DARK MATTER CANDIDATES IN COMPOSITE HIGGS MODELS

Daniel Murnane

University of Adelaide, University of Southern Denmark

Supervisors: Anthony G. Williams, Martin White,

Francesco Sannino

A NATURAL DM PARTICLE FROM A COMPOSITE HIGGS MODEL?

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2. Fine tuning of the minimal model
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5. A scalar singlet from the next-to-minimal model

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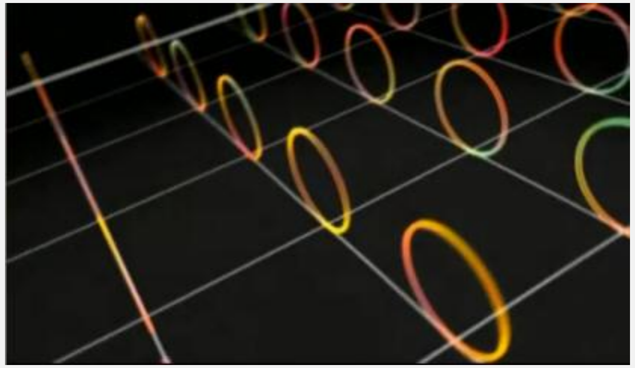

5D GAUGE THEORY

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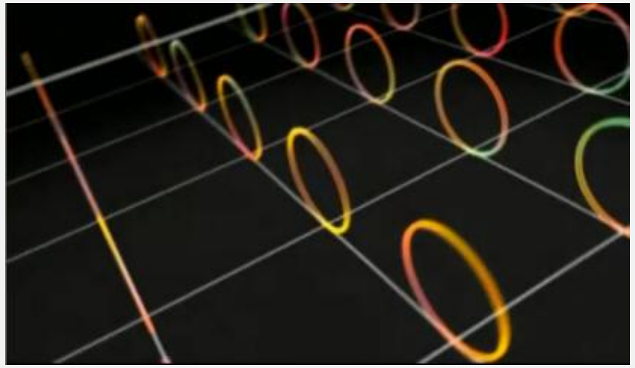
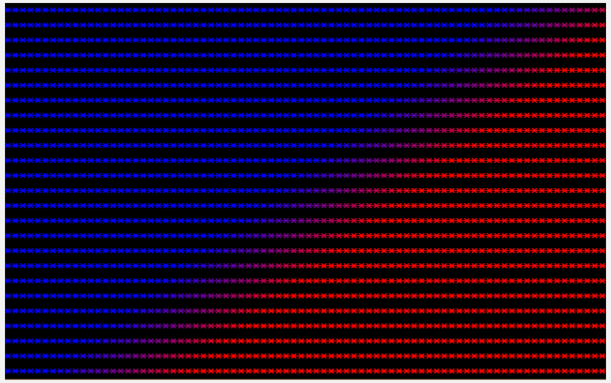


5D GAUGE THEORY

SU(2) TECHNICOLOR WITH TWO QUARKS



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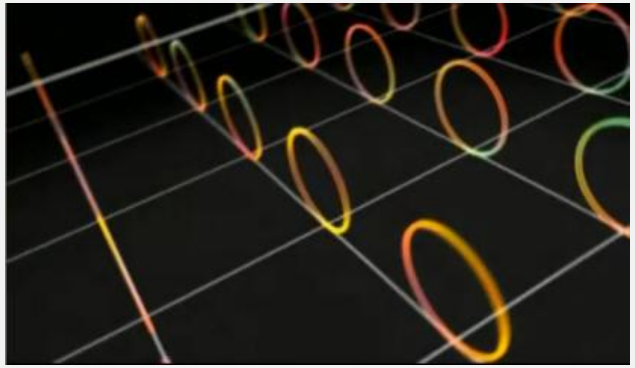

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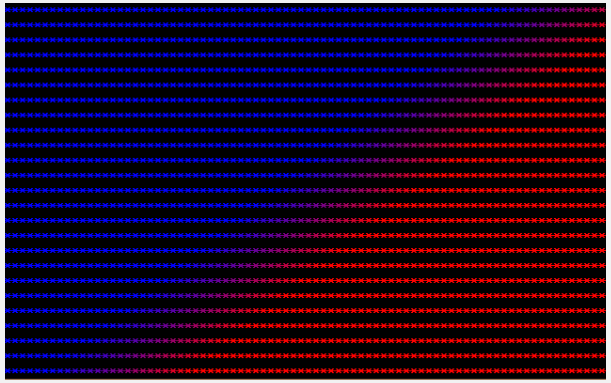

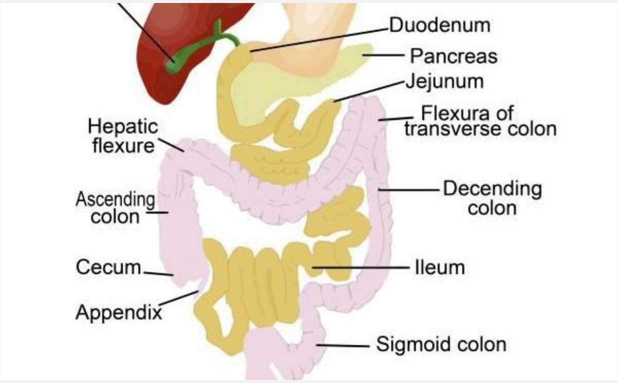

A GUT

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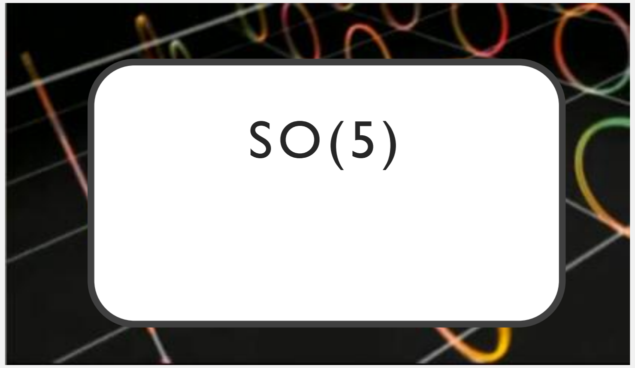

SO(5)

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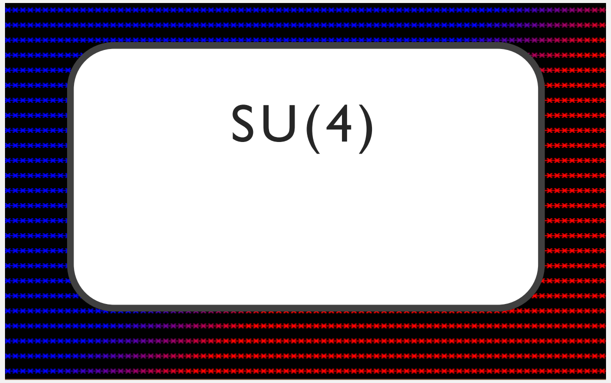
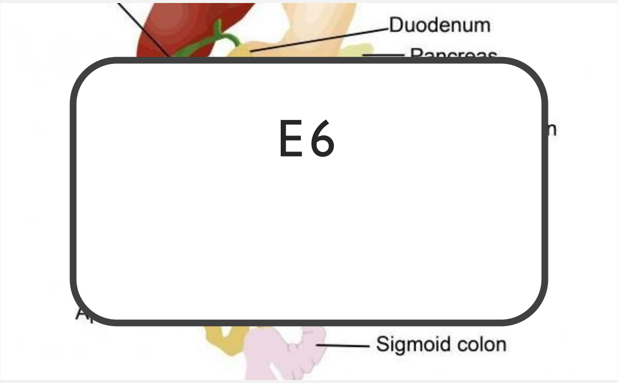


SU(4)



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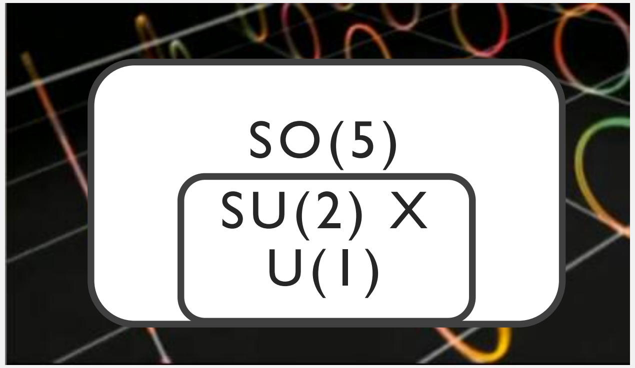
2. FIT THE ELECTROWEAK GROUP INTO IT



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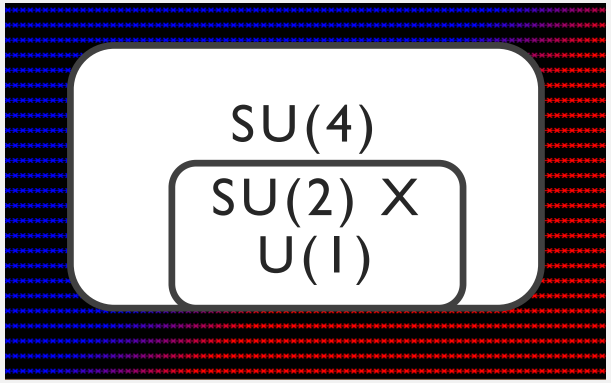

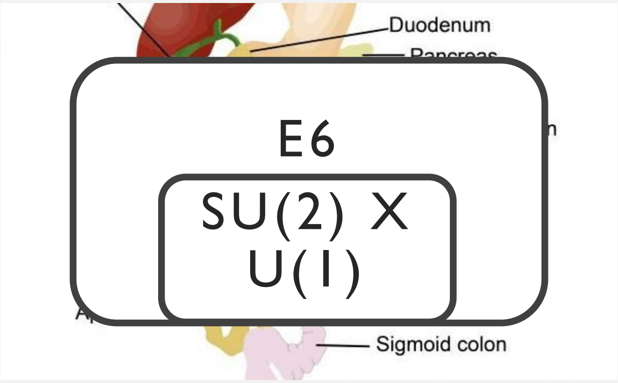

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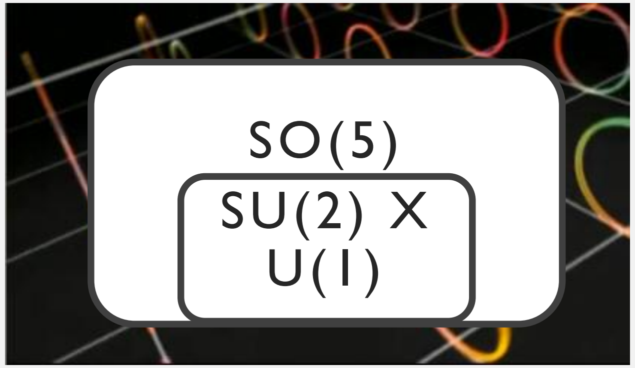

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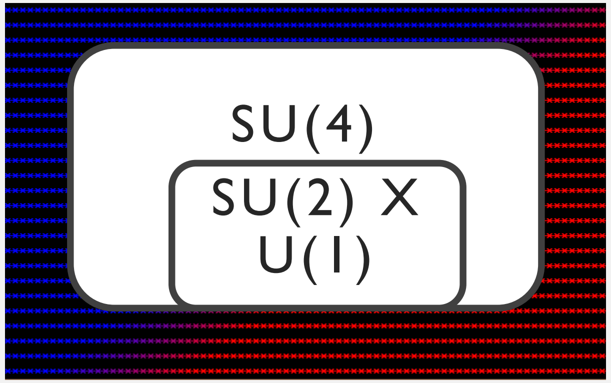

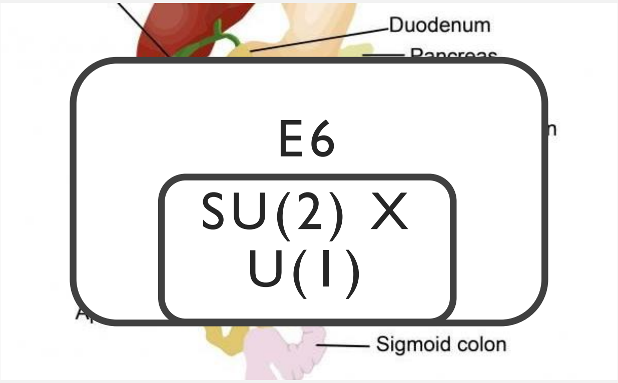

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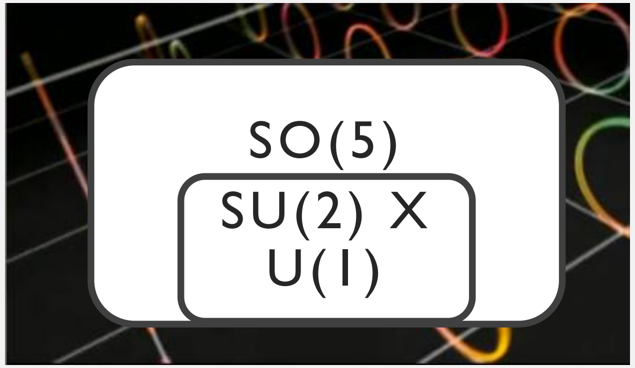

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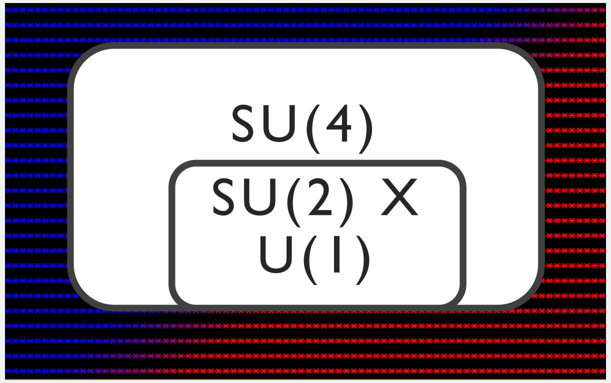

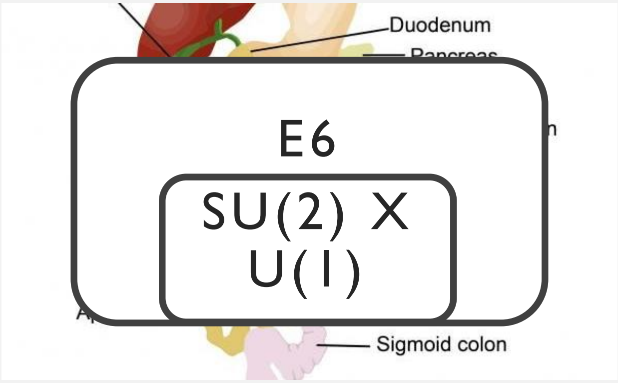

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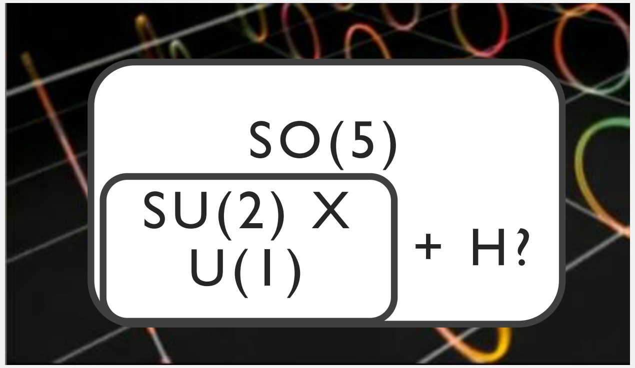

K. Agashe, R. Contino, A. Pomarol, *The Minimal Composite Higgs* (2005)

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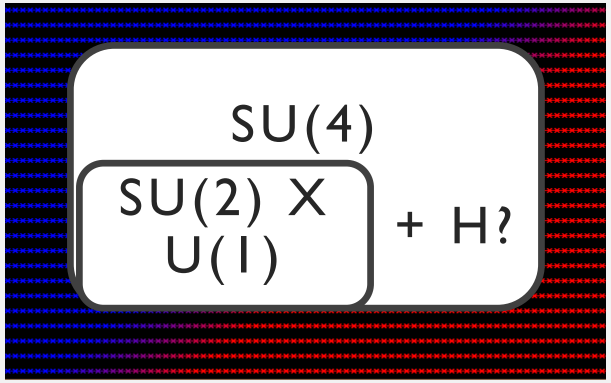

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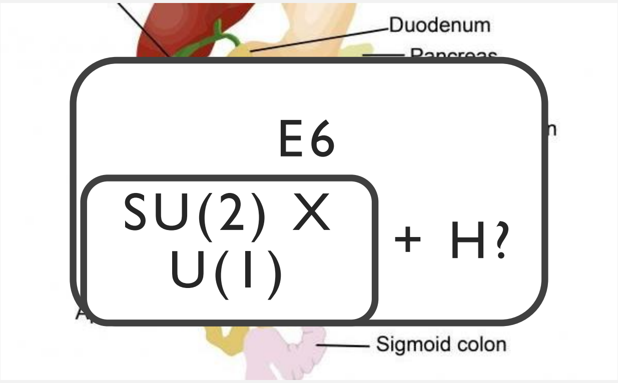

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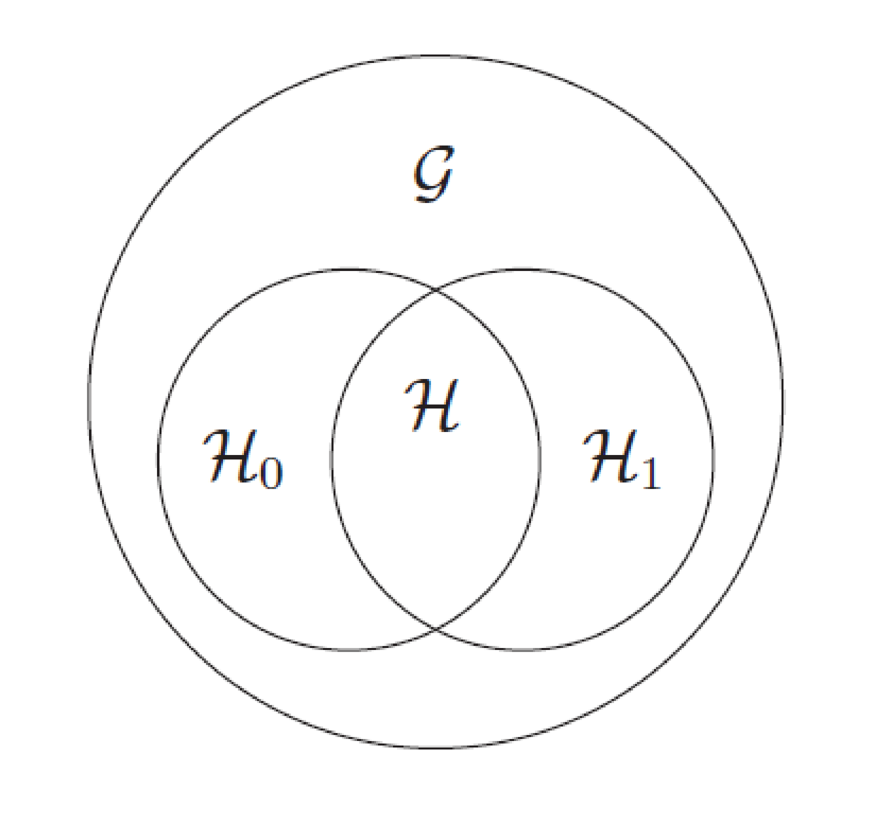
NAMBU-GOLDSTONE SYMMETRY BREAKING



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G → Global symmetry group

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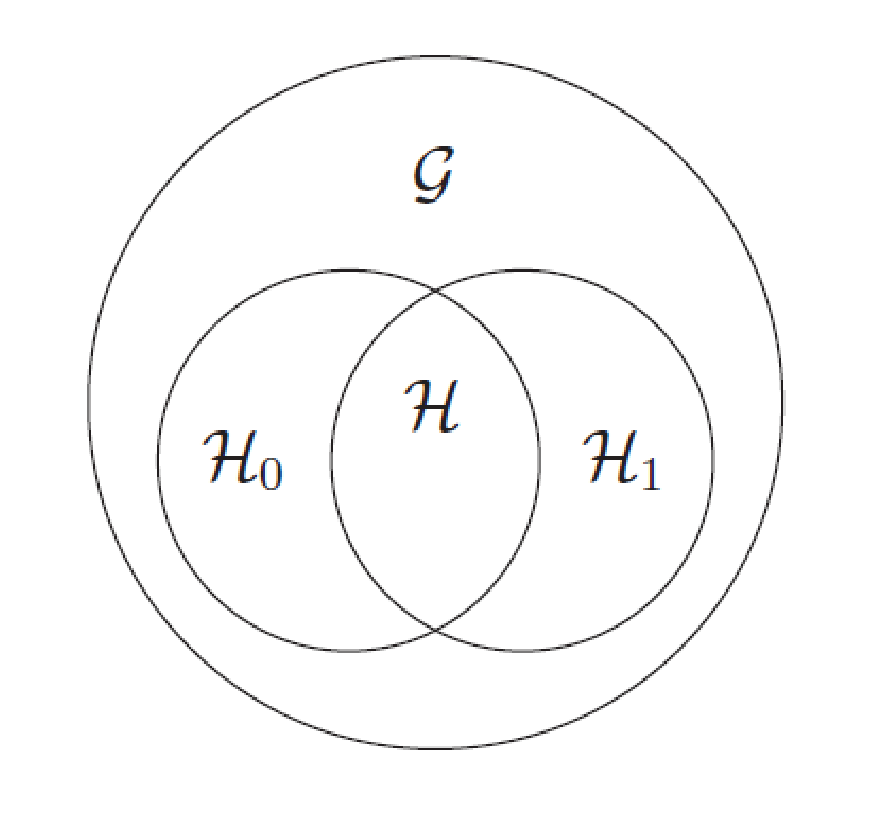

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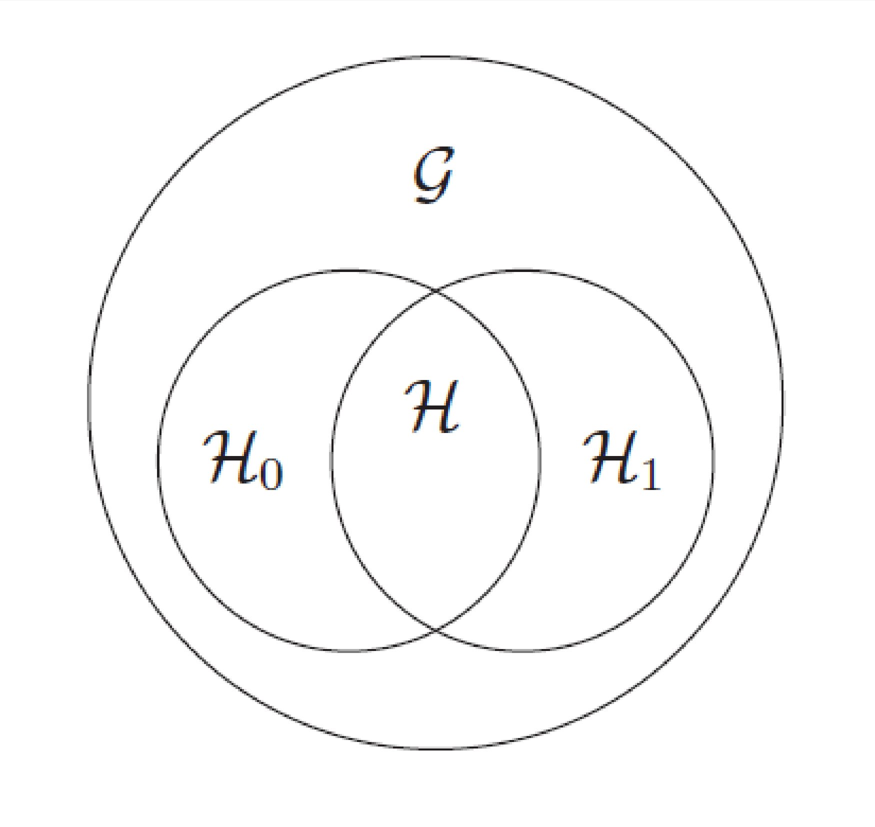

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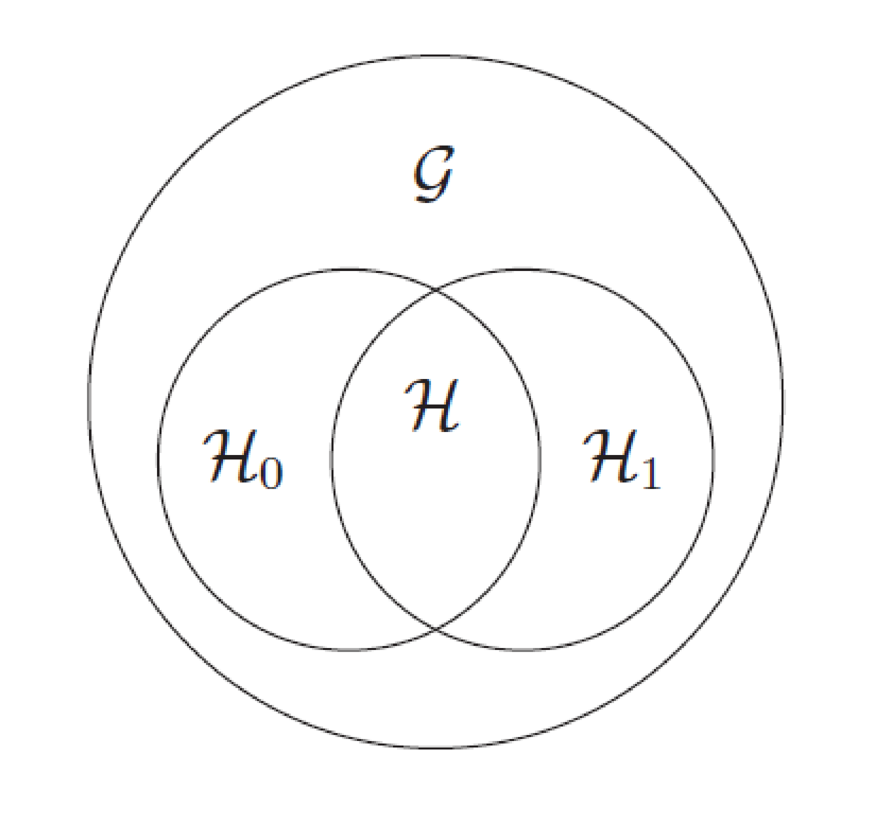

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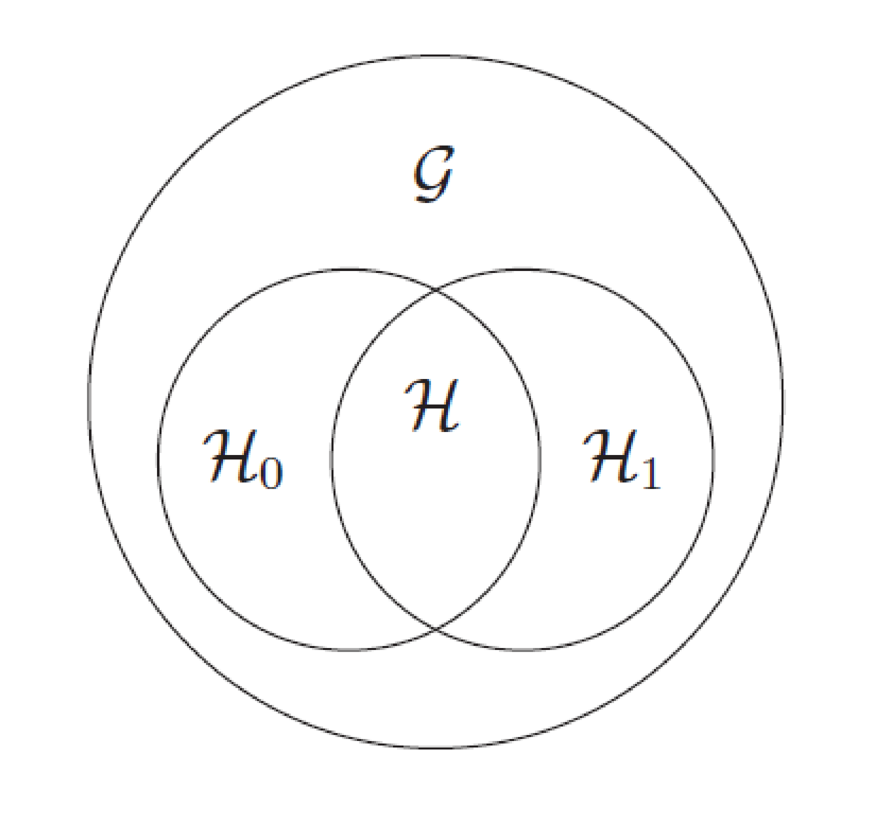

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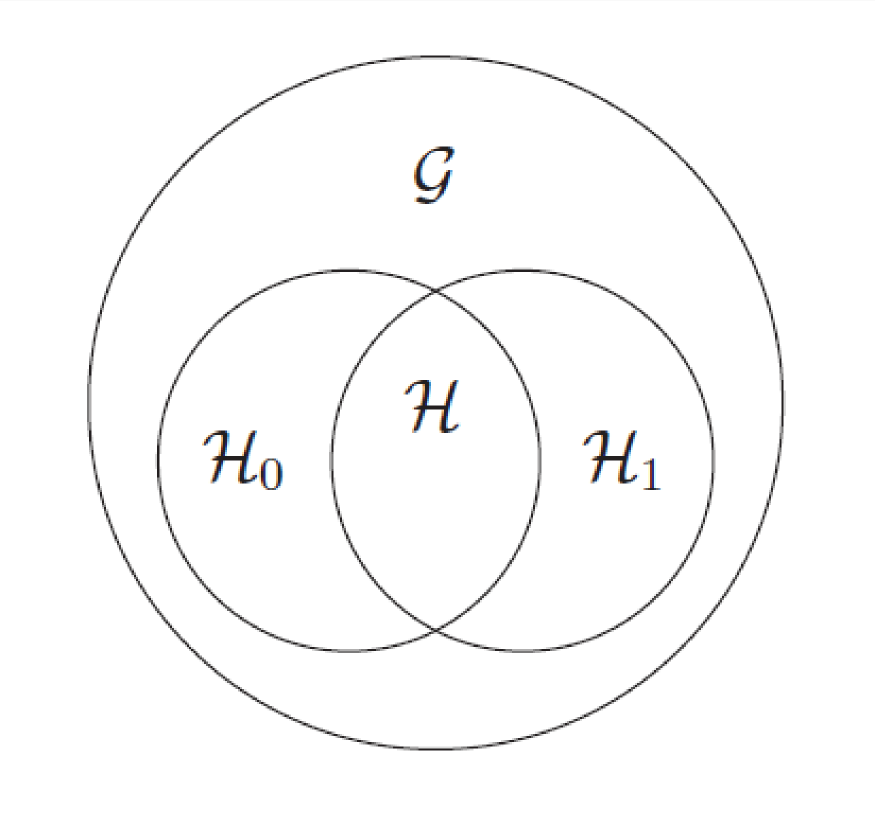
Electroweak group must fit inside H_1

Higgs doublet must fit inside G/H_1

AN EXAMPLE: CHIRAL SYMMETRY BREAKING



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G → $SU(3)_L \times SU(3)_R$ (global, 16 degrees of freedom)

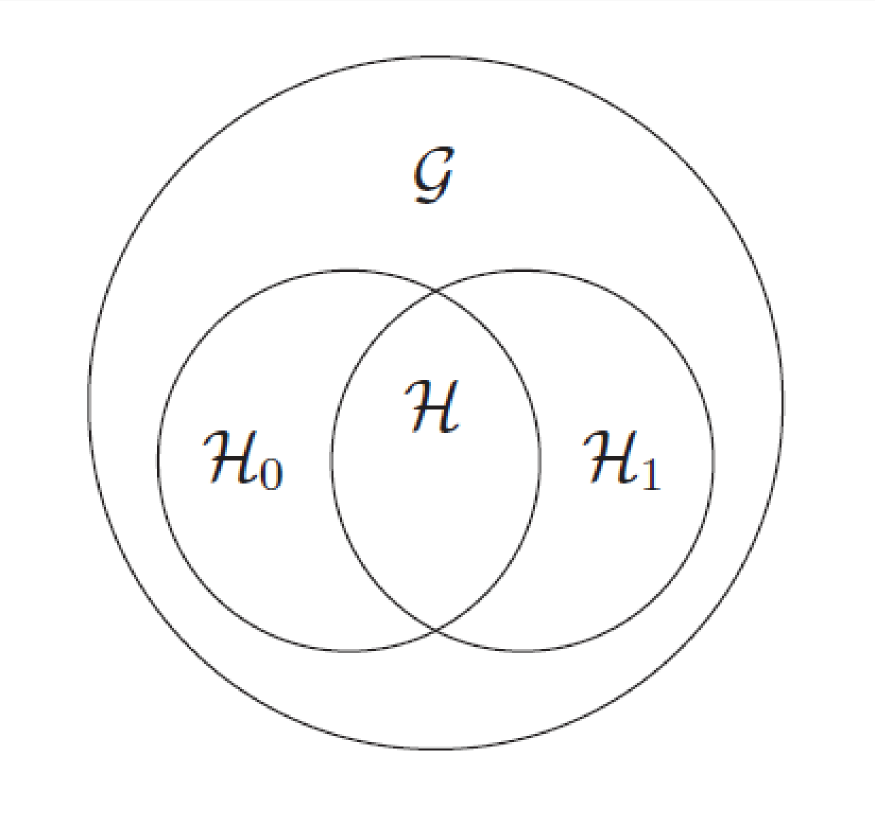
H_0 → Null – no gauging

H_1 → $SU(3)_V$ (global, 8 degrees of freedom)

H → Null – no gauging

G/H_1 → Contains pseudoscalar mesons (8 degrees of freedom), naturally light

THE MINIMAL COMPOSITE HIGGS MODEL (**MCHM**)



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G → SO(5) x U(1) (global, 10 degrees of freedom)

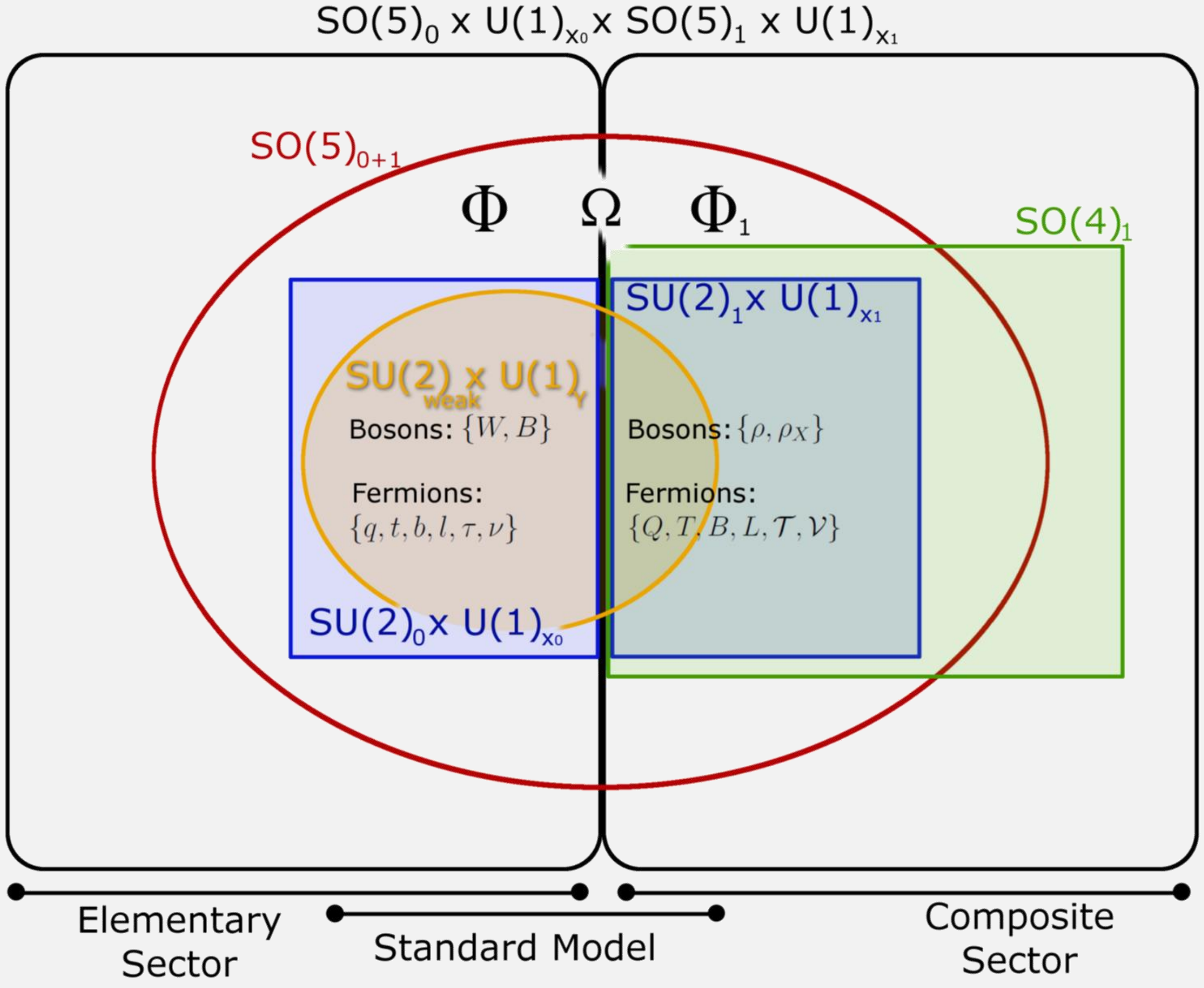
H_0 → H

H_1 → SO(4) x U(1) (global, 6 degrees of freedom)

H → SU(2) x U(1) (gauged)

G/H_1 → Contains Higgs doublet (4 degrees of freedom), naturally light

DERIVING THE **TWO SITE** MINIMAL COMPOSITE HIGGS MODEL (**MCHM**)



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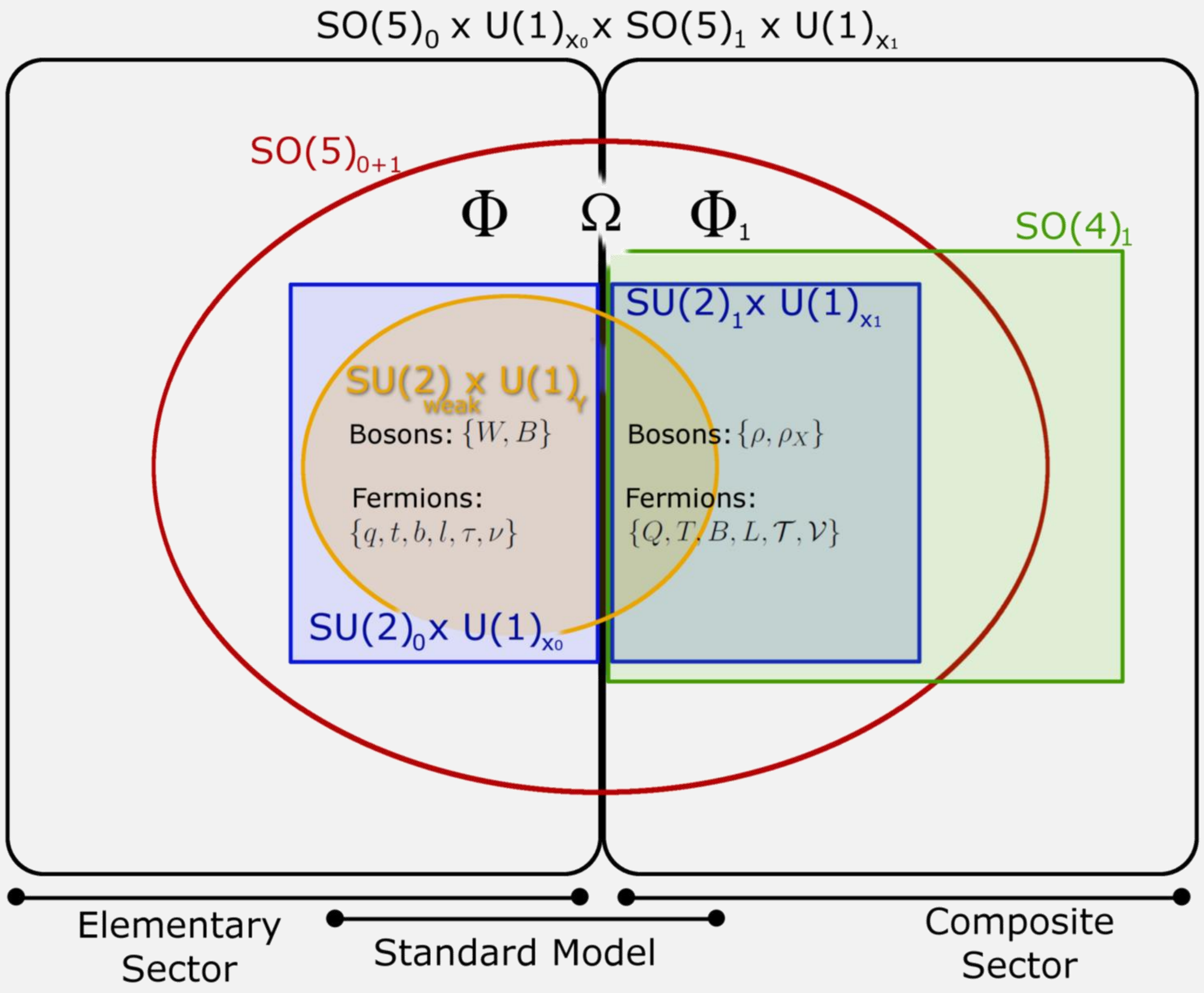

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Spurion invariant under SO(5)$_{0+1}$

$$\Phi = \frac{1}{\hat{h}} \sin \frac{\hat{h}}{f} (h^1, h^2, h^3, h^4, \hat{h} \cot \frac{\hat{h}}{f})^T$$

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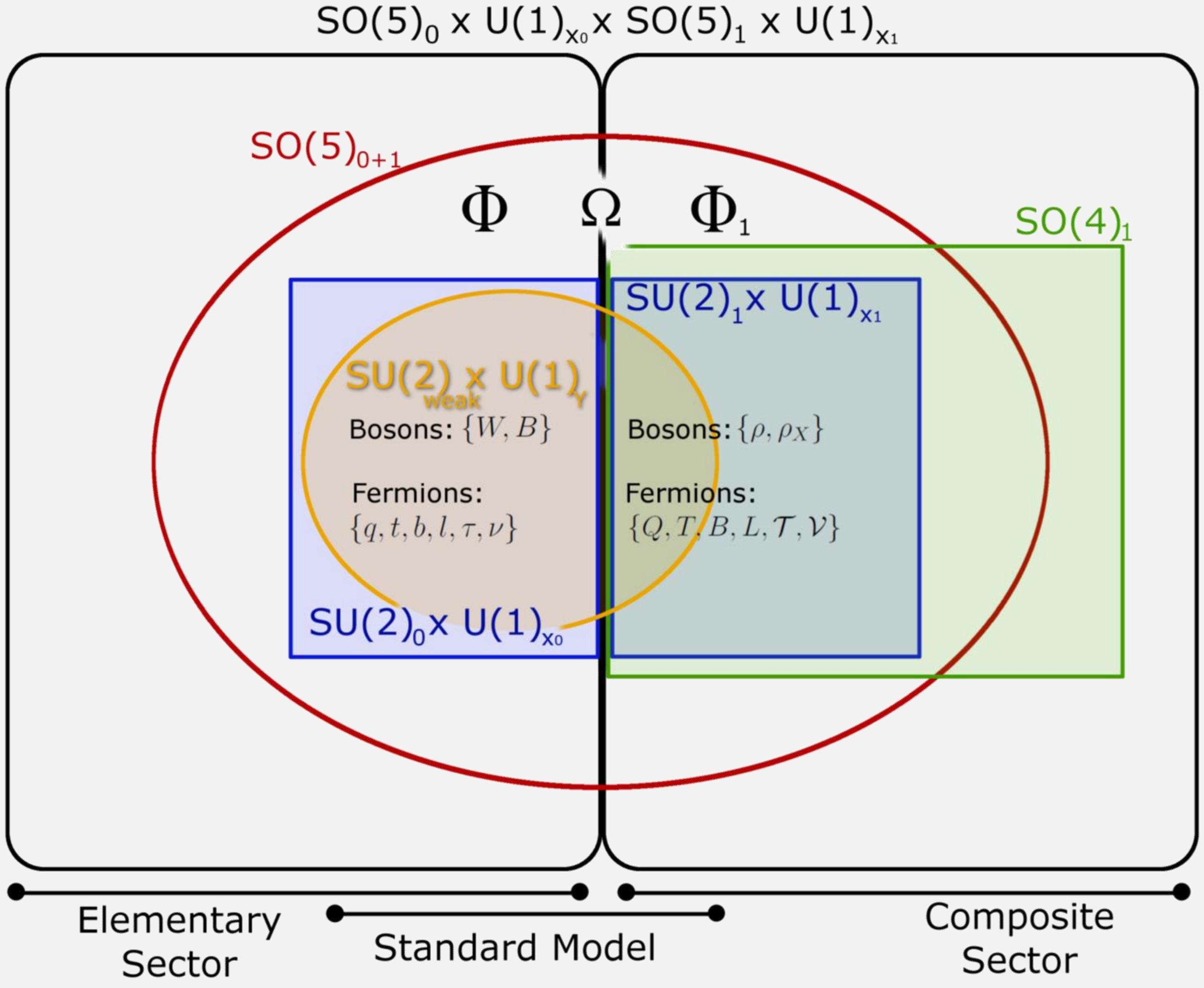

Spurion invariant under $SO(5)_{0+1}$

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Composite partners invariant under full $SO(5)_1$

$$Q^t, T \sim \mathbf{5}_{2/3} \quad \mathbf{5} = \begin{pmatrix} \mathbf{4} \\ \mathbf{1} \end{pmatrix}$$

$$Q = \begin{pmatrix} Q_{4_1} \\ Q_{4_2} \\ Q_{4_3} \\ Q_{4_4} \\ Q_1 \end{pmatrix}$$

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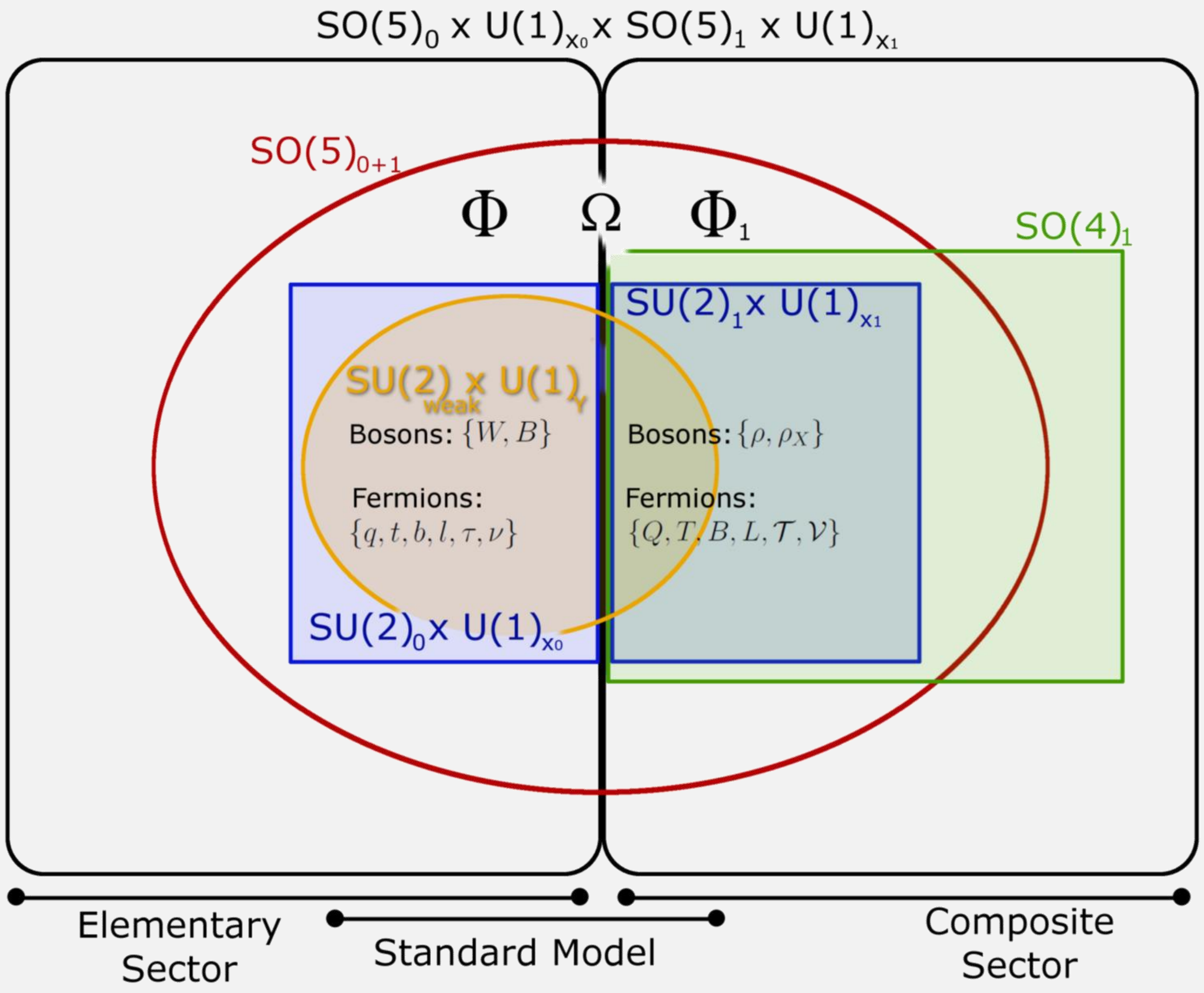

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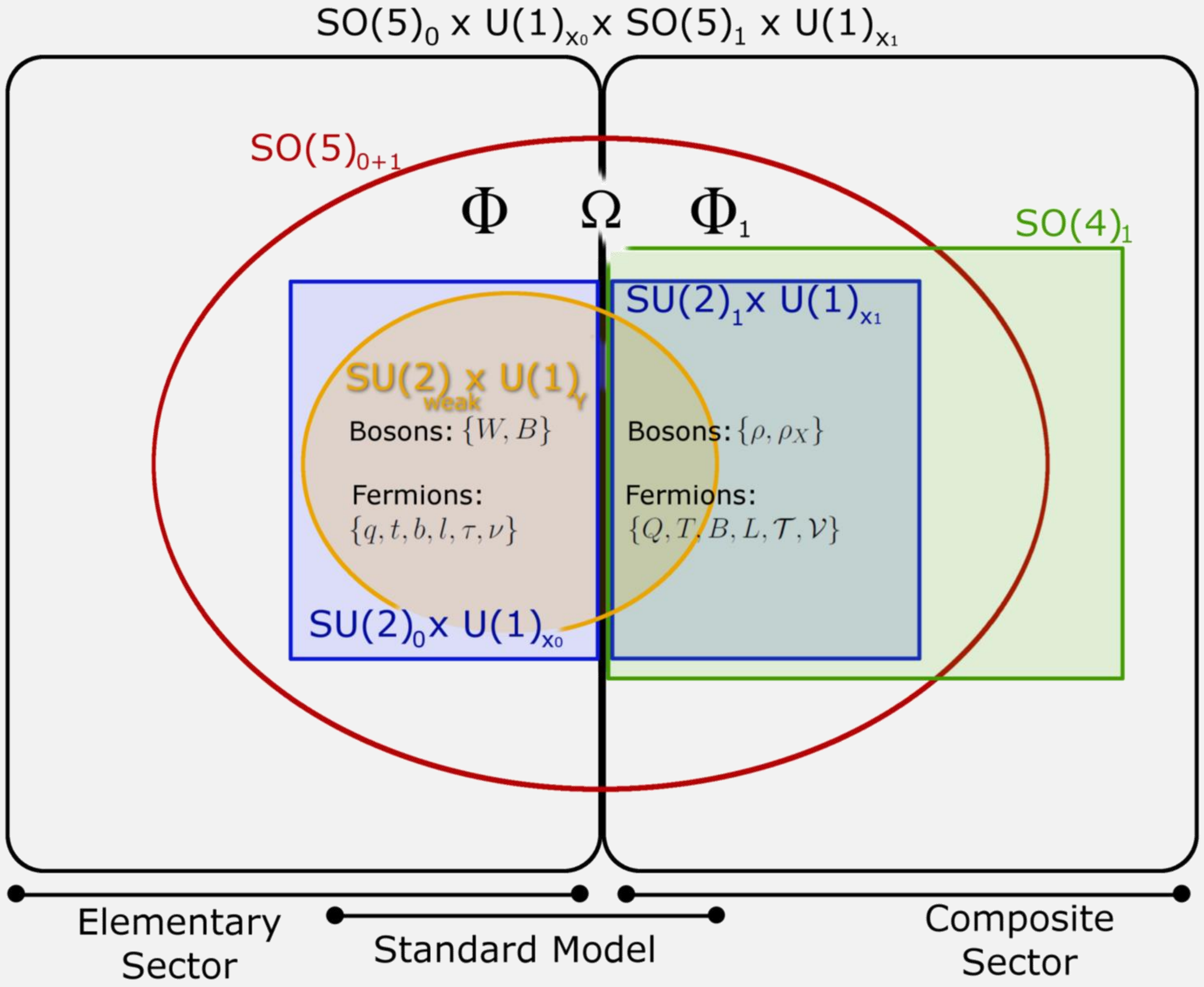
Elementary fermions invariant under incomplete SO(5)$_0$

$$\Psi_q = \begin{bmatrix} q_L \\ Q_L \end{bmatrix}$$

DERIVING THE MINIMAL COMPOSITE HIGGS MODEL (**MCHM**)



Create effective lagrangian from these fields

$$\mathcal{L}_{\text{eff}} = \frac{1}{2} P^T_{\mu\nu} \left[\Pi_W(p^2,h) W_\mu W_\nu + \Pi_B(p^2,h) B_\mu B_\nu + \Pi_{WB}(p^2,h) W^3_\mu B_\nu \right] + \Pi_t(p^2,h)\bar{t}\not{p}t + \Pi_b(p^2,h)\bar{b}\not{p}b + \Pi_{t^c}(p^2,h)\bar{t}^c\not{p}t^c + \Pi_{b^c}(p^2,h)\bar{b}^c\not{p}b^c + M_t(p^2,h)tt^c + M_b(p^2,h)bb^c +$$

Which gives a potential

$$V(h) = \int_0^\infty \frac{dp^2}{16\pi^2} p^2 \left(\frac{9}{2} \log \Pi_w \right) - 2 \sum_{\psi = t,b,\tau,\nu} Nc_\psi \int_0^\infty \frac{dp^2}{16\pi^2} p^2 \log \left[p^2 (1 + \Pi_\psi)(1 + \Pi_{\psi^c}) - |M_\psi|^2 \right]$$

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FINE TUNING IN THE **MCHM**

We have a choice in the **MCHM**…

Embed each fermion in the **1**, **5**, **10** or **14**

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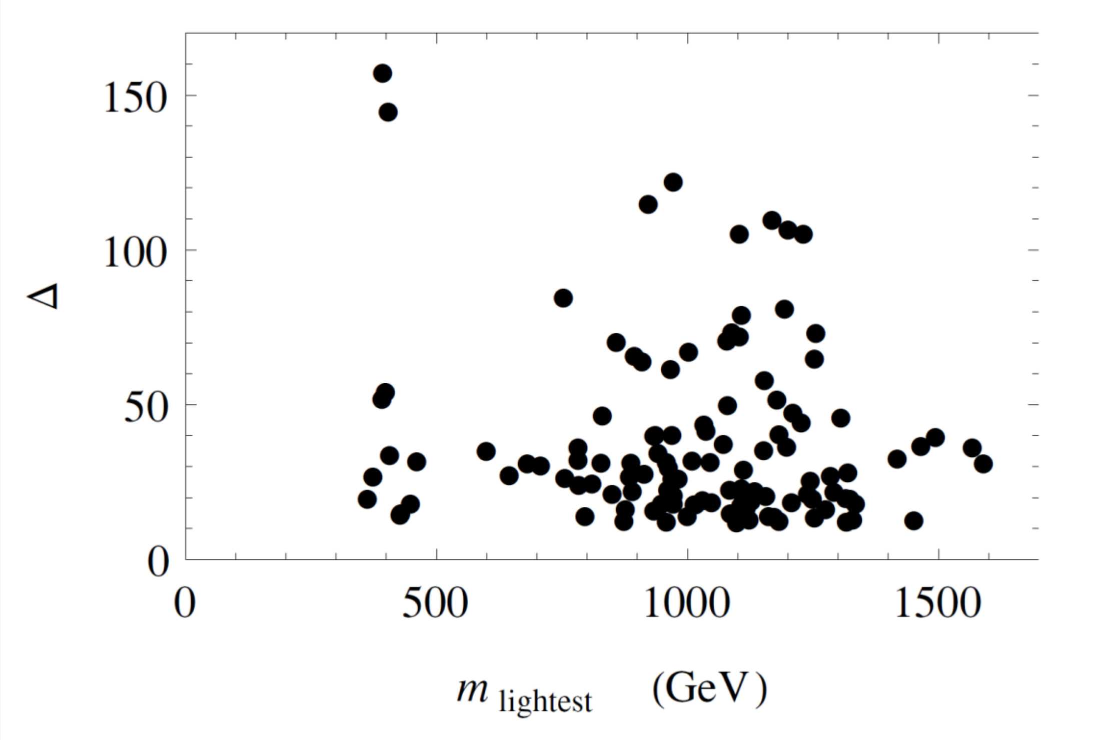

Fermions in the **5** representation

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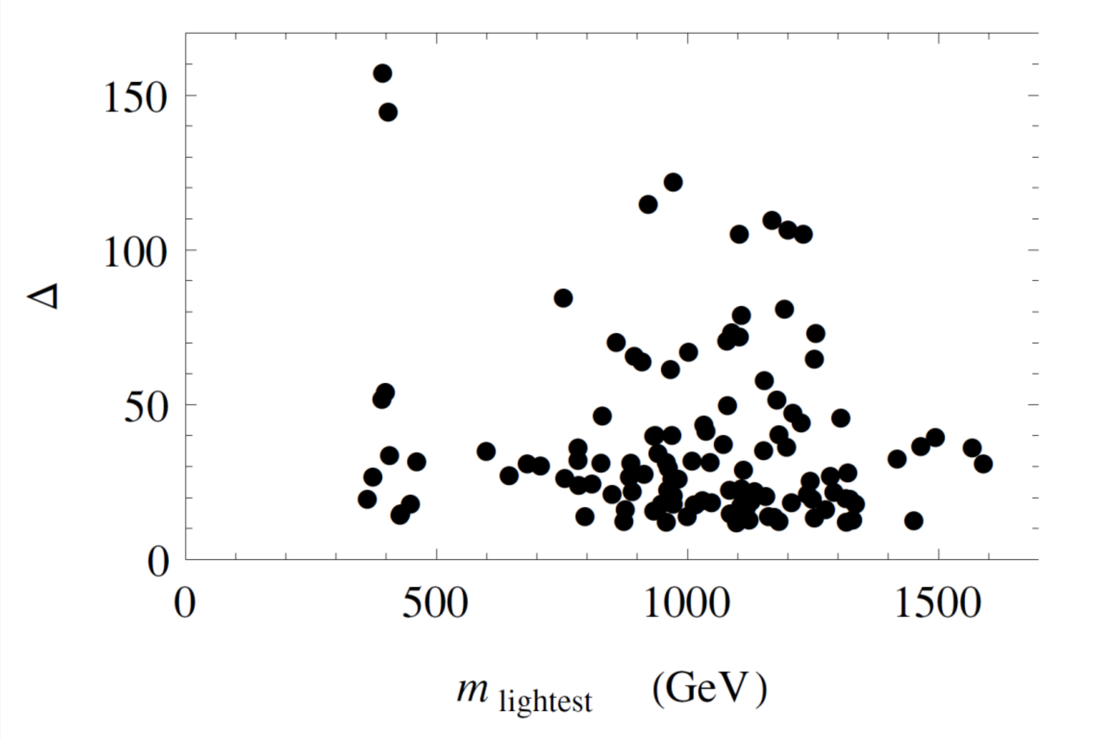

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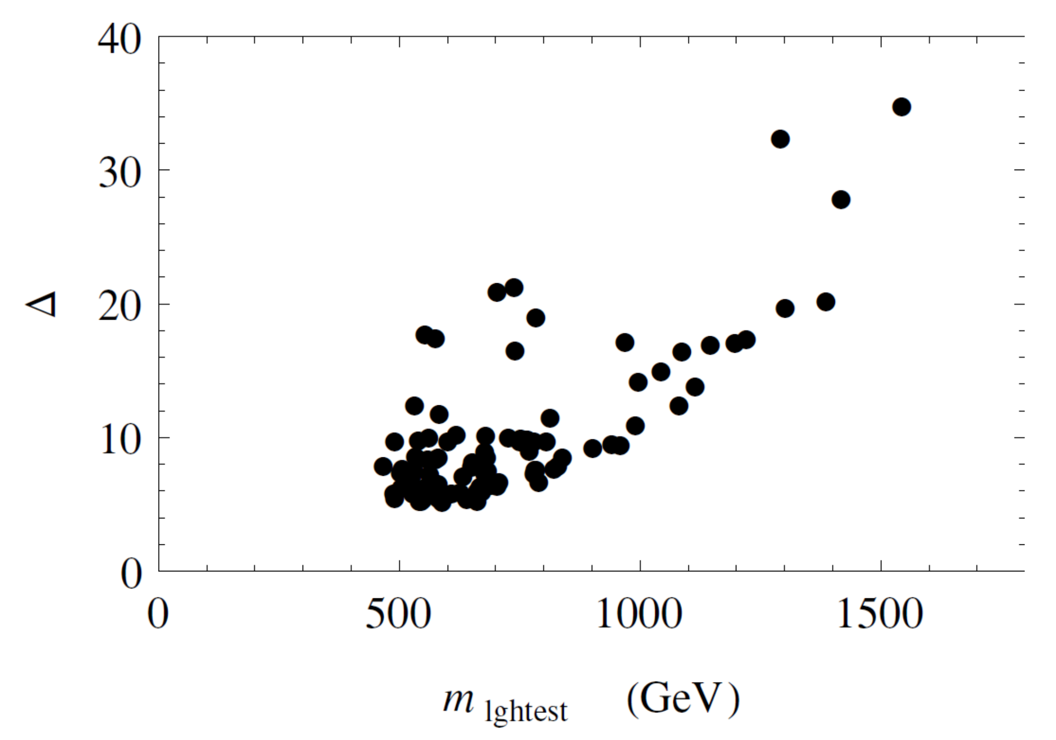

Fermions in the **14** representation

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THE DRAWBACK WITH BARBIERI-GIUDICE

What about $$\Delta_{BG} = \max_{i,a} \left| \frac{x_i}{\mathcal{O}} \frac{\partial \mathcal{O}}{\partial x_i} \right|_{\mathcal{O}=\mathcal{O}_{\exp}}$$?

THE DRAWBACK WITH BARBIERI-GIUDICE

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Then what about $$\Delta^{\mathcal{O}}_{BG,i} = \Delta^{\mathcal{O}}_{BG}(x_i) = \left| \frac{x_i}{\mathcal{O}} \frac{\partial \mathcal{O}}{\partial x_i} \right|_{\mathcal{O}=\mathcal{O}_{\text{exp}}}$$?

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What about $$\Delta_{BG} = \max_{i,a} \left| \frac{x_i}{\mathcal{O}} \frac{\partial \mathcal{O}}{\partial x_i} \right|_{\mathcal{O}=\mathcal{O}_{\rm exp}}$$? Doesn't punish endless parameters.

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A HIGHER ORDER FINE TUNING MEASURE

Would like a measure that treats each observable's $\{\mathcal{O}_a\}$ fine tuning $\nabla^{\mathcal{O}_a}$ as a vector:

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And combines them in an intuitive way:

$$\Delta_2^{ab} = \left| \begin{matrix} \nabla^{\mathcal{O}_a} . \nabla^{\mathcal{O}_a} & \nabla^{\mathcal{O}_a} . \nabla^{\mathcal{O}_b} \\ \nabla^{\mathcal{O}_a} . \nabla^{\mathcal{O}_b} & \nabla^{\mathcal{O}_b} . \nabla^{\mathcal{O}_b} \end{matrix} \right|^{\frac{1}{2}}_{\mathcal{O}=\mathcal{O}_{\mathrm{exp}}}$$

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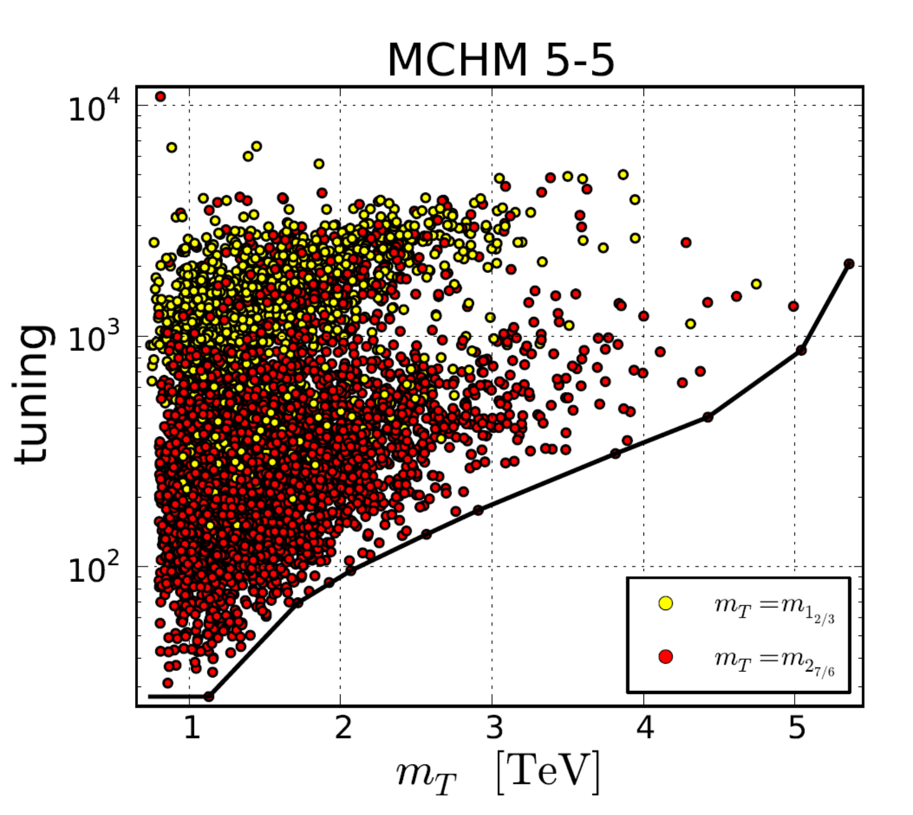
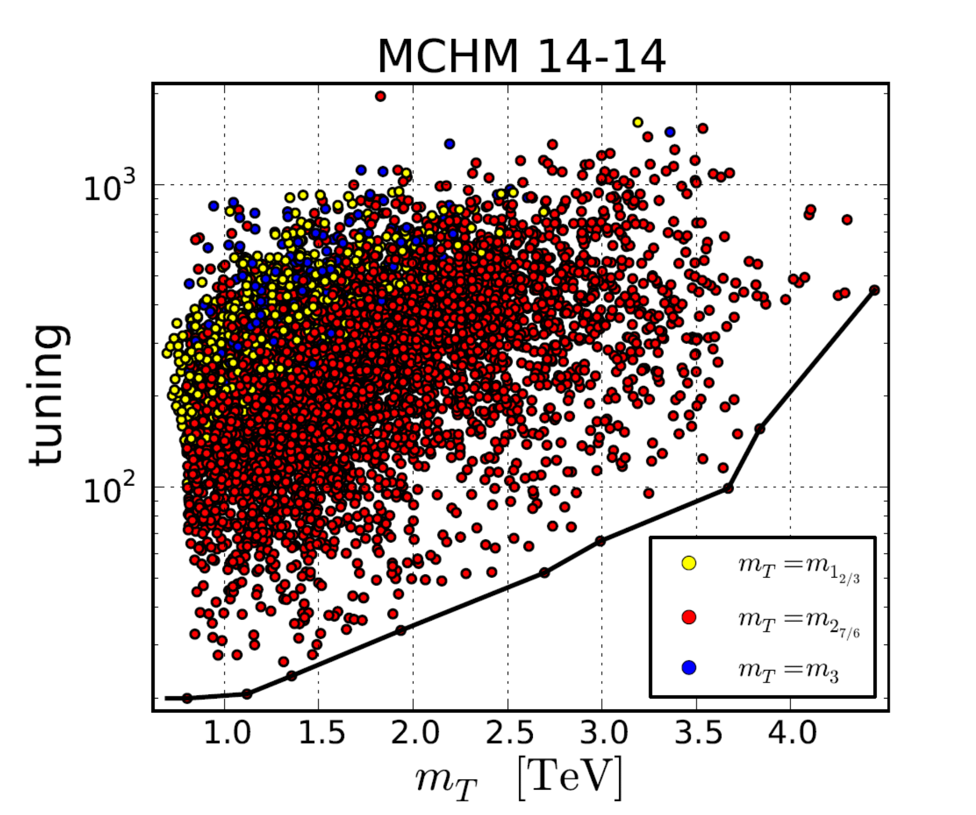
HIGHER ORDER TUNING IN **MCHM**

Not such a difference in fermion representations anymore:

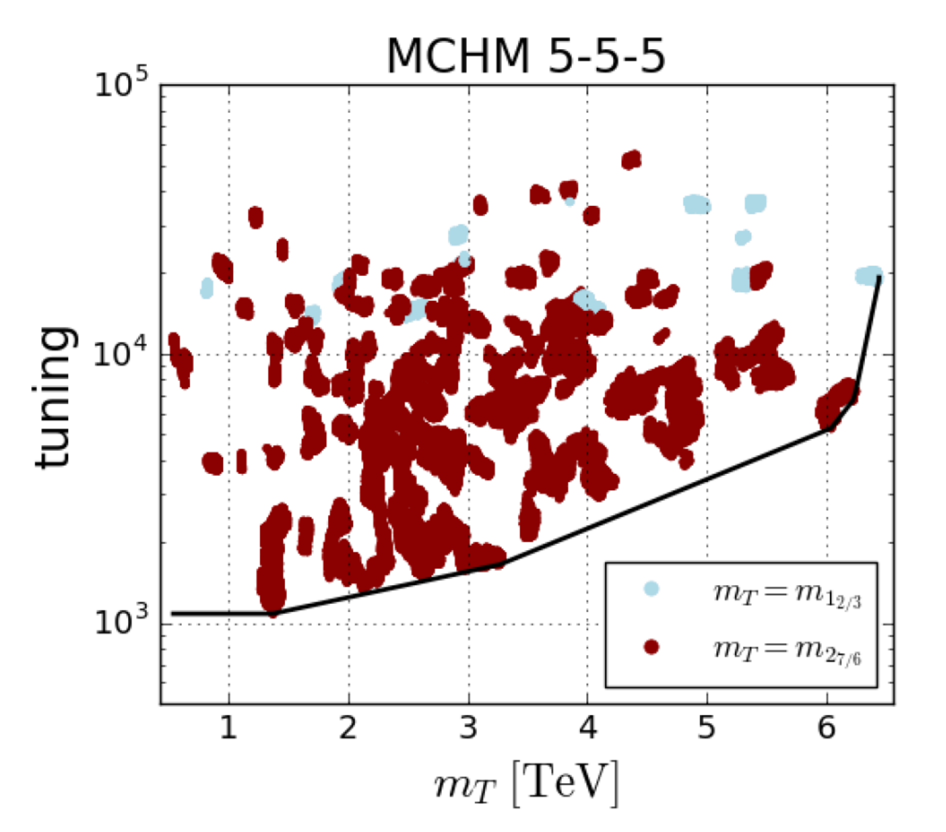


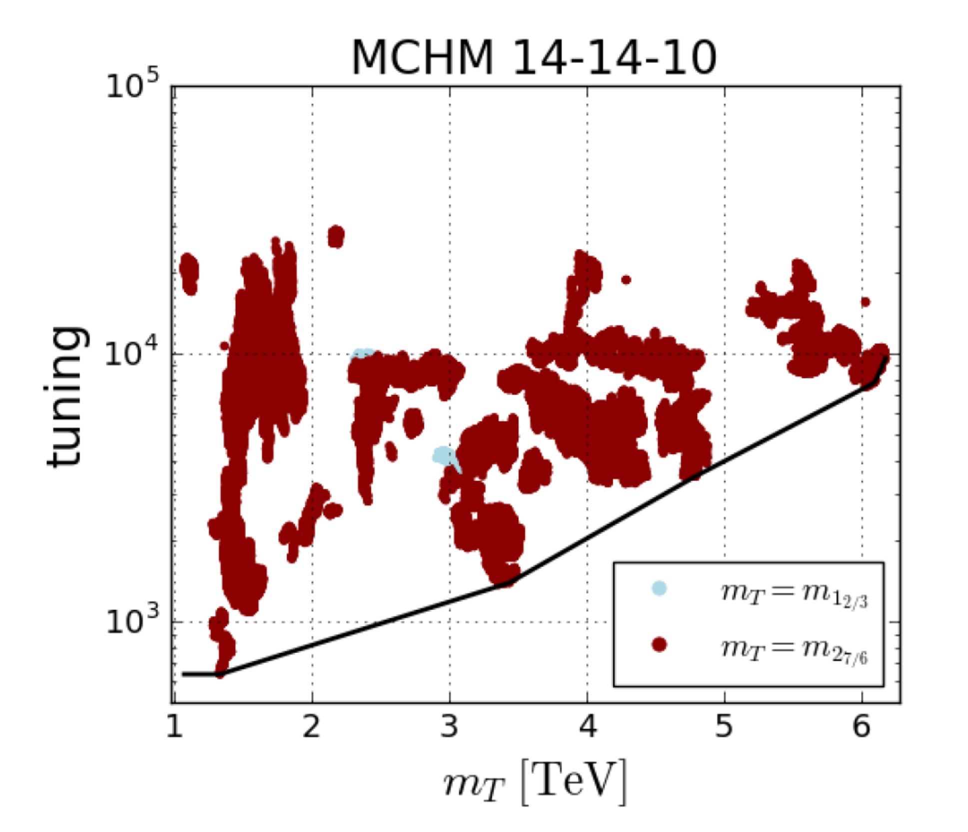


J. Barnard, M. White, *Collider constraints on tuning in composite higgs models* (2015)

HIGHER ORDER TUNING IN **MCHM-WITH-LEPTONS**

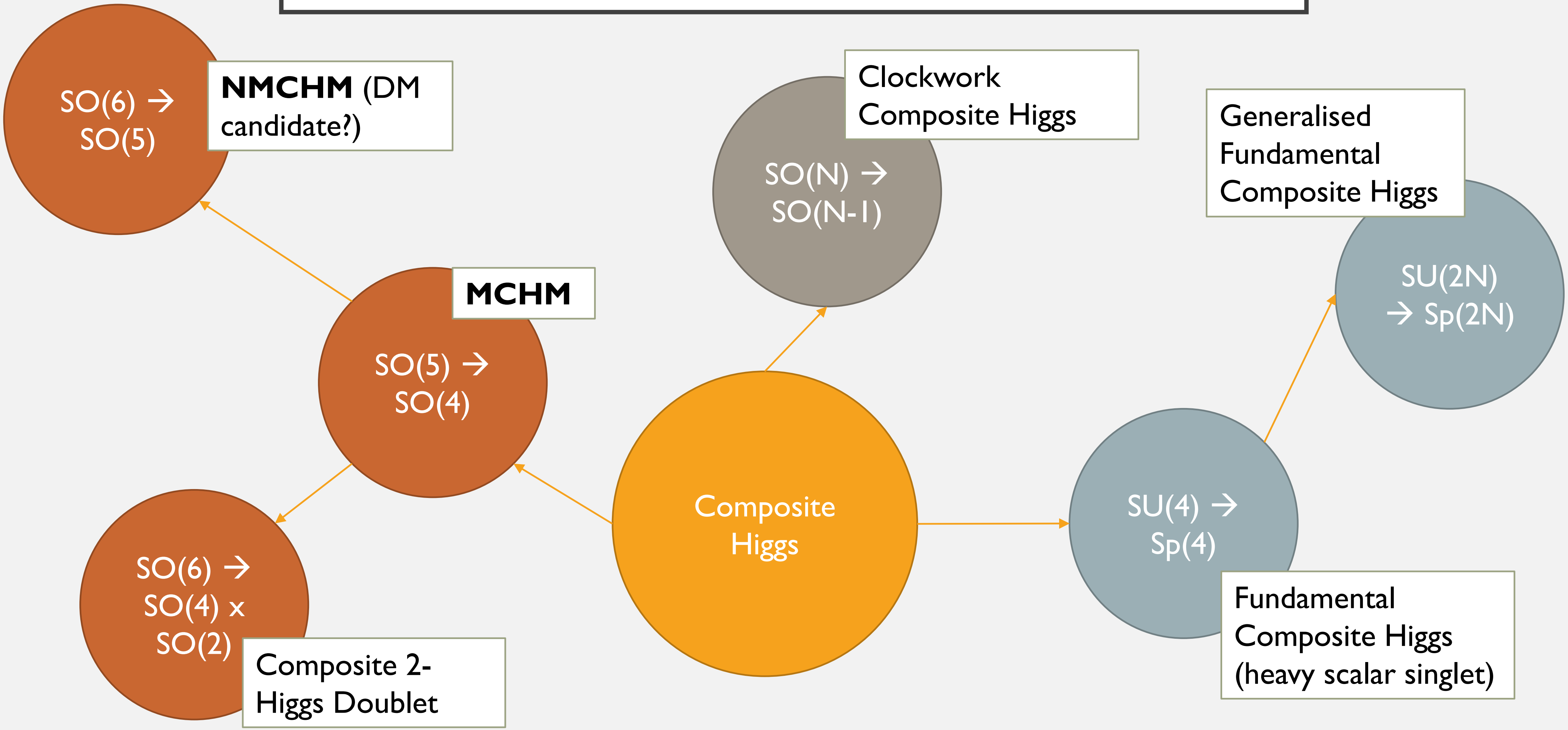
Even schemes where different representations should really reduce fine tuning, like including composite leptons:





J. Barnard, D. Murnane, M. White, AG. Williams, *Constraining fine tuning in composite higgs models with partially composite leptons* (2017)

THE ZOO OF COMPOSITE HIGGSES



A **N**EXT-TO-**M**INIMAL **CHM**

Recall the process:

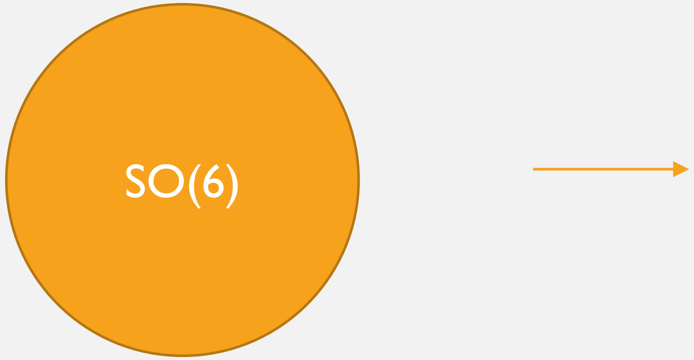
A **N**EXT-TO-**M**INIMAL **CHM**

Recall the process:

Start with large symmetry group

A NEXT-TO-MINIMAL CHM

Recall the process:

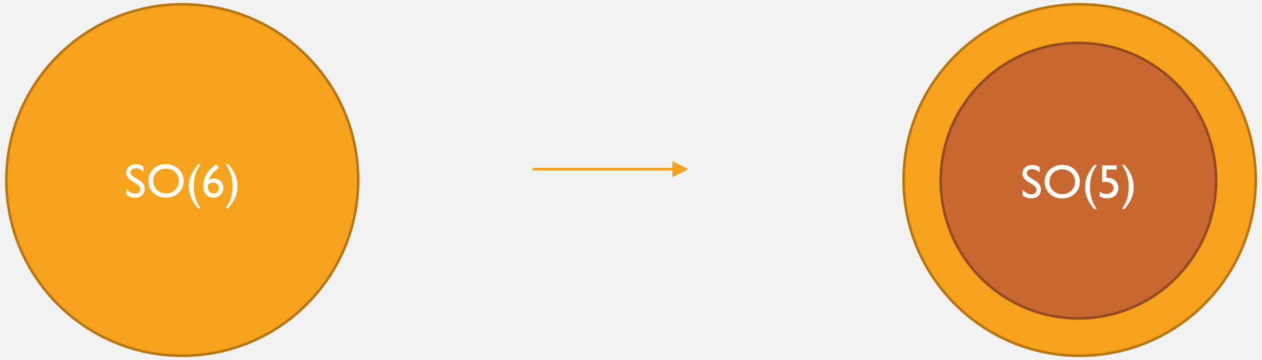


Start with large symmetry group

Break to smaller symmetry group

A NEXT-TO-MINIMAL CHM

Recall the process:



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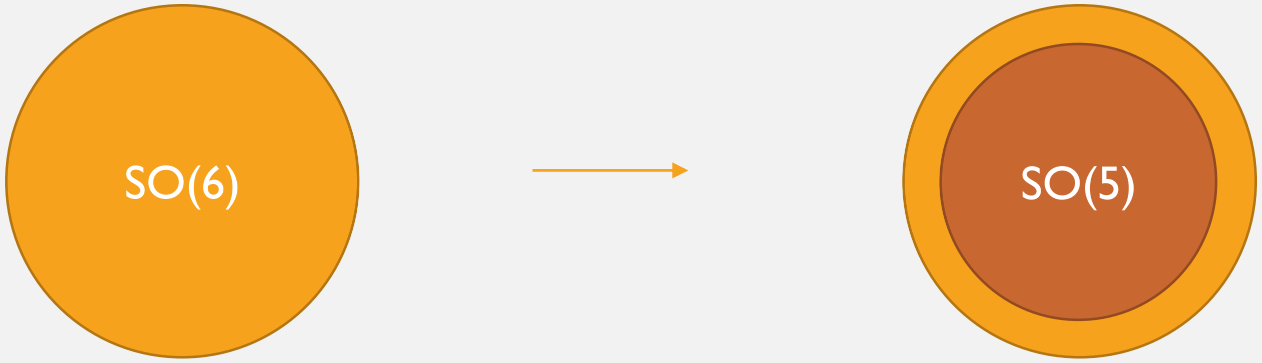


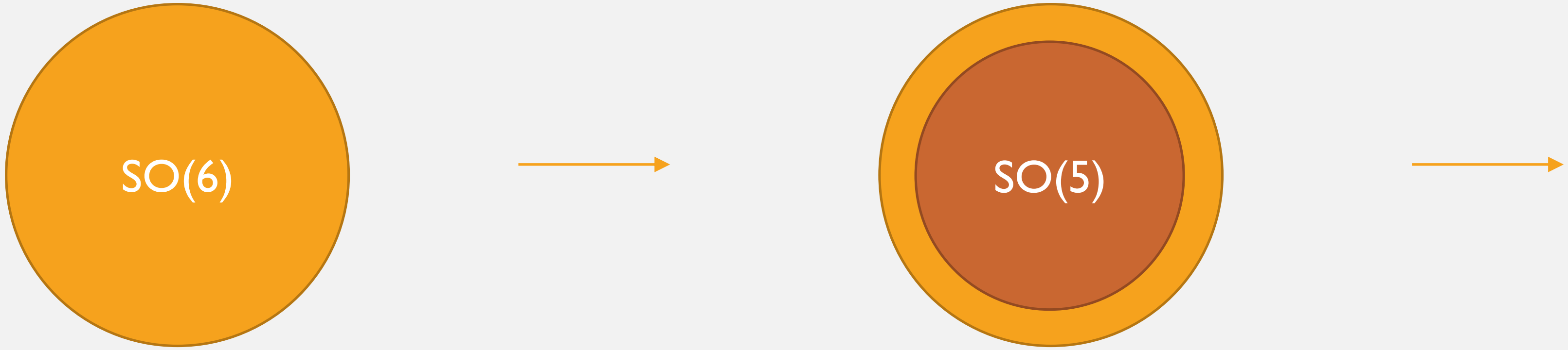
Start with large symmetry group

Break to smaller symmetry group

Find a pNGB doublet in the coset

A NEXT-TO-MINIMAL CHM

Recall the process:



Start with large symmetry group

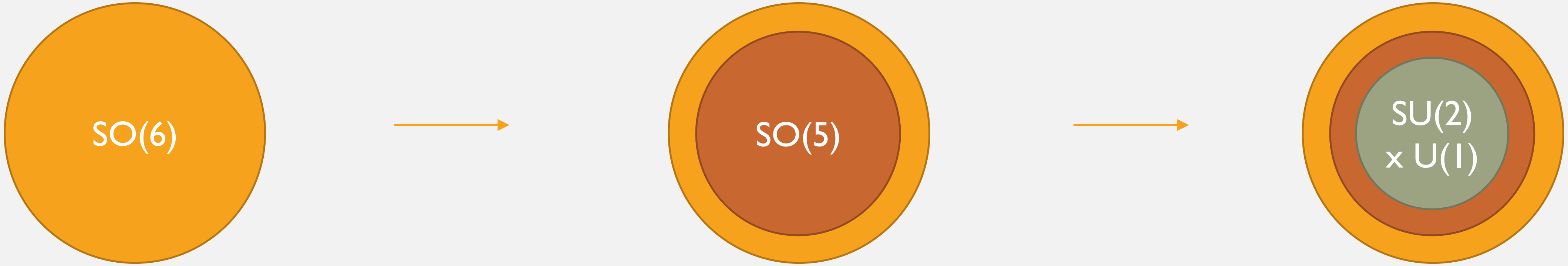
Break to smaller symmetry group

Find a pNGB doublet in the coset

Embed EW gauge group

A NEXT-TO-MINIMAL CHM

Recall the process:



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Break to smaller symmetry group

Find a pNGB doublet in the coset

Embed EW gauge group

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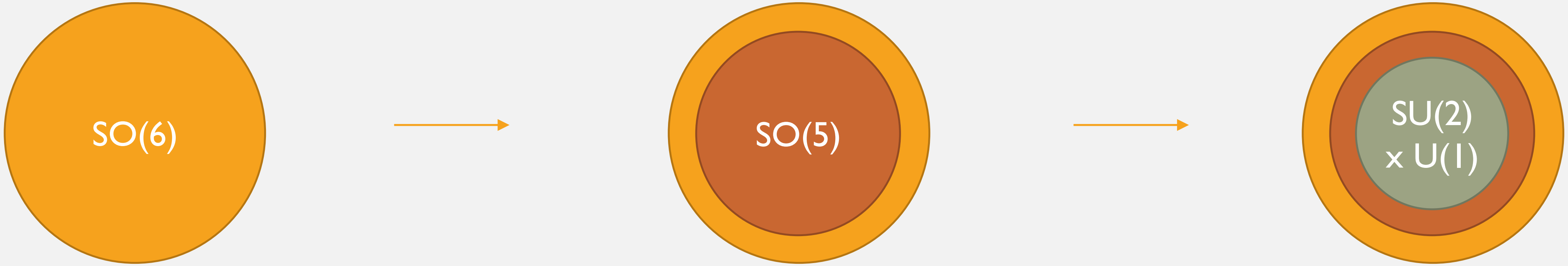


Start with large symmetry group

Break to smaller symmetry group

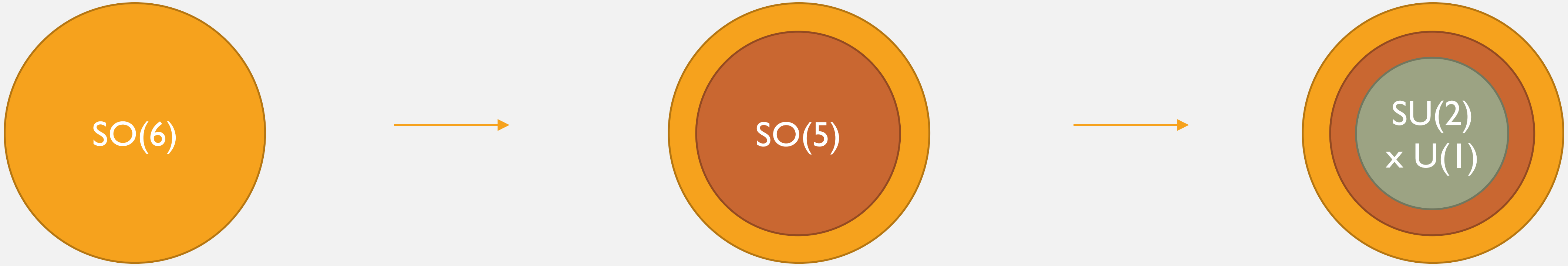
Find a pNGB doublet in the coset

Embed EW gauge group

Embed SM fermions

A NEXT-TO-MINIMAL CHM

Recall the process:



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Break to smaller symmetry group

Find a pNGB doublet in the coset

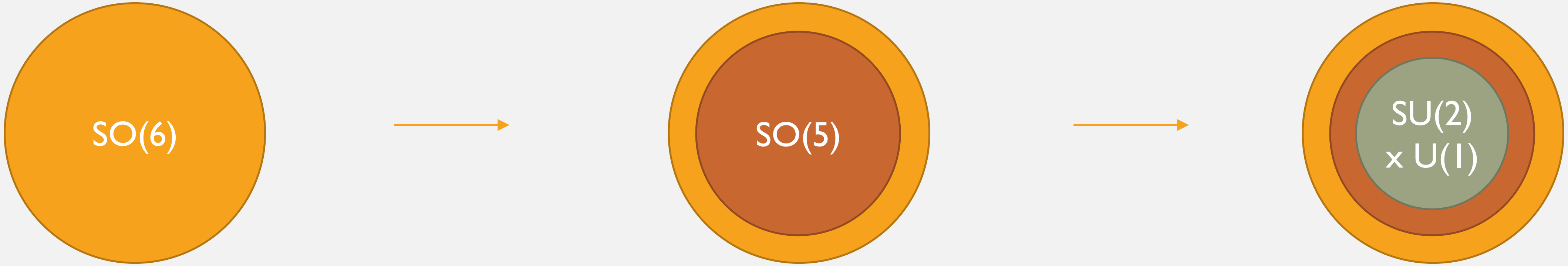
Embed EW gauge group

Embed SM fermions

Differences from **MCHM**:

A **N**EXT-TO-**M**INIMAL **CHM**

Recall the process:



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Embed EW gauge group

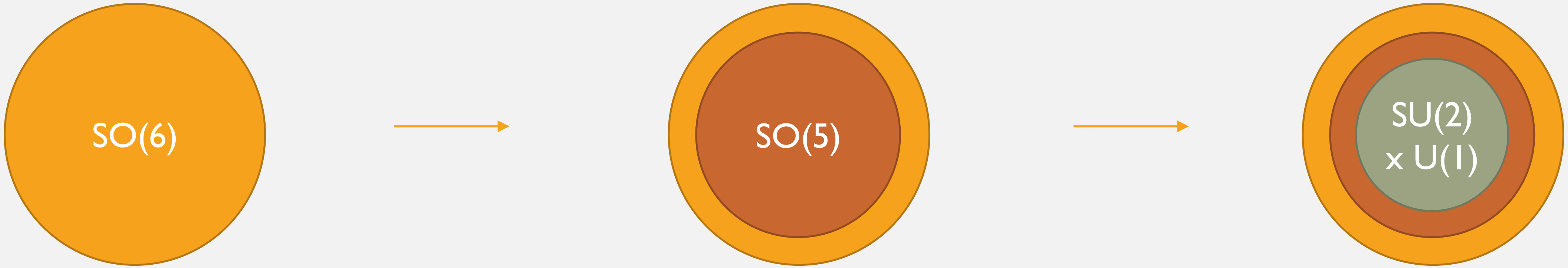
Embed SM fermions

Differences from **MCHM**:

Dim[SO(6)/SO(5)]
= Dim[SO(6)] – Dim[SO(5)]
= 15 – 10
= 5

A NEXT-TO-MINIMAL CHM

Recall the process:



Start with large symmetry group

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Find a pNGB doublet in the coset

Embed EW gauge group

Embed SM fermions

Differences from **MCHM**:

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= Dim[SO(6)] – Dim[SO(5)]
= 15 – 10
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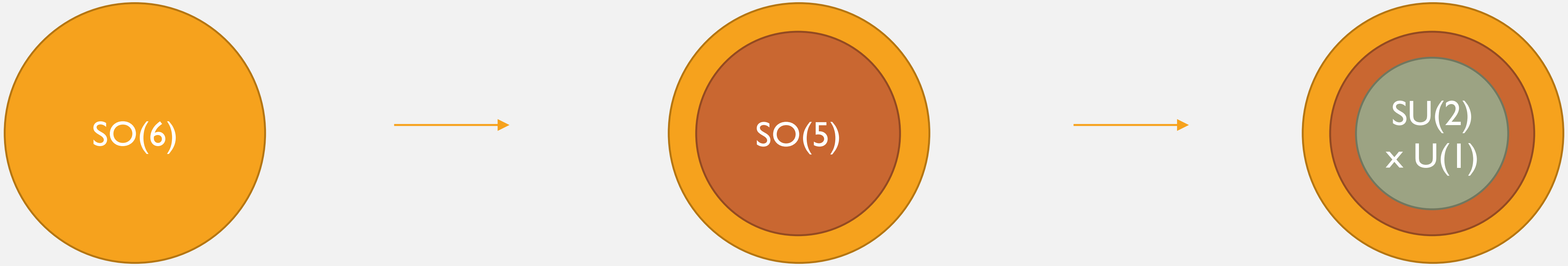
$$\Phi = \sin\frac{\varphi}{f}\left(\frac{h_1}{\varphi}, \frac{h_2}{\varphi}, \frac{h_3}{\varphi}, \frac{h_4}{\varphi}, \frac{s}{\varphi}, \cot\frac{\varphi}{f}\right)$$

A NEXT-TO-MINIMAL CHM

Recall the process:



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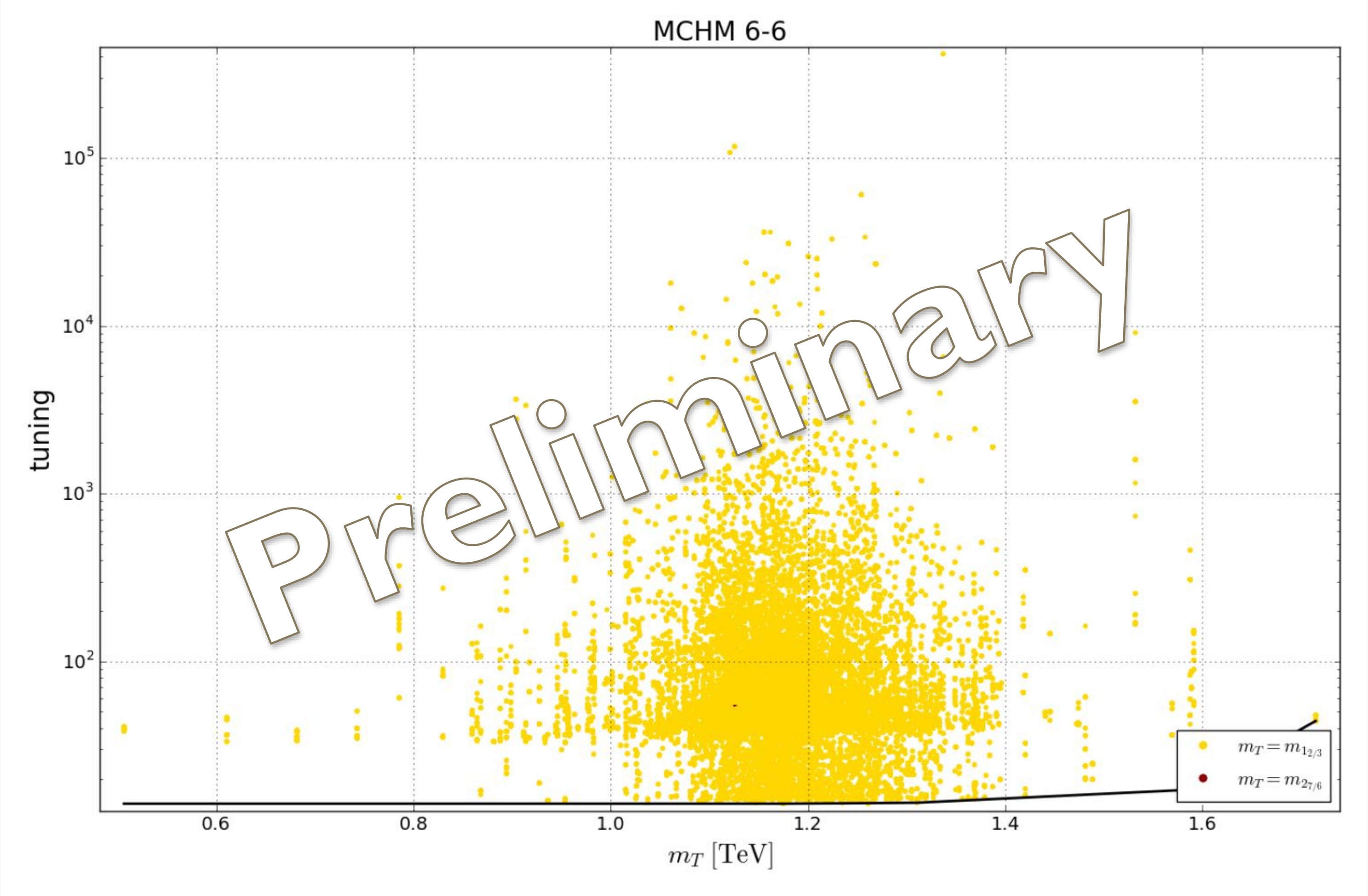
$$q_L \to \frac{1}{\sqrt{2}}\begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \\ 0 \end{pmatrix}, \quad t_R \to \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ e^{i\delta}\cos\theta t_R \\ \sin\theta t_R \end{pmatrix}$$

A NEXT-TO-MINIMAL CHM



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

SCANNING THE COMPOSITE HIGGS

MULTINEST

- Randomly distributes parameter points
- Selects number of least likely points
- Draws ellipses around remaining points
- Distributes next set of points within these ellipses
- BENEFIT: Can be used to find Bayesian evidence because of convenient relation with integral
- *arXiv:0809.3437*

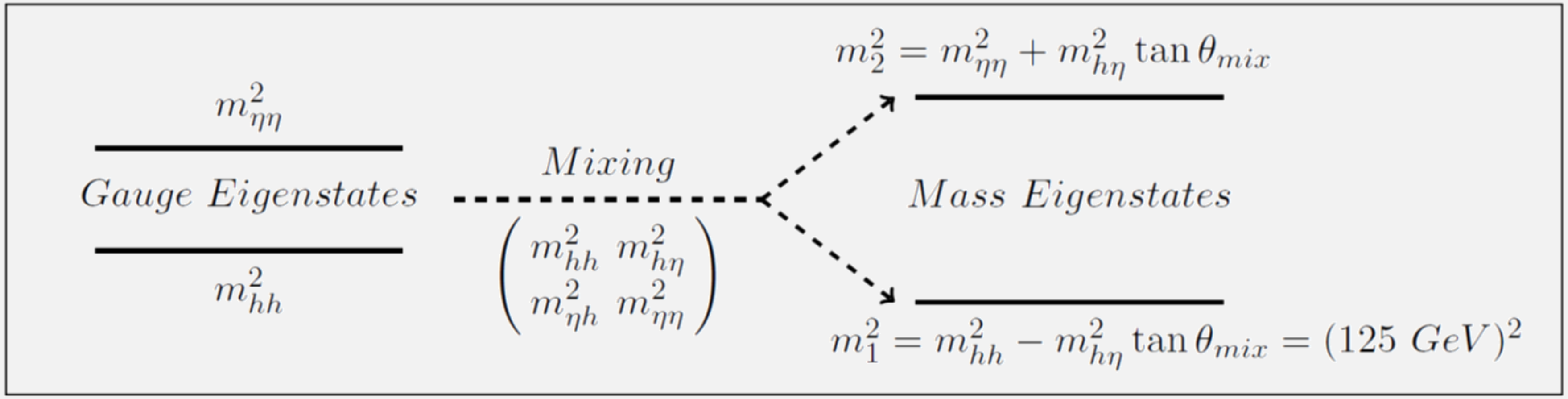
DIFFERENTIAL EVOLUTION

- Randomly distributes parameter points
- Randomly chooses two to breed ($v_a + v_b$), and two to cross fertilise (F.[$v_c - v_d$])
- Mutate the offspring by randomly selecting parameter entries (genes) from parents
- Select the child if it is more likely
- *arXiv:1705.07959*

NMCHM SCALAR MASS SPLITTING

ps controls mass splitting: mS ~ ps

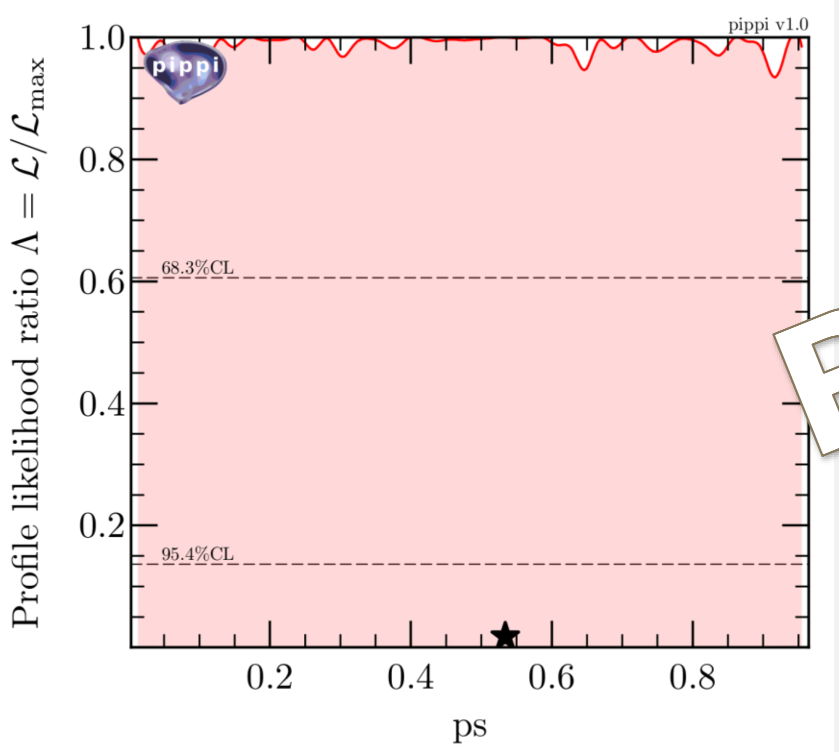
(Here, ps → theta)



T.S. Ray, et al., *Improving Fine-tuning in Composite Higgs Models,* arXiv:1703.08011

NMCHM SCALAR MASS SPLITTING

ps controls mass splitting: mS ~ ps

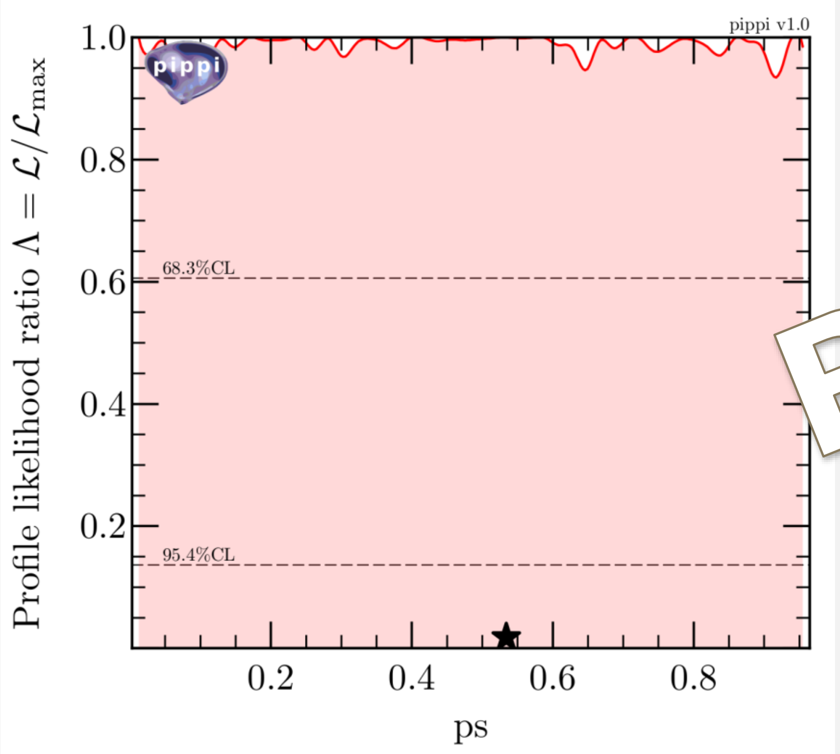


Preliminary

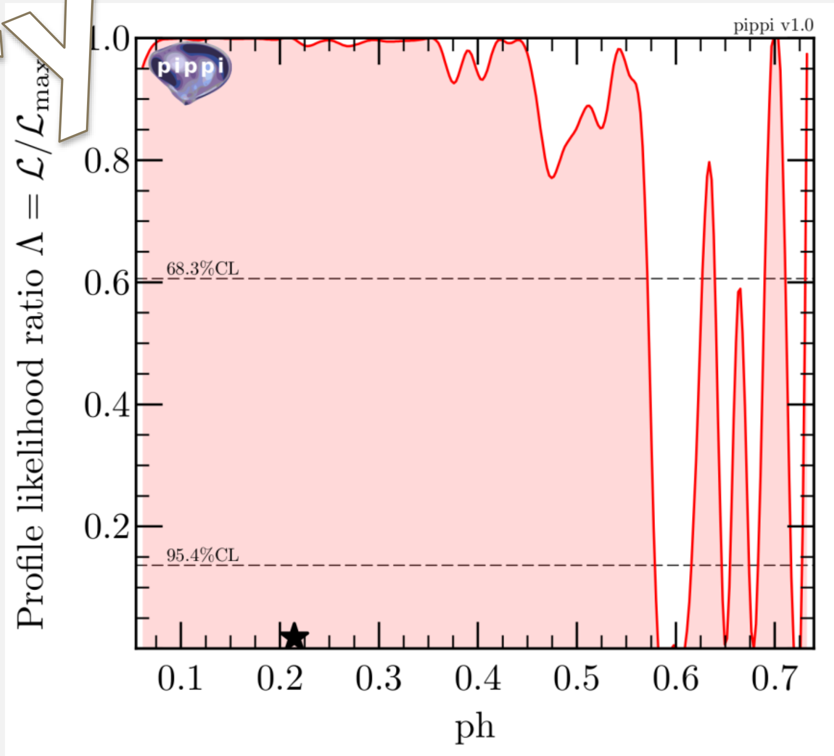
NMCHM SCALAR MASS SPLITTING

ps controls mass splitting: mS ~ ps

ph controls composite scale: f ~ ph



Preliminary

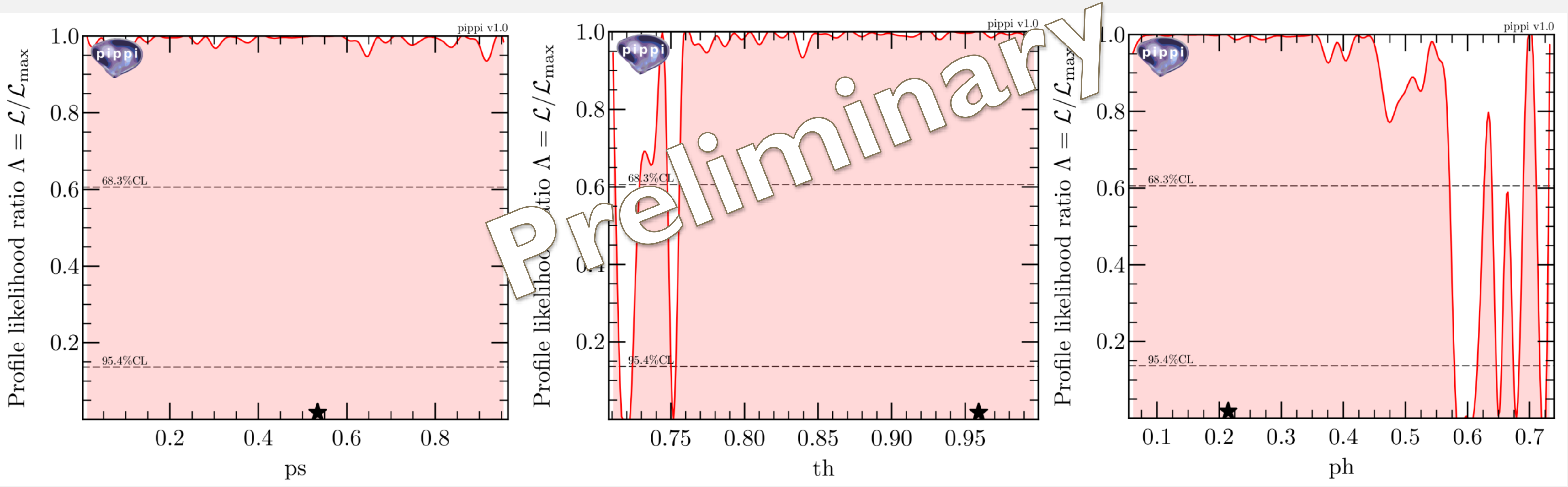


NMCHM SCALAR MASS SPLITTING

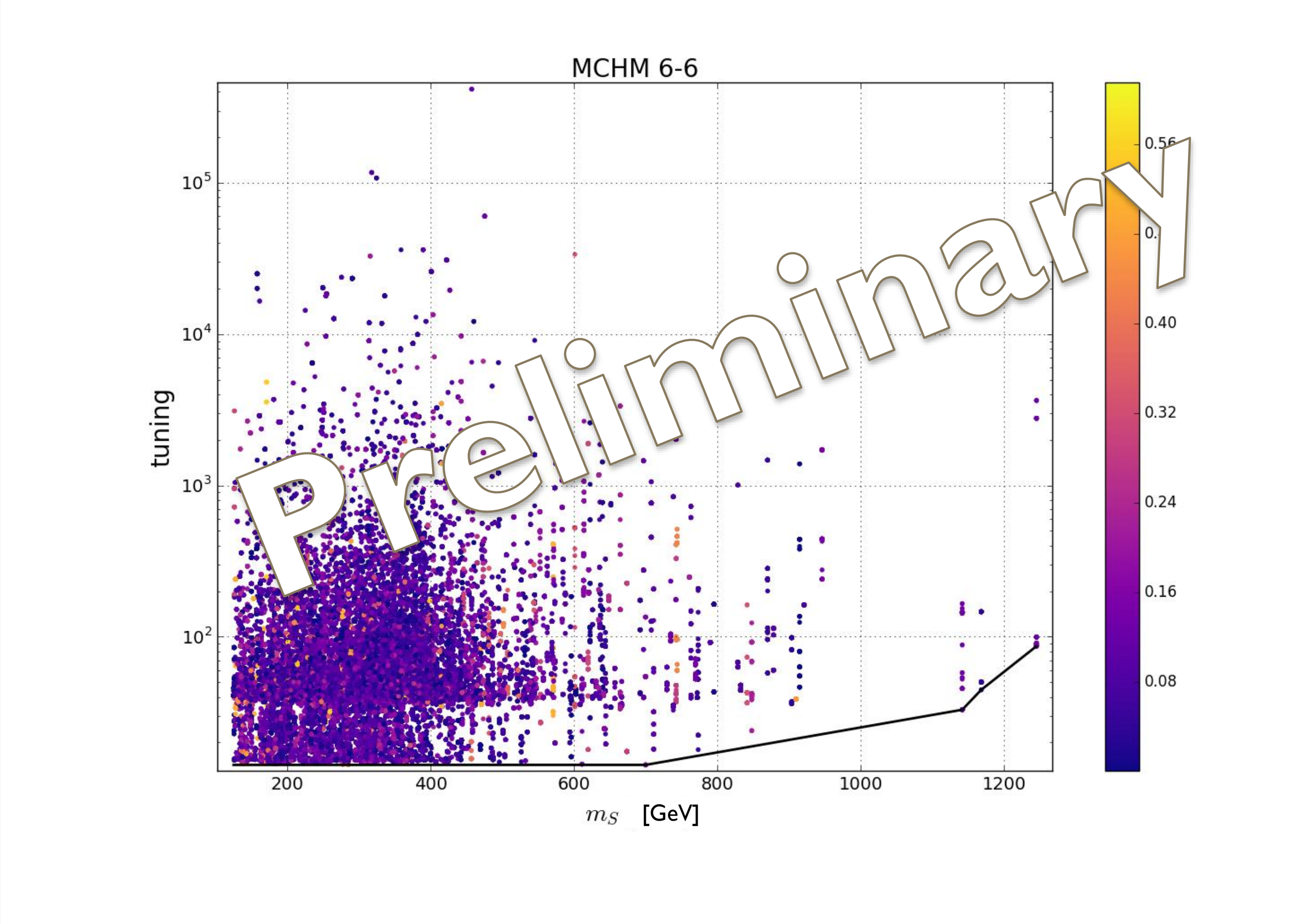
ps controls mass splitting: mS ~ ps

ph controls composite scale: f ~ ph

th controls interaction of top with scalar singlet: for th ~ 1, Z_2 symmetry



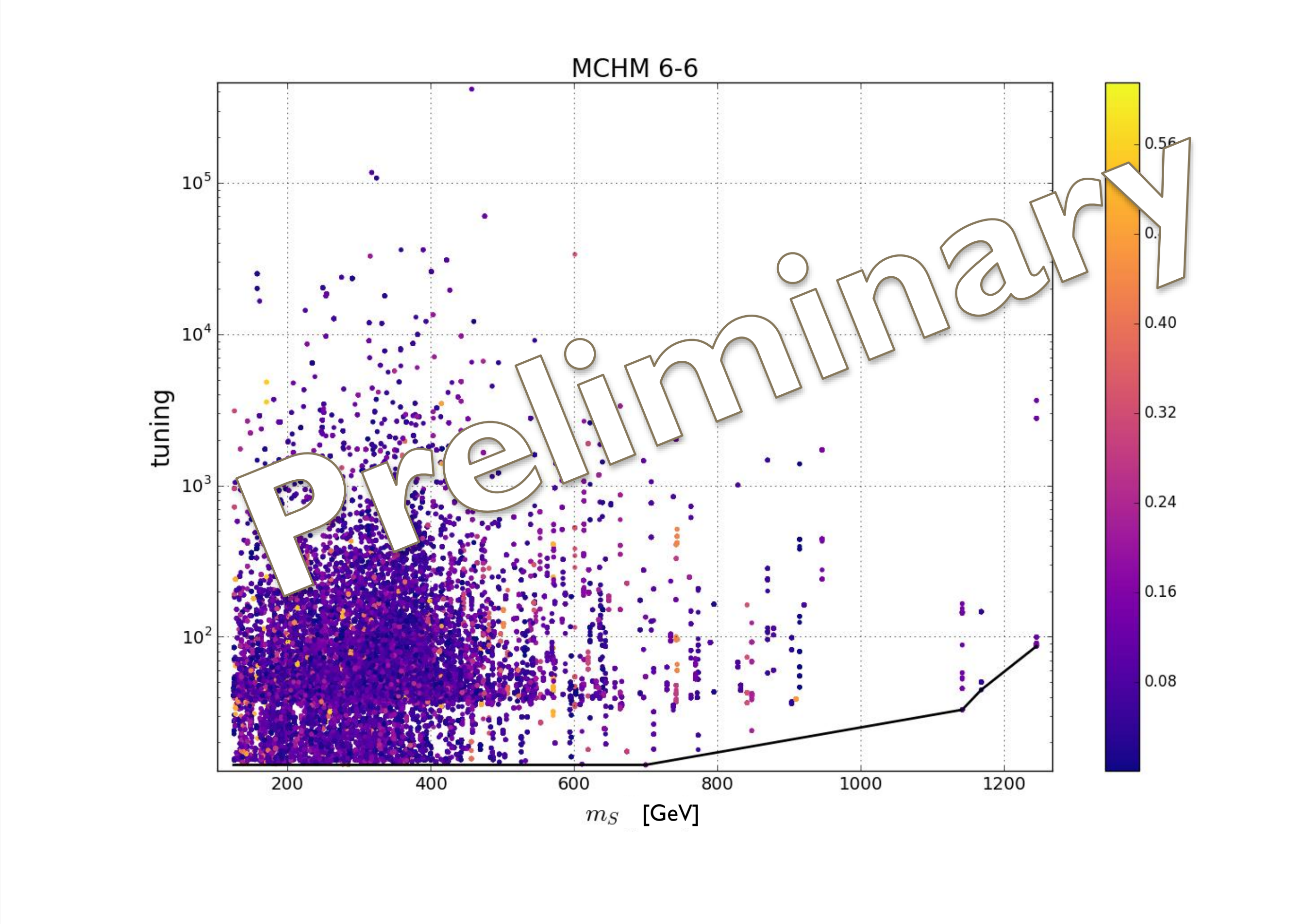
SCALAR SINGLET IN **NMCHM**



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

SCALAR SINGLET IN **NMCHM**

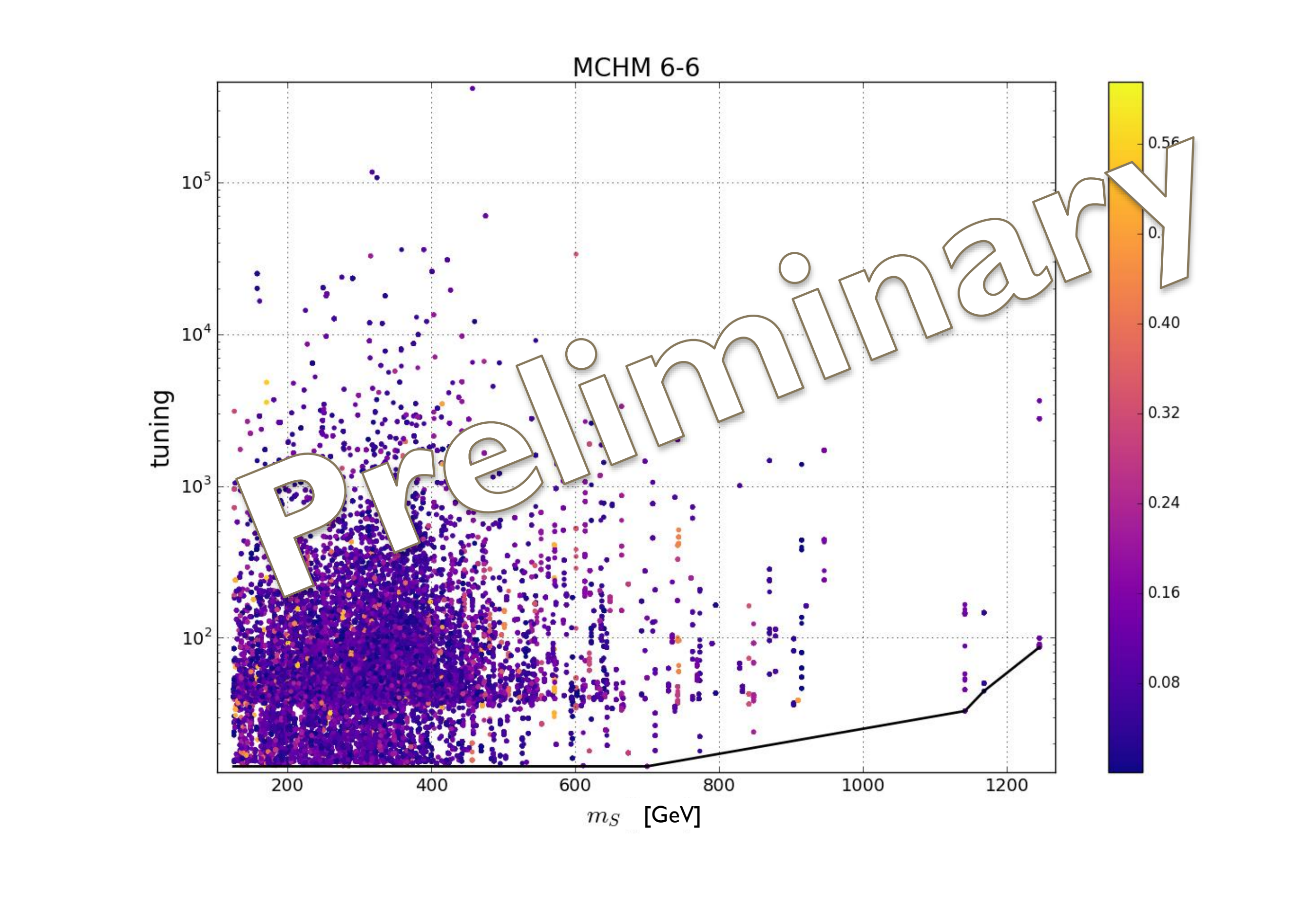
- Singlet that interacts with Higgs and heavy partners



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

SCALAR SINGLET IN **NMCHM**

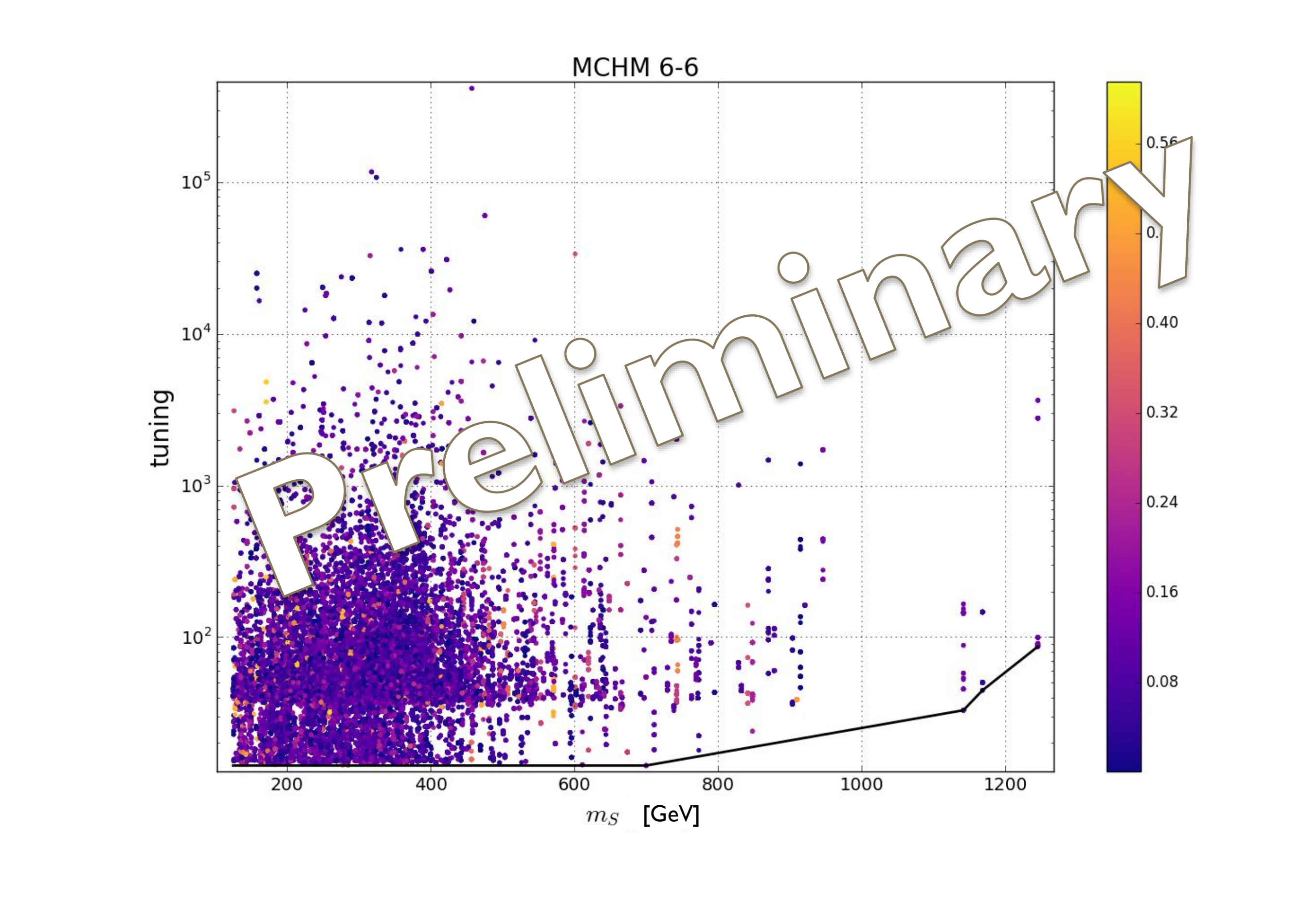
- Singlet that interacts with Higgs and heavy partners
- Higgs portal DM



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

SCALAR SINGLET IN **NMCHM**

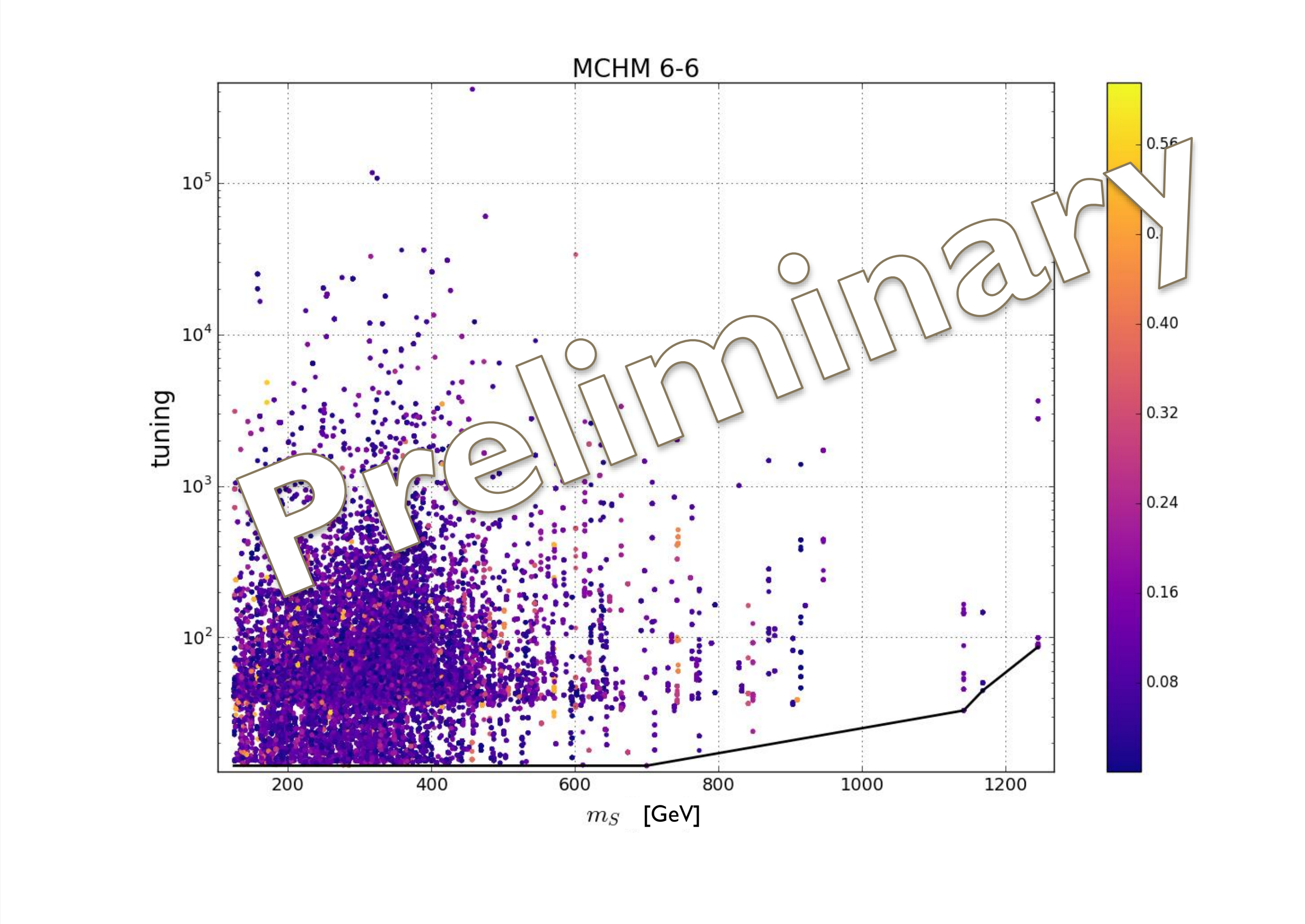
- Singlet that interacts with Higgs and heavy partners
- Higgs portal DM
- Collider detection



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

SCALAR SINGLET IN **NMCHM**

- Singlet that interacts with Higgs and heavy partners
- Higgs portal DM
- Collider detection
- SU(4) also produces this particle, since SO(6) ≈ SU(4), SO(5) ≈ Sp(4)



D. Murnane, M. White, AG. Williams, *under preparation* (2017)

TO DO

- A cosmological study of the scalar singlet
- Application of higher order fine tuning to other Composite Higgs models
- Application of higher order fine tuning to SUSY
- Explore extra top quark phase in NMCHM