COMETA workshop on BSM in Multiboson physics, July 8-10, 2026, Sarajevo

Novel Background for BSM searches in VBS in the scalar channel

SOFIE MARTINS, UNIVERSITY OF GRAZ

IN COLLABORATION WITH
PATRICK JENNY, AXEL MAAS, AND GEORG WIELAND

Outline

- How lattice practitioners think about weak physics
- Symmetries of the FMS framework
- Model building 2.0
- Lattice results for the novel background
- Summary & Outlook

How lattice practitioners think about weak physics

Scalar-gauge theories

- Take the theory

$$\mathscr{L} = -\frac{1}{4}W^a_{\mu\nu}W^{a,\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) - V(\phi)$$

  with gauge symmetry $SU(2)$

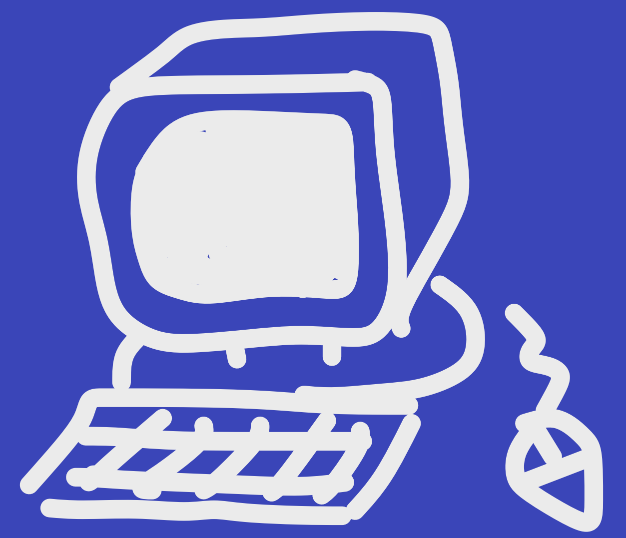
- This exhibits a Brout-Englert-Higgs effect if the minimum of the potential V is non-zero.

Structure of asymptotic states in the weak sector

Perturbation theory:

Scalar channel: ϕ (Higgs)

Vector channel: $W^a_{\mu\nu}$ (W, Z)



Lattice Gauge Theory

Pick the minimal operators with matching quantum numbers

Scalar channel: $\phi^\dagger\phi$ (Higgs)

Vector channel: $\tau^a\phi^\dagger D_\mu\phi$ (W, Z)

[Olynyk, Shigemitsu, PRD, 1985; Lee, Shigemitsu, Nucl. Phys. B, 1986; Shrock, Nucl. Phys. B, 1986 x2]

How does this fit together with perturbation theory?

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

2) Gauge fix and expand $\phi(x) = vn + h(x)$

3) Expansion in v yields PT result plus corrections

$$\langle(\phi^\dagger\phi)(x)(\phi^\dagger\phi)(y)\rangle_c = 4v^2\langle h^\dagger(x)h(y)\rangle_c + \mathcal{O}(v)$$

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

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$$\langle(\phi^\dagger\phi)(x)(\phi^\dagger\phi)(y)\rangle_c = \underbrace{4v^2\langle h^\dagger(x)h(y)\rangle_c}_{\text{FMS mechanism}} + \mathcal{O}(v)$$

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Additional effects

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

Symmetries of the FMS framework

Adding fermions: Custodial symmetry

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

$$\psi_L = \begin{pmatrix} \nu_{L,e} \\ e_L \end{pmatrix} \qquad X = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}$$

Combine to physical & observable fermion

E

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

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

Adding fermions: Custodial symmetry

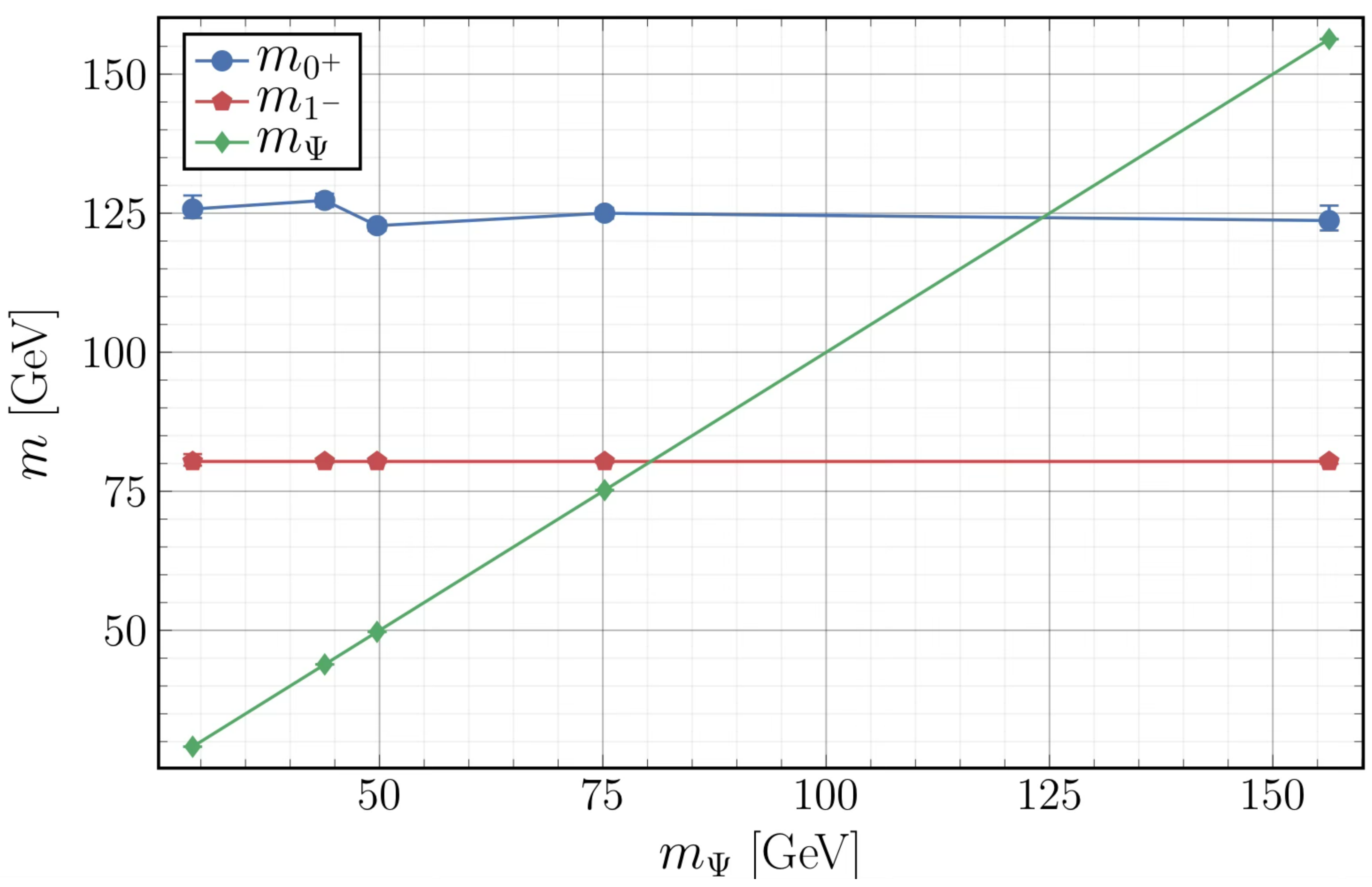
$$\begin{pmatrix} N \\ E \end{pmatrix} = (X^\dagger \psi_L)$$

When setting Yukawa couplings to zero, there is a global symmetry between physical electron and physical electron neutrino

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

Mass defects

- Physical electron mass is now non-perturbative
- When coupling fermions to the theory, the composite of Higgs and fundamental fermions becomes much lighter than the physical Higgs



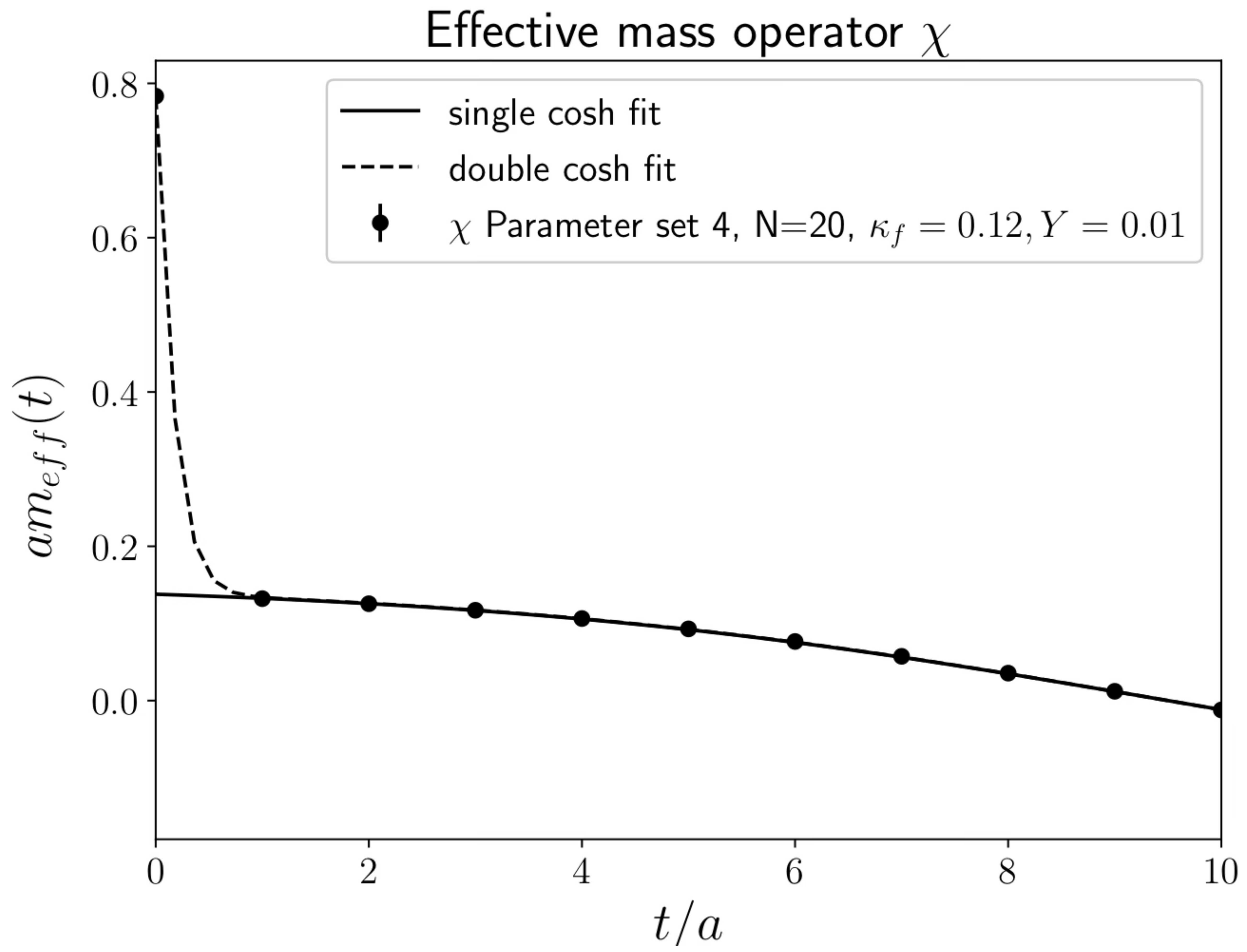
Adding right-handed fermions

- When adding Yukawa couplings, left and right handed fermions mix

- Global custodial and flavor symmetries break into a common flavor symmetry for chiral fermions

$$SU(2)_c \times SU(4)_f \rightarrow SU(2)_f$$

- In the case of lattice Dirac fermions the picture is more complicated



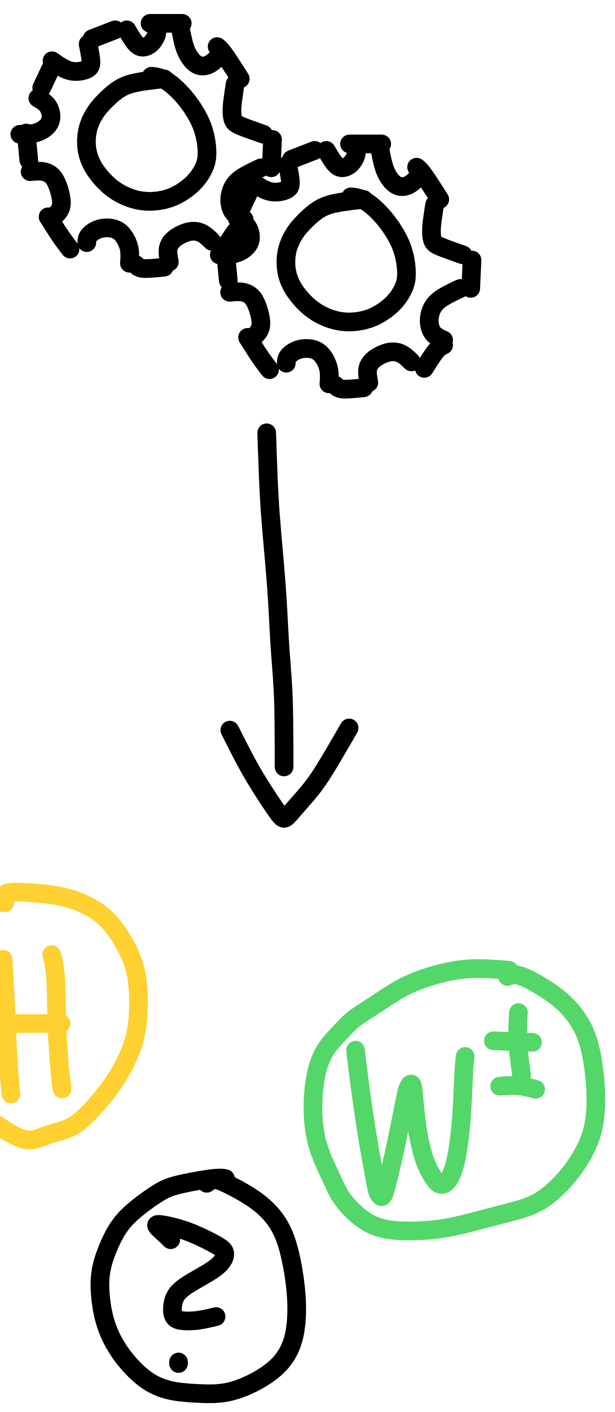
[Afferrante et. al., SciPost Phys., 2021]

Model building 2.0

This changes the model building approach

Model building

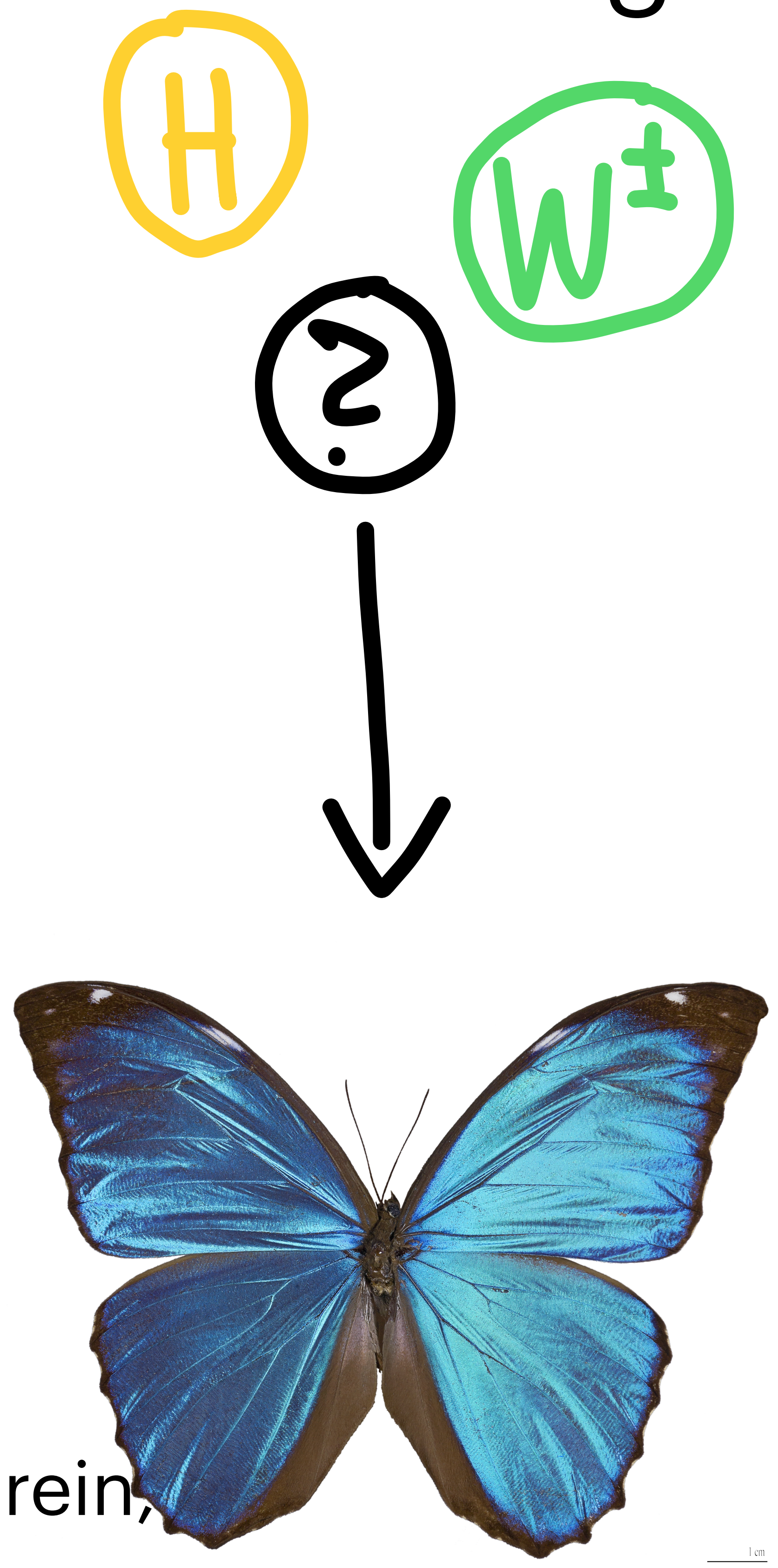
First the mechanism and symmetries



From this we predict a spectrum

Model building 2.0

We need to know the spectrum



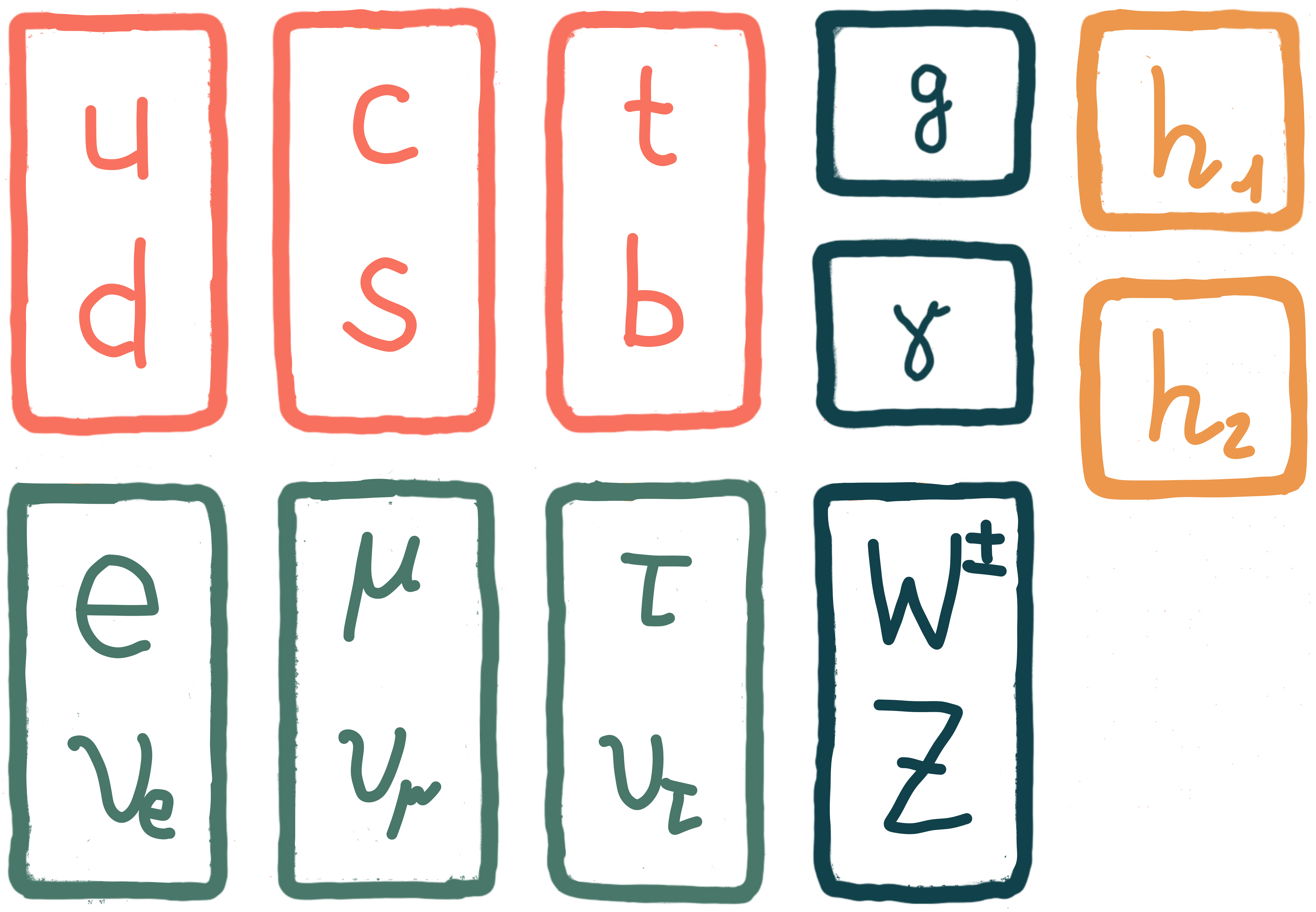
Conclude symmetries and symmetry breaking

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

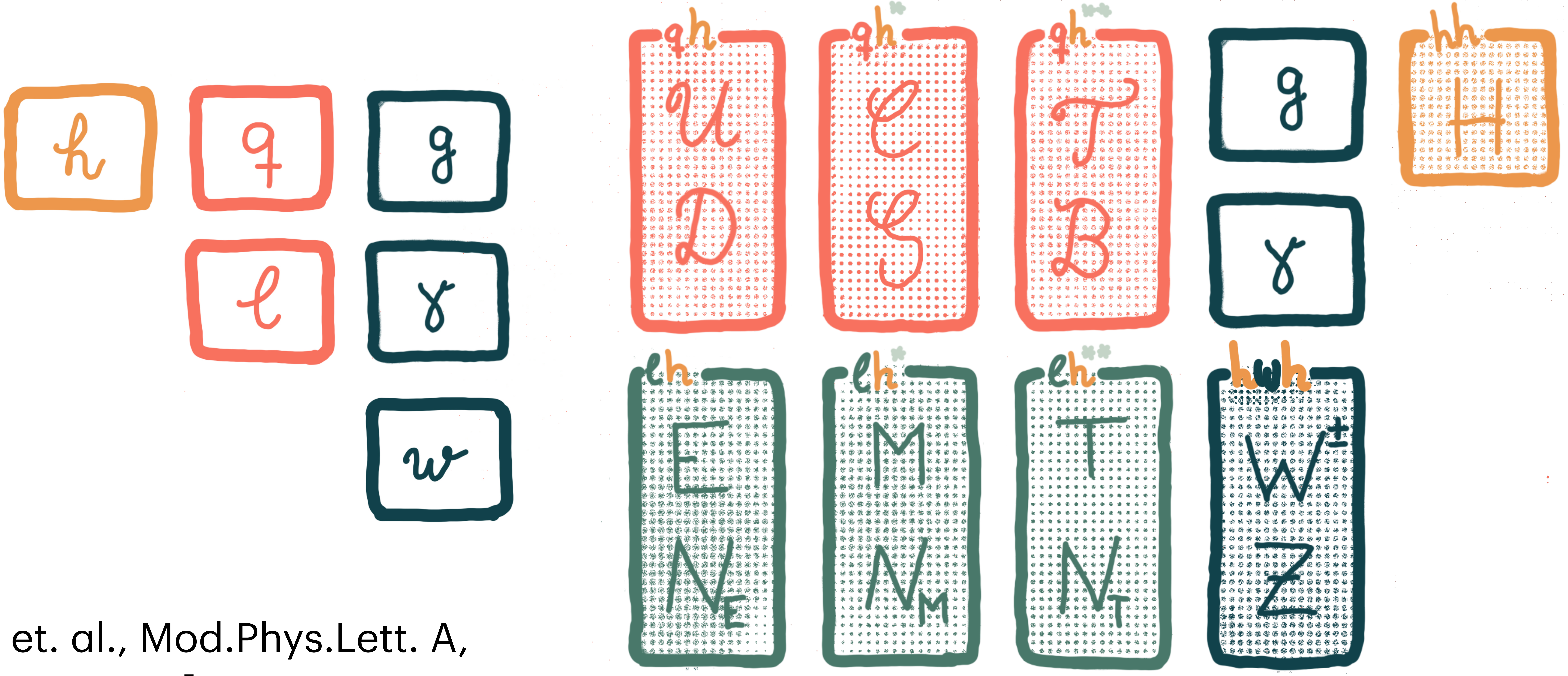
Implications for 2HDM models

Enlarged custodial symmetry

- Add a second Higgs doublet
- In this case the custodial symmetry is larger, because the matrix X has more dimensions



Standard model flavor symmetries



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

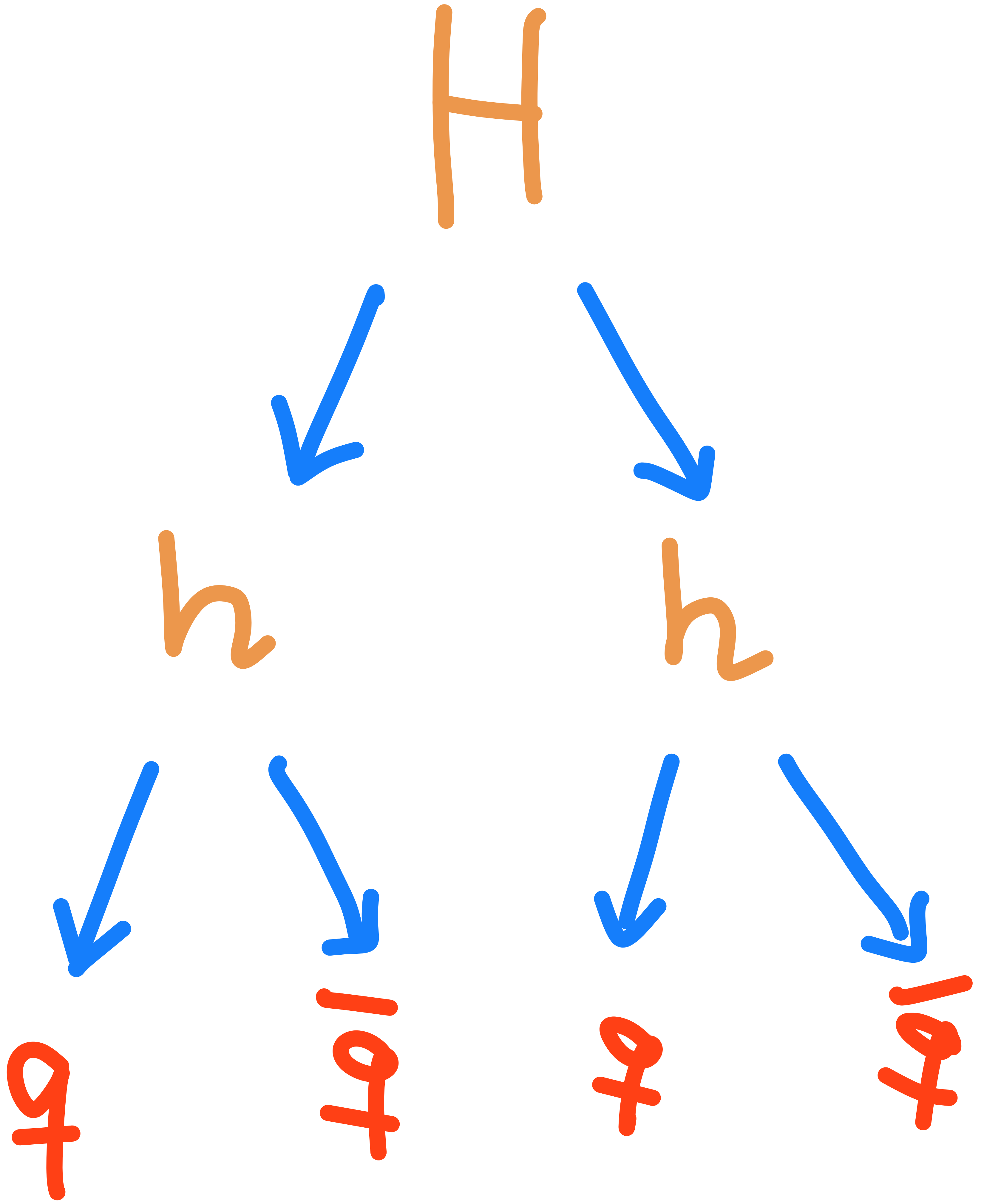
Technicolor and composite Higgs

- FMS requires a BEH effect, it is replaced by the chiral symmetry breaking of the new sector
- Composite representations of ϕ has to yield FMS with substructure

Physical Higgs

FMS mechanism

Techniquarks/
fundamental
color quarks



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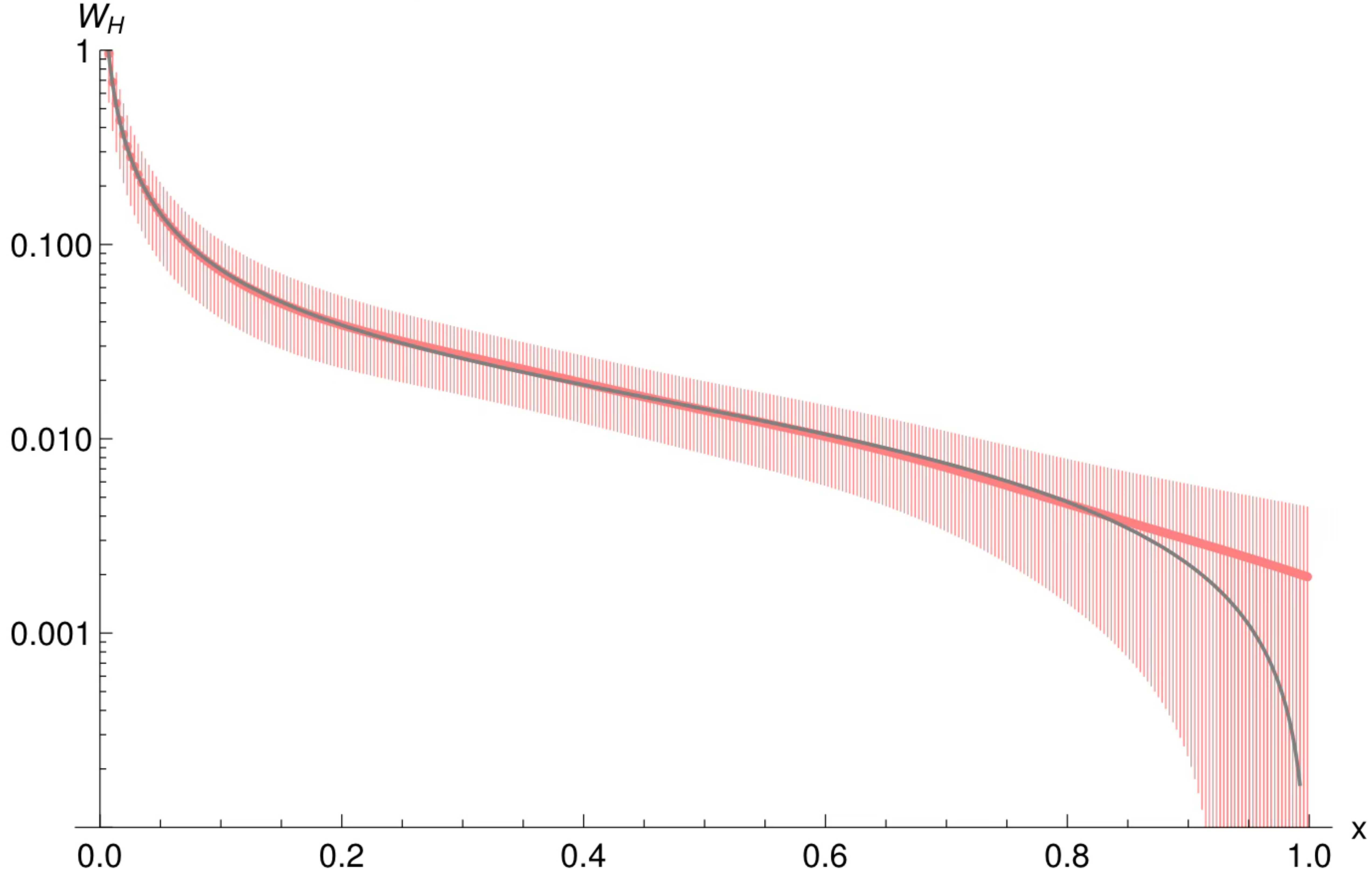
Lattice results for the novel background

PDFs and compositeness

Only gauge-scalar

- Complex structure of asymptotic states of FMS background could be visible in HL-LHC data
- Further structure in a technicolor case?
- How much precision is necessary to measure the difference?

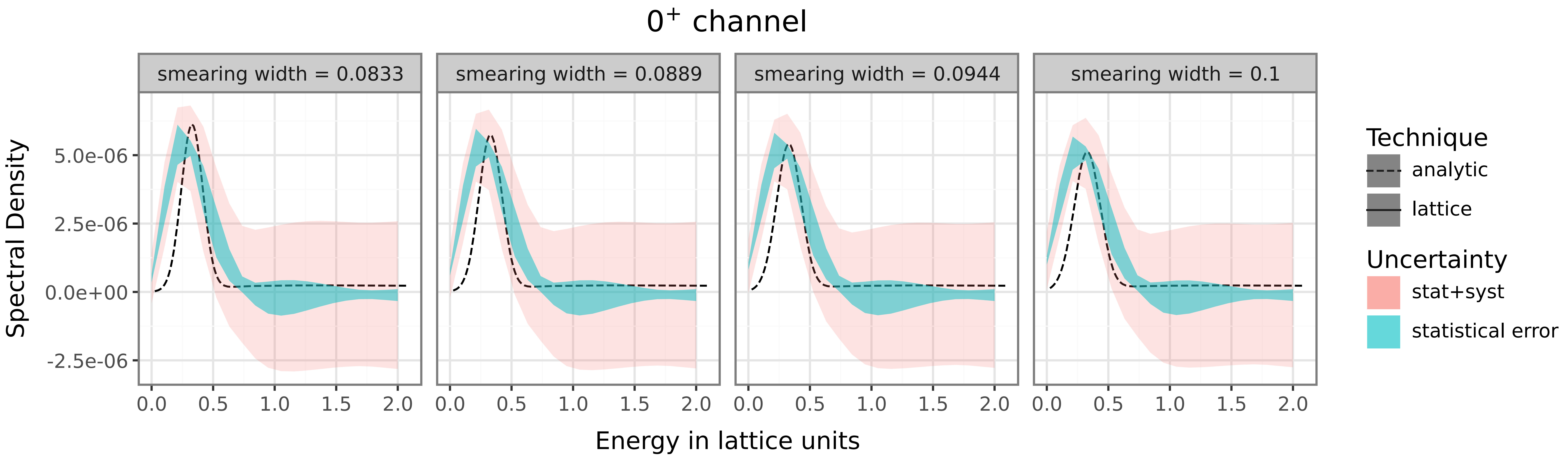
W boson PDF in H from lattice calculations



[Jenny, Maas, Wieland, in preparation]

Matching (augmented) perturbation theory & lattice

Including left-handed dynamic fermions, but Yukawa couplings are zero



Example: Smeared spectral densities

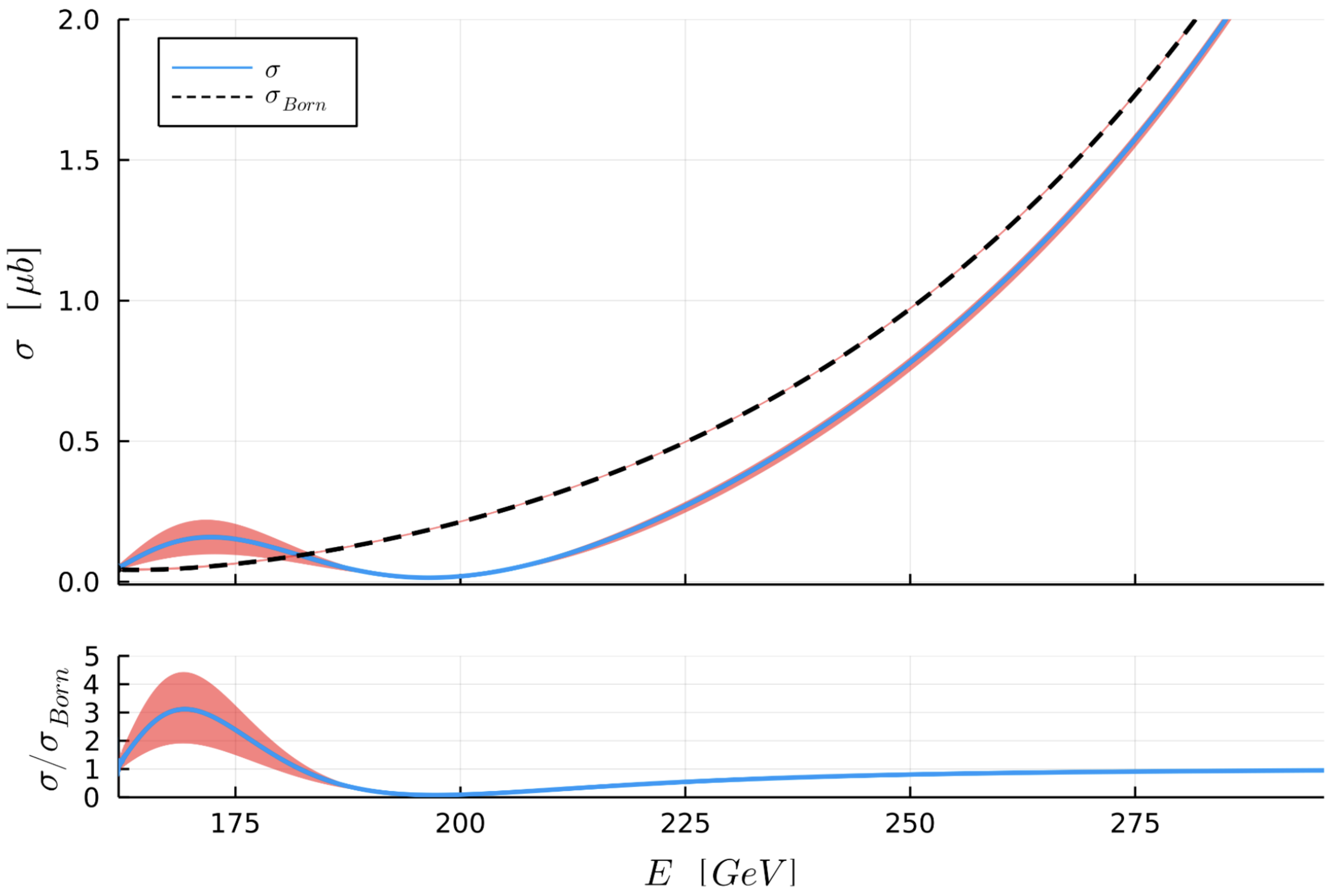
$$\rho(\sigma, E_\star) = \int_0^\infty \mathrm{d}E \Delta_\sigma(E_\star, E)\rho(E)$$

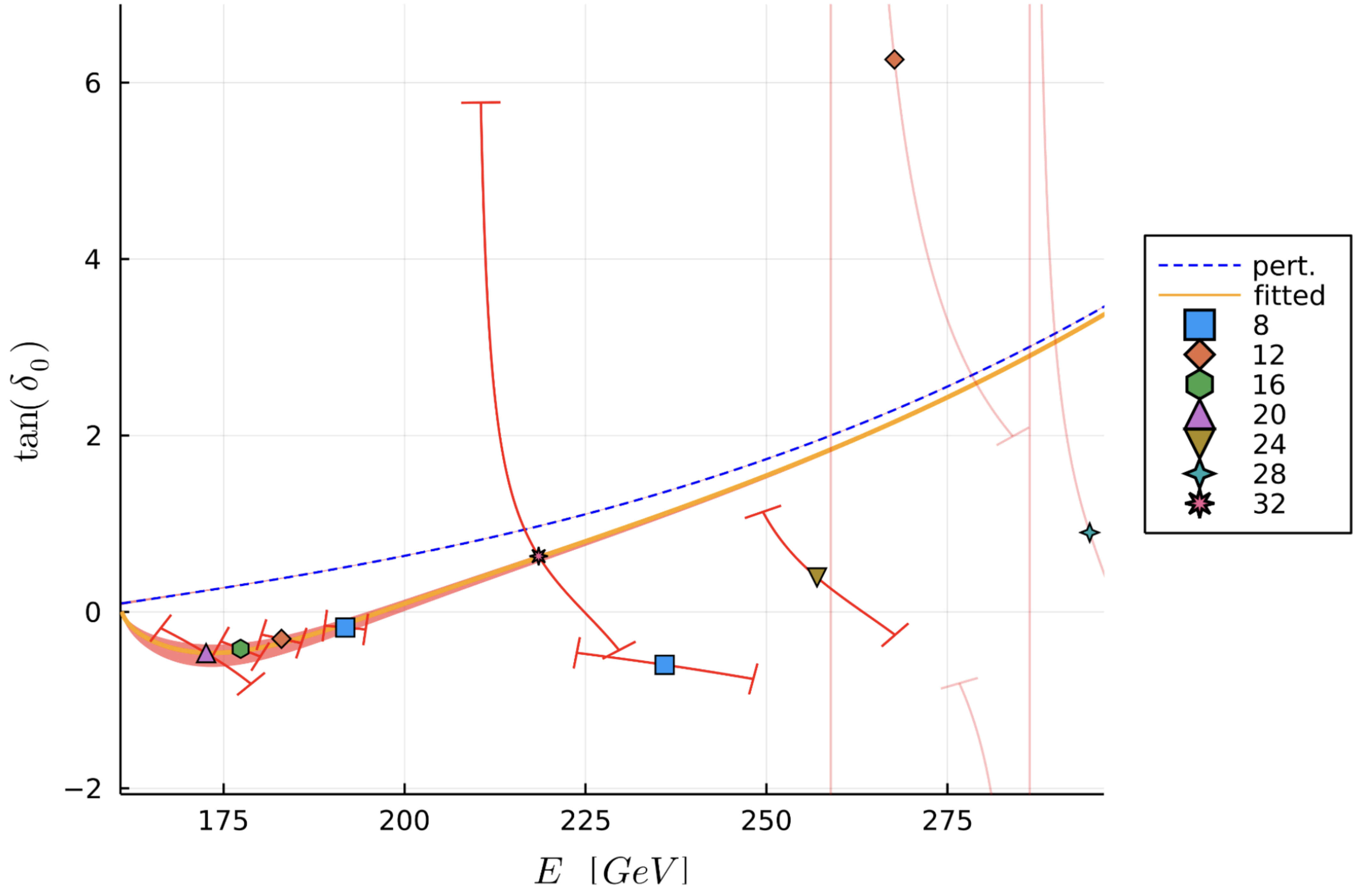
Analytic results from [Maas, Sondenheimer, Phys. Rev. D, 2020]

See also [Dudal et. al., Eur. Phys. J. C, 2021], lattice technique: [Hansen, Lupo, Tantalo, PRD, 2019]

Vector boson scattering in FMS

Only gauge-scalar





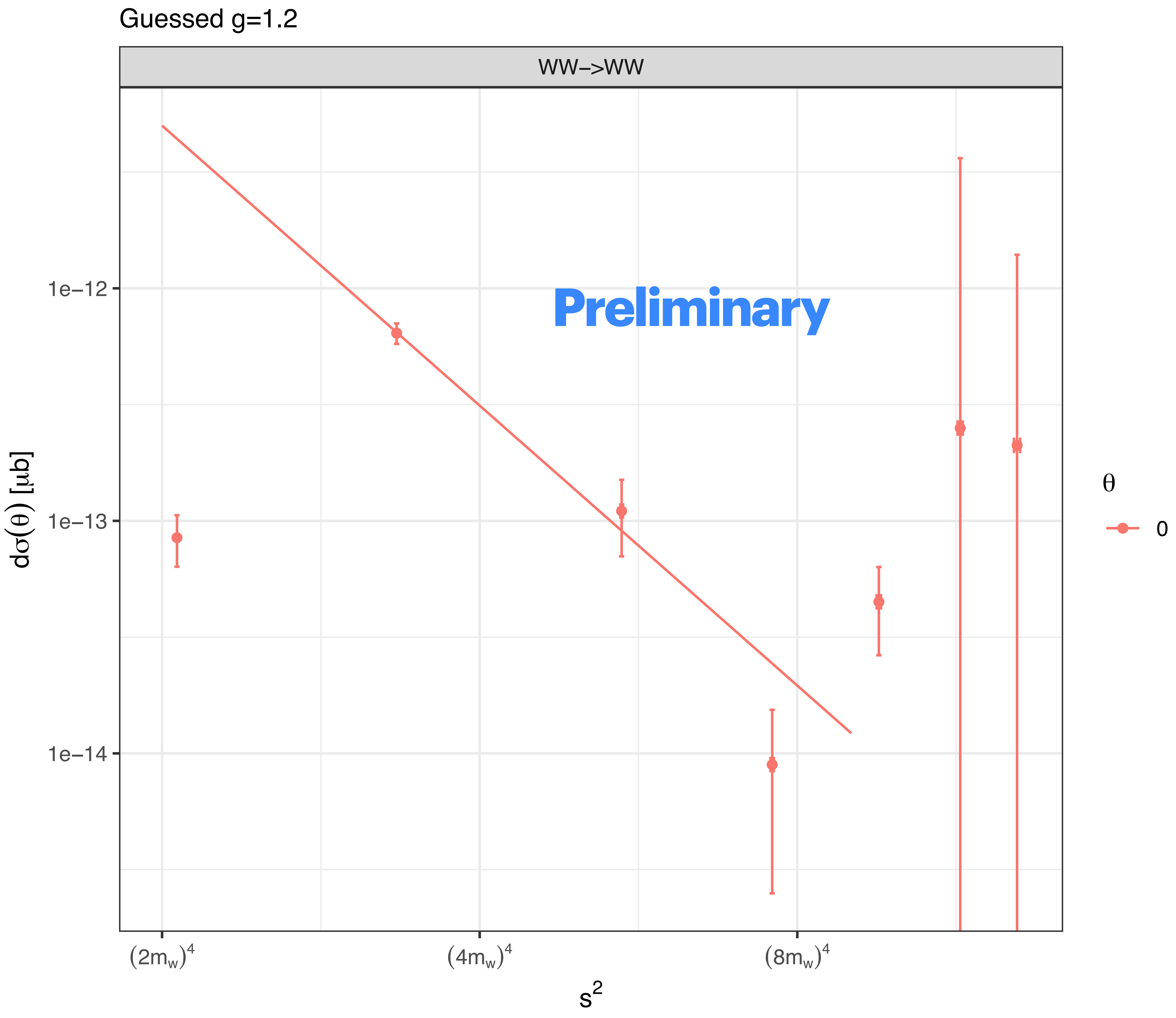
Expected deviations @ O(100 GeV)

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

Dynamic lattice results with new techniques

Including left-handed dynamic fermions, but Yukawa couplings are zero

- Noisy but above the inelastic threshold, matching APT



Lattice technique: [Bulava, Hansen, PRD, 2019]

Summary & Outlook

Summary

- If we are forced to work gauge-invariantly like on the lattice, asymptotic states end up composite
- This compositeness affects phenomenologically interesting quantities such as VBS in the scalar channel, which we need to have understood for BSM physics
- The mechanism can also reduce standard model symmetries, by explaining flavor and generation over an excited state structure
- Composite Higgs and technicolor background can be understood over non-perturbative computations of PDFs

Outlook

- Parameter space scans of VBS, spectral densities and (augmented) perturbation theory comparisons
- Dynamic simulations with Yukawa couplings and qualitative understanding of excited state structure

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Thank you for your attention!