Matter-Antimatter Asymmetry and Composite Higgs Models

Aika Marie Tada
with Andrei Angelescu, Andreas Bally, Florian Goertz and Maya Hager

Max-Planck-Institut für Kernphysik Heidelberg
aika.tada@mpi-hd.mpg.de

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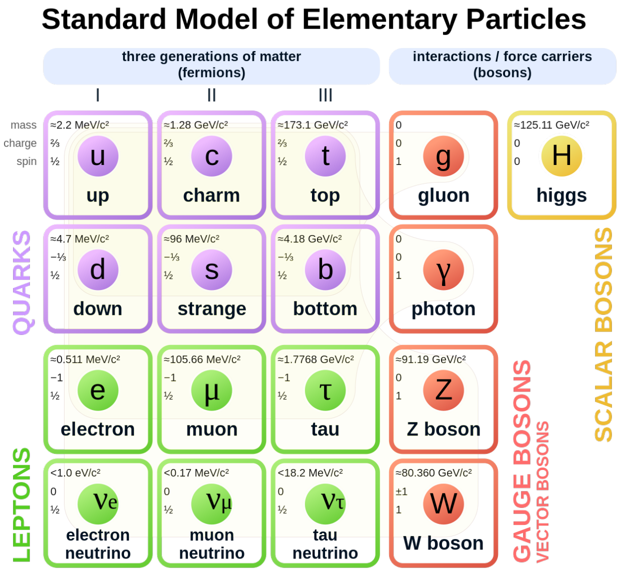
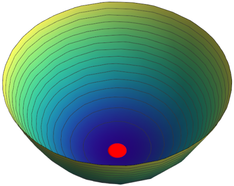
Outline



Masses of SM particles are obtained through the Higgs mechanism!

Goldstone's Theorem - Higgs Mechanism

For each "broken" generator in a spontaneously broken continuous symmetry, one massless mode arises.



Assume a scalar field H with

$$V(H) = \mu_h^2 |H|^2 + \lambda |H|^4$$

$$|\langle H(x) \rangle| = 0 \text{ for } \mu_h^2 > 0$$

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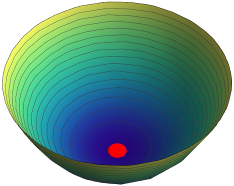
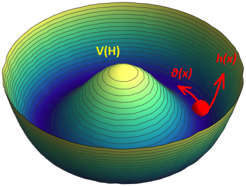


$\xrightarrow{\text{SSB: } \mu_h^2 < 0}$



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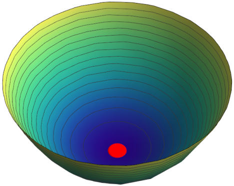

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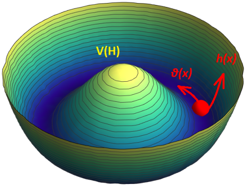

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$v_{\mathrm{SM}} = 246\,\mathrm{GeV}$ gives masses to SM particles $\rightarrow$ *Electroweak Phase Transition*

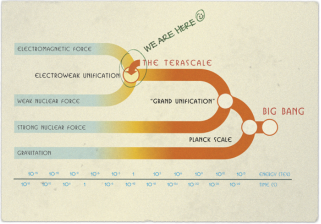
Why go *beyond* the Standard Model?

Experiment

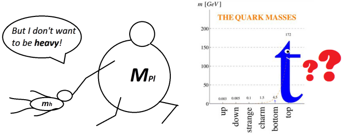
- Neutrino Masses
- Dark Matter
- Baryon Asymmetry

Theory

- Hierarchy Problem (HP)
- Grand Unified Theory (GUT), Gravity
- Hierarchy of quark masses, ...



interactions.org 2006



Goertz2022

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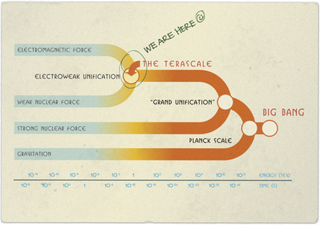

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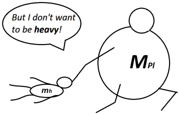

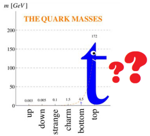

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Baryon Asymmetry in the Universe (BAU)

- Where is all the antimatter? $\eta_b = \dfrac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \cdot 10^{-10}$

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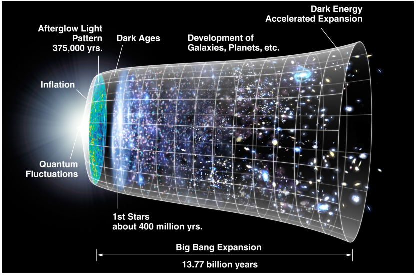

NASA/WMAP

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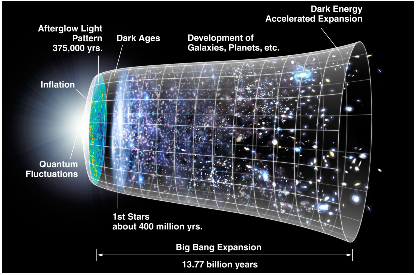
Sakharov Conditions

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium



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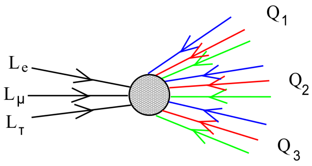

Sphaleron process, conserving $B-L$

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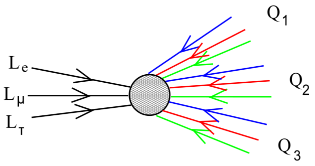

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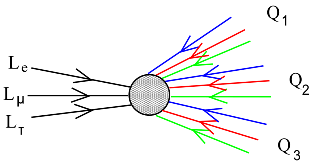

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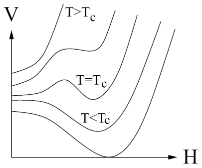
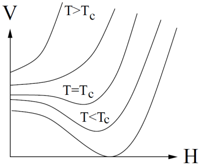
1st order PT

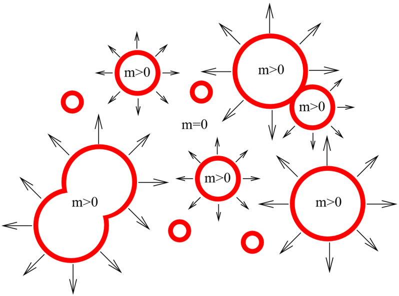


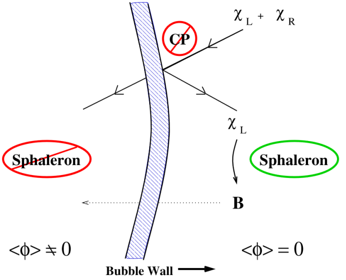
2nd order PT



Cline ph-0609145

Baryogenesis at the Electroweak Phase Transition





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Morrissey2012

- EW sphalerons convert leptons into baryons $\Delta B = \pm 3$ with interaction rate $\Gamma \propto e^{-\langle h \rangle / T}$
- C and CP violation ensures a baryon overdensity in front of the wall
- B absorbed by expanding bubbles of new vacuum

Electroweak Baryogenesis in the SM

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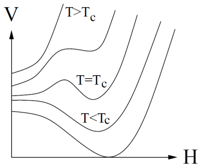

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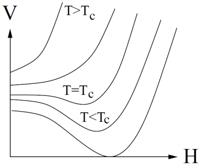

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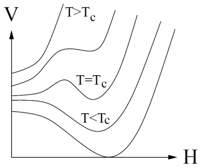

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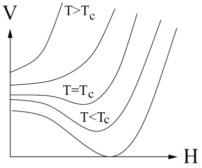

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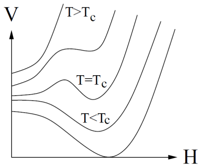

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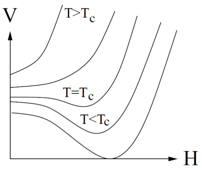

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  - e.g., SM + pseudoscalar singlet S

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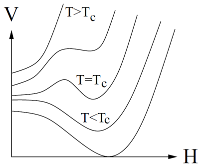

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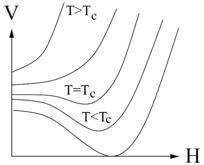

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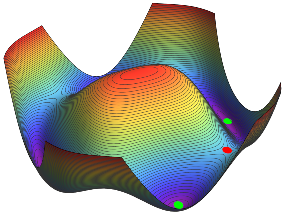
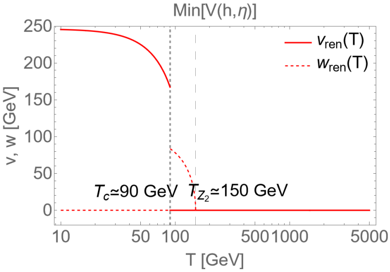
Enhancing the Electroweak Phase transition

Goal: obtain a jump in $\langle h \rangle$ in the thermal history

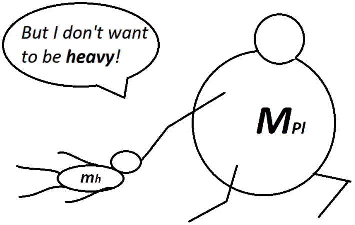
$$V = \frac{\mu_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{hS}}{2} h^2 S^2 + \frac{S^6}{\Lambda_{\rm NP}^2}$$

$$(\langle h \rangle, \langle S \rangle) = (0,0) \to (0,w) \to (v,0)$$





TOP-DOWN APPROACH



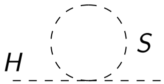
The Electroweak Hierarchy Problem

- $m_h = 125\,\text{GeV} \ll M_{\text{Pl}} \approx 10^{18}\,\text{GeV}$ – why care?
- QFT corrections to scalar mass parameter sensitive to *any* new physics (NP),

$$m^2_{h,\text{phys}} = m^2_{h,\text{UV}} - \Delta m^2_h\,,$$

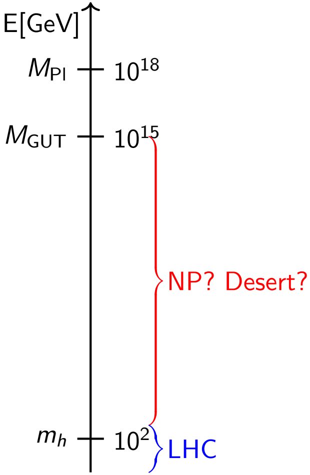
- E.g for a new heavy singlet S interacting with $-\lambda_{h\eta} H^2 S^2$:

$\Delta m_h^2 H^2 =$



$+ \dots$

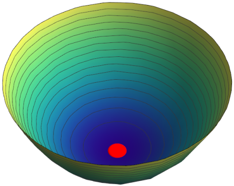
$$= H^2 \frac{\lambda_{h\eta}}{16\pi^2}\left[\Lambda^2_{\text{UV}} - 2 M_S^2 \ln\left(\frac{\Lambda_{\text{UV}}}{M_S}\right) + \dots\right]$$



$\rightarrow$ Supersymmetry, Composite Higgs (CH),...

Goldstone's Theorem

For each "broken" generator in a spontaneously broken continuous symmetry, one massless mode arises.



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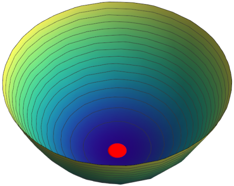
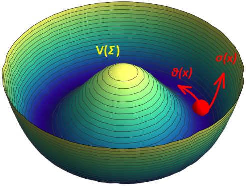


$\xrightarrow{\text{SSB}}$



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Goldstone's Theorem + Explicit Breaking

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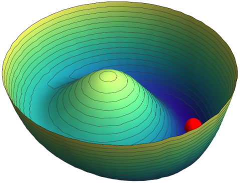
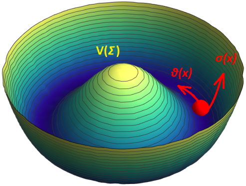


explicit breaking

$\longleftarrow$



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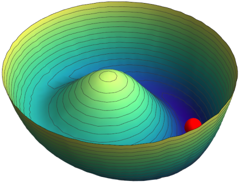

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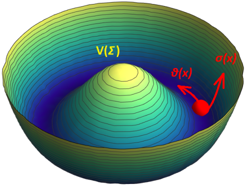

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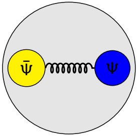
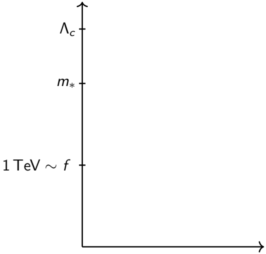
$\theta(x) \sim$ e.g. Pion in low energy QCD (χPT)

Composite Higgs Models

e.g. Panico & Wulzer [1506.01961]

Higgs $\sim$ Pion





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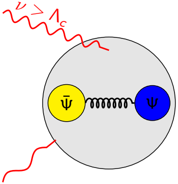
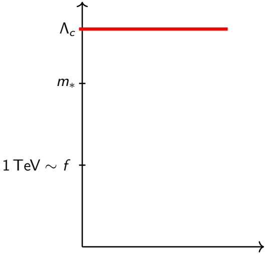
HIGGS ∼ PION

- H as a composite of new confining force





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HIGGS ~ PION

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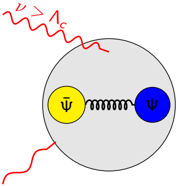
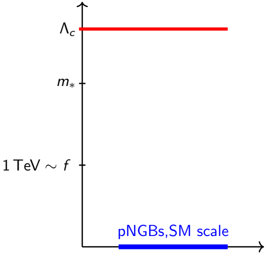
- Global symmetry $\mathbf{SO(6)} \overset{\text{SSB}}{\to} \mathbf{SO(5)}$ below Λ_c





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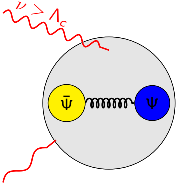
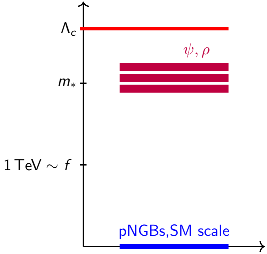
- H as a composite of new confining force
- Global symmetry **SO(6)** $\overset{\text{SSB}}{\rightarrow}$ **SO(5)** below Λ_c
  - H as Nambu-Goldstone-Boson, $V(H) = 0$
  - Massive resonances ψ, ρ





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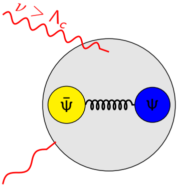
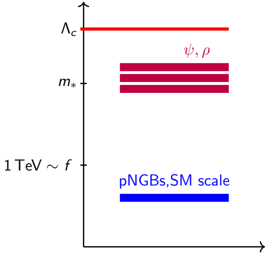
- Global symmetry **SO(6)** $\overset{\text{SSB}}{\rightarrow}$ **SO(5)** below Λ_c
  - H as Nambu-Goldstone-Boson, $V(H) = 0$
  - Massive resonances ψ, ρ
- Explicitly break $SO(6)$ by interaction with SM fermions and gauge bosons





Composite Higgs Models

e.g. Panico & Wulzer [1506.01961]

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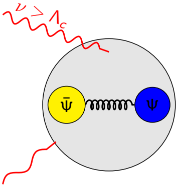

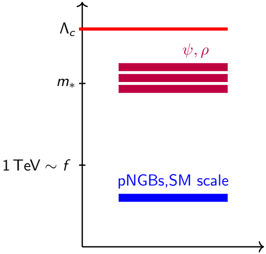

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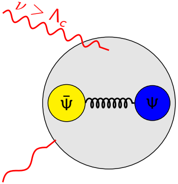
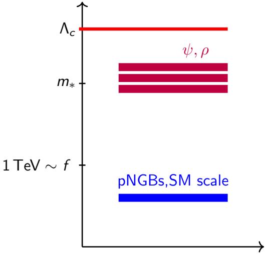


Solves Hierarchy Problem
& Higgs Potential is calculable!



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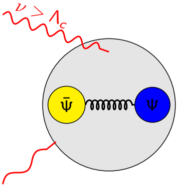
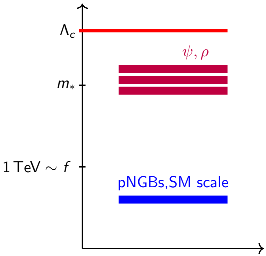
- e.g. $SO(6)/SO(5) \Rightarrow \frac{6\cdot5}{2} - \frac{5\cdot4}{2} = 5$ NGB dof
  - Complex H doublet + scalar singlet S



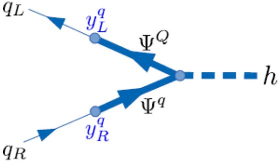


Constructing $V(h, S)$: Partial Compositeness

- Linear mixing between SM and composite particles,

$$\mathcal{L}_{\text{int}} \supset f\left(y_L^q \bar{q}_L' \psi_R^Q + y_R^q \bar{q}_R' \psi_L^q\right)$$

SM elementary + composite $(\psi, \rho) \xrightarrow{mass-diag}$ physical particles



FG 2020

- "Compositeness" determines fermion mass

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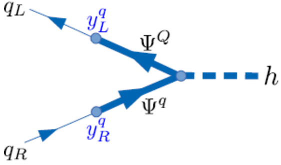
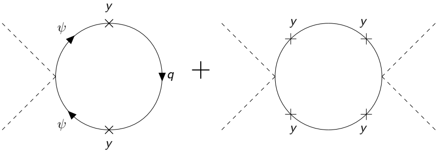


FG 2020

- "Compositeness" determines fermion mass
- Bounds on top partners ψ: $m \gtrsim 1.5\,\text{TeV}$ (e.g. [2210.15413])
- Bounds on SSB scale: $\left(\frac{v_{\text{EW}}}{f}\right)^2 \lesssim 0.1$, $f > 800\,\text{GeV}$

Constructing $V(h, S)$

- 1-loop Coleman-Weinberg Potential:

$V(h, S) \supset$  $+ \ldots$

$\sim y_{L,R}^2$ $\sim y_{L,R}^4$

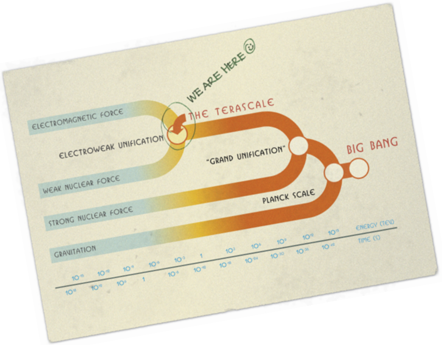
- Sensitive to representation of ψ and strength of $y_{L,R}$

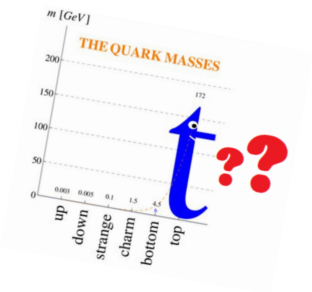
$$V = \underbrace{\frac{N_c m_\psi^4}{16\pi^2}}_{\text{dim factor}} \left(\frac{y_{L,R}}{g_*}\right)^{\#2q} \underbrace{c_{nm}}_{\overset{!}{\sim}\mathcal{O}(1)} \left(\frac{h}{f}\right)^{2n} \left(\frac{S}{f}\right)^{2m}$$

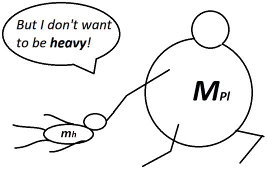
$$\overset{!}{=} \frac{\mu_h^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{hS}}{2} h^2 S^2 + \frac{S^6}{\Lambda_{\text{NP}}^2}$$

$\rightarrow$ Electroweak Baryogenesis

WHAT'S NEXT?



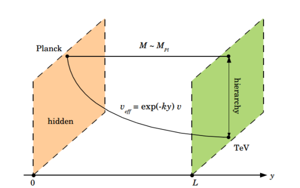




pics: interaction.org 2006, FG 2022, AT 2024

Explaining the Structure of the Standard Model?

- Structure of the SM from "natural" $O(1)$ parameters?
- Unification of forces?



pic: Bally2022

Two 4D branes at endpoints of warped extra dimension (Randall-Sundrum '99);

$+$

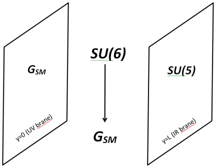
$$\left[\begin{array}{cc|c} W_\mu, B_\mu, \eta & X_\mu & H \\ {X_\mu}^\dagger & G_\mu, B_\mu, \eta & S_1 \\ \hline H^\dagger & S_1^\dagger & \eta \end{array}\right]$$

Higgs as 5^{th} component of a 5D gauge field

$\sim$ Composite Higgs in 4D

$=$ GAUGE-HIGGS GUT

Outlook



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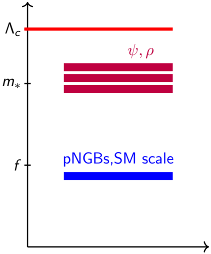

- $SU(6)/SU(5)$ CH model $\rightarrow$ Goldstone bosons
  $$\left[H(1,2)_{-\frac{1}{2}}, S_1(3,1)_{-\frac{1}{3}}\right] + \eta(1,1)_0$$
- Calculate the Higgs Potential analytically from 5D functions
- 2 additional scalars
  $\rightarrow$ Explore thermal history of this theory

Summary

- Electroweak Baryogenesis: enhanced EW phase transition + additional CP violation = BAU
- EW Hierarchy Problem: m_h sensitive to any new physics
- Composite Higgs: Higgs $\sim$ Pion (composite+global SSB)
- Structure of potential is calculable from symmetry considerations
- Natural candidate to realize EW Baryogenesis: pNGB singlet
- UV completion: Gauge-Higgs GUT in warped extradimension $\sim$ CH in 4D $\rightarrow$ explore thermal history and avenues for Baryogenesis

Thank You!

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- Physics from the Terascale: `http://interactions.org/cgi-bin/pd/pd.cgi?image=http://www.interactions.org/quantumuniverse/pd/images/postcard_13b_big.jpg&title=Terascale&form=form-basic.txt`, accessed via the internet archive for 10th October 2006
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- Singlet Assisted Baryogenesis in Composite Higgs Models: e.g.
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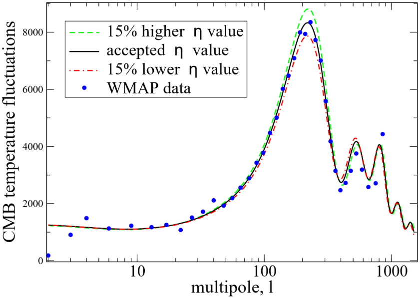
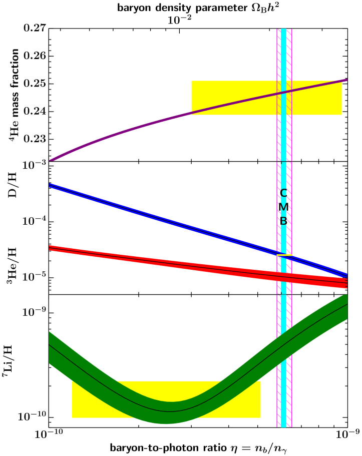
  - Angelescu, Bally, Goertz, Weber *SU(6) gauge-Higgs grand unification: minimal viable models and flavor*. JHEP 04 (2023), p. 012. doi: 10.1007/JHEP04(2023)012. arXiv: 2208.13782
  - Andrei Angelescu, Andreas Bally, Florian Goertz, and Maya Hager. *Restoring Naturalness via Conjugate Fermions*. Sept. 2023. arXiv: 2309.05698

Observed BAU



Dependence of CMB doppler peaks on η, [Cline2006]



Primordial abundances of light elements from BBN and observation. [PDG2023]

Creating a Matter-Antimatter Asymmetry: C and CP violation

Consider a particle decay that violates Baryon number, $X \to 2Q_{\mathrm{LH}}$. What would happen if...

- Charge conjugation (C) is a symmetry?
  - $\Gamma\left(X \to 2Q_{\mathrm{LH}}\right) = \Gamma\left(\bar{X} \to 2\bar{Q}_{\mathrm{RH}}\right)$
  - Overall, $\Delta B = 0$, therefore need $\not{C}$
- $\not{C}$ but Charge-Parity conjugation (CP) is a symmetry?
  - E.g., in terms of $SU(2)$ doublets Q and singlets q, $\Gamma(X \to 2Q_{\mathrm{LH}}) = \Gamma(\bar{X} \to 2\bar{q}_{\mathrm{RH}})$
  - $\dfrac{dB}{dt} \propto \Gamma(X \to 2Q_{\mathrm{LH}}) + \Gamma(X \to 2q_{\mathrm{RH}}) - (\Gamma(\bar{X} \to 2\bar{q}_{\mathrm{RH}}) + \Gamma(\bar{X} \to 2\bar{Q}_{\mathrm{LH}})) = 0$
  - additionally need $\not{C}\not{P}$

CP-violation in Singlet-Assisted EWBG

- introduce spontaneously CP-violating term

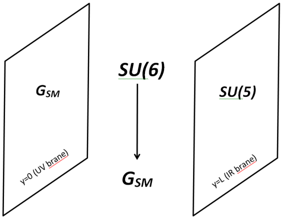
$$\bar{t}_L m_t e^{i\theta_t} t_R + \text{h.c.} = \bar{t}_L h \left(y_t + (a + ib)\frac{\eta}{f} \right) t_R + \text{h.c.},$$

- choose purely CP-odd η ($a = 0$); also ensures Z_2-sym. potential V
- change in $\langle \eta \rangle$ needed at the EWPhT to obtain the correct BAU estimated in Espinosa2012:

$$\Delta\theta_t \approx \frac{b}{y_t} \frac{\left| \langle \eta \rangle_{\text{EW}} - \langle \eta \rangle_{\text{Z2-broken}} \right|_{T_c}}{f} \overset{!}{\gtrsim} 0.1$$

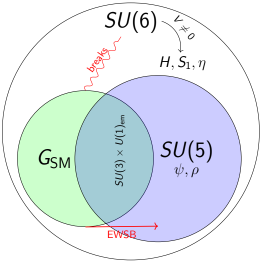
Holographic Composite Higgs

e.g. Contino TASI [1005.4269]



pic: Bally2022

$\approx$



Assume: full gauge symmetry and full fermion multiplets in bulk

$\downarrow$

Break by boundary conditions on branes.

SM particles = zero modes of KK tower

Assume: Global SSB + massive composite resonances Ψ, ρ

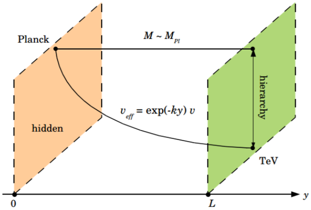
$\downarrow$

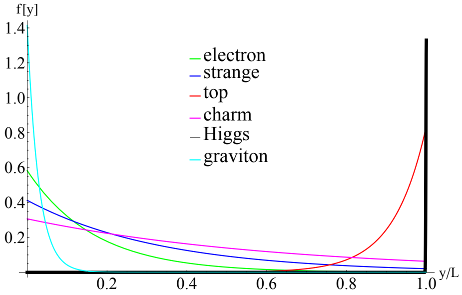
Break by coupling to SM sector

$\longrightarrow$

use particle content

Fermion mass hierarchies from localization in 5D

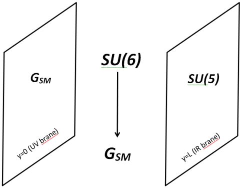




pics: Bally2022

A Viable Gauge-Higgs GUT [adapted from Angelescu2022]

- GHGUT → appealing model–building direction:
  - + unification of gauge interactions and EWSB
  - + GUTs w/o perturbative proton decay
  - + solution to gauge and flavour hierarchies
  - + Higgs mass calculable → microscopic understanding of EWSB



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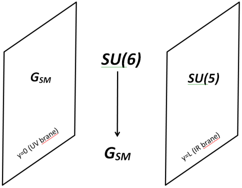
- Viable $SU(6)$ GUT [2104.07366,2208.13782]
  - + correct SM spectrum + flavour hierarchies, no dangerously light exotics
  - + correct EWSB (tuning $\sim 0.1\,\%$) $\Rightarrow$ correct m_h follows naturally
  - + scalar heavy Leptoquark $S_1(\mathbf{3},\mathbf{1})_{-\mathbf{1/3}}$ + scalar singlet
  - + flavour constraints, EW precision parameters, Leptoquark searches



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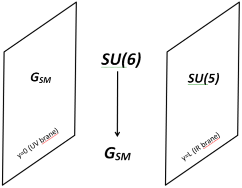

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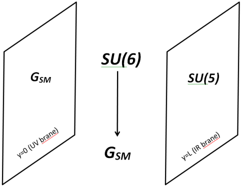

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$\rightarrow$ Obtain SM structure from natural parameters $+$ rich phenomenology!

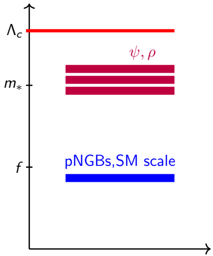
$\rightarrow$ Some things are easier in the dual description:
4D $SU(6)/SU(5)$ Composite Higgs model

What we can learn for the 4D Potential

- $SU(6)/SU(5)$ CH model $\rightarrow$ Goldstone bosons
  $\left[H(1,2)_{-\frac{1}{2}}, S_1(3,1)_{-\frac{1}{3}}\right] + \eta(1,1)_0$

$$\left[\begin{array}{cc|c} W_\mu, B_\mu, \eta & X_\mu & H \\ X_\mu{}^\dagger & G_\mu, B_\mu, , \eta & S_1 \\ \hline H^\dagger & S_1^\dagger & \eta \end{array}\right]$$

- Particle content from 5D:
  - Embedding of elem. particles in spurions
  - Vectorlike exotic $\omega(\mathbf{3}^*, \mathbf{1})_{-2/3}$ crucial to reproduce Higgs potential
  - Massive $X(3,2)_{-\frac{5}{6}}$ bosons
- Usually: light top partners needed to obtain correct $V(H)$ $\rightarrow$ rather make **exotic partners light**
- Scalar singlet, possible massive RH neutrino
  $\rightarrow$ Explore baryogenesis at EW scale



Constructing the Thermal Potential - In Practice

$$V_{\text{eff}}^{T}(\phi_c) = V_0(\phi_c) + V_{\text{1-loop}}^{0}(\phi_c) + V_{\text{1-loop}}^{T}(\phi_c)$$

$$V_{\text{1-loop}}^{0}(\phi_c) = \sum_{i=h,S,\Pi,W,Z,\gamma,q} \frac{n_i}{2} \int \frac{d^4k}{(2\pi)^4} \ln\left(k^2 + m_i^2(\phi_c)\right) ,$$

$$V_{\text{1-loop}}^{T}(\phi_c) = \sum_{i=h,S,\Pi,W,Z,\gamma} \frac{n_i T^4}{2\pi^2} J_B\left[\frac{m_i^2(\phi_c)}{T^2}\right] + \sum_{i=q} \frac{n_i T^4}{2\pi^2} J_F\left[\frac{m_i^2(\phi_c)}{T^2}\right] ,$$

With the thermal function

$$J_{B/F}\left[m_i^2/T^2\right] = \int_0^\infty dx\, x^2 \ln\left[1 \mp e^{-\sqrt{x^2+m_i^2/T^2}}\right] , \tag{1}$$

- $m_i^2(\phi_c)$ calculated by the 2-field derivative of $\mathcal{L}_0$
- n_i: dof of the contributing particle

Constructing the Thermal Potential - In Practice

Choosing high temperature expansion $T \gg m_i$:

$$V^T_{\text{1-loop}}(\phi_c) = \sum_{i=h,S,\Pi,W,Z,\gamma} \frac{n_i T^4}{2\pi^2} J_B\left[\frac{m_i^2(\phi_c)}{T^2}\right] + \sum_{i=q} \frac{n_i T^4}{2\pi^2} J_F\left[\frac{m_i^2(\phi_c)}{T^2}\right]$$

$$\approx \frac{1}{24}\sum_{i=bosons} n_i m_i^2(h,S)\, T^2 + \frac{1}{48}\sum_{i=fermions} n_i m_i^2(h,S)\, T^2 \,.$$

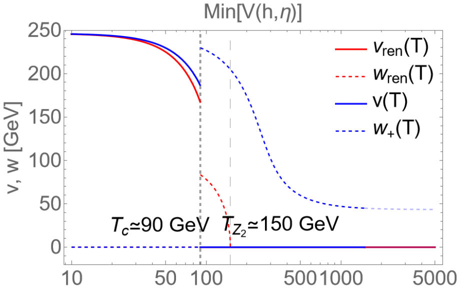
For example, for our SM+Singlet case:

$$V^T_{\text{1-loop}}(h,S) = \frac{T^2}{2}\left(\frac{1}{48}\left(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 4\lambda_{hS}\right)h^2 + \frac{\lambda_{hS}}{3} + \frac{\lambda_S}{4}S^2\right) + \frac{5T^2}{4\Lambda^2_{\text{NP}}}S^4\,,$$

which may give us a SFOPhT via

Spontaneous Z_2 breaking:
$(0,0) \rightarrow (w_{ren},0) \rightarrow (0, v_{ren})$

Z_2 Non-restoration:
$(w_+,0) \rightarrow (0,v)$

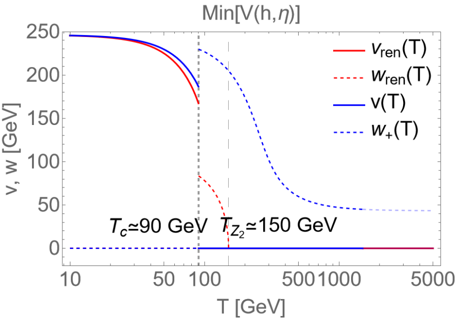


Z_2 Non-Restoration: High T effective Potential

EFT adding $D > 4$ operators: Z_2 SNR possible

$$V_0(h,S) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_S^2}{2}S^2 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{hS}}{2}h^2S^2 + \frac{S^6}{\Lambda_{\mathrm{NP}}^2}$$

$$V_T(h,S) = \frac{T^2}{2}\left(c_h h^2 + \underbrace{\left(\frac{\lambda_{hS}}{3} + \frac{\lambda_S}{4}\right)}_{<0} S^2\right) + \frac{5T^2}{4\Lambda_{\mathrm{NP}}^2}S^4$$

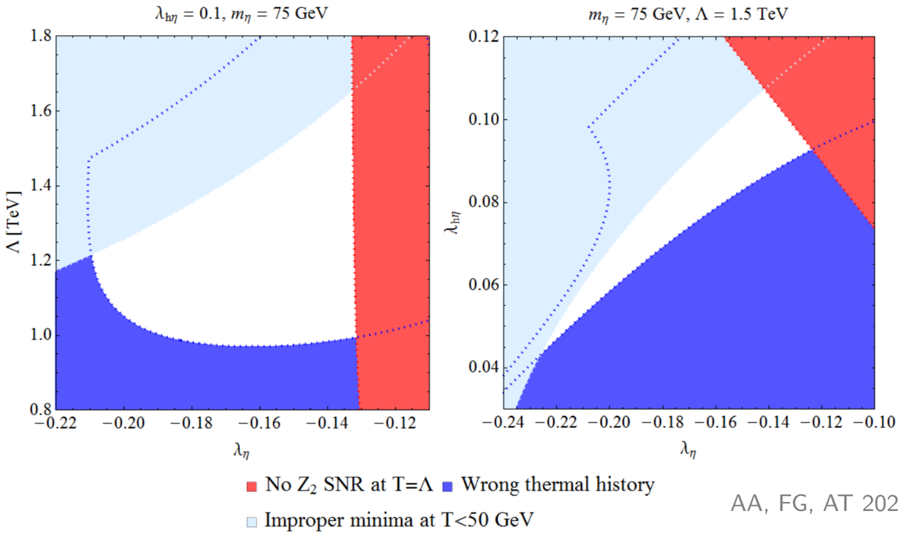


Spontaneous Z_2 breaking:
$(0,0) \to (w_{ren},0) \to (0,v_{ren})$

Z_2 Non-restoration:
$(w_+,0) \to (0,v)$

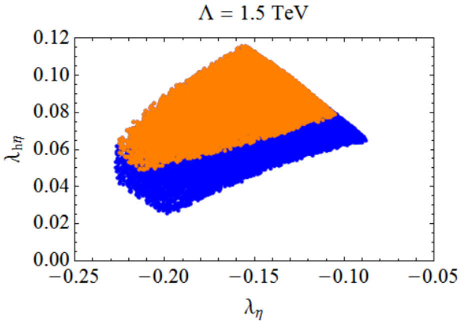
AA, FG, AT 2021
$\Lambda_{\mathrm{NP}} = 1.5\,\mathrm{TeV}, \lambda_S = -0.15,$
$\lambda_{hS} = 0.1,\ m_S = 75\,\mathrm{GeV}$

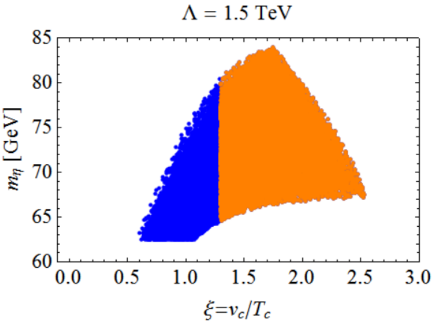
Z_2 Non-Restoration: General Constraints



AA, FG, AT 2021

Z_2 Non-Restoration: First Order Phase Transition





SFOPhT for $v_c/T_c \gtrsim 1$

- assume $m_\eta > m_h/2$, $\langle\eta\rangle_{T=0} = 0$

AA, FG, AT 2021

- $\lambda_{h\eta} \sim \mathcal{O}(0.1)$ as compared to $\mathcal{O}(1)$ in Z_2 2-step scenarios