JUNE '09

STOCKHOLM

BARYOGENESIS IN VARIANTS OF THE ELECTROWEAK PHASE TRANSITION

MICHAEL G. SCHMIDT
HEIDELBERG

(Almost) at the beginning of this workshop !

- SOME GENERAL PERSPECTIVES
- OVERVIEW OF SOME OLD AND MORE RECENT MODELS

PHASE TRANSITIONS IN THE EARLY UNIVERSE ARE MOST INTERESTING BECAUSE THEY MIGHT HAVE LEFT TRACES EXPLAINING THE PRESENT UNIVERSE.

CANDIDATES :

- QCD PHASE TRANS.

  BUT : CROSS OVER BEHAVIOR UNLESS LARGE μ (BARYON DENSITY)

  $\rightsquigarrow$ NEUTRON STARS ..?

- ELECTROWEAK PHASE TRANS. :

  THE SUBJECT OF THIS WORKSHOP AND OF THIS TALK $\rightarrow$

- INFLATION / GUT - PHASE TRANS. (.. HYBRID INFLATION)

  MOST IMPORTANT FOR STRUCTURE FORMATION

  BUT : AT 10^{15} GEV ? HARD TO CONTROL BY LABORATORY EXP.

  $\rightsquigarrow$ LOW SCALE INFLATION ?

THE ELECTROWEAK PHASE TRANSITION : $\langle H \rangle = 0 \Rightarrow \langle H \rangle \neq 0$

MIGHT PREDICT

- GRAVITATIONAL WAVES
- SEEDS FOR LARGE SCALE MAGNETIC FIELDS
- PRODUCTION OF A BARYON ASYMMETRY

HOPE TO LEARN MORE ABOUT IN THIS WORKSHOP

THE LATTER IS JUST ONE NUMBER, BUT MOST IMPORTANT FOR OUR UNIVERSE

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} = \left(6.1 \pm {}^{0.4}_{0.3}\right) \cdot 10^{-10}$$

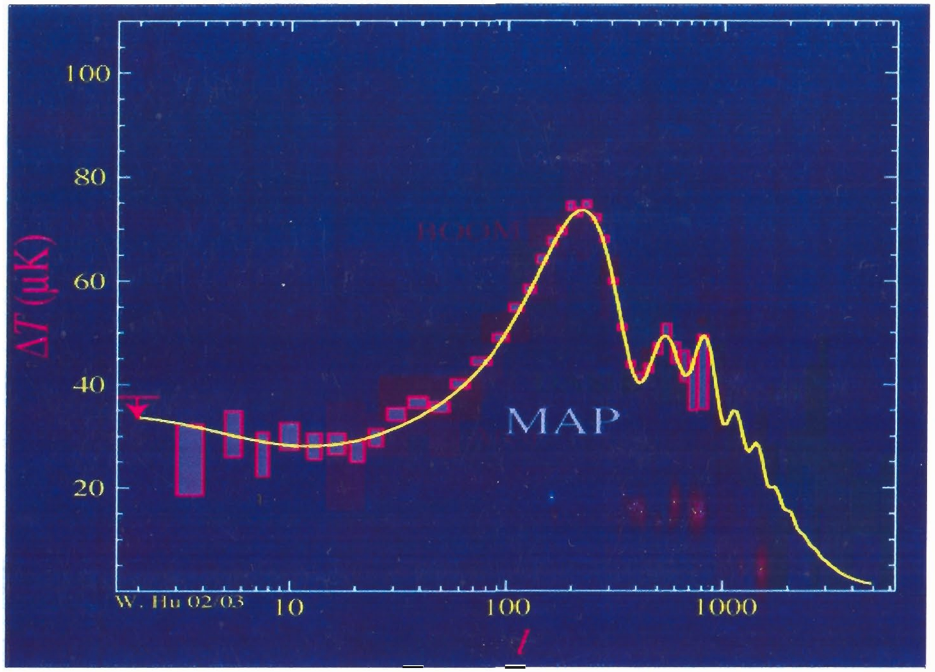
FROM WMAP

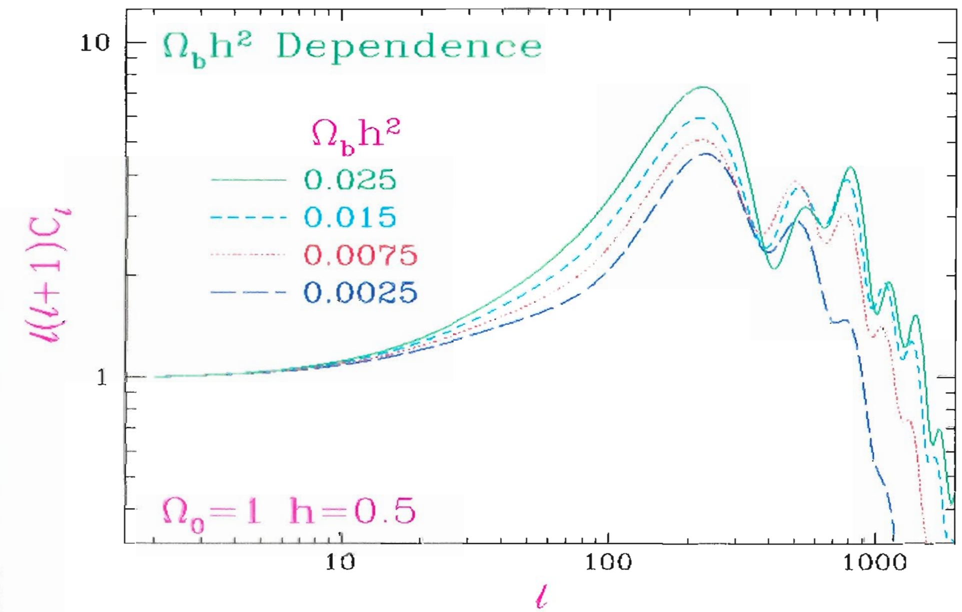
IN AGREEMENT WITH PRIMORDIAL NUCLEOSYNTHESIS

ITS EXPLANATION IS STRONGY RELATED TO ELEMENTARY PARTICLE PH. (SM AND "BEYOND" !)

- IT HAS TO BE GENERATED IN THE EARLY COSMOS AFTER INFLATION

Baryonic matter and cmbr





***baryons:** increase compression **(odd)** peaks, decrease rarefaction peaks*

INFLATION
- SOLVES CAUSALITY PROBLEM IN BIG BANG THEORY
- $\Omega = 1$ ($\rho = \rho_c$) FLAT UNIVERSE
- CREATES FLUCTUATIONS LEADING TO STRUCTURE FORM.

NO PARTICLES LEFT AFTER EXPON. GROWTH

→ HAVE TO CREATE BARYON ASYMMETRY

WELLKNOWN SAKHAROV NECESSARY CRITERIA

- B - VIOLATION ✓ ;
- C, CP - VIOLATION :

IN THE ABSENCE OF PREFERENCE FOR MATTER/ANTIMATTER:

B NONCONS. REACTIONS WILL PRODUCE B AND $\overline{B}$ AT THE SAME RATE;

- NON EQUILIBRIUM : CHEMICAL POT. FOR NONCONSERVED QUANTUM-N. VANISHES ; $m_B = m_{\overline{B}}$ (CPT) → SAME THERMAL DISTRIBUTION

• BARYOGENESIS

SAKHAROV '67

$\cancel{B}$

• ELECTROWEAK SPHALERON
• GUT
• MAJORANA NEUTRINO

$\cancel{C}$ $\cancel{CP}$

• CKM-MATRIX
• PHASES IN NON/EXT. SM
• SPONTANEOUS BREAKING

MODEL

NONEQUILIBRIUM

• EXPANDING UNIVERSE
• OUT OF EQUILIBRIUM DECAY
• PHASE TRANSITION

POSSIBLE IN
SM - ELECTROWEAK
PHASE TRANSITION?
SHAPOSHNIKOV '87

• SPHALERON TRANSITION

SU(2)$_L$ GAUGE THEORY IN SM VIOLATES B+L

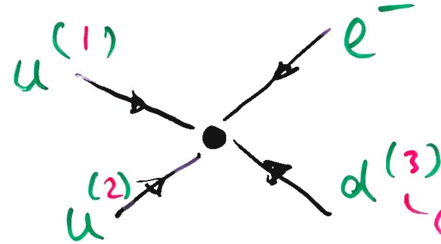
(B−L CONSERVED!)

$$\partial_\mu j^{\mu B} = \frac{g^2 N_F}{\dots} \mathrm{Tr}\, F_{\alpha\beta} \tilde{F}^{\alpha\beta}$$

$$\frac{d}{dt} \int d^3x\, j_0^B = \frac{d}{dt} \underbrace{\int d^3x\, K_0}_{\text{CHERN-SIMONS NUMBER } N_{CS}}$$

⇒ INSTANTON INDUCED TUNNELING IN N_{CS}

$(N \rightarrow N+1)$

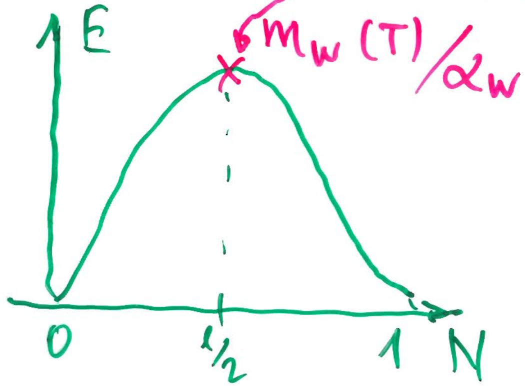


EFF. ACTION (1 GENER.)

$\sim e^{-8\pi^2/g_w^2}$

SMALL!

⇒ THERMAL SPHALERON TRANS.



$$\Gamma_{\not{B}} \sim \dots \alpha_W (\alpha_W T)^4 \exp\left(- \dots \frac{V(T)}{T}\right)$$

UNSUPPRESSED IN SYMMETRIC (HOT) PHASE

EQUILIBRATES INT-EQUILIBRIUM (→ B+L=0)

BÖDEKER, MOORE, RUMMUKAINEN

IN THERMAL TRANSITION FROM "HOT" SYMMETRIC PHASE: $\langle H \rangle = 0$

TO HIGGS PHASE: $\langle H \rangle \neq 0$

$$\langle H \rangle \sim V(T)$$

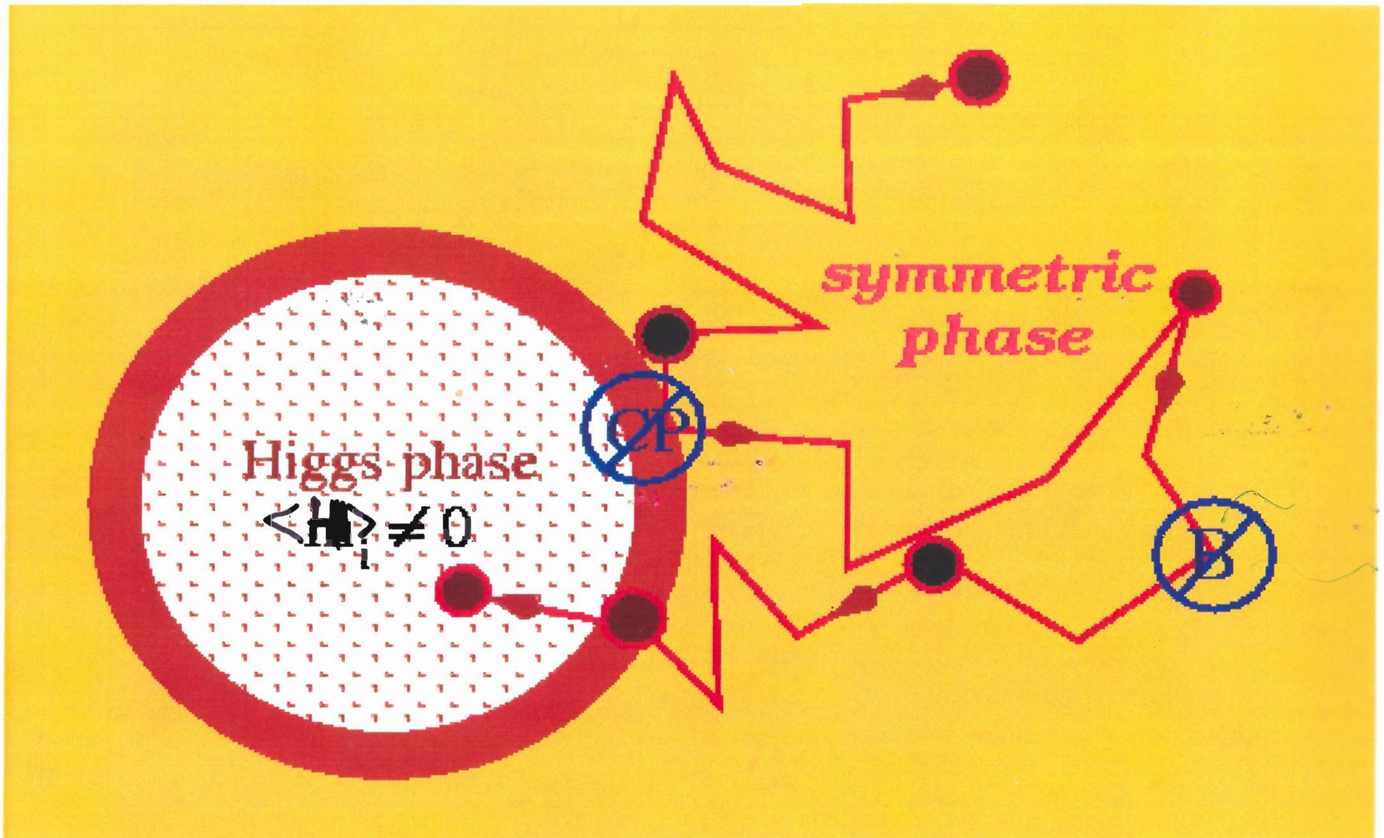
- BARYON ASYMMETRY GENERATED BY (UNSUPRESSED!) HOT SPHALERON TRANSITION ($V = 0$)
- WASH OUT BY SPHALERON ($V(T) \neq 0$) IN HIGGS PHASE STOPPED IF $V(T)/T \gtrsim 1$ (DETAILED LATER) $\Gamma_{SPH.} < H$

$\Rightarrow$ NEED STRONG FIRST ORDER PHASE TRANSITION

EARLY HOPE: PHASE TRANSITION IN SM?

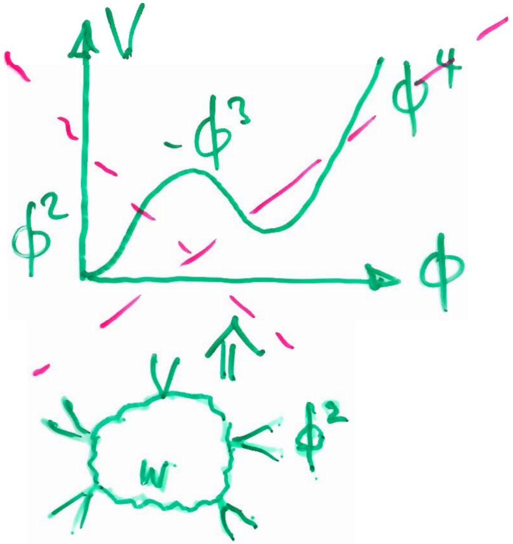
Electroweak baryogenesis at a strong 1st order transition

CHARGE TRANSPORT



- expanding bubbles of higgs phase
- CP violation on bubble walls ⇒ CREATE CHIRAL ASYMM.
- B violation in symmetric phase (SPHALERON)

NEED STRONG FIRST ORDER PHASE TRANSITION



"NAIV" → MORE CONCISE: "INTEGRATE OUT" $n \neq 0$ MATSUBARA MODES

1/2 LOOP PERT. TH. ✓

OBTAIN EFF. 3-DIM. THEORY

(AGAIN GAUGE THEORY WITH HIGGS FIELD, NO FERMIONS)

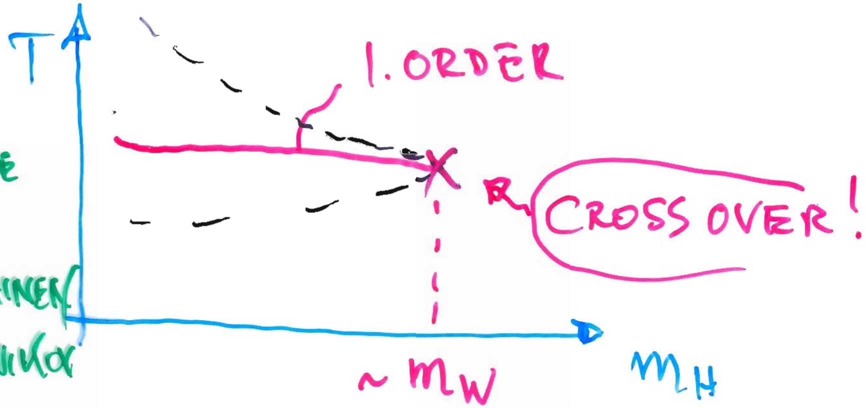
MASS SCALES

$M_H, T \Rightarrow g_W T \Rightarrow g_W^2 T$ CAN BE STRONGLY IR SENSITIVE (TRANSV. GAUGE B.)

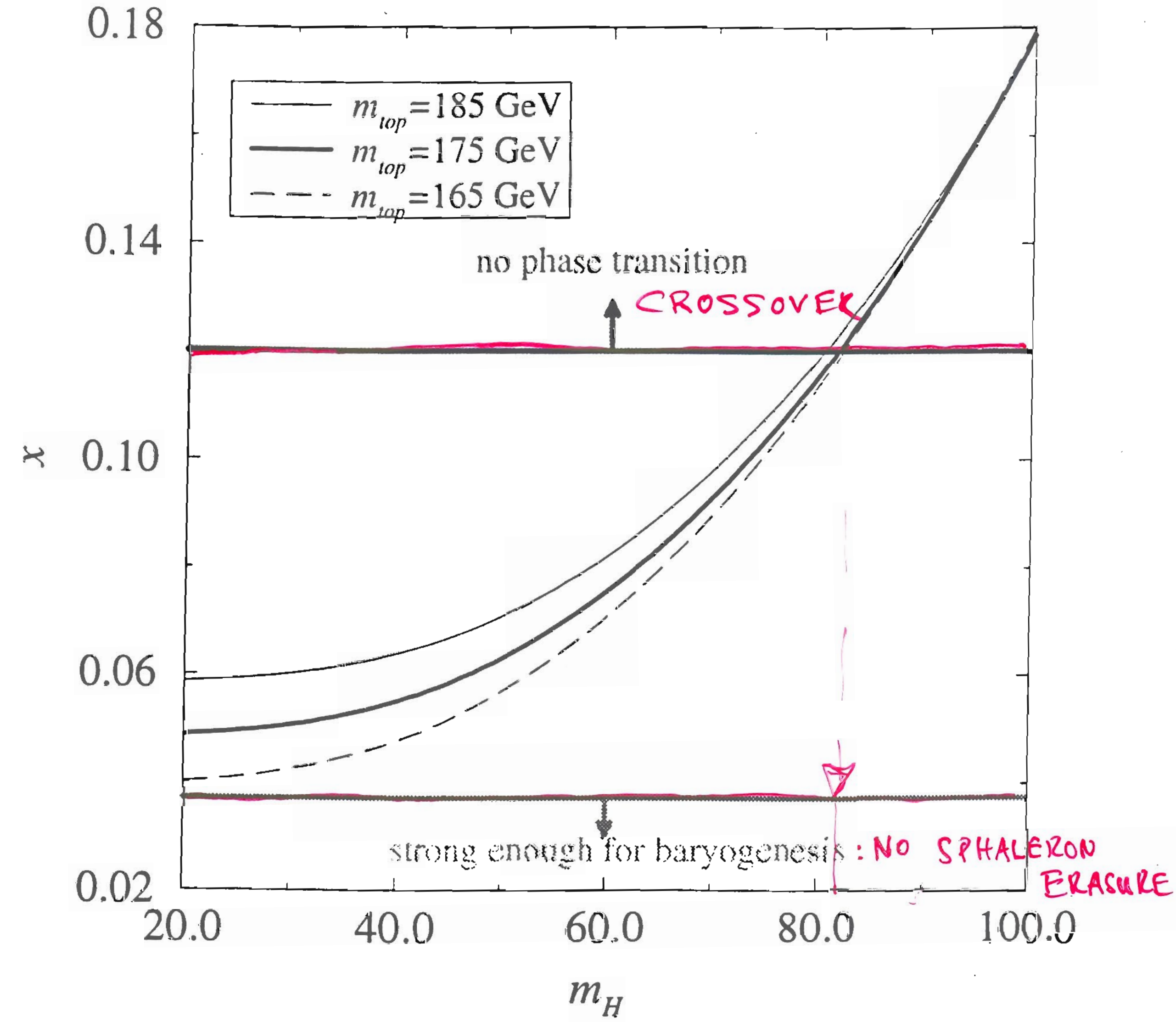
MATSUBARA — DEBYE — 3D THEORY

⇝ LATTICE GAUGE TH. CALC.

KAJANTIE
LAINE
RUMMUKAINEN
SHAPOSHNIKOV



⇒ NO FIRST ORDER PHASE TRANS. IN SM!



KAJANTIE
LAINE
RUMMUKAINEN
SHAPOSHNIKOV

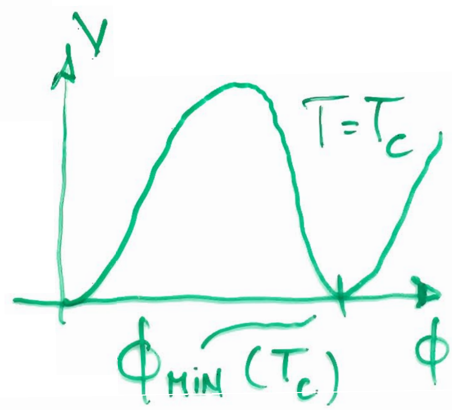
$$X = \underbrace{\frac{\lambda_3(T)}{g_3^2}}_{3D} \sim \underbrace{\lambda_T / g_{WEAK}^2}_{4D} \Longleftrightarrow m_{HIGGS}$$

$$\left(g_3^2 = g_{WEAK}^2 \, T (1 + \dots) \right)$$

$X \lesssim 0.04$

? STRONG 1. ORDER PT

$$\frac{\phi_{MIN}(T_c)}{T_c} \gtrsim 1$$



ALSO ~~CP~~ VERY SMALL !?? (ARGUMENT IN LIT.!)

JARLSKOG DETERMINANT:

$$\Delta_{CP} = J\,(m_u^2 - m_c^2)(m_c^2 - m_t^2)(m_t^2 - m_u^2)(m_d^2 - m_s^2)(m_s^2 - m_b^2)(m_b^2 - m_d^2)/v^{12} \approx 10^{-19}$$

T^{12} ?

WITH $J = |\mathrm{Im}\,(V_{fg} V_{hi} V_{fi}^{*} V_{hg}^{*})| = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta$

$\approx (3.0 \pm 0.3)\, 10^{-5}$

CKM-MATRIX

NOT SO SMALL

INTEGRATING OUT FERMIONS AND EXPANDING IN m^2_{DIAGONAL}

('PERTURBATIV')

MISSLEADING AT SMALL TEMPERATURES IN A TACHYONIC ELECTROWEAK TRANSITION WHERE $\langle \phi^{+}\phi \rangle$ IS INCREASING FROM 0 TO $v^2/2$?

$\rightsquigarrow$ 'COLD BARYOGENESIS'

(NONPERTURBATIV IN m^2)

$\rightsquigarrow$ ANDERS TRANBERG'S TALK!

(i) "FINITE TIME QUENCH" CHANGE SIGN OF ϕ^2-TERM!

MODEL: INTRODUCE INFLATON FIELD IN ELECTROWEAK SM

→ LOW SCALE HYBRID INFLATION

$$V(\sigma,\phi) = \frac{\lambda}{4}(\phi^2-\mu^2)^2 + \frac{1}{2}g^2\phi^2\sigma^2 + \frac{1}{2}m_\sigma^2\sigma^2 + \ldots$$

$\langle\phi^2\rangle \neq 0$ FOR $\sigma^2 < \frac{\lambda}{g^2}\mu^2$

σ DECREASING

INVERTED HYBRID INFLATION

ref. in
COPELAND
LYTH
RAJANTIE
TRODDEN

$$V(\sigma,\phi) = \frac{\lambda}{4}\phi^4 + \frac{1}{2}m^2\phi^2 - \frac{1}{2}g^2\phi^2\sigma^2 + \frac{1}{q}\kappa_q\sigma^q - \frac{1}{p}\kappa_p\sigma^p$$

$(q>p>4)$

$\langle\phi^2\rangle \neq 0$ FOR $\sigma^2 > \ldots$

σ INCREASING

HAS BETTER CONTROL OF RADIATIVE CORRECTIONS (KEEP INFLAT. POT "FLAT")

FIT TO COSMOL. DATA POSSIBLE (FINETUNING?)

HYBRID INFLATION

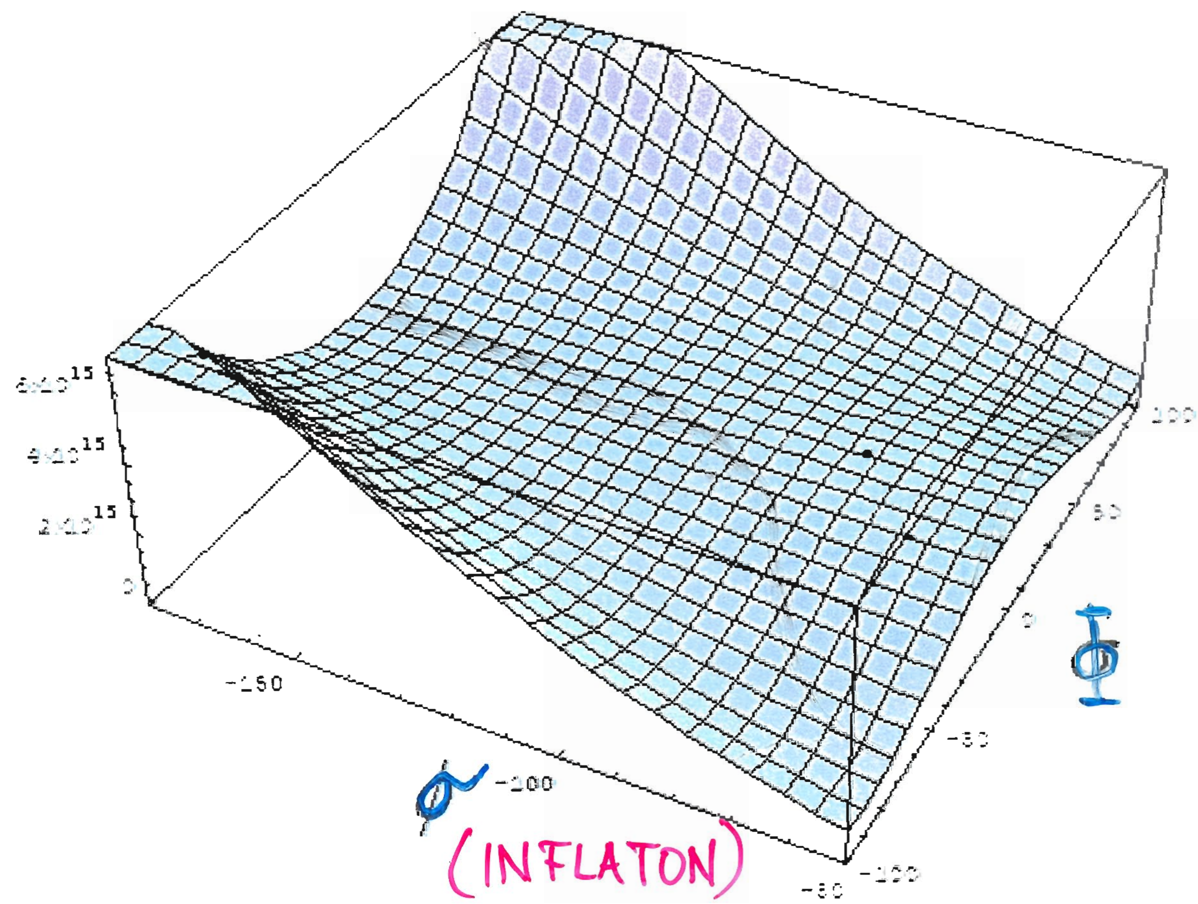


Figure 1: Hybrid Potential, using $m_{pl} = 10^9$, $\lambda = 10^4$, $g = 8 \cdot 10^3$, $m = 1.5 \cdot 10^{-5} m_{pl}$, and $M = 10^{-3} \cdot m_{pl}$.

SIMPL. • "FINITE TIME QUENCHES"

A. TRANBERG, J. SMIT, M. HINDMARCH, VAN DER MEULEN, SEXTY

$$\mu^2_{eff}(t)\,\phi^+\phi \quad \text{WITH} \quad \mu^2_{eff}\begin{cases} = \mu^2\left(1-\frac{2t}{t_Q}\right) & 0<t<t_Q \\ = -\mu^2 & t>t_Q \end{cases}$$

• TENTATIV CP VIOLATING TERM

$$\kappa\,\phi^+\phi\,F^{\mu\nu}\tilde{F}_{\mu\nu} \qquad \kappa = 3\delta_{CP}/16\pi^2 m_W^2 \qquad ??$$

?

• SOON AFTER μ^2_{eff} IS GETTING NEGATIV : "TACHYONIC PREHEATING"

IR MODES ARE GETTING UNSTABLE → GROWING → CLASSICAL EQS.

NONLINEAR TERMS IN EOM UNIMPORTANT

$$\ddot{\phi}_k + k^2\phi_k + \underbrace{\mu^2_{eff}(t)}_{neg.}\phi_k = 0 \qquad \phi_k \sim e^{(-\mu^2-k^2)t}$$

$k^2<|\mu^2|$ "IR"

• STUDY CLASSICAL EOM'S ON LATTICE WITH INITIAL CONDITIONS :

→ TIME DEPENDENCE OF $\langle\phi^+\phi\rangle$

→ $N_{CS}(t) - N_{CS}(0) = \frac{1}{16\pi^2}\int_0^t dt' \int d^3x\, F^{\mu\nu}\tilde{F}_{\mu\nu} \Leftrightarrow$ BARYON NUMBER

- ALSO 'HIGGS WINDING'

$$N_W = \frac{1}{24\pi^2}\int d^3x\, \epsilon_{ijk}\, \mathrm{Tr}\left[U^\dagger(\partial_i U)\, U^\dagger(\partial_j U)\, U^\dagger(\partial_k U)\right]$$

UNITARY GAUGE

$$U = \Phi \Big/ \left(\tfrac{1}{2}\mathrm{Tr}\,\Phi^\dagger\Phi\right)^{1/2}$$

START WITH $N_{CS} = N_W = 0$

FINALLY $N_{CS} = N_W \neq 0$

POSITIONS WITH $\phi^*\phi = 0$

IMPORTANT FOR CHANGE!

$\left(\Gamma_{SPHALERON} = \frac{d\,\Delta_{CS}}{dt} \right.$ in THERMAL EQUIL. $\Big)$

- $\frac{n_B}{n_\gamma} = (0.20 \pm 0.04) \times 10^{-3}\, \delta_{CP}$ FOR $m_H = 2m_W$, $m_H t_Q = 18$

OPTIMAL CHOICE

BUT: WHAT IS THE REAL ~~CP~~ TERM IN THE (EXT.?) SM?

EARLIER WORK BY GARCIA-BELLIDO, GRIGORIEV, SHAPOSHNIKOV, KUSENKO ...
COPELAND, LYTH, RAJANTIE, TRODDEN

(ii) DERIVE CP VIOLATING TERM(S) IN BOSONIZED SM :

EFFECTIVE ACTION INTEGRATING OUT FERMIONS

J. SMIT, METH. SALCEDO

A. HERNANDES
T. KONSTANDIN
M.G. SCH.

NEED SECOND ORDER (NEXT TO LEADING)
DERIVATIVE EXPANSION!
WORLDLINE METHOD OPTIMAL

OUTER GAUGE BOSONS
+ (PSEUDO) SCALARS

MONDRAGON, NELLEN, SCH., SCHUBERT
D'HOOKER, GAGNIER

$$S_{\cancel{CP}} = \frac{1}{8(4\pi)^2}\frac{3}{16} J\, \kappa^{CP} \epsilon^{\mu\nu\lambda\sigma} \frac{1}{\tilde{m}_c^2} \times$$

$$\int d^4x \left[Z_\mu W^+_{\nu\lambda} W^-_\alpha \left(W^+_\sigma W^-_\alpha + W^+_\alpha W^-_\sigma \right) + c.c \right]$$

$\kappa^{CP} \simeq 8.87$ $\quad J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta \simeq (3.0 \pm 0.3)\, 10^{-5}$

$$W^+_{\mu\nu} = \frac{\phi^+ W_{\mu\nu} \tilde{\phi}}{\phi^+\phi} \;\ldots\; W_\mu^+ = \frac{\phi^+ \mathcal{D}_\mu \tilde{\phi}}{\phi^+\phi} \quad Z_\mu = W_\mu^3 - B_\mu = \frac{\phi^+\mathcal{D}_\mu\phi - \tilde{\phi}\mathcal{D}_\mu\tilde{\phi}}{2\phi^+\phi}$$

$(\tilde{\phi} = \epsilon\, \phi^*)$

$$
\lim \frac{\kappa^{CP}}{\tilde m_c^2} = \frac{32}{9\tilde m_c^2\left(\tilde m_c^2-\tilde m_s^2\right)^3\left(\tilde m_c^2-\tilde m_t^2\right)^3\left(\tilde m_s^2-\tilde m_t^2\right)^2}\times
$$

$$
\Big(\tilde m_s^6\tilde m_t^6\left(\tilde m_s^2-\tilde m_t^2\right)^2+3\tilde m_c^{14}\left(\tilde m_s^2+\tilde m_t^2\right)
$$

$$
-5\tilde m_c^2\tilde m_s^4\tilde m_t^4\left(\tilde m_s^2-\tilde m_t^2\right)^2\left(\tilde m_s^2+\tilde m_t^2\right)-12\tilde m_c^{12}\left(\tilde m_s^4+\tilde m_t^4\right)
$$

$$
+\tilde m_c^4\tilde m_s^2\tilde m_t^2\left(\tilde m_s^2-\tilde m_t^2\right)^2\left(13\tilde m_s^4+28\tilde m_s^2\tilde m_t^2+13\tilde m_t^4\right)+18\tilde m_c^{10}\left(\tilde m_s^6+\tilde m_t^6\right)
$$

$$
+\tilde m_c^8\left(-12\tilde m_s^8+37\tilde m_s^6\tilde m_t^2-74\tilde m_s^4\tilde m_t^4+37\tilde m_s^2\tilde m_t^6-12\tilde m_t^8\right)
$$

$$
+\tilde m_c^6\left(3\tilde m_s^{10}-41\tilde m_s^8\tilde m_t^2+41\tilde m_s^6\tilde m_t^4+41\tilde m_s^4\tilde m_t^6-41\tilde m_s^2\tilde m_t^8+3\tilde m_t^{10}\right)\Big)
$$

$$
-\frac{64\,\tilde m_c^4\tilde m_s^2\tilde m_t^2\left(\tilde m_c^2-\tilde m_t^2\right)\left(\tilde m_c^2-3\tilde m_s^2+2\tilde m_t^2\right)\log\left[\frac{\tilde m_s^2}{\tilde m_c^2}\right]}{3\left(\tilde m_c^2-\tilde m_s^2\right)^4\left(\tilde m_s^2-\tilde m_t^2\right)^3}
$$

$$
+\frac{64\,\tilde m_c^4\tilde m_s^2\left(\tilde m_c^2-\tilde m_s^2\right)\tilde m_t^2\left(\tilde m_c^2+2\tilde m_s^2-3\tilde m_t^2\right)\log\left[\frac{\tilde m_t^2}{\tilde m_c^2}\right]}{3\left(\tilde m_c^2-\tilde m_t^2\right)^4\left(\tilde m_s^2-\tilde m_t^2\right)^3}
$$

ALREADY SIMPLIFIED!

FOR $\tilde m_u \to \tilde m_d \to 0$

$\tilde m_b \to \tilde m_c$

---

22 SALCEDO : • ~~CP~~ - PART FROM W^+ {P CONSERVING}

- • PROPOSAL FOR A DIRECT CALCULATION OF W^- VERY RECENT
- – WE JUST CHECK THIS

IN PROGRESS WORK WITH A. TRANBERG : "COLD BARYOGENESIS" WITH OUR ~~CP~~-TERM

REMARKS:

- IF AS A RESULT OF TIME VARIATION IN THE YUKAWA COUPLINGS QUARK MASSES WERE LARGE AT THE TIME OF THE ELWK. TRANS. THE KM MECHANISM IS STRONGLY ENHANCED

BERKOOZ
NIR
VOLANSKY
(WITH FN MECHAN.)

- THE SM ENLARGED BY R.H. SINGLET NEUTRINOS OFFERS VERY INTERESTING NEW POSSIBILITIES FOR CP VIOLATION, DARK MATTER ... "νMSM"

SHAPOSHNIKOV
ASAKA
GORBUNOV
KHLEBNIKOV
KUSENKO
TKACHEV

BARYOGENESIS: 3 SINGLET NEUTRINOS S_i WITH $M_2 \sim M_3 \sim$ GeV

$|M_2 - M_3| \sim M_1 \sim$ keV !

ASAKA, SHAPOSHNIKOV
$\rightsquigarrow$ AKHMEDOV, RUBAKOV, SMIRNOV

- OSCILLATE AND MIX WITH L.H. NEUTRINOS

LEPTON NUMBER IN 2,3 GENERATED VIA THERMALIZATION

$\xrightarrow{\text{HOT}}$ SPHALERON BARYON NUMBER

- S_1 NOT THERMALIZED ABOVE T_{PT} $\rightarrow$ DARK MATTER CAND.

(NO BARYON NUMBER GEN.!)

- STILL CLOSE TO THE SM : ELECTROWEAK PHASE TRANS. IN THE RANDALL-SUNDRUM MODEL

NARDINI
QUIROS
WULZER

→ CREMINELLI
NICOLIS
RATTAZZI

IR - BRANE SUBSTITUTED BY BLACK HOLE HORIZON AT LARGE TEMPERATURES, CONDENSATES TO USUAL RS-IR-BRANE. RADION IS STABILIZED BY GOLDBERGER-WISE MECHANISM. THE CRITICAL TEMPERATURE T_c IN SUB-TEV-RANGE, BUT ACTUAL NUCLEATION T_N IS ORDERS BELOW DUE TO THE FLATNESS OF THE RADION STABILIZING POTENTIAL (⇝ LOW SCALE INFLATION), i.e. STRONG SUPERCOOLING, STRONG FIRST ORDER PT

HIGGS ON THE IR BRANE ($\phi \neq 0$ IN EFF. TH.)

ADD CP-VIOLATION → BARYOGENESIS

NQW '07

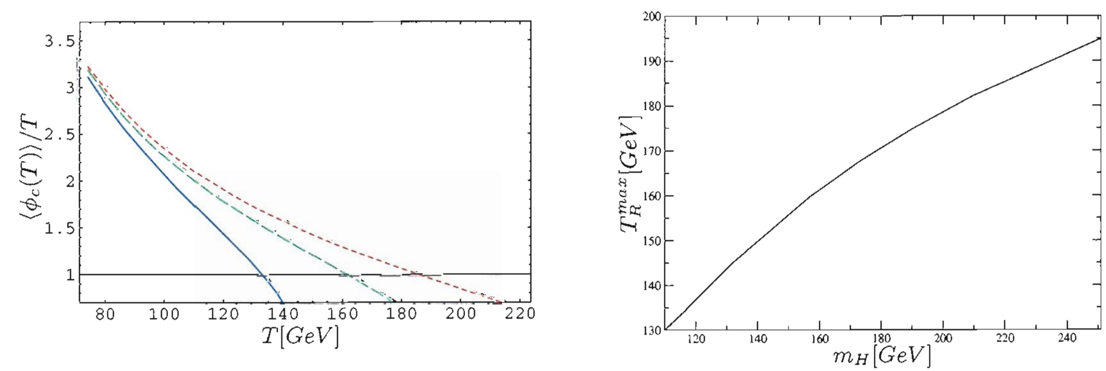


Figure 6: Left panel: Plot of $\langle\phi_c(T)\rangle/T$ as a function of the temperature in GeV for a Higgs mass of 115 GeV (solid line), 165 GeV (dashed) and 225 GeV (short dashed). Right panel: Plot of the temperature at which the SM potential is minimized at $\langle\phi_c(T)\rangle/T = 1$ as a function of the Higgs mass in GeV.

- HIGHER DIMENSION OPERATORS IN THE EFFECTIVE THEORY INCLUDING THE SM (RESP. MSSM ...)

ZHANG

BLUM, NIR ("BEYOND MSSM" + ref.!)

D. BÖDEKER
L. FROMME
S. HUBER !
M. SENIUCH

GROJEAN
SERVANT
WELLS

LOW SCALE CUT OFF, MODIFY SM - HIGGS SELF INTERACT.

- $$V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{1}{8M^2}\phi^6$$

- $$W_{DST} = \frac{\lambda_1}{M}(H_u H_d)^2 + \frac{\lambda_2}{M}\theta^2 m_{SUSY}(H_u H_d)^2$$

DINE, SEIBERG, THOMAS

HELPS TO OBTAIN STRONG FIRST ORDER PT

BEYOND THE SM MODELS

- TWO-HIGGS DOUBLET MODEL(S)

FROMME
HUBER
SENIUCH

- SUPERSYMMETRIC MODELS
  - MOST POPULAR MSSM
  - INCLUDE GAUGE SINGLET CHIRAL SUPERFIELD S

ELLWANGER ET. ..

S. HUBER
M.G. SCH.
FUNAKUBO ET AL.
...

NMSSM : $W = W_{MSSM} + \lambda S \mathbb{H}_1 \epsilon \mathbb{H}_2 - m^2 S + \frac{k}{3!} S^3 + \mu \mathbb{H}_1 \epsilon \mathbb{H}_2$

nMSSM : $W = W_{MSSM} + \lambda S \mathbb{H}_1 \epsilon \mathbb{H}_2 - m^2 S$

+ SUSY (SOFT) BREAKING TERMS

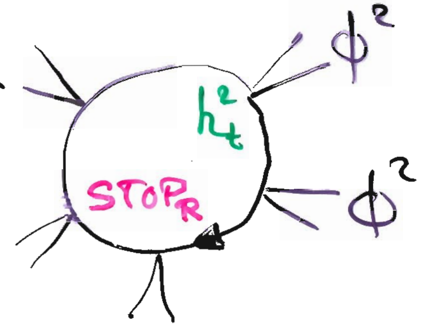
PANAGIOTKOPOULOS ET AL. PILAFTSIS

MENON, MORRISSEY, WAGNER
HUBER, KONSTANDIN, PROKOPEC, SCH.

MSSM

- INCREASE "ϕ^3"-TERM WITH A LIGHT S-TOP$_R$ IN THE LOOP

IN 3D EFFECTIVE THEORY : COLORED U SCALAR



$$m^2_{LOOP} = \underbrace{\tilde{m}_U^2}_{\text{SUSY BREAKING}} + \ldots T^2 + \log\ldots \quad \text{SMALL!}$$

$$\left(m^2_{STOP_R} = \tilde{m}_U^2 + \underbrace{m^2_{TOP}}_{h_t^2\phi^2} \quad \text{FOR } T=0 \right)$$

CARENA
QUIROS
WAGNER

$\tilde{m}_U^2$ NEGATIV

- GET $L_3^{EFF.}$ IN U AND H $\Rightarrow$ LATTICE CALC. / 2 LOOP PERT. TH. } ROUGHLY AGREE!

$\Rightarrow$ FOR A RANGE OF $\tilde{m}_U^2$ THERE IS AN (INTERMEDIATE?!) COLORED U PHASE

- CAN GET STRONG FIRST ORDER P.T. TO HIGGSPHASE $\left(\frac{V(T)}{T} \gtrsim 1\right)$

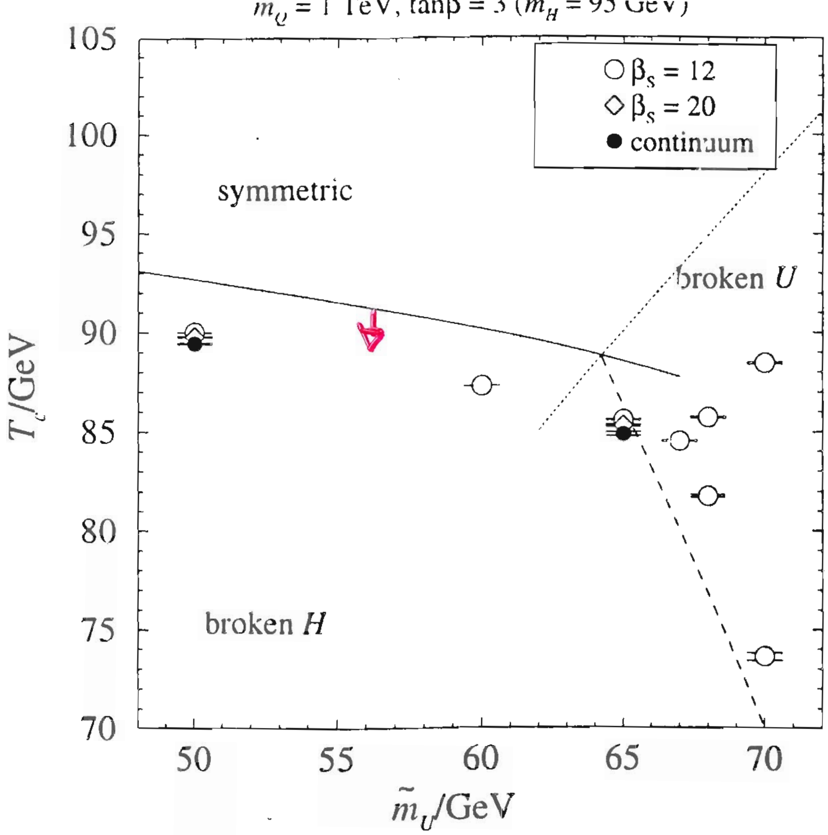


FIG. 1. The phase diagram and the critical temperatures. The continuous lines are from the 2-loop perturbative effective potential in the Landau gauge. Open symbols correspond to infinite volume extrapolations, and filled symbols to continuum limit extrapolations.

LATTICE

LAINE
RUMMUKAINEN
hep-ph/9804255

VS.

2-LOOP
PERT. TH.

BÖDEKER
JOHN
LAINE
SCH.

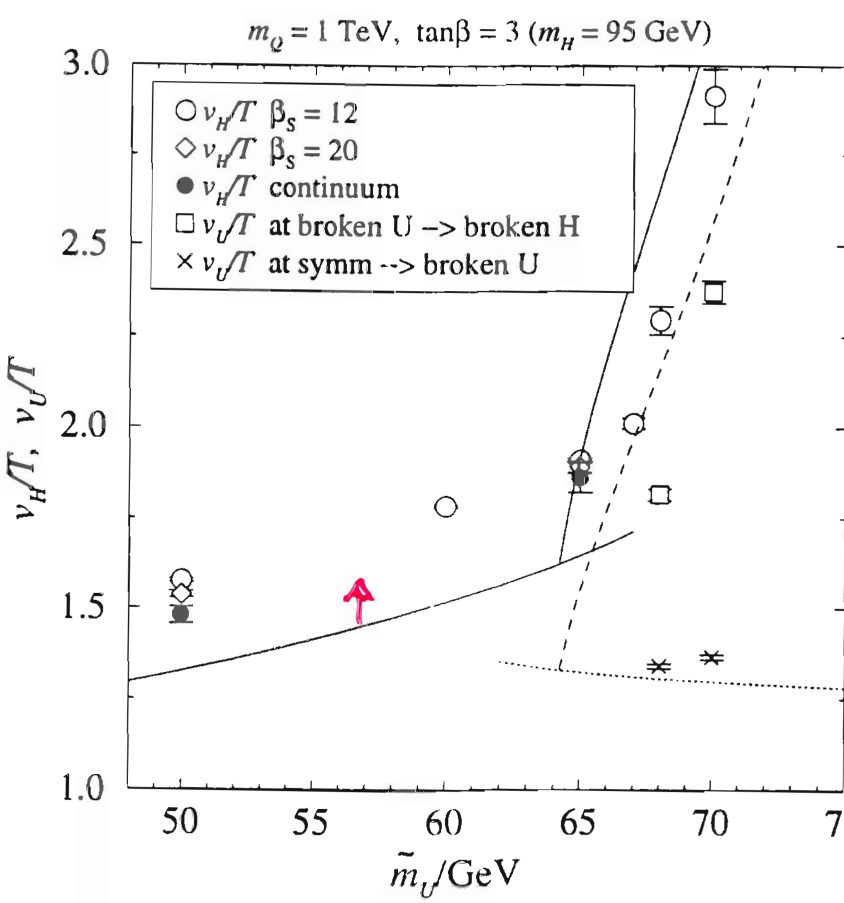


FIG. 3. The scalar field expectation values in the broken phases at T_c.

NONPERT.
EFFECTS:

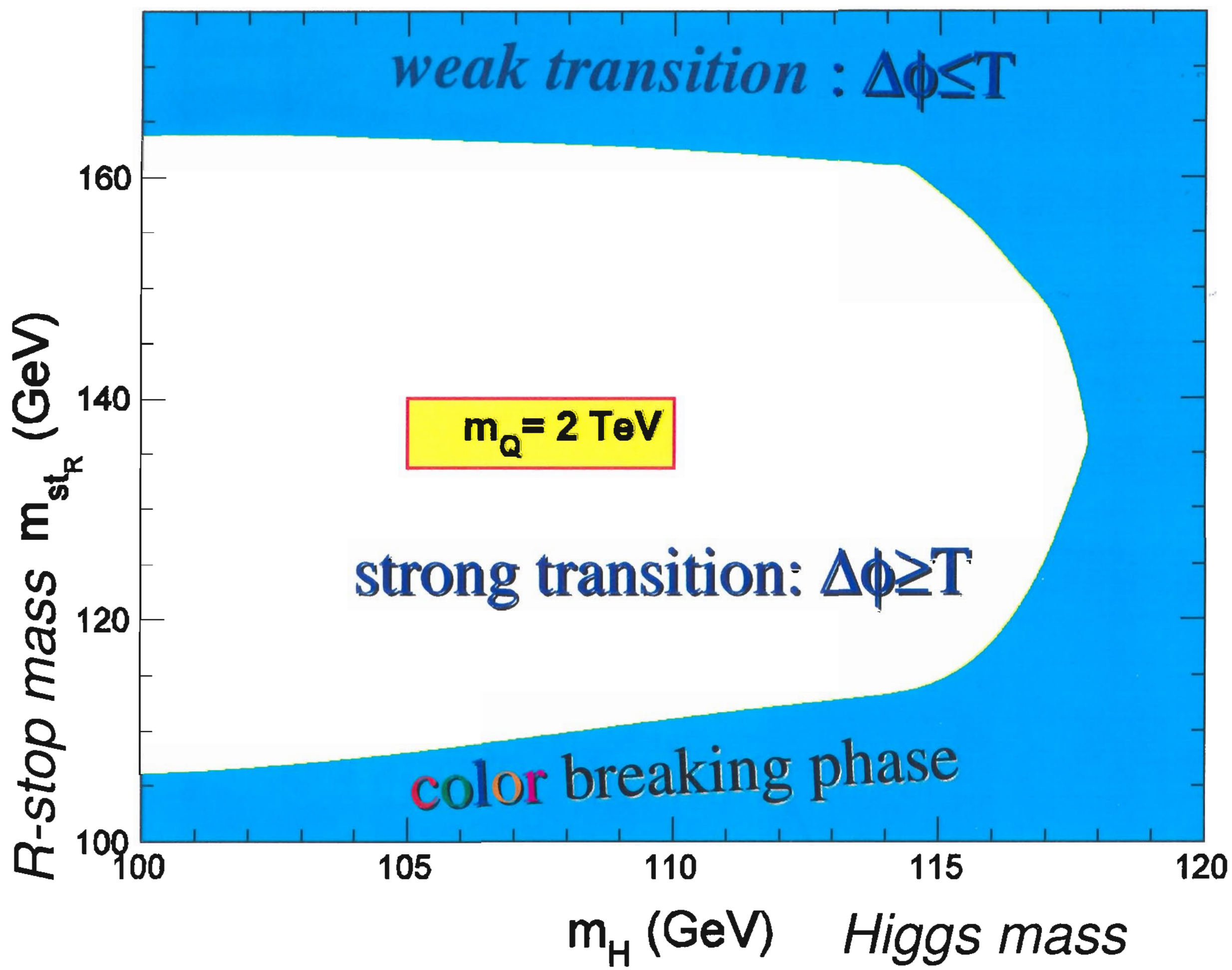
⇒ STRONGER
P.T.

! $\tilde{m}_u^2$ NEGATIV

Strong first order transition in MSSM

allowed "triangle" for MSSM:

Carena, Quiros, Seco, Wagner, 2000

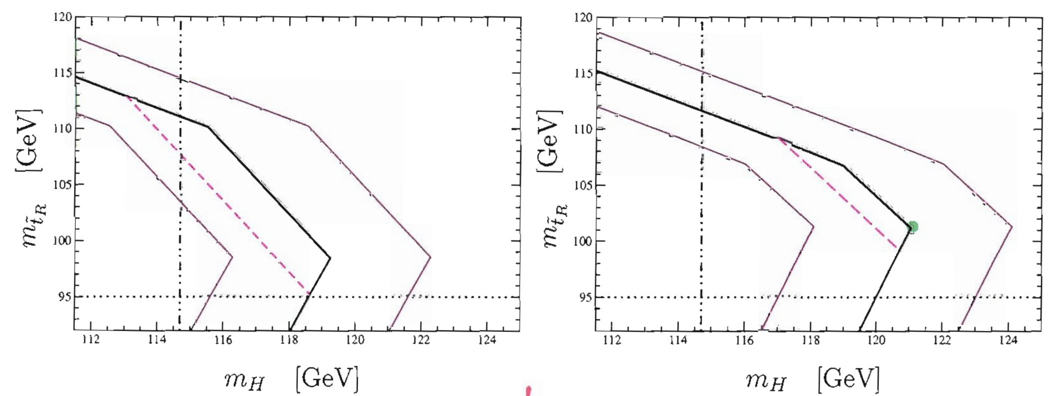


CARENA, NARDINI, QUIRÓS, WAGNER

'08 ANALYSE IN 1-LOOP IMPROVED (DAISY, "2-LOOP" LOG's) THEORY THE PHASE DIAGRAM. FIND EXTENSION OF "ALLOWED" REGION IN (m_{stop_R} - m_H) ADMITTING QUASI STABLE H-VACUA FOR LARGE SUSY MASS SCALE $\tilde{m}$

(!NOT IN EFF. 3D THEORY)

(THUS ALSO SUPPRESSING EDM)



!

Figure 3: Window where $\phi(T^c_H)/T^c_H \geq 0.9$ and $T^c_H \geq T^c_U + 1.6$ GeV in the m_H-$m_{\tilde{t}}$ plane for $\tilde{m} = 500$ TeV (left panel) and $\tilde{m} = 8000$ TeV (right panel). The allowed region is below the solid lines and dashed lines for $\tan\beta \leq 15$ and $\tan\beta \leq 5$, respectively. The thick solid line is obtained by ignoring the Higgs mass uncertainty, while the solid thin lines is obtained by including an uncertainty of 3 GeV in the Higgs mass computation. The Higgs (stop) mass lower bound is marked by a dotted–dashed (dotted) straight line. In green (right panel) the point that will be numerically analyzed in the tunneling analysis.

'09 FUNAKUBO, SENAHA

MSSM-BARYOGENESIS ANALYZED IN THE "LIGHT HIGGS BOSON SCENARIO" (LHS)

- $g_{hZZ} / g_h^{SM}{}_{ZZ} = \sin(\beta-\alpha)$ SMALL $\quad g_{HZZ} / g_h^{SM}{}_{ZZ} = \cos(\beta-\alpha)$ ...

($\simeq 0.5 \rightarrow m_h \sim 100$ GeV)

- CHOICE $m^2_{\tilde{t}_R}(T) = m^2_{\tilde{t}_R} + \cancel{cT^2} \approx 0.$ NEGLECTED ?! NO "DAISIES"

- REANALYSIS OF $v(T_{NUCLEATION})/T_N$ NEEDED FOR SPHALERON DECOUPLING > 1.38 ! ($\rightarrow$ "BARYOGENESIS INFEASABLE" ?!)

- RESTRICTIONS BY B-PHYSICS DATA

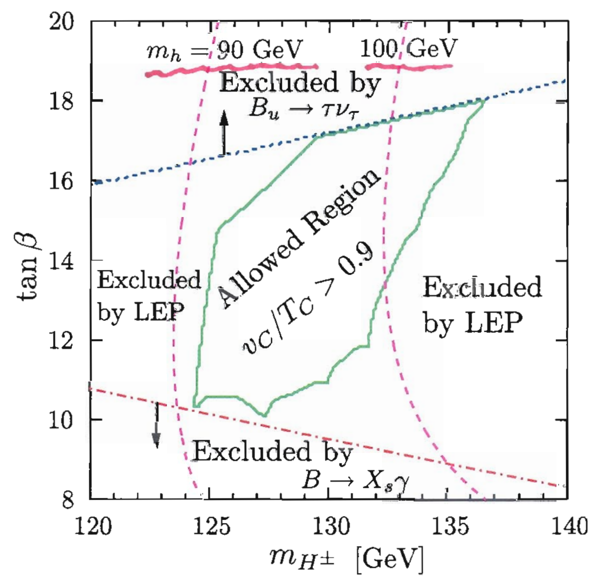
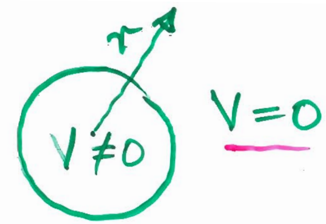


FIG. 3: The allowed region in the LHS. We take $A_t = A_b = -300$ GeV, $\mu = 100$ GeV, $m_{\tilde{q}} = 1200$ GeV, $m_{\tilde{t}_R} = 10^{-4}$ GeV and other input parameters are presented in the text.

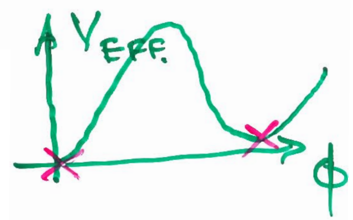
CONDITIONS FOR A STRONG FIRSTORDER ELWK. PT. MUCH EASIER TO FULFILL IN THE NMSSM, nMSSM → FIG.

GIVEN SUCH A STRONG PHASE TRANSITION THE PROCEDURE TO OBTAIN A BARYON ASYMMETRY HAS QUITE A FEW STEPS, <u>BUT</u> ALL OF THEM VERY CONCRETE AND FEASABLE

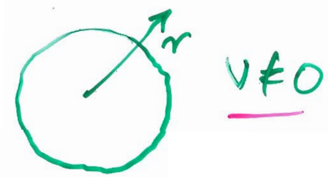
- CRITICAL BUBBLE (MULTIDIM. IN HIGGS FIELDS) → FIG. ("DET"!)



- TRANSITION PROBABILITY (LANGER FORM.) $\sim e^{-S_{EFF}}$

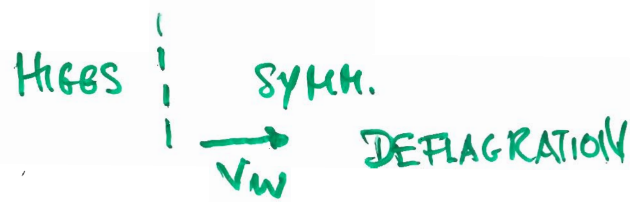


- SUPERCOOLING ("1 BUBBLE/UNIVERSE") NUCLEATION TEMPERATURE
- SPHALERON RATE (MULTIDIM. IN HIGGS F.) (FLUCTUATIONS!)



- STATIONARY EXPANSION OF BUBBLE

→ $V_W = ?$, WALL PROFILE



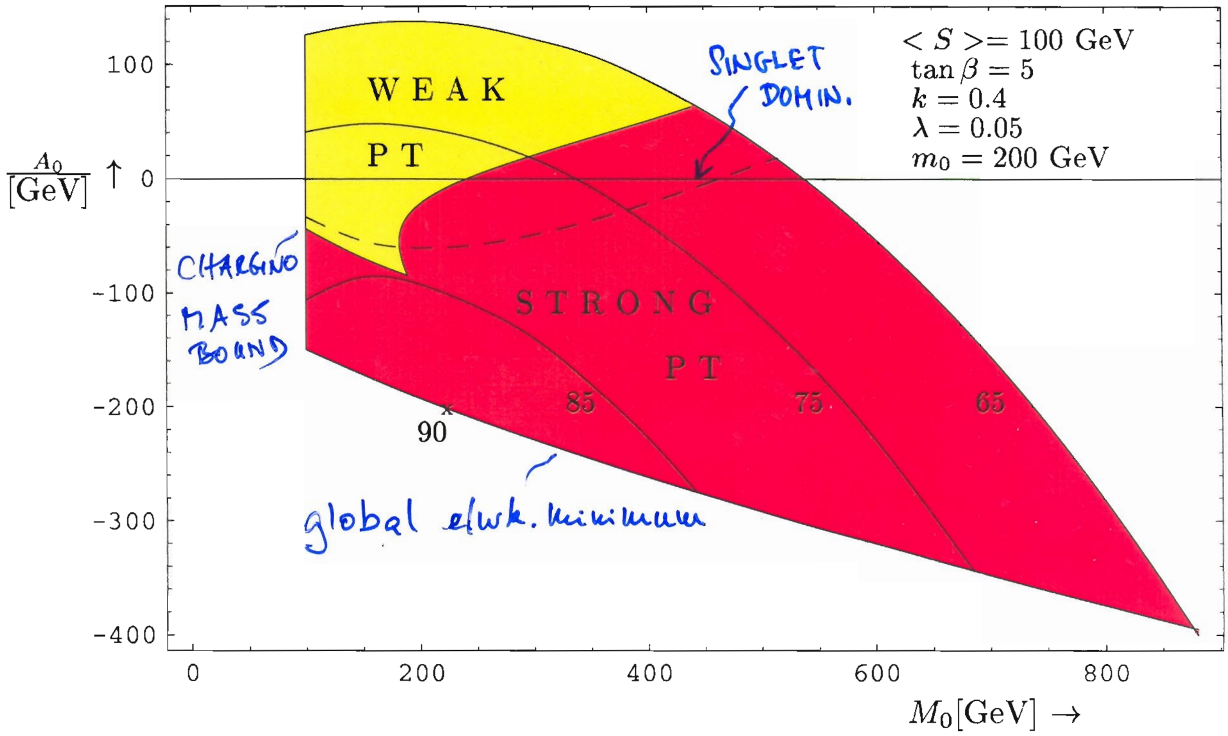
- DIFFUSION IN PRESENCE OF MOVING WALL

→ WITH CP-VIOLATING WALL OR EXPLICIT ~~CP~~ INTERACTION (QUANTUM) BOLTZMANN EQS. , GENERATE CHIRAL ASYMMETRY $n_{q_L} - n_{\bar{q}_L}$

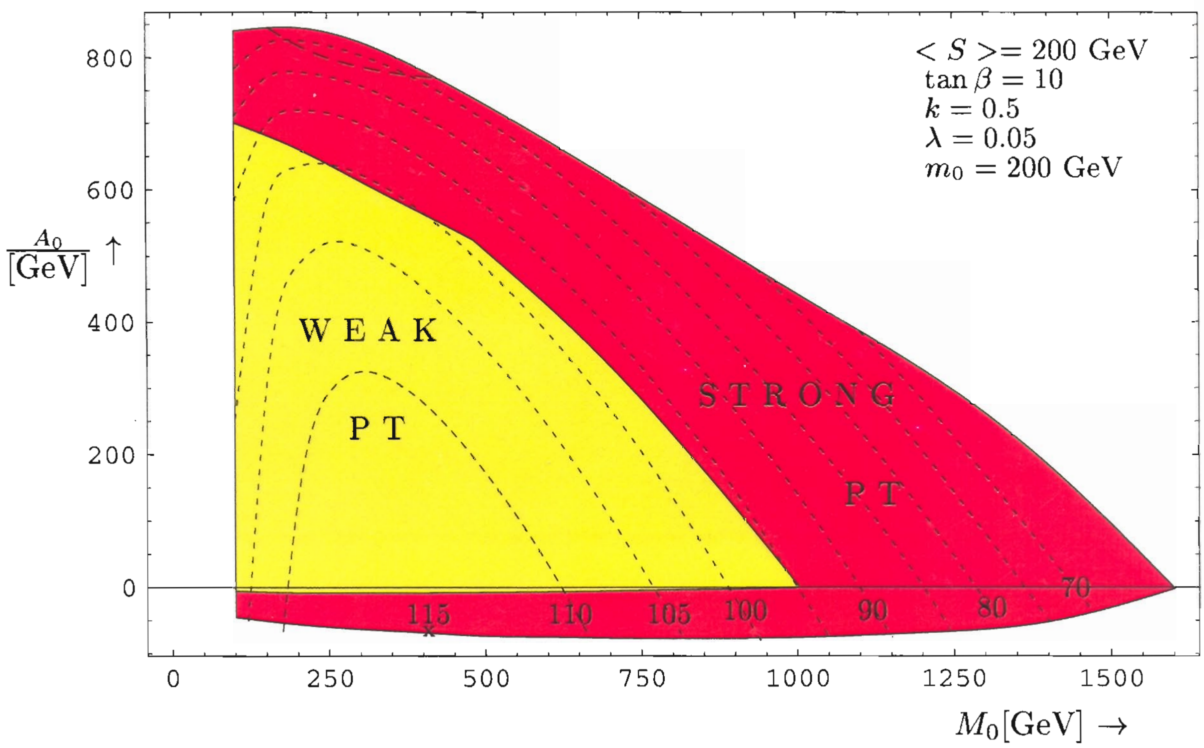
NMSSM | RESULTS for strength of the PT : 13

S. HUBER
M.G. SCH.

<S>=100 GeV



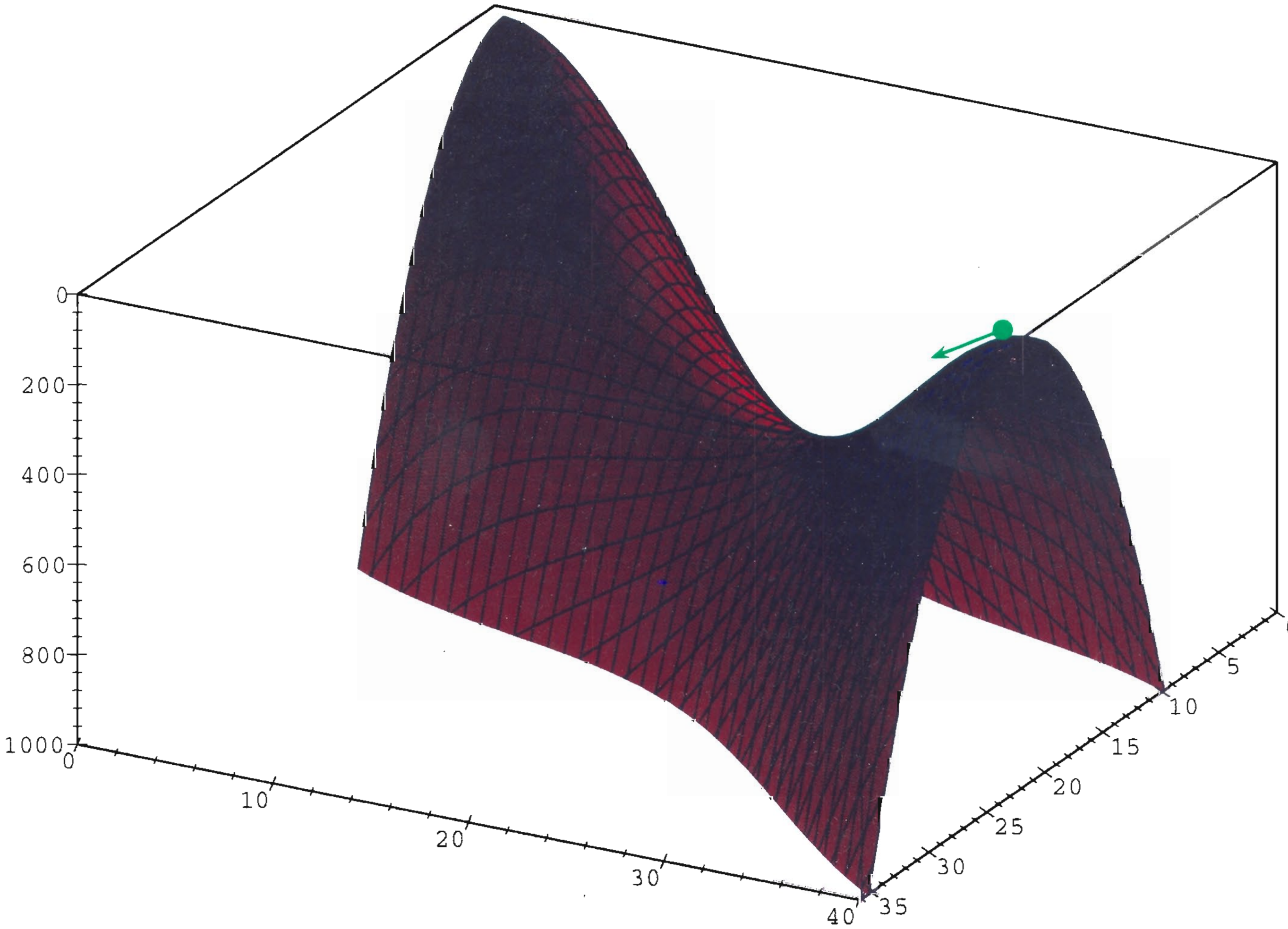
<S>=200 GeV



$M_H^{max} = 115$ GeV and $\frac{v_c}{T_c} > 1$

P. JOHN

Thermisches Tunneln mit mehr als einem Skalarfeld



MORE RECENT WORK BY S. HUBER + T. KONSTANDIN

- PRODUCTION OF LH QUARKS VIA DIFFUSION

  $\cancel{B}$ BY "HOT" SPHALERON OF ELWK. THEORY IN FRONT OF BUBBLE WALL

- FAST FREEZING OUT OF SPHALERON TRANSITION IN HIGGS PHASE CONSERVES BARYON ASYMMETRY

RECENT WORK

CHUNG
GARBRECHT
RAMSEY-MUSOLF
CIRIGLIANO
PROFUMO

$$\frac{V(T_N)}{T_N} > \dots$$

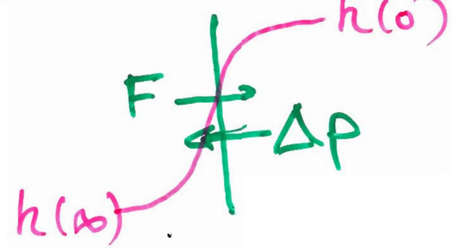
⇒ WALL VELOCITY v_w

! SMALL FOR BARYOGENESIS : $n_B \sim \frac{\Gamma_{SPH}^{(HOT)}}{v_w} \int_{-\infty}^{0} dz\, n_L(z) \exp\left(..z \frac{\Gamma_{SPH}^{(HOT)}}{v_w}\right)$

STATIONARY CASE :

BUBBLE PRESSURE - DIFFERENCE = - BUBBLE FRICTION

$$\Delta V_T = \int_{-\infty}^{+\infty} h' dx \left(h'' - \frac{\partial V}{\partial h}\right)$$



WALL FRAME $x = z + v_w t$, $\partial_t \delta = v_w \delta'$

ORDER v_w CALC.

G. MOORE
T. PROKOPEC

$$(*) \quad \underbrace{\Box h + \frac{\partial V_T}{\partial h}}_{\text{CONTRIB. TO PRESSURE}} + \underbrace{\sum_i \frac{\partial m_i^2}{\partial h} \int \frac{d^3p}{2E_i (2\pi)^3}\, \delta f_i(p,z)}_{\text{TO FRICTION}} = 0$$

" HEAVY PART. "

LINEARIZED IN δ_i $\quad f_i = \left(\exp\left(\frac{E_i + \delta_i}{T}\right) \mp 1\right)^{-1}$ $\qquad \delta_i = -\left[\delta\mu_i + \frac{E}{T}(\delta T_i + \delta T_{bg.}) + \frac{p_x}{T}(T\delta v_i + T\delta v_{bg.})\right]$

FLUID APPROXIMATION

BOLTZMANN EQS.

LINEARIZED!

DRIVING TERM $-f_0' \frac{\partial_t (m^2)}{2E}$

$$d_t f_i = \partial_t f_i + \dot{z} \frac{\partial}{\partial z} f_i + \dot{p}_z \frac{\partial}{\partial p_z} f_i = C(f_i)$$

$$f_i = f_{0i} + \underbrace{\delta f_i}_{\text{LIN. IN } \delta_i}$$

INTEGRATE $C(f_i)$ WITH $\underbrace{\left(\frac{1}{T^2}, \frac{E_i}{T^3}, \frac{p_z}{T^3}\right)}_{\vec{W}}$

FOR "HEAVY" + "LIGHT" PART. (BACKGROUND)

$$\int d^3p\, \vec{W}\, C(f) = (\Gamma) \begin{pmatrix} \delta\mu \\ \delta T + \delta T_{bg} \\ \delta v + \delta v_{bg} \end{pmatrix}$$ ⇐ CALCULATE IN VARIOUS MODELS!

SOLVE FLUID EQ. TO ELIMINATE $\delta T_{bg}, \delta v_{bg}$

⇒ FINAL FORM $\boxed{A\delta' + \Gamma\delta = F}$

MATRIX IN C_i, v_w

$F = \frac{v_w}{2T}\left[c_1 (m_i^2)', c_2 (m_i^2)', 0\right]$

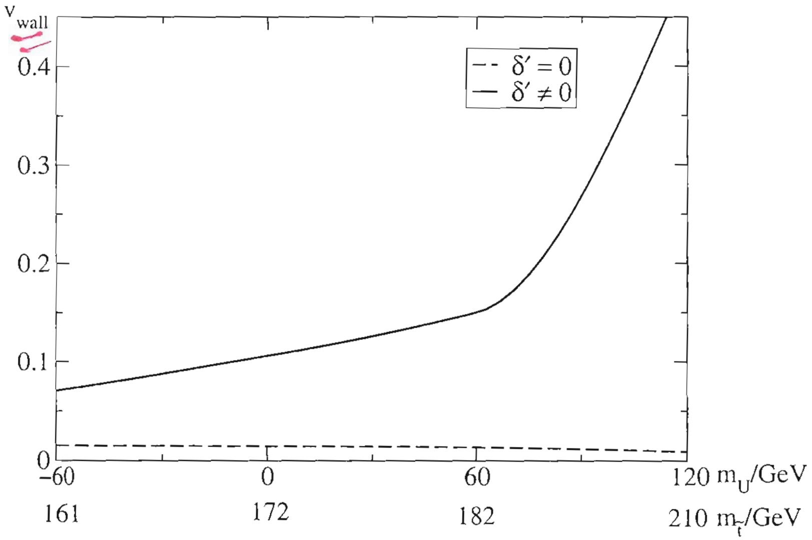
δ: INSERT IN FRICTION TERM(S) IN ⊛ ; SOLVE FOR v_w AND WALL PROFILE

ansatz $h(x) = \frac{h_{crit}}{2}\left(1 + \tanh\frac{x}{L}\right)$

MSSM: (i) "heavy": TOP, STOP$_R$, W

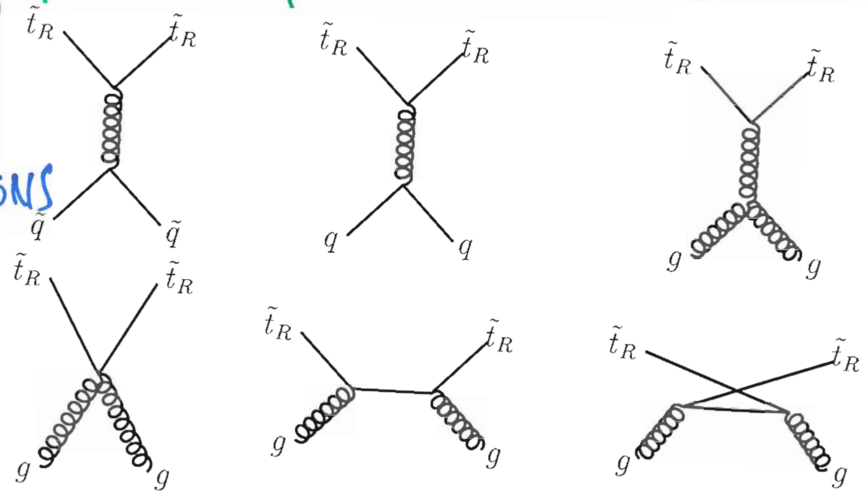
P. JOHN
M.G. SCH.

TWO HIGGSES $\Rightarrow$ APPROX.: ONE HIGGS WITH FIXED $\tan\beta$ ✓ (! BUT CP-VIOL.)..



Wall velocity for increasing stop mass parameter m_U.
The diagram is calculated for $\tan\beta = 3$, $A_t = \mu = 0$, and $m_A = 400$GeV.

COLLISIONS



COMBINE (i) AND (ii) !?

(ii) GAUGE BOSON PLASMA IN HOT PHASE: OVERDAMPED

G. MOORE (→ ARNOLD, SON, YAFFE)

$$\pi m_D^2/8k \, \frac{df}{dt} = -(\underbrace{k^2+m^2}_{E^2})f + \text{NOISE} \overset{!}{\approx} E^2 \delta f \qquad (f \sim A^2)$$

f_0

$\Rightarrow$ FRICTION $\dfrac{3 m_D^2 T}{16\pi L} \displaystyle\int_0^1 \frac{(1-x)\,dx}{x}$ $\quad (x = \phi/\phi_0)$ IR DIVERGENT

$\rightarrow$ CUTOFF AT $\phi/\phi_0 = \sqrt{\lambda/g^2}$

INFRARED DOMINATED!

ESTIMATE: $v_W \simeq 0.1$ FOR $\lambda/g^2 \cong 0.04$

$\Rightarrow$ TRANSPORT EQS. IN PRESENCE OF MOVING WALL

"THICK WALL" $L \gg$ MEAN FREE PATH ; $p \sim T \gg L^{-1}$

RELAT. THERMAL PART.

$\rightsquigarrow$ QUASICLASSICAL , DERIVATIVE EXPANSION

NEED ORDER $\hbar$ - ~~CP~~ DIRAC PARTICLES ! ($\rightsquigarrow$ WKB ?!)

imp. $\hbar^2$

SAFE FRAMEWORK : KADANOFF BAYM EQS.

$$\left(\not{k} + \frac{i}{2}\not{\partial} - P_L m e^{-\frac{1}{2}\overleftarrow{\partial}\cdot\partial_k} - P_R m^+ e^{-\frac{1}{2}\overleftarrow{\partial}\cdot\partial_k} \right) g^<(k, X) = \text{COLLISION TERM}$$

EXPAND! (Order $\hbar^2$)

$m = |m| e^{i\theta(z)}$

KAINULAINEN PROKOPEC SCH. WEINSTOCK

SPIN CONSERVED $\longrightarrow$ DECOUPLING

(ONE FLAVOR)

$g_s^< = 2\pi f_s \delta(k_0 - \omega_s)$

$$\boxed{\omega_s = \left(k_z^2 + k_{\parallel} + |m|^2\right)^{1/2} - s\,|m|^2\theta' / 2\omega_0\left(\omega_0^2 - k_{\parallel}^2\right)^{1/2}}$$

$\Rightarrow$ KINETIC EQ.

$$\boxed{\frac{k_x}{\omega_s}\partial_z f_s + F_s \partial_{k_z} f_s = \text{COLL. T.}}$$

WITH SEMICLASSICAL FORCE

$$F_s = -\underbrace{\frac{|m|^{2\prime}}{2\omega_s}}_{\text{DRIVING TERM}} + s\frac{\left(|m|^2\theta'\right)'}{2\omega_0\left(\omega_0^2 - k_{\parallel}^2\right)^{1/2}}$$

WKB ✓ S. HUBER

CP-VIOLATING

MSSM

$$\psi_R = \begin{pmatrix} \tilde{W}_L^+ \\ \tilde{h}_{1,R} \end{pmatrix} \qquad \psi_L = \begin{pmatrix} \tilde{W}_R^+ \\ \tilde{h}_{2,L} \end{pmatrix} \qquad m(z) = \begin{pmatrix} M_2 & g H_2^*(z) \\ g H_1^*(z) & \mu_c \end{pmatrix}$$

~~CP~~

$$g^< = g^<_{eq} + \delta g$$ LINEAR RESPONSE

→ KINETIC EQS. WITHOUT USE OF IN GENERAL NON ALGEBRAIC CONSTRAINTS !

T. KONSTANDIN
T. PROKOPEC
M.G. SCH.

(PHEN. DAMPING BY QU.T.)

$$k_z \partial_z \delta g + \frac{i}{2} \underbrace{[m^2, \delta g]}_{} + k_0 \Gamma \delta g = S(g^<_{eq})$$

FIRST ORDER IN GRAD. EXPANSION

(IN MASS EIGENBASIS)

OSCILLATIONS IN OFF-DIAGONAL DENSITIES !

CP VIOLATING SOURCES $S_\mu^{a,b,c}$

$$\circledast \quad S_\mu^c = -2 g^2 T_c^{-2} \, \mathrm{Im}(M_2 \mu_c) (H_2 \partial_z H_1 - H_1 \partial_z H_2) (\eta^0_{(0)} + 4 \eta^3_{(2)})$$

SECOND ORDER IN GRAD. EXPANSION :

MOM. INTEGRALS OF EQUIL. DISTR.

$$\left[\underbrace{S_0^d}_{\text{SEMICLASSICAL FORCE}} = 2 v_w g^2 T_c^{-4} \, \mathrm{Im}(M_2 \mu_c) (H_2 \partial_z^2 H_1 + H_1 \partial_z^2 H_2) \, \varphi^3_{(0)} \right]$$

IN $\circledast$ FOR MAXIMUM : ALMOST MASS DEGENERATE CHARGINOS !
OTHERWISE STRONG DAMPING !!!

DIFFERS FROM CARENA, MORENO, QUIROS, SECO, WAGNER !

$$\eta_{10} = \frac{n_B}{s_\gamma} \times 10^{10}$$

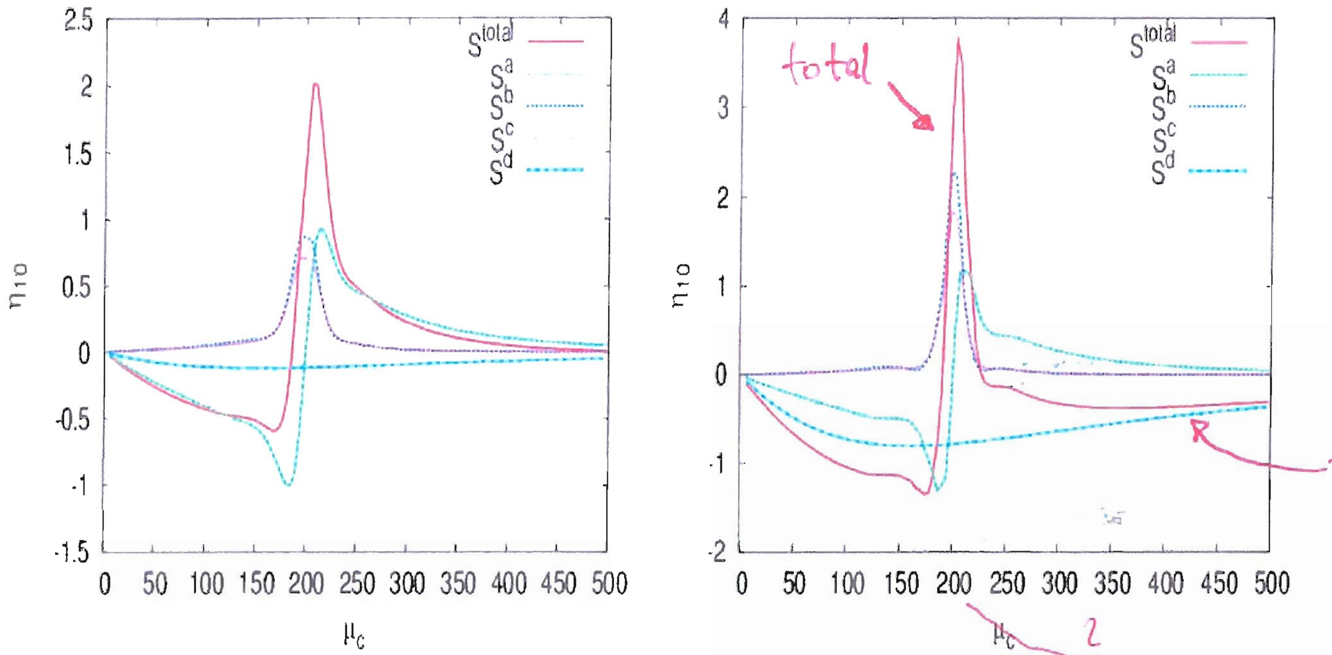


FIG. 2: This plot shows the first and second order sources as a function of μ_c with $M_2 = 200$ GeV. The plot on the left are the sources with the damping, $\Gamma = \alpha_w T_c$, while on the right plot, $\Gamma = 0.25\alpha_w T_c$.

MAXIMAL CP-VIOLATION ASSUMED

* MSSM

T. KONSTANDIN
T. PROKOPEC
M.G. SCH.
M. SECO

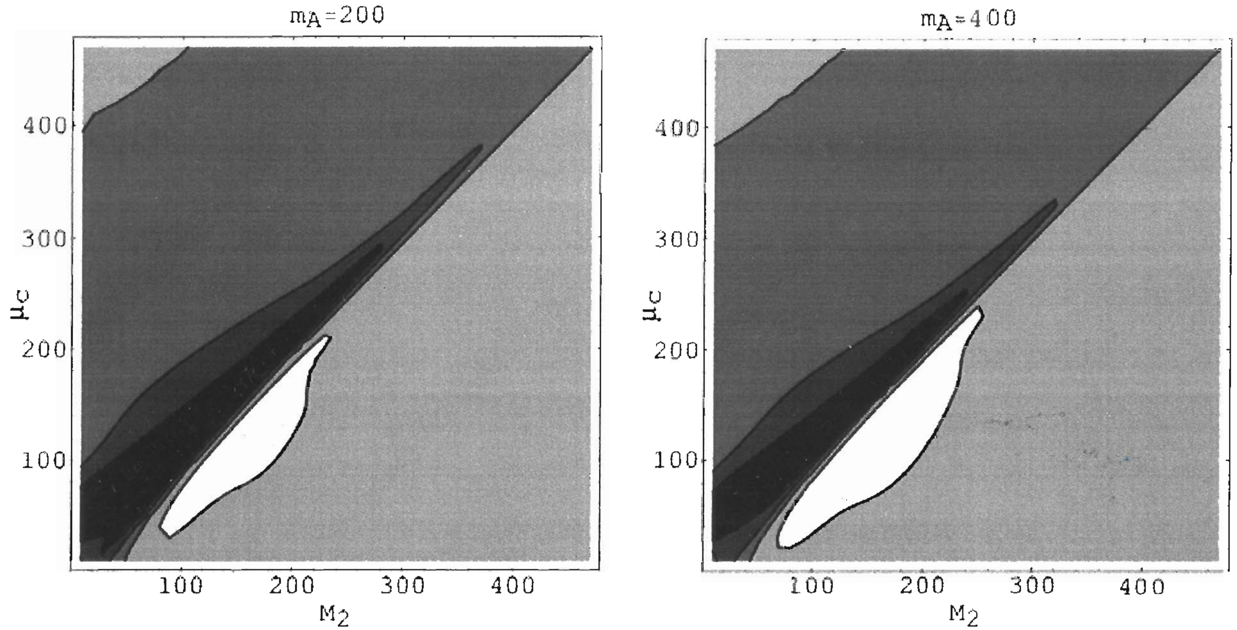


FIG. 5: The baryon-to-entropy ratio $\eta_{10} = 10^{10} \times \eta$ in the (M_2, μ_c) parameter space from (0 GeV,0 GeV) to (400 GeV,400 GeV). For the left plot the value $m_A = 200$ GeV is used, for the right plot $m_A = 400$ GeV. The black region denotes $\eta_{10} > 1$, where baryogenesis is viable. The other four regions are bordered by the values of η_{10}, $\{-0.5, 0, 0.5, 1\}$, beginning with the lightest color.

MAXIMAL CP-VIOLATION

$|d_e| \lesssim 1.6\ 10^{-27}$ ecm

Regan et al PRL 88 071805, 2002

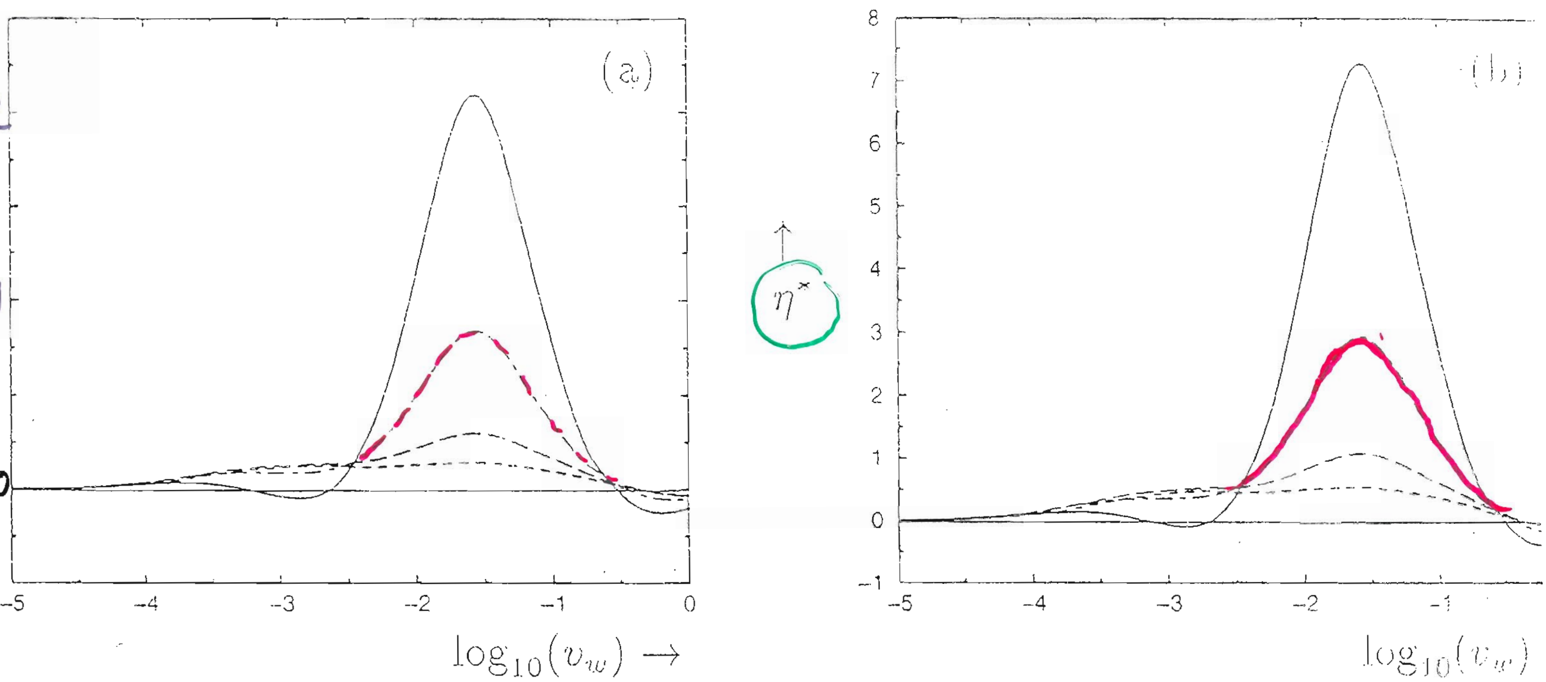
! RESTRICTIONS BY exp. n/e - ELECTRIC DIPOL LIMITS

~ CP-VIOL. PHASE < 0.1

$\eta^* = \eta_B / \eta_{B\,\text{observed}}$

NMSSM

S. HUBER
M. SCH.



ure 10: The chargino contribution to the baryon asymmetry in units of 2 ×
a function of the wall velocity for different values of the wall thickness
T, $10/T$, $5/T$, $3/T$ (from below). We use the squark spectrum C and the ex
explicit CP-violation considered in the context of fig. 6. (b): The same quanti
transitionally CP-violating bubble wall of fig. 7 and the squark spectrum D.

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{135\ \Gamma_{\text{SPHALERON}}}{g^* 2\pi^2 v_w T} \int_0^\infty d\bar{z}\ \mu_{B_L}(\bar{z})$$

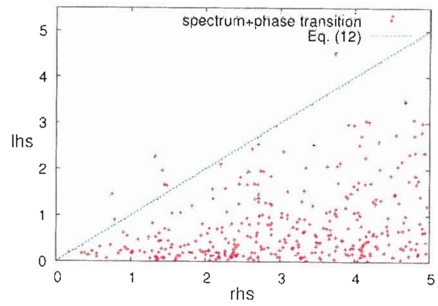
IN FRONT OF WALL

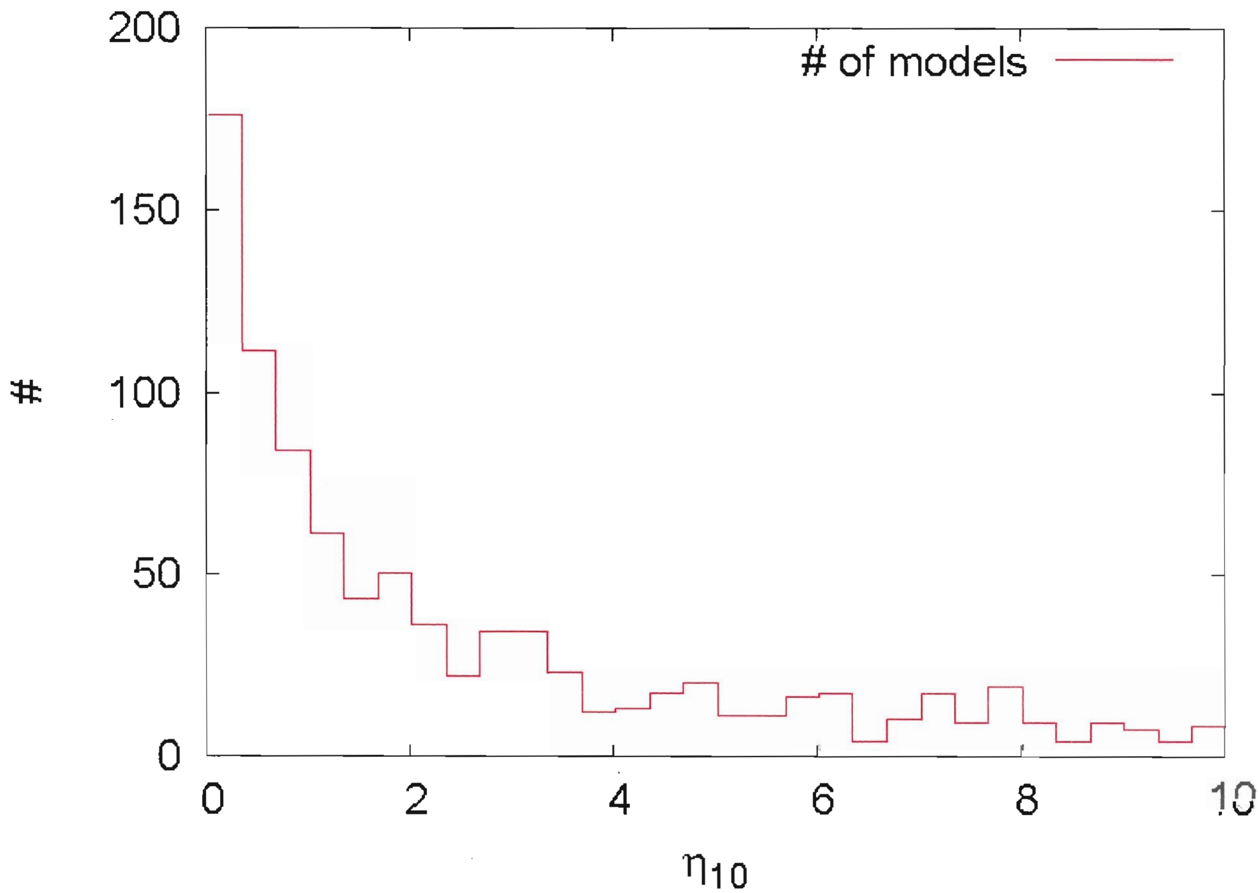
(η^* IN UNITS OF 2×10^{-11} !)

The nMSSM allows for a strong first order phase transition (PT) with only tree level dynamics. The criterion for a first order PT is on tree level given by

$$m_s^2 < \frac{1}{\tilde{\lambda}} \left| \frac{\lambda^2 t_s}{m_s} - m_s \tilde{a} \right| . \qquad (12)$$

what tends to persist even if one includes the one-loop potential.





Produced baryon asymmetry in random nMSSM models.

HUBER '06
KONSTANDIN
PROKOPEC
SCHMIDT

$\eta_{10} \simeq 1$ exp.

CONCLUSIONS + FINAL REMARKS

- INGREDIENTS OF MODELS FOR AN ELECTROWEAK PHASE TRANSITION CAN BE TESTED IN FORTHCOMING EXPERIMENTS
- IN MOST ELWK. BARYOGENESIS MODELS A VERY STRONG PHASE TRANSITION IS REQUIRED - "BEYOND THE SM" OR "EXTENDED" SM IS MANDATORY. → (NONTHERMAL) LEPTOGENESIS ?!

  MSSM RULED OUT ?! (FOR ELWK. BARYOGENESIS) NMSSM, nMSSM MUCH MORE FLEXIBLE (PROMISING ?)
- CP VIOLATION ALSO BY DERIVATIVE TERMS IN EFF. ACTION TRANSITIONAL ~~CP~~ ; edm BOUNDS
- ELECTROWEAK BARYOGENESIS A WELL FOUNDED PROCEDURE IN A GIVEN MODEL
- USEFUL FOR PRODUCTION OF GRAVITY WAVES, PRIMORDIAL MAGN. FIELDS ?

  NEED SMALL V_W FOR BARYOGENESIS (CHARGE TRANSPORT MECH.)

  LARGE V_W ? ('RUN AWAY' BÖDEKER, MOOR '09) ← WISHFUL THINKING ?

ELECTRIC DIPOLE MOMENT FROM MSSM

The current measurement bound of the electron electric dipole moment (EDM)

Regan et al, Phys. Rev. Lett. 88:071805, 2002

$$|d_e| \quad 1.6\times10^{-27}\,\text{ecm}$$

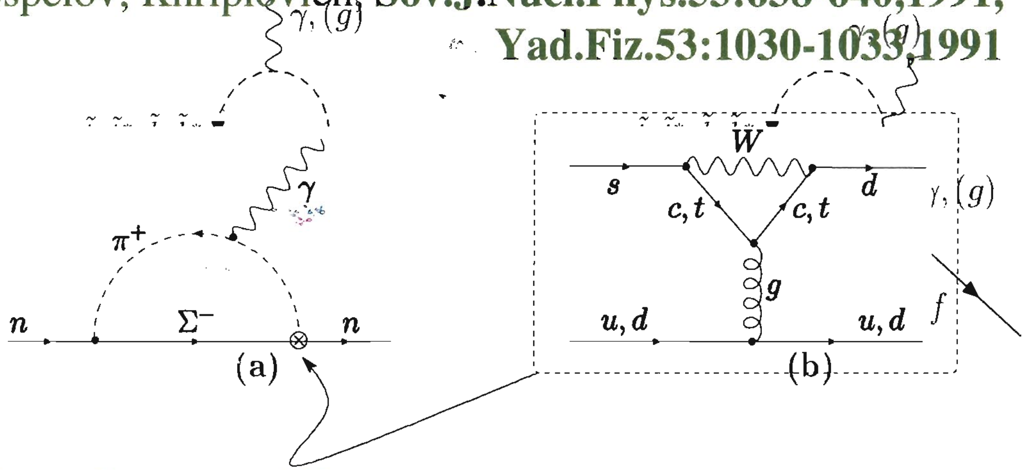
The standard model (MSM) value for eEDM (4 loop)

$$d_e^{CKM} \quad 1\times10^{-38}\,\text{ecm}$$

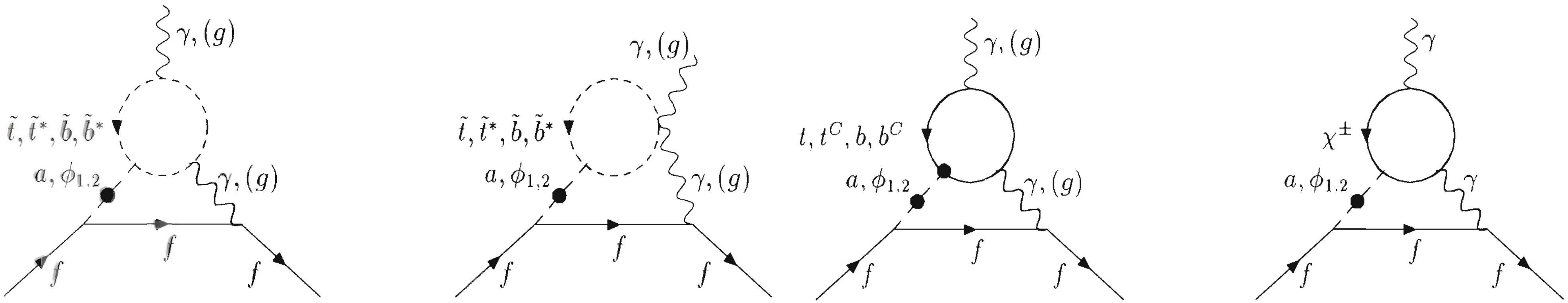
Pospelov, Khriplovich, Sov.J.Nucl.Phys.53:638-640,1991,
Yad.Fiz.53:1030-1033,1991

The standard model (MSM) value for neutron EDM (2 loop penguin)

$$d_n^{CKM} \sim 1\times10^{-32}\,\text{ecm}$$



The MSSM 2 loop Higgs contribution for electron EDM



(a) (b) (c) (d)

ALTERNATIVE : STRENGTHEN ϕ^3-TERM; FURTHER CP-VIOL.

- MSSM, NMSSM, nMSSM, 2-HIGGS ...
- LEPTOGENESIS, COHERENT BARYOGENESIS, AFFLECK-DINE BARYOGENESIS, ...

MY USUAL DIRECTION UP TO NOW

HOW TO GET (i) STRONG NONEQUILIBRIUM AND (ii) ENOUGH CP-VIOLATION IN (ALMOST) THE STANDARD MODEL?

(i) SWITCH SIGN OF $\phi^+\phi$ -TERM (HIGGS MASS)

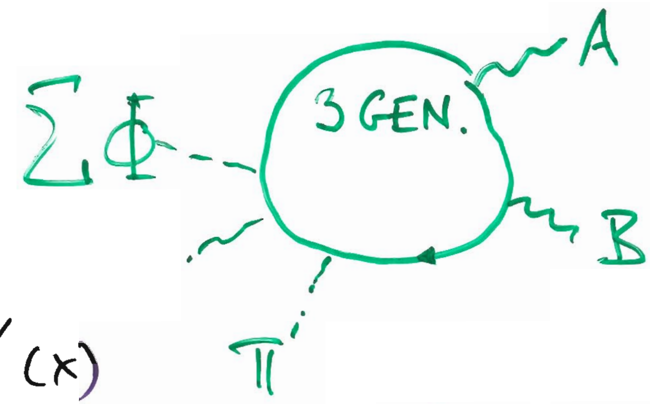
(ii) INTEGRATE OUT FERMIONS PROPERLY

A. HERNANDEZ
T. KONSTANDIN
M.G. SCH.

DERIVE CP VIOLATING TERM(S) IN BOSONIZED SM

- INTEGRATE OUT FERMIONS

  OBTAIN EFFECTIVE ACTION



$$-W = \log \mathrm{Det}[\mathcal{O}]$$

$$\mathcal{O} = \not\partial - i\,\Phi(x) - \gamma_5 \Pi(x) - \not A(x) - \gamma_5 \not B(x)$$

(EUCLIDEAN $t = -t_E$, $\not\partial = i\,\not\partial_E$)

$$-W = \underbrace{\log|\mathrm{Det}[\mathcal{O}]|}_{-W^+} + \underbrace{i\,\arg(\mathrm{Det}[\mathcal{O}])}_{-iW^-}$$

EVEN / ODD NUMBER OF γ_5 IN $W^{+/-}$, REAL / IMAG.

WORLDLINE METHOD OPTIMAL (PROPAGATING FERM. IN THE BACKGROUND OF x-DEP. SCALAR AND GAUGE FIELDS)

GET DERIVATIVE EXPANSION

MONDRAGON
NELLEN
SCH.
SCHUBERT

$\dashrightarrow$ D'HOKER
GAGNIER

LATER: VERY ELEGANT!

MAIN POINT FOR FERMIONS IN THE LOOP: TRANSLATE γ-MATRICES TO GRASSMANN VARIABLES IN ("FIRST QUANTIZED") WORLDLINE PATH INTEGRAL. NEED EVEN NUMBER OF γ'S. ($\rightsquigarrow$ SECOND ORDER FORM.)

... FINKLER

($\rightsquigarrow$ COHERENT STATE FORM.)

REAL PART: (i) $W^+ = -\frac{1}{2} \log \mathrm{Det}\,[\mathcal{D}\mathcal{D}^+] = -\frac{1}{2} \mathrm{Tr} \log [\mathcal{D}\mathcal{D}^+]$

(ii) $\mathcal{D} \to \Sigma_1 \equiv \begin{pmatrix} 0 & \mathcal{D} \\ \mathcal{D}^+ & 0 \end{pmatrix}$; $W^+ = -\frac{1}{4} \log \mathrm{Det}\,[\Sigma_1^2] = ..$

(8×8) Γ_A MATRICES $(A = 1, \dots, \underline{\underline{6}})$

$$\Sigma_1 = \underset{\begin{pmatrix} 0 & \gamma_\mu \\ \gamma_\mu & 0 \end{pmatrix}}{\Gamma_\mu} (p_\mu - A_\mu) - \underset{\begin{pmatrix} 0 & \gamma_5 \\ \gamma_5 & 0 \end{pmatrix}}{\Gamma_6}\, \Phi - \underset{\begin{pmatrix} 0 & i\mathbb{1}_4 \\ -i\mathbb{1}_4 & 0 \end{pmatrix}}{\Gamma_5}\, \Pi - i \Gamma_\mu \Gamma_5 \Gamma_6 B_\mu$$

BASIS WHERE $i\Gamma_5\Gamma_6$ DIAGONAL $\Rightarrow$ CHIRAL COVARIANT

$$\boxed{\tilde{\Sigma}_1 = \begin{pmatrix} \gamma_\mu (p_\mu - A^L_\mu) & -i\gamma_5 H \\ +i\gamma_5 H & \gamma_\mu (p_\mu - A^R_\mu) \end{pmatrix}}$$

$A^{L/R} = A +/- B$

$H = \Phi - i\Pi$

$\tilde{\Sigma}_1^2$ STILL WITH ODD COMB. OF γ ($\gamma_5 = \dots$)

(iii) $\gamma_A \to \hat{\Gamma}_A = \Gamma_A \otimes \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$ $\quad A = 1, \dots 5$

$$W^+ = \frac{1}{8} \int_0^\infty \frac{dT}{T} \, \mathrm{Tr}_{\Gamma, x} \exp\left(-T \hat{\Sigma}^2\right)$$

SCHWINGER PROPER TIME

$$\hat{\Sigma}^2 = (p - \mathcal{A})^2 + \mathcal{H}^2 + \frac{i}{2} \Gamma_\mu \Gamma_\nu \mathcal{F}^{\mu\nu} + i \Gamma_\mu \Gamma_5 (\mathcal{D}_\mu \mathcal{H})$$

$$\mathcal{A}_\mu = \begin{pmatrix} A_\mu^L & 0 \\ 0 & A_\mu^R \end{pmatrix}; \quad \mathcal{H} = \begin{pmatrix} 0 & iH \\ -iH & 0 \end{pmatrix}$$

(iv) WORLDLINE INTEGRAL

$$W^+ = \frac{1}{8} \int_0^\infty \frac{dT}{T} \int_{x(T) = x(0)} \mathcal{D}x \int \prod_A \mathcal{D}\psi_A \, \mathrm{tr}\, P \exp\left(-\int_0^T d\tau\, \mathcal{L}(\tau)\right)$$

$$\psi(T) = -\psi(0)$$

ANTIPERIODIC GRASSMANN

$$\mathcal{L}(\tau) = \dot{x}^2/4 - i \dot{x}_\mu \mathcal{A}^\mu + \frac{1}{2} \psi_A \dot{\psi}_A + \mathcal{H}^2 + i \psi_\mu \psi_\nu \mathcal{F}_{\mu\nu}$$
$$+ 2i \psi_\mu \psi_5 (\mathcal{D}_\mu \mathcal{H})$$

$A = 1, \dots 5$

EVALUATE : $X(\tau) = X_0 + y(\tau)$ WITH $\int_0^T d\tau\, y(\tau) = 0$

$\rightarrow \mathcal{D}x = \mathcal{D}y\, d^D x_0$

$$\langle y(\tau_1)\, y(\tau_2)\rangle = \frac{(\tau_1-\tau_2)^2}{T} - |\tau_1-\tau_2|$$

$$\langle \psi_A(\tau_1)\, \psi_B(\tau_2)\rangle = \frac{1}{2}\delta_{AB}\, \mathrm{sign}(\tau_1-\tau_2)$$

ψ ANTICOMM.

IMAGINARY PART :

- PREJUDICE ~~CP~~ WITH ~~P~~
- WRONG? SALCEDO
- LOWEST ORDER IN DER. EXP $\rightarrow$ J. SMIT $(\equiv 0\,!)$

CALCULATE CURRENTS (DER. OF ACTION W.R.T. FIELDS)

$$\delta W^- = \frac{1}{2}\delta\left(\log \mathrm{Det}[\mathcal{O}] - \log \mathrm{Det}[\mathcal{O}^+]\right)$$

$$= \frac{1}{2}\mathrm{Tr}\left(\delta\mathcal{O}\frac{1}{\mathcal{O}} - \delta\mathcal{O}^+\frac{1}{\mathcal{O}^+}\right)$$

$$= \frac{1}{2}\mathrm{Tr}\begin{pmatrix} 0 & \delta\mathcal{O} \\ -\delta\mathcal{O}^+ & 0\end{pmatrix}\begin{pmatrix} 0 & 1/\mathcal{O}^+ \\ 1/\mathcal{O} & 0\end{pmatrix} = \frac{1}{2}\mathrm{Tr}\underbrace{\begin{pmatrix}1_4 & \\ & 1_4\end{pmatrix}}_{\chi}\delta\Sigma_1\Sigma_1^{-1}$$

$$= \frac{1}{4}\mathrm{Tr}\,\chi\,[\delta\Sigma_1, \Sigma_1]\,\Sigma_1^{-2} = \frac{1}{4}\mathrm{Tr}\int_0^\infty dT\,\chi\,[\delta\Sigma_1, \Sigma]\exp(-T\Sigma_1^2)$$

$\Sigma_1 \rightarrow \tilde{\Sigma}_1 \quad (\chi \rightarrow \tilde{\chi} = \chi\underline{\underline{\gamma_5}})$, $\gamma_A \rightarrow \Gamma_A$ AS BEFORE

$$\Rightarrow \delta W^- = \frac{i}{8} \mathrm{Tr} \int_0^\infty dT \, \Gamma_7 \Gamma_6 \chi \, w(T) \exp(-T \hat{\Sigma}^2)$$

ABOVE

CHANGES BOUNDARY COND. FOR GRASSMANN ψ

FOR $\delta\tilde{\Sigma}_1 = -\gamma_\mu \delta A_\mu$

$$\delta W^- = \frac{1}{8} \mathrm{tr} \int_0^\infty dT \int \mathcal{D}x \int_A \mathcal{D}\psi_A \, \chi \, w(T) \, \mathcal{P}\exp \exp\left(-\int_0^T d\tau \, \mathcal{L}(\tau)\right)$$

$$w(T) = -4i \psi_c \psi_\nu \delta A_\mu \dot{x}_\nu - 2i \psi_5 \mathcal{D}_\mu \delta \phi_\mu - 2 \psi_\mu \{\delta \phi_\mu, \mathcal{X}\}$$

NOW PERIODIC $\rightarrow$ ZERO MODES

PRODUCE ϵ-TENSOR!

$$\psi_A(\tau) = \psi_A^0 + \psi'_A(\tau)$$

SAME CORRELATOR AS $\dot{X}$

(∴ EACH ZERO MODE ONCE!)

HAVE TO INTEGRATE δW^- TO OBTAIN EFF. ACTION

CONSISTENT VS. COVARIANT CURRENT

$$W^- = W_c^- + \Gamma_{\text{gauged WZW-ACTION}}$$

!

($\rightsquigarrow$ SALCEDO

CONTRIBUTES ONLY LOWEST ORDER IN DER. EXP)

"MATCHING"

ANSATZ FOR ACTION $\rightarrow$ DERIV. $\rightarrow$ COMPARE

EVALUATION

A. HERNANDEZ, T. KONSTANDIN, M.G. SCH.

- $\mathcal{H}$ is a 3×3 MASS MATRIX (x-DEP.!) – UNITARY GAUGE
  DIAGONALIZATION WITH CKM MATRIX V
- $SU(2)_L$ gauge FIELD STRENGTH IN FLAVOR SPACE $\mathcal{F}_L = \begin{pmatrix} F_0 & F^+V \\ V^+F^- & F_0 \end{pmatrix}$
- USE "LABELED OPERATOR NOTATION" FEYNMAN ... SALCEDO

E.G. $\langle \epsilon^{\mu\nu\lambda\sigma} \mathcal{H} \mathcal{F}_{\mu\nu} \mathcal{H}^3 \mathcal{F}_{\lambda\sigma} \rangle = \langle \epsilon^{\mu\nu\lambda\sigma} m_1 m_2^3 \mathcal{F}_{\mu\nu} \mathcal{F}_{\lambda\sigma} \rangle$

$$\nabla f(m_1, m_2) := \frac{f(m_1) - f(m_2)}{m_1 - m_2} \quad ; \quad \mathcal{D}_\mu f(m) = \nabla f(m_1, m_2) \mathcal{D}_\mu \mathcal{H}$$

$$\mathcal{D}_\mu (\mathcal{H}^3) = (m_2^2 + m_1 m_2 + m_1^2) \mathcal{D}_\mu \mathcal{H} = \frac{m_1^3 - m_2^3}{m_1 - m_2} \mathcal{D}_\mu \mathcal{H} = \nabla m^3(m_1, m_2) \mathcal{D}_\mu \mathcal{H}$$

$$\mathcal{L}(\tau) = \underbrace{\dot{x}^2/4 + \tfrac{1}{2}\varphi_A \dot{\varphi}_A + \mathcal{H}^2}_{\mathcal{L}_0(\tau)} + \mathcal{L}_1(\tau)$$

GAUSSIAN

$$P \exp\left(-\int_0^T d\tau \mathcal{L}(\tau)\right) = \exp\left(-\int_0^T d\tau \mathcal{L}_0(\tau)\right) \Big(- \int_0^T d\tau_1 \, e^{-T m_1^2 - \tau_1 (m_2^2 - m_1^2)} \mathcal{L}_1(\tau_1) \; !$$

$$+ \int_0^T d\tau_1 \int_0^{\tau_1} d\tau_2 \exp\left(-T m_1^2 - \tau_1 (m_2^2 - m_1^2) - \tau_2 (m_3^2 - m_2^2)\right) \mathcal{L}_1(\tau_1) \mathcal{L}_1(\tau_2) + \dots \Big)$$

- EXPAND AROUND X_0 — MOSTLY "AS USUAL"
- DO y - INTEGRATION
- DO ψ - INTEGRATION SATURATING ZEROMODES AND
- CONTRACTING WITH FERMIONIC GREENSF.
- DO τ, T INTEGRATION

HEAVY COMPUTER ALGEBRA (A. HERNANDEZ..)

NEXT TO LEADING ORDER : ALMOST ALL ~~CP~~ CONTR. CANCEL

REMAINS :

$$S_{\cancel{CP}} = \frac{1}{8(4\pi)^2}\frac{3}{16} J \kappa^{CP} \epsilon^{\mu\nu\lambda\sigma} \frac{1}{\tilde{m}_c^2} \times$$

$$\int d^4x \left[Z_\mu W^+_{\nu\lambda} W^-_\alpha \times \left(W^+_\sigma W^-_\alpha + W^+_\alpha W^-_\sigma \right) + c.c \right]$$

$\kappa^{CP} \simeq 9.87$ IN 'BROKEN' PHASE $\quad J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin\delta \cong (3.0 \pm 0.3)\, 10^{-5}$

$$W^+_{\mu\nu} = \frac{\phi^+ W_{\mu\nu} \tilde{\phi}}{\phi^+\phi} \quad \ldots \quad W^+_\mu = \frac{\phi^+ \mathcal{D}_\mu \tilde{\phi}}{\phi^+\phi} \quad Z_\mu = W^3_\mu - B_\mu = \frac{\phi^+ \mathcal{D}_\mu \phi - \tilde{\phi} \mathcal{D}_\mu \tilde{\phi}}{2\phi^+\phi}$$

$(\tilde{\phi} = \epsilon\, \phi^*)$