A naturally light Higgs without light Top Partners

CERN TH Retreat 2014

7.11.2014

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arXiv: 1410.8555

Adrian Carmona, FG

Introduction

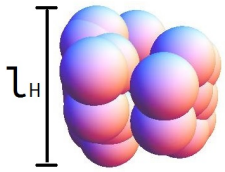
Introduction

Composite Higgs

Kaplan, Georgi, Dimopoulos,. . .

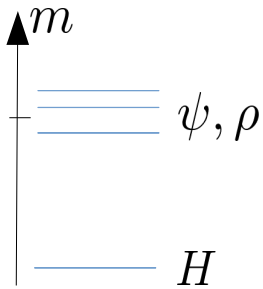
- Higgs is composite at small distances

  ➡ m_H saturated in IR ➡ Hierarchy Problem solved



- Higgs as (pseudo) Goldstone ➡ $m_H \ll m_\rho$

  [like pions in QCD]



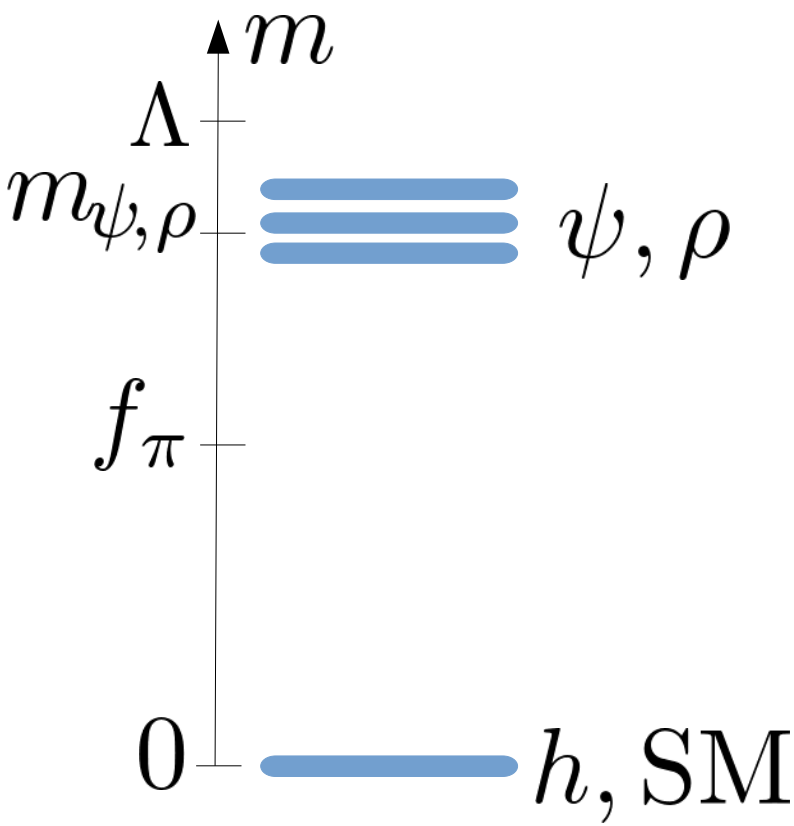
Contino, Nomura, Pomarol, ph/0306259

Agashe, Contino, Pomarol, ph/0412089

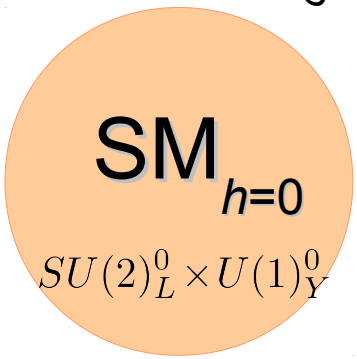
- Minimal Composite Higgs: SO(5)→SO(4)

  → 4 Goldstone dof, custodial symmetry

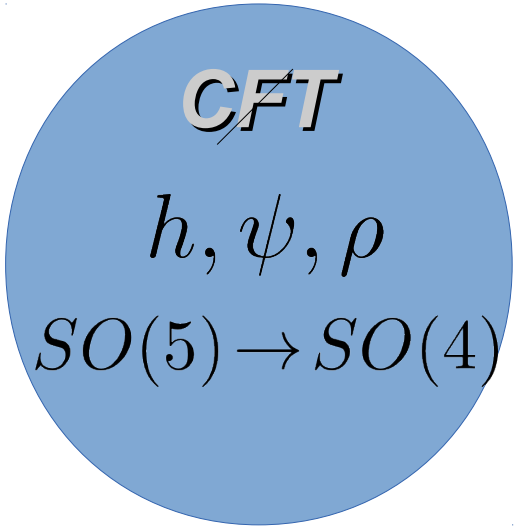
Introduction



elementary



composite

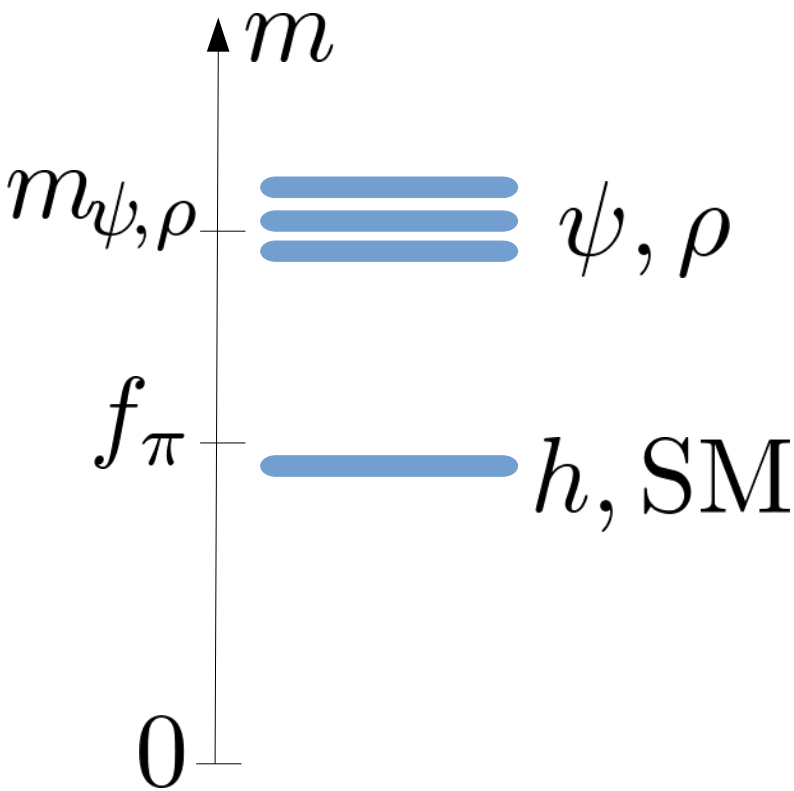


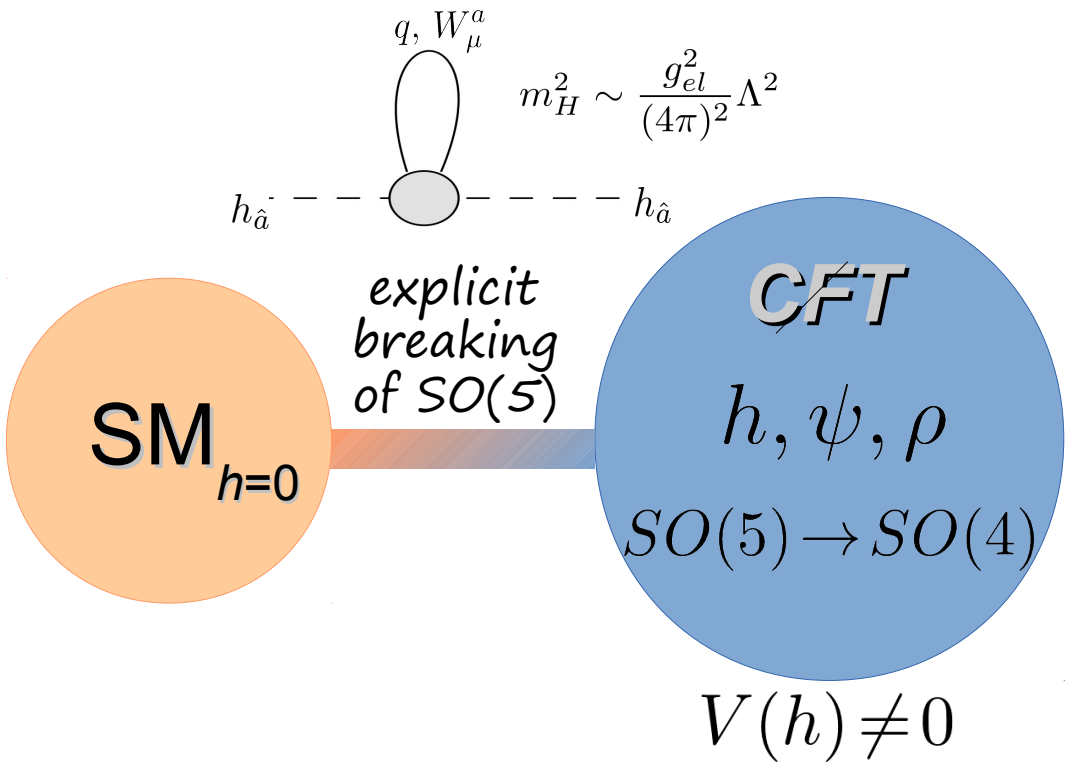
$V(h) \propto 0$

$$\boxed{\Sigma = U\,\Sigma_0}\,,\quad U = e^{i\frac{\sqrt{2}}{f_\pi} h_{\hat{a}} T^{\hat{a}}}$$

$$\Sigma_0 = (0,0,0,0,f_\pi)^T,\ T^{\hat{a}} : SO(5)/SO(4)$$

Introduction



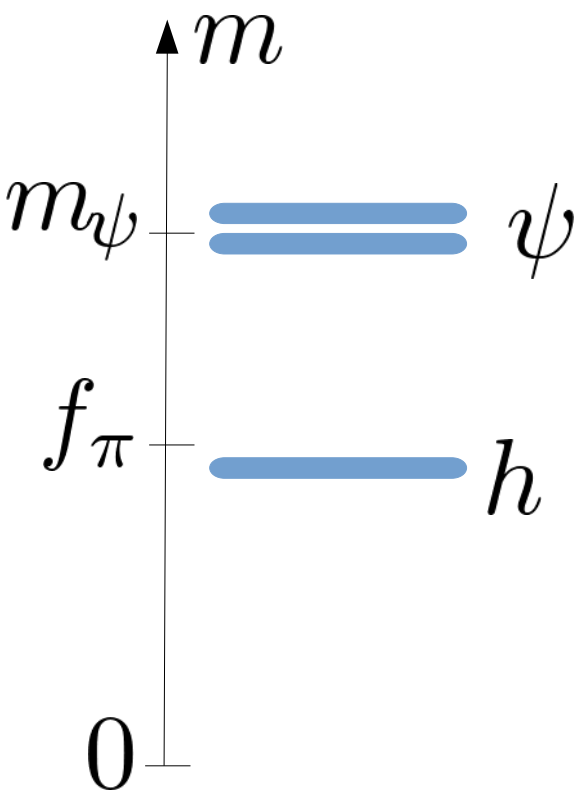


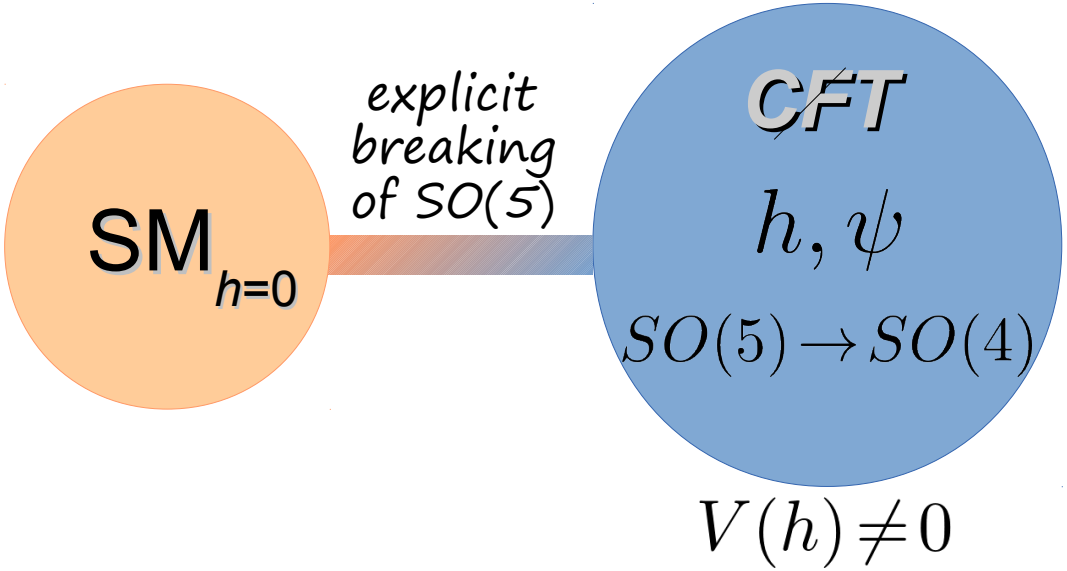
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}^{h=0} + \mathcal{L}_{\mathrm{CFT}} + W_\mu^\alpha \rho^{\mu\,\alpha}$$

subleading

$$- \boxed{y_L^q \; \bar{q}_L \cdot \Psi_R^Q \; - \; y_R^q \; \bar{q}_R \cdot \Psi_L^q} + \mathrm{h.c.}$$

Partial Compositeness

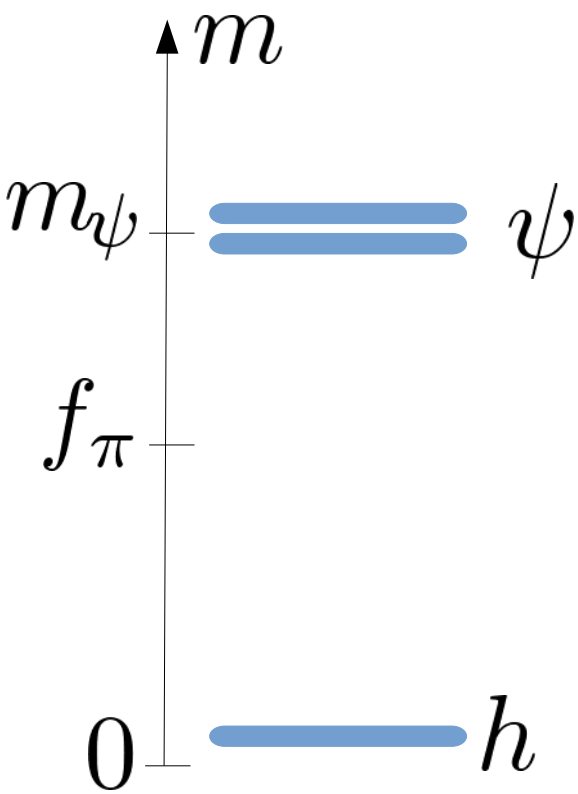


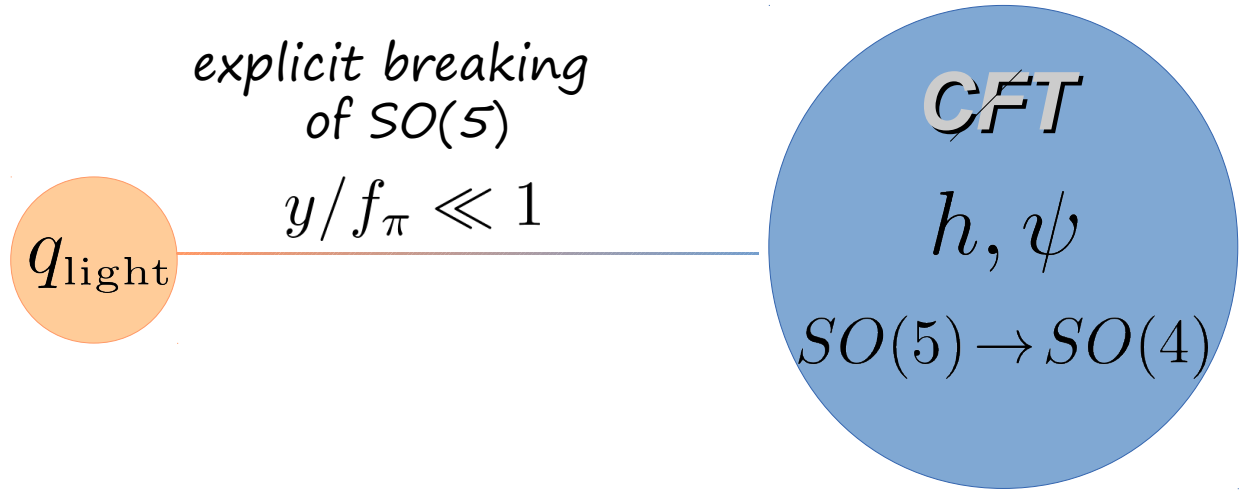


$$\mathcal{L} = \mathcal{L}_{\rm SM}^{h=0} + \mathcal{L}_{\rm CFT} + W_\mu^\alpha \rho^{\mu\,\alpha}$$

$$- \boxed{y_L^q \; \bar{q}_L \cdot \Psi_R^Q \; - \; y_R^q \; \bar{q}_R \cdot \Psi_L^q} + \text{h.c.}$$ → induce m_q

Partial Compositeness

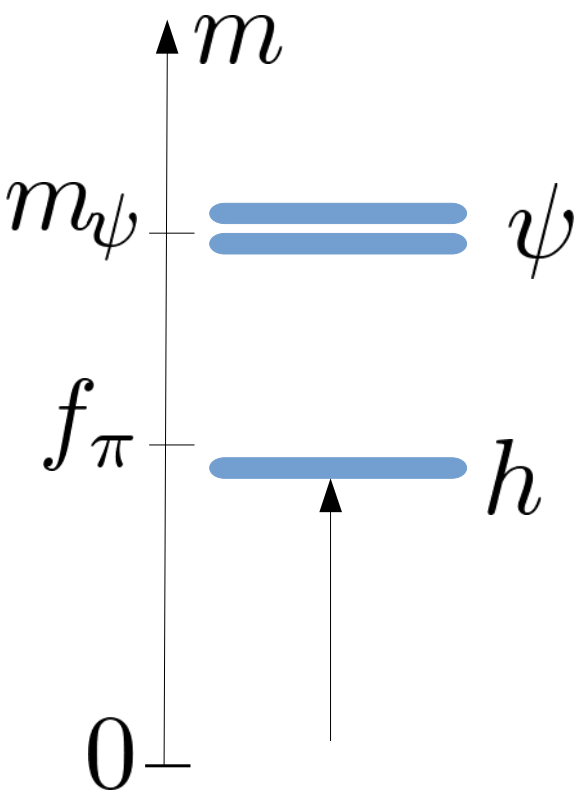


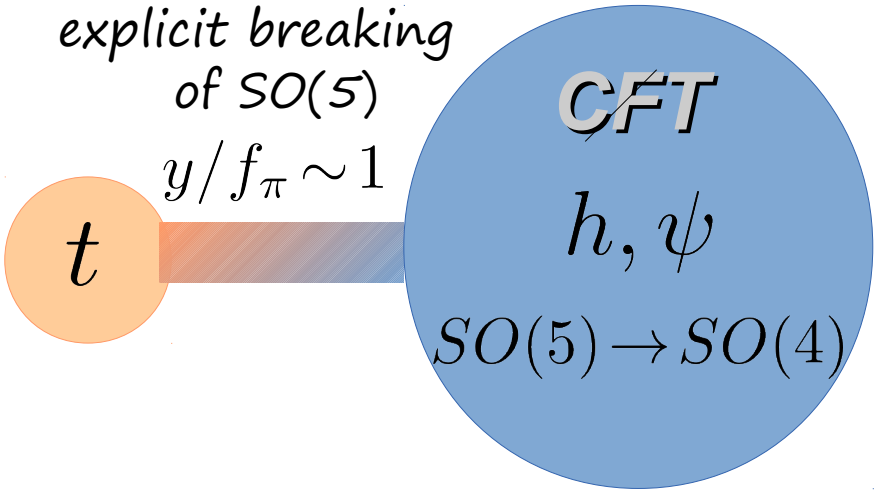


$$m_q \sim y_L^q y_R^q \frac{v}{f_\pi} f(m_{\psi_i}, ..)$$

$$\mathcal{L} \supset -y_L^q \, \bar{q}_L \cdot \Psi_R^Q - y_R^q \, \bar{q}_R \cdot \Psi_L^q + \text{h.c.}$$ → break SO(5)

Partial Compositeness





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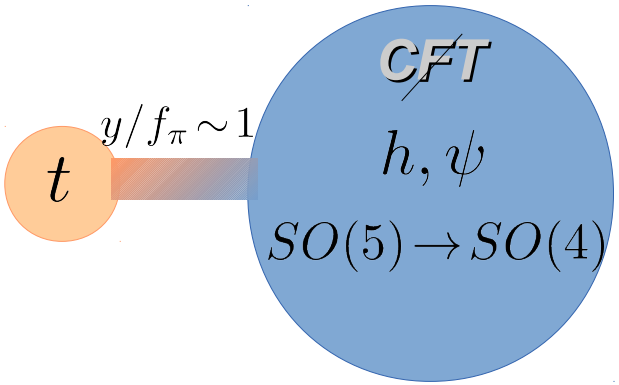
Partial Compositeness

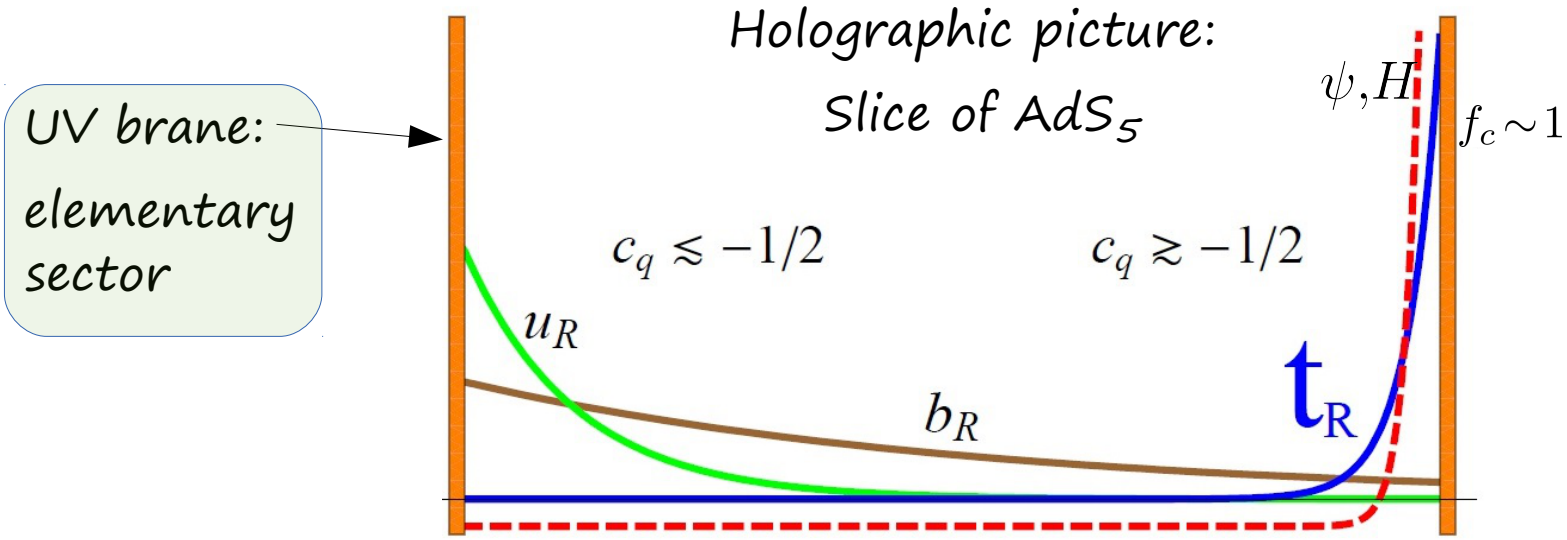
- Addresses the flavor puzzle:

$$y^q_{L,R} \leftrightarrow D[\mathcal{O}^q_{L,R}],\ \langle 0|\mathcal{O}^q_{L,R}|\Psi^{Q,q}\rangle \neq 0$$

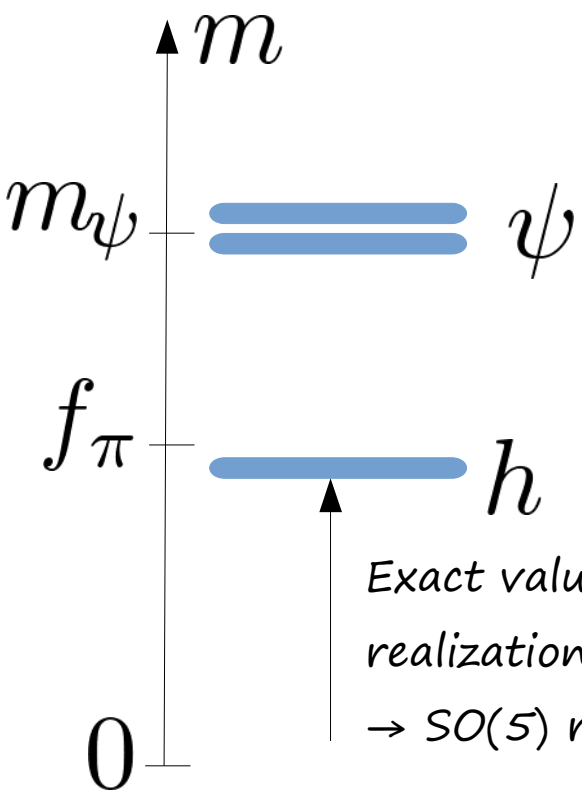
[compositeness ↔ anom. dimension of CFT operator]



- FCNC protection via GIM-like mechanism



Partial Compositeness

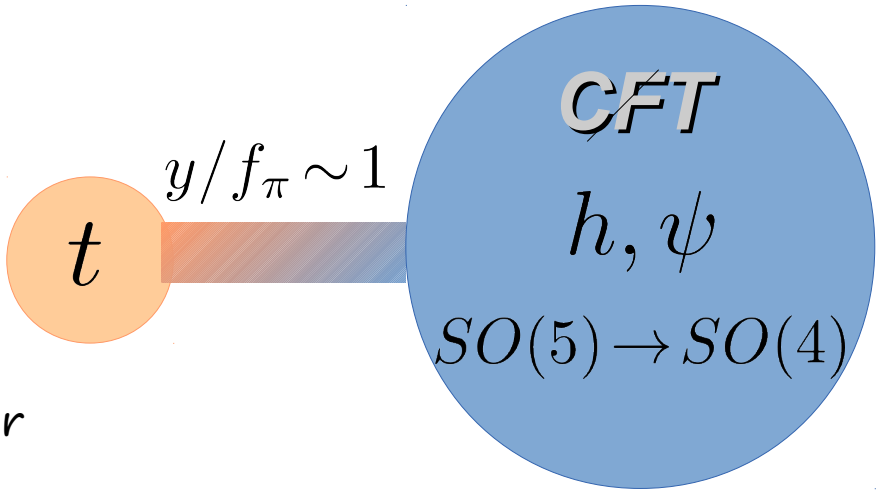


Exact value depends on particular realization of fermion sector → SO(5) representation

$MCHM_5$: fundamental

$MCHM_{10}$: adjoint

$MCHM_{14}$: symmetric



The Higgs Potential

The Higgs Potential

$$V(h) \approx \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi)\cos^2(h/f_\pi)$$

$$\hookrightarrow \boxed{\text{EWSB}: \alpha - \beta = -2\beta \sin^2(v/f_\pi)}$$

→ general tuning: $\boxed{\Delta^{-1} \sim v^2/f_\pi^2}$
(a priori)

$v \approx 246\,\text{GeV}$
$f_\pi \sim 1\,\text{TeV}$

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$v \approx 246\,\text{GeV}$
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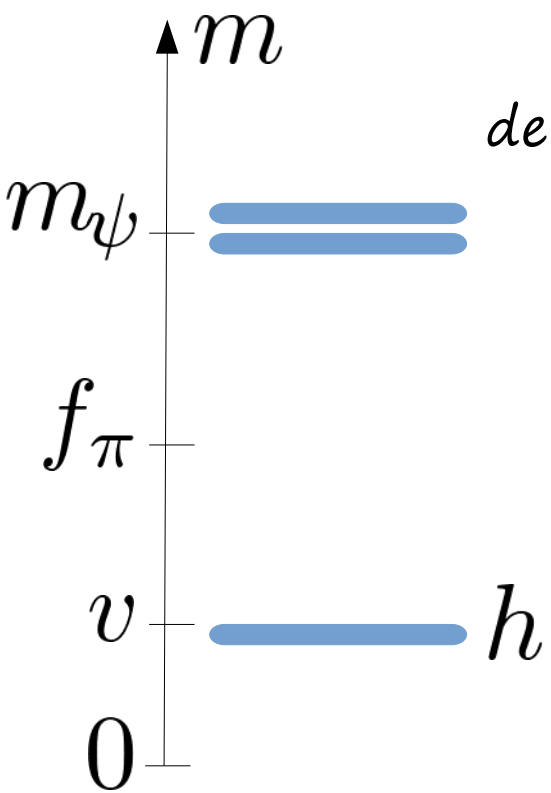
$$\boxed{m_H^2} = \frac{8}{f_\pi^2}\cos^2(v/f_\pi)\sin^2(v/f_\pi)\boxed{\beta}$$

$\beta_{\text{gauge}} \approx 0$

MCHM$_5$



decompose into reps of SO(4)

$$\psi = U(Q, \tilde{T})^T$$

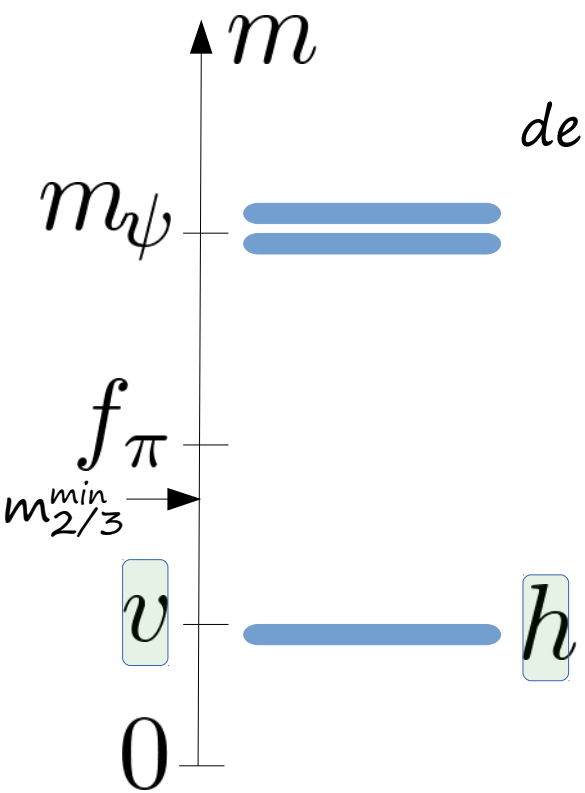
$$\alpha \sim y_{L,R}^{t\,2}/m_\psi^2\,, \quad \boxed{\beta \sim [y_{L,R}^{t\,2}]^2/m_\psi^4}$$

→ additional tuning in MCHM$_5$

Matsedonskyi, Panico, Wulzer, 1204.6333

$$\left[\begin{array}{l} V(h) \approx \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi)\cos^2(h/f_\pi) \\ \text{EWSB}: \alpha - \beta = -2\beta \sin^2(v/f_\pi) \end{array}\right]$$

MCHM$_5$



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$$m_H \sim \sqrt{\frac{3}{2\pi^2}}\, y_t^2\, v$$

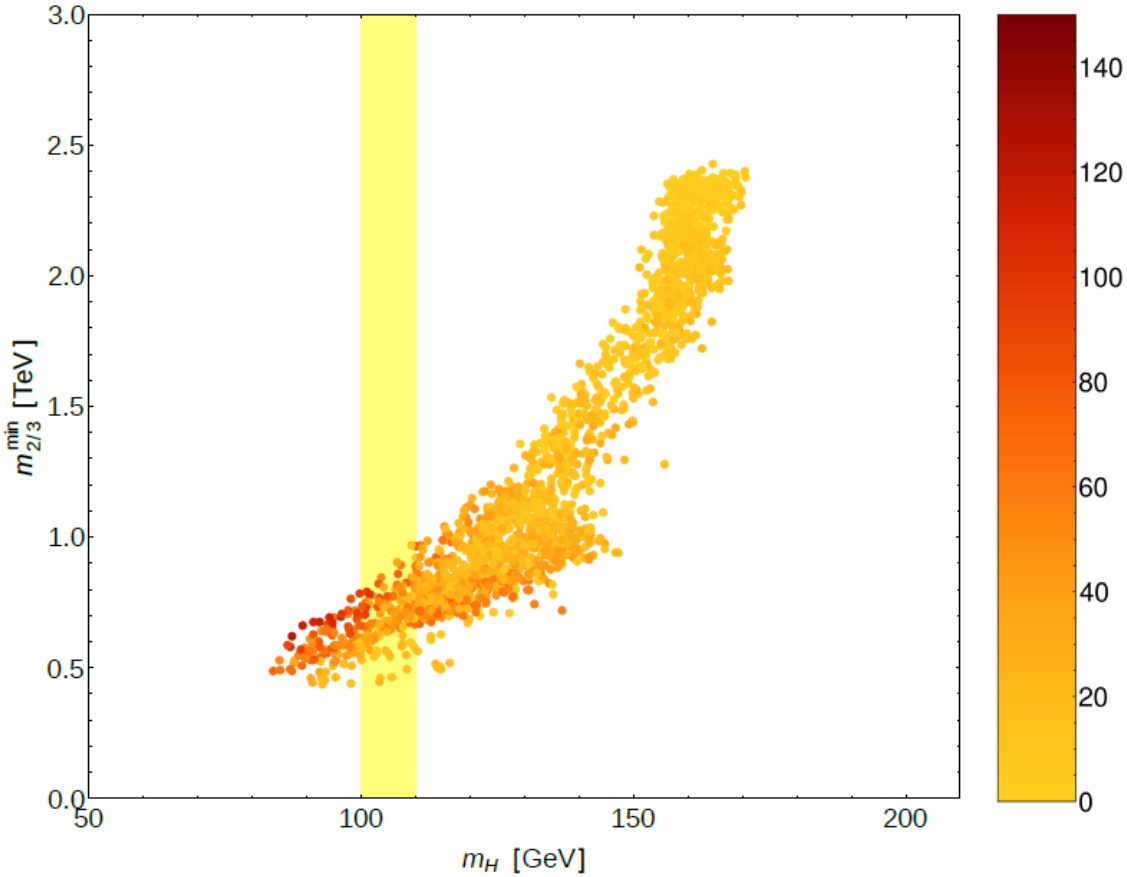
$$\sim \frac{\min(m_T, m_{\tilde{T}})}{f_\pi}\, m_t$$

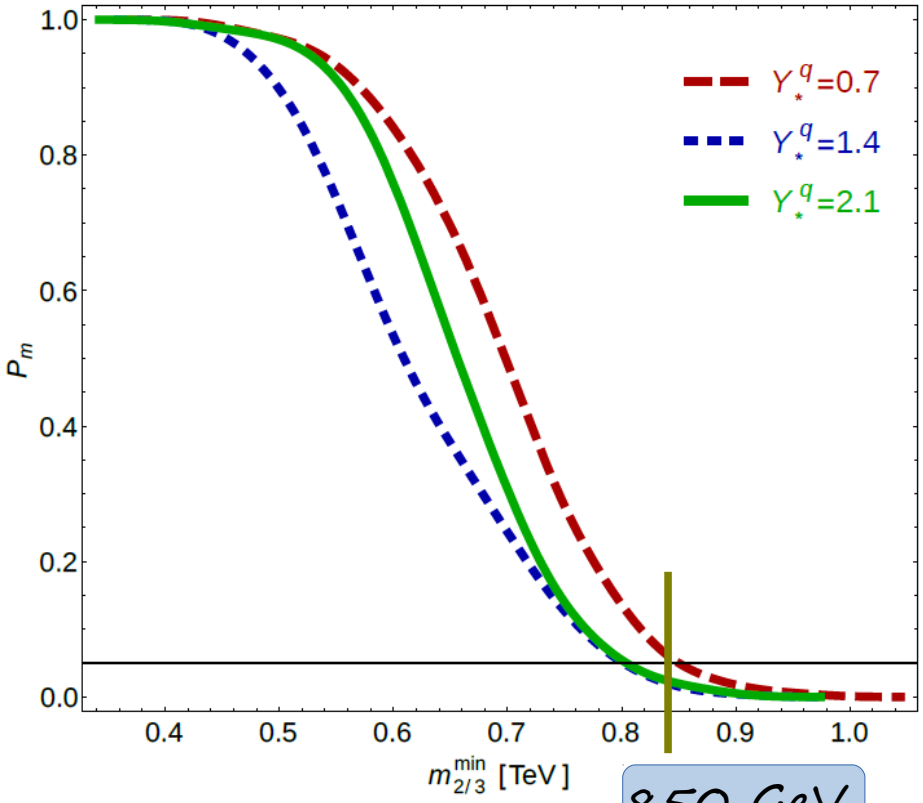
Matsedonskyi, Panico, Wulzer, 1204.6333

=> light top partners: min(m_T,$m_{\tilde{T}}$)<<f_π!

Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954; De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434

MCHM$_5$





850 GeV

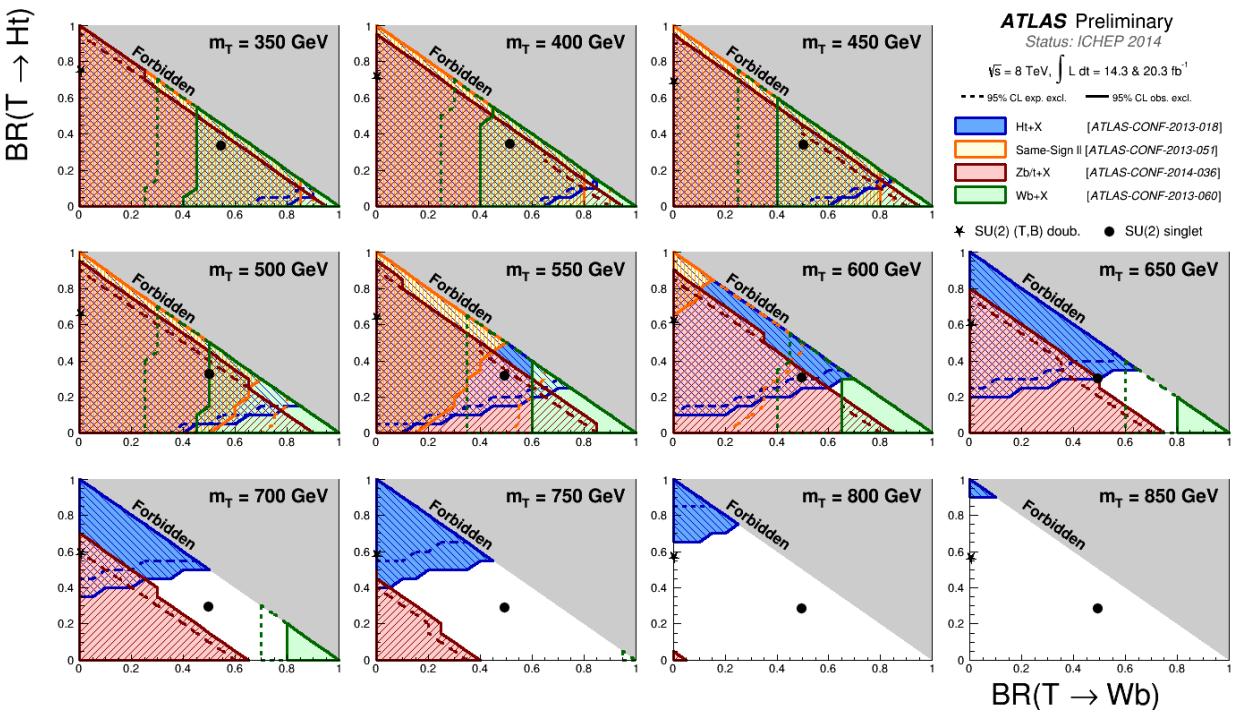
Max. "Yukawa" (IR brane mass)

similar MCHM$_{10}$: $m_{2/3}^{min} < 600$ GeV

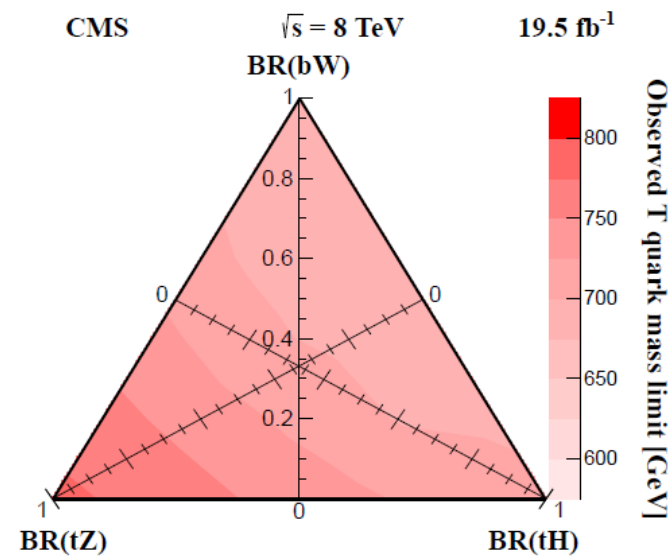
$f_\pi = 800\,\mathrm{GeV},\ Y_*^q = 0.7$

light top partners: min(m_T,$m_{\tilde{T}}$)<<f_π!

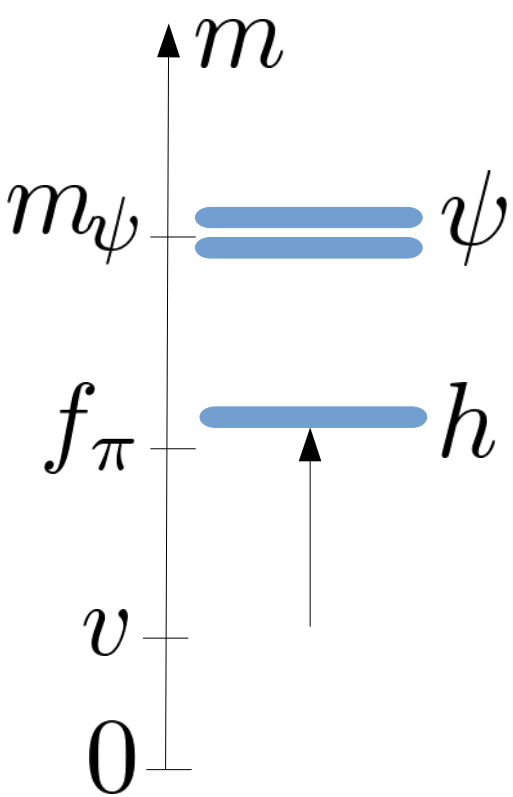
Direct Searches



$m_{2/3}^{min} > 600$ GeV



MCHM$_{14}$



$$V(h) \approx \alpha \sin^2(h/f_\pi) - \beta \sin^2(h/f_\pi)\cos^2(h/f_\pi)$$

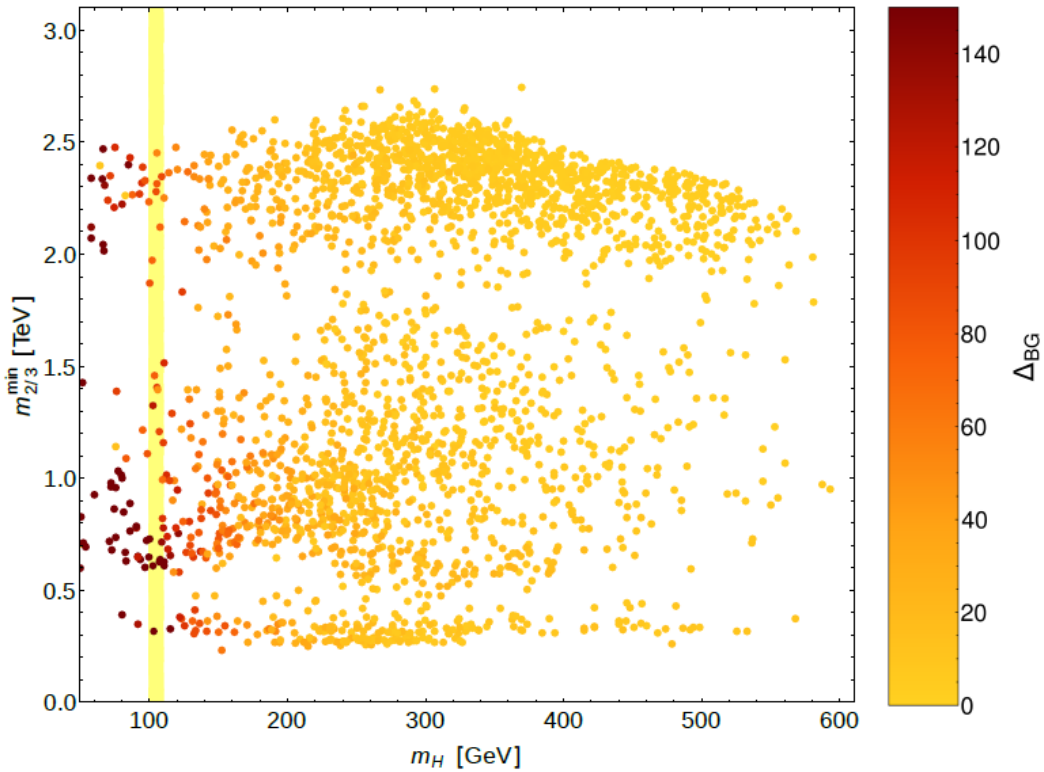
both $\alpha, \beta \sim y_{L,R}^{t\,2}/m_\psi^2$

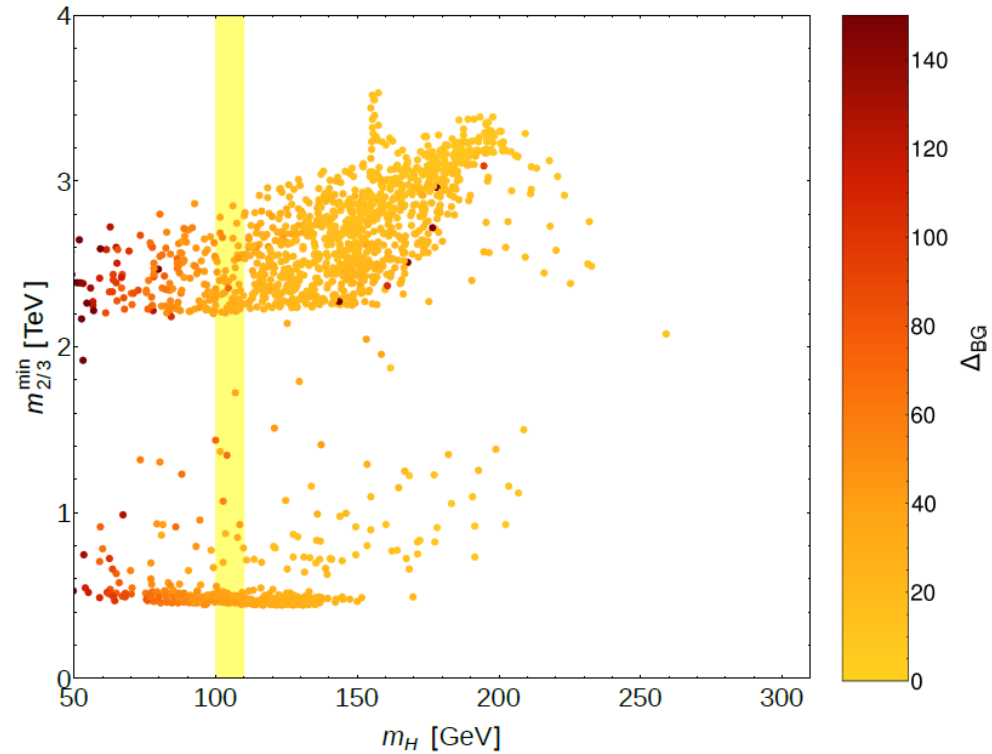
$$m_H \sim \frac{m_\Psi}{f_\pi} v \gg v$$

- "ad hoc tuning"
- However, possible to tune, without need for ultra-light partners

Panico, Redi, Tesi, Wulzer, 1210.7114;
Pappadopulo, Thamm, Torre 1303.3062

MCHM$_{14}$ MCHM$_{14-1_{t_L}1_{t_R}}$





- Enhanced (ad-hoc) tuning in m_H
- Significant enlargement of colored content at TeV scale

$$t'[-,+] \oplus \begin{pmatrix} \tilde{\Lambda}[-,+] & t[+,+] \\ \tilde{t}[-,+] & b[+,+] \end{pmatrix} \oplus \begin{pmatrix} \hat{\epsilon}_2[-,-] & \hat{\Lambda}''[+,-] & t'''[+,-] \\ \hat{\Lambda}[-,-] & t''[+,-] & b'''[+,-] \\ \hat{t}[-,-] & b''[+,-] & R'''[+,-] \end{pmatrix}$$

???

$$f_\pi = 800\,\mathrm{GeV}, \;\; Y_*^q = 0.7$$

The Impact of Leptons

Impact of Leptons

- Naively not important: $m_l \ll m_t \rightarrow y^l_{L,R} \ll y^t_{L,R}$
- However: Lepton Sector is different
  - Non-hierarchical mixings
  - Tiny neutrino masses → seesaw? ...

Impact of Leptons

- Naively not important: $m_l \ll m_t \rightarrow y^l_{L,R} \ll y^t_{L,R}$
- However: Lepton Sector is different
  - Non-hierarchical mixings
  - challenging smallness of FCNCs

  → Models with flavor symmetries,

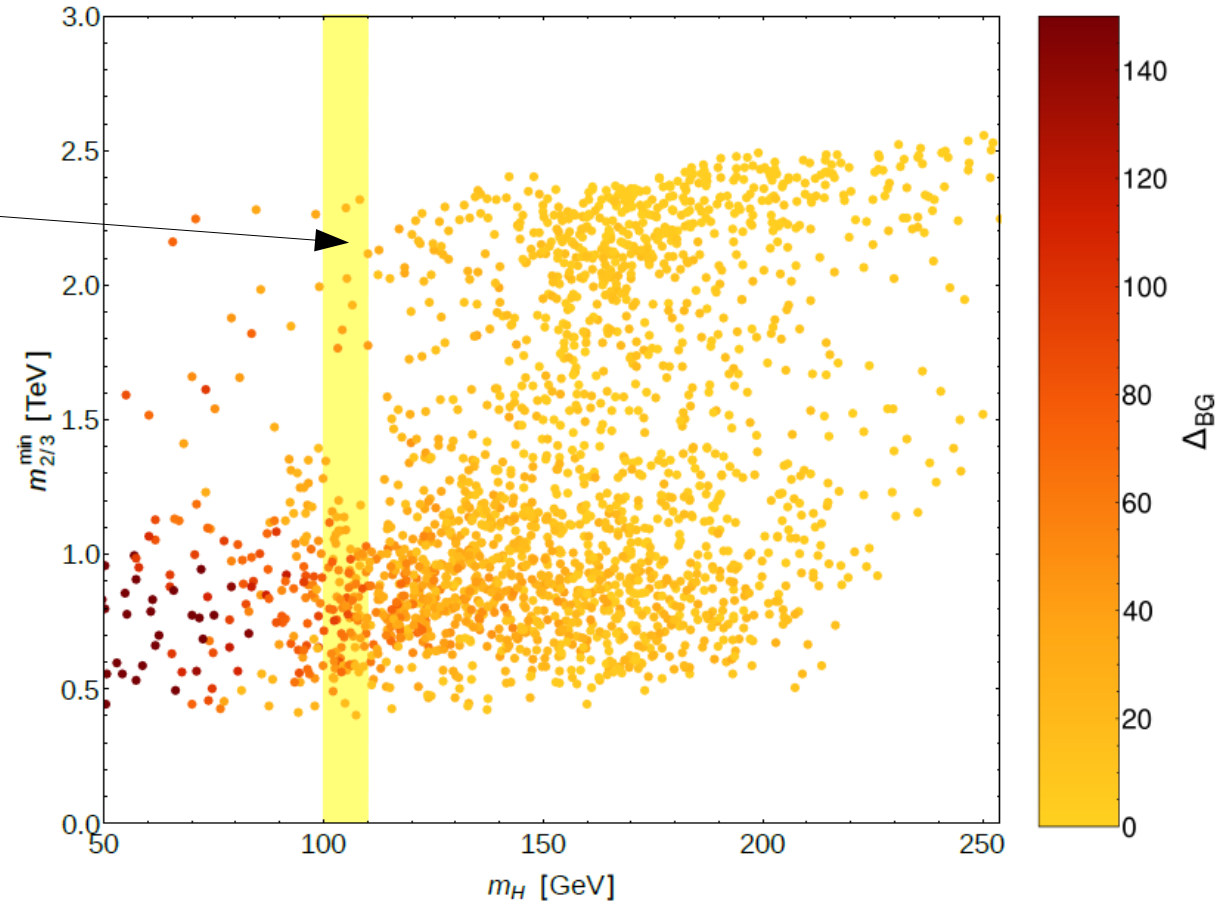
  left-handed sector strongly elementary

  → right handed compositeness: τ_R

  DelAguila, Carmona, Santiago, 1001.5151

$MCHM_5^{5-14}$

- tuning very mild: O(10%)
- destructive interference



Modest overall lepton effect (Yukawa suppression, $N_c \to 1$), however:

- Non-negligible impct on m_H: $\beta_\tau \sim (y_R^\tau/m_\psi)^2$, $\beta_t \sim (y_{L,R}^t/m_\psi)^4$
- Lowering m_H possible keeping $m_{2/3}^{min}$ fixed, no ad-hoc tuning in m_H

$$f_\pi = 800\,\mathrm{GeV},\ Y_*^q = 0.7, Y_*^l = 0.35$$

Impact of Leptons

Motivation for large representation: 14_R ?

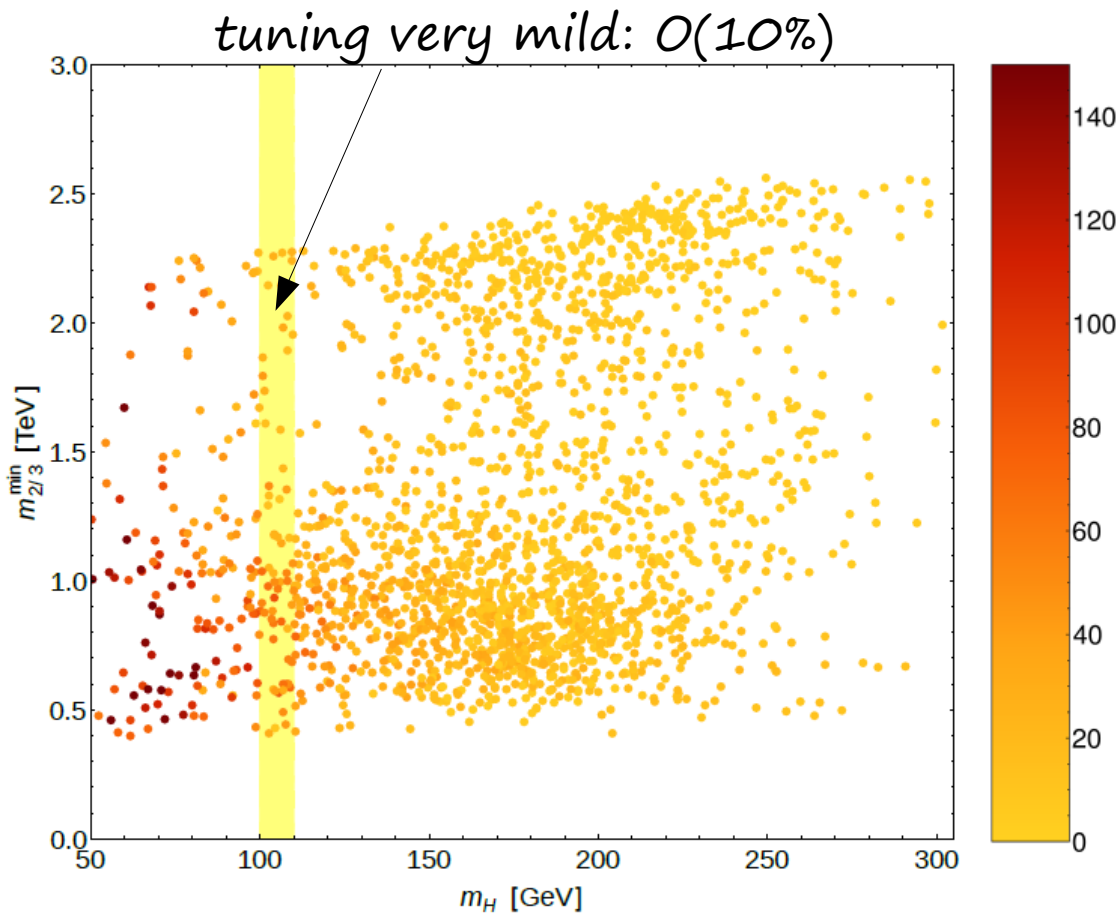
- Tiny neutrino masses → seesaw
- Type-III: $\ell_R \sim \mathbf{1}_{-1},\, l_L \sim \mathbf{2}_{-1/2},\, \Sigma_R \sim \mathbf{3}_0$

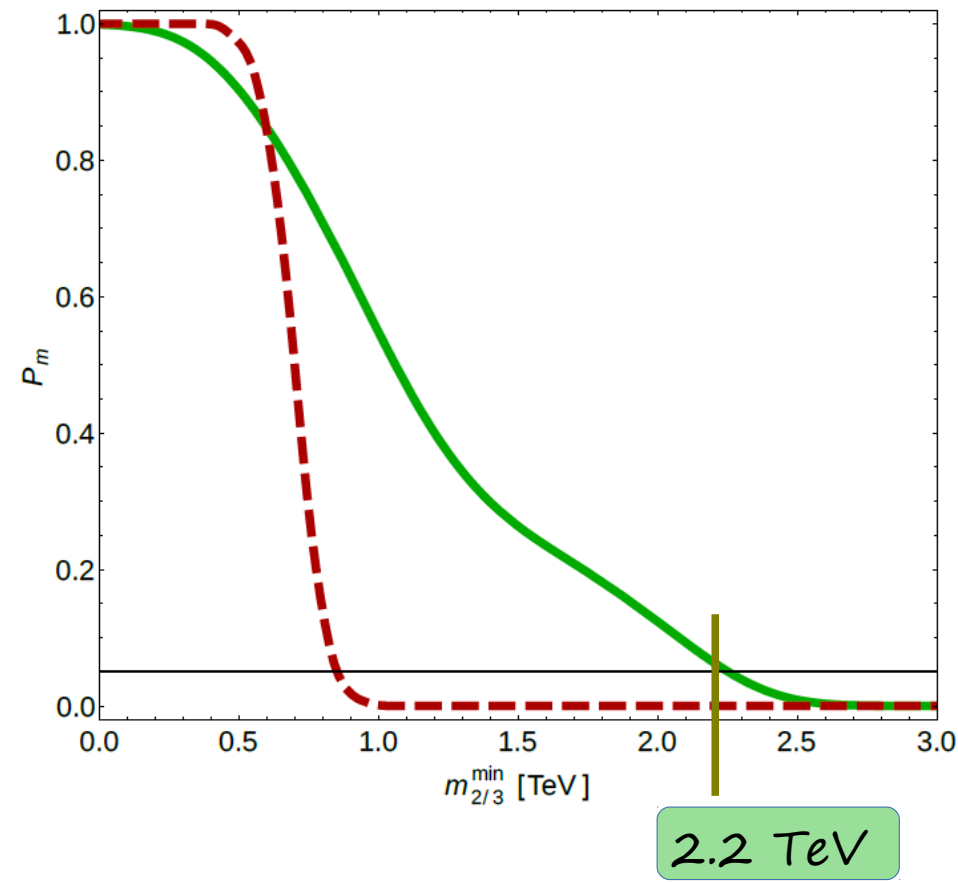
$$\xi_{2\tau} = \tau_2'[-,-] \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix} \oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

- Unification of RH lepton sector, compositeness dictated by seesaw!! $\mathrm{mMCHM}^{\mathrm{III}}$

No such unification possible with type-I

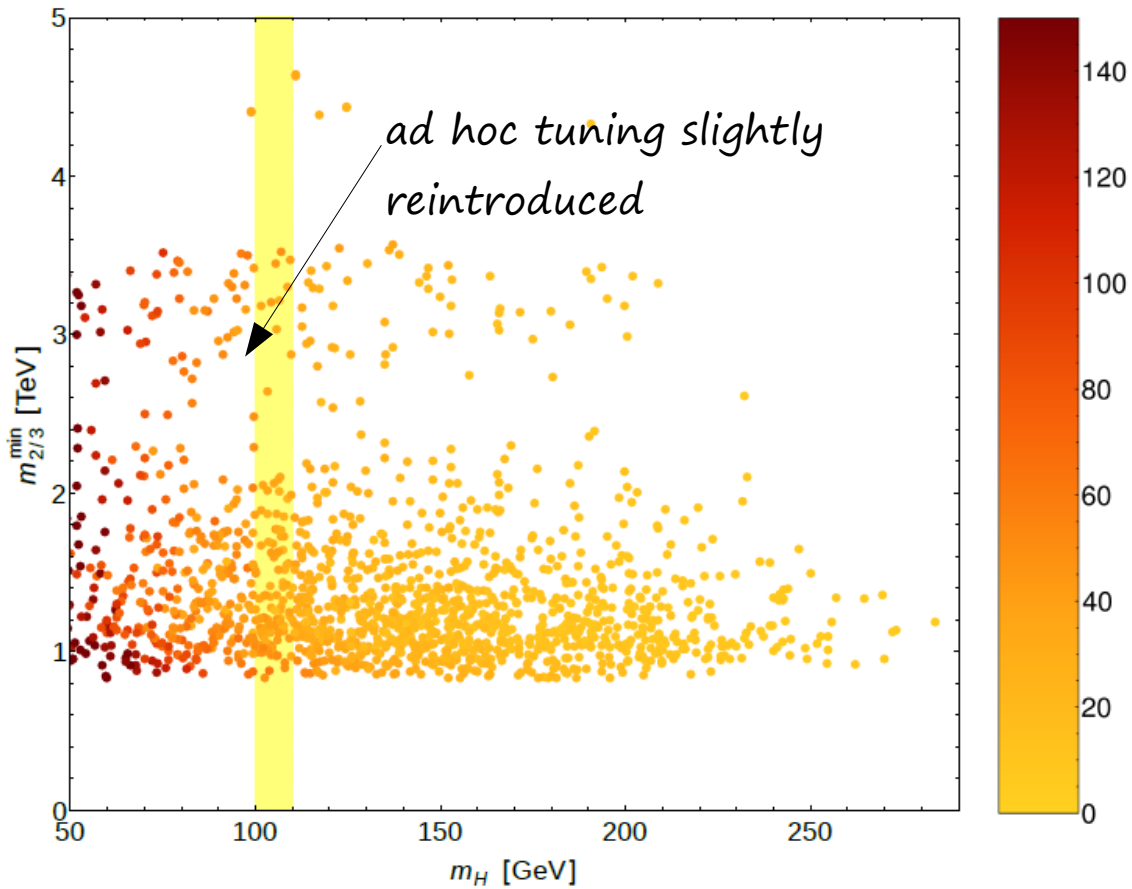
$mMCHM_5^{III}$

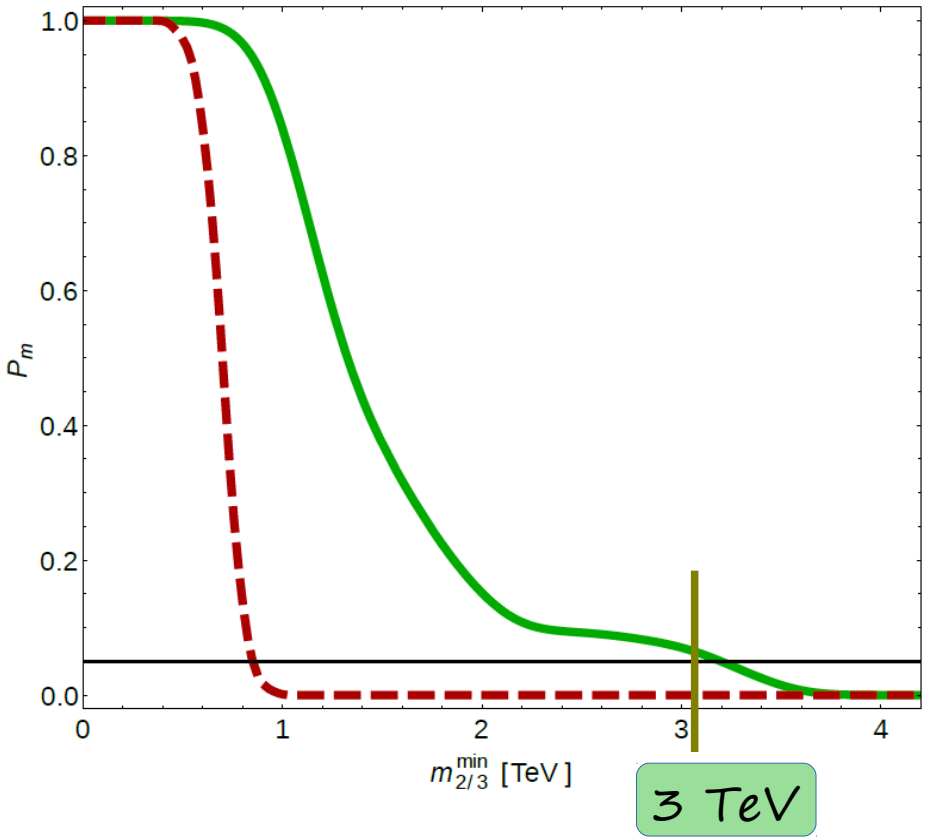




$$f_\pi = 800\,\mathrm{GeV},\ \ Y_*^q = 0.7, Y_*^l = 0.35$$

mMCHM$^{|||>}_{5-1}$

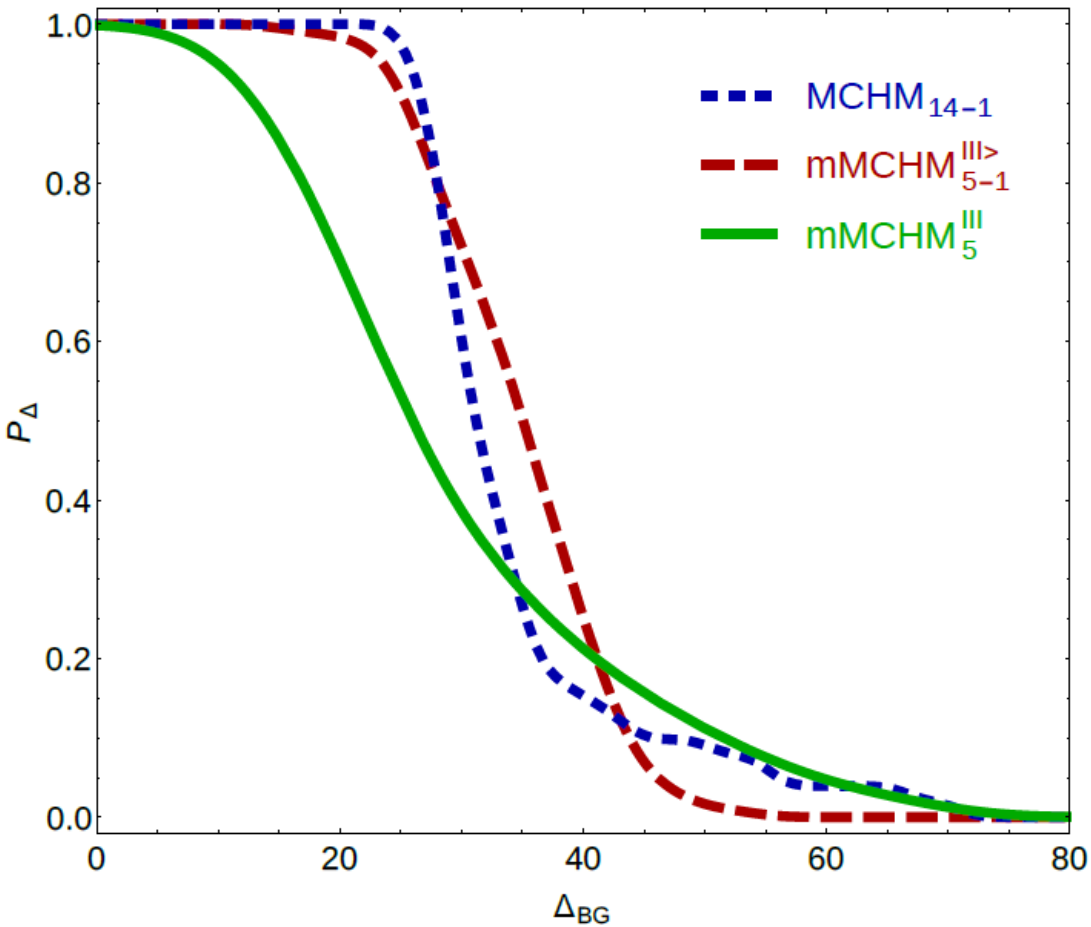




- Lifting "Yukawa suppression" (and due to N_g=3), leptons can even contribute to α, such as to allow for 5-1 in quark sector

$$f_\pi = 800\,\mathrm{GeV},\ Y_*^q = 0.7, Y_*^l = 0.7$$

Comparison of Tuning



- $\mathrm{mMCHM}^{\mathrm{III}}_{5}$ allows to reconcile minimal tuning with absence of ultra-light partners
- $\mathrm{mMCHM}^{\mathrm{III}>}_{5-1}$ features least dof of all SO(5)/SO(4) models

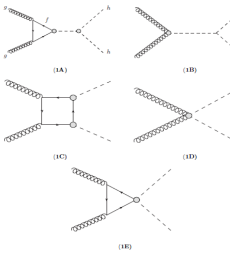
$$f_\pi = 800\,\mathrm{GeV},\ Y_*^q = 0.7,\ m_{2/3}^{min} > 1\,\mathrm{TeV}$$

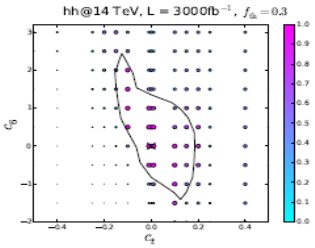
Conclusions

- Lepton sector allows to construct very economical MCHMs that
  - don't require ultra-light top partners
  - feature a Higgs which is naturally light

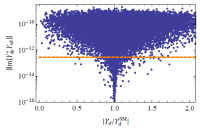
no $m_{2/3}^{min} < 1$ TeV
+ minimality
⇕
type-III seesaw

- Other recent projects (2012-14):
  - HH production in SM and D=6 EFT
    FG, Papaefstathiou, Yang, Zurita, 1301.3492, 1410.8555





  - Indirect handle on light-quark Yukawas
    FG, 1406.0102



  - Flavor physics in various models
    Gauld, FG, Haisch, 1308.1959, 1310.1082; Agashe et.al. 1310.1070, 1311.0299
  - Higgs physics in various models
    Carena, Casagrande, FG, Haisch, Neubert, 1204.0008; Carmona, FG, 1301.5856

Backup: $mMCHM^{|||>}_{5-1}$

- Lifting "Yukawa suppression" (and due to N_g=3), leptons can even contribute to α, such as to allow for 5-1 in quark sector

$$\xi_1^t = t'[-,+] \oplus \begin{pmatrix} \tilde{\Lambda}[-,+] & \boxed{t[+,+]} \\ \tilde{t}[-,+] & \boxed{b[+,+]} \end{pmatrix} \oplus \begin{pmatrix} \hat{\epsilon}_2[-,-] & \hat{\Lambda}''[+,-] & t'''[+,-] \\ \hat{\Lambda}[-,-] & t''[+,-] & b'''[+,-] \\ \hat{t}[-,-] & b''[+,-] & R'''[+,-] \end{pmatrix} \quad \xi_2^t$$

$$\xi_1^b \qquad\qquad \xi_2^b$$

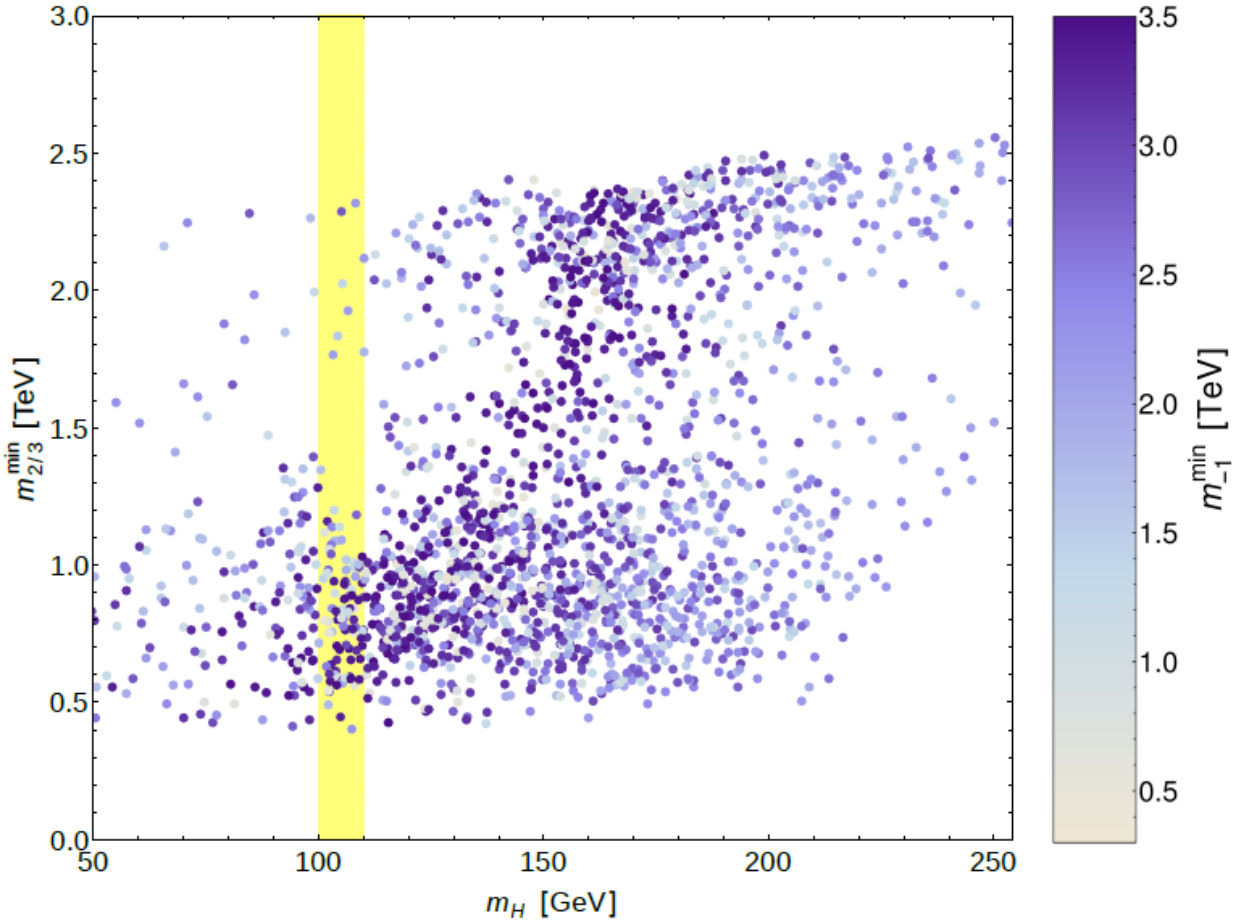
$$+ (5-1)_L$$

$$\xi_{2\tau} = \boxed{\tau_2'[-,-]} \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix} \oplus \begin{pmatrix} \boxed{\hat{\lambda}_2^\tau[-,-]} & \nu_2^{\tau\prime\prime}[+,-] & \tau_2'''[+,-] \\ \boxed{\hat{\nu}_2^\tau[-,-]} & \tau_2''[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \boxed{\hat{\tau}_2[-,-]} & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix} \quad \xi_2^\tau$$

$$+ (5-1)_Q$$

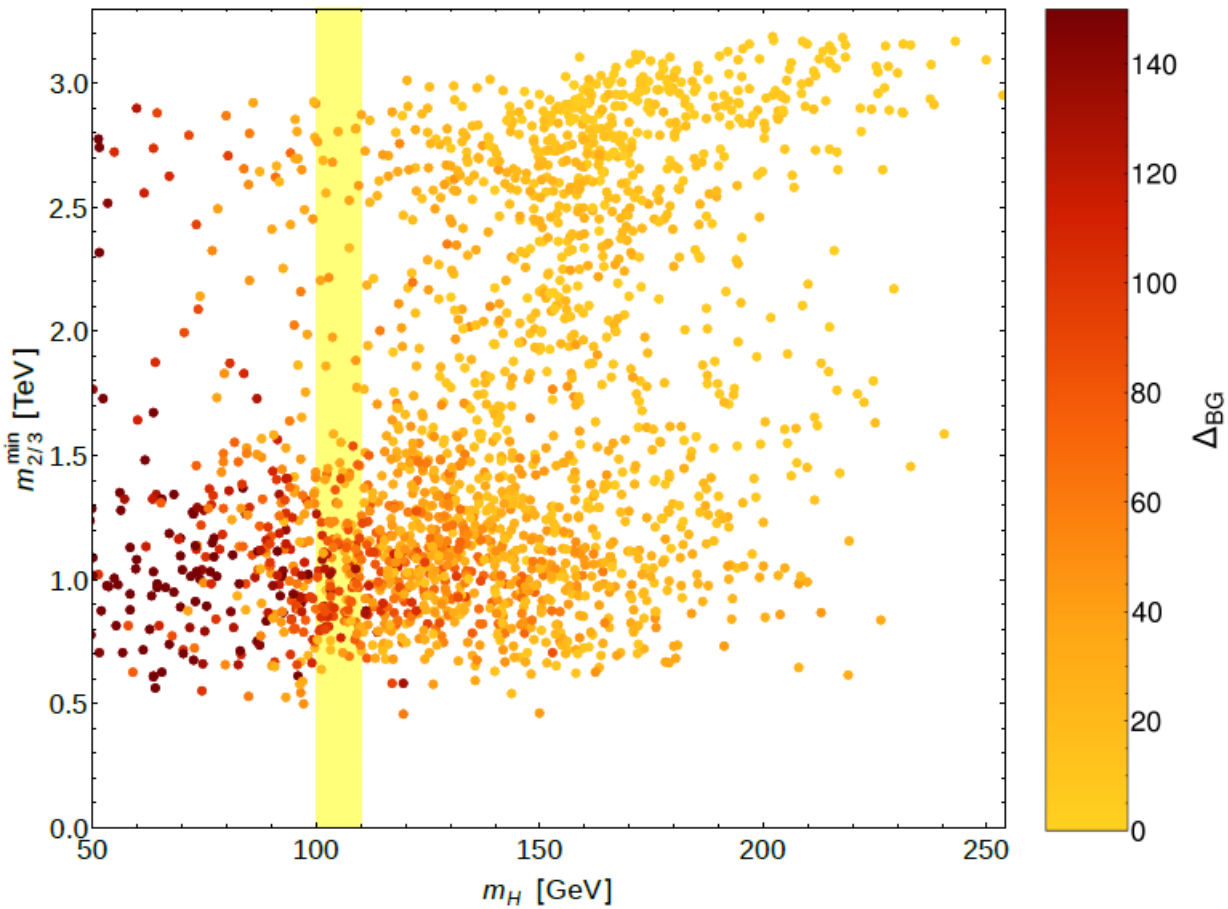
Enhanced minimality, just 2 composite mulitplets!

Backup: Tau Partner Mass



$$\mathrm{MCHM}_5^{5-14} \text{ with } f_\pi = 800\,\mathrm{GeV},\ Y_*^q = 0.7, Y_*^l = 0.35$$

Backup: $MCHM_5^{14}$



$$f_\pi = 1\,\mathrm{TeV},\ \ Y_*^q = 0.7, Y_*^l = 0.35$$