# The Physical Spectrum

# and

# Gauge Invariance

## in theories with one or more Higgs fields

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**with**
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UNI GRAZ

NAWI Graz
Natural Sciences

FWF
Der Wissenschaftsfonds.

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- Why it does not matter in the standard model
- Why it can matter beyond the standard model
- How this can be treated
  - Introducing gauge-invariant perturbation theory
  - Checking its validity

# 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 $W^a_\mu$ 

- Higgs $h_i$ 

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

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

$$W^a_\mu \to W^a_\mu \qquad h_i \to h_i + a^{ij} h_j + b^{ij} h_j^*$$

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't Hooft ASIB 80,
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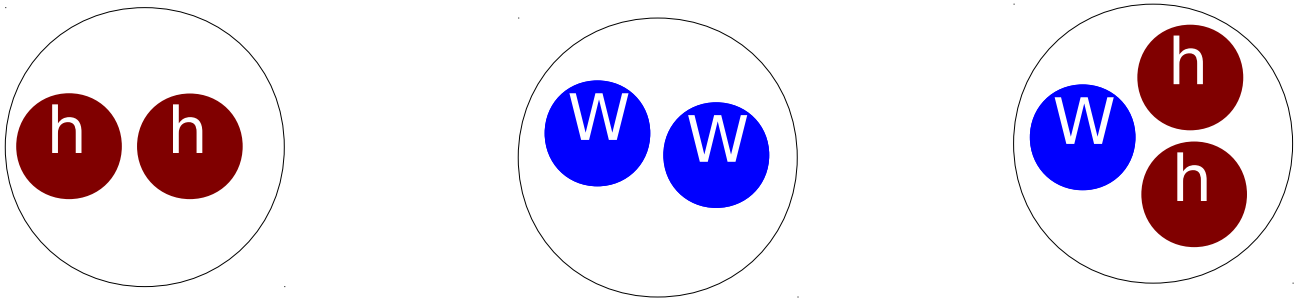

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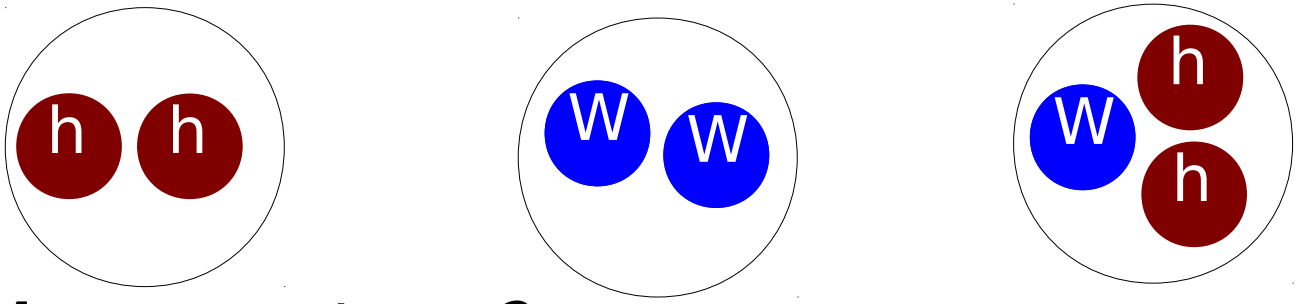


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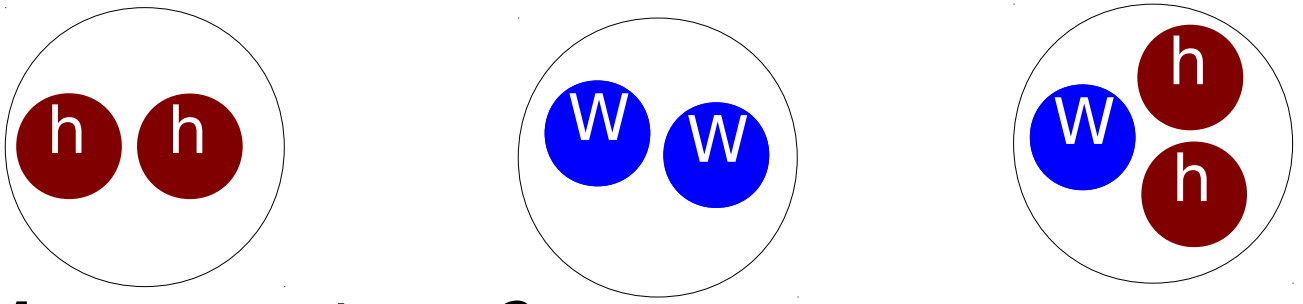


  - Mass spectrum?
  - Why does perturbation theory work?

# Why it does not matter in the standard model

Introducing gauge-invariant perturbation theory

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  - Fröhlich-Morchio-Strocchi (FMS) mechanism
  - Perturbative tool to calculate bound state masses
- Deeply-bound relativistic state
  - Mass defect~constituent mass
  - Cannot be described with quantum mechanics

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- Photons
  - QED similar but simpler

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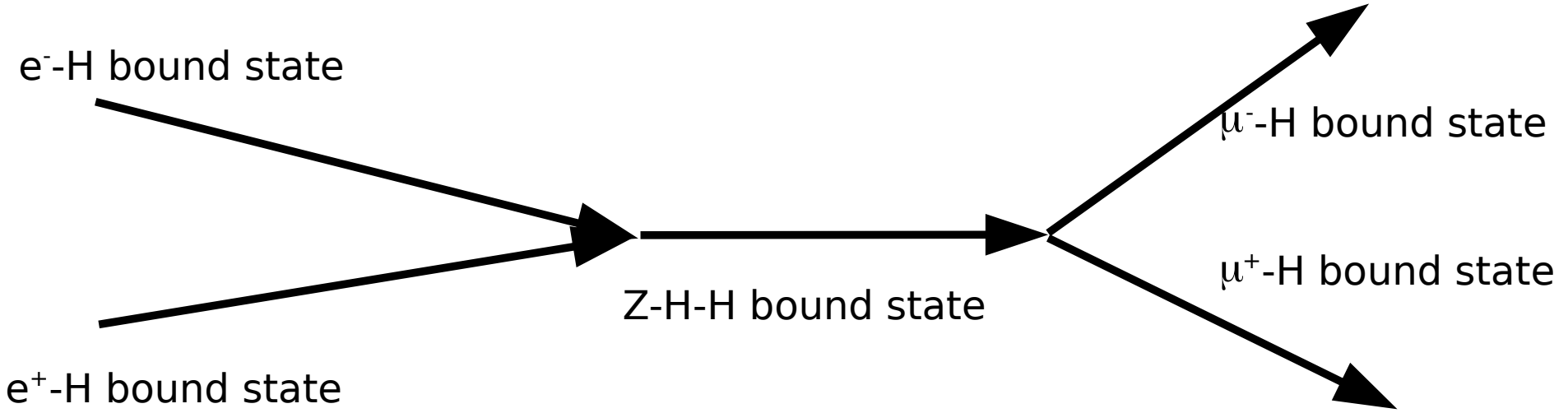
[Maas MPLA 12]

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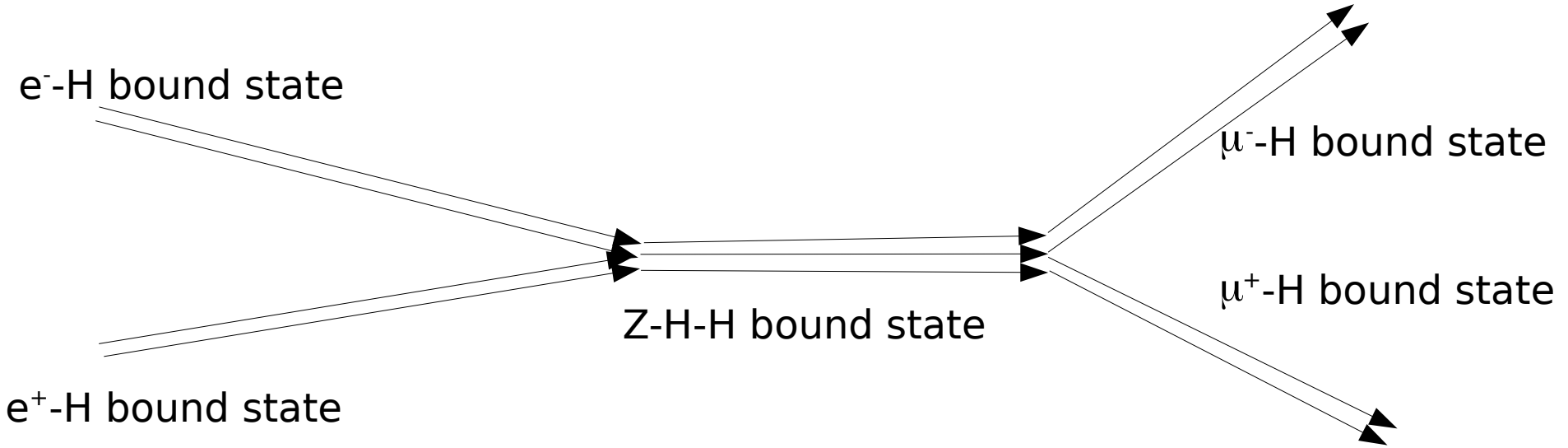


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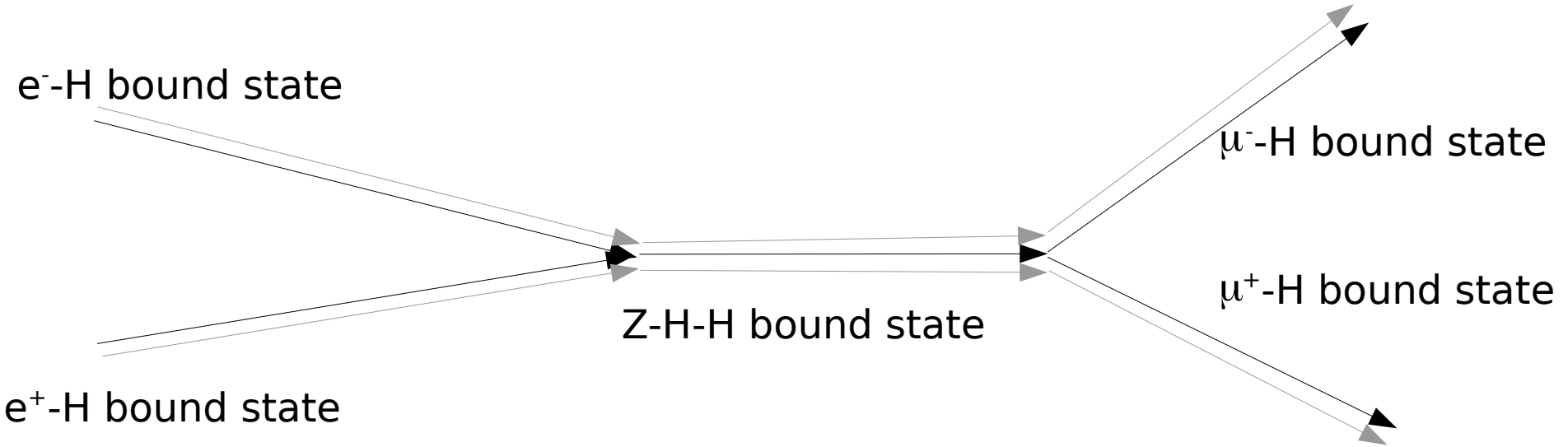


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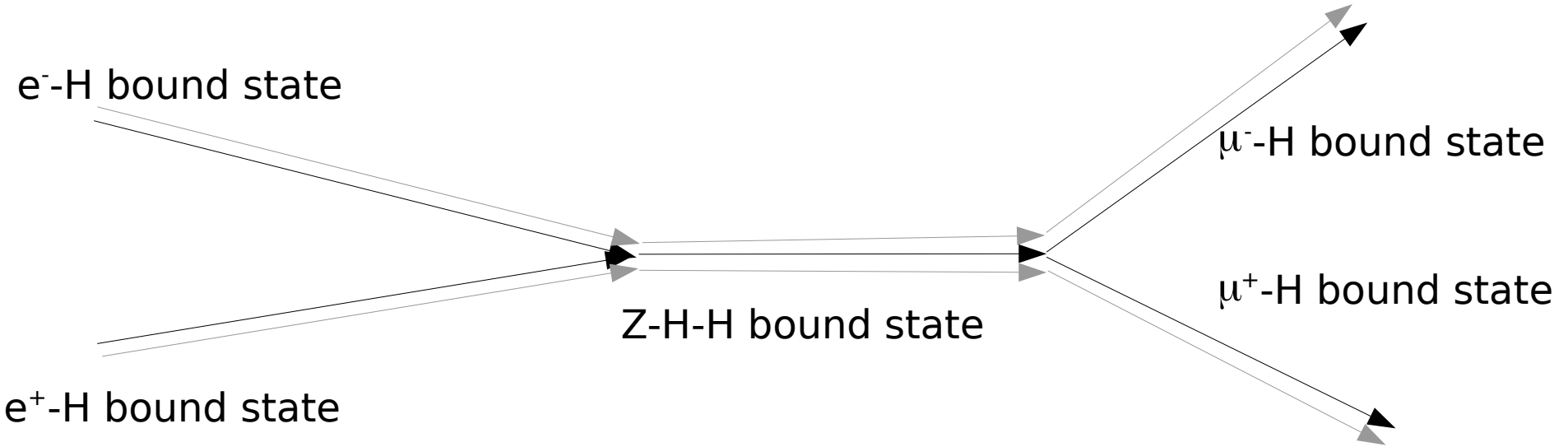


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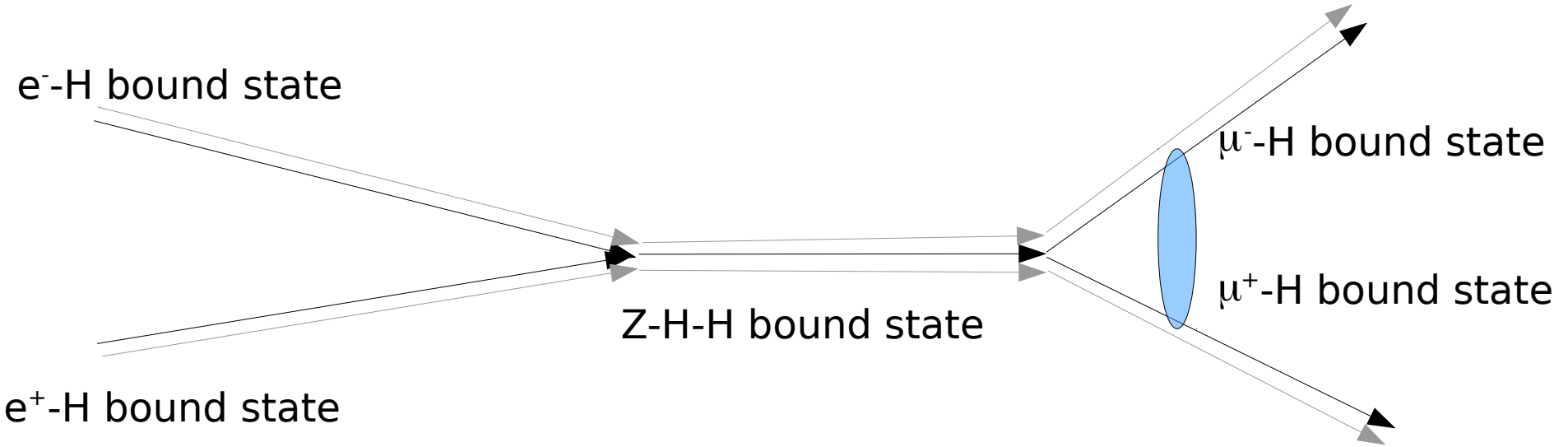


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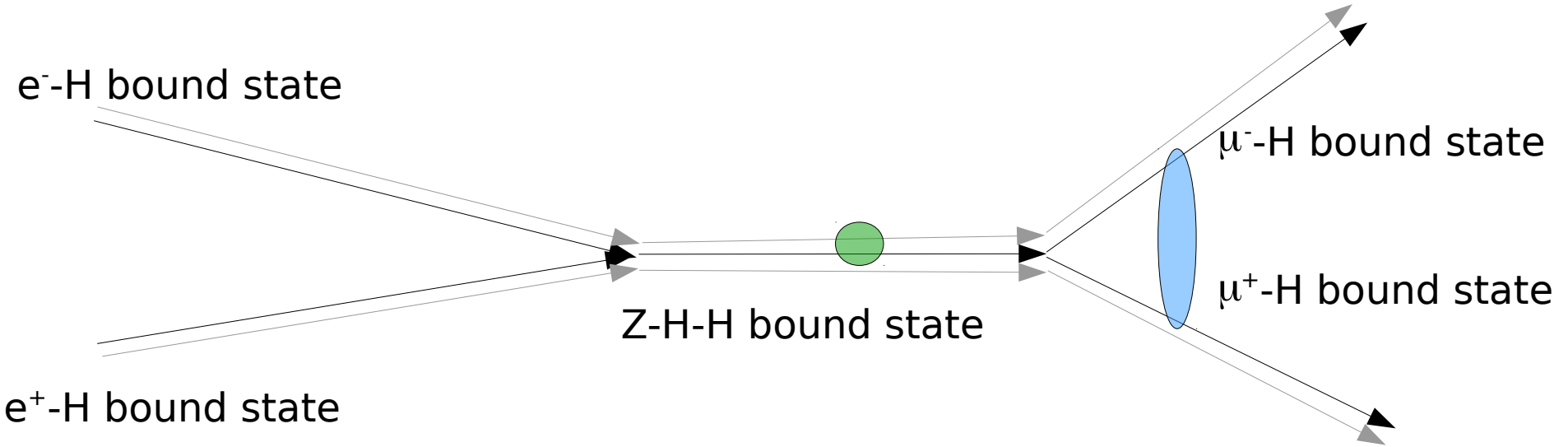


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  - New ones: Small, require more sensitivity

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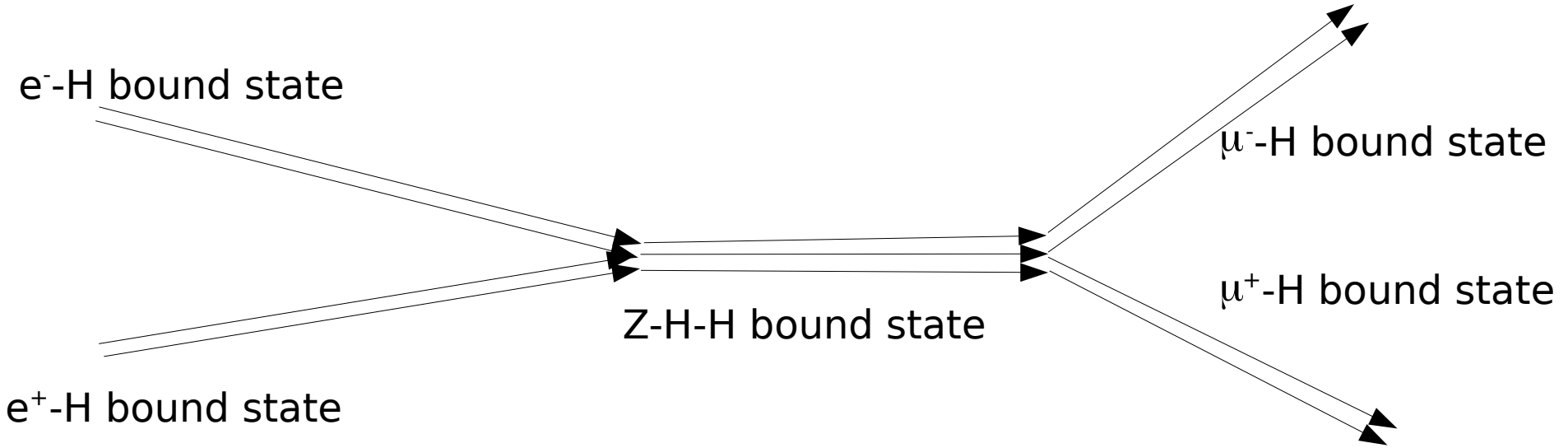


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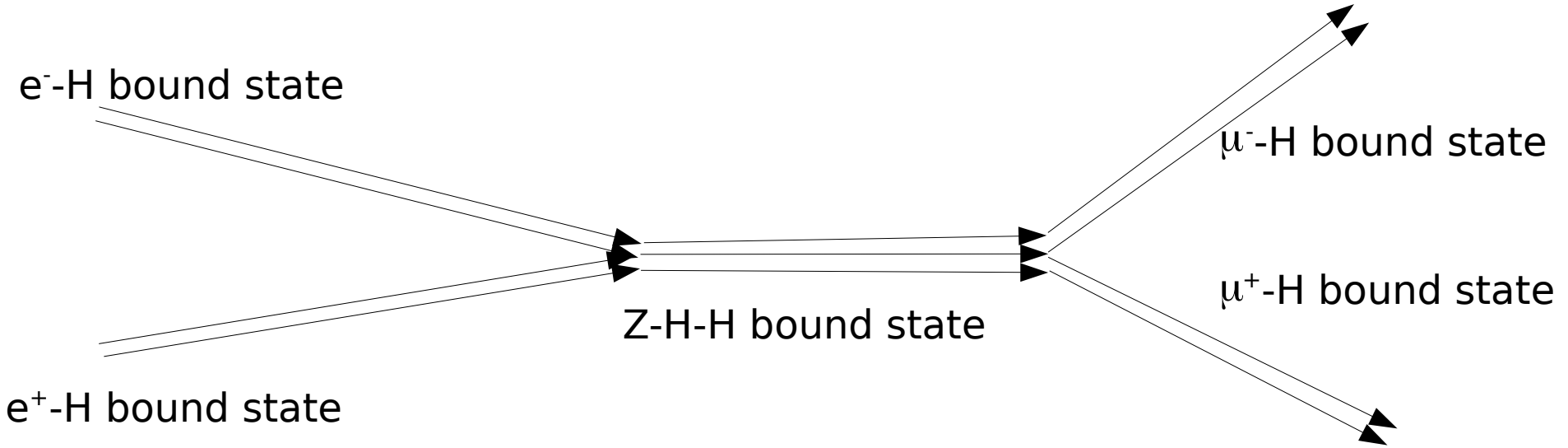


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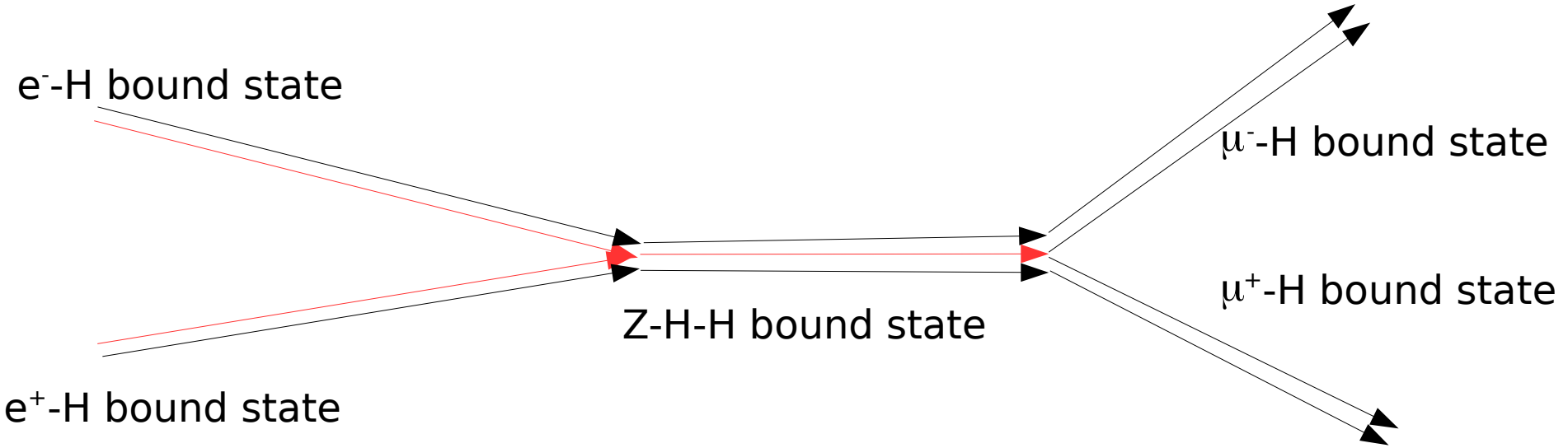


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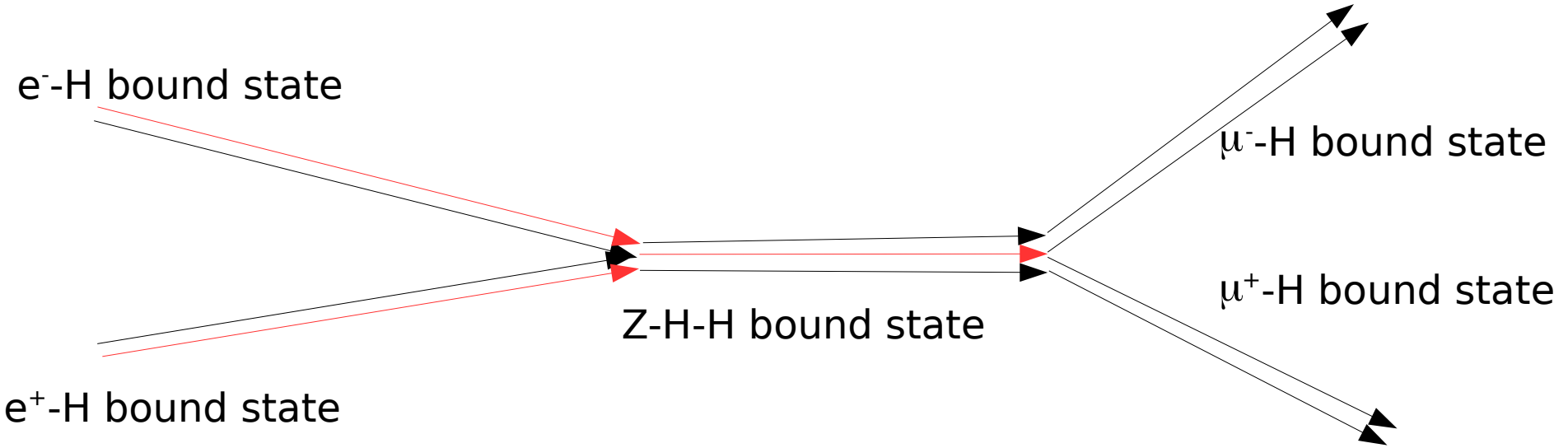


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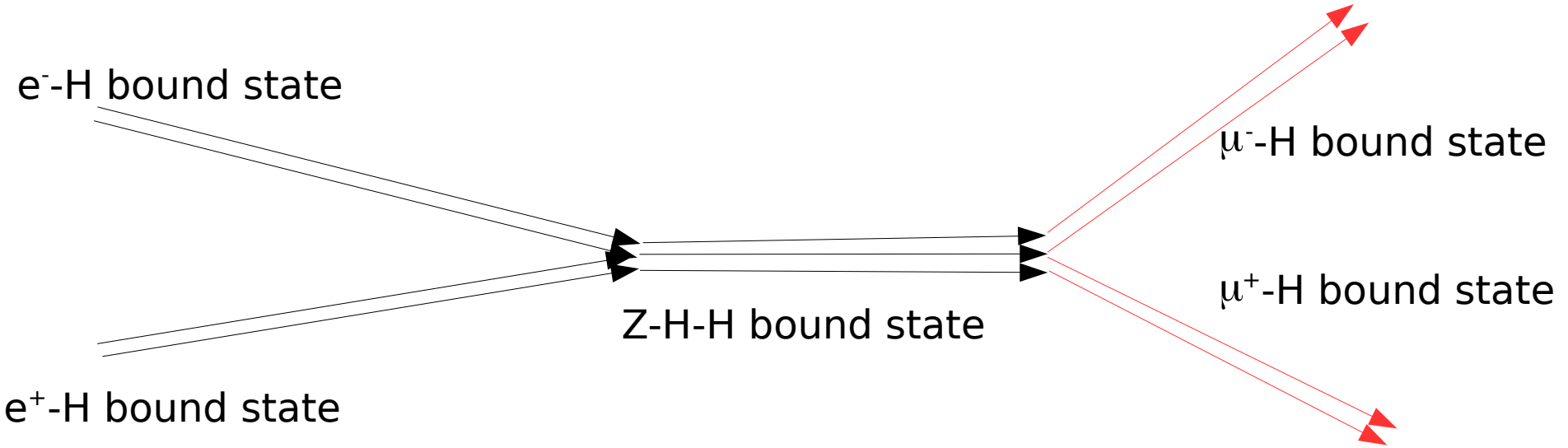


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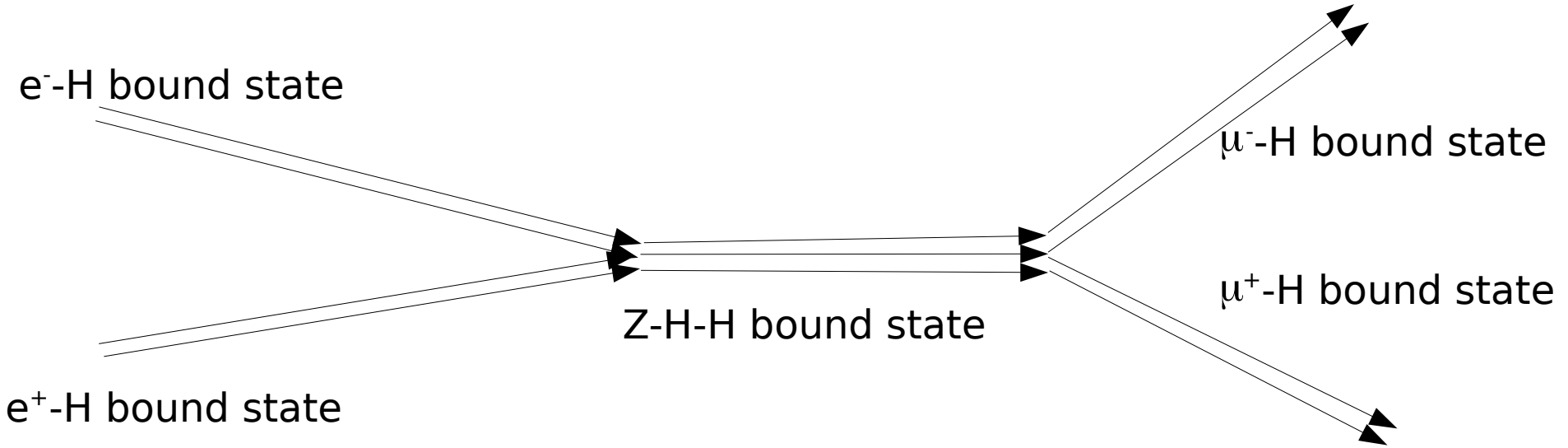


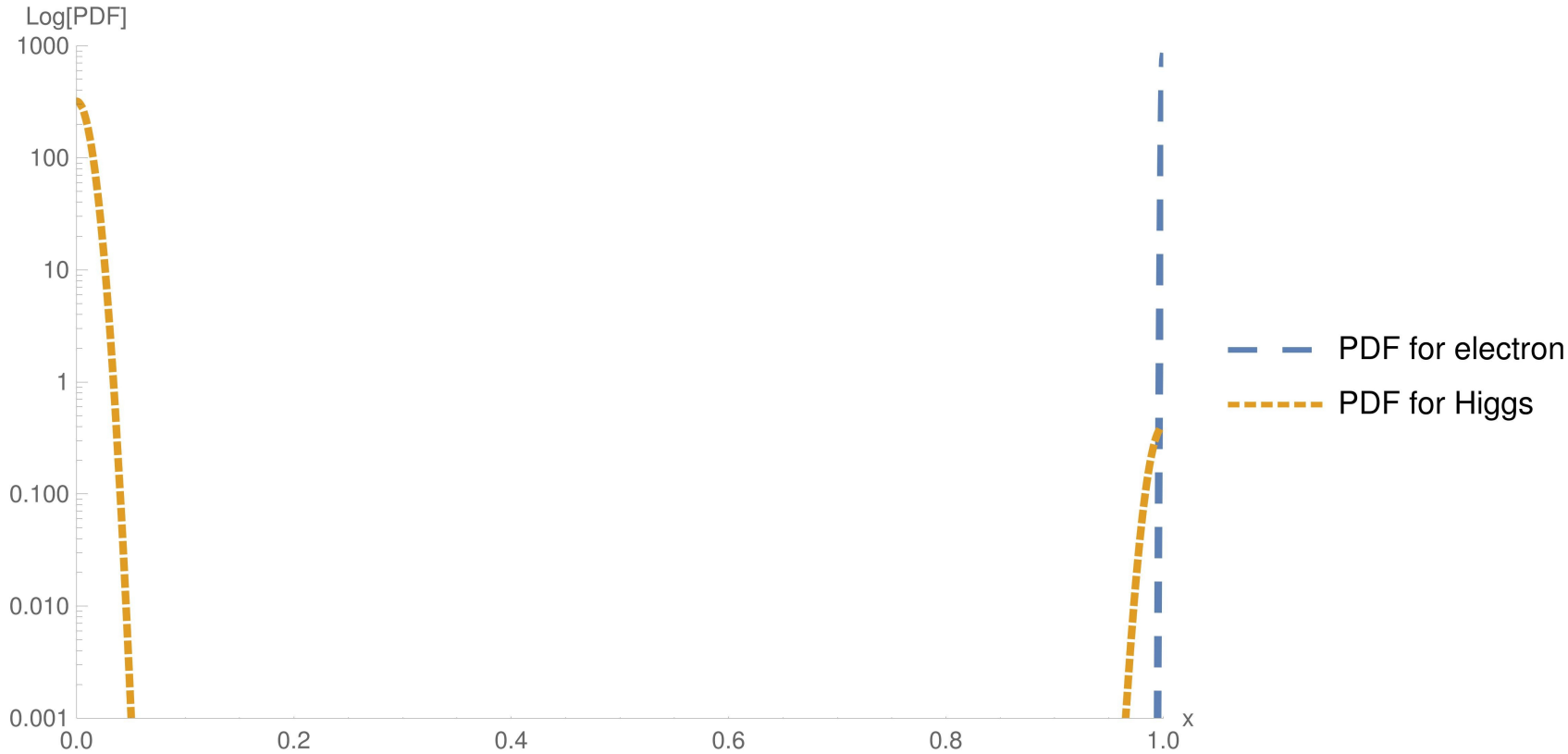

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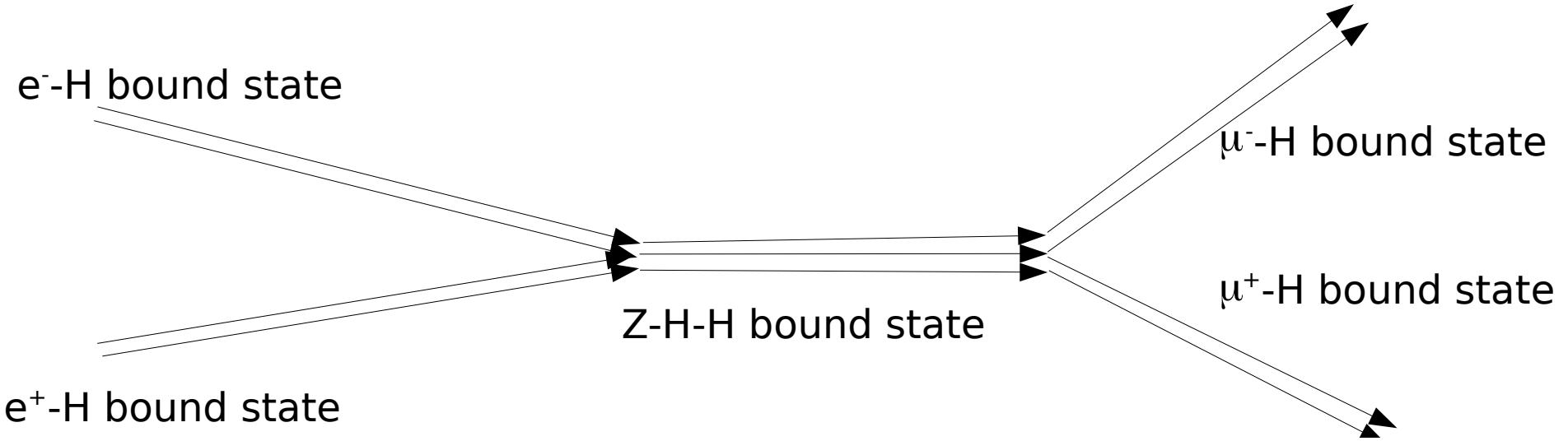


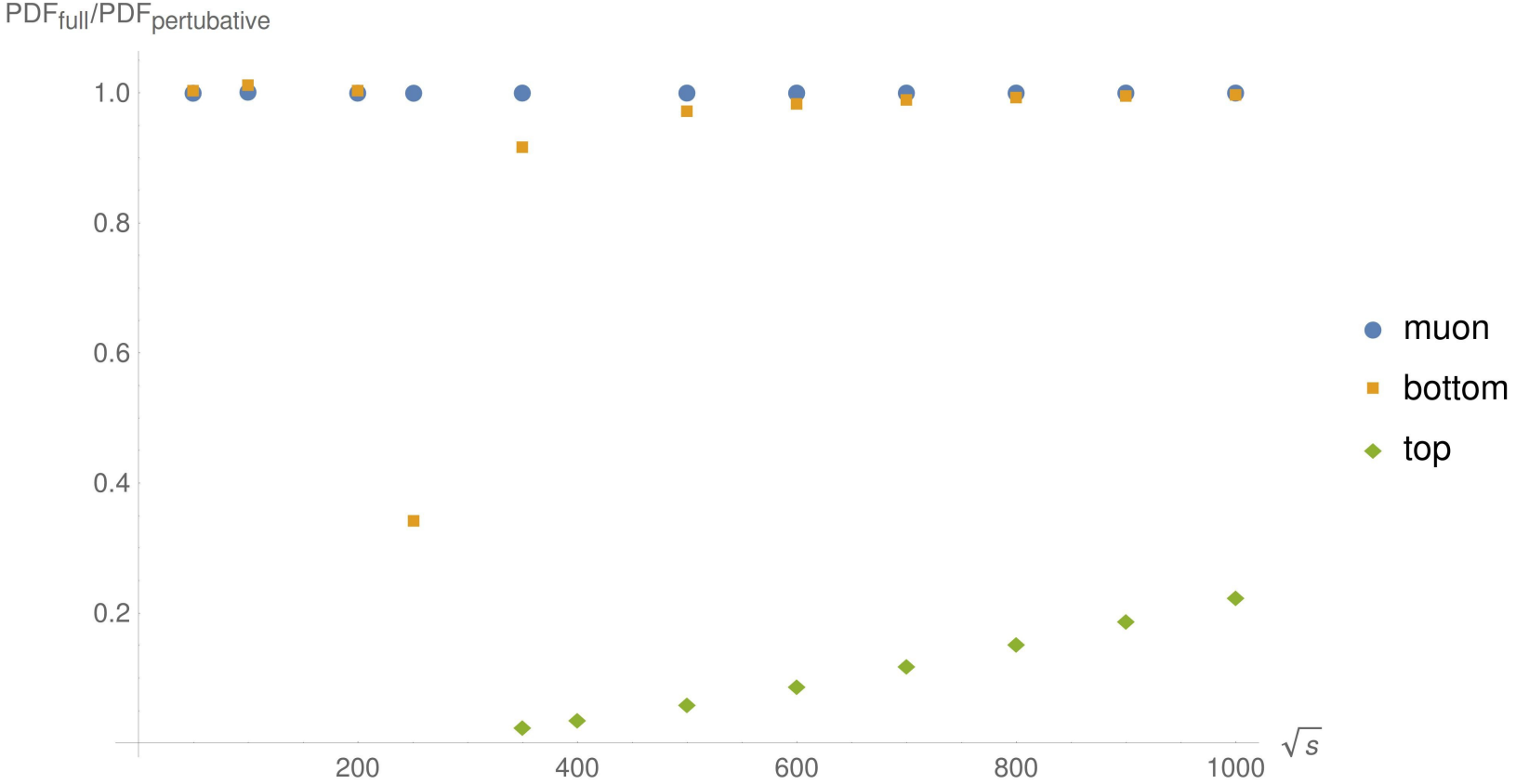

# Why it can matter beyond the standard model

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

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- Physical states are bound states
  - Observed in experiment
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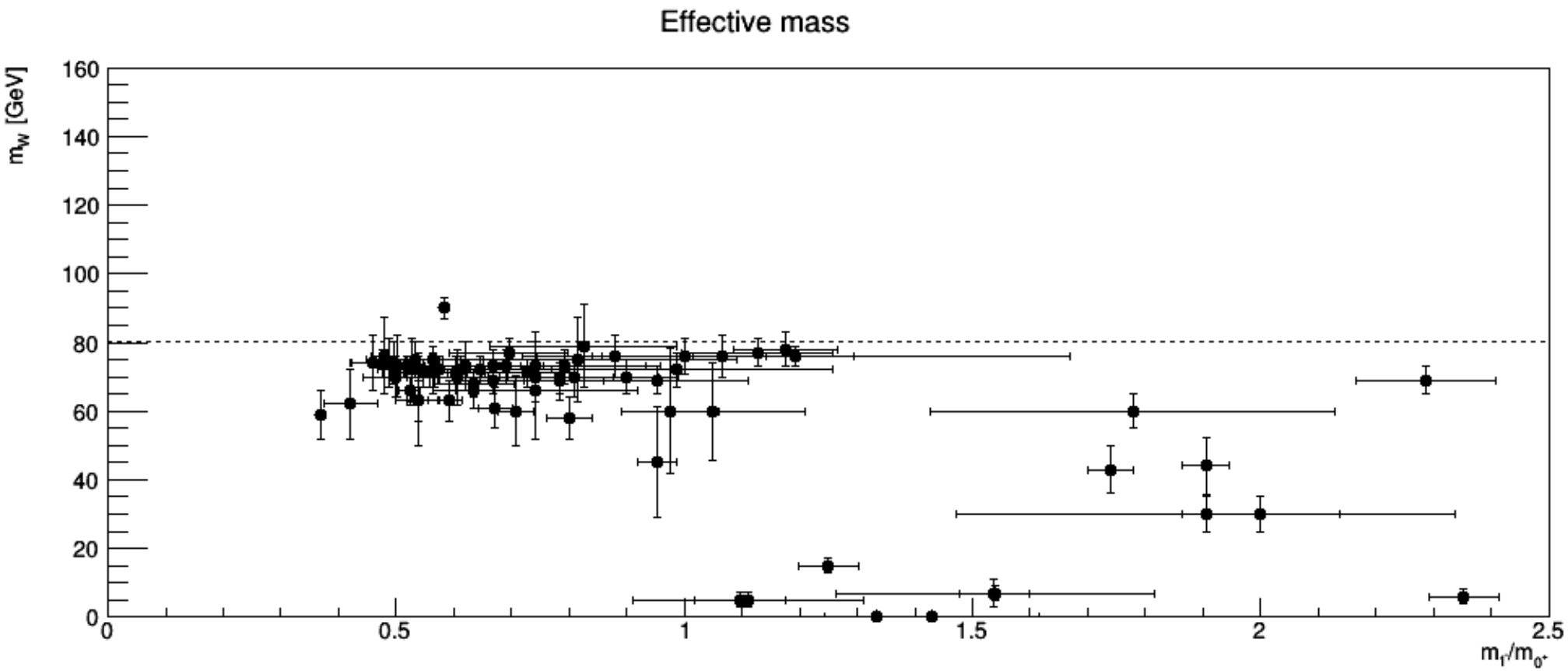
  - Fluctuations can invalidate it

# Limits

[Maas & Mufti JHEP 14]



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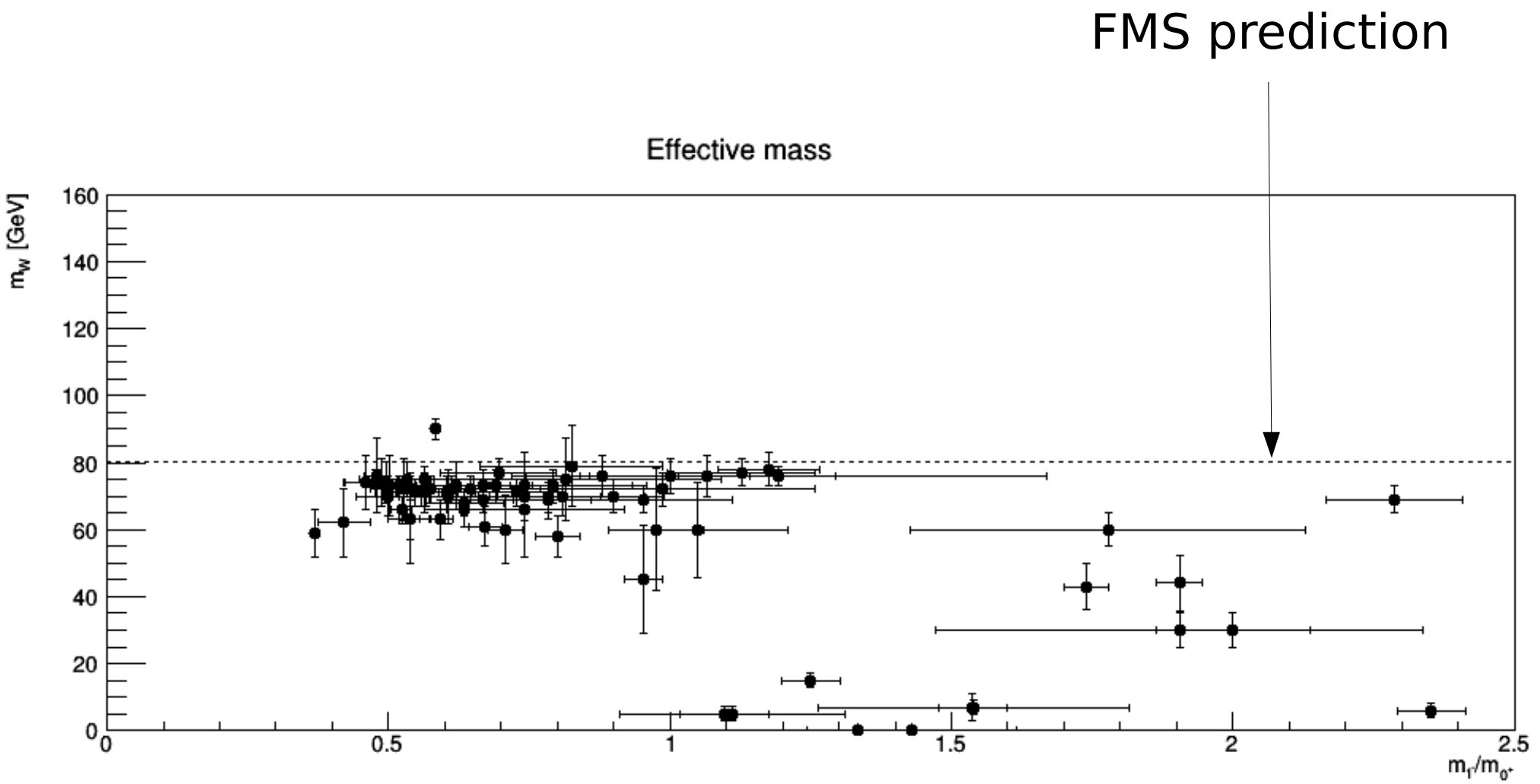

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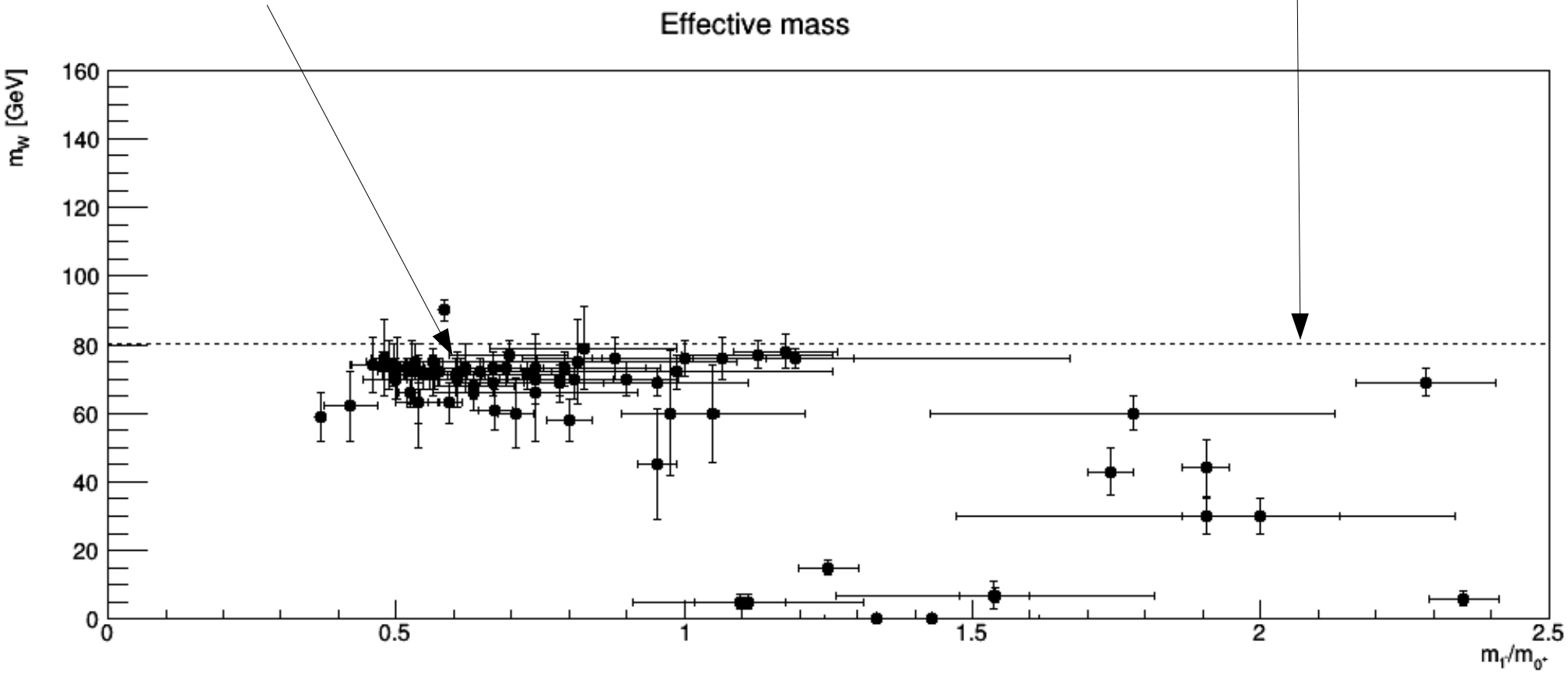

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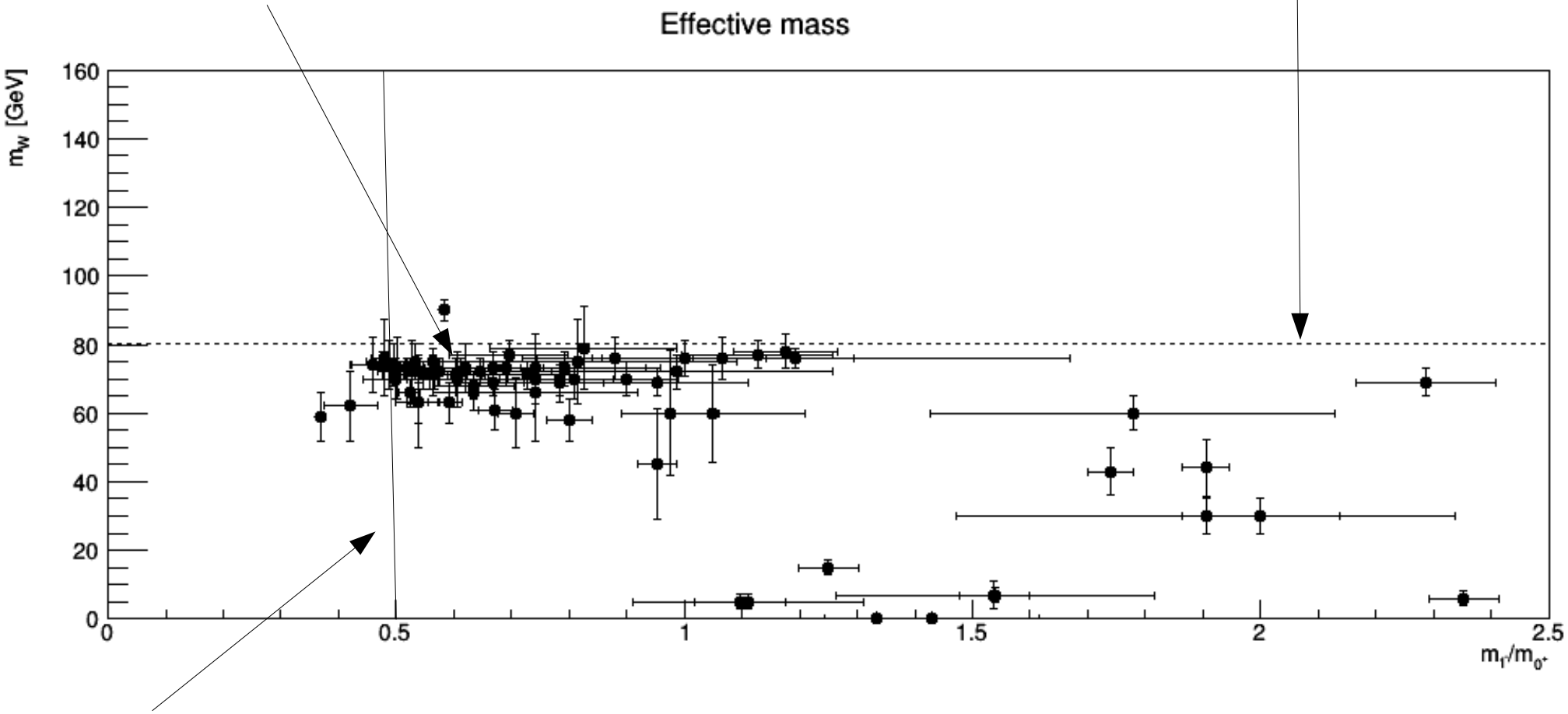


Elastic decay threshold

Higgs as resonance

Expensive, signal very bad

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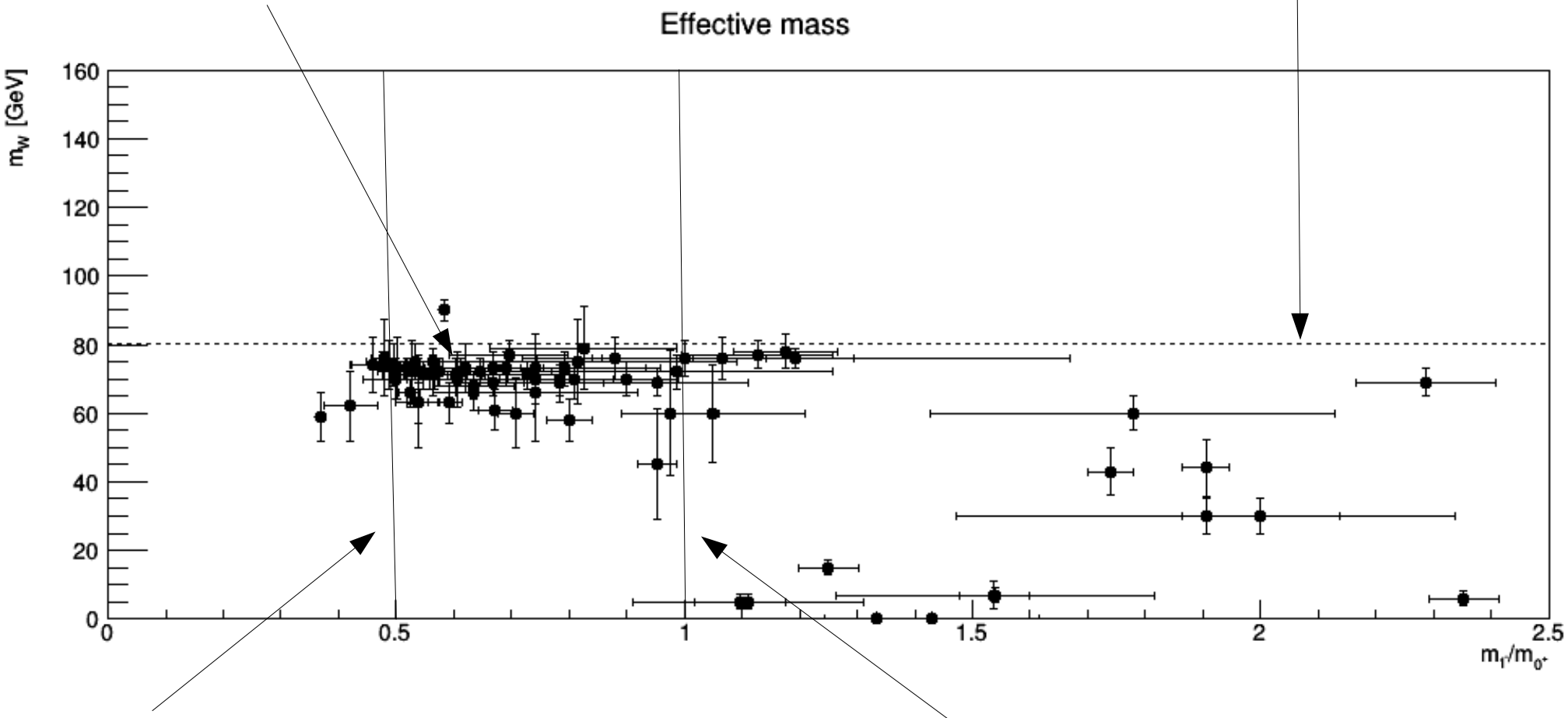
[Maas & Mufti JHEP 14]

FMS prediction

Too low: Finite volume effect

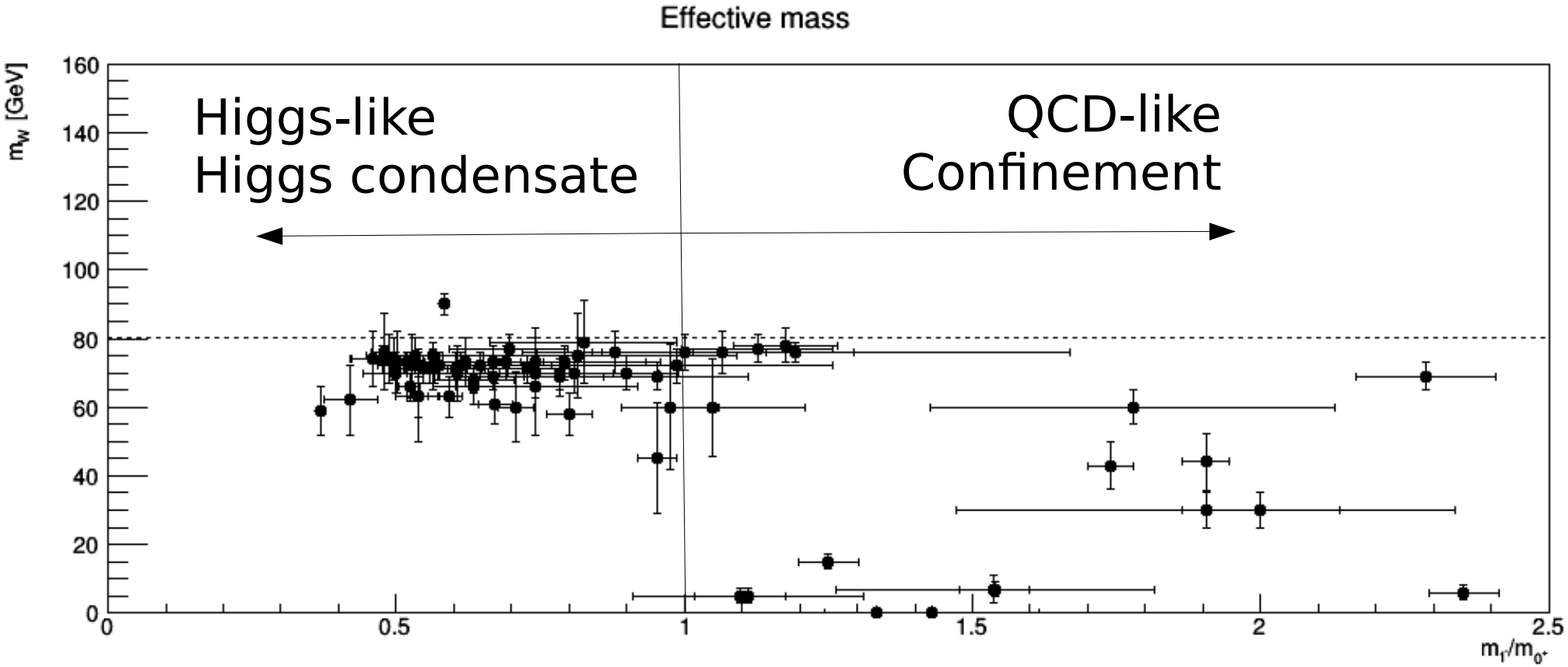



Elastic decay threshold
Higgs as resonance
Expensive, signal very bad

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

# Limits

[Maas & Mufti JHEP 14]



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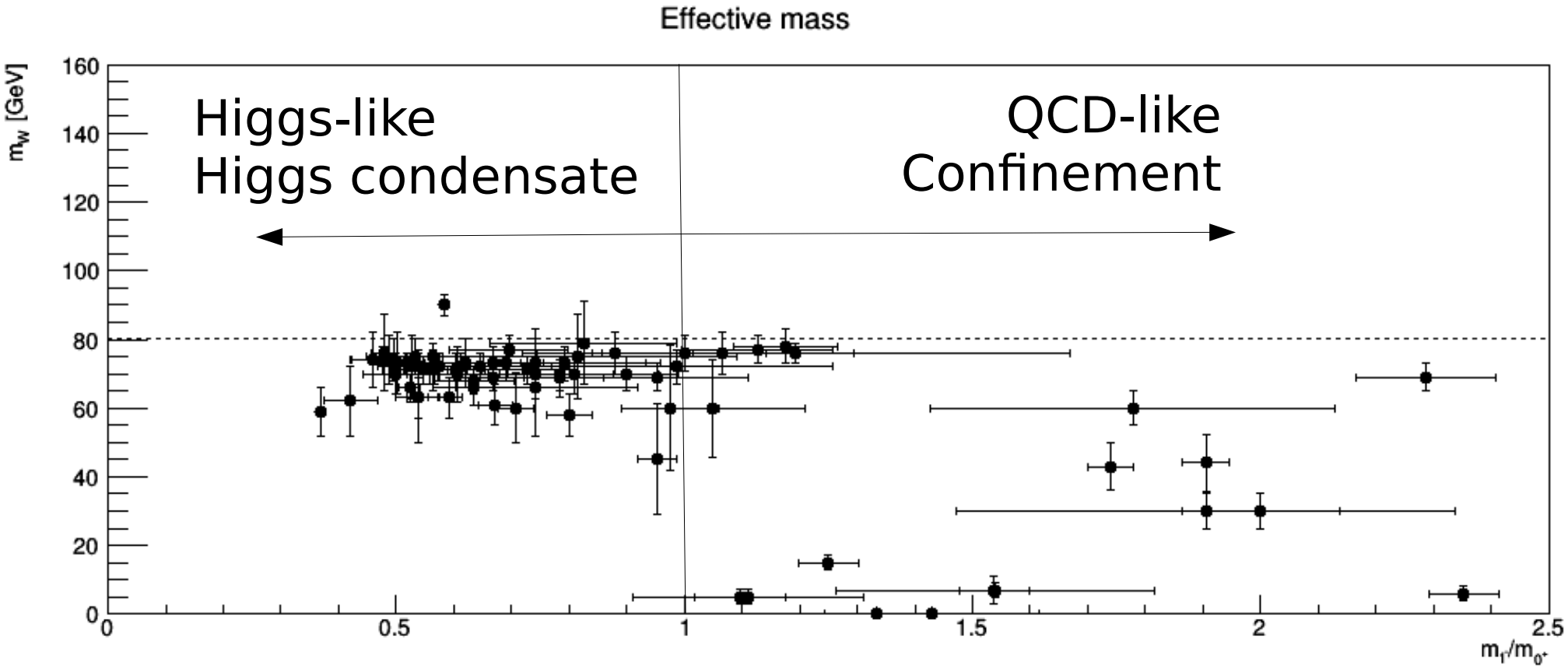
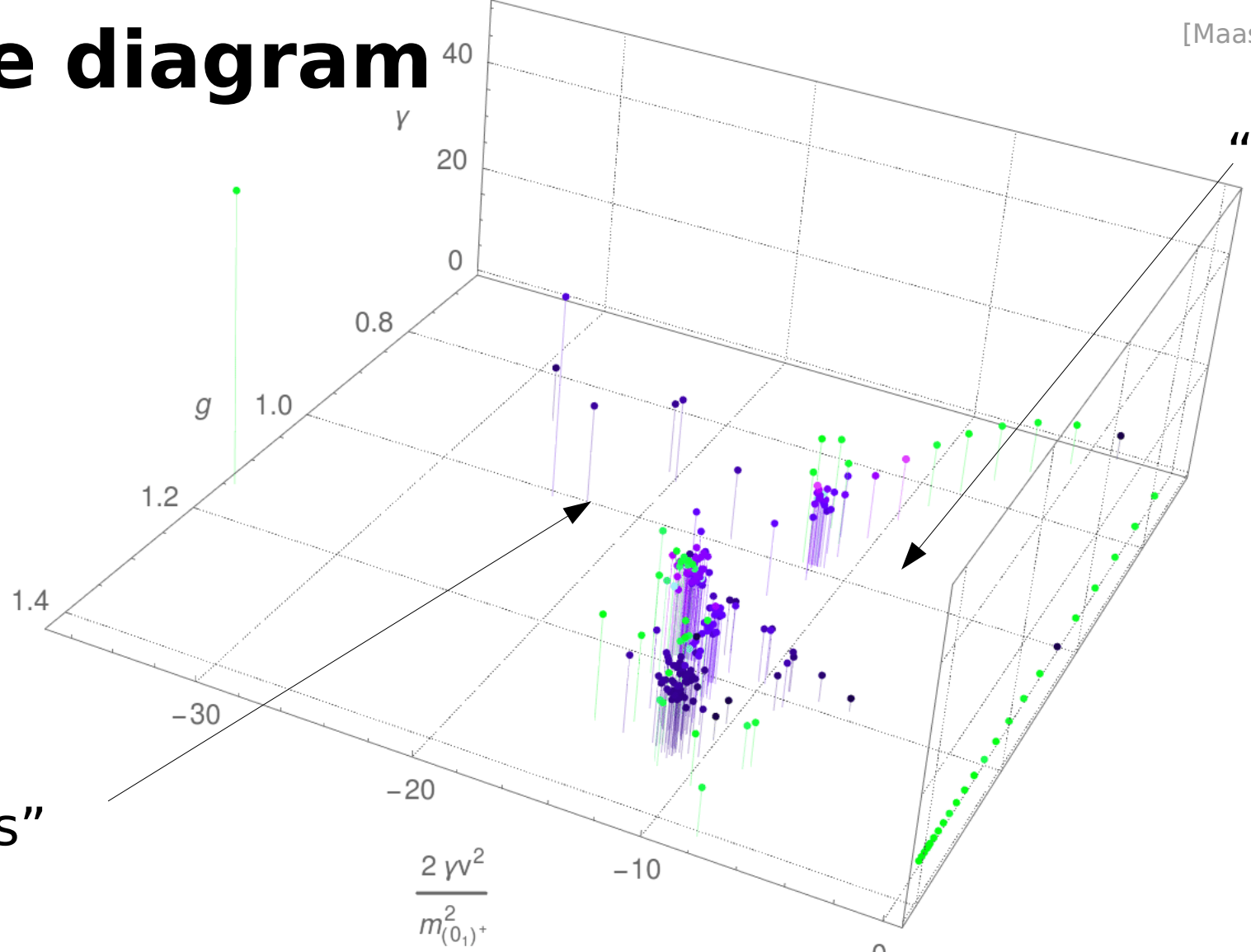



Does not coincide with weak/strong coupling transitions!

# Phase diagram

[Maas & Mufti PRD 15]




"QCD"

"Higgs"

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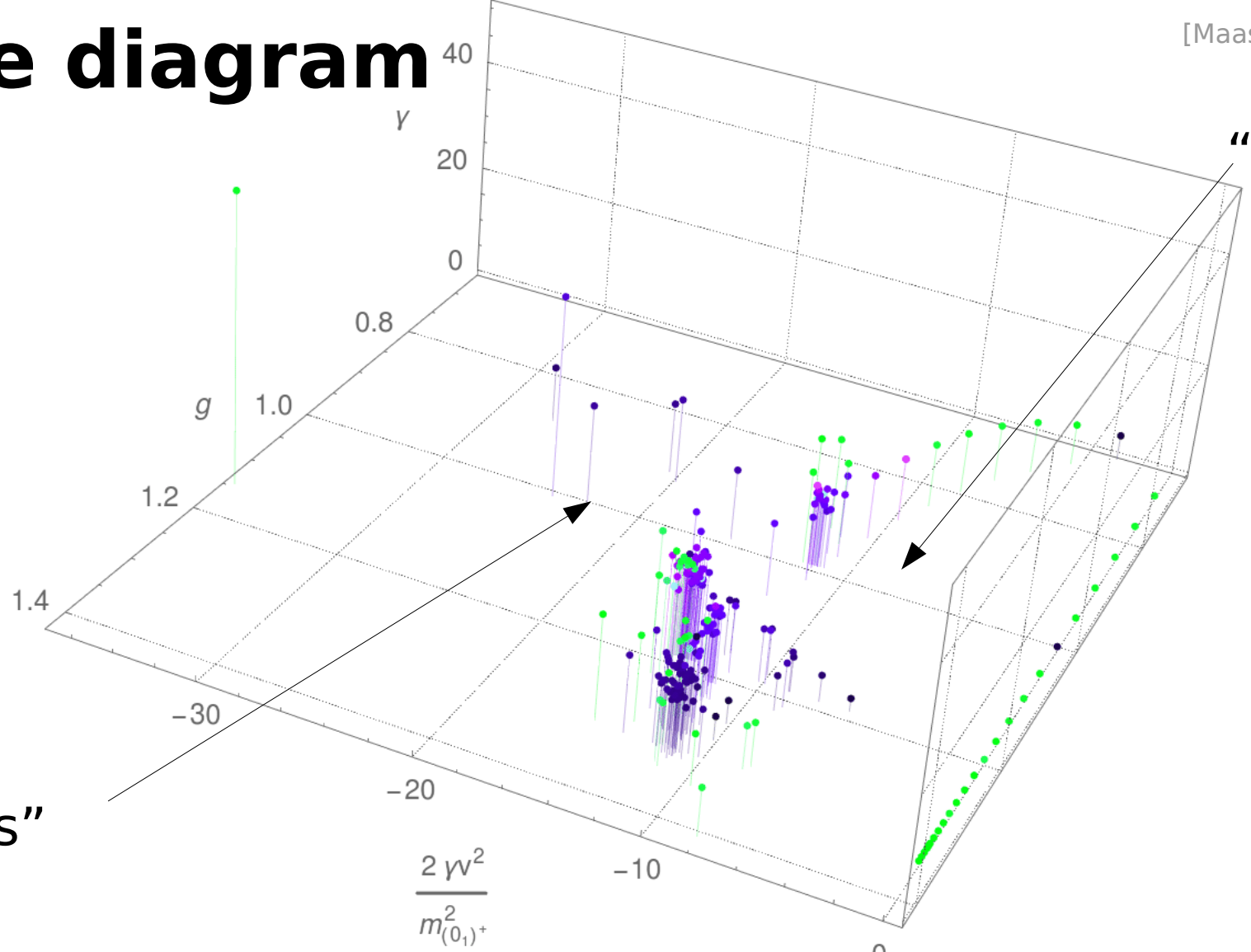


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- NB: Distinction subtle and gauge-dependent

# 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 MPLA 15, Maas & Mufti JHEP 14]
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  - Without Higgs: More subtle [Maas MPLA 15]

# Example 1: 2HDM

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

# Implications for 2HDM

[Maas MPLA 15,
Maas & Pedro PRD 16]

- Additional Higgs doublet
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[Maas MPLA 15,
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- FMS states for maximal custodial group:
  - Scalar sector Singlet

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- Discrete factor groups could yield doubling

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- 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 MPLA 15
Toerek & Maas '15, '16]

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  - ...or something else?

# Test for GUTs

[Maas MPLA 15
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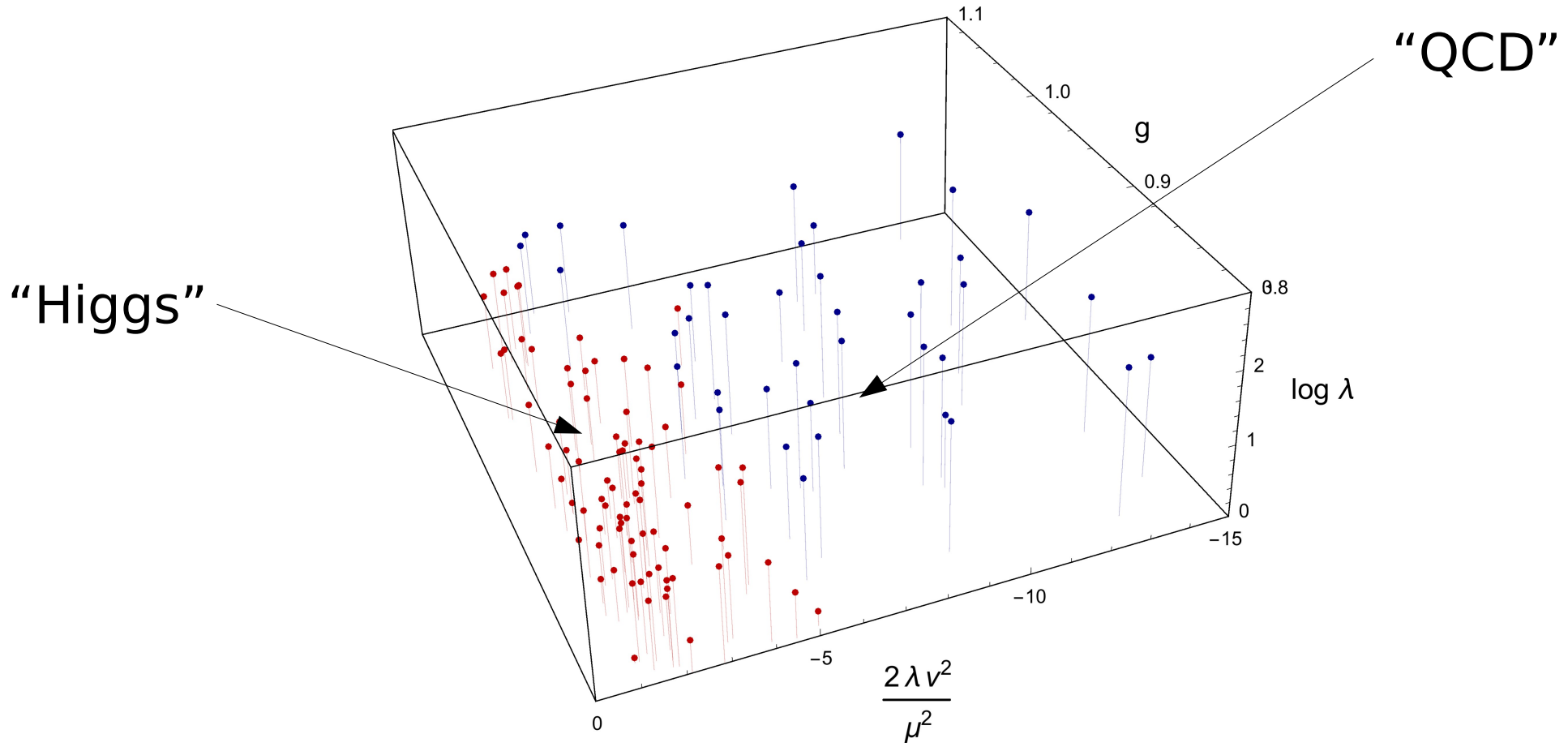


- Separation into Higgs-like and QCD-like

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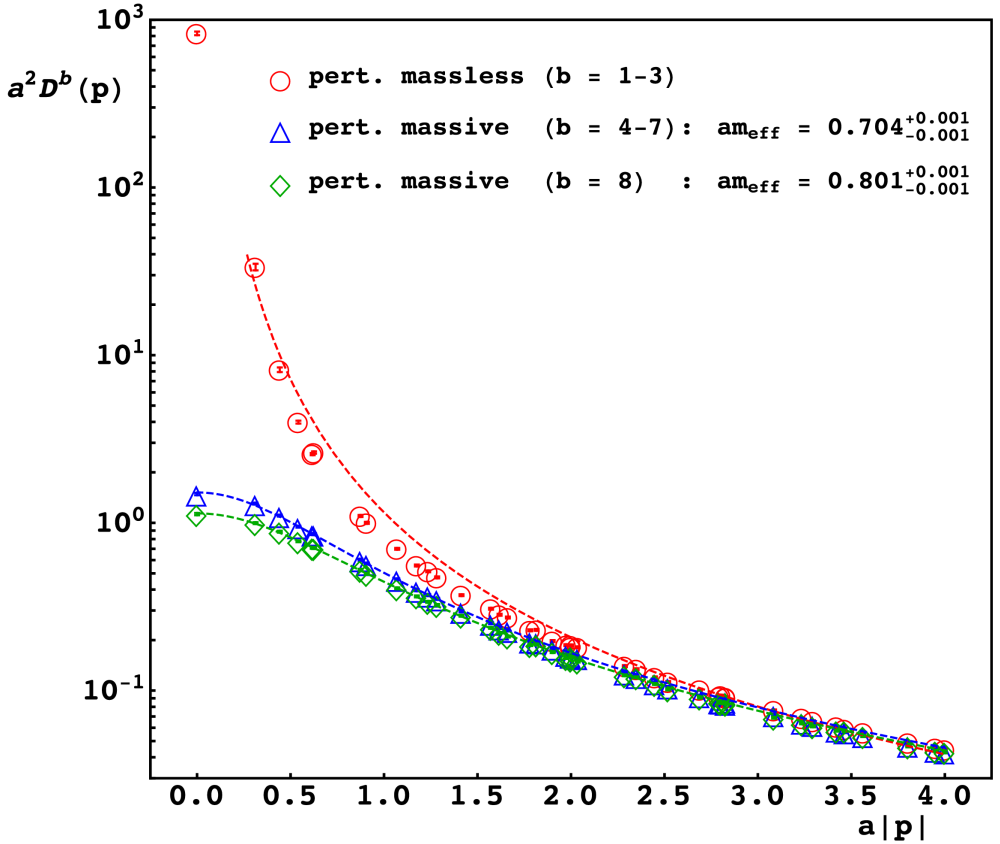


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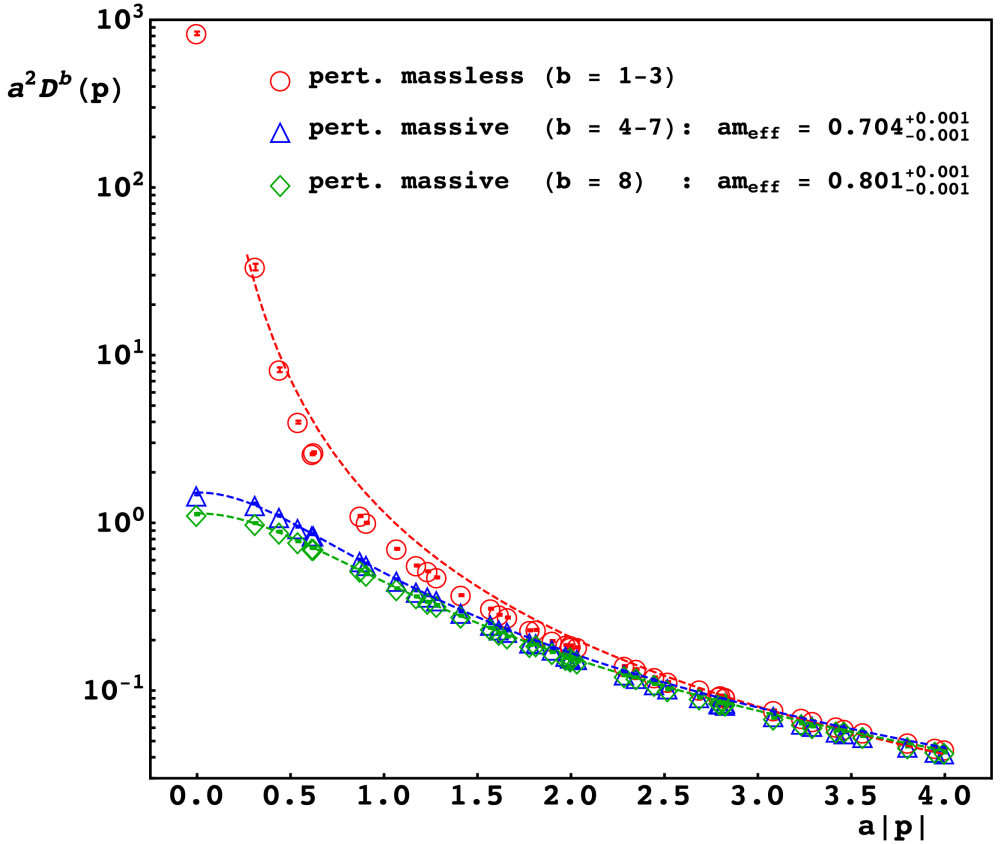


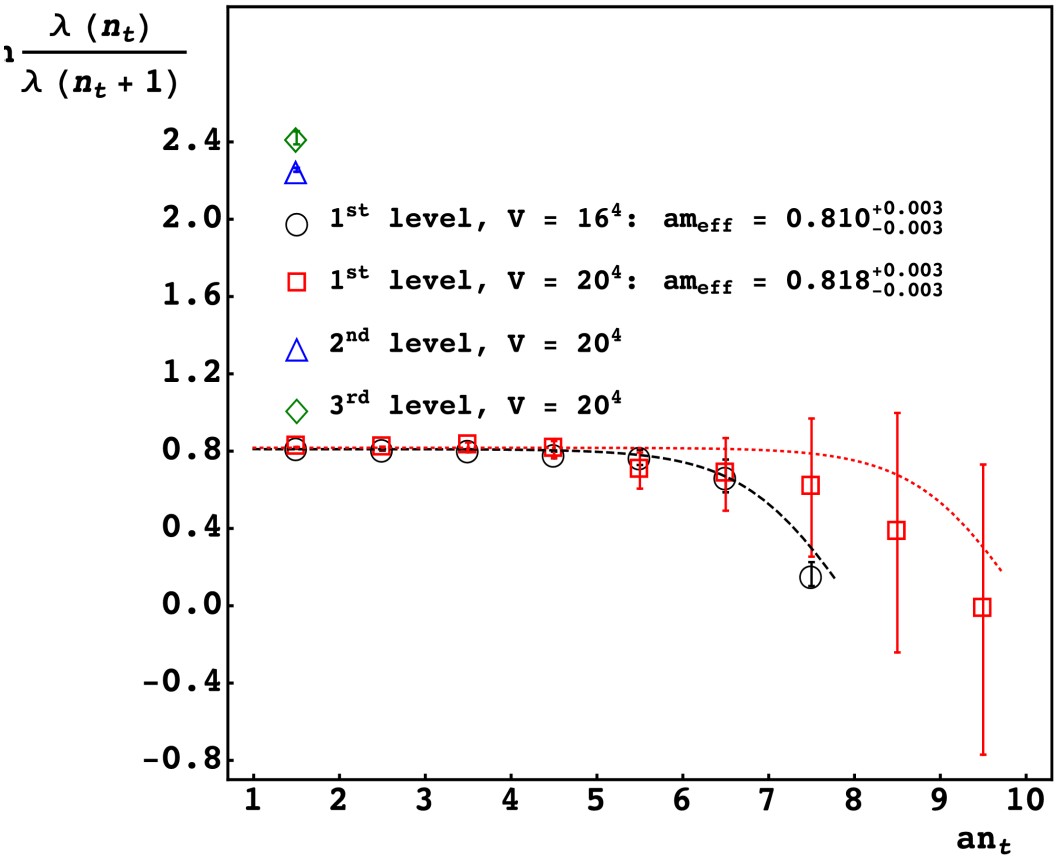


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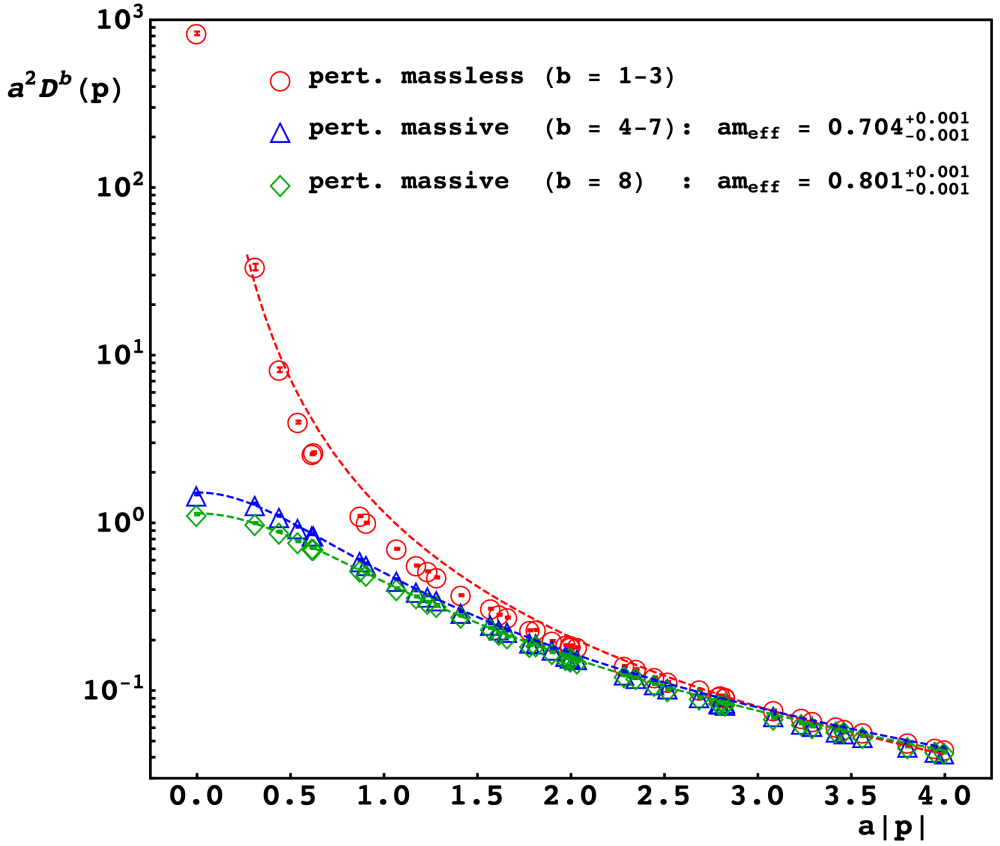


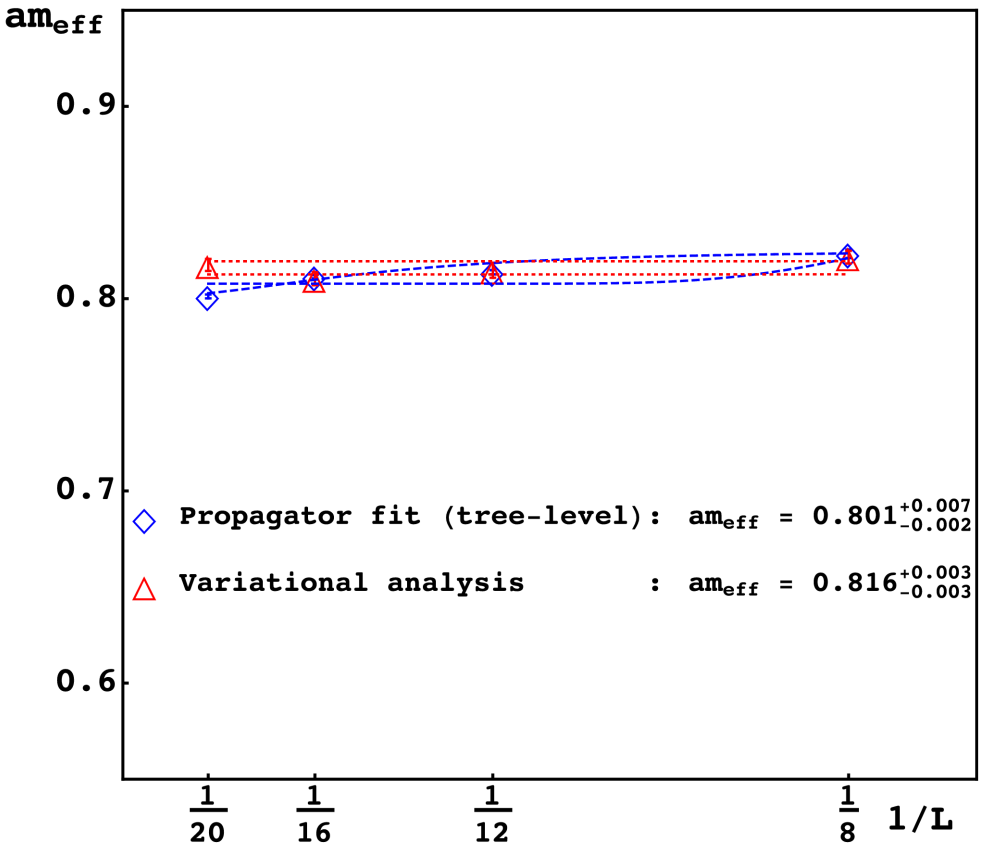


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# Summary

[Maas MPLA 12, 15]]

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  - 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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