Title: Baryogenesis of the Early Universe

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Collection/Series: Colloquium

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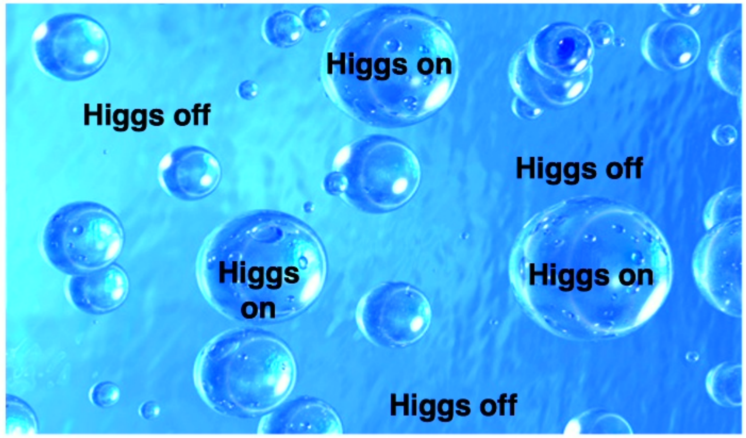
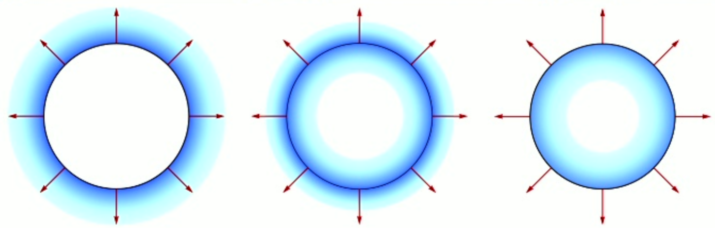
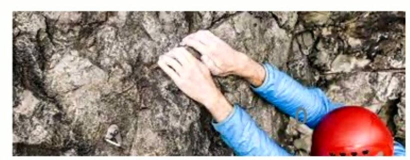
Baryogenesis in the Early Universe





Marcela Carena
Perimeter Institute for Theoretical Physics
March 13, 2025

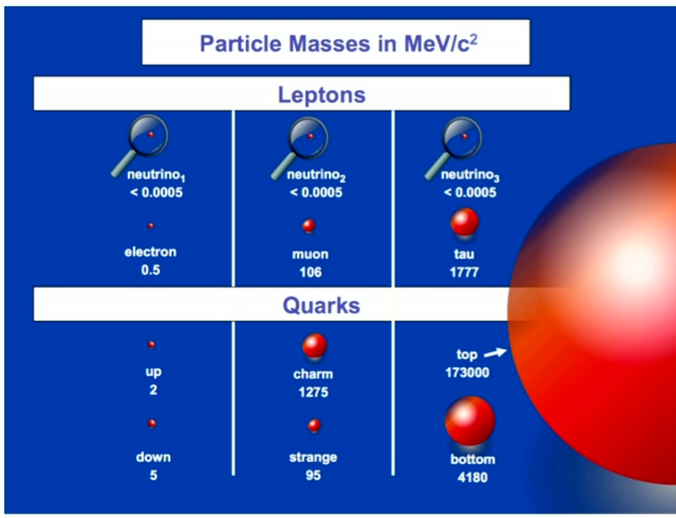


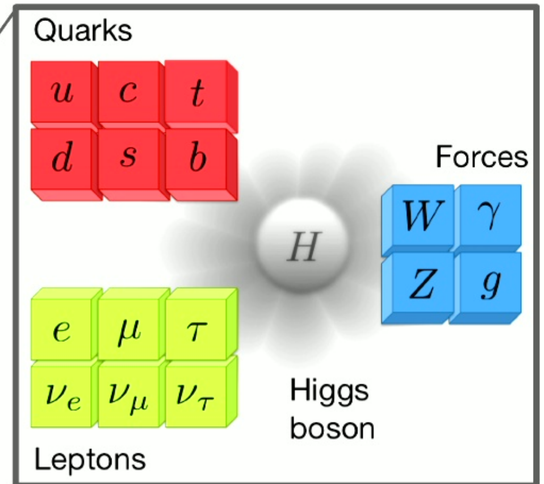
Outline

- The Particle Physics landscape:
  - -- the Higgs boson success and the many open questions
- The Higgs field and the origin of the matter-antimatter asymmetry of the Universe
- Electroweak Baryogenesis (EWBG) in the Standard Model?
- New models for electroweak baryogenesis
  - -- a singlet extension of the SM & the strength of the Electroweak Phase Transition
  - -- baryogenesis with dark CP violation
- Bubble Wall Dynamics and the Terminal Wall Velocity from first principles
- Impact of the Terminal Bubble Wall Velocity on the Baryon Asymmetry results and Gravitational Wave Signals

The Standard Model of Particle Physics

- 12 spin ½ fermion “matter particles”
- 4 spin 1 boson “force particles” mediating the strong, weak, and electromagnetic interactions
- **ONE spin 0 Higgs boson**



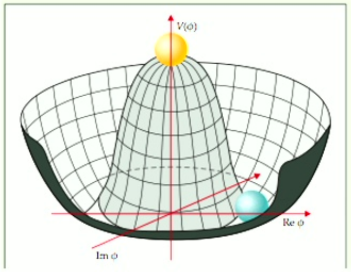


They have all been produced in the laboratory

They have very different masses

What causes fundamental particles to have mass?

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
- Because of the symmetry there are degenerate vacua

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

- 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

↓

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

Apply condensed matter ideas to particle physics

Now the quantum vacuum is the "medium"

"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**

The Brout-Englert-Higgs Mechanism and the Higgs Boson

- A scalar field with self-interactions causes Electroweak Symmetry Breaking in the vacuum and gives mass to the gauge bosons of the broken symmetry

- The Higgs boson also appears in the theory

The Mass Mechanism for quarks and leptons
(Weinberg and Salam)

- The symmetry of the theory gives different charges to nature's left- and right–handed fermions: they are chiral

  The SM is a $SU(2)_L \times U(1)_Y$ chiral gauge theory

- A massive fermion combines the left- and right-handed pieces but it is not possible to do it directly since they have different charges:

  the fermionic Yukawa interaction allows the Higgs field to connect, e.g.:

  the up quark, u_L, that lives in the $SU(2)_L$ doublet with the up quark, u_R ,that is an $SU(2)_L$ singlet and gives up-quarks mass through EWSB

The great success of the Higgs Boson

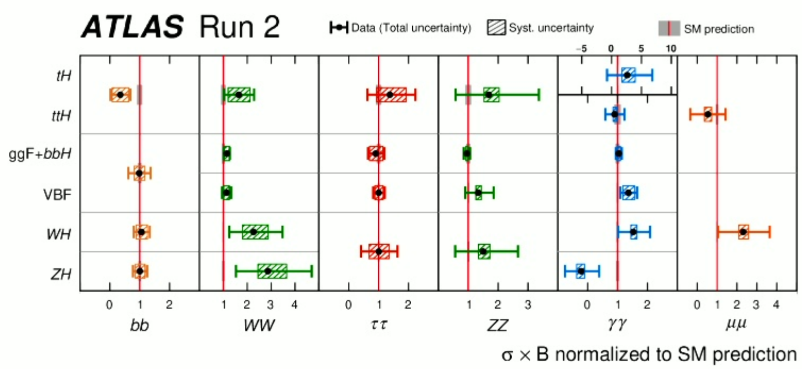
With M_H = 125 GeV, its mass is at a lucky spot to maximally allow us to measure its interactions with other particles

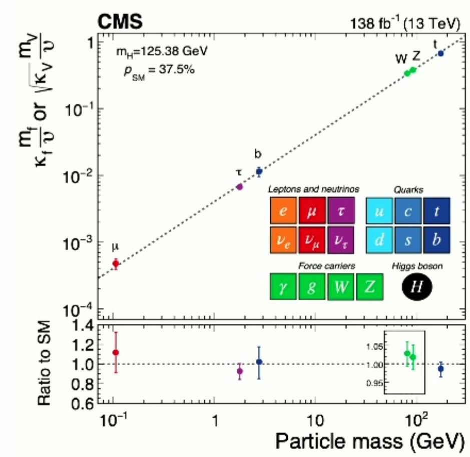
MC, Grojean, Kado, Sharma
https://pdg.lbl.gov/2024/reviews/rpp2024-rev-higgs-boson.pdf

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

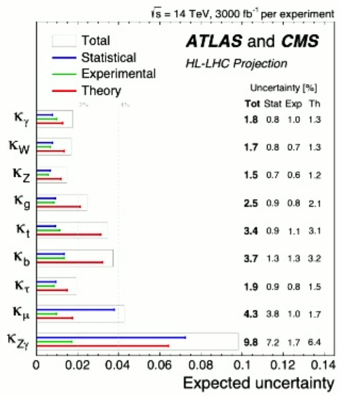




Nature 607, no.7917, (2022); [arXiv:2207.00092]; [arXiv:2207.00043]

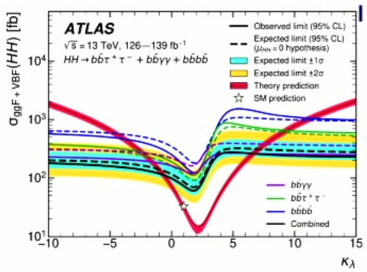
Precision Higgs Measurements and Di-Higgs Production

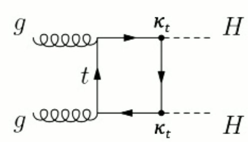
LHC experiments until circa 2040 have the power to address ambitious new questions

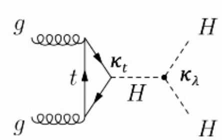


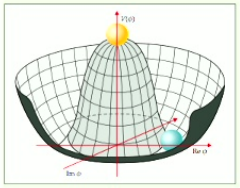
This could include **other Higgs bosons**, **new particles, new forces, new sources of CP violation** - the symmetry between matter and antimatter - **and connections with the dark sector**

Enhanced di-Higgs production being probed at LHC









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

What to expect ?

Consensus particle theorist's view of the road ahead: @LHC start in 2009

7 3/13/25

Consensus particle theorist's view of the road ahead: @LHC and elsewhere

8 3/13/25

The many particle physics topics NOT described by the Standard Model

What is the origin of Neutrino Masses?

What is behind the Hierarchy in Fermion Masses?

Why Electroweak Symmetry Breaking occurs?

What was the history of the Electroweak Phase Transition ?

What generated the observed Matter-Antimatter Asymmetry?

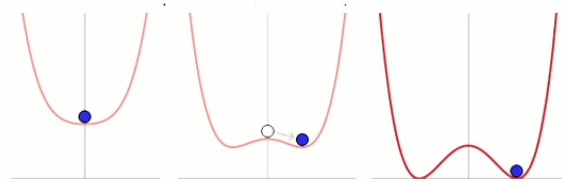
What is the nature of Dark Matter?

What caused Cosmic Inflation after the Big Bang?

What causes of the Universe's accelerated expansion?

What are the quantum properties of Gravity?

Electroweak Symmetry Breaking and the Phase Transition



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

- We put **by hand** the condition for EWSB
- There is no explanation for how the Higgs mass parameter and self-coupling are determined

What is behind the EWSB mechanism?

Radiative Breaking (like in Supersymmetry) or Compositeness

What was the history of the electroweak phase transition?

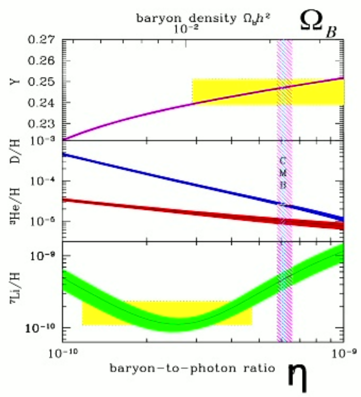
The Higgs discovery is strong evidence that the Higgs field turned on in the early moments of the Big Bang, an *event* we call the Electroweak Phase Transition

We need to understand its dynamics

- Today I will focus on the possibility of generating the matter-antimatter asymmetry of the universe when the Higgs turned on
- This is called **electroweak baryogenesis**

The Mystery of our Asymmetric Universe

Precision Cosmology: information on baryon abundance

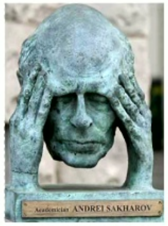


- Abundance of primordial elements
- Predictions from Big Bang Nucleosynthesis
- CMB

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

What generated the small observed baryon-antibaryon asymmetry ?

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 have been proposed that satisfy all 3 Sakharov conditions

➔ Electroweak Baryogenesis: **generation of the baryon asymmetry at the EWPT**

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 SM, because of a quantum anomaly

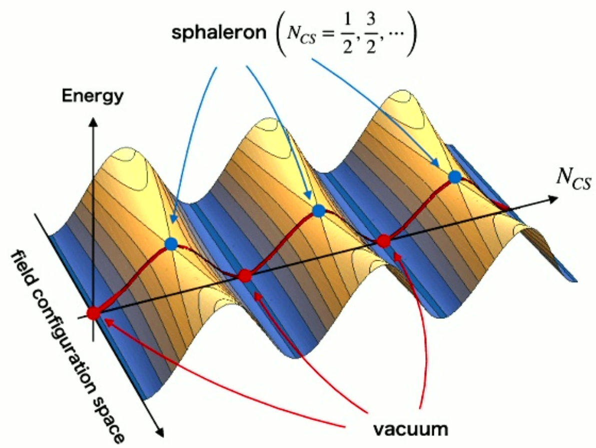
The anomaly is related to a winding number N_{CS} relating degenerate states of the $SU(2)_L$ gauge fields separated by energy barriers

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

J. Cline arXiv:hep-ph: 0609145; M. Shifman Phys. Reports 209 (1991) 341



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

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

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

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.):

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

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

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

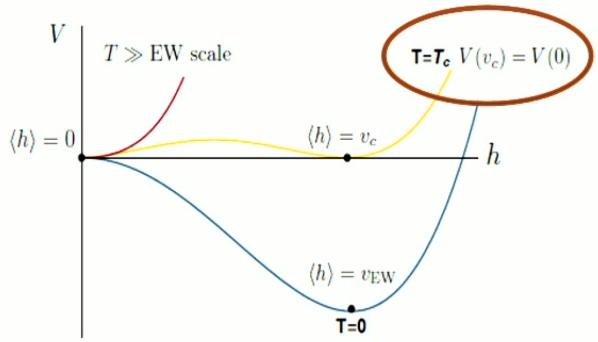
- In the absence of C violation this also implies $\Delta_L = -\Delta_R$, which implies conservation of baryon number

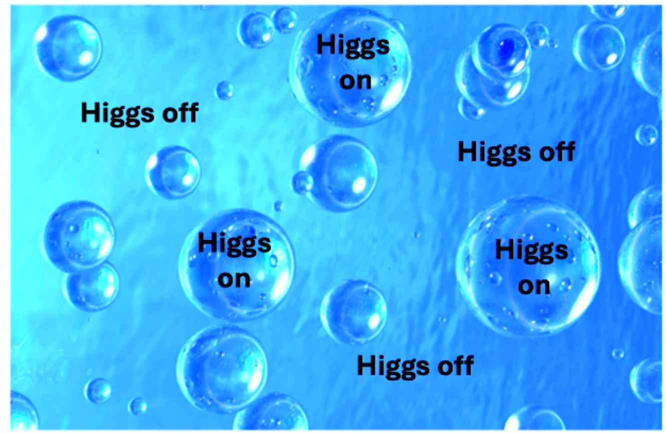
$$\Delta B = n_{u_L} - n_{\bar{u}_L} + n_{u_R} - n_{\bar{u}_R} = 0$$

- 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

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



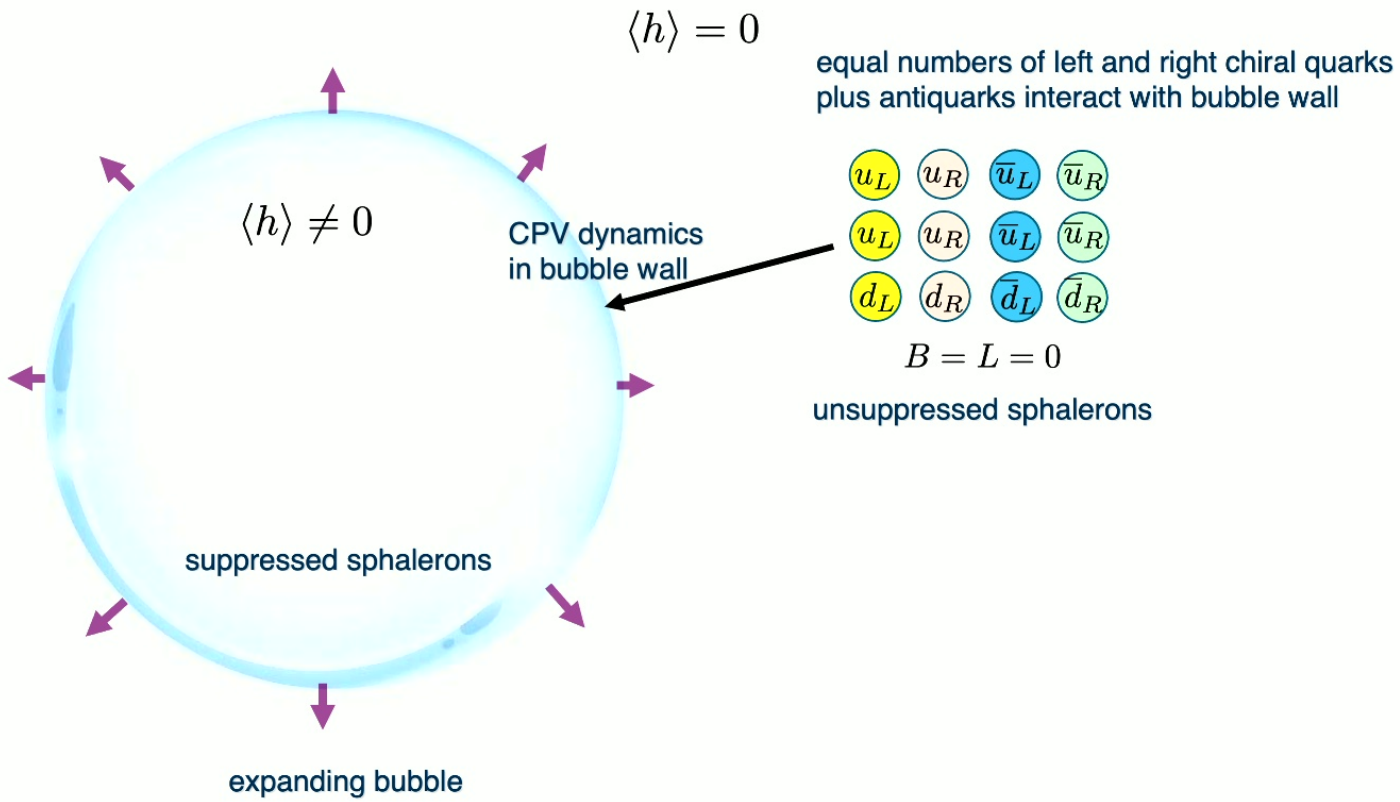


- Bubbles nucleate and expand in the presence of a plasma of SM particles
- Bubble wall moves at near the speed of light, depending on the frictional force the plasma particles exert on it – the precise v_W is relevant for EWBG and GW signals
- Processes near the wall highly out of equilibrium
- The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

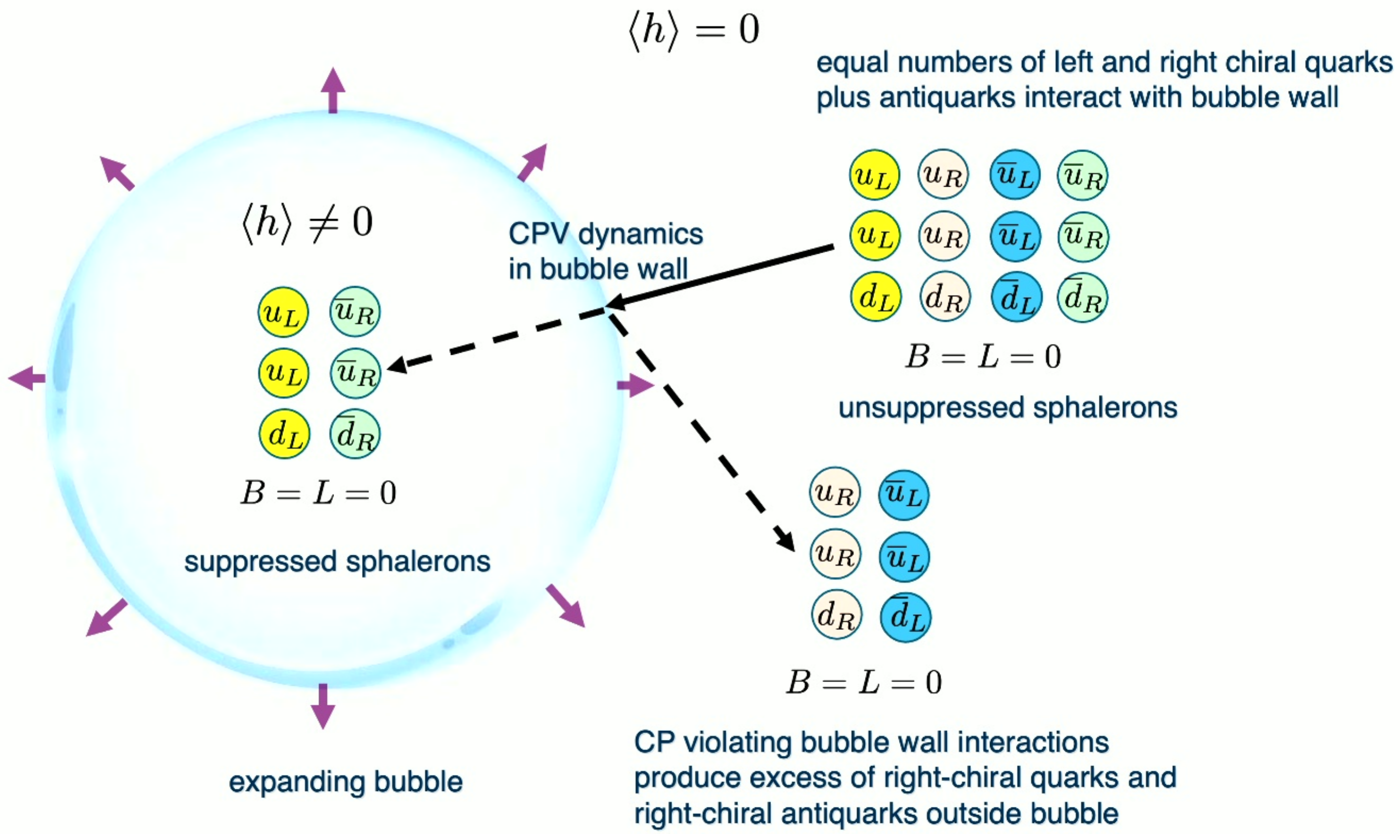
Now let's put all these pieces together to try and get

successful electroweak baryogenesis

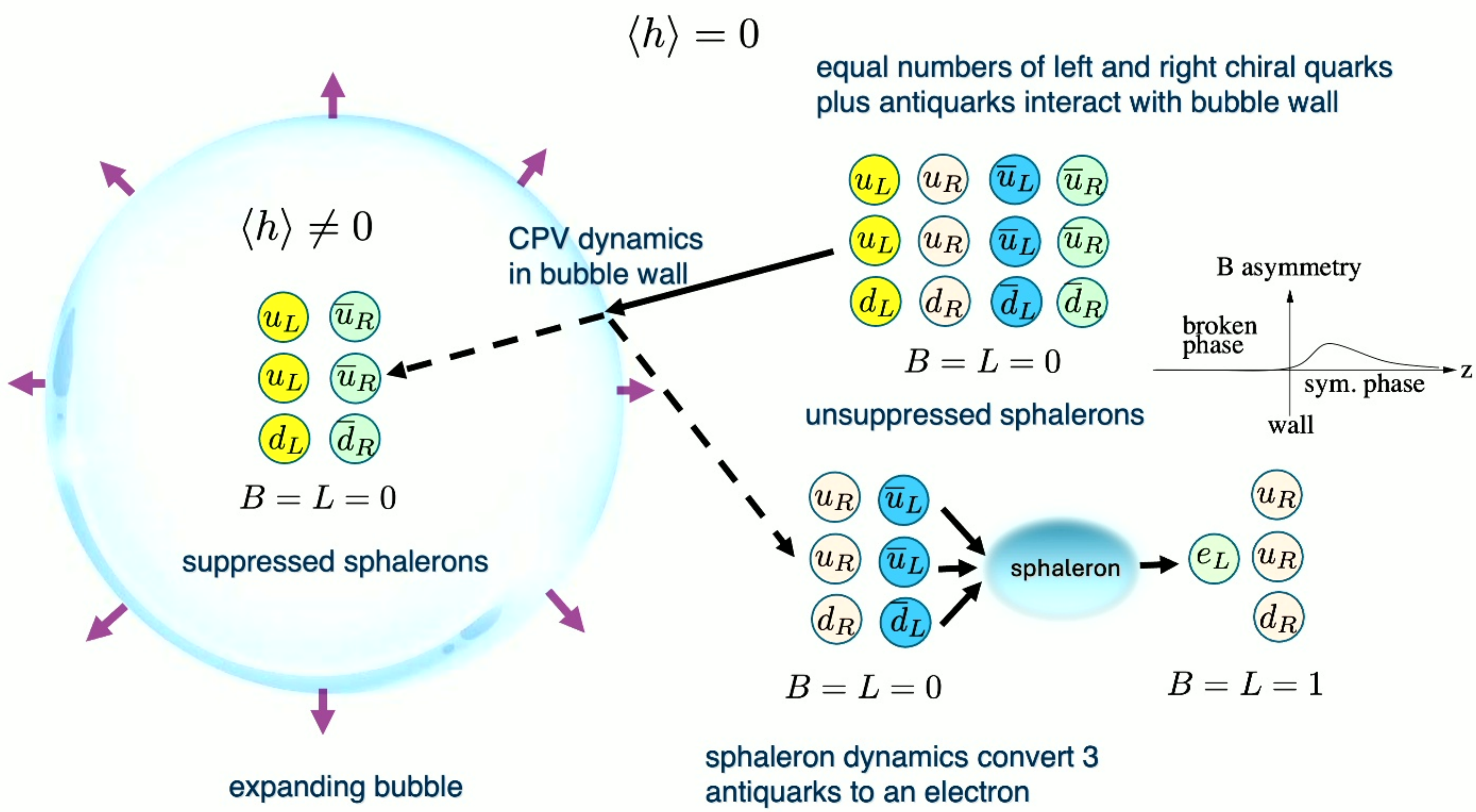
Simple example: single generation of quarks and leptons



Simple example: single generation of quarks and leptons

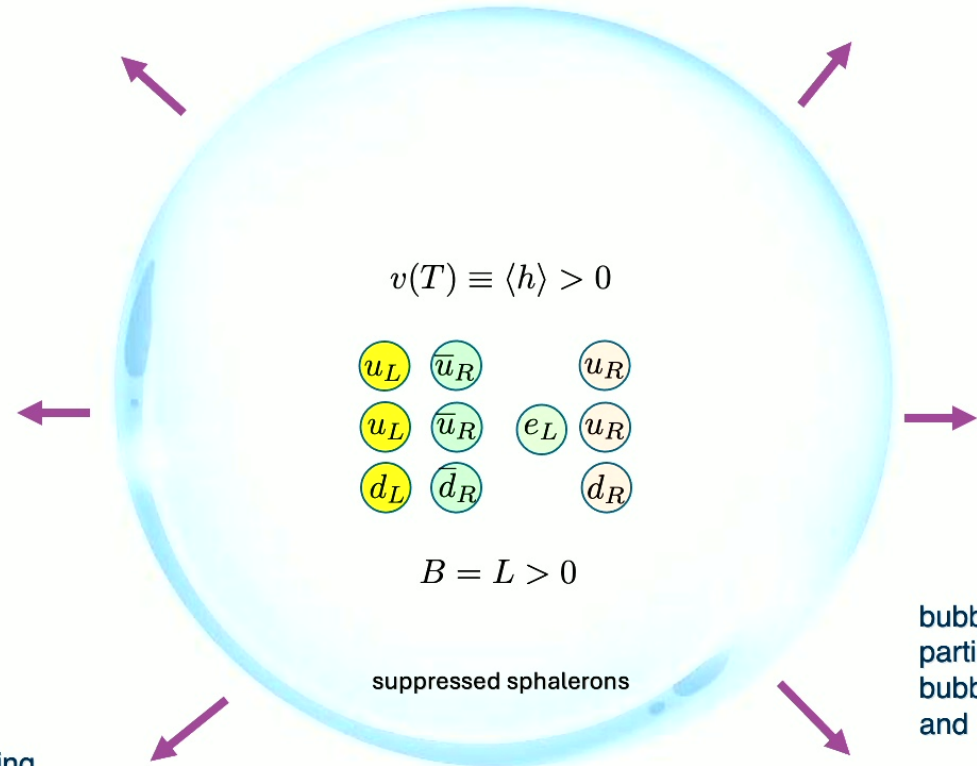


Simple example: single generation of quarks and leptons



Simple example: single generation of quarks and leptons

$\langle h \rangle = 0$



bubble expands to absorb particles outside the bubble wall, leaving net B and L inside the bubble

expanding bubble

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

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

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

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

Can successful electroweak baryogenesis take place in the SM?

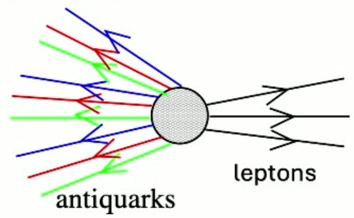
All three Sakharov's conditions can potentially be fulfilled

- 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

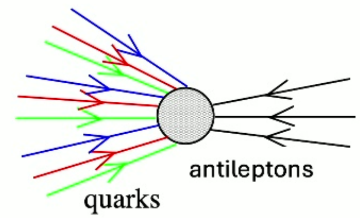
let's look in detail:

CPV induced by Higgs-quark interactions in the bubble wall will produce an excess of antiquarks just outside the bubble

Unsuppressed sphaleron process will produce an excess of B and L



is faster than



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

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

excess of quarks outside the bubble

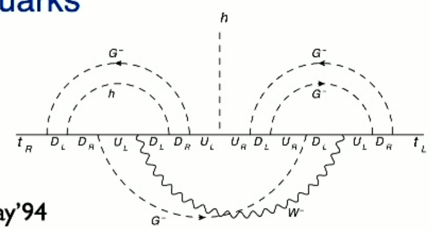
The Higgs boson discovery supports the occurrence of an EW phase transition

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.

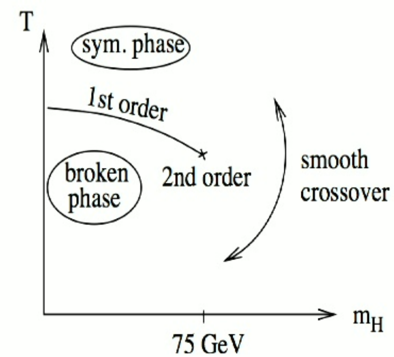
$$V = \mathrm{D}(\mathrm{T}^2 - \mathrm{T}_0^2)\phi^2 - \mathrm{E}_{\mathrm{SM}}\mathrm{T}\phi^3 + \lambda(\mathrm{T})\phi^4$$

Defining T_c and requiring that $<\phi(T_c)> = v(T_c)$ 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

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

Z_2 symmetric: $s \to -s$

- **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

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

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

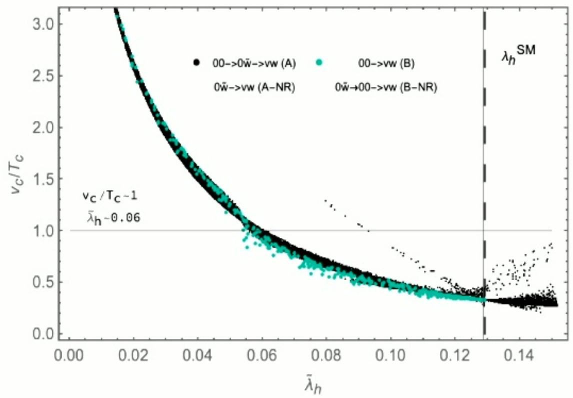
→ Different thermal histories, with 1 or 2 step phase transitions and strong first order EWPT

A Strong first-order Electroweak Phase Transition

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

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

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



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

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

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

- λ_m proportional to $\sin\theta$ (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

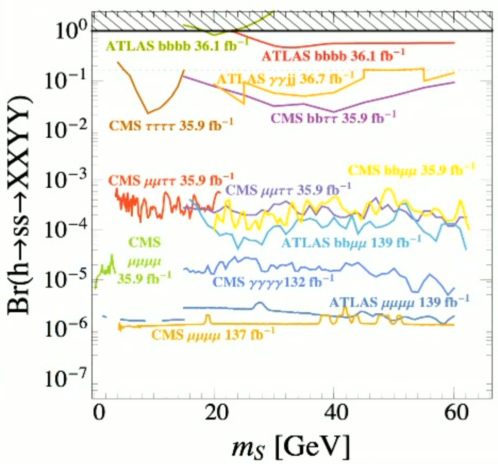
Probing Z_2-breaking Singlet Extensions via Exotic Higgs Decays

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

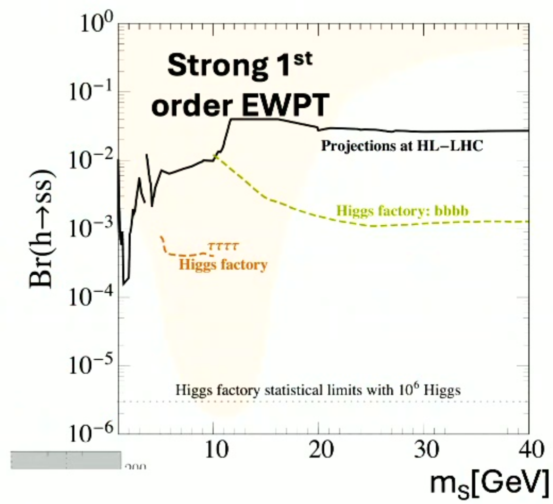
Bounds on exotic Higgs decays

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 projected reach on Br(h → ss) from Br(h → ss → XXYY)



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

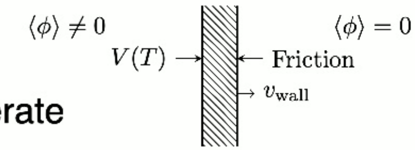
Direct search and Higgs precision measurements can probe large regions of space compatible with a strong 1st order EWPT

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 Dynamics

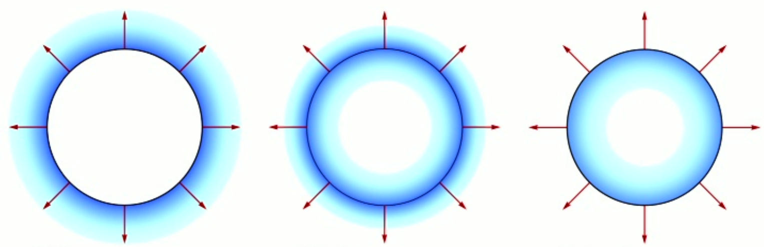


- The potential energy differential drives the bubble wall to accelerate
- This perturbs and hits the plasma, which then exerts a frictional force on the wall
- Once the frictional force balances the driving force, the wall reaches terminal velocity

$$\mathcal{P}_{\text{net}} = \mathcal{P}_{\text{fric}} - \mathcal{P}_{\text{drive}} = 0 \Rightarrow \text{terminal } v_w$$

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

Blue shaded regions indicate non-zero fluid velocity



Deflagration, $v_w < c_s$ | Hybrid, $c_s < v_w < v_J$ | Detonation, $v_J < v_w$

Detonation: Fast-moving bubble wall. Fluid at rest in front of the wall . Rarefaction wave of the perturbed fluid behind the wall.

Deflagration: plasma behind the wall is at rest + a shockwave precedes the wall

Hybrid: both a rarefaction wave behind the wall and a preceding shock wave between the wall and the shock wave front

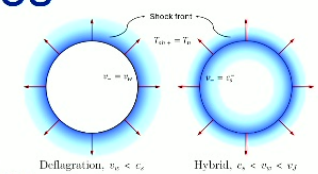
The fluid velocities (v±, defined in the wall frame) and temperatures (T±) on the two sides of the bubble wall are discontinuous, but are related by matching conditions

- Matching derived from energy-momentum conservation of the plasma + scalar system

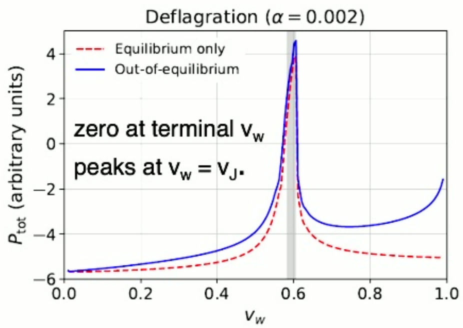
  and from the scalar field EOM $\partial_\mu T^{\mu\nu} = \partial_\mu \left(T_\phi^{\mu\nu} + T_f^{\mu\nu}\right) = 0 \qquad \Box\phi + \partial V_{\text{eff}}/\partial\phi = 0.$

Determining the Terminal Velocity from First Principles

requires knowledge of Nucleation Temperature + Scalar Potential



Deflagration for the Z_2 symmetric real singlet SM



Cline and Laurent, PRD 106, 2022

Local Thermal Equilibrium Approximation

Scalar EOM yields to entropy conservation condition

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

$$\partial_z (s\gamma v) = 0$$

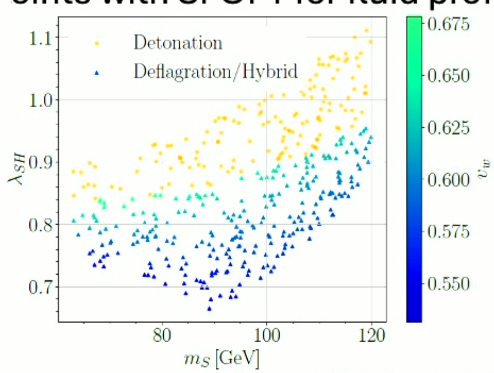
$$\downarrow$$

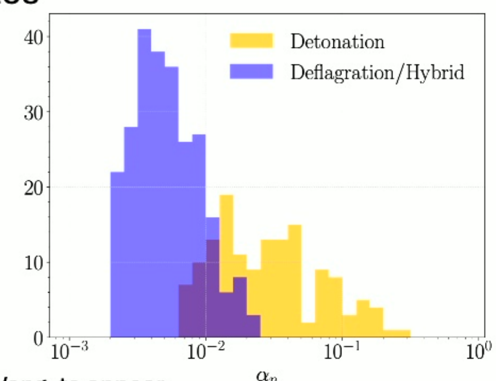
$$s_+\gamma_+ v_+ = s_-\gamma_- v_-$$

Allows to determine v_w in excellent agreement with results from the full pressure analysis

Terminal v_w significantly larger than assumptions in the literature

Points with SFOPT for fluid profiles





MC, Ireland, Ou, Wang, to appear

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

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

Dark CP Violation for EWBG

A new force: a U(1) gauged lepton number

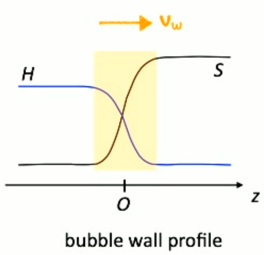
New particles: Z', S, χ (dark matter)

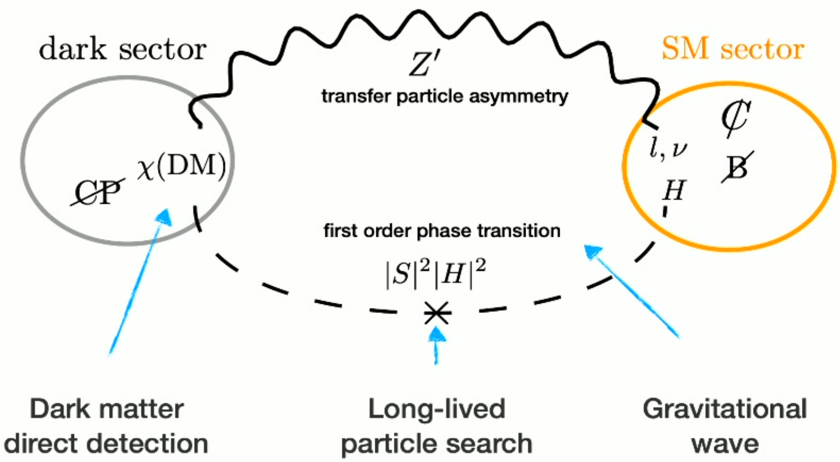
Z' portal to the dark sector

Higgs–Singlet portal to the dark sector

To avoid EDM bounds and still induce the required CP asymmetry:

CP violation comes via a SM gauge singlet
➔ only contributes to electron EDM through higher order quantum effects





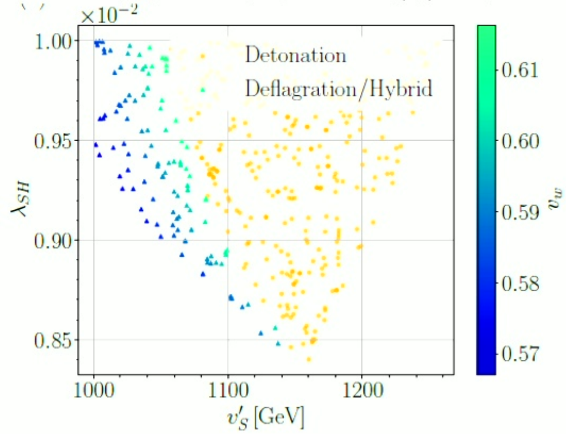
M.C., M. Quiros and Y. Zhang: Phys. Rev. Lett. 122 (2019) 20, 201802; Phys. Rev. D 101 (2020) 5, 055014
M.C., Y-Y. Li, T. Ou and Y. Wang, JHEP 02 (2023) 139

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

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



MC, A. Ireland, Tong Ou, I. Wang, to appear

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

Scalar sector: $\lambda_S,\ \lambda_{SH},\ v'_S \equiv \sqrt{v_S^2 + 2\kappa_S^2/\lambda_S},\ m_s,\ m_a,$

Dark fermion: $m_0,\ |\lambda_c|,\ \theta,$

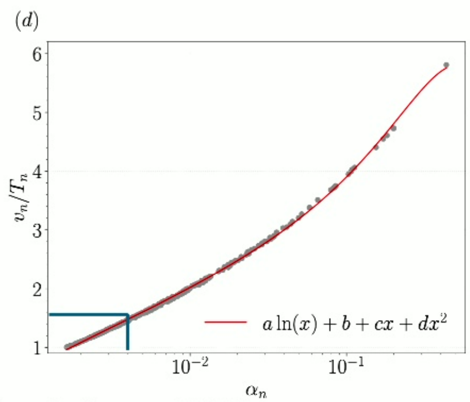
Also $m_a < m_h/2,\ m_s > m_h/2,\ m_0 > m_{a,s},$ and $\lambda_{SH} \lesssim 0.01,$

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

Histogram of α_n – strength of the phase transition in GW signals detonation vs deflagration/hybrid.

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

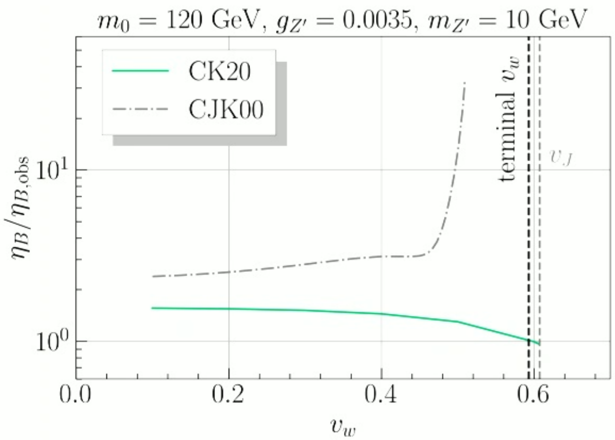
Important correlation between v_n/T_n and α_n



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

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, $\bar{\chi}_L$ & their charged conjugates scatter off the bubble wall at different rates, creating a chiral asymmetry
- To transfer this 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, to appear

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 CJK00, 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

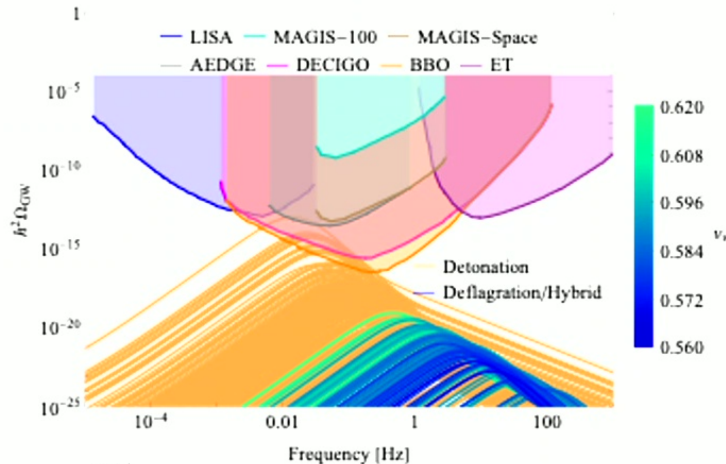
- Inverse time duration of the Phase transition $\beta/\mathrm{H} \approx \mathrm{T}\frac{\mathrm{d}(\mathrm{S_3/T})}{\mathrm{dT}}|_{\mathrm{T=Tn}}$
- Wall velocity v_w
- Strength of GW signature from the PT $\alpha_n = \left.\frac{\Delta V_{\rm eff} - \frac{T}{4}\frac{\partial \Delta V_{\rm eff}}{\partial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

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

Need to compute v_W from the fluid-scalar eqs. as a function of the model parameters



Fitted from numerical simulations

$$\Omega_{\rm sw}h^2 = 2.65\times 10^{-6} H\tau_{\rm sw}\left(\frac{\beta}{H}\right)^{-1}\left(\frac{\kappa_{\rm sw}\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{1/3} v_w \left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = 1.9\times 10^{-5}{\rm Hz}\frac{1}{v_w}\left(\frac{\beta}{H}\right)\left(\frac{T_n}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

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

Results for the CPV Dark model as a function of v_w

MC, A. Ireland, Tong Ou, I. Wang, to appear

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

Investigating possible EWBG for supersonic wall velocities – detonation profiles -

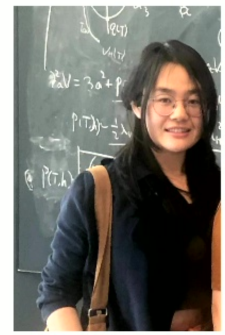
Quantum simulation formalism applied to real-time wave packet evolution to compute transmission and reflection dynamics at the bubble wall.
Real-Time Simulation of Asymmetry Generation in Fermion-Bubble Collisions
MC, Ying Ying Li, Tong Ou and Hersh Singh 2412.10365 [hep-ph]

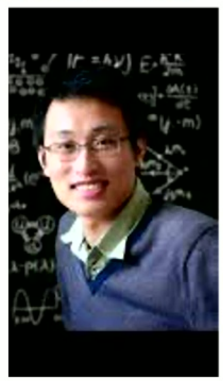
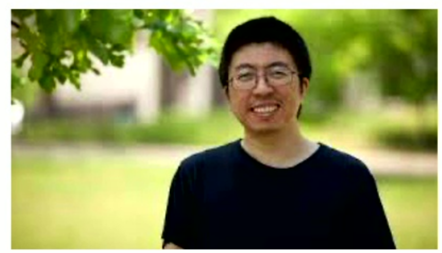
Thank you to
my amazing collaborators!!









Thank You !