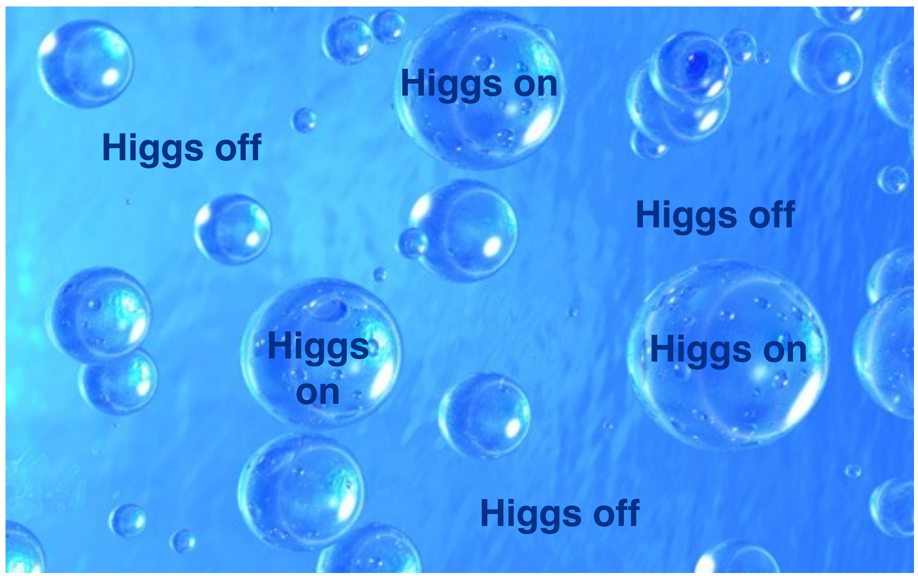
New Opportunities for Electroweak Baryogenesis



Marcela Carena
Fermilab/Uchicago
Higgs Hunting, September 13, 2022

THE UNIVERSITY OF CHICAGO

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The great success of the Higgs Boson

Its discovery and subsequent study of its properties at the LHC has provided *a first portrait* of the electroweak symmetry breaking mechanism

It ensures the calculability of the SM at high energies

It offers us a powerful tool for the exploration of fundamental questions in particle physics, e.g. Baryogenesis, Dark Matter, Inflation?

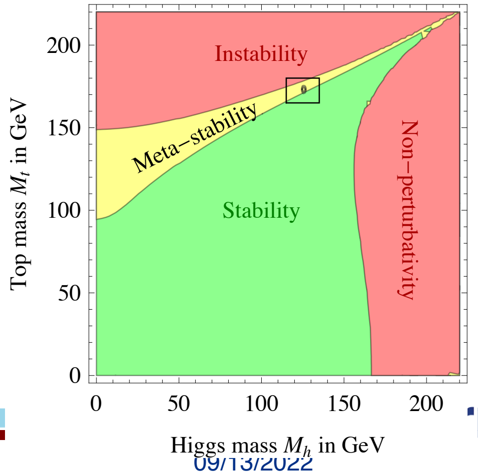
What is encoded in the Higgs potential?

$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

- What determines the values of the Higgs mass parameter and quartic coupling?

- Is there an explanation for the apparent metastability of the Higgs potential?

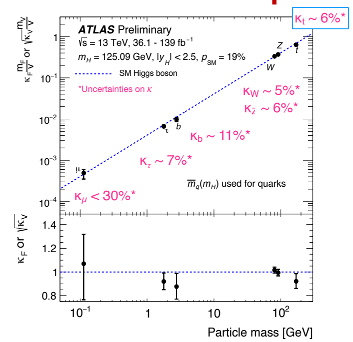
- Is it a part of a richer scalar potential ?
- If so, what is the dynamics of the electroweak phase transition ?



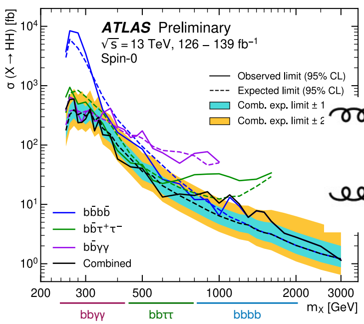
The Higgs boson: a lot to understand

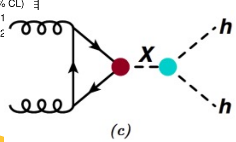
With M_H = 125 GeV, its mass is at a lucky spot to maximally allow us to look for surprises

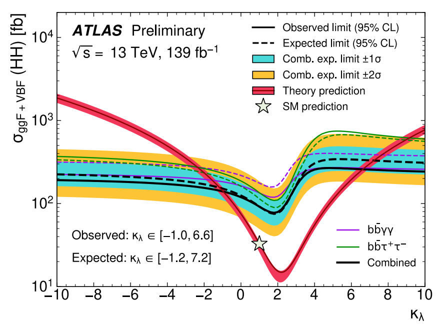
- We have verified that the Higgs boson is related to the Higgs mechanism of electroweak symmetry breaking
- We have verified that the Higgs boson couples most strongly to the heaviest SM matter particles

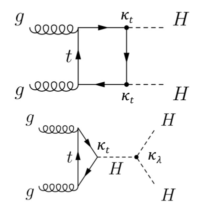


- Enhanced di-Higgs production is now starting to be probed already at the LHC

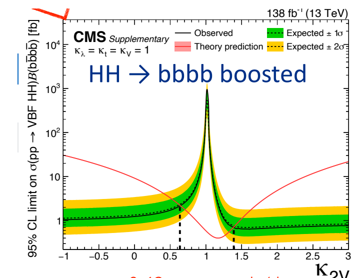






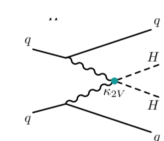


+ higher order EFT operators



$0.62 < \kappa_{2V} < 1.41$

$(0.66 < \kappa_{2V} < 1.37)$ @ 95% CL



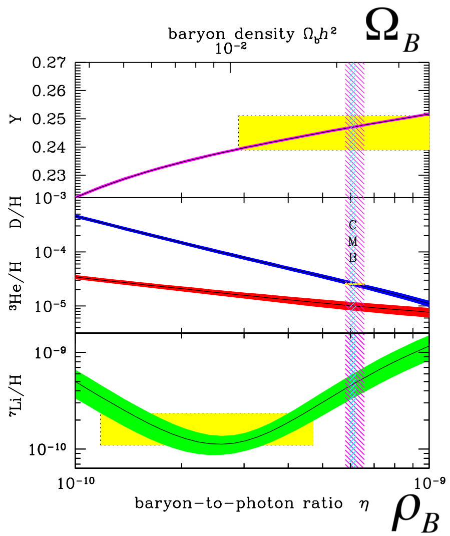
This can shed light on understanding the Higgs potential and the EW phase transition

Explore: Do all fermions get their masses from the same Higgs field?
Do Higgs couplings conserve flavor/CP? What about exotic/inv. Higgs decays?

What is behind the EWSB mechanism: Radiative breaking? Compositeness?

The Mystery of our Asymmetric Universe

Precision Cosmology: information on baryon abundance



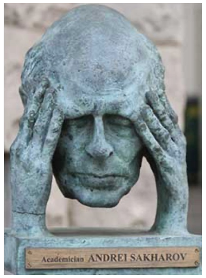
- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis
- CMB

$$\boxed{\eta = n_B / n_\gamma \approx 6.10^{-10}}$$

What generated the small observed baryon-antibaryon asymmetry?

Initial condition, or generated during the evolution of the universe?

Starting from a CPT conserving theory, the necessary Sakharov's conditions for baryogenesis are



- Baryon (or Lepton) number violation: if universe starts symmetric
- C and CP violation: treat baryon/anti-baryon differently (to remove antimatter)
- Out-of-thermal equilibrium: suppress inverse processes

All three requirements fulfilled in the SM – conditions are necessary but NOT sufficient to produced the OBSERVED asymmetry

Baryon Number Violation: Anomalous Processes

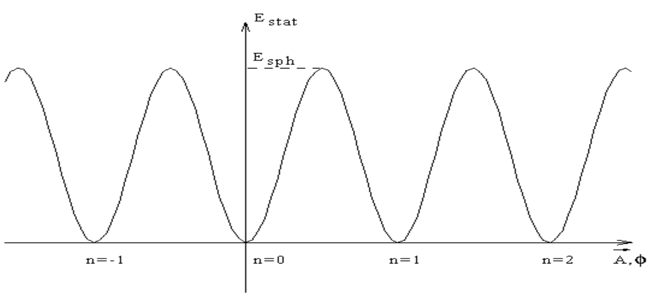
In the SM, Baryon Number conserved at classical level but violated at quantum level

- For gauge theories, one finds violation of classically preserved symmetries due to the quantization process: Anomalies Adler, Bell, Jackiw; Bardeen
- For the chiral weak interactions, gauge symmetry preservation yields the non-conservation of baryon and lepton currents

$$\partial_\mu j^\mu_{B,L} \propto F^a_{\mu\nu} F^a_{\rho\delta} \epsilon^{\mu\nu\rho\delta} \qquad \text{If} \quad S_{inst} = \frac{1}{16\pi}\int dx^4 Tr[FF] \neq 0 \quad \Longrightarrow \quad \Delta Q_{B,L} \neq 0$$

$$\Delta B = \Delta L = n \quad \text{(per generation)}$$

Anomalous processes violate both baryon and lepton number, hence violate B+L, but they preserve B – L. They can proceed by the production of "sphalerons"



$E_{sph} \sim 8\pi\, v(T) / g$

➔ height of the barrier separating vacua with different baryon number

Static configuration: middle point in the instanton tunneling

SM Baryon Number Violation at zero and finite Temperature

- At T = 0, B-violating sphaleron processes exponentially suppressed

$$\Gamma_{\Delta B\neq 0} \cong \exp(-2\pi/\alpha_W) \qquad \text{with } S_{inst} = 8\pi/\alpha_w$$

- At very high temperatures they are unsuppressed,

$$\Gamma_{\Delta B\neq 0} \propto T$$

- At finite temperature they are Boltzmann suppressed

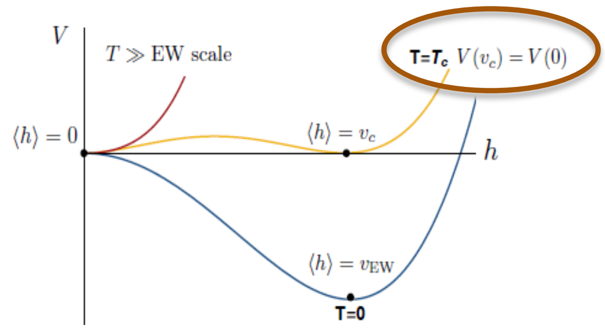
$$\Gamma_{\Delta B\neq 0} \cong \beta_0\, T \exp(-E_{sph}(T)/T) \qquad \text{with } E_{sph} \sim 8\pi\, v(T)/g$$

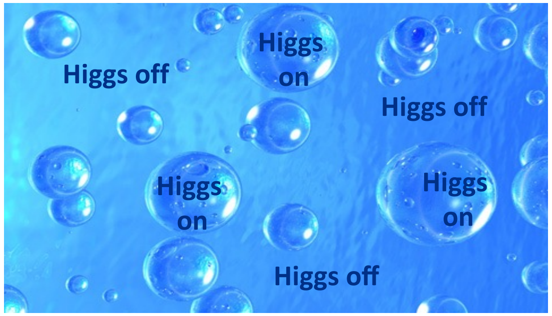
Klinkhammer and Manton'84; Arnold and Mc Lerran'88, Khlebnikov and Shaposhnikov '88

Baryon number generation at the Electroweak phase transition

Start from B = L = 0 at $T > T_c$

- In a first order EW phase transition, universe tunnels from h = 0 to h≠ 0 vacuum via bubble nucleation.



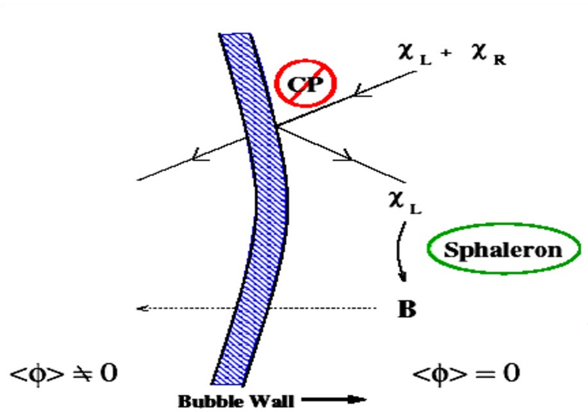


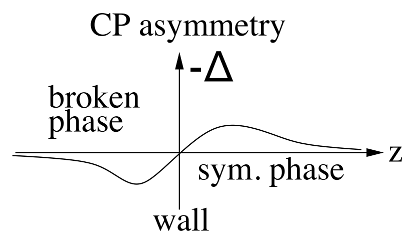
Bubbles expand at near speed of light. Processes near the wall highly out of equilibrium

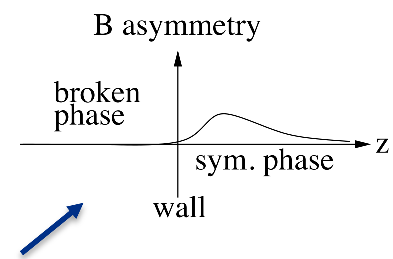
Effects of CPV and Baryon Number generation at the EWPT

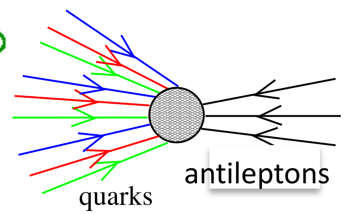
- Start with B = L = 0 at T>Tc
  - Particles flow into the expanding bubble wall and **CPV implies that the wall exerts different forces on particles and antiparticles creating a chiral asymmetry**

$$\sigma_{t_L \to t_R} \neq \sigma_{t_L^c \to t_R^c} \qquad \Delta \equiv n_{t_L} - n_{t_L^c} = -(n_{t_R} - n_{t_R^c}) \neq 0$$

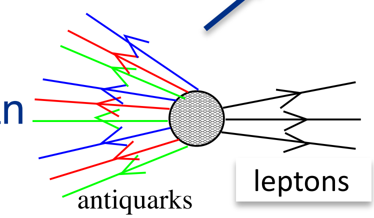








is slower than



- Outside the bubble, EW sphalerons allow a fraction "f" of the chiral asymmetry in quarks to be shared with leptons ➔ Sphalerons violate B+L, but conserve B-L

$$n_B - n_{\bar{B}} \propto \left[n_{t_R} - n_{t_R^c}\right] + (1-f)\left[n_{t_L} - n_{t_L^c}\right] = f\Delta$$

A net baryon asymmetry is generated this way

Baryon Asymmetry Preservation

For a short period, EW sphalerons work to generate the desired baryon asymmetry; Then need to shut off quickly to prevent washout.

if $n_B = 0$ at T > Tc, independently of the source of baryon asymmetry

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s}\exp\left(\underbrace{-\frac{10^{16}}{T_c(\mathrm{GeV})}\exp\left(-\frac{E_{sph}(T_c)}{T_c}\right)}_{\ll 1 \;\Rightarrow\; v(T_c)/T_c \gtrsim 1}\right)$$

Recall: $\Gamma_{\Delta B\neq 0} \cong \beta_0\, T \exp(-E_{sph}(T)/T)$

If $\Gamma_{\Delta B \neq 0} \lesssim H \sim T^2/M_{Pl}$

$\not{B}$ processes frozen

<< 1 ➔ $v(T_c)/T_c \gtrsim 1$

To preserve the baryon asymmetry demands a Strong First Order EWPT

Transition does not occur at T_c, but rather at T_n (bubble nucleation temp.) [$T_n < T_c$]

➔ actual transition from false vacuum to real one requires $S_{bounce}/T_n \sim 140$

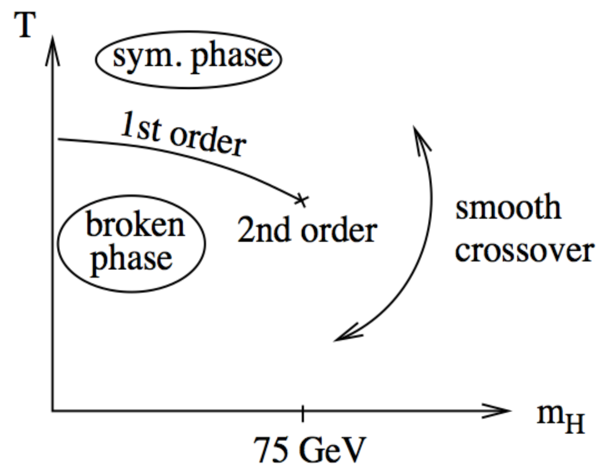
EW Baryogenesis in the SM fails

All three Sakharov's conditions could have been fulfilled

- Baryon number violation: Anomalous Processes/Sphalerons
- CP violation: Quark CKM mixing
- Non-equilibrium: At the Electroweak Phase Transition.

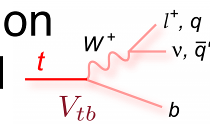
But

With the measured 125 GeV Higgs mass, lattice simulations show the EWPT is a cross over.

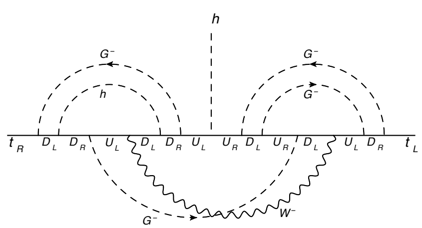


Kajantie, Laine, Rummukainen, Shaposhnikov '88

Contribution from CP violation (CKM) is highly suppressed



High order loop effects needed to generate a complex contribution to the top quark mass



Gavela et al '86

$$\delta_{\mathrm{CPV}} \sim \mathrm{Im\,Tr}(\mathcal{M}_u^2\mathcal{M}_d^2\mathcal{M}_u\mathcal{M}_d) \sim \left(\frac{\alpha_2}{M_W^2}\right)^6 s_1^2 s_2 s_3 \sin\delta\, m_t^4 m_b^4 m_c^2 c_s^2 < 10^{-20}$$

Electroweak Baryogenesis demands new Physics/ New Scalars

Basic Questions:

- What was **the mechanism** that triggered electroweak symmetry breaking? (SM gives a simple parameterization, not an explanation)
- Does this mechanism involve an expanded “Higgs sector” with other scalar boson fields, new forces, new fermions, new sources of CP violation ?
- Was the resulting phase transition strongly first order?
- Was there just one phase transition or a multi-step transition?
- Was there an electroweak phase transition at all?

The answers to these questions will inform whether electroweak baryogenesis is a viable explanation of the observed baryon excess in our universe

Higgs boson cousins may be the key to our Asymmetric Universe

To render the EWPT strongly first order and provide new sources of CPV

Many BSM scenarios have been studied which allow for EWBG

- Singlet extensions of the SM
- Two Higgs doublet Models
- Supersymmetric models
- ➢ MSSM: light stop scenario, ruled out by Higgs precision
- ➢ NMSSM: through additional scalars, is an appealing possibility
    - Importance of computing nucleation temperature
    - EWBG possible but new scalar boson states are hard to probe at colliders due to alignment proximity (LHC information)

- Models with Dark CP violation and gauged lepton/baryon number
- Models with heavy Fermions
- Models of EW symmetry non-restoration/delayed restoration, with multiple singlets and possibly with an inert doublet

Finite temperature Higgs Potential: general considerations

Need to consider: $V(\phi,T) = V_0(\phi) + V_1^{CW}(\phi,0) + V_1(\phi,T)$

V_1^{CW} yields renormalization scale independence, and $V_1(\phi,T)$ considers thermal contributions, e.g.

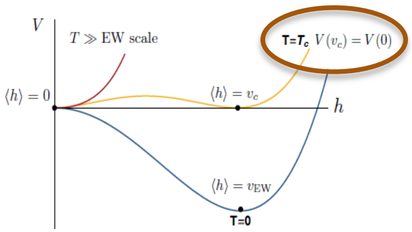
$$V_1(\phi,T) = \sum_{i=b,f}\left[\frac{n_i m_i^2(\phi)T^2}{48} - \frac{\eta_i m_i^4(\phi)}{64\pi^2}\log\left(\frac{m_i^2(\phi)}{T^2}\right)\right] - \sum_b \frac{m_b^3(\phi)T}{12\pi}$$

For $m_i(\phi) < 2T$, with $\eta_i = n_i\,(-1)^{2S}$

Review Standard Model example: ➔ $V = D(T^2 - T_0^2)H^2 + E_{SM}T\,H^3 + \frac{\lambda(T)}{2}H^4$

- D: contributions at one-loop proportional to the sum of the couplings of all bosons and fermions squared, responsible for symmetry restoration
- E: contributions from to the sum of the cube of all light boson particle couplings: $E_{SM} \approx \frac{2}{3}\left(\frac{2M_W^3 + M_z^3}{\sqrt{2}\pi\, v^3}\right)$

Defining T_c and requiring that $<\phi(T_c)> = v\,(T_c)$ is a minimum yields



$v\,(T_c)\,/\,T_c \sim E\,/\,\lambda$ that controls the strength of the phase transition

Since $\lambda = m_H^2/v^2$ then $\frac{v(T_c)}{T_c} > 1$ implies $m_H < 40$ GeV

Perturbative result to be compared with lattice computations yielding $m_H < 75$ GeV

Finite temperature Higgs Potential: general considerations

Going beyond the Standard Model to allow for a first order phase transition, sufficiently strong, one needs to add new particles and look in the direction of the transition

$V(\phi,T) = V_0(\phi,S,H_{BSM}) + V_1^{CW}(\phi, S, H_{BSM},0) + V_1(\phi, S, H_{BSM},T)$

The scalar potential can have many fields

- Tree-level Effects

  New fields coupling directly with the Higgs, modifying the potential at tree level

  $V(h, S, H_{BSM}, \ldots)$ $\lambda \to \lambda_{\rm eff}$ $[\ E \to E_{\rm eff}^{\rm tree}\ ]$

- Zero Temperature loop effects

  Modifying the potential through radiative corrections involving new particles

  $\lambda \to \lambda_{\rm eff}$

- Thermal effects

  Modifying the thermal potential through thermal loops involving new particles

  $E \to E_{\rm BSM} \propto y_t^3$

- Higher order operators: if new particles heavy → V_{eff}

Enhancing the EWPT strength through a singlet scalar

Scalar couples to the Higgs and affects the tree level potential

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \; + V_0^{\text{explicit}}(h,s)$$

We have separated out terms that explicitly break the Z_2 symmetry: $s \longrightarrow -s$

Possible scenarios:

- Explicit Z_2 breaking → $V_0^{explicit}(h,s) = a_1 h^2 s + b_1 s + b_3 s^3$
- Z_2 - preserving (at T=0) → $\langle (h,s) \rangle = (v_{\text{EW}}, 0)$
- Spontaneously Z_2 breaking → $\langle (h,s) \rangle = (v_{\text{EW}}, w_{\text{EW}})$

The last case follows naturally in scenarios where, e.g., the singlet is the Higgs-like boson of a complex scalar in the dark sector that spontaneously breaks a dark gauge symmetry

➔ Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT

To determine phase transition pattern requires finite temperature potential

$$V(h,s,T) = V_0(h,s) + V_{\text{CW}}(h,s;T) + V_T(h,s,T)$$

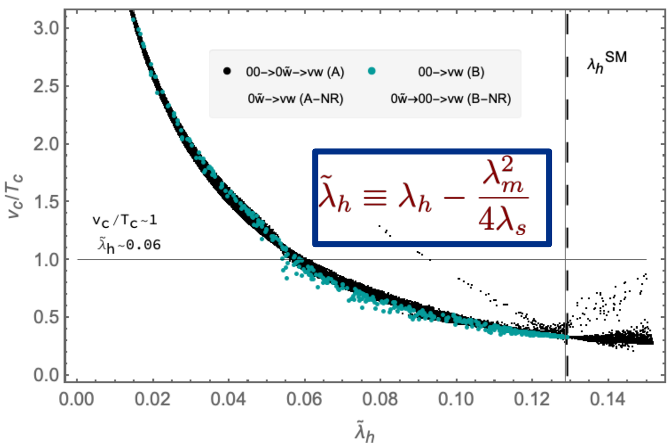
$$V^{\text{high}-\text{T}}(h,s,T) \approx \frac{1}{2}(-\mu_h^2 + c_h T^2)h^2 - ETh^3 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}(\mu_s^2 + c_s T^2)s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

Exotic Higgs decays as a potent probe of viable EWBG models

The electroweak phase transition strength – Spontaneous Z_2 breaking scenario

$$\frac{v_c}{T_c} = \frac{2E}{\tilde{\lambda}_h} = \frac{2E}{\lambda_h^{SM}}\left[1+\sin^2\theta\left(\frac{m_H^2}{m_S^2}-1\right)\right]$$

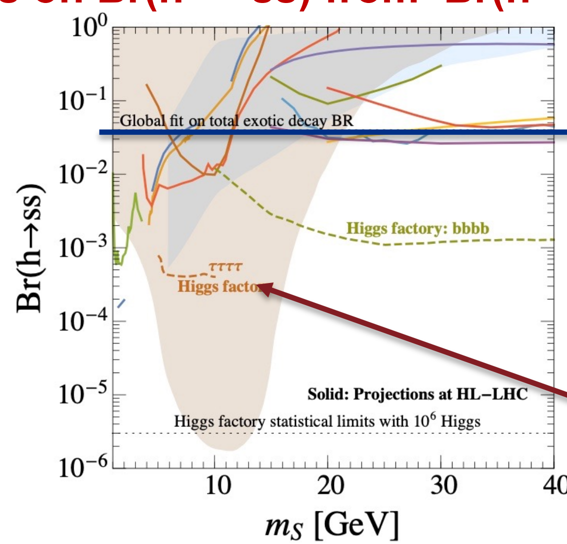
Parameters $\{\mu_h^2, \mu_s^2, \lambda_h, \lambda_s, \lambda_m\} \longleftrightarrow \{v_{EW}, m_H, \tan\beta, m_S, \sin\theta\}$



$$\tilde{\lambda}_h \equiv \lambda_h - \frac{\lambda_m^2}{4\lambda_s}$$

- Quartic mixing coupling proportional to mixing between mass eigenstates - strongly constrained by Higgs precision measurements ➔ $\sin\theta \lesssim 0.4$
- Strength of the EWPT enhanced for small m_S - light singlet

Bounds on Br(h → ss) from Br(h → ss → XXYY)



Global fit:
BR[H→exotics] < 4%

Z_2 spontaneous breaking with SFOEWPT

Ke-Pan Xie, Yikun Wang, et al, Snowmass WP '22

- Sizeable $s^2\,|H|^2$ coupling needed for a strongly 1st order EWPT

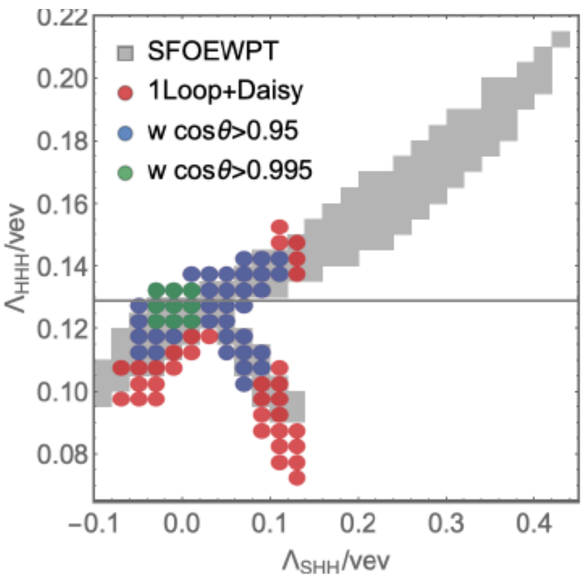
➔ BR (H→SS) to be bounded from below

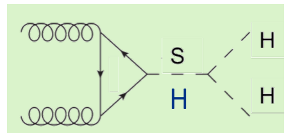
Exotic Higgs decays are a potent probe of Singlet extensions with viable EWBG

EWPT and Higgs Pair Production: Higgs Trilinear Coupling

Z_2 spontaneous Symmetry Breaking Scenario

M.C, Z. Liu, Y. Wang, '19



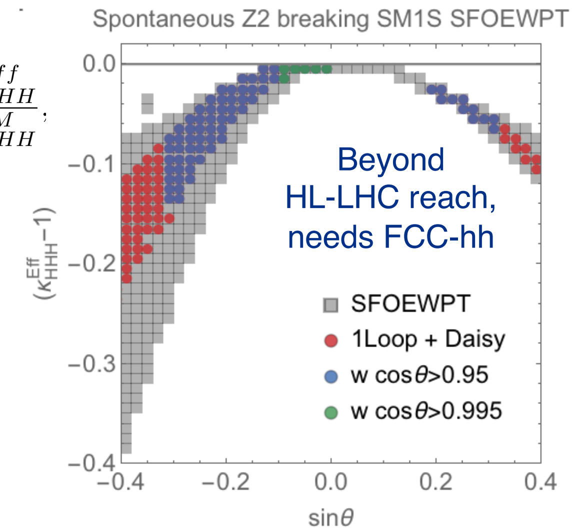


$$\kappa^{Eff}_{HHH} \equiv \frac{\Lambda^{Eff}_{HHH}}{\Lambda^{SM}_{HHH}};$$

$$\Lambda^{\rm Eff}_{HHH} \simeq \frac{2}{3}\sin\theta\Lambda_{SHH} + \cos\theta\Lambda_{HHH}.$$

$$\Lambda_{HHH} = \frac{m_H^2\left(-\sin^3\theta + \tan\beta\cos^3\theta\right)}{2\tan\beta\ v}$$

$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\ v}.$$

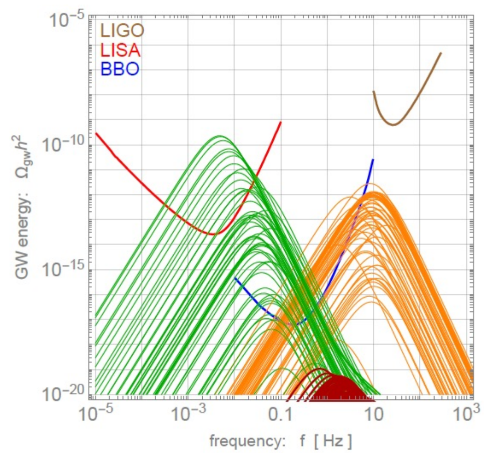


Gravitational Waves:

Bubble nucleation: expanding bubbles collide and produce stochastic GW through:

- **sound waves propagation**
- magnetohydrodynamic turbulence
- bubble collisions

Many parameters affect the GW signal



May be too weak to be probed after including all radiative corrections (red curves)

Further RG improvement may help

A SUSY example: the Next-to-Minimal Supersymmetric SM

A more extended Higgs sector: two Higgs doublets + a singlet

both charged under the EW gauge group

provides flexibility enhancing the PT strength

The NMSSM with the scalar potential

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$
$$+ \left(\lambda A_\lambda S H_u \cdot H_d + \frac{\kappa}{3} A_\kappa S^3 + \text{h.c.}\right) + \frac{g_1^2 + g_2^2}{8}\left(|H_d|^2 - |H_u|^2\right)^2 + \frac{g_2^2}{2}\left|H_d^\dagger H_u\right|^2$$

from Z3-NMSSM superpotential

Without loss of generality, we consider the 3-dim. field space $\langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}$ $\langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$ $\langle S \rangle = v_S$

$$\text{CP even interaction states } \boxed{\{H^{\rm SM}, H^{\rm NSM},\ H^S\}} \quad \rightarrow \quad \text{CP even mass states } \{h_{125}, H,\ h_S\}$$

Higgs basis

The EW vacuum $\langle H^{\rm SM} \rangle = v, \quad \langle H^{\rm NSM} \rangle = 0, \quad \langle H^{\rm SM} \rangle = v_S$

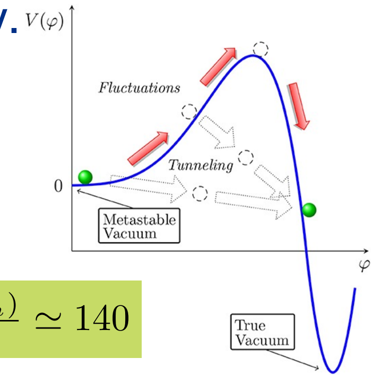
After minimization conditions, replacing mass parameters by vev's and suppress mixing of H^{NMS} and H^S with H^{SM} to be consistent with Higgs 125 GeV phenomenology

Parameter space: $\left\{ v \equiv \sqrt{v_d^2 + v_u^2}\ ,\ \tan\beta \equiv v_u/v_d\ ,\ \mu \equiv \lambda v_S,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa \right\} \rightarrow \{\mu,\ \tan\beta,\ \kappa,\ A_\kappa\}$

EWPT in the NMSSM - nucleation is more than critical

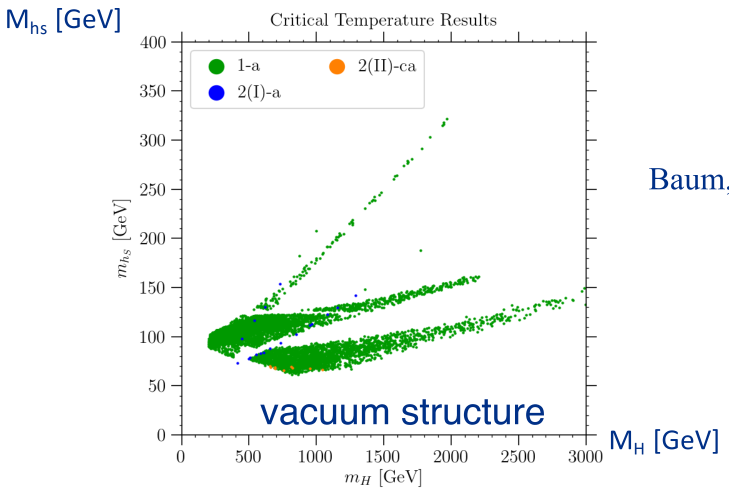
The vacuum structure gives little information about tunneling probability.

➔ the higher the barrier, and the larger the distance between the minima, the lower the nucleation probability



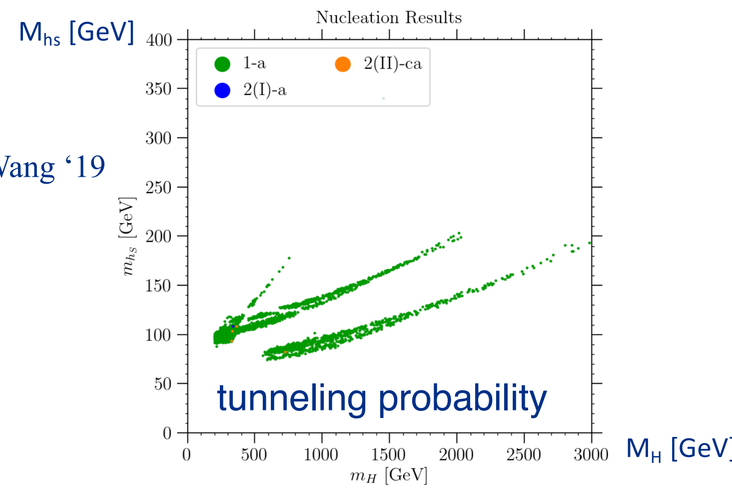
The bubble nucleation rate per unit volume: $\Gamma/V \propto T^4 e^{-S_3/T}$

requiring the nucleation probability to be approx. one per Hubble volume and Hubble time leads to the nucleation condition → $\frac{S_3(T_n)}{T_n} \simeq 140$



$T_c \longrightarrow T_n$

Baum, M.C, Shah, Wagner, Wang '19



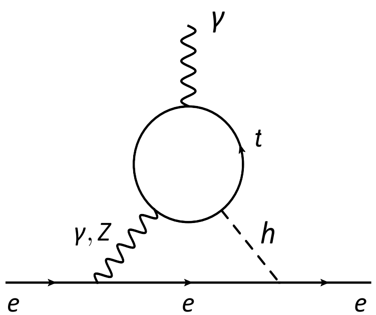
Collider and Dark Matter opportunities

- Strong EWPT consistent with light to heavy non-SM-like Higgs boson and a singlet
- Despite light masses, these states are hard to probe at LHC (best: $H \rightarrow h_{125} + h_S$)
- The most promising dark matter scenario is a bino-like lightest neutralino

The challenge of new CPV sources for EW Baryogenesis

The observed baryon asymmetry requires new CPV sources that are in usually in tension with Electric Dipole Moment experimental bounds

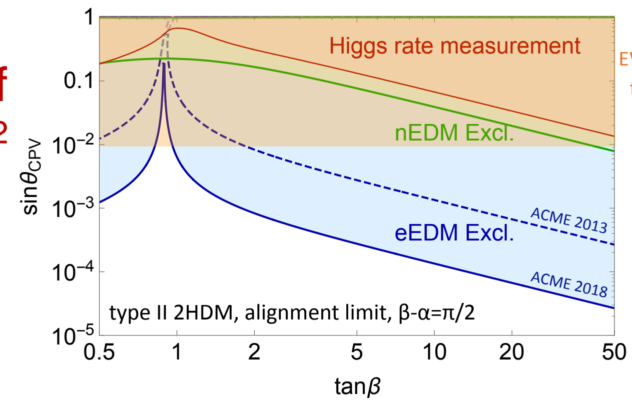
Electron EDM and the ACME experiment



Weak scale CPV $\quad d_e \sim \dfrac{e\, G_F\, m_e}{(16\pi^2)^2}\, \vartheta_{\rm CPV} \sim 10^{-26}\, \vartheta_{\rm CPV}\, e\, {\rm cm}$

2018 electron EDM measurement ==> $\quad d_e < 1.1 \times 10^{-29}\, e\, {\rm cm}$

Most New Physics models of EWBG require $\sin\theta_{CPV} \geq 10^{-2}$



Shu, Y. Zhang,'13 Inoue, Ramsey-Musolf, Y. Zhang'14

Electron EDM can be suppressed if the CP violating fermion is a SM gauge singlet
- doesn't couple to photons -

Leading EDM arises at higher loops, naturally suppressed by one or two orders of magnitude below current limit for CPV sources of order one

How to transfer CP violation in the early universe?

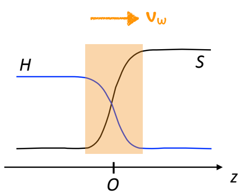
A new mechanism for EW Baryogenesis: Dark CP violation

MC, Quiros and Yue Zhang.19

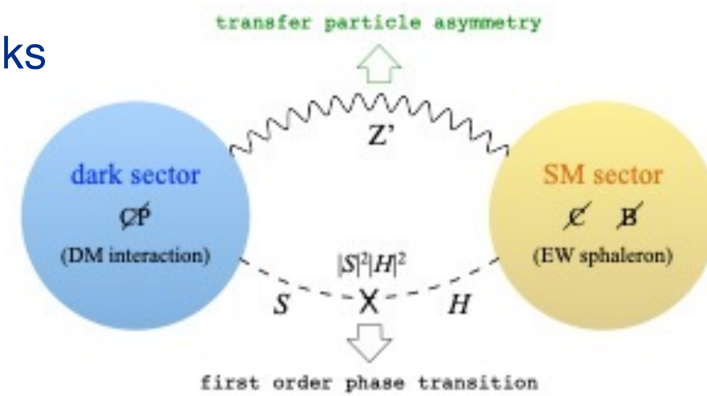
A model with gauged lepton number

- **Higgs portal** (sourcing CP violation & phase transition)
- **Z' portal** (for transfer of CP violation)

A dark fermion χ (DM) talks to the Higgs boson via a new SM singlet scalar S



bubble wall profile



EW sphalerons cannot touch the chiral charge asymmetries in the χ SU(2) singlet

new U(1) gauge boson Z' couples to the dark fermions and SM leptons and transfers CPV to SM sector

A varying mass m_χ along the z direction, together with the S vev, generates **a chiral charge asymmetry in χ particles**

This in turn generates a Thermal Equilibrium Asymmetry in SM leptons

Sphaleron processes yield $\Delta N_L = \Delta N_B$

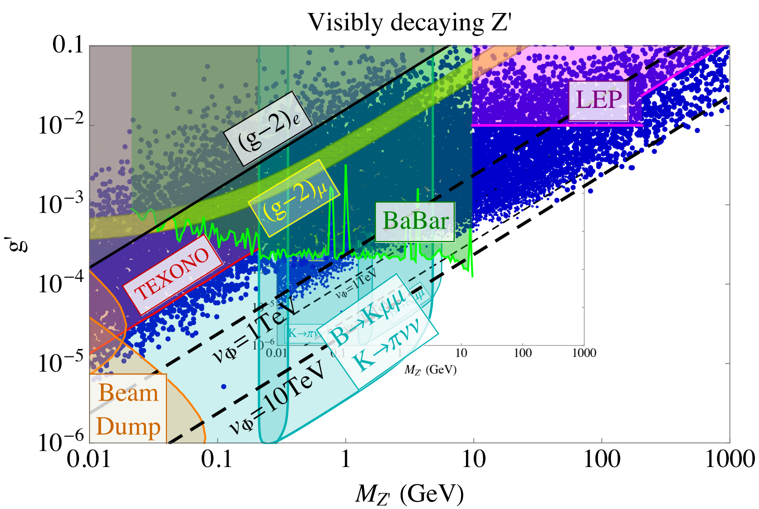
$SU(2)_L$ anomalons, besides DM, must decouple from thermal number density

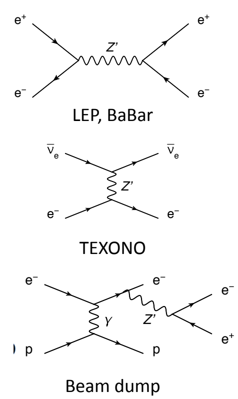
A new scalar-Higgs interaction, $\lambda_{SH}|S|^2|H|^2$, can trigger strong first order EWPT

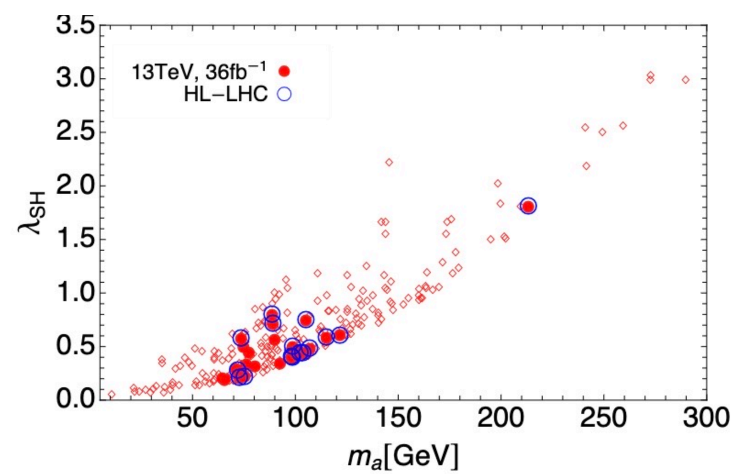
Dark CPV: Phenomenology

MC, Quiros and Yue Zhang'19
MC, Y-Y li, T. Ou, W. Wang, to appear

- Predicts the existence of a new force carrier *Z'*, leptophilic ➔ *Z'* searches.
- Predicts very small EDM's, but can be at reach in next round of experiments
- Predicts a new Higgs portal scalar *S*, which could mainly decay into *Z'* s.
- The χ particle qualifies to be a thermal dark matter candidate







Leptophilic *Z'*:
Target and Searches

LHC searches for
long-lived scalars

Outlook: Electroweak Baryogenesis

An appealing mechanism to explain the matter-antimatter asymmetry:

It requires a strongly first order electroweak phase transition and additional CPV beyond the SM.

It may come with interesting new collider signatures and may even accommodate DM

Gravitational wave signatures can be interesting probes of the nature of the phase transition at the reach of planned instruments

Some examples:

- Singlet extensions to the SM can enhance the EWPT, which exhibits rich thermal history and collider phenomenology.
- Extended Higgs sectors with large tree level barriers and multi dimensional field space: important differences between the critical temperature study versus the nucleation temperature study
- Baryogenesis generation with CPV in a dark sector can circumvent EDM current restrictions and provide a novel mechanism for EWBG in models with gauged lepton (or quark number), with CPV transmitted by a new force

Merci !

22

Extras

Simplest Case:
A singlet extension of the Standard Model

Enhancing the EWPT strength through a Singlet extension

A singlet scalar that couples to the Higgs and affects the tree level potential

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \; + \; V_0^{\text{explicit}}(h,s)$$

- Generic Potential: Explicit Z2 breaking → $V_0^{explicit}(h,s) = a_1 h^2 s + b_1 s + b_3 s^3$

  Espinosa, Quiros '93, Profumo, Ramsey-Musolf, Shaughnessy '07, Choi, Volkas '93, Huang, Joglekar, Li, Wagner '16, Kozaczuk, Ramsey-Musolf, Shelton '19

- Z2 - preserving (at T=0) → $\langle (h,s) \rangle = (v_{\rm EW}, 0)$

Espinosa, Konstandin, Riva '11, Curtin, Meade, Yu '15, Barger, Chung, Long, Wang '12, Kozaczuk, Ramsey-Musolf, Shelton '19

- Spontaneously Z_2 breaking → $\langle (h,s) \rangle = (v_{\rm EW}, w_{\rm EW})$ M.C, Liu Wang '19

  In connection with a dark gauge symmetry, spontaneously broken by a dark Higgs vev.

Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT –

→ Distinct rich phenomenology at Colliders: Higgs precision, Higgs trilinear coupling, double Higgs production, direct new scalar searches, possible effects of CPV

Enhancing the EWPT strength through a Singlet extension

A singlet scalar that couples to the Higgs and affects the tree level potential

$$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2 \quad + \quad V_0^{\text{explicit}}(h,s)$$

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- Spontaneously Z_2 breaking → $\langle (h,s) \rangle = (v_{\rm EW}, w_{\rm EW})$ M.C, Liu Wang '19

  In connection with a dark gauge symmetry, spontaneously broken by a dark Higgs vev.

To determine phase transition pattern requires finite temperature potential

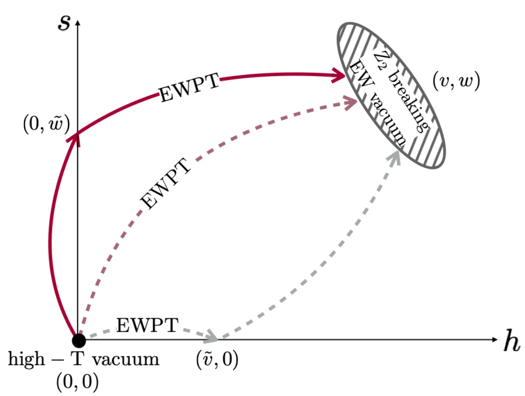
$$V(h,s,T) = V_0(h,s) + V_{\rm CW}(h,s;T) + V_T(h,s,T)$$

The SM singlet extension: EWPT paths for baryogenesis

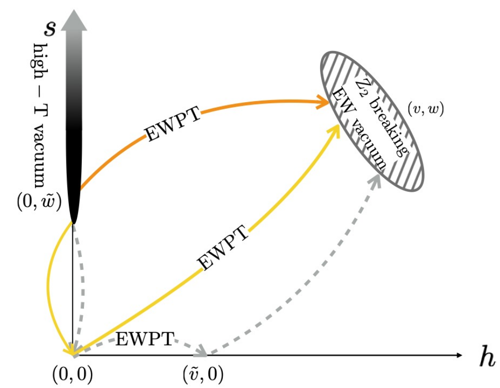
Is it possible that the EW symmetry or/and the Z_2 symmetry is/are Non-Restored (NR)?

- EW-NR demands many, many singlets (+ possibly an inert doublet) MC, Krauss, Liu, Wang '21
- Z_2-NR: Yes

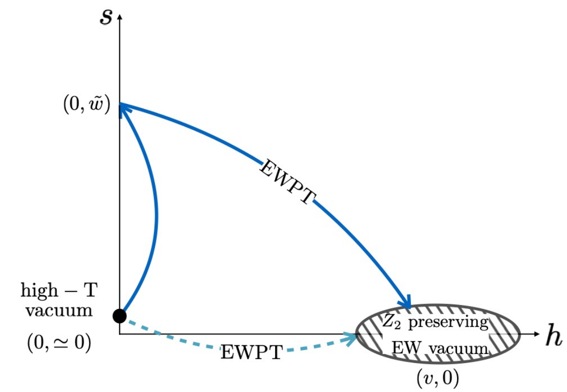
Solid lines: EWPT can be strongly first-order



Z_2 spontaneous breaking scenarios *with symmetry restoration* at high T



Z_2 spontaneous breaking scenarios *without symmetry restoration* at high T



Z2 preserving or explicit breaking scenarios

- The step where the EW symmetry is first broken is required to be strongly first-order.
- To enable a strongly first-order phase transition, the singlet should have significant couplings to the Higgs, to induce a sufficiently large deformation to the scalar potential in the early universe

EWPT with Spontaneous Z_2 Breaking: The full analysis

Tree-level Potential $$V_0(h,s) = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

Parameters $\{\mu_h^2, \mu_s^2, \lambda_h, \lambda_s, \lambda_m\} \longleftrightarrow \{v_{\rm EW}, m_H, \tan\beta, m_S, \sin\theta\}$

Thermal potential $$V_T(h,s,T) = \frac{T^4}{2\pi^2}\left[\sum_{i=\{B\}} n_i J_B\left(\frac{m_i^2(h,s)}{T^2}\right) + \sum_{f=\{F\}} n_f J_F\left(\frac{m_f^2(h,s)}{T^2}\right)\right]$$

expanding the J_B and J_F functions in terms of small α $=m^2/T^2$

$$J_B^{\rm high-T}(\alpha) = {\rm Re}\Big[-\frac{\pi^4}{45} + \frac{\pi^2}{12}\alpha - \frac{\pi}{6}\alpha^{\frac{3}{2}} + \cdots\Big],$$
$$J_F^{\rm high-T}(\alpha) = {\rm Re}\Big[\frac{7\pi^4}{360} - \frac{\pi^2}{24}\alpha + \cdots\Big].$$

$$V^{\rm high-T}(h,s,T) \approx \frac{1}{2}(-\mu_h^2 + c_h T^2)h^2 - ETh^3 + \frac{1}{4}\lambda_h h^4 + \frac{1}{2}(\mu_s^2 + c_s T^2)s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_m h^2 s^2$$

One Loop Coleman-Weinberg potential and daisy resummation also considered

$$V_{\rm CW}(h,s) = \tfrac{1}{64\pi^2}\left(\sum_B n_B m_B^4(h,s)\Big[\log\left(\tfrac{m_B^2(h,s)}{Q^2}\right) - c_B\Big] - \sum_F n_F m_F^4(h,s)\Big[\log\left(\tfrac{m_F^2(h,s)}{Q^2}\right) - \tfrac{3}{2}\Big]\right)$$

$$m_i^2(h,s) \to m_i^2(h,s,T) = m_i^2(h,s) + d_i T^2$$

EWPT with Spontaneous Z_2 Breaking: The full analysis

The electroweak phase transition strength

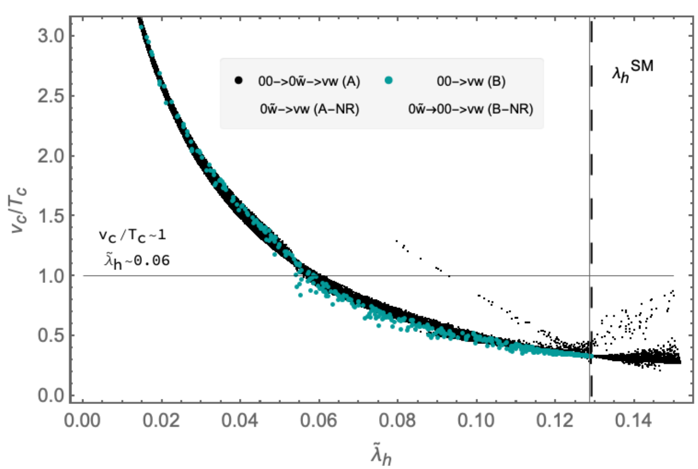
$$\frac{v_c}{T_c} = \frac{2E}{\tilde{\lambda}_h} = \frac{2E}{\lambda_h^{\rm SM}}\left[1+\sin^2\theta\left(\frac{m_H^2}{m_S^2}-1\right)\right]$$

- Bare parameters

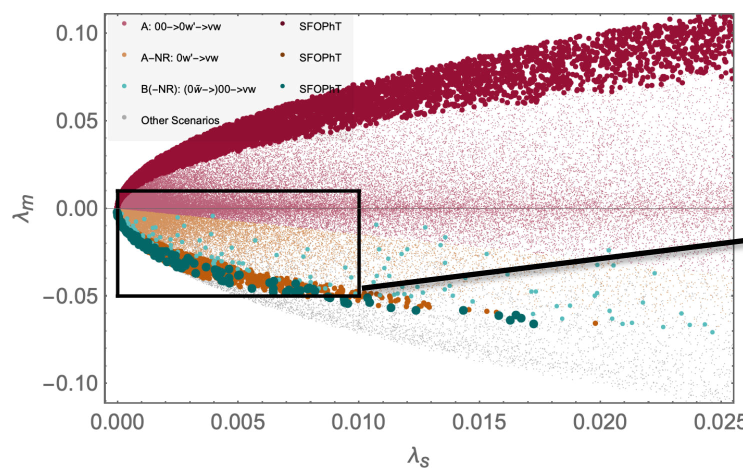
$$\tilde{\lambda}_h \equiv \lambda_h - \frac{\lambda_m^2}{4\lambda_s} \qquad \frac{v_c}{T_c} \propto \tilde{\lambda}_h^{-1}$$

- Physical parameters

$\sin\theta \lesssim 0.4$ bounded by Higgs precision measurements



Small m_S renders SFOPhT: light singlet



Exotic Higgs decay bounds

- Full one-loop effective potential with daisy resummation allows for all types of solutions shown in the thermal only analysis.
- Results robust against the Nucleation calculation

Phenomenology of SM plus Singlet models

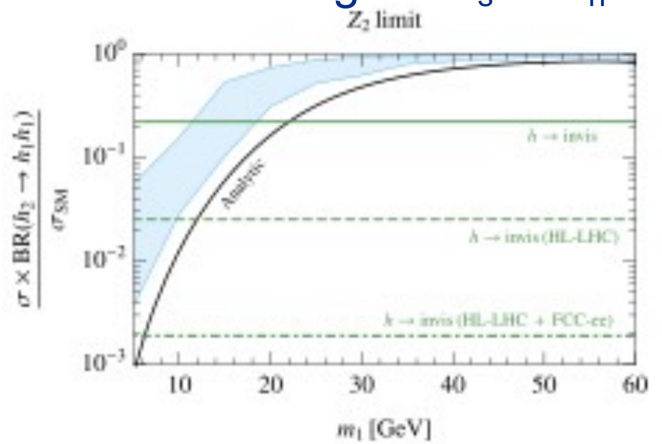
- Z_2-symmetric (at T=0) scenario: Invisible Decays

➢ Requires sizeable $s^2\, |H|^2$ coupling for a 2 step strongly 1st order EWPT, [(0,0)→(0,v_S) →(v,0)], that calls for a careful treatment of perturbativity

➢ **No S-H mixing – S is stable** (invisible decays)

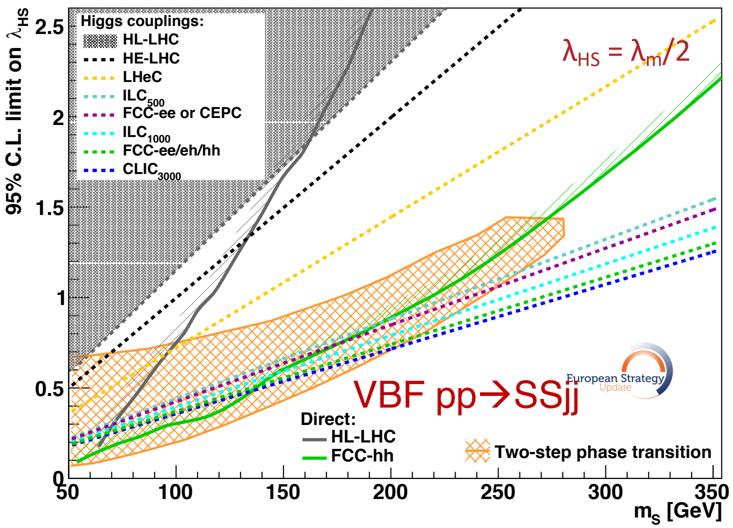
Lower bound on BR(H) $_{inv}$ or pp →VSS (AP) pp →SSjj (VBF)

Low mass singlet: $m_s < m_h/2$



Kozaczuk, Ramsey-Musolf, Shelton '19

$m_s > m_h/2$



Current bounds imply $m_S < 20$ GeV

EWBG scenario to be fully probed by full FCC or CLIC

Scenarios for EWBG based on EW symmetry non restoration can also be tested via Higgs invisible decays M.C, Krause, Z. Liu, Y Wang'21

Higgs Exotic Decay Phenomenology in Singlet models

If singlet sufficiently light ➔ BR (H→SS) to be bounded from below for a strongly 1st order EWPT that demands significant S-H couplings

➔ exotic Higgs decays are a potent probe of Singlet extensions with viable EWBG
Specifics of the exotic Higgs decays depend on Z_2 symmetry realization

- Z_2 spontaneously breaking scenario

➢ Requires sizeable s^2 $|H|^2$ coupling for a strongly 1st order EWPT
Only 3 parameters after defining Higgs mass and v.e.v

→ quartic mixing coupling proportional to S-H mixing – strongly constrained by Higgs precision measurements

→ strength of the EWPT is enhanced for small m_S - light singlet -

- Z_2 explicitly breaking scenario

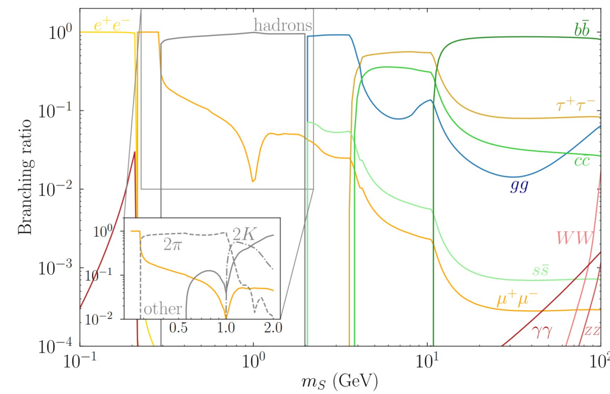
➢ Not only the s^2 $|H|^2$ coupling is relevant for a strongly 1st order EWPT, but also terms in s^3 and $s\,|H|^2$ play a role
(more free parameters; quartic mixing coupling independent of S-H mixing)

➢ A strong 1st order EWPT and a small amount of H-S mixing compatible with Higgs properties, with a looser lower bound on BR[H→SS]

Probing Z_2 breaking Singlet Extensions via Higgs Exotic Decays

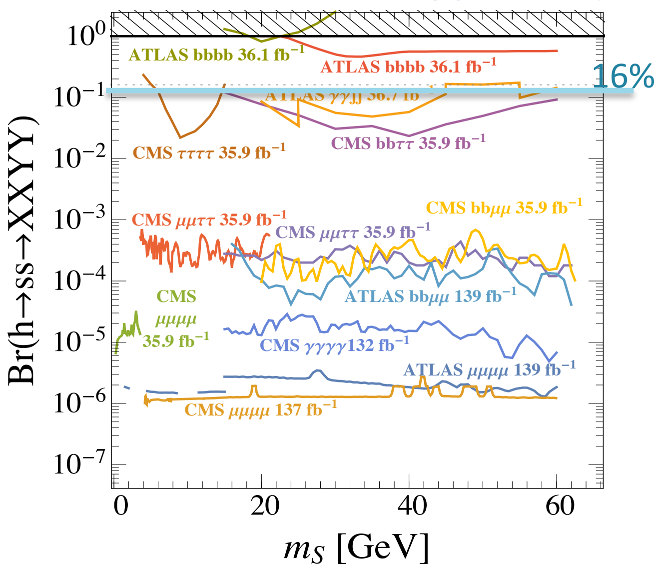
Currently: BR[H→ exotics] < 16%

H→ SS can lead to many final states with S inheriting Higgs-like hierarchical BR's, mediated through mixing

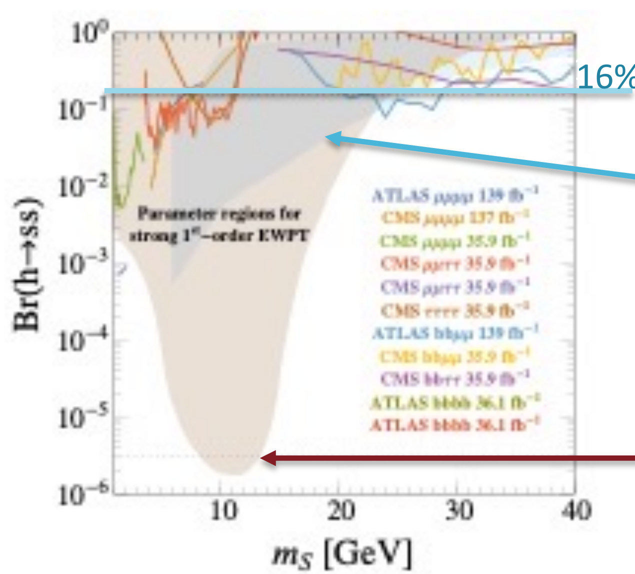


Final state dominated by h → ss → bbbb for $m_s > 2m_b$, and by jjjj, jjττ, and ττττ for m_s < 10 GeV

Bounds on exotic Higgs decays



Bounds on Br(h → ss) from Br(h → ss → XXYY)



Z_2 explicit breaking with SFOEWPT

Z_2 spontaneous breaking with SFOEWPT

Besides the 4b's final state, the rest involves at least a pair of EW states

Ke-Pan Xie, Yikun Wang, et al, Snowmass WP '22

Probing Z_2 breaking Singlet Extensions via Higgs Exotic Decays

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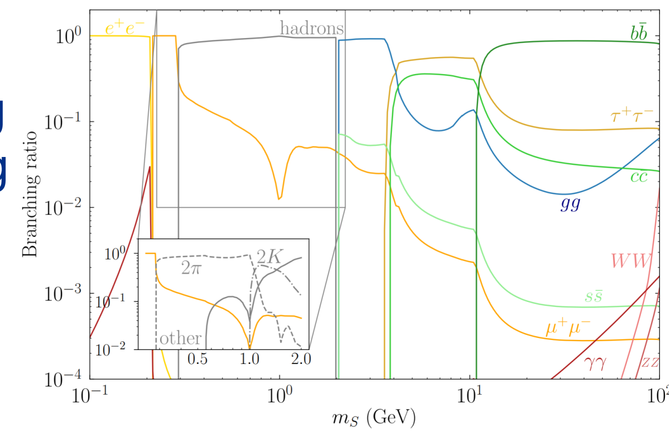

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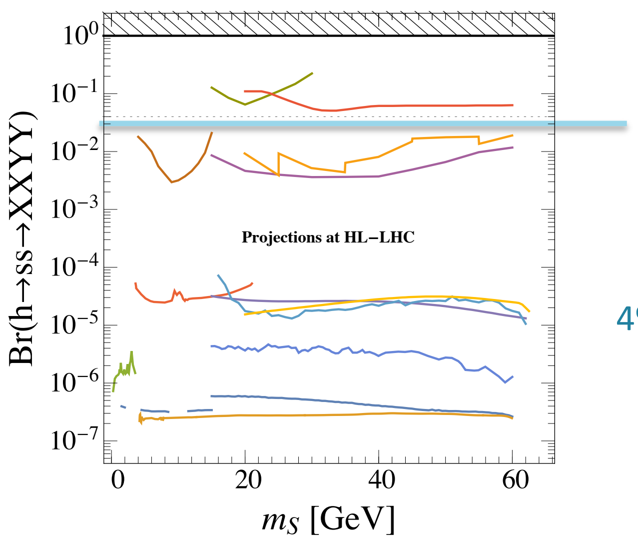
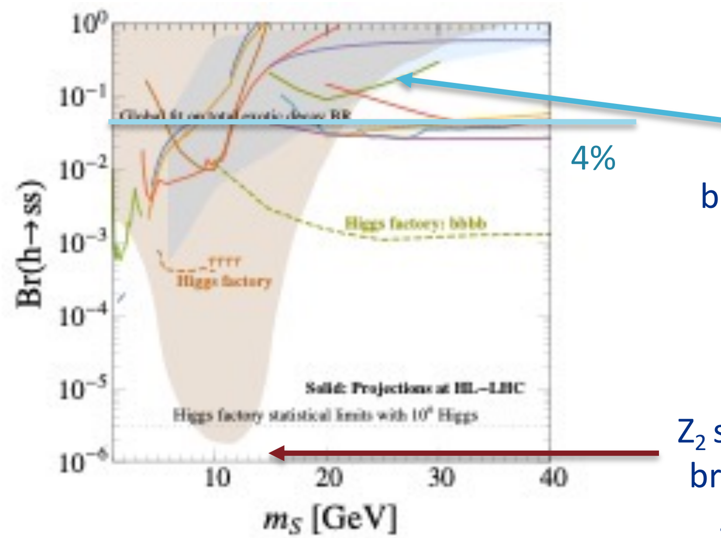
Bounds on exotic Higgs decays



4%

Bounds on Br(h → ss) from Br(h → ss → XXYY)



4%

Z_2 explicit breaking with SFOEWPT

Z_2 spontaneous breaking with SFOEWPT

Besides the 4b's final state, the rest involves at least a pair of EW states (same color coding)

Ke-Pan Xie, Yikun Wang, et al, Snowmass WP '22

Extended Higgs sectors: a SUSY example

The Electroweak Phase Transition in the NMSSM

EWPT in the NMSSM: alignment limits and parameter space

Defining $\mathcal{M}_S^2$ in the in the Higgs basis $\quad m_{h_{125}}^2 \simeq \mathcal{M}_{S,11}^2 = m_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta)$

To be consistent with the current Higgs phenomenology, the mass eigenstate h_{125} needs to be dominantly composed of H^{SM} - need to suppress mixing of H^{NMS} and H^S with H^{SM}

decoupling limit $\qquad$ decoupling limit

$$\left|\mathcal{M}_{S,12}^2\right| \ll \left|\mathcal{M}_{S,22}^2 - \mathcal{M}_{S,11}^2\right|, \qquad \left|\mathcal{M}_{S,13}^2\right| \ll \left|\mathcal{M}_{S,33}^2 - \mathcal{M}_{S,11}^2\right|$$

alignment without decoupling $\qquad$ alignment without decoupling

The alignment conditions –without decoupling, imply $\quad m_H, m_A, m_{H^\pm} \sim 2\mu/\sin 2\beta$

$$\mathcal{M}_{S,12}^2 = 0 \quad \rightarrow \quad \lambda^2 = \frac{m_{h_{125}}^2 - m_Z^2\cos(2\beta)}{2v^2\sin^2\beta}, \qquad \mathcal{M}_{S,13}^2 = 0 \quad \rightarrow \quad A_\lambda = \frac{2\mu}{\sin 2\beta}\left(1 - \frac{\kappa}{\lambda}\sin 2\beta\right)$$

For small to moderate tanβ: λ ~ 0.6 - 0.7

The parameter space

$$\{v,\ \tan\beta,\ \mu,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa\} \quad \rightarrow \quad \{\mu,\ \tan\beta,\ \kappa,\ A_\kappa\}$$

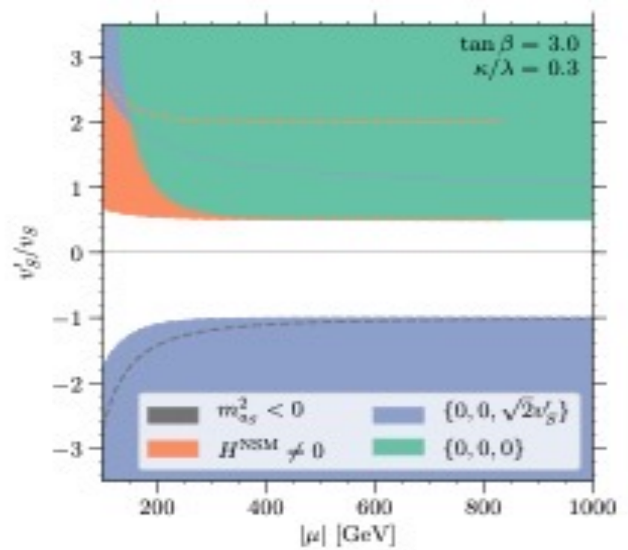
EWPT in the NMSSM: alignment limits and parameter space

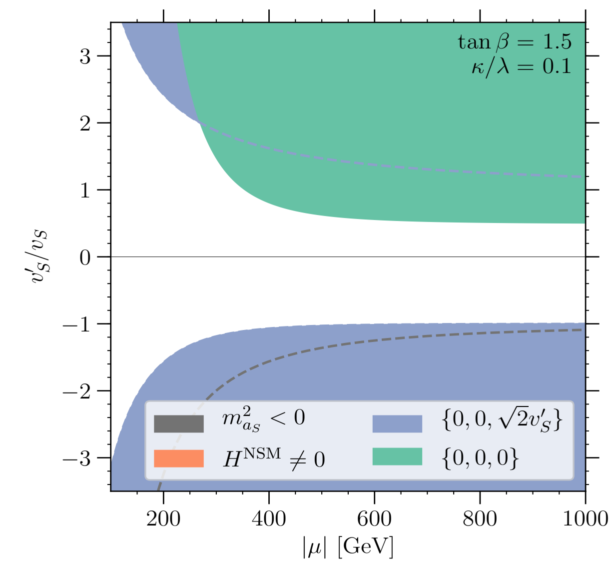
The parameter space

$\{v,\ \tan\beta,\ \mu,\ \lambda,\ \kappa,\ A_\lambda,\ A_\kappa\} \quad \to \quad \{\mu,\ \tan\beta,\ \kappa,\ A_\kappa\} \longrightarrow \left\{\tan\beta\ ,\ \mu\ ,\ \frac{\kappa}{\lambda}\ ,\ \frac{v'_S}{v_S}\right\}$

- 125 GeV mass eigenstate without large radiative corrections $\tan\beta \lesssim 5$
- Avoid Landau poles (GUT) $\sqrt{\lambda^2+\kappa^2} \lesssim 0.7$
- Avoid tachyonic masses, e.g. $m_{a_S}^2 \geq 0$
- Correct vacuum structure at zero temperature $\{H^{\mathrm{SM}}, H^{\mathrm{NSM}}, H^{\mathrm{S}}\} = \{0,0,0\} \vee \left\{0,0,\sqrt{2}v'_S\right\} \vee \left\{0,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \left\{\sqrt{2}v,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \cdots$

$$v'_S \equiv -\left(\frac{\mu}{\lambda}+\frac{A_\kappa}{2\kappa}\right)$$





Baum, M.C Shah, Wagner, Wang ‘19

EWPT in the NMSSM - the effective potential

Radiative corrections (zero temperature)

Integrating out heavy degrees of freedom (sfermions, gluinos etc) are integrated out. A new operator by matching:

$$V_0^{\text{eff}} = V_0 + \frac{\Delta\lambda_2}{2}\left|H_u\right|^4$$

with $\Delta\lambda_2$ fixed by 125 GeV Higgs mass

Light degrees of freedom: CW potential

$$B = \{h_i, a_i, H^\pm, G^0, G^\pm, Z, W^\pm\}$$

$$F = \{\widetilde{\chi}_i^0, \widetilde{\chi}_i^\pm, t\}$$

$$V_{1-\text{loop}}^{\text{CW}} = \frac{1}{64\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i \widehat{m}_i^4 \left[\log\left(\frac{\widehat{m}_i^2}{m_t^2}\right) - C_i\right]$$

Introducing counterterms to maintain boundary conditions

$$\delta\mathcal{L} = -\delta_{m_{H_d}^2}\left|H_d\right|^2 - \delta_{m_{H_u}^2}\left|H_u\right|^2 - \delta_{m_S^2}\left|S\right|^2 - \delta_{\lambda A_\lambda}\left(SH_u\cdot H_d + \text{h.c.}\right) - \frac{\delta_{\lambda_2}}{2}\left|H_u\right|^4$$

Finite temperature effective potential

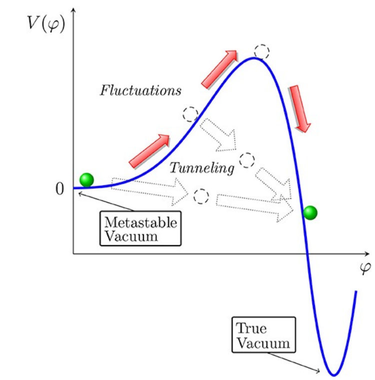
$$V_1(T) = V_0^{\text{eff}} + V_{1-\text{loop}}^{\text{CW}}(\widetilde{m}_i^2) + V_{1-\text{loop}}^{T\neq 0}(\widetilde{m}_i^2)$$

with

$$V_{1-\text{loop}}^{T\neq 0} = \frac{T^4}{2\pi^2}\sum_{i=B,F}(-1)^{F_i} n_i J_{B/F}\left(\frac{\widetilde{m}_i^2}{T^2}\right)$$

EWPT in the NMSSM - nucleation is more than critical

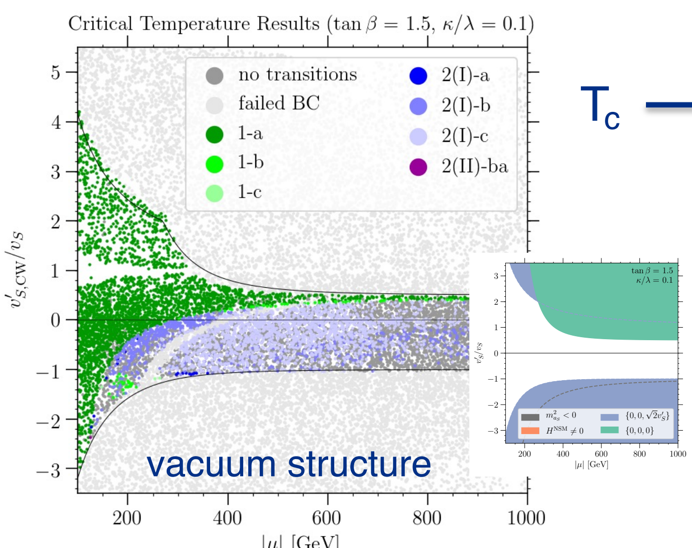
The phase transition proceeds by tunneling through the barrier separating local minima, the so-called bubble nucleation.
➔ the higher the barrier, and the larger the distance between the minima, the lower the nucleation probability



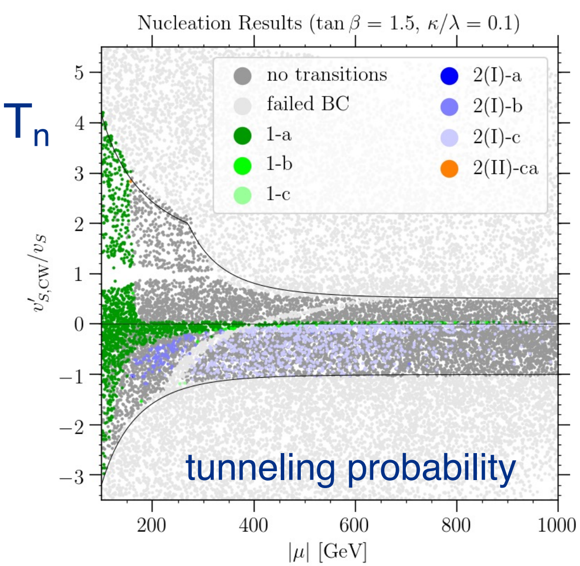
The bubble nucleation rate per unit volume: $\Gamma/V \propto T^4 e^{-S_3/T}$

requiring the nucleation probability to be approx. one per Hubble volume and Hubble time leads to the nucleation condition → $\frac{S_3(T_n)}{T_n} \simeq 140$

$(0,0,0) \to (v,0,v_S)$ $(0,0,0) \to (0,0,\tilde{v}_S) \to (v,0,v_S)$ $(0,0,0) \to (\tilde{v},\tilde{v}_{\rm NSM},0) \to (v,0,v_S)$



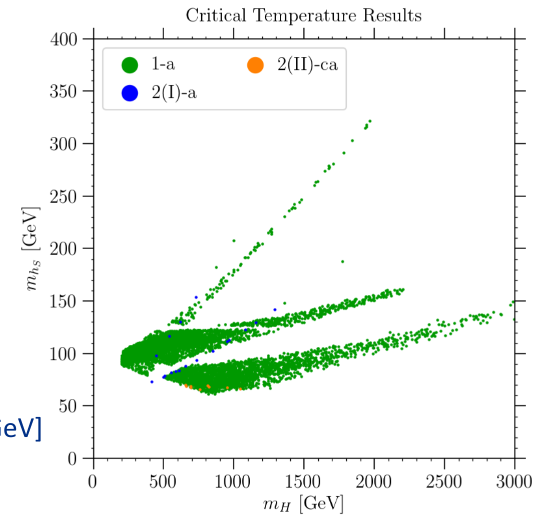
T_c ⟶ T_n



- **Integer : # of steps**
- **Roman number:**
  Intermediate phase
  (I): singlet-only direction
- (II): EWS broken phase
- **Lower case letter:**
  Strength of the EWPT
  a: SFOEWPT
  b: weakly 1st order
  c: 2nd order

Baum, M.C Shah, Wagner, Wang '19

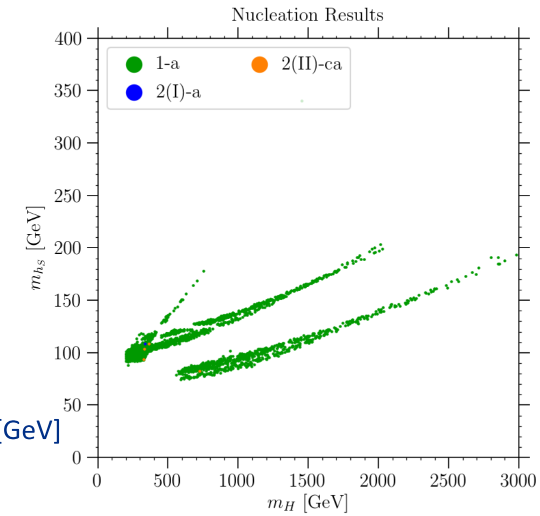
EWPT in the NMSSM: collider and dark matter pheno



M_{hs} [GeV]

M_H [GeV]

$T_c \longrightarrow T_n$



M_{hs} [GeV]

M_H [GeV]

Collider phenomenology:

- The SFOEWPT consistent with light to heavy non-SM-like Higgs boson and a singlet
- Despite the light masses, these states are hard to probe in colliders
  - Production of the singlet-like state suppressed due to small NSM component
  - Decay modes of the doublet-like states make it hard to be probed
  - Promising channels to probe: final states containing at least one singlet-like boson

Dark Matter:

- The most promising dark matter scenario is a bino-like lightest neutralino
  - Small interaction cross sections
  - well-tempered scenario for the correct relic density

Baryogenesis with Dark CP Violation:

A model with gauged lepton number

Dark CPV: The Higgs Portal

Sourcing CP Violation

MC, Quiros and Yue Zhang '19

The direct coupling between a SM gauge singlet fermion χ and the Higgs boson would be higher dimensional. To write a renormalizable theory introduce a new scalar S

Scalar S - also SM singlet - couples to dark fermion (DM) $\mathcal{L} \sim \bar{\chi}_L(m_0 + yS)\chi_R + \text{h.c.}$

In the presence of a relative phase between m_0 and y, **a chiral charge asymmetry in χ particles can be generated** $\Delta \equiv n_{\chi_L} - n_{\chi_L^c} = -(n_{\chi_R} - n_{\chi_R^c}) \neq 0$

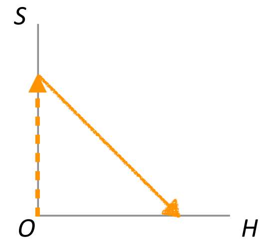
This requires m_χ to vary along the z direction, together with the S vev

A new EW phase transition

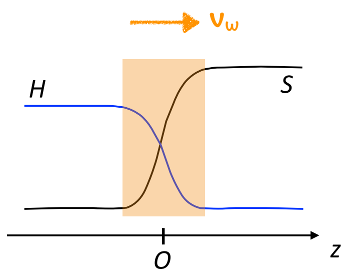
A new scalar-Higgs interaction,

$\lambda_{SH}|S|^2|H|^2$, with $\lambda_{SH} > 0$,

can trigger strong first order EWPT



field space



bubble wall profile

z is distance from bubble wall

Need at least $\delta V(S) = \mu_S^2 S^2$ to avoid CPV being redefined away

Espinosa, Konstandin, Riva, 1107.5441; MC, Y.Y Li, Ou and Wang, in prep.

Dark CPV: The role of the Z' Portal

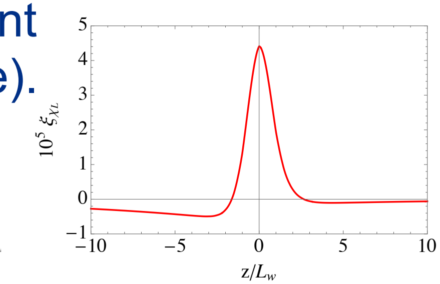
EW sphalerons cannot touch the chiral charge asymmetries in χ because it is an SU(2) singlet — must transfer such CPV effect in other ways to the SM sector

Introduce a new U(1) gauge boson couples to the dark fermions and SM leptons

$$g' Z'_\alpha \left[\underbrace{q_{\chi_L} \bar{\chi}_L \gamma^\alpha \chi_L}_{\Delta} + \underbrace{q_{\chi_R} \bar{\chi}_R \gamma^\alpha \chi_R}_{-\Delta} \right]$$

α =0 component

- If $q\chi_L \neq q\chi_R$ (required by anomaly cancellation), there is a net charge density, that generates a background for the Z'_0 component (static electric potential analogue).

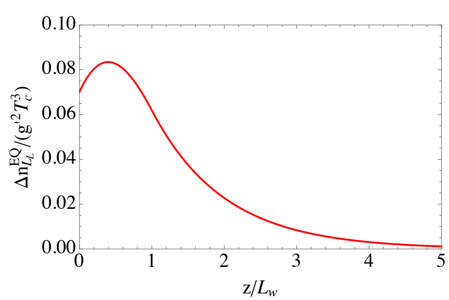


- Z' couples to SM leptons

$$g' Z'_\alpha \sum_{i=1}^{3} \left[q_{L_{L_i}} \bar{L}_{L_i} \gamma^\alpha L_{L_i} + q_{e_{R_i}} \bar{e}_{R_i} \gamma^\alpha e_{R_i} + q_{\nu_{R_i}} \bar{\nu}_{R_i} \gamma^\alpha \nu_{R} \right.$$
$$\left. + q_{Q_{L_i}} \bar{Q}_{L_i} \gamma^\alpha Q_{L_i} + q_{u_{R_i}} \bar{u}_{R_i} \gamma^\alpha u_{R_i} + q_{d_{R_i}} \bar{d}_{R_i} \gamma^\alpha d_{R_i} \right]$$

- The Z'_0 background generates a chemical potential for them.

This in turn generates a Thermal Equilibrium Asymmetry in SM leptons



$$\Delta n^{\rm EQ}_{L_L}(z) = \frac{2 N_g T_c^2}{3} \mu_{L_L}(z) = \frac{2 g' N_g T_c^2}{3} \langle Z'_0(z) \rangle$$

Dark CPV: Baryogenesis

- Solving the corresponding Boltzman equation , considering sphaleron rate suppressed inside the bubble wall, one generates a lepton asymmetry ΔN_L

$$\frac{\partial \Delta n_{L_L}(z,t)}{\partial t} = \Gamma_{\rm sph}(z - v_\omega t)\left[\Delta n_{L_L}^{\rm EQ}(z - v_\omega t) - \Delta n_{L_L}(z,t)\right] \longrightarrow \Delta n_{L_L} = \frac{\Gamma_0}{v_\omega}\int_0^\infty dz\, \Delta n_{L_L}^{\rm EQ}(z) e^{-\Gamma_0 z/v_\omega} .$$

Γ_{sph} exponentially suppressed after the bubble wall has passed

- Sphaleron processes conserve B-L ➔ equal asymmetries are generated $\Delta N_L = \Delta N_B$

$$\eta_B = \frac{\Delta n_B}{s}$$ ➔ $\eta_B \simeq 0.9\ 10^{-10}$ as needed

Crucial Condition: Non-vanishing lepton asymmetry depends on the EFT at EW scale having an anomalous lepton number, but a gauged $U(1)_l$ should be anomaly free

Anomalons in a gauged $U(1)_l$

Particle	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_\ell$
ν_R^i	1	1	0	1
$L'_L = (\nu'_L, e'_L)^T$	1	2	-1/2	$\mathtt{q}$
e'_R	1	1	-1	$\mathtt{q}$
χ_R	1	1	0	$\mathtt{q}$
$L''_R = (\nu''_R, e''_R)^T$	1	2	-1/2	$\mathtt{q} + N_g$
e''_L	1	1	-1	$\mathtt{q} + N_g$
χ_L	1	1	0	$\mathtt{q} + N_g$

e.g. l = e+μ+τ (N_g = 3)

Z' couples to $SU(2)_L$ current, governing L/B violating processes

$$\mathcal{J}^\mu = \sum_{i=1}^{N_g} \bar{L}_{L_i}\gamma^\mu L_{L_i} + \mathtt{q}\bar{L}'_L\gamma^\mu L'_L + (\mathtt{q}+N_g)\bar{L}''_R\gamma^\mu L''_R + \cdots$$

$$\partial_\mu \mathcal{J}^\mu \propto {\rm tr}(\ell\tau^a\tau^b)W^a\widetilde{W}^b \propto \underbrace{[N_g\times 1 + \mathtt{q} - (\mathtt{q}+N_g)]}\,{\rm tr}(W\widetilde{W}) = 0\ ,$$

$$\Delta n_{L,\rm eff}^{\rm EQ} = \Delta n_{L_L}^{\rm EQ} + \Delta n_{L'_L}^{\rm EQ} - \Delta n_{L''_R}^{\rm EQ} = [N_g\times 1 + \mathtt{q} - (\mathtt{q}+N_g)]\ \frac{2}{3}T_c^2 g' \langle Z'_0\rangle$$

SU(2)$_L$ anomalons must decouple from thermal number density