ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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A minimally tuned composite Higgs model from an extra dimension

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in collaboration with D. Pappadopulo and R. Torre

based on hep-ph/1303.3062

Outline

- Motivation
- A composite Higgs
- The 5D construction
- Numerical analysis and results
- Conclusions and outlook

Motivation

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- Higgs-like particle discovered
- need new physics at Λ_{NP} to understand EWSB
  expect solution to hierarchy problem
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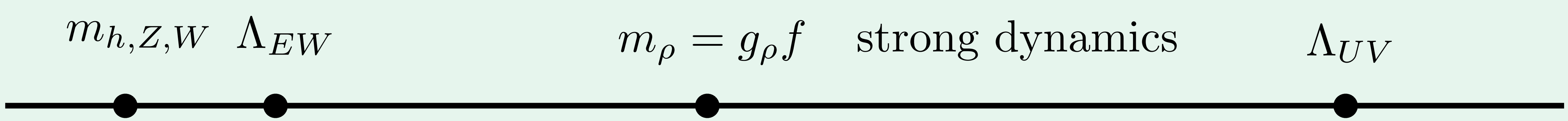


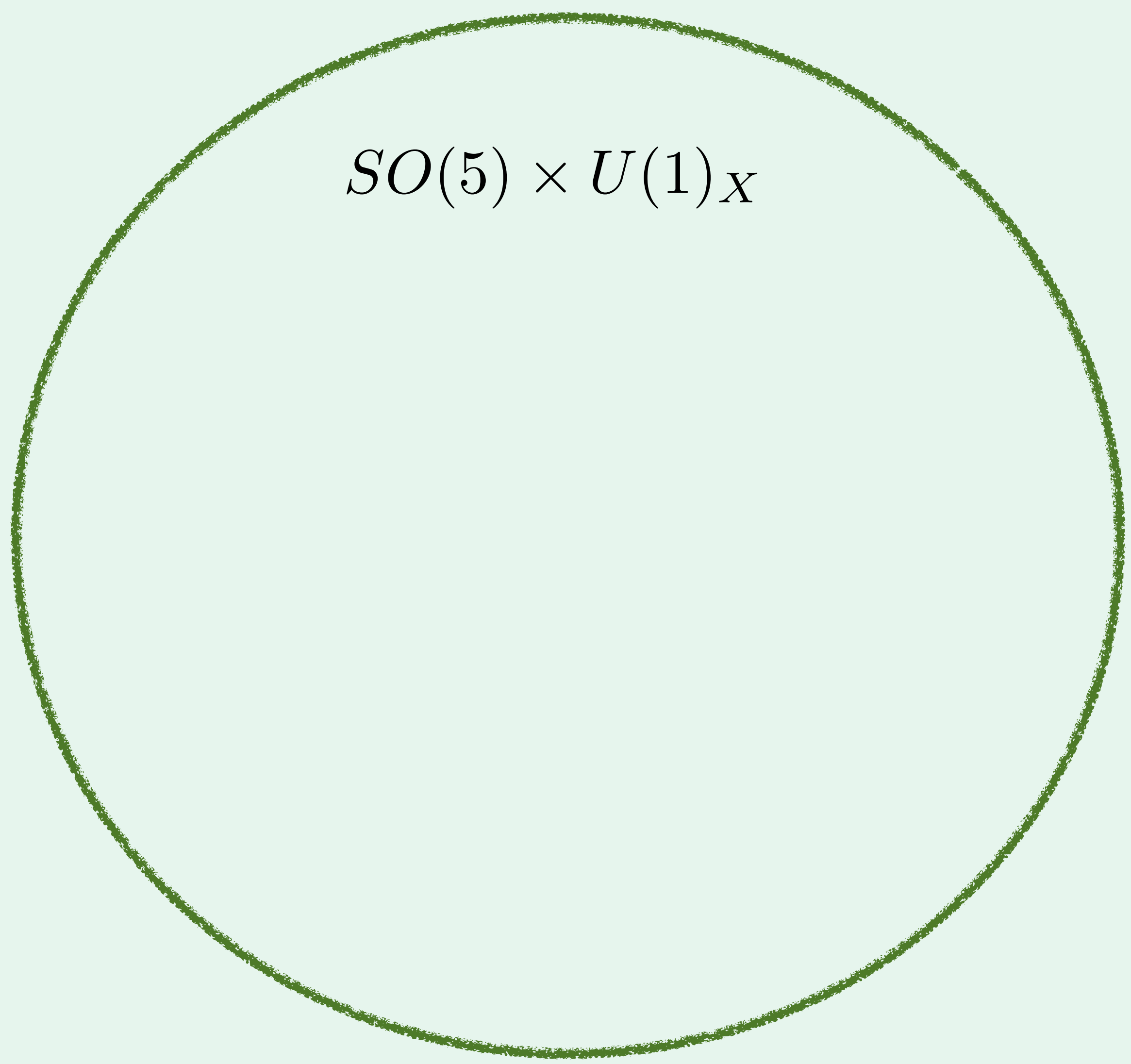
- light Higgs → pseudo - Goldstone boson
  of spontaneously broken global symmetry

A composite Higgs

The Higgs as a pGB

- minimal model SO(5)/SO(4)
  quadruplet of GB: 3 eaten, 1 Higgs
- breaking scale $f > v$

[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: 0706.0432]



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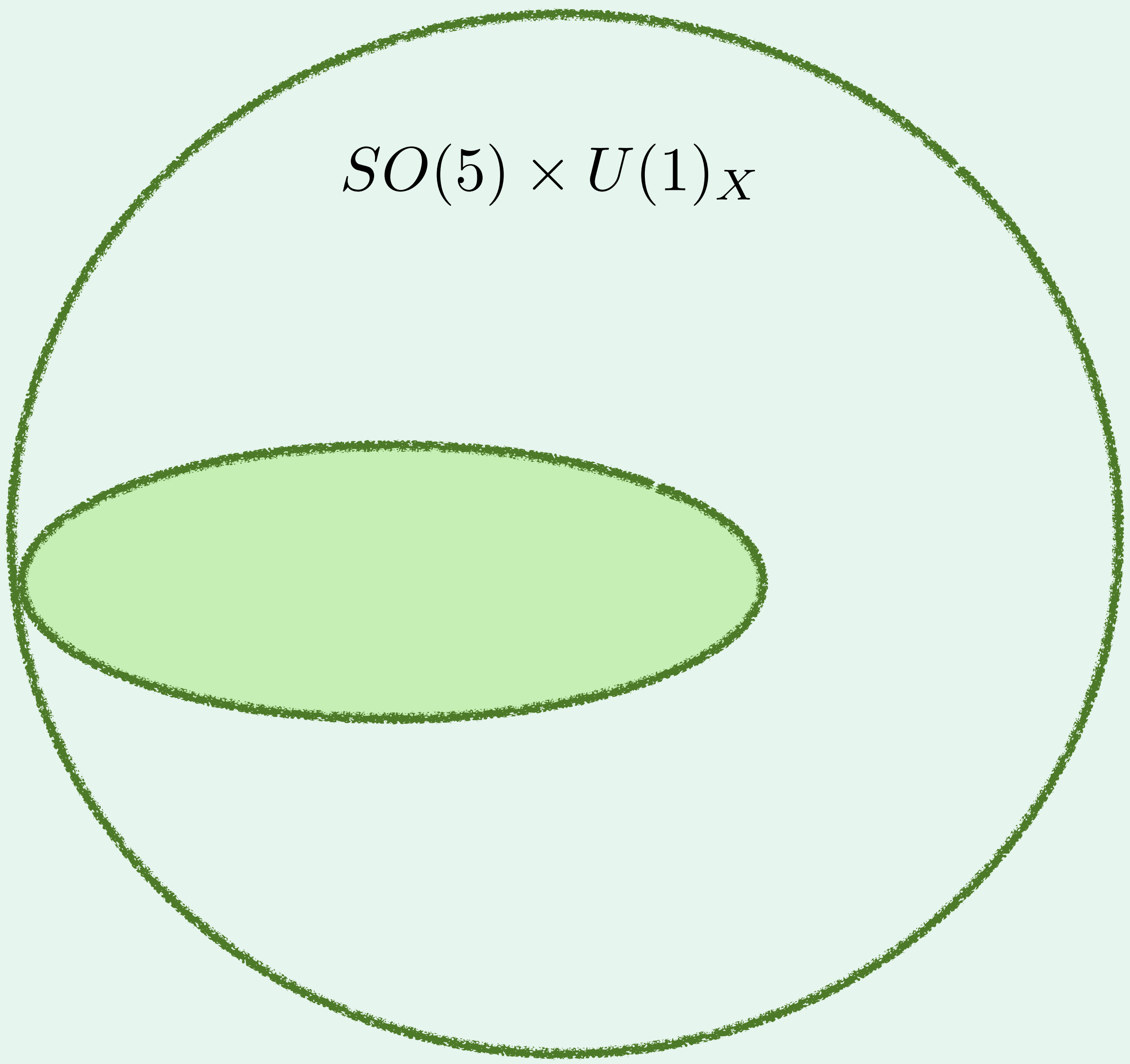

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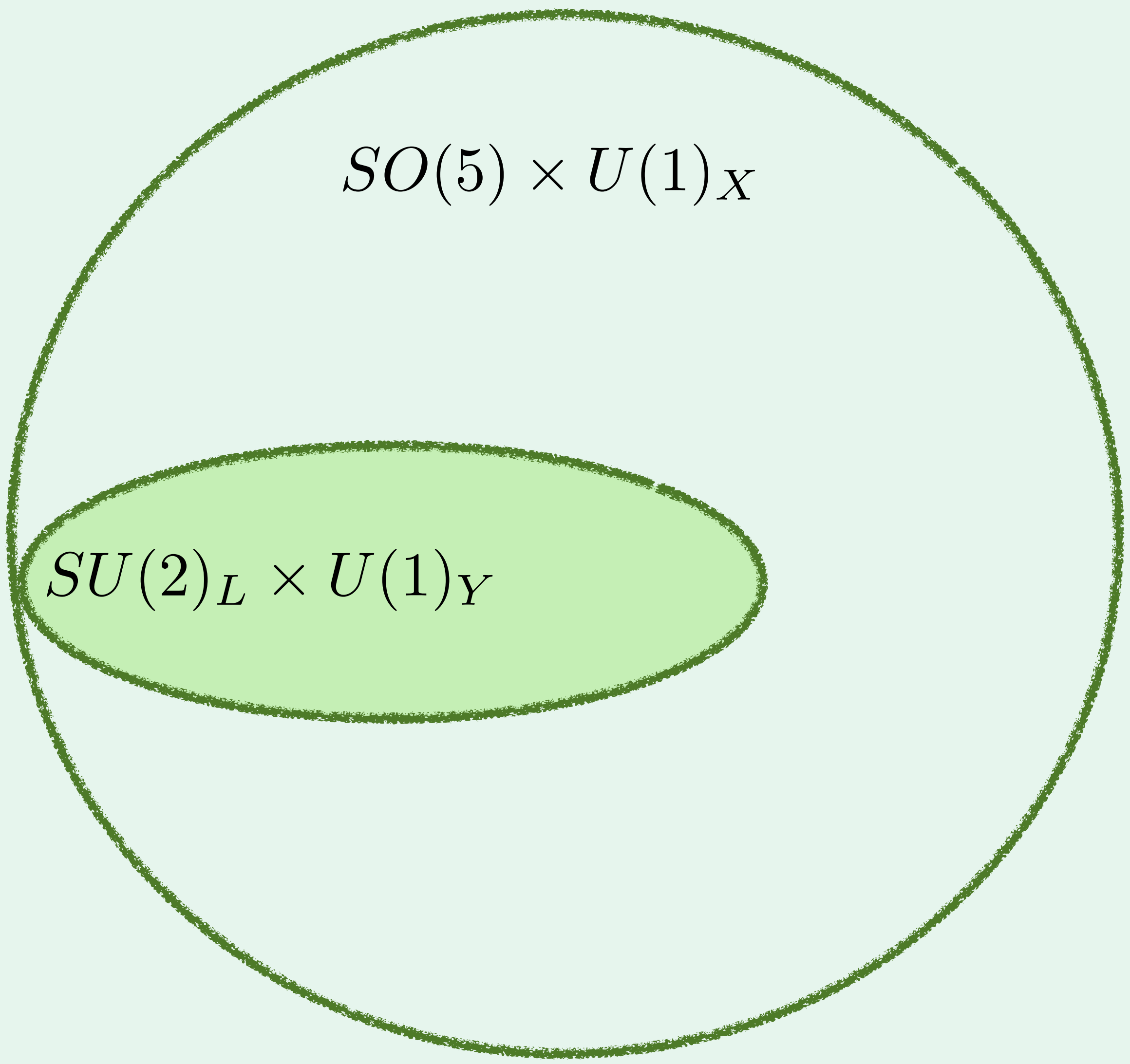

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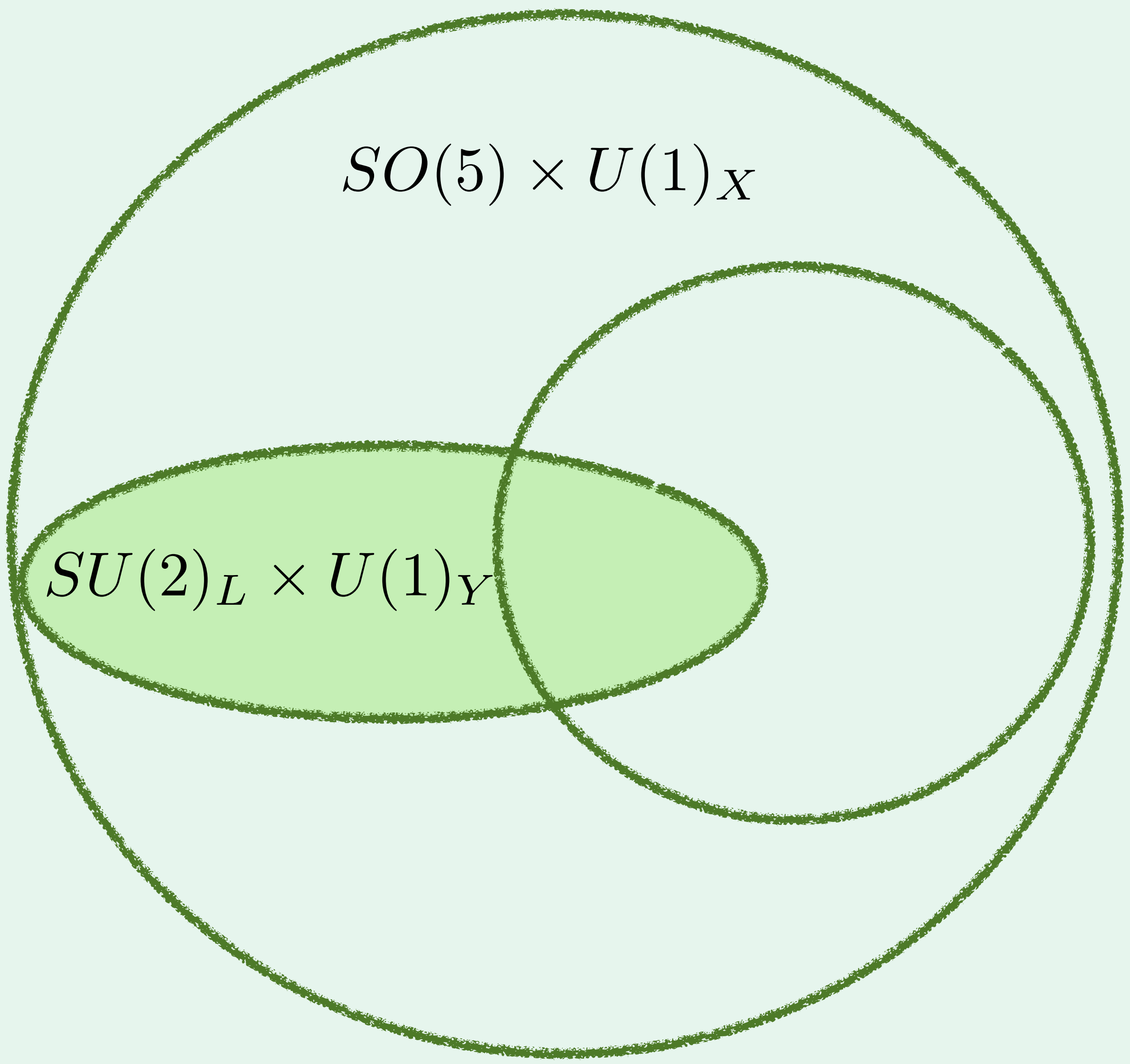

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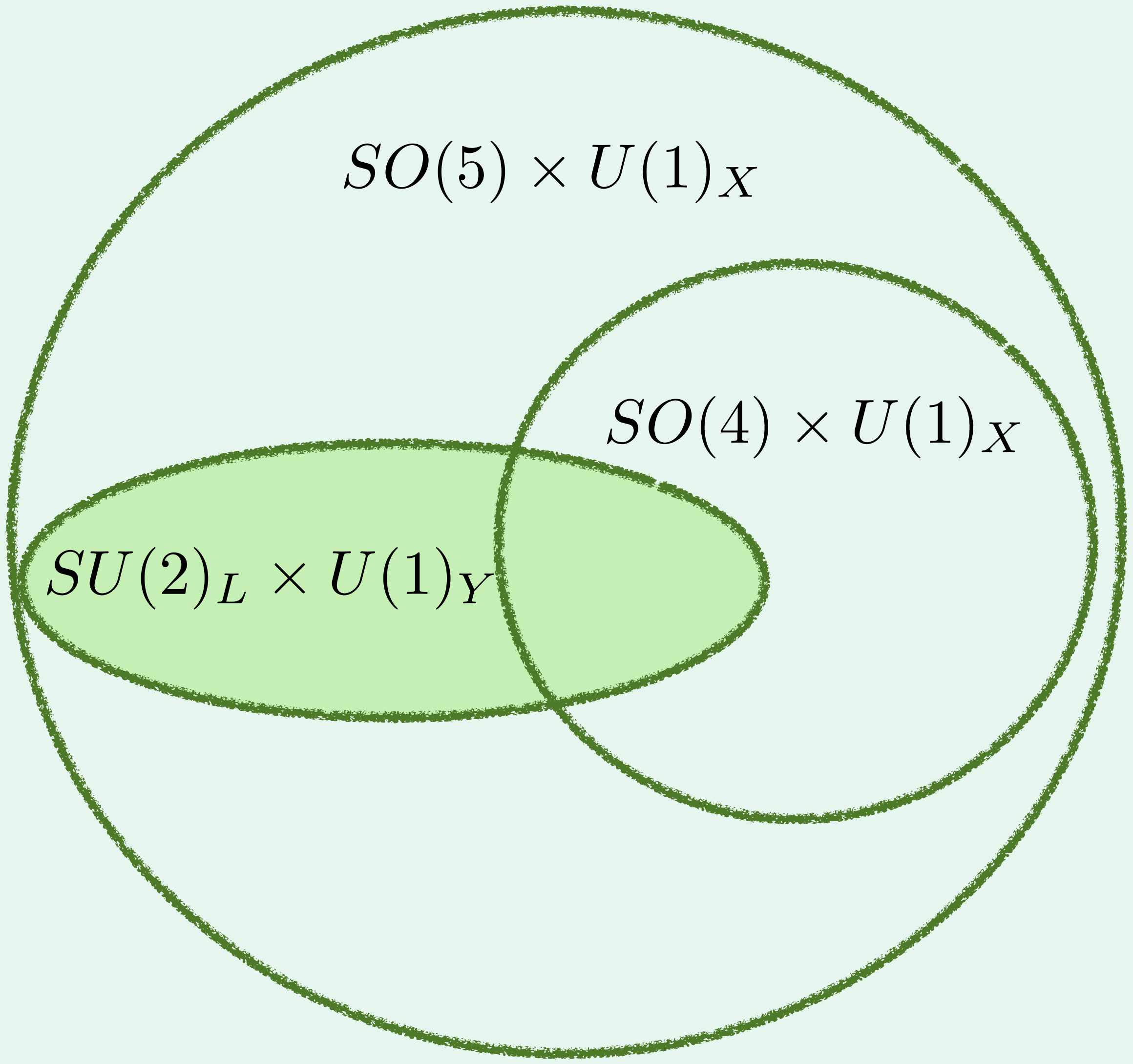

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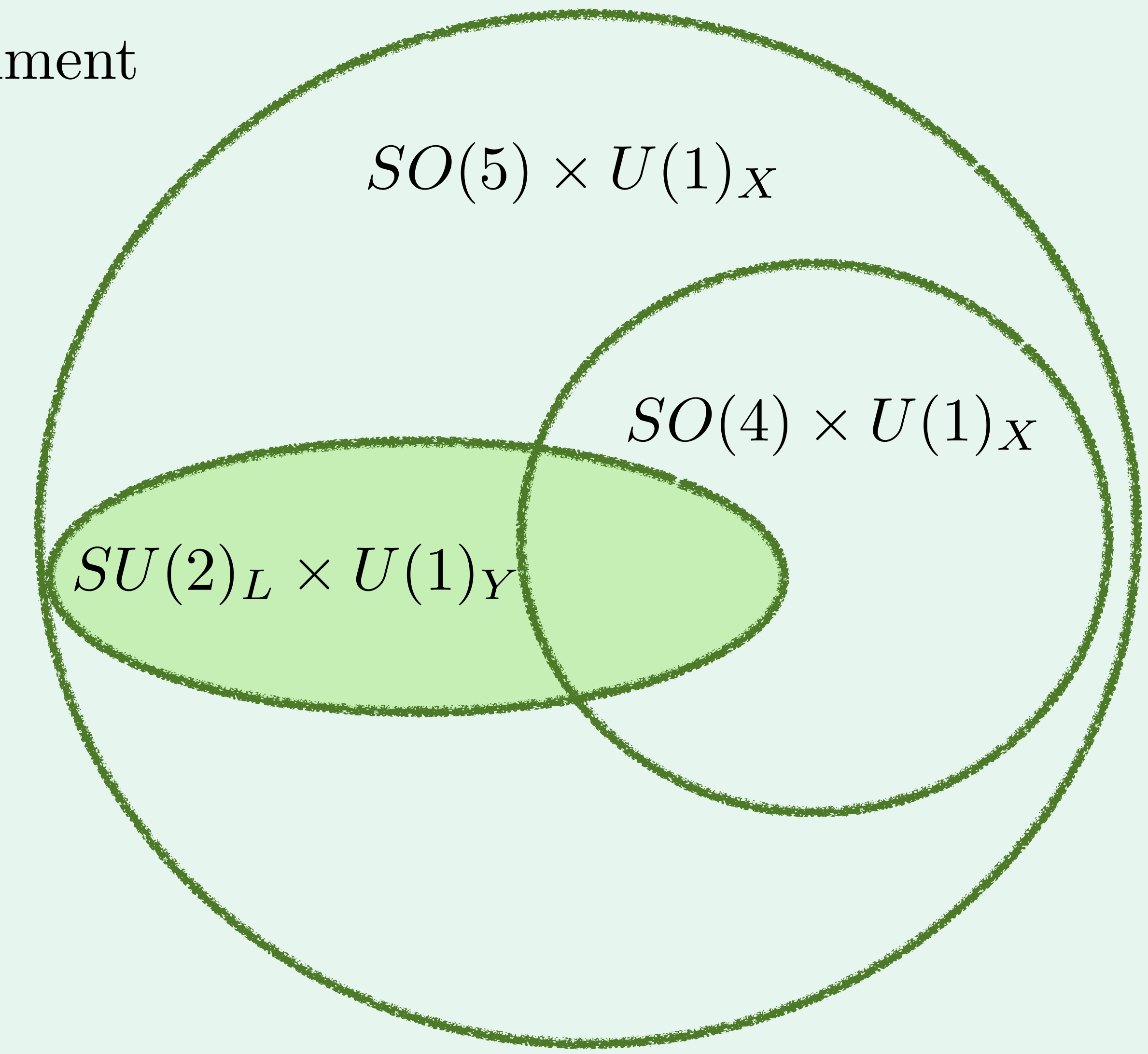
vacuum misalignment



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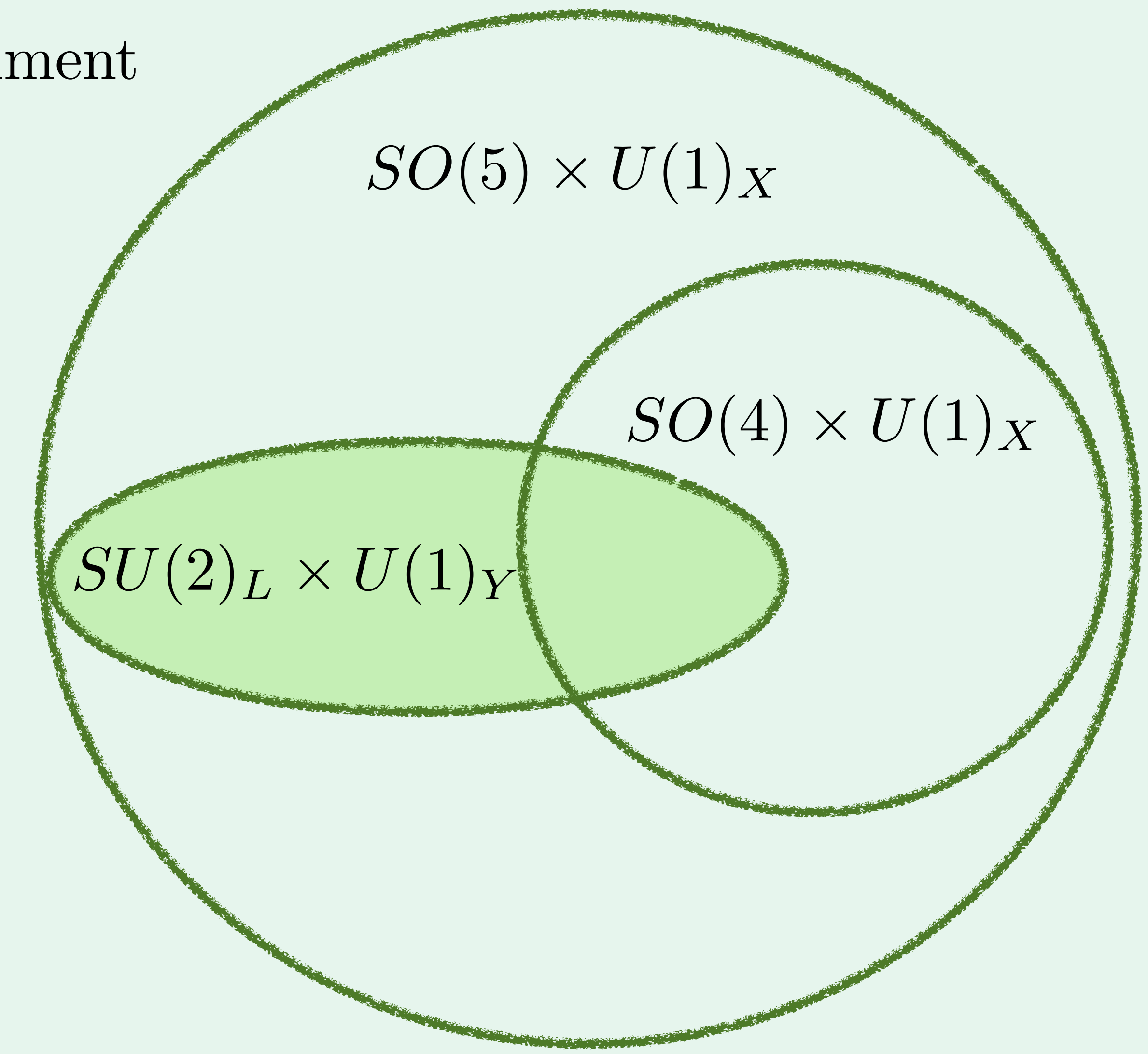
$$\sin\theta = \frac{v}{f}$$



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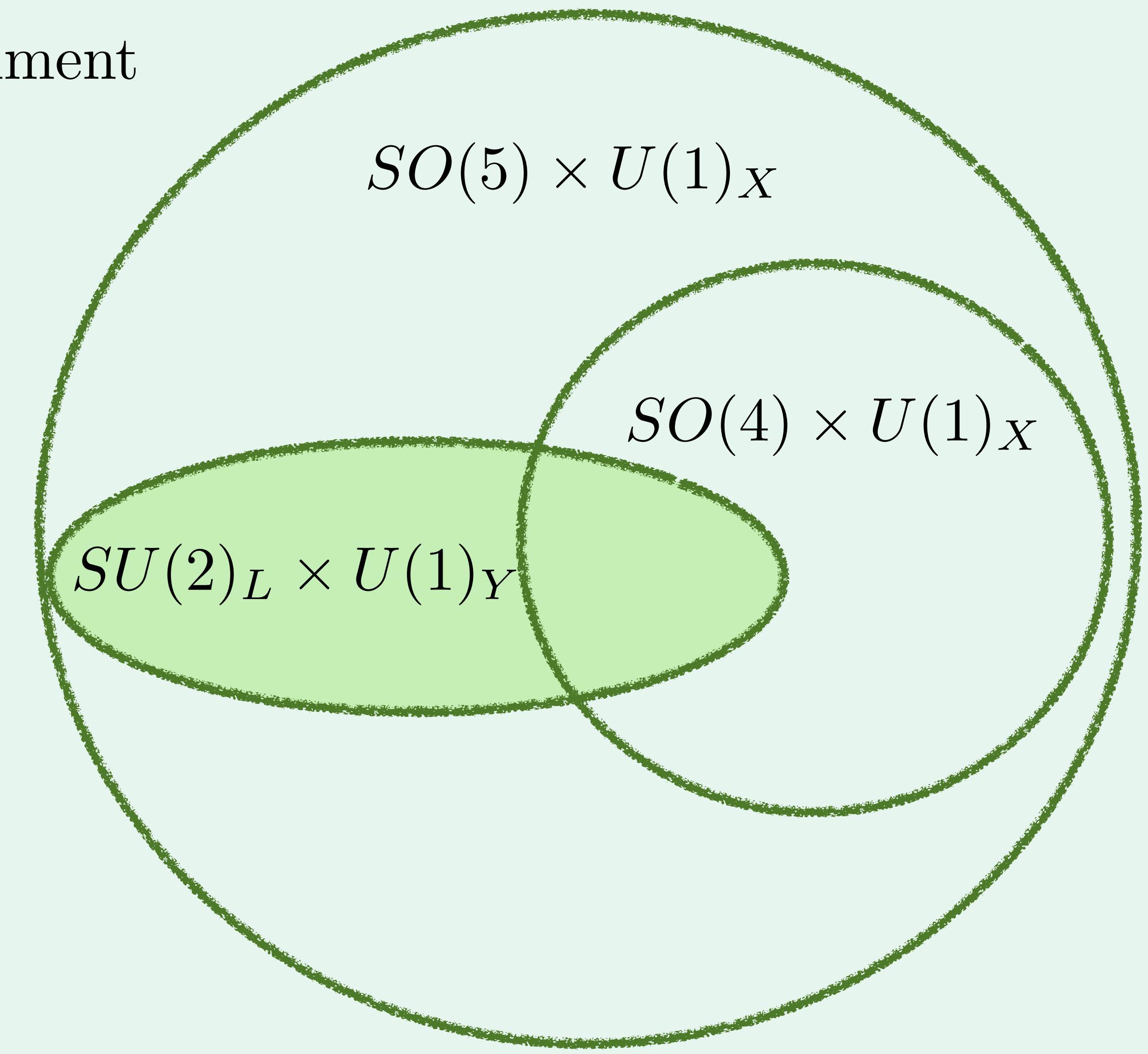

$$U(h) = \exp\left(i\frac{\sqrt{2}h^{\hat{a}}T^{\hat{a}}}{f}\right)$$

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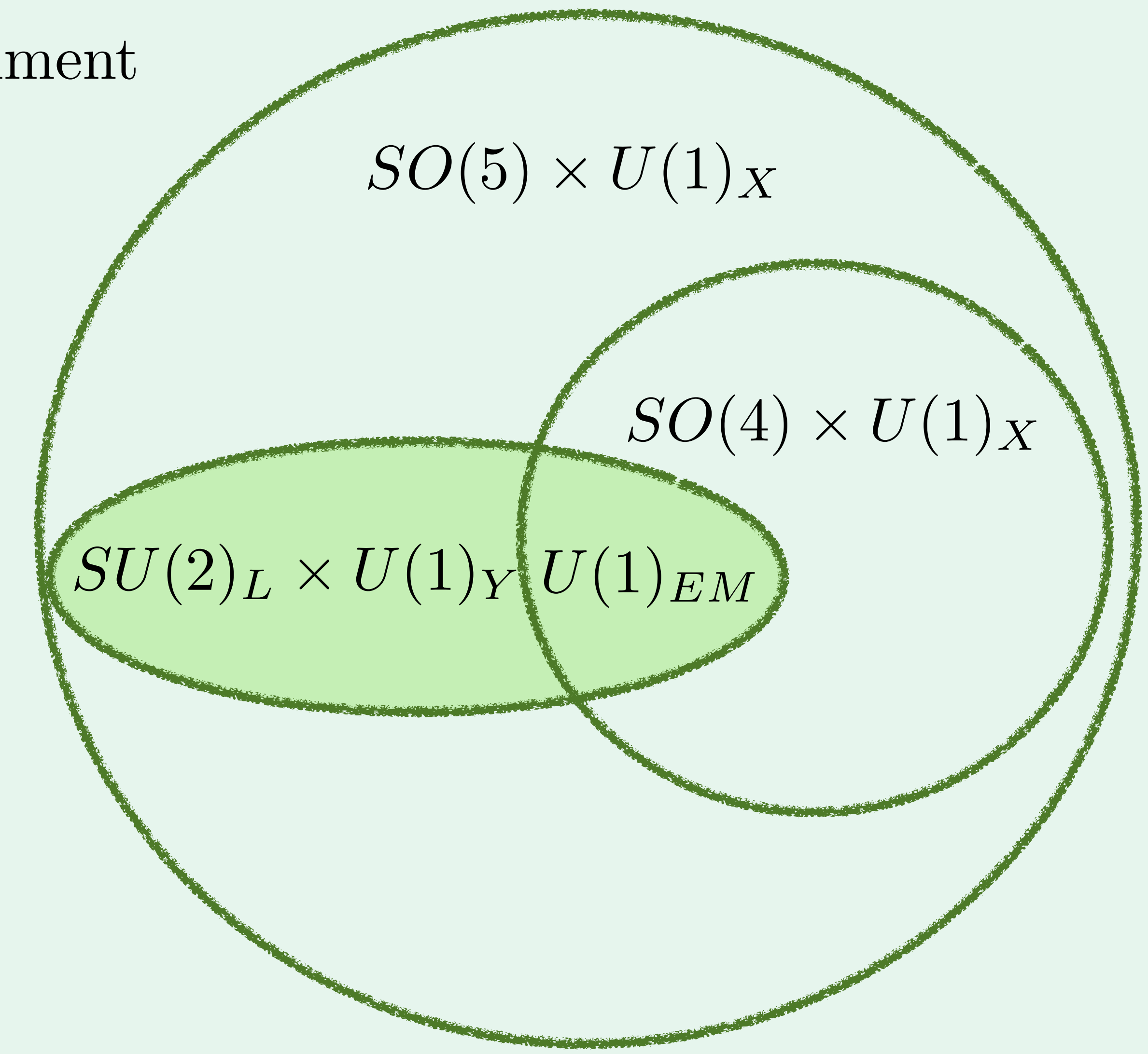

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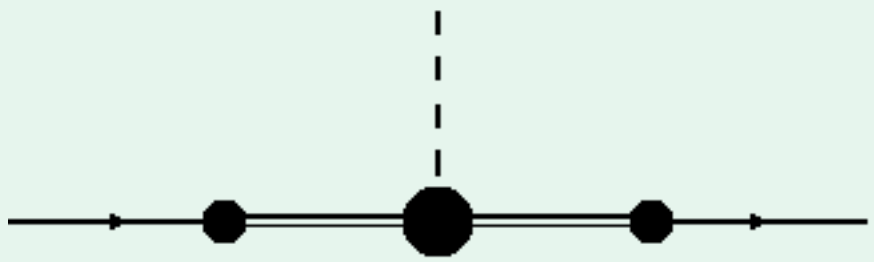
Partial Compositeness

[Kaplan: NPB 365 259]
[Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi, Vecchi: 1205.5803]

- linear mixings between elementary and composite fields

$$\mathcal{L}_{\rm mix} = \lambda_L \, q_L \mathcal{O}_L^q + \lambda_R \, t_R \mathcal{O}_R^t + \text{h.c.} + g \, A_\mu \mathcal{J}^\mu$$

- Yukawa couplings generated



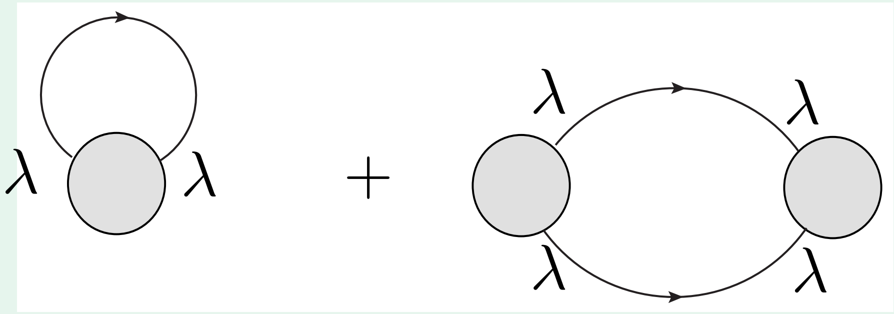
$$y_t \sim \frac{\lambda_L \lambda_R}{g_\psi} = \epsilon_L \epsilon_R g_\psi$$

- couplings break $SO(5)$ ⟶ Higgs potential generated

Higgs Potential

- structure of potential

$$V(h) = f^2 m_\Psi^2 \left(\frac{g_\psi}{4\pi}\right)^2 \left(\epsilon^2 \mathcal{F}_1^{(1)}(h/f) + \epsilon^4 \mathcal{F}_2^{(1)}(h/f) + \ldots\right) + \ldots$$



$$\mathcal{F} = \sum_i c_i I_i \left(\frac{h}{f}\right)$$

- need cancellation to obtain $\xi \ll 1$
- for $\mathcal{O}^q, \mathcal{O}^t \in \mathbf{5}$ only a single invariant $\epsilon^2 \mathcal{F}_1^{(1)} = c_1 \epsilon^2 s_h^2$

  cancellation with higher order $\epsilon^4 \mathcal{F}_2^{(1)} = \left(c_2 \epsilon^2\right) \epsilon^2 s_h^2 \left(1 - s_h^2\right)$

  → tuning of order $c_1 \approx c_2 \epsilon^2$ → **double tuning**

  → tuning worsened from ξ to $\xi \times \epsilon^2$ *[Panico, Redi, Tesi, Wulzer: 1210.7114]*
- for $\mathcal{O}^q \in \mathbf{14}$ and $\mathcal{O}^t \in \mathbf{1}$: two invariants in $\mathcal{F}_1^{(1)}$

  → **minimal tuning**

$$I_1 \equiv (U^\dagger P_L^\alpha P_{L\alpha}^\dagger U)_{55} = 1 - \frac{3}{4} s_h^2$$

$$I_2 \equiv (U^\dagger P_L^\alpha U)_{55} (U^\dagger P_{L\alpha}^\dagger U)_{55} = s_h^2 c_h^2$$

Higgs Potential

- linear couplings to strong sector break $SO(5)$
  $\longrightarrow$ Coleman - Weinberg potential for MCHM14 at 1-loop

$$V(h) = \alpha c_h^2 + \beta s_h^2 c_h^2 = (\beta - \alpha) s_h^2 - \beta s_h^4$$

$$\alpha = -\frac{3}{4}\int \frac{d^4 p_E}{(2\pi)^4}\frac{\Pi_1}{\Pi_0}\left(1 + \frac{2\Pi_0 + \Pi_0^X}{2\left(\Pi_0 + \Pi_0^X\right)}\right) - 6N_c \int \frac{d^4 p_E}{(2\pi)^4}\frac{\Pi_1^q}{\Pi_0^q}$$

$$\beta = -2N_c \int \frac{d^4 p_E}{(2\pi)^4}\left(\frac{\Pi_2^q}{\Pi_0^q} - \frac{|M_1^t|^2}{p_E^2\,\Pi_0^q\,\Pi_0^t}\right)$$

- where $\xi = \frac{\beta - \alpha}{2\beta}$ $\qquad m_h^2 = -\frac{8\beta}{f^2}\xi(1-\xi)$

- form factors can be computed in explicit model,
  but estimate α and β using spurionic symmetries and NDA

$$V(h) \approx N_C \frac{m_\psi^4}{16\pi^2}\frac{\lambda_L^2}{g_\psi^2}\left(a_1 I_1 + a_2 I_2\right) \qquad \hat{S} \approx 10^{-3}\left(\frac{\xi}{0.1}\right)\left(\frac{4}{g_\rho}\right)^2$$

$$m_h^2 \approx (380\ \text{GeV})^2 \frac{1}{\epsilon_R^2}\left(\frac{g_\psi}{4}\right)^2 |a_2| \longrightarrow$$

- need fully composite t_R $(\epsilon_R \approx 1)$
- small g_ψ and $|a_2| \sim O(1)$
- OR $|a_2| \lesssim 1$

5D Construction

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[Contino, Nomura, Pomarol, hep-ph/0306259]
[Contino, Pomarol, hep-th/0406257]
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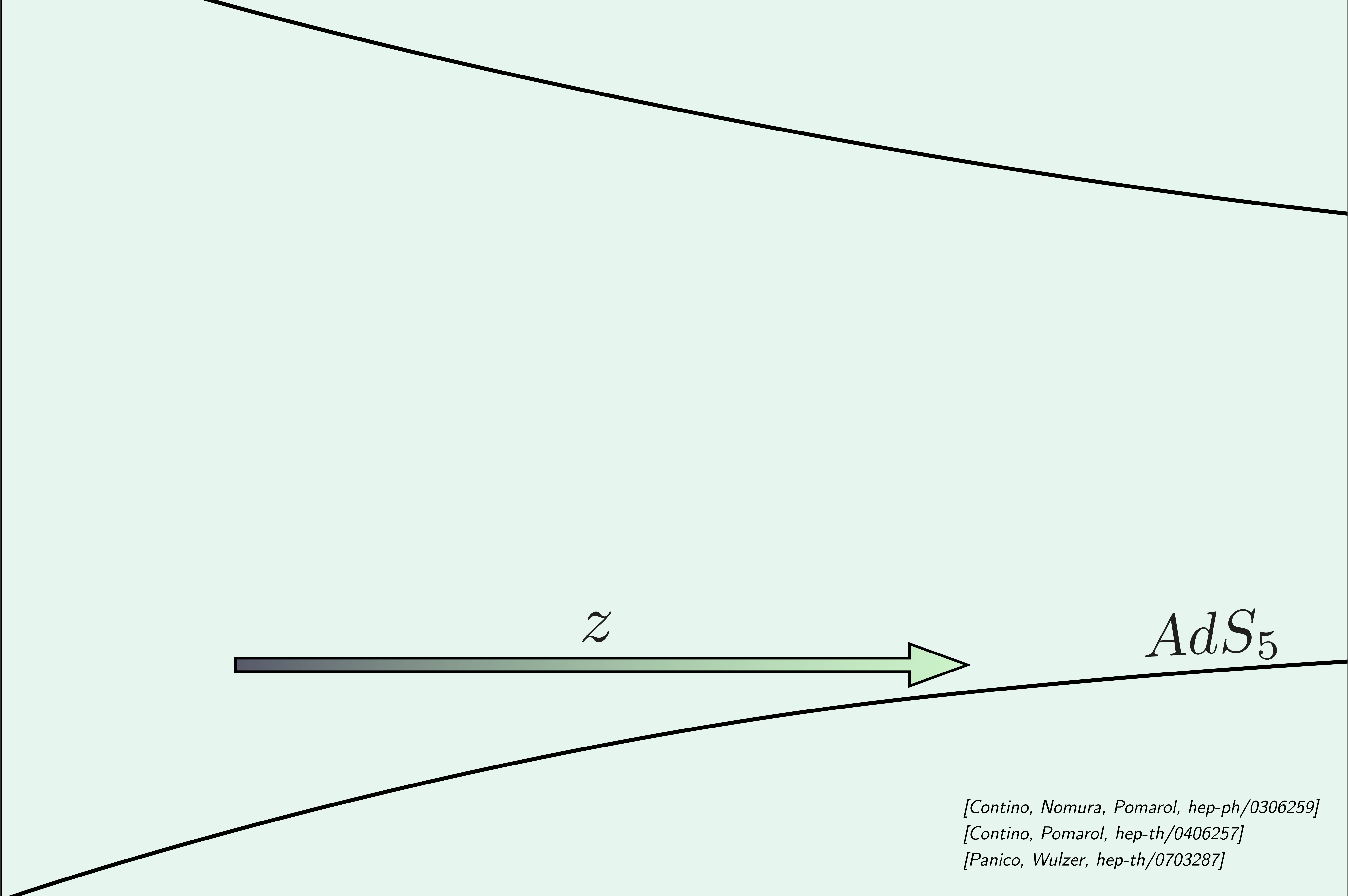

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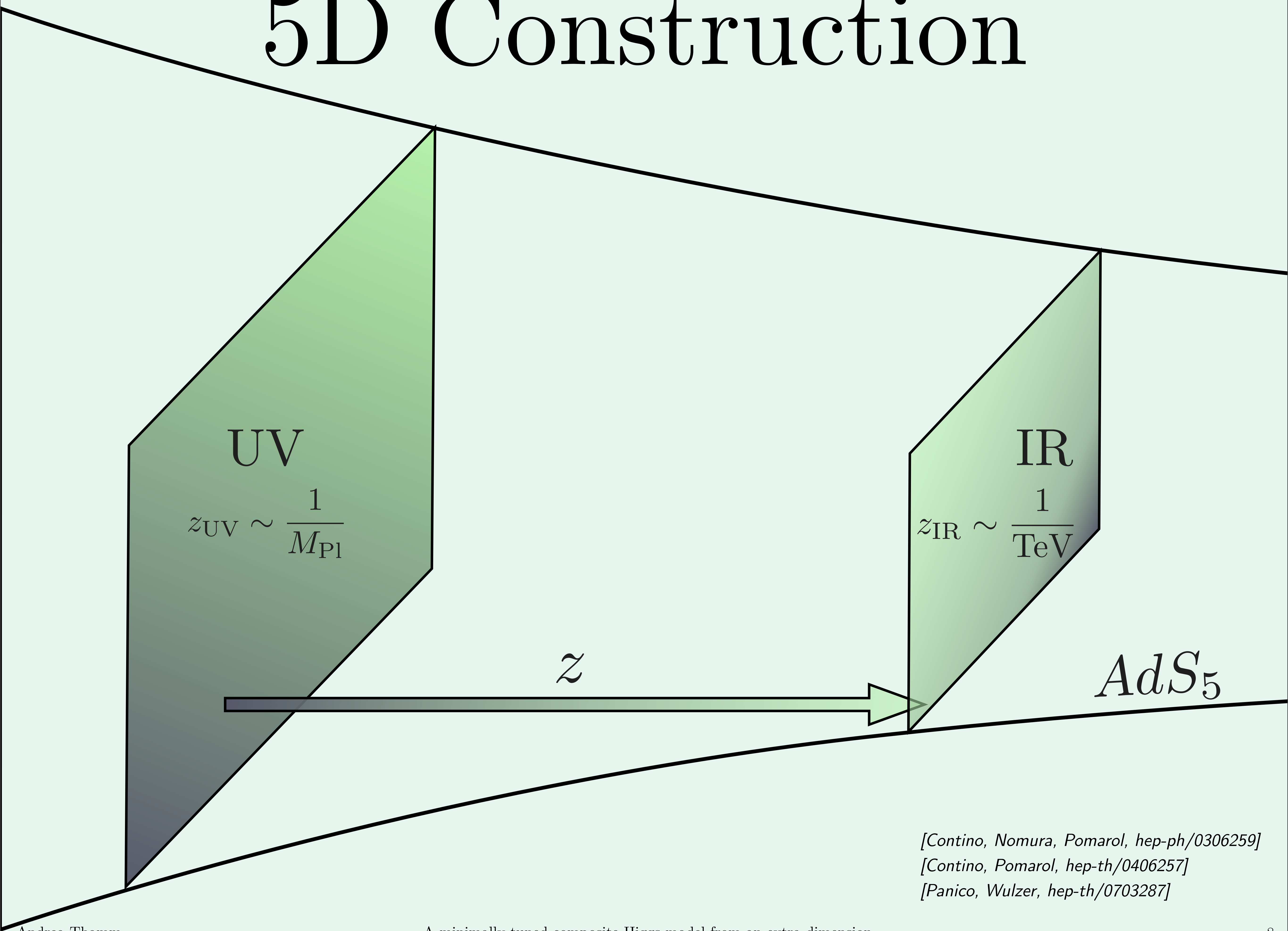

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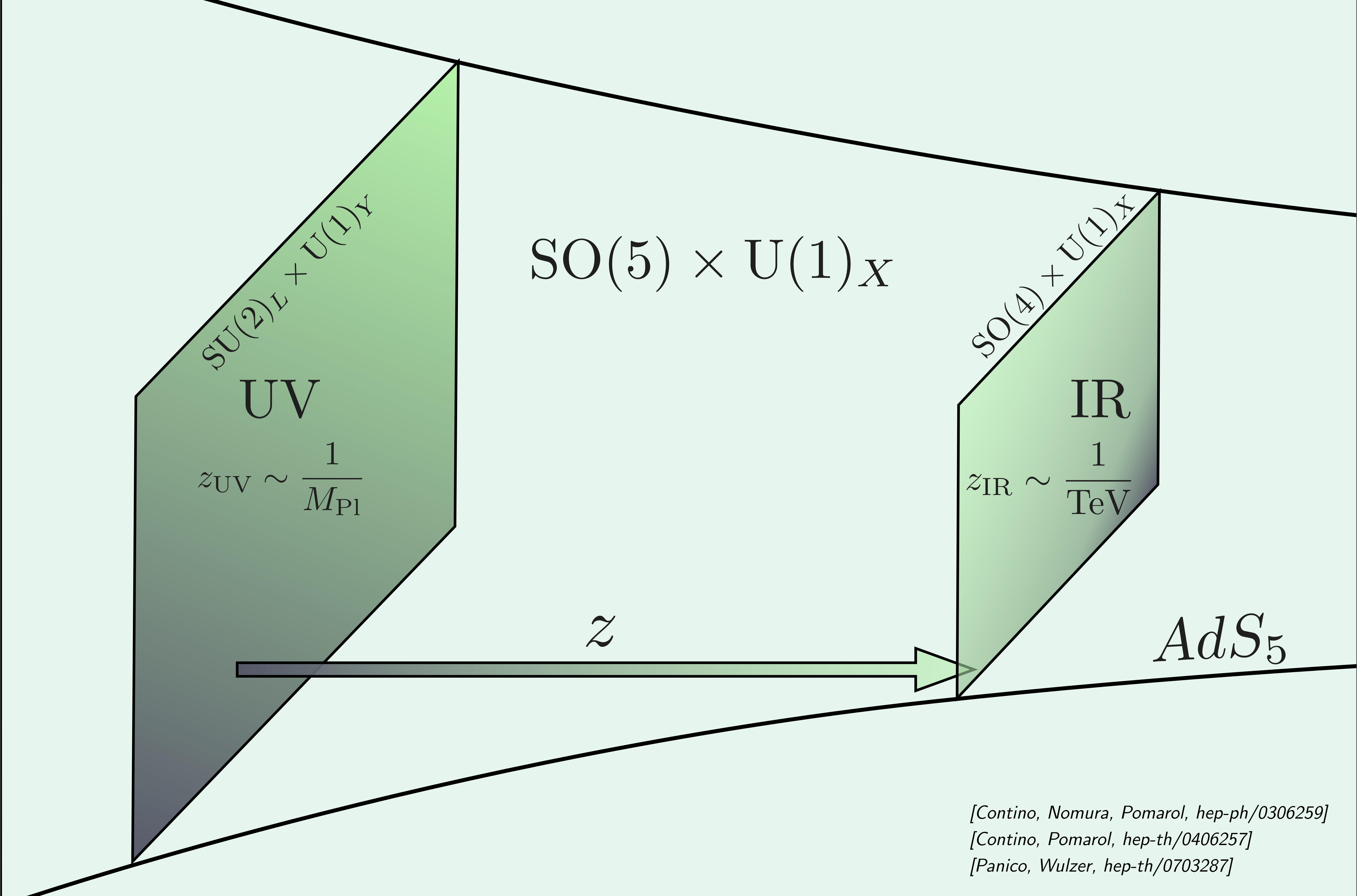

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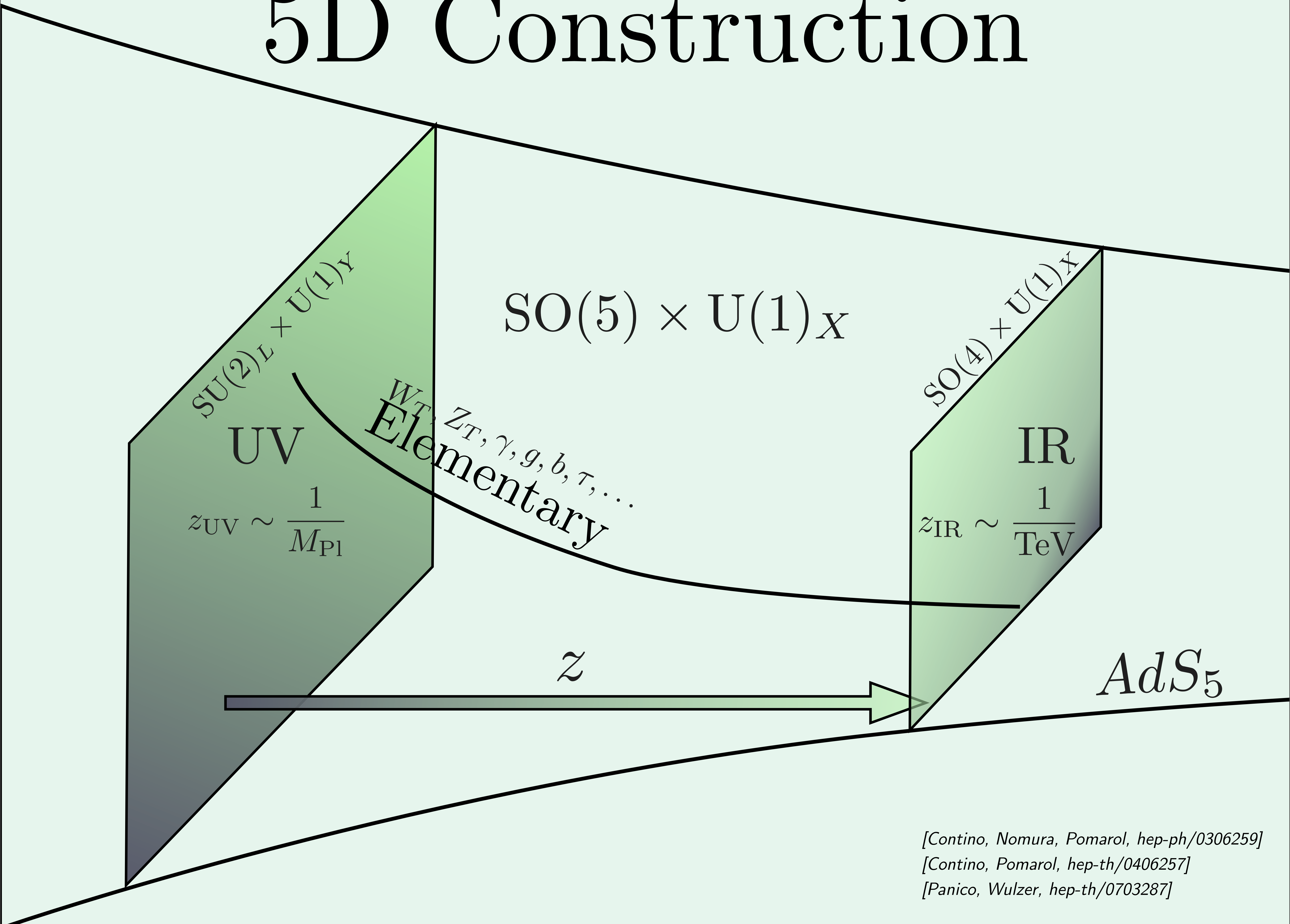

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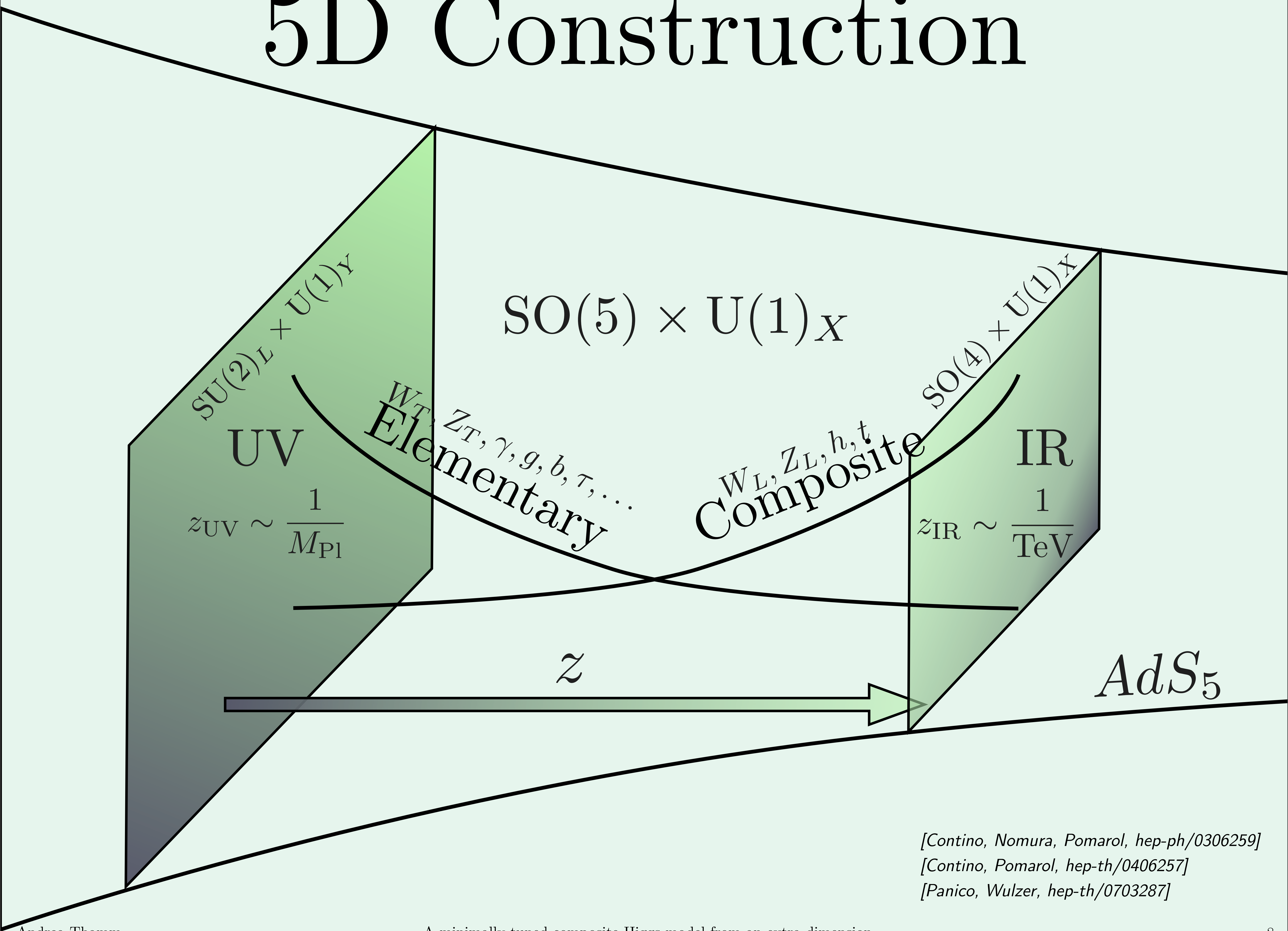

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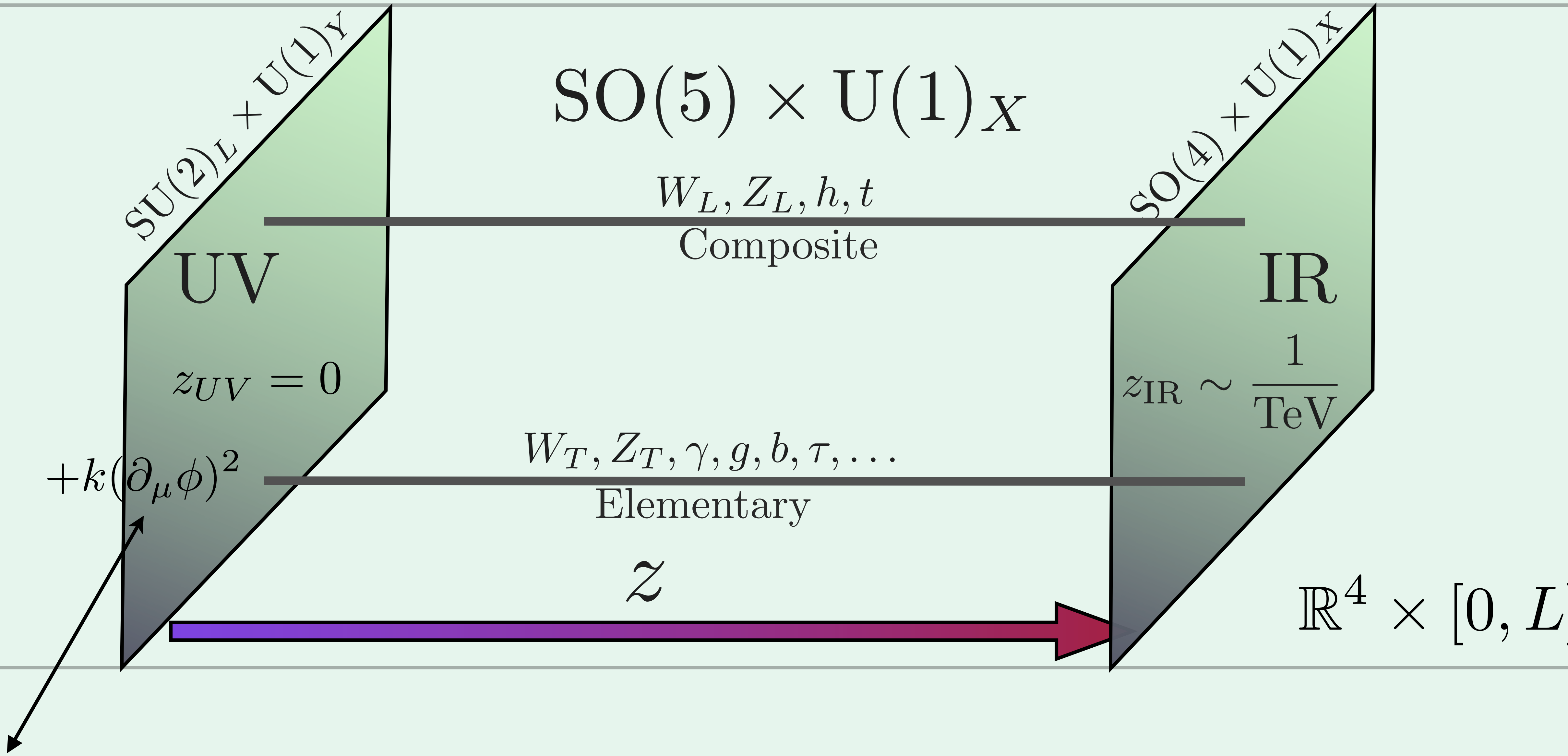
5D Construction

[Scrucca, Serone, Silvestrini hep-ph/0304220]
[Barbieri, Pomarol, Rattazzi hep-ph/0310285]
[Serone 0909.5619]
[Panico, Safari, Serone 1012.2875]
[Pappadopulo, Thamm, Torre, 1303.3062]



Large UV kinetic terms $k \gg 1$ suppress elementary states wave functions and interactions, implement PC: $1/k \sim \epsilon^2$

The gauge sector

- bulk action $S^g_{5D} = -\int d^4x \int_0^L \frac{dz}{L} \left[\frac{1}{4g_5^2} \mathrm{Tr}[F^2_{MN}] + \frac{1}{4g_X^2} \left(F^X_{MN}\right)^2 \right]$
- symmetry broken on boundaries by BC
- localised kinetic terms at $z = 0$ for holographic fields

$$S^g_{\mathrm{UV}} = -\int d^4x \left[\frac{1}{4g_2^2} \left(W^a_{\mu\nu}\right)^2 - \frac{1}{4g_1^2} \left(B_{\mu\nu}\right)^2 \right]$$

- integrate out bulk fields → form factors, GB kinetic term

$$\mathcal{L}_{\mathrm{kin}} = -\frac{1}{2g_5^2 L^2} \mathrm{Tr}[(U^\dagger \partial_\mu U)^2] \qquad V_g(s_h) = -\frac{1}{L^4} \frac{63\zeta(3)}{256\pi^2} \left(1 + \frac{t_W^2}{3}\right) \frac{g_2^2}{g_5^2} c_h^2$$

- relations

$$\frac{1}{g^2} = \frac{1}{g_2^2} + \frac{1}{g_5^2}\left(1 - \frac{\xi}{3}\right) \approx \frac{1}{g_2^2} \qquad \frac{1}{g'^2} = \frac{1}{g_1^2} + \frac{1}{g_X^2} + \frac{1}{g_5^2}\left(1 - \frac{\xi}{3}\right) \approx \frac{1}{g_1^2}$$

$$m_W^2 \approx \frac{1}{L^2} \frac{g_2^2 \xi}{2g_5^2} \qquad M_{KK} = \frac{\pi}{2L} \qquad f^2 = \frac{2}{L^2} \frac{1}{g_5^2}$$

- $\hat{S}$ paramter $\qquad \hat{S} \equiv g^2 \Pi'_{30}(0) \approx \frac{g_2^2 \xi}{3g_5^2}$

The fermionic sector

- bulk action $S^f_{5D} = \int d^4x \int_0^L \frac{dz}{L}\ \mathrm{Tr}[\overline{\Psi}_q \left(i\not{D} + M_{\Psi_q}\right)\Psi_q] + \Psi_t \left(i\not{D} + M_{\Psi_t}\right)\Psi_t$
- BC

$$\Psi_t = (\psi_{tL}(-+) \qquad \psi_{tR}(+-))$$

$$\Psi_q \supset \begin{cases} \psi^{(\mathbf{1})}_{qL}(--) & \psi^{(\mathbf{1})}_{qR}(++) \\ \psi^{(\mathbf{4})}_{qL} = \begin{pmatrix} q'_L(-+) \\ q_L(++) \end{pmatrix} & \psi^{(\mathbf{4})}_{qR} = \begin{pmatrix} q'_R(+-) \\ q_R(--) \end{pmatrix} \\ \psi^{(\mathbf{9})}_{qL}(-+) & \psi^{(\mathbf{9})}_{qR}(+-) \end{cases}$$

- boundary actions

$$S^f_{\mathrm{IR}} = \int d^4x \int_0^L dz \Big[\left(k^t_1 \overline{\psi}_{tL} i\not{D}\psi_{tL} + k^q_1 \overline{\psi}^{(\mathbf{1})}_{qR} i\not{D}\psi^{(\mathbf{1})}_{qR} + k^q_4 \overline{\psi}^{(\mathbf{4})}_{qL} i\not{D}\psi^{(\mathbf{4})}_{qL} + k^q_9 \overline{\psi}^{(\mathbf{9})}_{qL} i\not{D}\psi^{(\mathbf{9})}_{qL}\right)$$

$$+ \left(m_{11}\overline{\psi}^{(\mathbf{1})}_{qR}\psi_{tL} + \mathrm{h.c.}\right)\Big]\,\delta(z-L)$$

$$S^f_{\mathrm{UV}} = \int d^4x \int_0^L dz\ \left[Z_q\,\overline{q}_L i\not{D} q_L + Z_t\,\overline{q}_R i\not{D} q_R\right]\delta(z)$$

- integrate out bulk fields $\longrightarrow$ form factors

Results

Numerical Analysis

- parameters of the model:

$$L$$

$$M_q, M_t, m_{11}, k_4^q, k_9^q, Z_q, g_5$$

- relations due to

$$m_W^2 \approx \frac{1}{L^2}\frac{g_2^2\xi}{2g_5^2} \qquad m_t^2 = \frac{1}{L^2}\frac{\xi}{Z_q}F_t(\{p_i\}) \qquad m_h^2 = \frac{1}{L^2}\frac{N_C g_5^2}{(4\pi)^2}\frac{\xi}{Z_q}F_h(\{p_i\})$$

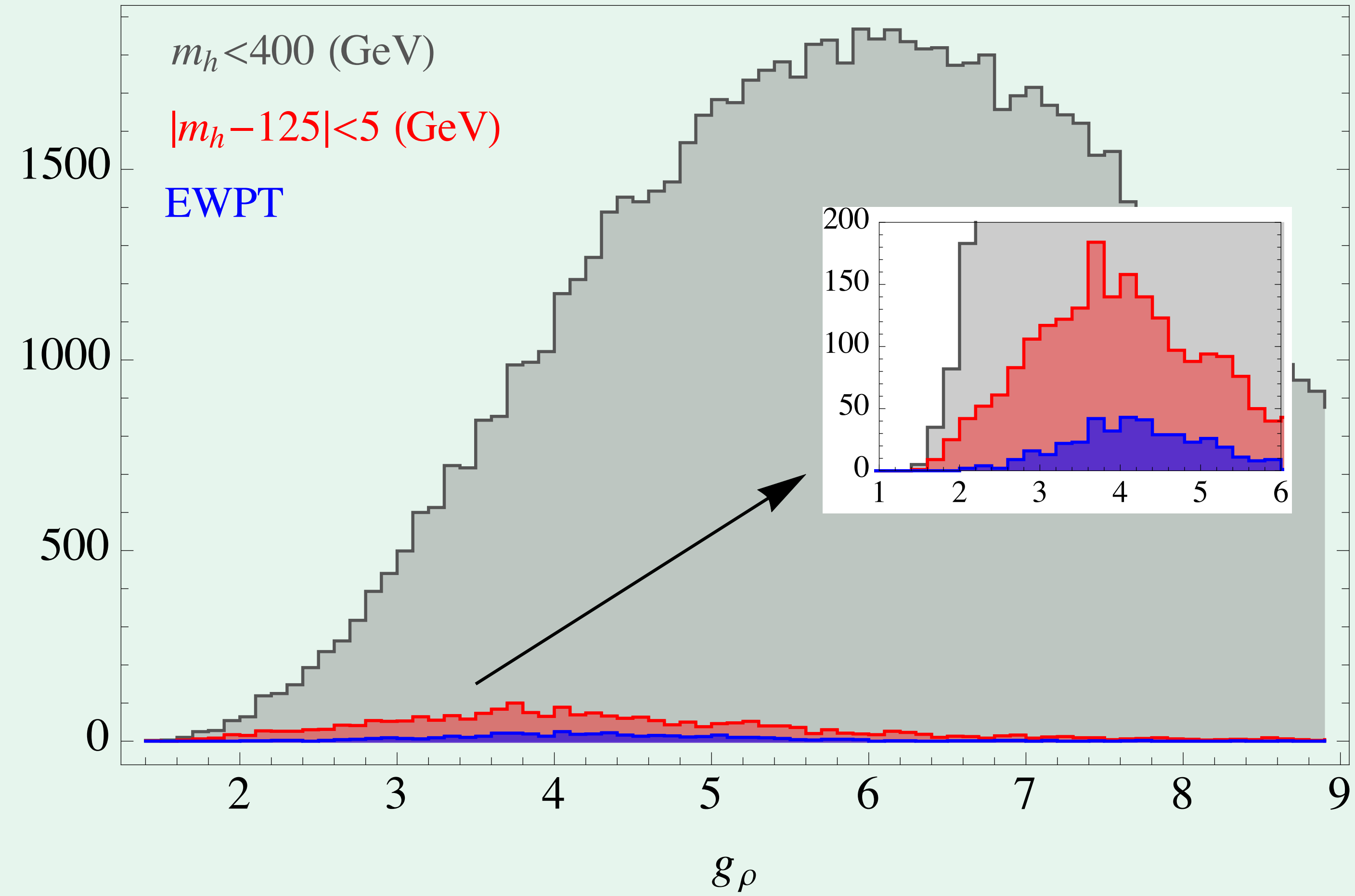
$\longrightarrow$ could fix g_5, Z_q and L $\longrightarrow$ but actually use only m_W

- random scan within the interval

$M_qL,\ M_tL$	:	$(-2 \div 2)$
$m_{11}L$	:	$(0.3 \div 2)$
$k_4^q,\ k_9^q$	:	$(0 \div 2)$
$\sqrt{Z_q}$	:	$(0 \div 10)$
g_5	:	$(1 \div 9)$

$$m_W = 81\,\text{GeV}$$
$$148\,\text{GeV} \leq m_t \leq 154\,\text{GeV}$$
$$120\,\text{GeV} \leq m_h \leq 130\,\text{GeV}$$

- distribution of points passing



- EWPT at 99% C.L.

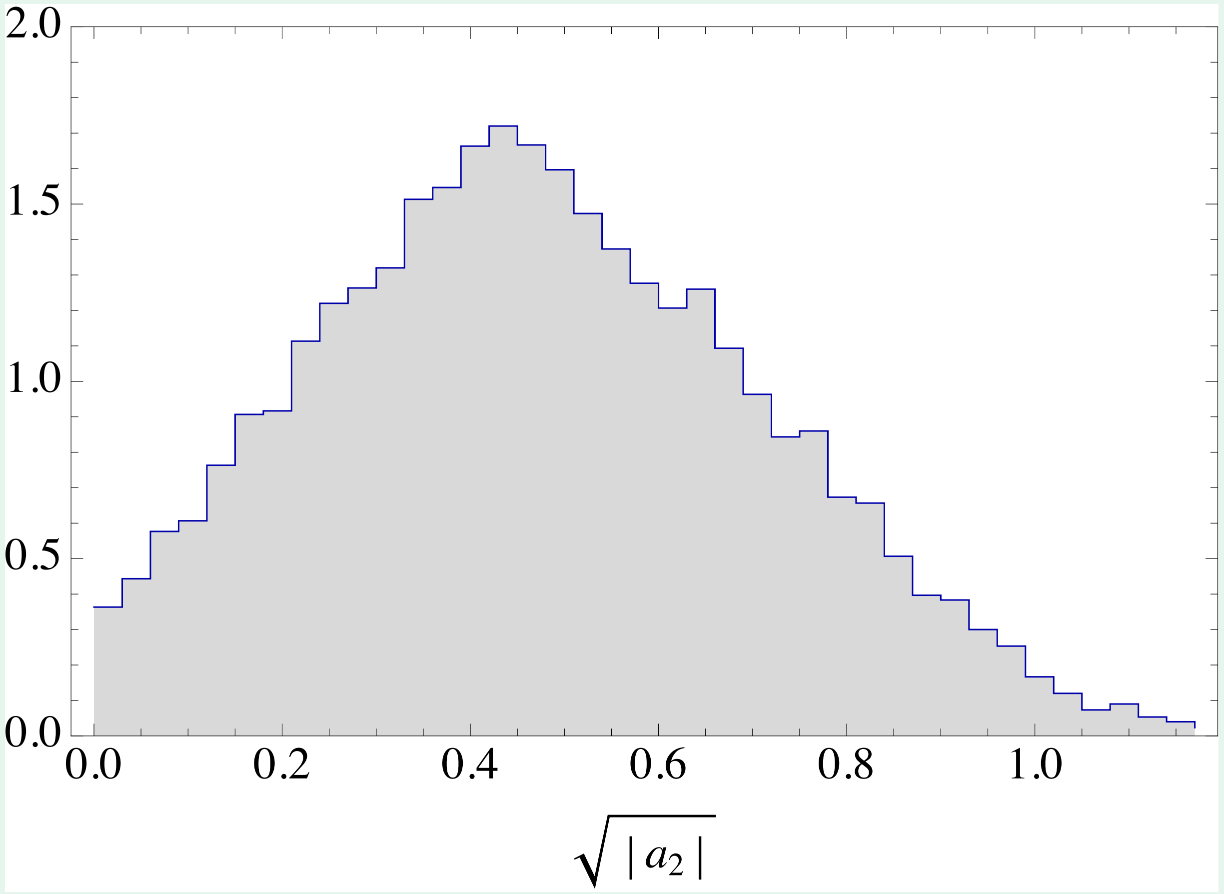
$$\hat{S} = (0.39 \pm 0.70)\, 10^{-3}$$
$$\hat{T} = (0.60 \pm 0.56)\, 10^{-3}$$
$$\rho = \begin{pmatrix} 1 & 0.91 \\ 0.91 & 1 \end{pmatrix}$$

- scaling of m_h implies small g_ρ

$$m_h^2 \sim N_C \frac{g_\psi^2}{2\pi^2} \frac{g_\psi^2}{\lambda_R^2} y_t^2 v^2 |a_2| (1-\xi) \approx (380\ \text{GeV})^2 \frac{1}{\epsilon_R^2} \left(\frac{g_\psi}{4}\right)^2 |a_2|$$

need to know distribution

- find natural value of a_2 by scanning without requirement



$|a_2| \approx 0.2$

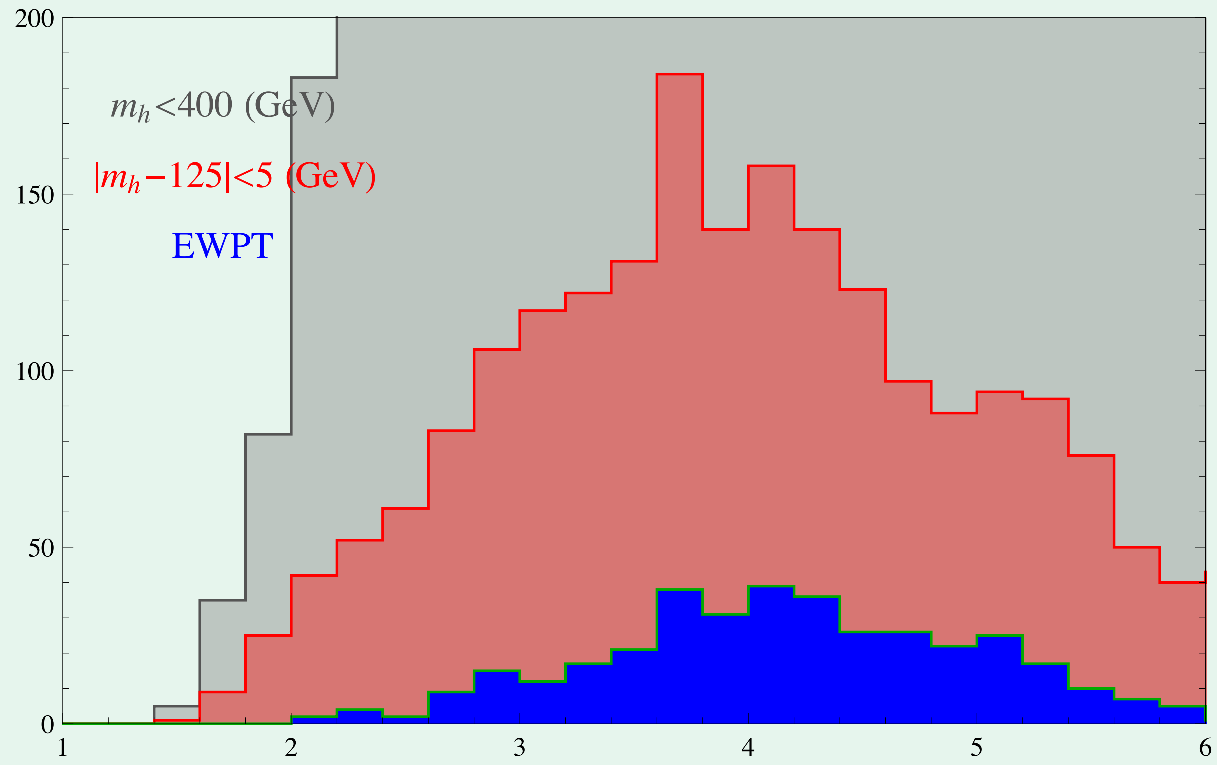
- value not due to a cancellation, but to numerical factors
  $\longrightarrow$ no increase in tuning!
- rewrite NDA estimate for m_h

$$m_h^2 \approx (150\ \text{GeV})^2 \frac{1}{\epsilon_R^2} \left(\frac{g_\psi}{4}\right)^2 |a_2|$$

← *natural value is 1*

- in this model, Higgs is naturally light

- distribution of points passing



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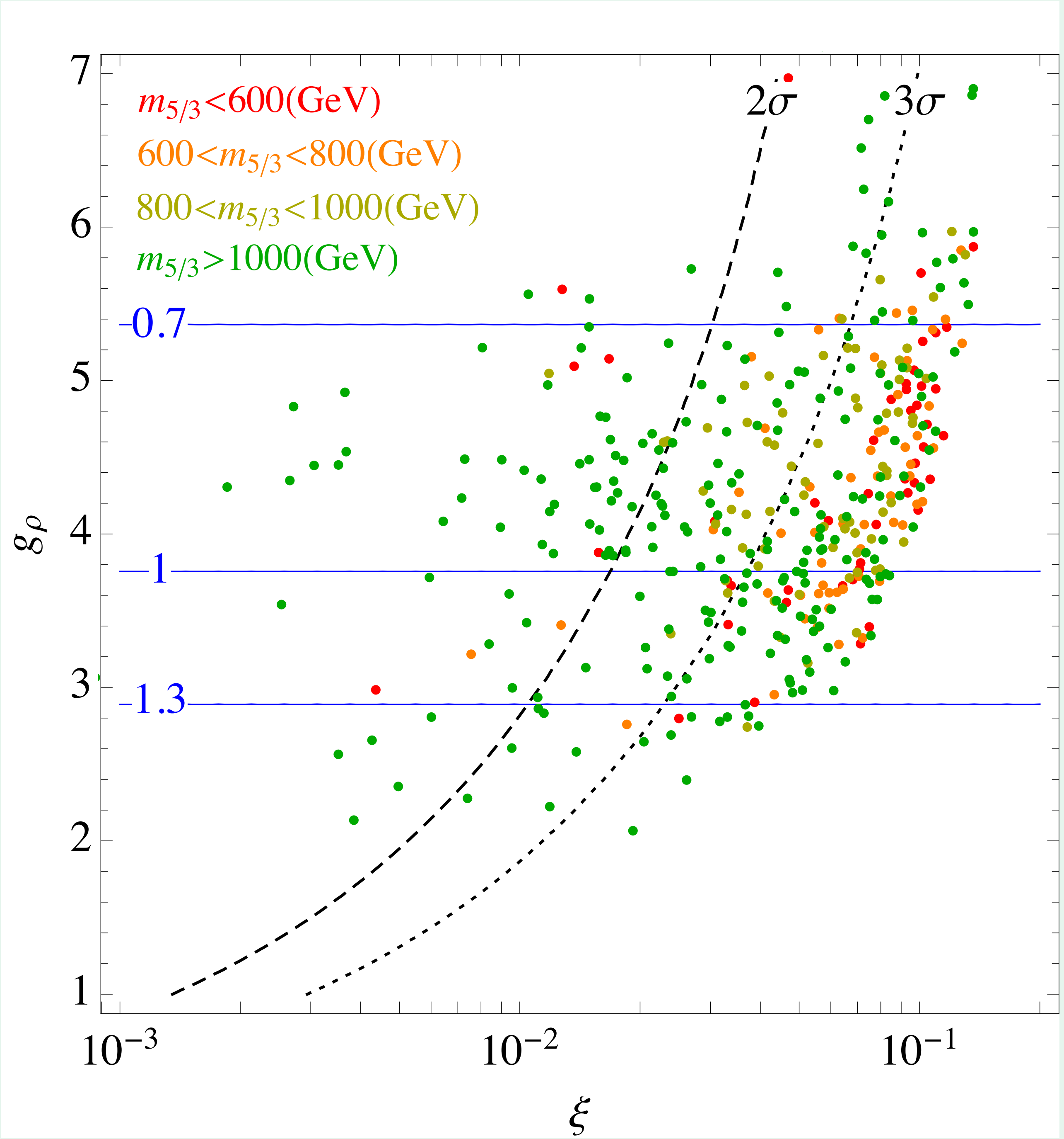
- definition of tuning: $\Delta = \frac{n(m_h)}{n(EWPT)}$

  $\longrightarrow$ parameter space region left after imposing constraints

	EWPT	EWPT $(+\Delta\hat{T} = 10^{-3})$
%	4.5 ± 0.4	18 ± 1

- spectrum of fermionic resonances



- many points with light spectrum
- but according to NDA

$$m_\psi \sim g_\rho f$$

expect $m_\psi = 3\,\text{TeV}$

for $g_\rho = 4$ and $\xi = 0.1$

[Matsedonskyi, Panico, Wulzer 1204.6333]
[Marzocca, Serone, Shu 1205.0770]
[Pomarol, Riva 1205.6434]
[Panico, Redi, Tesi, Wulzer 1210.7114]
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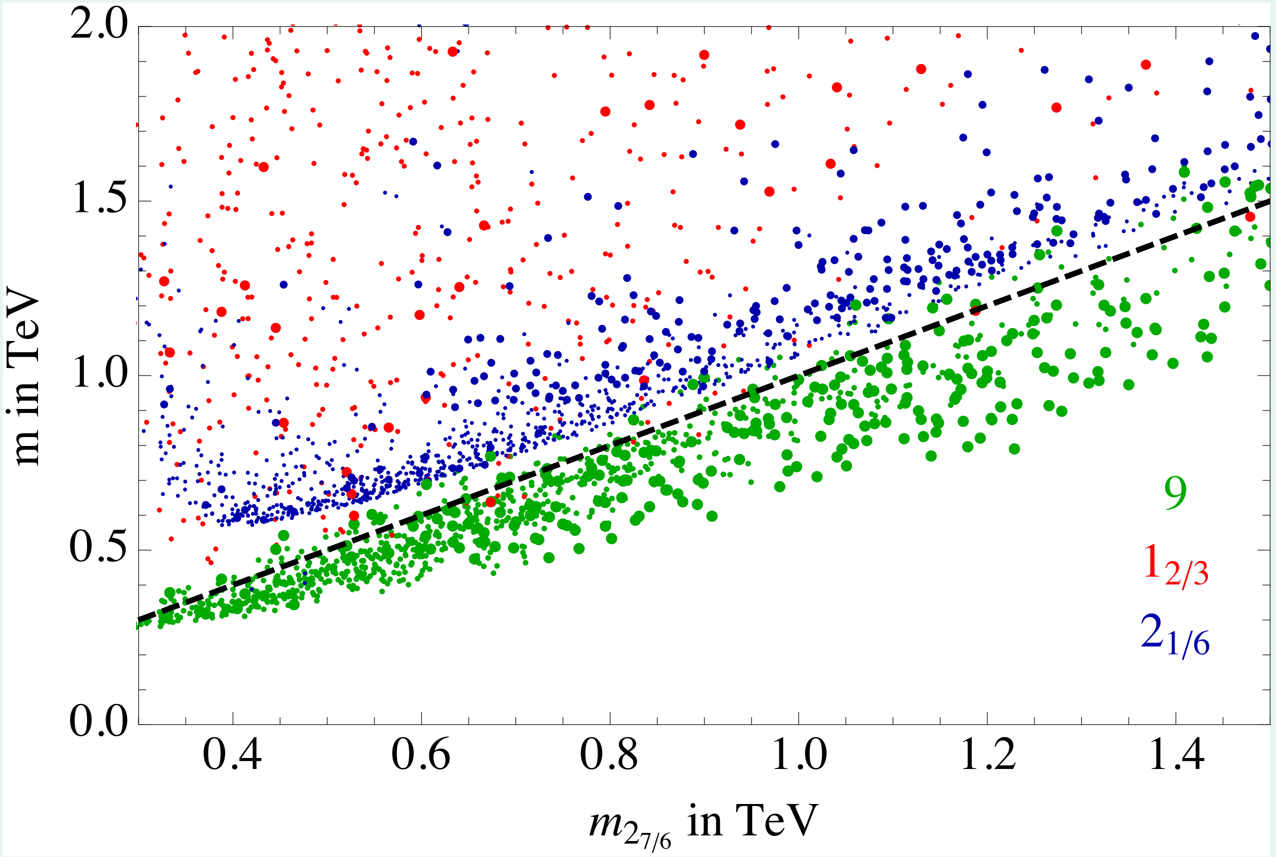
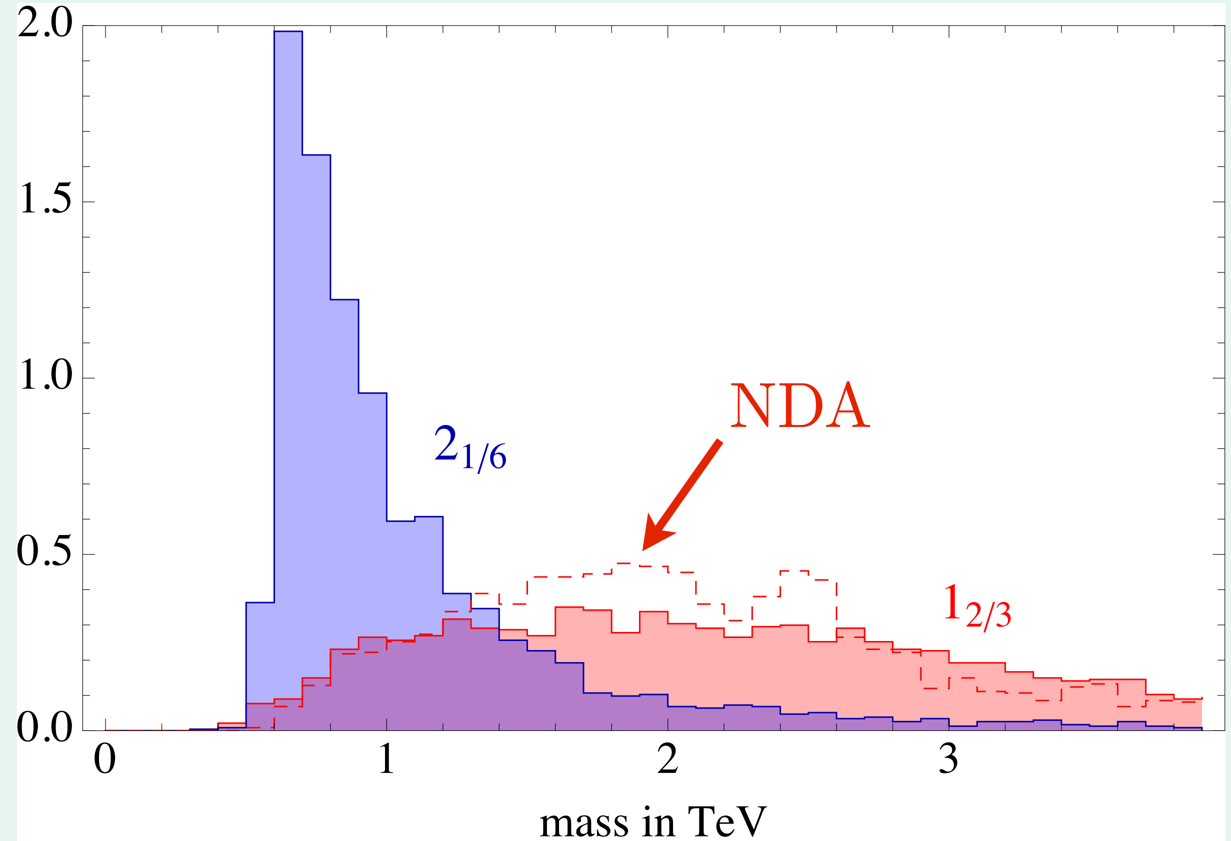
[Pappadopulo, Thamm, Torre 1303.3062]





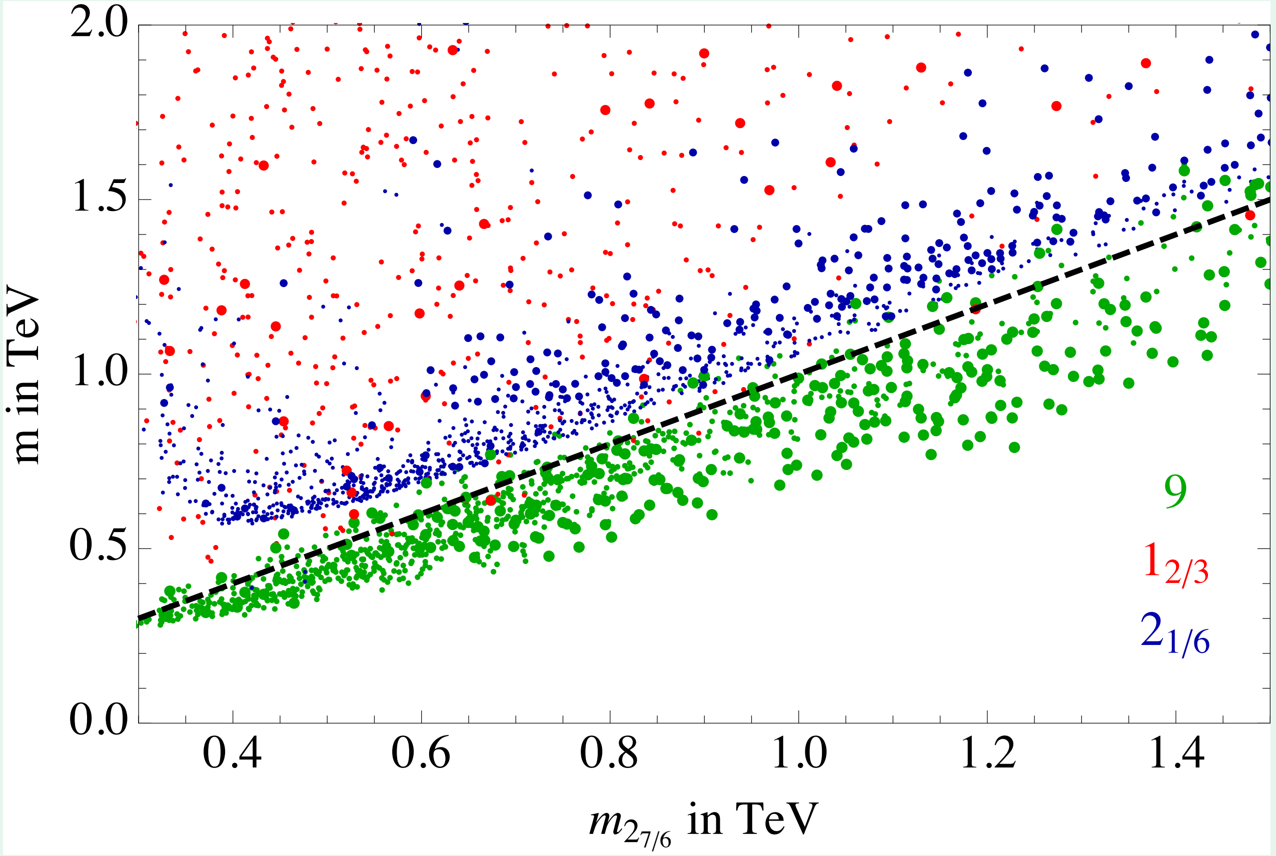
mass hierarchy: $m_{\mathbf{9}} < m_{\mathbf{2}_{7/6}} < m_{\mathbf{2}_{1/6}} \ll m_{\mathbf{1}_{2/3}}$

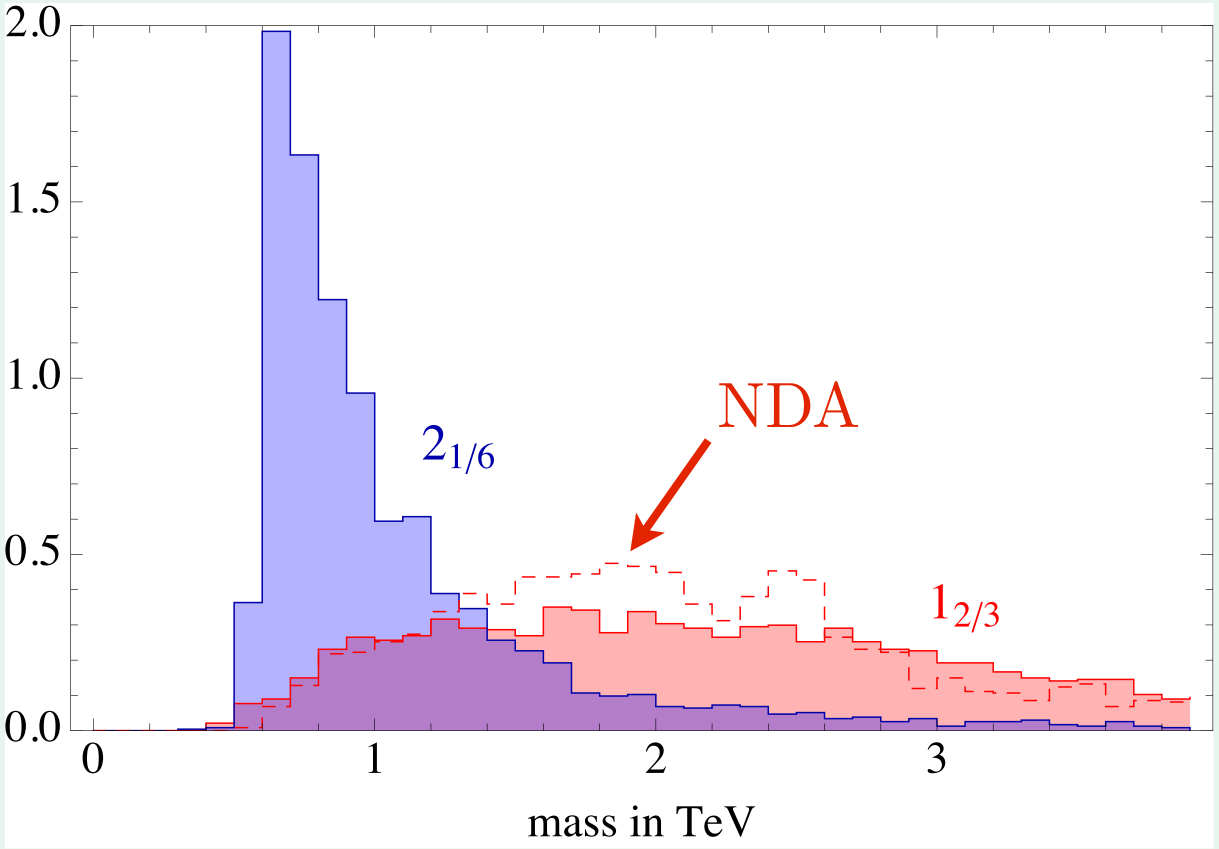
only $\mathbf{1}_{2/3}$ matches NDA

- due to constraint $$\frac{m_t^2}{m_W^2} = \frac{g_5^2}{g_2^2}\frac{5|M_{\Psi_q}L|}{Z_q + e^{2|M_{\Psi_q}L|}k_9^q} \quad \rightarrow \quad M_{\Psi_q} \lesssim -1$$

mass	$\mathbf{9},\ \mathbf{2}_{7/6},\ \mathbf{2}_{1/6}$	$\mathbf{1}_{2/3}$
zeros of	$M_{\Psi_q} + \omega_q \cot \omega_q L$	$M_{\Psi_t} + \omega_t \cot \omega_t L$
solution	$p \sim 2\lvert M_{\Psi_i}\rvert e^{-\lvert M_{\Psi_i}\rvert L}$	$M_{\Psi_i} L \lesssim 0$

$\longrightarrow$ parametric suppression



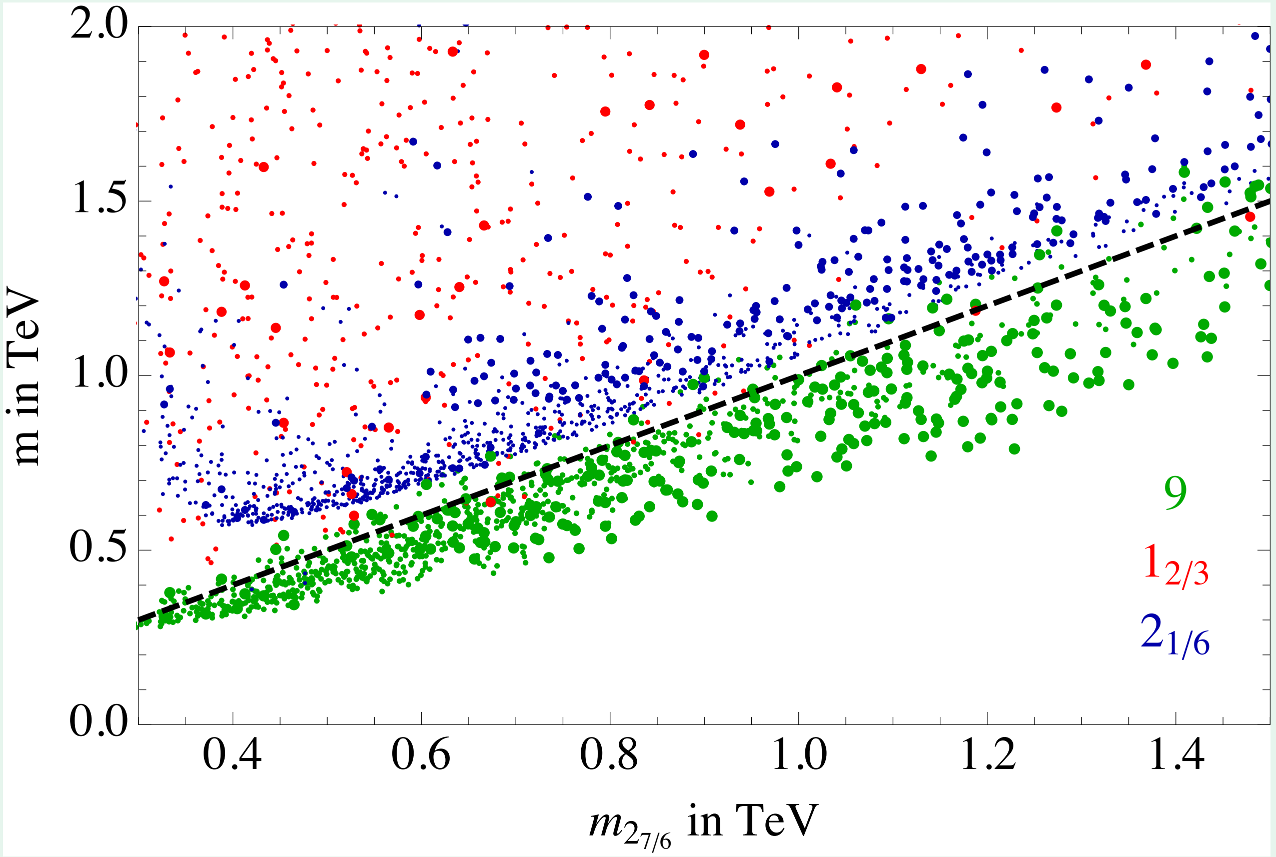


mass hierarchy: $m_{\mathbf{9}} < m_{\mathbf{2}_{7/6}} < m_{\mathbf{2}_{1/6}} \ll m_{\mathbf{1}_{2/3}}$

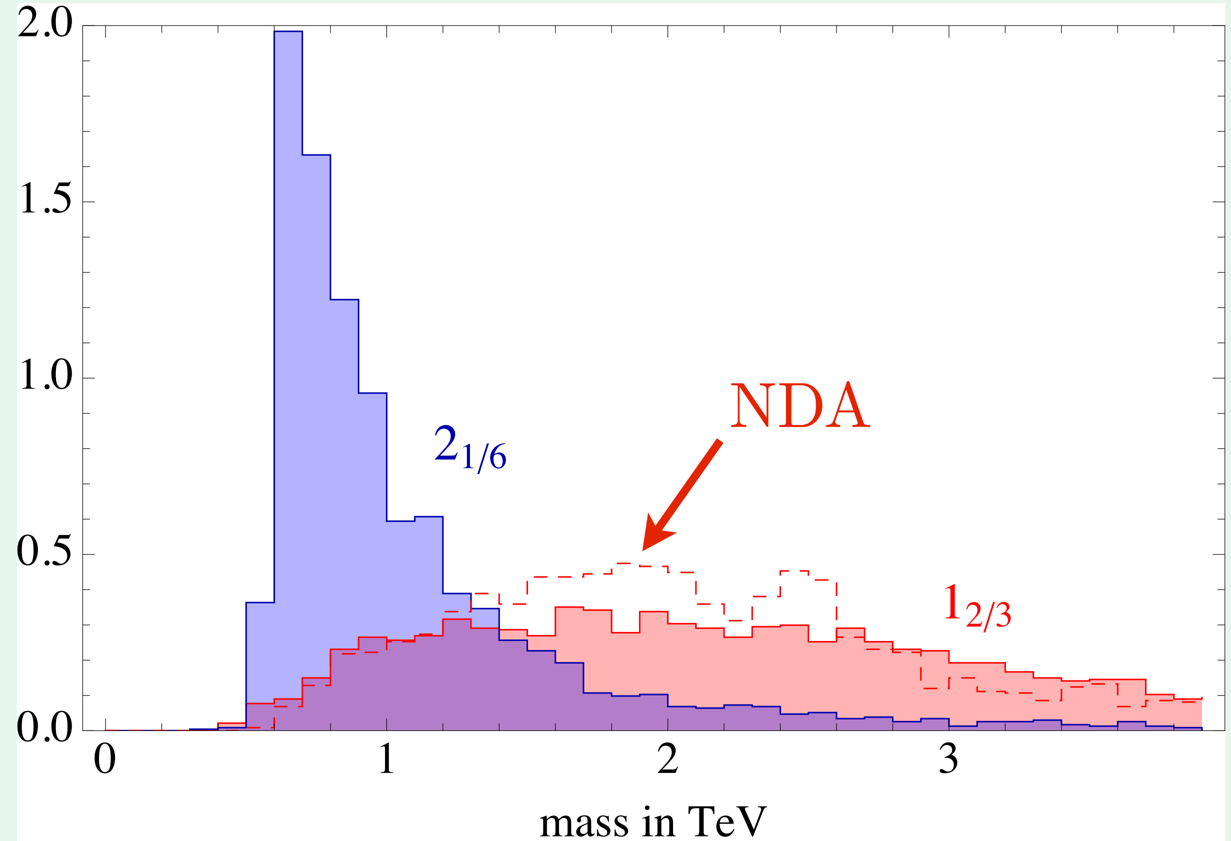
only $\mathbf{1}_{2/3}$ matches NDA

- mass splitting between $\mathbf{9}$ and $\mathbf{2}_{7/6}$ proportional to $(k_4^q - k_9^q)$
  EWSB prefers $k_4 < k_9$ $\longrightarrow$ $m_{\mathbf{9}} < m_{\mathbf{2}_{7/6}}$
- mass splitting between $\mathbf{2}_{7/6}$ and $\mathbf{2}_{1/6}$ due to different UV BC
  $m_{\mathbf{2}_{7/6}}$ / $m_{\mathbf{2}_{1/6}}$ given by poles / zeros of $\tilde{\Pi}_0^q = Z_q + \dfrac{1}{M_{\Psi_q} L + \omega_q L \cot \omega_q L}$

$\longrightarrow$ $m_{\mathbf{2}_{7/6}} < m_{\mathbf{2}_{1/6}}$



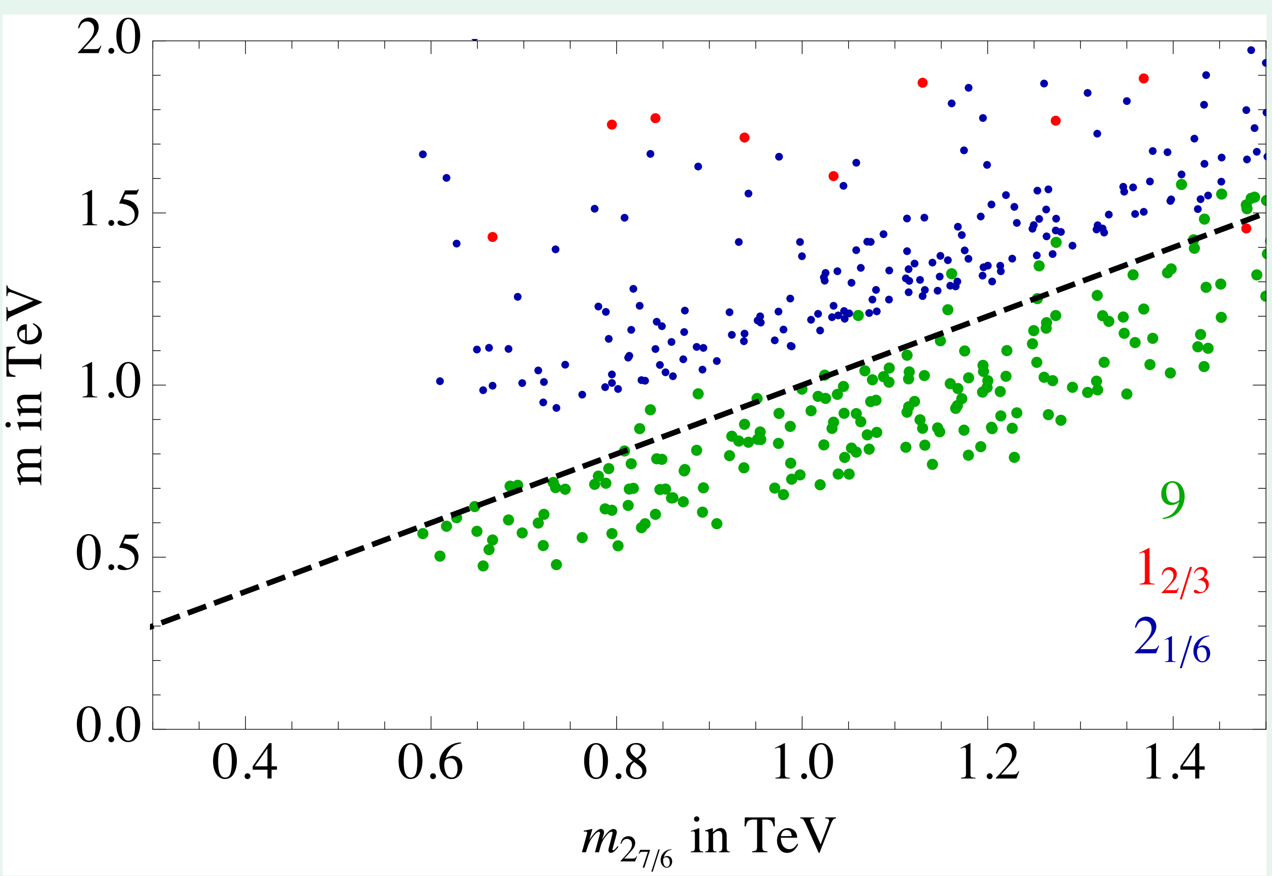
2.0
1.5
1.0
0.5
0.0
0.4
0.6
0.8
1.0
1.2
1.4
m in TeV
$m_{2_{7/6}}$ in TeV
9
$1_{2/3}$
$2_{1/6}$



2.0
1.5
1.0
0.5
0.0
0
1
2
3
mass in TeV
NDA
$2_{1/6}$
$1_{2/3}$

↓ + EWPT

↓ + EWPT



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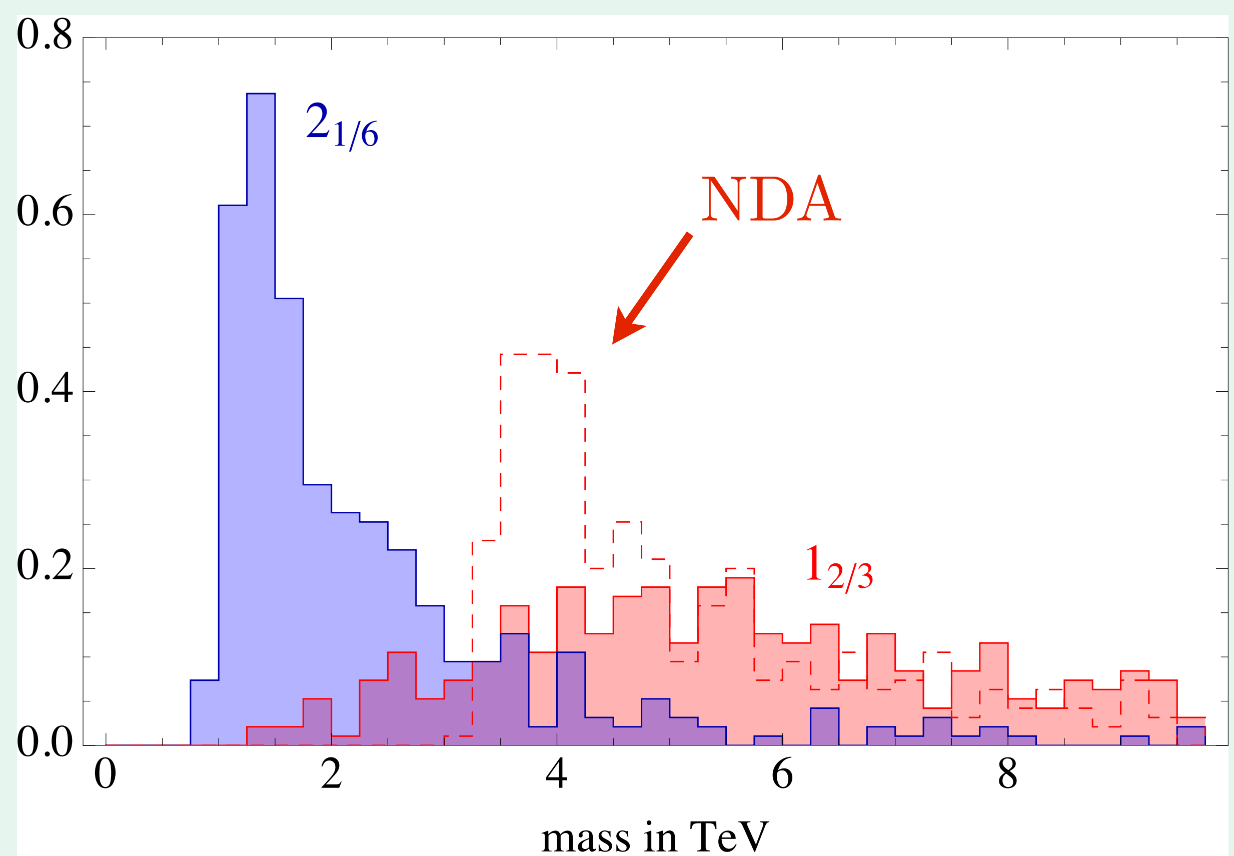

0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
mass in TeV
$2_{1/6}$
NDA
$1_{2/3}$

Conclusions

- discussed model with $\mathcal{O}_L^q \in \mathbf{14}_{2/3}$ and $\mathcal{O}_R^t \in \mathbf{1}_{2/3}$
  - moderate tuning
  - obtain light Higgs
  - somewhat heavier spectrum of top partners
- expect exclusion or confirmation soon
  - search for charge $8/3$ colored fermions

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