# *New Opportunities for Electroweak Baryogenesis*

Universidad
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Higgs
on

Higgs off

Higgs off

Higgs
on

Higgs
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Higgs off

Marcela Carena
Fermilab/UChicago
XIV The Latin American Symposium on High Energy Physics
Universidad San Francisco de Quito, November 16, 2022

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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 ?



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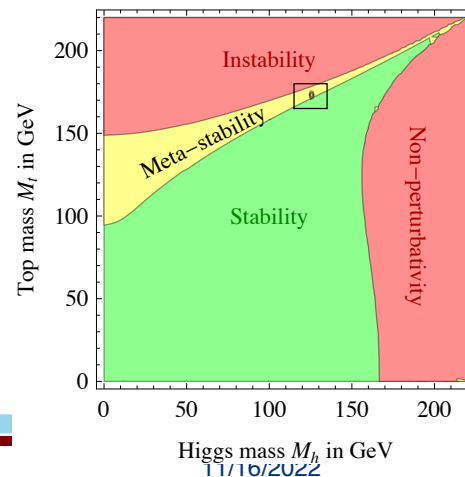
# The Higgs boson: a lot to understand

With $M_H$ = 125 GeV, its mass is at a l...

- We have verified that the Higgs ... mechanism of electroweak symm...

- We have verified ... ... to the heaviest S...

- Enhanced di-Higgs...
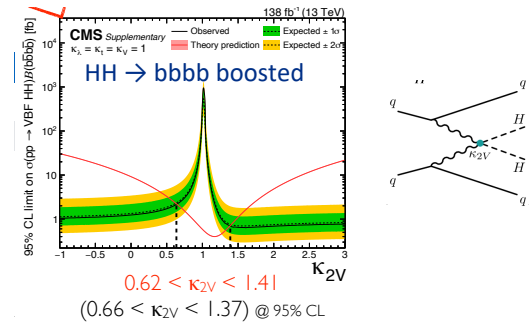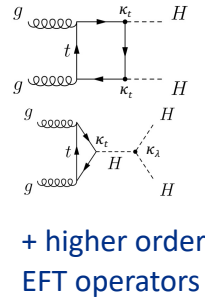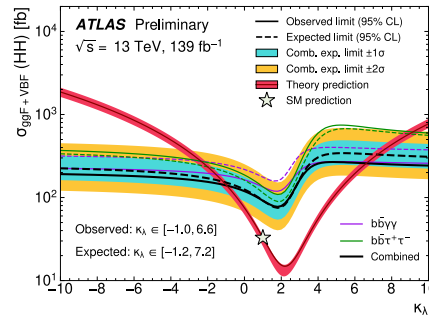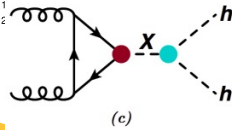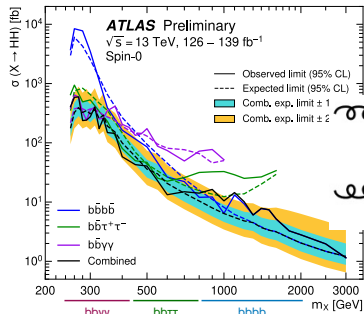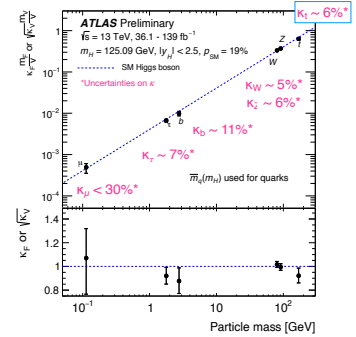
**This can shed light on the Higgs potential and the EW phase transition**

**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**
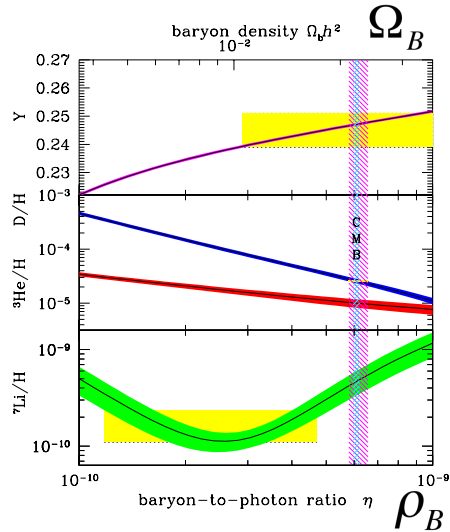


- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis
- CMB

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

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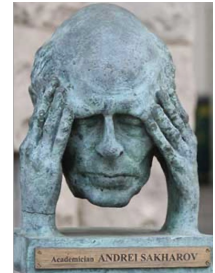
All three requirements fulfilled in the SM – conditions are necessary but NOT sufficient to produced the OBSERVED asymmetry

# 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
- For the chiral weak interactions, gauge symmetry preservation yields the non-conservation of baryon and lepton currents

Adler, Bell, Jackiw; Bardeen

$$\partial_\mu j^\mu_{B,L} \propto F^a_{\mu\nu} F^a_{\rho\delta}$$

$a:$ Weak Interaction Indeces

$$\partial_\mu j^\mu_{B,L} \propto F^a_{\mu\nu} F^a_{\rho\delta} \epsilon^{\mu\nu\rho\delta} \overset{\sim}{=} \frac{\epsilon_{\mu\nu\rho\sigma}}{2} F^{\rho\sigma} \tilde{F}_{\mu\nu} = \frac{1}{16\pi}\int dx^4 Tr[FF] \neq 0 \implies \Delta Q_{B,L} \neq 0$$

$$\tilde{F}_{\mu\nu} = \frac{\epsilon_{\mu\nu\rho\sigma}}{2} F^{\rho\sigma}$$

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

If $\int F_{\mu\nu}\tilde{F}^{\mu\nu} \neq 0 \implies \Delta Q_{B,L} \neq 0$

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"

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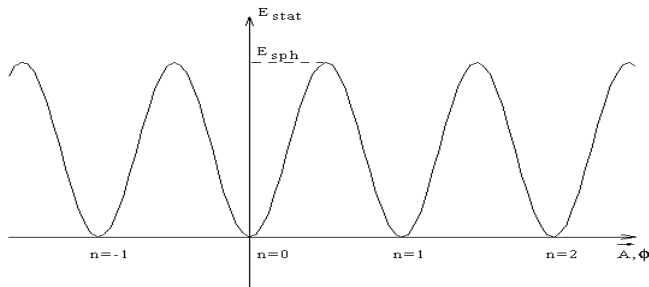


$E_{sph} \sim 8\pi\, v(T) / g$

➜ 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

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

- At very high temperatures they are unsuppressed,

$$\Gamma_{\Delta B \neq 0} \propto T$$
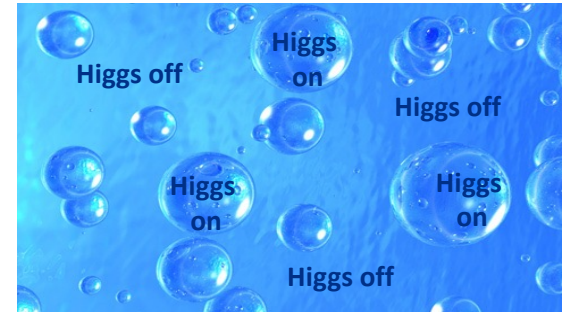
- At finite temperature they are Boltzmann suppressed

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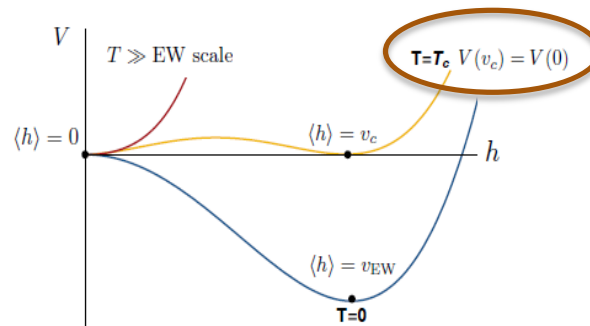


Bubbles expand at near speed of light. Processes near the wall highly out of equilibrium

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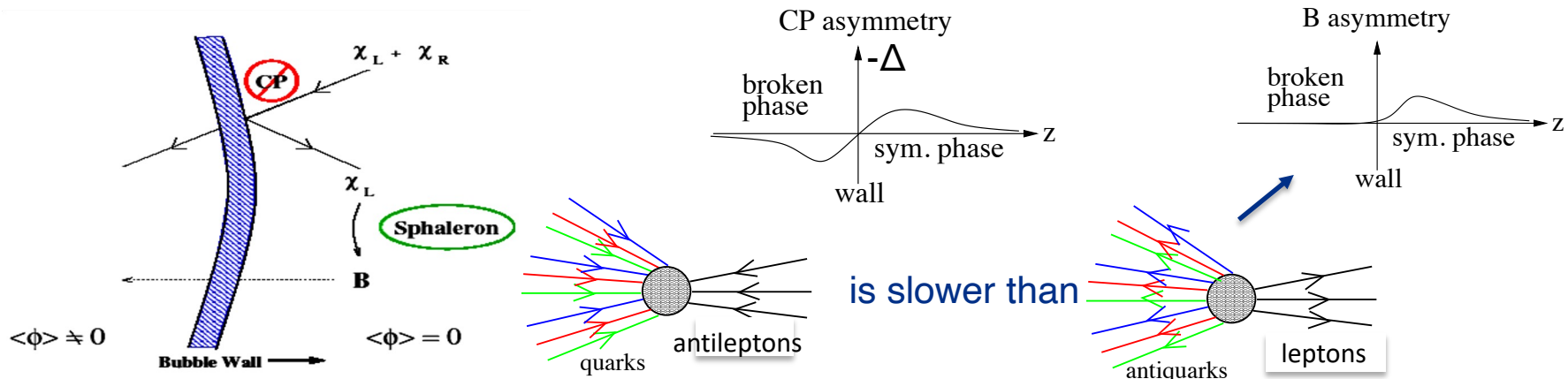# Effects of CPV and Baryon Number generation at the EWPT

- 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**

$$\sigma_{t_L \to t_R} \neq \sigma_{t_L^c \to t_R^c}$$

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

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

CP asymmetry

B asymmetry

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**

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# 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 $T > T_c$, independently of the source of baryon asymmetry

$$\frac{n_B}{s} = \frac{n_B(T_c)}{s} \exp\left(-\frac{10^{16}}{T_c(\text{GeV})}\exp\left(-\frac{E_{\text{sph}}(T_c)}{T_c}\right)\right)$$

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

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

$\ll 1$ ➜ $v(T_c)/T_c \gtrsim 1$

$\cancel{B}$ processes frozen

**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 $S_{\text{bounce}}/T_n \sim 140$
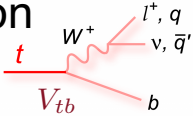
# EW Baryogenesis in the SM fails

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.
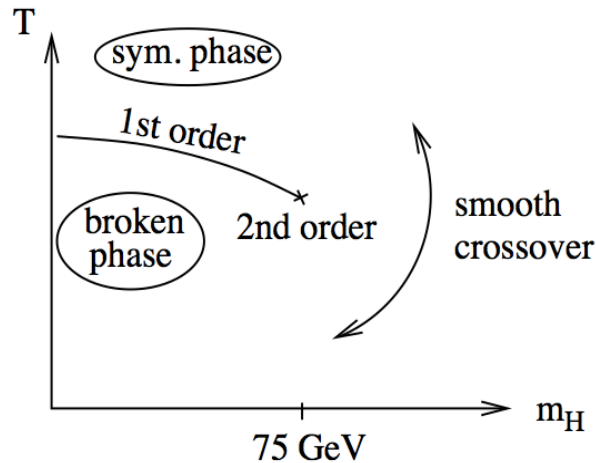
But

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

Contribution from CP violation (CKM) is highly suppressed



High order loop effects needed to generate a complex contribution to the top quark mass
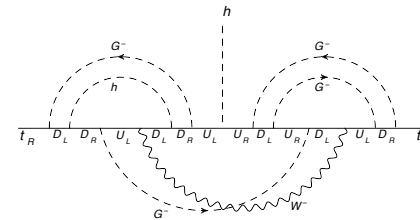
Gavela et al '86

Kajantie, Laine, Rummukainen, Shaposhnikov '88

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

$\mathcal{M}_q = Y_q Y_q^\dagger$

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# 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

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# 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

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# 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
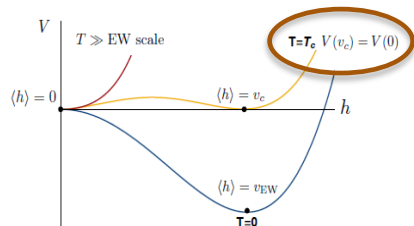


$v\,(T_c)\,/\,T_c \sim E\,/\,\lambda$    that controls the strength of the phase transition

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

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

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# 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

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

The scalar potential can have many fields

- Tree-level Effects

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

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

- Zero Temperature loop effects

  Modifying the potential through radiative corrections involving new particles

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

- Thermal effects

  Modifying the thermal potential through thermal loops involving new particles

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

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

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# Simplest Case:
# A singlet extension of the Standard Model

# 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: $s \to -s$

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

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

To determine phase transition pattern requires finite temperature potential

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

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

**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 =m²/T²**

$$J_B^{\mathrm{high-T}}(\alpha) = \mathrm{Re}\left[-\frac{\pi^4}{45} + \frac{\pi^2}{12}\alpha - \frac{\pi}{6}\alpha^{\frac{3}{2}} + \cdots\right],$$

$$J_F^{\mathrm{high-T}}(\alpha) = \mathrm{Re}\left[\frac{7\pi^4}{360} - \frac{\pi^2}{24}\alpha + \cdots\right].$$

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

**One Loop Coleman-Weinberg potential and daisy resummation also considered**

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

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

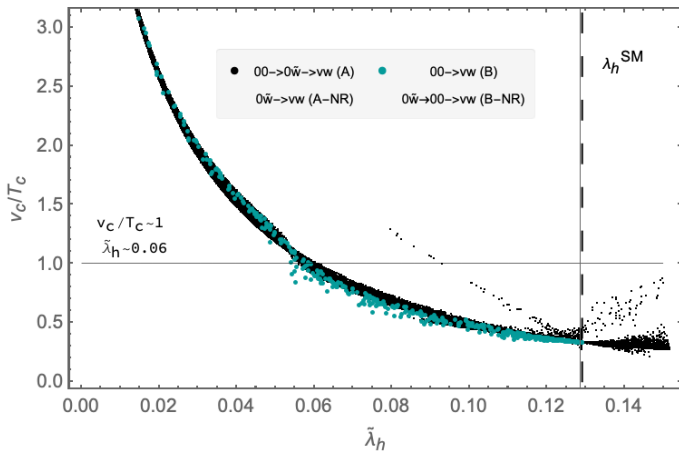THE UNIVERSITY OF CHICAGO

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# EWPT with Spontaneous $Z_2$ Breaking: a Strong 1$^{st}$ order EWPT

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

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



- $v_c/T_c \sim 1$
- $\tilde{\lambda}_h \sim 0.06$

Legend: 00→0w̃→vw (A) · 00→vw (B) · 0w̃→vw (A–NR) · 0w̃→00→vw (B–NR) · $\lambda_h^{SM}$

➤ Sizeable $s^2 |H|^2$ coupling needed for a SFOEWPT
Only 3 parameters after defining Higgs mass and v.e.v

• quartic mixing coupling is proportional to S-H mixing – strongly constrained by Higgs precision measurements
$$\sin\theta \lesssim 0.4$$

• strength of the EWPT is enhanced for a light singlet

If singlet sufficiently light, the Higgs can have exotic decay: H→SS, and a SFOEWPT demands significant S-H couplings ➔ Hence BR(H → SS) is bounded from below

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

Specifics of the exotic Higgs decays depend on $Z_2$ symmetry breaking realization

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# Exotic Higgs decays as a potent probe of viable EWBG models

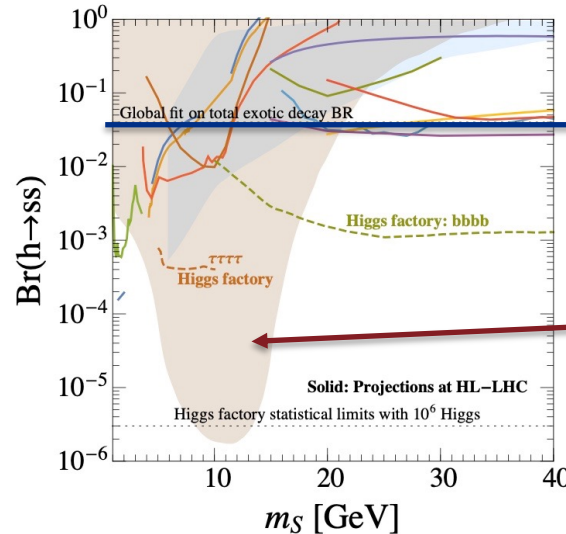H→ SS can lead to many final states with S inheriting Higgs-like hierarchical BR's, mediated through mixing

Final state dominated by $h \to ss \to bbbb$ for $m_s > 2m_b$, and by jjjj, jjττ, and ττττ for $m_s < 10$ GeV
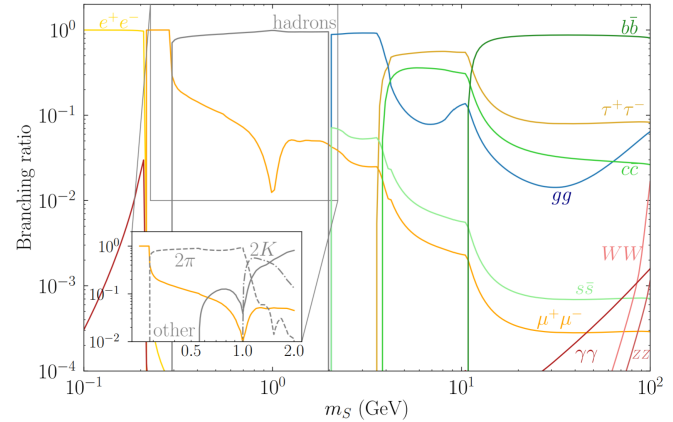
Bounds on exotic Higgs decays
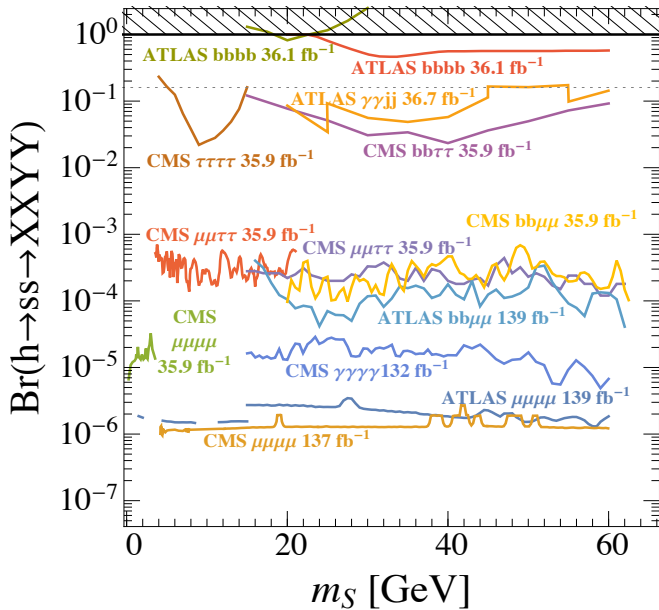
**Bounds on Br(h → ss) from Br(h → ss → XXYY)**
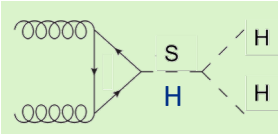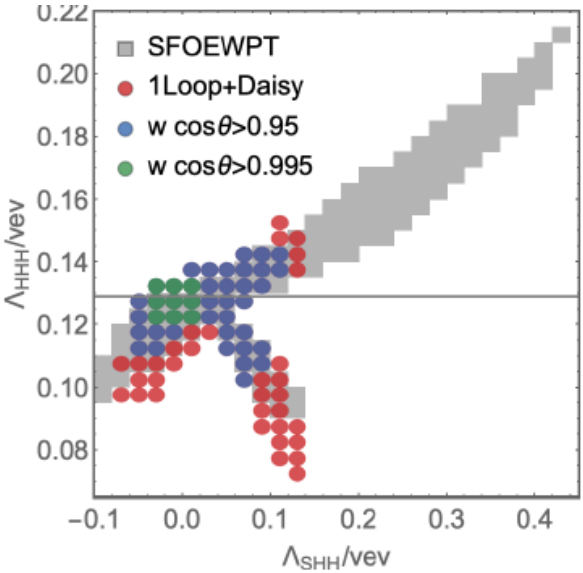
Global fit:
BR[H→exotics] < 4%

$Z_2$ spontaneous breaking with SFOEWPT

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

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

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# EWPT and Higgs Pair Production: Higgs Trilinear Coupling

## $Z_2$ spontaneous Symmetry Breaking Scenario

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



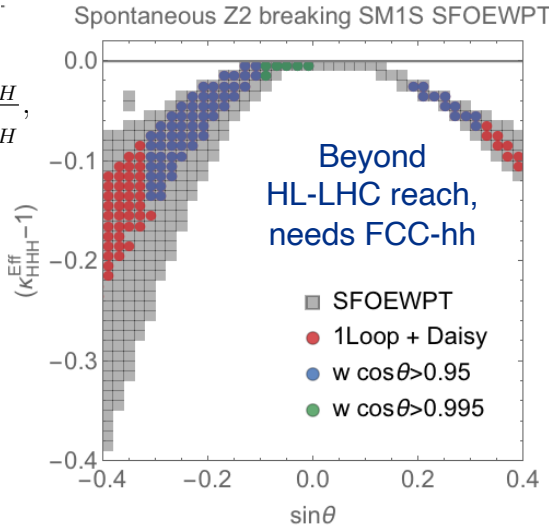$$\kappa_{HHH}^{Eff} \equiv \frac{\Lambda_{HHH}^{Eff}}{\Lambda_{HHH}^{SM}},$$

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

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

$$\Lambda_{SHH} = \frac{(2m_H^2 + m_S^2)(\sin\theta + \tan\beta\cos\theta)\sin 2\theta}{4\tan\beta\,v}.$$
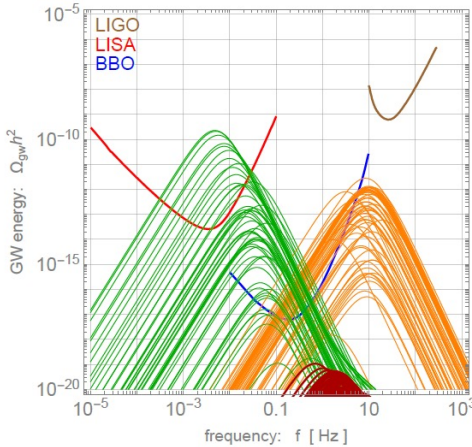
Beyond
HL-LHC reach,
needs FCC-hh

## 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

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# Extended Higgs sectors: a SUSY example

# The Electroweak Phase Transition in the NMSSM

# 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    $\langle H_d \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}$    $\langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}$    $\langle S \rangle = v_S$

CP even interaction states $\left\{ H^{\mathrm{SM}}, H^{\mathrm{NSM}}, H^S \right\}$ $\rightarrow$ CP even mass states $\left\{ h_{125}, H, h_S \right\}$

Higgs basis

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

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

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

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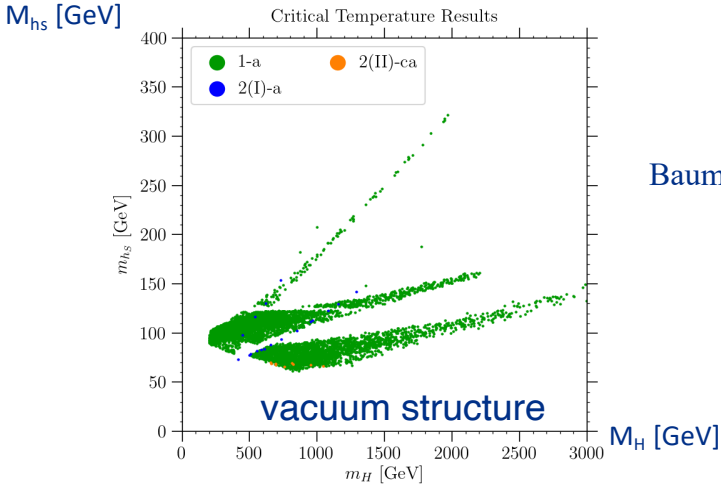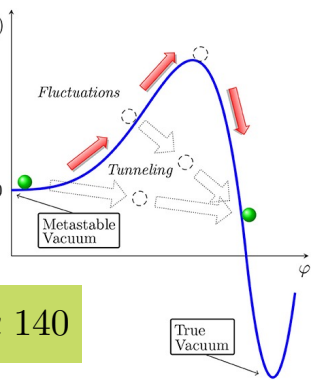# EWPT in the NMSSM - nucleation is more than critical

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: $\Gamma/V \propto T^4 e^{-S_3/T}$
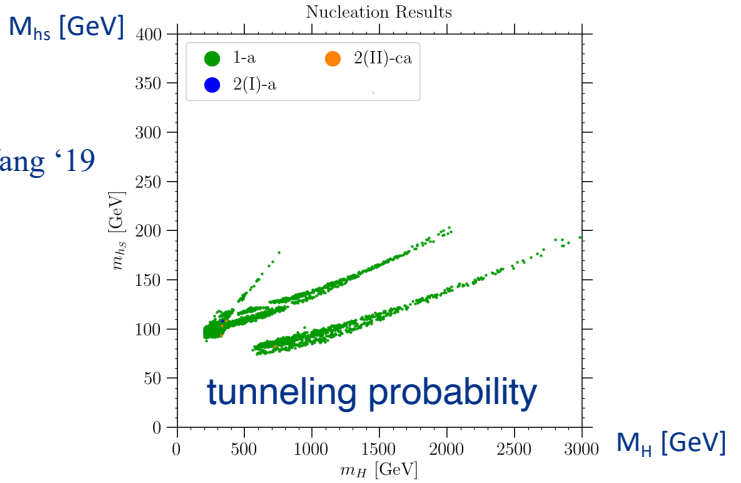
requiring the nucleation probability to be approx. one per Hubble volume and Hubble time leads to the nucleation condition

$$\frac{S_3(T_n)}{T_n} \simeq 140$$

M$_{hs}$ [GeV]



$T_c \longrightarrow T_n$

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

vacuum structure

M$_H$ [GeV]

M$_{hs}$ [GeV]

tunneling probability

M$_H$ [GeV]

## 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

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# Baryogenesis with Dark CP Violation:

# A model with gauged lepton number

# The challenge of new CPV sources for EW Baryogenesis

The observed baryon asymmetry requires new CPV sources that are usually in tension with Electric Dipole Moment experimental bounds
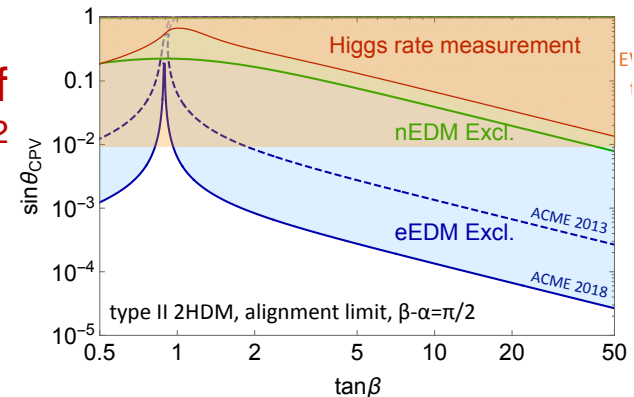
Electron EDM and the ACME experiment
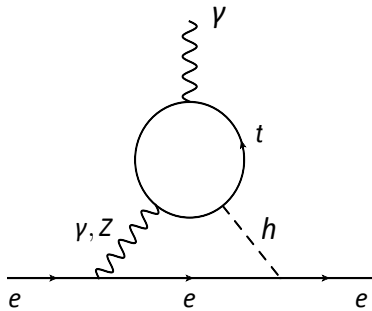
Weak scale CPV

$$d_e \sim \frac{e\, G_F\, m_e}{(16\pi^2)^2} \vartheta_{CPV} \sim 10^{-26} \vartheta_{CPV}\, e\, cm$$

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

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

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

Higgs rate measurement

nEDM Excl.

eEDM Excl.

ACME 2013

ACME 2018

type II 2HDM, alignment limit, $\beta-\alpha=\pi/2$

$\sin\theta_{CPV}$ vs $\tan\beta$

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

**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?**
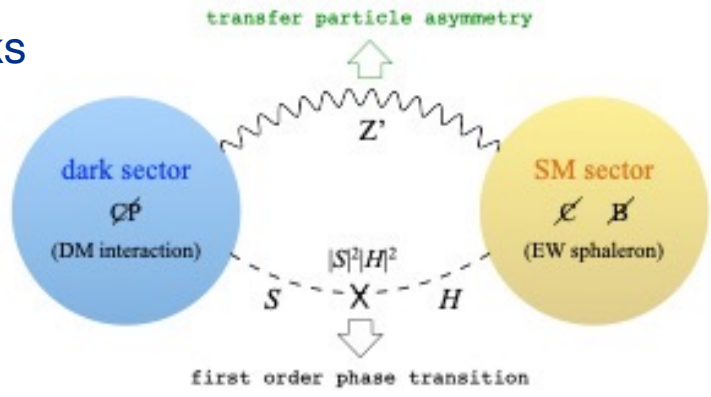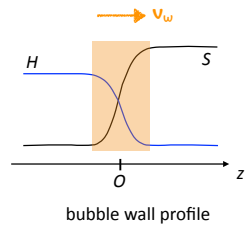
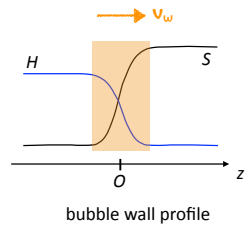# A new mechanism for EW Baryogenesis: Dark CP violation

A model with U(1)$_l$ gauged lepton number

MC, Quiros and Yue Zhang.19

**Particle content: SM , Z', S, $\chi_L$, $\chi_R$**

- **Higgs–Singlet 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

A varying mass $m_\chi$ , along the wall direction,
together with the S vev, generates **a chiral
charge asymmetry in χ particles**

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

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# A new mechanism for EW Baryogenesis: Dark CP violation
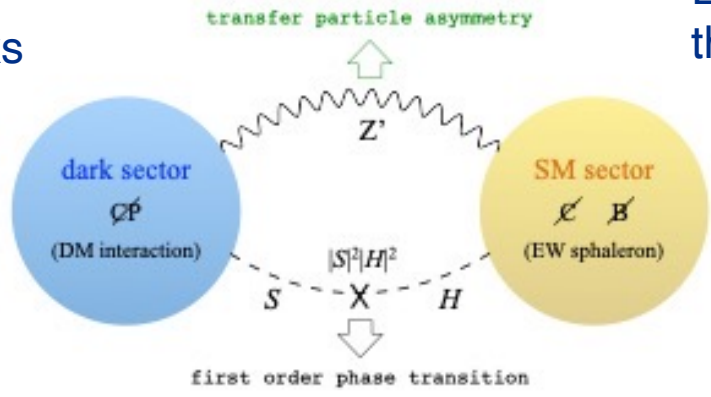
A model with U(1)$_l$ gauged lepton number

### Particle content: SM , Z', S, $\chi_L$, $\chi_R$

- **Higgs–Singlet 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

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



bubble wall profile

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

A varying mass m$_\chi$ along the z direction, together with the S vev, generates **a chiral charge asymmetry in χ particles**

This in turn generates a net Chiral Thermal Equilibrium Asymmetry in SM leptons

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

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

**SU(2)$_L$ anomalons, besides DM, must decouple from thermal number density**
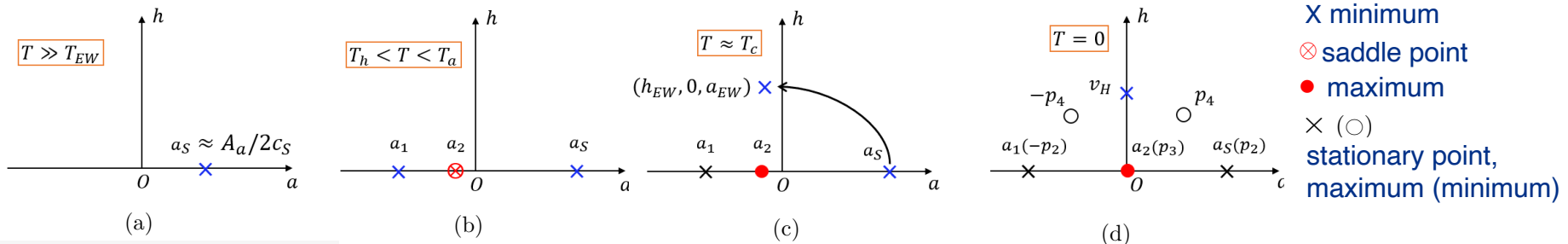
# A new EW phase transition

$$V_0 = \lambda_H(|H|^2 - v_H^2)^2 + \lambda_S(|S|^2 - v_S^2)^2 + \lambda_{SH}|S|^2|H|^2 + \delta V, \qquad H = \frac{1}{\sqrt{2}}\begin{pmatrix} G_1 + iG_2 \\ h + iG_3 \end{pmatrix}, \quad S = \frac{1}{\sqrt{2}}(s + ia)$$

Need at least $\delta V(S) = \kappa_S^2 S^2$ to avoid CPV being redefined away, and in term of h. s, a fields

$$V_0 = -\frac{1}{2}\mu_H^2 h^2 + \frac{1}{4}\lambda_H h^4 + \frac{1}{4}\lambda_{SH}h^2(s^2 + a^2) - \frac{1}{2}\mu_S^2(s^2 + a^2) + \frac{1}{4}\lambda_S(s^2 + a^2)^2 + \kappa_S^2(s^2 - a^2)$$

with   $\mu_{H(S)}^2 = \lambda_{H(S)}v_{H(S)}^2$.   and   $v_S'^2 = v_S^2 + 2\kappa_S^2/\lambda_S$.   a stationary point in the a direction at T=0 that facilitates an SFOEWPT

- Full one-loop potential: $V_0 + V_{CW} + V_{CT} + V^T_{1\text{-loop}}$ and resummation of higher loop daisy diagrams to ensure validity of the analysis at the $T_c/T_n$

- Implement T=0 boundary conditions: Bounded form Below (BFB), non tachyonic solutions, physical minimum at $(v_H,0,0)$ to be the global minimum

- Careful study of finite temperature conditions to ensure a 1st order phase transition and not a role over



(a)   (b)   (c)   (d)

X minimum
⊗ saddle point
● maximum
× (○)
stationary point, maximum (minimum)

Marcela Carena I New Opportunities for Electroweak Baryogenesis         11/16/2022

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# Sourcing CP Violation

A direct coupling between a SM gauge singlet fermion χ and the Higgs boson would be higher dimensional.

To build a renormalizable theory introduce a new SM singlet composite scalar S

S couples to dark fermion (DM)     $\bar{\chi}_L(m_0 + \lambda_c S)\chi_R + \text{h.c.}$

and contributes to its mass     $\mathcal{L}_{M} \sim \bar{\chi}_L(m_0 + \lambda_c S)\chi_R + \text{h.c.})$     $\lambda = |\lambda_c| \text{ and } \theta = \arg(\lambda_c)$

During the EWPT, the phase of Mχ varying in the direction of the expanding bubble wall, derived from $m_0$ and the $\lambda_c$ and S vev phases. This is the physical source of CP violation.

**This induces a chiral asymmetry in the χ particles:**

$$\Delta \equiv n_{\chi_L} - n_{\chi_L^c} = -(n_{\chi_R} - n_{\chi_R^c}) \neq 0$$

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# Transferring CP Violation

EW sphalerons cannot touch the chiral charge asymmetries in $\chi$ 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

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

$\Delta$    $\Delta$    $-\Delta$

$\alpha = 0$ 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).
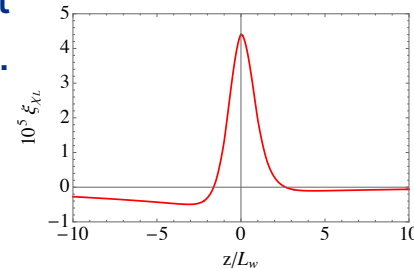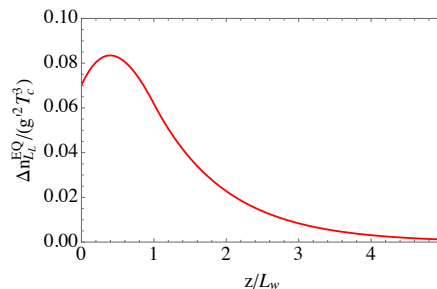


- Z' couples to SM leptons

$$g' Z'_\alpha \sum_{i=1}^{3} \left[ q_{L_{L_i}} \bar{L}_{L_i} \gamma^\alpha L_{L_i} + q_{e_{R_i}} \bar{e}_{R_i} \gamma^\alpha e_{R_i} + q_{\nu_{R_i}} \bar{\nu}_{R_i} \gamma^\alpha \nu_{R_i} \right.$$

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

This in turn generates a net Chiral Thermal Equilibrium Asymmetry in SM leptons



$$\Delta n_{L_L}^{\mathrm{EQ}}(z) = \frac{2 N_g T_c^2}{3} \mu_{L_L}(z) = \frac{2 g' N_g T_c^2}{3} \left\langle Z'_0(z) \right\rangle$$

# Dark CPV: Baryogenesis

- Solving the corresponding Boltzman equation , considering sphaleron rate suppressed inside the bubble wall, one generates a lepton asymmetry $\Delta n_L$

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

$\Gamma_{\text{sph}}$ unsuppressed outside the bubble but exponentially suppressed inside the bubble

$$\Gamma_{\text{sph}}(z - v_w t) = \begin{cases} \Gamma_0, & t < z/v_w \\ \Gamma_0 e^{-M_{\text{sph}}/T_n}, & t > z/v_w \end{cases} \qquad \Gamma_0 \simeq 10^{-6} T_n, \ M_{\text{sph}} = 4\pi h_{EW}(T_n) B/g_2$$

- Sphaleron processes conserve B-L ➔ equal asymmetries are generated $\Delta n_L = \Delta n_B$

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

**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

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

# Dark CPV and EWBG: Phenomenology

MC, Quiros and Yue Zhang'19
MC, Y-Y Li, T. Ou, Y. Wang' 22

Model parameters in the Scalar, Z' and dark sectors need to accommodate to:

- Produce a SFOEWPT, yield the observed baryon asymmetry and DM relic density

- Fulfil experimental constraints / open new opportunities:

  ➢ 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 $\chi$ particle qualifies as a thermal DM candidate ➔ direct detection searches

  ➢ SFOEWPT can generate stochastic gravitational wave signatures possibly observable at current/future GW detectors
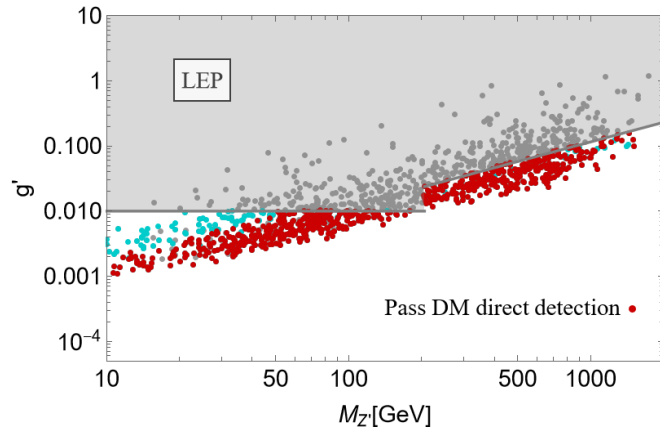
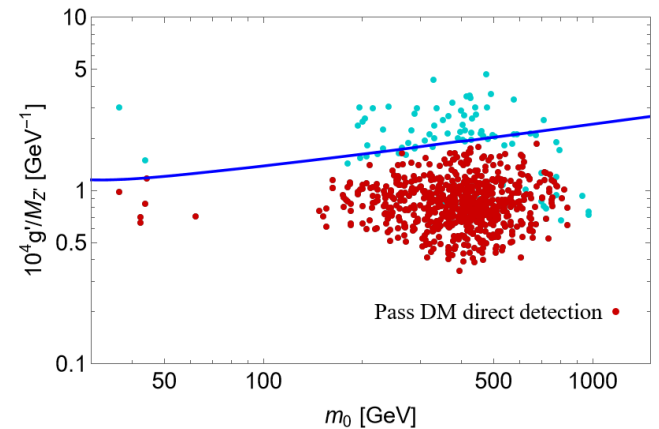# Dark CPV and EWBG: Phenomenology

Results presented varying model parameters

which are highly correlated and restricted by SFOEWPT, BAU, DM relic and Z' searches

$$\text{fixed parameters}: \quad \{\lambda_H, v_H\},$$
$$\text{scalar sector parameters}: \quad \{\lambda_S, v'_S, \lambda_{SH}, m_a, m_s\},$$
$$\text{dark fermion parameters}: \quad \{m_0, \lambda, \theta\},$$
$$Z' \text{ parameters}: \quad \{g', M_{Z'}\}.$$
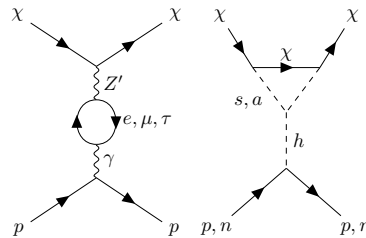


Direct DM detection channels

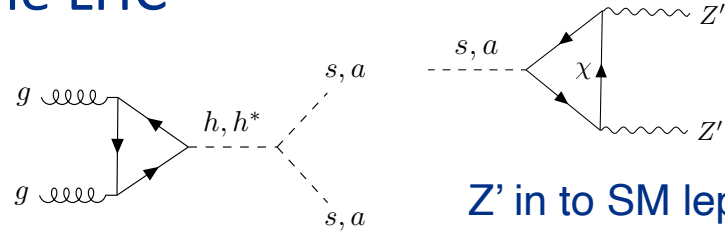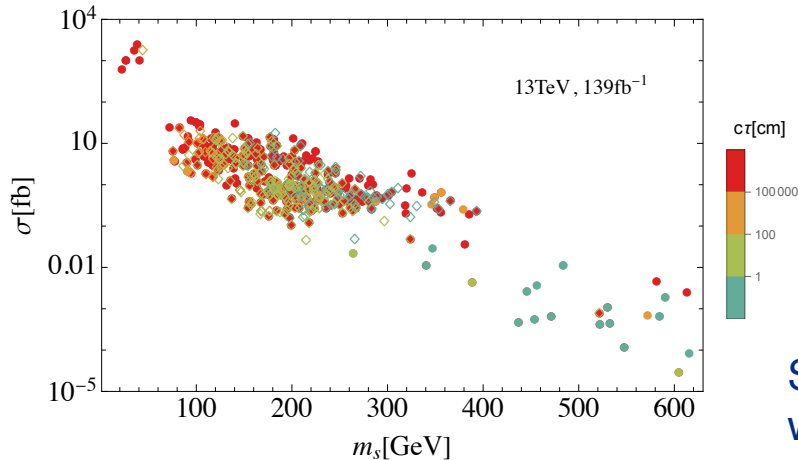Z' exchange dominant besides for large $m_0$ (hence $m_\chi$ ) and small $g'^2/m^2_{Z'}$



BAU proportional to $g'^2/m^2_{Z'}$

Most relevant annihilation channel for relic density $\chi\chi \rightarrow$ ss,aa,sa $\rightarrow$ $\lambda$-$m_0$ connection

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# Dark CPV and EWBG: Phenomenology

## Searches for long- lived scalars at the LHC



13TeV, 139fb$^{-1}$

$c\tau$[cm]

$$\sigma(gg \to ss(aa) \to l^+ l^- + X)$$

Z' in to SM leptons

On/off shell Z's

Solid circles pass both a and s search constraints, while open diamond are excluded with current data.

## Gravitational wave signals

Total power spectrum: a linear combination of sound waves and MHD turbulence contributions

ma < m$_h$/2 (dark green curves) and ma > m$_h$/2 (light green curves). The power-law integrated sensitivity prospective curves shown for comparison.
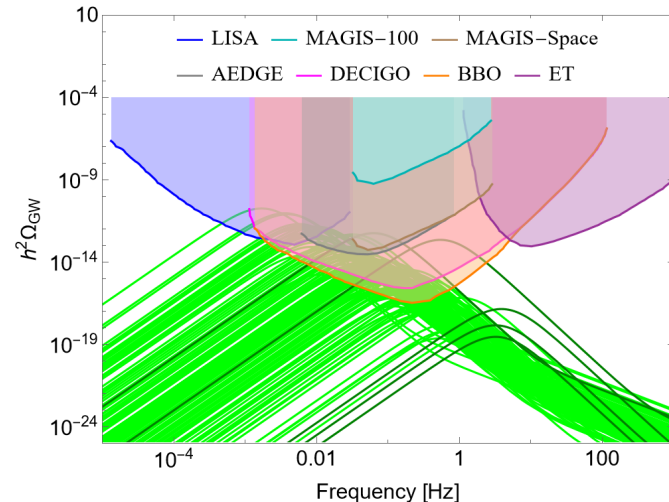


A first study, more exploration needed

# Outlook: Electroweak Baryogenesis

An appealing mechanism to explain the matter-antimatter asymmetry:

It requires a strongly first order electroweak phase transition and additional CPV sources beyond the SM, usually in tension with EDM bounds

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 – a new portal -

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*Gracias!*

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# 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

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

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

  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) → $\langle (h,s) \rangle \equiv (v_{EW}, 0)$

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

- Spontaneously $Z_2$ breaking → $\langle (h,s) \rangle \equiv (v_{EW}, w_{EW})$  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

To determine phase transition pattern
requires finite temperature potential

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

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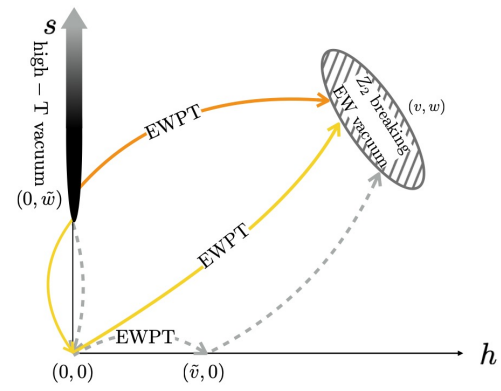# The SM singlet extension: EWPT paths for baryogenesis

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
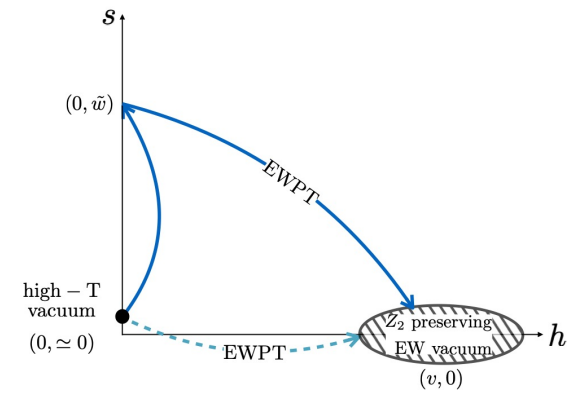- $Z_2$-NR: Yes

Solid lines: EWPT can be strongly first-order
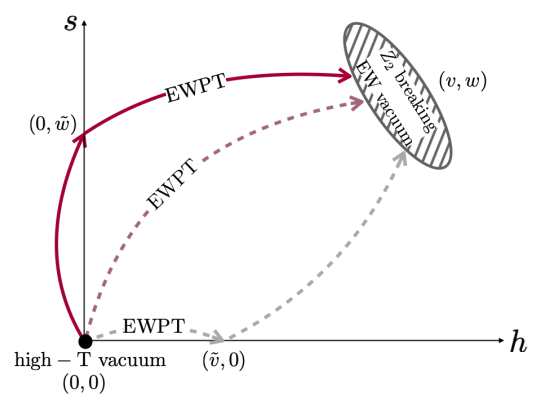


$Z_2$ spontaneous breaking scenarios *with symmetry restoration* at high T

$Z_2$ 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

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# EWPT with Spontaneous $Z_2$ Breaking: The full analysis

The electroweak phase transition strength

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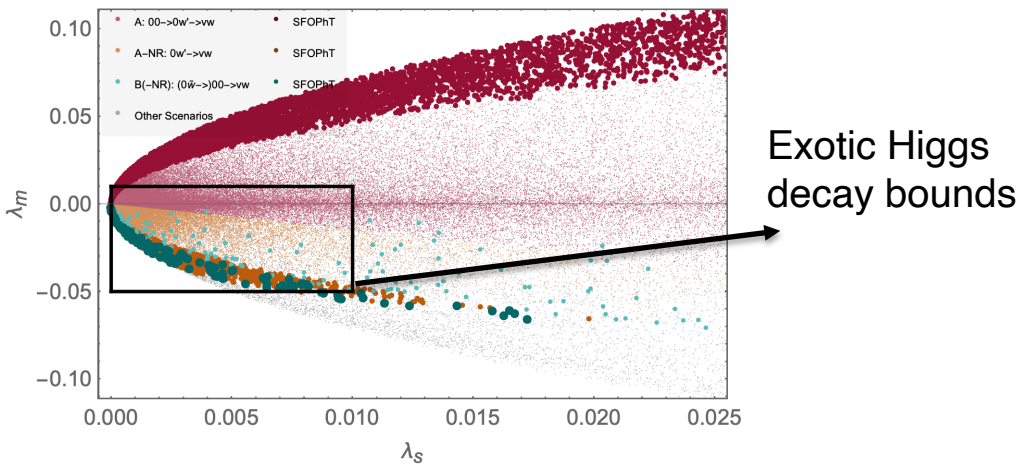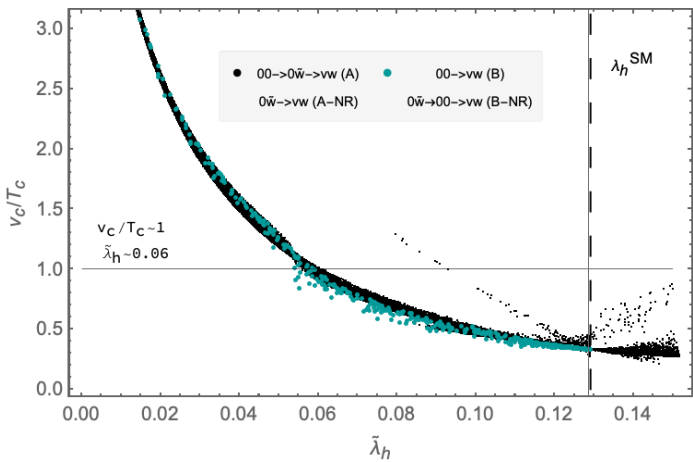
- Bare parameters

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

- 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

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# 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]
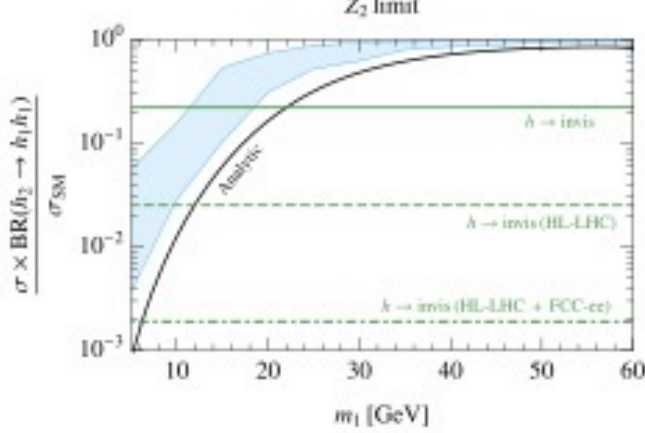
# Phenomenology of SM plus Singlet models

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

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

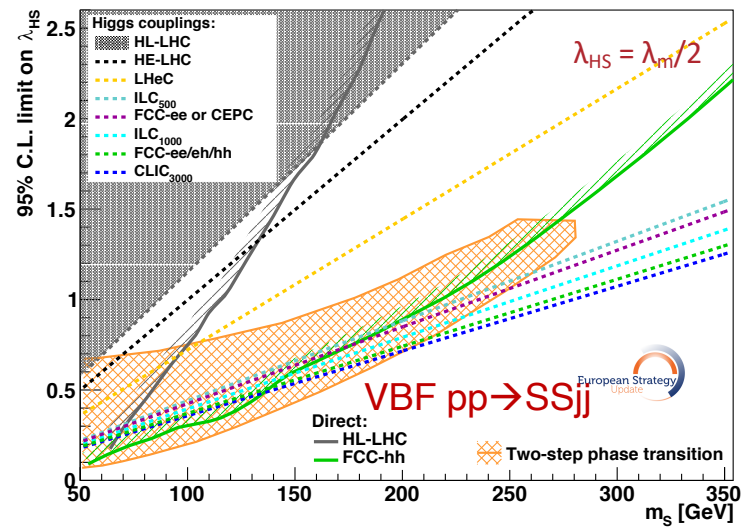➢ **No S-H mixing – S is stable** (invisible decays)

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

Low mass singlet: $m_s < m_h/2$

$m_s > m_h/2$



Kozaczuk, Ramsey-Musolf, Shelton '19

**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

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# Probing $Z_2$ breaking Singlet Extensions via Higgs Exotic Decays
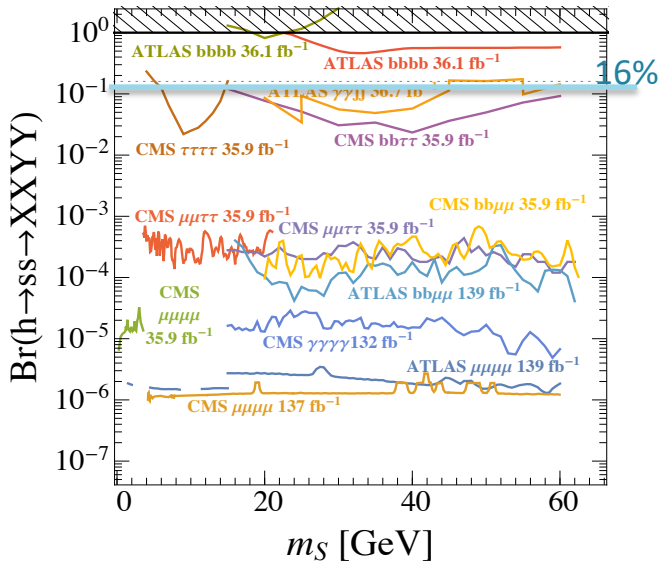
Currently: BR[H→ exotics] < 16%

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
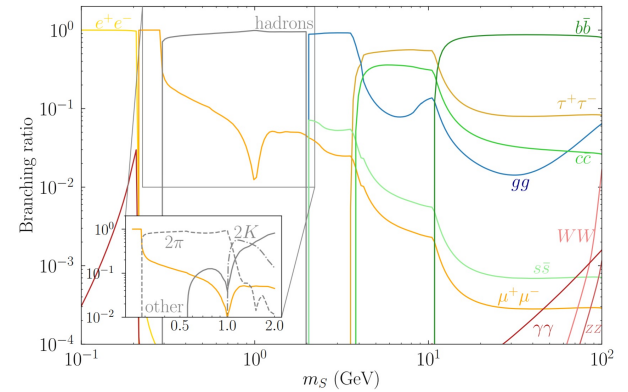


Bounds on exotic Higgs decays



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 Z₂ 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

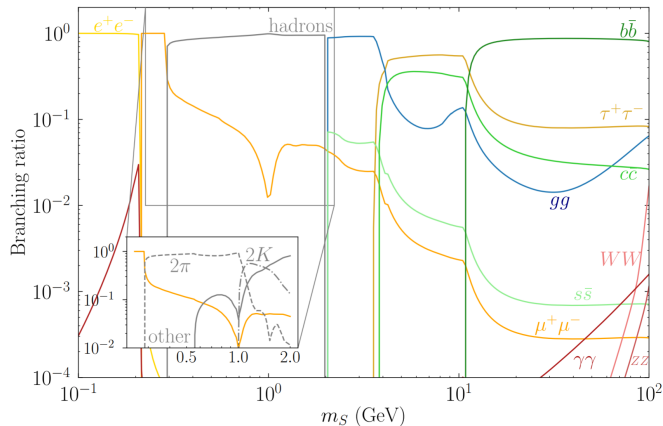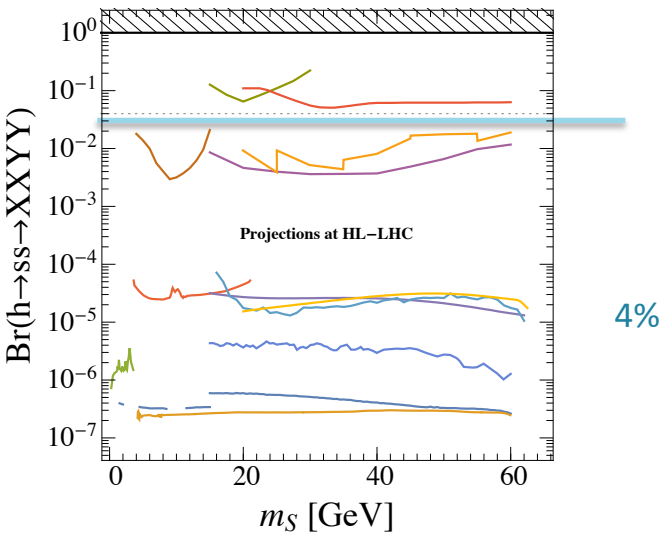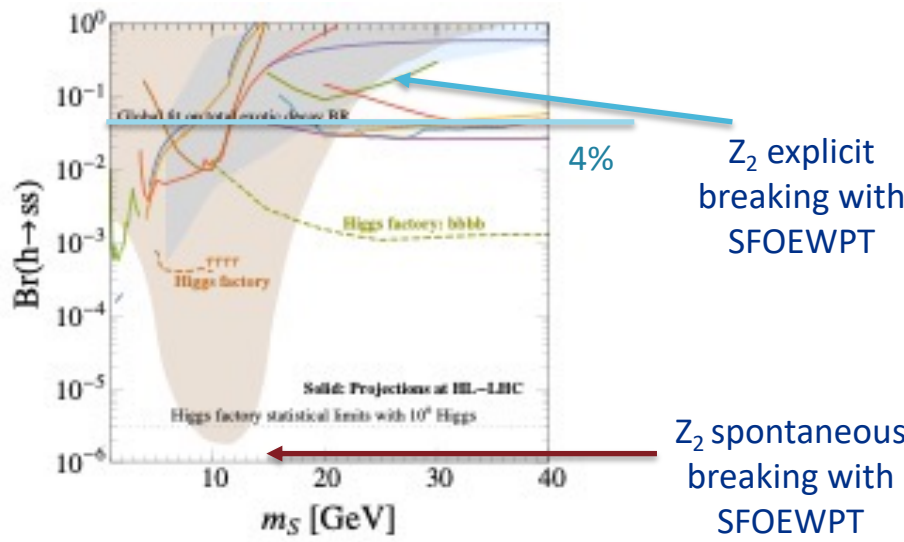Final state dominated by h → ss → bbbb for $m_s > 2m_b$, and by jjjj, jjττ, and ττττ for $m_s < 10$ GeV



**Bounds on exotic Higgs decays**



4%

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

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



4%

Z₂ explicit breaking with SFOEWPT

Z₂ spontaneous breaking with SFOEWPT

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

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# 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

$$m_{h_{125}}^2 \simeq \mathcal{M}_{S,11}^2 = m_Z^2 \cos^2(2\beta) + \lambda^2 v^2 \sin^2(2\beta)$$

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 $\qquad\qquad$ 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 $\qquad\qquad$ alignment without decoupling

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

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

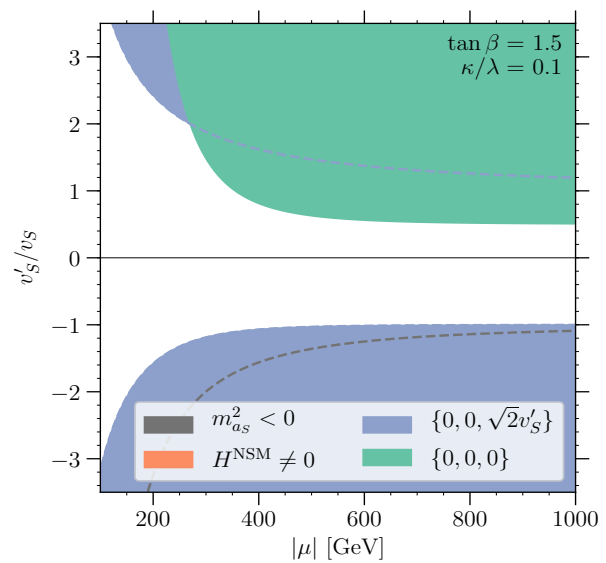For small to moderate tanβ: λ ~ 0.6 - 0.7

## The parameter space

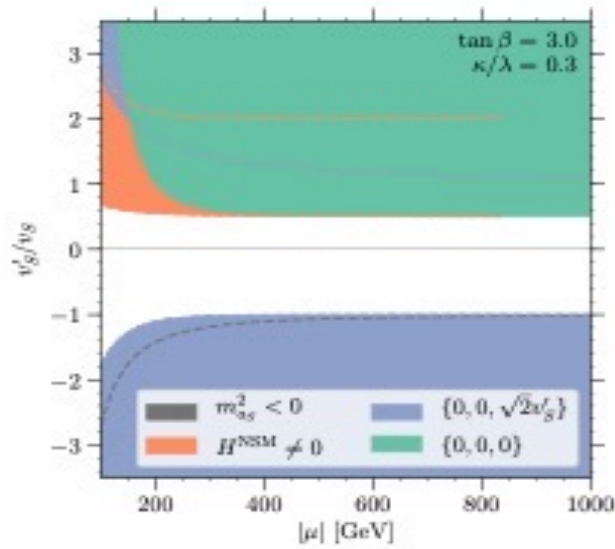$$\{v, \ \tan\beta, \ \mu, \ \lambda, \ \kappa, \ A_\lambda, \ A_\kappa\} \quad \rightarrow \quad \{\mu, \ \tan\beta, \ \kappa, \ A_\kappa\}$$

# EWPT in the NMSSM: alignment limits and parameter space

## The parameter space

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

- 125 GeV mass eigenstate without large radiative corrections $\quad \tan\beta \lesssim 5$

- Avoid Landau poles (GUT) $\quad \sqrt{\lambda^2 + \kappa^2} \lesssim 0.7$

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

- Avoid tachyonic masses, e.g. $\quad m_{a_S}^2 \geq 0$

- Correct vacuum structure at zero temperature $\quad \{H^{\mathrm{SM}}, H^{\mathrm{NSM}}, H^{\mathrm{S}}\} = \{0,0,0\} \vee \left\{0,0,\sqrt{2}v'_S\right\} \vee \left\{0,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \left\{\sqrt{2}v,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \cdots$



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# EWPT in the NMSSM - the effective potential

Radiative corrections (zero temperature)

**Integrating out heavy degrees of freedom** (sfermions, gluinos etc)

A new operator by matching:

$$V_0^{\text{eff}} = V_0 + \frac{\Delta\lambda_2}{2}|H_u|^4 \qquad \text{with} \quad \Delta\lambda_2 \text{ fixed by 125 GeV Higgs mass}$$

**Light degrees of freedom: CW potential**

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

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

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

Introducing counterterms to maintain boundary conditions

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

**Finite temperature effective potential**

with

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

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

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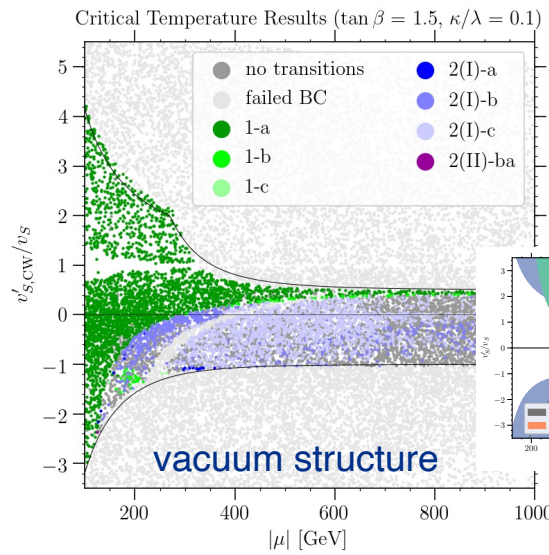
➔ **the higher the barrier, and the larger the distance between the minima, the lower the nucleation probability**

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
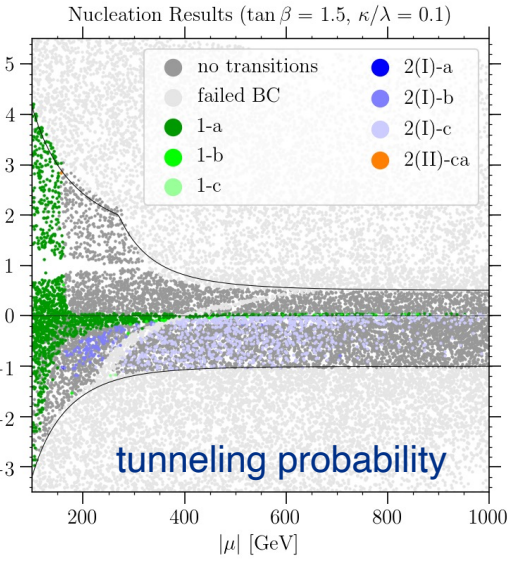
$$\frac{S_3(T_n)}{T_n} \simeq 140$$
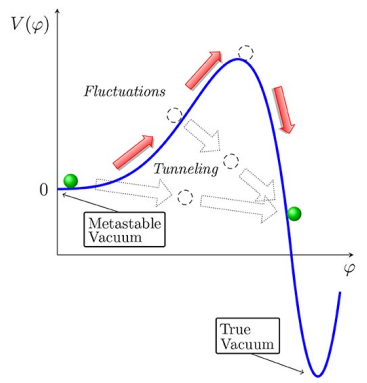


🟢 $(0,0,0) \rightarrow (v,0,v_S)$   🔵 $(0,0,0) \rightarrow (0,0,\tilde{v}_S) \rightarrow (v,0,v_S)$   🟠 $(0,0,0) \rightarrow (\tilde{v},\tilde{v}_{\text{NSM}},0) \rightarrow (v,0,v_S)$
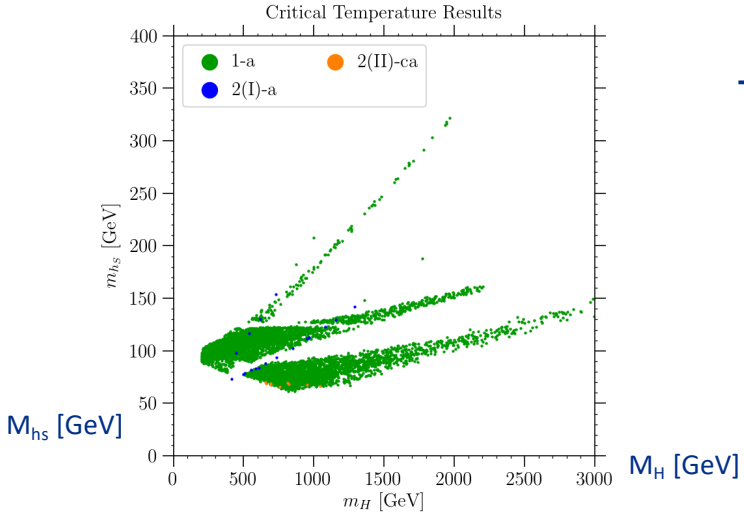


Critical Temperature Results ($\tan\beta = 1.5$, $\kappa/\lambda = 0.1$)

vacuum structure

$T_c \longrightarrow T_n$

Nucleation Results ($\tan\beta = 1.5$, $\kappa/\lambda = 0.1$)
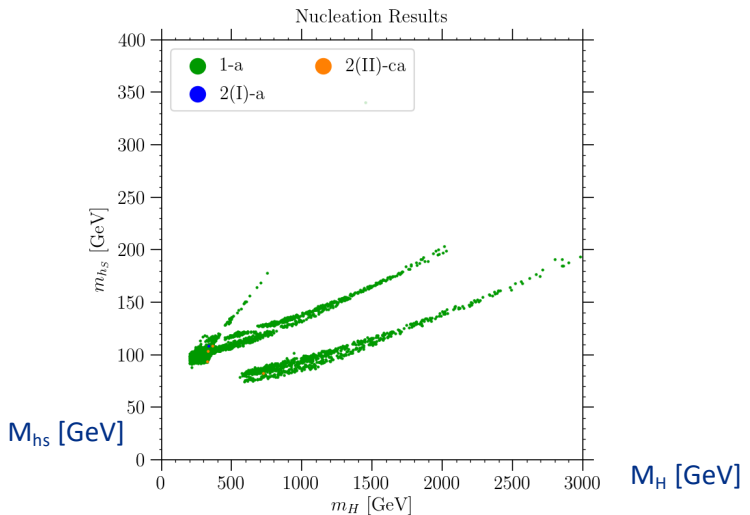
tunneling probability

- **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**

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# EWPT in the NMSSM: collider and dark matter pheno



**Critical Temperature Results**

$T_c \longrightarrow T_n$

**Nucleation Results**

## 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

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# Baryogenesis with Dark CP Violation:

# A model with gauged lepton number

# 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 ΔN_L = ΔN_B

$$\eta_B = \frac{\Delta n_B}{s}$$ ➜ η_B ≃ 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 | $SU(3)_c$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_\ell$ |
|---|---|---|---|---|
| $\nu_R^i$ | 1 | 1 | 0 | 1 |
| $L'_L = (\nu'_L, e'_L)^T$ | 1 | 2 | -1/2 | q |
| $e'_R$ | 1 | 1 | -1 | q |
| $\chi_R$ | 1 | 1 | 0 | q |
| $L''_R = (\nu''_R, e''_R)^T$ | 1 | 2 | -1/2 | q + $N_g$ |
| $e''_L$ | 1 | 1 | -1 | q + $N_g$ |
| $\chi_L$ | 1 | 1 | 0 | q + $N_g$ |

e.g. l = e+μ+τ (N_g = 3)

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

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

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

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

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

# Dark CPV: Phenomenology

- 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 $\chi$ particle qualifies to be a thermal dark matter candidate
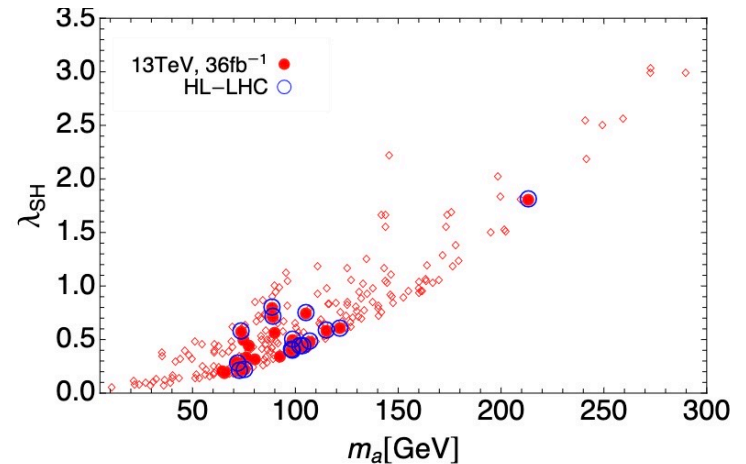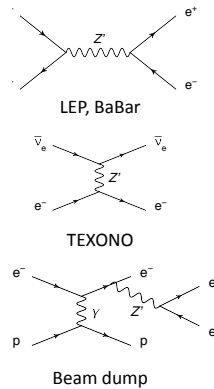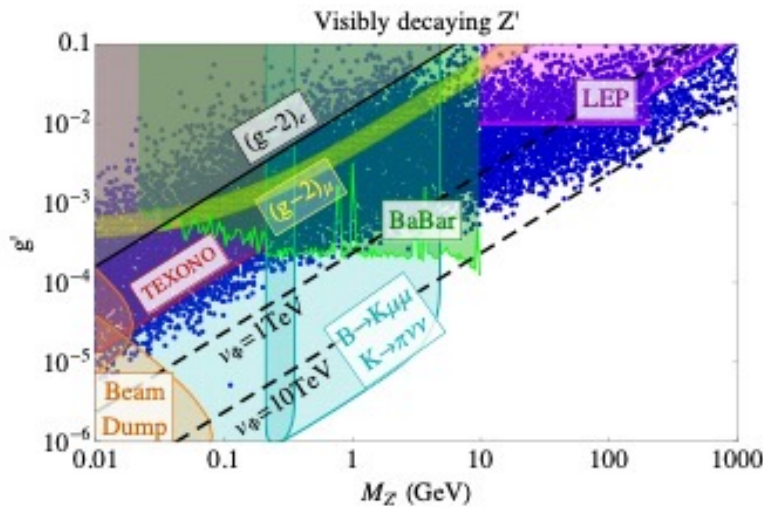


**Leptophilic *Z'*:
Target and Searches**

**LHC searches for
long-lived scalars**