# Weak and Higgs physics from the lattice

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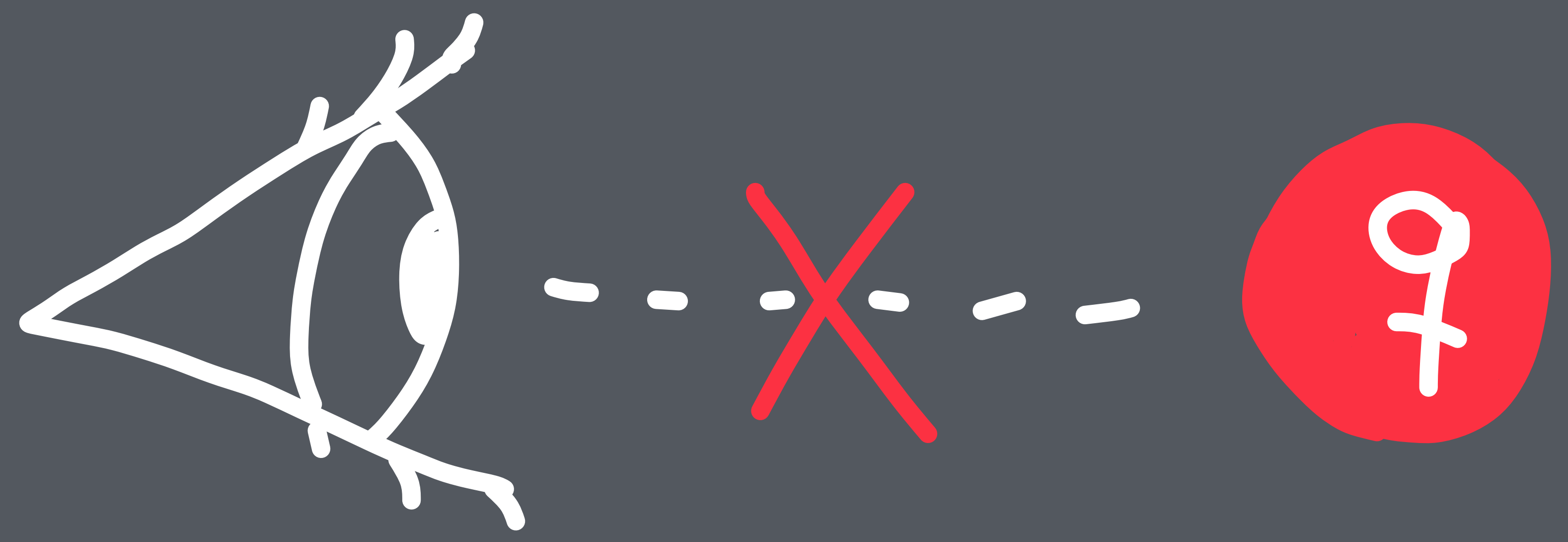
University of Edinburgh

# Introduction

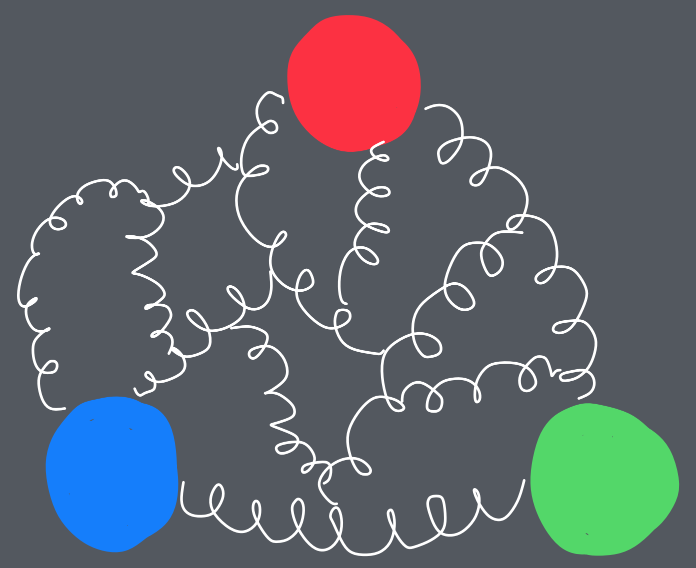
# Confinement in QCD (SU(3))

1. Observers are color blind



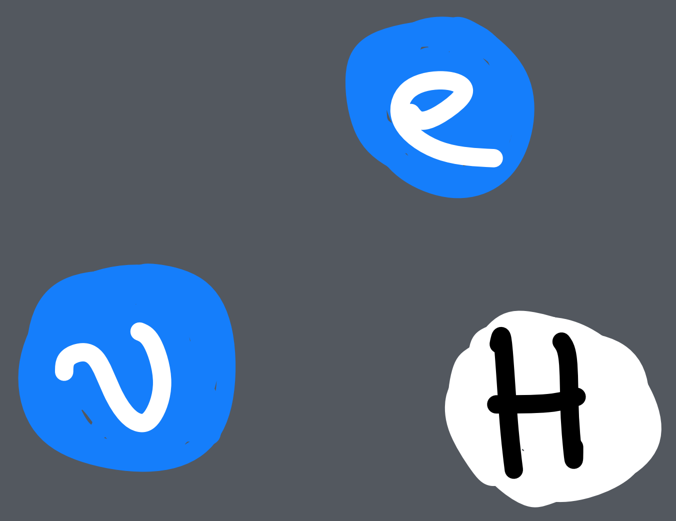
2. Physical objects are color singlets

3. Predictions require non-perturbative techniques



# Some claims about the weak interaction

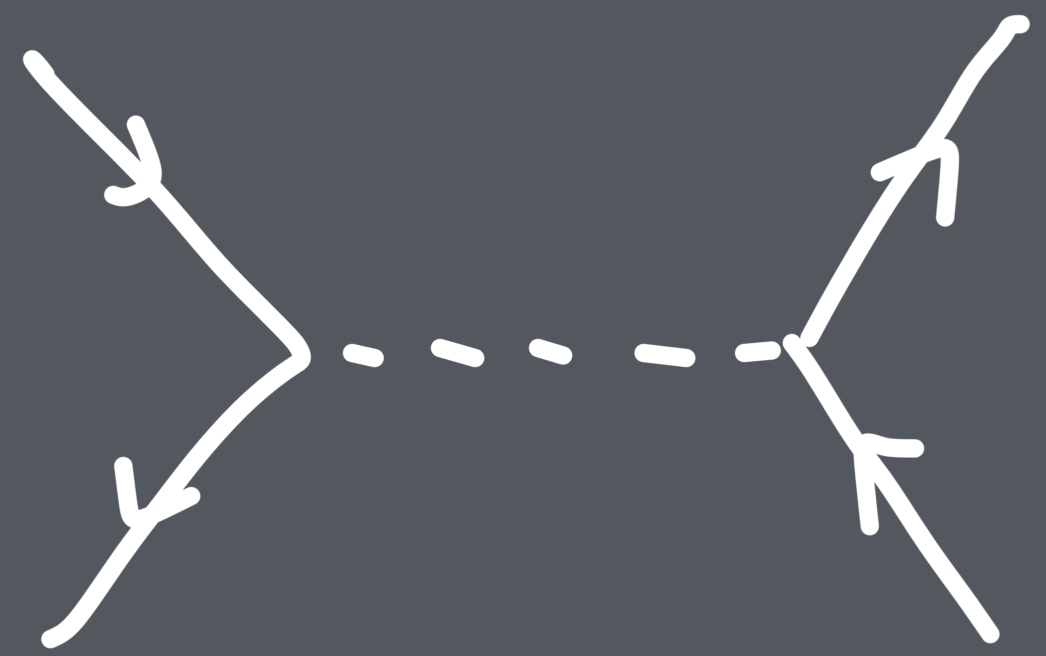
1. Observers are **not** weak isospin blind





2. Leptons and neutrinos are individually observable

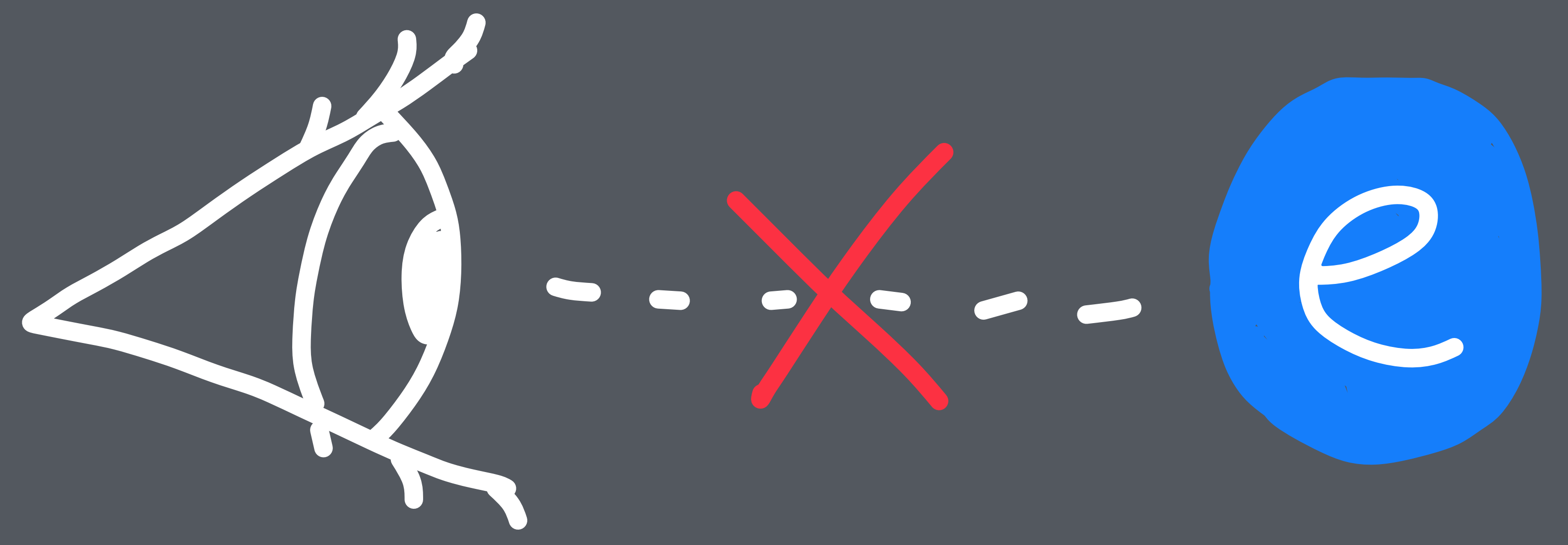
3. Perturbative treatment possible using the BRST construction



**Elitzur's theorem: Gauge symmetries cannot be spontaneously broken!**

# What would make more sense

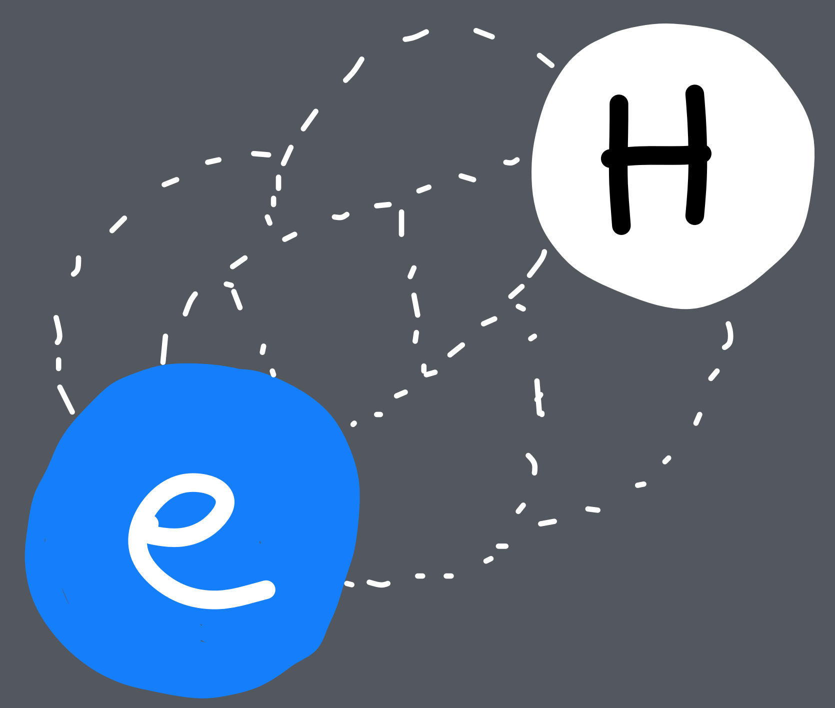
1. Observers are weak-isospin blind





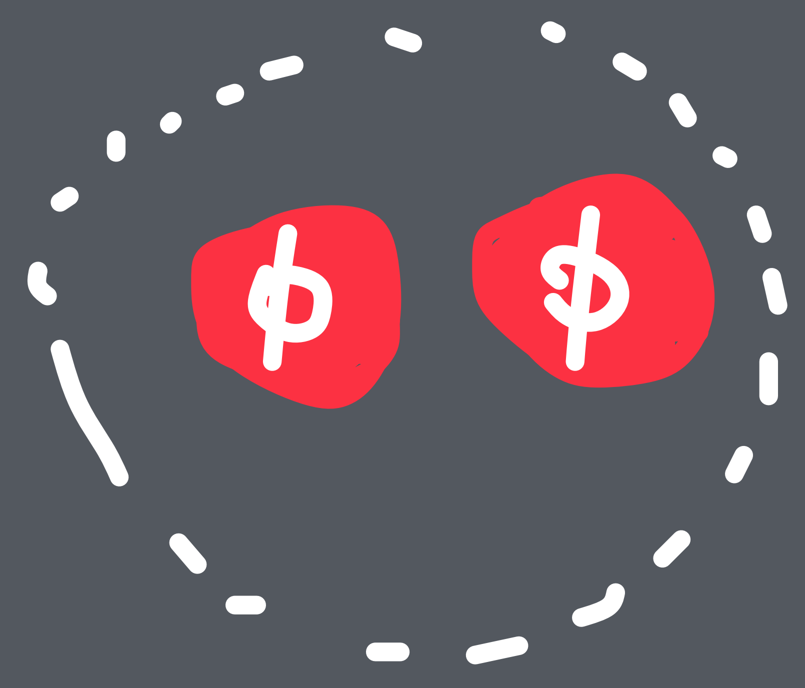
2. Physical fermions are composite

3. Predictions require non-perturbative techniques

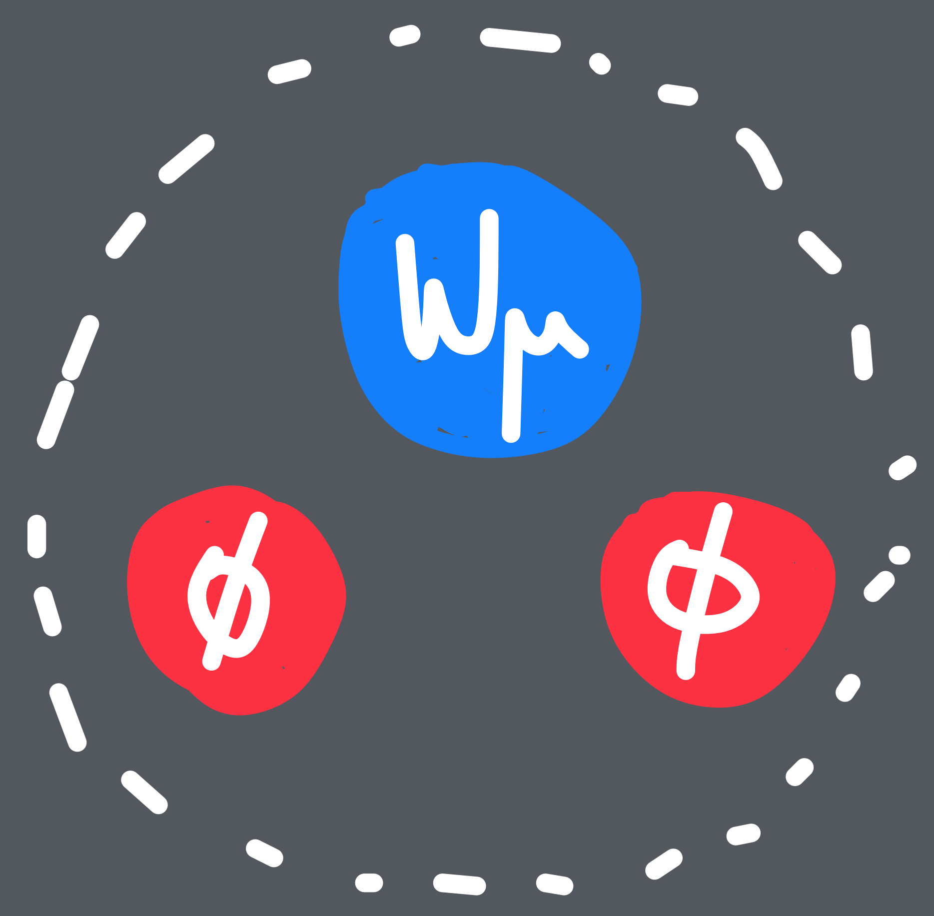


# More operators

SCALAR




VECTOR BOSON




LEFT-HANDED FERMION


[A. Maas, Prog. Part. Nucl. Phys., 2019, 1712.04721] and references therein

# Lattice Approach

Target theory

GAUGE SCALAR

$$\mathcal{L} = -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} + \frac{1}{2} \mathrm{tr}\left[ (D_\mu X^\dagger)(D^\mu X) \right]$$

$$- \lambda \left( \frac{1}{2} \mathrm{tr}(X^\dagger X) - f^2 \right)$$

+ LEFT-HANDED & RIGHT-HANDED FERMIONS

+ YUKAWA - COUPLINGS

LATTICE

PDFs:

GAUGE + SCALAR

SPECTROSCOPY:

GAUGE + SCALAR + LEFT-HANDED FERMIONS

[A. Maas, Prog. Part. Nucl. Phys., 2019, 1712.04721] and references therein

# Augment established perturbation theory

1) Write down an asymptotic state: It's has to be gauge invariant

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3) Expansion in $v$ yields PT result plus corrections

$$\langle O_\phi^\dagger O_\phi \rangle = v^2 n_i n_j \langle O_\eta^\dagger O_\eta \rangle + O(v)$$

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3) Expansion in $v$ yields PT result plus corrections

$$\langle O_\phi^\dagger O_\phi \rangle = \underbrace{v^2 n_i n_j \langle O_h^\dagger O_h \rangle}_{\text{FMS mechanism}} + O(v)$$

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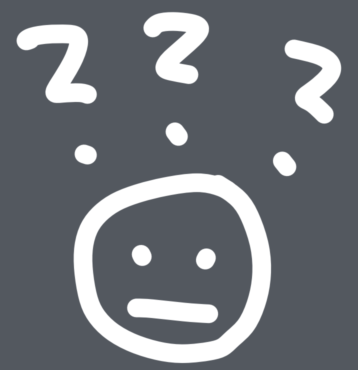
↑ Actual Standard Model effects

[A. Maas, Prog. Part. Nucl. Phys., 2019, 1712.04721] and references therein

# Why you should care



To not confuse a BSM with NP SM effects

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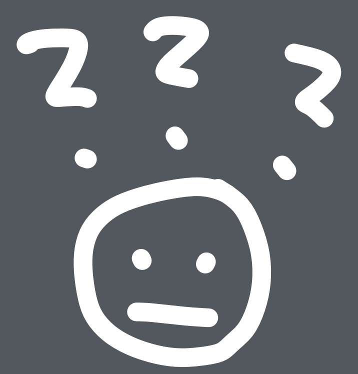

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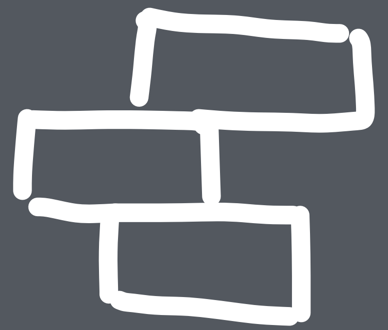

To correctly build extensions of the SM on top of the weak sector

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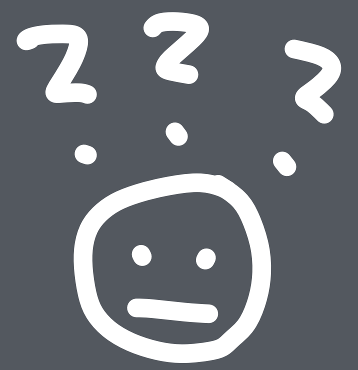

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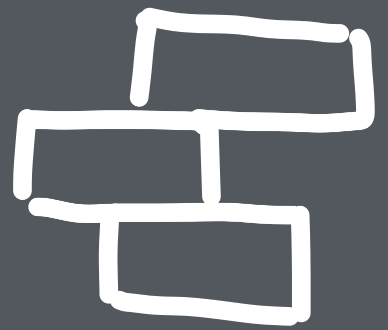

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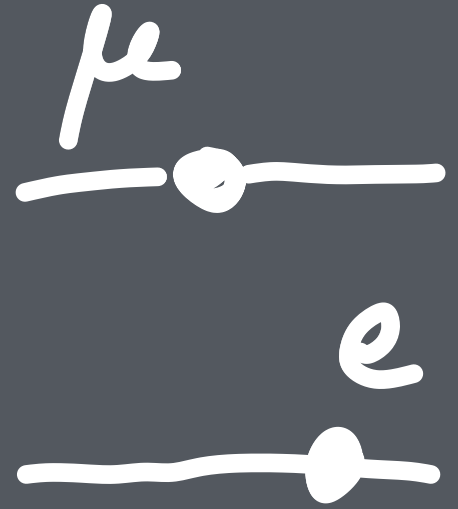
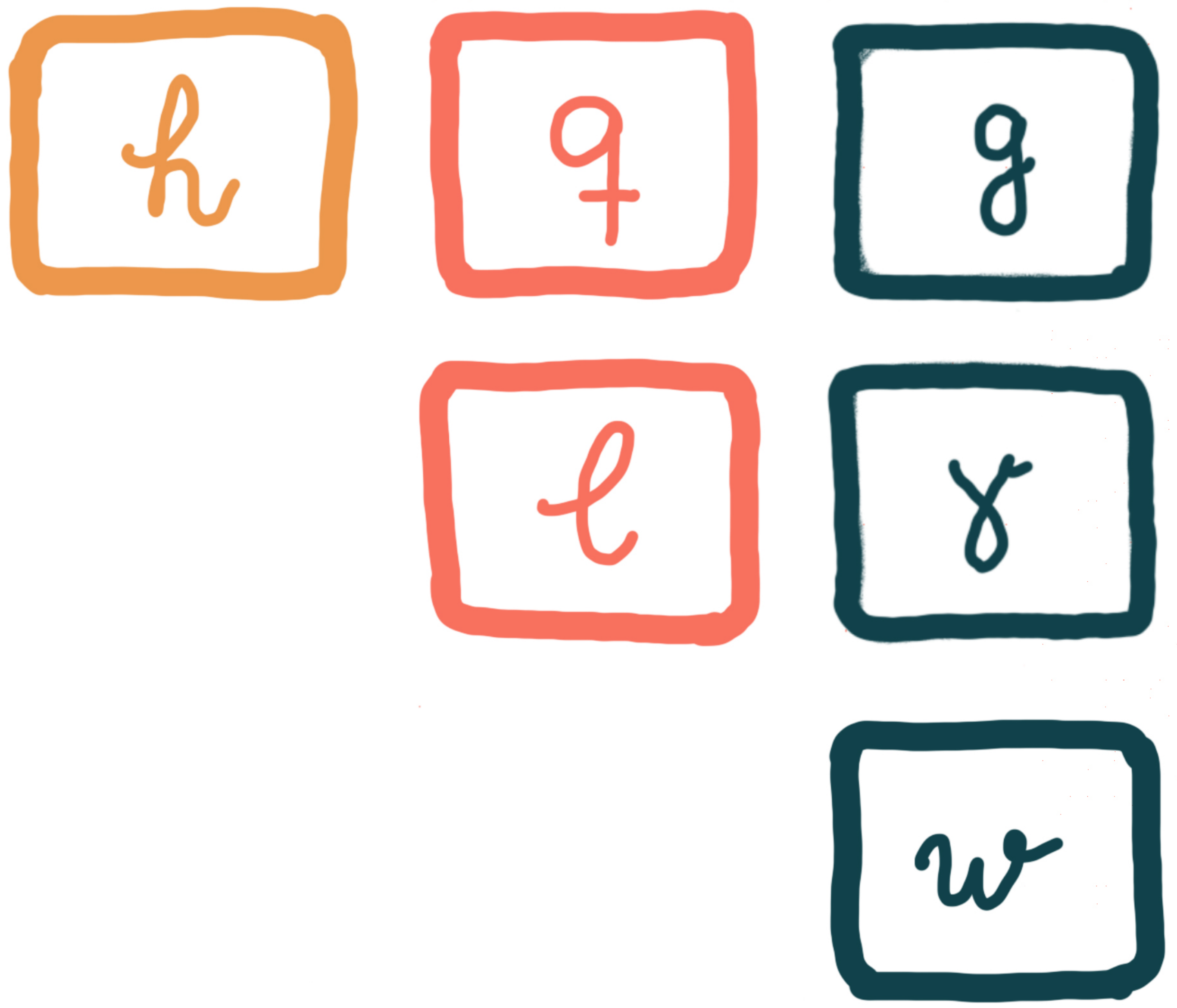
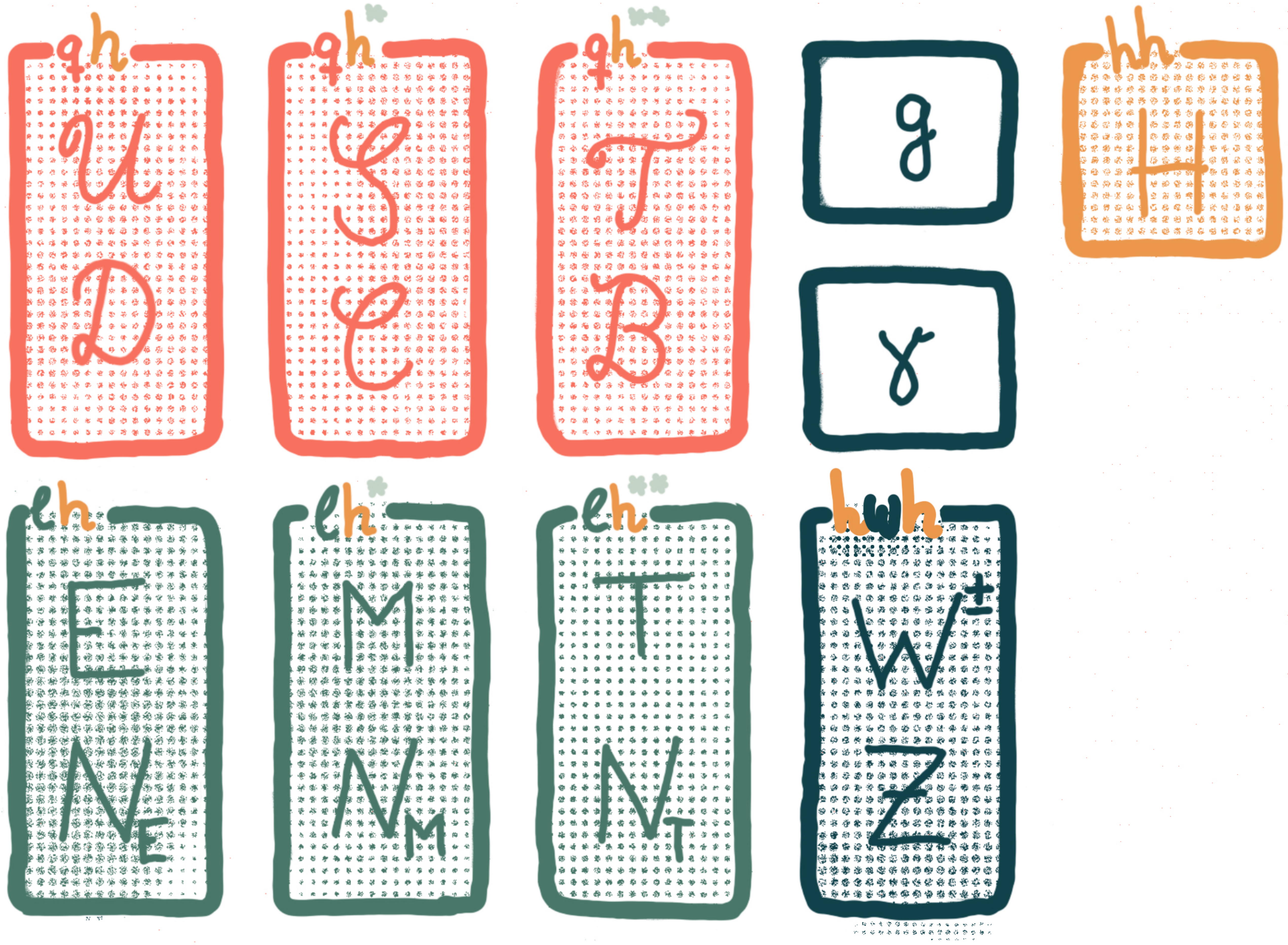



It is consistent with the PDG that lepton & quark generations are levels of excited states -> compute CKM/PMNS matrix elements from the lattice

[Egger et. al., Mod.Phys.Lett. A, 2017, 1701.02881]

# The standard model but simpler

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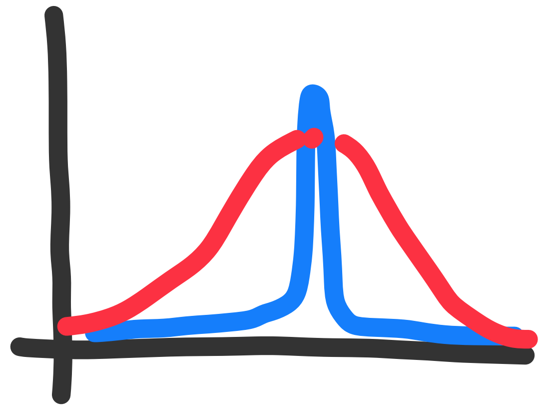
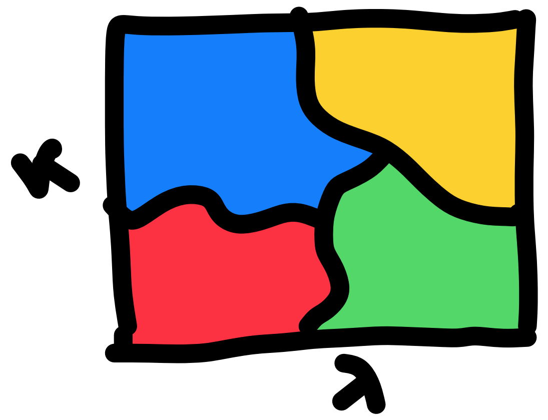
# Outline



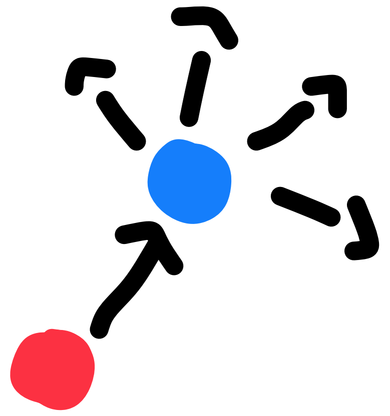
1. Quasi-PDFs

*How much internal structure do we see theoretically?*



2. Physical Phases and Mass Hierarchies in the system

*How does the theory behave?*



3. Cross-sections obtained from spectral densities

*Identify deviations from perturbation theory*

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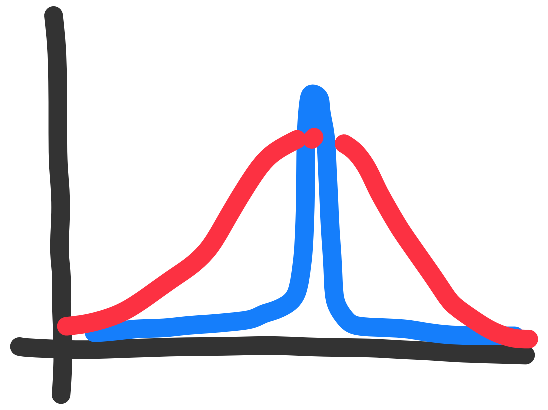

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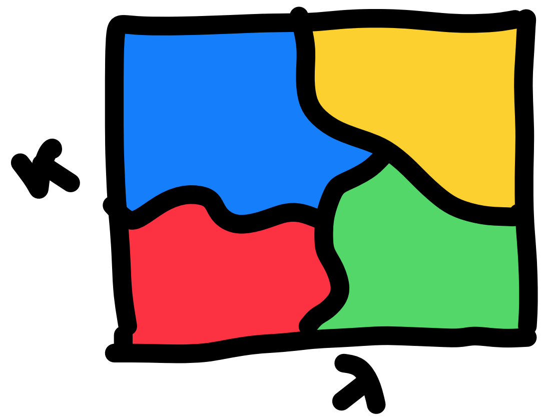

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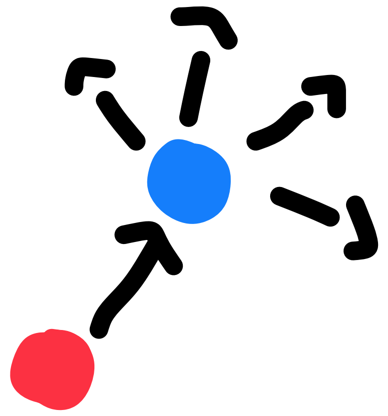


3. Cross-sections obtained from spectral densities

   *Identify deviations from perturbation theory*

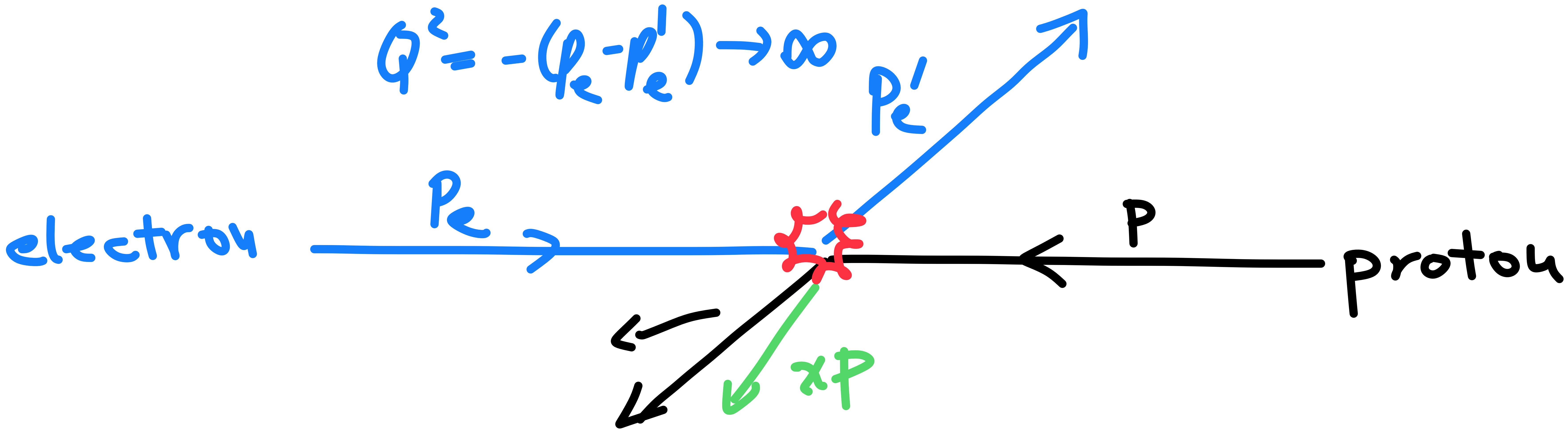
See excited states!

# Parton Distribution Functions for electroweak physics

# Parton Distribution Functions

Example: Deep-inelastic scattering of the proton

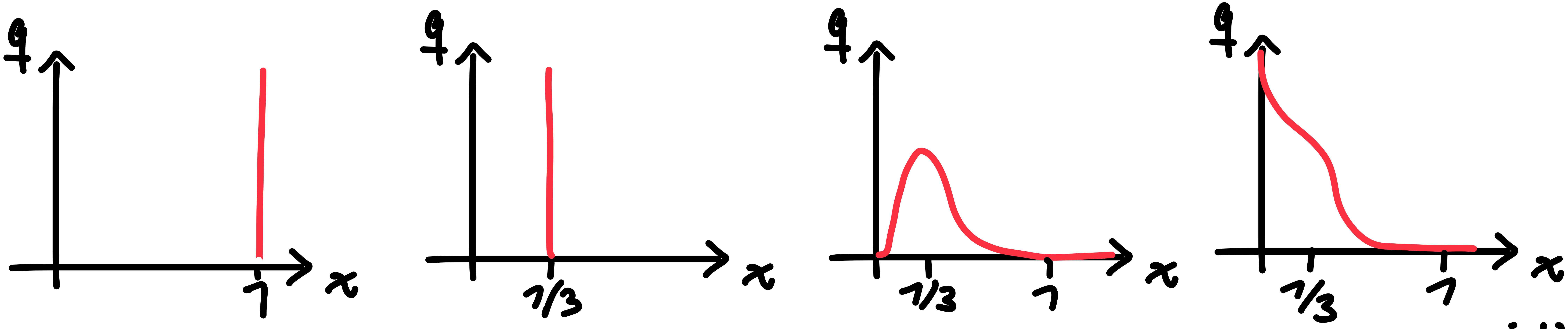
- Shows the distribution of a **single constituent momentum** relative to the total momentum
- Is computed in the Bjorken Limit: Infinite momentum transfer



# Parton Distribution Functions

Example: Deep-inelastic scattering of the proton

- Contains information about the **internal structure** of the proton




A fundamental proton

A proton consisting of 3 free quarks

A proton consisting of 3 bound quarks

A proton consisting of
* 3 bound quarks
* sea quarks
* self-interacting gluons

# Lattice PDFs: Quasi-PDFs

- We cannot achieve the Bjorken limit: Infinite momentum
- Instead we use large but **finite momenta**

PDF: $q(x)$ from structure functions in Bjorken limit

Quasi-PDF: $\tilde{q}(x, P_3) = \int_{-\infty}^{\infty} \frac{dz}{4\pi} e^{-izxP_3} \langle p | \mathcal{O}(z,0) | p \rangle$

Without proof: $q(x) = \tilde{q}(x, P_3) + \mathcal{O}\left(\frac{\alpha}{2\pi}\right)$

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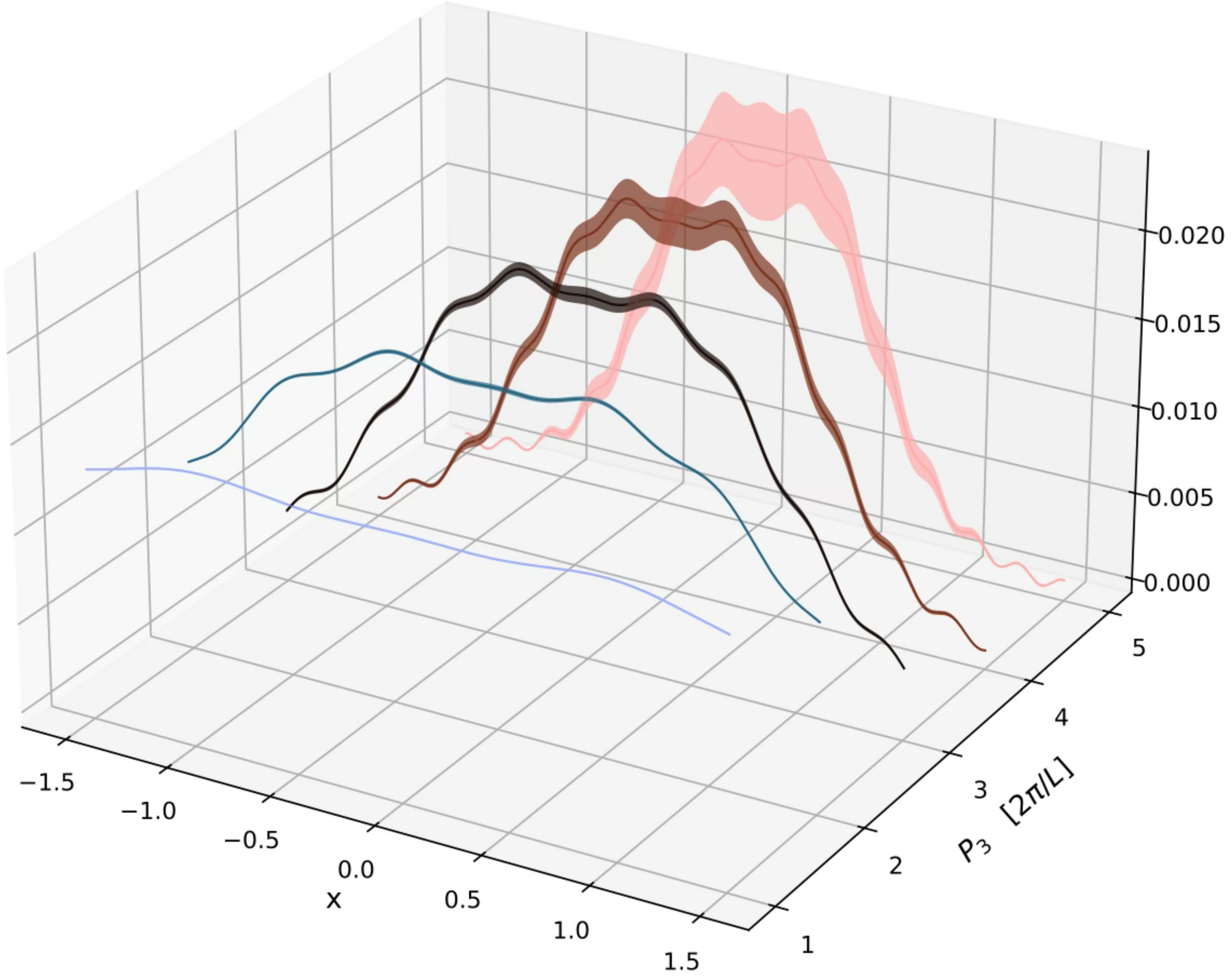
$$q(x) = \tilde{q}(x, P_3) + \mathcal{O}\left(\frac{\alpha}{2\pi}\right)$$

Strong interaction = strong effect

Weak interaction = better control!

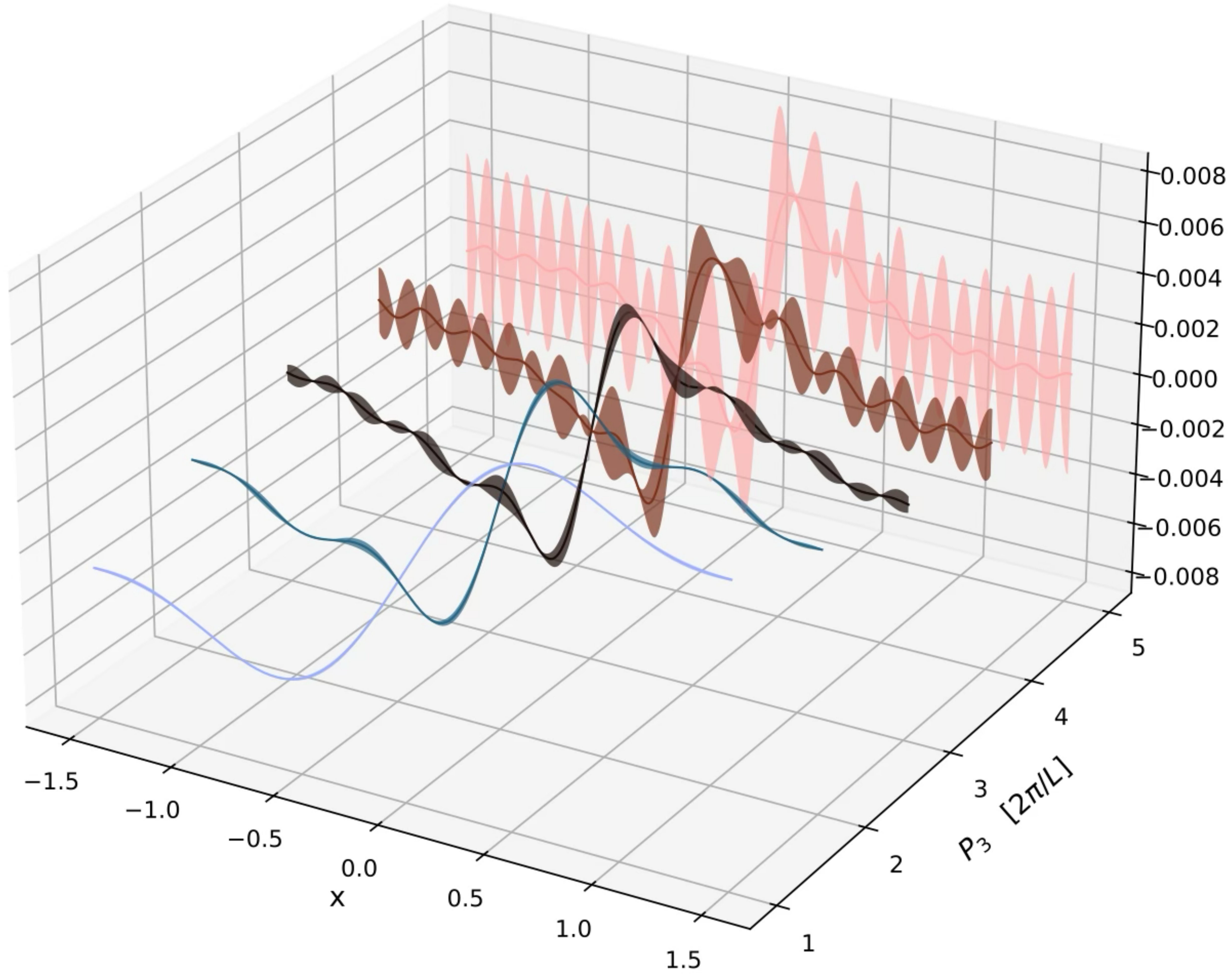
# FMS W-boson PDF

- $x\tilde{w}^{(2)}_{W_{||}}(x; P_3)$ for $L_T = 16$
- Shows the internal structure of physical W under the assumption of FMS



# FMS Higgs-boson PDF

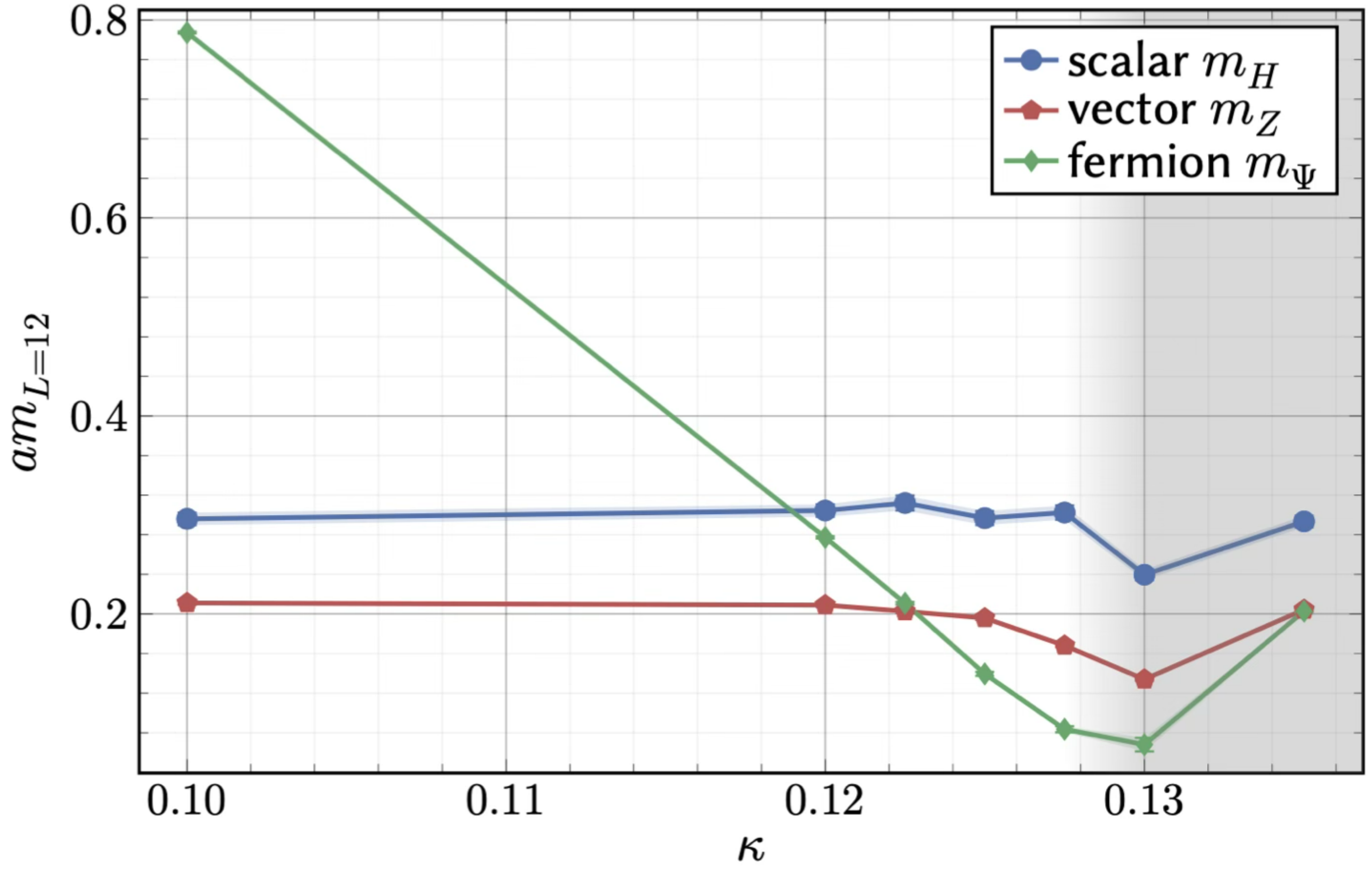
- $x\tilde{h}_H^{(1)}(x; P_3)$ for $L_T = 16$
- We may be able to compare this to results from the High-Luminosity LHC



# Lattice Spectroscopy

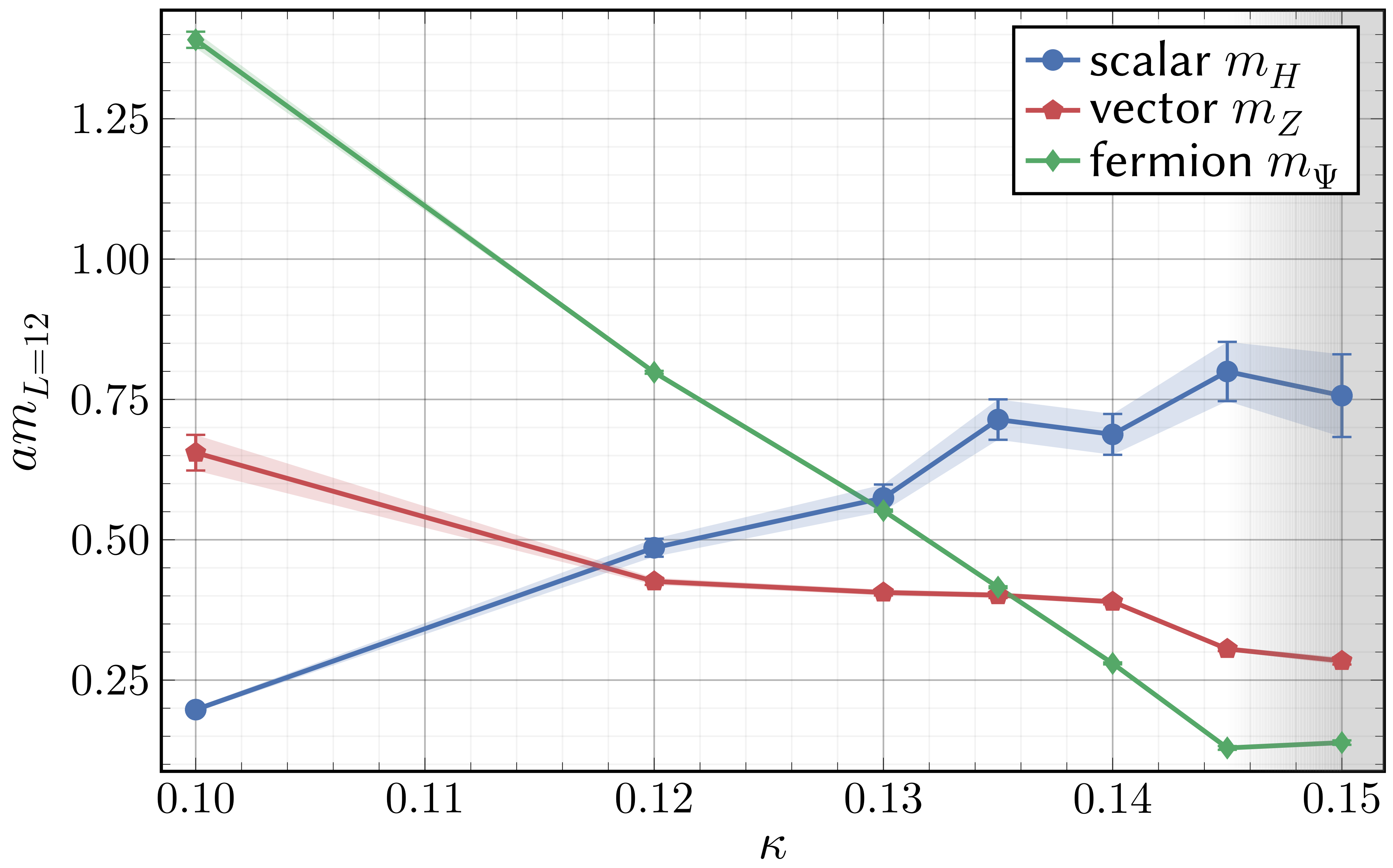
# Parameter Regions

## Phase space, without GEVP, future precision will be increased




**Higgs-like region**

stable Higgs
Scalar = Higgs much heavier than vector = W/Z




**QCD-like region**

inverted mass hierarchy with vector heavier than scalar

[Wieland, Maas, PoS, 2025]

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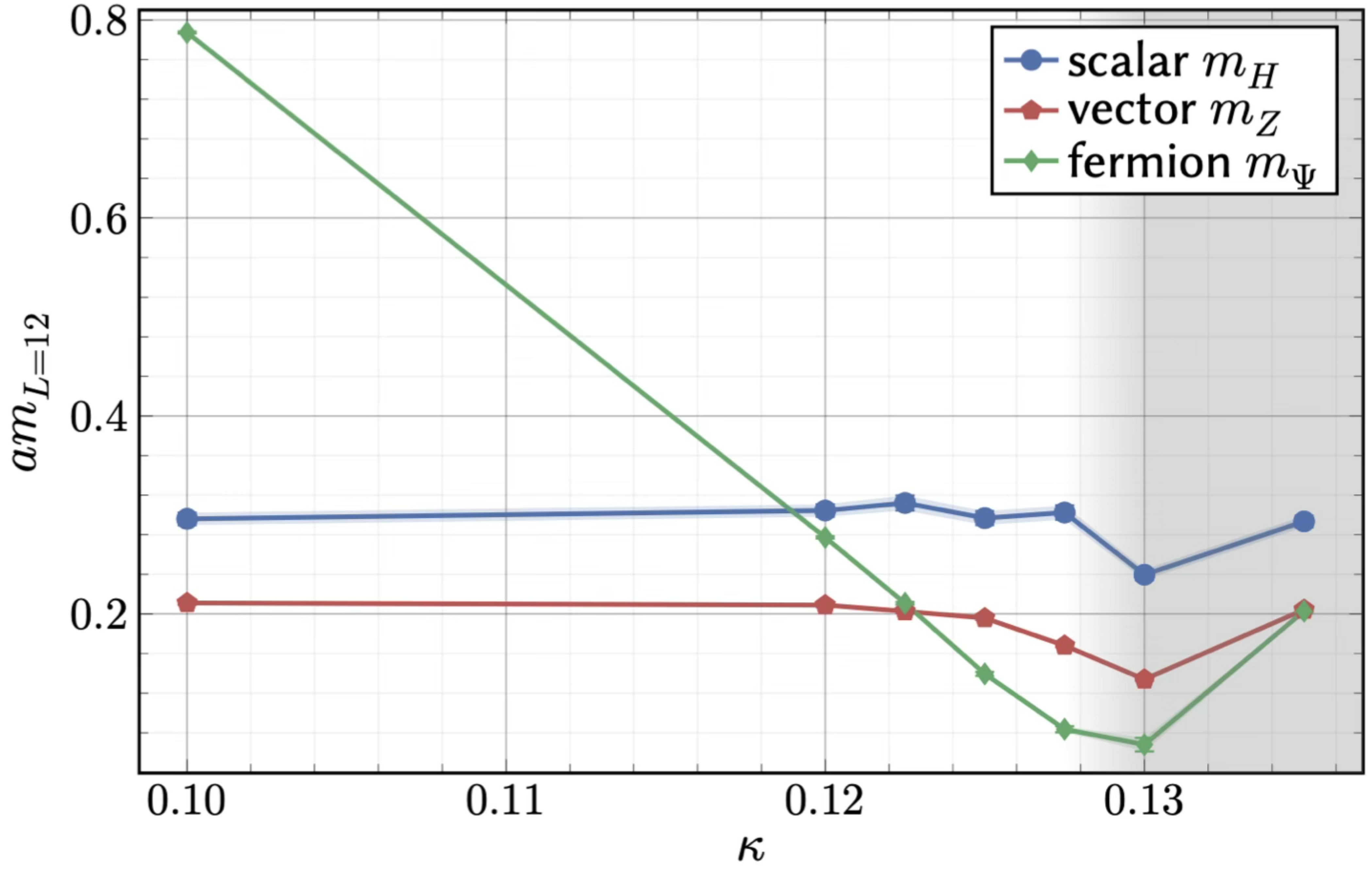
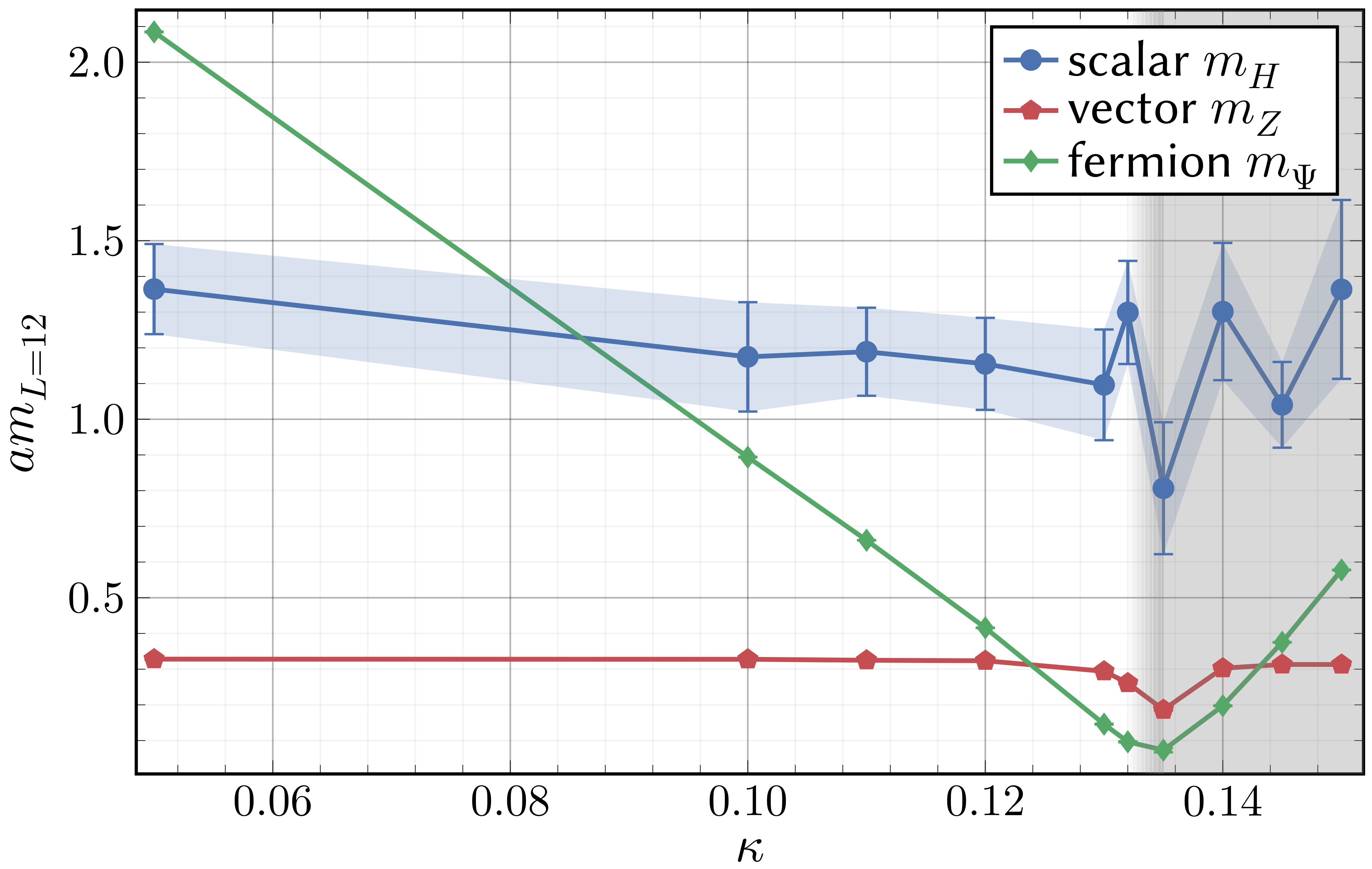



**Stable Higgs**

Higgs mass lighter than two vector boson state




**Unstable Higgs**

Higgs mass heavier than two vector boson state

[Wieland, Maas, PoS, 2025]

# Structure of asymptotic states

We expect the following states to be the physical Higgs, W/Z-bosons and leptons

$$\mathcal{O}_{0^+}(x) = \frac{1}{2}\,\mathrm{tr}[X^\dagger(x) X(x)] = \phi^\dagger(x)\phi(x) \quad \text{Higgs}$$

$$\mathcal{O}^{a,\mu}_{1^-}(x) = -\frac{i}{2}\,\mathrm{tr}[\tau^a X^\dagger(x) U^\mu(x) X(x+\hat{\mu})] \quad \text{W/Z}$$

$$\mathcal{O}^{\hat{\imath},\alpha}_{\mathrm{I}}(x) = X^{\dagger\, i\hat{\imath}}_{i}(x)\,\psi^{i,\alpha}(x) \quad e,\ \nu_e$$

# Stable Higgs: structure of asymptotic states

A larger operator basis has largely no impact on ground state masses and unquenching effects are small

$O_{0^+}(p=0)$

$O_{0^+}(p=0)\,O_{0^+}(p=0)$

$O_{1^-}(p=0)\,O_{1^-}(p=0)$

$O_{0^+}(p=(0,0,1))\,O_{0^+}(p=(0,0,-1))$

$O_{1^-}(p=(0,0,1))\,O_{1^-}(p=(0,0,-1))$

$+ 2$ $O_{0^+}$ alternatives

| | EVP Basis 1, Bootstrap | GEVP Basis 2, gamma method | Quenched, GEVP Basis 2, gamma |
|---|---|---|---|
| **Scalar mass** | 0.296(10) | 0.287(12) | 0.299(14) |
| **Vector Mass** | 0.1990(16) | 0.1969(12) | 0.1971(13) |

Preliminary

See [Jenny, Maas, Riederer, Phys. Rev. D., 2022]

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Basis 1

$O_{0^+}(p=0)$

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$O_{1^-}(p=0)\,O_{1^-}(p=0)$ Basis 2

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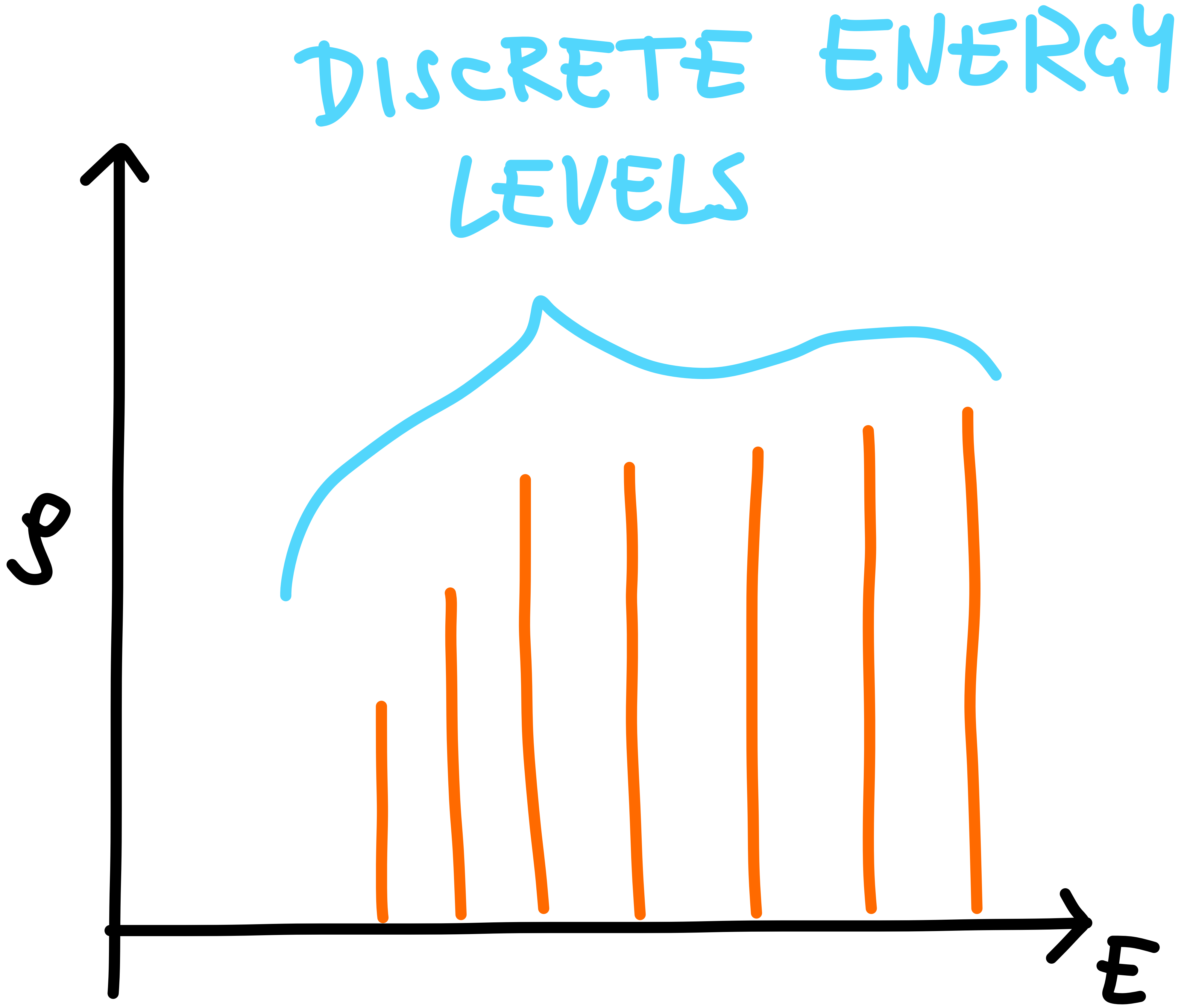
# Spectral densities

# Backus Gilbert Approach

[Backus, Gilbert, 1968 & 1970]


Continuum




Lattice / Finite Volume

# Hansen-Lupo-Tantalo Method

[Hansen et. al, 2019]

Expand kernel in functional basis preserving backpropagation

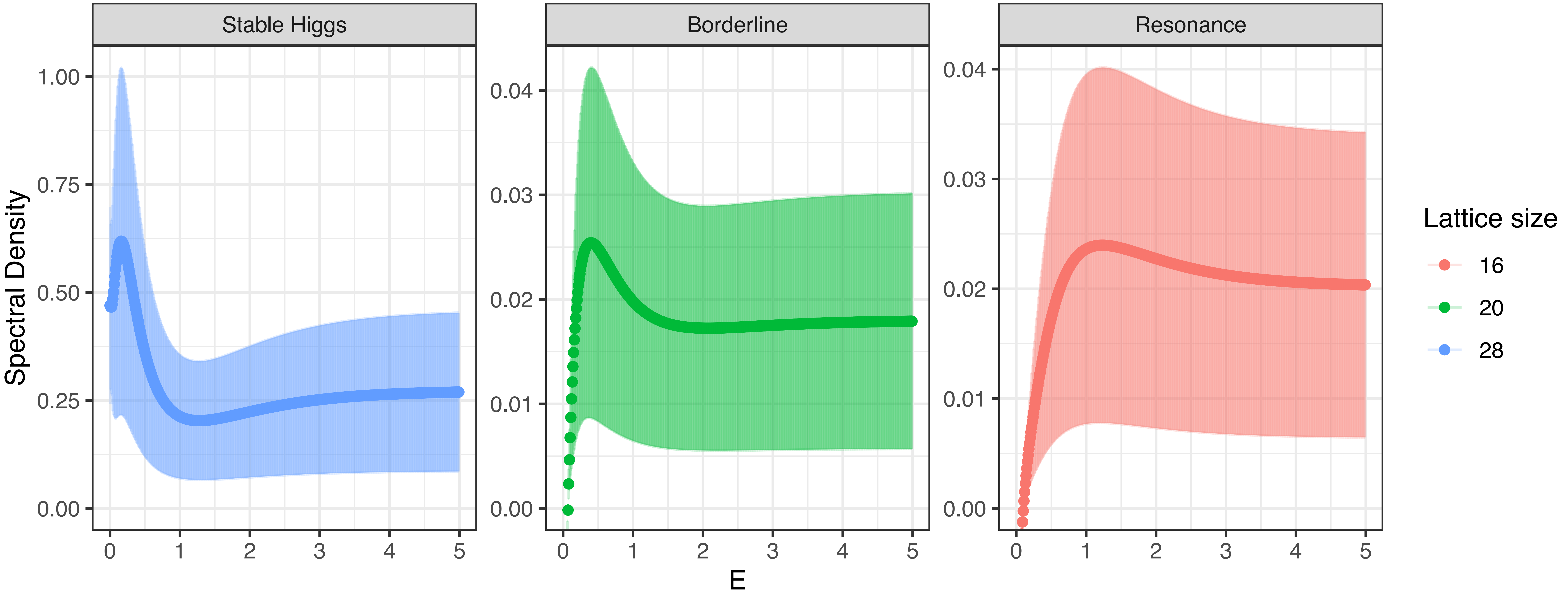
$$\Delta(E_*, E) = \sum_{t=0}^{1} g_t(E_*) \left[ e^{-tE} + e^{-(T-t)E} \right]$$

Balance systematic and statistical uncertainties

$$[g] = \int_{E_0}^{\infty} dE \left| \bar{\Delta}_\sigma(E_*, E) - \Delta_\sigma(E_*, E) \right|^2 \qquad \frac{\mathrm{Var}(C(t))}{C^2(0)}$$

# Spectral Density Functions

## Obtained using HLT, statistic and systematic errors




Technique: [Hansen, Lupo, Tantalo, Phys. Rev. D, 2019, 1903.06476]



Picture: [Martins et. al., submitted to PoS, 2026]

# Stable Higgs: Lattice vs. analytic


Higgs spectral densities obtained from HLT with systematic effects suppressed compared with an analytic computation that was smeared with the same smearing parameter from [Maas, Sonderheimer, Phys. Rev. D., 2020]

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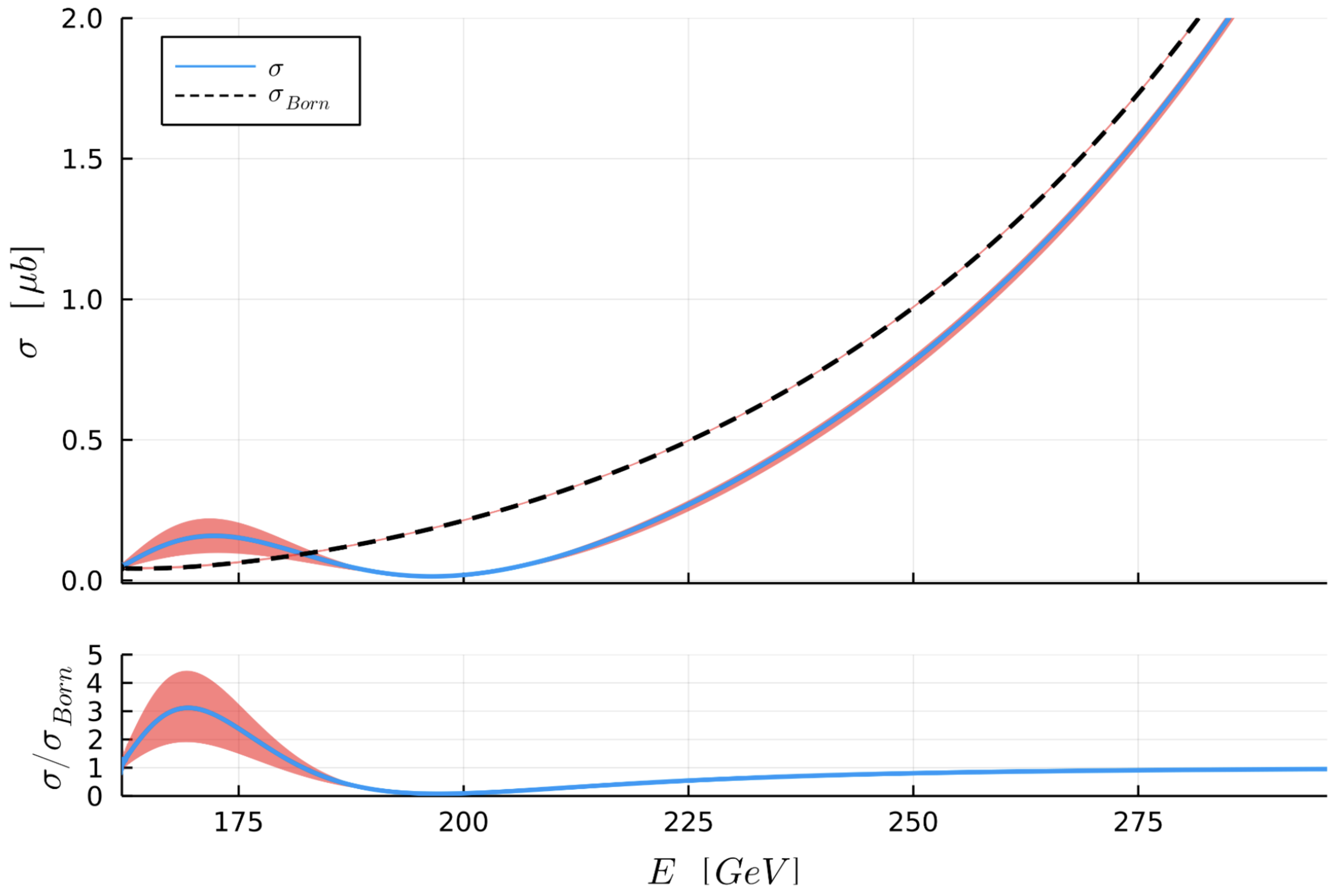
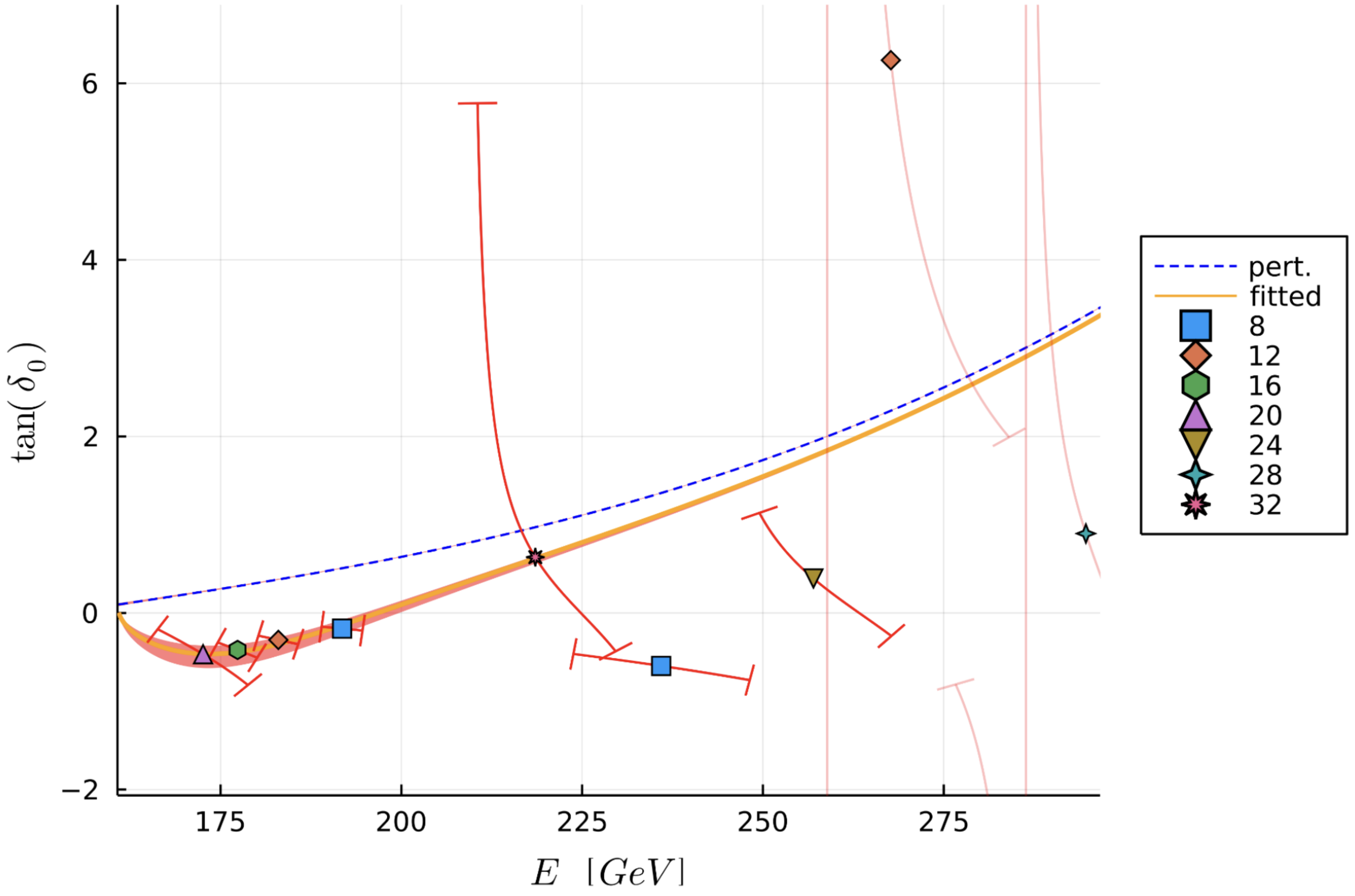
# Predictions for cross-sections of Higgs and Vector Boson Scattering

# Exclusive Decay Rates

## Phenomenology predicts measurable differences in $ZZ \to H \to ZZ$



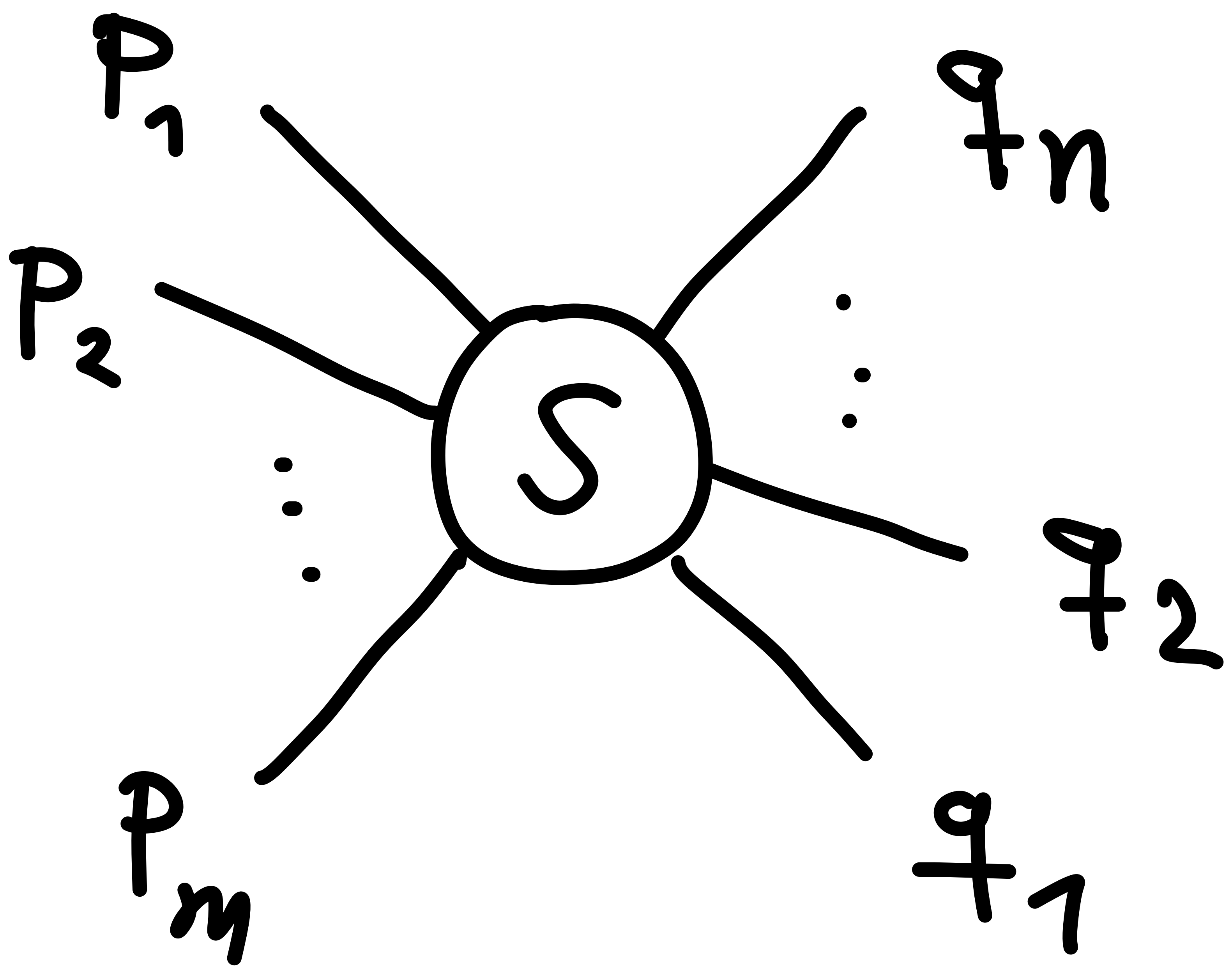




Figures: [Jenny, Maas, Riederer, Phys. Rev. D, 2022, 2204.02756]

- Expected deviations @ O(100 GeV)
- Avoid mistaking signal for BSM physics

[Bulava, Hansen, 2019]

# Computing a transition probability




$$\rightsquigarrow \quad P = |{}_{out}\langle \{p_f\} | \{q_i\} \rangle_{in}|^2$$

With definite momenta $p_f$ and $q_i$

Physical theory encoded in S-Matrix

# Bulava/Hansen method

[Bulava, Hansen, 2019]

$m$ particles out, $n$ particles in

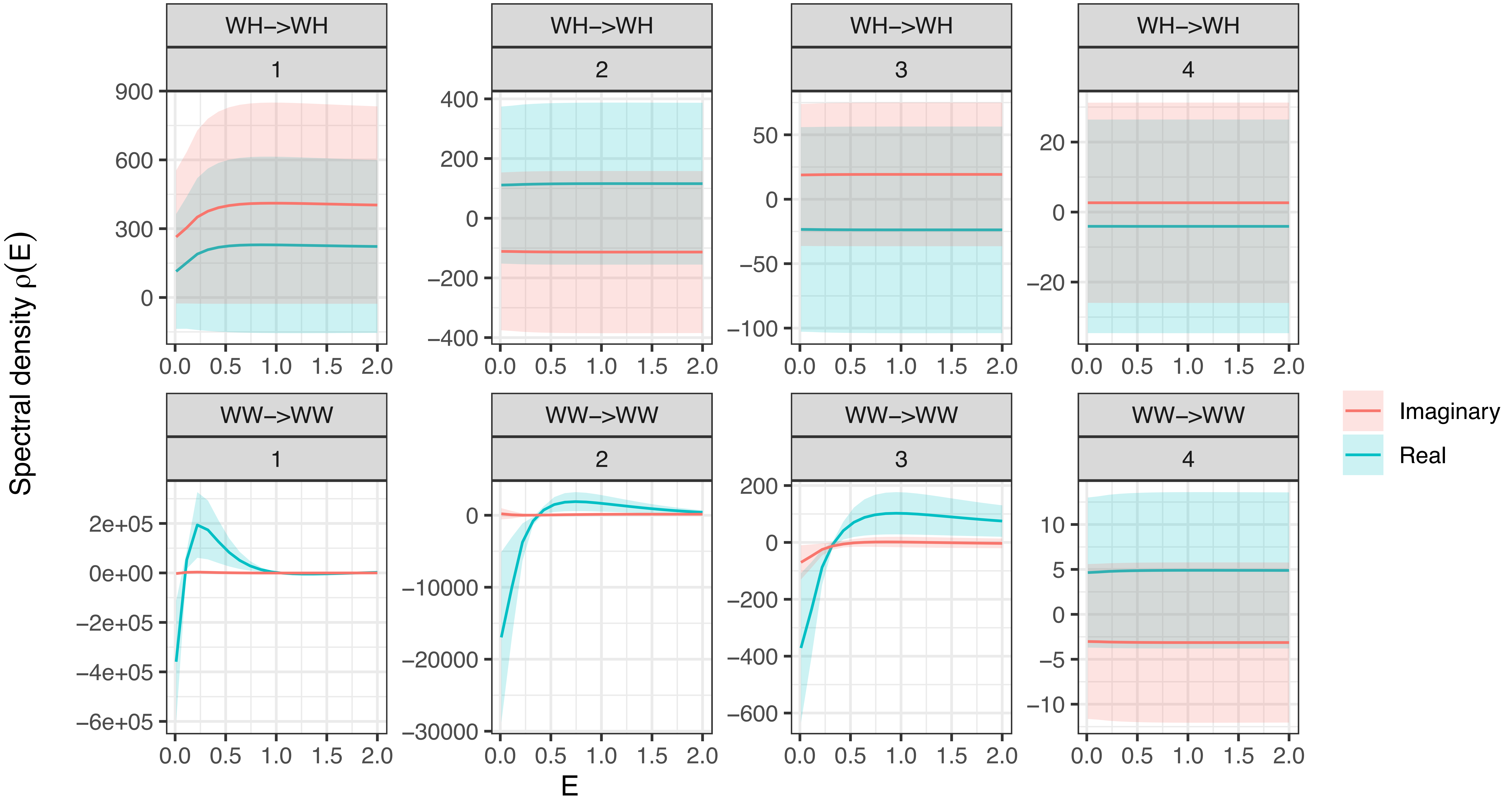
- Disassemble amplitude spectrally

$$i\mathcal{M}_c(\{p_f\}|\{q_i\}) \propto \rho_{p_m q_1}(\{p_f\}\backslash p_m, \{q_i\}\backslash q_1)$$

- Compute this spectral function by solving inverse problem

$$C_{p_m q_1}(\{p_f\}\backslash p_m, \{q_i\}\backslash q_1) = \int \frac{d^r E}{\pi^r} e^{-\sum E \Delta t} \rho_{p_m q_1}(\{p_f\}\backslash p_m, \{q_i\}\backslash q_1)$$

# Matrix element spectral decomposition



# Summary

- PDFs show internal structure that can be probed at the LHC
- Scalar + Gauge + Fermionic theory shows the expected phases and asymptotic states predicted by the FMS mechanism
- Augmented perturbation theory agrees with lattice spectral densities

# Outlook

- Compare cross sections with analytical results for simulations with dynamical fermions
- Yukawa couplings if we find excited states consistent with generations/flavors
- Mixing angles between exited leptonic states

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**Thank you for your attention!**