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4D Composite Higgs Models with partially composite leptons

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2312.06027(E. Carragher, K. Goh, WS, M. White, A.Williams)

Outline

- Naturalness and M4DCHM
- Study strategies
- Results about naturalness
- Conclusion

Naturalness

Hierarchy: 100 GeV → 10^{16} -10^{19} GeV. (SUSY?)

Naturalness

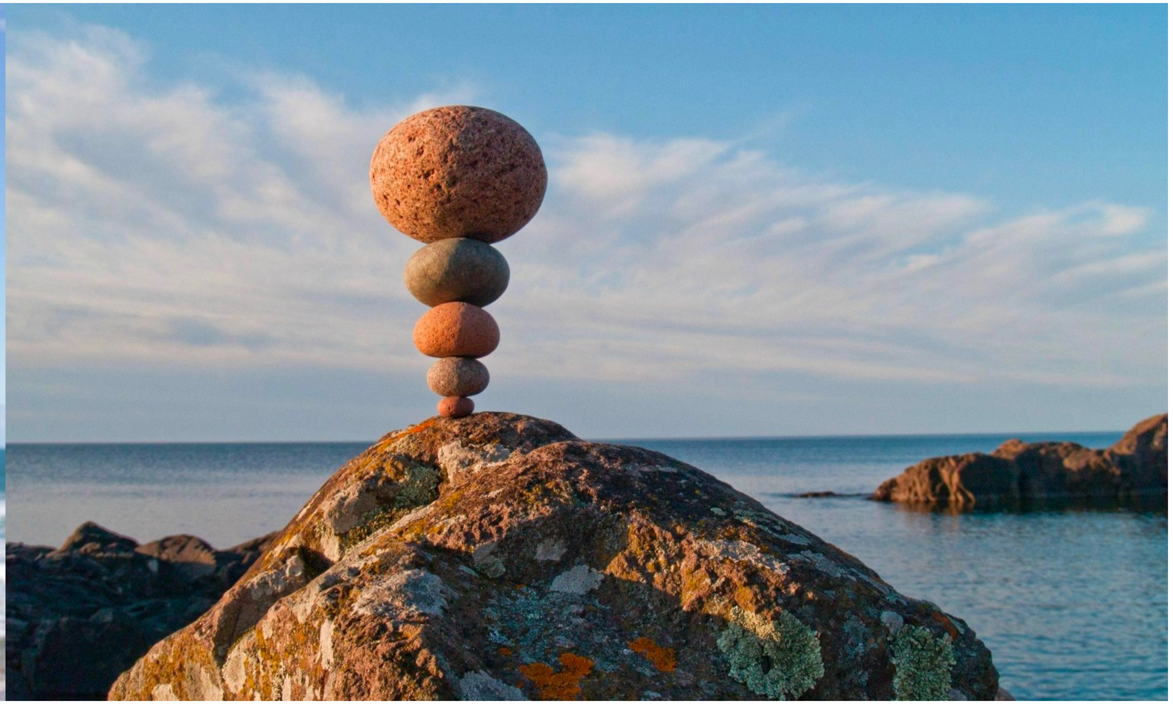
Hierarchy: 100 GeV → 10^16 -10^19 GeV. (SUSY?)

No explicit BSM signal

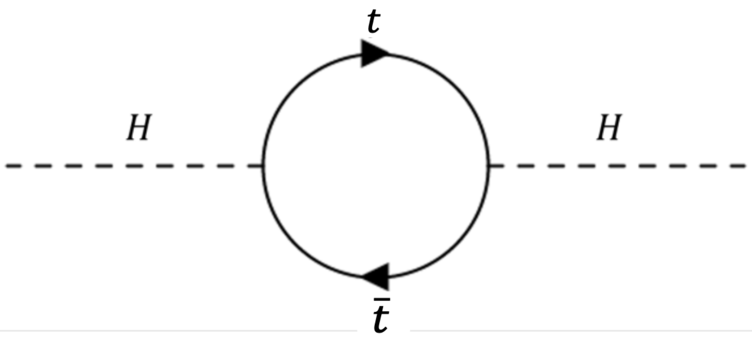
Naturalness

Little Hierarchy : 100 GeV → 5,000-10,000 GeV

(Mirror Twin Higgs, **Composite** …
)

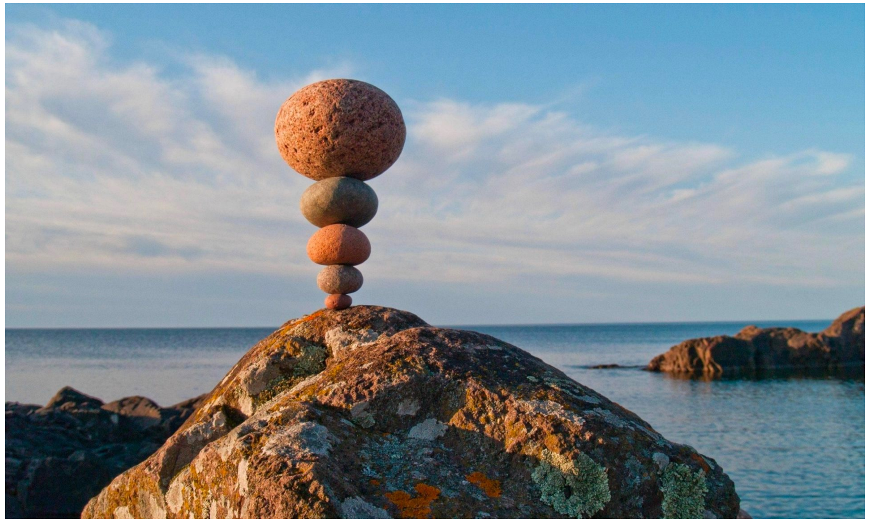


Naturalness of the Higgs mass



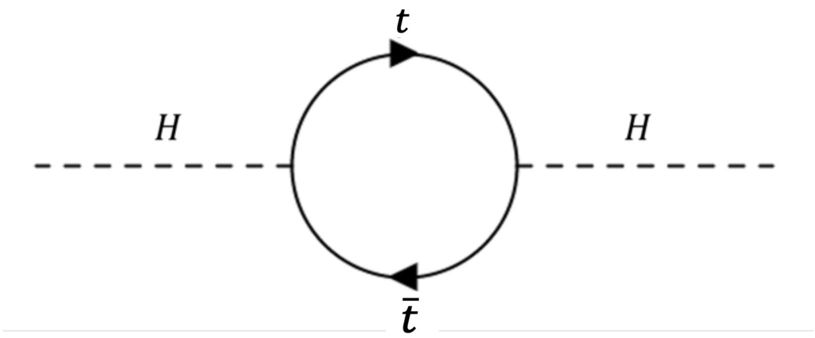
$$m_H^2 = m_0^2 + \Delta m^2$$

$$\Delta m^2 = -\frac{3y_t^2}{8\pi^2}\Lambda_{UV}^2 + \mathcal{O}\left(m_t^2 \log\frac{\Lambda_{UV}}{m_t}\right)$$



Naturalness problem

Naturalness of the Higgs m



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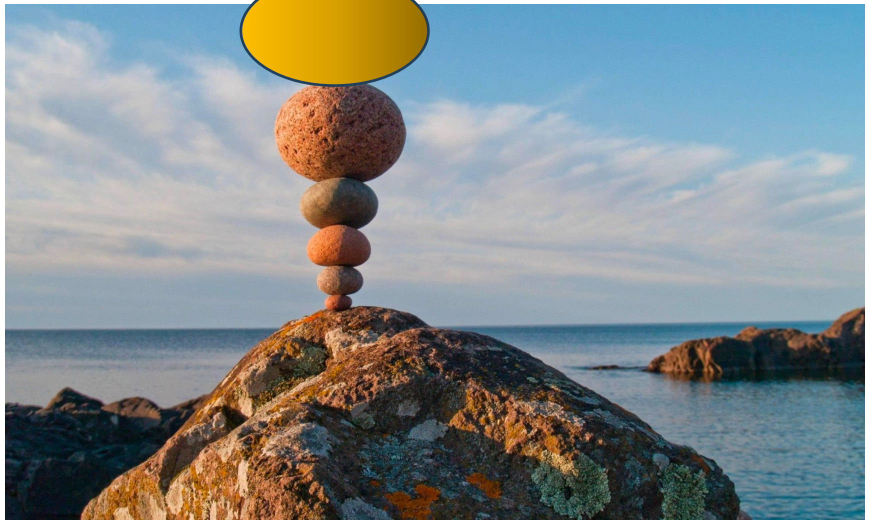
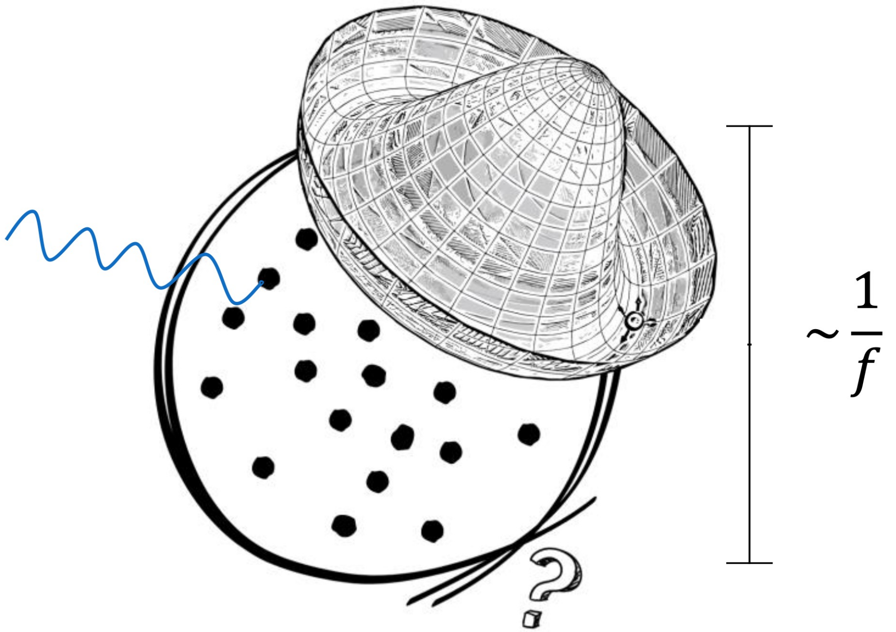
Naturalness problem



$10^{32} + (125^2) - 10^{32}$

CHM: Composite Higgs models

- Consider some strongly interacting dynamics at scale, f (~ TeV)
- Higgs appears as spin-0 bound state of said dynamics (finite size)
- Loop integrals are cut off at scale f



CHM: Composite Higgs models

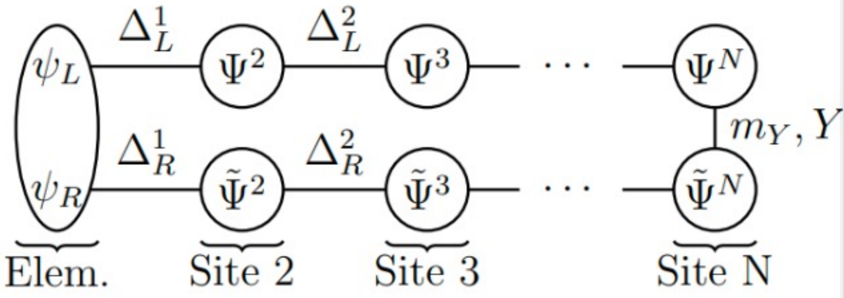
- ❖ Higgs is a pseudo Nambu-Goldstone boson (as pions in QCD)
- ❖ SM particles get masses by mixing with their partners in the composite sector
- ❖ TeV-scale composite resonances

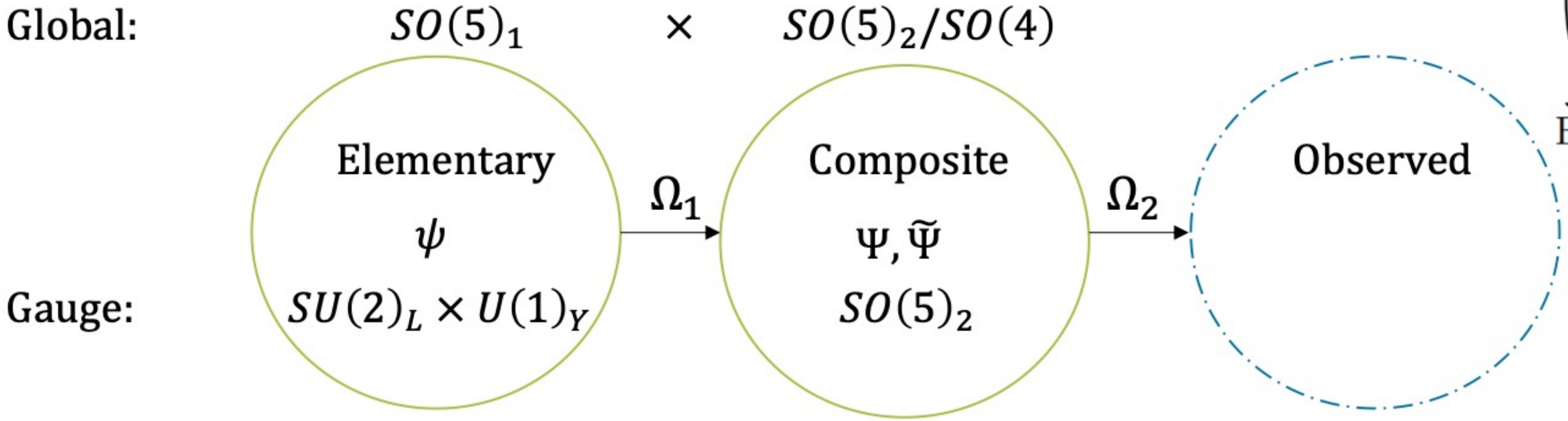
M4DCHM: Minimal 4D CHM

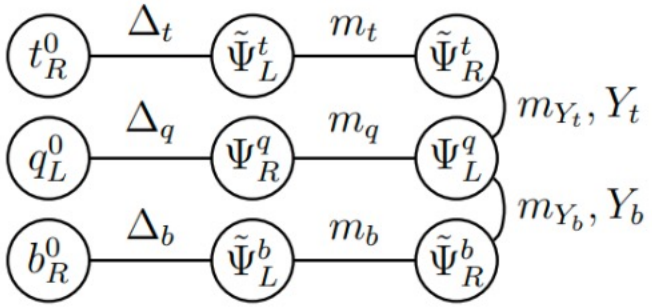
- SM has global $SU(2)_L \times SU(2)_R$ symmetry

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

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







- Various fermion representations (**1**, **5**, **10**, **14**, …)

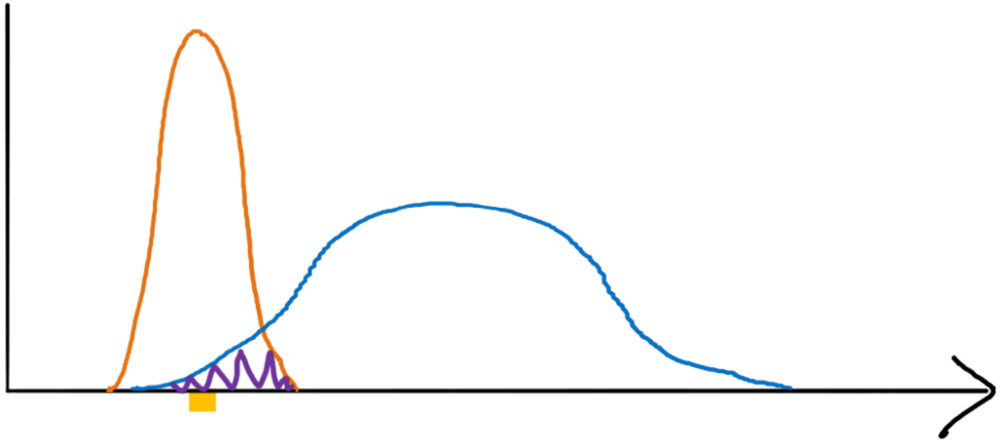
M4DCHM: Minimal 4D CHM with partially composite leptons

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

$$\left(q_L = {}^{t_L}_{b_L}, t_R, b_R\right) \longleftrightarrow \left(l_L = {}^{\nu_L}_{\tau_L}, \tau_R\right)$$

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

MTH: study method



- 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:

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

MTH: study method

- **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

$$L \subset -m_{\Psi}\bar{\Psi}\Psi - \tilde{m}_{\Psi}\bar{\tilde{\Psi}}\tilde{\Psi} + \Delta_L \psi_{\mathrm{L}} \Psi_{\mathrm{R}} + \Delta_R \psi_{\mathrm{R}} \tilde{\Psi}_{\mathrm{L}} + m_Y \bar{\Psi}_L \Psi_R + \cdots$$

- Only 3rd generation fermions couple to composite sector

MTH: study method

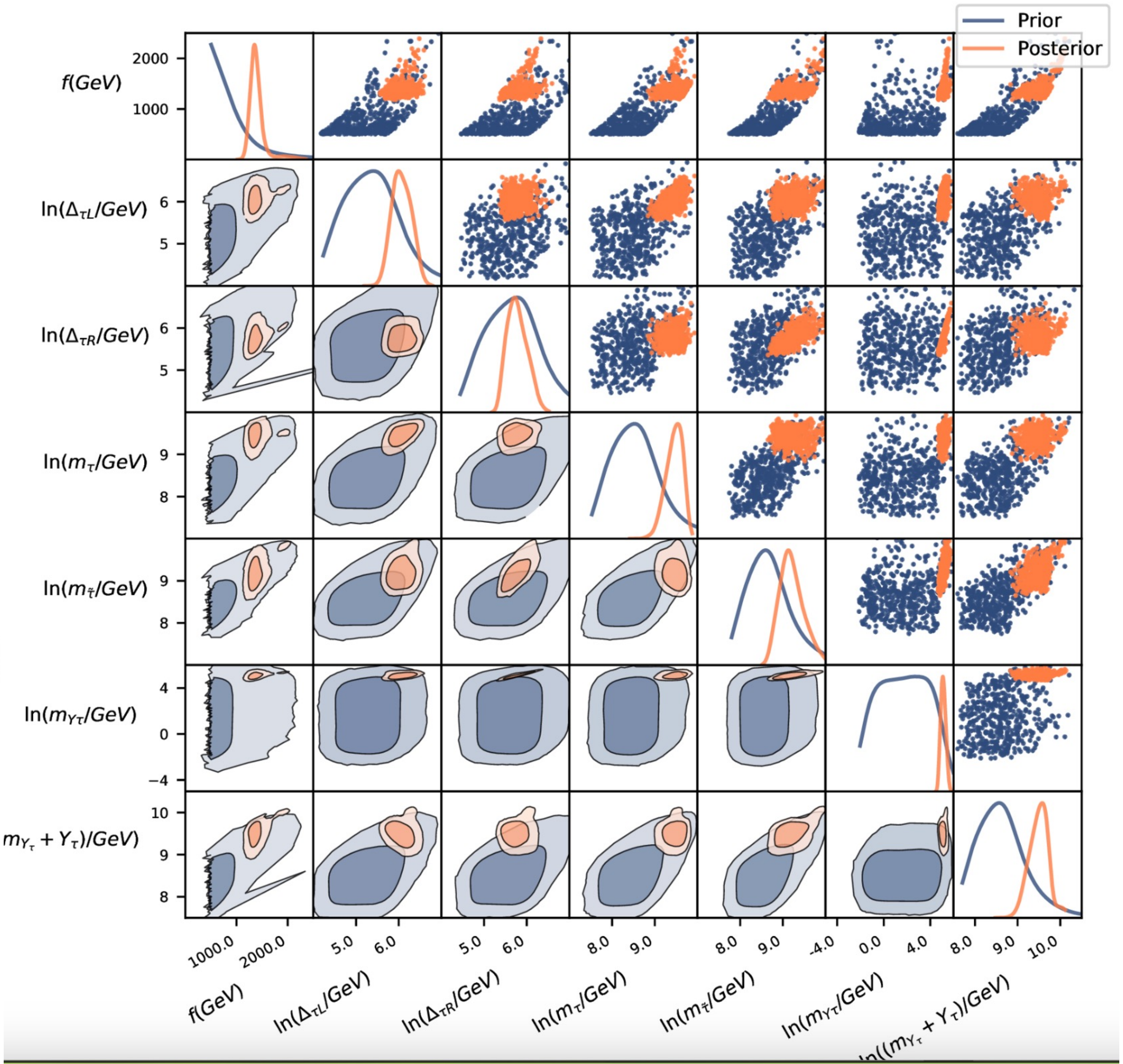
LM4DCHM	**5 − 5**	**14 − 10**
Decay constants	$f,\ f_1,\ f_X,\ f_G$	$f,\ f_1,\ f_X,\ f_G$
Gauge couplings	$g_\rho,\ g_X,\ g_G$	$g_\rho,\ g_X,\ g_G$
Quark link couplings	$\Delta_{t_L},\ \Delta_{t_R},\ \Delta_{b_L},\ \Delta_{b_R}$	$\Delta_{t_L},\ \Delta_{t_R},\ \Delta_{b_L},\ \Delta_{b_R}$
Quark on-diagonal masses	$m_t,\ m_{\tilde{t}},\ m_b,\ m_{\tilde{b}}$	$m_t,\ m_{\tilde{t}},\ m_b,\ m_{\tilde{b}}$
Quark off-diagonal masses	$m_{Y_t},\ m_{Y_b}$	$m_{Y_t},\ m_{Y_b}$
Quark proto-Yukawa couplings	$Y_t,\ Y_b$	$Y_t,\ Y_b$
Lepton link couplings	$\Delta_{\tau_L},\ \Delta_{\tau_R}$	$\Delta_{\tau_L},\ \Delta_{\tau_R}$
Lepton on-diagonal masses	$m_\tau,\ m_{\tilde{\tau}}$	$m_\tau,\ m_{\tilde{\tau}}$
Lepton off-diagonal masses	m_{Y_τ}	
Lepton proto-Yukawa couplings	Y_τ	Y_τ
Dimensionality	25	24

Table 1. Parameters present in each model.

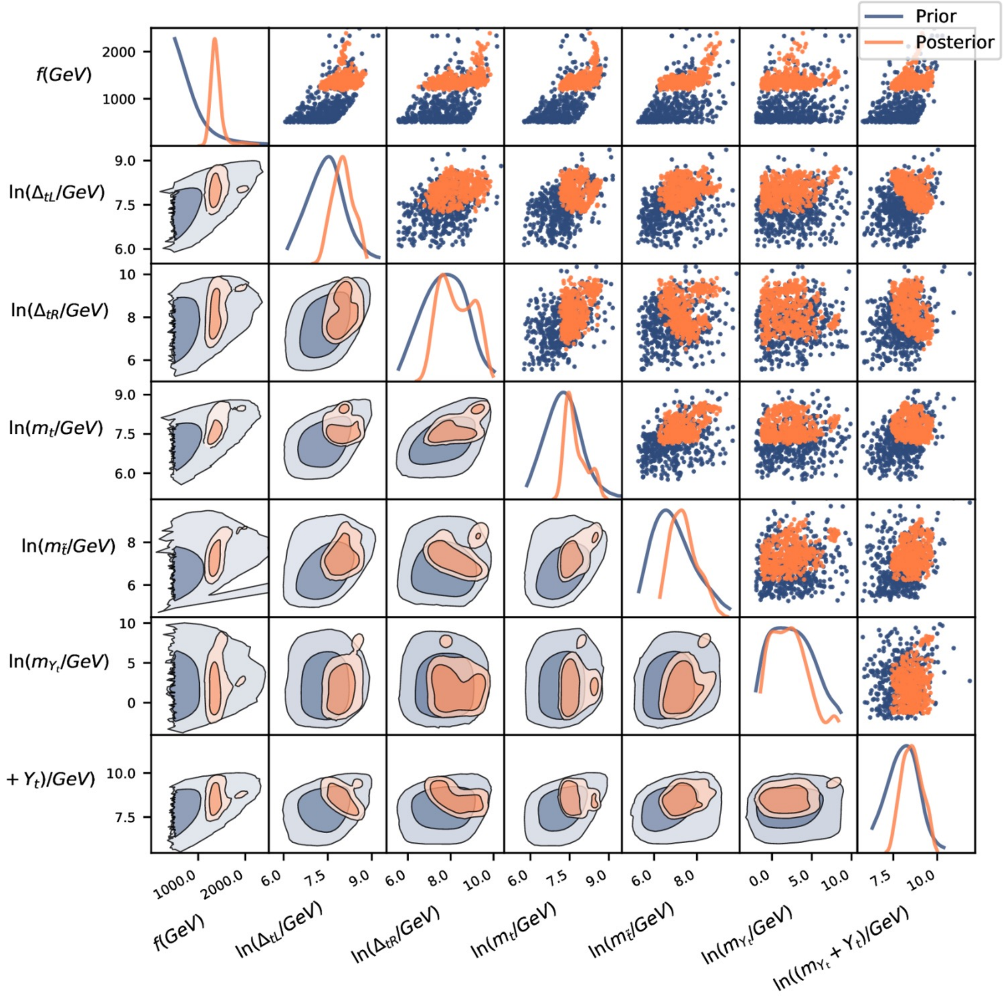
Model	Parameters	Scan Range	Prior
Both	$m_\rho/f,\ m_a/f$	$[1/\sqrt{2}, 4\pi]$	Uniform
	$f_X/f,\ f_G/f$	$[0.5, 2\sqrt{3}]$	
	$g_\rho,\ g_X,\ g_G$	$[1.0, 4\pi]$	
	Δ_{t_L}/f	$[e^{-0.25}, e^{1.5}]$	Logarithmic
	Δ_{t_R}/f	$[e^{-0.75}, 4\pi]$	
	Δ_{b_L}/f	$[e^{-5.0}, e^{-3.0}]$	
	Δ_{b_R}/f	$[e^{-0.5}, 4\pi]$	
	$m_t/f,\ m_{\tilde{b}}/f$	$[e^{-0.5}, e^{1.5}]$	
	$m_{\tilde{t}}/f$	$[e^{-1.0}, 4\pi]$	
	m_b/f	$[e^{-1.0}, e^{1.5}]$	
	m_{Y_t}/f	$[e^{-8.5}, 4\pi]$	
	m_{Y_b}/f	$[e^{-0.25}, 4\pi]$	
	$(m_{Y_t}+Y_t)/f$	$[e^{-0.5}, 8\pi]$	
	$(m_{Y_b}+Y_b)/f$	$[e^{-8.5}, e^{-0.5}]$	
$\text{LM4DCHM}^{5-5-5}_{5-5}$	m_τ/f	$[e^{1.25}, 4\pi]$	Logarithmic
	$m_{\tilde{\tau}}/f$	$[e^{1.5}, 4\pi]$	
	$m_{Y\tau}/f$	$[e^{-8.5}, e^{-1.5}]$	
	$(m_{Y\tau}+Y_\tau)/f$	$[e^{1.35}, 8\pi]$	
	$\Delta_{\tau L}/f$	$[e^{-2.1}, e^{-0.5}]$	
	$\Delta_{\tau R}/f$	$[e^{-1.8}, e^{-0.2}]$	
$\text{LM4DCHM}^{5-5-5}_{14-10}$	m_τ/f	$[e^{-0.5}, 4\pi]$	Logarithmic
	$m_{\tilde{\tau}}/f$	$[e^{-0.5}, 4\pi]$	
	$m_{Y\tau}/f$	$[e^{-1.5}, 4\pi]$	
	$\Delta_{\tau L}/f$	$[e^{-1.5}, 4\pi]$	
	$\Delta_{\tau R}/f$	$[e^{-4.0}, e^{-1.5}]$	

Results

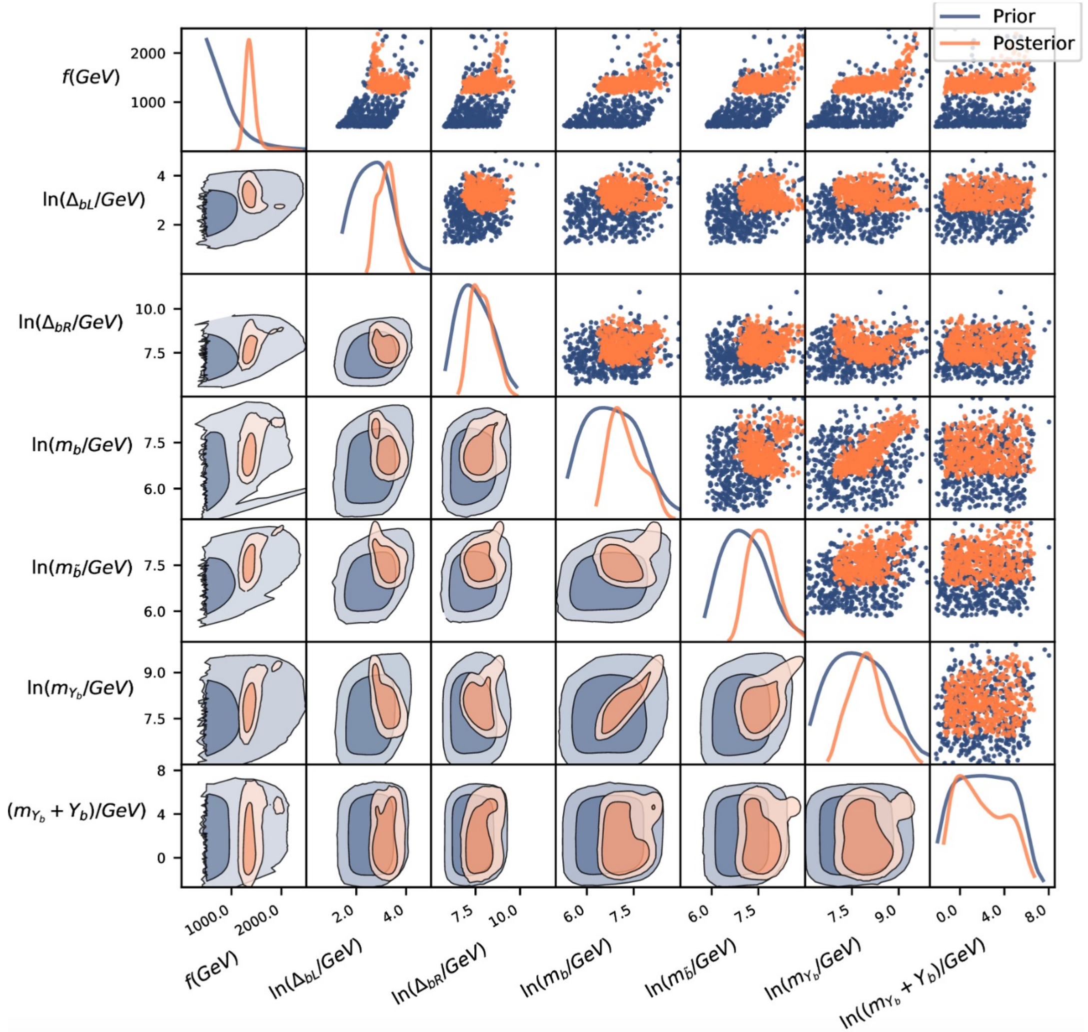
$$\mathrm{LM4DCHM}^{5-5-5}_{5-5}$$



Results



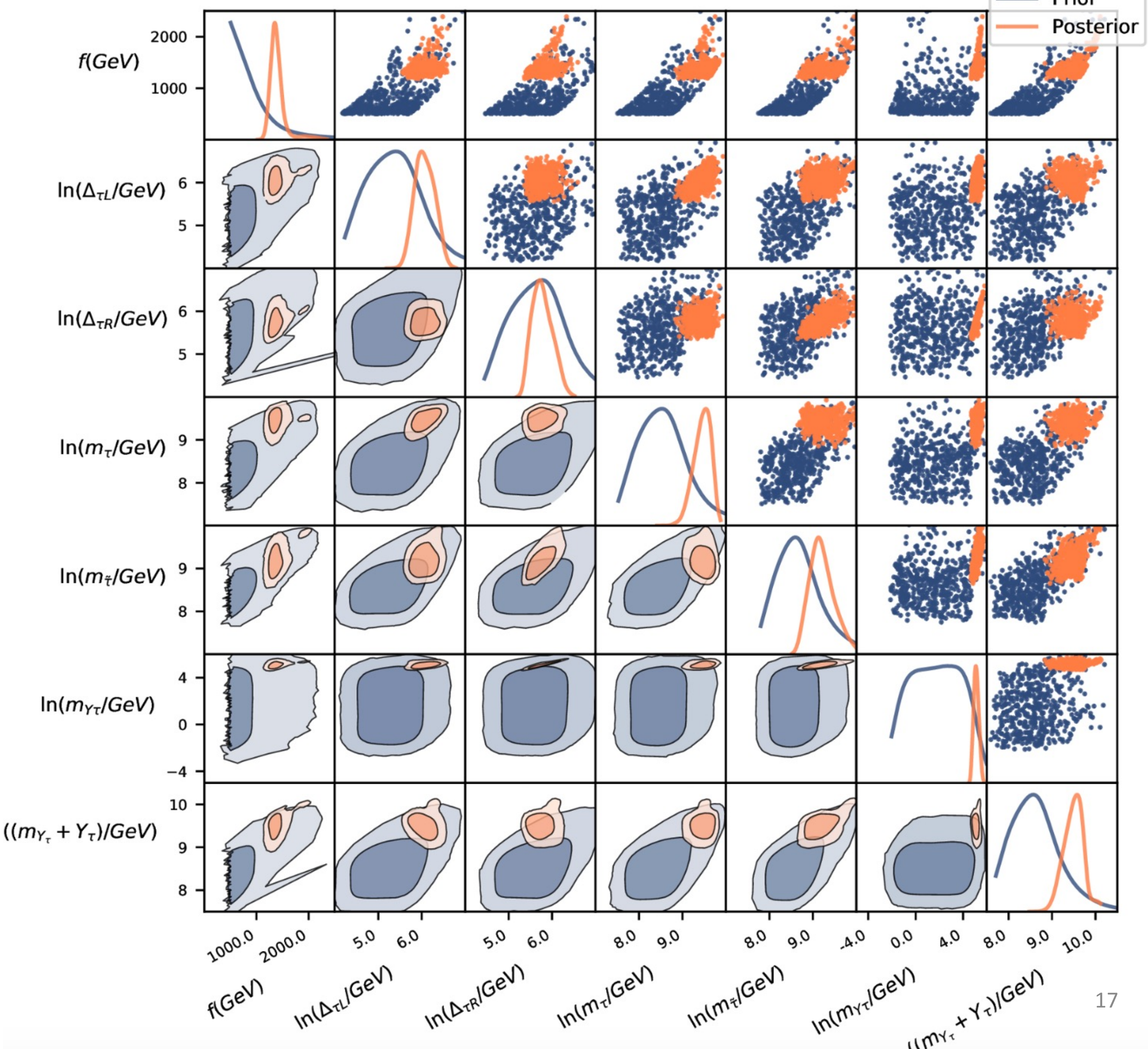
Prior
Posterior
f(GeV)
ln(Δ_tL/GeV)
ln(Δ_tR/GeV)
ln(m_t/GeV)
ln(m_t̃/GeV)
ln(m_Yt/GeV)
ln((m_Yt + Y_t)/GeV)



Prior
Posterior
f(GeV)
ln(Δ_bL/GeV)
ln(Δ_bR/GeV)
ln(m_b/GeV)
ln(m_b̃/GeV)
ln(m_Yb/GeV)
ln((m_Yb + Y_b)/GeV)

Results

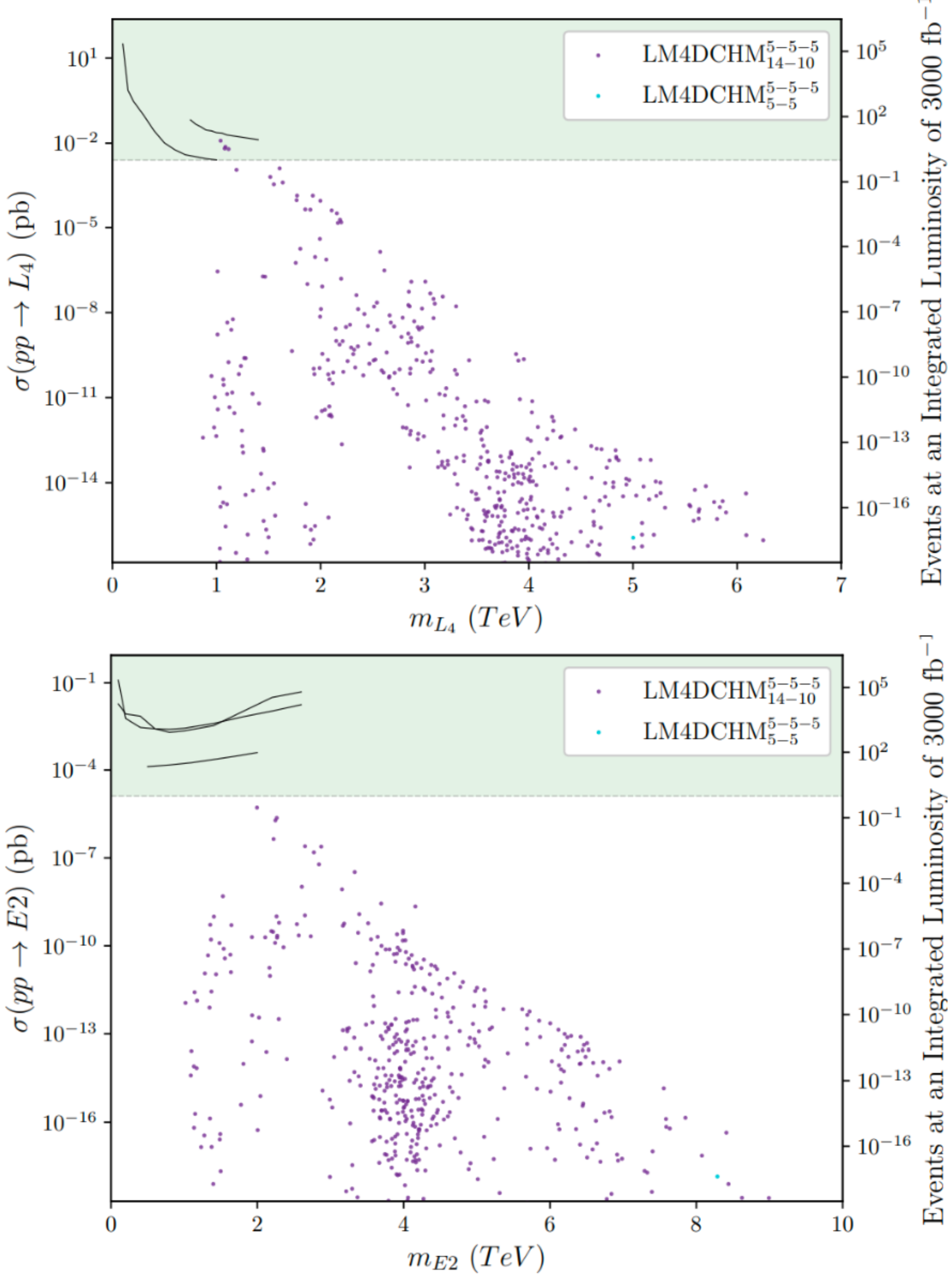
$$\mathbf{LM4DCHM}^{\mathbf{5-5-5}}_{\mathbf{14-10}}$$



Results

Model	$\ln(\mathcal{Z})$	$\langle \ln(\mathcal{L}) \rangle_P$	$\max \ln(\mathcal{L})$	D_{KL}
$\mathrm{LM4DCHM}^{5-5-5}_{5-5}$	-45.60 ± 0.06	-17.27	-10.79	28.33
$\mathrm{LM4DCHM}^{5-5-5}_{14-10}$	-36.30 ± 0.05	-14.63	-9.13	21.67

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



Results : 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

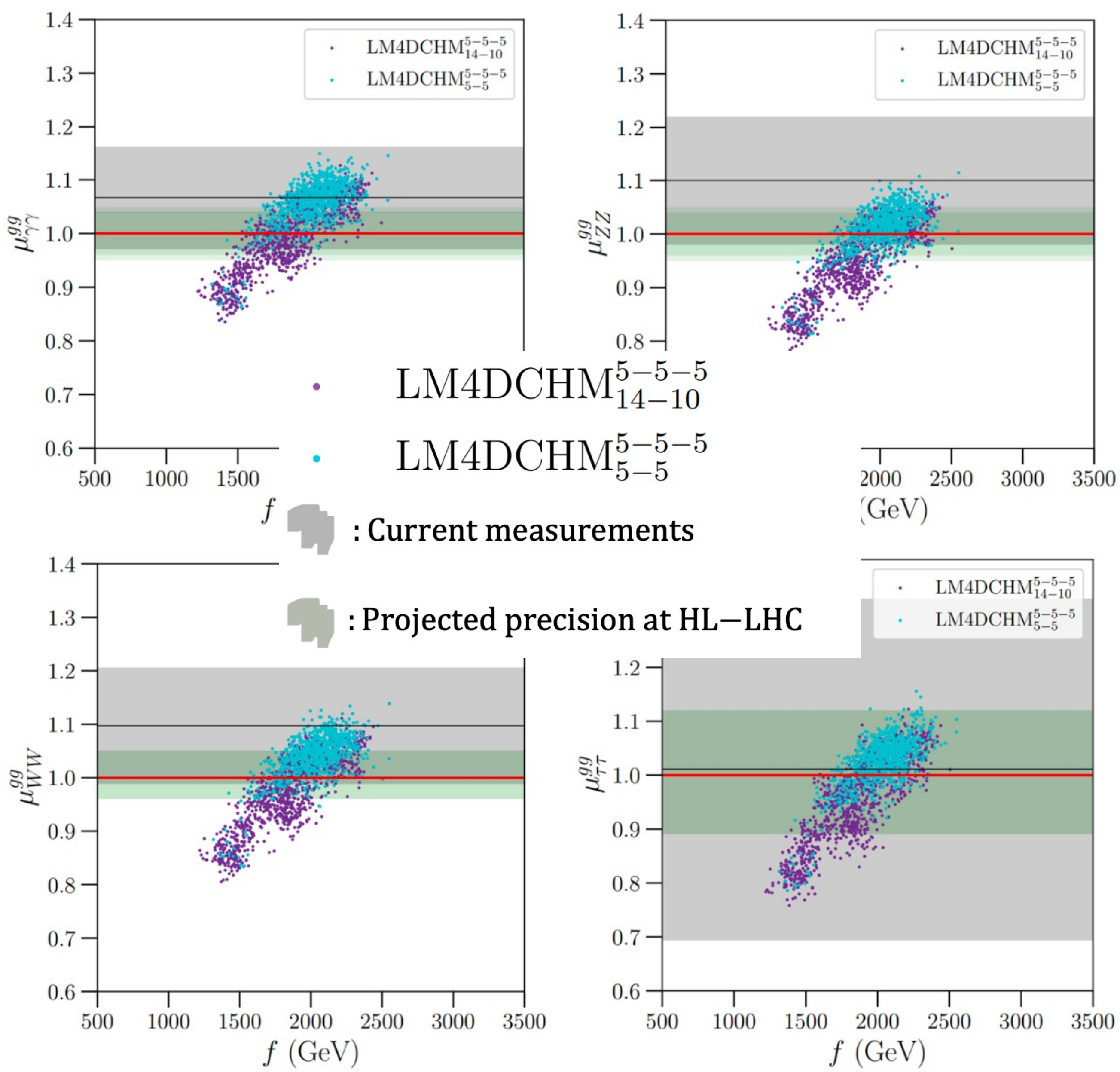
• LM4DCHM$^{5-5-5}_{14-10}$

• LM4DCHM$^{5-5-5}_{5-5}$

: Producable range at HL−LHC

— : 13 TeV search bounds

Results : Indirect detection



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

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

Conclusion

- 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

2025 新物理冬季学校

2025 新物理冬季学校 - 2025 Winter Institute of new physics in Elementary Particle Physics (WINP2025)

3-13 January 2025
Asia/Shanghai timezone

- Overview
- Timetable
- Registration
- Participant List

自2012年大型强子对撞机LHC成功探测到希格斯玻色子以来，粒子物理学领域便开启了一个崭新的纪元，即自洽的标准模型和多种新物理现象共存。相关问题，诸如中微子质量起源、暗物质本质等根本性问题，正引领着我们深入探索未知的奥秘。同时，粒子物理学与粒子天体物理学、宇宙学的交叉融合，也催生了一系列前沿且富有挑战性的研究课题。在此背景下，超越标准模型的新物理研究已成为粒子物理学界的热门焦点，亦是国内众多科研机构竞相发展的重点方向。

鉴于此，拟举办粒子物理“新物理冬季学校”，旨在促进培养新时代的新物理方向学者与后备人才。
第一期粒子物理“新物理冬季学校”于2025年1月3日至1月13日，由中山大学理学院主办，由北京大学、东南大学、中国科学院高能物理研究所、南京师范大学、河南师范大学、中山大学物理学院、上海交通大学合办，共同资助。地点位于广东省深圳市光明区公常路66号中山大学深圳校区。

新物理冬季学校委员会(姓氏排序)
顾问指导委员会：毕效军，曹俊杰，曹庆宏，何红建，李田军，李志兵，廖益，刘纯，刘韬，罗民兴(院士)，吕才典，乔从丰，舒菁，司宗国，王贻芳(院士)，王青，肖振军，邢志忠，杨金民，周宇峰, **(更新中...)**

组织委员会：安海鹏，边立功，葛韶锋，顾嘉荫，黄永盛，李数，刘佳，刘佐伟，马小东，任婧，宋宁强，苏伟，唐健，王少江，王雯宇，王小平，武雷，鲜于中之，许勋杰，岩斌，于江浩，袁强，张昊，张

- https://indico.itp.ac.cn/event/288/

此次新物理冬季学校包含以下课程

基础课程：EW+QCD，BSM（CHM，SSM/2HDM，SUSY，EFT）

第一天：电弱相互作用3课时、CHM 2课时(张宏浩)，强相互作用3课时(刘晓辉)，

第二天：SSM+2HDM 2课时(苏伟)，SUSY 2课时（曹俊杰），EFT4课时（顾嘉荫）

核心课程：36课时，包含

暗物质(宋宁强、安海鹏)、中微子(李玉峰，丁桂军)、AI（吴永成，刘炳萱）

拓展课程：16课时，包含 对撞机物理 (岩斌，张昊)，相变 (边立功，张阳)

	3(周五)	4	5	6(周一)	7	8	9	10(周五)	11	12	13
上午12	报道注册	EW	CHM	EFT	暗物质	中微子	暗物质	中微子	AI	AI	讨论
上午3-4		QCD	EFT	对撞机	对撞机	暗物质	中微子	相变	相变	AI	
下午5-6		EW+QCD	SUSY	暗物质	暗物质	中微子	AI	讨论	AI	相变	离会
下午7-8		2HDM	对撞机	对撞机	中微子	暗物质	中微子		AI	相变	
晚上		讨论班									
备注	下划线表示时间已经和任课老师确定										

Thanks for your attention

BACKUP

MTH: study method

M4DCHM	**5 − 5 − 5**	**14 − 14 − 10**	**14 − 1 − 10**
Decay constants	$f,\ f_1,\ f_X,\ f_G$	$f,\ f_1,\ f_X,\ f_G$	$f,\ f_1,\ f_X,\ f_G$
Gauge couplings	$g_\rho,\ g_X,\ g_G$	$g_\rho,\ g_X,\ g_G$	$g_\rho,\ g_X,\ g_G$
Link couplings	$\Delta_{t_L},\ \Delta_{t_R},\ \Delta_{b_L},\ \Delta_{b_R}$	$\Delta_q,\ \Delta_t,\ \Delta_b$	$\Delta_q,\ \Delta_t,\ \Delta_b$
On-diagonal masses	$m_t,\ m_{\tilde{t}},\ m_b,\ m_{\tilde{b}}$	$m_q,\ m_t,\ m_b$	$m_q,\ m_t,\ m_b$
Off-diagonal masses	$m_{Y_t},\ m_{Y_b}$	m_{Y_t}	
Proto-Yukawa couplings	$Y_t,\ Y_b$	$Y_t,\ Y_b,\ \tilde{Y}_t$	$Y_t,\ Y_b$
Dimensionality	19	17	15

Table 2. Parameters present in each model.

	Parameters	Scan Range	Prior
All Models	$m_\rho/f,\ m_a/f$	$[1/\sqrt{2}, 4\pi]$	Uniform
	$f_X/f,\ f_G/f$	$[0.5, 2\sqrt{3}]$	
	$g_\rho,\ g_X,\ g_G$	$[1.0, 4\pi]$	
M4DCHM^{5-5-5}	Δ_{t_L}/f	$[e^{-0.25}, e^{1.5}]$	Logarithmic
	Δ_{t_R}/f	$[e^{-0.75}, 4\pi]$	
	Δ_{b_L}/f	$[e^{-5.0}, e^{-3.0}]$	
	Δ_{b_R}/f	$[e^{-0.5}, 4\pi]$	
	$m_t/f,\ m_{\tilde{b}}/f$	$[e^{-0.5}, e^{1.5}]$	
	$m_{\tilde{t}}/f$	$[e^{-1.0}, 4\pi]$	
	m_b/f	$[e^{-1.0}, e^{1.5}]$	
	m_{Y_t}/f	$[e^{-8.5}, 4\pi]$	
	m_{Y_b}/f	$[e^{-0.25}, 4\pi]$	
	$(m_{Y_t}+Y_t)/f$	$[e^{-0.5}, 8\pi]$	
	$(m_{Y_b}+Y_b)/f$	$[e^{-8.5}, e^{-0.5}]$	
$\text{M4DCHM}^{14-14-10}$	Δ_q/f	$[e^{-1.0}, e^{2.0}]$	Logarithmic
	Δ_t/f	$[e^{-2.5}, e^{2.0}]$	
	Δ_b/f	$[e^{-4.0}, e^{2.0}]$	
	m_q/f	$[e^{-1.0}, 4\pi]$	
	m_t/f	$[e^{-2.5}, 4\pi]$	
	m_b/f	$[e^{-2.0}, 4\pi]$	
	m_{Y_t}/f	$[e^{-8.5}, 4\pi]$	
	$(m_{Y_t}+\frac{1}{2}Y_t)/f$	$[e^{-8.5}, 1.0]$	
	$(m_{Y_t}+\frac{4}{5}(Y_t+\tilde{Y}_t))/f$	$[e^{-3.0}, 2.6\times 4\pi]$	
	Y_b/f	$[e^{-4.0}, 4\pi]$	
$\text{M4DCHM}^{14-1-10}$	$\Delta_q/f,\ \Delta_t/f,\ Y_t/f$	$[e^{-5.0}, 4\pi]$	Logarithmic
	Δ_b/f	$[e^{-7.0}, 4\pi]$	
	$m_q/f,\ m_b/f$	$[e^{-3.0}, 4\pi]$	
	m_t/f	$[e^{-9.0}, 4\pi]$	
	Y_b/f	$[e^{-6.0}, 4\pi]$	