Lepton Extensions Of Minimal Composite Higgs Models

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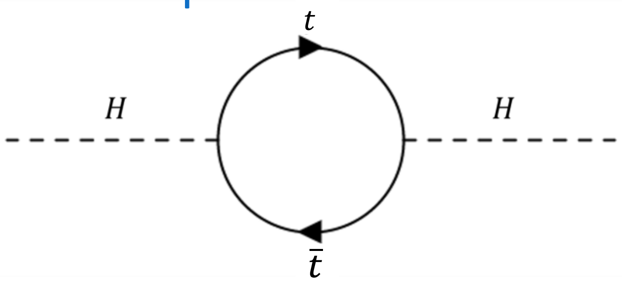
Naturalness of the Higgs mass

If the Standard Model is accurate up to some high energy scale Λ_{UV},

Higgs mass will receive loop contributions that scale with Λ_{UV}, mainly from t-quark:

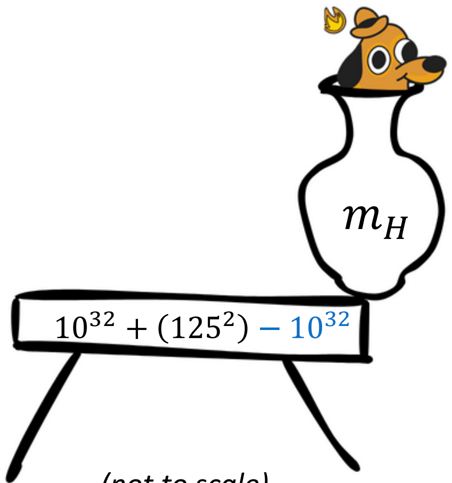


$$m_H^2 = m_0^2 + \Delta m^2, \text{ where } \Delta m^2 = -\frac{3y_t^2}{8\pi^2}\underline{\Lambda_{UV}^2} + \mathcal{O}(m_t^2 \log\frac{\Lambda_{UV}}{m_t})$$

<u>Fine-tuning</u>

- If Λ_{UV} (e.g. Planck scale) $\gg m_H$, require very precise cancellation from m_0^2

  to restore $m_H = 125\ \text{GeV}$

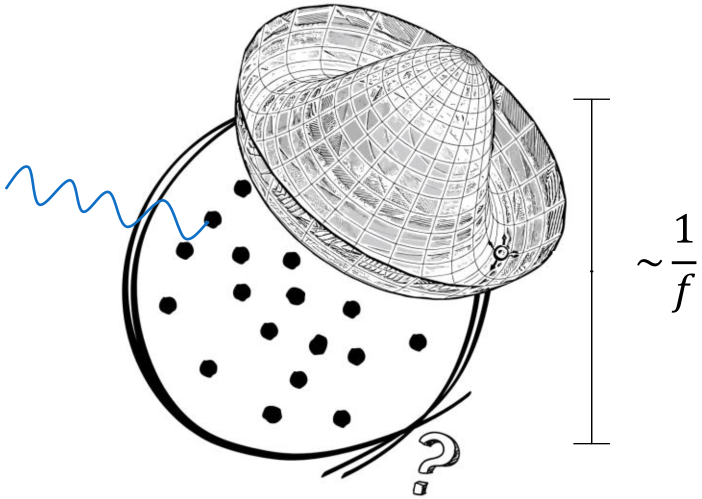


(not to scale)

Why a composite Higgs?

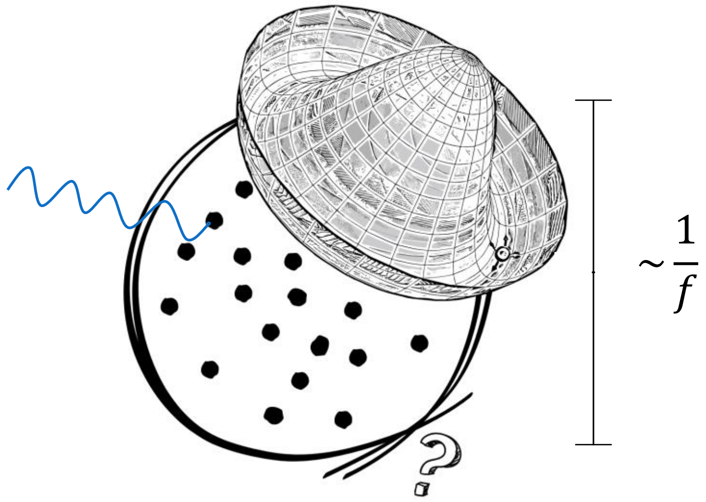
- Consider some strongly interacting dynamics at scale, f ($\sim$ TeV)

- Higgs appears as spin-0 bound state of said dynamics (finite size)



- Loop integrals are cut off at scale f

Composite Higgs Models (CHMs)



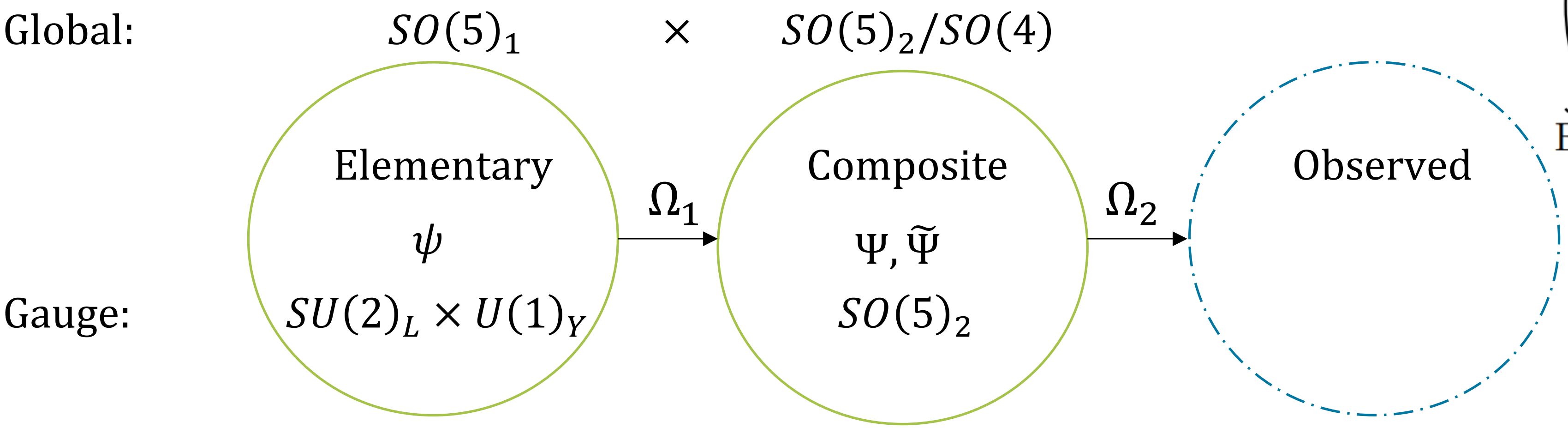
- Higgs is a **pseudo Nambu-Goldstone boson** (like pions in QCD)
- SM particles get masses by mixing with their partners in the composite sector
- TeV-scale composite resonances

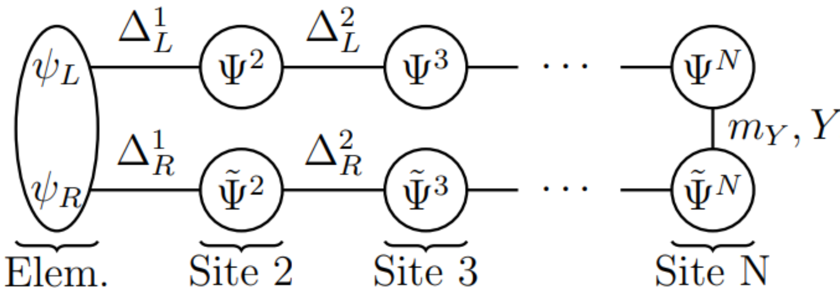
Minimal Composite Higgs Models (MCHMs)

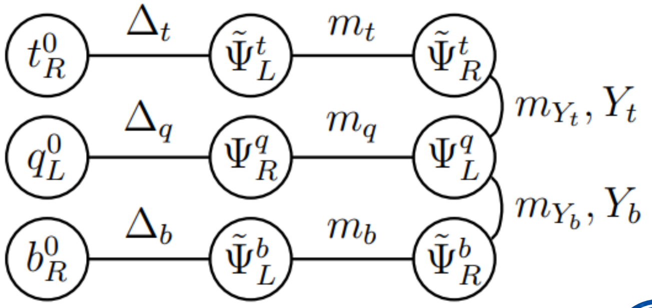
- SM has global $SU(2)_L \times SU(2)_R$ symmetry

- $SO(5) \rightarrow SO(4)$ gives exactly 4 Higgs doublet fields

  - $SO(4) \cong SU(2)_L \times SU(2)_R$
  - $\dim(SO(N)) = \frac{N(N-1)}{2}$







- Various fermion representations $(\mathbf{1}, \mathbf{5}, \mathbf{10}, \mathbf{14}, \ldots)$

Minimal Composite Higgs Models (MCHMs)

In this work

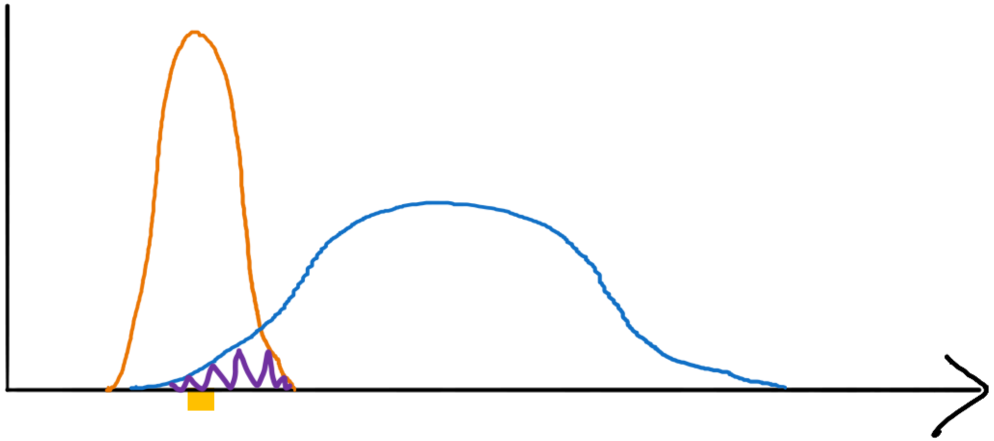
- **Quarks** are embedded in $(5-5-5)$; **Leptons** in $(14-10)$ and $(5-5)$

$\left(q_L = {}^{t_L}_{b_L}, t_R, b_R\right)$

$\left(l_L = {}^{\nu_L}_{\tau_L}, \tau_R\right)$

- Choice of representations based on work by:
  - M. Carena, L. Da Rold and E. Pont´on (JHEP 06 (2014) 159, [1402.2987])
    - Looked at models that could fit collider constraints
  - J. Barnard and M. White (JHEP 09 (2017) 049, [1703.07653])
    - Explored leptonic-inclusive models based on fine-tuning, given by BG-measure
  - E. Carragher, W. Handley, D. Murnane, P. Stangl, W. Su, M. White (JHEP 21 (2021) 237, [2101.00428])
    - First convergent global fits with partially-composite 3rd generation quarks

Segue: Bayesian statistics



- Prior $\pi(p)$: Initial guess of some parameter (Distribution of points p)
- Likelihood $L(p)$: How well data fits a point
- Posterior $P(p)$: Updating guess based on the likelihood(p)

$$P(p) = \frac{L(p)\pi(p)}{Z}$$

- Kullback-Leibler (KL) Divergence:

$$D_{\mathrm{KL}} = \int dp P(p) \ln(P(p)/\pi(p))$$

- Evidence:

$$Z = \int dp\, L(p)\pi(p) \quad \rightarrow\ \ln(Z) = \langle \ln(L) \rangle_P - D_{\mathrm{KL}}$$

Fitting the models

Models

$\mathrm{LM4DCHM}^{5-5-5}_{5-5}$ $\mathrm{LM4DCHM}^{5-5-5}_{14-10}$

Constraints

SM masses, EW precision observables, Z boson decay ratios, Higgs signal strengths, LHC fermion partner bounds

Tools

Nested sampling (`PolyChord`) allows efficient exploration of param space

- Log-spaced priors (Flash subset of table of
- Likelihood is taken to be Gaussian in observables
- Lots of parameters to scan over

$$L \subset -m_{\Psi}\bar{\Psi}\Psi - \tilde{m}_{\Psi}\bar{\tilde{\Psi}}\tilde{\Psi} + \Delta_L \psi_L \Psi_R + \Delta_R \psi_R \tilde{\Psi}_L + m_Y \bar{\Psi}_L \Psi_R + \cdots$$

- Only 3rd generation fermions couple to composite sector

Scan Params

Model	Parameters	Scan Range	Prior
	$m_\rho/f,\ m_a/f$	$[1/\sqrt{2}, 4\pi]$	
	$f_X/f,\ f_G/f$	$[0.5, 2\sqrt{3}]$	Uniform
	$g_\rho,\ g_X,\ g_G$	$[1.0, 4\pi]$	
	Δ_{t_L}/f	$[e^{-0.25}, e^{1.5}]$	
	Δ_{t_R}/f	$[e^{-0.75}, 4\pi]$	
Both	Δ_{b_L}/f	$[e^{-5.0}, e^{-3.0}]$	
	Δ_{b_R}/f	$[e^{-0.5}, 4\pi]$	
	$m_t/f,\ m_{\tilde{b}}/f$	$[e^{-0.5}, e^{1.5}]$	Logarithmic
	$m_{\tilde{t}}/f$	$[e^{-1.0}, 4\pi]$	
	m_b/f	$[e^{-1.0}, e^{1.5}]$	
	m_{Y_t}/f	$[e^{-8.5}, 4\pi]$	
	m_{Y_b}/f	$[e^{-0.25}, 4\pi]$	
	$(m_{Y_t}+Y_t)/f$	$[e^{-0.5}, 8\pi]$	
	$(m_{Y_b}+Y_b)/f$	$[e^{-8.5}, e^{-0.5}]$	

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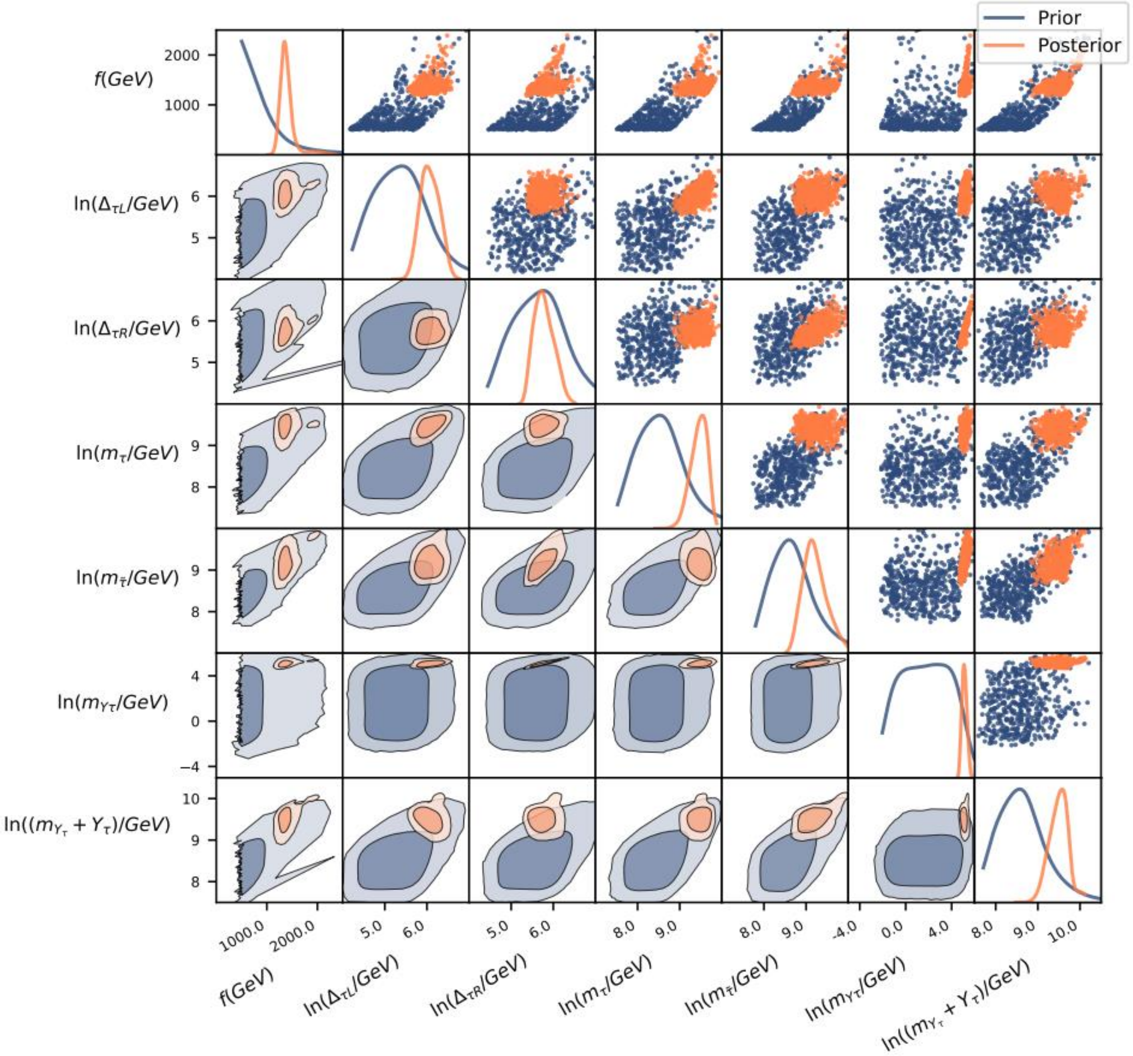
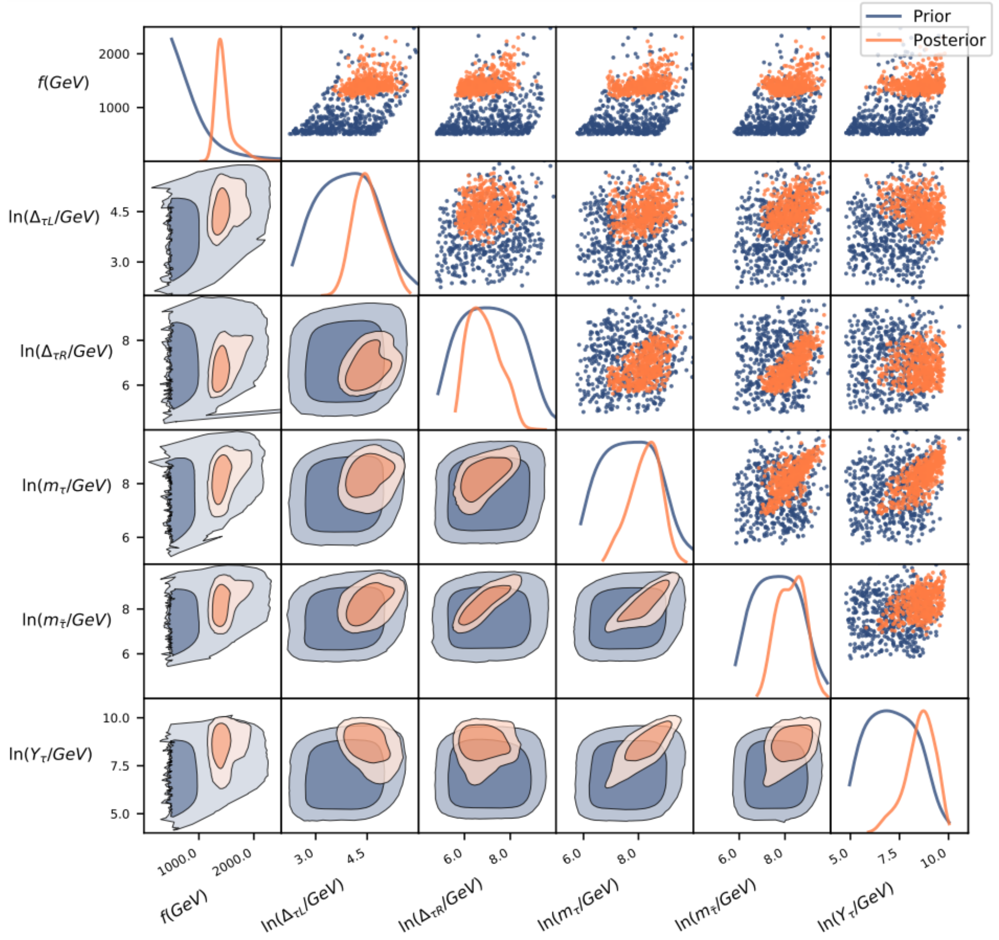
Results

$\mathrm{LM4DCHM}^{5-5-5}_{5-5}\ (5-5)$

Prior
Posterior

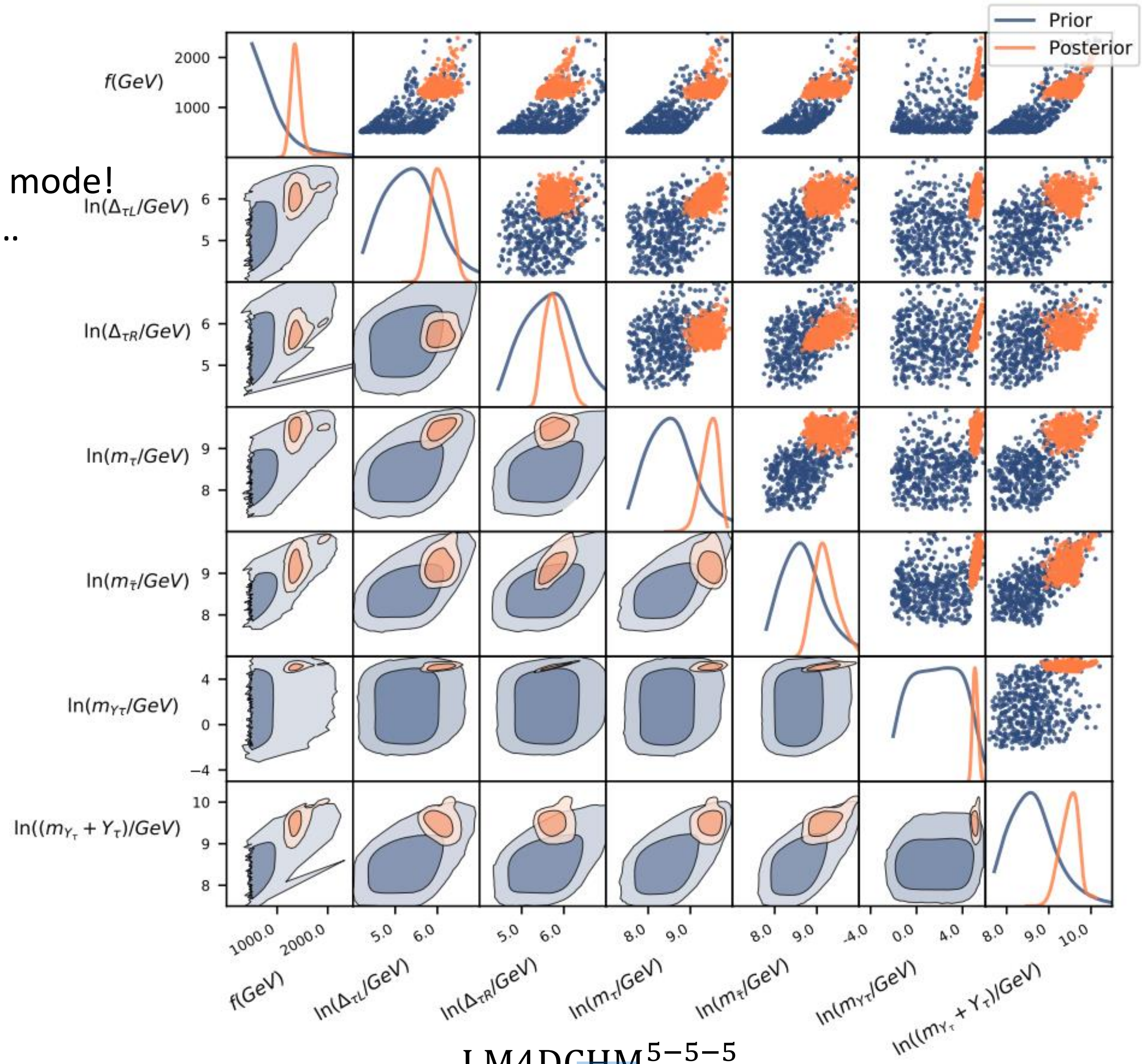
$\mathrm{LM4DCHM}^{5-5-5}_{14-10}\ (14-10)$





Results

$(5-5)$ has small, separate mode!
This will be important later…



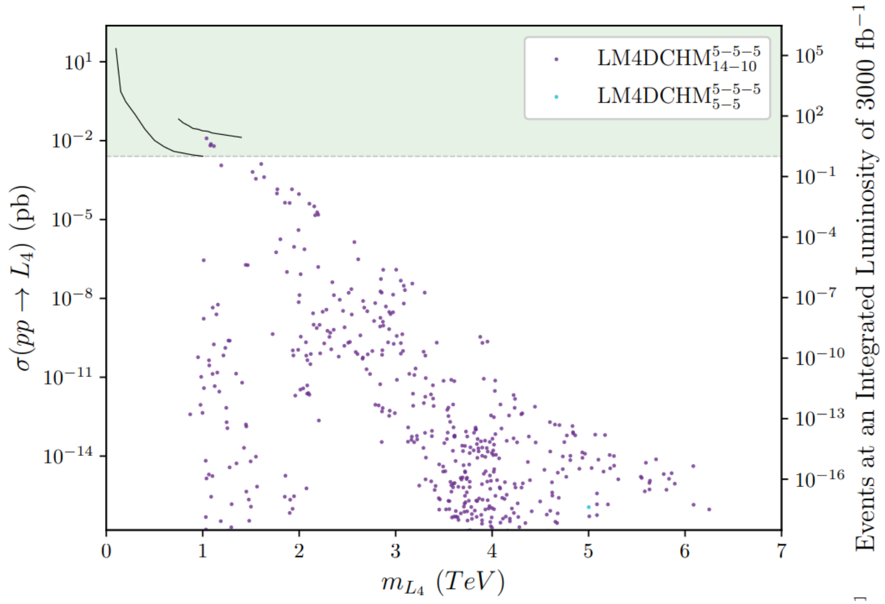
$\text{LM4DCHM}^{5-5-5}_{5-5}$

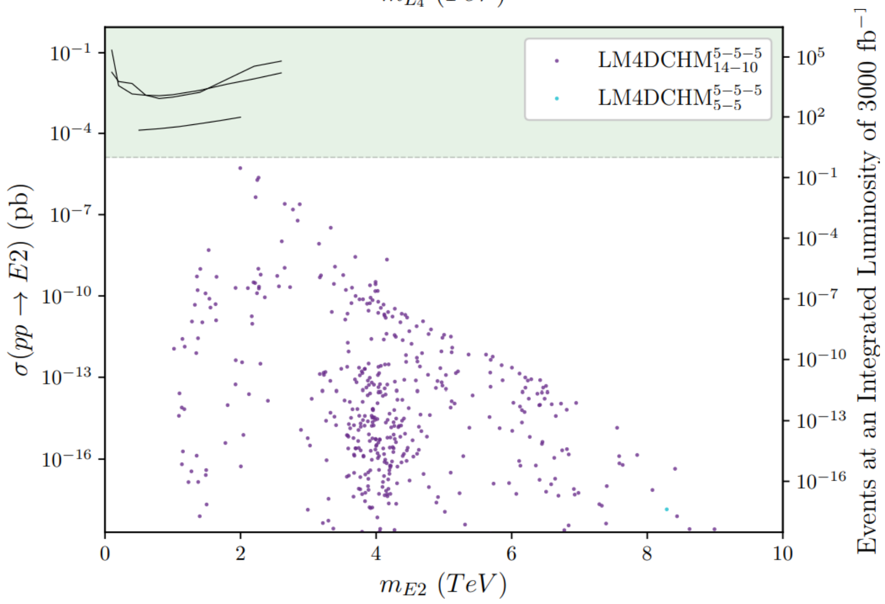
Results

Model	$\ln(\mathcal{Z})$	$\langle \ln(\mathcal{L}) \rangle_P$	D_{KL}
$\mathrm{LM4DCHM}^{5-5-5}_{5-5}$	-45.60 ± 0.06	-17.27	28.33
$\mathrm{LM4DCHM}^{5-5-5}_{14-10}$	-36.30 ± 0.05	-14.63	21.67

- Both scans are convergent
- Model with leptons in $14-10$ is a better fit from a Bayesian perspective

Direct detection





- As a product of these scans, we can then look at their phenomenological signatures
- Each model has a number of heavy quark and lepton partners
- We can try and look for these at the LHC

• $LM4DCHM^{5-5-5}_{14-10}$

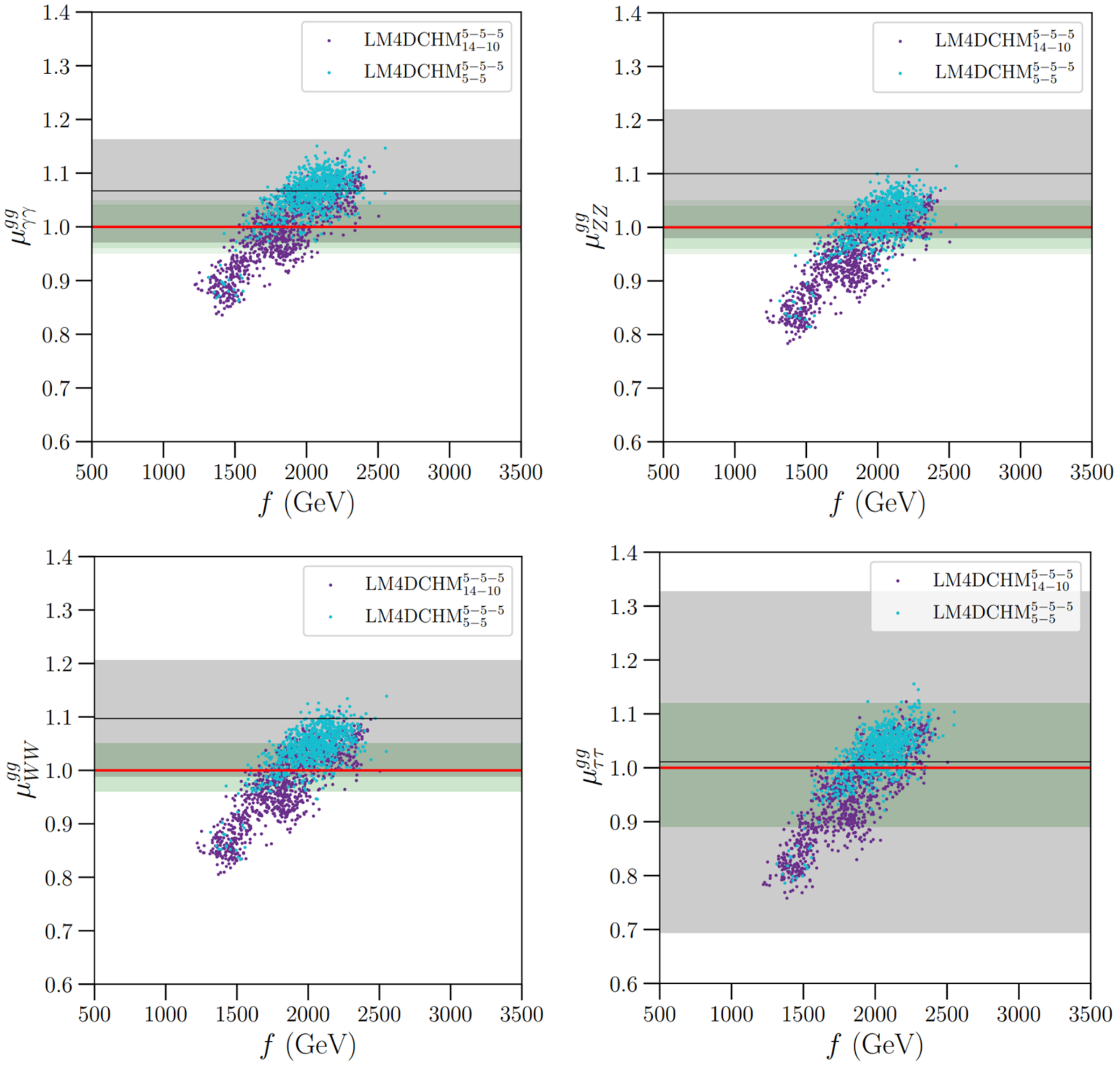
• $LM4DCHM^{5-5-5}_{5-5}$

: Producable range at HL−LHC

— : 13 TeV search bounds

Not really…

Indirect testing



- Another avenue is Higgs signal strengths (gluon fusion)
- Sensitive to modifications of Higgs couplings to SM gauge bosons and fermions, as well as loop contributions from composite resonances

$$\mu^{gg}_{jj} = \frac{[\sigma(gg \to H)BR(H \to jj)]_{measured}}{[\sigma(gg \to H)BR(H \to jj)]_{SM}}$$

- LM4DCHM$^{5-5-5}_{14-10}$
- LM4DCHM$^{5-5-5}_{5-5}$

: Current measurements

: Projected precision at HL−LHC

: SM

Takeaway

- Scans of lepton-inclusive MCHMs are convergent
- Both models satisfy all imposed experimental constraints
- But $(14 - 10)$ is a better Bayesian fit than $(5 - 5)$

- SM partners are generally too heavy to be seen, even at HL-LHC
- Best shot is indirect tests via Higgs signal strengths

arXiv:2312.06027 [hep-ph]

Back up slide(s?)

Lagrangians and gauge sector

$$\mathcal{L}_{\text{boson}} = -\frac{1}{4}\text{Tr}[G^0_{\mu\nu}G^{0\mu\nu}] - \frac{1}{4}\text{Tr}[W^0_{\mu\nu}W^{0\mu\nu}] - \frac{1}{4}B^0_{\mu\nu}B^{0\mu\nu} \quad \Big\} \text{ elementary}$$

$$-\frac{1}{4}\text{Tr}[\rho_{G\mu\nu}\rho^{\mu\nu}_G] - \frac{1}{4}\text{Tr}[\rho_{\mu\nu}\rho^{\mu\nu}] - \frac{1}{4}\rho_{X\mu\nu}\rho^{\mu\nu}_X \quad \Big\} \text{ composite}$$

$$+\sum_{i=1,X,G}\frac{f_i^2}{4}Tr[(D_\mu\Omega_i)^\dagger(D^\mu\Omega_i)] + \frac{f_2^2}{2}(D_\mu\Omega_2\Phi_0)^\dagger(D^\mu\Omega_2\Phi_0) \quad \Big\} \text{ NGB}$$

$$SO(5)^0 \times SO(5)^1 : \Omega_1 \to g_0\Omega_1 g_1^{-1}, \qquad U(1)^0_X \times U(1)^1_X : \ \Omega_X \to g_0\Omega_X g_1^{-1}$$

$$SO(5)^1 \times SO(4) \ : \Omega_2 \to g_1\Omega_2 h^{-1}, \qquad SU(3)^0_C \times SU(3)^1_C : \Omega_G \to g_0\Omega_G g_1^{-1}$$

$$\mathcal{L}_{\text{fermion}} = \bar{\psi}i\not{D}\psi \quad \Big\} \text{ elementary kinetic}$$

$$+\sum_{k=2}^{N}\left(\bar{\Psi}^k(i\not{D} - m_L^k)\Psi^k + \bar{\tilde{\Psi}}^k(i\not{D} - m_R^k)\tilde{\Psi}^k\right) \quad \Big\} \text{ composite kinetic}$$

$$+\sum_{k=1}^{N}\left(\Delta_L^k\bar{\Psi}_L^k\Omega_k\Psi_R^{k+1} + \Delta_R^k\bar{\tilde{\Psi}}_L^k\Omega_k\tilde{\Psi}_R^{k+1}\right) + \text{h.c.} \quad \Big\} \text{ link}$$

$$-m_Y\bar{\Psi}_L^N\tilde{\Psi}_R^N - Y\bar{\Psi}_L^N\Phi\Phi^\dagger\tilde{\Psi}_R^N + \text{h.c.} \quad \Big\} \text{ Yukawa-like.}$$

Higgs vev

$$\mathcal{L}^{\text{eff}}_{\text{comp. fermions}} = \sum_{\psi=t,b,\nu,\tau} [\bar{\psi}^0_L \not{p}(1+\Pi_{\psi L}(p^2))\psi^0_L + \bar{\psi}^0_R \not{p}(1+\Pi_{\psi R}(p^2))\psi^0_R$$
$$+ \bar{\psi}^0_L M_\psi(p^2)\psi^0_R + h.c.]$$

$$\gamma_{\text{gauge}} = -\frac{9m_\rho^4\left(m_a^2 - m_\rho^2\right)t_\theta}{64\pi^2\left(m_a^2 - (1+t_\theta)\,m_\rho^2\right)} \ln\left[\frac{m_a^2}{(1+t_\theta)\,m_\rho^2}\right]$$

$$V^{\text{eff}}_{\text{fermion}}(h) = -2\sum_{\psi=t,b,\tau,\nu} N_\psi \int \frac{dp_E^2}{16\pi^2} \ln\left[(1+\Pi_{\psi L}(-p_E^2))(1+\Pi_{\psi R}(-p_E^2)) - \frac{|M_\psi(-p_E^2)|^2}{p_E^2}\right]$$

$$V(h) := \gamma^2 s_h^2 + \beta^4 s_h^4 \qquad s_{\langle h\rangle} = \frac{\gamma}{2\beta} \qquad m_H := \sqrt{8\beta(1-s^2_{\langle h\rangle})}\frac{s_{\langle h\rangle}}{f}$$

masses of the lightest composite gauge bosons m_ρ and m_a

$$m_\rho^2 := \frac{1}{2}g_\rho^2 f_1^2, \qquad m_a^2 := \frac{1}{2}g_\rho^2(f_1^2 + f_2^2).$$

Constraints

- SM masses: $\mathrm{m_t}, \mathrm{m_b}, \mathrm{m_\tau}, \mathrm{m_H}$
- Oblique parameters: S and T

$$S = \frac{1}{4\,\alpha_{\mathrm{em}}}\left(1 - \frac{m_W^2}{m_Z^2} - \frac{g_{Zee}^R}{2(g_{Zee}^R - g_{Zee}^L)}\right)$$

$$\mathrm{T} = \frac{1}{\alpha_{\mathrm{em}}}\left(\frac{\Pi_{WW}^T(p^2 = 0)}{m_W^2} - \frac{\Pi_{ZZ}^T(p^2 = 0)}{m_Z^2}\right)$$

- Z decay ratios: $R_i = \frac{\Gamma(Z \to i\bar{i})}{\Gamma(Z \to q\bar{q})}$, for $i = b, e, \mu, \tau$
- Higgs signal strengths: $\mu_{jj}^{gg} = \frac{[\sigma(gg \to H) BR(H \to jj)]_{measured}}{[\sigma(gg \to H) BR(H \to jj)]_{SM}}$
- Collider searches*

  (lower mass bounds for fermion resonances)

Lepton resonance	Lower Mass Bound
N	90.3 GeV
$E2$	370 GeV
$L_{\mathbf{1}}$	300 GeV
$L_{\mathbf{2}}$	790 GeV
$L_{\mathbf{3}}$	225 GeV

Symmetries

$$SO(5)^0 \times SO(5)^1 : \Omega_1 \to g_0 \Omega_1 g_1^{-1}, \qquad U(1)_X^0 \times U(1)_X^1 : \ \Omega_X \to g_0 \Omega_X g_1^{-1},$$
$$SO(5)^1 \times SO(4) \ : \Omega_2 \to g_1 \Omega_2 h^{-1}, \qquad SU(3)_C^0 \times SU(3)_C^1 : \Omega_G \to g_0 \Omega_G g_1^{-1},$$

where g_a denotes transformations from Site a, and $h \in SO(4)$. The decay constants f_i in the NGB terms correspond to the scales of these symmetry breakings. Most NGBs are unphysical and can be gauged away, with the sole exception of the Higgs field, which is parameterised in the product $\Omega := \Omega_1 \Omega_2$. Because of this, it has an associated symmetry breaking scale f given by

$$\frac{1}{f^2} = \frac{1}{f_1^2} + \frac{1}{f_2^2}.$$

This is related to the Higgs vev v by

$$f \equiv \frac{v}{s_{\langle h \rangle}} = \frac{246}{s_{\langle h \rangle}} \text{ GeV},$$

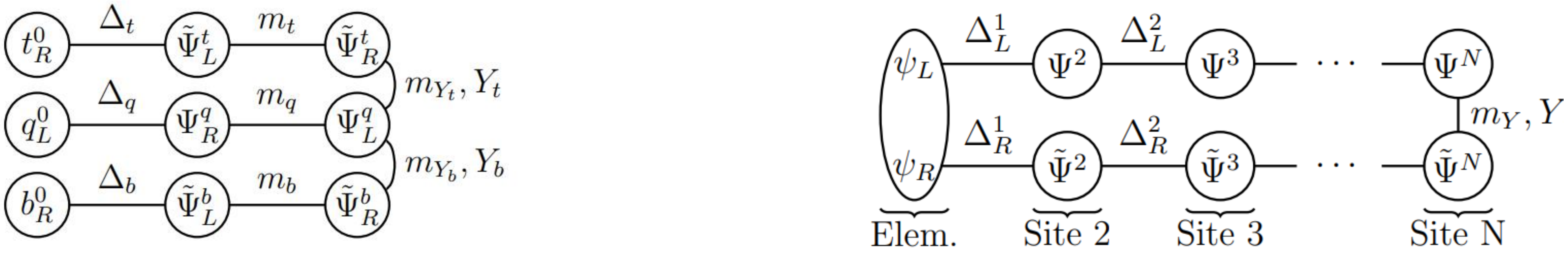
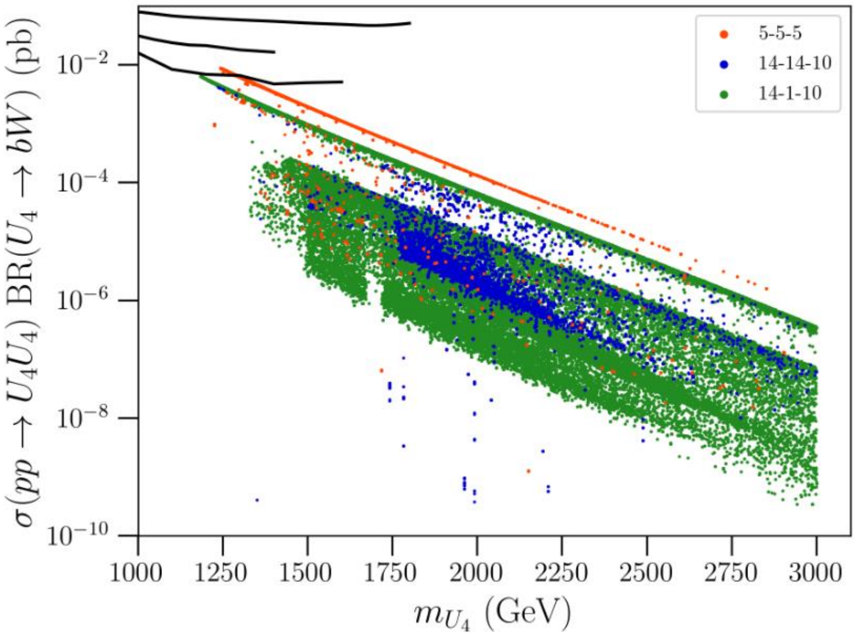


Figure 4.1: Structure of couplings between elementary and composite fermions.

Quark partner direct detection



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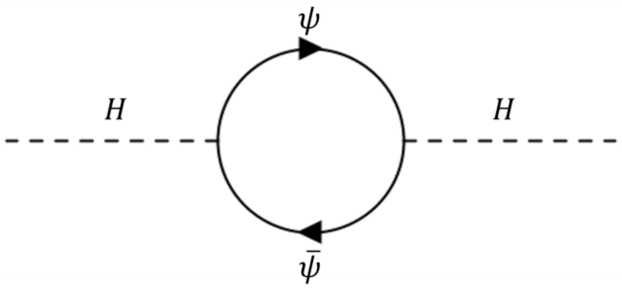
$$m_H^2 = m_0^2 + \Delta m^2$$



$$= iN_C\left(-i\frac{\lambda_\psi}{\sqrt{2}}\right)^2 \int \frac{d^4k}{(2\pi)^4}\frac{\mathrm{Tr}[(p+k+m_\psi)(k+m_\psi)]}{((p+k)^2-m_\psi^2-i\epsilon)(k^2-m_\psi^2-i\epsilon)}$$

Branching ratios