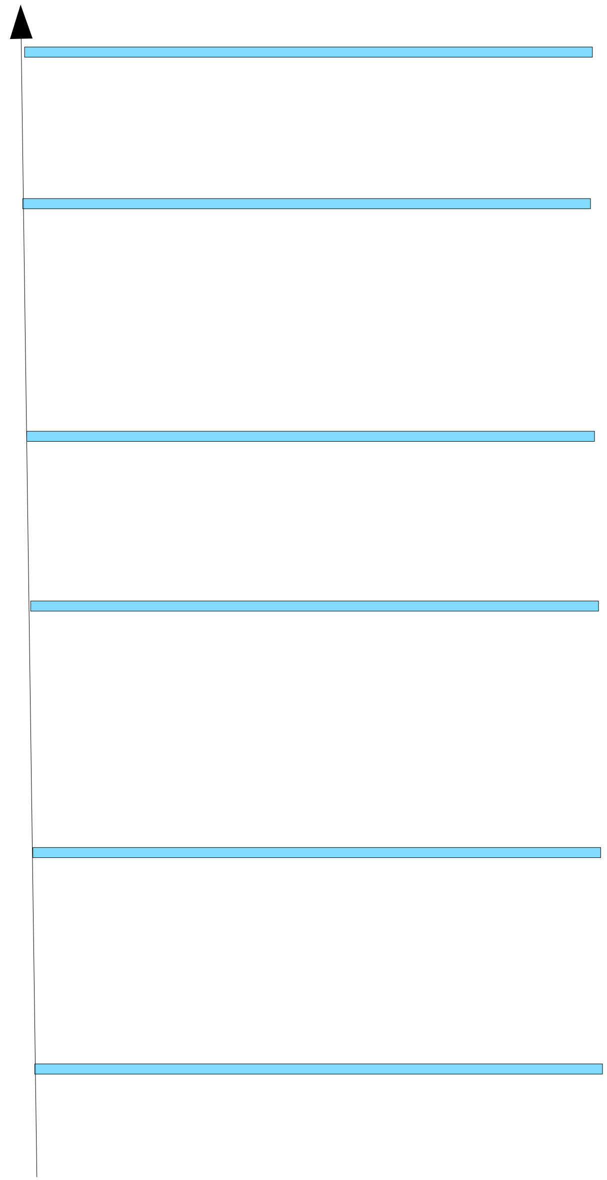
- (Lattice-regularized) phase diagram continuous
  - Separation only in fixed gauges
- Same asymptotic states in confinement and Higgs pseudo-phases
- Same asymptotic states irrespective of coupling strengths
- Other states than 'Higgs' and 'W'?



Excited states on the lattice

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



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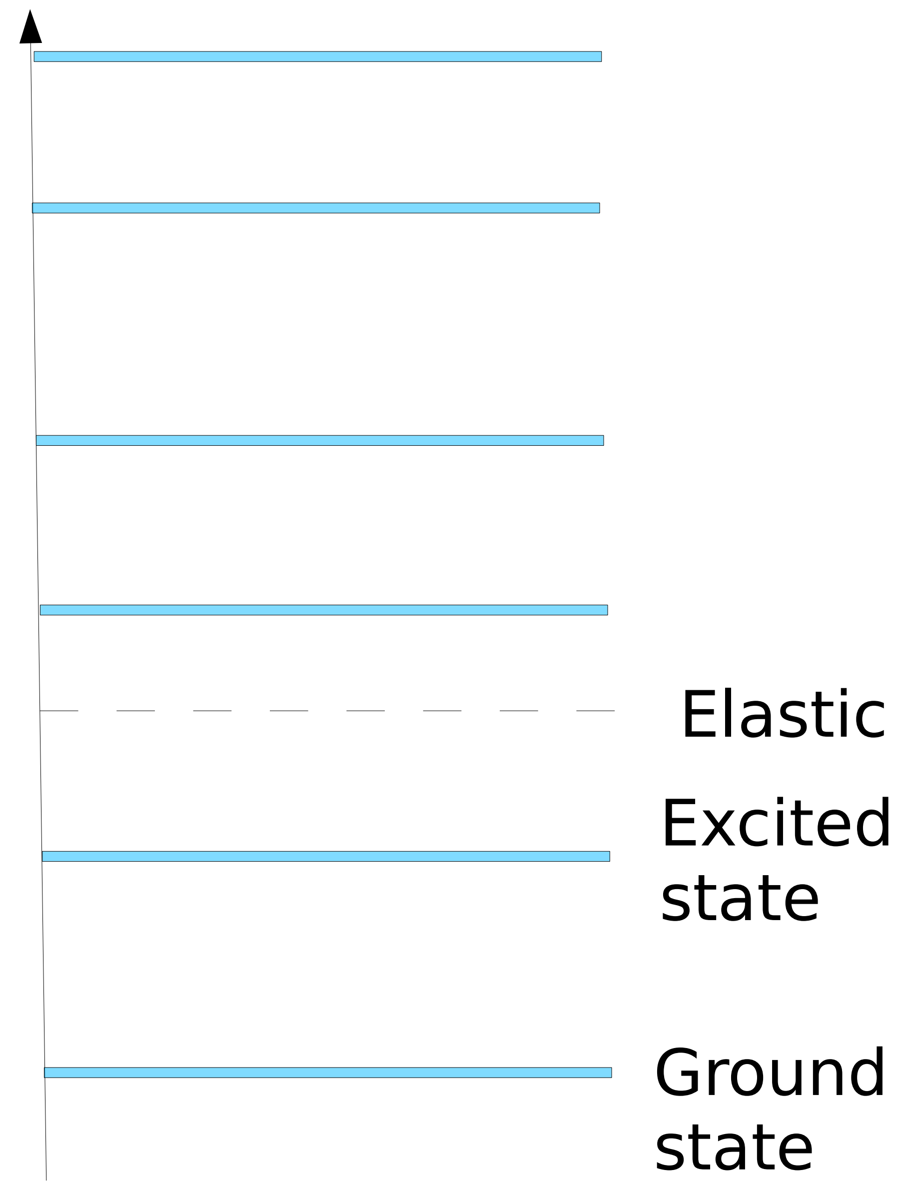

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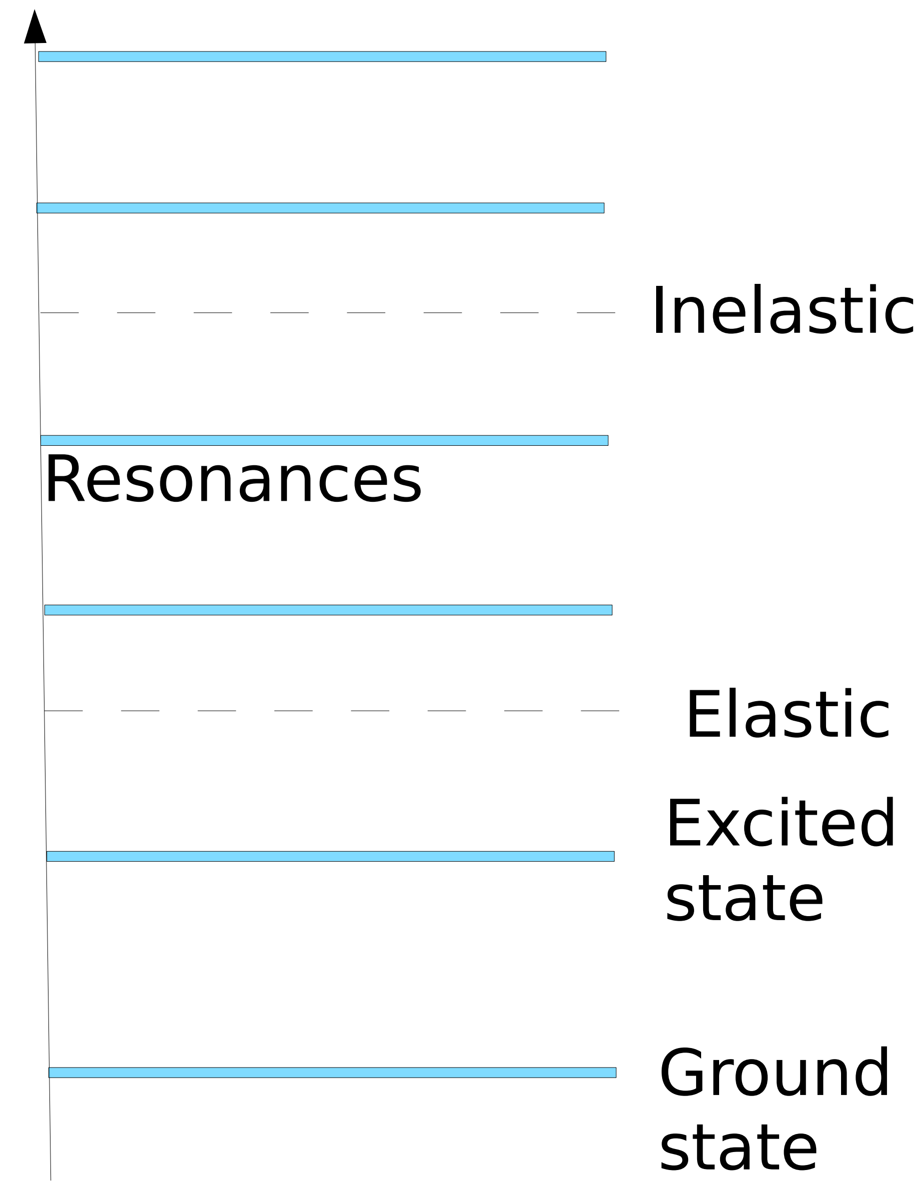

Excited states on the lattice

- Each quantum number channel has a spectrum
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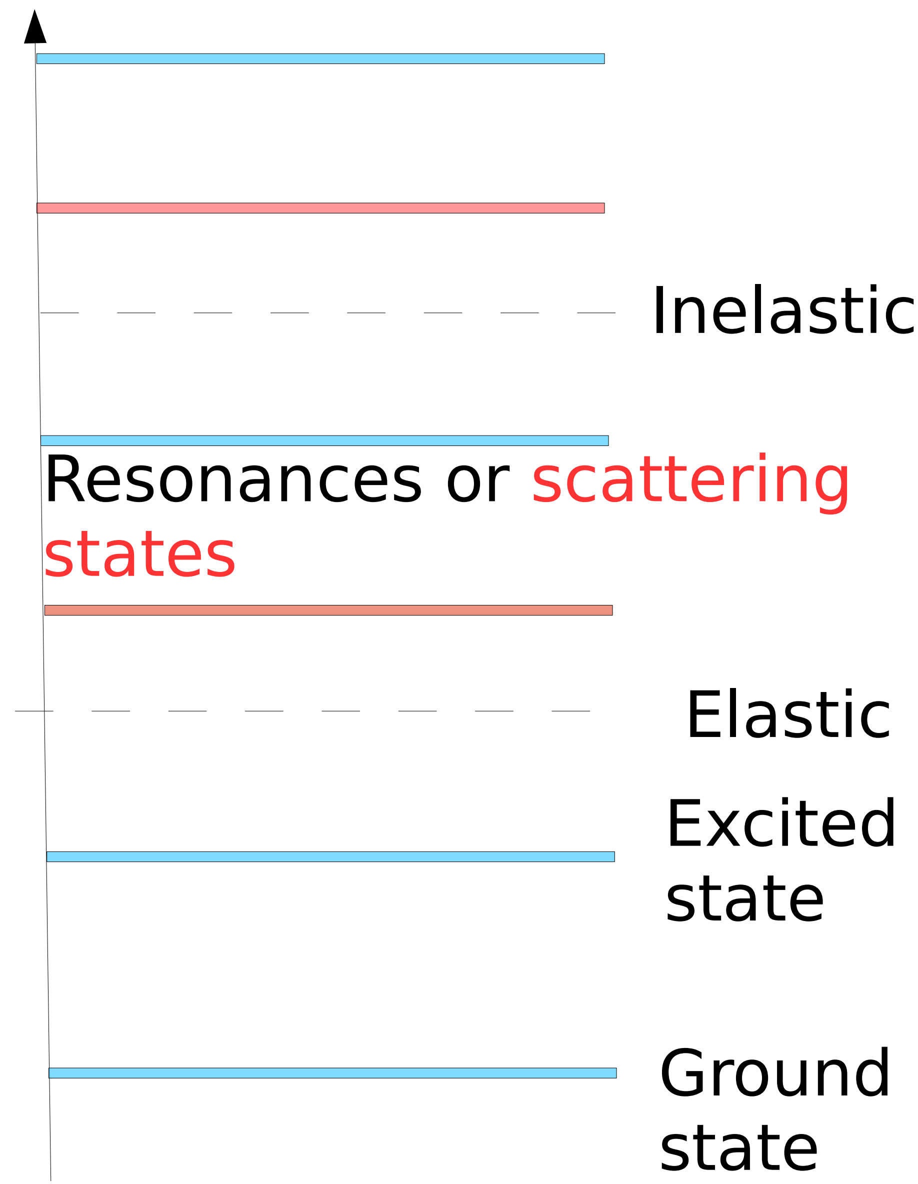
- States can be either stable, excited states, resonances or scattering states

Excited states on the lattice

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



Exponential volume dependency
- if stable against decays into other channels

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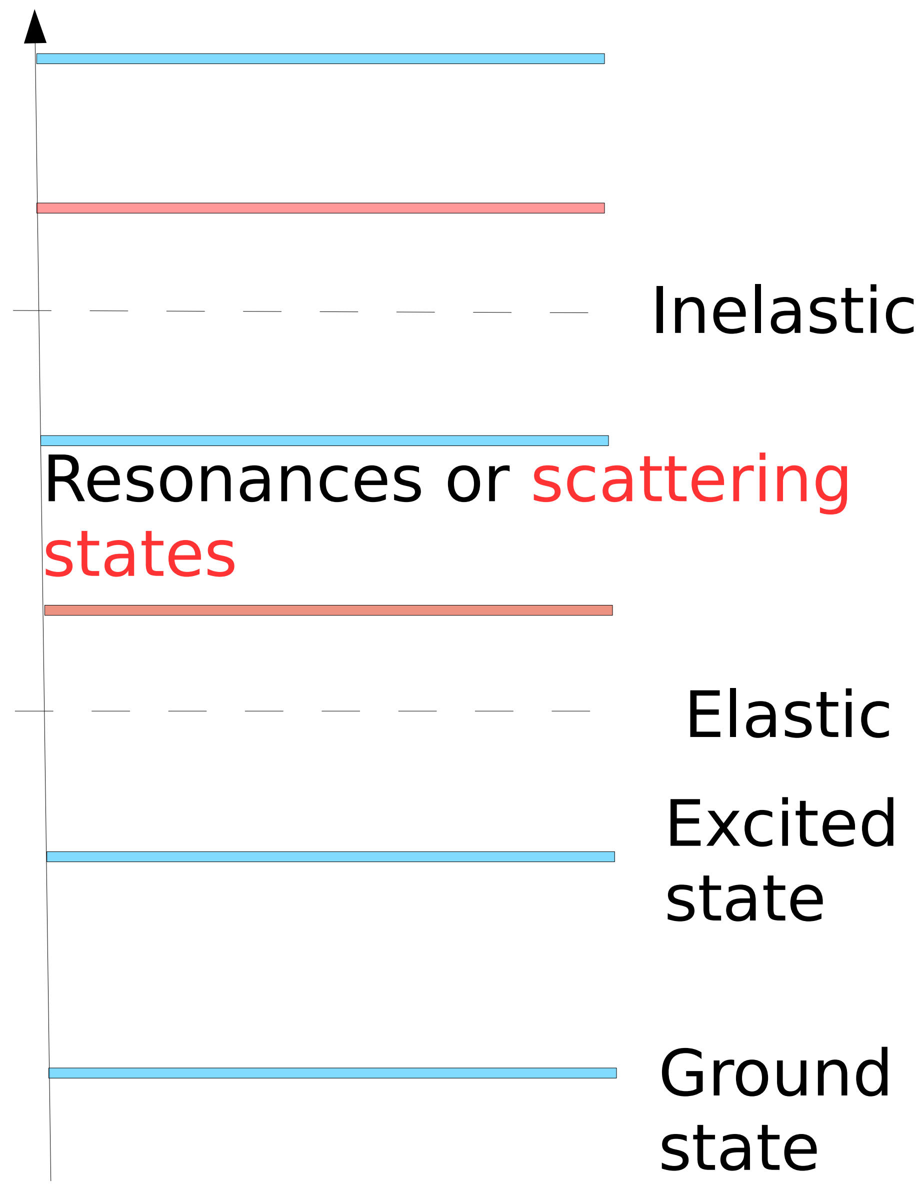


- Polynominal (inverse) volume dependence
- Width and nature from phase shifts below the inelastic threshold

Exponential volume dependency
- if stable against decays into other channels

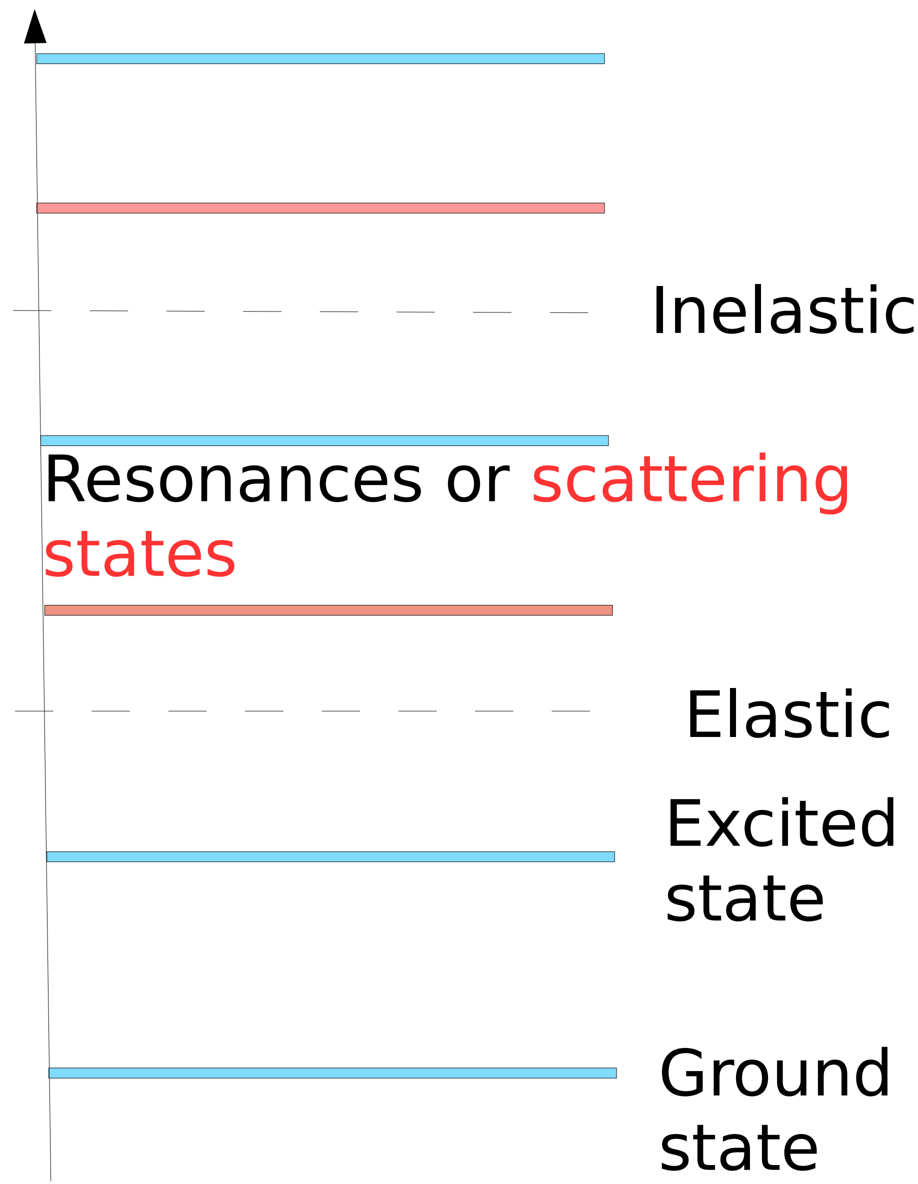
Excited states on the lattice

[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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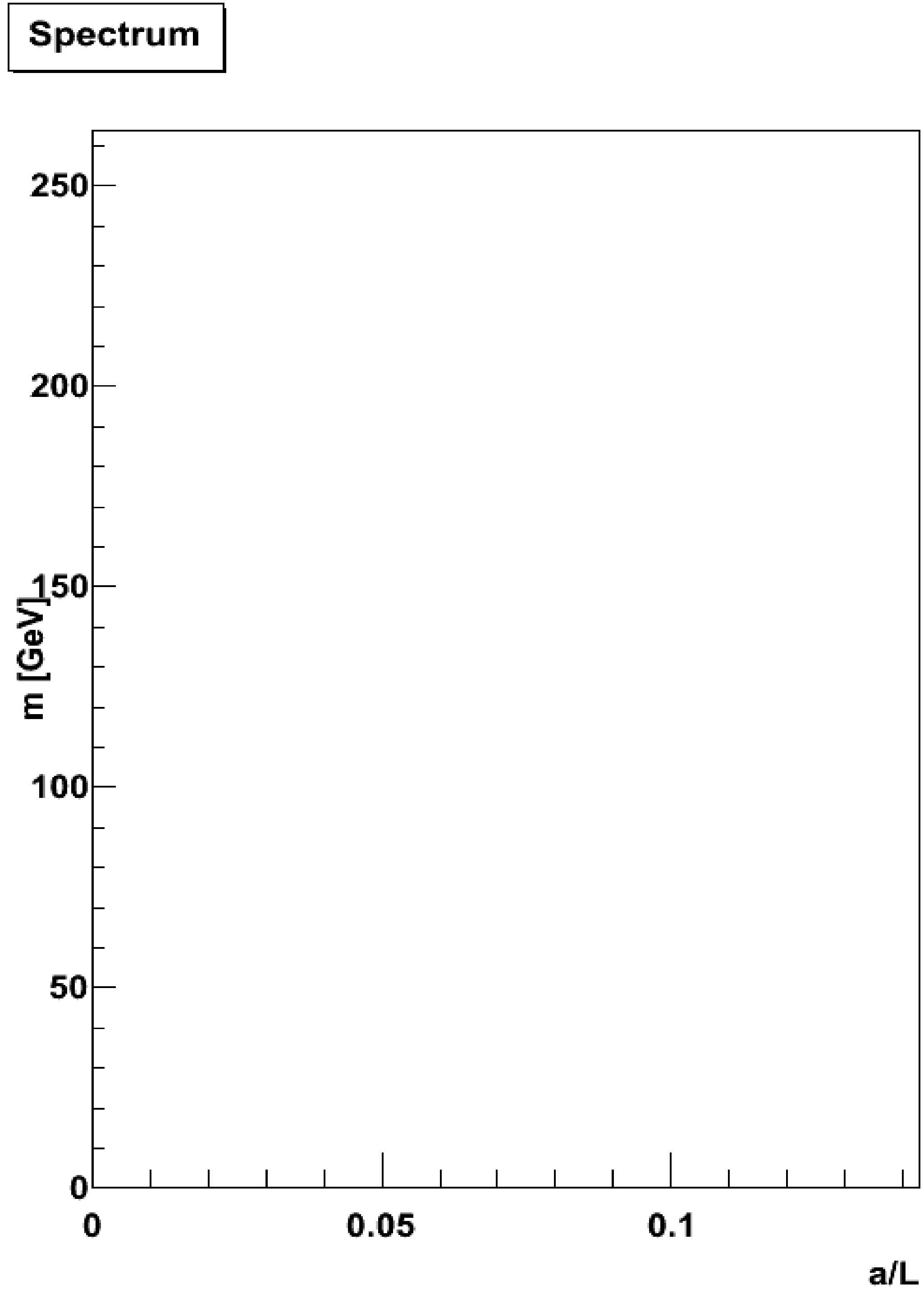

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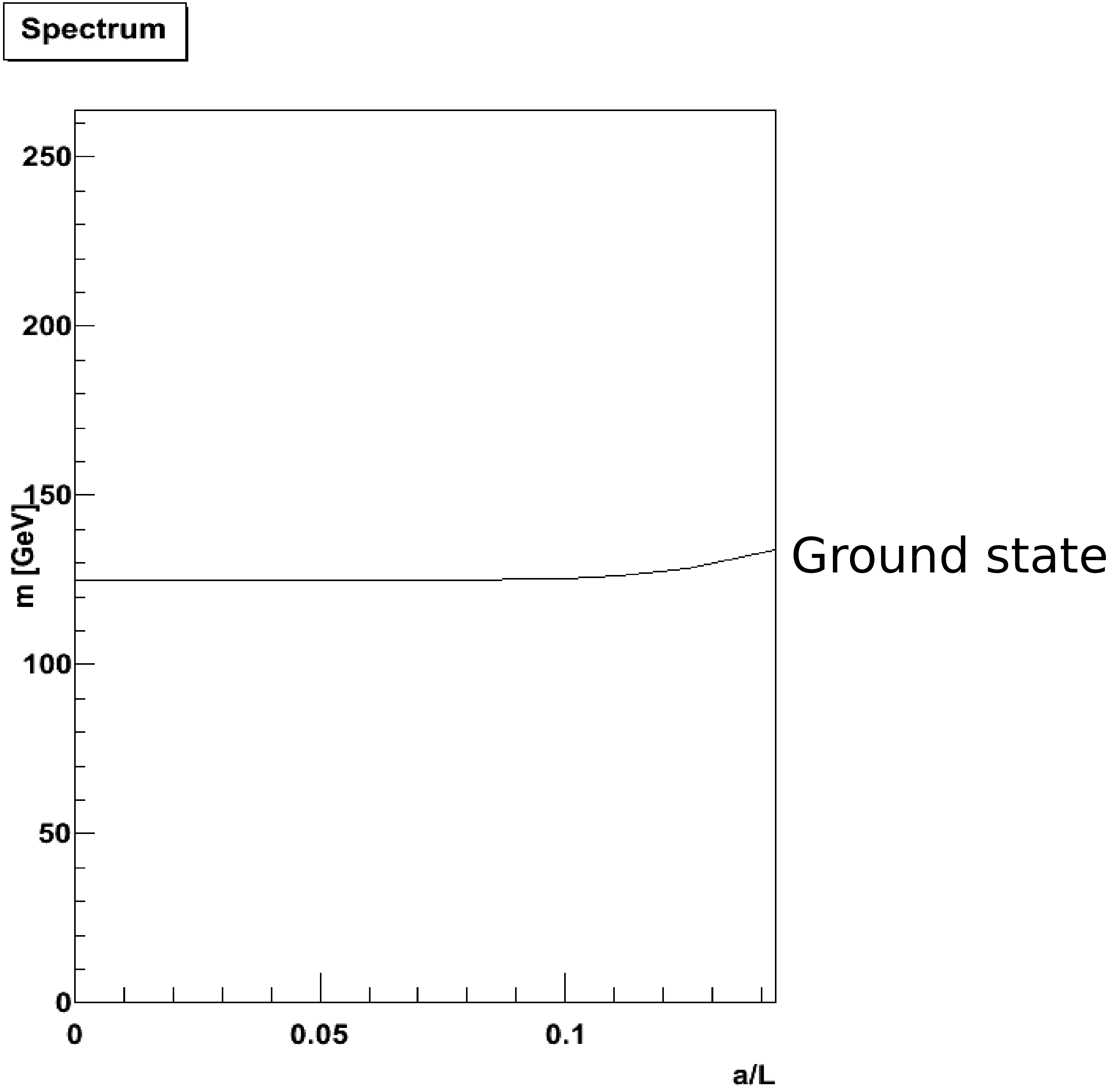

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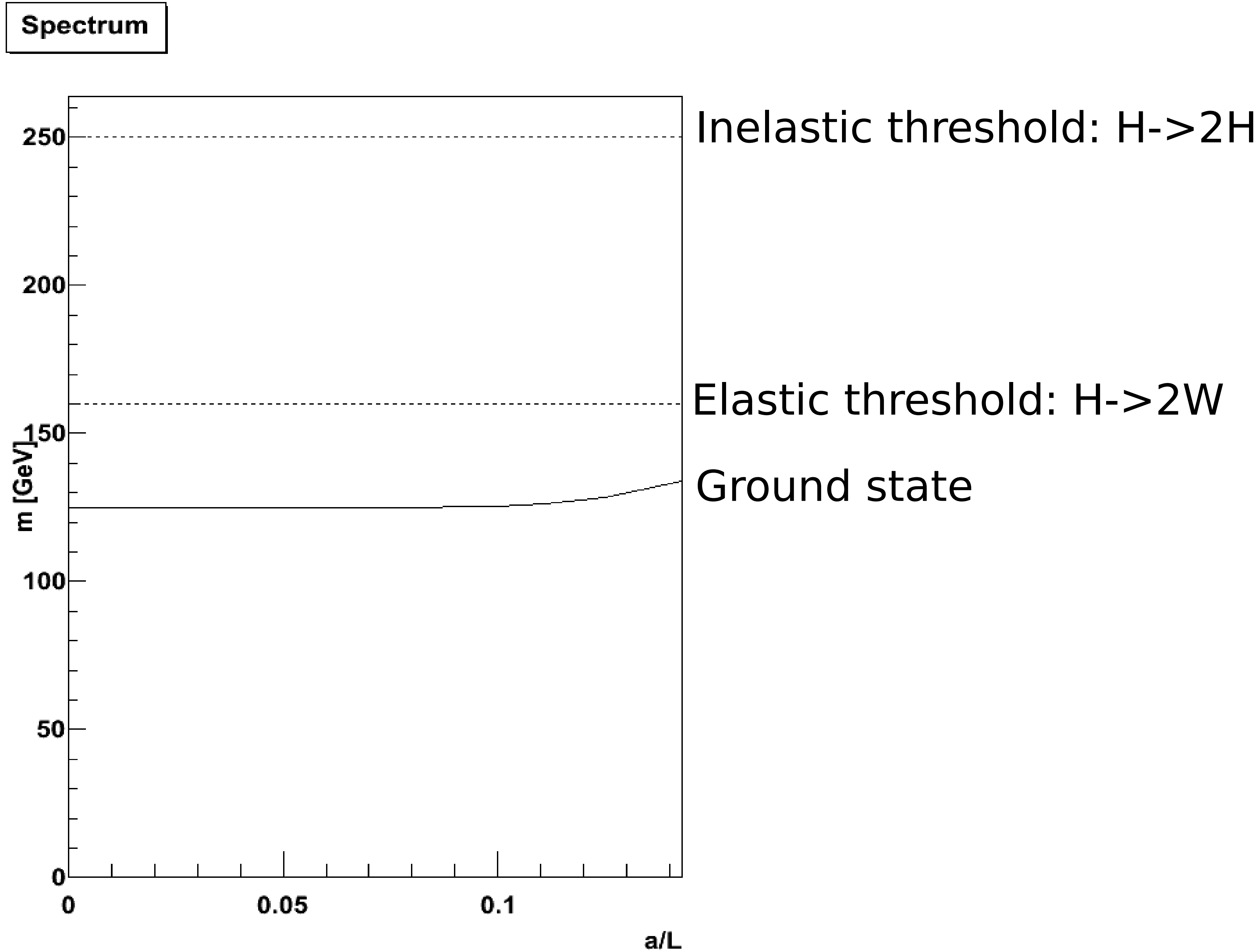

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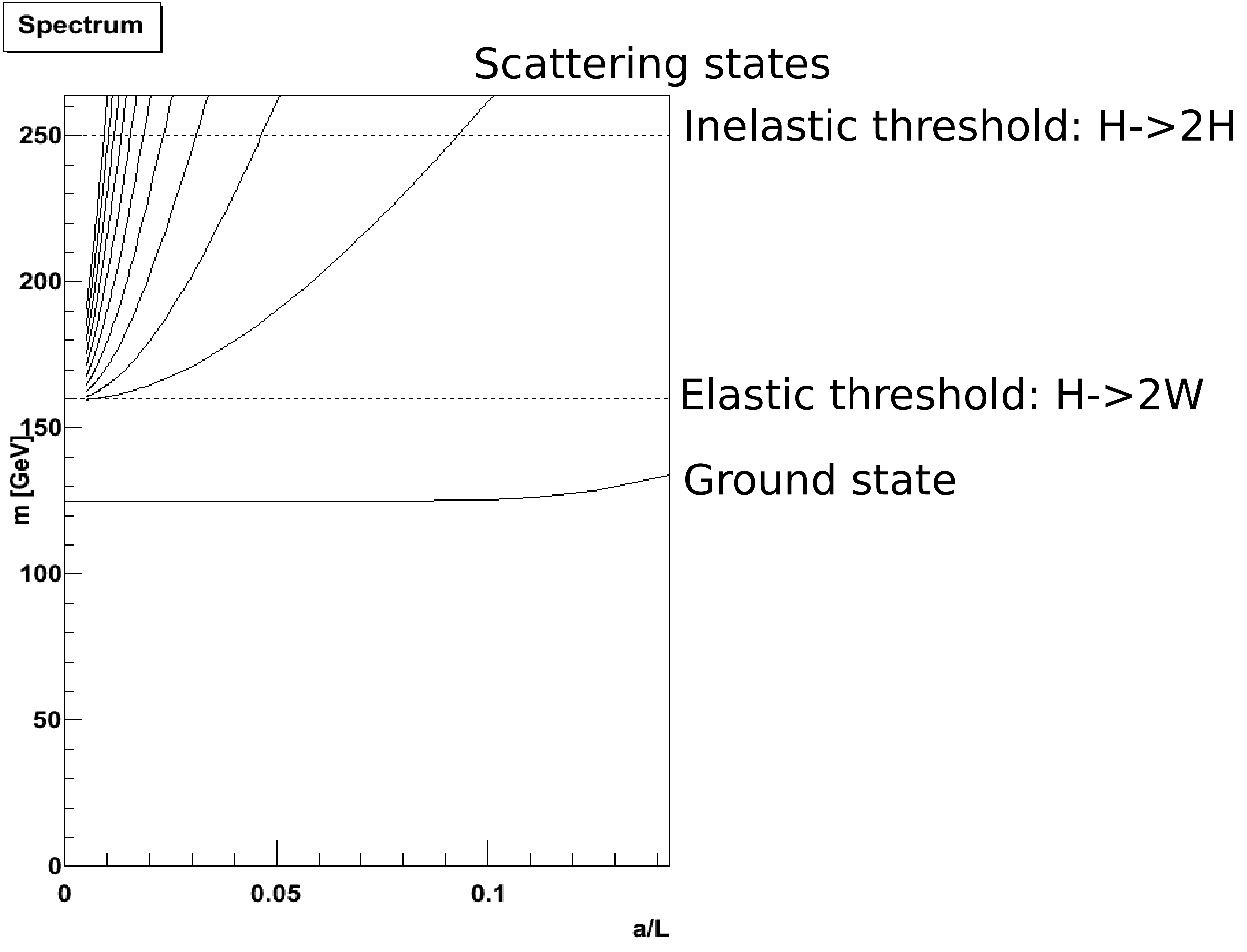

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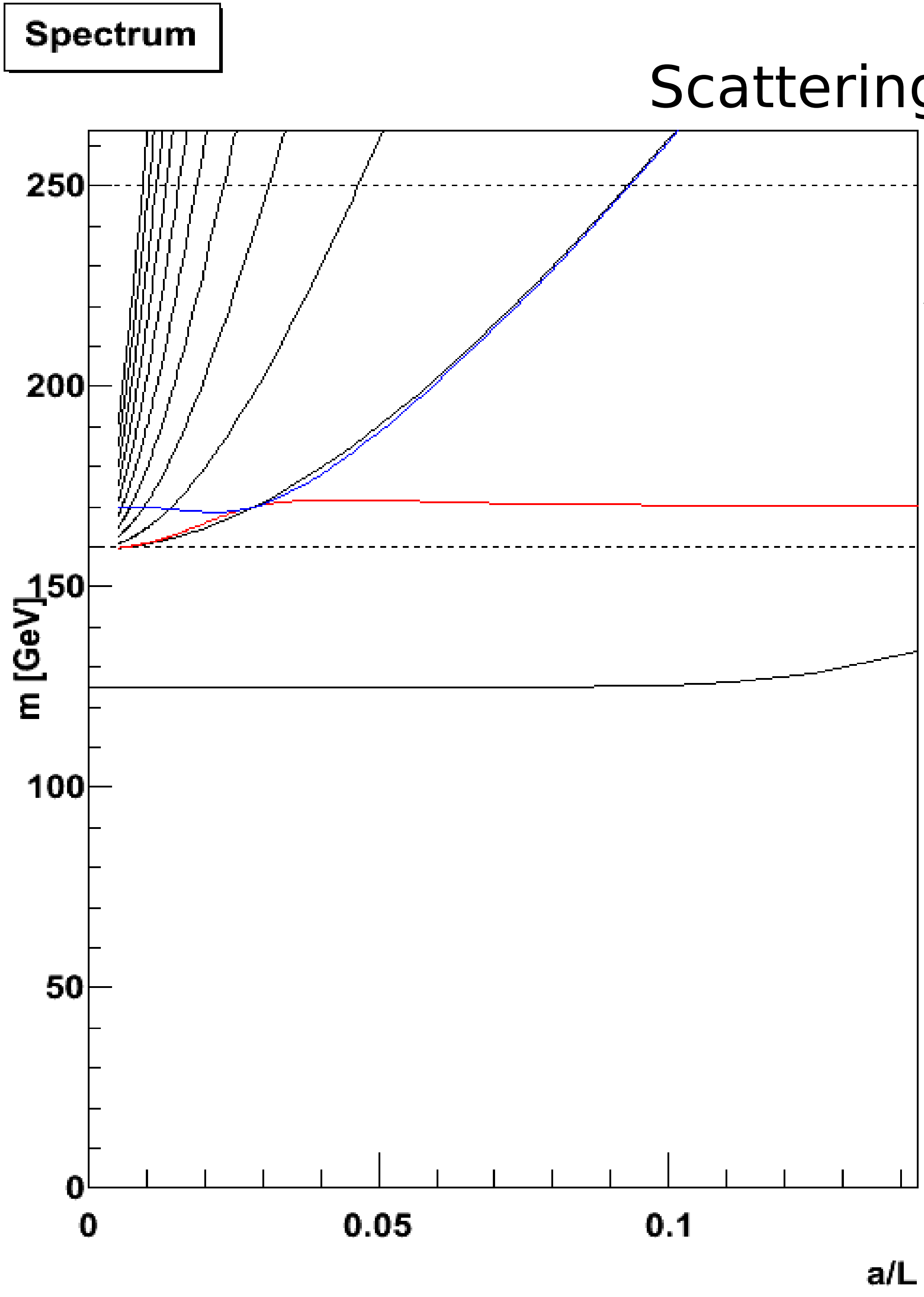


Scattering states

Inelastic threshold: H->2H

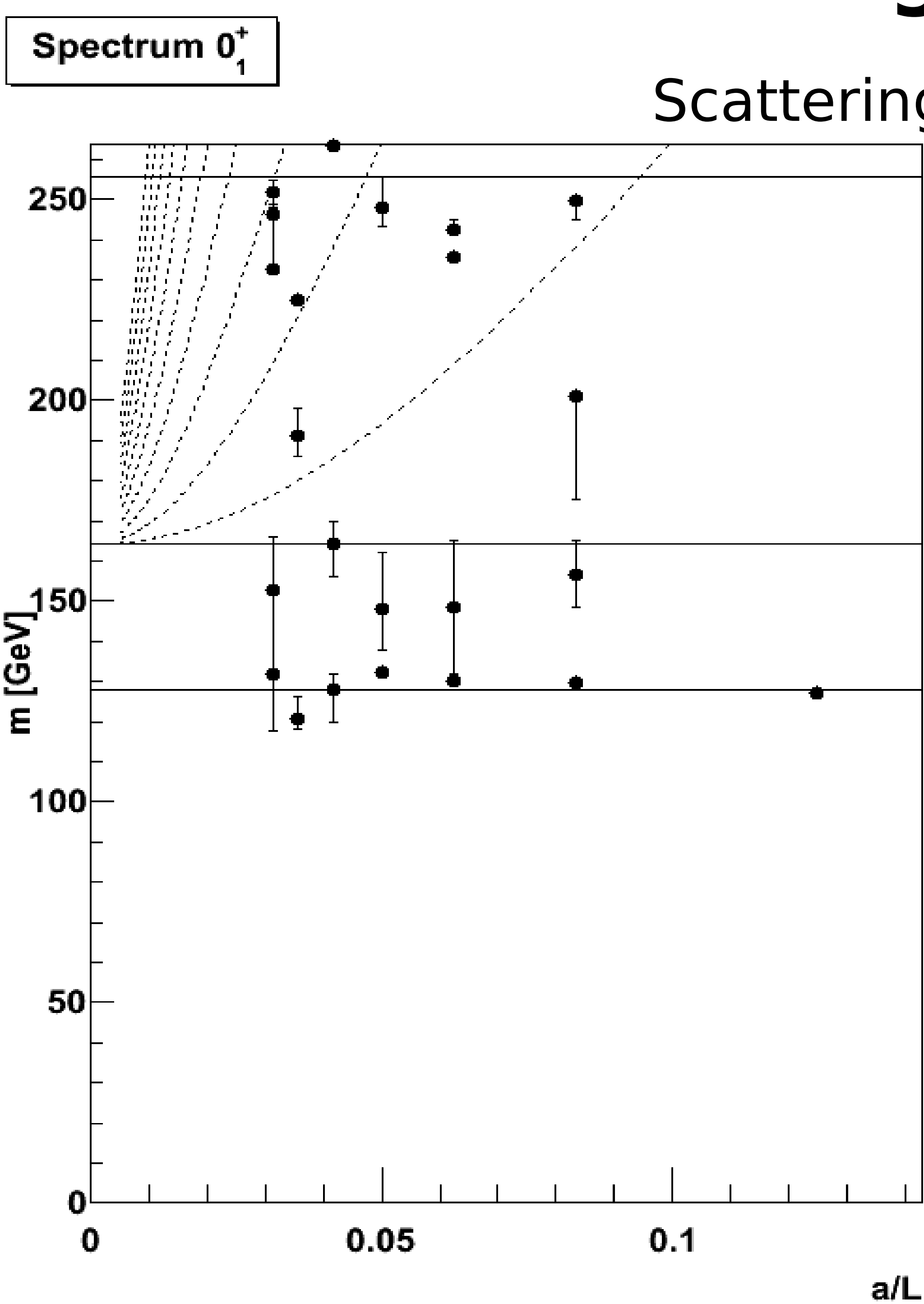
Avoided level crossing
Identification and widths from phase shifts

Elastic threshold: H->2W

Ground state

Search: Excited Higgs

[Maas et al.'14]



Scattering states

Inelastic threshold

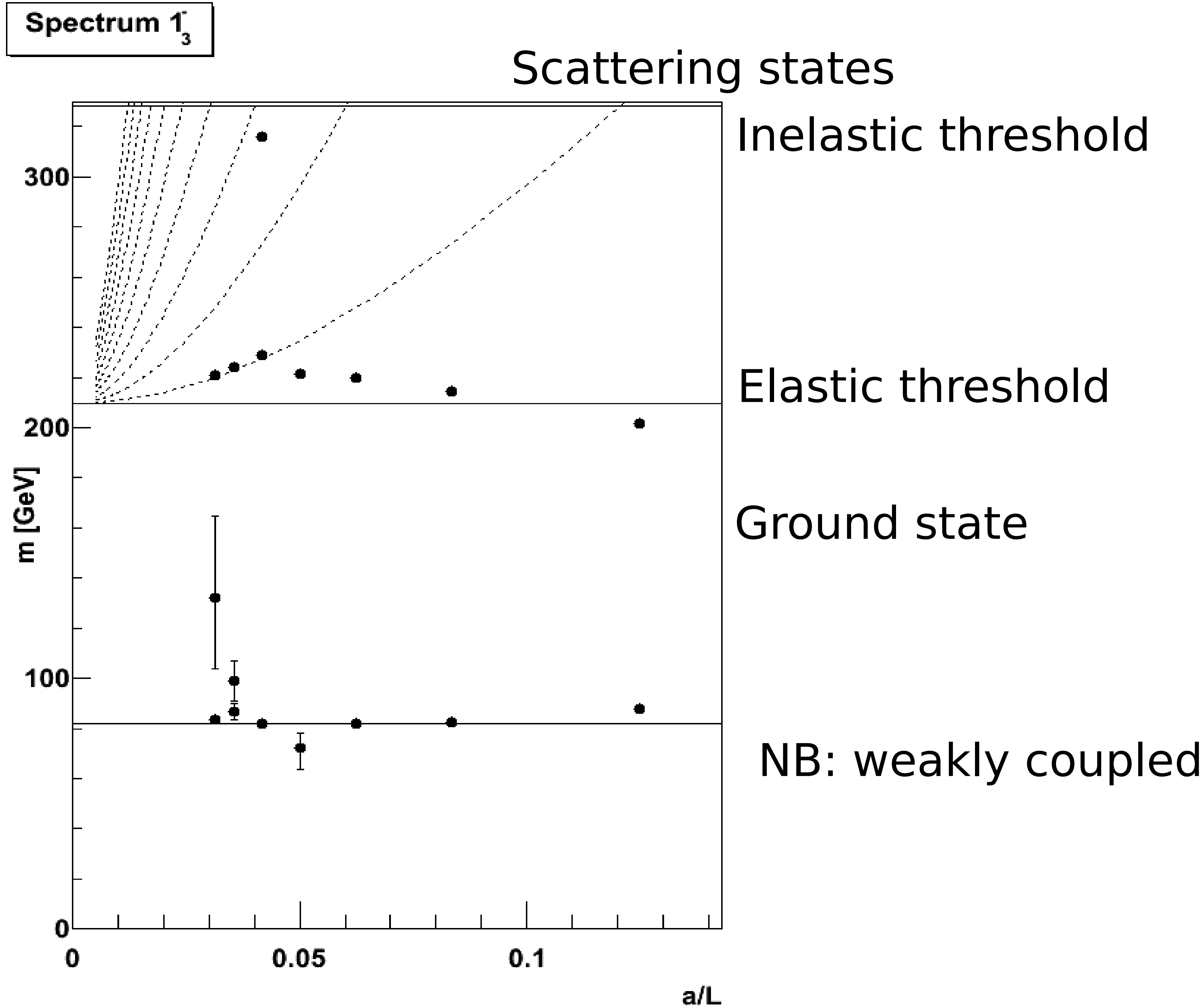
Elastic threshold

Ground state

NB: weakly coupled

Search: Z'

[Maas et al.'14]



NB: weakly coupled

Typical spectra

[Maas, Mufti '13,'14,
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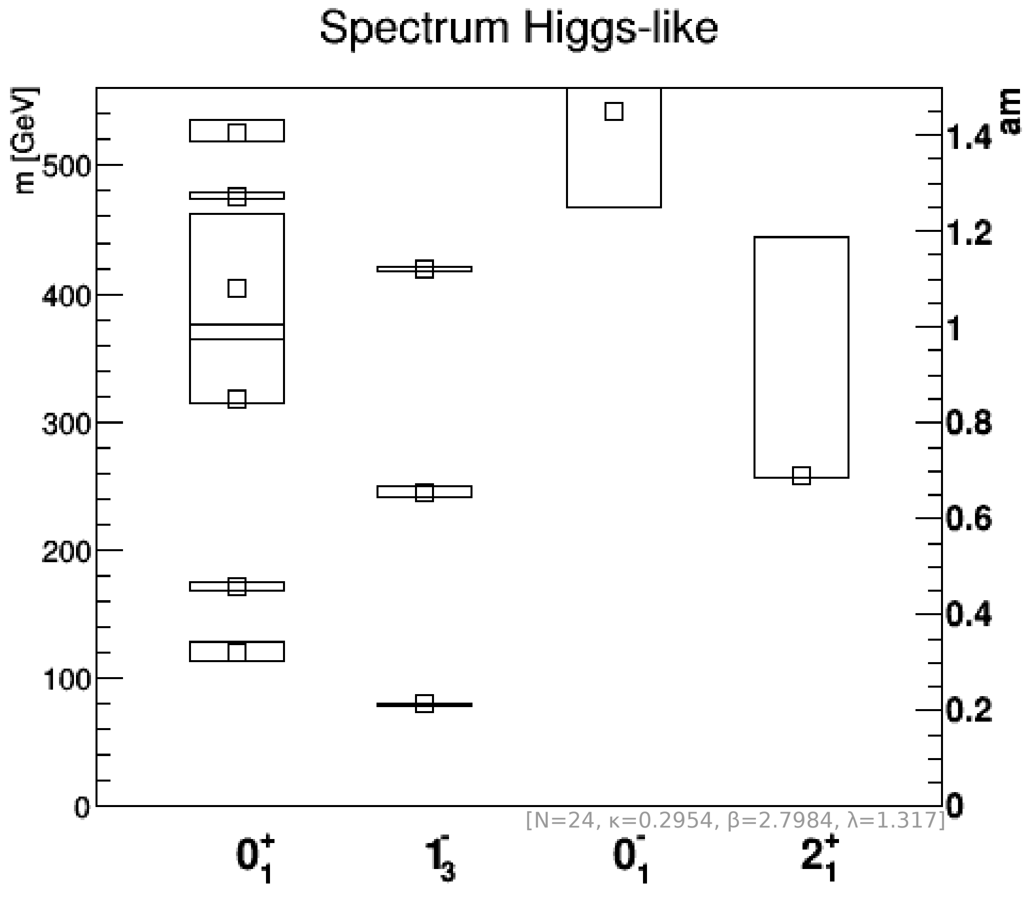

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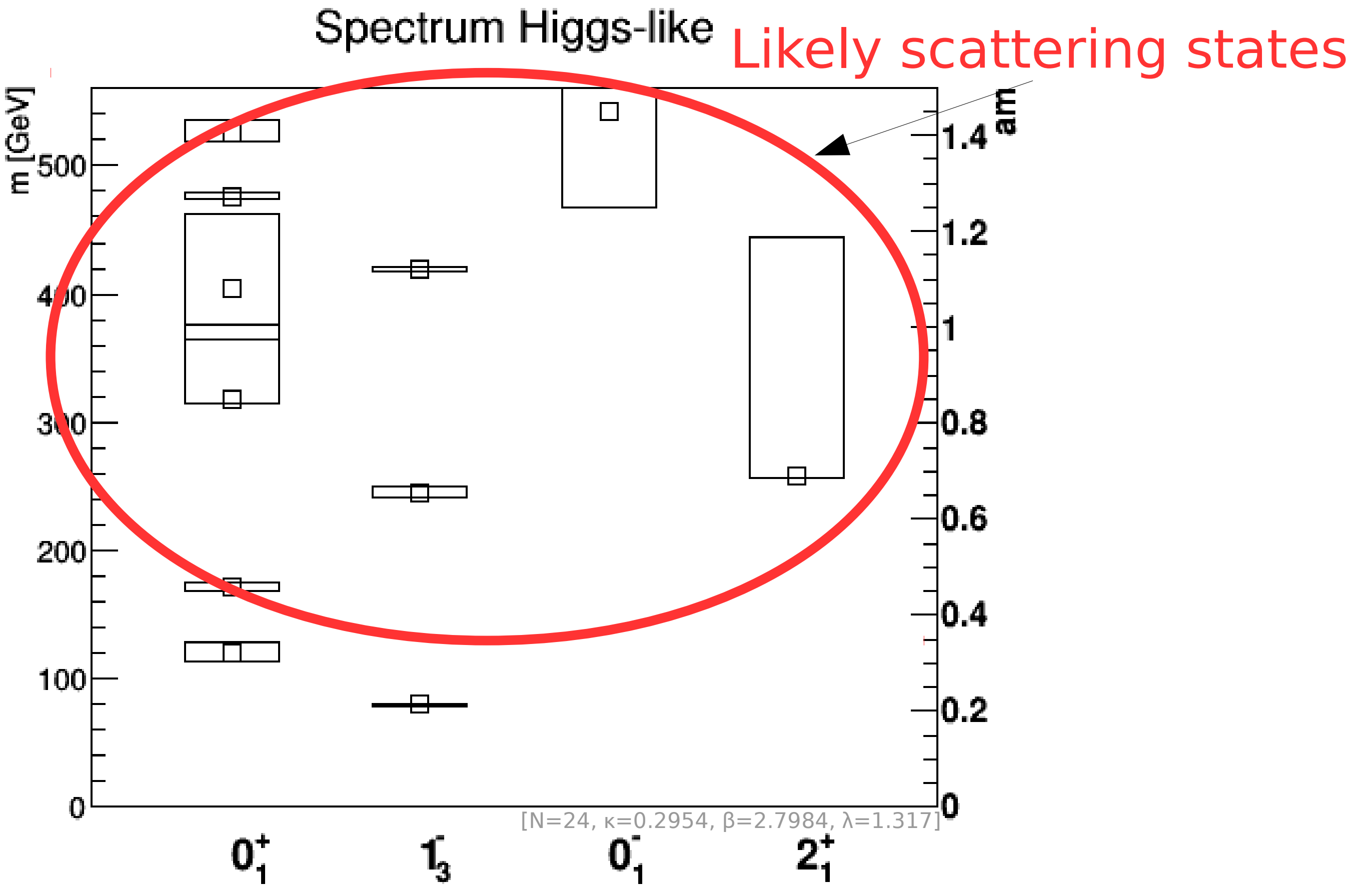

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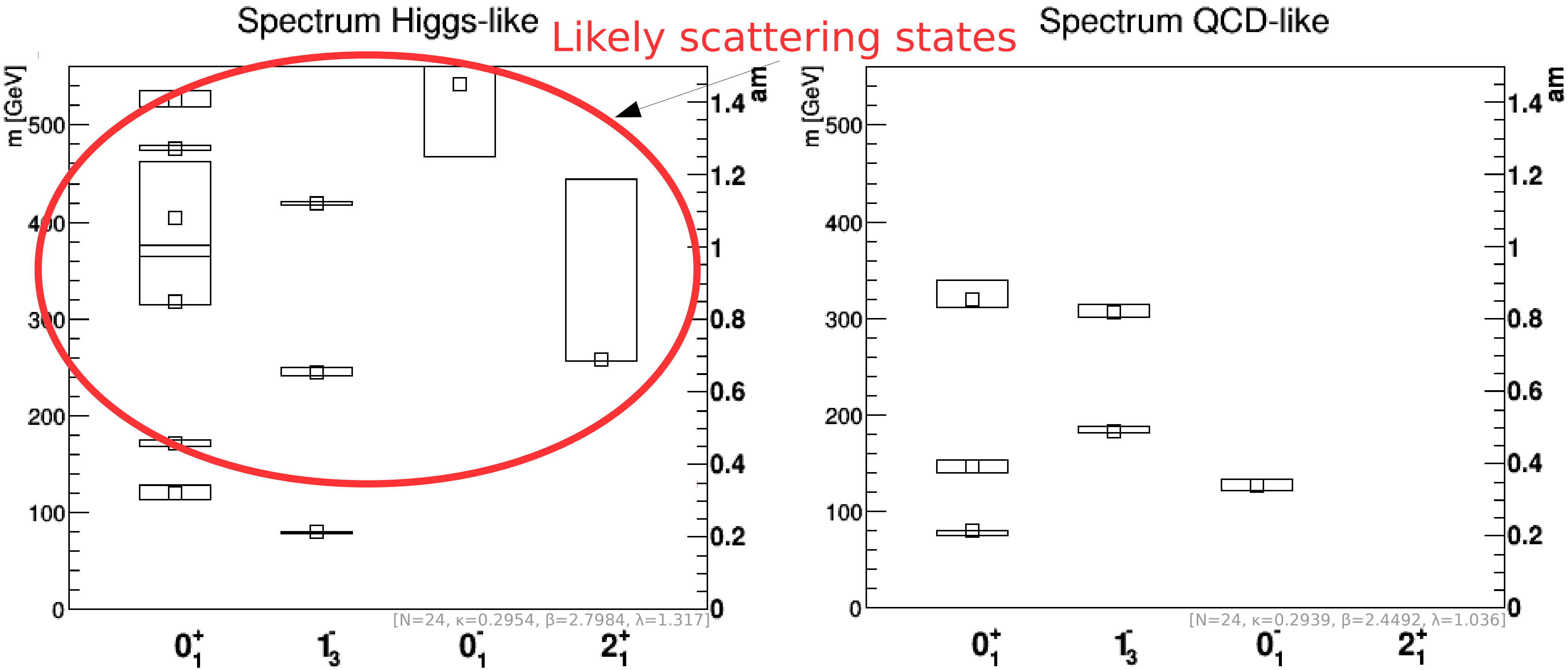

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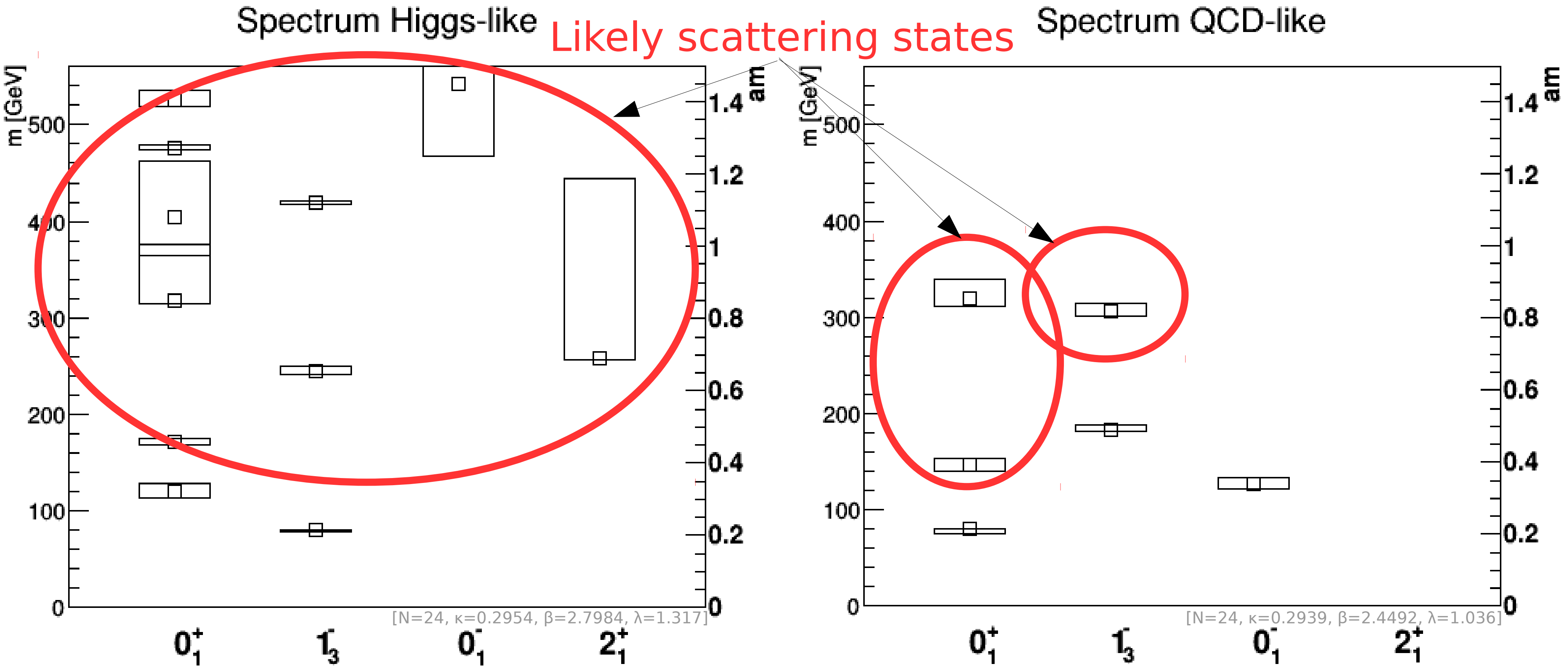

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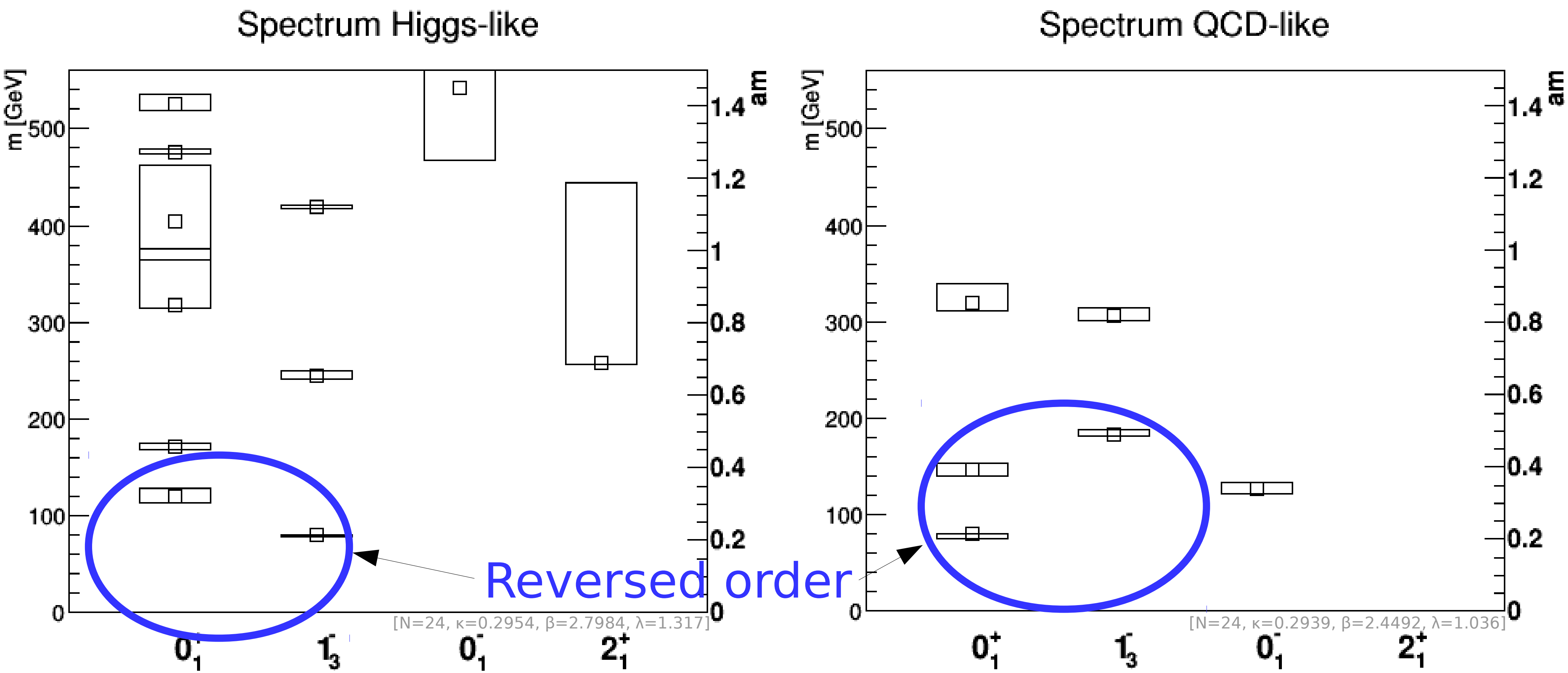

- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
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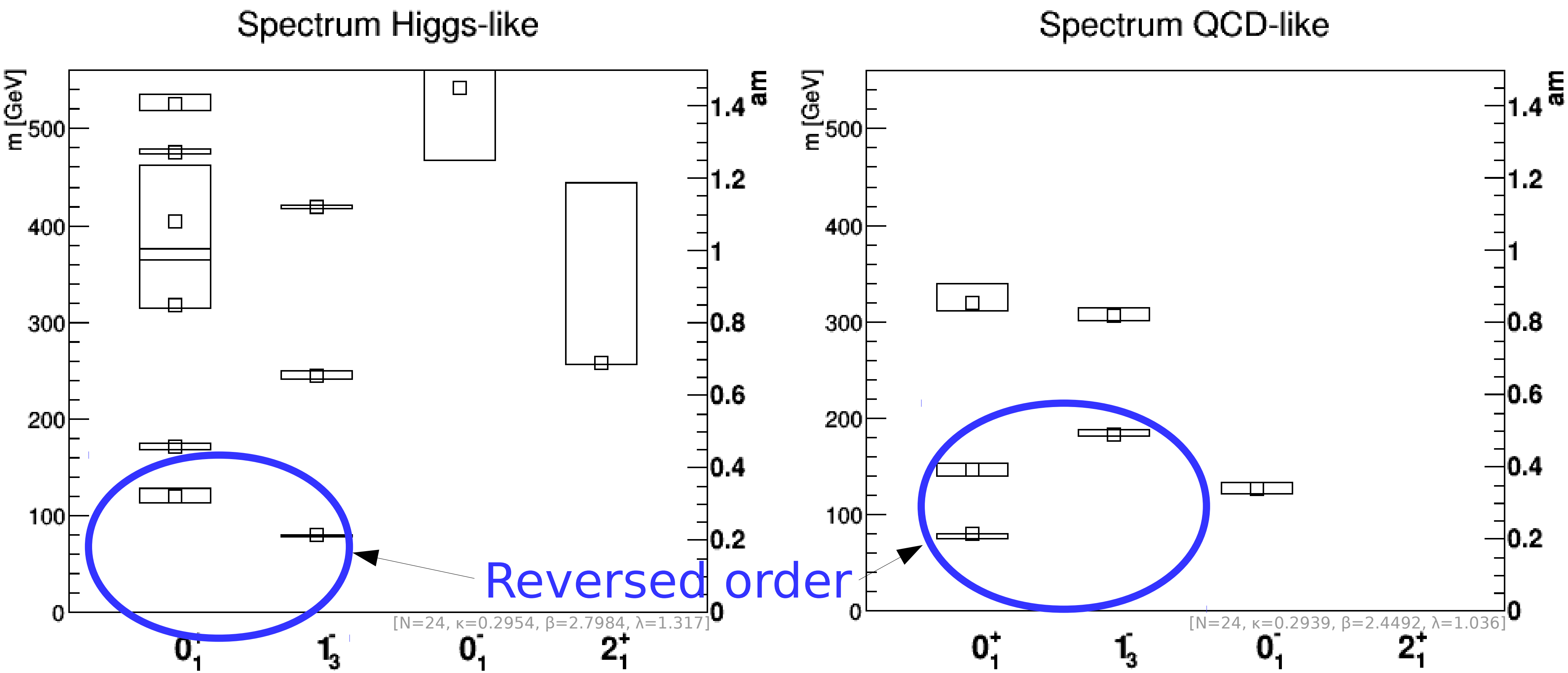
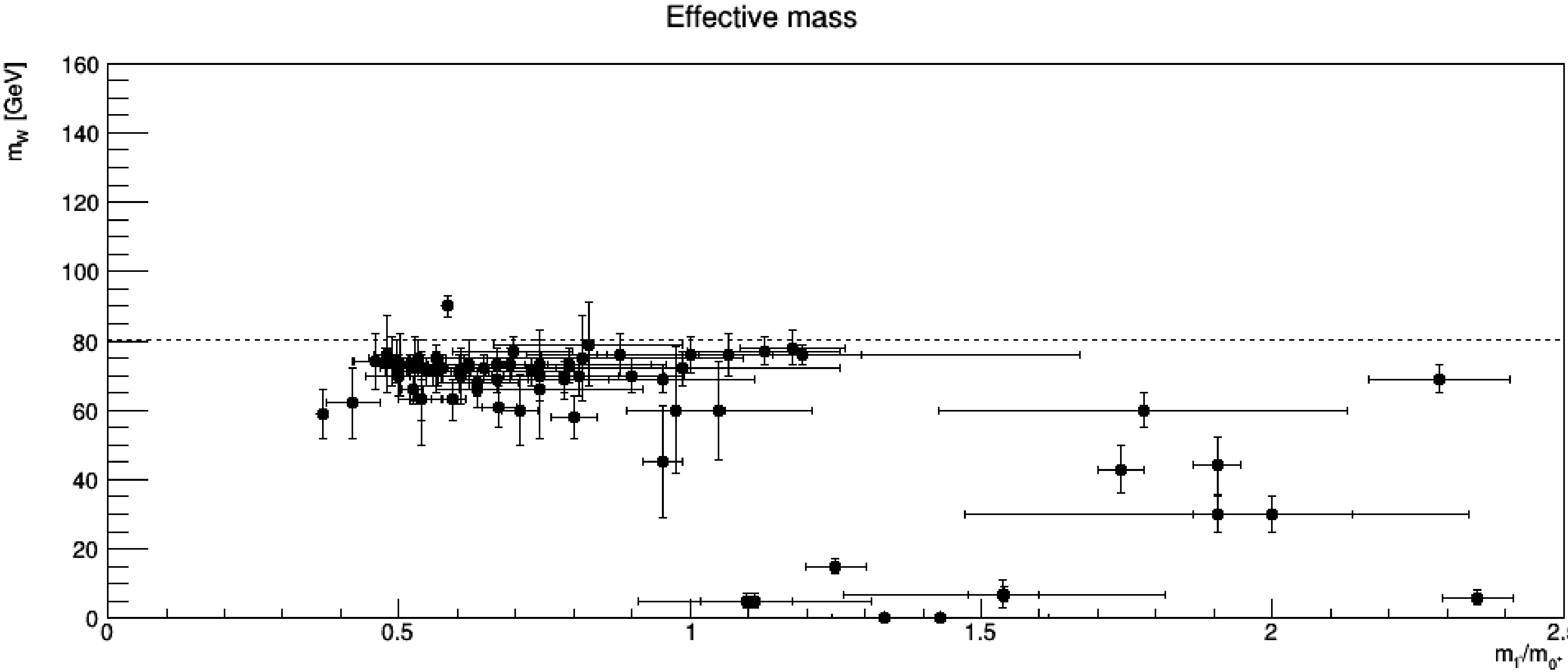


- Generically different low-lying spectra
  - 0^+ lighter in QCD-like region
  - 1^- lighter in Higgs-like region
- Coincides with gauge-dependent definitions

Limits

[Maas & Mufti'14]



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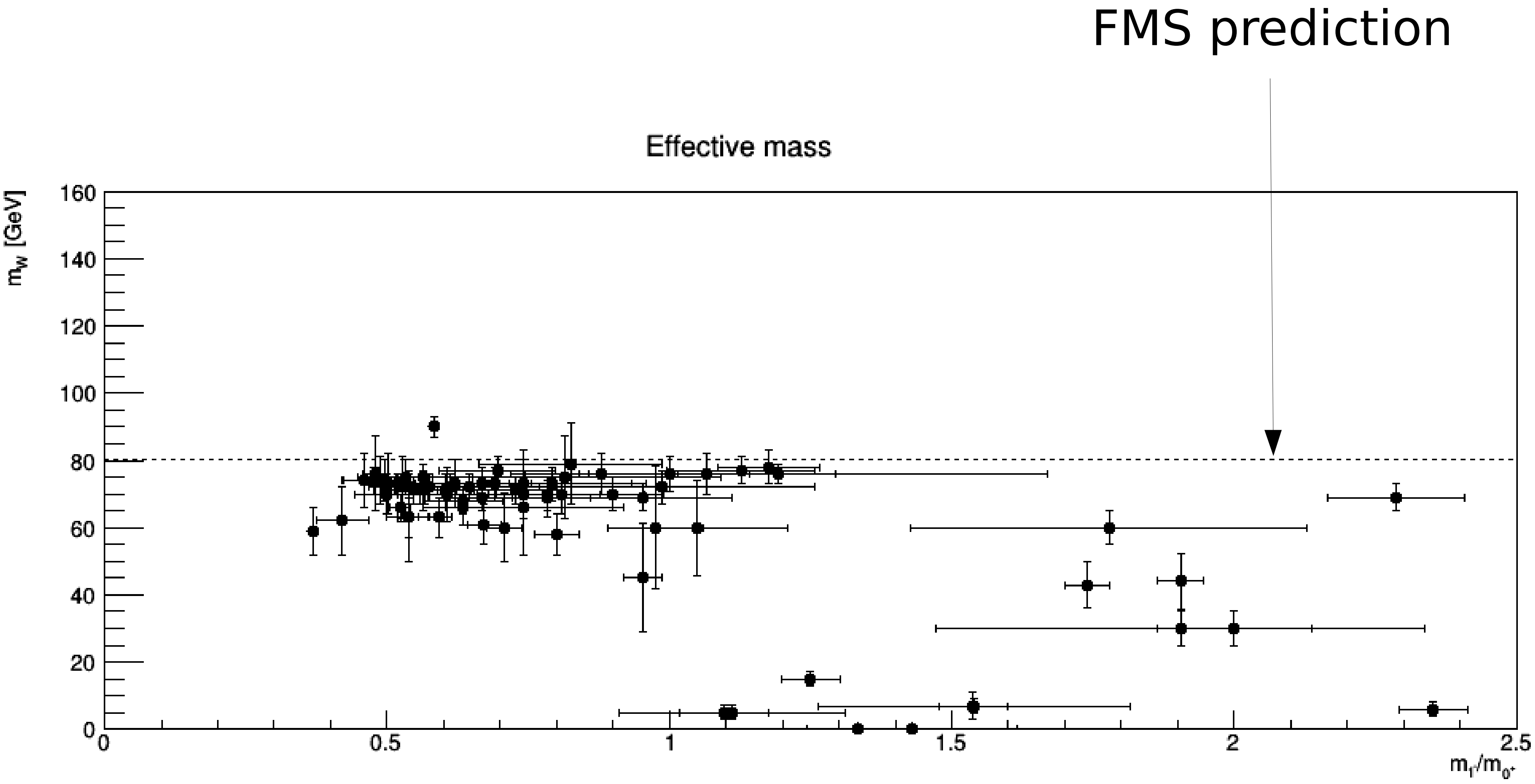
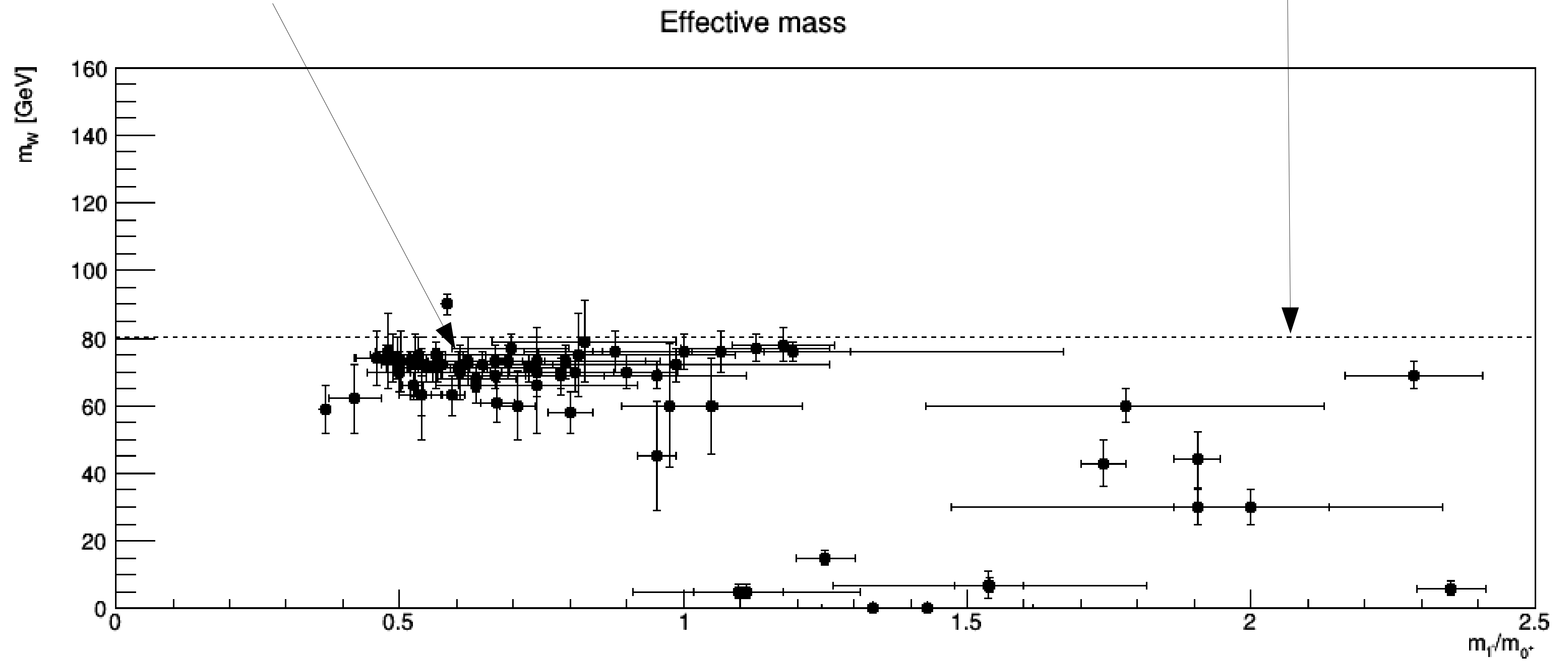


Limits

[Maas & Mufti'14]

FMS prediction

Too low: Finite volume effect



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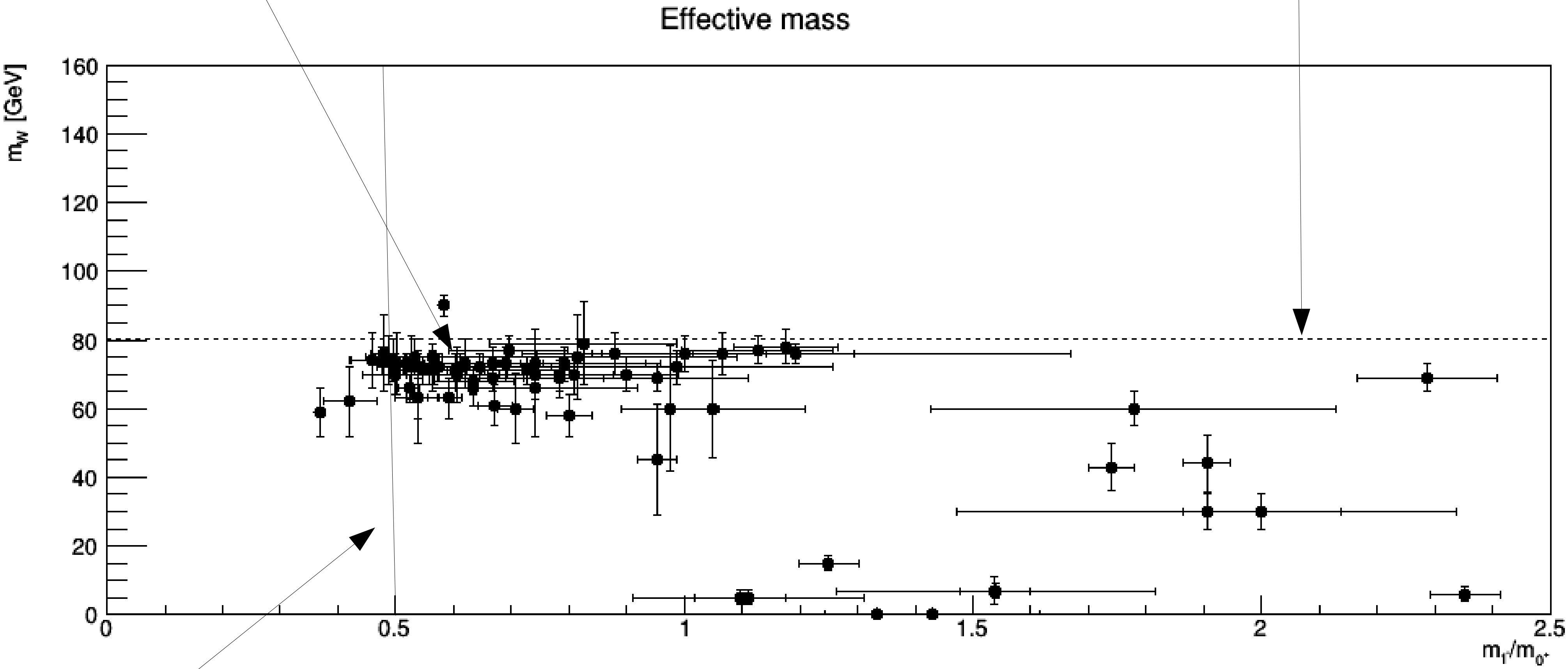

Elastic decay threshold
Higgs as resonance
Expensive, signal very bad

Limits

[Maas & Mufti'14]

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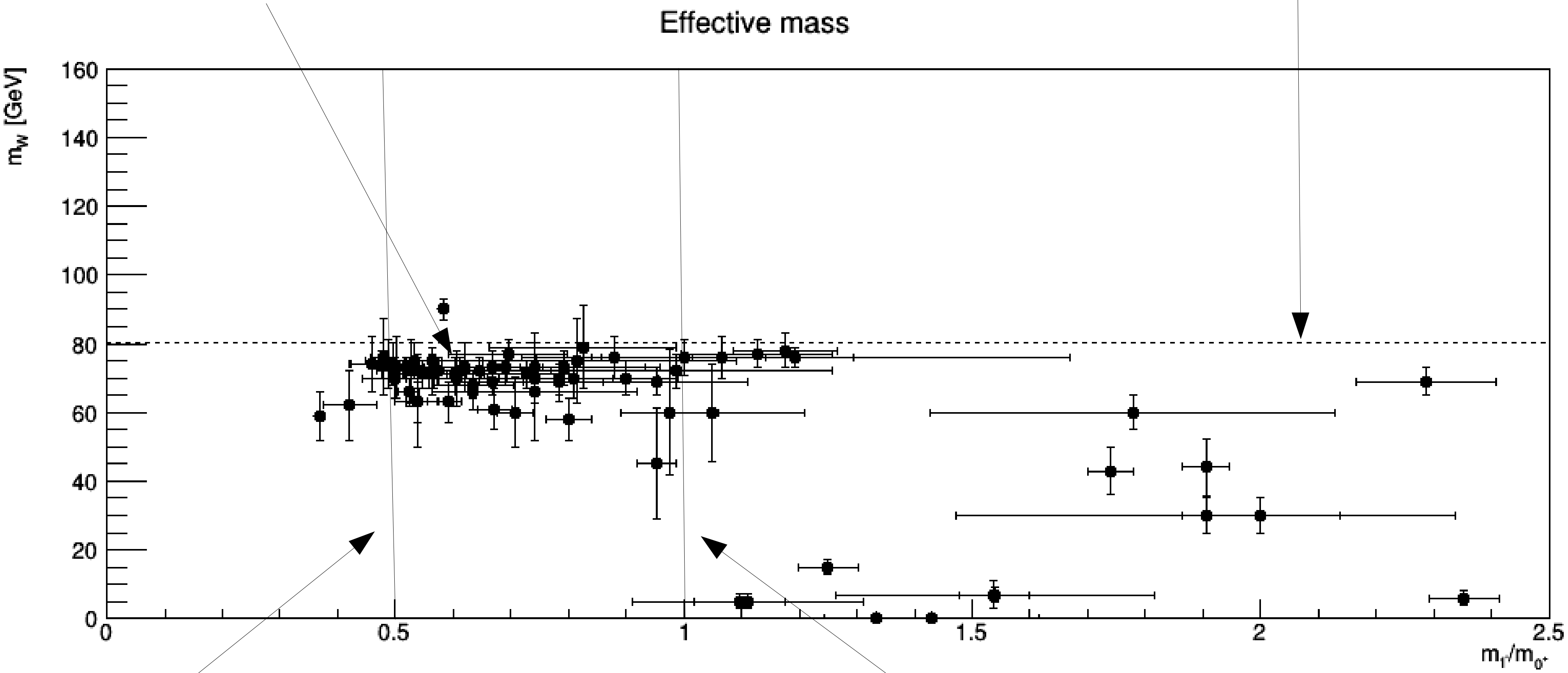
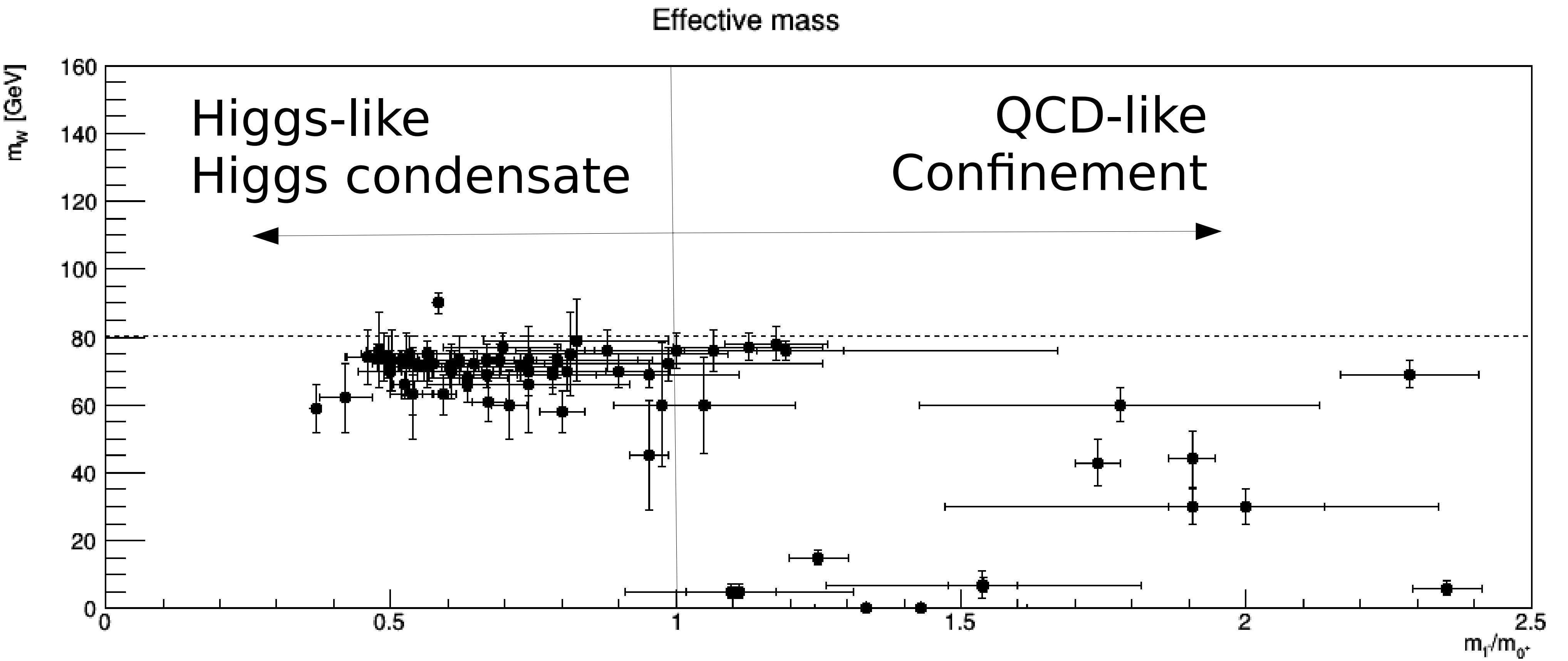


Elastic decay threshold
Higgs as resonance
Expensive, signal very bad

Higgs and W mass agrees
FMS stops working
So does Brout-Englert-Higgs!

Limits

[Maas & Mufti'14]



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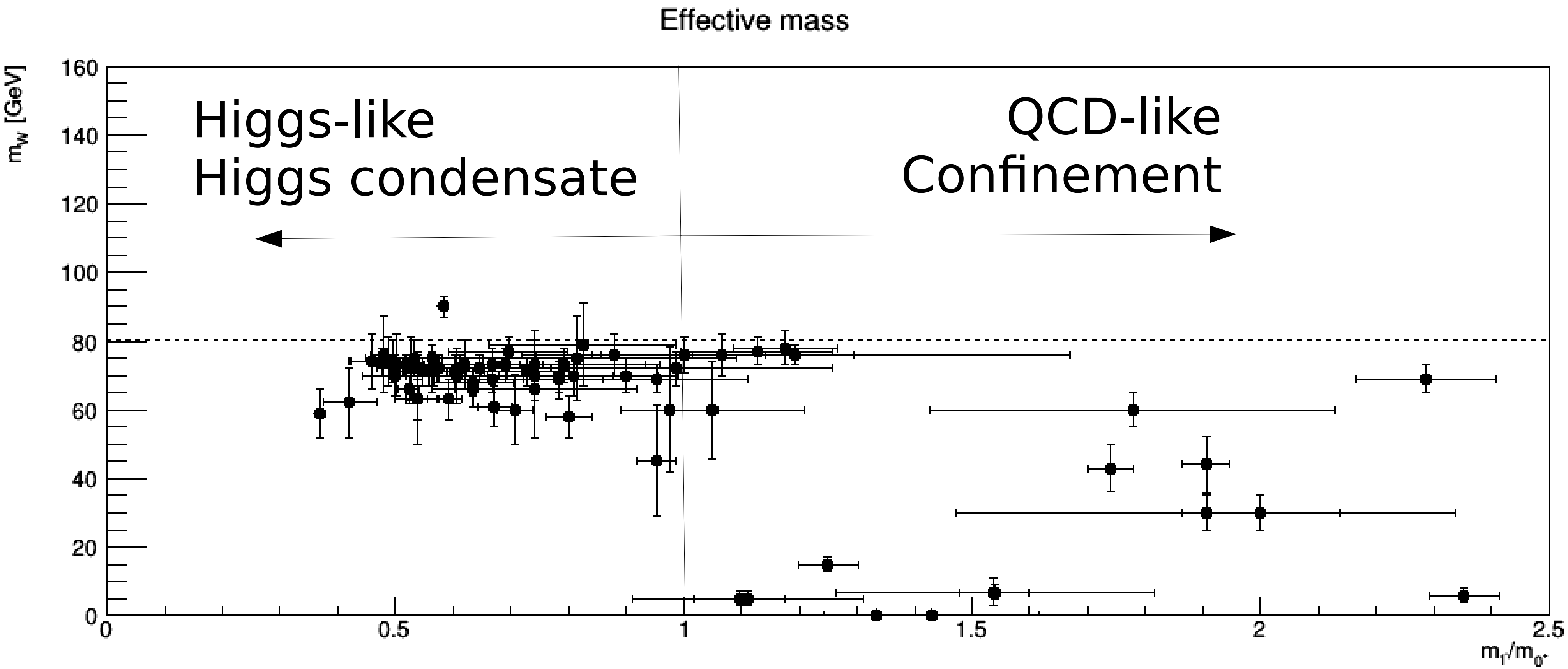
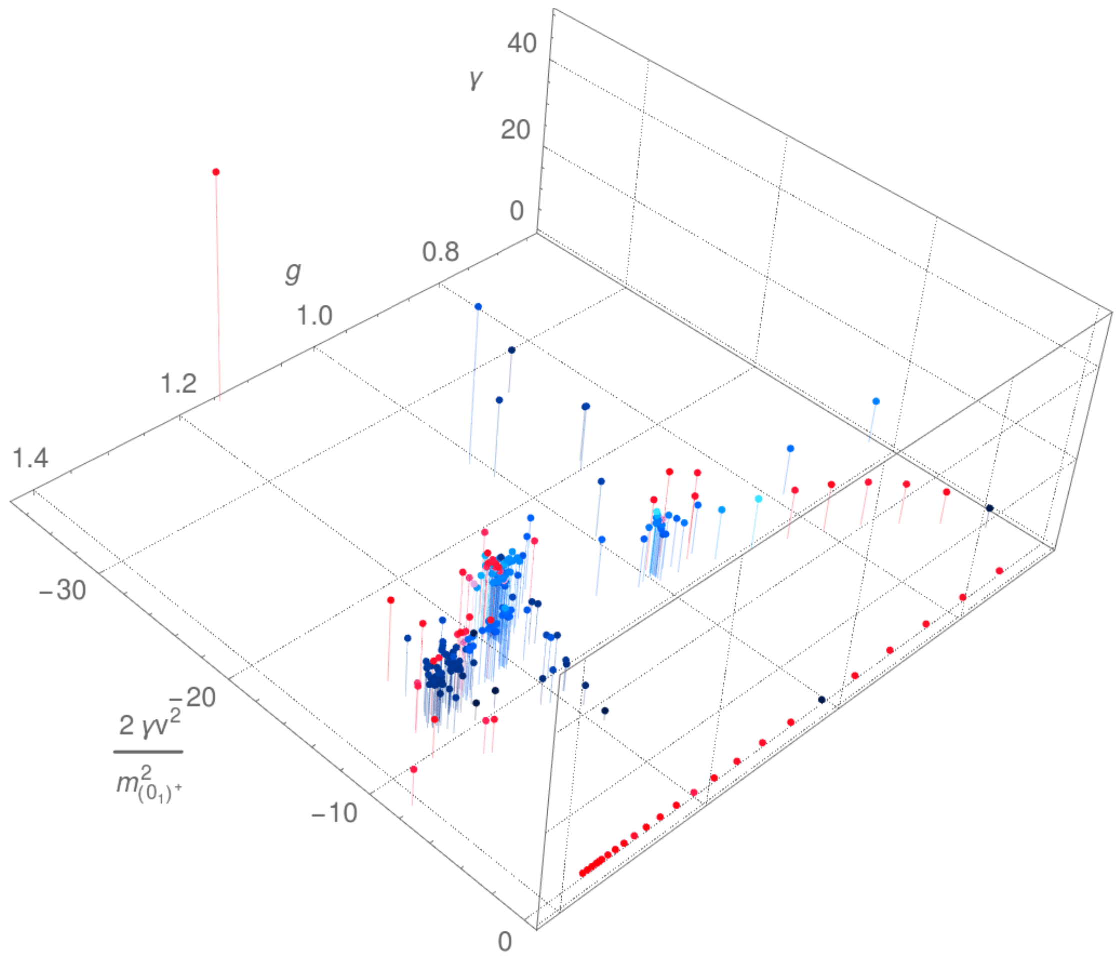


Does not coincide with weak/strong coupling transitions!

Phase diagram

[Maas & Mufti'15]



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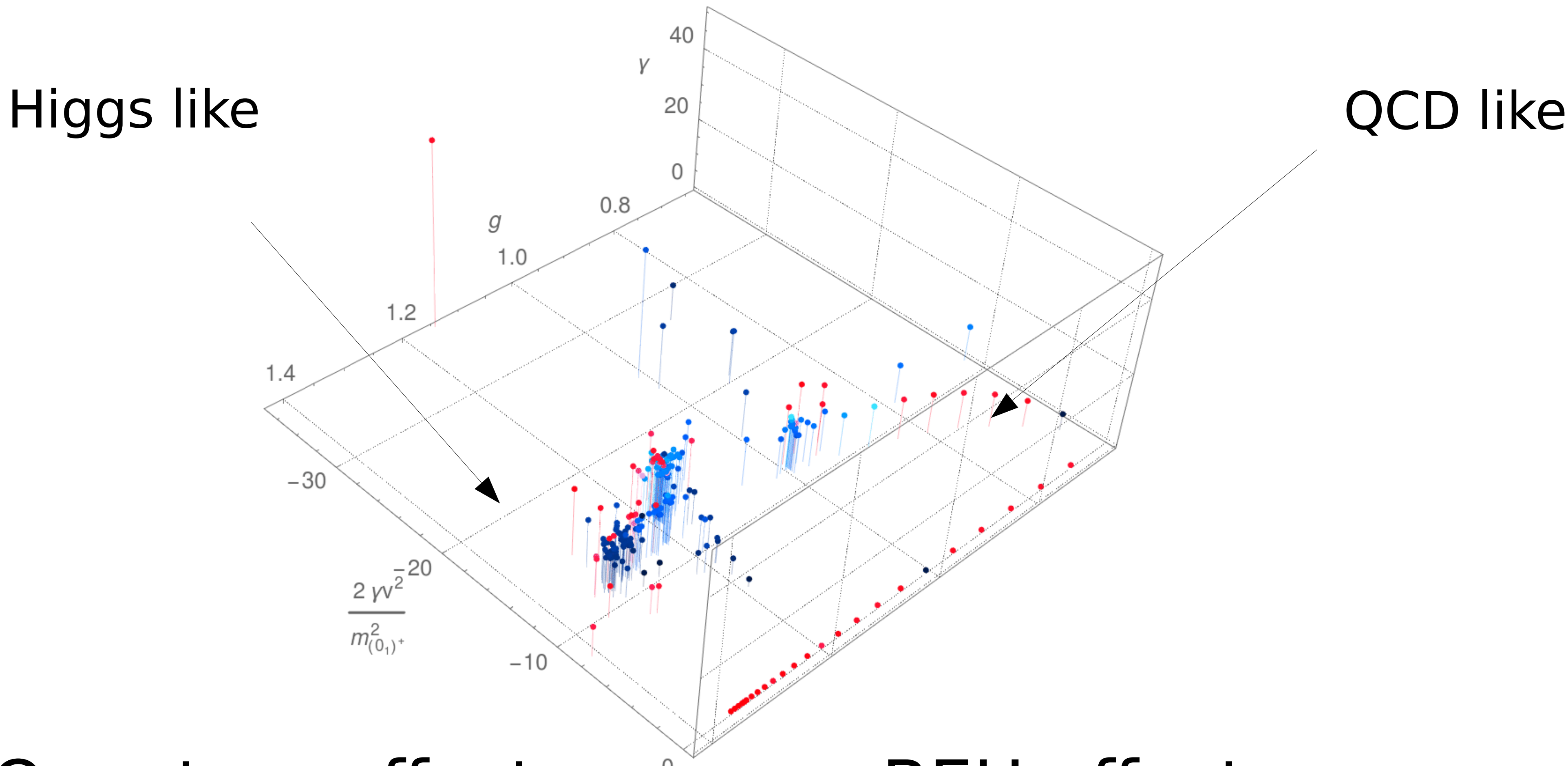

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  - Opposite does not happen

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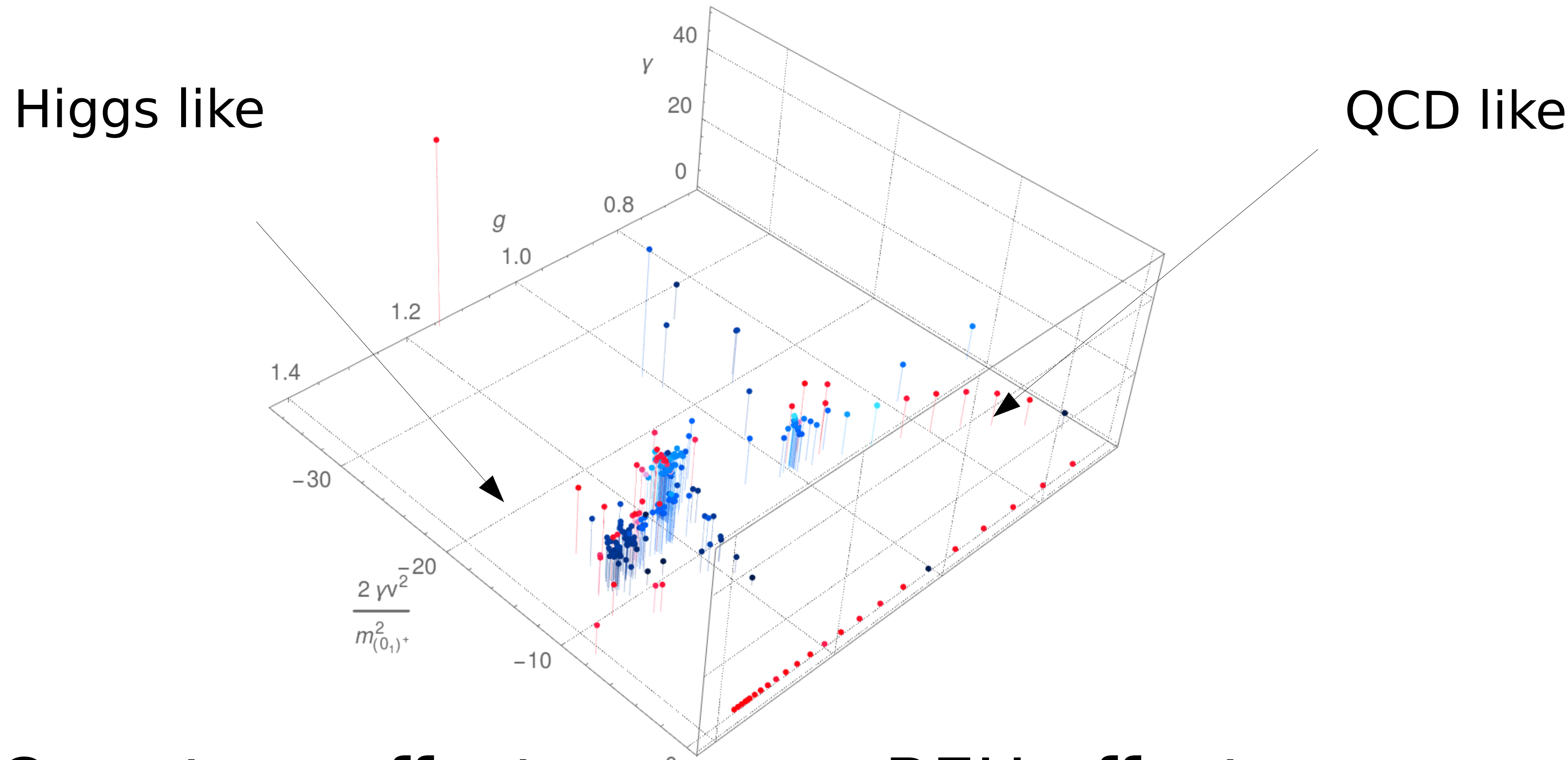

- Quantum effects remove BEH effect
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- Interacting continuum limit? [Gies & Zambelli'15]

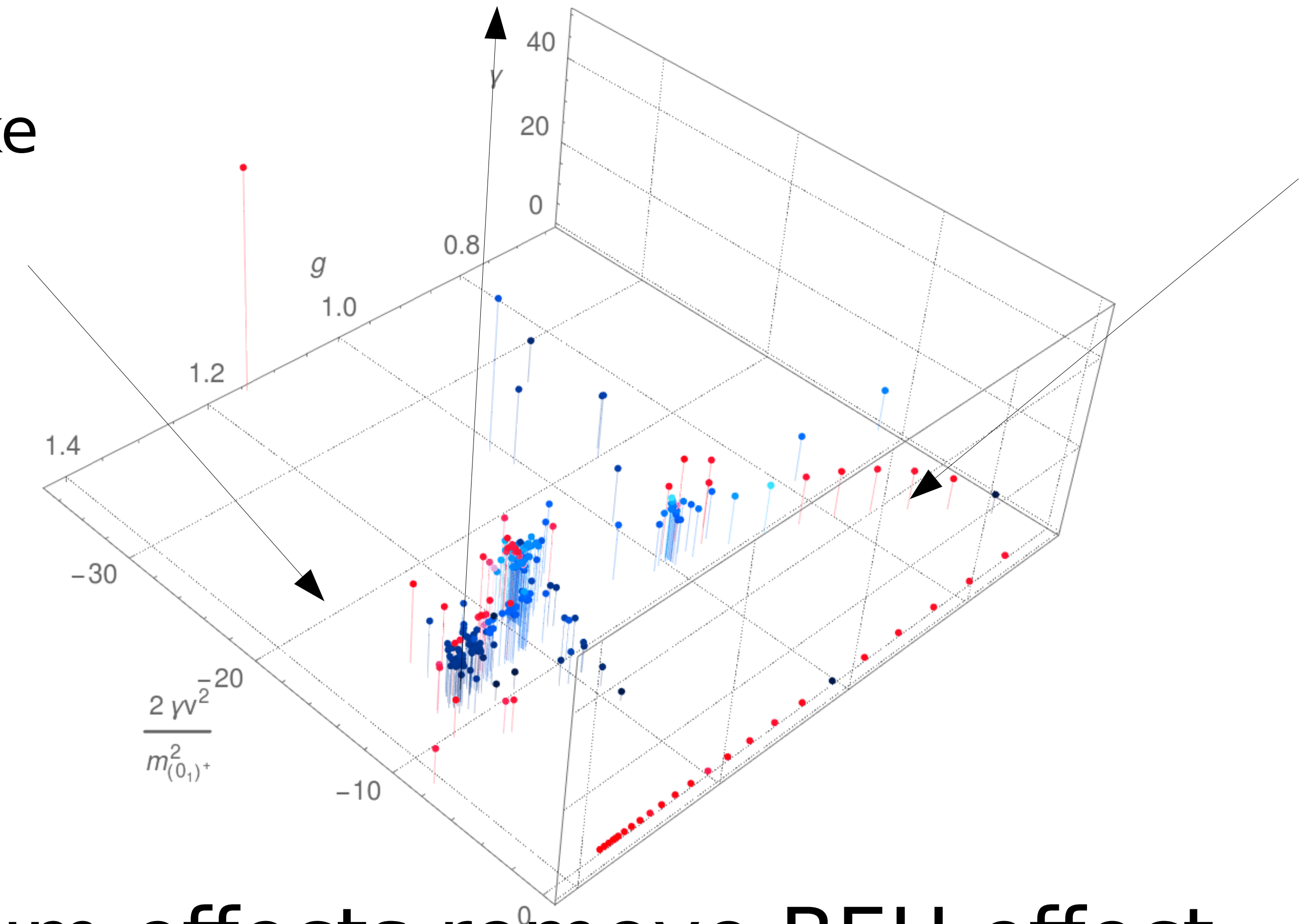
Phase diagram

[Maas & Mufti'15]

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

Higgs like

QCD like



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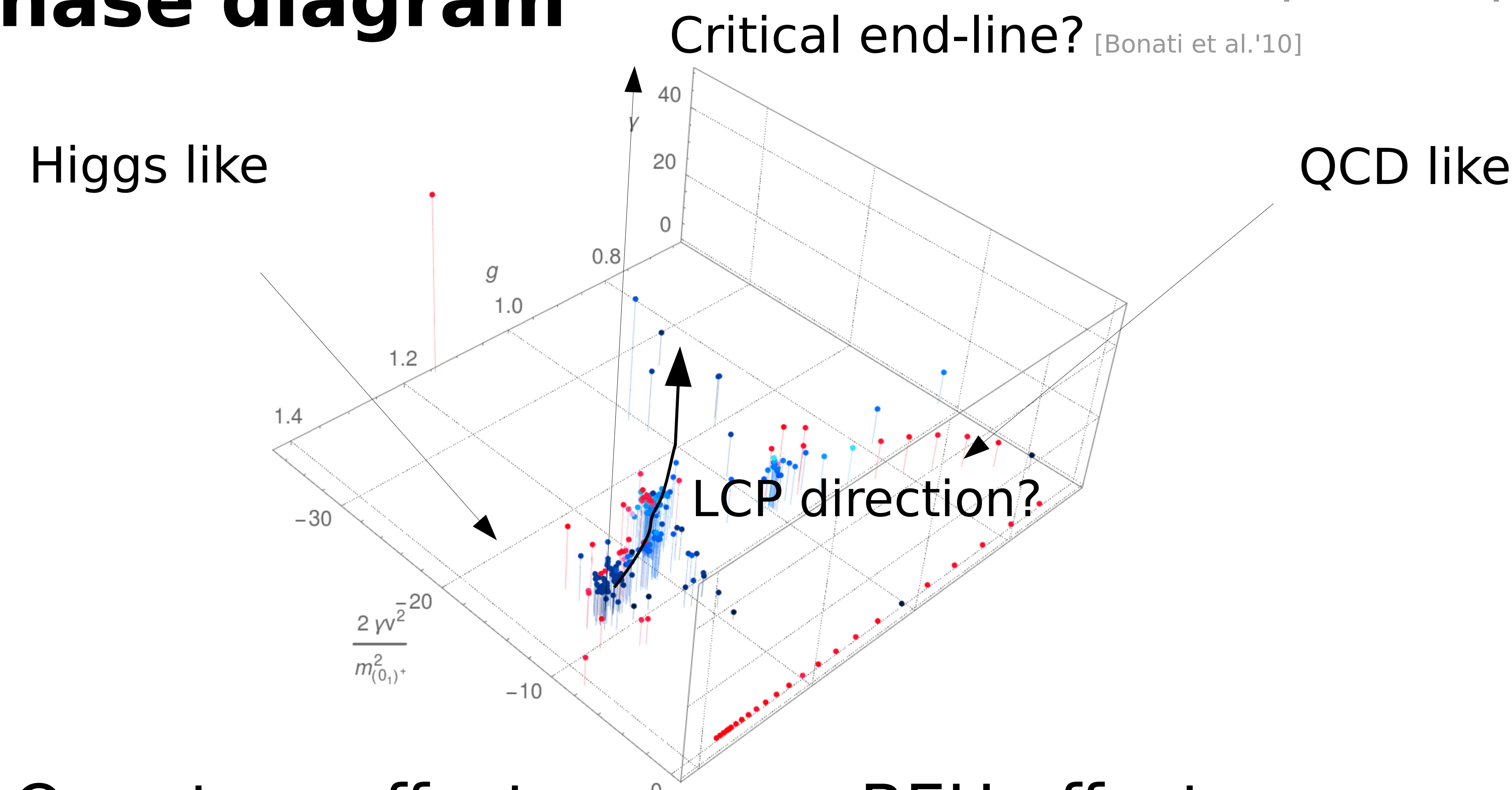

- Quantum effects remove BEH effect
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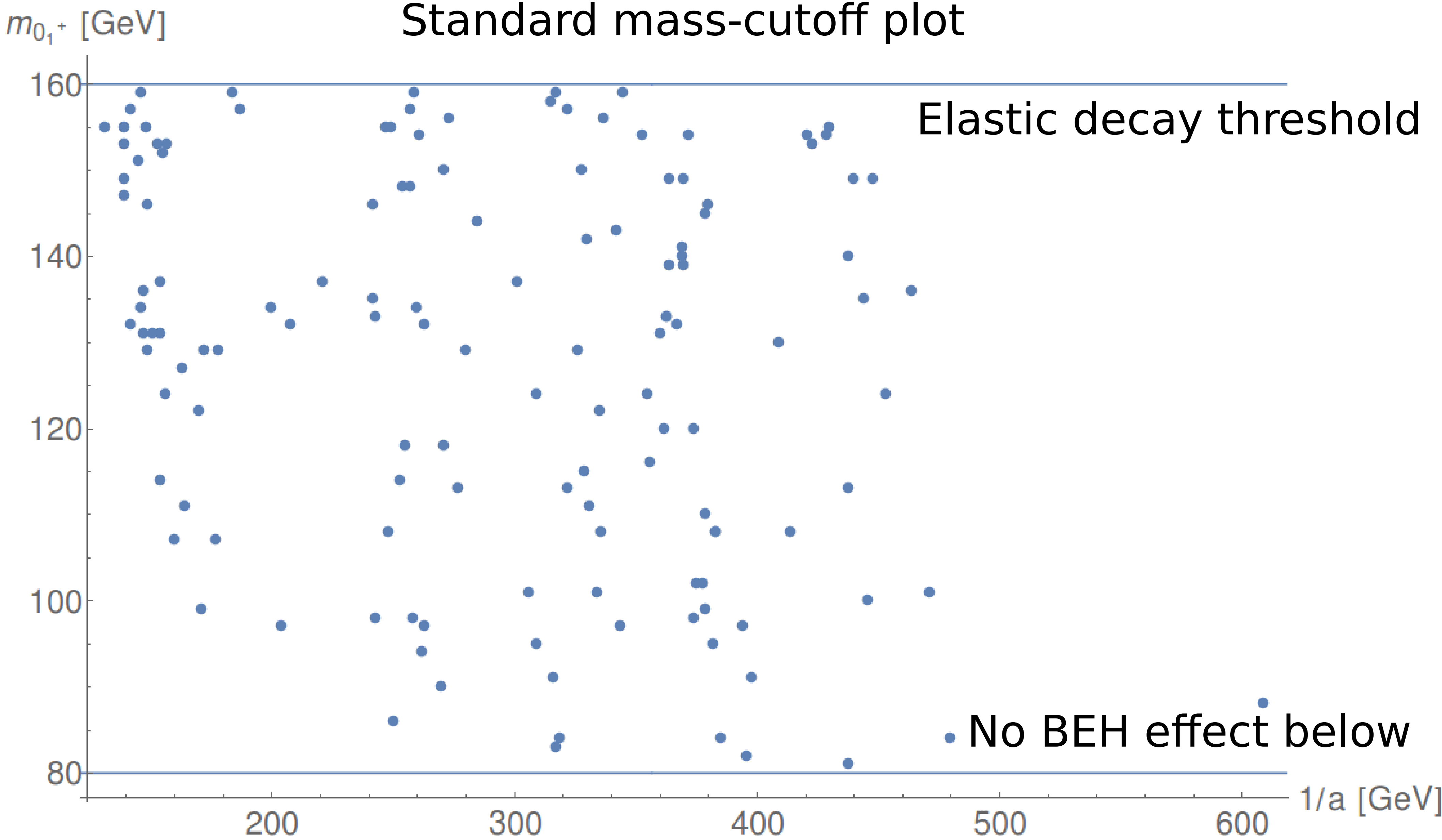
- Interacting continuum limit? [Gies & Zambelli'15]
  - LCP: 0^+, 1^- masses, $\alpha(200\,GeV)$ (miniMOM scheme)

Higgs mass

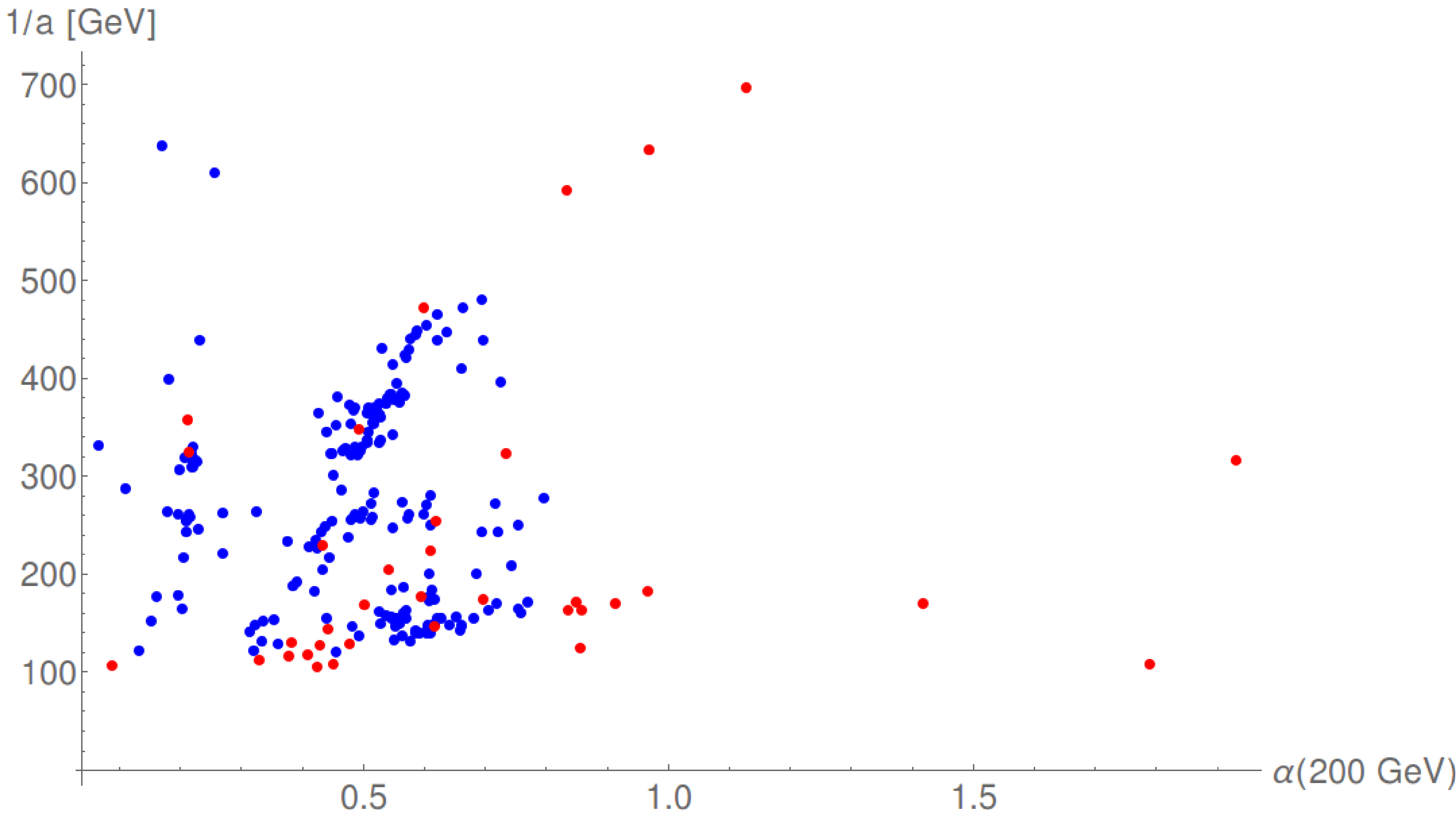
[Maas & Mufti'15]

Standard mass-cutoff plot



No strong dependence of mass range on cutoff - expected

Perturbative predictivity: Coupling



[Maas, unpublished]

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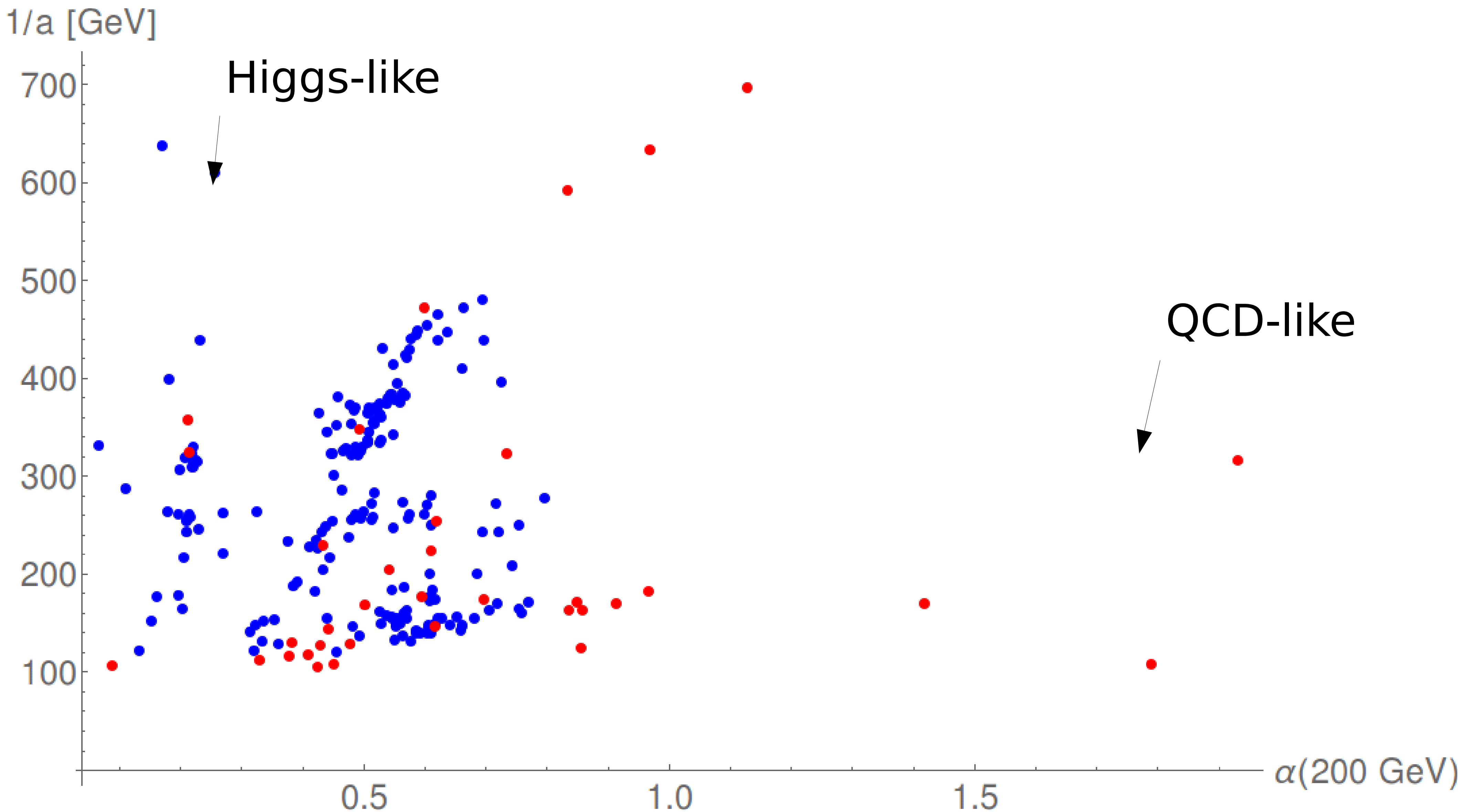

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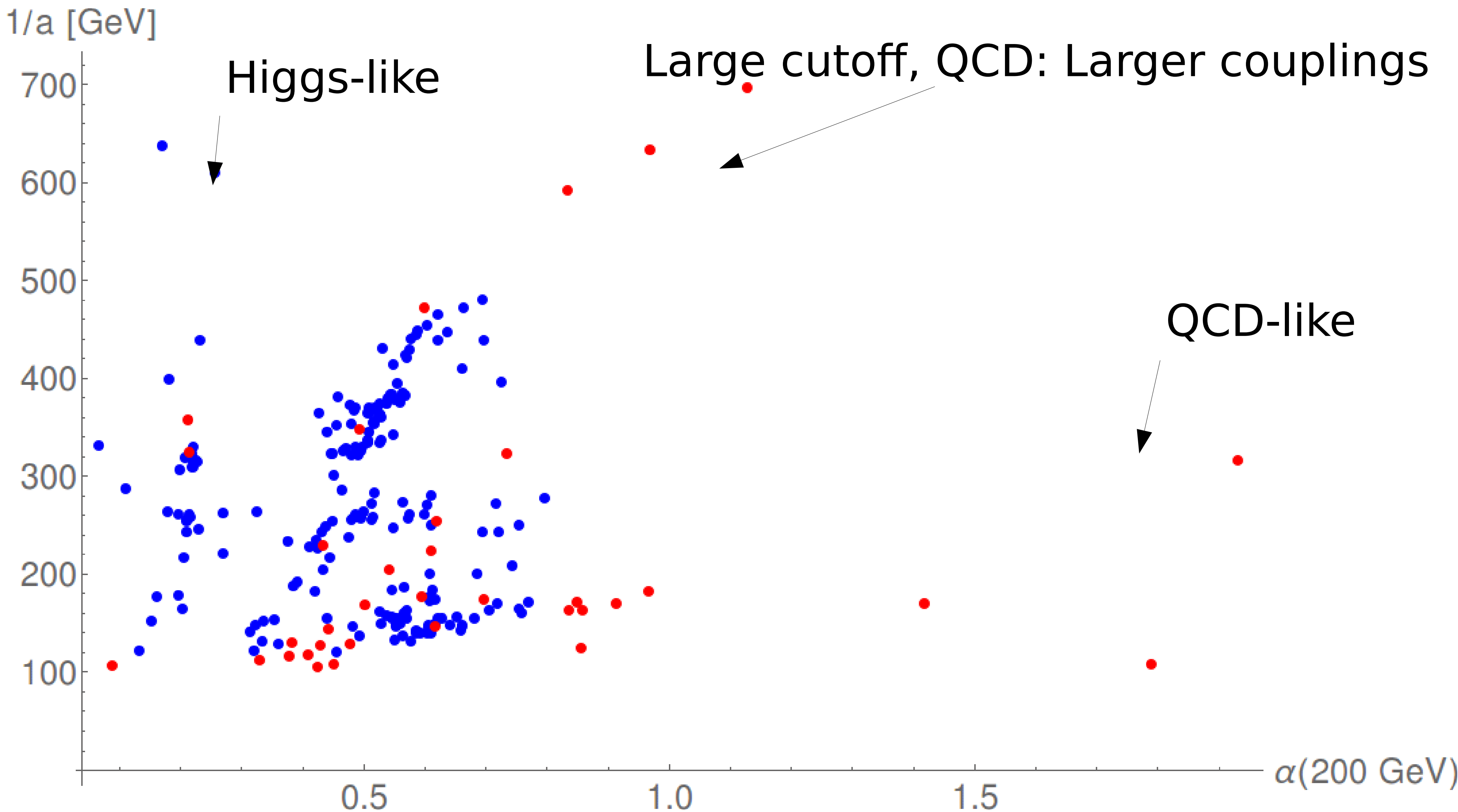

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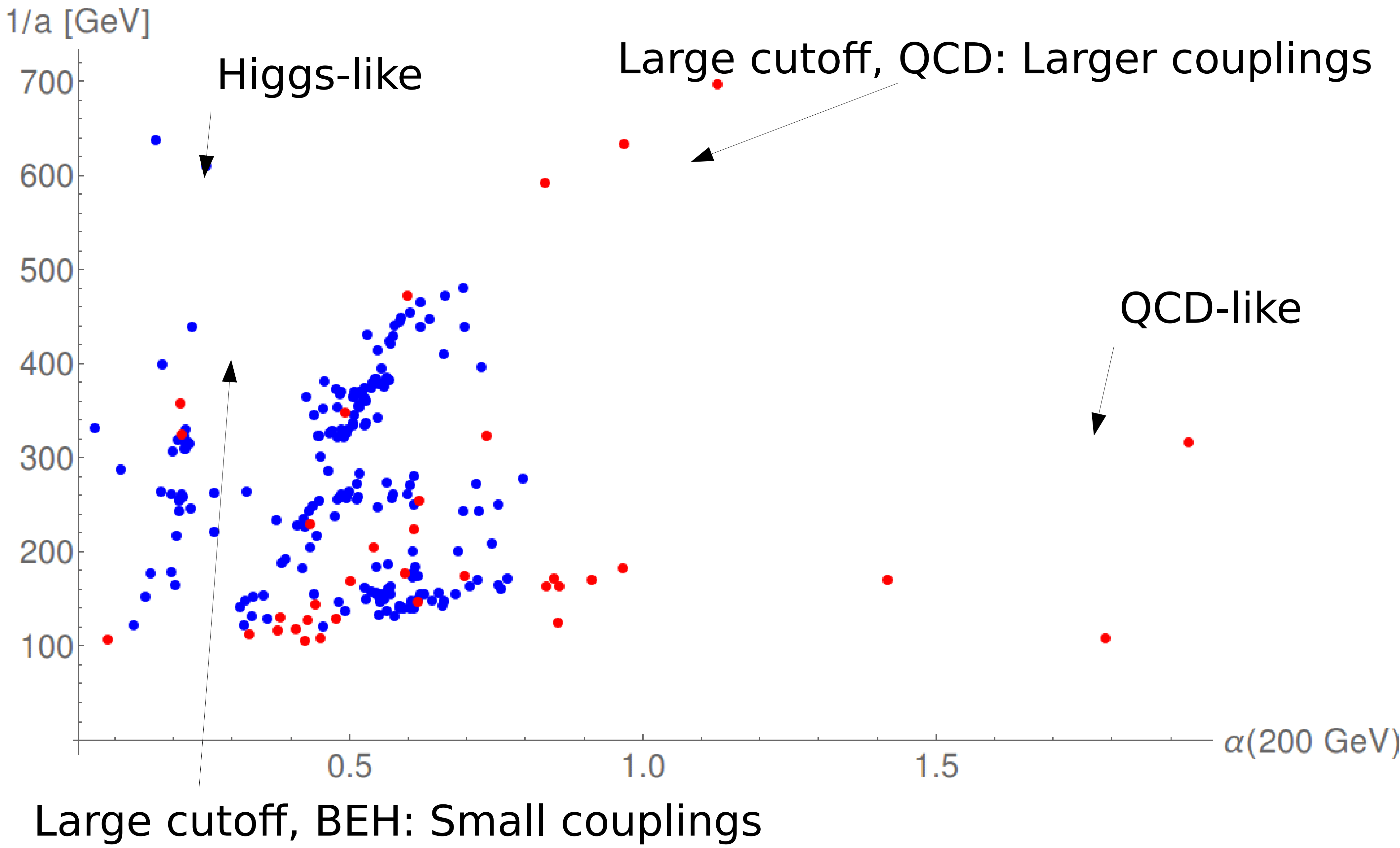

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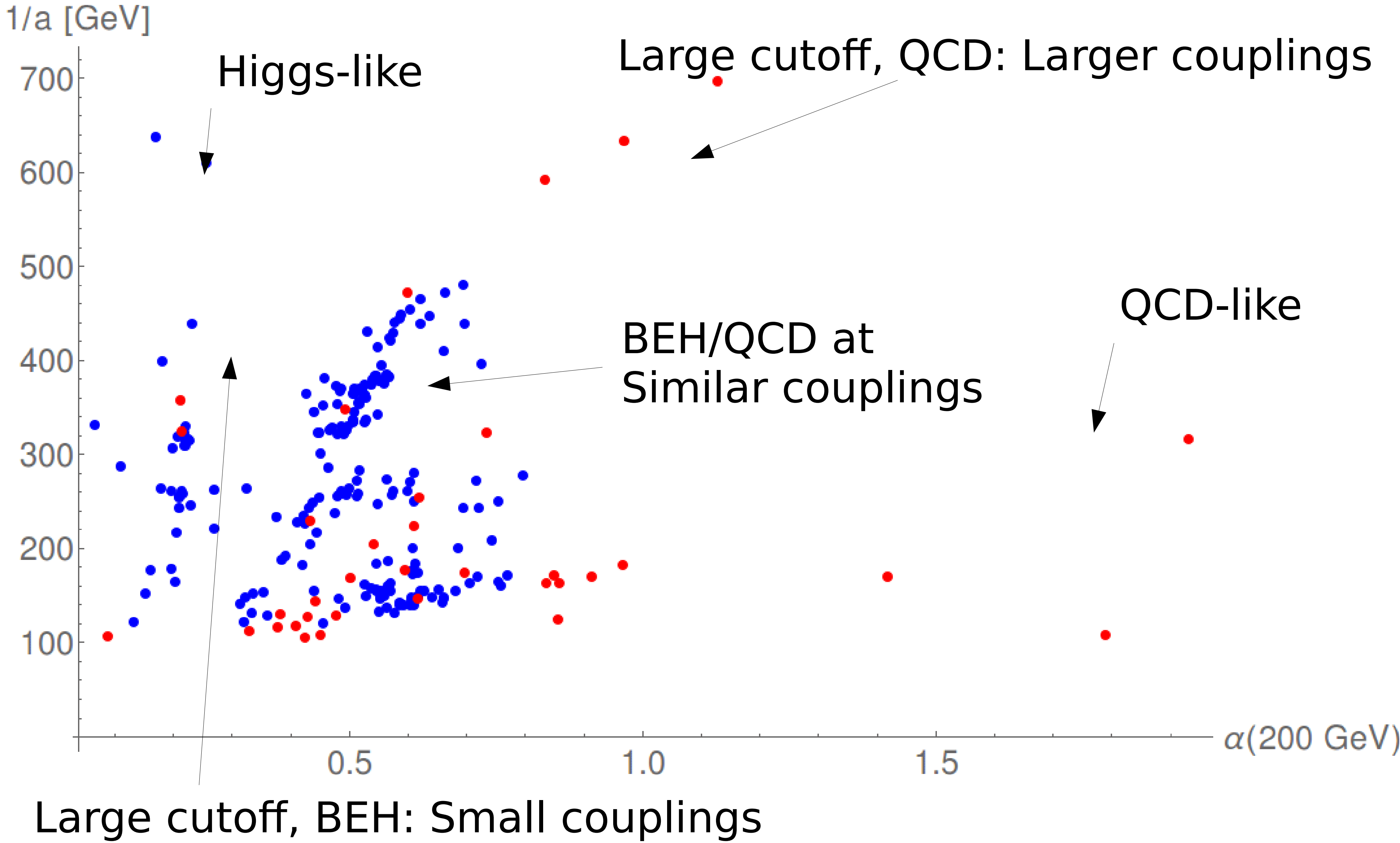

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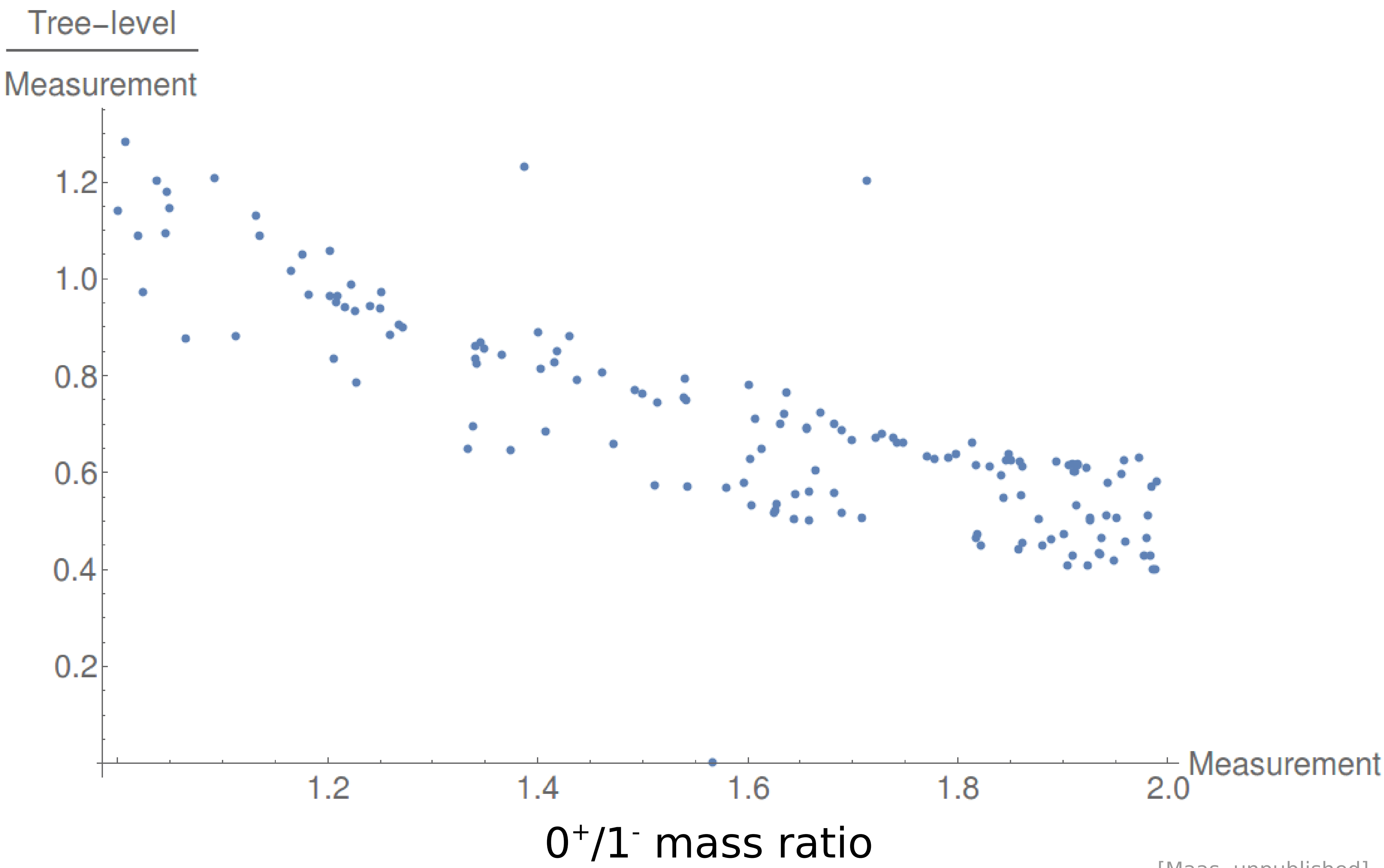
Perturbative predictivity: Mass ratios



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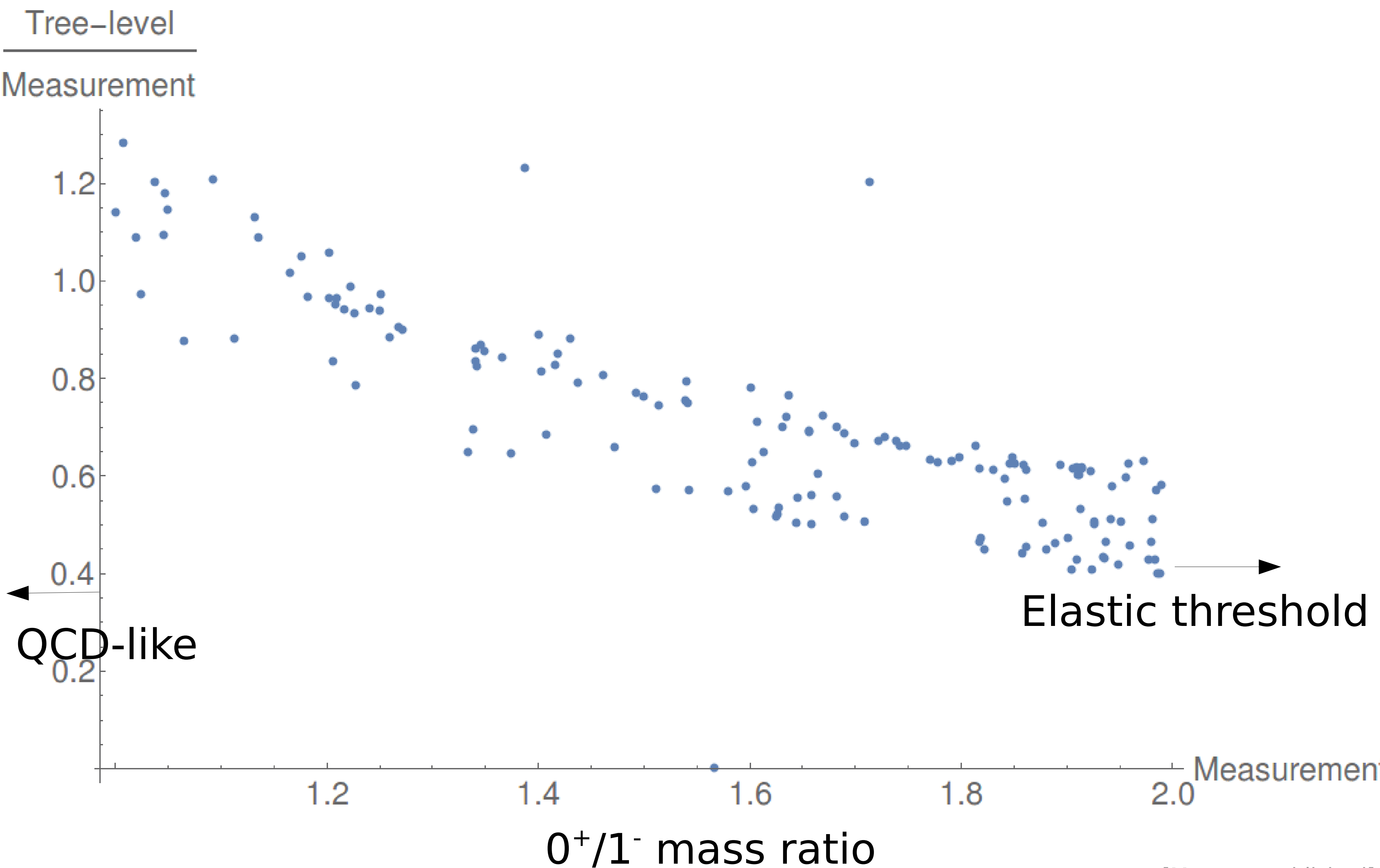

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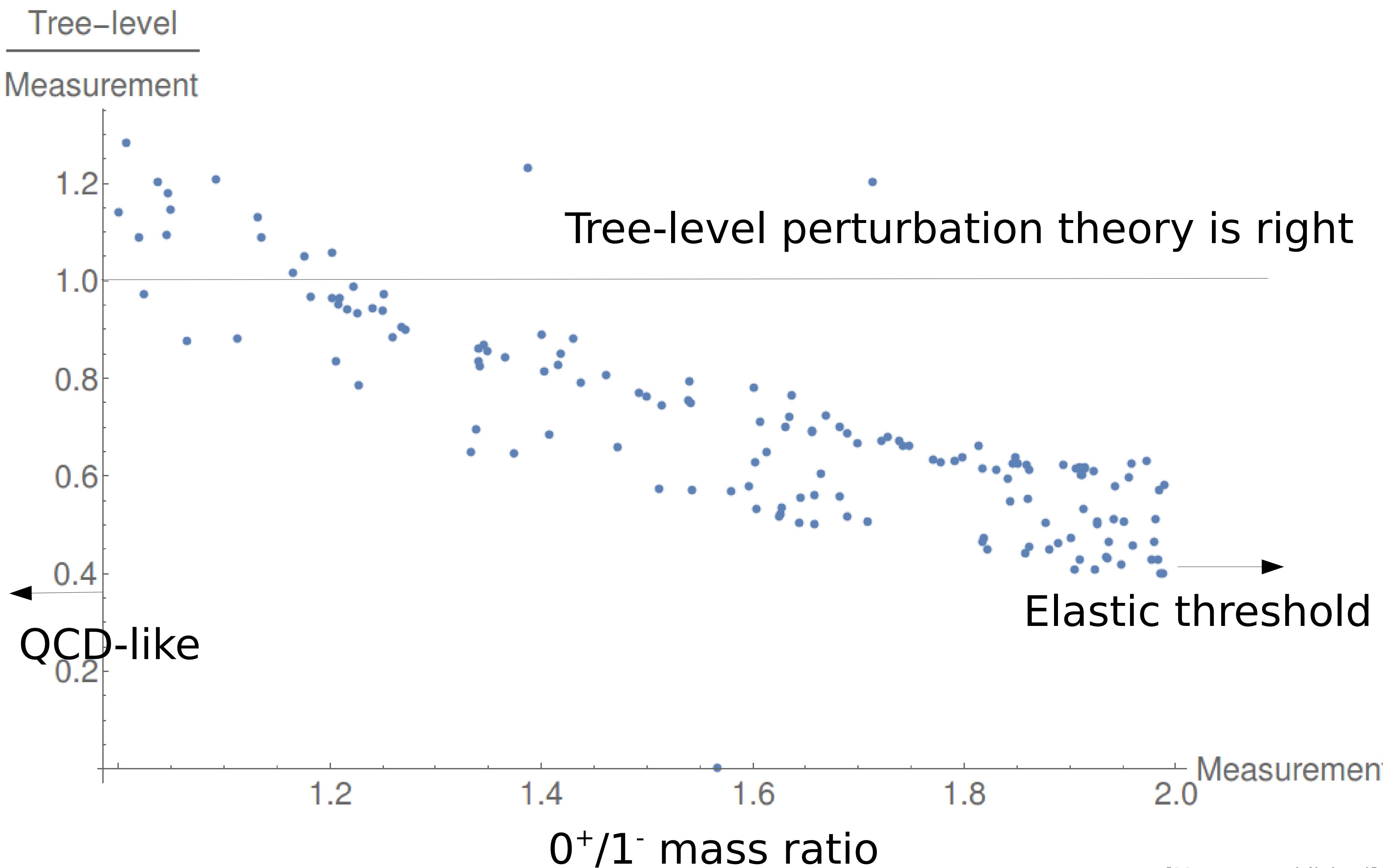

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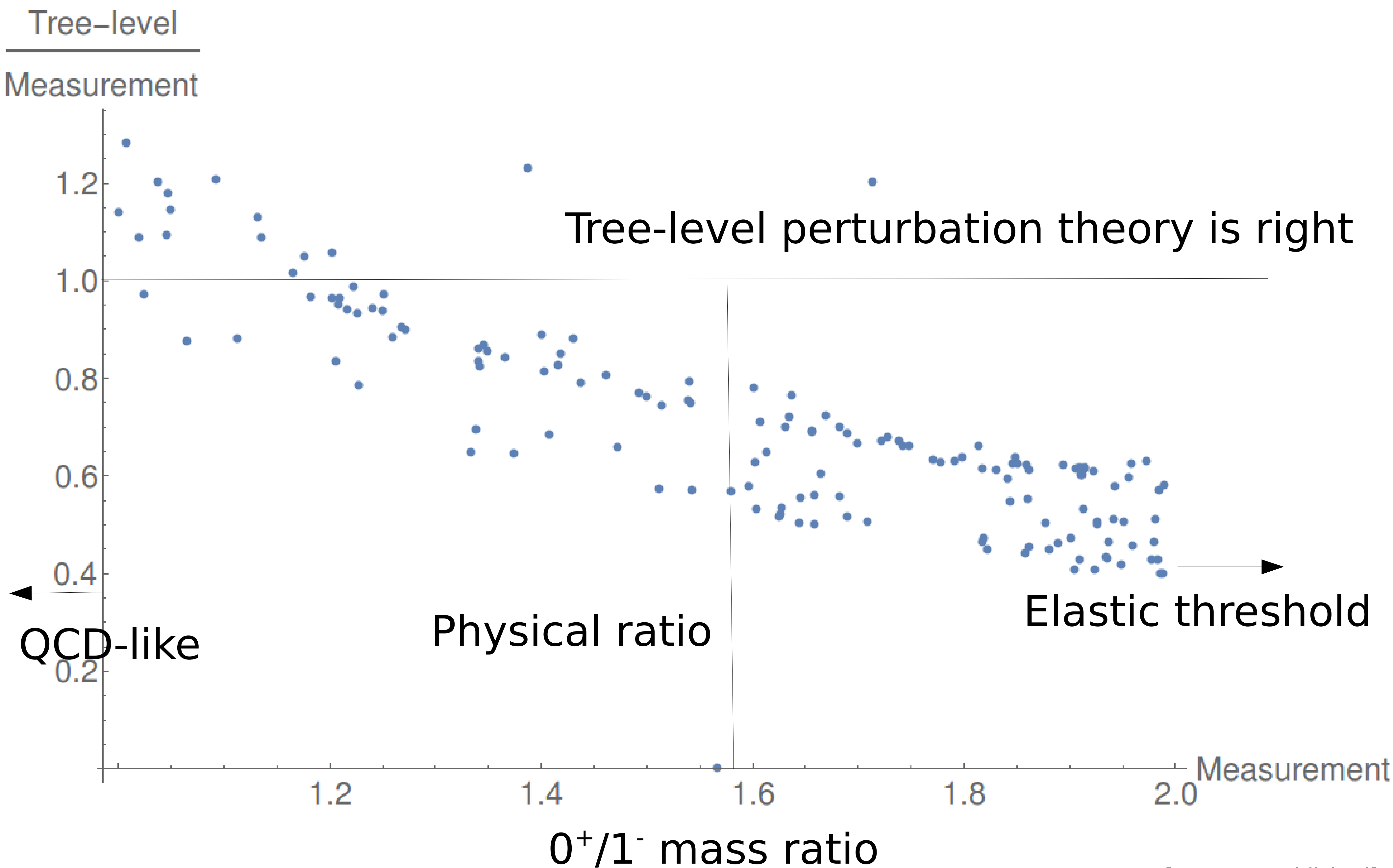

[Maas, unpublished]

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]
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  - Without Higgs: More subtle [Maas'15]

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

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

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

  - Scalar Sector Quadruplet

$$\langle (a^+ \Gamma a)(x)(a^+ \Gamma a)(y)\rangle \approx const. + \langle \eta_a^+(x)\Gamma \eta_a(y)\rangle + O(\eta_a^3)$$

    - Splitted into 1+3 states for broken group

Implications for 2HDM

[Maas'15,
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  - Scalar Sector Quadruplet

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    - Splitted into 1+3 states for broken group
  - Vector triplet

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  - All other states expand to scattering states

Implications for 2HDM

[Maas'15, Maas & Pedro'16]

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- Validity: Requires non-perturbative check
- 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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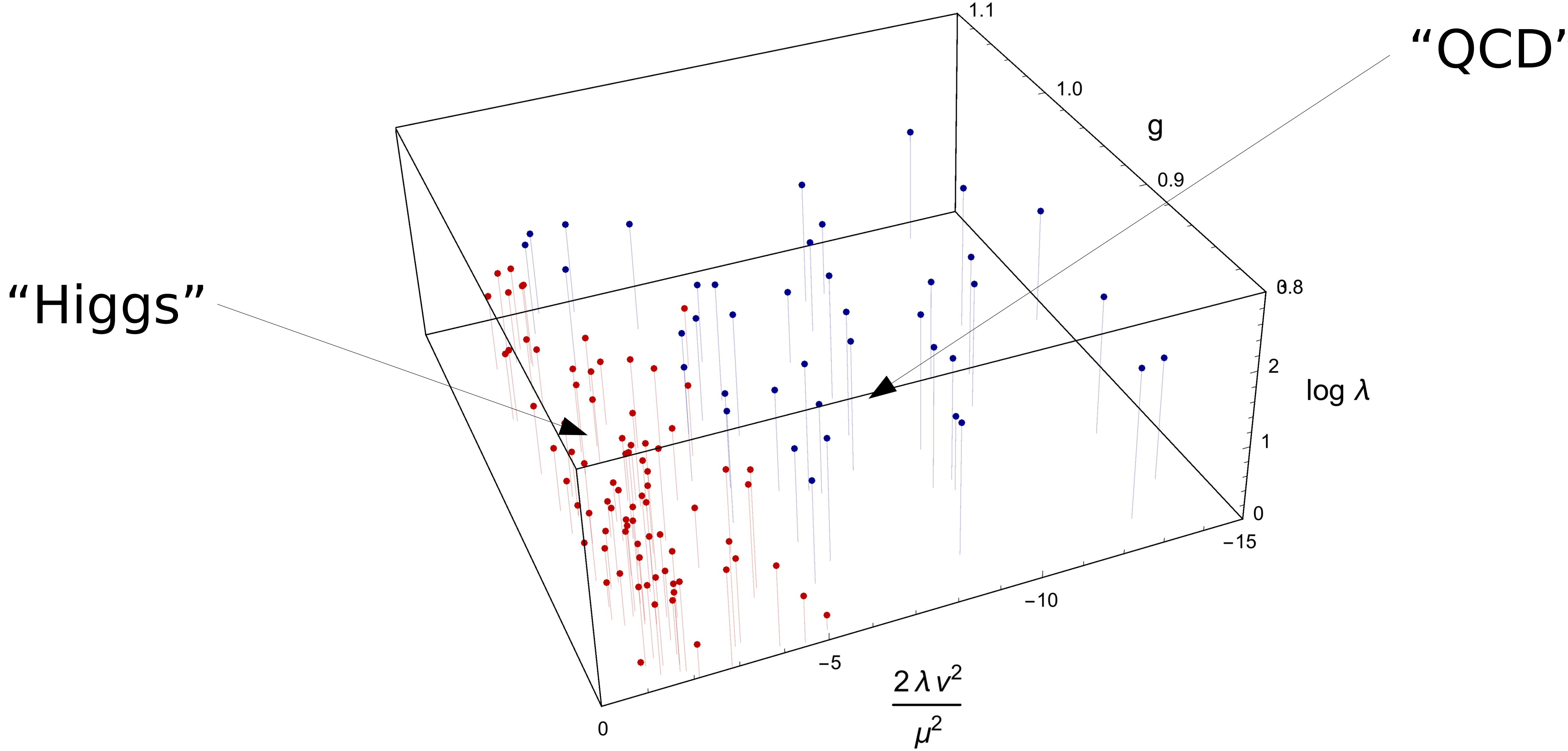
  - ...or something else?

Test for GUTs

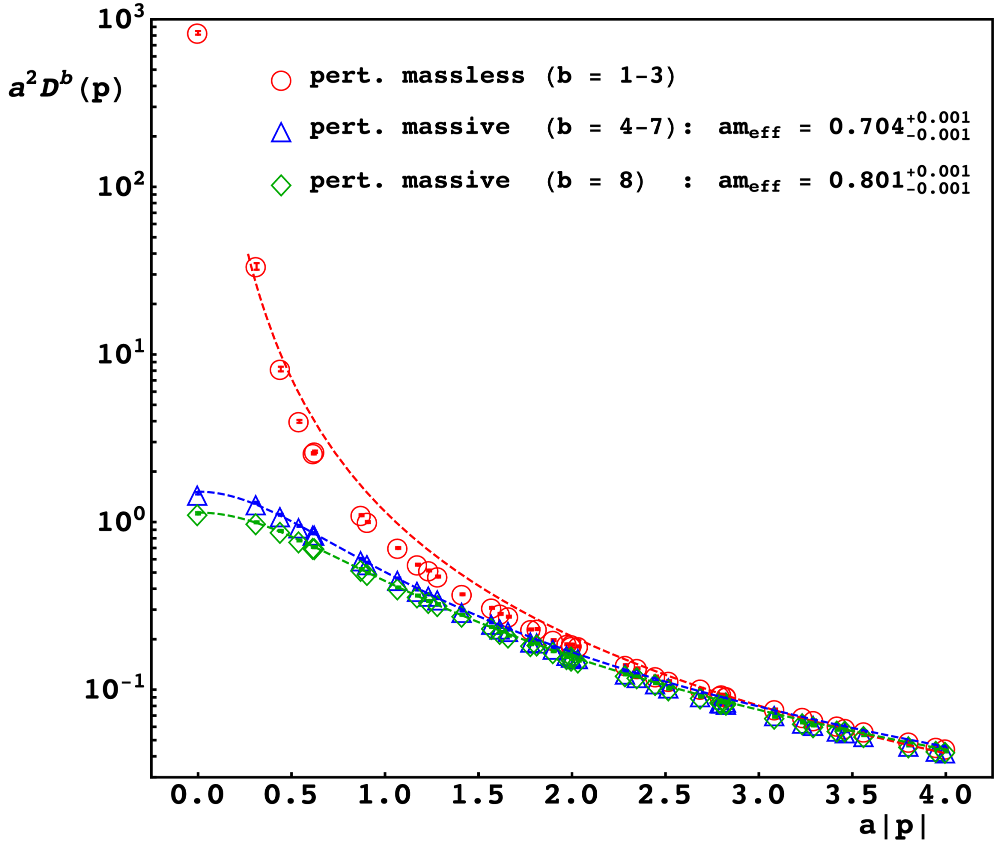
[Maas & Törek'16]



- Separation into Higgs-like and QCD-like

Test for GUTs

[Maas & Törek'16]



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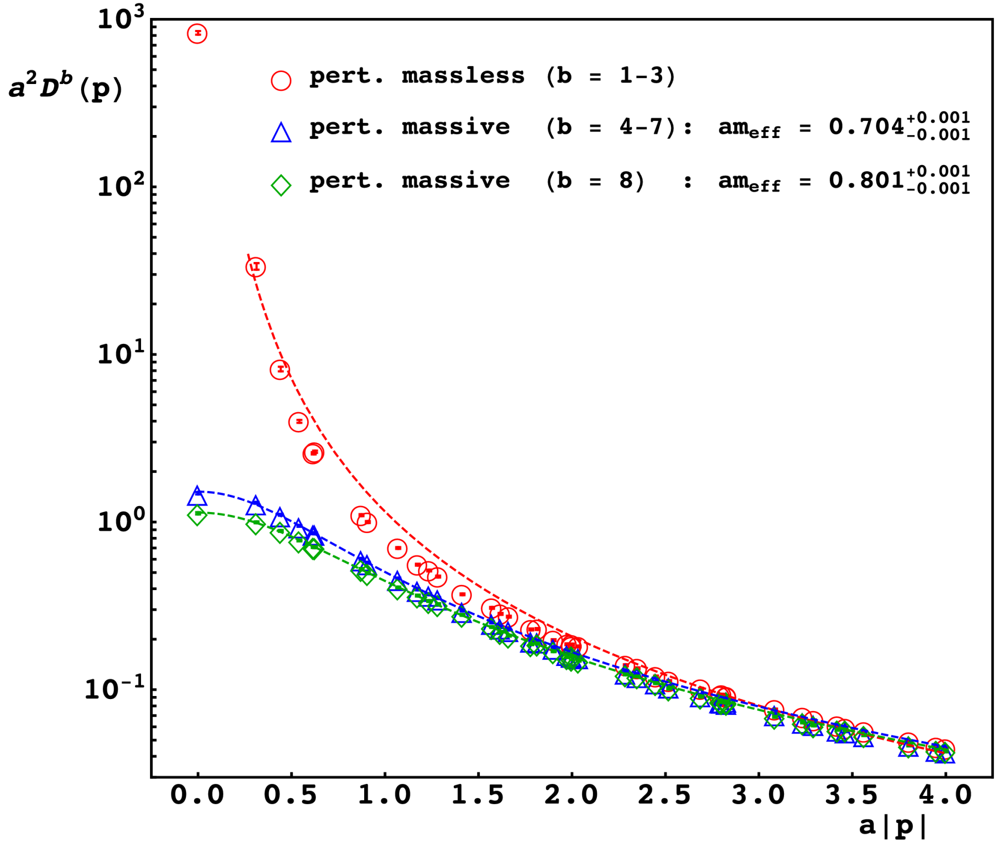

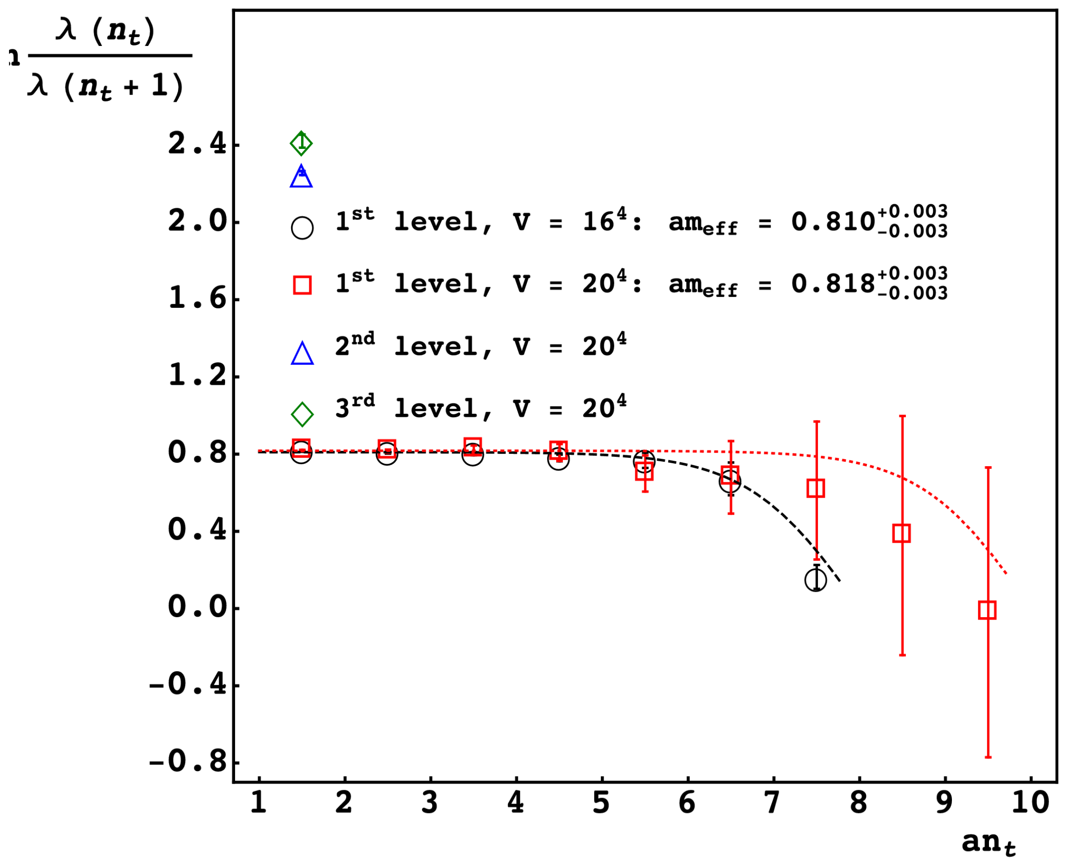

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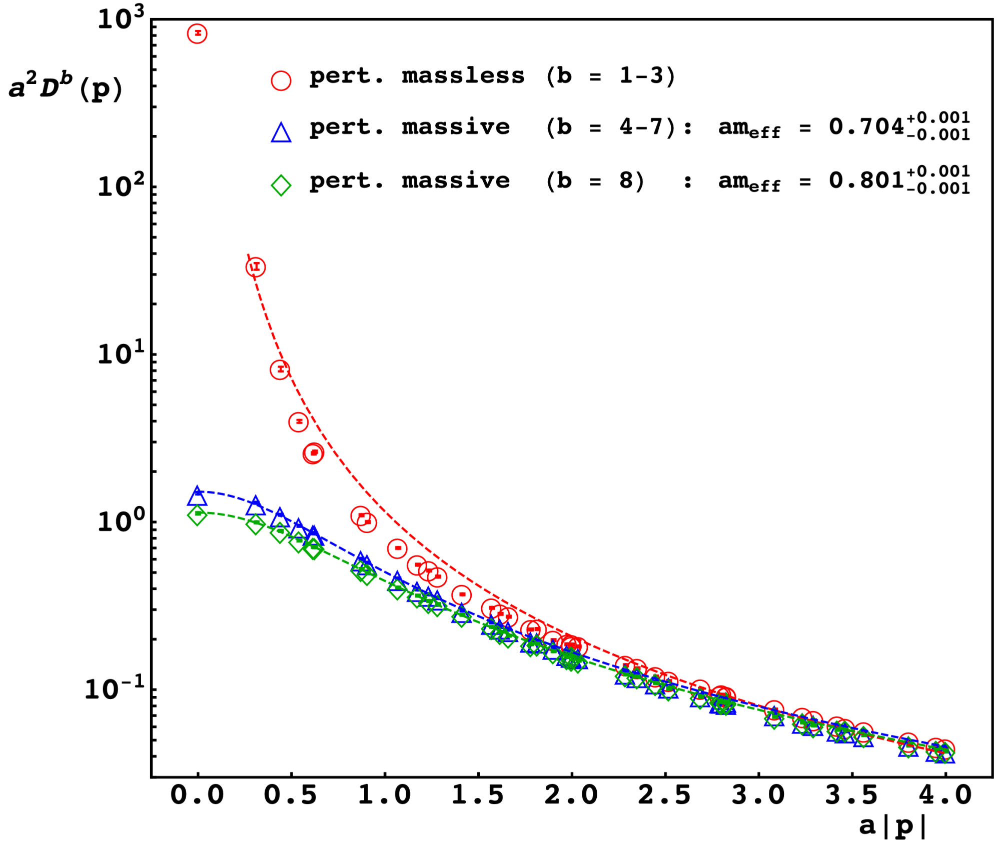

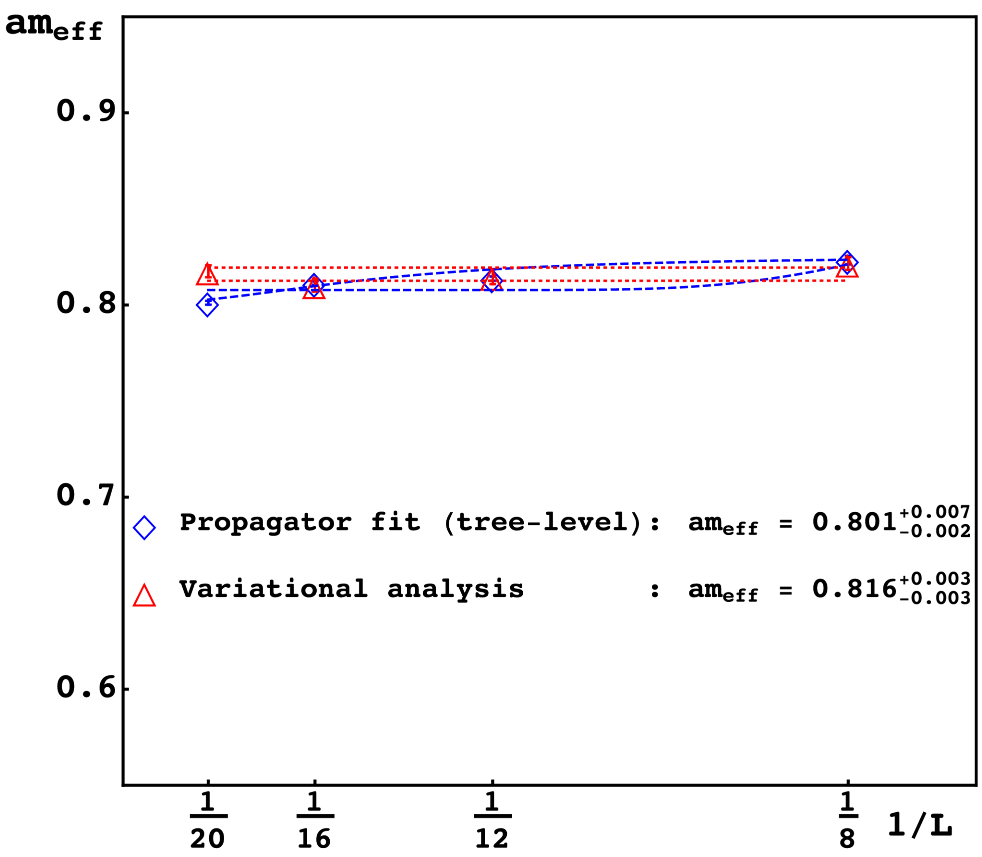

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  - Expected splitting in gauge boson spectrum
- Physical vector: Massive, non-degenerate
  - Agrees with FMS prediction

Example 3: Technicolor

No gauge-invariant perturbation theory
but
interesting implications

Implications for Technicolor

[Maas,'15]

- Higgs replaced by bound state of new fermions (techniquarks) and new gauge interaction (technicolor)

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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

[Maas'12,'15
Törek & Maas'16]

- Observable spectrum must be gauge-invariant

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  - Requires a Brout-Englert-Higgs effect
  - Yields the same results for the standard model
  - More robust
  - Mostly not much more complicated

Summary

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- Observable spectrum must be gauge-invariant
- In non-Abelian gauge theories: Bound states
- Gauge-invariant perturbation theory as a tool
  - Requires a Brout-Englert-Higgs effect
  - Yields the same results for the standard model
  - More robust
  - Mostly not much more complicated
- Applicable to beyond-the standard model
  - Structural requirement: Multiplets must match
  - Dynamical requirement: Small fluctuations
  - Verification requires non-perturbative methods

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