Non-perturbative Weak Physics using the FMS Mechanism

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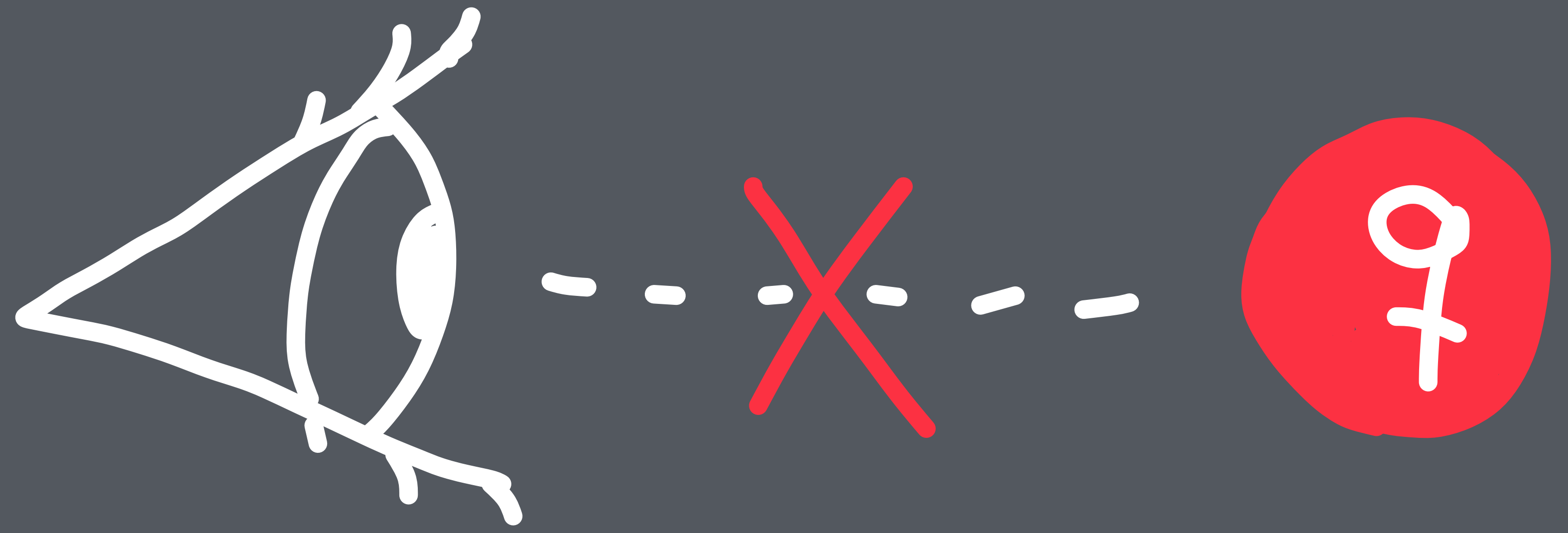
International Symposium of Lattice Field Theory 2025
5th November 2025
TIFR Mumbai

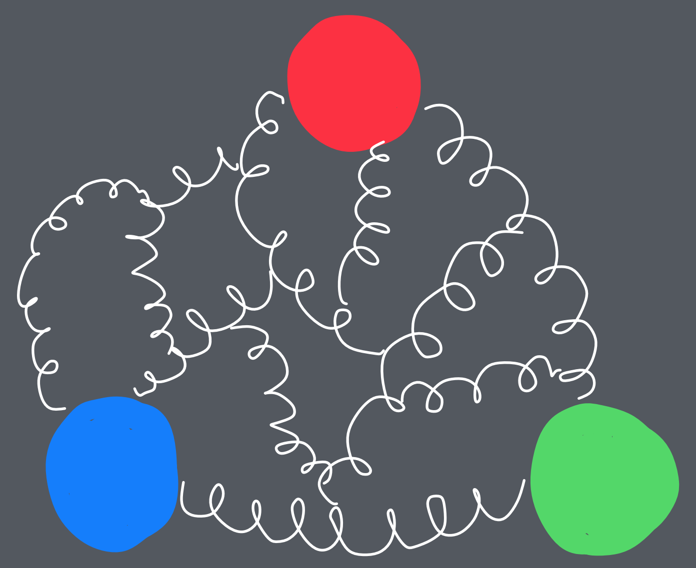
Confinement in QCD (SU(3))

1. Observers are color blind



2. Physical objects are color singlets

3. Predictions require non-perturbative techniques

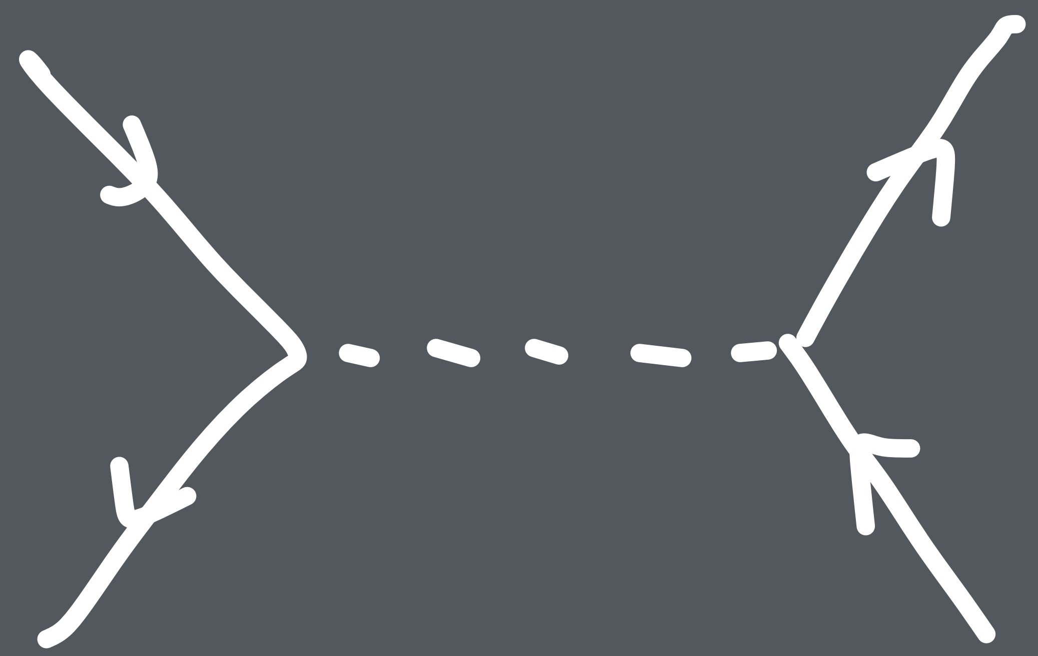


Some claims about the weak interaction

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

2. Leptons and neutrinos are individually observable

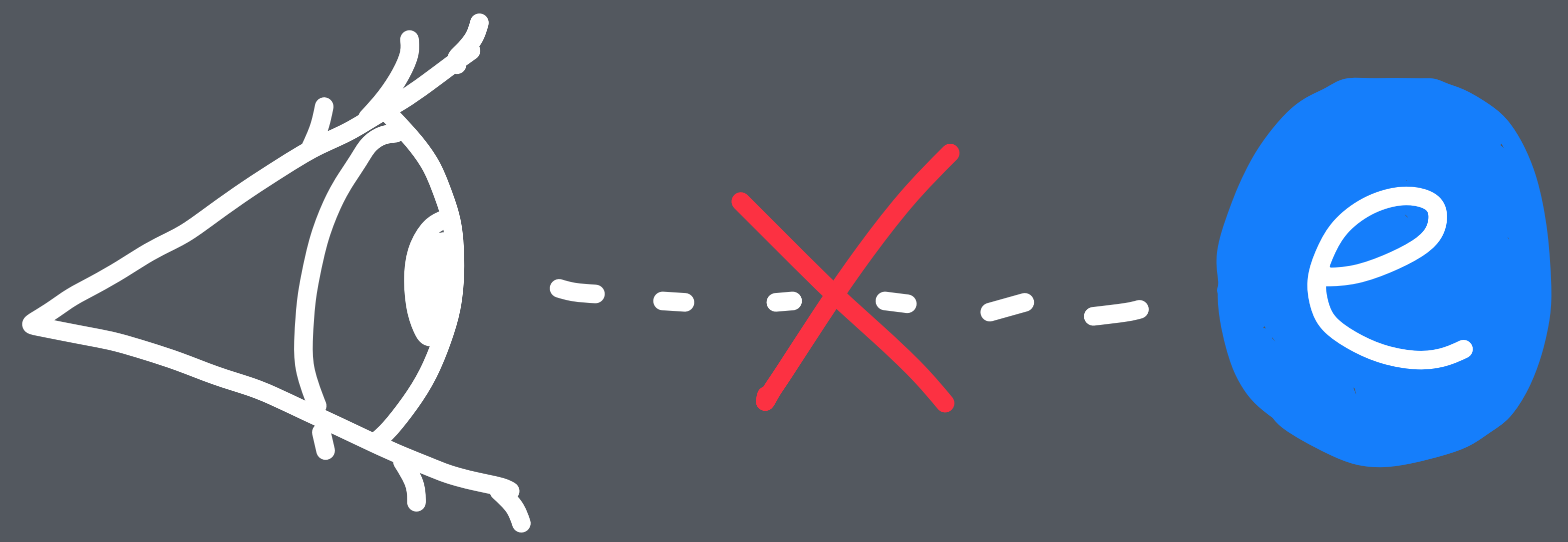
3. Perturbative treatment possible using the BRST construction

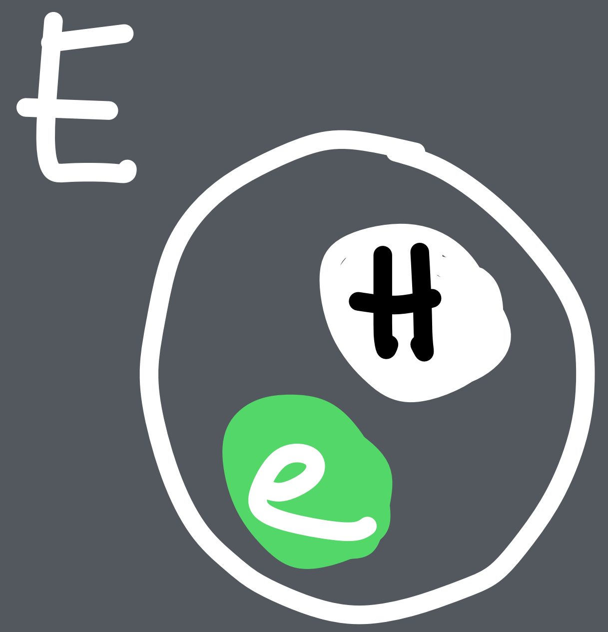


Elitzur's theorem: Gauge symmetries cannot be spontaneously broken!

What would make more sense

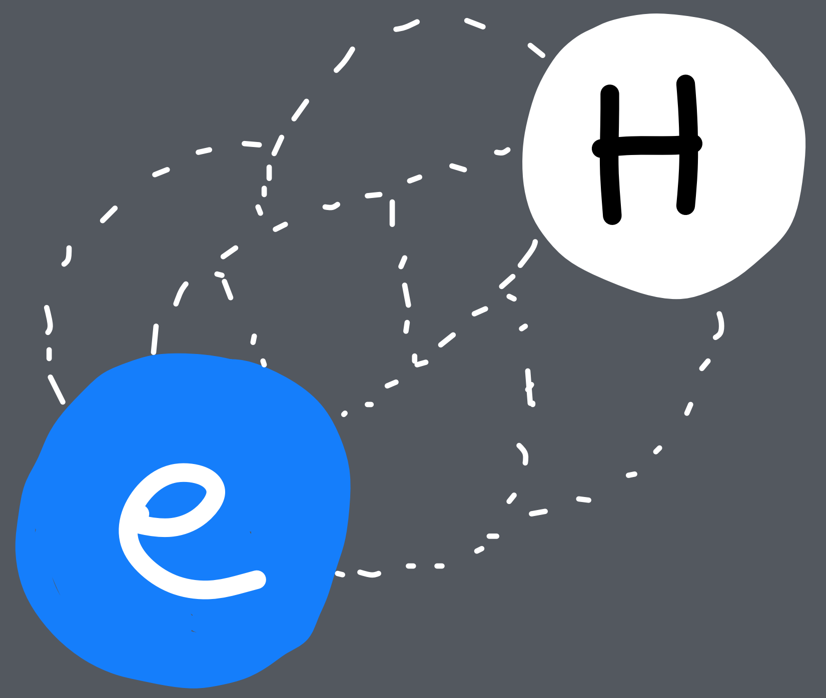
1. Observers are weak-isospin blind





2. Physical fermions are composite

3. Predictions require non-perturbative techniques



For example …

Fundamental left-handed fermion doublet and Higgs doublet reorganized in matrix X

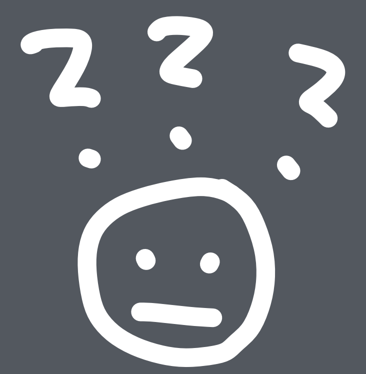
$$\psi = \begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad X = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}$$

Combine to physical & observable fermion

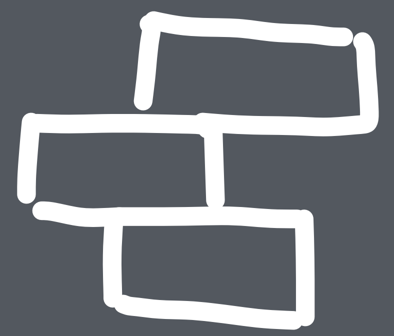
$$= \begin{pmatrix} N \\ E \end{pmatrix}_2 = (X^\dagger \psi)_2$$

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

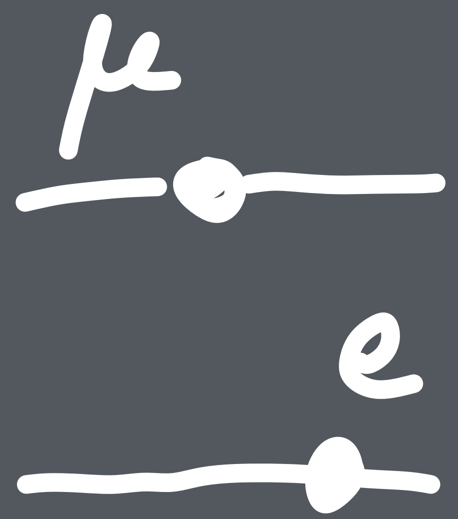
Why you should care



To not confuse a BSM with NP SM effects



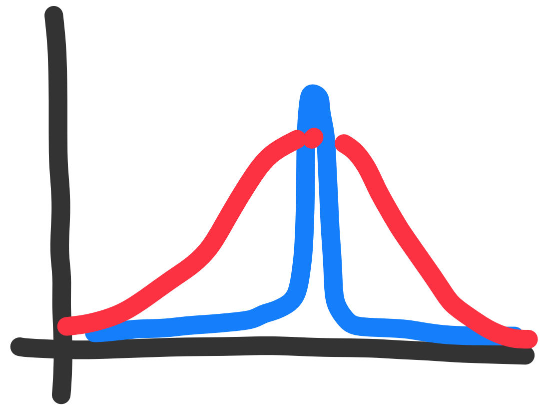
To correctly build extensions of the SM on top of the weak sector



We suspect that lepton & quark generations are levels of excited states -> compute CKM/PMNS matrix elements from the lattice

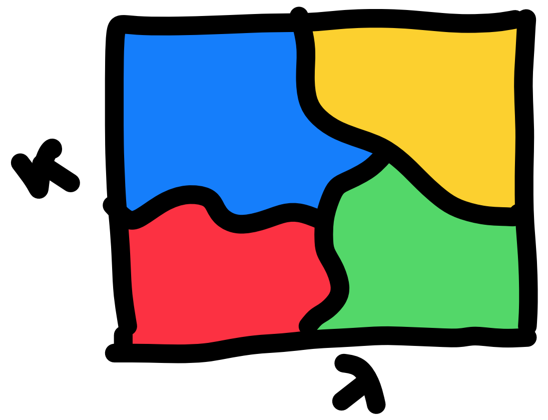
[Egger et. al., Mod.Phys.Lett. A, 2017, 1701.02881]

Outline



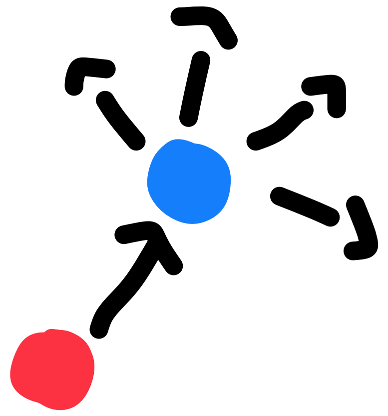
1. Quasi-PDFs

How much internal structure do we see theoretically?



2. Physical Phases and Mass Hierarchies in the system

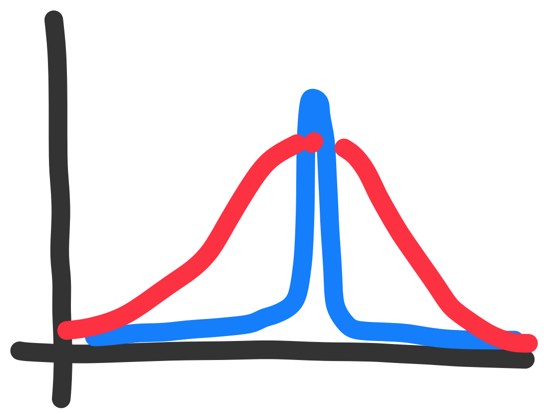
How does the theory behave?



3. Cross-sections obtained from spectral densities

Identify deviations from perturbation theory

Outline



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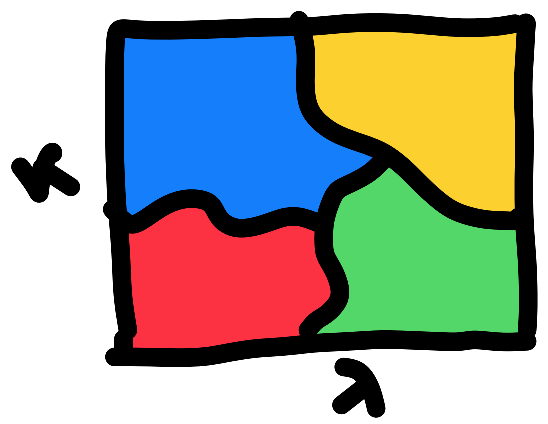

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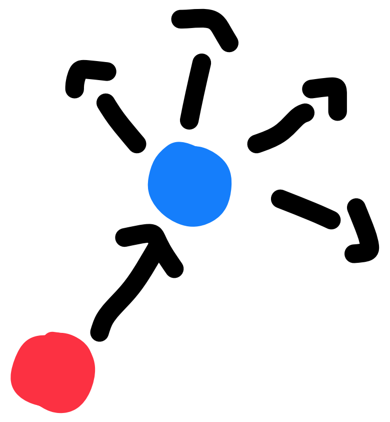


3. Cross-sections obtained from spectral densities

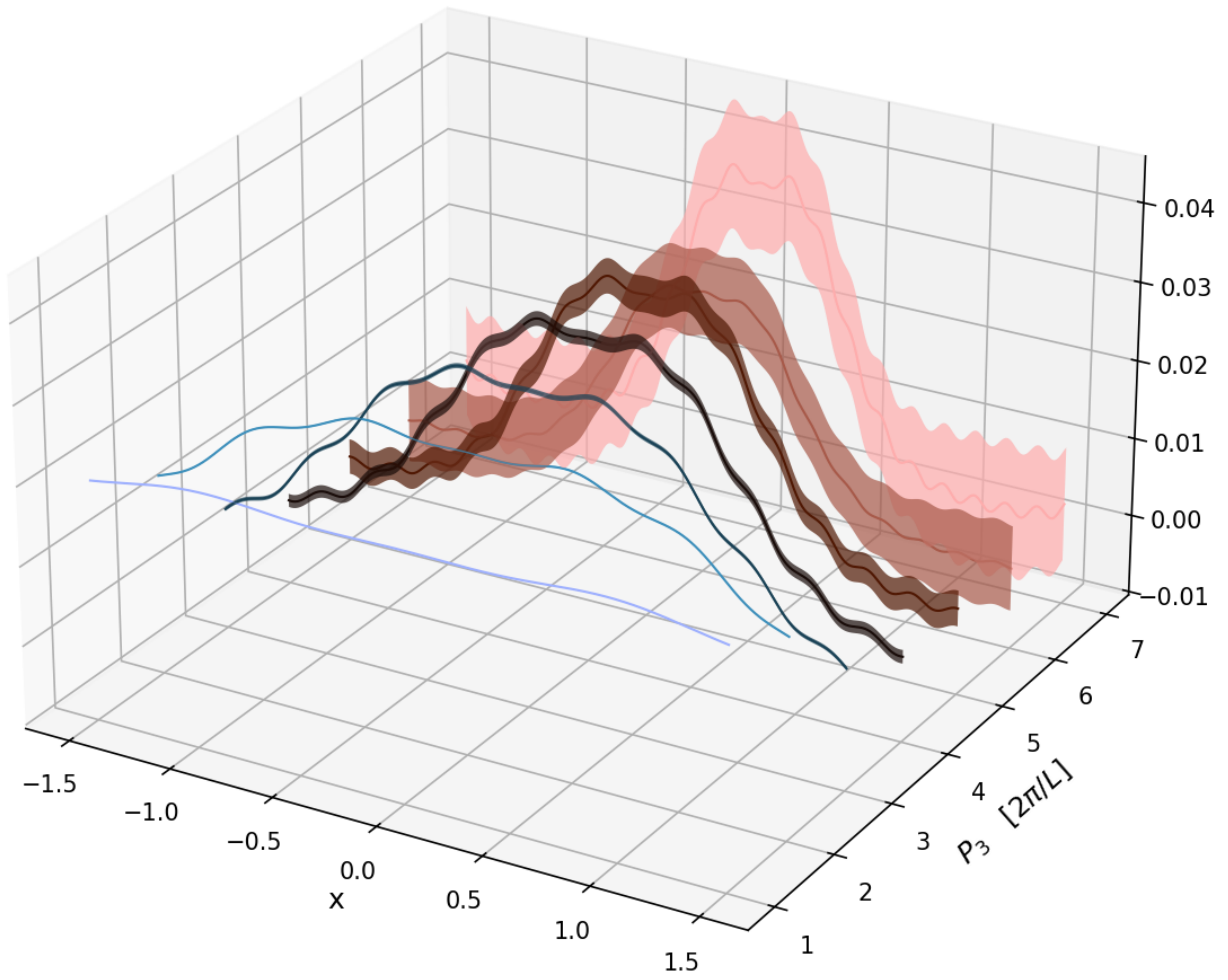
   Identify deviations from perturbation theory

See excited states!

(Quasi-)Parton Distribution Functions

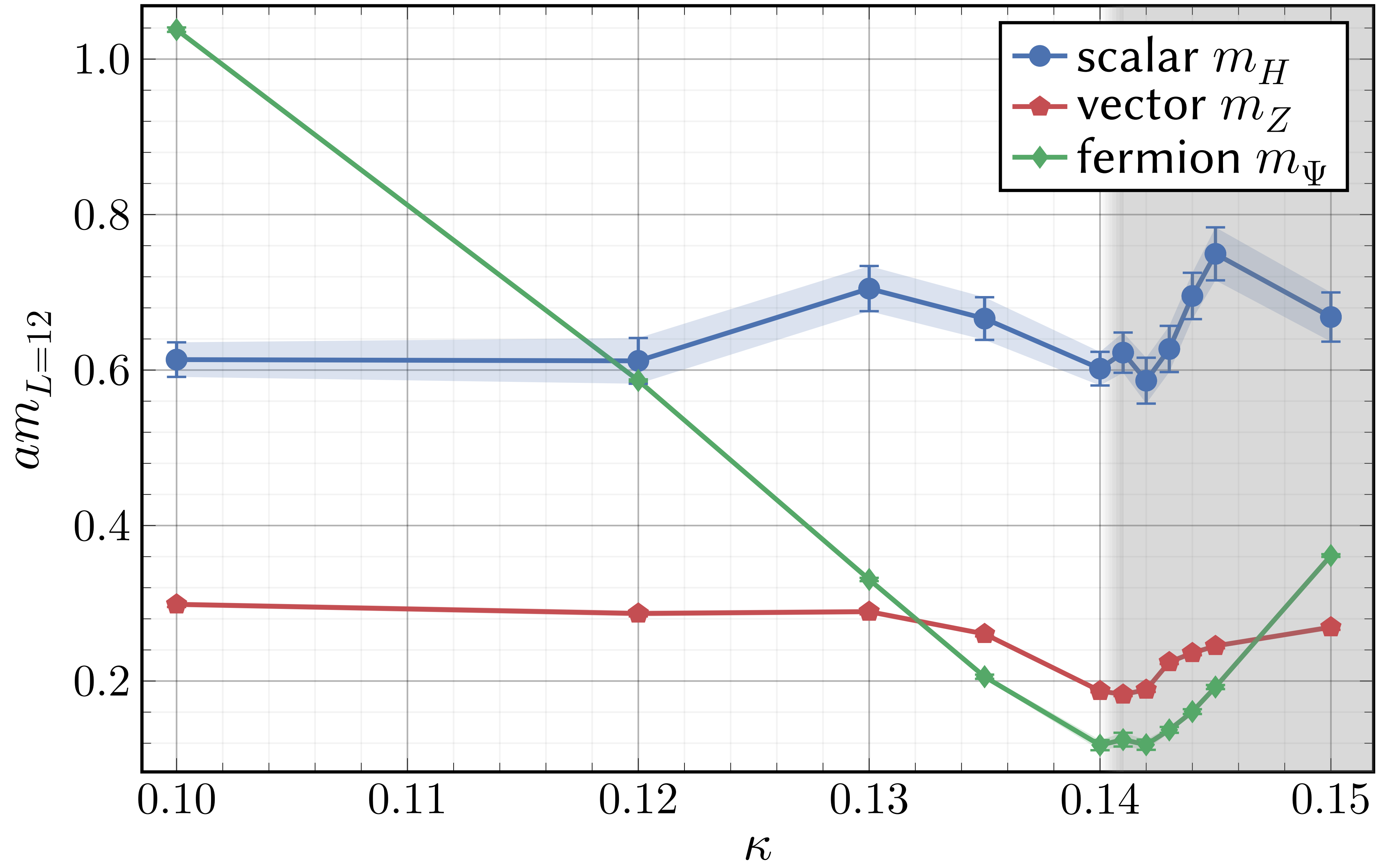
Resolve theoretically expected composite structure, quenched

- $x\tilde{w}^{(2)}_{W_{||}}(x; P_3)$ for $L_T = 16$
- Shows the internal structure of physical W
- Can't yet resolve the same structure for Higgs

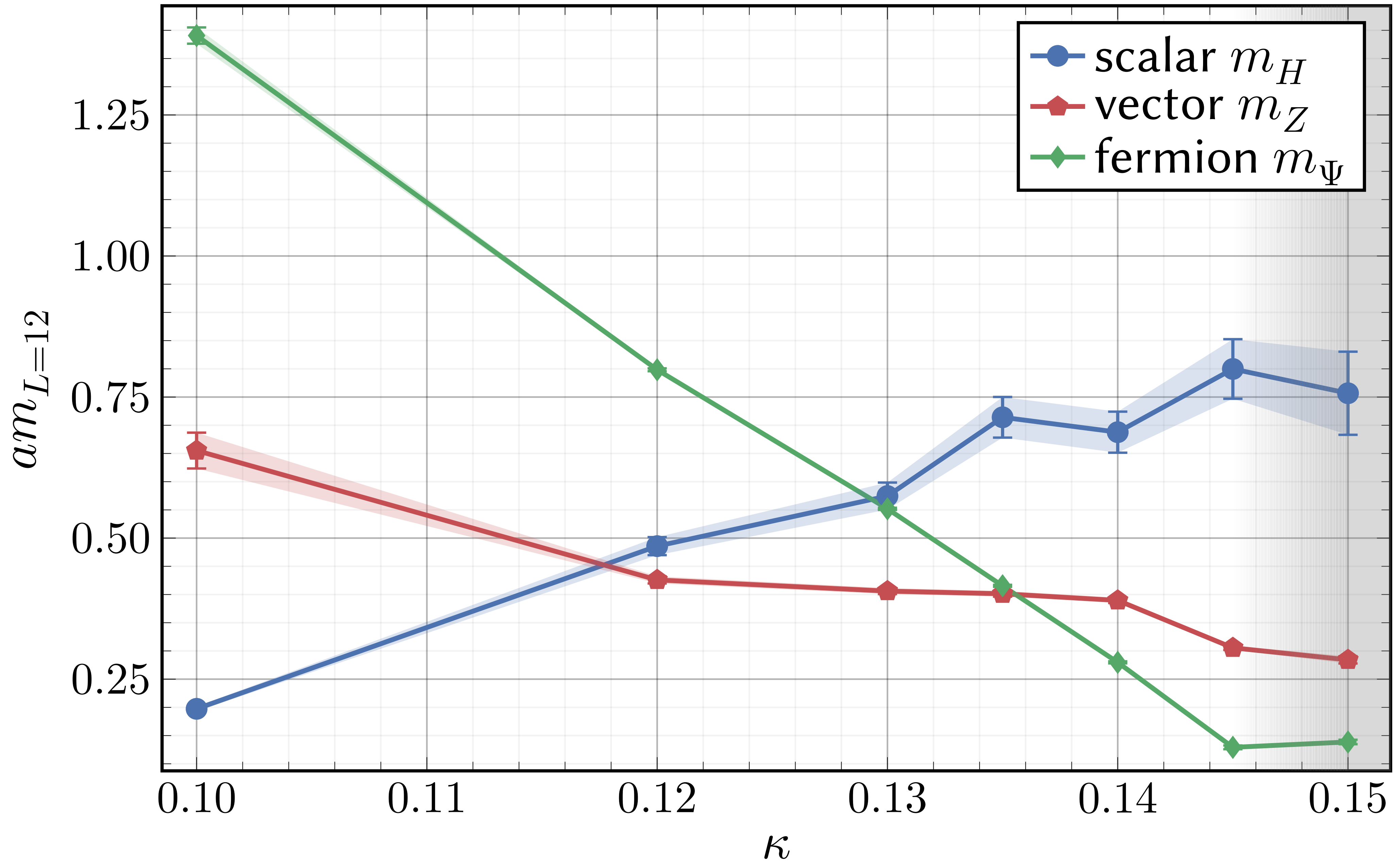


Parameter Regions

Phase space, without GEVP, future precision will be increased



Higgs-like region



QCD-like region

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

inverted mass hierarchy with vector heavier than scalar

[Wieland, Maas, PoS, 2025, to appear]

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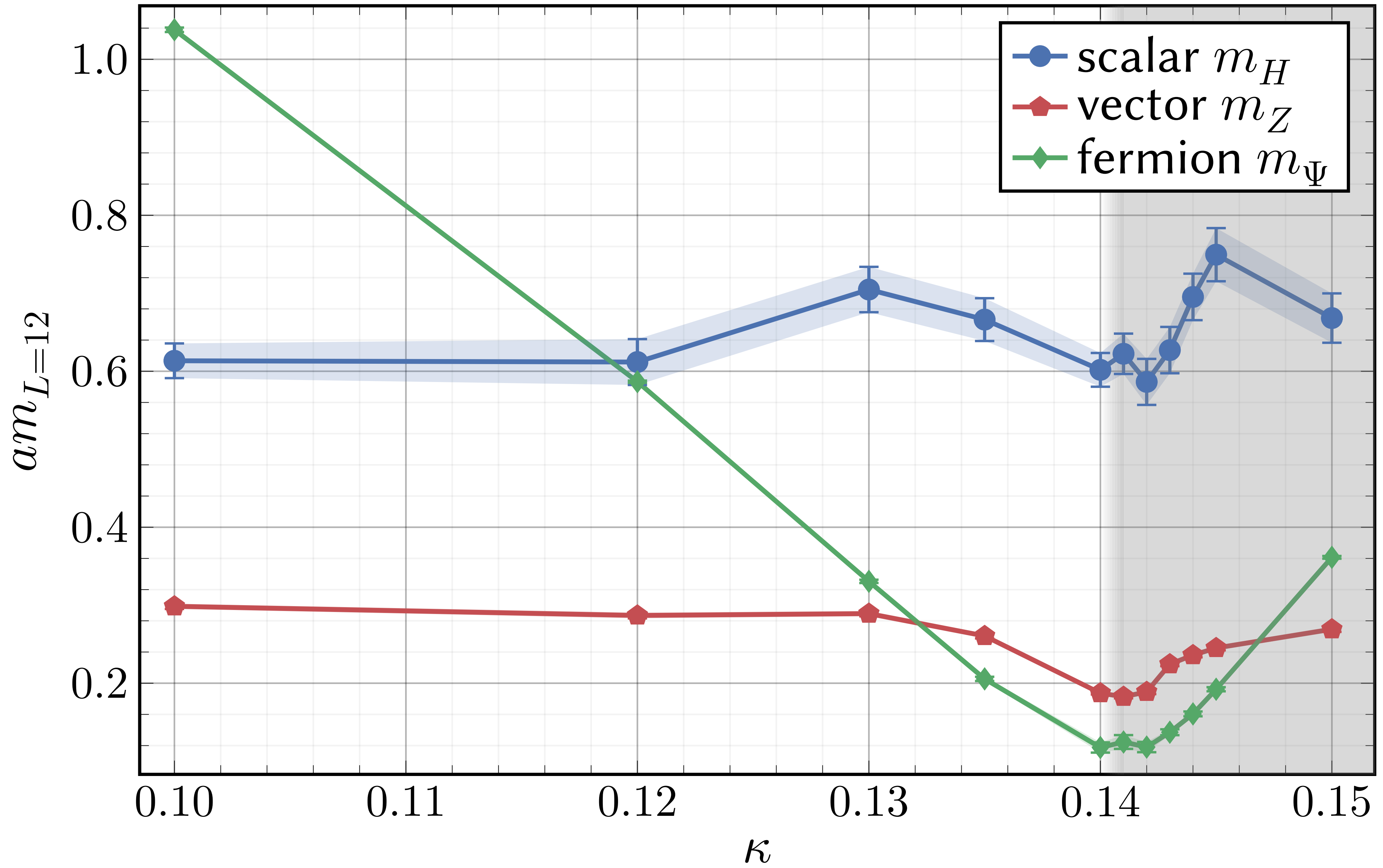
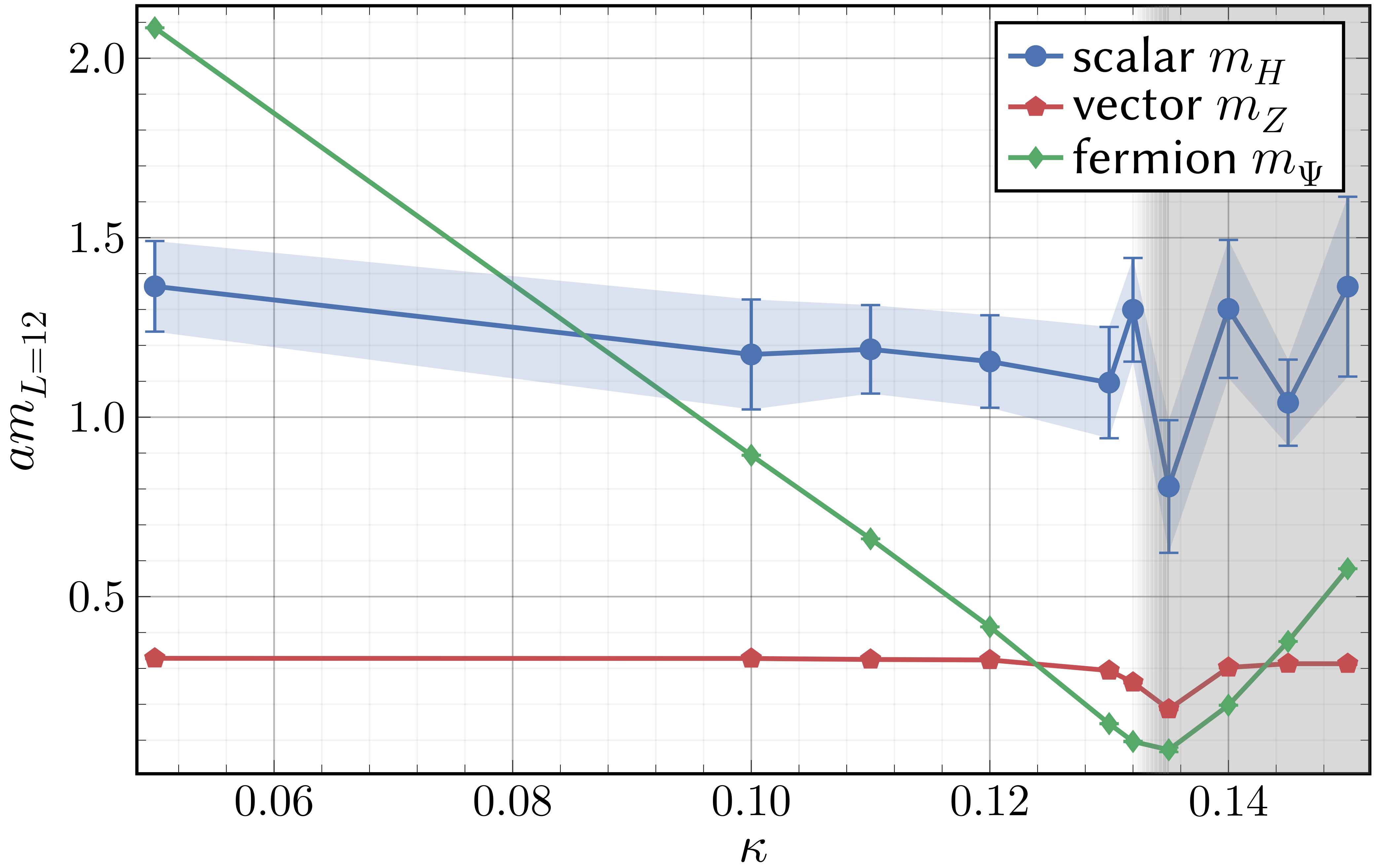


Stable Higgs

Scalar = Higgs much heavier than vector = W/Z



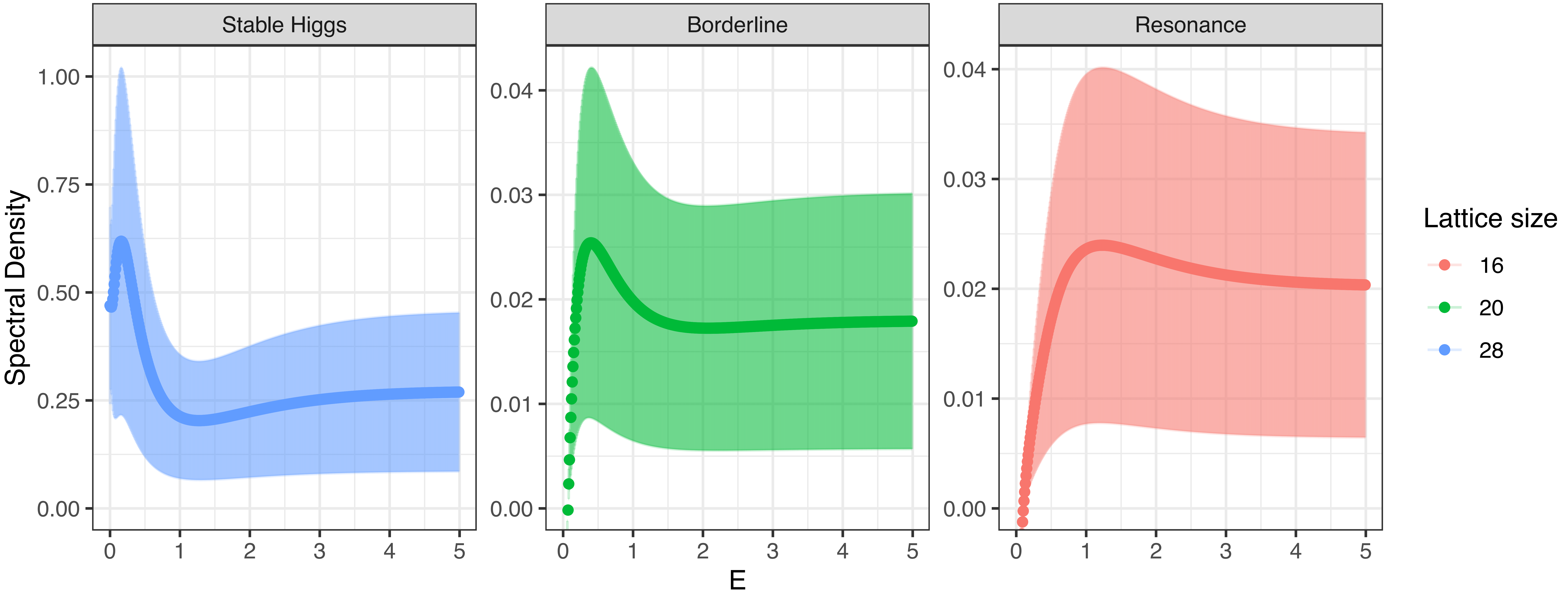
Unstable Higgs

inverted mass hierarchy with vector heavier than scalar

[Wieland, Maas, PoS, 2025, to appear]

Spectral Density Functions

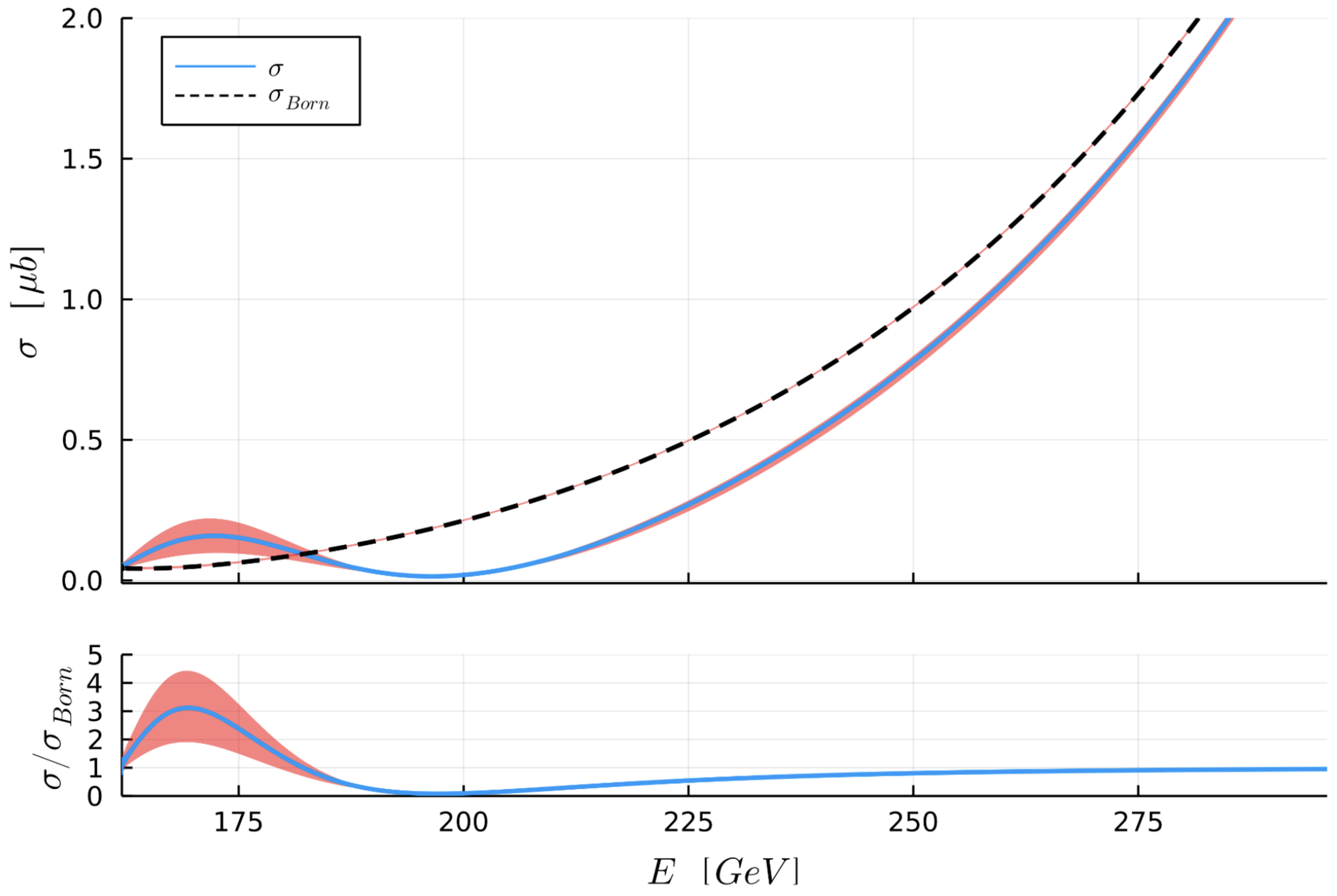
Obtained using HLT

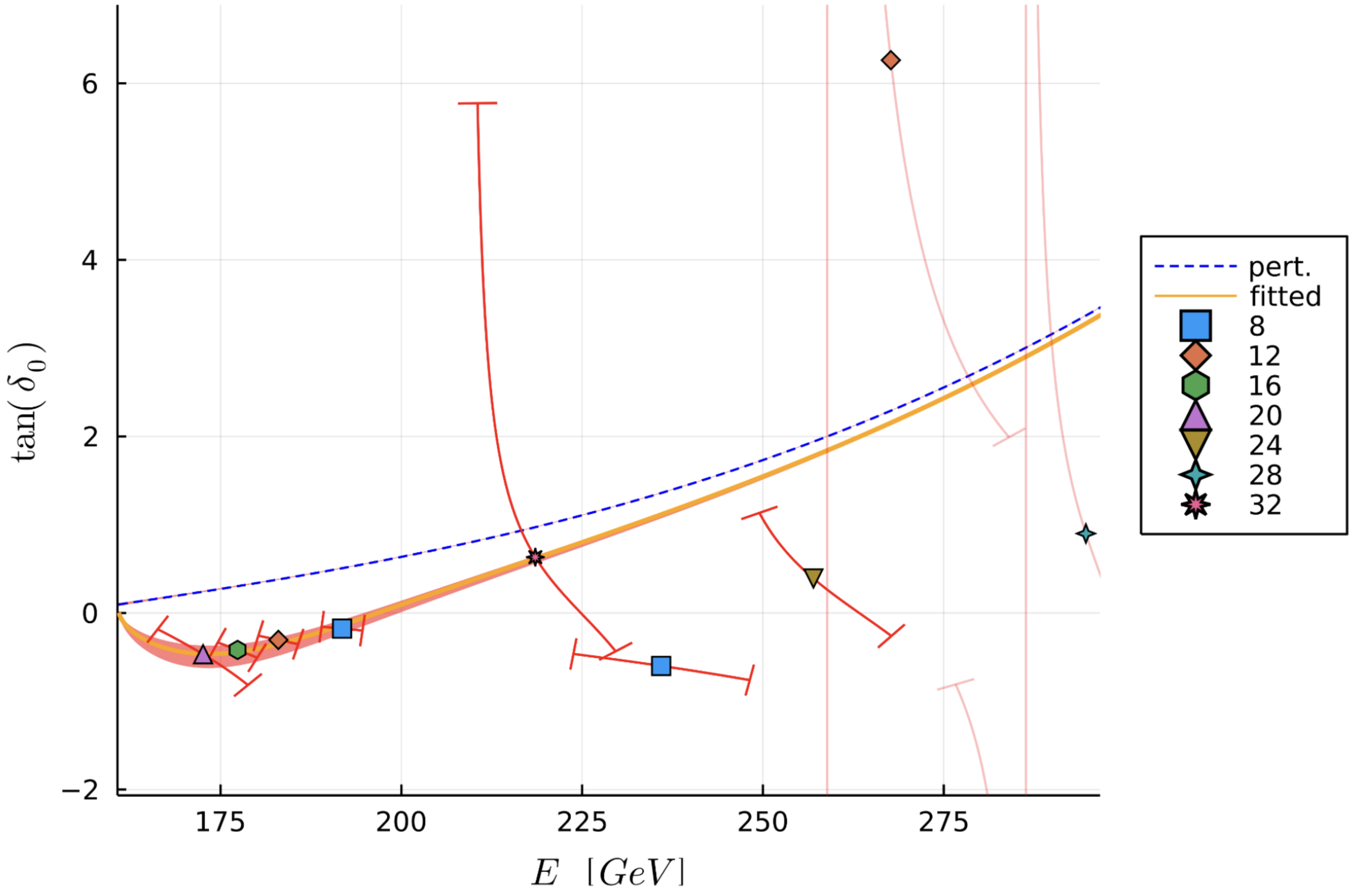


Technique: [Hansen, Lupo, Tantalo, Phys. Rev. D, 2019, 1903.06476]

Exclusive Decay Rates

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





- Expected deviations @ O(1 GeV)
- Avoid mistaking signal for BSM physics

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

Inclusive Decay Rates (proof of concept)

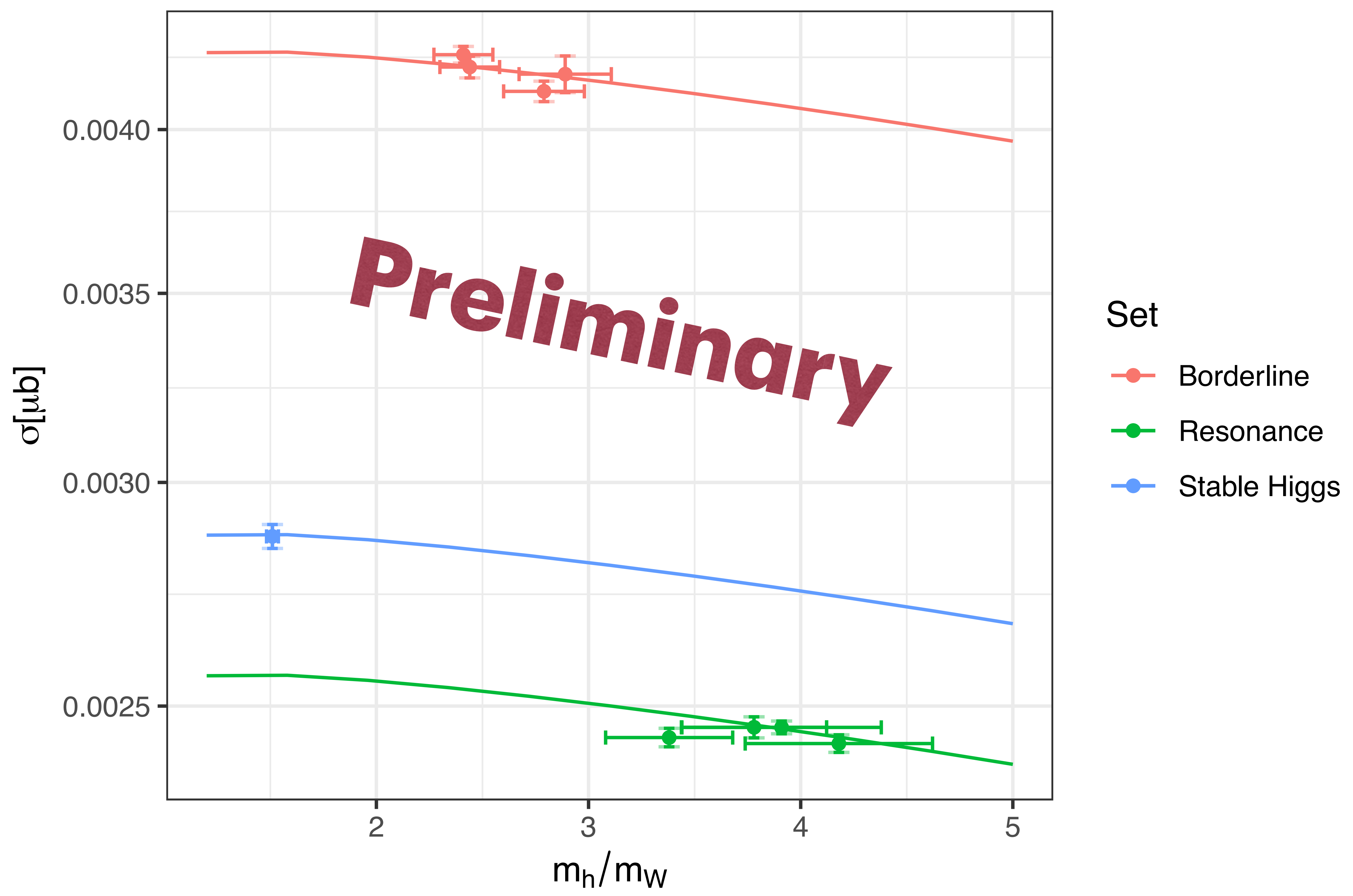
(Preliminary) Lattice extraction from spectral function

Technique: [Bulava, Hansen, Phys. Rev. D, 2019]
quenched couplings: [Jenny et. al., Phys. Rev. D, 2022]

	$\alpha^{\text{quenched}}[m^2_{W,\text{exp}}]$	$\alpha^{\text{tl,fit}}[m^2_{W,\text{exp}}]$
Borderline	0.835(9)	0.39(4)
Resonance	0.270(3)	0.30(4)
Stable Higgs	-	0.32(6)

- Evaluated diff cross-sections of $WH \to WH$ for $\mathbf{p} = \mathbf{0}$, $\sqrt{s} = m_{W,\text{exp}}$
- Dependency on $\sqrt{s}$ is work in progress
- Large FV effects expected at this point

Plot not considering systematic effects



Outlook

- Precision on spectral densities + extraction with other methods
- Higher momenta operators
- 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!

Backup slides

Operator choices & quantum numbers

- 0^+ Channel: scalar meson, scalar glueball A_1, Higgs operator

$$O_H(x) = (\phi^\dagger \phi)(x)$$

- 1^- Channel: vector glueball T_1, W operator

$$W_\mu^a(x) = (\tau^a \phi^\dagger D_\mu \phi)(x)$$

- Spin 1/2 Fermionic operators: Standard FMS physical fermion

$$O_F(x) = (X^\dagger \psi)(x)$$

$SU(2)^4$ nucleons (FMS Baryons)

- Center of Mass operator combinations $O(-p)O(p)$

- Vary momenta & smearing levels of full & spatial APE smearing

- Glueball blocking

Lattice Action

- Action, 4 fermions: electron, electron neutrino, muon, muon neutrino; scalar Higgs field

$$\mathscr{L} = - W^a_{\mu\nu} W^{a,\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \lambda(\phi^\dagger \phi - f^2)^2 + \text{Fermions}$$

- Symmetry

$$G = \mathscr{G} \times \mathscr{C} \qquad \mathscr{G} = \mathscr{C} = SU(2)$$

- Discretization: Wilson fermions using *HiRep*, note that this replaces Weyl Fermions with Dirac Fermions

[Del Debbio et. al., Phys. Rev. D, 2010;
Toniato et. al., LATTICE2017;
Drach et. al., 2025, 2503.06721]

Scale setting, Lattice spacing, LOCP

- Set $am_W^{\text{lattice}} = m_W^{\text{exp}}$
- This acts as LOCP interpolation & scale setting
- A proper LOCP can't be done at the moment because too many free parameters: m_H, g, λ, κ