The Origin of Matter

Cosmic Energy Budget

- Dark Matter: 27%
- Baryons: 5%
- Dark Energy: 68%
Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model.
Symmetries & Cosmic History
Symmetries & Cosmic History

EW Symmetry Breaking: Higgs

Standard Model Universe

QCD: q+g → n,p…
QCD: n+p → nuclei
Astro: stars, galaxies,…
Symmetries & Cosmic History

EW Symmetry Breaking: Higgs

Standard Model Universe

QCD: $q+g \rightarrow n,p…$

QCD: $n+p \rightarrow$ nuclei

Astro: stars, galaxies,…
What is the nature of the EW phase transition?

EW Symmetry Breaking: Higgs

Standard Model Universe

QCD: $q+g \rightarrow n,p…$

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Symmetries & Cosmic History

What is the nature of the EW phase transition? → Origin of matter?

EW Symmetry Breaking: Higgs

Standard Model Universe

QCD: $q+g \rightarrow n,p,\ldots$

QCD: $n+p \rightarrow$ nuclei

Astro: stars, galaxies,..
Symmetries & Cosmic History

EW Symmetry Breaking: Higgs

New Forces?

Standard Model Universe

QCD: $q+g \rightarrow n,p$...

QCD: $n+p \rightarrow$ nuclei

Astro: stars, galaxies,..
What is the Origin of Matter


\[ Y_B = \frac{n_B}{S_\gamma} = (9.29 \pm 0.34) \times 10^{-11} \]
What is the Origin of Matter


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EW Baryogenesis: testable w/ EDMs + colliders

Leptogenesis: less testable, look for ingredients w/ νs

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Other Scenarios:
- GUT baryogenesis
- Affleck-Dine
- Asymmetric DM
- Post sphaleron…

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Symmetries & the Origin of Matter


EW Baryogenesis: testable with EDMs + colliders

Leptogenesis: less testable, look for ingredients withνs

Can new TeV scale physics explain the abundance of matter?
If so, how will we know?

\[ Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11} \]
Questions for This Workshop

• What happened ~ 10ps after the Big Bang?
Questions for This Workshop

• What happened ~ 10ps after the Big Bang?
• Single step (cross over) transition?
• More d.o.f. with a richer pattern of EWSB?
  • Single or multiple steps?
  • First or second order?
  • Coupled to origin of matter?
Questions for This Workshop

- What happened ~ 10ps after the Big Bang?
- Single step (cross over) transition?
- More d.o.f. with a richer pattern of EWSB?
  - Single or multiple steps?
  - First or second order?
  - Coupled to origin of matter?
- What are collider signatures that could provide clues?
  - Modified Higgs properties (production, decays)
  - New states
Recent Developments:

• **BICEP2 CMB B-mode observation** → **Evidence for primordial gravitational radiation associated with inflation**

• **Discovery of BEH-like boson** → **Paradigm of symmetry-breaking in particle physics driven by a fundamental scalar likely correct**

• **Non-observation (so far) of physics beyond the Standard Model at the LHC**
Recent Results

• Discovery of BEH-like scalar at the LHC

• Non-observation (so far) of sub-TeV particles at LHC
Recent Results

• Discovery of BEH-like scalar at the LHC
  • Idea of $\phi$-driven spontaneous EW symmetry breaking is likely correct

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Recent Results

• Discovery of BEH-like scalar at the LHC
  • Idea of $\phi$-driven spontaneous EW symmetry breaking is likely correct

• Non-observation (so far) of sub-TeV particles at LHC
  • Sub-TeV BSM spectrum is compressed
  • Sub-TeV BSM is purely EW or Higgs portal
  • BSM physics lies at very different mass scale
Outline

• Portals & the Early Universe
• Why the Higgs Portal
• Scalar Fields in Particle Physics & Cosmology
• General Considerations
• Illustrative Higgs Portals: Simplest Extensions
I. Portals & Early Universe

Standard Model

“Hidden Sector”: DM, early universe dynamics (EWPT)…
Portals

Two approaches:

• Specific model (MSSM….)
• “Model independent”
Model Independent Portals

- Vector portal ("dark photons"
- Neutrino portal
- Axion portal
- Higgs portal
- Higher dimensional op’s portal
Model Independent Portals

• Vector portal ("dark photons"…)
• Neutrino portal
• Axion portal
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Model Independent Portals

- Vector portal (“dark photons”…)
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- Higher dimensional op’s portal
Higgs Portal: DM

\[ \mathcal{O}_4 = \lambda_{\phi H} \; \phi^\dagger \phi \; H^\dagger H \]

- Renormalizable
- \(Z_2\) symmetric
- Dimensionless coupling
- \(\phi\) (DM): singlet or charged under \(SU(2)_L \times U(1)_Y\)
Higgs Portal: Phase Transitions

\[ \mathcal{O}_4 = \lambda_{\phi_H} \phi^\dagger \phi \ H^\dagger H \]

- Renormalizable ✔
- \(Z_2\) symmetric ✗
- Dimensionless coupling ✗
- \(\phi\) (DM): singlet or charged under \(SU(2)_L \times U(1)_Y\)
Higgs Portal: Higher Dim Op’s

\[ O_5 = \frac{\lambda_{\chi H}}{\Lambda} \bar{\chi} \chi H^\dagger H \]  

+...

- Renormalizable \times
- \( \mathbb{Z}_2 \) symmetric \checkmark
- Dimensionless coupling \times
- \( \chi \) (DM): singlet or charged under \( SU(2)_L \times U(1)_Y \)
II. Why the Higgs Portal?
Stable EW Vacuum?

Preserving EW Min

\[ V_{\text{EFF}} \]

**EW vacuum**

**top loops**

\[
\beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4 \right) \]

sets \( m_H \)

top loops
Stable EW Vacuum?

Preserving EW Min

"Funnel plot"

\[ V_{\text{EFF}} \]

\( \phi \)

top loops

EW vacuum

perturbativity

\[ \beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4 \right) \]

sets \( m_H \)

top loops
Stable EW Vacuum?

Preserving EW Min: $V_{\text{eff}}$ (EW vacuum) and top loops.

“Funnel plot”: perturbativity.

$\beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 \right) - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4$

sets $m_H$, top loops.
Stable EW Vacuum?

Preserving EW Min

“Funnel plot”

$V_{\text{EFF}}$

EW vacuum

top loops

naïve stability scale $\Lambda$

$perturbativity$

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sets $m_H$

top loops

SM stability & pert’vity

$m_H$

SM unstable above ~ $10^8 - 10^{15}$ TeV
Stable EW Vacuum?

Preserving EW Min

“Funnel plot”

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EW vacuum

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$\beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4 \right)$

sets $m_H$

top loops

Higgs portal interactions → more robust stability?

SM stability & pert’vity

$M_W$

$\Lambda$

$\sim 10^8 - 10^{13}$ TeV

SM unstable above
What is the BSM Energy Scale $\Lambda$?

BSM: $\mathcal{O}_{BSM} = c / \Lambda^2 \rightarrow \Lambda \sim 10 \text{ TeV}$

EWPO: data favor a "light" SM-like Higgs scalar

$\sim 10^{-3}$ agreement with EWPO

LHC: so far no sub-TeV BSM physics

Higgs Portal: new low scale d.o.f.?
III. Scalar Fields in Particle Physics & Cosmology

$\varphi$
Scalar Fields in Cosmology

What role do scalar fields play (if any) in the physics of the early universe?
Scalar Fields in Cosmology

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<thead>
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• Could experimental discovery of additional scalars point to early universe scalar field dynamics?

• Are there signatures in modified Higgs properties, new states, or EW precision tests?
### Scalar Fields in Cosmology

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**Focus of this talk, but perhaps part of larger role of scalar fields in early universe**
IV. General Considerations
**Thermal DM:** $\Omega_{CDM} \ & \sigma_{SI}$

**Thermal DM: WIMP**

**Direct detection: Spin-indep DM-nucleus scattering**
Thermal DM: $\Omega_{CDM} \& \sigma_{SI}$

**Thermal DM: WIMP**

\[ \Omega h^2 \approx 0.1 \times \left( \frac{(\sigma v)_{\text{freeze}}}{3 \times 10^{-26} \text{ cm}^3 \text{s}^{-1}} \right)^{-1} \]

freeze out \rightarrow \Omega x h^2

\[ x = M_x / T \]

CDMS 2013
K McCarthy APS '13

WIMP-nucleon cross-section [cm$^2$]

WIMP Mass [GeV/c$^2$]

hep-ex:0695502
EWPT & EW Baryogenesis
EW Phase Transition: New Scalars & CPV
EW Phase Transition: New Scalars & CPV

Increasing $m_h$
EW Phase Transition: New Scalars & CPV

Increasing $m_h$  

New scalars
**EW Phase Transition: New Scalars & CPV**

Increasing $m_h$ → *New scalars*

“Strong” 1\textsuperscript{st} order EWPT

**Baryogenesis**

**Gravity Waves**

**Scalar DM**

**LHC Searches**
**EW Phase Transition: New Scalars & CPV**

- **Increasing** $m_h$
- **New scalars**

**Baryogenesis**
- Gravity Waves
- Scalar DM
- LHC Searches

- "Strong" **1st order EWPT**
- Bubble nucleation

**EWSB**
**EW Phase Transition: New Scalars & CPV**

- **1st order EWPT**
  - Bubble nucleation

- **1st order** vs **2nd order**

- **Increasing** $m_h$
  - New scalars

- **Baryogenesis**
- **Gravity Waves**
- **Scalar DM**
- **LHC Searches**

- $Y_B$ : CPV & EW sphalerons

- **EWSB**
**EW Phase Transition: New Scalars & CPV**

- Increasing $m_h$
- New scalars

**Baryogenesis**
- Gravity Waves
- Scalar DM
- LHC Searches

- "Strong" 1st order EWPT
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- $Y_B$: CPV & EW sphalerons
- EWSB

- BSM
**EW Phase Transition: New Scalars & CPV**

Increasing $m_h$ → **New scalars**

**Baryogenesis**
- Gravity Waves
- Scalar DM
- LHC Searches

"Strong" 1st order EWPT → Bubble nucleation

$Y_B$ diffuses into interiors → EWSB

1st order EWPT

2nd order
**EW Phase Transition: New Scalars & CPV**

- **1st order**
  - New Scalars
  - Y$_B$ initial: diffuses into interiors
  - EWSB

- **2nd order**
  - Increasing $m_h$
  - EWSB

**Baryogenesis**
- Gravity Waves
- Scalar DM
- LHC Searches

**Gravity Waves**

**Quench**
- EW sph

**Strong**
- 1st order EWPT
- Bubble nucleation

**Preserve**
**EW Phase Transition: New Scalars & CPV**

- 1st order
- 2nd order

**Increasing** $m_h$

- New scalars

**Baryogenesis**
- Gravity Waves
- Scalar DM
- LHC Searches

---

**“Strong” 1st order EWPT**

- Preserve $Y_B^{initial}$
- Bubble nucleation

- Quench EW sph
- $Y_B$ : diffuses into interiors

- EWSB
**EW Phase Transition: Gravity waves**

- **1st order**
- **2nd order**

---

**“Strong” 1st order EWPT**

- Detonation & turbulence
- Bubble nucleation

---

**EW Spectra:**

- $\Delta Q$
- $\Delta t_{EW}$

---

**GW Spectra:**

$F(\phi)$
**EW Phase Transition: New Scalars & CPV**

Increasing $m_h$  

New scalars

**Baryogenesis**  
**Gravity Waves**  
**Scalar DM**  
**LHC Searches**

"Strong"  
1st order EWPT

Preserve $Y_B^{initial}$  
Bubble nucleation

Quench EW sph  
$Y_B$: diffuses into interiors  
EWSB
Electroweak Phase Transition
**EW Phase Transition: St’d Model**

**Lattice: Endpoint**

<table>
<thead>
<tr>
<th>Lattice</th>
<th>Authors</th>
<th>$M_h^C$ (GeV)</th>
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<tbody>
<tr>
<td>4D Isotropic</td>
<td>[76]</td>
<td>80 ± 7</td>
</tr>
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Increasing $m_h$

**S’td Model: 1st order EWPT requires light Higgs**
EW Phase Transition: New Scalars

Increasing $m_h$  

New scalars

MSSM: Light RH stops

PT: Carena et al,…

Lattice: Laine, Rummukainen

Decreasing RH stop mass

CCB Vac

EWPT

$1^{st}$ order

$2^{nd}$ order
**EW Phase Transition: MSSM**

- Increasing $m_h$
- New scalars

**MSSM: Light RH stops**

*Carena et al 2008: Higgs phase metastable*
EW Phase Transition: MSSM

1st order  2nd order

Increasing $m_h$  →  New scalars

MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable
**EW Phase Transition: MSSM**

- Increasing $m_h$
- New scalars
- **MSSM: Light RH stops**
  - Carena et al 2008: Higgs phase metastable

---

**1st order**

**2nd order**
**EW Phase Transition: Higgs Portal**

Increasing $m_h$ → 1st order

New scalars

$$\mathcal{O}_4 = \lambda_{\phi H} \phi \phi H^\dagger H + \ldots$$
**EW Phase Transition: Higgs Portal**

- **Increasing** $m_h$
- **New scalars**

$$\mathcal{O}_4 = \lambda_{\phi H} \phi \phi^{\dagger} H^{\dagger} H + \ldots$$

- Renormalizable
- $\phi$: singlet or charged under $SU(2)_L \times U(1)_Y$
- Generic features of full theory (NMSSM, GUTS...)
- More robust vacuum stability
- Novel patterns of SSB
**EW Phase Transition: Higgs Portal**

- 1st order
- 2nd order

Increasing $m_h$ → New scalars

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## Higgs Portal: Simple Scalar Extensions

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<td>✔</td>
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<tr>
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<tr>
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May be low-energy remnants of UV complete theory & illustrative of generic features
May be low-energy remnants of UV complete theory & illustrative of generic features (NMSSM, GUTs, Hidden Valley....)

### Higgs Portal: Simple Scalar Extensions

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May be low-energy remnants of UV complete theory & illustrative of generic features (NMSSM, GUTs, Hidden Valley....)
The Simplest Extension

Simplest extension of the SM scalar sector: add one real scalar $S$ (SM singlet)

$$V_{HS} = \frac{a_1}{2} \left( H^\dagger H \right) S + \frac{a_2}{2} \left( H^\dagger H \right) S^2$$

**EWPT:** $a_{1,2} \neq 0$ & $\langle S \rangle \neq 0$

**DM:** $a_1 = 0$ & $\langle S \rangle = 0$

O’Connel, R-M, Wise; Profumo, R-M, Shaugnessy; Barger, Langacker, McCaskey, R-M Shaugnessy; He, Li, Li, Tandean, Tsai; Petraki & Kusenko; Gonderinger, Li, Patel, R-M; Cline, Laporte, Yamashita; Ham, Jeong, Oh; Espinosa, Quiros; Konstandin & Ashoorioon…
The Simplest Extension, Cont’d

Mass matrix

\[ M^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}/2 \\ \mu_{hs}/2 & \mu_s^2 \end{pmatrix} \]

\begin{align*}
\mu_h^2 & \equiv \frac{\partial^2 V}{\partial h^2} = 2\lambda_0 v_0^2 \\
\mu_s^2 & \equiv \frac{\partial^2 V}{\partial s^2} = b_3 x_0 + 2b_4 v_0^2 - \frac{a_1 v_0^2}{4x_0} \\
\mu_{hs}^2 & \equiv \frac{\partial^2 V}{\partial h \partial s} = (a_1 + 2a_2 x_0) v_0 \\
\end{align*}

\[
(h_1) = \begin{pmatrix} \sin \theta & \cos \theta \end{pmatrix} (h) \\
(h_2) = \begin{pmatrix} \cos \theta & -\sin \theta \end{pmatrix} (s)
\]

\[
\tan \theta = \frac{y}{1 + \sqrt{1 + y^2}}, \quad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}
\]

\[
m_{1,2}^2 = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2} \sqrt{1 + y^2}
\]

\( x_0 = <S> \)
The Simplest Extension, Cont’d

**Mass matrix**

\[
\begin{align*}
\mu_h^2 & \equiv \frac{\partial^2 V}{\partial h^2} = 2\bar{\lambda}_0 v_0^2 \\
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\mu_{hs}^2 & \equiv \frac{\partial^2 V}{\partial h \partial s} = (a_1 + 2a_2 x_0) v_0 \\
\tan \theta & = \frac{y}{1 + \sqrt{1 + y^2}}, \quad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2} \\
m_{1,2}^2 & = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2} \sqrt{1 + y^2}
\end{align*}
\]

New topologies
The Simplest Extension, Cont’d

Mass matrix

Mass matrix

$\mu_h^2 \equiv \frac{\partial^2 V}{\partial h^2} = 2\lambda_0 v_0^2$

$\mu_s^2 \equiv \frac{\partial^2 V}{\partial s^2} = b_3 x_0 + 2 b_4 x_0^2 - \frac{a_1 v_0^2}{4 x_0}$

$\mu_{hs}^2 \equiv \frac{\partial^2 V}{\partial h \partial s} = (a_1 + 2 a_2 x_0) v_0$

$\tan \theta = \frac{y}{1 + \sqrt{1 + y^2}}$,  \quad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}$

Stable S (dark matter)

• Tree-level $Z_2$ symmetry: $a_1=0$ to prevent $s$-$h$ mixing and one-loop $s \rightarrow hh$

• $x_0 = 0$ to prevent $h$-$s$ mixing & $s \rightarrow hh$
The Simplest Extension

**DM Scenario**

\[ V_{HS} = \] 

\[ + \frac{\alpha_2}{2} \left( H \dagger H \right) S^2 \]
The Simplest Extension

DM Scenario

\[ V_{HS} = - \frac{a_2}{2} \left( H^\dagger H \right) S^2 \]

\[ \Omega_{DM} & \sigma_{SI} \]

Signal Reduction Factor

Production

Decay

DM Scenario
DM Phenomenology

Relic Density

He, Li, Li, Tandean, Tsai

Direct Detection

He, Li, Li, Tandean, Tsai

Barger, Langacker, McCaskey, R-M, Shaugnessy
New Scalars EW Vacuum Stability

Preserving EW Min

“Funnel plot”

\[ V_{\text{eff}} \]

EW vacuum

top loops

naïve stability scale \( \Lambda \)

[Diagram showing EW vacuum, top loops, and naive stability scale.]

[Graph showing "Funnel plot" with perturbativity and SM stability & pert'vity.]

\[ \beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4 \right) \]

[Equation for DM-H coupling and top loops.]

Gonderinger, Li, Patel, R-M; Gonderinger, Lim, R-M
New Scalars EW Vacuum Stability

Preserving EW Min

“Funnel plot”

SM stability & pert’vity

$m_H$

SM + singlet: stable but non-pertur’tive

$V_{\text{eff}}$

EW vacuum

top loops

naïve stability scale $\Lambda$

$\beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4 \right)$

DM-H coupling

top loops

Gonderinger, Li, Patel, R-M; Gonderinger, Lim, R-M
**LHC & Higgs Phenomenology**

**LHC discovery potential**

**Signal Reduction Factor**

\[ \xi_i^2 = \frac{V_{ij}^2 \text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})} \]

Production  \hspace{5cm} Decay
LHC & Higgs Phenomenology

LHC discovery potential

Signal Reduction Factor

$$\xi^2_i = V_{1j}^2 \frac{\text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})}$$

Production → Decay

$$V_{1j} < 1: \text{mixed states } h_j$$

New decays: $$h_2 \rightarrow h_1 h_1$$
**LHC & Higgs Phenomenology**

**LHC discovery potential**

**Signal Reduction Factor**

\[
\xi_i^2 = V_{ij}^2 \frac{BF(H_j \to X_{SM})}{BF(h_{SM} \to X_{SM})}
\]

Production  \quad Decay

\(V_{1j} < 1: \text{mixed states } h_j\) \quad \text{New decays: } h_2 \rightarrow h_1 h_1

**Dark matter:** no mixing  \rightarrow states are \(h,S\)

New decays \(h \rightarrow SS \) (invisible!) possible
LHC & Higgs Phenomenology

LHC discovery potential

Invisible decays

Signal Reduction Factor

$$\xi_i^2 = V_{ij}^2 \frac{\text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})}$$

Production

Decay

He, Li, Li, Tandean, Tsai

Invis search

CMS 30 fb\(^{-1}\)

ATLAS, CMS @ 30 fb\(^{-1}\)
**LHC & Higgs Phenomenology**

**LHC discovery potential**

**Invisible decays**

**Signal Reduction Factor**

\[ \xi_i^2 = \frac{V_{1j}^2}{\text{BF}(h_{SM} \rightarrow X_{SM})} \frac{\text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})} \]

Production \quad \text{Decay}

He, Li, Li, Tandean, Tsai

**Dijet azimuthal distribution**

Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld ‘00)
LHC & Higgs Phenomenology

LHC discovery potential

Invisible decays

Signal Reduction Factor

\[ \xi_i^2 = \frac{V_{ij}^2 \text{BF}(H_j \to X_{SM})}{\text{BF}(h_{SM} \to X_{SM})} \]

Production
Decay

See Ketevi Assamagan & Jianming Qian Talks

Dijet azimuthal distribution

Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld ’00)
Real Singlet: EWPT

\[ V_{HS} = \frac{a_1}{2} \left( H^\dagger H \right) S + \frac{a_2}{2} \left( H^\dagger H \right) S^2 \]

Stable S (dark matter?)

Tree-level Z

\[ a_1 = b_3 = 0 \] to prevent s-h mixing and one-loop s

\[ x = 0 \] to prevent h-s mixing

EWPT: Signal Reduction Factor

Production

Decay
Real Singlet: EWPT

$$V_{HS} = \frac{a_1}{2} \left( H^\dagger H \right) S + \frac{a_2}{2} \left( H^\dagger H \right) S^2$$

- Raise barrier
- Lower $T_C$
Real Singlet: EWPT

Low energy phenomenology

\[ V_{HS} = \frac{a_1}{2} (H^\dagger H) S + \frac{a_2}{2} (H^\dagger H) S^2 \]

- Raise barrier
- Lower \( T_C \)
- Mixing
- Modified BRs

Two mixed (singlet-doublet) states w/ reduced SM branching ratios
EWPT & LHC Phenomenology

Signatures

$m_2 > 2 m_1$

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

$m_1 > 2 m_2$

Profumo, R-M,
Shaughnessy ‘07
EWPT & LHC Phenomenology

Signatures

Light: all models
Black: LEP allowed
Scan: EWPT-viable model parameters
LHC exotic final states: 4b-jets, γγ + 2 b-jets...

Profumo, R-M, Shaugnessy ‘07
MWPT & LHC Phenomenology

Signatures

\[ m_2 > 2 m_1 \]

\[ m_1 > 2 m_2 \]

Light: all models
Black: LEP allowed

Scan: EWPT-viable model parameters

LHC: reduced BR(h → SM)

Signal Reduction Factor

\[ \xi_i^2 = \frac{V_{iJ}^2 \text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})} \]

Production

Decay

Profumo, R-M, Shaugnessy ‘07
**EWPT: Resonant Di-Higgs Production**

**Signatures**

$m_2 = 270$ GeV “un-boosted”
$m_2 = 370$ GeV “boosted”

$bb\tau^+\tau^- : \text{discovery with } \sim 100 \text{ fb}^{-1} \text{ in } \tau_{lep} \tau_{had} \text{ channel}$

**Scan: EWPT-viable model parameters**

**Light: all models**
**Black: LEP allowed**

*R-M & No, arXiv:1310.6035*
**EWPT: Resonant Di-Higgs Production**

**Signatures**

\[ m_2 = 270 \text{ GeV "un-boosted"} \]
\[ m_2 = 370 \text{ GeV "boosted"} \]

**bb\(\tau^+\tau^-\) : discovery with \(~ 100 \text{ fb}^{-1}\) in \(\tau_{\text{lep}} \tau_{\text{had}}\) channel**

---

R-M & No, arXiv:1310.6035
EWPT & LHC Phenomenology

Signatures

$m_2 > 2 m_1$

Mixed States:
Precision ↔ ILC

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

$m_1 > 2 m_2$

See Peter Winslow Talk

Profumo, R-M,
Shaugnessy ’07
### Higgs Portal: Simple Scalar Extensions

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</tr>
<tr>
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<td>✔</td>
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<tr>
<td>Real Triplet</td>
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*May be low-energy remnants of UV complete theory & illustrative of generic features*
Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Spontaneously & softly broken global $U(1)$\[<s> \neq 0\]

$$V_{HS} = \frac{\delta^2}{2} H^\dagger H |\tilde{S}|^2 = \frac{\delta^2}{2} H^\dagger H (S^2 + A^2)$$

Controls $\Omega_{CDM}$, $T_C$, & H-S mixing

$$V_{\tilde{S}} = \frac{b_2}{2} |\tilde{S}|^2 + \frac{b_1}{2} \tilde{S}^2 + \text{c.c.} + \cdots$$

Gives non-zero $M_A$
Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Consequences:

Three scalars: \( h_1, h_2 \): mixtures of \( h \) & \( S \)

\( A \): dark matter

Phenomenology:

- Produce \( h_1, h_2 \) w/ reduced \( \sigma \)
- Reduce BR (\( h_j \rightarrow \text{SM} \))
- Observation of BR (invis)
- Possible obs of \( \sigma^{SI} \)
# Higgs Portal: Simple Scalar Extensions

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Simplest non-trivial EW multiplet
Real Triplet

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]

\[ V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2 \]

**EWPT:** \( a_{1,2} \neq 0 \) & \( <\Sigma^0> \neq 0 \)

**DM & EWPT:** \( a_1 = 0 \) & \( <\Sigma^0> = 0 \)

*Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]*
Real Triplet

$$\Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0)$$

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**EWPT:** $a_{1,2} \neq 0 \& \langle \Sigma^0 \rangle \neq 0$

**DM & EWPT:** $a_1 = 0 \& \langle \Sigma^0 \rangle = 0$

**Small:** $\rho$-param

*Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]*
Real Triplet: DM

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]

\[ V_{H \Sigma} = \frac{a_2}{2} H\dagger H \text{ Tr } \Sigma^2 \]

EWPT: \( a_{1,2} \neq 0 \) & \( <\Sigma^0> \neq 0 \)

DM & EWPT: \( a_1 = 0 \) & \( <\Sigma^0> = 0 \)

Small: \( \rho \)-param

EW Phase Transition: Higgs Portal

1st order  2nd order

Increasing $m_h$  →

New scalars

Real Triplet  $\Sigma \sim (1,3,0)$

Two-step EWPT &

dark matter

Quench sphalerons

Small entropy dilution

Baryogenesis

$\Sigma$ dark matter

Patel, R-M: arXiv 1212.5652; Fileviez-Perez, Patel, RM, Wang
**Higgs Diphoton Decays**

LHC: \( H \rightarrow \gamma \gamma \)

**Real Triplet: EWPT**

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]


\[
V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2
\]

Two-step EWSB

1. Break SU(2)_L x U(1)\_Y w/ \( \Sigma \) vev
2. Transition to Higgs phase w/ small or zero \( \Sigma \) vev

EWB favorable
Real Triplet: EWPT

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]

\[ V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2 \]

Two-step EWSB

1. Break SU(2)_L x U(1)_{Y} w/ \Sigma vev

2. Transition to Higgs phase w/ small or zero \Sigma vev

Real Triplet: DM Search

Mass splitting due to EW symmetry breaking:

\[ M_{\Sigma^\pm} - M_{\Sigma^0} \sim \frac{\alpha}{4\pi} M_W \]

\[ \Sigma^+ \rightarrow \Sigma^0 + \pi^+ \text{ (soft)} \]

Generalizes to higher dim EW multiplets
**Real Triplet : DM Search**

**Basic signature:**
\[ x_0 = 0 : H^\pm \rightarrow H_2 \pi^\pm \]

**Charged track disappearing after \(~5\) cm**
\[ q\bar{q} \rightarrow W^\pm \rightarrow H^\pm H_2 \quad q\bar{q} \rightarrow Z^*,\gamma^* \rightarrow H^+H^- \]

**SM Background:**
- QCD jZ and jW w/ 
- \( Z \rightarrow \nu\nu \) & \( W \rightarrow l\nu \)

**Trigger:** Monojet (ISR) + large \( \not{E}_T \)

*Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]*
Real Triplet : DM Search

**Basic signature:**
\[ x_0 = 0 : H^\pm \rightarrow H_2 \pi^\pm \]

**Charged track disappearing after \( \sim 5 \) cm**
\[ q\bar{q} \rightarrow W^\pm \rightarrow H^\pm H_2 \quad q\bar{q} \rightarrow Z^*, \gamma^* \rightarrow H^+ H^- \]

**Trigger:** Monojet (ISR) + large \( E_T \)

**SM Background:**
QCD \( jZ \) and \( jW \) w/ \( Z \rightarrow \nu\nu \) & \( W \rightarrow l\nu \)

**Cuts:**
- large \( E_T \)
- hard jet
- One 5cm track

EW Phase Transition: Higgs Portal

Do good symmetries today need to be good symmetries in the early Universe?

Increasing $m_h$  
New scalars

Symmetry Breaking & Restoration

Do good symmetries today need to be good symmetries in the early Universe?

Rochelle salt: $\text{KNaC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$

Increasing $T$ →

creasing $m_h$ →

New scalars

J. Valasek
EW Phase Transition: Higgs Portal

Do good symmetries today need to be good symmetries in the early Universe? No

- O(n) x O(n): Weinberg (1974)
- SU(5), CP…: Dvali, Mohapatra, Senjanovic (‘79, 80’s, 90’s)
- Cline, Moore, Servant et al (1999)
- EM: Langacker & Pi (1980)

**EW Phase Transition: Higgs Portal**

Do good symmetries today need to be good symmetries in the early Universe? No

- $O(n) \times O(n)$: Weinberg (1974)
- $SU(5)$, CP…: Dvali, Mohapatra, Senjanovic ('79, '80's, '90's)
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---

**Color Breaking & Restoration**

Two illustrative cases:  

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H. Patel, R-M, Wise  
1303.1140 (2013)
## Color Breaking & Restoration

Two illustrative cases: H. Patel, R-M, Wise 1303.1140 (2013)

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**Spontaneous B violation**
EW Phase Transition: Higgs Portal

1. Break SU(3)$_C$

2. Restore SU(3)$_C$

Increasing $m_h$

New scalars

Colored Scalars (triplet)

Color breaking & restoration

Summary: Workshop Questions

- What happened ~ 10ps after the Big Bang?

- Single step (cross over) transition?

- More d.o.f. with a richer pattern of EWSB?
  - Single or multiple steps?
  - First or second order?
  - Coupled to origin of matter?

- What are collider signatures that could provide clues?
  - Modified Higgs properties (production, decays)
  - New states
Back Up Slides
Ingredients for Baryogenesis

- B violation (sphalerons)
- C & CP violation
- Out-of-equilibrium or CPT violation

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Ingredients for Baryogenesis

- B violation (sphalerons)
- C & CP violation
- Out-of-equilibrium or CPT violation

Scenarios: leptogenesis, EW baryogenesis, Affleck-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis...

Standard Model | BSM
--- | ---
✔ | ✔
✖ | ✔
✖ | ✔
Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Affleck-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

Testable
Standard Model BSM

• B violation (sphalerons) ✔ ✔
• C & CP violation ✗ ✔
• Out-of-equilibrium or CPT violation ✗ ✔
Baryon Number Preservation

“Washout factor”

\[ S \equiv \frac{\rho_B(\Delta t_{EW})}{\rho_B(0)} > e^{-N} \]

Two quantities of interest:

- \( T_C \) from \( V_{\text{eff}} \)
- \( E_{\text{sph}} \) from \( \Gamma_{\text{eff}} \)

\[ \ln S \sim A(T_C) e^{\zeta} \]

\[ \zeta = F(\varphi) \]

\[ \zeta \equiv \left. \frac{\hat{E}_{\text{sph}}}{T} \right|_{T=T_C} \]
Daisy Resummation

Convergence of PT: going beyond $\bar{h}_l$ expansion

Light stop scenario

For given $T$, increasingly negative $m_i^2$ increases difference between two minima

Increased $\Delta V$ $\rightarrow$ Lowered $T_C$
DM Phenomenology

Relic Density

He, Li, Li, Tandean, Tsai

Direct Detection

He, Li, Li, Tandean, Tsai

Higgs pole

Barger, Langacker, McCaskey, R-M, Shaugnessy

$\lambda$, $\sigma_\text{aa}$ (cm$^2$), $\sigma_\text{DM}$, $\Omega_\text{DM}$

$S \rightarrow H \rightarrow _\tilde{f} f$
**Real Triplet: EWPT**

$\Sigma^0, \Sigma^+, \Sigma^-$ \sim (1, 3, 0)  


\[ V_{H\Sigma} = \frac{a_2}{2} H \dagger H \ Tr \ \Sigma^2 \]

**Two-step EWSB**

1. **Break SU(2)_L x U(1)_Y w/ $\Sigma$ vev**
2. **Transition to Higgs phase w/ small or zero $\Sigma$ vev**

![Diagram showing the relationship between $m_H$, $a_2$, and $\delta$ with the SM as a reference point.](image)
Real Triplet: EWPT

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]


Two-step EWSB

\[ V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2 \]
Real Triplet: EWPT

\[ \Sigma^0, \Sigma^+, \Sigma^- \sim (1, 3, 0) \]


Two-step EWSB

1. Break SU(2)_L x U(1)\_\gamma w/ \Sigma vev
2. Transition to Higgs phase w/ small or zero \Sigma vev
# Color Breaking & Restoration

Two illustrative cases:  

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“Light”: special flavor structure  

Spontaneous B violation
## Color Breaking & Restoration

**Two illustrative cases:**

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- heavy: generic flavor structure
- Spontaneous B violation

SM + Color Triplet

H. Patel, R-M, Wise
1303.1140 (2013)

\[ V = -\mu_H^2 (H^\dagger H) - \mu_C^2 (C^\dagger C) + \frac{\lambda_H}{2} (H^\dagger H)^2 \]
\[ + \frac{\lambda_C}{2} (C^\dagger C)^2 + \lambda_{HC} (H^\dagger H)(C^\dagger C). \]

Decays: \[ C \rightarrow \langle C \rangle = \nu_C \] : B violation

\[ L_Y = C \bar{u}_R g_{uL} L_L + C \bar{Q}_L g_{Qe} e_R + \text{h.c..} \]
**SM + Color Triplet**


\[
V = -\mu_H^2 (H^\dagger H) - \mu_C^2 (C^\dagger C) + \frac{\lambda_H}{2} (H^\dagger H)^2 \\
+ \frac{\lambda_C}{2} (C^\dagger C)^2 + \lambda_{HC} (H^\dagger H)(C^\dagger C).
\]

**Upper bound on** \( m_C \):

\[
\begin{align*}
m_h^2 &= 2\mu_H^2 = 2\lambda_H v_H^2 > 0 \\
m_C^2 &= -\mu_C^2 + \lambda_{HC} v_H^2 > 0
\end{align*}
\]

\[
m_C < (\sqrt{\lambda_{HC}}) v_H \simeq (174 \text{ GeV}) \sqrt{\lambda_{HC}}
\]
SM + Color Triplet + Singlet


\[ \Delta V = -\frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{HC} (H^\dagger H)(C^\dagger C) + \frac{\lambda_{HS}}{2} (H^\dagger H)S^2 + \frac{\lambda_{CS}}{2} (C^\dagger C)S^2 + \frac{e_S}{3} S^3 + e_C C^\dagger CS + e_H H^\dagger HS. \]

Heavier colored scalar

\[ m_C^2 = -\mu_C^2 + \lambda_{HC} v_H^2 + \frac{\lambda_{CS}}{2} v_S^2 + e_C v_S \]
**Higgs Decays: All Channels**

**ATLAS Preliminary**

- $WZ \to bb$
  - $\mathcal{L} = 7 \text{ TeV}, L = 4.7 \text{ fb}^{-1}$
  - $\mathcal{L} = 8 \text{ TeV}, L = 13 \text{ fb}^{-1}$
- $H \to \tau\tau$
  - $\mathcal{L} = 7 \text{ TeV}, L = 4.6 \text{ fb}^{-1}$
  - $\mathcal{L} = 8 \text{ TeV}, L = 13 \text{ fb}^{-1}$
- $H \to WW^{(*)} \to h\nu\nu$
  - $\mathcal{L} = 7 \text{ TeV}, L = 4.6 \text{ fb}^{-1}$
  - $\mathcal{L} = 8 \text{ TeV}, L = 20.7 \text{ fb}^{-1}$
- $H \to \gamma\gamma$
  - $\mathcal{L} = 7 \text{ TeV}, L = 4.8 \text{ fb}^{-1}$
  - $\mathcal{L} = 8 \text{ TeV}, L = 20.7 \text{ fb}^{-1}$
- $H \to ZZ^{(*)} \to 4l$
  - $\mathcal{L} = 7 \text{ TeV}, L = 4.6 \text{ fb}^{-1}$
  - $\mathcal{L} = 8 \text{ TeV}, L = 20.7 \text{ fb}^{-1}$

**Combined**

- $\mathcal{L} = 7 \text{ TeV}, L = 4.6 - 4.8 \text{ fb}^{-1}$
- $\mathcal{L} = 8 \text{ TeV}, L = 13 - 20.7 \text{ fb}^{-1}$

**CMS Preliminary**

$m_h = 125.7 \text{ GeV}$

- $p_{SM} = 0.65$
- $H \to bb$
  - $\mu = 1.15 \pm 0.82$
- $H \to \tau\tau$
  - $\mu = 1.10 \pm 0.41$
- $H \to \gamma\gamma$
  - $\mu = 0.77 \pm 0.27$
- $H \to WW$
  - $\mu = 0.68 \pm 0.20$
- $H \to ZZ$
  - $\mu = 0.92 \pm 0.28$

Best fit $\sigma/\sigma_{SM}$

$\mathcal{L} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1}$
$\mathcal{L} = 8 \text{ TeV}, L \leq 19.8 \text{ fb}^{-1}$
Theoretical Issues

Gauge-dependence in $V_{\text{EFF}}(\varphi, T)$

$V_{\text{EFF}}(\varphi, T) \rightarrow V_{\text{EFF}}(\varphi, T; \xi)$

Ongoing research: approaches for carrying out tractable, GI computations

- C. Wainwright, S. Profumo, MRM Phys Rev. D84 (2011) 023521
- H. Gonderinger, H. Lim, & MRM, arXiv:1202.1316
Origin of Gauge Dependence

Effective Action

\[ \Gamma[\phi_{c1}(x)] = W[j] - \int d^4 x j(x) \phi_{c1}(x) \]

\[ W[j] = -i \ln Z[j] \]

\[ Z[j] = \int \mathcal{D}\phi \mathcal{D}A \mathcal{D}\eta \mathcal{D}\eta^\dagger e^{i \int d^4 x \left[ \mathcal{L}(x; j, \xi) \right]} \]

Effective Potential

\[ \phi_{c1}(x) \rightarrow \phi_{c1} \quad \Gamma(\phi_{c1}) = -(\text{vol}) V_{\text{eff}}(\phi_{c1}) \]

Source term:

\[ \int d^d x j(x) \phi(x) \]

Not GI
Nielsen Identities

Identity:

\[
\frac{\partial \Gamma}{\partial \xi} = \int d^d x \ d^d y \left[ C(\phi, A; x, y) \frac{\delta \Gamma}{\delta \phi(x)} + E_\mu(\phi, A; x, y) \frac{\delta \Gamma}{\delta A_\mu^a(x)} \right]
\]

Extremal configurations:

\[
\frac{\delta \Gamma}{\delta \phi(x)} = \frac{\delta \Gamma}{\delta A_\mu^a(x)} = 0 \quad \Rightarrow \quad \frac{\partial \Gamma}{\partial \xi} = 0
\]

Effective potential:

\[
\phi \rightarrow \phi_{\text{min}}(\xi)
\]

\[
\frac{\partial V_{\text{eff}}}{\partial \xi} = -\tilde{C}(\phi, \xi) \frac{\partial V_{\text{eff}}}{\partial \phi} = 0
\]
Baryon Number Preservation

\[ S \equiv \frac{\rho_B(\Delta t_{EW})}{\rho_B(0)} > e^{-N} \]

\[ \ln S \sim A(T_C) e^{\zeta} \]

\[ \zeta = F(\varphi) \]

\[ \zeta \equiv \frac{E_{\text{sph}}}{T} \bigg|_{T=T_C} \]

Two qtns of interest:

- \( T_C \) from \( V_{\text{eff}} \)
- \( E_{\text{sph}} \) from \( \Gamma_{\text{eff}} \)
Baryon Number Preservation: Pert Theory

\[ S \equiv \frac{\rho_B(\Delta t_{EW})}{\rho_B(0)} > e^{-N} \]

Conventional treatments

Gauge Dep

“Baryon number preservation criterion” (BNPC)

H. Patel & MRM, JHEP 1107 (2011) 029

\[ \zeta = F(\varphi) \]
Baryon Number Preservation: Pert Theory

\[ S \equiv \frac{\rho_B(\Delta t_{EW})}{\rho_B(0)} > e^{-N} \]

Conventional treatments

\[ \zeta = F(\varphi) \]

Gauge Dep

“Baryon number preservation criterion” (BNPC)

- GI \( T_C \) from hbar exp, \( V_{\text{eff}}(\phi^*\phi) \), or Hamiltonian formulation
- Use GI scale in \( E_{\text{sph}} \) computation

H. Patel & MRM, JHEP 1107 (2011) 029
Nielsen Identities: Application to $T_C$

Critical Temperature

$$V_{\text{eff}}(\phi_{\text{min}}, T_C) = V_{\text{eff}}(0, T_C)$$

Apply consistently order-by-order in $\hbar$

$$V_{\text{eff}}(\phi, T) = V_0(\phi) + \hbar V_1(\phi, T) + \hbar^2 V_2(\phi, T) + \ldots$$

$$\phi_{\text{min}} = \phi_0 + \hbar \phi_1(T, \xi) + \hbar^2 \phi_2(T, \xi) + \ldots$$

Implement minimization order-by-order (defines $\phi_n$)

$$V_{\text{eff}}[\phi_{\text{min}}(T), T] = V_0(\phi_0) + \hbar V_1(\phi_0, T)$$

$$+ \hbar^2 \left[ V_2(\phi_0, T, \xi) - \frac{1}{2} \phi_1(T, \xi) \frac{\partial^2 V_0}{\partial \phi^2} |_{\phi_0} \right] + O(\hbar^3)$$

References:
- Fukuda & Kugo '74: $T=0$ $V_{\text{EFF}}$
- Laine '95: 3D high-T Eff Theory
- Patel & R-M '11: Full high T Theory
Obtaining a GI $T_C$

Track evolution of minima with $T$ using $\hbar$ expansion

$n=1$

$n=2$

$n=3$

Track evolution of different minima with $T$ using

$V_{\text{eff}}[\phi_{\text{min}}(T), T] = V_0[\phi_{0}^{(n)}] + \hbar V_1[\phi_{0}(n), T]$

Illustrative results in SM:

$V_{\text{eff}}(\phi_{\text{min}}(T), T) = V_0(\phi) + \hbar V_1(\phi, T)$

Full $\phi$

$V_{\text{eff}}[\phi_{\text{min}}(T), T] = V_0(\phi_0) + \hbar V_1(\phi_0, T)$