Dynamics of a two-step Electroweak Phase Transition

in Collaboration with
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Michael J. Ramsey-Musolf
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MAX-PLANCK-GESELLSCHAFT

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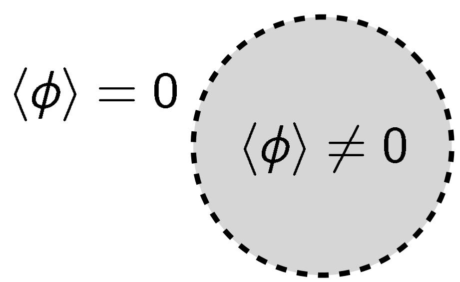
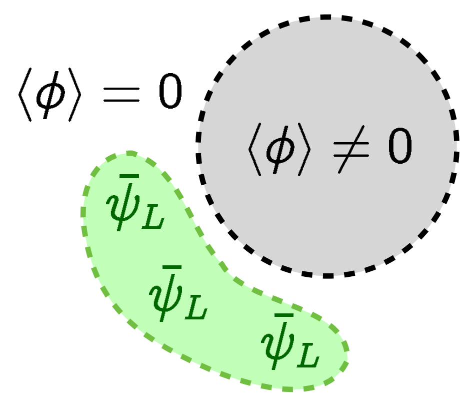
Electroweak Baryogenesis
and
Sakharov's Criteria

$\cancel{e^{-\beta \hat{H}}}$ First order electroweak phase transition

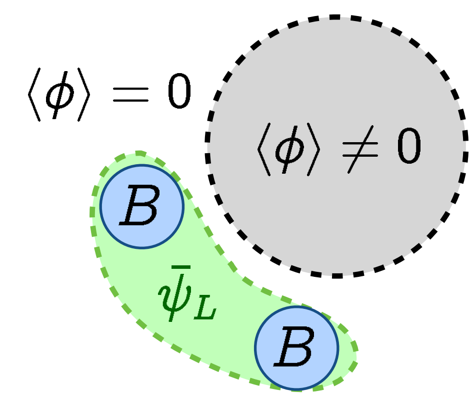


via bubble nucleation

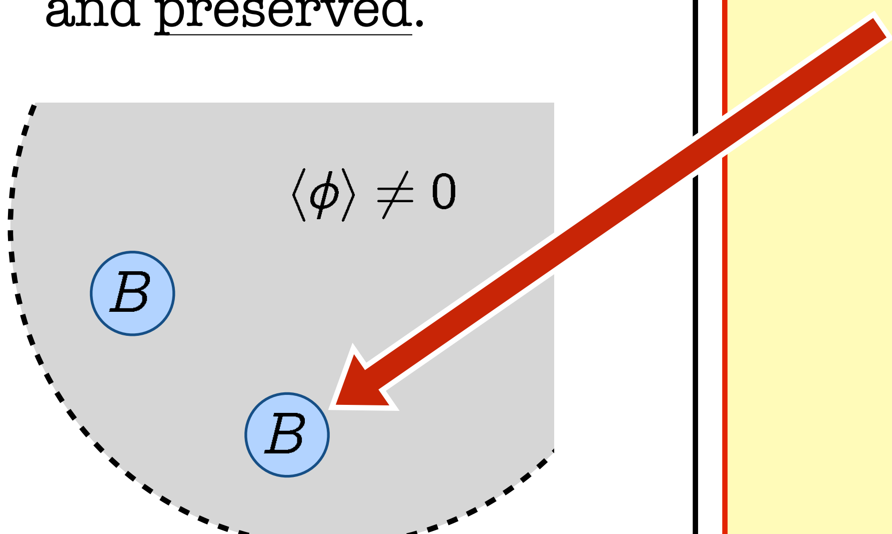
$\cancel{C, CP}$ Generation of particle/antiparticle asymmetry



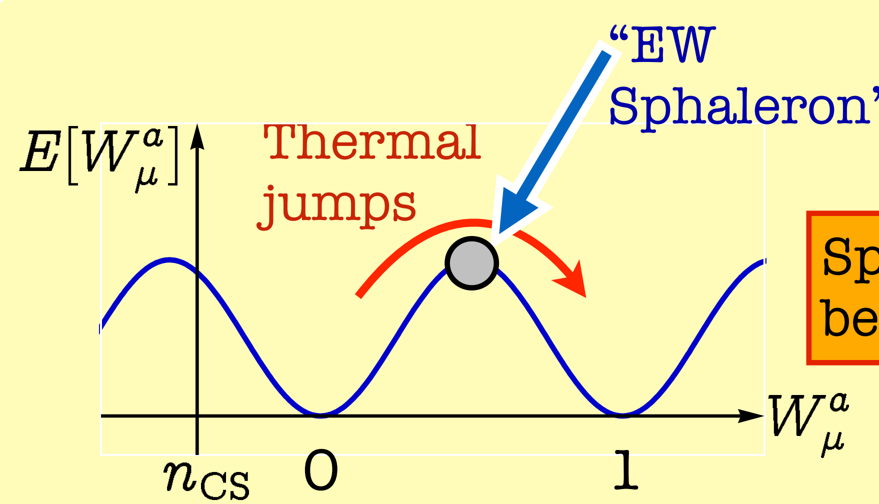
$\cancel{B}$ Generation of baryon asymmetry



baryons captured, and preserved.



B+L-violating EW Sphalerons convert baryons back to anti-leptons.



Sphaleron proc. must be quenched!

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Electroweak Baryogenesis

Kinetic theory: sphaleron rate related to its mass (energy)

$$\Gamma_{\text{sph.}} \sim (gT)^4 e^{-E_{\text{sph}}/T}$$

Sphaleron mass dependent on Higgs field value inside bubble

$$E_{\text{sph}} \sim 4\pi\langle\phi\rangle/g$$

At phase transition, need ratio to be large.

$$\frac{\langle\phi\rangle}{T_c} \gtrsim 1$$

Baryon number preservation criterion on strength of phase transition.

This talk (outline):
set C, CP-violation aside

1. New Strategy to strengthen phase transition

   Two-step phase transition

   H.Patel, M.J. Ramsey-Musolf, PRD 88 (2013), 035013

   Connection to colliders

   P. Fileviez Pérez, H.Patel, M.J. Ramsey-Musolf, K. Wang. PRD 79 (2009), 055024

2. Gauge dependence

   Problem:
   This is gauge dependent

   H.Patel, M.J. Ramsey-Musolf, JHEP 1107 (2011), 029

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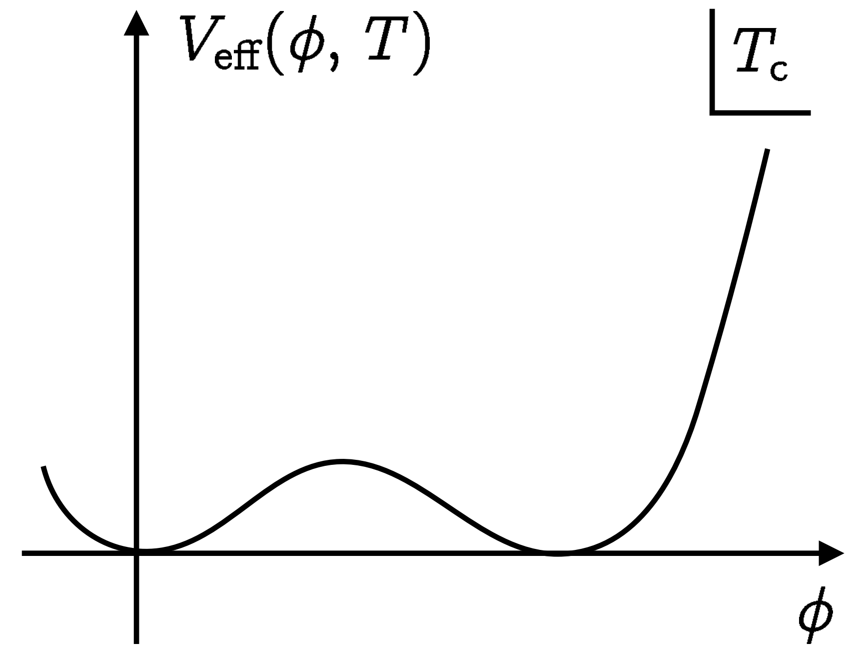
Previous Strategies
(to strengthen phase transition)

Central quantity of interest: Effective Potential

$$V_{\text{eff}}(\phi,\, T) = D(T^2 - {T_0}^2)\,\phi^2 - E(\xi) T\,\phi^3 + \frac{\bar{\lambda}}{4}\,\phi^4 + \ldots$$

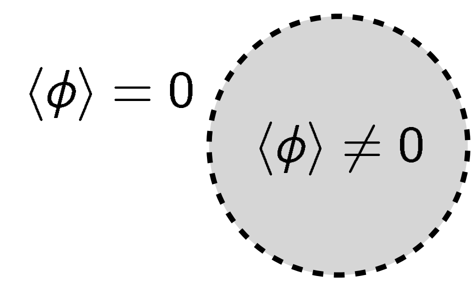


Condition from requiring quenched sphalerons:

$$1 \lesssim \frac{\langle\phi\rangle(\xi)}{T_c} = \frac{2E(\xi)}{\bar{\lambda}}$$

related to model parameters

Tune **parameters**, or **add new fields** (DoF) to model to:



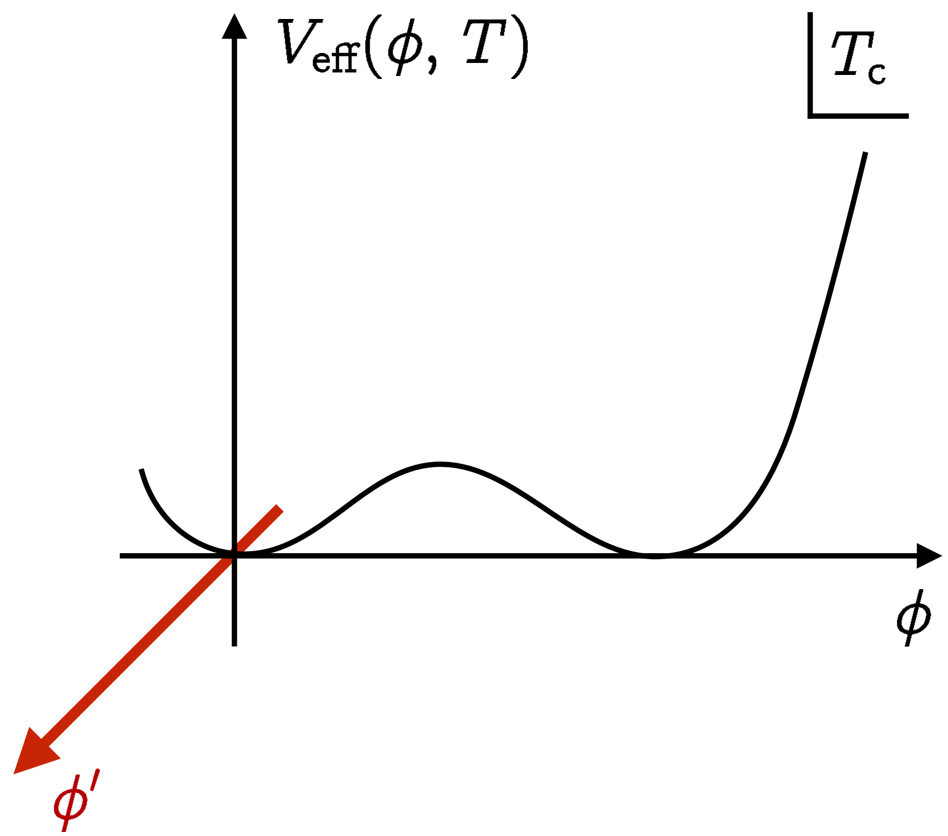
Make $E(\xi)$ bigger.

Make $\bar{\lambda}$ smaller.

In general, very difficult.

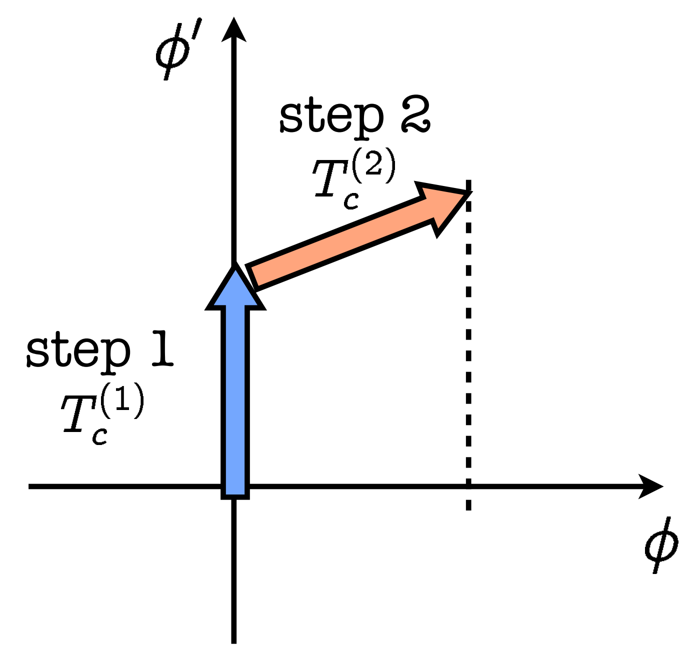
Previous Strategies
(to strengthen phase transition)

Extend model with extra scalar degrees of freedom.



Effective potential a function of multiple order parameters.

In regions of parameter space, structure of free energy is such that there could be a multi-step phase transition.



If extra degrees of freedom are SM-gauge singlets, EW sphaleron not affected in essential way,

Condition on phase transition strength

$$\frac{\langle \phi \rangle}{T_c{}^{(2)}} \gtrsim 1$$

Applied only on final step.

If extra scalar degrees of freedom carry gauge quantum numbers,

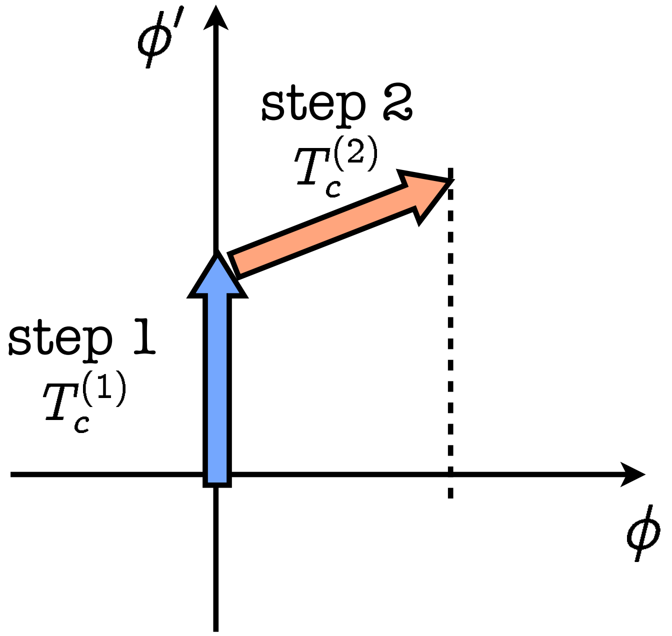
Sphalerons would couple to scalar field, phase transitions induced by these could influence them.

(model-builder's POV)

In this setup, it may be easier to generate a strong first order phase transition at step 1.

underlying parameters controlling this step are largely unconstrained.

(but possibly measured at LHC)



ΣSM – Formulation

P. Fileviez Pérez, H.Patel,
M.J. Ramsey-Musolf, K. Wang.
PRD 79 (2009), 055024

Scalar Field Content:

Higgs doublet

$$H \equiv (1, \mathbf{2}, \tfrac{1}{2}) = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(H^0 + i\phi^0) \end{pmatrix}$$

SU(2) real triplet

$$\Sigma = (1, \mathbf{3}, 0) = \vec{T} \cdot \vec{\Sigma} = \frac{1}{2} \begin{pmatrix} \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -\Sigma^0 \end{pmatrix}$$

Couplings: (renormalizable)

Fermiophobic – incompatible hypercharge

Gauge-couplings: couples to W, Z and EM field

Scalar potential:

Standard model

new particle
mass + self coupling

Higgs portal interaction

$$V(H, \Sigma) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^4 \boxed{-\frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2} \boxed{+a_1 H^\dagger \vec{\Sigma} H + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2}$$

Four unmeasured
parameters μ_Σ^2, b_4, a_1, a_2

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Phenomenological Constraints

In general, potential permits VEVs for both Σ and H.

Triplet VEV contributes to W mass (but not Z)

$$\mathcal{L}_{\text{kin.}} = (D_\mu H)^\dagger (D^\mu H) + \text{Tr}(D_\mu \Sigma)^2$$

$$\longrightarrow \quad \underbrace{\frac{g^2}{4}(v^2 + \boxed{4\langle\Sigma\rangle^2})}_{\text{W mass}} W^+_\mu W^{\mu-} + \underbrace{\frac{1}{2}\frac{v^2}{4}(g^2 + g'^2)}_{\text{Z mass}} Z_\mu Z^\mu$$

SM relation: weak charged and neutral current rates upset

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos\theta_{\rm w}} \quad \overset{\text{SM (L.O.)}}{=1} \quad \overset{\Sigma\text{SM}}{\longrightarrow 1 + \boxed{\frac{4\langle\Sigma\rangle}{v^2}}}$$

Experimentally, SM relation satisfied to high prec.

$$\rho_{\rm exp} = \delta_{\rm SM} + \delta\rho \qquad \delta\rho = 0.0004^{+0.0003}_{-0.0004}$$

(95% conf.)

Translates to bound:
$\langle\Sigma\rangle \leq 3$ GeV

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Easy and natural explanation of smallness:

$\langle\Sigma\rangle$ depends linearly on a_1 (for small values):

$\langle\Sigma\rangle \sim \mathcal{O}(a_1) \quad \Rightarrow$ a_1 is $\mathcal{O}(3\text{ GeV})$ (1% EW scale)

Technically natural, but make simplifying assumption: $a_1 = 0$

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^4 \boxed{-\frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2} \boxed{\cancel{+a_1 H^\dagger \vec{\Sigma} H} + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2}$$

Three unmeasured parameters $\mu_\Sigma^2,\ b_4,\ \cancel{a_1},\ a_2$

Potential is now SO(3) symmetric and has Z_2 symmetry: $\vec{\Sigma} \to -\vec{\Sigma}$

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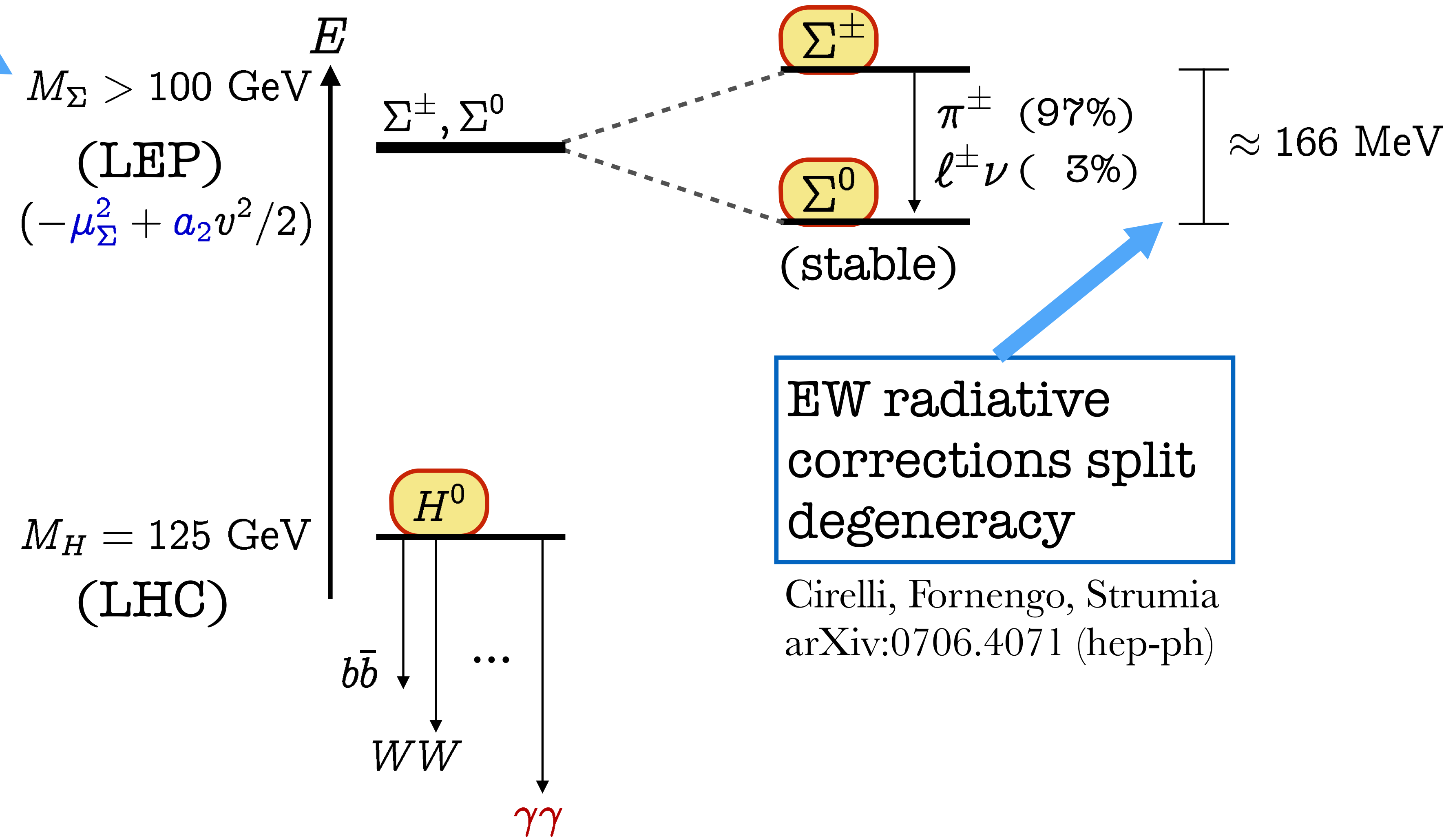
Particle Spectrum

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^4 - \frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2 + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2$$

Three new scalar states

$J^P = 0^+$



Fix $a_1 = 0 \quad \Rightarrow \langle \Sigma \rangle = 0$

$\Rightarrow$ no H^0 / Σ^0 mixing

EW radiative corrections split degeneracy

Cirelli, Fornengo, Strumia
arXiv:0706.4071 (hep-ph)

$\Sigma^\pm$ long-lived ($c\tau \sim 6$ cm)

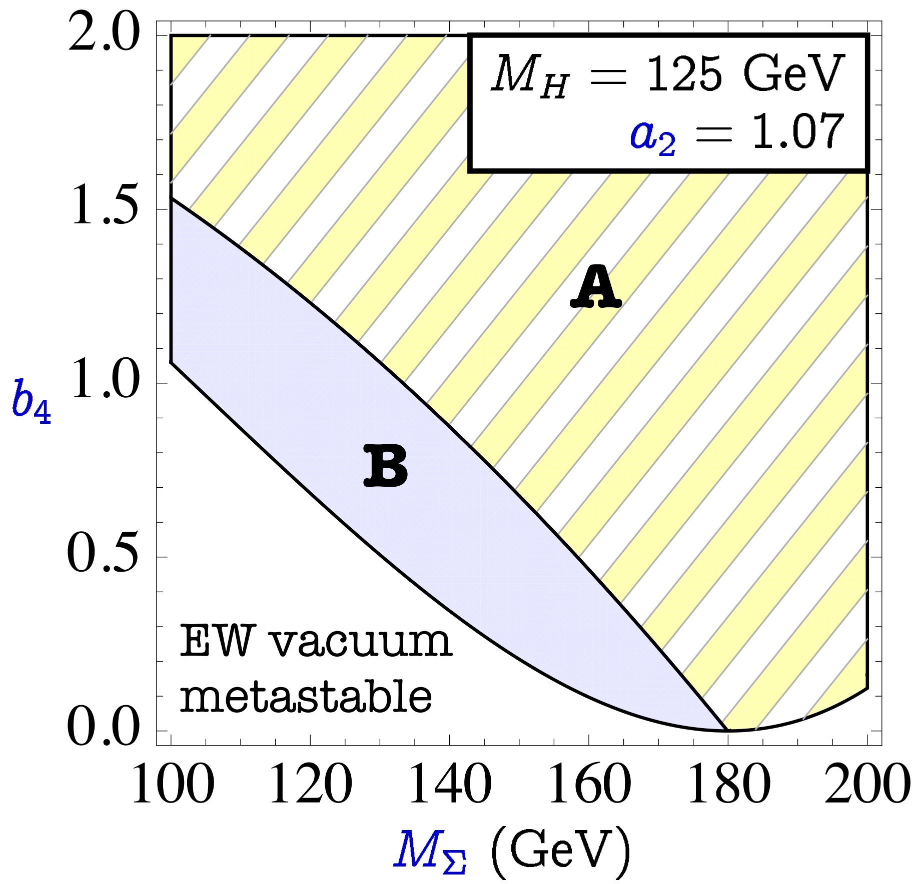
Σ^0 is stable DM cand

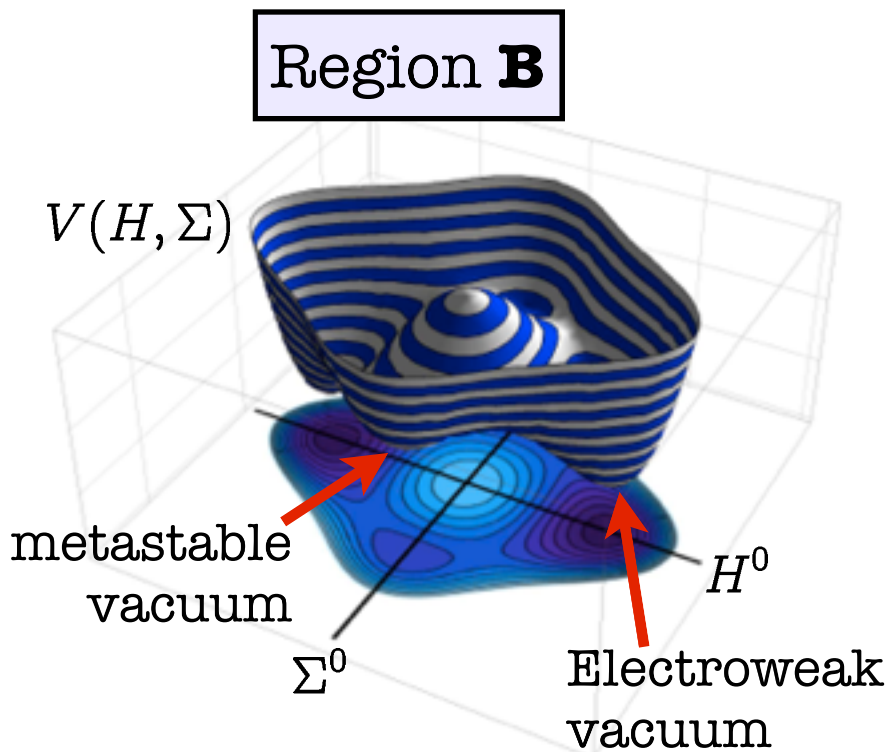
Modified $\Gamma(H^0 \to \gamma\gamma)$ mode

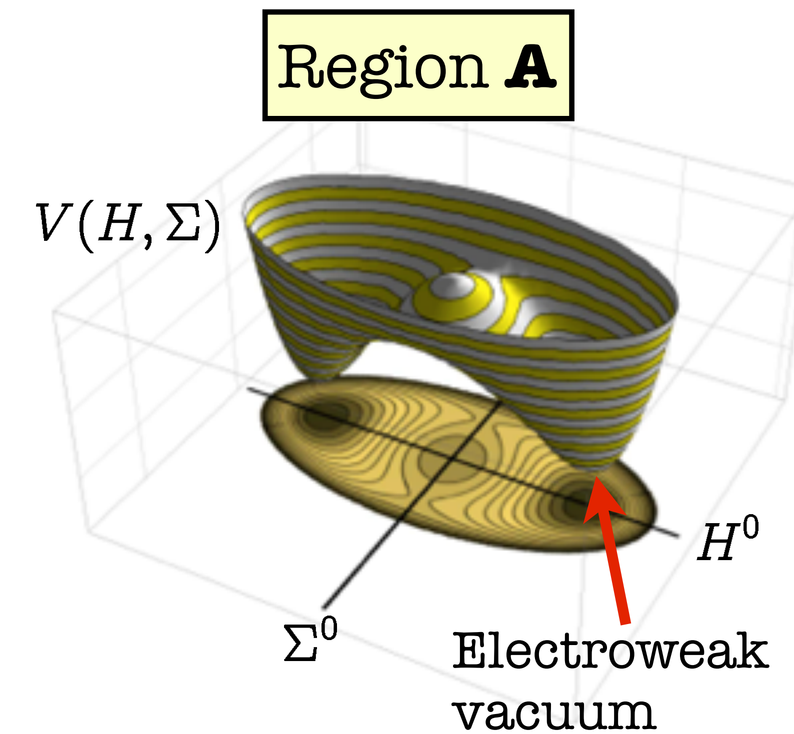
Zero-temperature Vacuum Structure

H.Patel, M.J. Ramsey-Musolf,
PRD 88 (2013), 035013

Pattern of phase transition influenced by zero-T vacuum structure

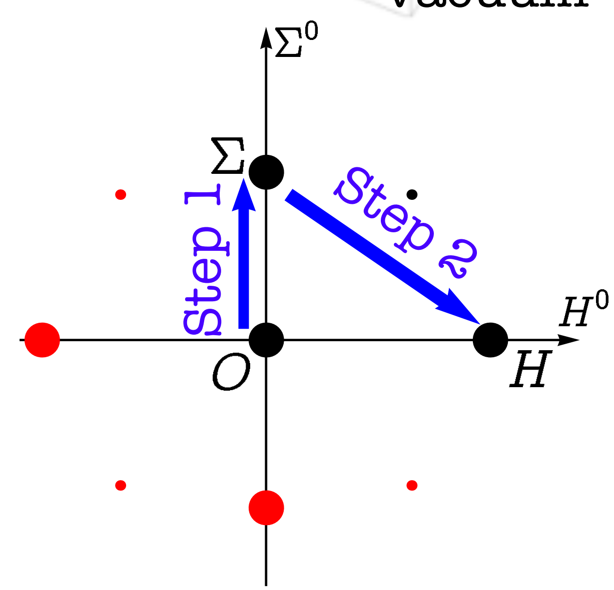


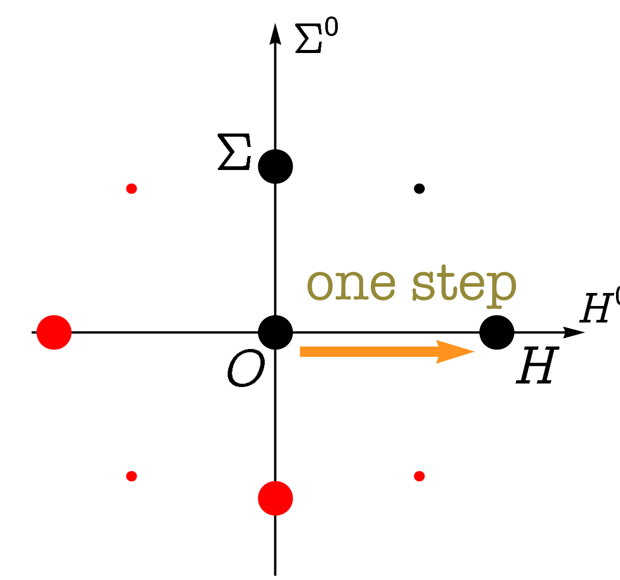




model potential

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^4$$
$$-\frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2 + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2$$





Finite temperature:

Baryon asymmetry generation in first step

O : $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
Σ : $\mathrm{U}(1)_L \times \mathrm{U}(1)_Y$
H : $\mathrm{U}(1)_{em}$

O : $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
H : $\mathrm{U}(1)_{em}$

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’t Hooft—Polyakov Monopoles

Peculiar feature: Sigma phase resembles Glashow-Salam model of EW interactions (no weak-neutral currents)

’t Hooft and Polyakov showed stable **magnetic monopole solution**.

=> early universe populated by monopoles

=> subsequently wiped out after 2nd phase transition to EW phase.

Rubakov effect: scattering with Fermions **violates B+L exactly like sphalerons**.

In addition to sphaleron processes, monopoles would also wipeout baryon asymmetry

But to what extent?

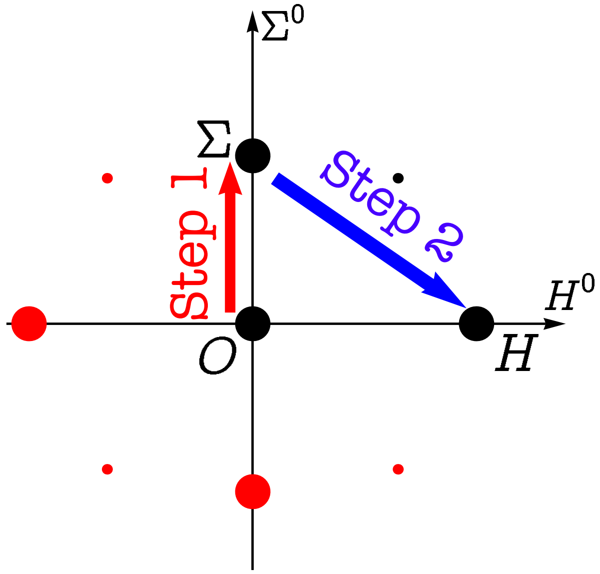
Depends on monopole concentration:

1. Kibble mechanism
2. Thermal production (**Dominant**)
   (monopole-antimonopole pair-production)

$$\left(\text{equil. monopole} \atop \text{number density}\right) \sim e^{-m_M(T)/T}$$

Bigger $\langle\Sigma\rangle \Rightarrow$ Higher mass $\Rightarrow$ Lower concentration

Baryon preservation



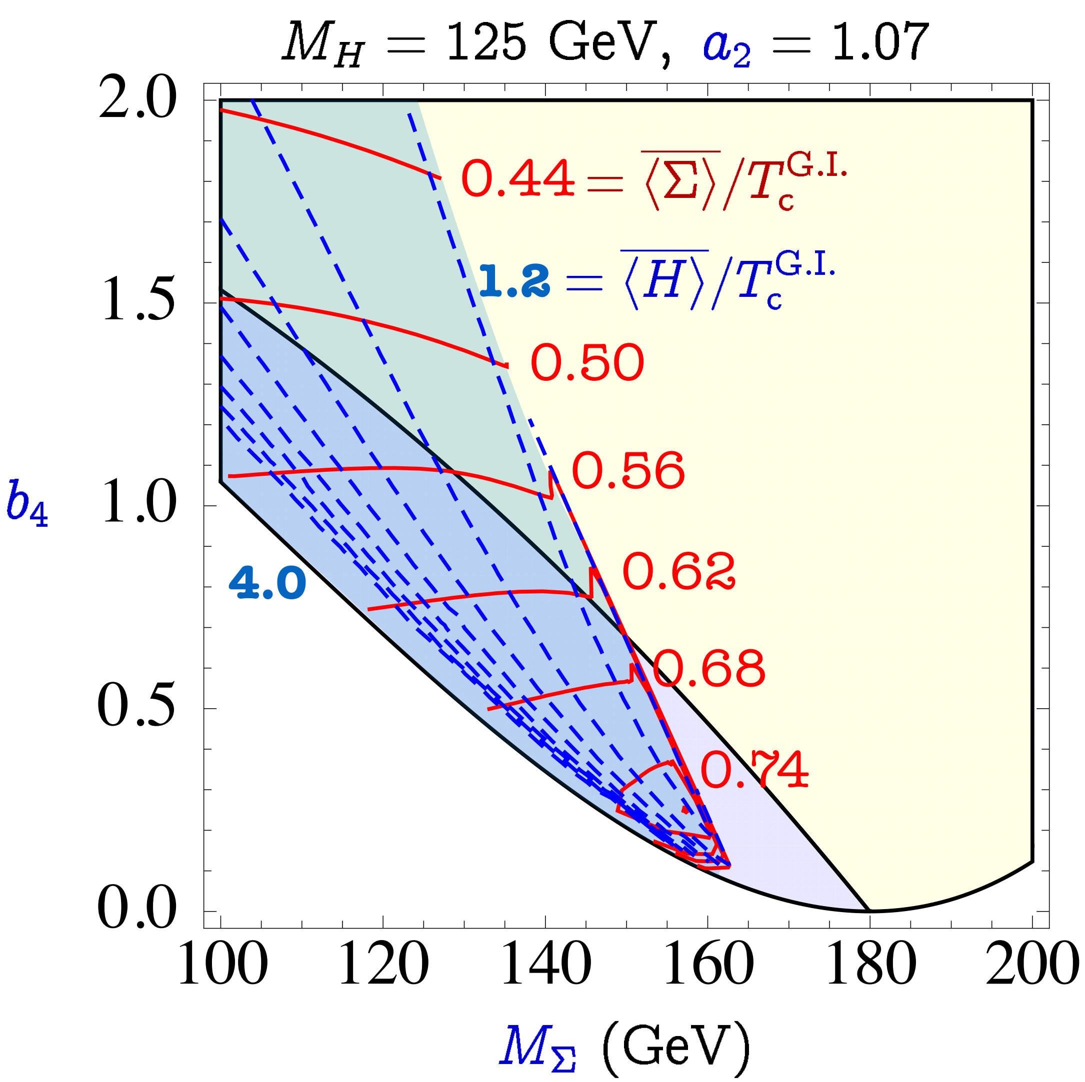
model potential

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^4 - \frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2 + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2$$

Step 1: $\vec{\Sigma}$ couples to W, Z fields:

- Sphalerons rates suppressed
- Monopole density suppressed

stronger Step 1 $\Rightarrow$ greater suppression



Qualitatively: (gauge-dep) Step 1

$$V_{\text{eff}}(\phi, T) = D(T^2 - T_0{}^2)\,\phi^2 - E\,T\,\phi^3 + \frac{b_4}{4}\phi^4 + \dots$$

Smaller b_4 leads to stronger transition:

$$\frac{\langle\Sigma\rangle}{T_c} = \frac{2E}{b_4}$$

Step 2: H couples to W, Z fields:

- SM EW Klinkhamer-Manton Sphalerons rates suppressed

always **sufficiently** strong

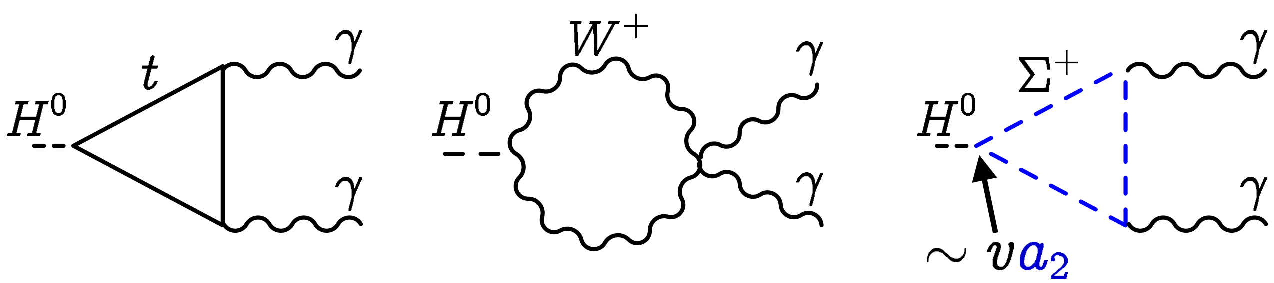
Modified Higgs Decay

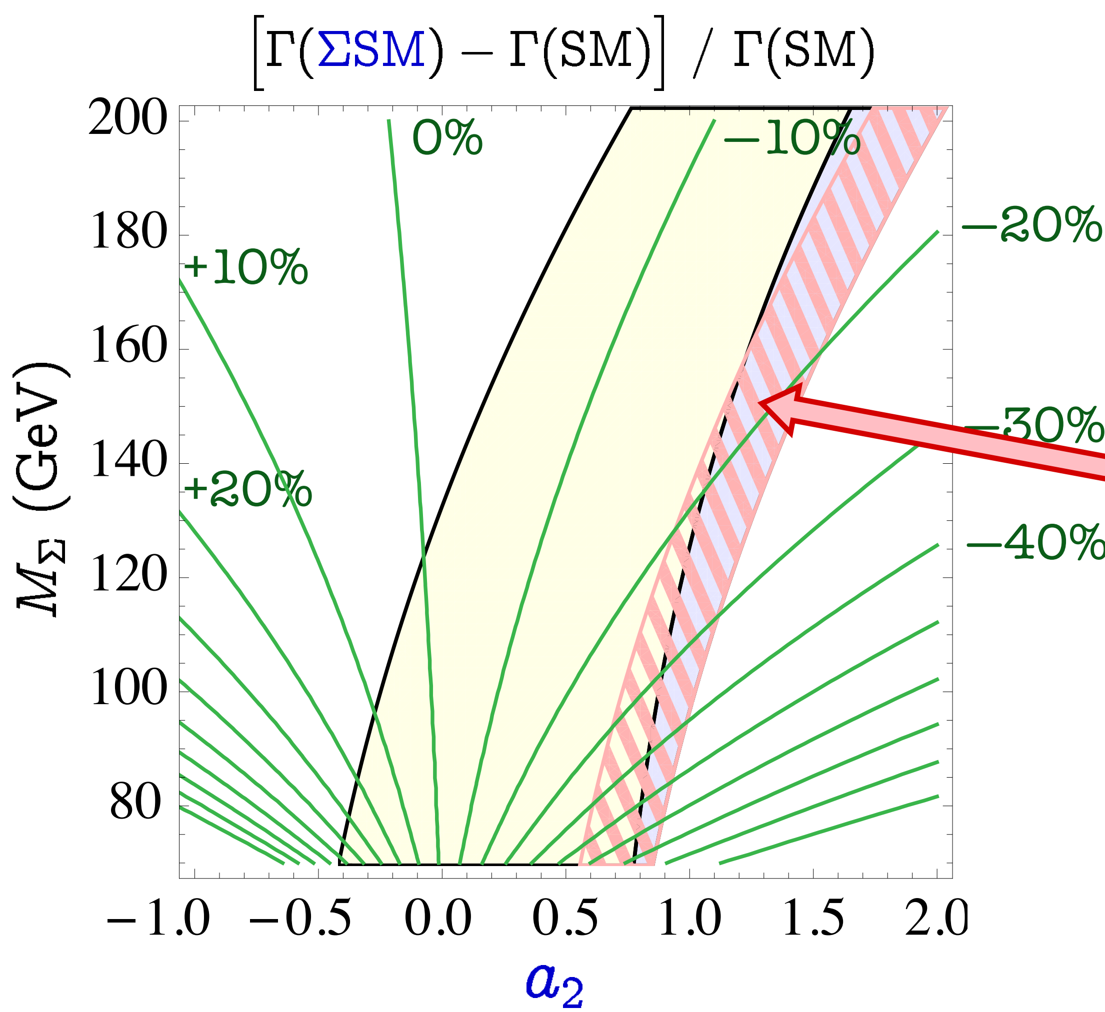
Currently, most sensitive to $\Gamma(H^0 \to \gamma\gamma)$

Higgs-portal coupling a_2 adds new contribution to amplitude

model potential

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^4$$
$$-\frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2 + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2$$





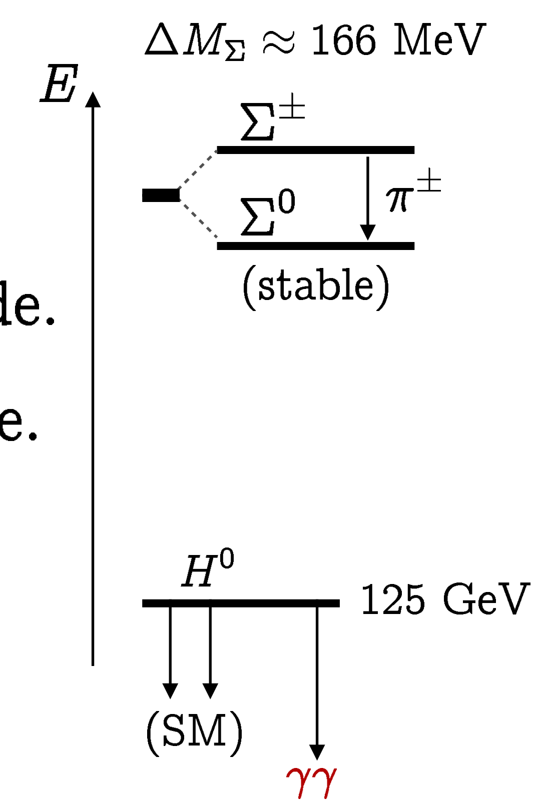
Positive a_2 suppresses $\gamma\gamma$ mode.

Negative a_2 enhances $\gamma\gamma$ mode.

(b_4 indep.)

Two-step EWPT occurs for positive a_2.

$J^P = 0^+$



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Modified Higg

Currently, most sensitive to $\Gamma(H^0 \to \gamma\gamma)$

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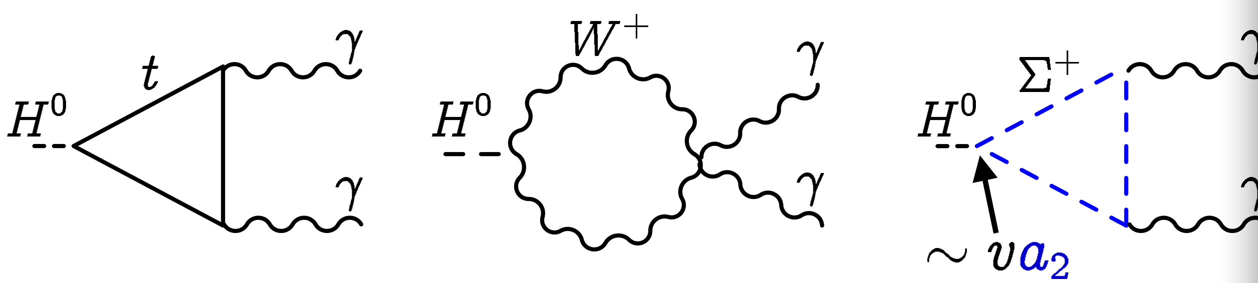
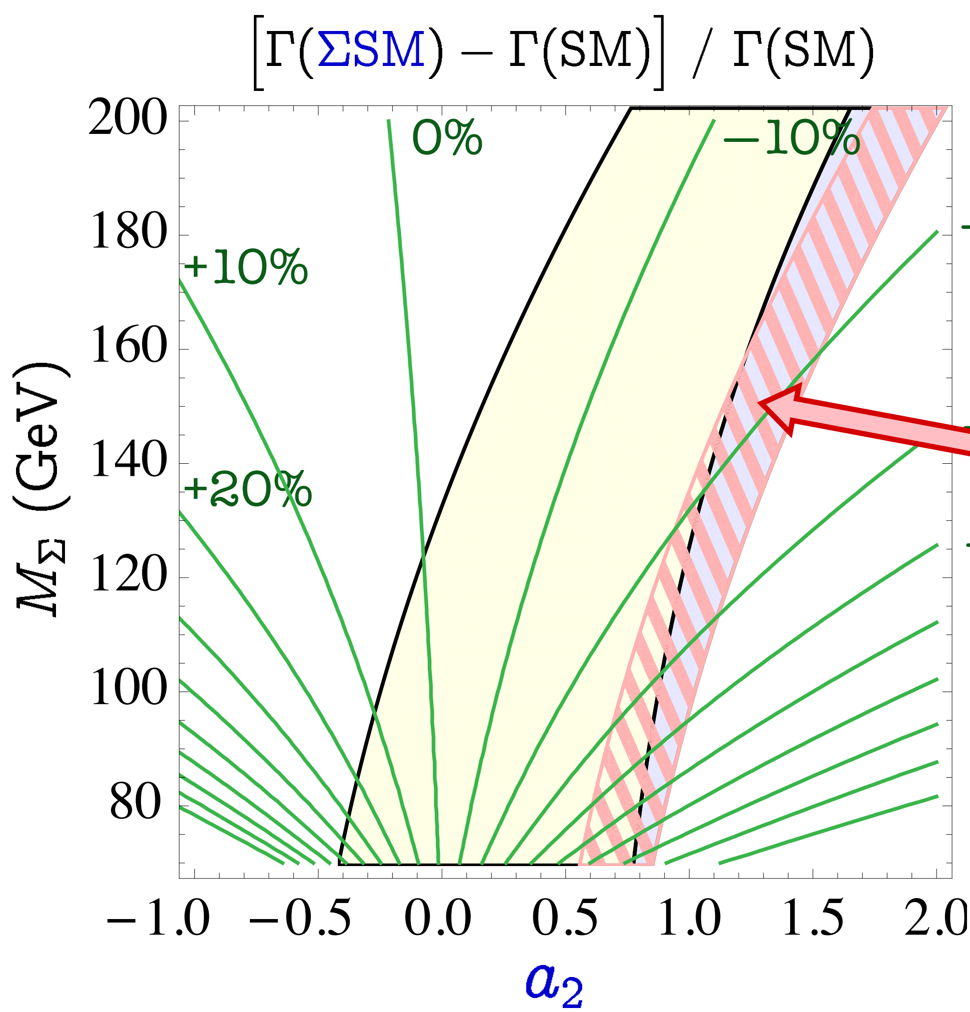




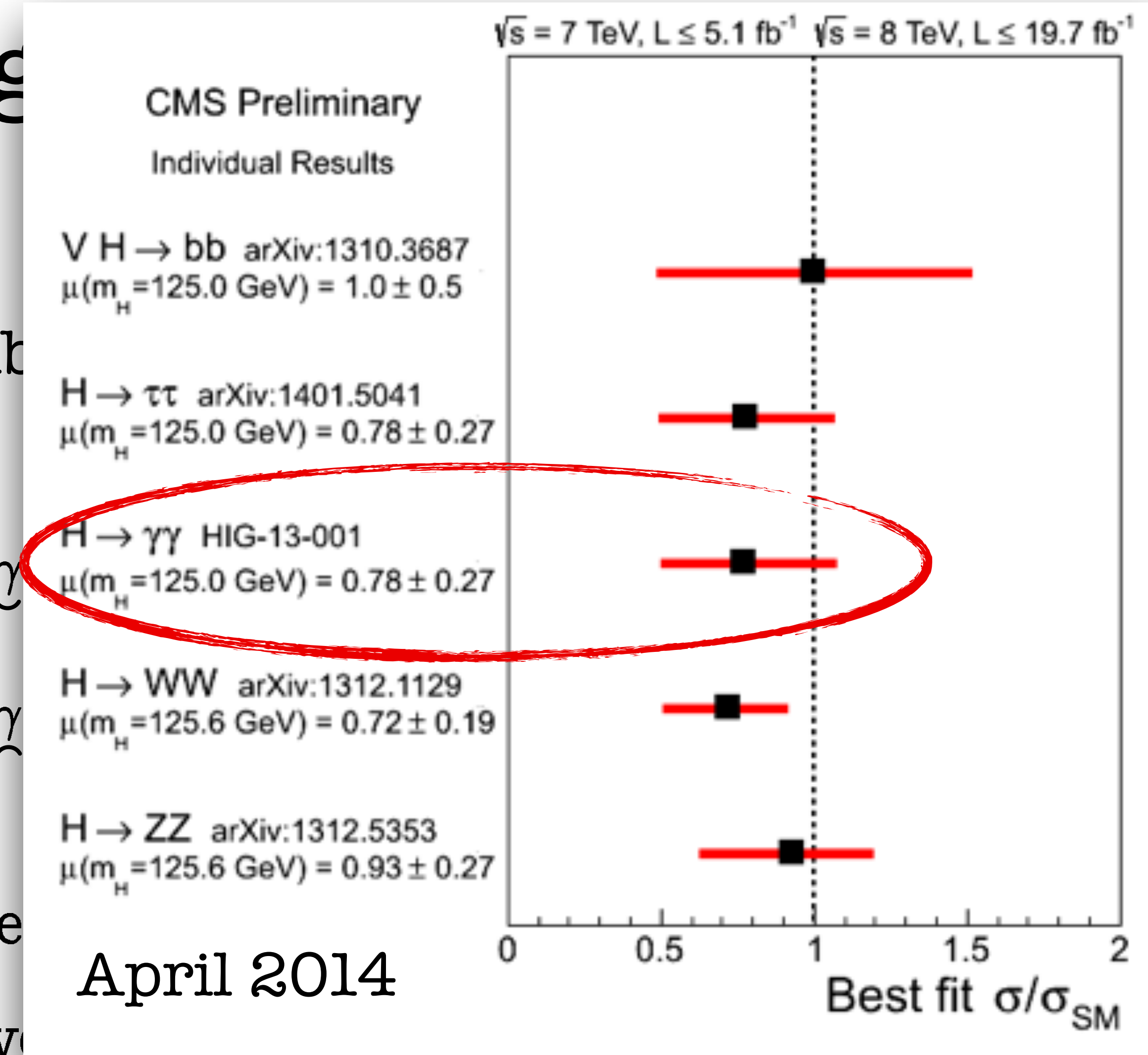
Positive

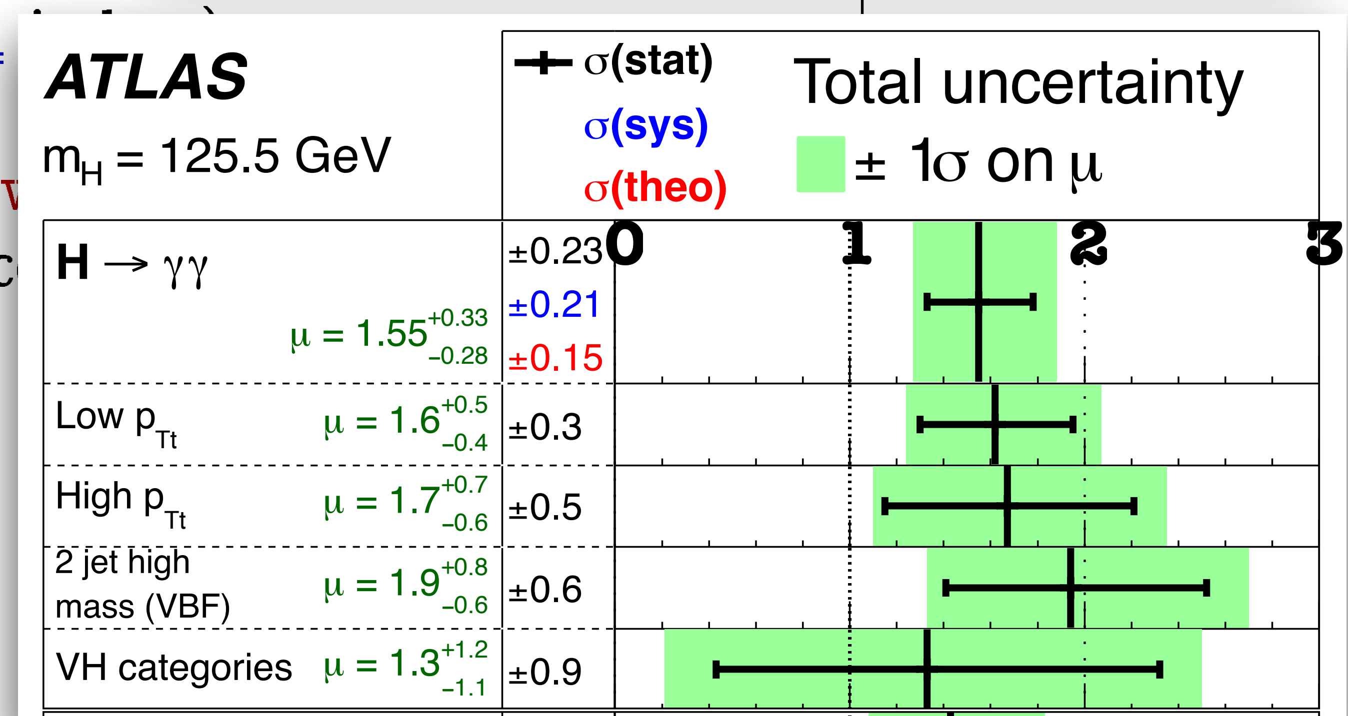
Negativ

(b_4

Tw

oc





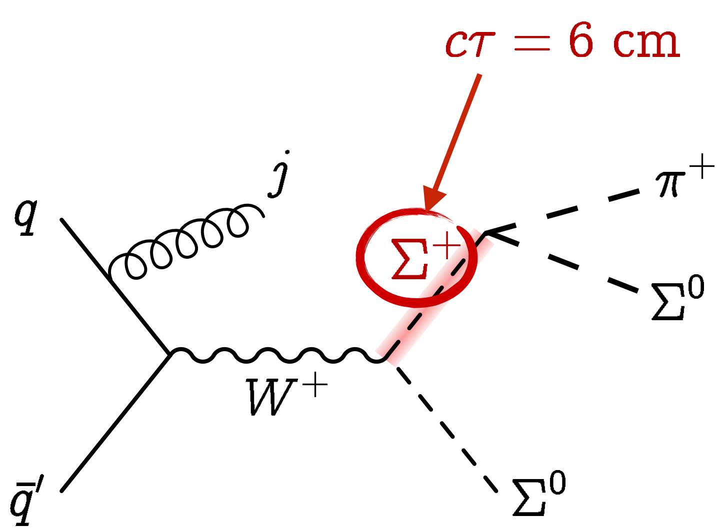
LHC Production: $\Sigma^{\pm}$

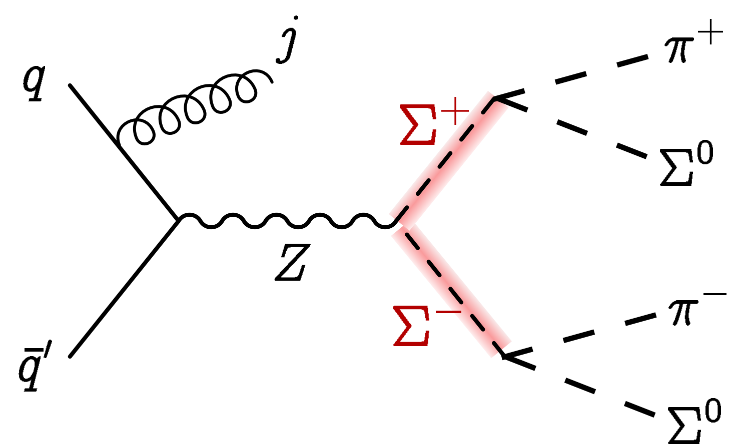
Potential has Z_2 symmetry:
associated production of Σ.

model potential

$$V(H,\Sigma) = -\mu^2 H^\dagger H + \lambda(H^\dagger H)^4 - \frac{1}{2}\mu_\Sigma^2 \vec{\Sigma}^2 + \frac{b_4}{4}(\vec{\Sigma}^2)^2 + \frac{a_2}{2} H^\dagger H \vec{\Sigma}^2$$

Distinctive LHC signature

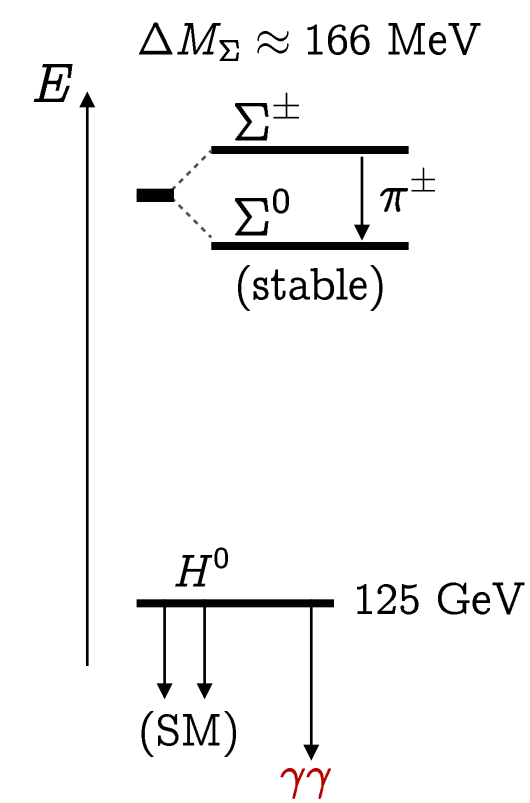




1 charged track
missing $\not{E}_T$

2 charged tracks
missing $\not{E}_T$

$J^P = 0^+$



Production cross section:

$M_\Sigma = 200$ GeV	$M_\Sigma = 1$ TeV
$\sigma_{\text{prod}} \approx 10$ fb	$\sigma_{\text{prod}} \approx 10^{-2}$ fb

Σ^0 as a CDM candidate

Annihilation channels:

$$\Sigma^0\Sigma^0 \longrightarrow W^+W^-,\ \gamma\gamma,\ \ldots$$

M. Cirelli, A. Strumia, M. Tamburini. Nucl. Phys. **B787**, 152 (2007)

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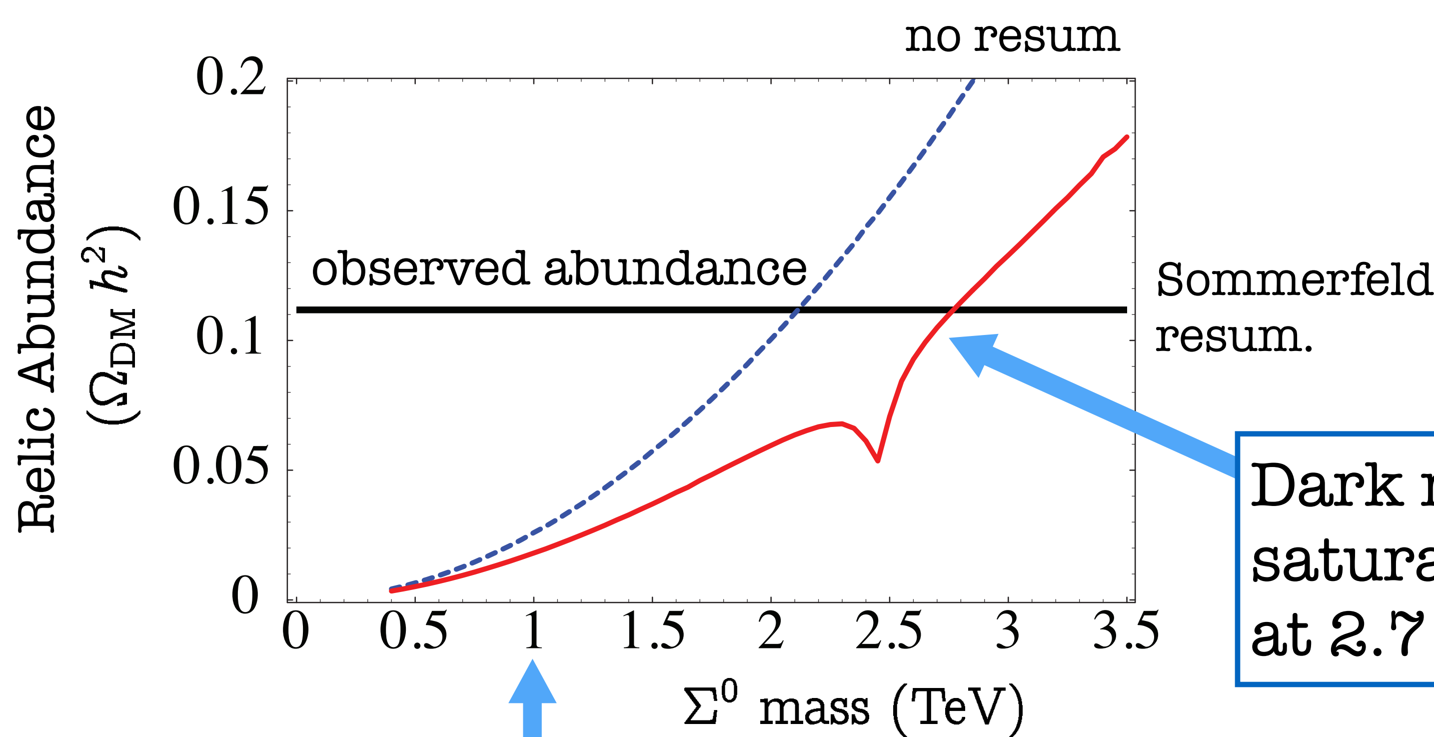
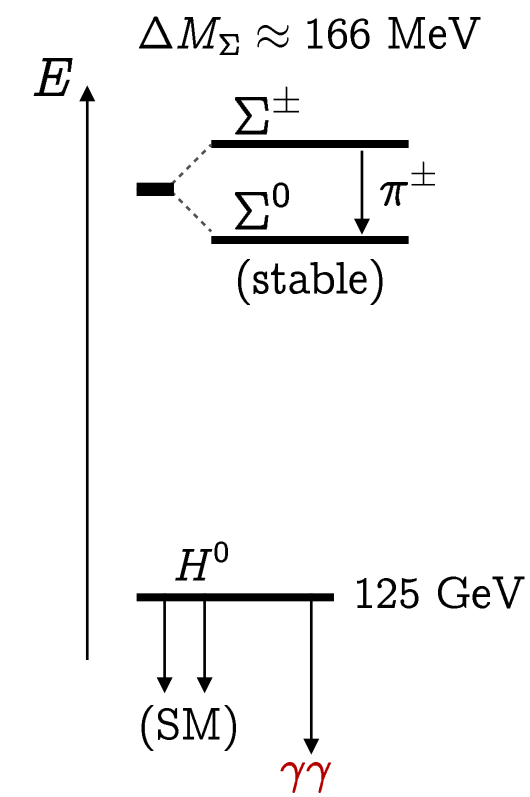


Dark matter saturation at 2.7 TeV

14 TeV LHC: $M_\Sigma = 1$ TeV, production $\sigma \approx 10^{-2}$ fb

$J^P = 0^+$



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Connection to colliders

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Problem:
This is gauge dependent

H.Patel, M.J. Ramsey-Musolf, JHEP 1107 (2011), 029

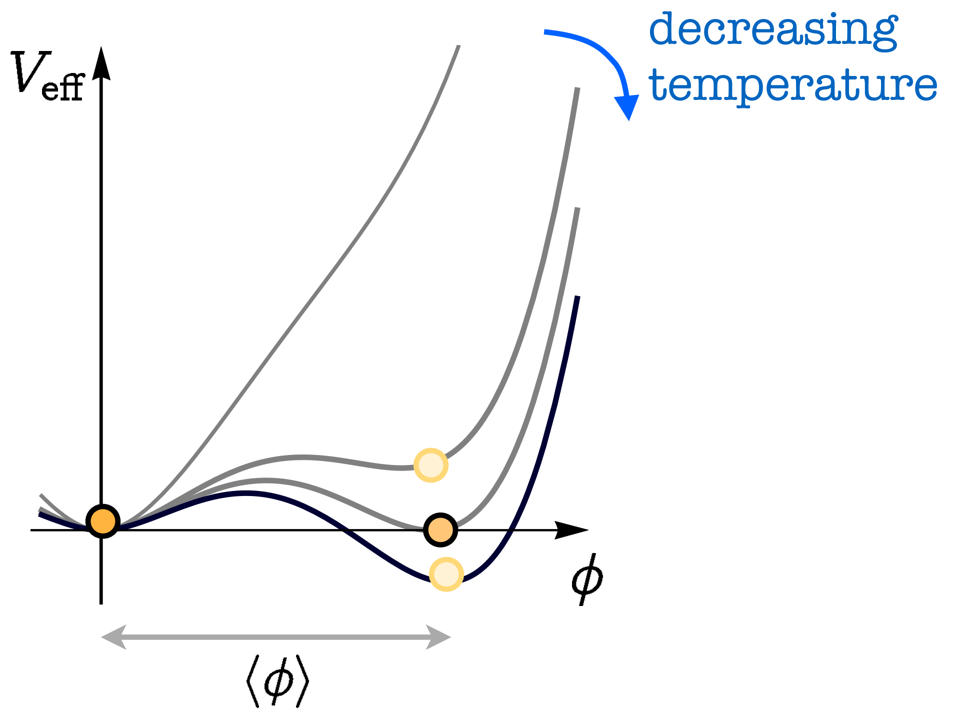
(standard) Computation of $\frac{\langle\phi\rangle}{T_c}$

1. Track evolution of minima in V_{eff} as a function of temperature.

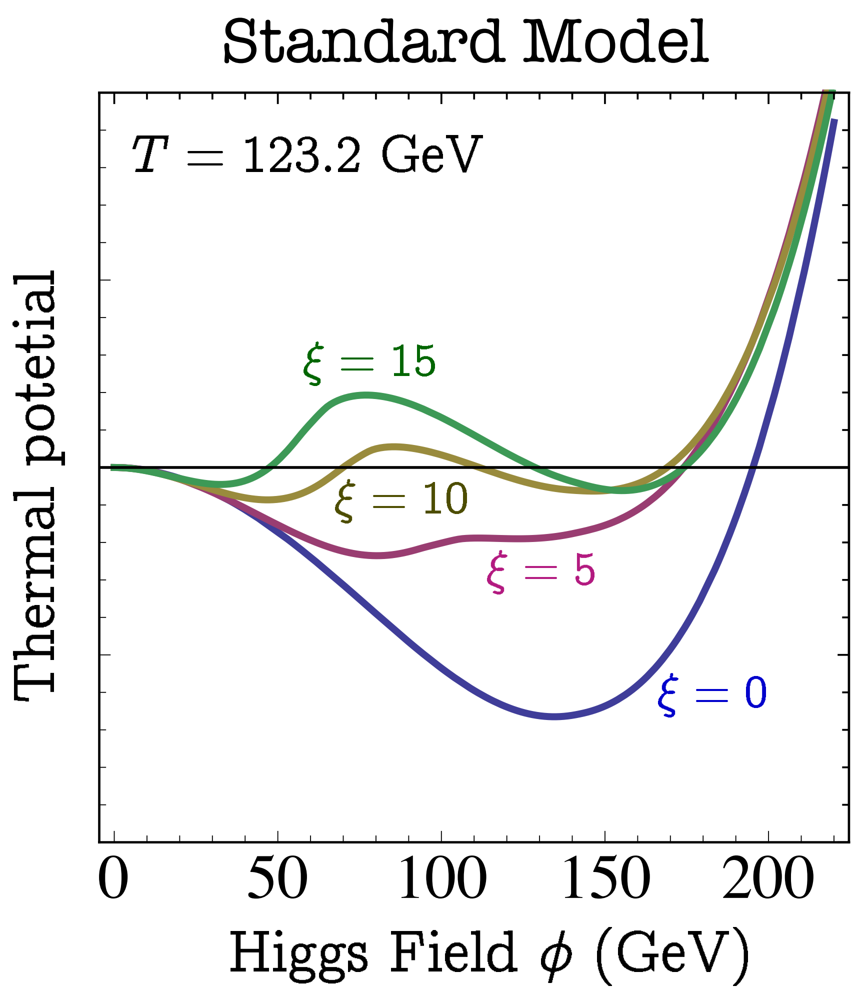
2. Numerically solve minimization and degeneracy condition equations:

1 $$\frac{\partial}{\partial\phi}V_{\text{eff}}(\phi_{\text{min}},\,T_c)=0$$

2 $$V_{\text{eff}}(0,\,T_c)=V_{\text{eff}}(\phi_{\text{min}},\,T_c)$$



In a gauge theory, the effective potential is gauge dependent.



Computed T_c and $\langle\phi\rangle$ depends on gauge parameter

Diagnosis & Resolution I

Determination of T_c (or T_N)

$$\frac{\langle \phi \rangle}{T_c} \gtrsim 1$$

~*Diagnosis*~

- Nielsen identity $\Longrightarrow$ T_c gauge-independent
- valid order-by-order in loop-expansion
- But, numerical solution to minimization condition

$$\boxed{1. \quad V'_{\text{eff}}(\phi_{\text{min}}, T_c) = 0}$$

$$2. \quad V_{\text{eff}}(0, T_c) = V_{\text{eff}}(\phi_{\text{min}}, T_c)$$

leads to inconsistent truncation in loop-expansion!

~*Resolution*~

"h-bar Expansion method"

Minimize by an inversion of series

counts # of loops

$$\begin{cases} V(\phi, T) = V_0 + \hbar V_1 + \hbar^2 V_2 + \ldots \\ \phi_{\text{min}} = \phi_0 + \hbar \phi_1 + \hbar^2 \phi_2 + \ldots \end{cases}$$

Equation for ea. power of $\hbar$; yields ϕ_{min}.

Subs. into each side;

$$\boxed{\begin{aligned} V(\phi_{\text{min}}, T) &= V_0(\phi_0) + \hbar V_1(\phi_0, T) \\ &\quad + \hbar^2 \left[V_2(\phi_0, T, \xi) - \frac{1}{2} \phi_1^2(\xi) \frac{\partial^2 V_0}{\partial \phi^2}\Big|_{\phi_0} \right] + \ldots \end{aligned}}$$

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$$\frac{\langle\phi\rangle}{T_c}$$

~Diagnosis~

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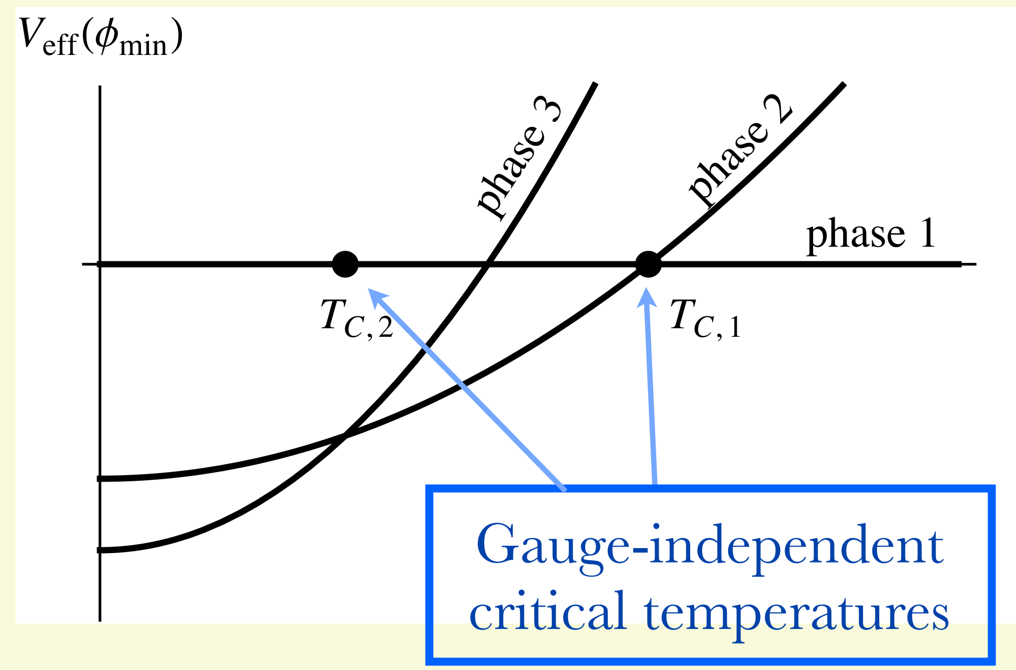
leads to inconsistent truncation in loop-expansion!

Expression gives gauge independent minima of the effective potential.



consistent with Nielsen identity. (explicitly checked at 1-loop)

in.

$$+\hbar^2\left[V_2(\phi_0, T, \xi) - \frac{1}{2}\phi_1^2(\xi)\frac{\partial^2 V_0}{\partial\phi^2}\Big|_{\phi_0}\right] + \ldots$$

Diagnosis & Resolution II

Determination of $\langle\phi\rangle$.

$$\frac{\langle\phi\rangle}{T_c} \gtrsim 1$$

Bottom line

Gauge-invariant baryon number preservation criterion:

$$\frac{\langle\phi\rangle}{T_c} \longrightarrow \frac{\bar{v}(T_c^{\text{G.I.}})}{T_c^{\text{G.I.}}}$$

1. Use gauge invariant sphaleron scale
2. Determine Tc gauge-invariantly

~Resolution~

1. Compute sphaleron energy based on gauge-invariant $\mathcal{O}(T^2)$ effective action.

$$\Gamma(T) \sim -\frac{1}{4}F^a_{ij}F^a_{ij} + (D\phi)^2 + V_0(\phi) + \alpha\phi^2 T^2$$

2. Extract gauge-invariant scale from $\Gamma(T)$.

$$\bar{v}(T) = v_0\sqrt{1 - T^2/T_0^2}$$

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