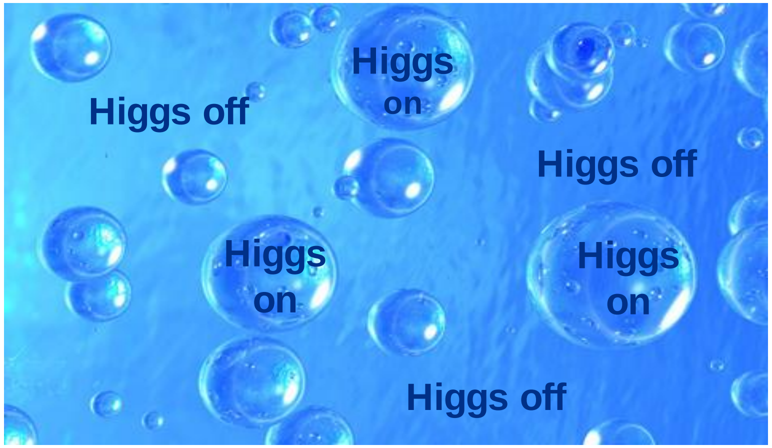
Models of Electroweak Baryogenesis with Dark Matter



Marcela Carena

Fermilab/UChicago

The Dark Side of the Universe – DSU2024

Corfu Summer Institute, September 14, 2024

Outline

The Higgs field, the electroweak phase transition and the possible origin of the matter-antimatter asymmetry of the Universe

Electroweak Baryogenesis (EWBG) in the Standard Model?

- the electroweak phase transition in the early universe
- the need for new sources of CP violation

Models for electroweak baryogenesis

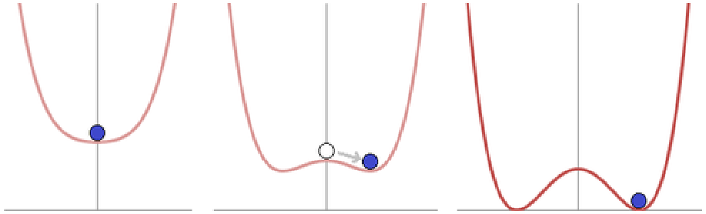
- a singlet extension of the Standard Model
- A 2HDM + a Singlet: the NMSSM, with a viable DM candidate
- Baryogenesis with dark CP violation with Singlets and Dark Matter

Outlook and future directions

Electroweak Symmetry Breaking and the Phase Transition

- We put **by hand** the condition for EWSB

- There is no explanation for how the Higgs mass parameter and self-coupling are determined



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

What is behind the EWSB mechanism?

Radiative Breaking (like in Supersymmetry) or Compositeness

What was the history of the electroweak phase transition?

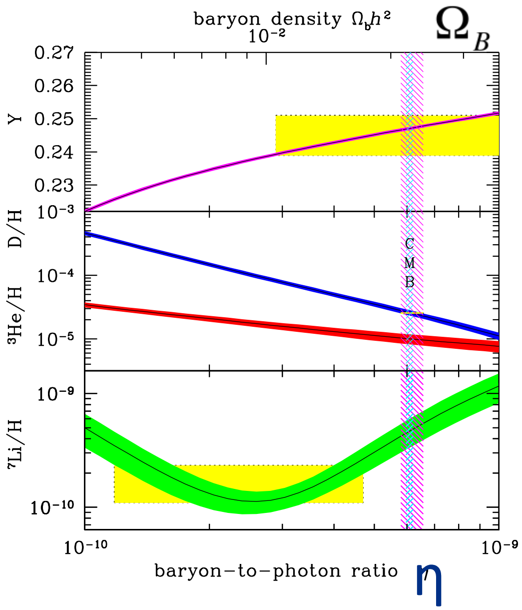
The Higgs discovery is strong evidence that the Higgs field turned on in the early moments of the Big Bang; the Electroweak Phase Transition took place
We need to understand its dynamics

- Today I will focus on the possibility of generating the matter-antimatter asymmetry of the universe at the moment the Higgs turned on ➔ **electroweak baryogenesis**

The Mystery of our Asymmetric Universe

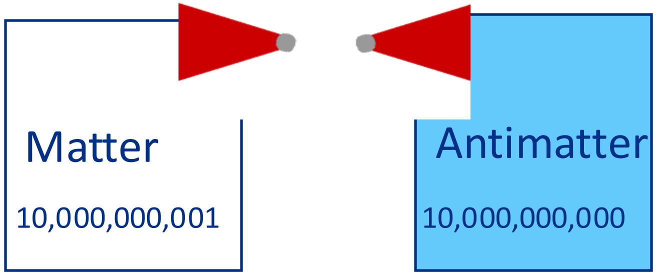
- Antimatter is governed by the same interactions as matter.
- Observable Universe is mostly made of matter
- Antimatter only seen in cosmic rays, radiative decays or is produced in the lab

Precision Cosmology: **information on baryon abundance**



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

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$



Matter

10,000,000,001

Antimatter

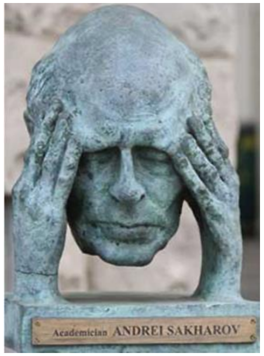
10,000,000,000

What generated the small observed baryon-antibaryon asymmetry ?

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

Sakharov conditions for baryogenesis

- 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



A number of mechanisms for baryogenesis have been proposed that satisfy all three Sakharov conditions

- Electroweak Baryogenesis (EWBG), involving the Higgs field
- Other alternatives: e.g. Leptogenesis, involving neutrinos, dark sector BG, etc

Can successful electroweak baryogenesis take place in the SM?

- Discuss the process of generation of the baryon asymmetry at the EWPT, introducing all the elements we need to satisfy the Sakharov conditions
- Consider the conditions to preserve such generated baryon asymmetry after it is produced at the electroweak phase transition
- Investigate the particle content and specific properties of the SM and how they impact the possibility of EWBG

Sakharov Condition #1: breaking B and L conservation

After quantization, the SM conserves B-L, because B-L is tied to the SU(2)$_L$ gauge symmetry of the weak interactions

B + L is *not* conserved in the Standard Model, because of a quantum anomaly

The anomaly is related to the existence of a winding number N_{CS} relating degenerate states of the SU(2)$_L$ gauge fields separated by energy barriers

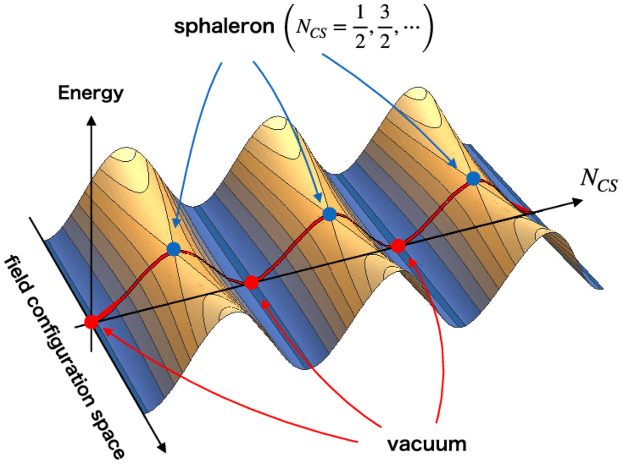
Creates a nonzero B and an equal nonzero L:

$$\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = N_f \partial_\mu K^\mu \qquad \partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \widetilde{F}^{a,\mu\nu}$$

$$N_{CS} = \int d^3x \, K^0$$

Such that $\Delta B = \Delta L = 3\Delta N_{CS}$

“sphalerons” (blue dots) are gauge + Higgs field configurations that approximate a transition that “goes over the hill” from one winding state to the next



- At finite temperature, the sphaleron process occurs, with the usual Boltzmann factor:

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T)/T) \quad \text{with} \quad E_{sph} \cong 8\pi \, v(T)/g \quad \text{and} \quad v(T) \text{ the Higgs v.e.v.}$$

Sakharov Condition #2: C and CP violation

- CP violation occurs in the Standard Model from a complex “CKM” phase in the couplings of the Higgs field to quarks
- This may also be true for leptons, but we need better data (DUNE experiment)

- As a result of quark CP violation there are processes where (e.g.):

$$\sigma_{u_L \to u_R} \neq \sigma_{\overline{u}_L \to \overline{u}_R}$$

- This can result in asymmetries between the number density of quarks & antiquarks

$$\Delta_L = n_{u_L} - n_{\bar{u}_L} \neq 0 \qquad \Delta_R = n_{u_R} - n_{\bar{u}_R} \neq 0$$

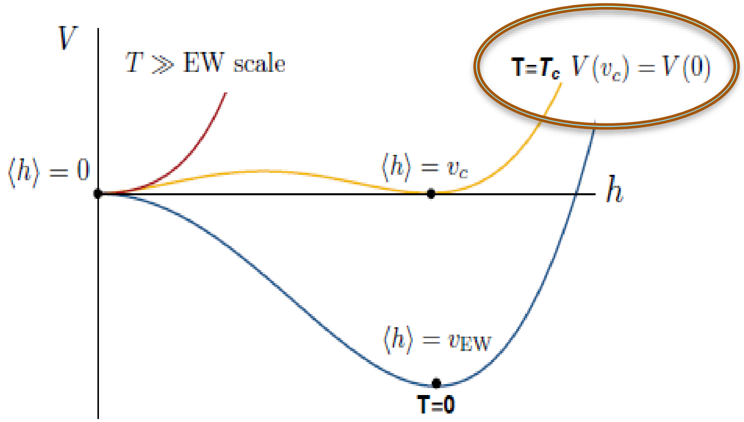
- In the absence of C violation this also implies $\Delta_L = -\Delta_R$, which implies conservation of baryon number

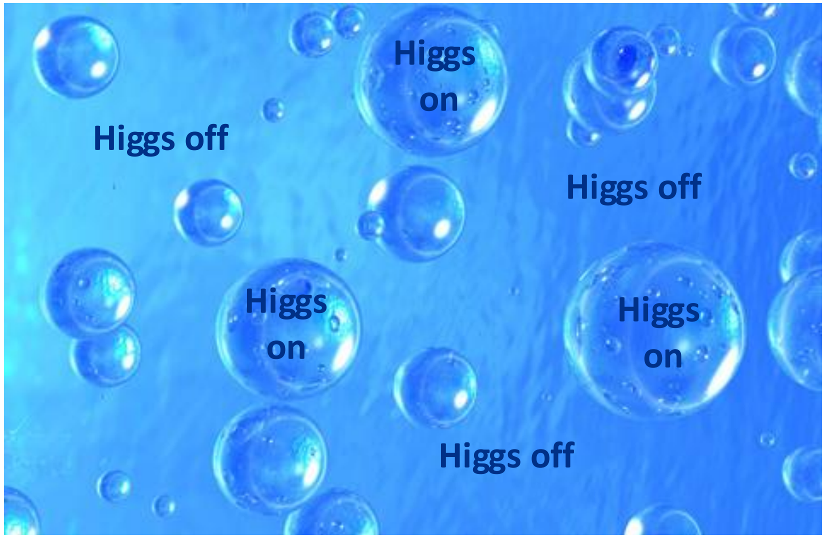
$$\Delta B = n_{u_L} - n_{\bar{u}_L} + n_{u_R} - n_{\bar{u}_R} = 0$$

- As we shall see sphalerons will do the job of violating the C symmetry because they couple only to left-handed quarks and leptons

Sakharov Condition #3: Out of Equilibrium

- Assume B = L = 0 at high temperatures (T>Tc)
- In a **first order** electroweak phase transition, universe tunnels from <h> = 0 to <h> ≠0 vacuum via bubble nucleation.



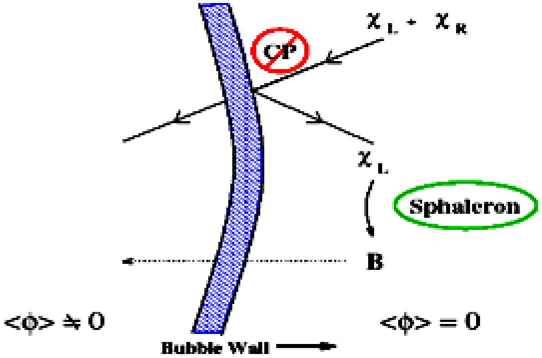


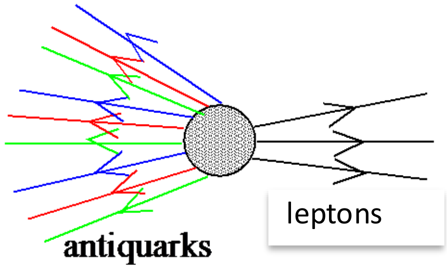
- Bubbles nucleate and expand in the presence of a plasma of SM particles
- Bubble wall moves at near the speed of light, depending on the frictional force the plasma particles exert on it – the precise v_W is relevant for EWBG and GW signals
- Processes near the wall highly out of equilibrium
- The CP violating dynamics can occur **in the bubble walls**

CPV effects and baryon number generation at the EWPT

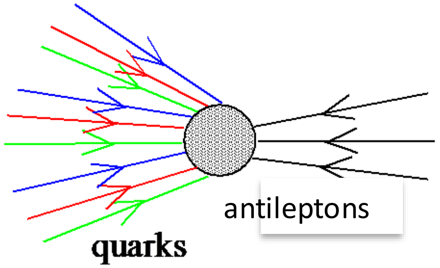
- Start with B = L = 0 at T >Tc
- Due to CPV induced by Higgs-quark interactions, particle flow into the expanding bubble wall **creates a chiral asymmetry -** an excess of SU(2) doublet antiquarks and singlet quarks - just outside the bubble

$$\sigma_{u_L \to u_R} \neq \sigma_{\bar{u}_L \to \bar{u}_R} \qquad \Delta_L = n_{u_L} - n_{\bar{u}_L} \neq 0 \qquad \Delta_L = -\Delta_R$$





is faster than



Unsuppressed sphaleron process will produce an excess of B and L, in equal quantities but just for the left-handed chiral particles

Before Sphalerons $\Delta B = n_{u_L} - n_{\bar{u}_L} + n_{u_R} - n_{\bar{u}_R} = 0$

After Sphalerons $\Delta B = n_{u_R} - n_{\bar{u}_R} + (1-f)(n_{u_L} - n_{\bar{u}_L}) = -f\Delta_{uL} > 0$

an excess of quarks just outside the bubble

The Higgs boson discovery supports the occurrence of an EW phase transition

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 of the asymmetry

if $n_B = 0$ at $T > T_c$

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

$\ll 1 \rightarrow v(T_c)/T_c \gtrsim 1$

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

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

$\not{B}$ 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.) $[T_n < T_c]$
We use semiclassical arguments to estimate the nucleation probability to be approx. one per Hubble time to determine T_n

The failures of EW Baryogenesis in the Standard Model

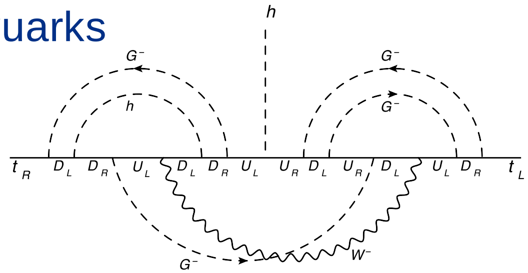
All the ingredients to fulfil Sakharov's conditions

- Baryon number violation: Sphalerons
- CP violation: CP violating phase in mixing of the three generations of quarks
- Non-equilibrium: At the Electroweak Phase Transition

BUT

#1. Contribution from CP violation cannot catalyze enough of an asymmetry

CPV is proportional to the so-called Jarlskog's invariant, that is proportional to the CKM mixing angles appearing in W boson interactions with the 3 generations of quarks



High order loop effects needed to generate a complex contribution to the top quark - Higgs interaction in the bubble wall

$$\eta_{SM} = n_B/n_\gamma \simeq 10^{-20}$$

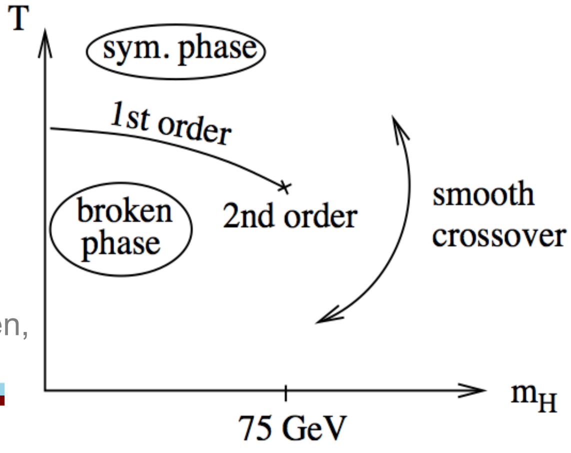
Gavela, Hernandez, Orloff, Pene, Quimbay'94

#2. With the measured 125 GeV Higgs mass, the EWPT is a crossover.

To sufficiently suppress sphaleron processes in the true vacuum and prevent washout of the asymmetry

$v(T_c)/T_c > 1$ ➔ $m_H < 40$ GeV (perturb)

Kajantie, Laine, Rummukainen, Shaposhnikov '88



Electroweak Baryogenesis needs new phenomena

To provide new sources of CPV that catalyze enough of a chiral asymmetry to seed the observed baryon asymmetry via sphaleron processes

To render the EWPT strongly first order that allows to freeze sphaleron effects as the universe tunnels into the real vacuum

Many possible SM extensions with new Higgs particles and possibly also other new particles/new forces at the EW scale - at the reach of existing and future experiments

- Singlet extensions of the Standard Model
- Two Higgs doublet models (+ singlet extensions)
- Supersymmetric models: with 2 Higgs Doublets + possibly extra singlets:
- ➢ MSSM: light stop scenario, ruled out by Higgs precision
- ➢ NMSSM: through additional scalars with CP violation - an appealing possibility
- Models with Dark CP violation
- Models with heavy Fermions
- SM effective theory with additional higher order operators
- Models of EW symmetry non-restoration/delayed restoration – many new Higgs singlets (+ possibly an inert doublet)

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

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

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) → $\langle (h,s) \rangle = (v_{\rm EW}, 0)$
- Spontaneously Z_2 breaking → $\langle (h,s) \rangle = (v_{\rm EW}, w_{\rm EW})$

Natural 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

To determine phase transition patterns requires to compute temperature and quantum effects on the potential

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

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

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

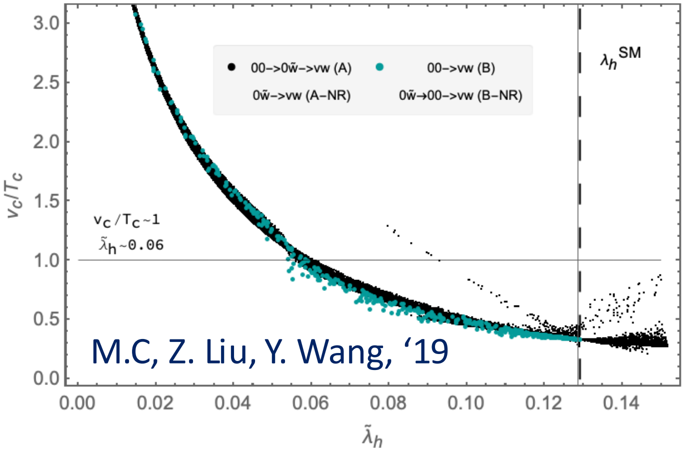
EWPT with Spontaneous Z_2 Breaking: a Strong 1st order EWPT

The electroweak phase transition strength – Spontaneous Z_2 breaking scenario

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

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

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



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

- ➢ Sizeable quartic mixing coupling λ_m needed for a strong 1st order EWPT ➔ v (T_c) / T_c >1

  Only 3 parameters after defining Higgs mass and v.e.v

- λ_m proportional to sinθ (the h-s mixing parameter), and strongly constrained by Higgs precision measurements
- a light singlet: m_S < 50 GeV is required

If singlet sufficiently light, the Higgs can have exotic decay: H→SS

Also, v (T_c) / T_c >1 demands significant S-H couplings

➔ Hence, BR(h → SS) is bounded from below

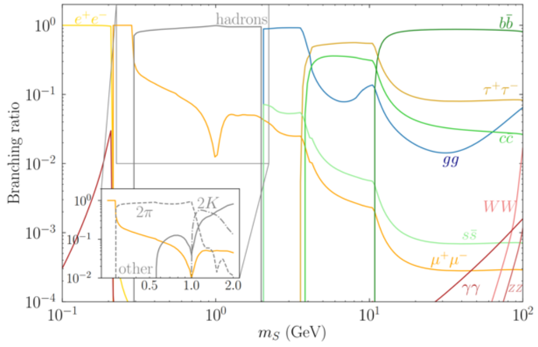
Exotic Higgs decays are a potent probe of Singlet extensions with viable EWBG

Many ongoing searches at ATLAS and CMS for h → ss → 4b, 4μ, 4τ, 4γ, bbμμ, bbττ,…

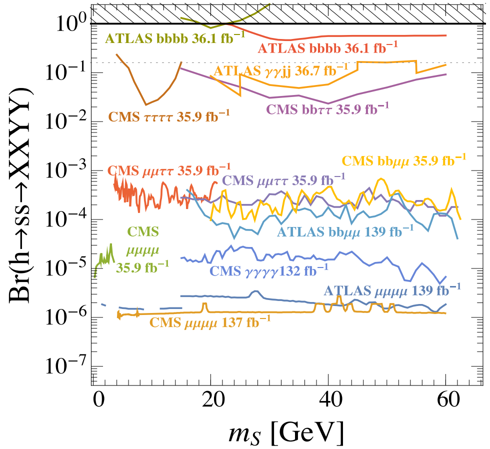
Probing Z_2-breaking Singlet Extensions via Exotic Higgs Decays

Current LHC data from global fit to Higgs couplings constrains BR[H → exotics] < 16%

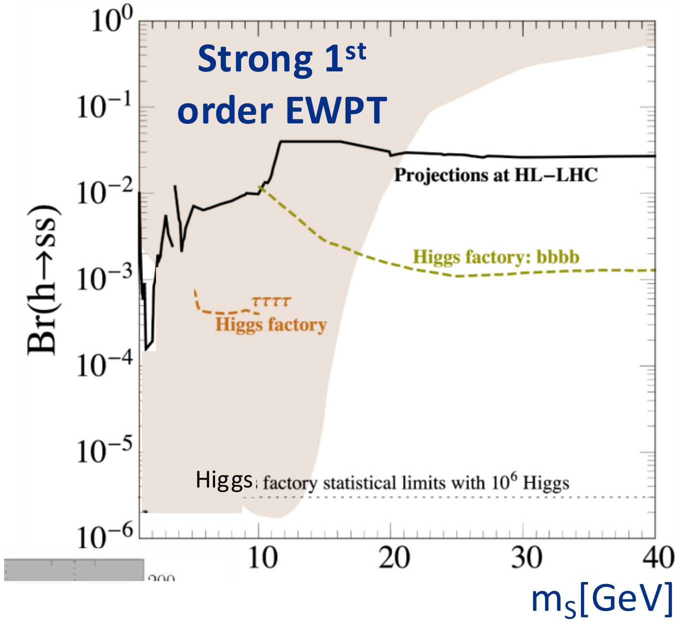
H → SS can lead to many final states with S inheriting Higgs-like hierarchical BR's via mixing



Bounds on exotic Higgs decays



HL-LHC projected reach on Br(h → ss) from Br(h → ss → XXYY)



M.C., Tong Ou, Yikun Wang, et al, *LHEP* 2023 (2023)

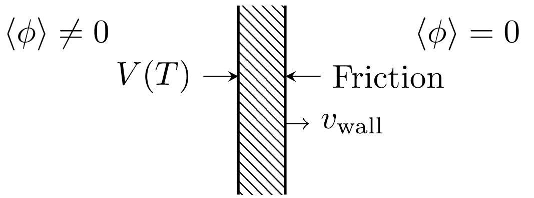
Direct search and Higgs precision measurements can probe large regions of space compatible with a strong 1st order EWPT

Probing Singlet Extensions for EWBG via Gravitational Waves

Motion of the bubble wall and energy budget

See Balazs' talk

$$\Box\phi + \frac{\partial V_{\mathrm{eff}}(\phi, T)}{\partial \phi} = \mathcal{K}(\phi) \longrightarrow$$ friction term



scalar + plasma dynamics

-Wall wants to expand ("pressure"), as the scalar field value changes

-Wall is pushed back by plasma ("friction")

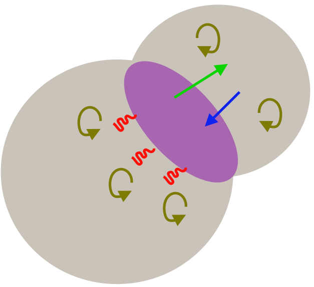
Sources of stochastic GWs power spectrum

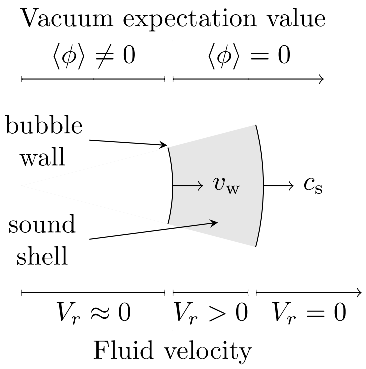
collisions of bubbles

compression/sound waves of plasma

plasma turbulence

$$h^2\Omega_{\mathrm{GW}} \simeq h^2\Omega_{\phi} + h^2\Omega_{\mathrm{sw}} + h^2\Omega_{\mathrm{turb}}$$





Case of interest for EWBG:

Bubbles that achieve a relativistic terminal velocity - sizable friction from the plasma

Vacuum energy release creates a sound shell and a turbulent flow in the plasma, sourcing the GW

It is important to compute the bubble wall velocity from first principles/the fluid equations as a function of the model parameters Laurent and Cline , 2022

Probing Singlet Extensions for EWBG via Gravitational Waves

The main parameters controlling the stochastic GW background power spectrum

- Inverse time duration of the Phase transition $\beta/\mathbf{H} \approx \mathbf{T}\frac{\mathbf{d(S_3/T)}}{\mathbf{dT}}\Big|_{\mathbf{T=Tn}}$
- Wall velocity v_w
- Strength of GW signature from the PT

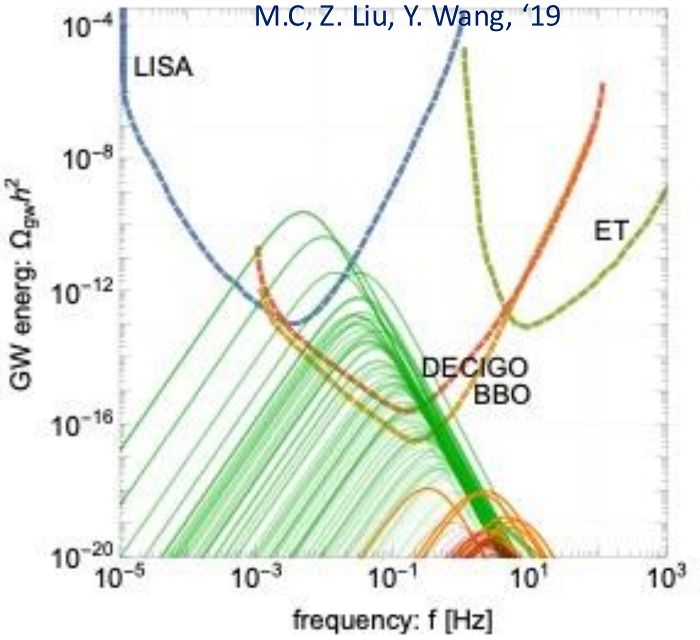
$$\alpha = \frac{\rho(\phi_S) - \rho(\phi_{EW})}{\rho^*_{\rm rad}} = \Delta V_{\rm eff}(T_n) - \frac{T}{4}\frac{\partial \Delta V_{\rm eff}}{\partial T}\Big|_{T_n}$$

Fitted from numerical simulations

$$h^2\Omega_{\rm sw}(f) = 2.65 \times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\, S_{\rm sw}(f)$$

$$h^2\Omega_{\rm turb}(f) = 3.35 \times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\, \alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{1/3} v_w\, S_{\rm turb}(f)$$

Peak frequency set by the average bubble separation $f_{\rm peak} \sim O(\beta/v_w)$


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

Fixed subsonic velocity: $v_w = 0.5$; $T_n \sim 50$ -100 GeV

Computation of the bubble wall velocity from first principles for the model parameters compatible with a SFOPT render subsonic velocities in the proximity of $v_w = 0.5$

M.C., A. Ireland, T. Ou , Isaac Wang, in preparation

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 multiple field space scalar potential makes the study of phase transitions challenging

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

from Z3-NMSSM superpotential

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

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

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

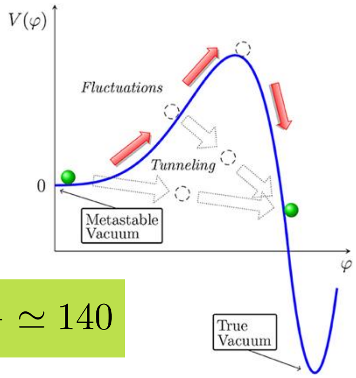
After considering temperature and quantum effects, many benchmarks yield the desired EW vacuum structure and sphaleron rate suppression at the critical temperature

EWPT in the NMSSM - nucleation is more than critical

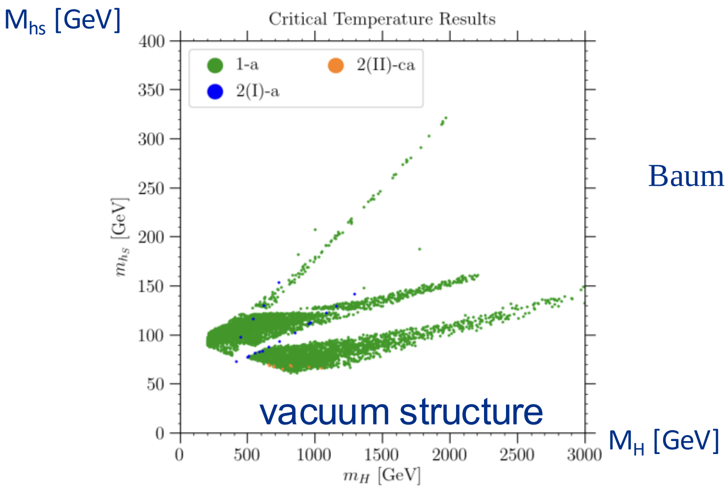
The vacuum structure gives little information about tunneling probability.

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

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



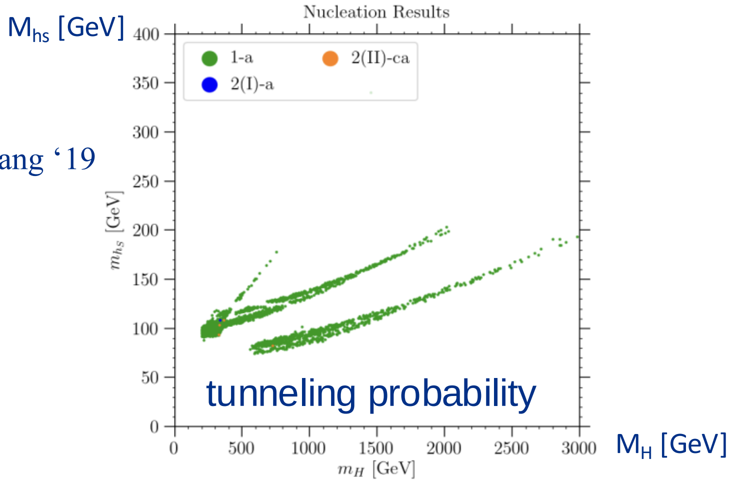
requiring the nucleation probability to be approx. one per Hubble volume and Hubble time leads to the nucleation condition → $\frac{S_3(T_n)}{T_n} \simeq 140$



vacuum structure

$T_c \longrightarrow T_n$

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



tunneling probability

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

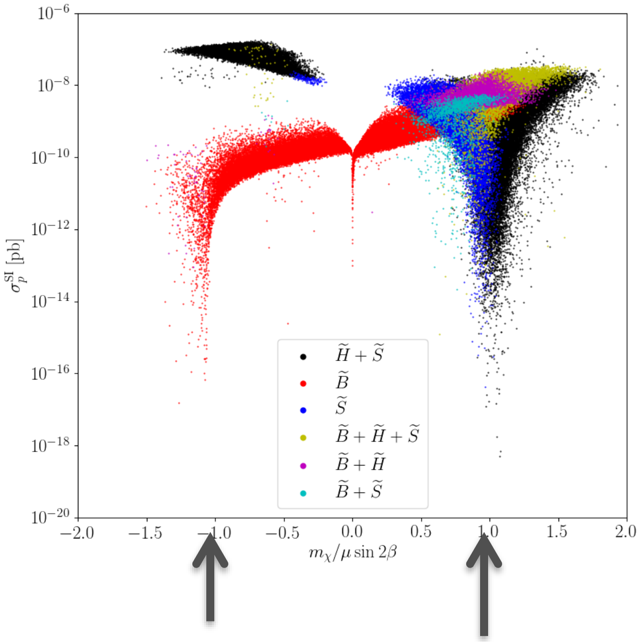
Dark Matter Direct Detection: Blind Spots

Possible to have a three-way cancellation between the hs, h and H contributions

$$\sigma_{SI} \propto \left\{ \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) \frac{2\, t_\beta}{m_h^2} + \frac{t_\beta}{m_H^2} + \frac{1}{m_{h_S}^2} \left(2\, S_{h,s} + \frac{\lambda\, v}{\mu} \right) \left[\frac{\lambda\, v}{\mu^2} m_\chi + S_{h,s} \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) + \frac{\kappa\, \mu}{\lambda^2\, v} \right] \right\}^2 .$$

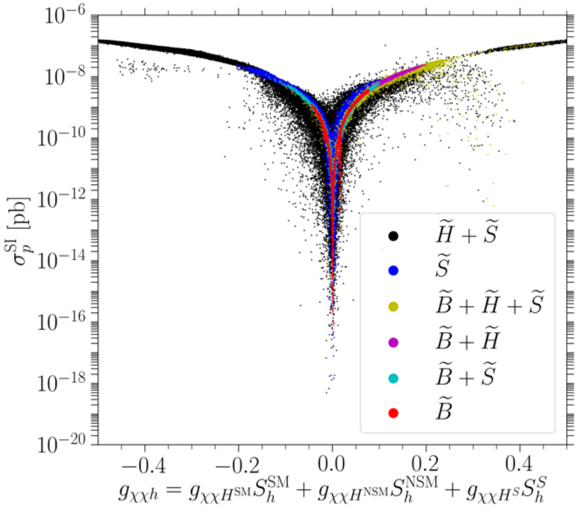
$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_S}^2)}$$

Cheung, Papucci, Sanford, Shah, Zurek ’14



μ < 0

μ > 0



Higgs Mixing Effects:

Couplings to the 125 GeV Higgs tend to be suppressed close to the blind spots. However, they remain relevant in the singlino region, denoting the presence of relevant interferences

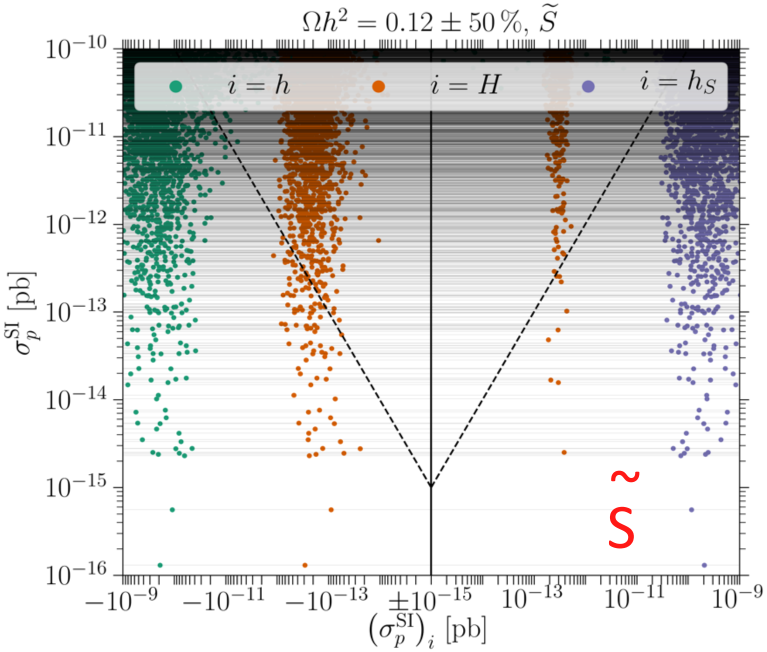
A SM-like Higgs would have couplings that vanish when $m_\chi = \pm\mu \sin(2\beta)$. The plus and minus signs correspond to the cases in which the neutralino is Singlino-Higgsino or Bino-Higgsino admixtures.

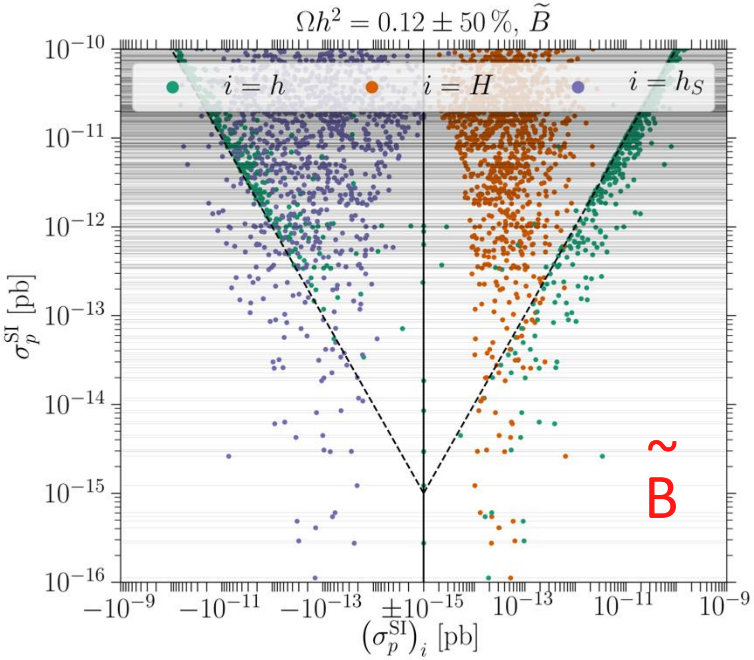
Baum, M.C. Shah, Wagner ‘18

NMSSM opens up new possibilities for the WIMP Miracle

Contributions to SI XS of the different (scalar) Higgs bosons

and sign of the different scalar contributions to the SI cross section.





Mostly singlinos: coupling to SM-like Higgs larger than for Bino ➔ to be close to blind spot, a destructive interference with singlet contribution is needed

Thermal Relic can be obtained via Z (G) annih.

Mostly Binos: SM-like Higgs provides the dominant contribution.

NEW Bino well-tempered region, with small couplings to Higgs and proximity to blind spot

Thermal Relic density via resonant Z, Higgs annih, or co-annihilation of bino with singlino

Baryogenesis with Dark CP Violation:

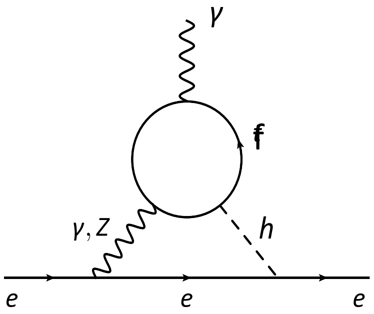
A model with gauged lepton number

A new force in nature to transmit CP violation from a dark sector

- Electroweak Baryogenesis demands new, sizeable CPV sources
- Electric Dipole Moment (EDM) experiments set constrains on new sources of CVP

Electron EDM and the latest ACME/JILA experiment results → $d_e < 4.1 \times 10^{-30} \mathrm{e\ cm}$

[In the SM $d_e \sim 10^{-39}$ e cm]



Weak scale CPV:

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

M.C., M. Quiros and Y. Zhang: Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014

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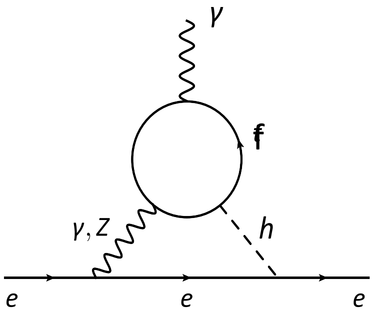


[In the SM $d_e \sim 10^{-39}$ e cm]

Weak scale CPV:

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

Problem: most models of electroweak baryogenesis require $\sin\theta_{\mathrm{CPV}} \geq 10^{-2}$

Solution: new agent of CP violation is a SM gauge singlet, hence can only contribute to electron EDM through higher order quantum corrections

New Challenge: How to transfer CP violation in the early universe?

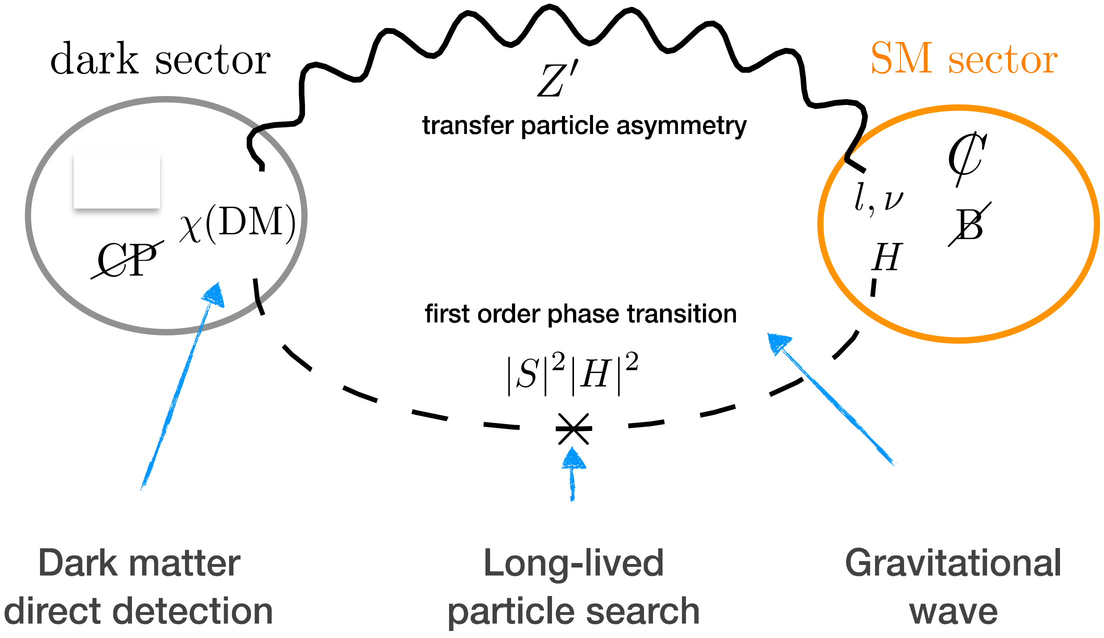
Through a new force that connects the dark sector to ours

M.C., M. Quiros and Y. Zhang: Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014

Dark CP Violation

A new force: a U(1) gauged lepton number **New particles:** Z’, S, χ (dark matter)

- **Higgs–Singlet portal to the dark sector**
- **Z’ portal to the dark sector**



transfer particle asymmetry

first order phase transition

Dark matter direct detection

Long-lived particle search

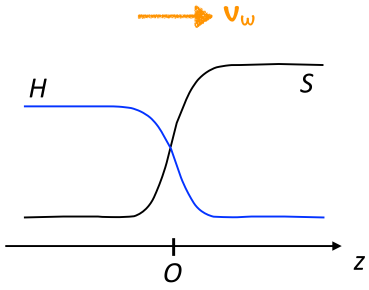
Gravitational wave

M.C., M. Quiros and Y. Zhang: Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014

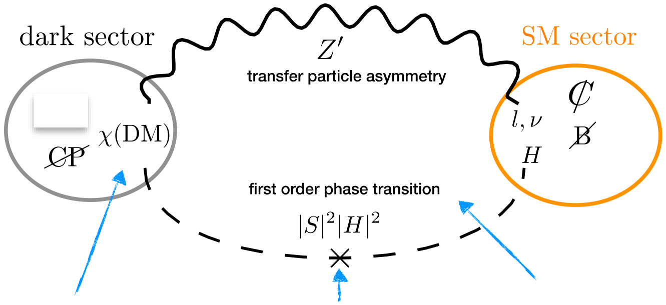
A New Mechanism for Electroweak Baryogenesis:

- **Higgs–Singlet portal to the dark sector**
  to source CP violation and induce a first order phase transition

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



bubble wall profile



Dark matter direct detection

Long-lived particle search

Gravitational wave

A varying mass m_χ, along the expanding bubble wall direction, together with the S vev, generates **a CP asymmetry in the *χ dark matter* particles**

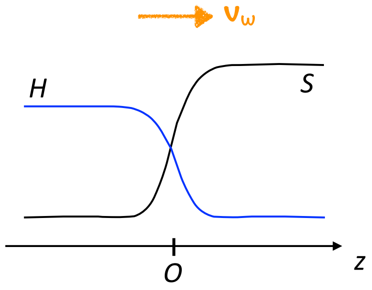
A new scalar-Higgs interaction, $\lambda_{SH} |S|^2 |H|^2$, can trigger strong first order EWPT

M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

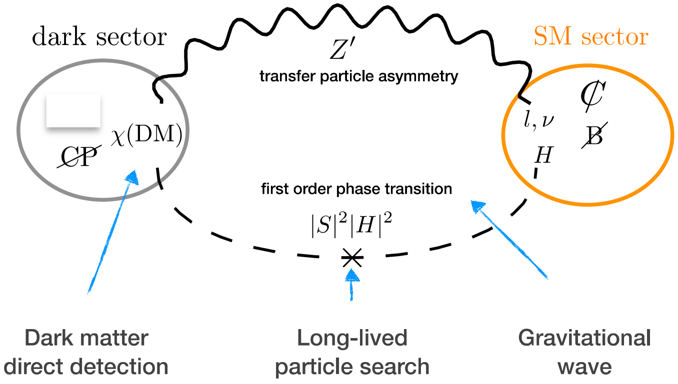
A New Mechanism for Electroweak Baryogenesis:

- **Higgs–Singlet portal to the dark sector**
  to source CP violation and induce a first order phase transition
- **Z' portal:** to transfer the CP violation to the SM sector

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



bubble wall profile



EW sphalerons cannot touch the CP asymmetries in the χ electroweak singlet

The new gauge boson Z' couples to χ and SM leptons; Z' transfers CPV to us and generates a lepton CP asymmetry at T_n

A varying mass m_χ, along the expanding bubble wall direction, together with the S vev, generates **a CP asymmetry in the *χ dark matter* particles**

The sphalerons, active outside the bubble wall create equal asymmetries in B and L number ➔ $\Delta N_L = \Delta N_B$

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

M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

Dark CPV: The Higgs Portal to the Dark Sector

Sourcing CP Violation

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) $\mathcal{L} \sim \bar{\chi}_L (m_0 + yS)\chi_R + \text{h.c.}$

and contributes to its mass $M_\chi = m_0 + \lambda \exp(i[\theta + \arg(S)])|S|$ $\lambda = |\lambda_c|$ and $\theta = \arg(\lambda_c)$

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

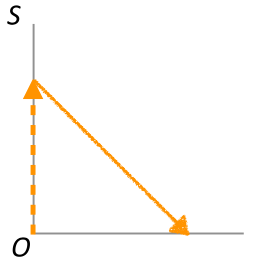
This requires m_χ to vary along the z direction, together with the S vev

A new EW phase transition

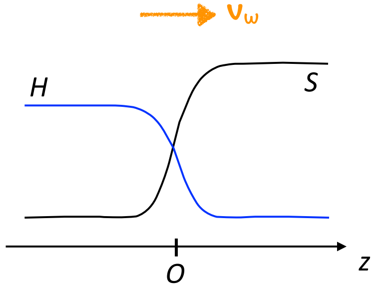
A new scalar-Higgs interaction,

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

M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

Dark CPV: The role of the Z' Portal

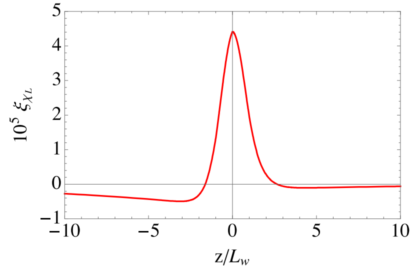
EW sphalerons cannot touch the chiral charge asymmetries in χ because it is an SU(2) singlet — must transfer such CPV effect in other ways to the SM sector

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

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

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).

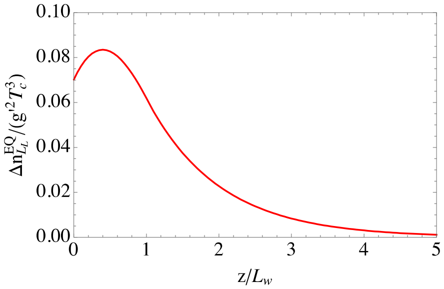


- Z' couples to SM leptons

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

- 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

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

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

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

- Sphaleron processes generate equal asymmetries for B and L → $\Delta n_L = \Delta n_B$

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

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

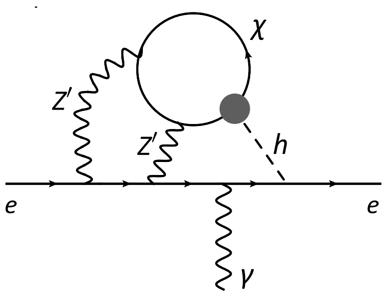
M.C., M. Quiros and Y. Zhang : Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014

M.C., Y.Y Li, Ou and Wang, JHEP 02 (2023) 139

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

- Strong 1st order EWPT, yield the observed baryon asymmetry and DM relic density
- Fulfill 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 χ particle qualifies as a thermal DM candidate ➔ direct detection searches
  - Strong 1st order EWPT can generate stochastic gravitational wave signatures possibly observable at current/future GW detectors

Leading EDM arises at higher loops



naturally suppressed by one or two orders of magnitude below current limit for CPV sources of order one

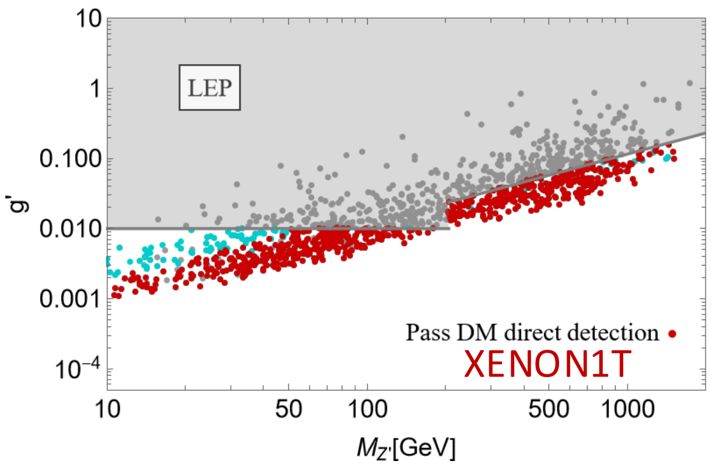
New forces and dark matter searches

Benchmark models for dark CP violation baryogenesis

- generate the observed baryon asymmetry of the universe (BAU) at a strong first order electroweak phase transition
- reproduce the observed dark matter relic density

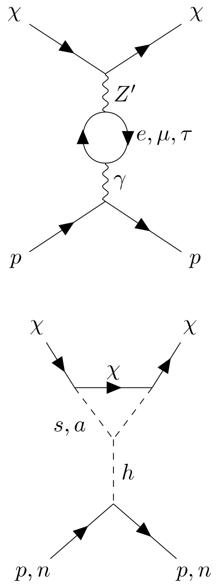
fixed parameters : $\{\lambda_H, v_H\}$,
scalar sector parameters : $\{\lambda_S, v'_S, \lambda_{SH}, m_a, m_s\}$,
dark fermion parameters : $\{m_0, \lambda, \theta\}$,
Z' parameters : $\{g', M_{Z'}\}$.

Z' mass and new force coupling strength



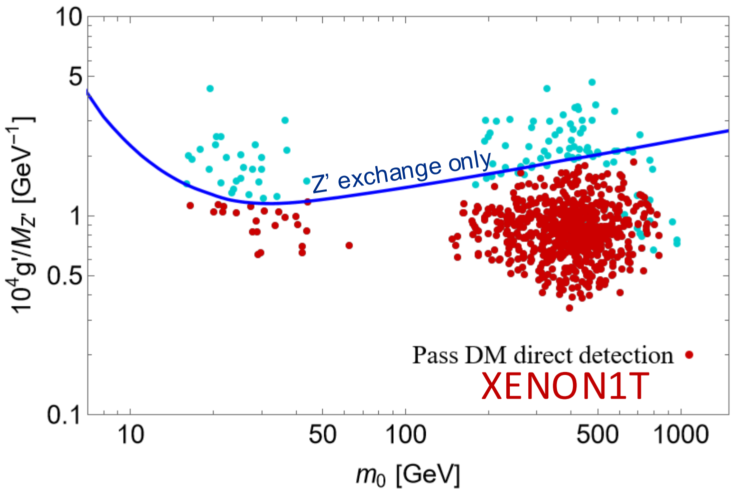
BAU proportional to $g'^2/m^2_{Z'}$

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



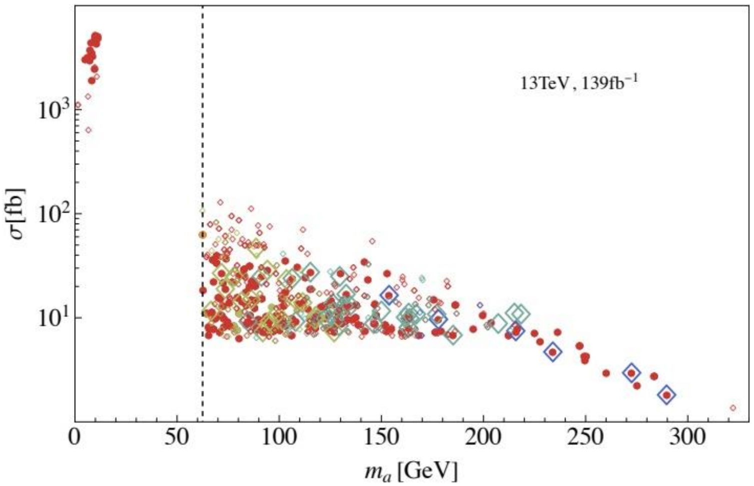
Direct Dark Matter detection

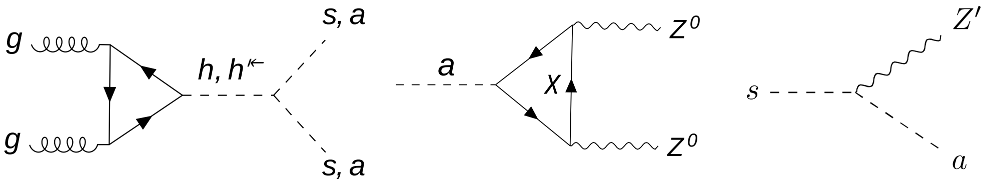
Z' exchange dominant besides for large m_0 (hence $m\chi$) and small $g'^2/m^2_{Z'}$



Signals of strong first order electroweak phase transition

Searches for long-lived scalars at the LHC





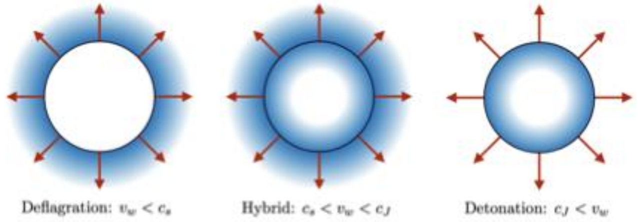
Z’ into SM leptons, with on/off shell Z’s

Solid circles pass both a and s search constraints, while open diamonds are excluded via prompt and long-lived searches, with current data

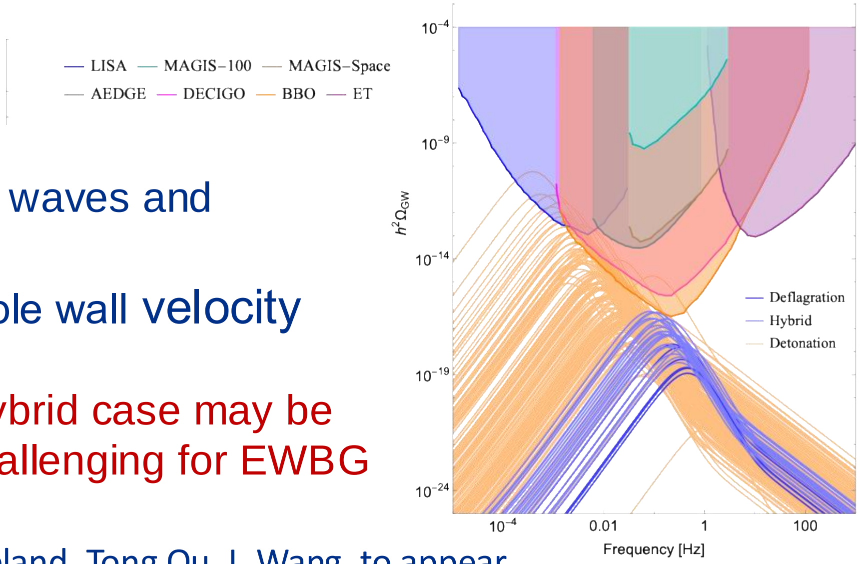
Gravitational wave signals

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

New results from first-principles calculation of bubble wall velocity



Detonation/Hybrid case may be impossible/challenging for EWBG



M.C., Ireland, Tong Ou, I. Wang, to appear

Outlook

- Baryogenesis is one of the most compelling problems in particle physics and cosmology
- Electroweak baryogenesis, while not the only possible solution, gives the opportunity to connect this fundamental problem to another one: the origin and cosmic history of electroweak symmetry breaking
- Electroweak baryogenesis requires new phenomena at the electroweak scale **– new CPV sources and, most likely new Higgs bosons -** providing interesting targets for LHC experiments as well as gravity wave observations and EDM experiments
- And as we have seen, there is the possibility to connect EWBG to features of the dark sector, with targets at direct dark matter detection experiments

Future directions and work in progress

- Explore relations between EW phase transition parameters governing the sphaleron process and the strength of gravity wave signals.
- First principles determination of bubble wall parameters
- Investigating EWBG for hybrid and detonation conditions

M.C., A. Ireland, T. Ou, I. Wang

- Resummation of large thermal corrections to multi-field effective potentials for accurate prediction of phase transitions and better determination of gravity wave signals.

H Bahl, M.C., A. Ireland, C. Wagner, arXiv:2404.12439

- Quantum simulation formalism applied to real-time wave packet evolution to compute transmission and reflection dynamics at the bubble wall.

M.C., Y-Y. Li, T. Ou, H. Singh

Extras

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

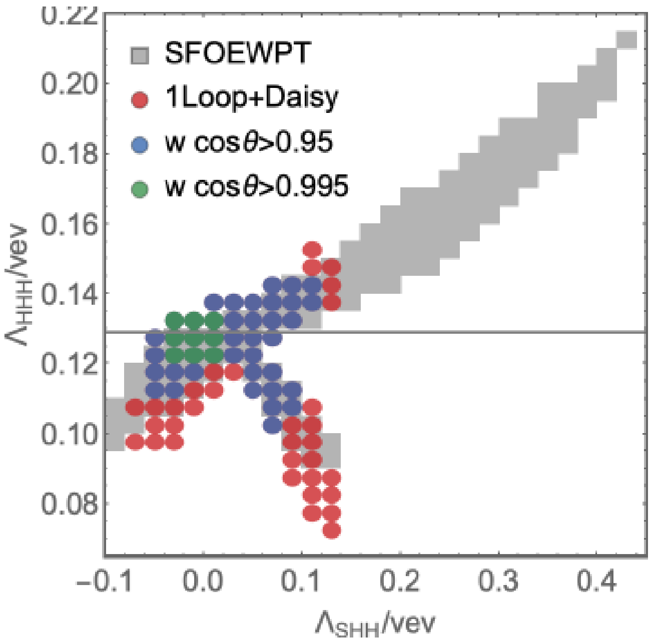
$$V_{\rm CW}(h,s) = \frac{1}{64\pi^2}\left(\sum_B n_B m_B^4(h,s)\Big[\log\left(\frac{m_B^2(h,s)}{Q^2}\right) - c_B\Big] - \sum_F n_F m_F^4(h,s)\Big[\log\left(\frac{m_F^2(h,s)}{Q^2}\right) - \frac{3}{2}\Big]\right)$$

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

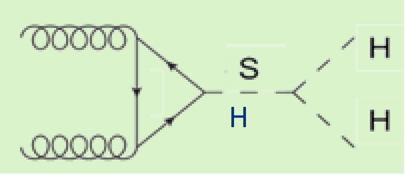
EWPT and Higgs Pair Production: Higgs Trilinear Coupling

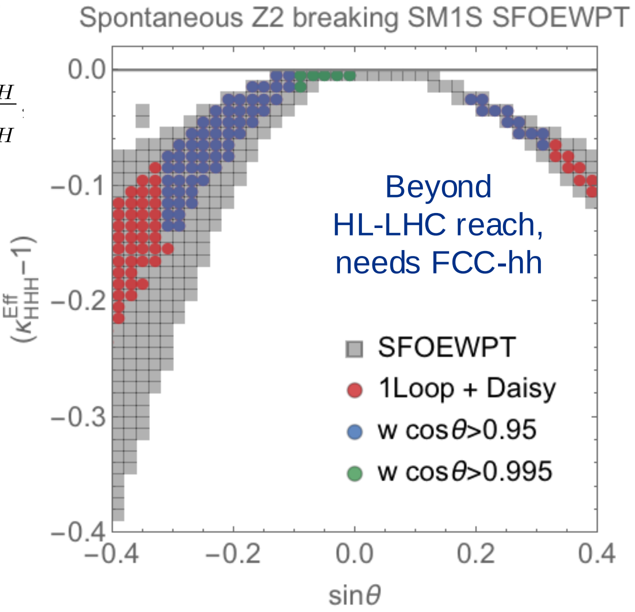
Z_2 spontaneous Symmetry Breaking Scenario

M.C, Z. Liu, Y. Wang, ‘19



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





Beyond HL-LHC reach, needs FCC-hh

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

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

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

Dark CPV: A new EW phase transition

M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

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

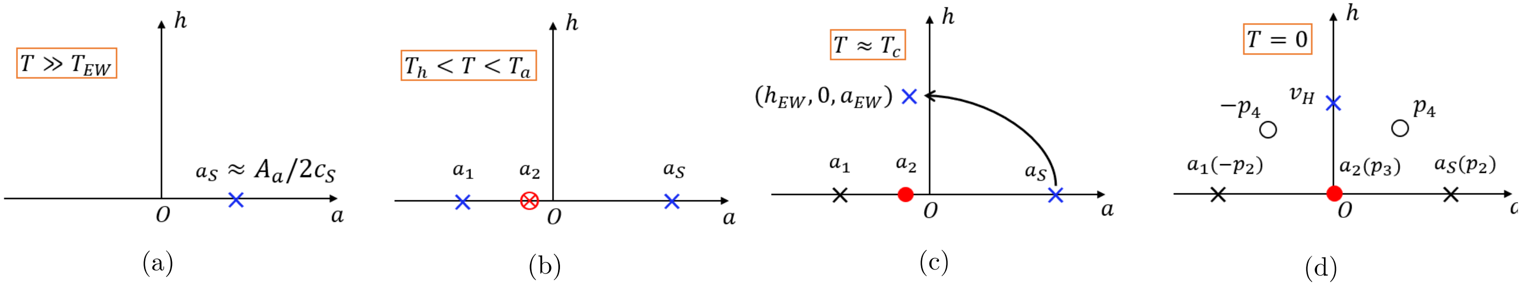
Need at least $\delta V(S) = \kappa_S^2 S^2$ to avoid CPV being redefined away.

In terms of h, a, s 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 a strong 1st order EWPT

- 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 T_c and T_n
- Implement T= 0 boundary conditions: bounded from below, 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 cross over**



X minimum

⊗ saddle point

● maximum

× (○) stationary point, maximum (minimum)

Extended Higgs sectors: a SUSY example

The Electroweak Phase Transition in the NMSSM

EWPT in the NMSSM: the extended Higgs sector

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

both charged under the EW gauge group

provides flexibility enhancing the PT strength

Well motivated UV completion → the Next-to-Minimal Supersymmetry Standard Model (NMSSM), with the scalar potential – from Z3-NMSSM superpotential-

$$V_0 = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + \lambda^2 |S|^2 \left(|H_d|^2 + |H_u|^2\right) + \left|\lambda H_u \cdot H_d + \kappa S^2\right|^2$$

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

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

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

Higgs basis

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

After minimization conditions and squared replacing mass parameters by vev's

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

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}

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

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decoupling limit

decoupling limit

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alignment without decoupling

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

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

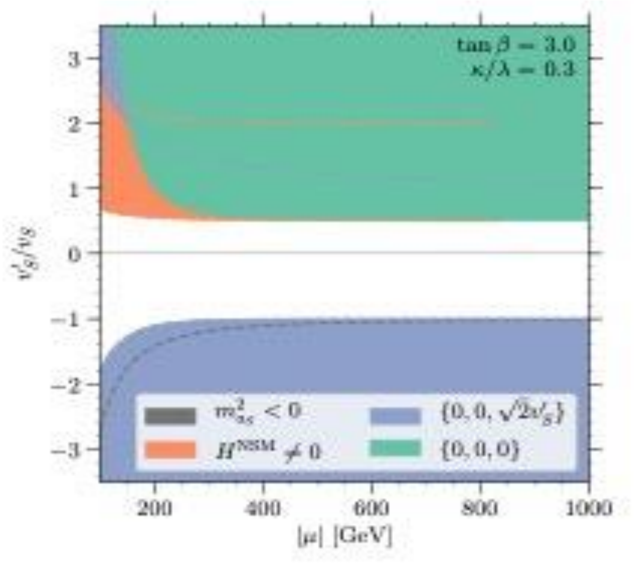
EWPT in the NMSSM: alignment limits and parameter space

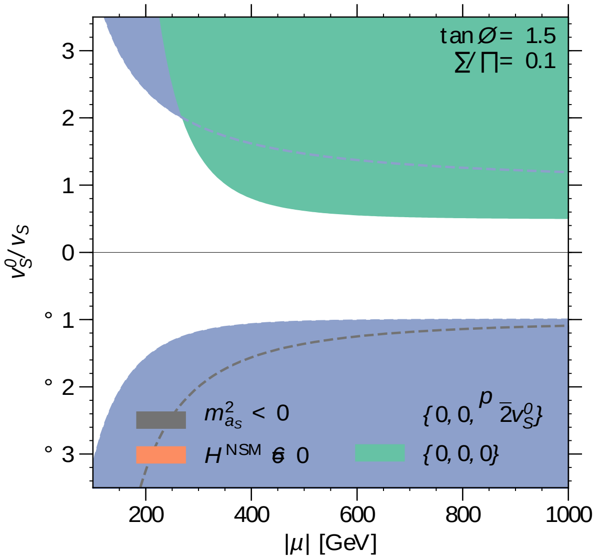
The parameter space

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

- 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 $\{H^{\rm SM}, H^{\rm NSM}, H^{\rm S}\} = \{0,0,0\} \vee \left\{0,0,\sqrt{2}v'_S\right\} \vee \left\{0,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \left\{\sqrt{2}v,0,\frac{\sqrt{2}\mu}{\lambda}\right\} \vee \cdots$

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





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)

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

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

Naturalness and the Alignment in the NMSSM

M.C, Haber, Low, Shah, Wagner.'15 Also Kang, Li, Liu, Shu'13; Agashe, Cui, Franceschini '13

Superpotential λ S H_uH_d ➔ μ_{eff} = λ <S>

- Well known additional contributions to m_h

$$m_h^2 \simeq \lambda^2 \frac{v^2}{2} \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{\tilde{t}}$$

- Less known, sizeable contributions to the mixing between MSSM CP-even eigenstates

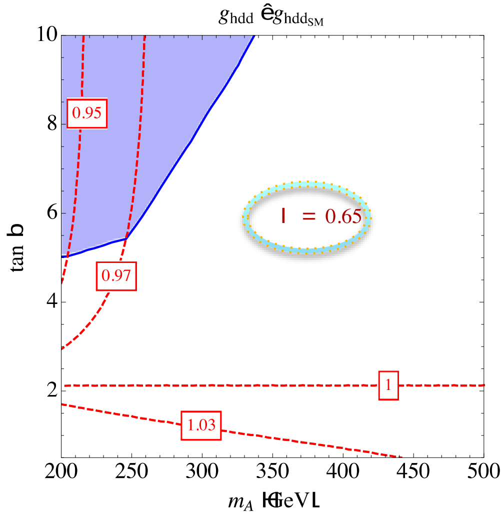
$$M_S^2(1,2) \simeq \frac{1}{\tan\beta}\left(m_h^2 - M_Z^2 \cos 2\beta - \lambda^2 v^2 \sin^2\beta + \delta_{\tilde{t}}\right)$$

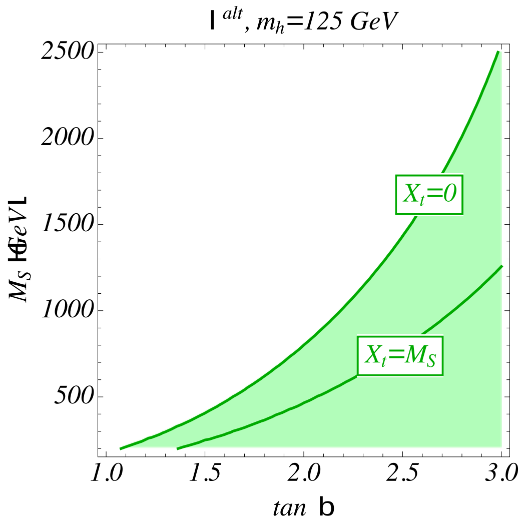
Last term from MSSM; small for moderate/small μA_t and small tanβ

$$\lambda^2_{\text{alt}} = \frac{m_h^2 - M_Z^2 \cos 2\beta}{v^2 \sin^2\beta}$$

Alignment leads to λ in the restricted range 0.62 to 0.75, in agreement with perturbativity up to the GUT scale

Higgs-Bottom coupling in the NMSSM





Alignment in the doublet Higgs sector of the NMSSM allows for light stops

Aligning the Singlet

For a singlet at LHC reach, precision Higgs data demands high degree of alignment.

The mixing mass matrix element between the singlet and the SM-like Higgs is

$$M_S^2(1,3) \simeq 2\lambda v\mu \left(1 - \frac{m_A^2 \sin^2 2\beta}{4\mu^2} - \frac{\kappa \sin 2\beta}{2\lambda}\right)$$

Needs to vanish in alignment

For tanβ < 3, λ ~ 0.65 and κ in the perturbative regime, small mixing in the Higgs sector implies that m_A and μ are correlated

$$\boxed{\mathbf{m_A \approx \frac{2|\mu|}{\sin 2\beta}}}$$

Unlike the MSSM, alignment without decoupling implies small μ, hence, again alignment and naturalness come together beautifully in the NMSSM

Moreover, this ensures also that all parameters are small and the CP-even and CP-odd singlets and singlino become self consistently light

$$\mathbf{m_{\tilde{S}} = 2\mu\frac{\kappa}{\lambda}}$$

of interest for Dark Matter

NMSSM properties close to Alignment

Singlet spectra and decays (to SM via mixing with doublet or invisibly to DM)

- Heavier CP-even Higgs can decay to lighter ones: $2\,m_{hs} < M_H$
- CP-even light scalar, $h_{S,}$ mainly decays to bb and WW ;
- CP odd light scalar, $a_{S,}$ mainly decays to bb
- Anti-correlation between singlet –like CP-even and CP-odd masses

Doublet-like A and H decays:

-- **A/H decay significantly into top pairs; BRs ~ 20% to 80% (dep. on tanβ)**

decays may be depleted by decays into charginos/neutralinos (10% to 50%)

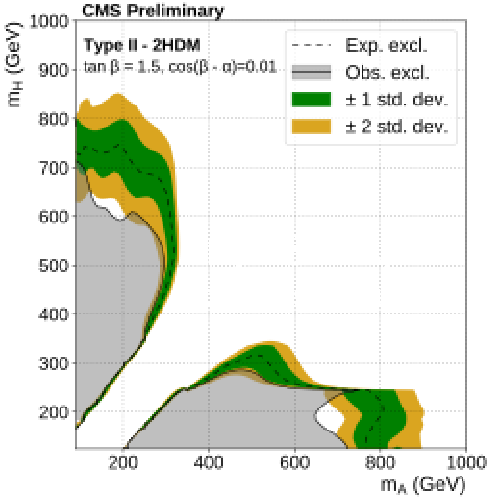
-- **Other relevant decays: $H \rightarrow hh_S$ and $A \rightarrow Zh_S$ (20% to 50%, dep on mass)**

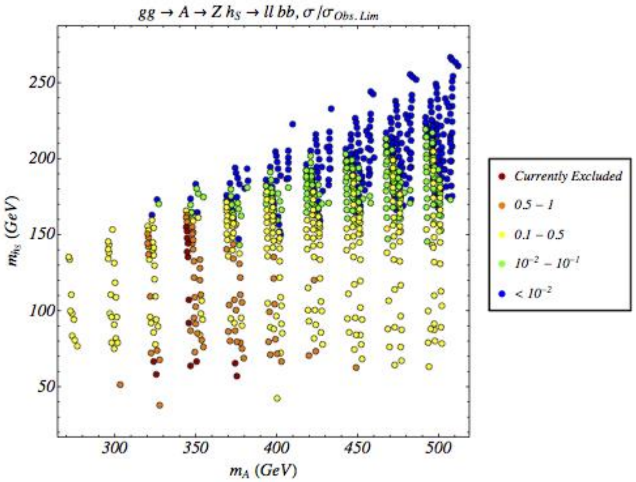
$H \rightarrow hh$ and $A \rightarrow hZ$ decays strongly suppressed due to alignment

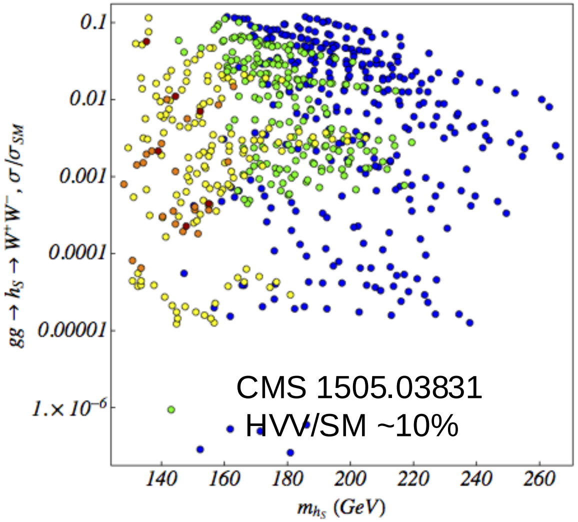
Others: $H \rightarrow$hs hs; $H \rightarrow$As Z; $A \rightarrow$As hs; $A \rightarrow$As h of order 10% or below

Ongoing searches at the LHC are probing exotic Higgs decays

- Complementarity between gg →A→ Z h_S →ll bb and gg→ h_S → WW searches







CMS 1505.03831
HVV/SM ~10%

Observed exclusion CMS-PAS-HIG-18−012
similar to CMS-PAS-HIG-15 −001 result

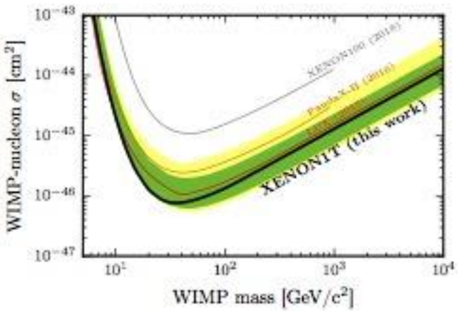
For M > 200 GeV also CMS-PAS-HIG-17-033

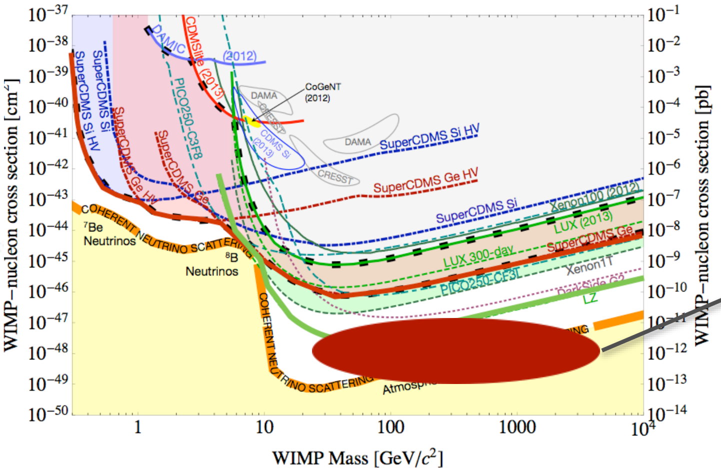
- **Promising H→ h h_S channels with h_S→ bb or WW (4b's or bb WW)**

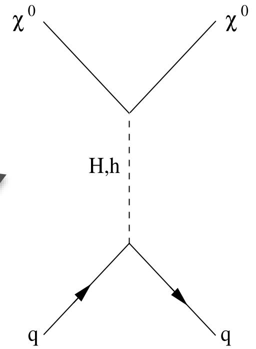
Searches for H → ZA or A→ ZH should replace Z by h_{125} (Di-Scalar Search)

- Channels with missing energy: A → h a_s; H → Z a_s with a_s → Dark Matter

Dark Matter Direct Detection: Starting to probe the Higgs portal





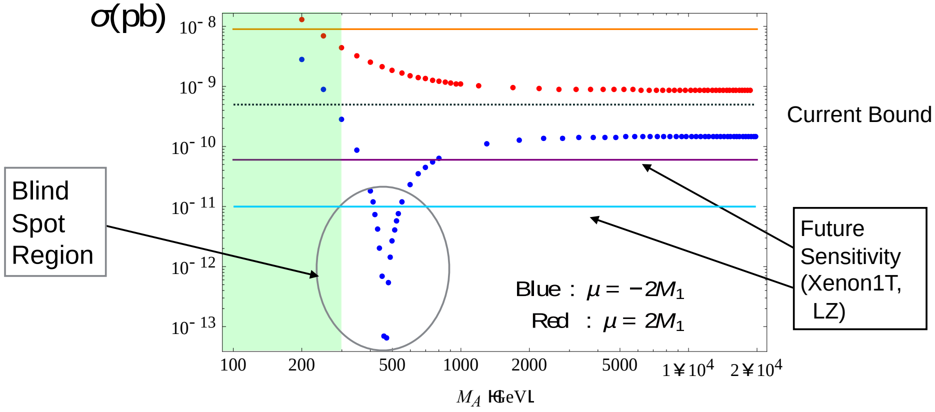


Close to Alignment (MSSM)

$$\sigma_p^{SI} \sim \left[(F_d^{(p)} + F_u^{(p)})(m_\chi + \mu\sin 2\beta)\frac{1}{m_h^2} + \mu\tan\beta\cos 2\beta\,(-F_d^{(p)} + F_u^{(p)}/\tan^2\beta)\frac{1}{m_H^2}\right]^2$$

$$\boxed{2\,(m_\chi + \mu\sin 2\beta)\frac{1}{m_h^2} \simeq -\,\mu\tan\beta\,\frac{1}{m_H^2}}$$

Huang, Wagner, '15



Destructive interference between h and H contributions for negative values of μ (cos2β negative)

Still room for a SUSY WIMP miracle

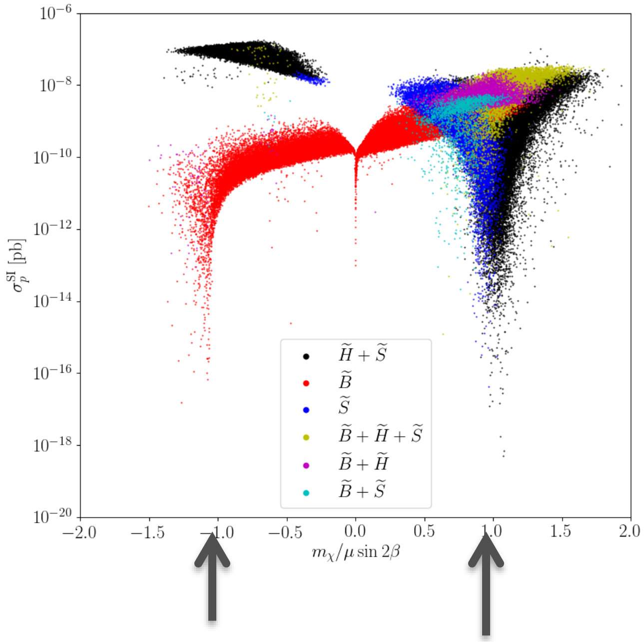
Blind Spots in Direct DM detection in the NMSSM

Possible to have a three way cancellation between the hs, h and H contributions

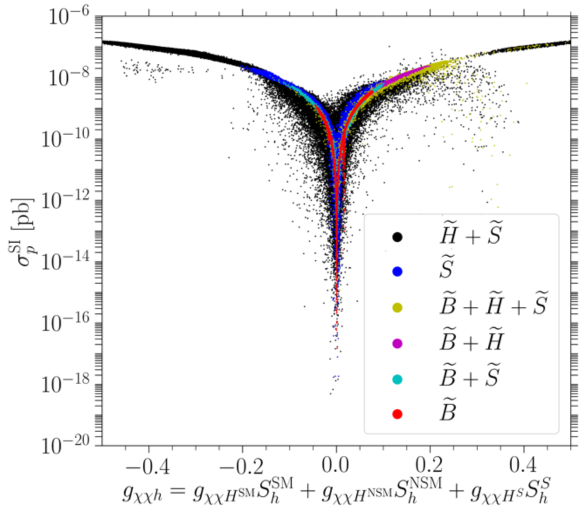
$$\sigma_{SI} \propto \left\{ \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) \frac{2\, t_\beta}{m_h^2} + \frac{t_\beta}{m_H^2} + \frac{1}{m_{h_S}^2} \left(2\, S_{h,s} + \frac{\lambda\, v}{\mu} \right) \left[\frac{\lambda\, v}{\mu^2} m_\chi + S_{h,s} \left(\frac{2}{t_\beta} - \frac{m_\chi}{\mu} \right) + \frac{\kappa\, \mu}{\lambda^2\, v} \right] \right\}^2 .$$

$$S_{h,s} \approx \frac{-2\lambda v \mu \epsilon}{(m_h^2 - m_{h_S}^2)}$$

Cheung, Papucci, Sanford, Shah, Zurek '14



$\mu < 0$ $\mu > 0$



Higgs Mixing Effects:

Couplings to the 125 GeV Higgs tend to be suppressed close to the blind spots. However, they remain relevant in the singlino region, denoting the presence of relevant interferences

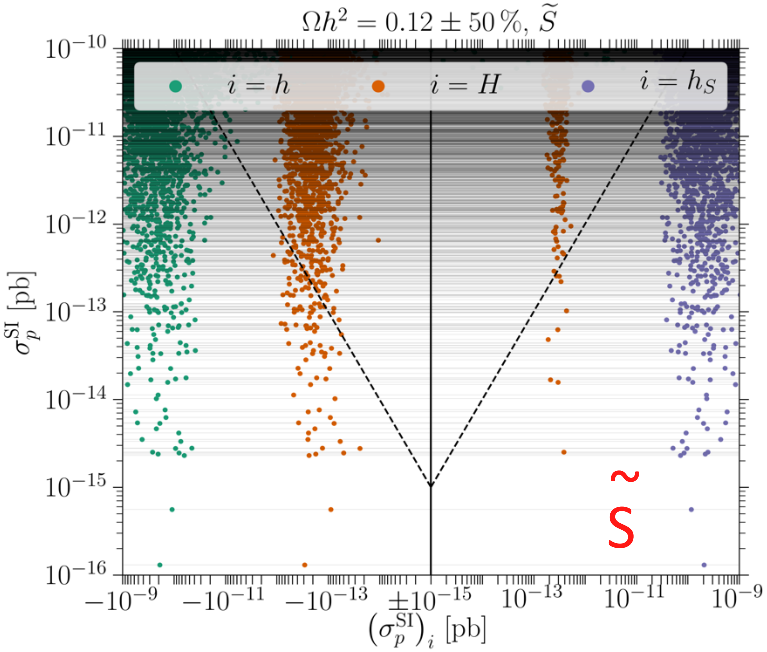
A SM-like Higgs would have couplings that vanish when $m_\chi = \pm \mu \sin(2\beta)$. The plus and minus signs correspond to the cases in which the neutralino is Singlino-Higgsino or Bino-Higgsino admixtures.

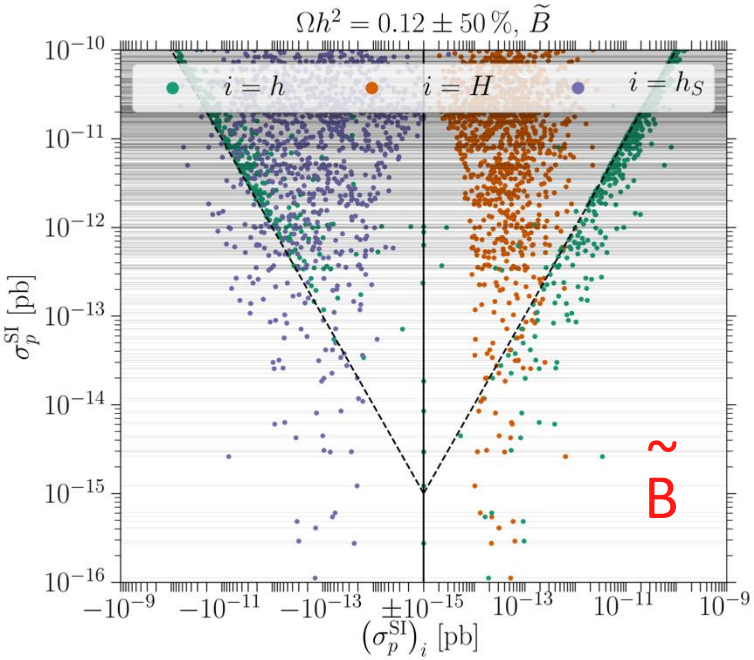
Baum, M.C. Shah, Wagner '18

NMSSM opens up new possibilities

Contributions to SI XS of the different (scalar) Higgs bosons

and sign of the different scalar contributions to the SI cross section.





Mostly singlinos: coupling to SM-like Higgs larger than for Bino ➔ to be close to blind spot, a destructive interference with singlet contribution is needed
Thermal Relic can be obtained via Z (G) annih.

Mostly Binos: SM-like Higgs provides the dominant contribution.
NEW Bino well-tempered region, with small couplings to Higgs and proximity to blind spot
Thermal Relic density via resonant Z, Higgs annih, or co-annihilation of bino with singlino