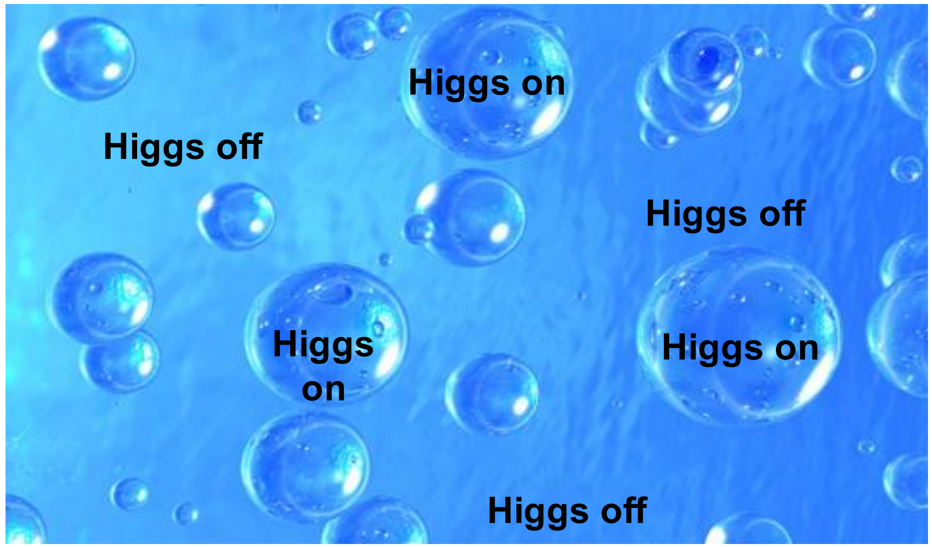
Opportunities for Electroweak Baryogenesis



17–21 Aug 2026
Helsinki, Finland

Strong and Electro-Weak Matter 2026

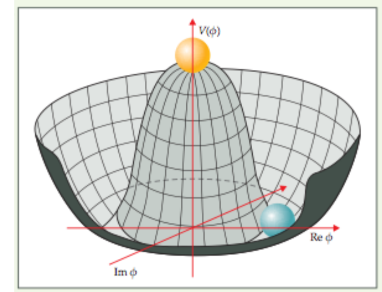
Marcela Carena
Perimeter Institute for Theoretical Physics

Helsinki, August 21, 2026

Outline

- Higgs exploration and the many open questions
- Electroweak Baryogenesis (EWBG)
    - The short-comings in the Standard Model
    - New models for electroweak baryogenesis:
        -- singlet extensions
        -- CP violation in the Dark Sector
- Bubble Wall Dynamics and the Terminal Wall Velocity
- Impact of the Terminal Bubble Wall Velocity on the Baryon Asymmetry results and Gravitational Wave Signals

The Idea of the Higgs Mechanism



What turned the Higgs field on? How did it happen?

- The Higgs field potential describes the energetics of turning on the Higgs field to a certain (complex) value

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

- Because of the symmetry there are degenerate vacua
- Because of the infinite degrees of freedom in Quantum Field Theory, once one of the degenerate ground states is chosen it is hard to transition to another

↓

Spontaneous Electroweak Symmetry Breaking (EWSB) $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

- A scalar field with self-interactions causes EWSB in the vacuum and gives mass to the gauge bosons of the broken symmetry
- The Higgs boson appears in the theory

Apply condensed matter ideas to particle physics

> "The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention" **-- Peter Higgs, 1964**

Now the quantum vacuum is the "medium"

- Adding the Yukawa interactions, the Higgs field also give masses to the chiral fermions of the Standard Model

The great success of the Higgs Boson

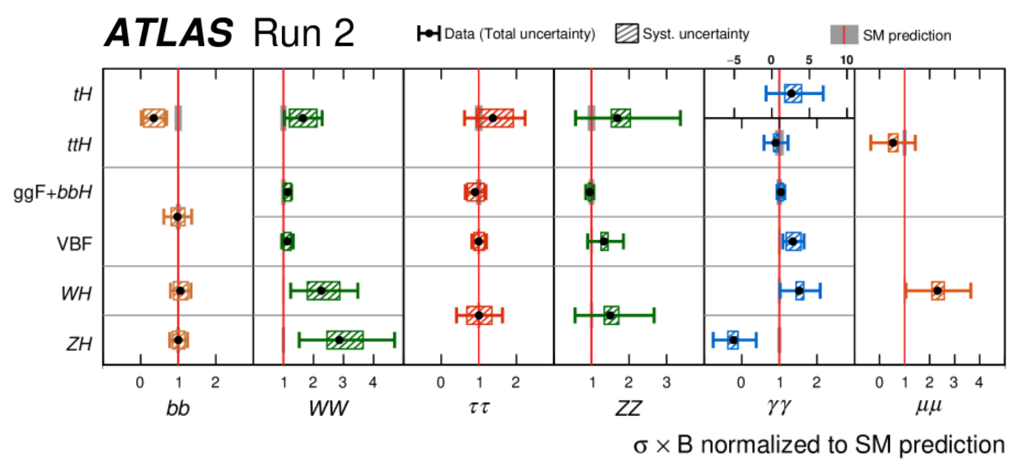
With M_H = 125 GeV, its mass is at a lucky spot to maximally allow us to measure its interactions with other particles

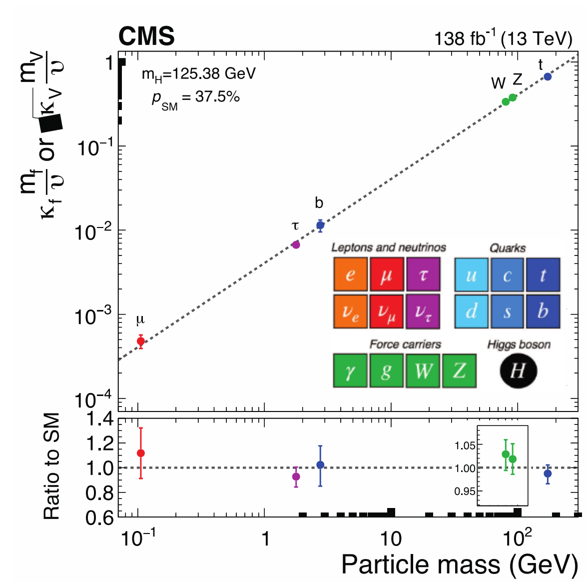
MC, Grojean, Kado, Sharma
https://pdg.lbl.gov/2024/reviews/rpp2024-rev-higgs-boson.pdf

The LHC data favors a SM-like Higgs boson

LHC experiments have verified that the discovered boson:

- is related to the mechanism of electroweak symmetry breaking
- couples most strongly to the heaviest Standard Model fermions

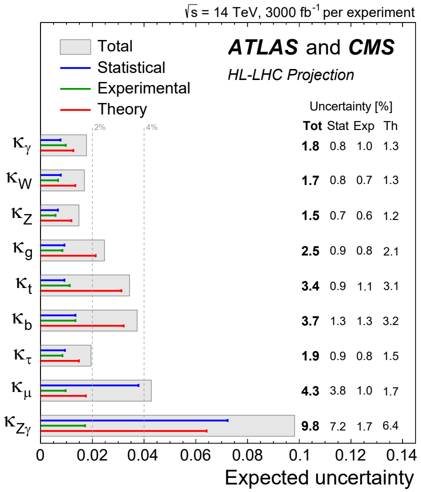




Nature 607, no.7917, (2022); [arXiv:2207.00092]; [arXiv:2207.00043]

Precision Higgs Measurements and Di-Higgs Production

LHC experiments until circa 2040 have the power to address ambitious new questions

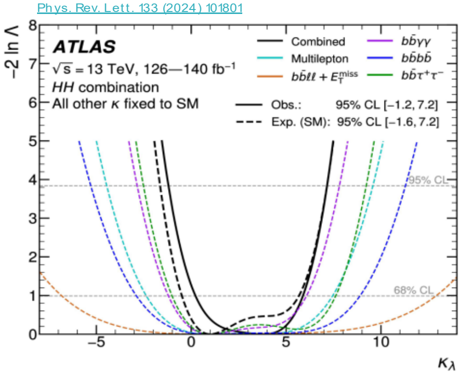


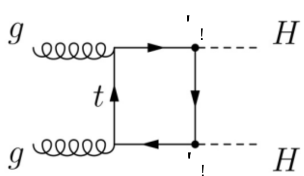
This could include **other Higgs bosons**, **new particles, new forces, new sources of CP violation** - the symmetry between matter and antimatter - **and connections with the dark sector**

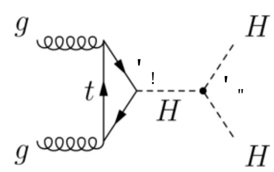
HL-LHC will confirm SM expectations at the 2-4 % level for couplings to gauge bosons, 3rd gen. fermions plus 2nd gen. charged leptons

HL-LHC will measure Di-Higgs production in the SM

Phys. Rev. Lett. 133 (2024) 101801



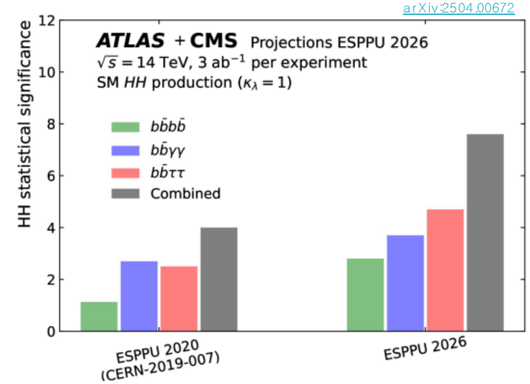




$\kappa_\lambda = \lambda/\lambda^{SM}$

SM predicts κ_λ

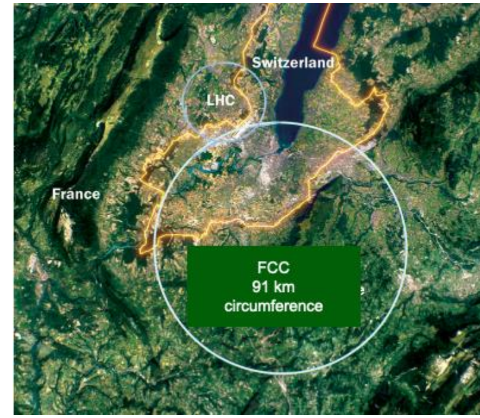
arXiv:2504.00672



can shed light on the Higgs potential and how the electroweak breaking occurred

Higgs Measurements: an exploration tool at FCC-ee

The electron–positron Future Circular Collider at CERN



- FCC-ee programme:

-- can measure Higgs production inclusively as a recoil in e+e-→ HZ, yielding an absolute measurement of the HZZ coupling and a model independent extraction of Γ_H **(1.3% precision)**

Coupling	HL-LHC	linear colliders (250 or 380 GeV)	circular colliders (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5^{*}	0.73	0.43 / 0.33
κ_Z [%]	1.3^{*}	0.29	0.17 / 0.14
κ_g [%]	2^{*}	1.4	0.90 / 0.77
κ_γ [%]	1.6^{*}	1.4	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10^{*}	10	10 / 10
κ_c [%]	–	2.0	1.3 / 1.1
κ_t [%]	3.2^{*}	3.1	3.1 / 3.1
κ_b [%]	2.5^{*}	1.1	0.64 / 0.56
κ_μ [%]	4.4^{*}	4.2	3.9 / 3.7
$\kappa_{\boxtimes}$ [%]	1.6^{*}	1.1	0.66 / 0.55
BR_{inv} (<%, 95% CL)	1.9^{*}	0.26	0.20 / 0.15
BR_{unt} (<%, 95% CL)	4^{*}	1.8	1.0 / 0.88

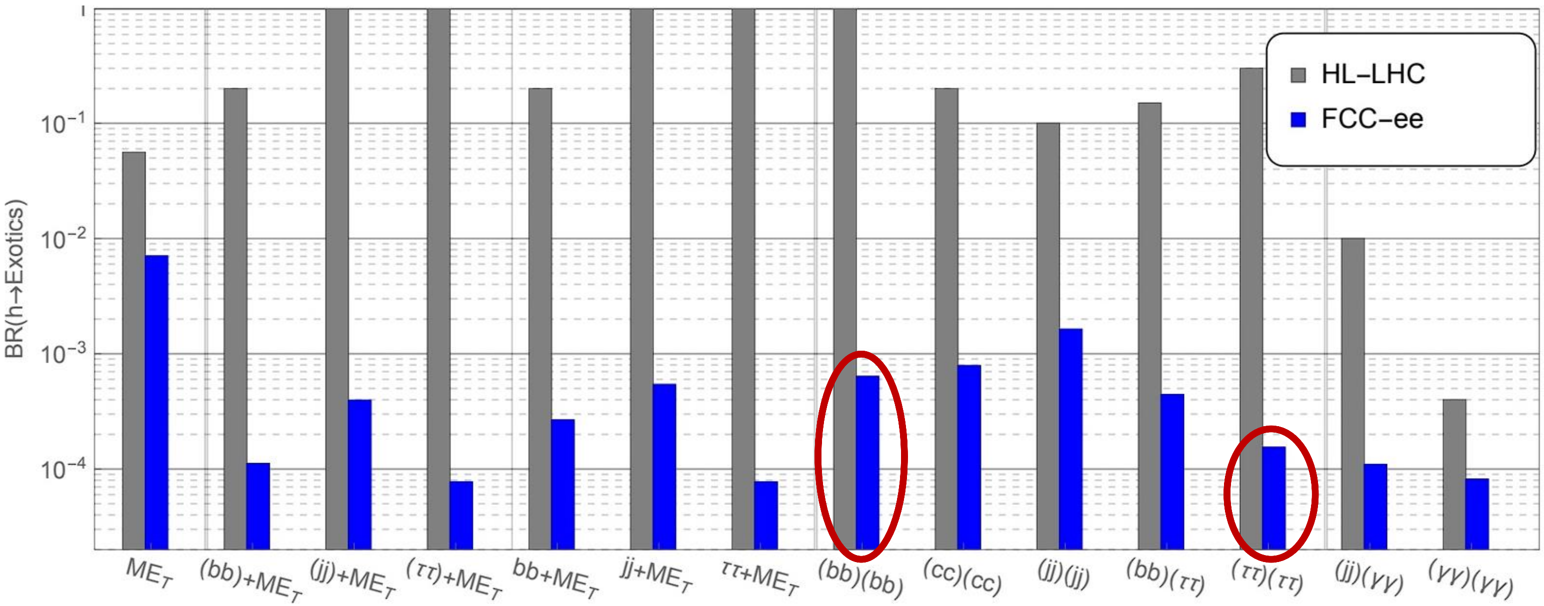
With σ_{HZ} and Γ_H known, FCC-ee programme aims at measuring Higgs couplings (in non-rare decays) at **percent to sub-percent level**

Higgs rare/exotic decays bounded below the 1% level

This assumes no-flavor violation couplings, but flavor violating channels should be explored

HL-LHC & FCC-ee coverage in selected Higgs Exotic Decay BRs

95% C.L. upper limit limit on BR(H → exotics)



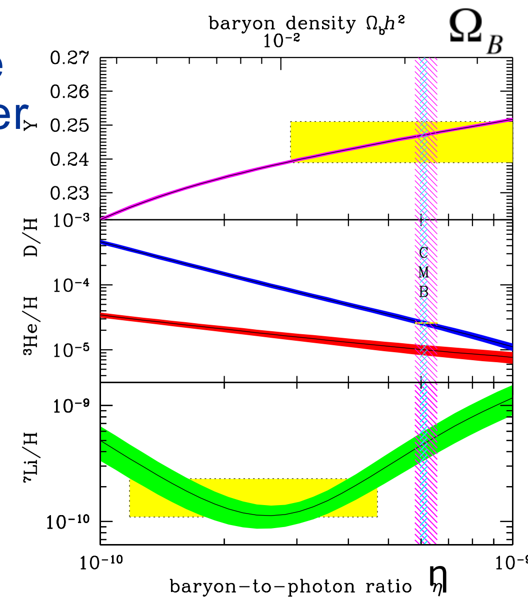
Based on Zhang, Liu, Wang, 1612.09284, with updates

HL-LHC: from various studies and projections available in the literature
FCC—ee are from arXiv:1612.09284 and $ee \to ZH$ (except for the first channel, $h \to inv$)

Missing E_T , e.g. in SUSY/DM models yields about 2-4 orders of magnitude improvement
H → 4 f, e.g. in extended Higgs sectors and/or Higgs portals yields about 2-3 orders of magnitude improvement

The mystery of the matter-antimatter asymmetry

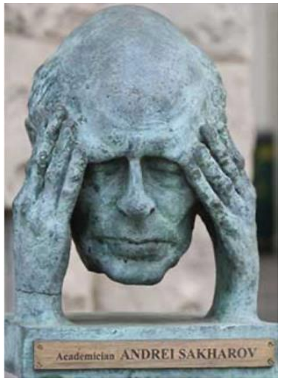
- Precision Cosmology tell us the observable Universe is made almost entirely of matter — essentially no primordial antimatter
  - Abundance of primordial elements
  - Predictions from Big Bang Nucleosynthesis
  - CMB determinations



➔ The baryon-to-photon ratio: $\eta \approx 6 \times 10^{-10}$
— what generated this small but crucial number?

Sakharov conditions for baryogenesis (1967)

- 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 proposed that satisfy Sakharov conditions

This talk: generate baryogenesis at the Electroweak Phase Transition

We need to understand the dynamics and the history of the EWSB mechanism

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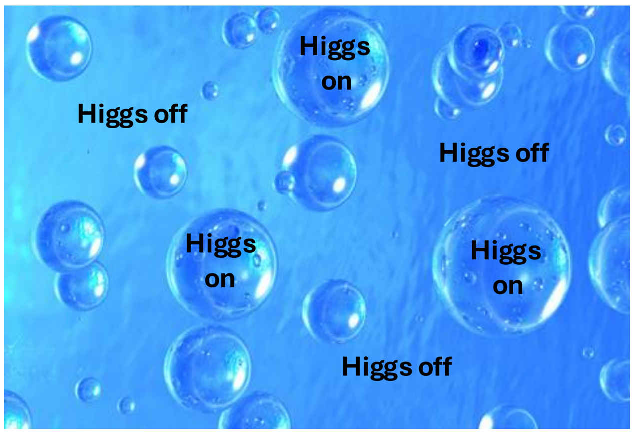
Can successful Electroweak Baryogenesis take place in the SM?

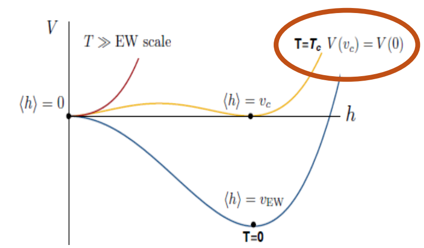
- Baryon number violation: Sphalerons
- CP and C violation: CP violating phase in mixing of the **three** generations of quarks;
  C violation through Sphalerons/SU(2)$_L$ interactions
- Non-equilibrium: At the Electroweak Phase Transition



In a first-order EW Phase Transition, the universe tunnels from the symmetric phase (Higgs off) to the broken phase (Higgs on) — via bubble nucleation

Bubbles nucleate and expand in the plasma of SM particles

Bubble wall moves at near the speed of light – the precise v_W is relevant for EWBG and GW signals



- CPV in the bubble wall cause different forces for particles and antiparticles, creating a chiral asymmetry
- EW sphalerons active outside the bubble wall profit from the chiral asymmetry and violating B and L create a net B = L≠0.
- The sphalerons freeze out inside the bubble wall (broken phase) to avoid erasing the created B and L asymmetries ➔ needs a strong first order EWPT ~ $v(T_n)/T_n \gtrsim 1$

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 $T > Tc$ and create $n_B\ (T_c)$:

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

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

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

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

$\not{B}$ processes frozen

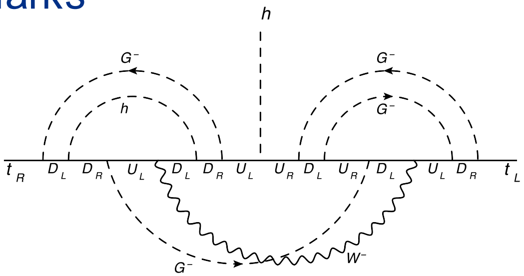
To preserve the baryon asymmetry demands a Strong First Order EWPT

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

#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

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

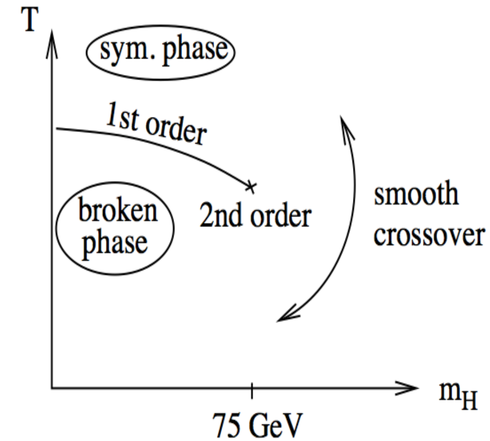
Gavela, Hernandez, Orloff, Pene, Quimbay'94

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

$$V = \mathrm{D}(\mathrm{T}^2 - \mathrm{T}_0^2)\phi^2 - \mathrm{E}_{\mathrm{SM}}\mathrm{T}\phi^3 + \lambda(\mathrm{T})\phi^4$$

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

$v(T_c) / T_c \sim E_{SM} / \lambda$ controls the strength of the phase transition



Since $\lambda = m_H^2/v^2$, to sufficiently suppress sphaleron processes in the true vacuum and prevent washout of the asymmetry

$v(T_c)/T_c > 1 \Rightarrow m_H < 40$ 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 potential new particles and new forces - 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 scenario
- 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)
- ...

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

To determine phase transition pattern requires finite temperature potential

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

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

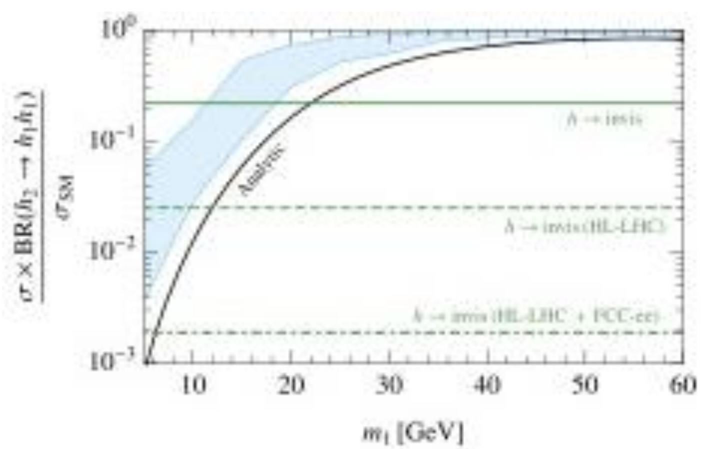
➔ Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT

Collider prospects to determine the EWSB thermal history

- 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)

} $BR(H)_{inv}$ bounds (Missing E_T) **or** pp →VSS (AP) pp →SSjj (VBF) Universal shift in coupling via σ(ZH)

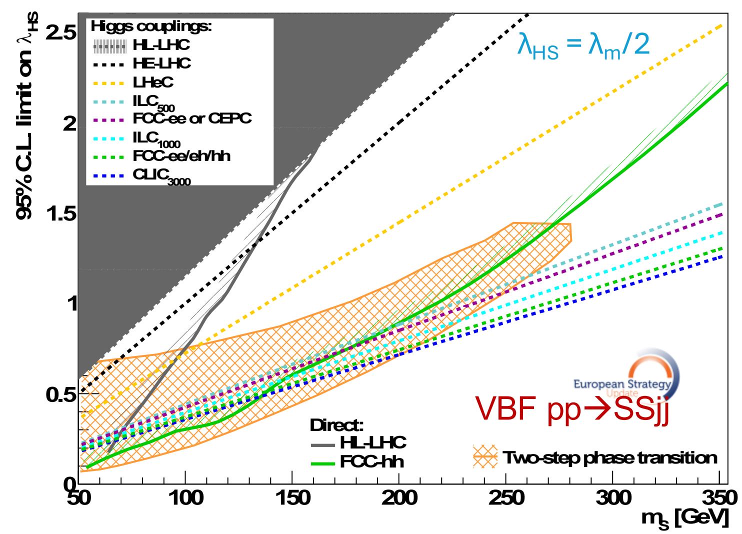
Low mass singlet: $m_s < m_h/2$



Kozaczuk, Ramsey-Musolf, Shelton '19

Current bounds imply $m_S < 20$ GeV

$m_s > m_h/2$



Scenarios for EW baryogenesis 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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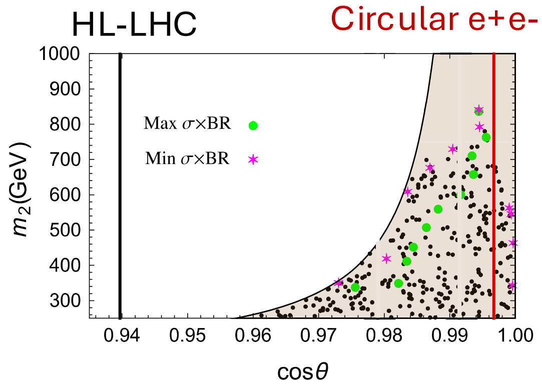
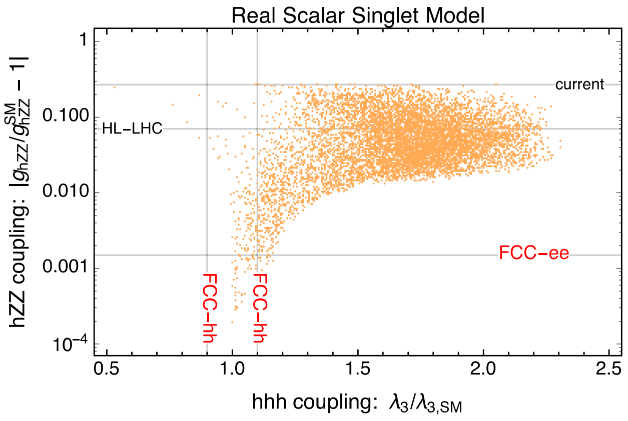
Higgs Phenomenology in Singlet models with H-S mixing

- Heavy Singlet ➔ $m_s > m_h/2$. -- Explicit Z_2 breaking

Mixing between doublet and singlet states implies reduction in Higgs signal strengths compared to SM Higgs boson; equivalently one can observed deviations in HZZ coupling and Higgs self coupling





- Light Singlet ➔ $m_s < m_h/2$ ➔ Higgs Exotic Decays: H➔ SS
  Spontaneous Z_2 breaking or Explicit Z_2 breaking

➔ exotic Higgs decays are a potent probe of Singlet extensions with viable EW Baryogenesis

Specifics of Higgs exotic decays depend on Z_2 symmetry breaking mechanism

A Strong first-order Electroweak Phase Transition

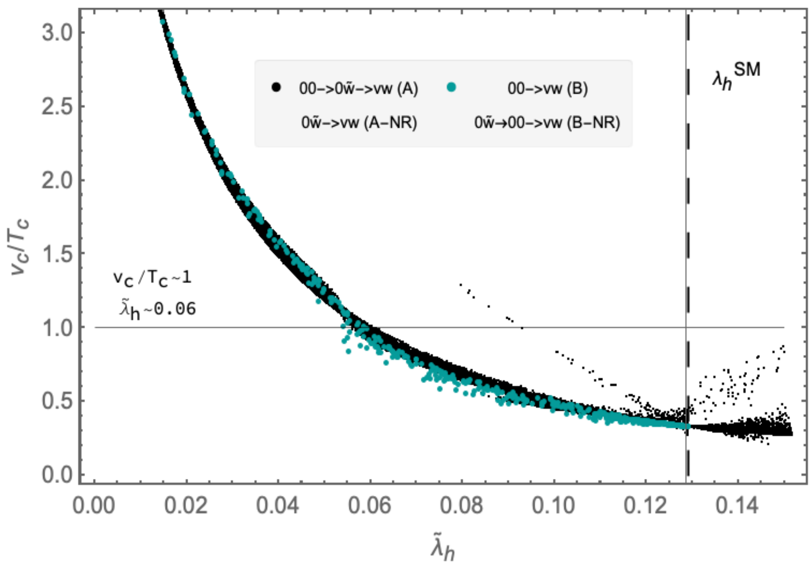
- **Spontaneous Z2 breaking case**

Similarly to the SM we can compute the expression of the order parameter v $(T_c)/T_c$

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

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

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



M.C, Z. Liu, Y. Wang, *JHEP* 08 (2020) 107

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

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

The Higgs can have exotic decay: H→SS

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

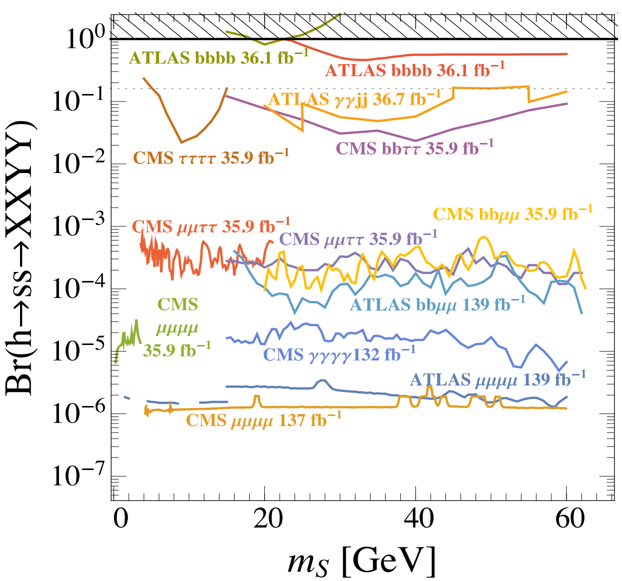
➔ Hence, BR(H → SS) is bounded from below

Probing Spontaneous Z_2-breaking Singlet Extensions via Exotic Higgs Decays

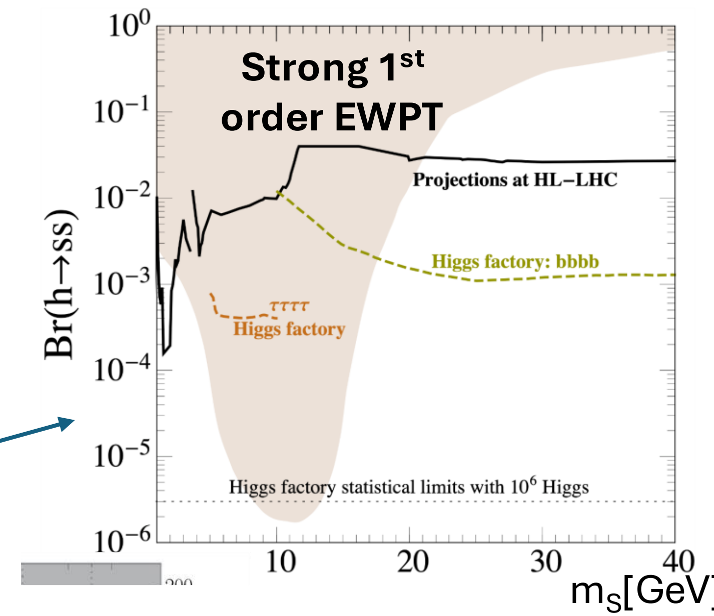
- LHC data from global fit to Higgs couplings constrains BR[H→ exotics] < 16%
- Bounds on exotic Higgs decays

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

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



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



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

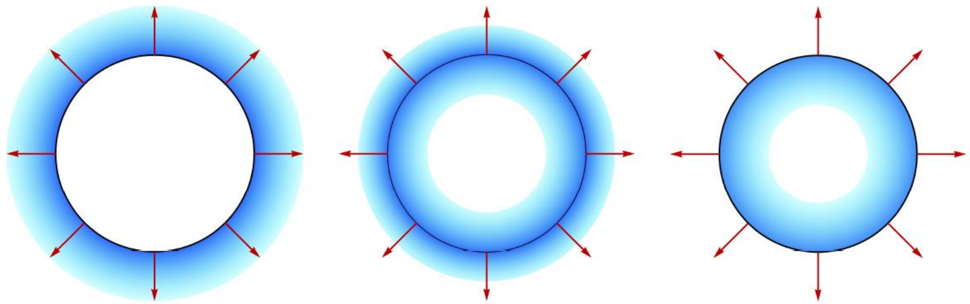
Direct search and Higgs precision measurements at HL-LHC and FCC-ee can probe large regions of space compatible with a strong 1st order EWPT

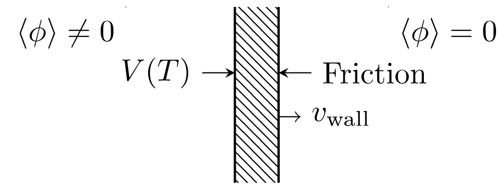
Models with Strong First Order Phase Transitions in the Early Universe

- are a necessary ingredient for a successful generation of EWBG
- induce Gravitational Wave signals that may become detectable in the future

The bubble wall dynamics plays a crucial role in both processes

Bubble Wall and Fluid Dynamics – computation of v_W





$\mathcal{P}_{\rm net} = \mathcal{P}_{\rm fric} - \mathcal{P}_{\rm drive} = 0$ ➔ terminal v_w

Three possible fluid profiles can form around the expanding bubbles, depending on v_W

The fluid velocities v±, defined in the wall frame, and temperatures T± on the two sides of the bubble wall are discontinuous.

They are connected by energy-momentum conservation of the scalar + fluid system, when using proper boundary conditions for each type of solution

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left(T^{\mu\nu}_\phi + T^{\mu\nu}_f \right) = 0$$

To compute the wall terminal velocity, v_w, one needs to consider the scalar field EOM

$$\Box\phi + \partial V_{\rm eff}/\partial\phi = 0$$

The full study involves consideration of the Equations of State for the total pressure and energy of the scalar fluid system

Energy-Momentum Tensor (EMT) Conservation Conditions

$$\partial_\mu T^{\mu\nu} = \partial_\mu \left(T_\phi^{\mu\nu} + T_f^{\mu\nu} \right) = 0 \qquad \text{with} \qquad T_\phi^{\mu\nu} = \partial^\mu \phi \partial^\nu \phi - \eta^{\mu\nu} \left(\frac{1}{2}(\partial\phi)^2 - V_0 \right)$$

Assuming the fluid is in local thermal equilibrium (LTE) => $f = f_{\rm eq}(T(z), v(z))$

EMT can be written in terms of the thermal quantities:

$$T_{f,\mathrm{LTE}}^{\mu\nu} = w_f\, u^\mu u^\nu - p_f\, \eta^{\mu\nu}$$

With the fluid velocity: $u^\mu(z) = \gamma(z)\,(1, 0, 0, -v(z))$,

The fluid pressure density is $\mathbf{p_f = -V_T}$ **,** and enthalpy w_f , entropy s_f and energy densities e_f :

$$w_f = T\frac{\partial p_f}{\partial T}\,, \quad s_f = \frac{\partial p_f}{\partial T}\,, \quad e_f = T\frac{\partial p_f}{\partial T} - p_f$$

With scalar contributions: $p = p_f - V_0\,, \quad e = e_f + V_0$

working in the wall frame, ignore curvature of the bubble — the only spatial dependence is in the direction of bubble expansion, then EMT conservation reduces to two equations:

$$\partial_z T^{z0} = 0\,, \quad \partial_z T^{zz} = 0\,.$$

Substituting the EMT expressions above, the two matching conditions:

Condition 1: $w_+\gamma_+^2 v_+ = w_-\gamma_-^2 v_-$

Condition 2: $w_+\gamma_+^2 v_+^2 + p_+ = w_-\gamma_-^2 v_-^2 + p_-$

Ai, Laurent, van de Vis, JCAP 07 (2023) 002

Equation of Motion Condition and Entropy Conservation

Multiply both sides of EMT conservation by u_ν, we get

$$u_\nu \partial^\nu \phi \left(\Box\phi + \frac{\partial V_{\text{eff}}}{\partial \phi} \right) + T\partial_\mu (u^\mu s) = 0$$

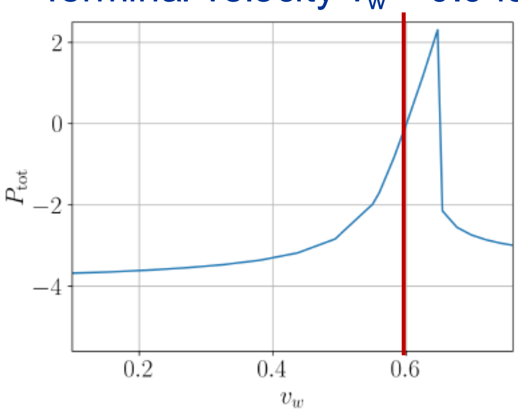
Equation of motion for the scalar field imposes that **$\Box\phi + \partial V_{eff}/\partial\phi = 0$**. We get the third matching condition — entropy conservation:

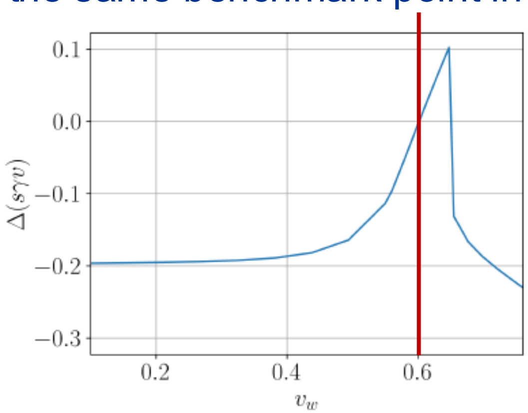
$$\partial_z (s\gamma v) = 0 \quad \Rightarrow \quad \text{Condition 3:} \quad s_+\gamma_+ v_+ = s_-\gamma_- v_-$$

Ai, Laurent, van de Vis, JCAP 07 (2023) 002

This shows the equivalence of the scalar field EOM with entropy conservation **under LTE.**

Terminal velocity $v_w = 0.6$ for the same benchmark point in the Z_2 symmetric singlet SM extension





zero at terminal v_w, peaks at $v_w = v_J$.

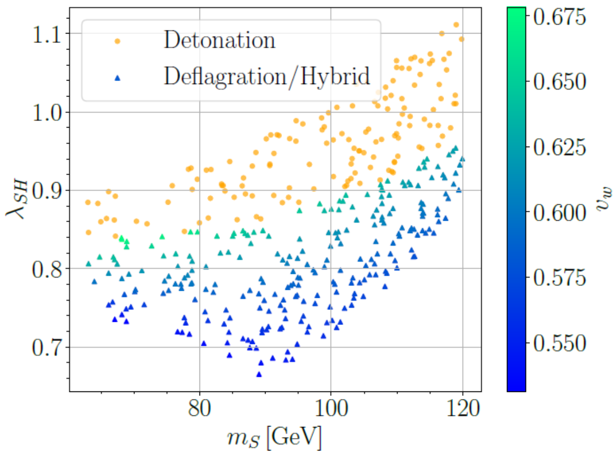
Both calculations, as a function of total pressure or entropy conservation yield qualitatively identical behavior and cross zero at the same value of v_w.

MC, Ireland, Ou, Wang, JHEP 09, 2025

Determining the Terminal Velocity from First Principles – LTE -

requires knowledge of Nucleation Temperature + Scalar Potential

The Z_2 symmetric real singlet SM ➔ v_w ~ 0.55 – 0.67 for deflagration/hybrid



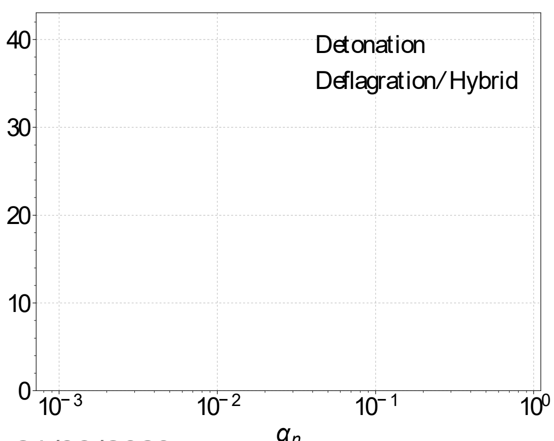
Points with SFOPT for fluid profiles

Scalar EOM yields to entropy conservation condition

Allows to determine v_w in excellent agreement with results from the LTE pressure analysis (e.g. EOM along the bubble wall)

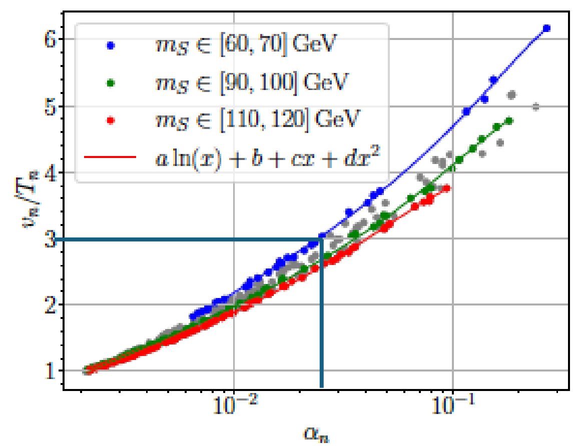
Terminal v_w significantly larger than assumptions in the literature

Histogram of α_n – strength in GW signals - for detonation vs deflagration/hybrid fluid solutions.



$$\alpha_n = \left. \frac{\Delta V_{\rm eff} - \frac{T}{4}\frac{\partial \Delta V_{\rm eff}}{\partial T}}{g_* T^4 \pi^2/30} \right|_{T_n}$$

Important correlation between v_n/T_n and α_n



Laurent, Cline PRD106, 2022

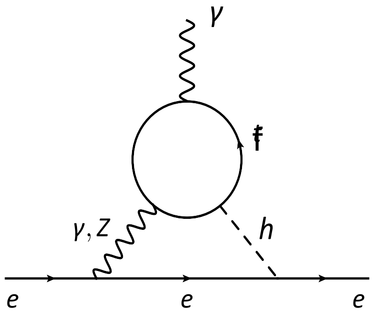
MC, Ireland, Ou, Wang, JHEP 09, 2025

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:

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

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

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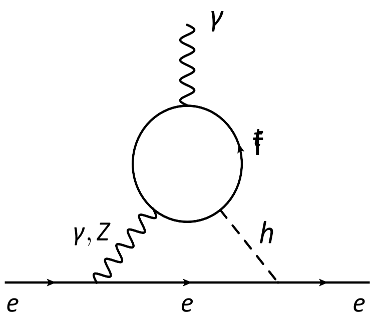

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Problem: most models of electroweak baryogenesis require $\sin\theta_{CPV} \geq 10^{-2}$

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

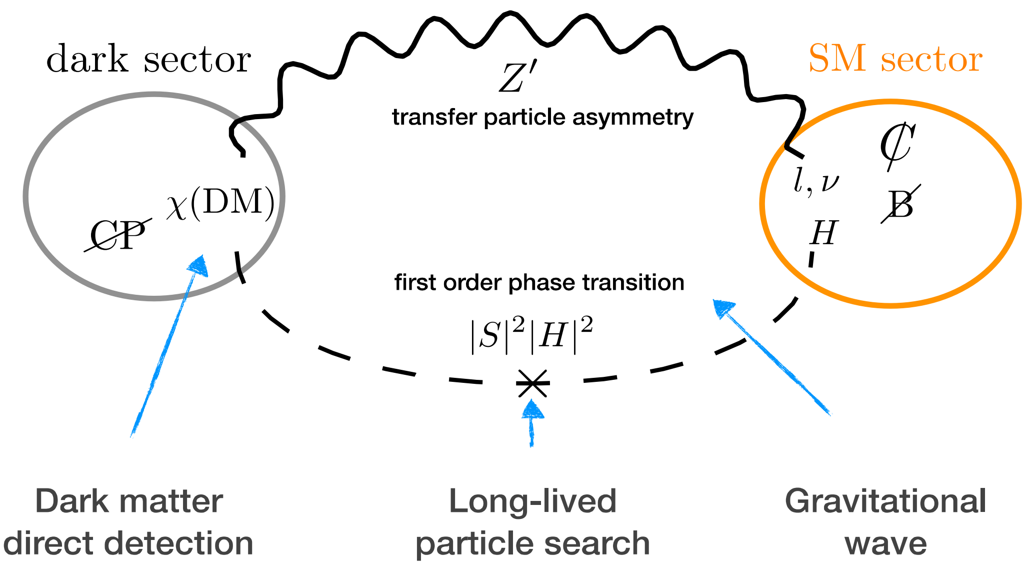
M.C., M. Quiros and Y. Zhang: Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014

Dark CPV: a New mechanism for EW Baryogenesis

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

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

- **Z' portal to the dark sector**
  to transfer the CP violation to the SM sector



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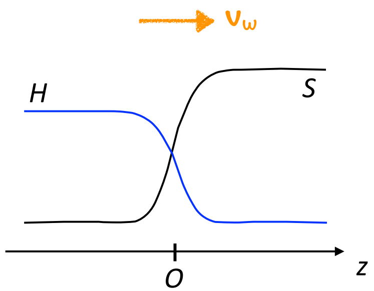
M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

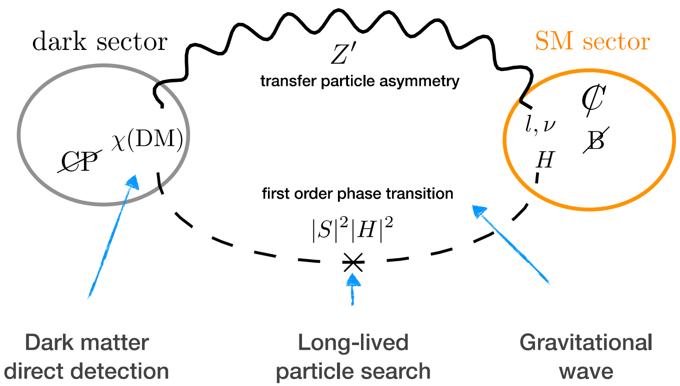
A New Mechanism for Electroweak Baryogenesis:

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

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



bubble wall profile



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:

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- **Z' portal:** to transfer the CP violation to the SM sector

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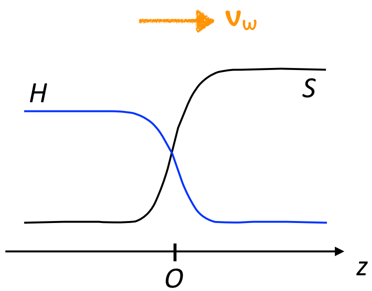
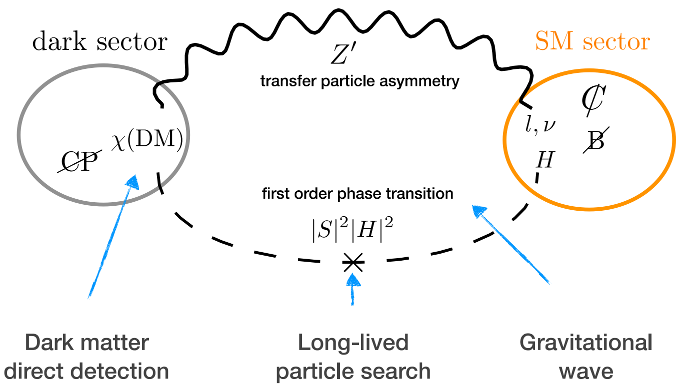


bubble wall profile



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

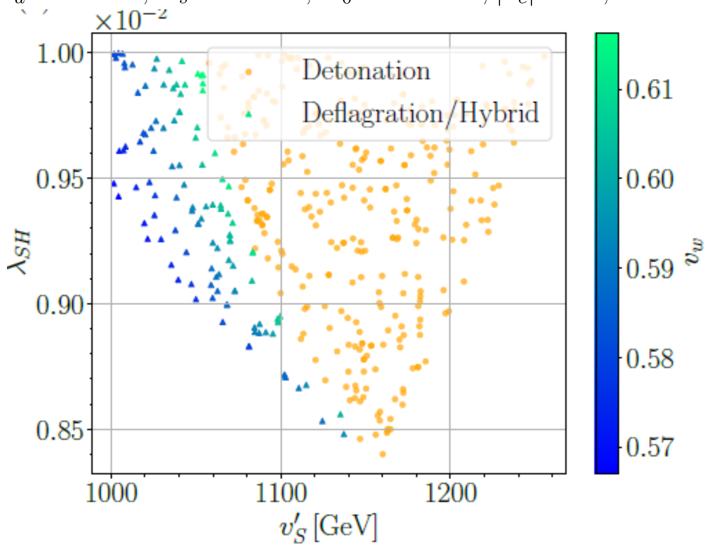
M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

Wall Velocity Calculation in the Dark CPV Model

Strong first-order EWPT points and terminal v_w calculated from first principles

➔ $v_w \sim 0.56 - 0.62$ for deflagration/hybrid

$m_a = 10\,\text{GeV}$, $m_s = 70\,\text{GeV}$, $m_0 = 120\,\text{GeV}$, $|\lambda_c| = 0.3$, $\theta = -0.25$.



Model free parameters after imposing SM Higgs mass and vev And fixing m_0 and κ^2_S to be real, leaving $\theta \equiv \arg(\lambda c)$

$$\text{Scalar sector: } \lambda_{\mathbb{S}},\ \lambda_{\mathbb{S}H},\ v'_{\mathbb{S}} \equiv \sqrt{v_{\mathbb{S}}^2 + 2\kappa_{\mathbb{S}}^2/\lambda_{\mathbb{S}}},\ m_s,\ m_a,$$
$$\text{Dark fermion: } m_0,\ |\lambda_c|,\ \theta,$$

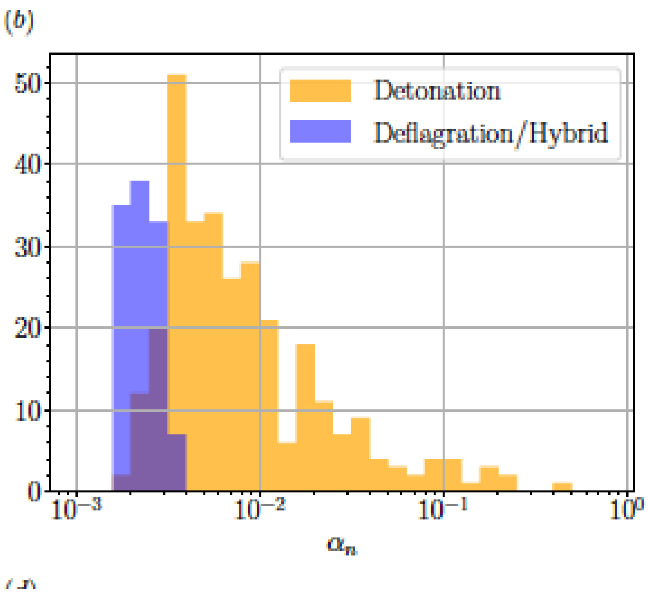
Also $m_a < m_h/2,\ m_s > m_h/2,\ m_0 > m_{a,s},\ \text{and } \lambda_{SH} \lesssim 0.01,$

to secure SFOPT, observed relic density, Higgs exotic and invisible decay bounds, & observed baryon number asymmetry

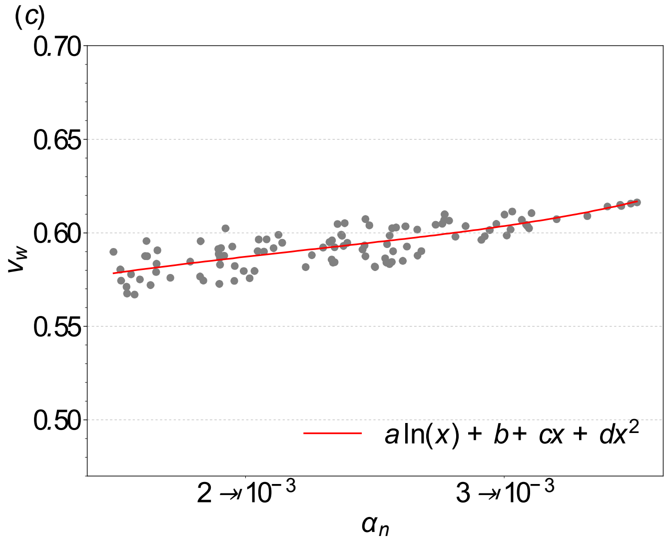
MC, A. Ireland, Tong Ou, I. Wang, JHEP 09, 2025

Histogram of α_n in GW signals with detonation vs deflagration/hybrid.

$$\alpha_n = \left.\frac{\Delta V_{\text{eff}} - \frac{T}{4}\frac{\partial \Delta V_{\text{eff}}}{\partial T}}{g_* T^4 \pi^2/30}\right|_{T_n}$$

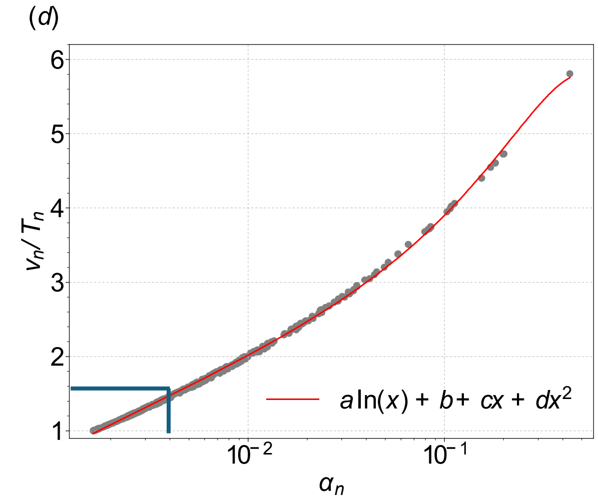


Gravitational Wave Strength Correlations with Model Quantities



v_n/T_n characterizes the degree of electroweak Sphaleron suppression in the broken phase

α_n below 4×10^{-3} for deflagration/hybrid



MC, A. Ireland, Tong Ou, I. Wang, JHEP 09, (2025)

Strong correlation between vw and α_n as well as between. v_n/T_n and α_n

v_w (for the deflagration/hybrid points) and v_n/T_n (for all the strong first-order phase transition points) can be fitted by the same functional form of α_n.

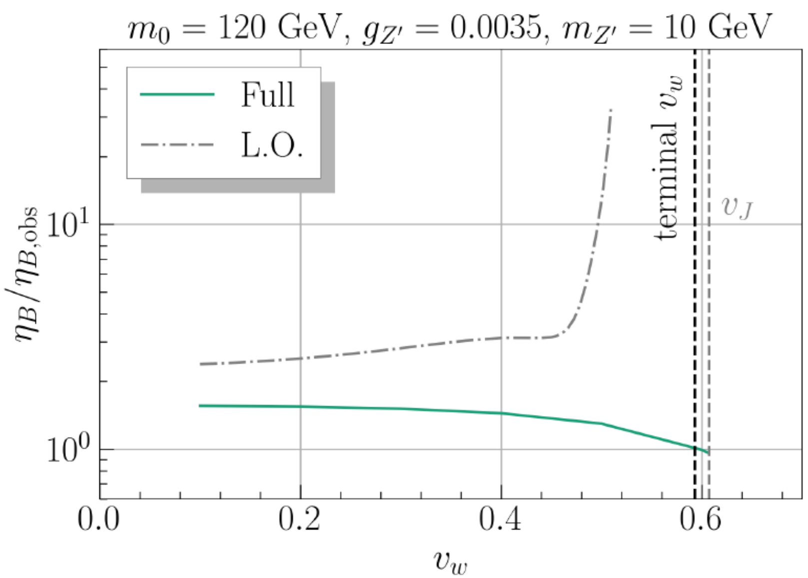
$$v_w = f(\omega_n): \; a = 0.15, \; b = 1.64, \; c = -95.07, \; d = 1.05 \times 10^4.$$

$$\frac{v_n}{T_n} = f(\omega_n): \; a = 0.54, \; b = 4.44, \; c = 8.01, \; d = -9.10.$$

The results of the terminal velocity for deflagration/hybrid points is much larger than previously assumed in the literature (e.g. for the Z_2 singlet extension of the SM, v_w ~0.1)
➔ impact on baryogenesis calculation and GW signals

Electroweak Baryogenesis in the DarkCPV Model

- Varying complex mass $M_\chi = m_0 + |\lambda_c| \exp(i[\theta + \arg(\mathbb{S})])|\mathbb{S}|$. ➔ the chiral fermion χ_L, $\overline{\chi_L}$ & their charged conjugates scatter off the bubble wall at different rates, creating a chiral asymmetry
- To transfer the chiral asymmetry to the SM, we gauge the lepton number to $U(1)_l$ with a Z', and assign $U(1)_l$ charges to χ and S ➔ χ and the SM leptons are connected via the Z' portal.
- Sphalerons turn the transferred chiral asymmetry in SM leptons into a net baryon asymmetry



The terminal v_w falls in a range where the baryon asymmetry calculation based on small v_w assumption becomes questionable.

MC, A. Ireland, Tong Ou, I. Wang,, JHEP 09, 2025

Baryon asymmetry calculation with full dependence on v_W (CK20 method, Phys. Rev. D 101, 2020)
➔ good results for values of the terminal bubble wall velocity computed from first principles

The low v_W assumption (e.g. method at LO, JHEP 07, 2000) yield results that diverge at $v_w \gtrsim 0.5$

What to expect for Gravitational Waves Signals

Main parameters controlling the stochastic GW background power spectrum

- Inverse time duration of the Phase transition $\beta/\mathbf{H} \approx \mathbf{T}\frac{\mathbf{d(S_3/T)}}{\mathbf{dT}}|_{\mathbf{T=Tn}}$
- Strength of GW signature from the PT $\alpha_n = \left.\frac{\Delta V_{\text{eff}} - \frac{T}{4}\frac{\partial \Delta V_{\text{eff}}}{\partial T}}{g_* T^4 \pi^2/30}\right|_{T_n}$
- Wall velocity v_w

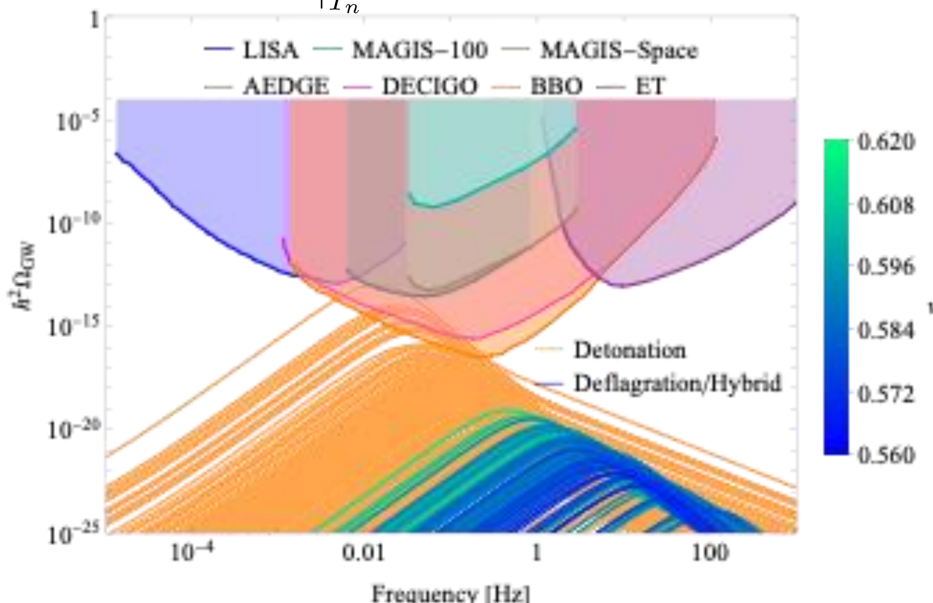
Case of interest for EWBG

Bubbles with a deflagration/hybrid fluid profile
- sizable friction from the plasma -

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

Fitted from numerical simulations

Caprinia, Hindmarsh, Huber et. Al, 2015.



$$\Omega_{\text{sw}}h^2 = 2.65\times10^{-6} H\tau_{\text{sw}}\left(\frac{\beta}{H}\right)^{-1}\left(\frac{\kappa_{\text{sw}}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} v_w \left(\frac{f}{f_{\text{sw}}}\right)^3\left(\frac{7}{4+3(f/f_{\text{sw}})^2}\right)^{7/2}$$

$$f_{\text{sw}} = 1.9\times10^{-5}\text{Hz}\frac{1}{v_w}\left(\frac{\beta}{H}\right)\left(\frac{T_n}{100\text{ GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

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

Results for the CPV Dark model as a function of v_w

MC, Ireland, Ou, Wang, JHEP 09, 2025

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; MC, Ireland, Ou and Wang, JHEP 09 (2025)

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

➢ 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

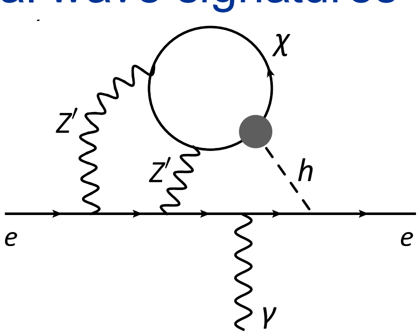
➢ **Predicts a new Higgs portal scalar *S*, which could mainly decay into *Z'* s.**

➢ The χ particle qualifies as a thermal DM candidate ➔ strongly constrained by direct detection searches

➢ Strong 1st order EWPT can generate stochastic gravitational wave signatures possibly observable at 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



Bubble velocity beyond LTE

An open window for GW signals in Electroweak Baryogenesis models?

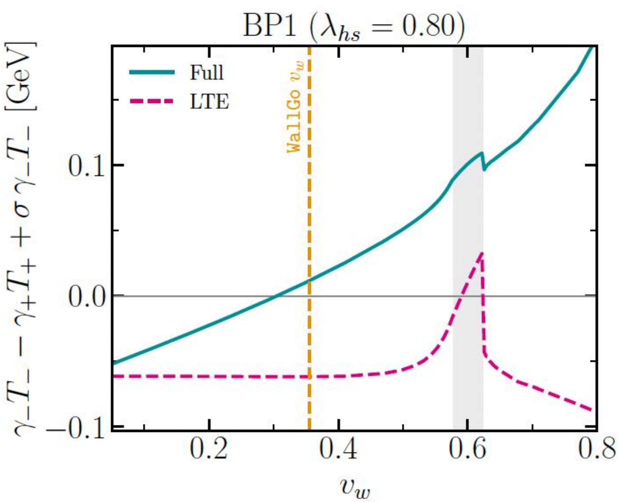
- Considering the effect of deviations from equilibrium on the distribution fuction

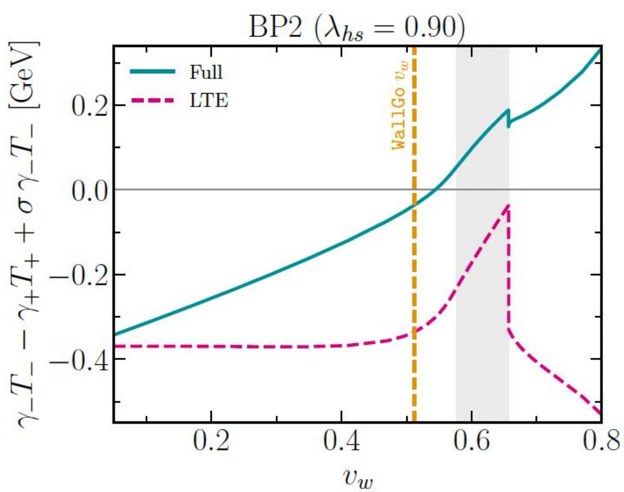
  $f = f_{eq} + \delta f$. ➔ entropy production such that

Benoit Laurent's Talk

$$\Delta S \approx -\frac{\gamma v}{2T}\sum_i \int dz\, \partial_z m_i^2 \int \frac{d^3p}{(2\pi)^3 E_i}\delta f_i = \frac{\gamma v}{T}\mathcal{P}_{\text{out}}.$$

Since $\Delta S > 0$ ➔ out–of eq. frictional pressure is positive and v_w decreases





Some/ Many detonation Benchmarks turn into Hybrid or Deflagration cases due to out-of eq. effects (?)

No change in GW strength

New Benchmark points available

Example we have: Benchmark points for the Z_2 symmetric singlet extension

MC, Ireland, Laurent, Ou, Wang, in preparation

Conclusions

Electroweak Baryogenesis remains an exciting possibility to explain the observed baryon asymmetry

Models may also provide Dark Matter candidates and have interesting signals, e.g new scalars, new particles/forces @colliders, GW/EDM signals, DM direct detection…

Evaluation of model capabilities to produce Electroweak Baryogenesis and GW signals requires detailed understanding of the bubble wall dynamics

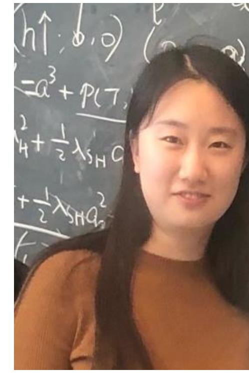
We showed correlations between EW phase transition parameters governing the sphaleron process and the strength of gravity wave signals.

Future directions

Investigate BSM EWBG models and bubble wall dynamics from entropy production

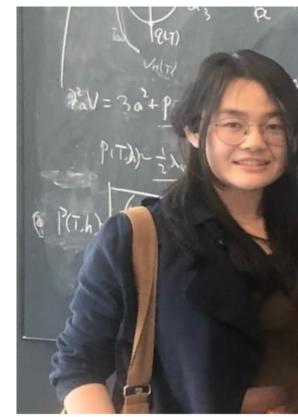
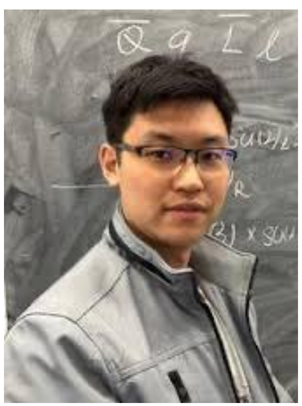
Quantum simulation formalism applied to real-time wave packet evolution to compute transmission and reflection dynamics at the bubble wall.
Real-Time Simulation of Asymmetry Generation in Fermion-Bubble Collisions
MC, Ying Ying Li, Tong Ou and Hersh Singh 2412.10365 [hep-ph]

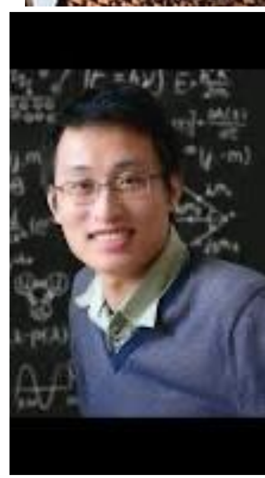
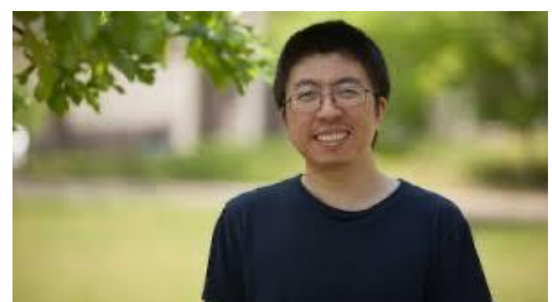
Thank you to
my amazing collaborators!!





Thank You !