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The W-Z-top Bags, sphalerons and baryonic asymmetry of the Universe

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Papers and collaborators

- **The W-Z-Top Bags. Marcos Crichigno, Victor Flambaum, Michael Kuchiev, ES arXiv:1006.0645**
- **Quantum Corrections to Multi-Quanta Higgs-Bags in the Standard Model. Marcos P. Crichigno, ES arXiv:0909.5629 ,PRD**
- **Possible Role of the WZ-Top-Quark Bags in Baryogenesis. Victor V. Flambaum, ES, arXiv:1006.0249,PRD**
- The Standard Model CP Violation near the W -bags and Baryogenesis**, Yannis Burnier +ES, in progress**

outline

- Can Higgs-mediated attraction lead to multiquanta bound states? – recent history
- W-Z bags: 3 polarizations, E-L mix, L repelled, M simple
- Adding the top/antitops: “no-Higgs” vs “inverted” bags
- Baryogenesis and hybrid cosmological scenario
- Hot spots = W bags, COS (finite size) sphalerons
- Adding the tops: their recycling by sphalerons
- Estimates for the standard model (CKM) CP violation

Can Higgs-mediated forces lead to many-quanta bound states?

- Scalar is like gravity (spins 0 and 2): no screening, **universal attraction proportional to mass, so for large enough particle number it becomes strong**. Gravity is very weak yet it makes planets, stars and black holes!
- ``strong interaction Higgs” is the sigma meson. It may even gets massless at QCD critical point (if reachable)

(reminder: nuclear physics has a separate scale, distinct from hadronic physics, because sigma attraction is nearly exactly canceled by omega repulsion)

existing ``theories” (e.g. technicolor) predict vectors much heavier then Higgs (1-2 TeV vs .1 TeV) thus we **do not expect such cancellations** (LHC will soon tell)

History, starting with the 12, $t+\bar{t}$

- C. D. Froggatt and H. B. Nielsen, Surveys High Energ. Phys. 18, 55 (2003) suggested 6 t+6 anti-t **deeply bound**

$$\frac{g_t^2}{4\pi}N = 0.08N \sim 1$$

- M. Y. Kuchiev, V. V. Flambaum and E. Shuryak, Phys. Rev. D 78, 077502 (2008) [arXiv:0808.3632]: **no, weakly bound for massless or light Higgs, but not bound at all for real mass** (> 100 GeV)
- J. M. Richard, Few Body Syst. 45, 65 (2009) [arXiv:0811.2711] confirmed our conclusions and improved binding a bit by a more sophisticated trial function, no binding for M_H>50 GeV

W bosons in a Higgs bag

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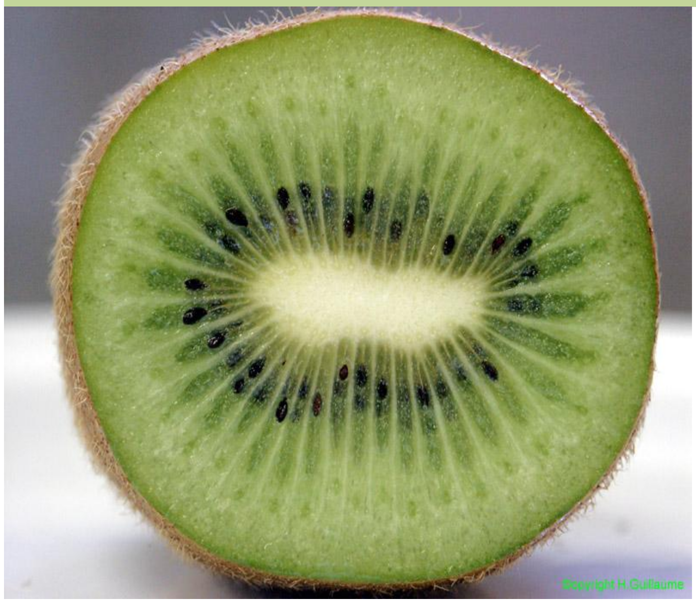
(Dated: January 27, 2010)

We consider energy levels of W and Z-bosons captured to the bags with a strongly depleted Higgs VEV inside. Such bags are formed after Big Bang and stabilised by captured heavy particles (t-quarks,W,Z). They may play an important role in the Bariogenesis. We found that in some bags the W levels may be above t-quark levels, so t-quark can not decay to Wb. This dramatically increases the life-time of $t-$quarks. Deep bags with kink-like sharp edges may induce spontaneus W-production.



The main questions:

- Which modes are the lowest, M, E or L?
- What are the smallest number which can be bound, how does it depend on M_H?
  (O(1000) if M_H>100 GeV)
- How those levels are related with those of the tops in the bag?
- **2 kinds of bags:**

"No-Higgs" (phi=0 inside)

"inverted" (phi changes sign on the boundary)

(inverted)

Magnetic, electric and longitudinal

$$\mathbf{Y}^{(e)}_{jm} = \boldsymbol{\nabla}_n Y_{jm}/\sqrt{j(j+1)}\,,$$
$$\mathbf{Y}^{(l)}_{jm} = \mathbf{n}\, Y_{jm}\,,$$
$$\mathbf{Y}^{(m)}_{jm} = \mathbf{n} \times \mathbf{Y}^{(e)}_{jm}\,.$$

$$\Delta_n \mathbf{Y}^{(e)}_{jm} = -j(j+1)\,\mathbf{Y}^{(e)}_{jm} + 2\sqrt{j(j+1)}\,\mathbf{Y}^{(l)}_{jm},$$
$$\Delta_n \mathbf{Y}^{(l)}_{jm} = 2\sqrt{j(j+1)}\,\mathbf{Y}^{(e)}_{jm} - (j(j+1)+2)\mathbf{Y}^{(l)}_{jm}$$
$$\Delta_n \mathbf{Y}^{(m)}_{jm} = -j(j+1)\mathbf{Y}^{(m)}_{jm}\,.$$

$$\left(\frac{d^2}{dr^2} + \omega^2 - M_W^2\phi^2 - \frac{j(j+1)}{r^2}\right) f_m(r) = 0 \qquad (2.4)$$

M has eqn as a scalar except j=1,2…

The electrolongitudinal mode is described by two radial wave functions $f_e(r)$ and $f_l(r)$:
$\mathbf{W} = \mathbf{Y}^{(e)}_{jm} f_e(r)/r + \mathbf{Y}^{(l)}_{jm} f_l(r)/r$.
Corresponding equations are

$$\left(\frac{d^2}{dr^2} + \omega^2 - M_W^2\phi^2 - \frac{j(j+1)}{r^2}\right) f_e(r) + \qquad (2.5)$$
$$-\frac{2\sqrt{j(j+1)}(1 - r\frac{d\ln\phi}{dr}) f_l(r)}{r^2} = 0.$$

E-L mixing

$$\left(\frac{d^2}{dr^2} + \omega^2 - M_W^2\phi^2 - \frac{j(j+1)}{r^2}\right) f_l(r) + \qquad (2.6)$$
$$+2r\frac{d}{dr}\left(\frac{f_l(r)}{r}\frac{d\ln\phi}{dr}\right) - \frac{2\sqrt{j(j+1)} f_e(r)}{r^2} = 0$$

New term for L which is singular at zeros of Higgs! Indeed, where W is massless, there should not be any L modes…

Bags without zero

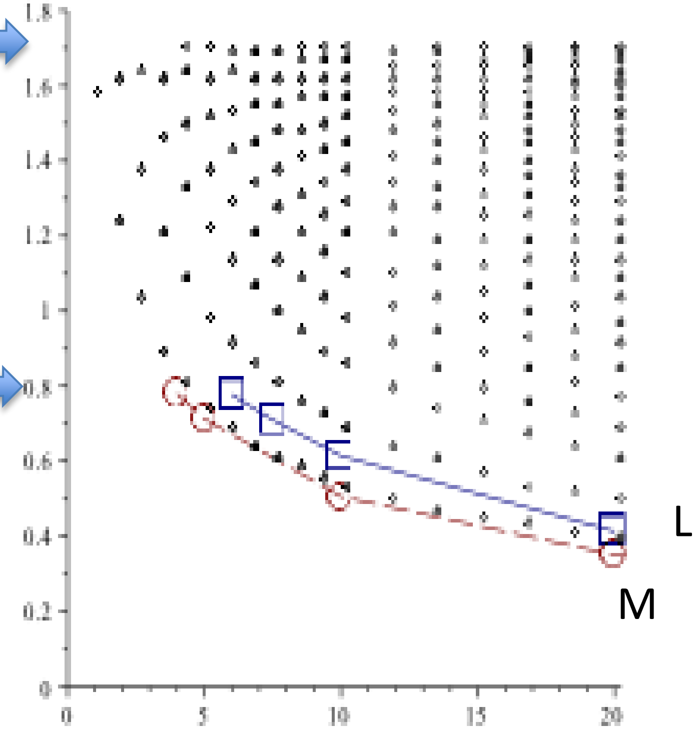
We use the Gaussian ansatz

$$\phi(r) = 1 - \eta \exp(-r^2/w^2)$$

$\eta < 1$

M_t=1.73

m_W=0.8



- j=0 L is already higher than j=1 M
- J=1 M is very close to the lowest levels of the tops, in spite of large mass difference

FIG. 1: The energy of the levels $E_W/(100\,GeV)$ versus the size of the bag $R(100\,GeV)$, for the Gaussian ansatz for the Higgs and $\eta = 0.9$ (no zero case). Small (black) circles are fermionic levels. Large (red) circles are for $j = 1$ M-mode, large (blue) boxes are for $j = 0$ L mode.

1d kinks, an approximation for very large inverted spherical bags with zero of phi

- Qualitative argument: fermions have **zero mode for topological reasons**

- **Scalars,M and E have osc.potential**

$$|\phi(x)^2| \sim (x - x_0)^2$$

And thus an oscillator level >0

- **But where are the L modes? Very high. The zero of phi is an inpenetrable barrier**

The W-Z-Top Bags

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(Dated: June 1, 2010)

We discuss a new family of multi-quanta bound states in the Standard Model, which exist due to the mutual Higgs-based attraction of the heaviest members of the SM, namely, gauge quanta W, Z and (anti)top quarks, $\bar{t}, t$. We use a self-consistent mean-field approximation, up to a rather large particle number N. In this paper we do not focus on weakly-bound, non-relativistic bound states, but rather on "bags" in which the Higgs VEV is significantly modified/depleted. The minimal number N above which such states appear strongly depends on the ratio of the Higgs mass to the masses of $W, Z, \bar{t}, t$: For a light Higgs mass $m_H \sim 50\,GeV$ bound states start from $N \sim O(10)$, but for a "realistic" Higgs mass, $m_H \sim 100\,GeV$, one finds metastable/bound W, Z bags only for $N \sim O(1000)$. We also found that in the latter case pure top bags disappear for all N, although top quarks can still be well bound to the W-bags. Anticipating cosmological applications (discussed in a companion paper) of these bags as "doorway states" for baryosynthesis , we also consider the existence of such metastable bags at finite temperatures, when SM parameters such as Higgs, gauge and top masses are significantly modified.

The so-called Dirac parameter κ is defined as

$$\kappa = \begin{cases} -(l+1) & \text{for } j = l + 1/2 \\ l & \text{for } j = l - 1/2 \end{cases} \qquad (30)$$

and runs over all nonzero integers, being positive for anti-parallel spin and negative for parallel spin. Dirac's equation reads (See Appendix

$$\begin{aligned} (\varepsilon - m\,\phi)\,F &= -G' + (\kappa/r)\,G \qquad (31) \\ (\varepsilon + m\,\phi)\,G &= F' + (\kappa/r)\,F \end{aligned}$$

The form of these equations presumes that the eigenvalue ε is positive. A negative eigenvalue would correspond to a state in the lower fermion continuum. If so, a charge conjugation transformation turns it into a positive eigenvalue for an antifermion. The Higgs equation of motion reads

$$\phi'' + \frac{2}{r}\phi' + \frac{m_H^2}{2}\phi\,(1-\phi^2) = \frac{(N-1)m}{4\pi\,v^2}\,\frac{F^2 - G^2}{r^2} \qquad (32)$$

$$\varepsilon_\pm^2 = m\phi'(r_0) + \kappa^2/r_0^2 \pm \sqrt{m^2\phi'^2(r_0) + \frac{1}{r_0^4}}. \qquad (35)$$

We see from this expression that the levels ε_+ are finite for $r \to \infty$, while ε_- goes to zero. The latter correspond to the would-be zero modes in the 1 dimensional case. Therefore, for large enough bags these will be below any other level (see Appendix B for explicit results) and in what follows we consider these levels only. Note that to order $O(\frac{1}{r_0})$,

$$\varepsilon_- \simeq \frac{|\kappa|}{r_0}, \qquad (36)$$

hence in this approximation the spectrum is independent of the mass of the fermion and the value for the first level (κ=-1) is less than 2.04, which appears for the volume bag. Thus, not

If Higgs goes through zero, there is a quasi-Zero mode for large bags and analytic solution

Magic numbers and levels

	n_r	κ	l	j	$Deg.(\bar{t}t)$	color
1	0	-1	0	1/2	12	blue
2	0	-2	1	3/2	24	red
3	0	-3	2	5/2	36	green
4	0	1	1	1/2	12	black
5	1	-1	0	1/2	12	blue
7	0	2	2	3/2	24	yellow
8	1	-2	2	3/2	24	red
9	0	3	3	5/2	36	violet
10	1	-3	2	5/2	36	green

TABLE I: The properties of some levels, including the number of radial nodes n_r, Dirac parameter κ, orbital momentum l, total angular momentum j, multiplicity of states Deg(for $t\bar{t}$ bags) and color code used in our figures. Obviously, for pure top bags the multiplicity is halved.

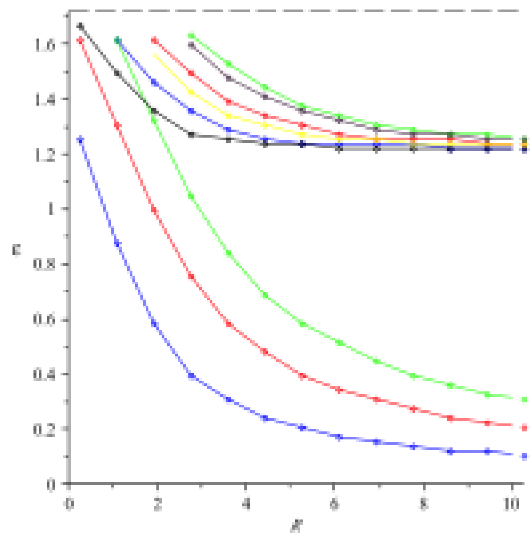


FIG. 5: (color online) Dependence of some bound state levels energy ε in units of $100\,GeV$ on the size of the bag, expressed as the parameter R in units $1/100\,GeV^{-1}$ for a bag with $\eta = 1$. The color coding of the levels and their quantum numbers are listed in Table I.

At a realistic higgs mass, there are no stable pure top bags at any N
But if be lighter (say 50 GeV) there would be “another nuclear physics”

Comparing M mode of W to tops

- In general, due to existence of the zero mode,
  the lowest top levels are below the W modes for large bags
- So, up to 12+24=36 tops on those 2 levels cannot decay into W+b, and
  have much longer lifetime than W,Z themselves

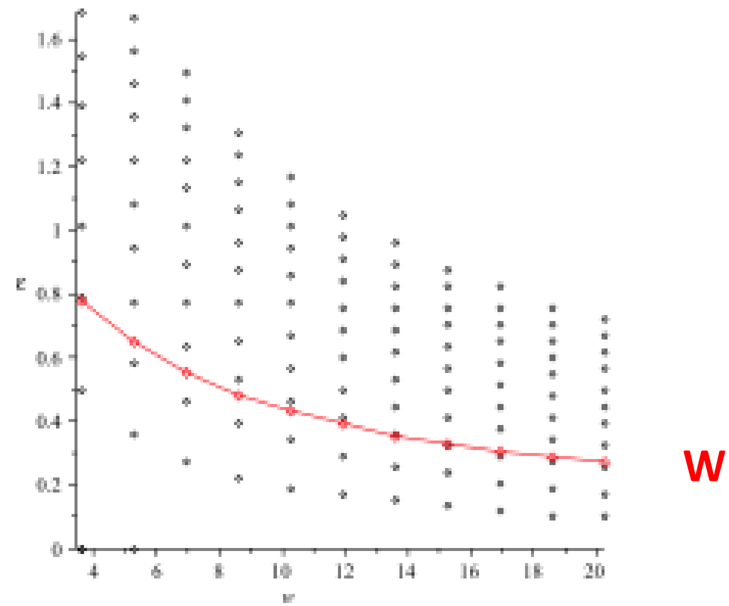


FIG. 6: The energy of the levels $E_W/100\,GeV$ versus the size of the bag $w \cdot 100\,GeV$, for the Gaussian ansatz for the Higgs and $\alpha = 1.2$ (with zero case). Black (small) circles are some fermionic levels with $\kappa < 0$ and the large (red) circles correspond to the W magnetic level for $j = 1$.

Baryogenesis in the hydbrid model

Baryogenesis

- Sakharov (1967) had formulated 3 conditions => **B-violation, CP-violation, non-equilibrium**
- All 3 are there in the Standard Model (SM)
- And yet we do not know how $n_B/n_\gamma = 6*10^{-10}$ has been obtained… as way too small numbers are obtained
- beyond the SM? (very popular)
  or beyond the standard cosmology instead?

Hybrid (cold) scenario

combines establisment of the EW broken phase with the end of inflation

J. Garcia-Bellido, D.Y. Grigoriev, A. Kusenko and M.E. Shaposhnikov, Phys. Rev. D 60 (1999) 123504 [hep-ph/9902449]. L.M. Krauss and M. Trodden, PRL 83 (1999) 1502 [hep-ph/9902420].

J. Garcia-Bellido, M. Garcia-Perez and A. Gonzalez-Arroyo, Phys. Rev. D **69**, 023504 (2004) [arXiv:hep-ph/0304285].
A. Tranberg and J. Smit, JHEP **0311**, 016 (2003) [arXiv:hep-ph/0310342].

- Real-time lattice simulations
- Only bosons: 2 scalars (Higgs and inflaton) and the gauge fields (photons, W,Z)
- Mostly focused on generation of primordial magnetic field (not to be discussed in this talk)
- They study a diffusion in the Chern-Simons number => **B violation** rate

Hybrid (cold) scenario (cont)

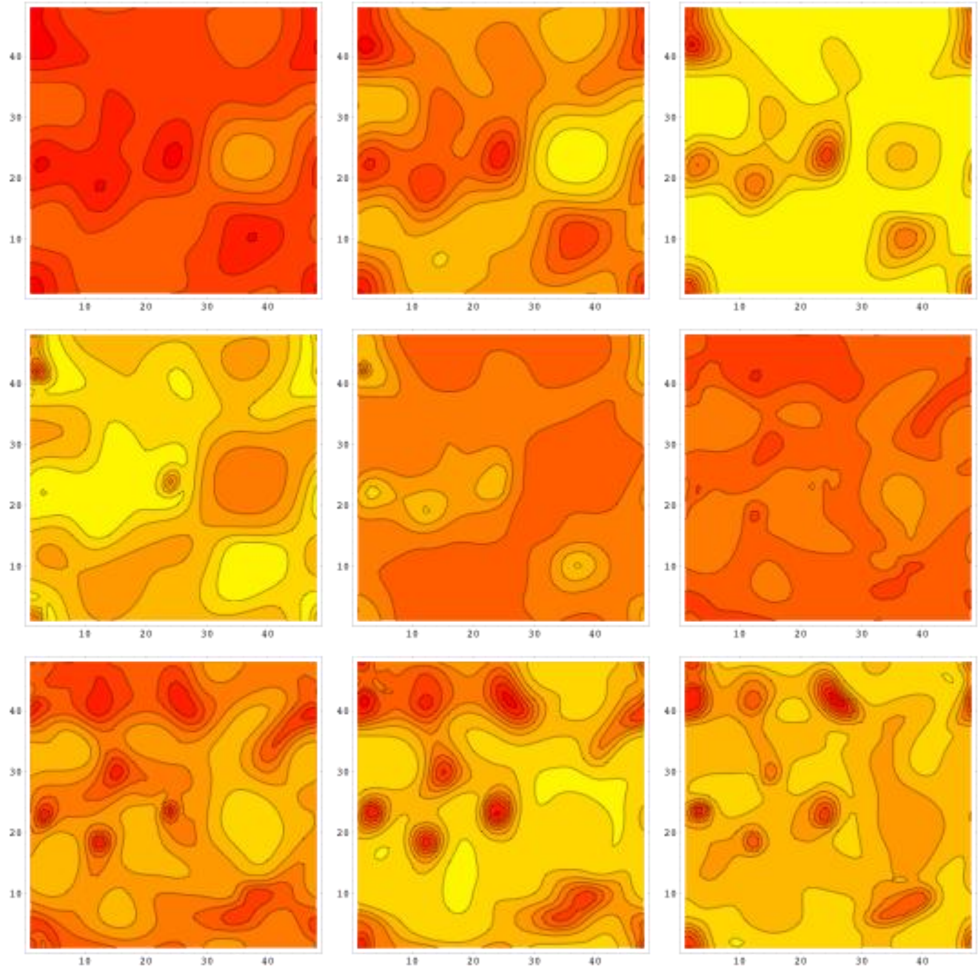
- Subsequent time snapshots of the **Higgs VEV modulus** shows appearance of the **``hot spots”**

(red) which have near-zero Higgs VEV

They remain for

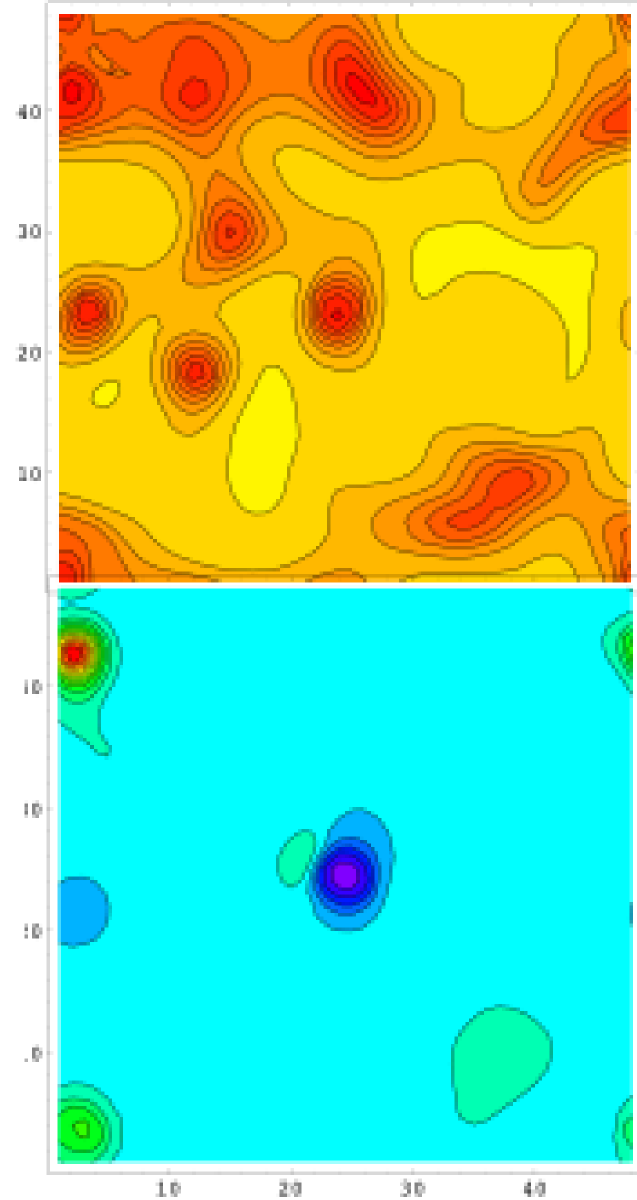
t m about 20

(m is the mass scale, in this simulation it is 240 GeV)



Hybrid (cold) scenario (cont)

- **Topological charge Q** = GG_{dual} is also localized
- The topological transitions happen **only inside (some of) the "hot spots"**
- **Hot spots take volume fraction of few percents, sphalerons in them also have P of few percents**
- $=>\Gamma/T^4$ about 10^{-4},
- Integrated in time 10^{-3}



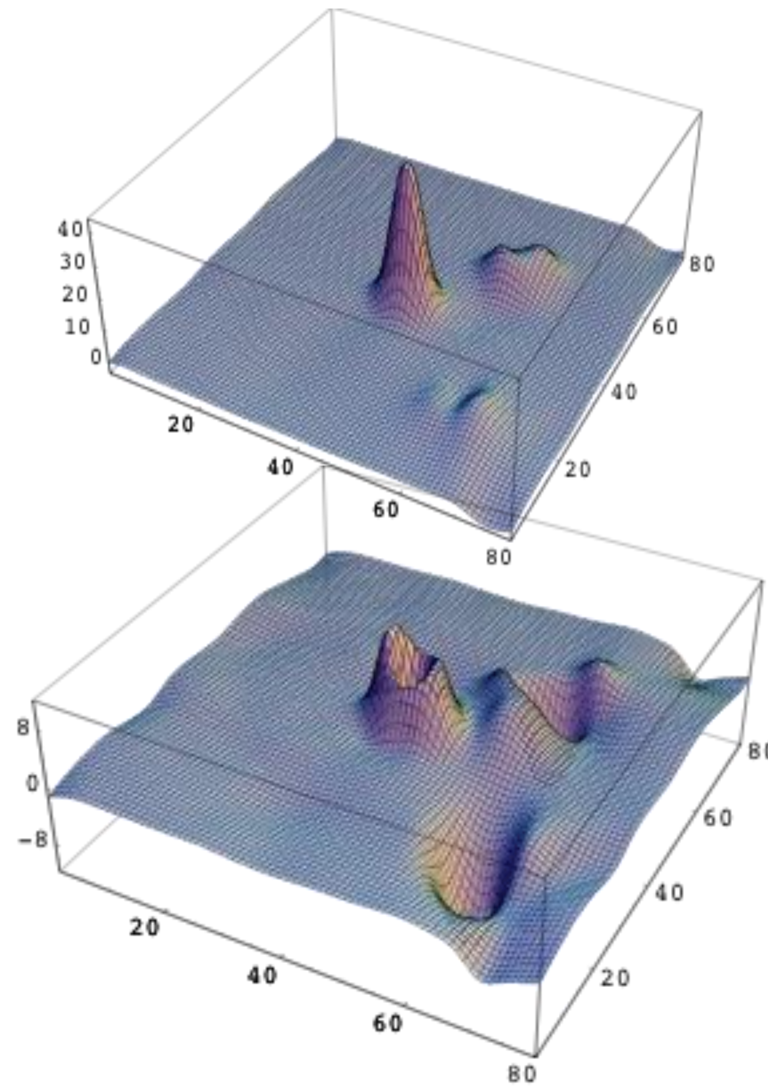
$|\phi|$

T m=19
The same
Time and
place

Q(x)

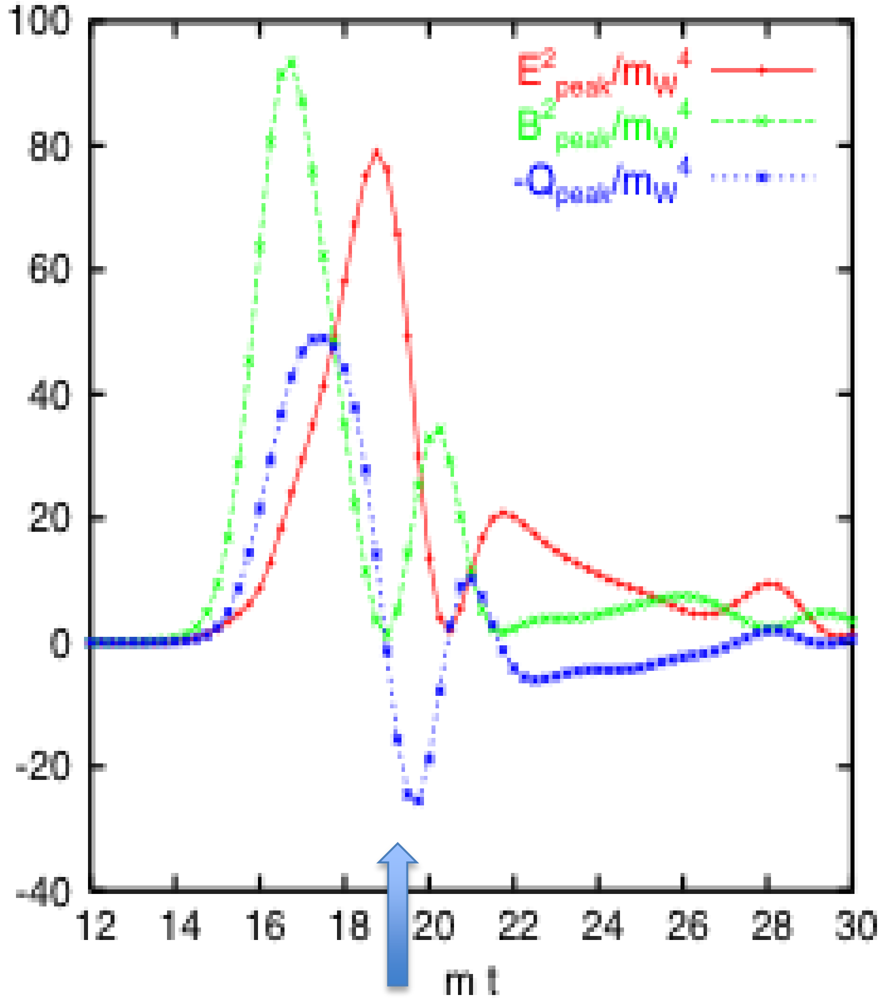
Hybrid (cold) scenario (cont)

- Topological charge explodes after a peak
- Then spherical explosion with an empty shell



Hybrid (cold) scenario (cont)

- Further details:
- Magnetic field B first
- Then electric E
- Note that topology has sign inversion, before it comes back



Explaining numerical results, for (bosonic) hybrid cosmology

Hot spots as thermal W bags

(mechanically but not thermally equilibrated)

What we consider here are a very simple variant of the bag model. Let us assume that rescattering are rapid enough to make kinetic equilibrium inside the bag. There is no *chemical* equilibrium, as the number of Ws produced are determined by early time dynamics: so we need to introduce both the internal temperature T_{in} and the fugacity ξ_W

$$N_W = V_{spot} g_W \int \frac{d^3k}{(2\pi)^3} \frac{1}{\xi_W exp(\epsilon(k)/T_{in}) - 1} \quad (11)$$

with the number of gauge degrees of freedom $g_W = 6$.

Condition of mechanical stability we will write as

$$p_{in} = B + p_{bulk} \quad (12)$$

with the bag constant B created by the Higgs potential, assuming zero VEV inside

$$B = \lambda v^4/4 = m^2 v^2/4 \quad (13)$$

(loop and T-dependent corrections can be easily included but are are ignored. All other degrees of freedom of the SM such as quarks and leptons are ignored here because they have not yet been produced.) Using further Boltzmann approximation and also ignoring p_{bulk} for the estimate, one gets the mechanical stability condition in a form

$$B = g_W \xi_W \frac{\pi^2 T_{in}^4}{45} \quad (14)$$

or the internal temperature

$$T_{in} \xi_W^{1/4} = .66m \approx 174\, GeV \quad (15)$$

which is indeed well above the equilibrium $T_c \sim 100\, GeV$.

T_{in} = 174 GeV > Tc >> T_{bulk} = 50 GeV

COS sphalerons

(Carter,Ostrovsky,Shuryak, Phys.Rev. D 66, 036004 (2002)

- What is the minimal potential energy of static Yang-Mills field, consistent with the constraints:

(i) the given value of (corrected) Chern-Simons number.

(ii) the given value of the r.m.s. size $< r^2 >= \int d^3x r^2 \mathcal{B}^2 / \int d^3x \mathcal{B}^2$

- Solution (found by D.Ostrovsky) is a ball made of three magnetic gluon fields (out of 8 in SU(3)) rotated around x,y,z axes

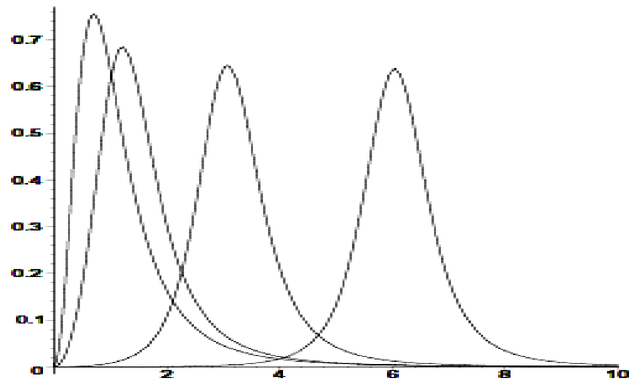
$B^2/2 = 24(1-\kappa^2)^2\rho^4/(r^2+\rho^2)^4$

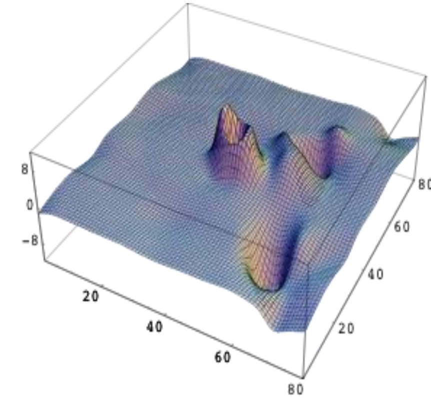
$E_{stat} = 3\pi^2(1-\kappa^2)^2/(g^2\rho)$ $\tilde{N}_{CS} = \mathrm{sign}(\kappa)(1-|\kappa|)^2(2+|\kappa|)/4.$

Eliminating κ one gets the topological potential energy,

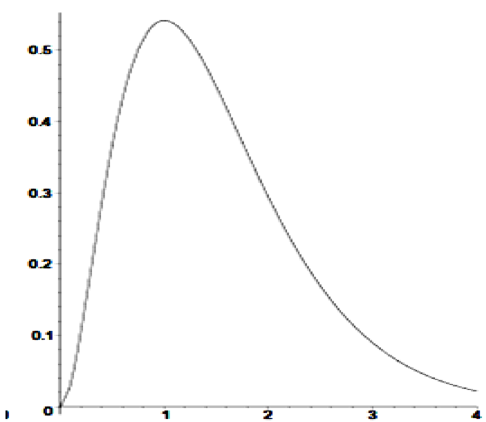
$\kappa = 0$ gives the sphaleron

COS sphaleron explosion





- Solved both numerically (G.Carter) and analytically (by D.Ostrovsky based on work by Luescher and Schehter from 1977 which can also be via conformal transformation -Zahed)
- Sphalerons at $t = 0$ => (at large t) into a spherical transverse wave $4\pi e(r,t) = \frac{8\pi}{g^2\rho^2}(1-\kappa^2)^2\left(\frac{\rho^2}{\rho^2+(r-t)^2}\right)^3$



- ES+Zahed: new solution to the Dirac equation in exploding backgroun obtained by inversion of the fermionic O(4) zero mode of O(4) symmetric solution.

It explicitly shows how the quark acceleration occurs, starting from zero energy at t=0 to the final spectrum

- The sphalerons produce one level crossing $N_F \overline{L}R$ quarks, and the antisphaleron-like clusters the chirality opposite.

COS sphalerons in QCD

Semiclassical Theory of High Energy Collisions based on
Instantons and Sphalerons

- ''pomeron from instantons'':

ES, Zahed PRD62:085014,2000 hep-ph/0005152

D. E. Kharzeev, Y. V. Kovchegov and E. Levin Nucl. Phys. A **690**, 621 (2001) [hep-ph/0007182].

M. A. Nowak, ES and Zahed, PRD 64, 034008 (2001) [hep-ph/0012232].

G.W.Carter,D.Ostrovsky and ES, Phys. Rev. D **65**, 074034 (2002) [hep-ph

- the turning states and their explosion

D.Ostrovsky, G.W.Carter and ES, hep-ph/0204224,PRD

- Landau method for cross section - rescaled YM sphalerons are produced

D. Diakonov and V. Petrov, Phys. Rev. D **50**, 266 (1994) R. A. Janik, ES and Zahed, hep-ph/0206005.

- Explicit solution of the Dirac eqn in the exploding field background: an end of ''the fermion puzzle''?

ES and Zahed, hep-ph/0206022.

- Gluonic cluster production in double-Pomeron processes (e.g. $pp->$ $pp\eta'$; $ppf_0(1600)$, pp+cluster) compared to data; ES and Zahed,2002
- Instanton-induced Double DIS $\gamma^*\gamma^*$)ES and Zahed,2003

Can numerically observed topological fluctuations be described by COS sphalerons?

Does the magnetic field fits well to COS sphaleron solution? The profile of the the magnetic field in COS configuration is given by the following simple expression

$$B^2(r) = \frac{48\rho^4}{g^2(r^2+\rho^2)^4} \qquad (19)$$

which (unlike the KM one) is just spherically symmetric. This form does indeed fit well the observed shape of the B^2 at the sphaleron moment. The maximum of B^2/g^2 can be related with its radius, yielding $m\rho \approx 3.9$, which is very close to optimal size we got above. This value corresponds to the total energy of the COS sphaleron (5)

$$E_{tot} = 3\pi^2/g^2\rho \approx 2\,TeV \qquad (20)$$

As we already mentioned in the INtroduciton, it is 7 times less than the KM sphaleron mass, and for the temperatures we are dealing with $T_{in} = 200 - 100\,GeV$ it makes a huge difference for he rate.

- The shape and the size => the barrier height

Can numerically observed topological fluctuations be described by COS sphalerons?

The sphaleron Boltzmann factor can now be estimated, as we know both the total energy and the internal temperature T_{in} from our bag model for the hot spot:

$$exp(-E_{tot}/T_{in}) \approx exp(-2000\,GeV/174\,GeV) \approx 10^{-5} \quad (21)$$

This is not yet the end of the estimate, since semiclassical sphaleron rate has also a significant preexponent. It has not been calculated for COS sphaleron yet, so we use the KM one

$$\frac{\Gamma}{Vm^4} \approx \frac{\omega_- T^3}{2\pi m^4} N_{tr} N_{rot} (\frac{\alpha_w}{4\pi\alpha_3^3})^3 exp(-\frac{E_{tot}}{T}) \quad (22)$$

which includes the unstable frequency $\omega_- \approx 2M_W$, as well as the numbers due to translational modes $N_{tr} = 26$ and rotational modes $N_{rot} \approx 5300$. There are also factor $\sim O(1)$ from the non-zero mode determinants. We used here $\alpha_3 = g_3^2/4\pi = \sqrt{2M_W/g_w^2 T}$.

Combining all the factors we find that numerical value of preexponent and exponent nearly cancels out, leaving crudely

$$\Gamma/Vm^4 \sim 10^{-1} \quad (23)$$

with accuracy say an order of magnitude or so. With that accuracy it agrees with the results of the simulations which also finds that the number of sphaleron transitions per spot is indeed about several percents.

- Now let us evaluate the optimal size from the rate

$$\Gamma_{sph}(\rho) \sim exp\left[-\frac{\Delta F}{T_{in}}(\frac{4\pi\rho^3}{3}) - \frac{3\pi^2}{g^2\rho T_{in}}\right]$$

$$\rho_* = (\frac{3\pi}{4g^2\Delta E})^{1/4}$$

Which is about 4/m, numerically observed.

The rate also crudely works!

Adding (top) quarks to the hybrid cosmology

Production of the tops and their collection into the "spots"

(i) their fugacity is expected to be larger, due to more rapid production rate of t
(ii) the degeneracy factor is twice larger

$$g_{\bar{t},t} = 12 \tag{26}$$

(iii) their stronger coupling to Higgs (larger masses outside) makes it easier to satisfy the mechanical stabilization condition.

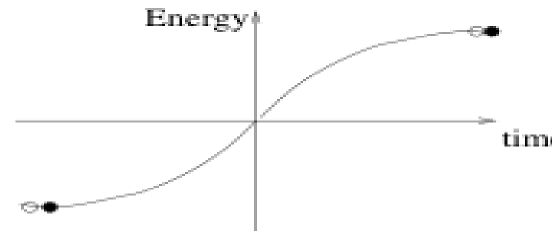
The first question is at what time and how the top quarks would be produced. Top quark has the largest coupling to Higgs: so it is produced first via $HH \to \bar{t}t$ process. Let us crudely compare its rate relative to that of $HH \to WW$

$$\frac{\Gamma(HH \to \bar{t}t)}{\Gamma(HH \to WW)} \sim (\frac{m_t}{m_W})^4 \sim 20 \tag{27}$$

in equilibrium broken phase bulk density is small, $n_{bulk} = n_{in}/300$, compared to their thermal density **inside** the hot spots.
$\Rightarrow$99% should either be annihilated or
collected into the spots!

The next step is concentration of top quarks into the hot spots. The simple reason this is happening is that they are massive in the broken phase and massless in the symmetric one. Another less trivial reason is that a "1d kink" of the HIggs field (a point where it crosses zero) possesses fermion zero modes. In practice it means that top quarks can glue themselves to the $\phi = 0$ surfaces and be transported along them, eventually into the remaining island of the symmetric phase.

Do tops change the sphalerons? (top recycling)



The well known Adler-Bell-Jackiw anomaly require that a change in gauge field topology by $\Delta Q \pm 1$ must be accompanied by a corresponding change in baryon and lepton numbers, B and L. More specifically, such topologically nontrivial fluctuation can thus be viewed as a "t'Hooft operator" with 12 fermionic legs. Particular fermions depend on orientation of the gauge fields in the electroweak SU(2): since we are interested in utilization of top quarks, we will assume it to be "up". In such case the produced set contains $t_r t_b t_g c_r c_b c_g u_r u_b u_g \tau \mu, e$, where r, b, g are quark colors. to which we refer below as the $0 \to 12$ reaction. Of course, in matter with a nonzero fermion density many more reactions of the type $n \to (12 - n)$ are allowed, with n (anti)fermions captured from the initial state.

Let us show by simple estimates that under conditions we are discussing the $0 \to 12$ fermion production process is actually impossible. The final kinetic energy for fermion produced by COS sphaleron is $E_q = 3/\rho$ which is $\approx 200\,GeV$ for the $m\rho = 3.9$ example displayed as typical in Fig.3. Multiplied by 12 fermionic species produced it would require $2.4\,TeV$ of energy which apparently exceeds the total available energy of the gauge fields in the topological fluctuations observed numerically.

The $3 \to 9$ fermion process saves a lot of energy, as in it the initial top quark energy can be completely transferred from the "sphaleron doorway state" to the gauge field during the compression stage. In the example we discuss, with $m\rho = 3.9$, this mean energy of 3 top quarks is

$$\Delta E = 3 * 3/\rho \approx 600\,GeV \qquad (39)$$

An estimate with exponential accuracy we find its enhancement by the factor of about

$$F_{recycling} \sim \exp(\Delta E/T) \sim 20 \qquad (40)$$

The CP violation

CP violation in the SM

- Jarlskog factor J appears (for 4 Ws) which gives the area of unitary triangles of CKM
- If any two masses of upper or lower quarks coinside, **no CP =>** ?

No summation

$$\mathrm{Im}\left[V_{ab}V^{\dagger}_{bc}V_{cd}V^{\dagger}_{da}\right] = J\sum_{e,f}\epsilon_{ace}\epsilon_{bdf},$$

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin(\delta);$$

$$\begin{aligned}\Delta_{CP} &= v^{-12}\mathrm{Im\,Det}\left[m_u m_u^{\dagger}, m_d m_d^{\dagger}\right]\\ &= J\,v^{-12}\prod_{i<j}(\tilde{m}_{u,i}-\tilde{m}^2_{u,j})\prod_{i<j}(\tilde{m}^2_{d,i}-\tilde{m}^2_{d,j}) \simeq 10^{-19}.\end{aligned}$$

$$m_d m_d^{\dagger} = D\tilde{m}_d^2 D^{\dagger}, \quad m_u m_u^{\dagger} = U\tilde{m}_u^2 U^{\dagger}.$$

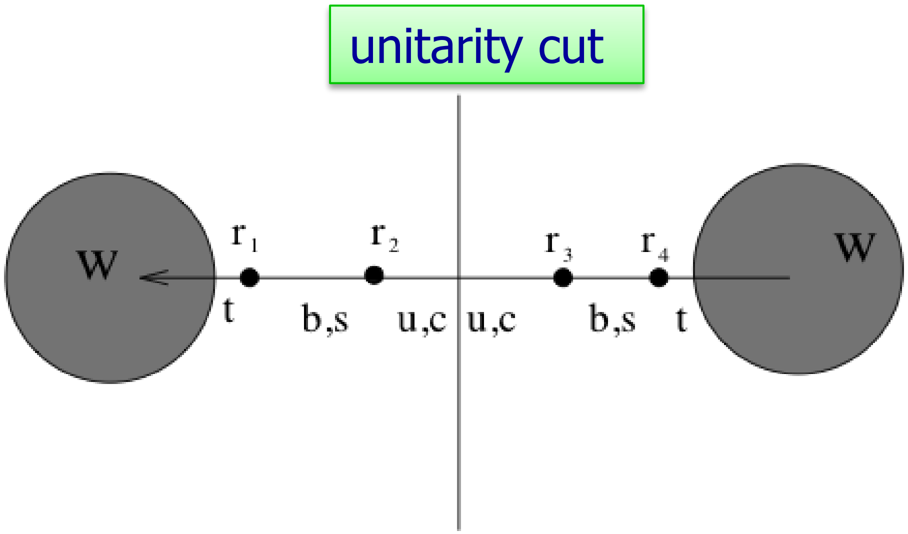
Not true in general, only if **the scale is above all masses**, in denominators
Not so for K and B decays!
Loops at intermediate scales have other way to vanish => e.g. log(m_i/m_j)=0
for equal masses as well, no need to have a difference as a factor…

If so, forget the SM Baryogenesis!

The Standard Model CP Violation near the W -bags and Baryogenesis, Yannis Burnier and Edward Shuryak

- Consider a process, 4-th order in weak interaction, describing interferences between various paths by which a quark can get into the W bag => Top-antitop population difference in the bag

$$J = \sin(\delta)\sin(\theta_{12})\sin(\theta_{13})\cos(\theta_{23})$$
$$*\cos(\theta_{12})\cos^2(\theta_{13})\cos(\theta_{23}) \approx 2*10^{-5}$$



$$M_t - M_{\bar t} = 2iJ(S_{23}^{u} - S_{23}^{c})$$
$$(-S_{34}^{s} * S_{12}^{b} - S_{34}^{d} * S_{12}^{s} + S_{34}^{d} * S_{12}^{b}$$
$$+S_{12}^{d} * S_{34}^{s} - S_{12}^{d} * S_{34}^{b} + S_{12}^{s} * S_{34}^{b})$$

Flavor-independent part of S cancels out, small flavor-dependent phases remain

$$M_t - M_{\bar t} \approx J\frac{m_b^4 m_c^2 m_s^2 r_{23} r_{12} r_{34}(r_{12} + r_{34})}{16E^4}$$

$$exp(i\int dx\sqrt{E^2 - m_i^2}) \approx exp[i(E - m_i^2/2E)r_{ij}]$$

Everything cancels till the 4th order in phases!

estimates

Let us start with a "naive" estimate, which ignores top quark binding in the bag. Furthermore, let us for now assume that there is no possibilities to absorb any amount of energy on the way, so that E in the formulae above needs to be close to the final one, namely $E \approx m_t = 173\,GeV$. If this is the case, the calculated CP asymmetry is negligibly small. In fact the reader familiar with the history of the CP literature will immediately recognize an old Jarlskog argument [?], stated that if

But if top is near-massless in the bag, one can use E being much smaller, Like $g_w T$ or m_b scale of few GeV! If so, the CP difference in t and anti-t is

$$P_{t-\bar{t}} \sim 2 * 10^{-9} < m_b^4 r_{12} r_{34} r_{23} (r_{12} + r_{34}) > \sim 10^{-7\pm 2}$$

Where we assumed **that the field at points 1,4 are from the bag** and 2,3 from the surrounding plasma.

Together with the sphaleron rate giving 10^{-3} we get Total baryonic asymmetry around observed 10^{-10}

Summary:

- **Numerical studies of hybrid cosmology can be explained by COS sphalerons inside the "hot spots": size, rates…**
- **Tops have stronger coupling than Ws and produced more copiously: they will be collected into spots and help to stabilize them**
- **Lifetime and top recycling increase the sphaleron rate by about O(10), from 10^{-3} to 10^{-2}**
- **leaving about 8 orders of magnitude to CP violation: seem to be doable in the SM, after all!**
- **(subject to further scrutiny of many details…)**

Deriving EOM

$$\left(\nabla^2 + M_W^2\phi^2\right) W^\mu - \nabla^\mu\nabla^\nu W_\nu = 0 \ . \tag{1.8}$$

Taking a covariant derivative in Eq.(1.8) one finds

$$\nabla_\mu(\phi^2 W^\mu) = \phi^2\nabla_\mu W^\mu + W^\mu\nabla_\mu(\phi^2) = 0 \ . \tag{1.9}$$

Evaluating $\nabla_\mu W^\mu$ from Eq.(1.9) and substituting the result back into Eq.(1.8) one rewrites the latter one in a more transparent form

$$\left(\nabla^2 + M_W^2\phi^2\right) W^\mu + \nabla^\mu\left(\frac{W^\nu\nabla_\nu\phi^2}{\phi^2}\right) = 0. \tag{1.10}$$

Singular near zero of Higgs

B-violation in SM/SC

- Electroweak **instantons**

$$\Gamma_{tunneling}/T^4 \sim \exp(-4\pi/\alpha_w) \sim 10^{-170}$$

- Electroweak **sphalerons** by Klinkhammer-Manton, the barrier's height in the broken vacuum E_{KM}=14 TeV >> Tc (about .1 TeV): too high to climb!

$$\ln(\Gamma/T^4) \approx -40..50$$

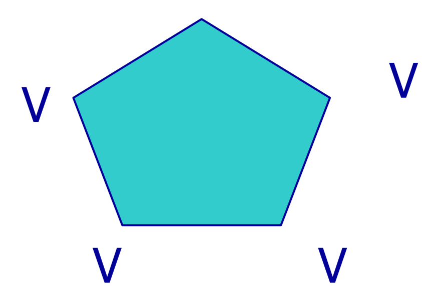
- corrected to T<Tc gives rates
- In the symmetric phase T>Tc rate is too large and can erase any prior asymmetry => bubbles at Tc then?
- No bubbles, as for M_{higgs}>80 GeV electroweak transition is NOT the 1st order (lattice)
- (Experimentally Higgs mass is likely to be in the window around 120 GeV or M_{higgs}>160 GeV)

Recent development in CP

A. Hernandez, T. Konstandin and M. G. Schmidt, Nucl. Phys. B **812**, 290 (2009) [arXiv:0810.4092 [hep-ph]].
A. Tranberg, A. Hernandez, T. Konstandin and M. G. Schmidt, arXiv:0909.4199 [hep-ph].

$$J\frac{\kappa_{CP}}{M^2}\epsilon^{\mu\nu\lambda\sigma}\left(Z_\mu W^+_{\nu\lambda}W^-_\alpha\left(W^+_\sigma W^-_\alpha + W^+_\alpha W^-_\sigma\right) + c.c.\right)$$

The authors claim that this dim-6 next-to-leading order effective action
1) has **J from 4 Ws** as expected, and κ_{CP}(all m's) vanishes for equal masses
2) But converges at the low scale of only the 2nd generations =>
$M^2=m_c^2$ and it has no other small factors (?!?)
The second paper then finds (in real time simulation for the hybrid scenario)
the overall **baryon asymmetry 10^{-6}**
(or 4 orders larger than needed!)



CP violation in hybrid scenario: (my comments)

- **W^4Z operator, dim 6. The field is much larger inside the sphalerons than anywhere else => should be happening in sphalerons?**
- **No, it was not derived for a strong scale field!**

Let us now try to optimize the effect, by looking at all scales $F = m_t, m_b, m_c, m_s$, subsequently. The corresponding expressions and numerical values (for $J = 10^{-5}$ and actual quark masses) are

$$\delta L_{CP}(m_t) \sim \frac{J}{m_t^4}(m_c^2 - m_u^2)(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) \approx 3 * 10^{-13} GeV^4$$

<=at strong field there is Jarlskog suppression

$$\delta L_{CP}(m_b) \sim J(m_c^2 - m_u^2)(m_s^2 - m_d^2) \approx 4 * 10^{-7} GeV^4$$

<=The (LL) fermion mass at T=50 GeV is about (5 GeV)^2 or at m_b scale

$$\delta L_{CP}(m_c) \sim J m_c^2 (m_s^2 - m_d^2) \approx 4 * 10^{-7} GeV^4$$

$$\delta L_{CP}(m_s) \sim m_s^4 J \approx 4 * 10^{-9} GeV^4$$

outside the ``spots" when gauge field is of mb scale, one can generate CP of the right magnitude 10^(-7) or so (also Tranberg, private communication)

1d kinks, an approximation for very large spherical bags with zero

$$-\frac{d^2F(x)}{dx^2} + M_W^2\phi(x)^2F(x) = \omega^2F(x) \qquad (4.1)$$

The effective potential is thus $M_W^2\phi(r)^2$, as it would be for a scalar. If $\phi(x) \sim x$ at small x, this potential is quadratic, creating the oscillatory-like levels with positive ω^2.

The longitudinal polarization gets extra terms in the equation

$$-\frac{d^2L(x)}{dx^2} + M_W^2\phi(x)^2L(x) \qquad (4.2)$$

$$-\frac{2}{\phi(x)}\frac{dL}{dx}\frac{d\phi}{dx} - \frac{2}{\phi}\frac{d^2\phi}{dx^2}L(x) + \frac{2}{\phi^2}\frac{d\phi}{dx}L(x) = \omega^2L(x)$$

which contains the first derivative of the function. In order to remove it the following substitution is used

$$L(x) = \frac{\psi(x)}{\phi(x)} \qquad (4.3)$$

$$\omega^2\psi(x) = -\frac{d^2\psi(x)}{dx^2} + M_W^2\phi(x)^2)$$
$$-\frac{d^2\phi}{dx^2}\frac{\psi(x)}{\phi(x)} + 2\psi(x)\frac{(d\phi(x)/dr)^2}{\phi(x)^2}$$

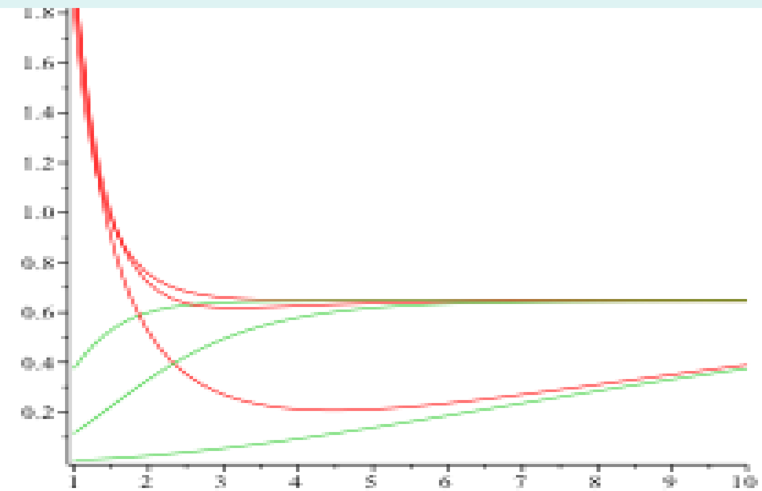


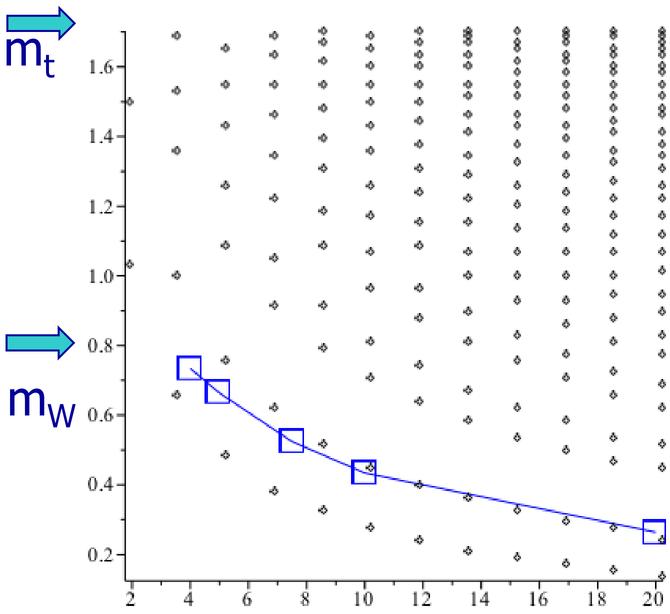
FIG. 2: The effective potential for the W levels $V/(100\,GeV)$ versus the distance $x(100\,GeV)$ from the kink center. The lower (green) curves are for the M modes, the upper (red) ones are for the longitudinal L ones. Three cases shown are for $A/(100GeV) = 0.1, 0.45 and 1$, from bottom to top, respectively.

The lifetime of the top bags: weak decays

t=> b W in vacuum is possible,
(m_t=172 GeV > m_W=80 GeV)
But is it so in the bag?

Not always!

The reason is fermions prefer to have surface bags
And they have zero mode
While the Ws do not!



From Flambaum,ES,
"Ws in the top bags"

The levels vs the bag size.
Large boxes – W levels,
small circles – the t levels

The lifetime of the top bags: strong annihilation

- Calculate assuming thermal bag
- Regulate angular logs

$$\frac{d\sigma_{t\bar{t}\to gg}}{dt} = \frac{4\pi\alpha_s^2}{s^2}[1 + u^2/s^2]$$

$$\frac{d\sigma_{t\bar{t}\to gg}}{dt} = \frac{4\pi\alpha_s^2}{s^2}\left(\frac{t^2 + u^2}{ut}\right)\left(\frac{8}{3} - \frac{6ut}{s^2}\right)$$

$$\tau_{t\bar{t}} = 1/\Gamma_{t\bar{t}} \approx 200/T$$

The time is about 10 times the lifetime of W hot spots in simulations

Do tops change the sphalerons? (the exponent)

Qualitatively speaking, one would expect that as there are more particles in the bags their size would grow and the internal temperature to decrease, with two effects trying to cancel each other.

$$\frac{S(\kappa)}{S(0)} = (\frac{1}{4})[1 + (\frac{7}{4})\kappa]^{5/8} + \frac{3}{4}\frac{1}{[1 + (\frac{7}{4})\kappa]^{3/8}} \qquad (38)$$

Plotting this variation as a function of κ one finds that it changes very little: e.g. for $\kappa = 0.5, 1, 2$ it is 0.96, 0.98, 1.06. We thus find that this effect is basically zero, on the level of uncertainties of the model,and conclude that the bag stabilization condition turns out to be robust enough to keep the exponent of the sphaleron rate basically unchanged.

Kappa is a parameter, the ratio of trapped t in units of trapped W, In “hot spots”