Baryogenesis, EDMs, and The Higgs Boson

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Theoretical Nuclear, Particle, Astrophysics & Cosmology

http://www.physics.wisc.edu/groups/particle-theory/

FNAL Seminar, Oct 2008

What is the origin of baryonic matter ?

Cosmic Energy Budget

Dark Matter

Baryogenesis & EDMs

D. Chung	Wisconsin
V. Cirigliano	LANL
B. Garbrecht	Wisconsin
C. Lee	LBL
Y. Li	Wisconsin
S. Profumo	UC Santa Cruz
S. Tulin	Caltech
G. Shaugnessy	Wisconsin

PRD 71: 075010 (2005)
PRD 73: 115009 (2006)
JHEP 0607:002 (2006)
JHEP 0807:010 (2007)
ArXiv 0806.2693/hep-ph
ArXiv 0808.1144/hep-ph

Higgs Phenomenology

V. Barger	Wisconsin
P. Langacker	IAS
M. McCaskey	Wisconsin
D. O'Connell	IAS
G. Shaugnessy	Wisconsin
M. Wise	Caltech

PRD 75: 037701 (2007)
PRD 77: 035005 (2008)

Baryogenesis: Myths

Outline

I. *Baryogenesis: General Features*

II. *Computing Y_B systematically: progress & challenges*

III. *Illustrative phenomenology in MSSM: EDMs, Colliders, & DM*

IV. *Probing EW phase transition w/ Higgs boson phenomenology*

Baryogenesis: Ingredients

Sakharov Criteria

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

Anomalous B-violating processes

$$\Gamma(A+B \to C) \neq \Gamma(\bar{A}+\bar{B} \to \bar{C})$$

Prevent washout by inverse processes

EW Baryogenesis: Standard Model

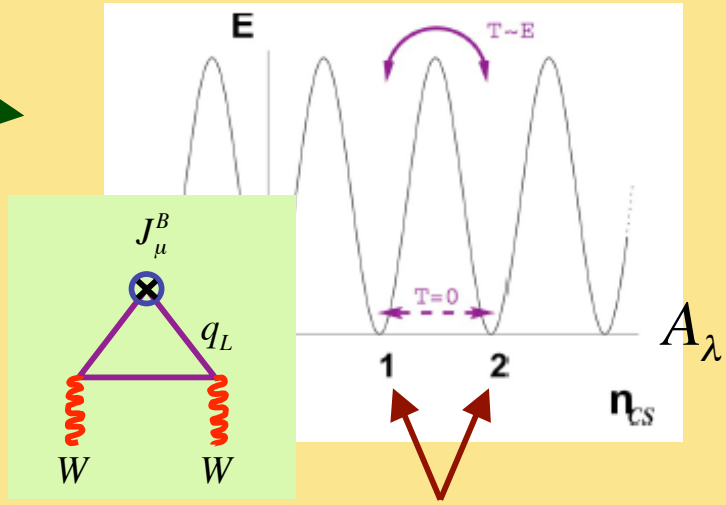
Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

Kuzmin, Rubakov, Shaposhnikov
McLerran,…

Anomalous Processes



Different vacua: $\Delta(B+L)= \Delta N_{CS}$

Sphaleron Transitions

EW Baryogenesis: Standard Model

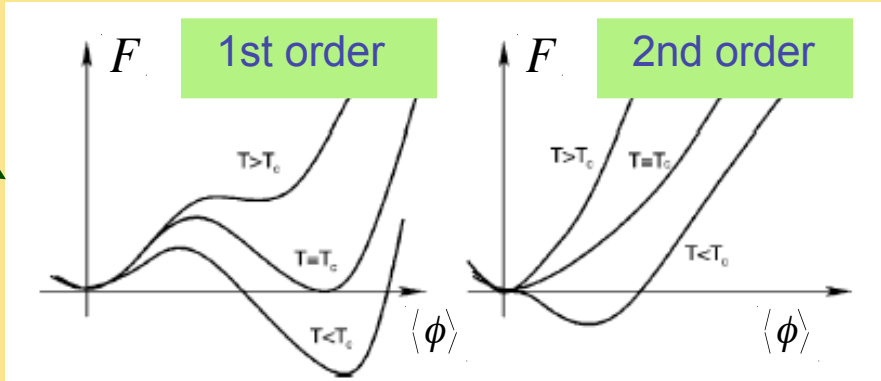
Shaposhnikov

Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Sakharov, 1967

$$J = s_{12}\, s_{13}\, s_{23}\, c_{12}\, c_{13}^2\, c_{23} \sin\delta_{13}$$
$$= (2.88 \pm 0.33) \times 10^{-5}$$
$$\frac{m_t^4}{M_W^4}\frac{m_b^4}{M_W^4}\frac{m_c^2}{M_W^2}\frac{m_s^2}{M_W^2} \approx 3 \times 10^{-13}$$



Increasing m_h →

- CP-violation too weak
- EWPT too weak

Baryogenesis: New El

Systematic baryogenesis: SD equations + power counting

Weak Scale Baryogenesis

- B viola
- C & CP violation
- Nonequilibrium dynamics

$V_{eff}(\phi,T)$: Requirements on Higgs sector extensions & expt'l probes

Unbr

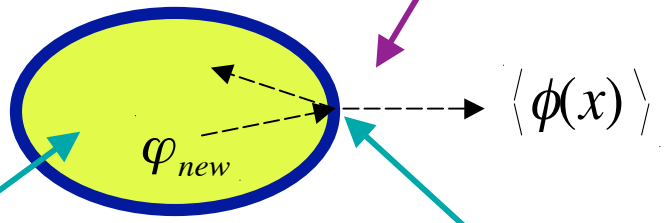
1st order phase transition

Quantum Transport

$\Gamma(A+B\to C)\neq\Gamma(\bar{A}+\bar{B}\to\bar{C})$ *CPV*

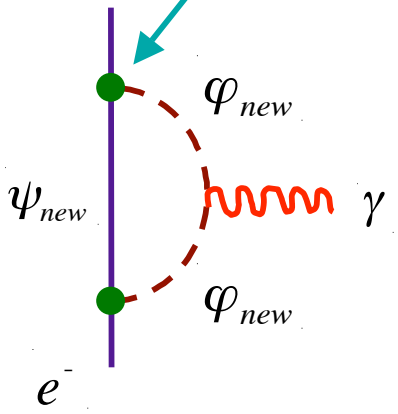
$\Gamma(A+B\leftrightarrow C)$ *Chem Eq*

$Y_B\sim S^{\rm CPV}/\sqrt{\Gamma}$ *R-M et al*



Broken phase

CP Violation



Theoretical Issues:

Strength of phase transition (Higgs sector)

Bubble dynamics (numerical)

Transport at phase boundary (non-eq QFT)

EDMs: many-body physics & QCD

EDMs: New CPV?

In units of e cm, selected EDM limits are:

CKM

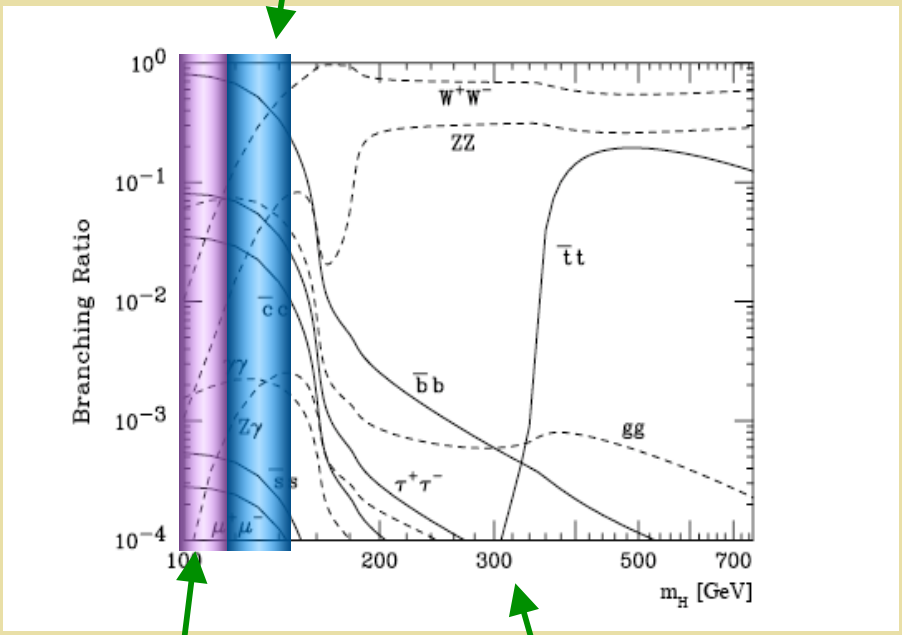
Particle	EDM limit	System	SM Prediction	New Physics
e	1.9×10^{-27}	Tl atom	10^{-38}	10^{-27}
μ	1.1×10^{-19}	rest frame $\vec{E}$	10^{-35}	10^{-22}
τ	3.1×10^{-16}	$e^+e^- \to \tau^+\tau^-\gamma$	10^{-34}	10^{-20}
p	6.5×10^{-23}	TlF molecule	10^{-31}	10^{-26}
n	2.9×10^{-26}	UCN	10^{-31}	10^{-26}
^{199}Hg	2.1×10^{-28}	atom cell	10^{-33}	10^{-28}

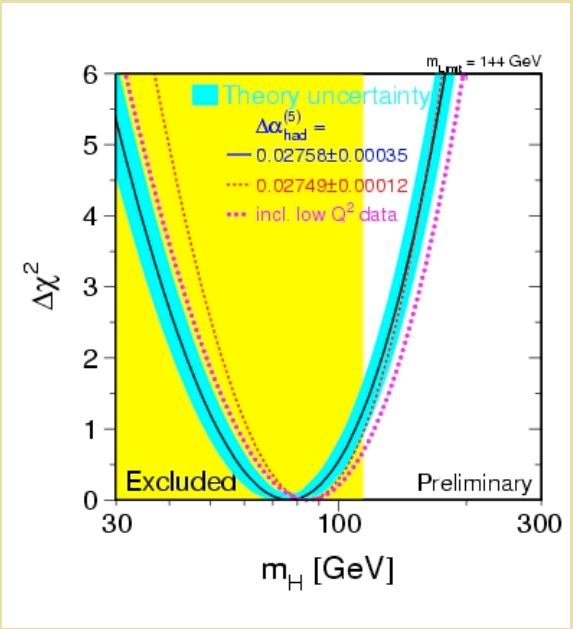
A non-exhaustive list:

Leptonic EDMs		Hadronic EDMs	
System	Group	System	Group
Cs (trapped)	Penn St.	n (UCN)	SNS
Cs (trapped)	Texas	n (UCN)	ILL
Cs (fountain)	LBNL	n (UCN)	PSI
YbF (beam)	Imperial	n (UCN)	Munich
PbO (cell)	Yale	^{199}Hg (cell)	Seattle
HBr^+ (trapped)	JILA	^{129}Xe (liquid)	Princeton
PbF (trapped)	Oklahoma	^{225}Ra (trapped)	Argonne
GdIG (solid)	Amherst	^{213,225}Ra (trapped)	KVI
GGG (solid)	Yale/Indiana	^{223}Rn (trapped)	TRIUMF
muon (ring)	J-PARC	deuteron (ring)	BNL?

EWSB: Higgs?

EW Precision Data:
95% CL (our fit-GAPP)



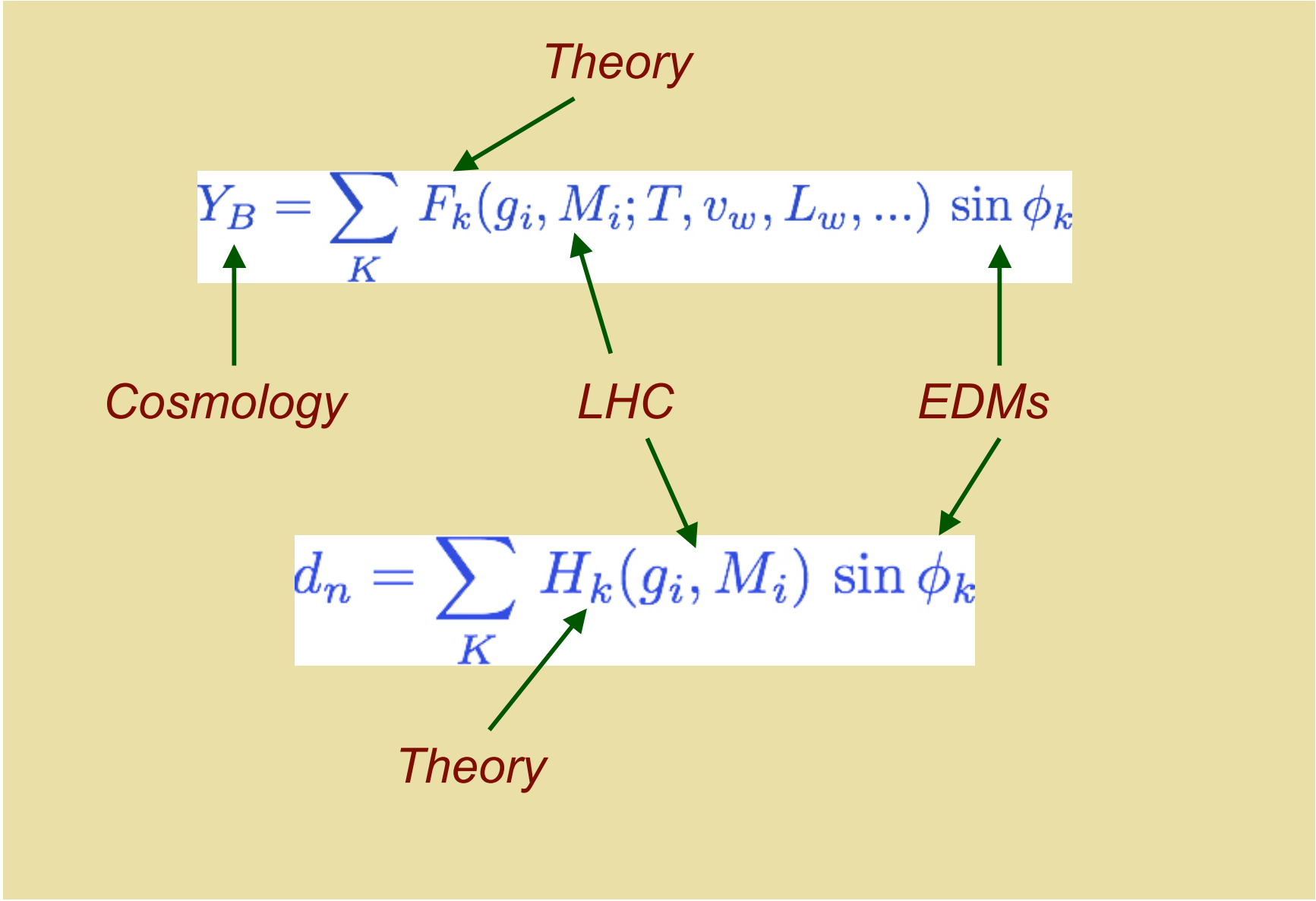


LEP Exclusion

Non-SM Higgs(es) ?

LEPEWWG

Baryogenesis: EDMs & Colliders

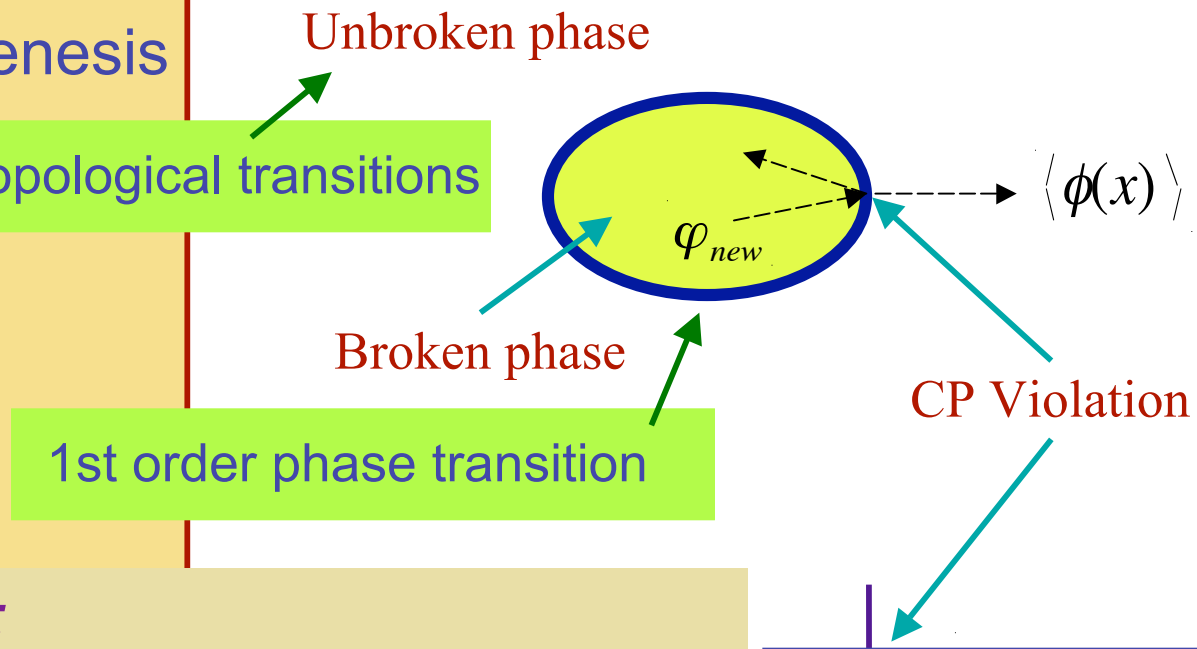


Baryogenesis: New Electroweak Physics

90's: *Cohen, Kaplan, Nelson*
Joyce, Prokopec, Turok

Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*



Theoretical Issues:
Strength of phase transition (Higgs sector)
Bubble dynamics (expansion rate)
Transport at phase boundary (non-eq QFT)
EDMs: many-body physics & QCD

"Gentle" departure from equilibrium & scale hierarchy
Cirigliano, Lee, R-M,Tulin

Systematic Baryogenesis

Goal: Derive dependence of Y_B on parameters $\mathcal{L}_{new}$ systematically (controlled approximations)

$$Y_B = \sum_k F_k(g_i, M_i; T, v_w, L_w, \ldots)\ \sin\phi_k$$

Parameters in $\mathcal{L}_{new}$

Bubble & PT dynamics

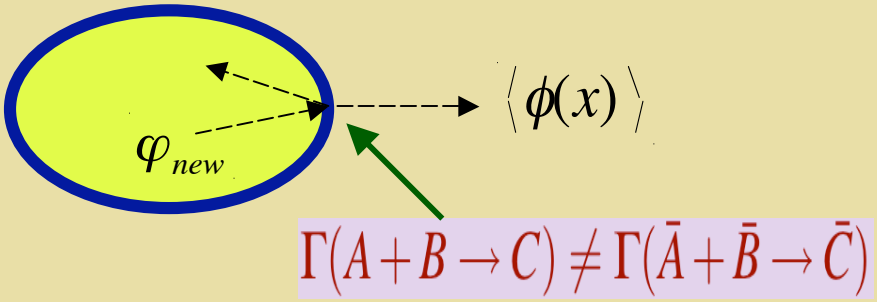
CPV phases

Departure from equilibrium

- *Earliest work: QM scattering & stat mech*
- *New developments: non-equilibrium QFT*

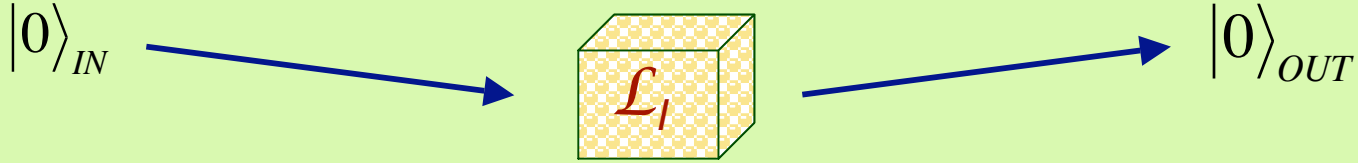
Quantum Transport & Baryogenesis

Electroweak Baryogenesis



1. *Evolution is non-adiabatic: $v_{wall} > 0$ -> decoherence*
2. *Spectrum is degenerate: $T > 0$ -> Quasiparticles mix*
3. *Density is non-zero*

Particle Propagation: Beyond familiar (Peskin) QFT

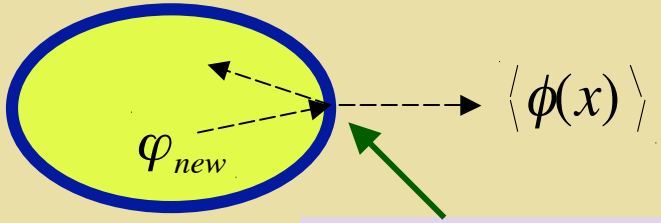


Assumptions:

1. *Evolution is adiabatic*
2. *Spectrum is non-degenerate*
3. *Density is zero*

Quantum Transport & Baryogenesis

Electroweak Baryogenesis



$$\Gamma(A+B\to C)\neq\Gamma(\bar{A}+\bar{B}\to\bar{C})$$

Systematically derive transport eq's from $\mathcal{L}_{new}$

Competing Dynamics

CPV $\Gamma(A+B\to C)\neq\Gamma(\bar{A}+\bar{B}\to\bar{C})$

Ch eq $\Gamma(A+B\leftrightarrow C)$

Cirigliano, Lee, Tulin, R-M

Scale Hierarchy:

Fast, but not too fast

$\varepsilon_d = v_w (k / \omega) << 1$

Hot, but not too hot

$\varepsilon_p = \Gamma_p / \omega << 1$

Dense, but not too dense

$\varepsilon_\mu = \mu / T << 1$

Work to lowest, non-trivial order in ε's

Error is $O(\varepsilon) \sim 0.1$

Cirigliano, Lee, R-M

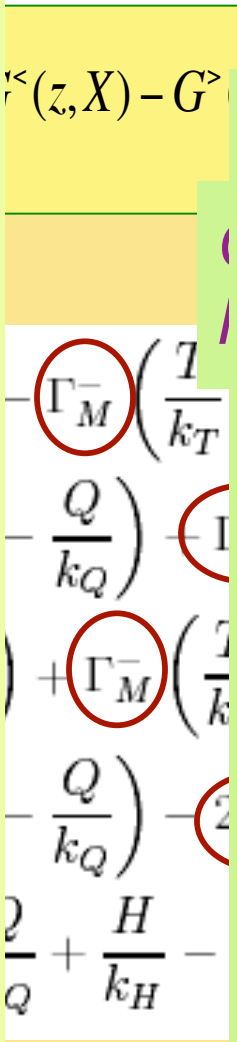
Quantum Transport Equations

Approximations

- Neglect $O(\varepsilon^3)$ terms
- Others under scrutiny

R-M, Chung, Tulin, Garbrecht, Lee, Cirigliano

- *Γ_Y >> other rates? (No)*
- *Majorana fermions ? (densities decouple)*
- *Particle-sparticle eq?*
- *Density indep thermal widths?*



violation and baryon sector

Currents

From S-D Equations:

- *S^{CPV}*

Riotto, Carena et al, R-M et al, Konstandin et al

- *Γ_M, Γ_H, Γ_Y …*

R-M et al

Objectives:

- *Determine param dep of S^{CPV} and all Γs and not just that of S^{CPV}*
- *Develop general methods for any model with new CPV*
- *Quantify theor uncertainties*

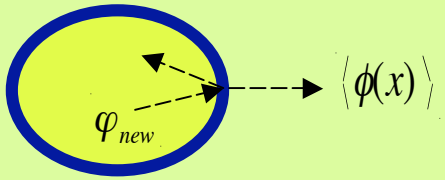
Illustrative Study: MSSM

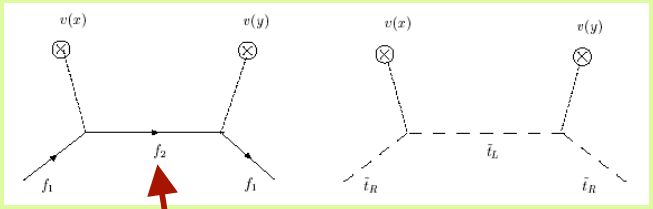
Chargino Mass Matrix

$$M_C = \begin{pmatrix} M_2 & m_W\sqrt{2}\cos\beta \\ m_W\sqrt{2}\sin\beta & \mu \end{pmatrix}$$

CPV

T ~ T_{EW}





$q\,,\tilde{W}\,,\tilde{B}\,,\tilde{H}_{u,d}$

Resonant CPV: $M_{1,2} \sim \mu$

Neutralino Mass Matrix

$$M_N = \begin{pmatrix} M_1 & 0 & m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W \\ 0 & M_2 & -m_Z \cos\beta \cos\theta_W & m_Z \cos\beta \cos\theta_W \\ -m_Z \cos\beta \sin\theta_W & m_Z \cos\beta \cos\theta_W & 0 & -\mu \\ m_Z \sin\beta \sin\theta_W & -m_Z \sin\beta \sin\theta_W & -\mu & 0 \end{pmatrix}$$

Baryon Number: MSSM

$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi_\mu + \phi_A)$$

$$F_1 \propto \frac{S_{\tilde{H}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

$$F_2 \propto \frac{S_{\tilde{t}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

Higgsinos

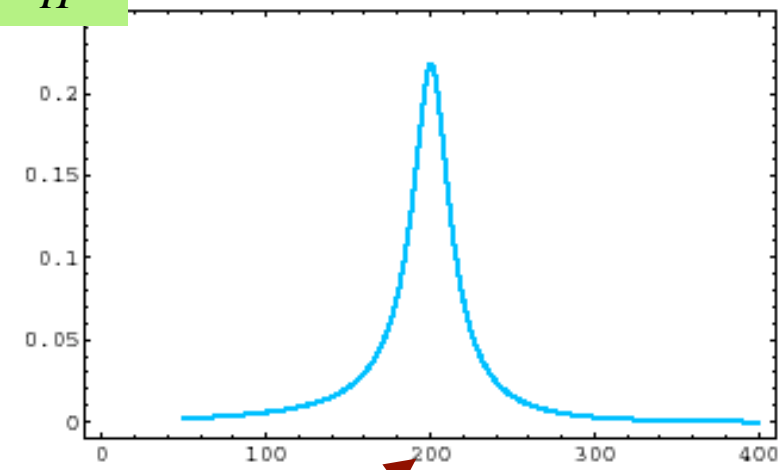
Squarks

Impt to compute both num and den consistently

Resonant CPV & Relaxation

$\hat{S}_{\tilde{H}}$

CP violation



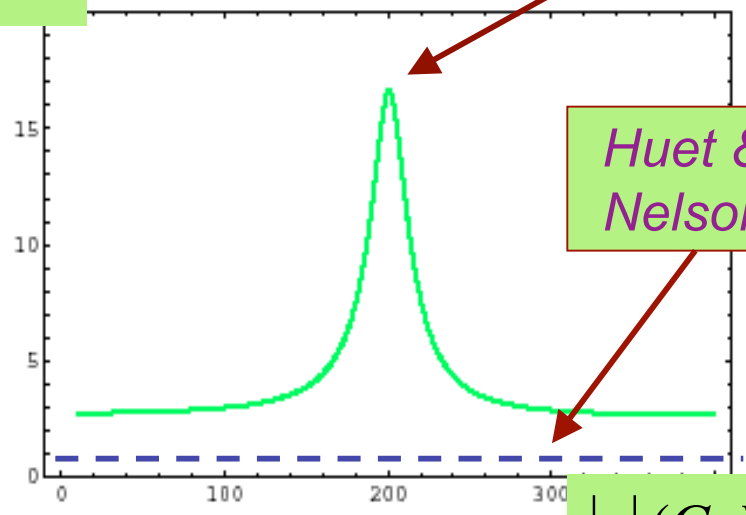
$|\mu|\,(GeV)$

$M_{\tilde{W}}$

R_Γ

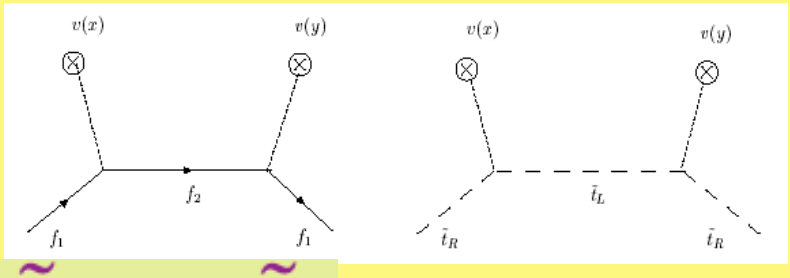
Relaxation

$M_{\tilde{W}}$



Huet & Nelson

$|\mu|\,(GeV)$



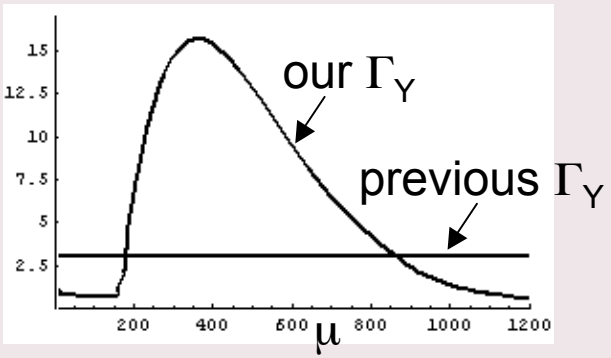
$\tilde{H} \leftrightarrow \tilde{W}$

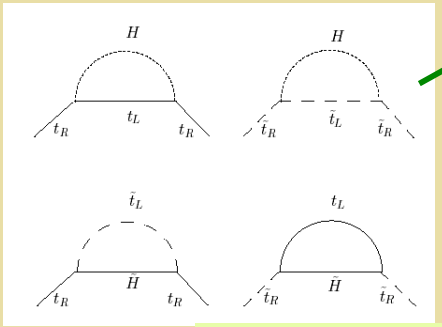
$$F_1 \propto \frac{S_{\tilde{H}}^{CPV}}{\sqrt{\Gamma}} \frac{\Gamma_{WS}}{\Gamma_{diff}}$$

Baryon Number & Γ_Y

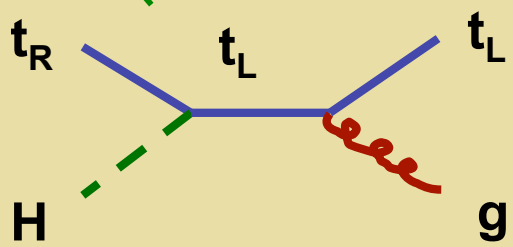
$$Y_B = \frac{\rho_B}{s_\gamma} = F_1 \sin\phi_\mu + F_2 \sin(\phi$$

$$F_i = F_i^\infty \left[1 + \Delta\left(\frac{\Gamma_H}{\Gamma_Y}\right) \right]$$





$O(\alpha_s^0)$



$O(\alpha_s)$

Cirigliano, Lee, R-M, Tulin

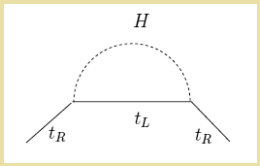
Joyce, Prokopec, Turok

Baryogenesis: tan β effects

Transport, Spectrum, & EDMs

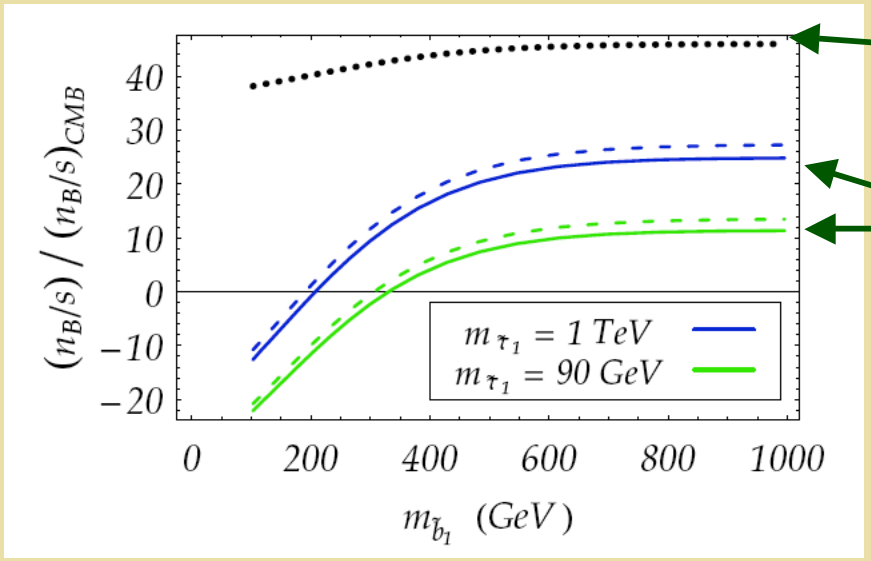
Chung,Garbrecht, R-M, Tulin: 0808.1144

$$Y_B = \sum_K F_k(g_i, M_i; T, v_w, L_w, ...) \sin\phi_k$$



+ SUSY

$$\frac{Y^{\rm MSSM}_{b,\tau}}{Y^{\rm SM}_{b,\tau}} = \tan\beta$$



Small tanβ : negligible $Y_{b,\tau}$ effects

tanβ=20: impt $Y_{b,\tau}$ effects

$$n_{\rm left} \simeq n_q + n_\ell = \frac{k_q}{k_Q} Q + \frac{k_\ell}{k_L} L \qquad (6)$$
$$\simeq \left[\frac{k_q}{k_H}\left(\frac{k_B - k_T}{k_Q + k_B + k_T}\right) + \frac{k_\ell}{k_H}\left(\frac{k_\tau}{k_L + k_\tau}\right)\right] H \ .$$

Small tan β: n_{left}=5Q+4T

$$Q = \frac{(k_B - 9k_T)k_Q}{(9k_T + 9k_Q + k_B)k_H} H$$
$$T = \frac{(9k_T + 2k_B)k_T}{(9k_T + 9k_Q + k_B)k_H} H$$

Canceling t,b (s)quark contributions

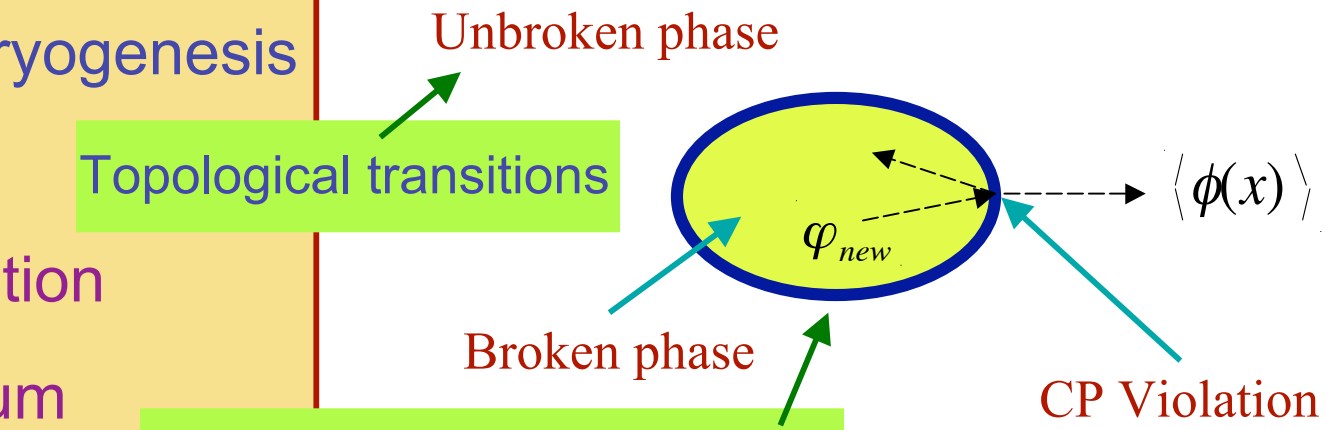
Enhanced light stau contributions

Baryogenesis: New Electroweak Physics

90's: *Cohen, Kaplan, Nelson*
Joyce, Prokopec, Turok

Weak Scale Baryogenesis

- B violation
- C & CP violation
- Nonequilibrium dynamics



Theoretical Issues:
Strength of phase transition (Higgs sector)
Bubble dynamics (expansion rate)
Transport at phase boundary (non-eq QFT)
EDMs: many-body physics & QCD

Elementary particle EDMs: N>>1

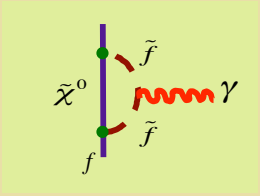
Many-body EDMs:

Engel,Flambaum, Haxton, Henley, Khriplovich,Liu, R-M

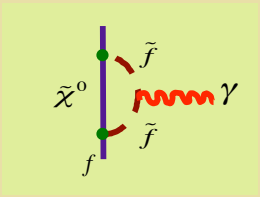
EDMs: Complementary Searches

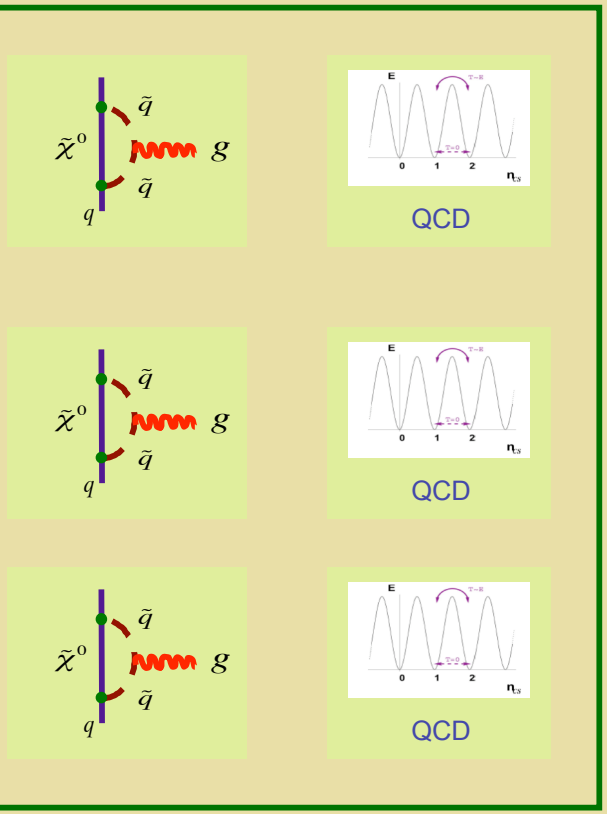
Improvements of 10^2 to 10^3

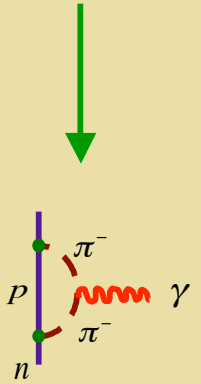
Electron



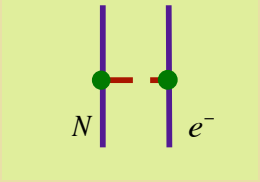
Neutron

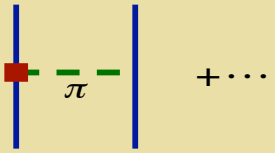




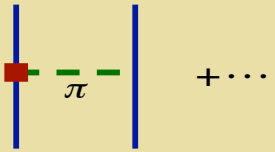


Neutral Atoms



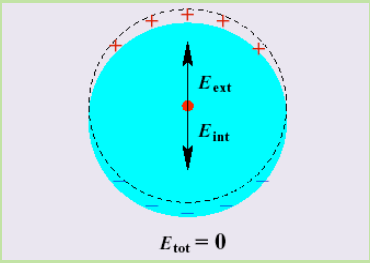


Deuteron



EDMs: Theory

Schiff Screening



Atomic effect from nuclear finite size: Schiff moment

Improvements of 10^2 to 10^3

Nuclear Schiff Moment

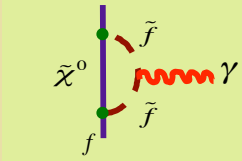
$$S \sim \int d^3x\, x^2\, \vec{x}\, \rho(\vec{x})^{\mathrm{CPV}}$$

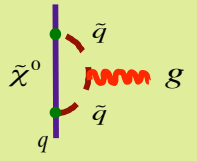
Nuc

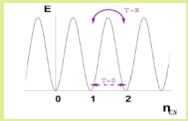
ChPT for d_n: van Kolck et al

$$d_{\mathrm{nuc}} \sim \int d^3x\, x\, \rho(x)^{\mathrm{CPV}}$$

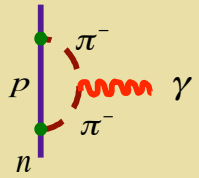
Neutron







QCD

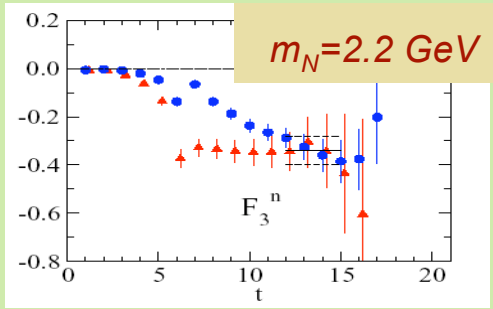


Neutron EDM from LQCD:

$$S_\theta = \frac{g^2\bar{\theta}}{32\pi^2}\int d^4x\,\mathrm{Tr}(G\tilde{G})$$

Two approaches:

- *Expand in θ & average over topological sectors (Blum et al, Shintani et al)*
- *Compute ΔE for spin up/down nucleon in background E field (Shintani et al)*

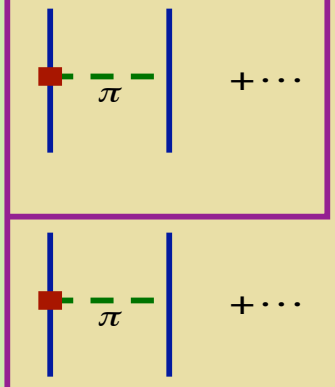


m_N=2.2 GeV

$$d_n^\theta/\bar{\theta} = -1.83(60)\times 10^{-15}\, e-\mathrm{cm}$$

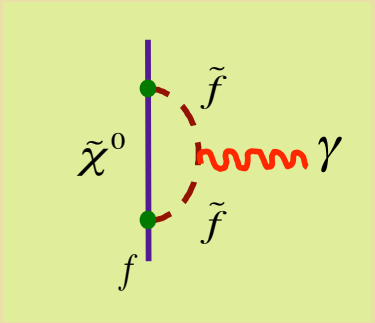
QCD SR (Pospelov et al)

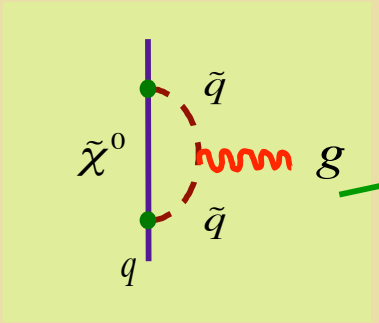
$$d_n^\theta/\bar{\theta} = (2.5\pm 1.2)\times 10^{-16}\, e-\mathrm{cm}$$

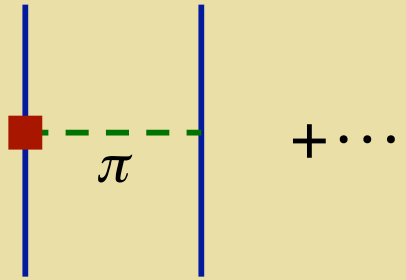


EDMs & Schiff Moments

One-loop







EDM: q, l, n…

Chromo-EDM: q, n…

Dominant in nuclei & atoms

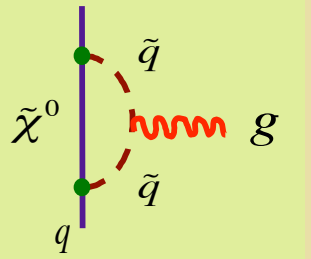
Schiff Moment in ^{199}Hg

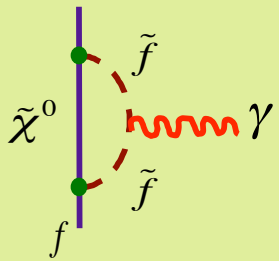
New nuclear calc's needed !

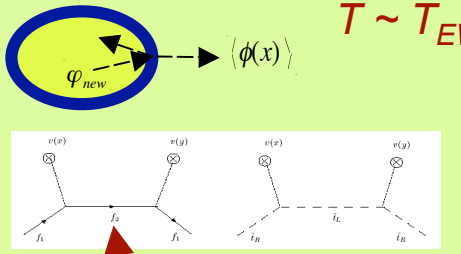
Liu et al: New formulation of Schiff operator

$$\hat{S}^{\lambda} = \frac{1}{10}\int d^3y\,\hat{\rho}(y)\,y^2\left\{y^{\lambda} - \frac{5}{3Z}\left(\hat{d}_N^{\lambda} - \frac{4\sqrt{2\pi}}{5}\left[\hat{d}_N \otimes Y_2(\hat{y})\right]_1^{\lambda}\right)\right\} + \ldots$$

One Loop EDMs & Baryogenesis

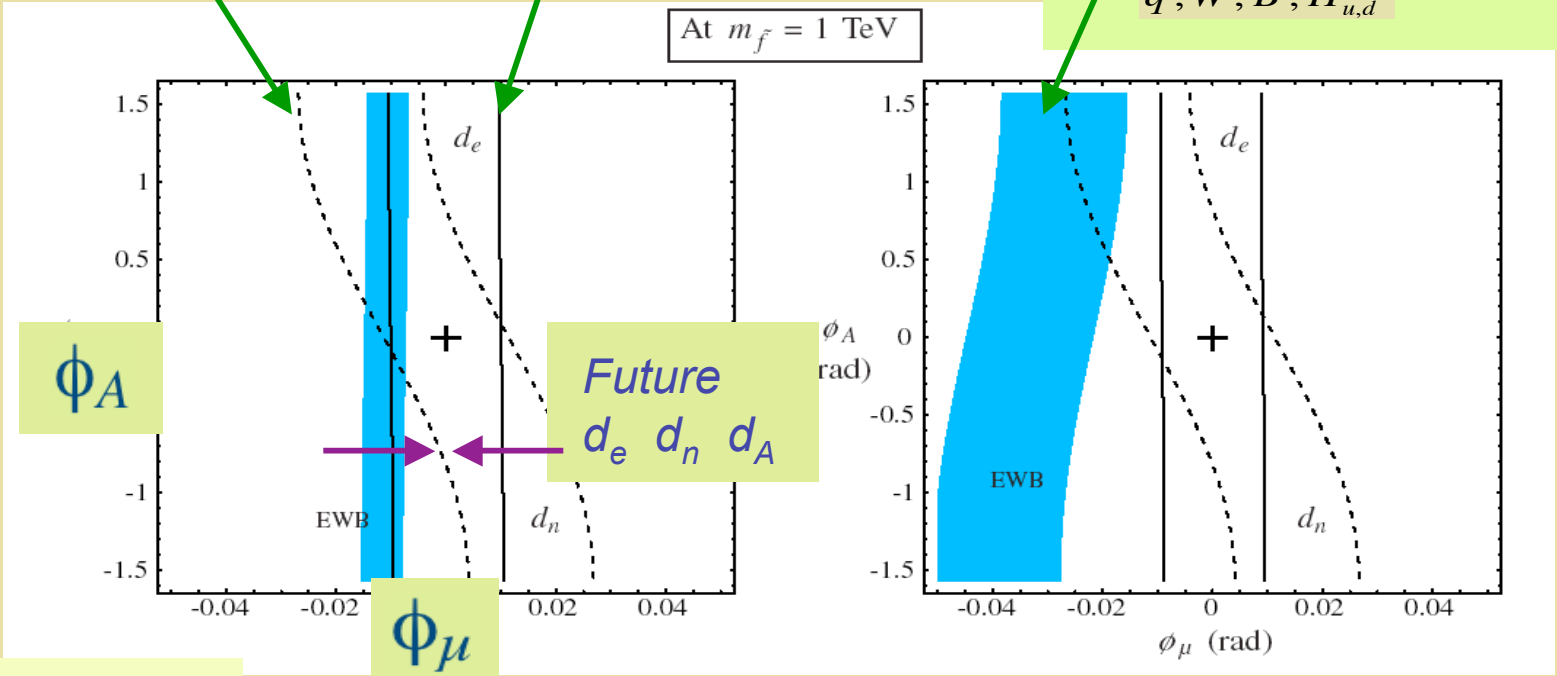






$T \sim T_{EW}$

$q\,,\tilde{W}\,,\tilde{B}\,,\tilde{H}_{u,d}$



ϕ_A

ϕ_μ

Future
d_e d_n d_A

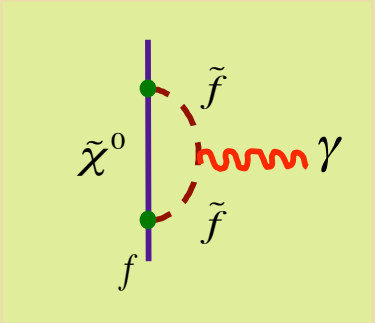
Cirigliano, Lee, Tulin, R-M

Resonant

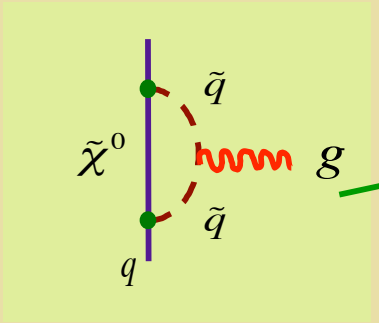
Non-resonant

EDMs in SUSY

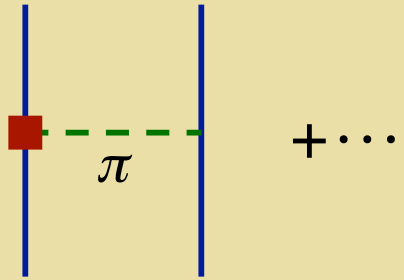
One-loop



EDM: q, l, n…



Chromo-EDM: q, n…

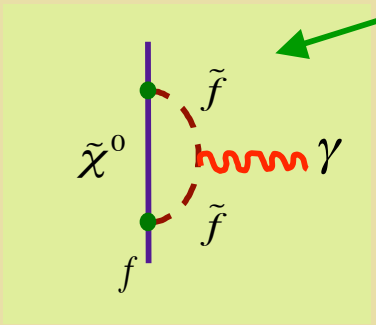


Dominant in nuclei & atoms

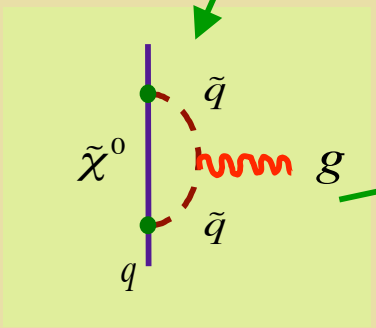
EDMs in SUSY

Decouple in large $m_{\tilde{f}}$ limit

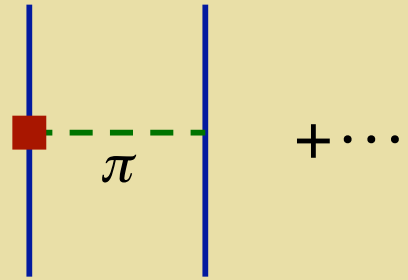
One-loop



EDM: q, l, n…

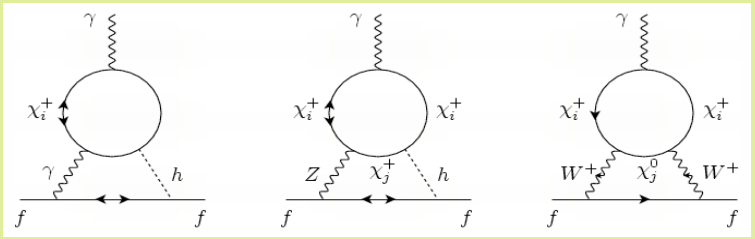


Chromo-EDM: q, n…

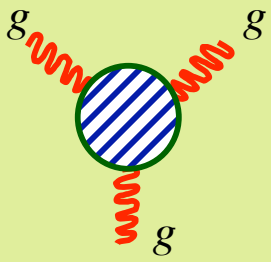


Dominant in nuclei & atoms

Two-loop



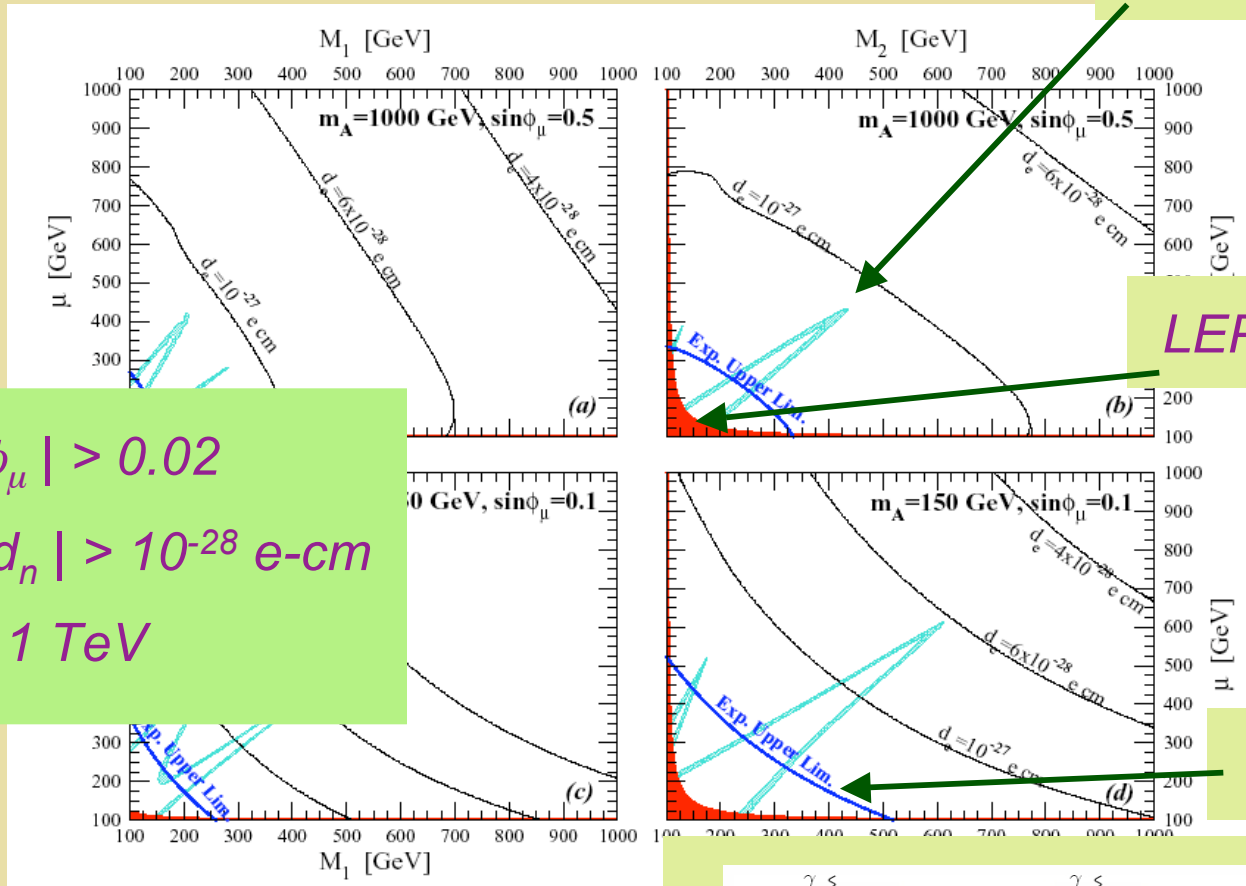
EDM only: no chromo-EDM



Weinberg: small matrix el's

EDM constraints & SUSY CPV

Baryogenesis



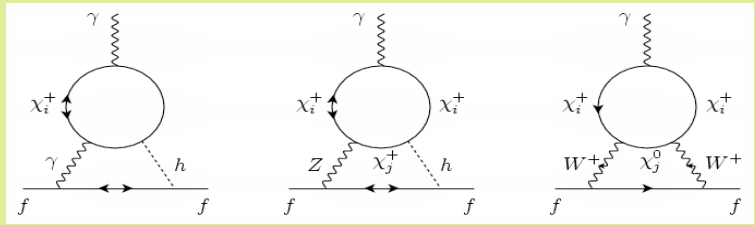
LEP II Exclusion

$|\sin\phi_\mu| > 0.02$

$|d_e, d_n| > 10^{-28}$ e-cm

$M_\chi < 1$ TeV

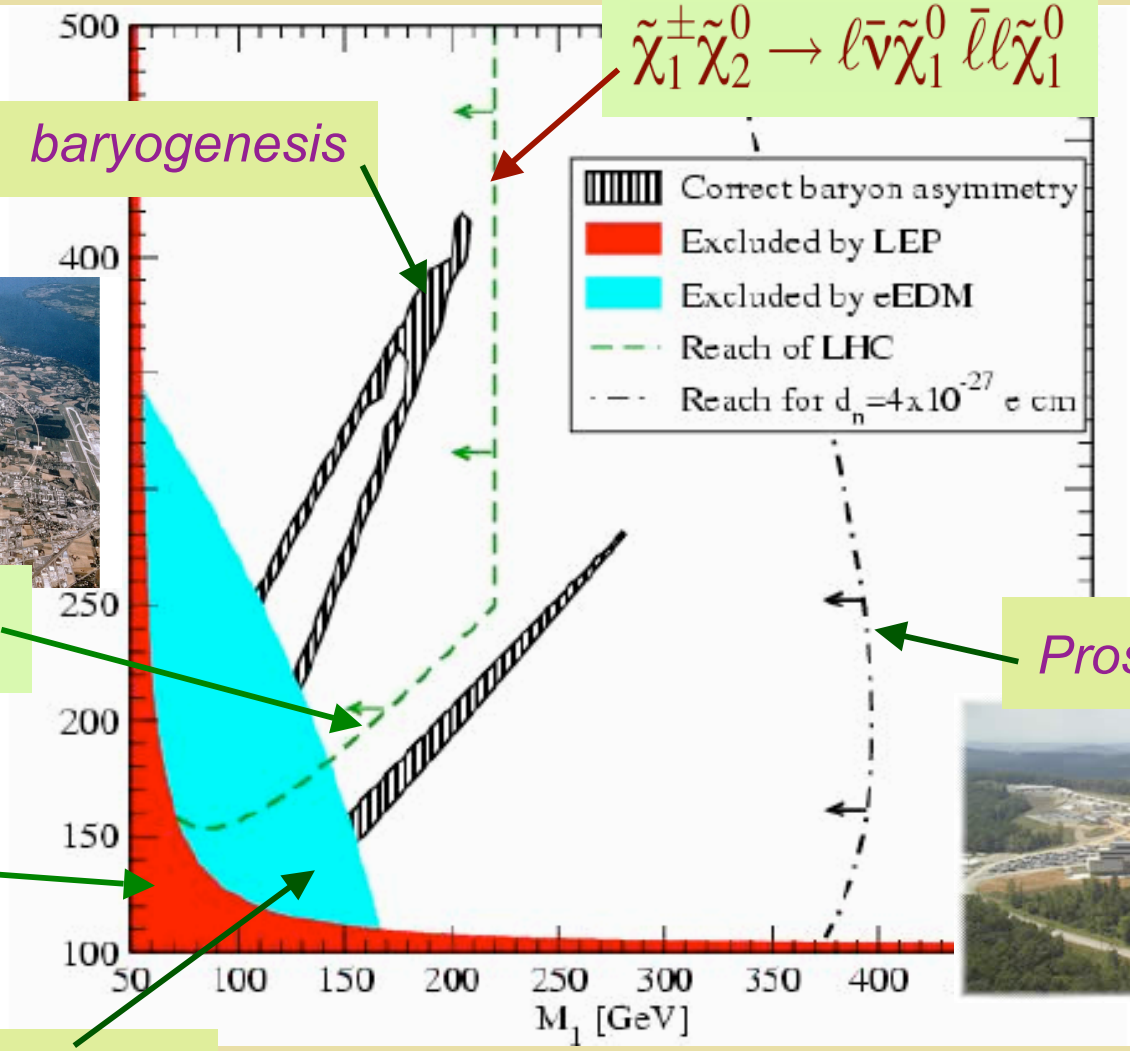
Two loop d_e



Cirigliano, Profumo, R-M

SUGRA: $M_2 \sim 2M_1$

Baryogenesis: EDMs & Colliders



LHC reach

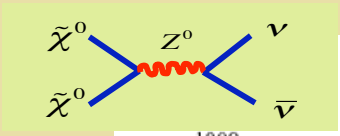
Prospective d_n

LEP II excl

Present d_e

Cirigliano, Profumo, R-M

Dark Matter: Future Experiments



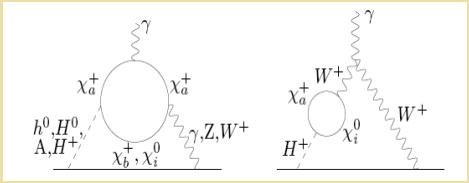
Assumes
$\Omega_\chi \sim \Omega_{CDM}$

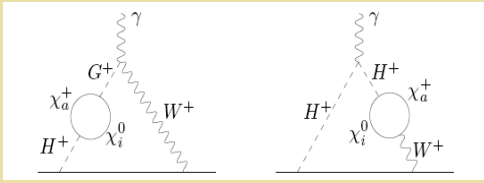
Cirigliano, Profumo, R-M

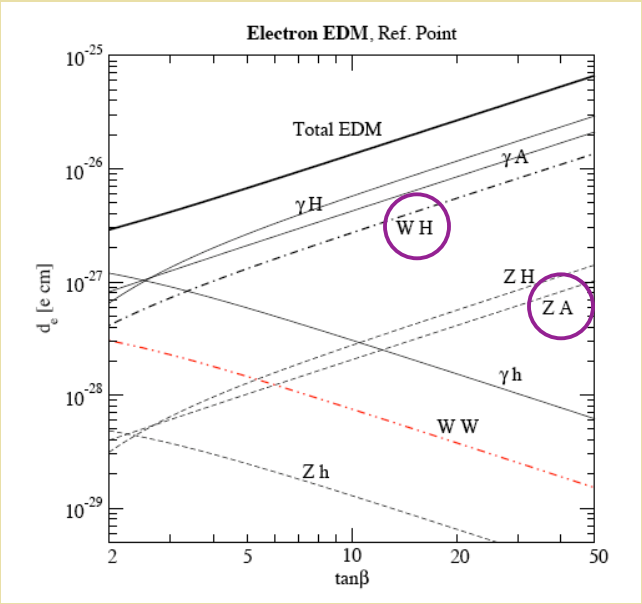
EDMs in SUSY: Full Two-Loop

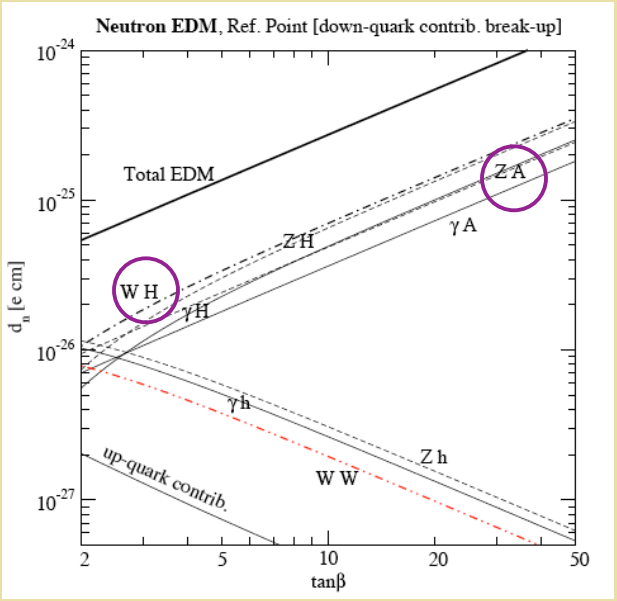
Higgs Boson Masses

Li, Profumo, R-M: 0608.2693









m_A=300 GeV, μ=300 GeV, M_2=2M_1=290 GeV

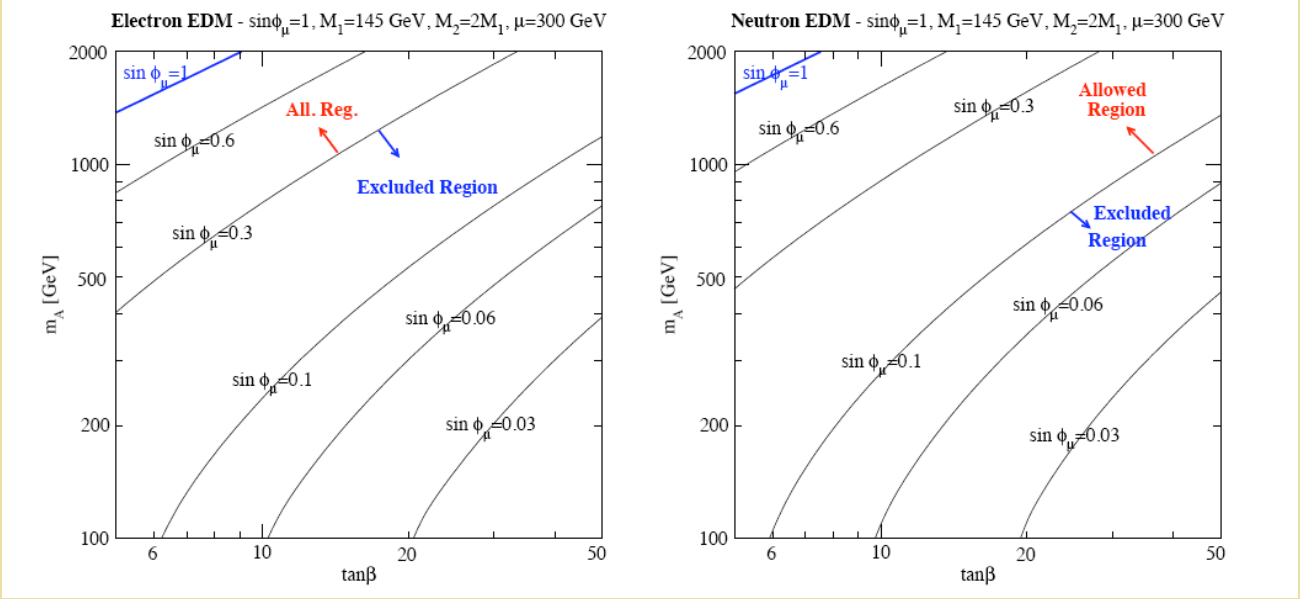
$$d_n = \sum_K H_k(g_i, M_i) \sin\phi_k$$

WH Loops dominate for neutron & comparable to γH, γA for electron

EDMs in SUSY: Full Two-Loop

Higgs Boson Masses

$$d_n = \sum_K H_k(g_i, M_i) \sin\phi_k$$

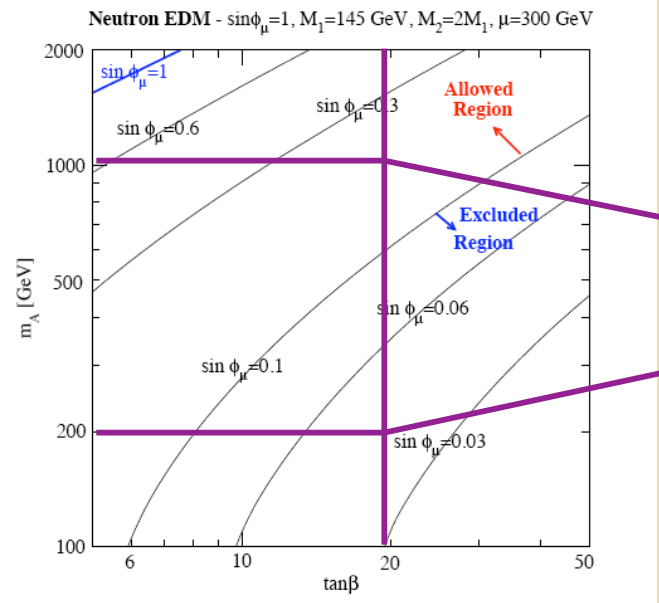


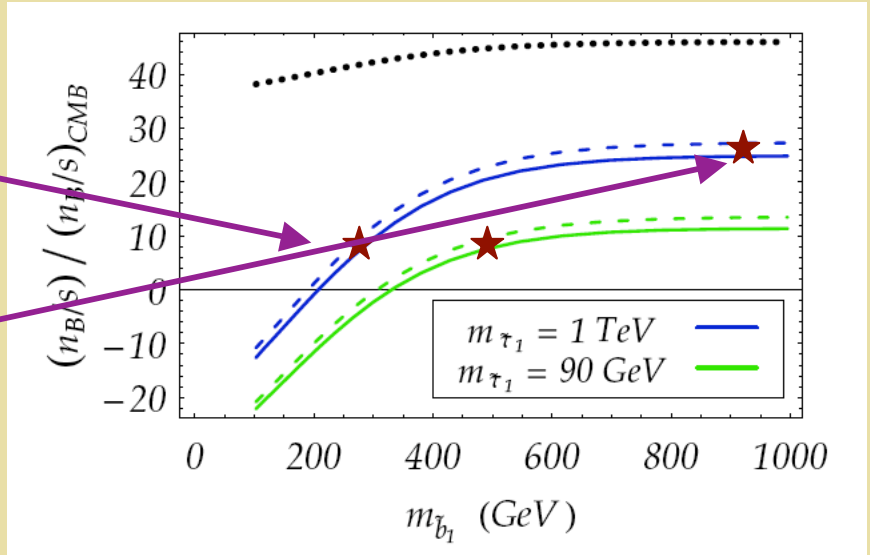
Stronger limits on ϕ_{CPV} for light Higgses & large tanβ

Baryogenesis: EDMs & Colliders

Higgs Boson Masses

$$Y_B = \sum_K F_k(g_i, M_i; T, v_w, L_w, ...) \sin\phi_k$$





$$d_n = \sum_K H_k(g_i, M_i) \sin\phi_k$$

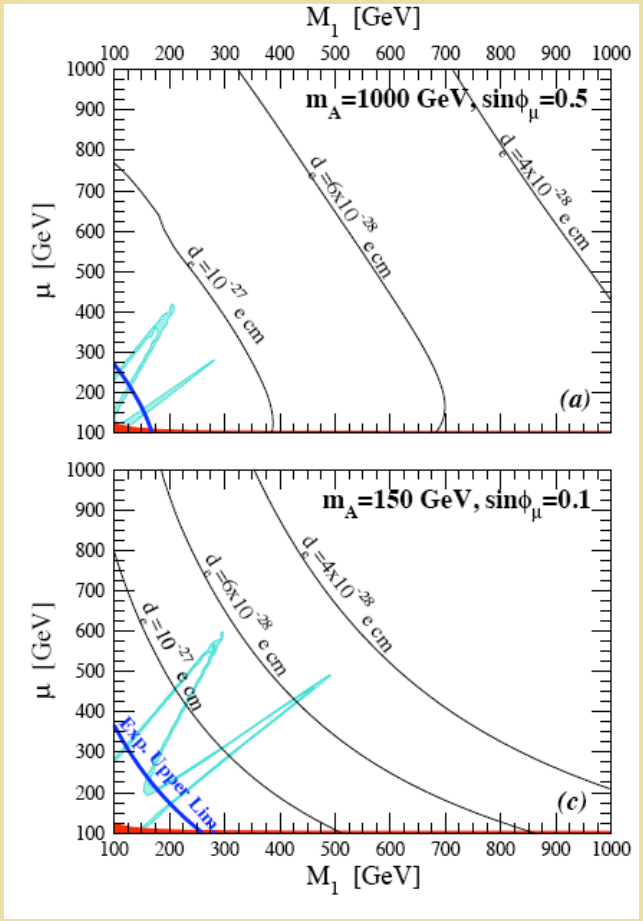
Examples w/ tanβ=20, m_{stop} = 150 GeV:
m_A=1 TeV, sin ϕ_μ=0.2; m_A=1 TeV, sin ϕ_μ=0.05

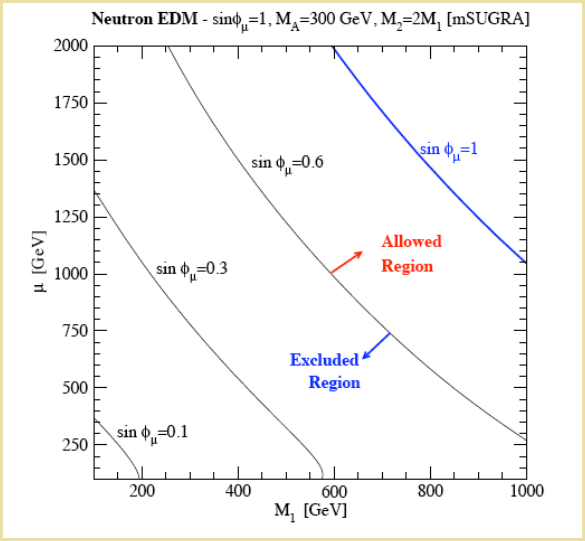
Stronger limits on ϕ_{CPV} for light Higgses & large tanβ

RH sbottom and stau masses correlated

Baryogenesis: EDMs & Colliders

Higgsino & Gaugino Mases





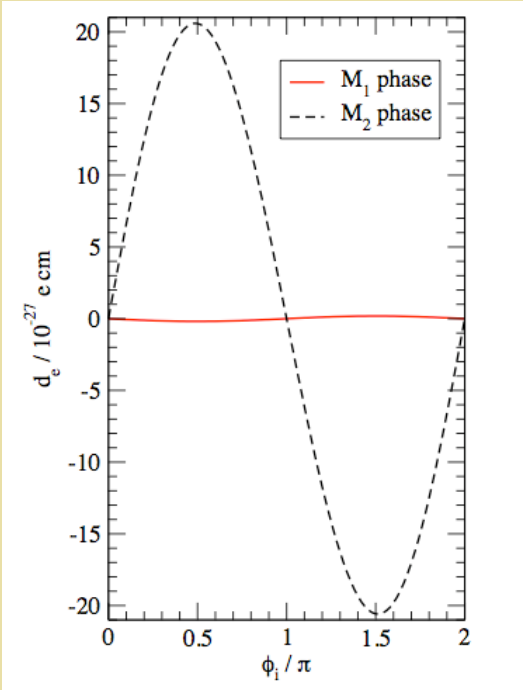
$$d_n = \sum_K H_k(g_i, M_i)\ \sin\phi_k$$

$$Y_B = \sum_K F_k(g_i, M_i; T, v_w, L_w, ...)\ \sin\phi_k$$

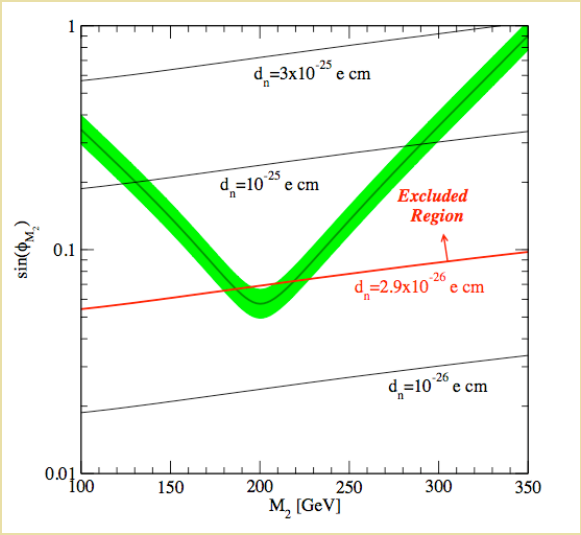
Larger m_A: EDM contours & EWB regions contract

Baryogenesis: EDMs & Colliders

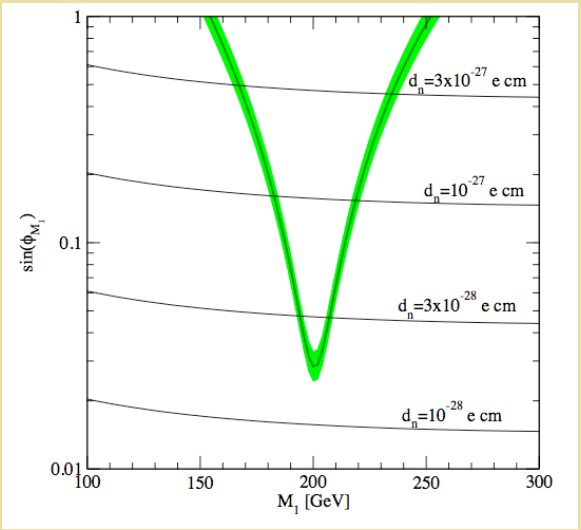
$Arg(\mu M_1 b^*) \neq Arg(\mu M_2 b^*)$



Weak dependence of d_e , d_n on $Arg(\mu M_1 b^*)$



Res χ^+ EWB not compatible with d_n



Res & non-res χ^0 EWB compatible with future d_n , light m_A, & moderate tanβ

Baryogenesis: New Electroweak Physics

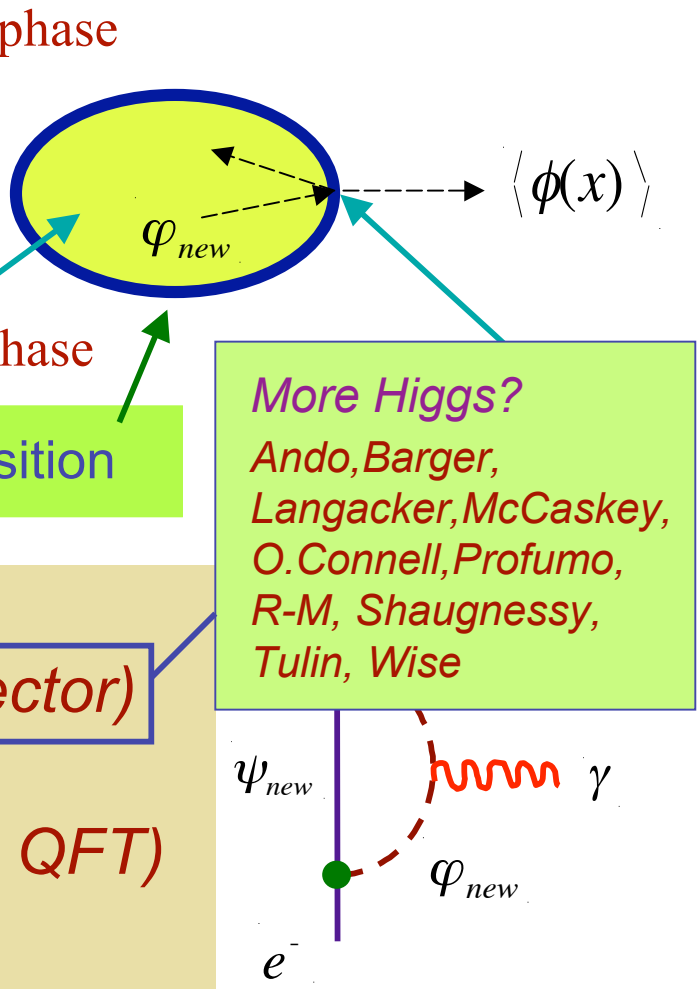
90's: *Cohen, Kaplan, Nelson*
Joyce, Prokopec, Turok

Weak Scale Baryogenesis

- *B violation*
- *C & CP violation*
- *Nonequilibrium dynamics*

Topological transitions

1st order phase transition



More Higgs?
Ando,Barger, Langacker,McCaskey, O.Connell,Profumo, R-M, Shaugnessy, Tulin, Wise

Theoretical Issues:

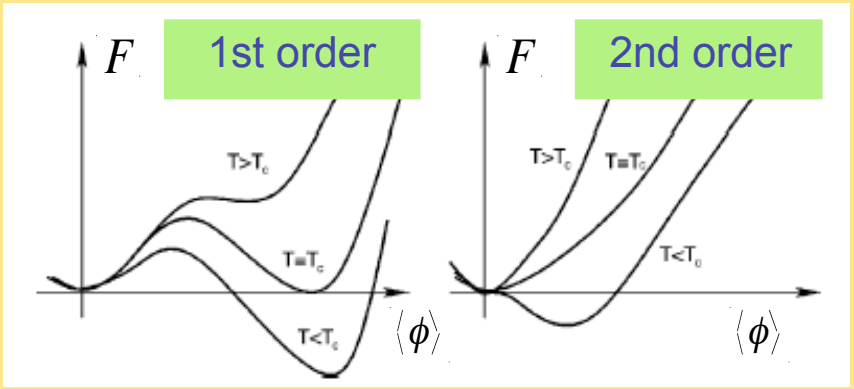
Strength of phase transition (Higgs sector)

Bubble dynamics (expansion rate)

Transport at phase boundary (non-eq QFT)

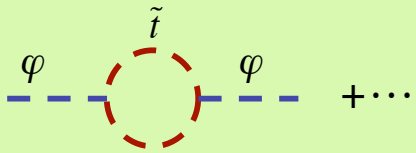
EDMs: many-body physics & QCD

Electroweak Phase Transition & Higgs



Increasing m_h ⟶

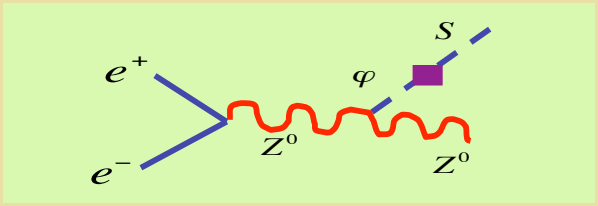
Stop loops in V_{Eff}

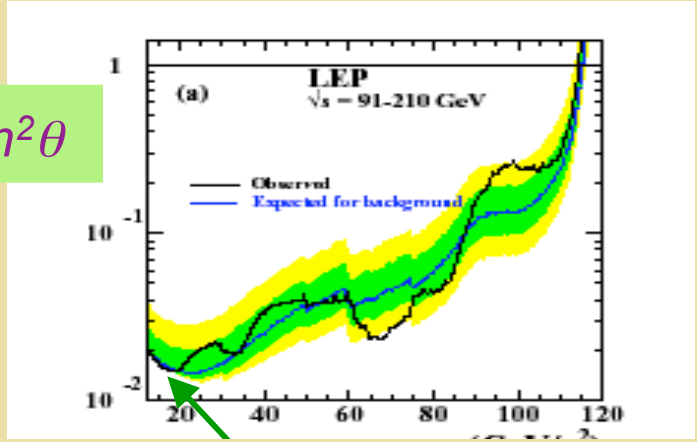


$E_{MSSM} \sim 10\, E_{SM}$: $m_H < 120$ GeV

Light RH stop w/ special $M^2_{\tilde{t}_R}$

e Transition & Higgs

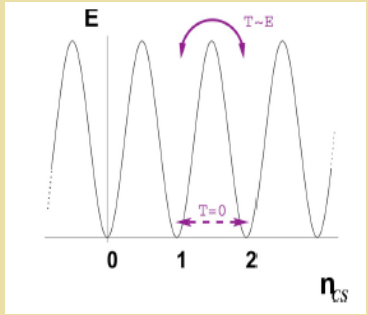




$$V_{EFF}(\varphi,T) = D(T^2 - T_0^2)\varphi^2 - ETe^3 + \frac{\lambda}{4}\varphi^4$$

Need

$$\frac{\varphi(T_C)}{T_C} = E\left(\frac{M_{WK}^2}{m_H^2}\right) > 1$$



So that $\Gamma_{sphaleron}$ is not too fast

Computed E_{SM} : $m_H < 40$ GeV

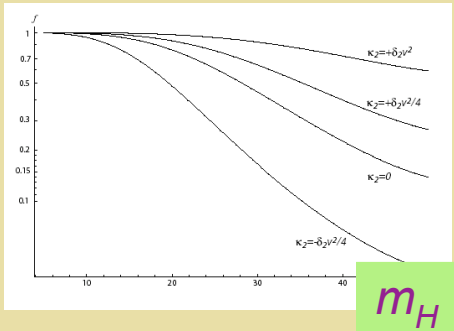
Can an augmented Higgs sector

- *Generate a strong 1st order EWPT ?*
- *Allow for a heavier SM-like Higgs than in the MSSM ?*
- *Alleviate the tension between direct Higgs search bounds and the EWPO ?*
- *Be discovered at the LHC ?*
- *Can its necessary characteristic probed at the LHC and a future e^+e^- collider ?*

e Transition & Higgs

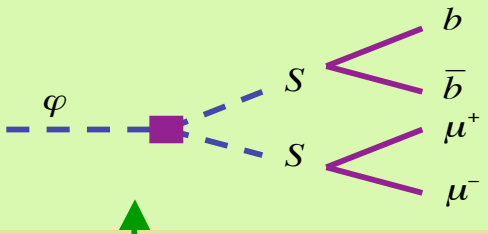
Reduced SM Higgs branching ratios

B.R. reduction



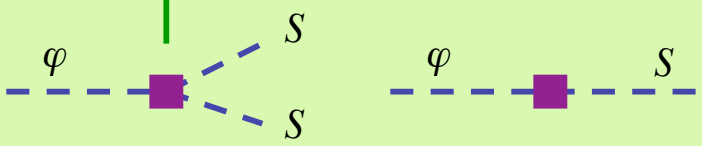
m_H

Unusual final states



O'Connell, R-M, Wise

Non-doublet Higgs (w / wo SUSY)

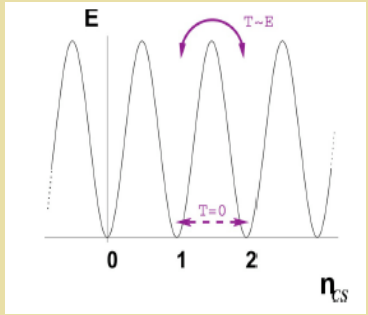


Decay *Mixing*

$$V_{EFF}(\varphi,T) = D(T^2 - T_0^2)\varphi^2 - ETe^3 + \frac{\lambda}{4}\varphi^4$$

Need

$$\frac{\varphi(T_C)}{T_C} = E\left(\frac{M_{WK}^2}{m_H^2}\right) > 1$$



So that $\Gamma_{sphaleron}$ is not too fast

Computed E_{SM} : m_H < 40 GeV

The Simplest Extension

Simplest extension of the SM scalar sector: add one real scalar S

- *Goal: identify generic features of models with extended scalar sectors that give a strong, 1st order EWPT*
- *Determine low-energy phenomenology (Higgs studies, precision ewk)*
- *Address CPV with a different mechanism*

The Simplest Extension, Cont'd

Mass matrix

$$M^2 = \begin{pmatrix} \mu_h^2 & \mu_{hs}^2/2 \\ \mu_{hs}^2/2 & \mu_s^2 \end{pmatrix}$$

$$\mu_h^2 \equiv \frac{\partial^2 V}{\partial h^2} = 2\bar{\lambda}_0 v_0^2$$

$$\mu_s^2 \equiv \frac{\partial^2 V}{\partial s^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

$$\mu_{hs}^2 \equiv \frac{\partial^2 V}{\partial h \partial s} = (a_1 + 2a_2 x_0)\, v_0$$

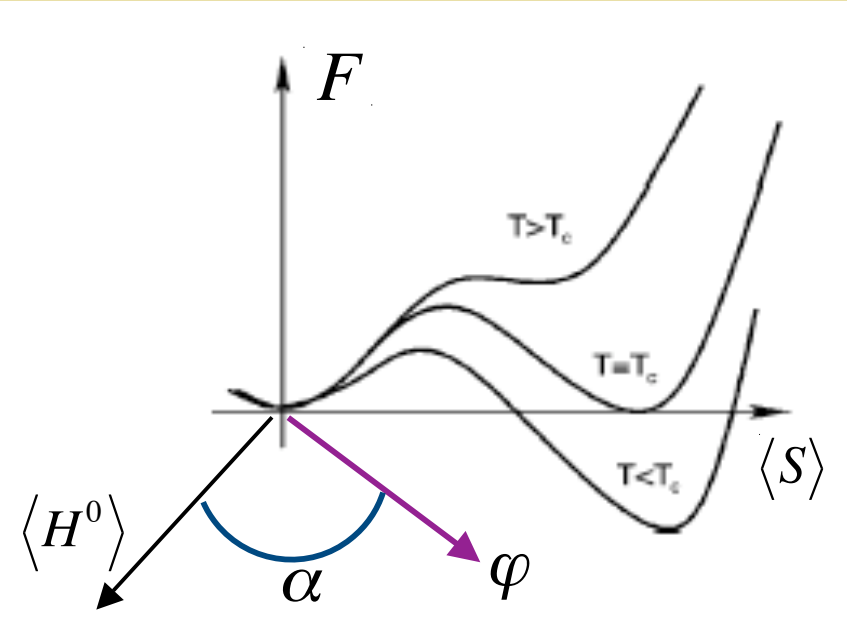
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

$$\tan\theta = \frac{y}{1+\sqrt{1+y^2}}, \qquad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}$$

Stable S (dark matter?)

- *Tree-level Z_2 symmetry: a_1=b_3=0 to prevent s-h mixing and one-loop s→hh*
- *x_0 =0 to prevent h-s mixing*

Finite Temperature Potential



Cylindrical Co-ordinates

$$\langle H^0 \rangle = v/\sqrt{2} \equiv \varphi \cos\alpha$$
$$\langle S \rangle = x \equiv \varphi \sin\alpha$$

- *What is the pattern of symmetry breaking ?*
- *What are conditions on the couplings in V(H,S) so that $\langle H^0 \rangle / T > 1$ at T_C ?*

- *Compute $V_{eff}(\phi, \alpha, T)$*
- *Minimize w.r.t ϕ , α*
- *Find T_C*
- *Evaluate $v(T_C)/T_C \sim \cos\alpha(T_C)\ \phi(T_C)/T_C$*

Finite Temperature Potential

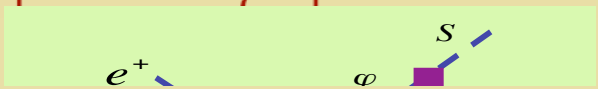
Potential

$$V_{eff}(\varphi,\alpha,T) = \bar{\lambda}\varphi^4 + (e - \varepsilon T)\varphi^3 + \left[2\bar{D}(T^2 - T_0^2) + (b_2 \sin^2\alpha)/2\right]\varphi^2 + BT^2\varphi + \cdots$$

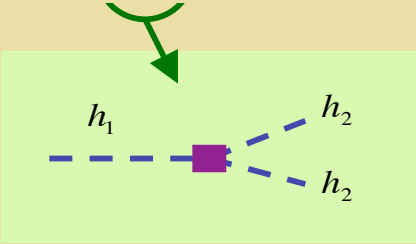
Electroweak Symmetry Breaking

Strong first order EWPT

$$\sqrt{2}\cos\alpha_c \left(\frac{\varepsilon - e/T_c}{2\bar{\lambda}}\right) \left[1 + \gamma\frac{|V_0|}{T_c^4}\right] + \cdots \gtrsim 1$$

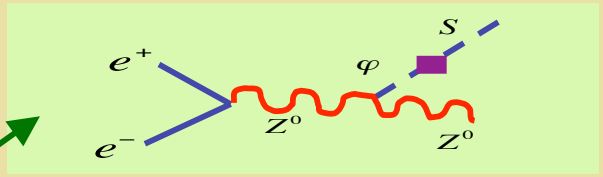


- Increase ε
- Large $e < 0$
- Reduce λ
- Nonzero V_0

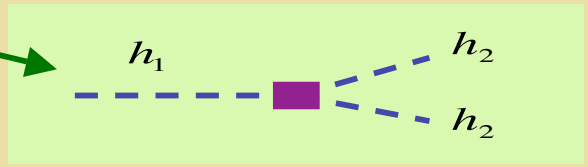


Electroweak Symmetry Breaking

Strong first order EWPT



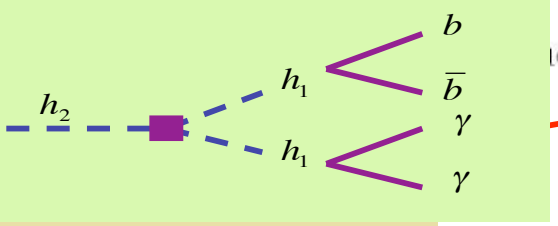
$$\frac{4E_{SM}\cos^4\alpha_c - \sqrt{2}\cos\alpha_c\sin\alpha_c\left(a_1\cos^2\alpha_c/2 + b_3\sin^2\alpha_c/3\right)/T_c}{2\bar{\lambda}_0(T_c)\cos^4\alpha_c + a_2\cos^2\alpha_c\sin^2\alpha_c + b_4\sin^4\alpha_c/4} \gtrsim 1$$



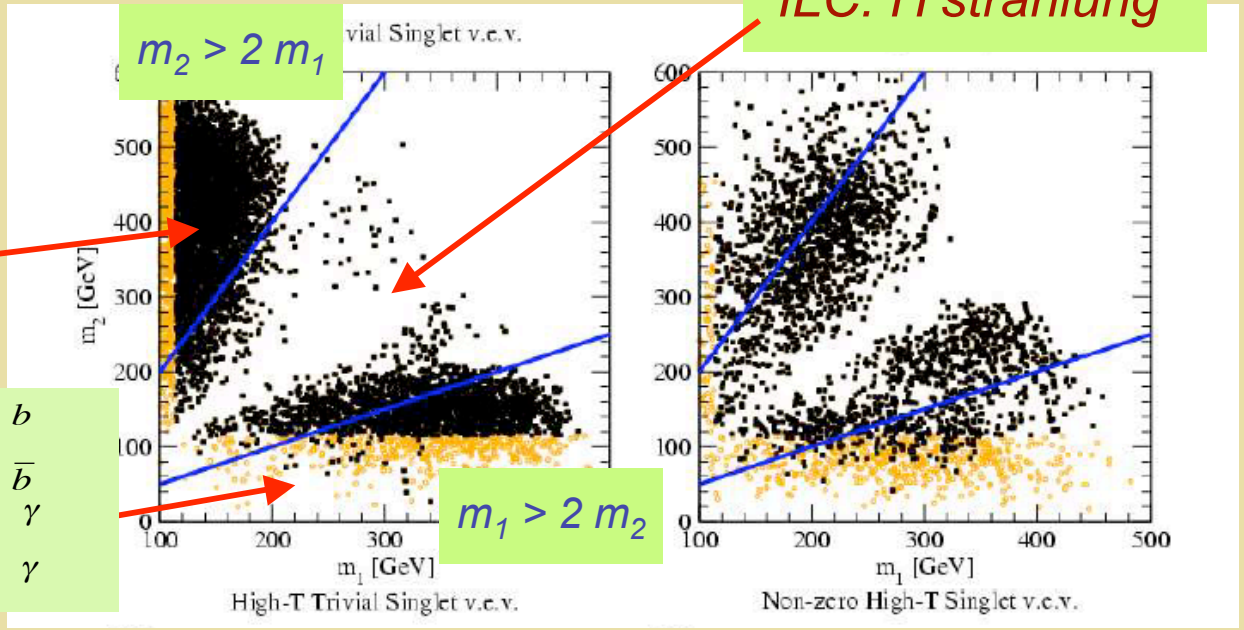
Phenomenology

Colliders

LHC exotic final states: 4b-jets, γ γ + 2 b-jets…



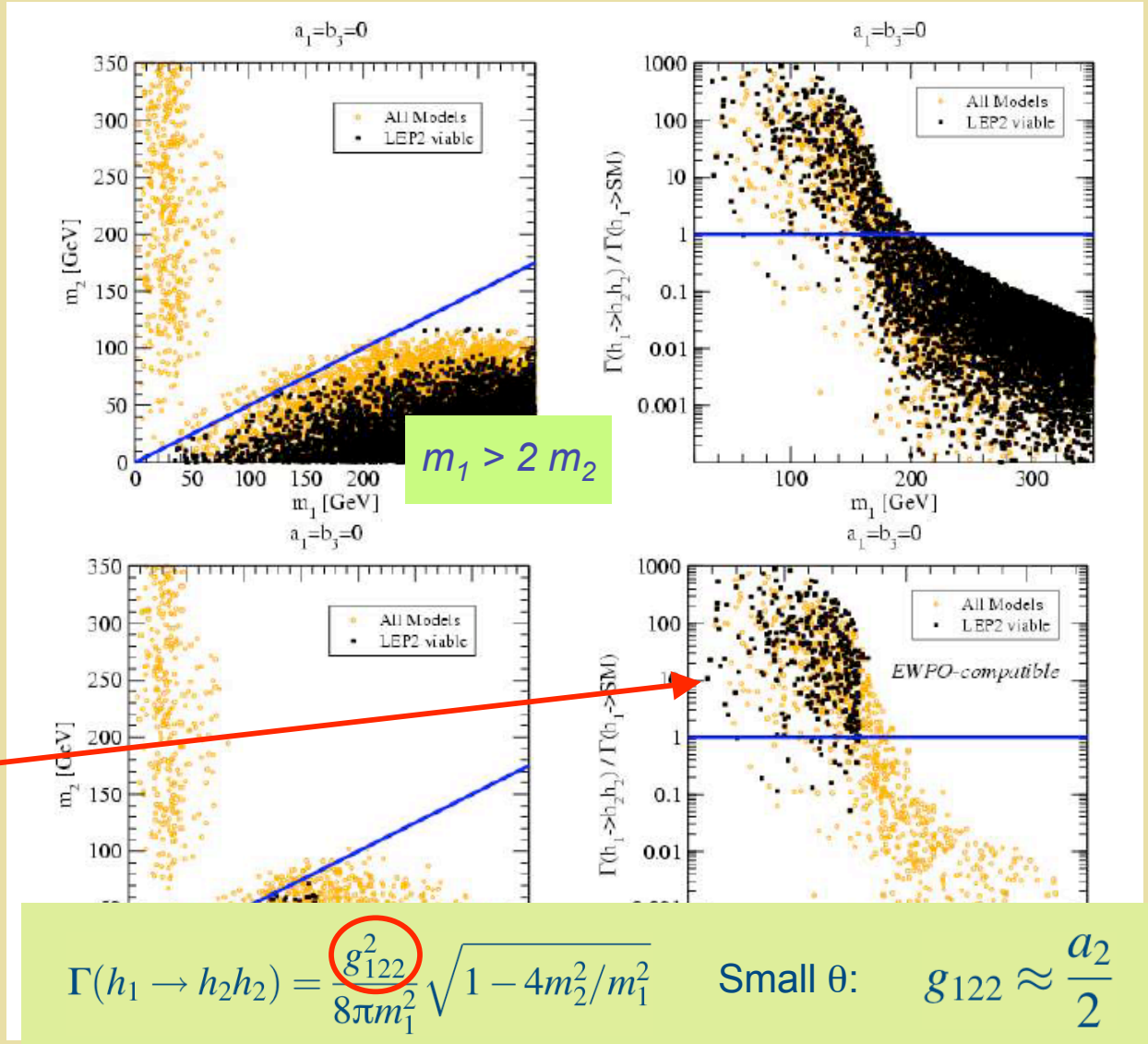
ILC: H'strahlung



Phenomenology

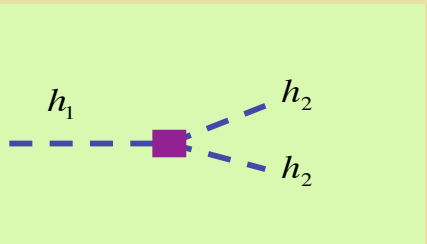
Colliders

Z_2 Symmetry



$m_1 > 2\, m_2$

LHC: reduced BR(h → SM)



$$\Gamma(h_1 \to h_2 h_2) = \frac{g_{122}^2}{8\pi m_1^2}\sqrt{1-4m_2^2/m_1^2}$$

Small θ: $g_{122} \approx \frac{a_2}{2}$

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Controls Ω_{CDM} & EWPT

$$V = \frac{m^2}{2}H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2}H^\dagger H|\mathbb{S}|^2 + \left(|a_1|e^{i\phi_{a_1}}\mathbb{S} + c.c.\right) + \left(\frac{|b_1|e^{i\phi_{b_1}}}{4}\mathbb{S}^2 + c.c.\right) + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4$$

No domain walls

DM mass

Key features for EWPT & DM:

In progress…

(1) Softly broken global U(1)

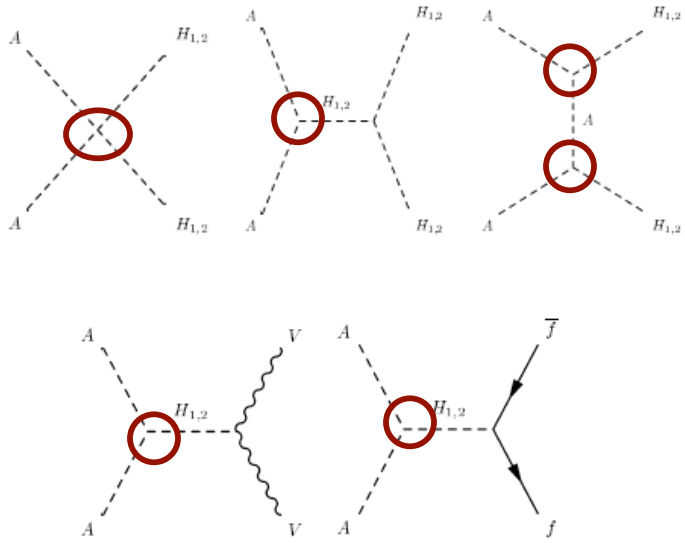
(2) Closes under renormalization

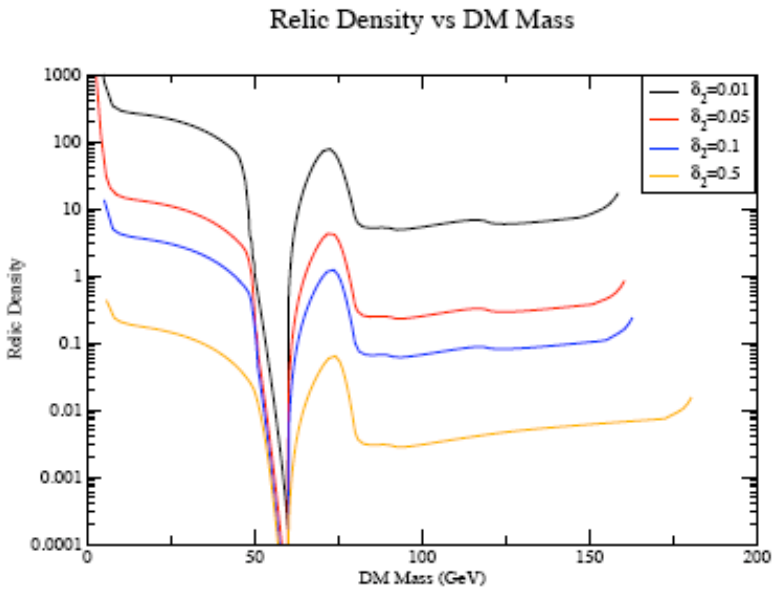
(3) SSB leading to two fields: S that mixes w/ h and A is stable (DM)

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

δ_2 controls Ω_{CDM} & EWPT





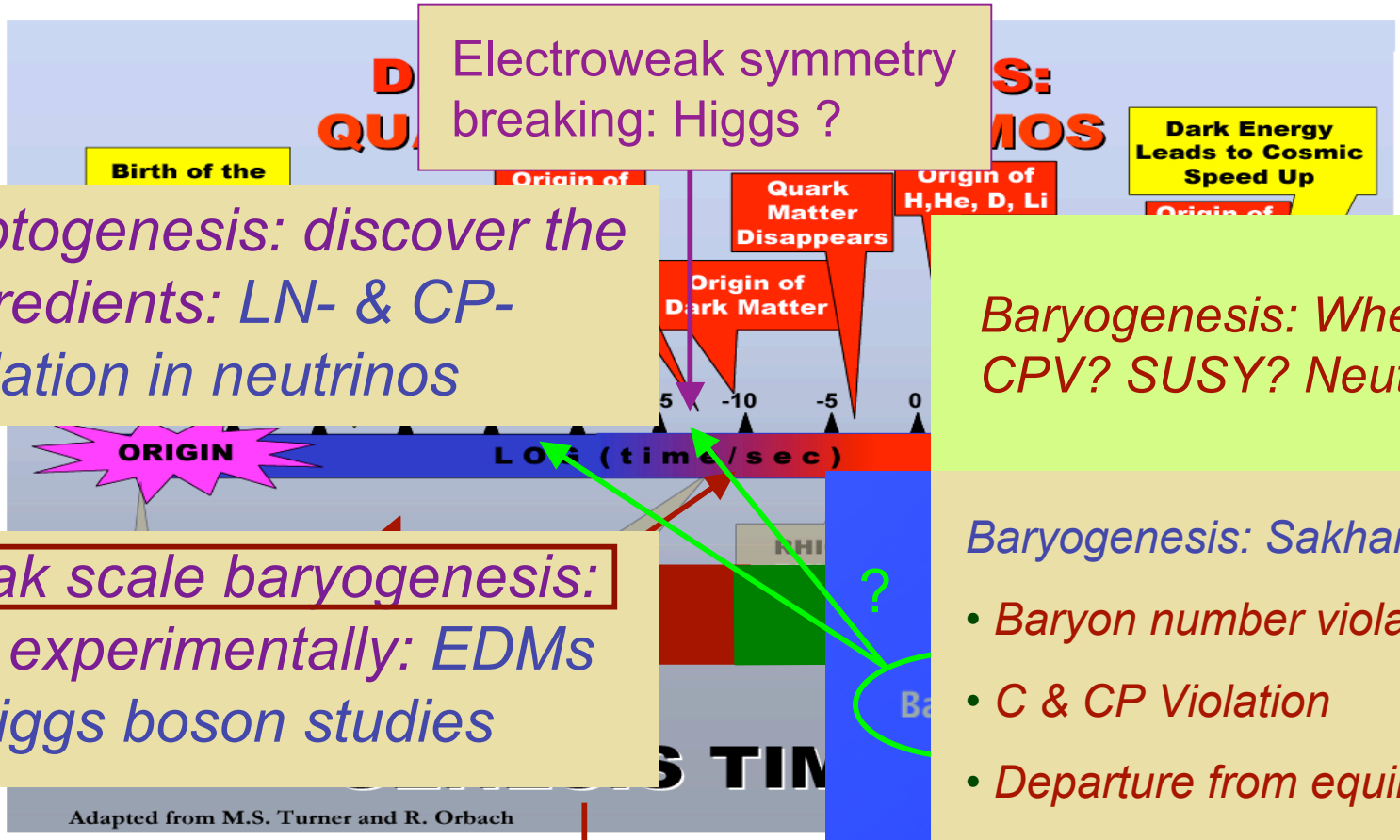
In progress…

Summary

- *EW baryogenesis remains a viable and testable mechanism for producing the observed baryon asymmetry*
- *Extensions of the Higgs sector of the SM can readily yield a strong 1st order EWPT, and these extensions can be probed at LHC and ILC*
- *We've made progress in computing Y_B systematically, but challenges remain: no one's (yet) perfect !*
- *EDM searches provide our most powerful probe of new EW CPV needed for Y_B*

Back Matter

Baryogenesis Scenarios



Electroweak symmetry breaking: Higgs ?

Leptogenesis: discover the ingredients: LN- & CP-violation in neutrinos

Baryogenesis: When? CPV? SUSY? Neutrinos?

Weak scale baryogenesis: test experimentally: EDMs & Higgs boson studies

Baryogenesis: Sakharov

- *Baryon number violation*
- *C & CP Violation*
- *Departure from equilibrium*

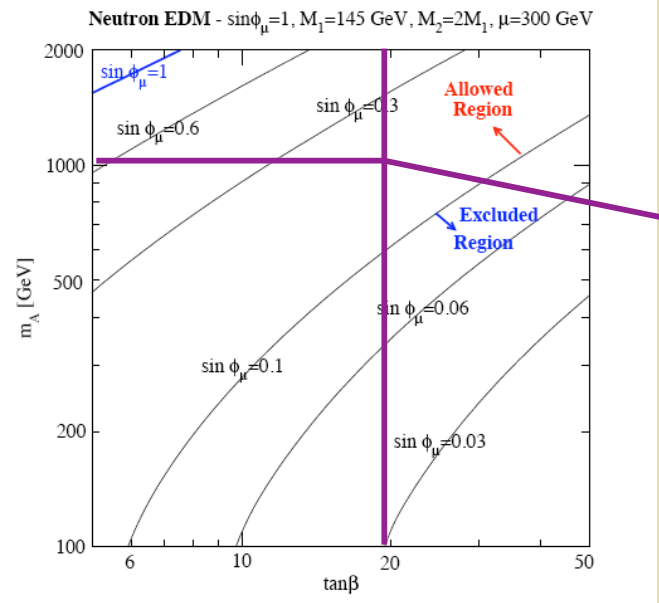
Beyond the SM

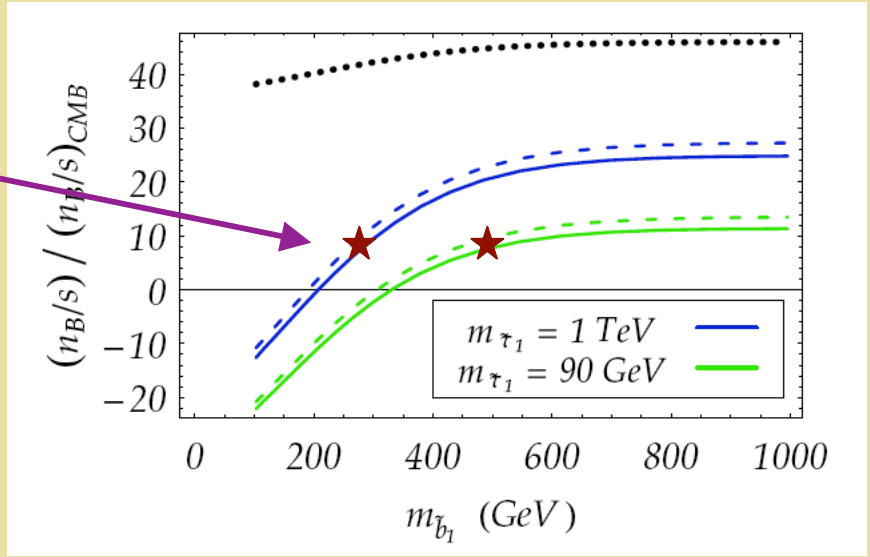
Cosmic Energy Budget

Baryogenesis: EDMs & Transport

Higgs Boson Masses

$$Y_B = \sum_K F_k(g_i, M_i; T, v_w, L_w, ...) \sin\phi_k$$

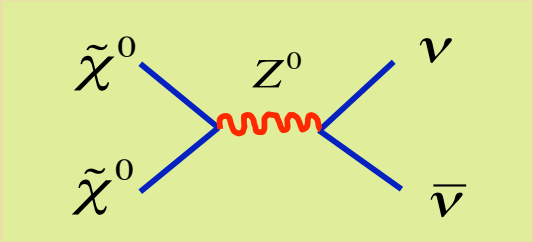




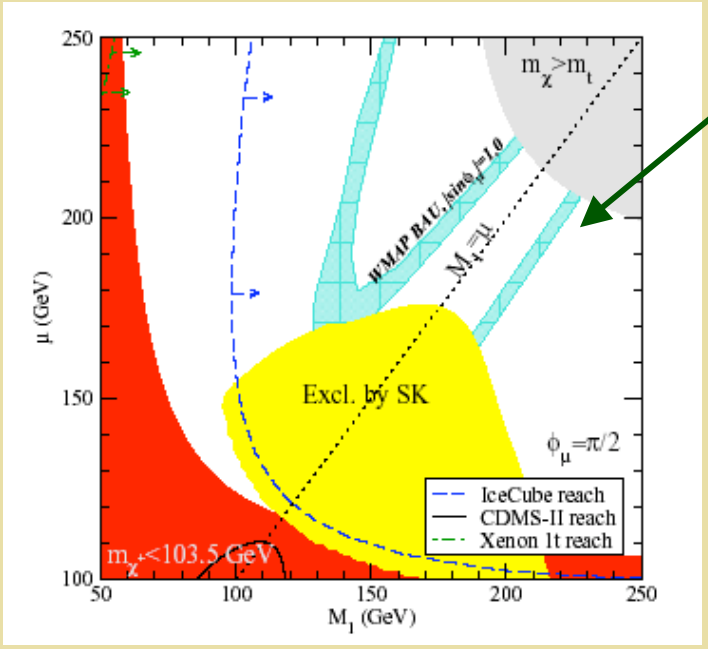
$$d_n = \sum_K H_k(g_i, M_i) \sin\phi_k$$

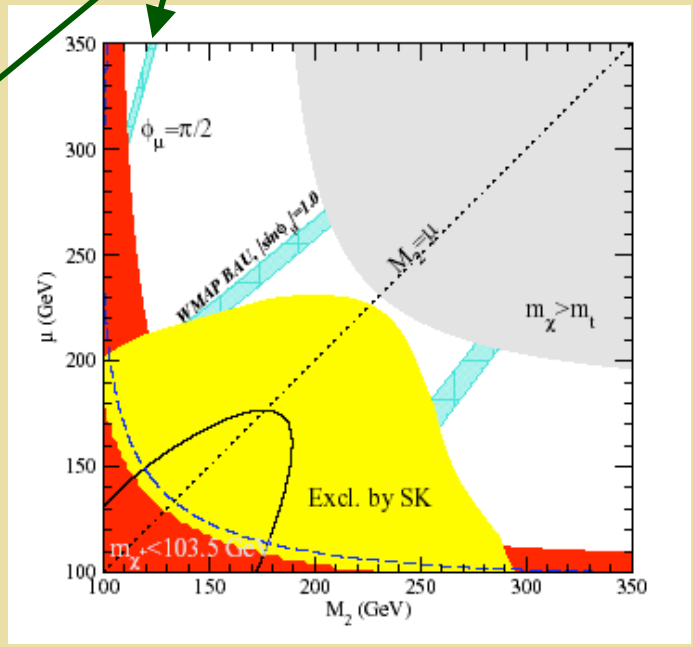
Stronger limits on ϕ_{CPV} for light Higgses & large tanβ

Dark Matter: Neutrinos in the Sun



Neutralino-driven baryogenesis

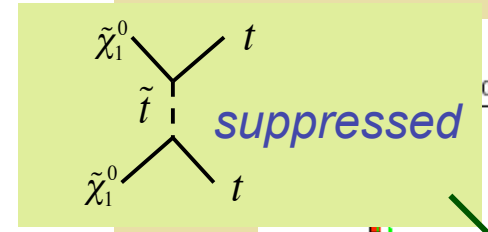




SUGRA: $M_2 \sim 2M_1$

AMSB: $M_1 \sim 3M_2$

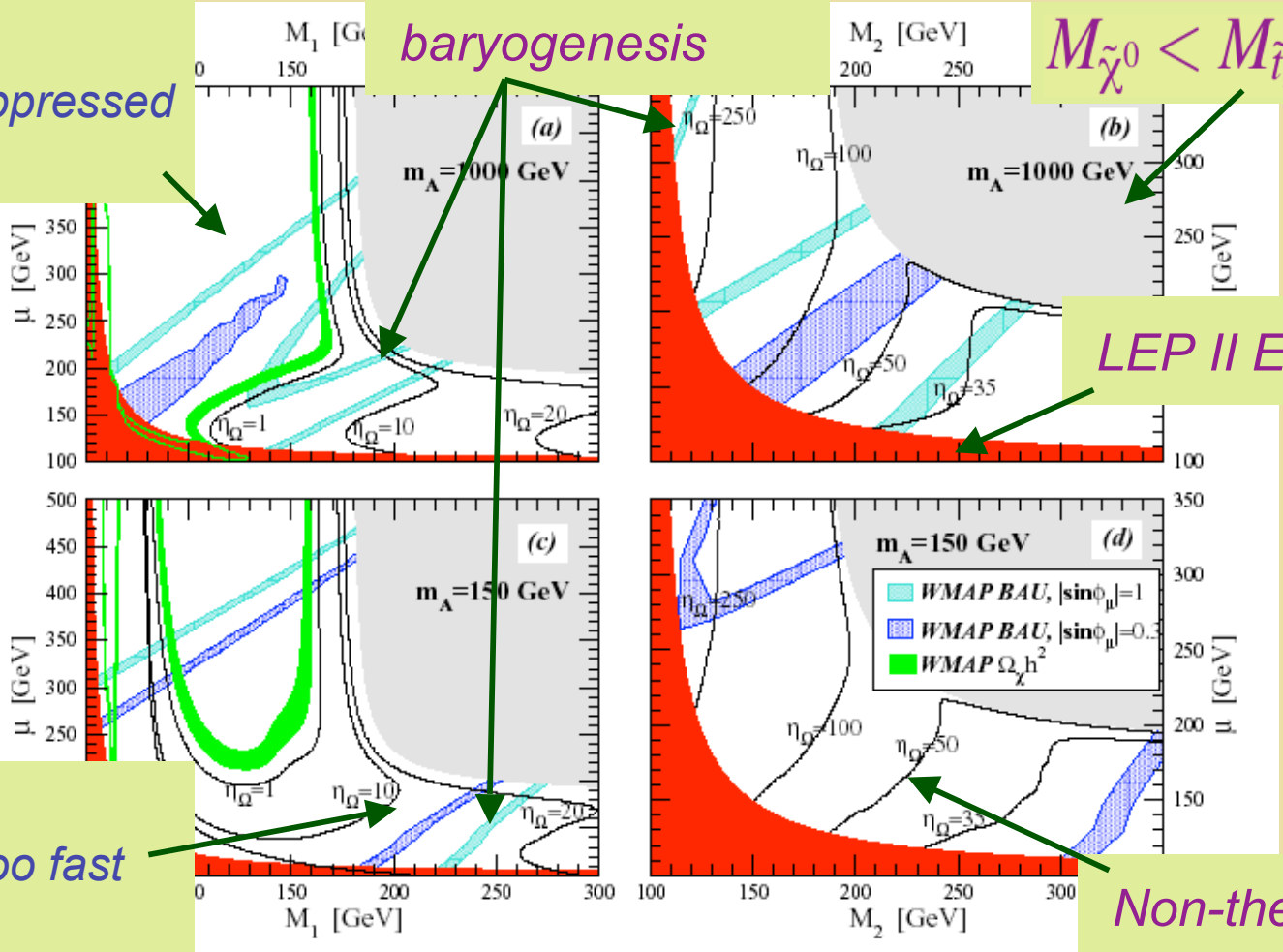
Dark Matter: Relic Abundance



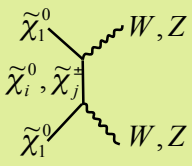
suppressed

Neutralino-driven baryogenesis

$M_{\tilde{\chi}^0} < M_{\tilde{t}_R} < M_t$



LEP II Exclusion



too fast

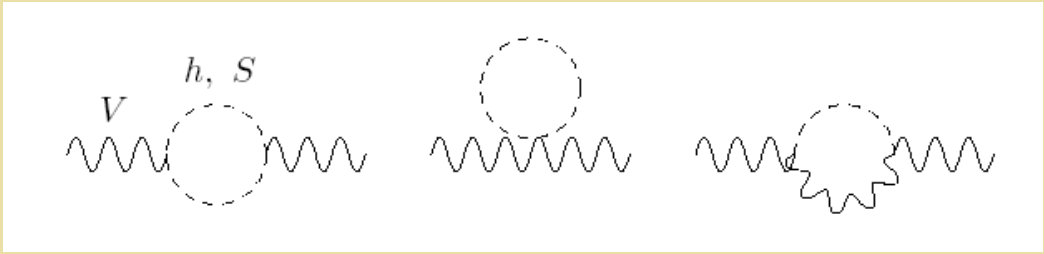
Non-thermal χ^0

SUGRA: $M_2 \sim 2M_1$

AMSB: $M_1 \sim 3M_2$

Phenomenology: EWPO

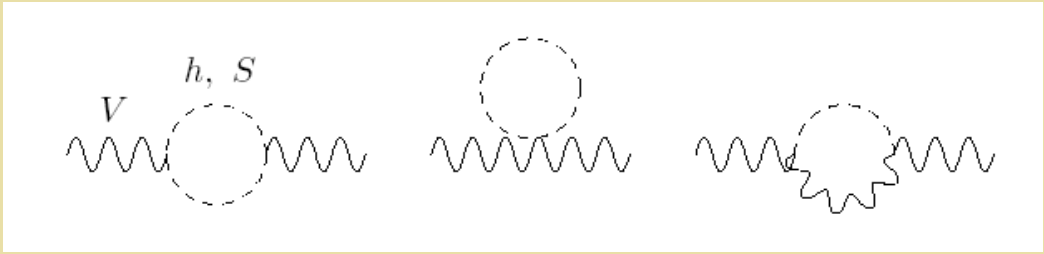
Electroweak Precision Observables (EWPO)



SM: global fit favors light scalar (m_h~ 85 GeV)

Phenomenology: EWPO cont'd

Electroweak Precision Observables (EWPO)



- *Fix m_H=114 GeV & fit S,T,U*
- *Require*

$O(m_1, m_2, \sin\theta) - O_{SM}$

to lie inside 95% CL ellipse

Oblique parameters

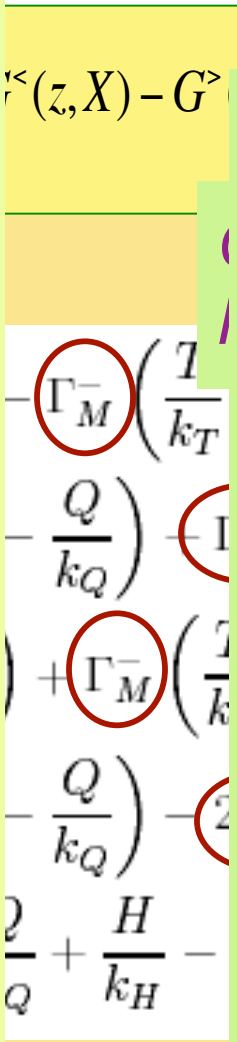
Quantum Transport Equations

Approximations

- Neglect $O(\varepsilon^3)$ terms
- Others under scrutiny

R-M, Chung, Tulin, Garbrecht, Lee, Cirigliano

- *Γ_Y >> other rates? (No)*
- *Majorana fermions ? (densities decouple)*
- *Particle-sparticle eq?*
- *Density indep thermal widths?*



violation and baryon sector

Currents

From S-D Equations:

- *S^{CPV}*

Riotto, Carena et al, R-M et al, Konstandin et al

- *Γ_M, Γ_H, Γ_Y …*

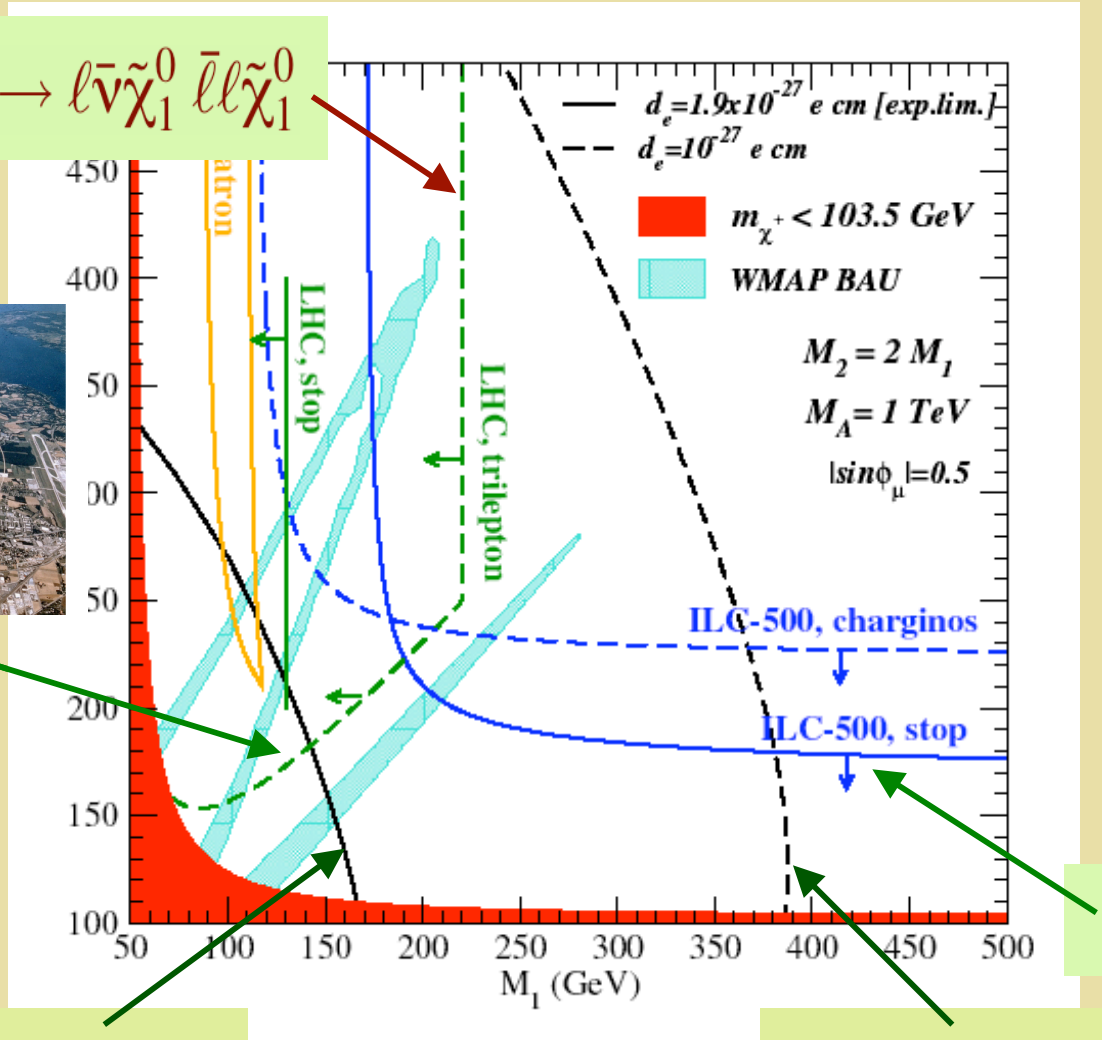
R-M et al

Objectives:

- *Determine param dep of S^{CPV} and all Γs and not just that of S^{CPV}*
- *Develop general methods for any model with new CPV*
- *Quantify theor uncertainties*

SUSY Baryogenesis & Colliders

LHC reach



ILC reach

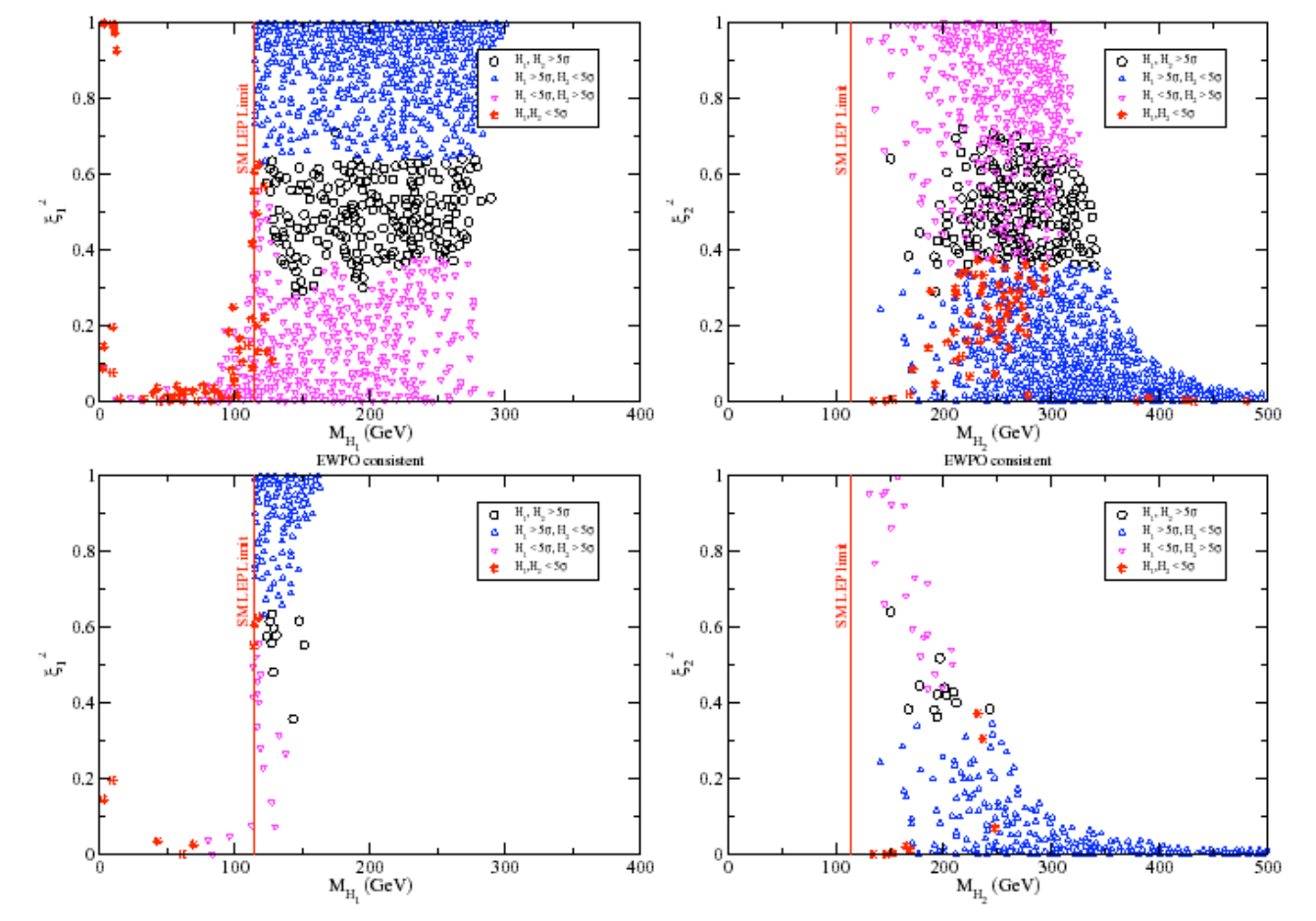
Present d_e

Prospective d_e

LHC Phenomenology

Discovery Potential

Barger, Langacker, McCaskey, R-M, Shaughnessy

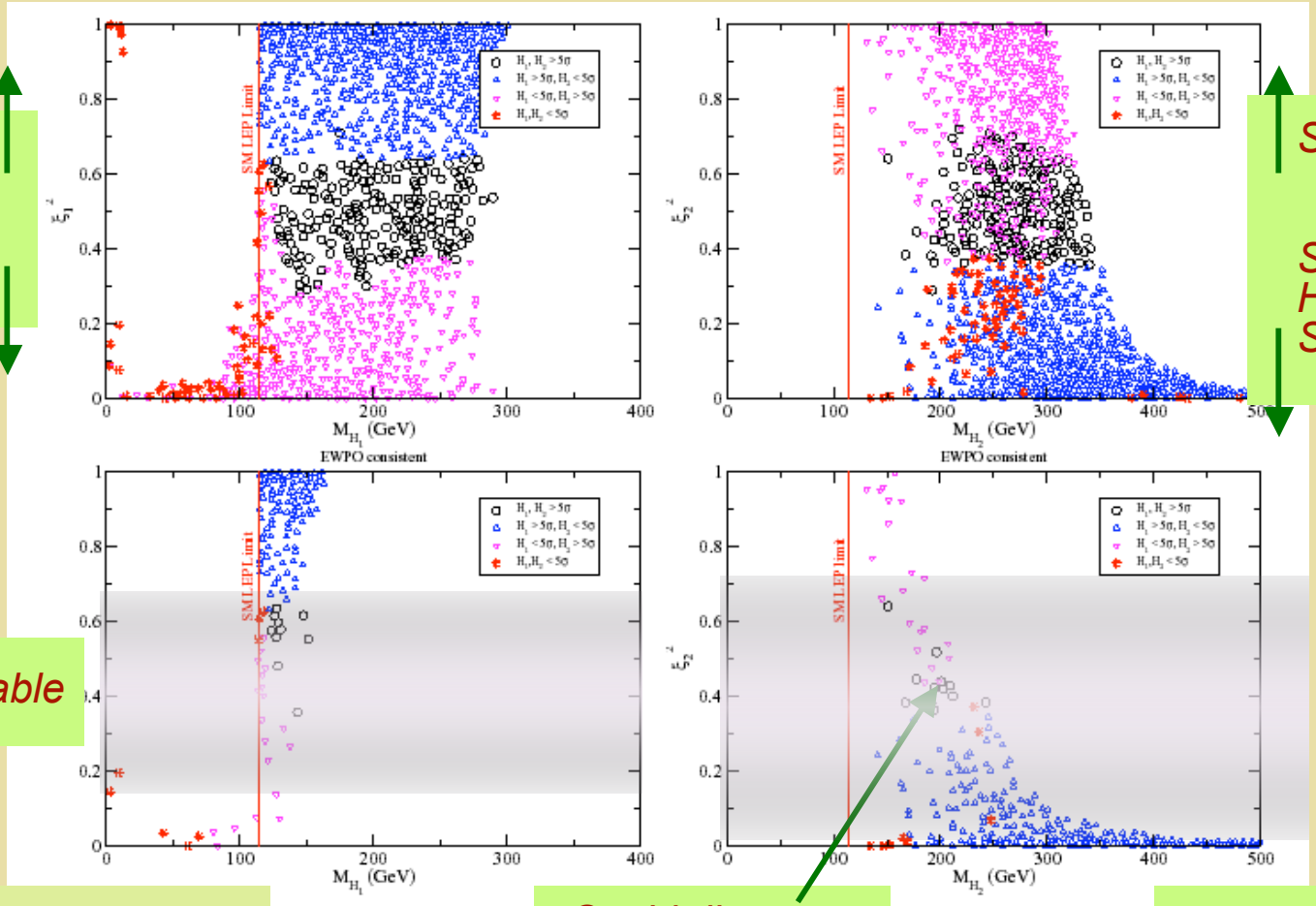


CMS 30 fb^{-1}

LHC Phenomenology

Discovery Potential

Barger, Langacker, McCaskey, R-M, Shaughnessy



SM-like

Singlet-like

SM-like

SM-like w/ $H_2 \to H_1H_1$ or Singlet-like

~ EWB Viable

Could discovery heavy H_2

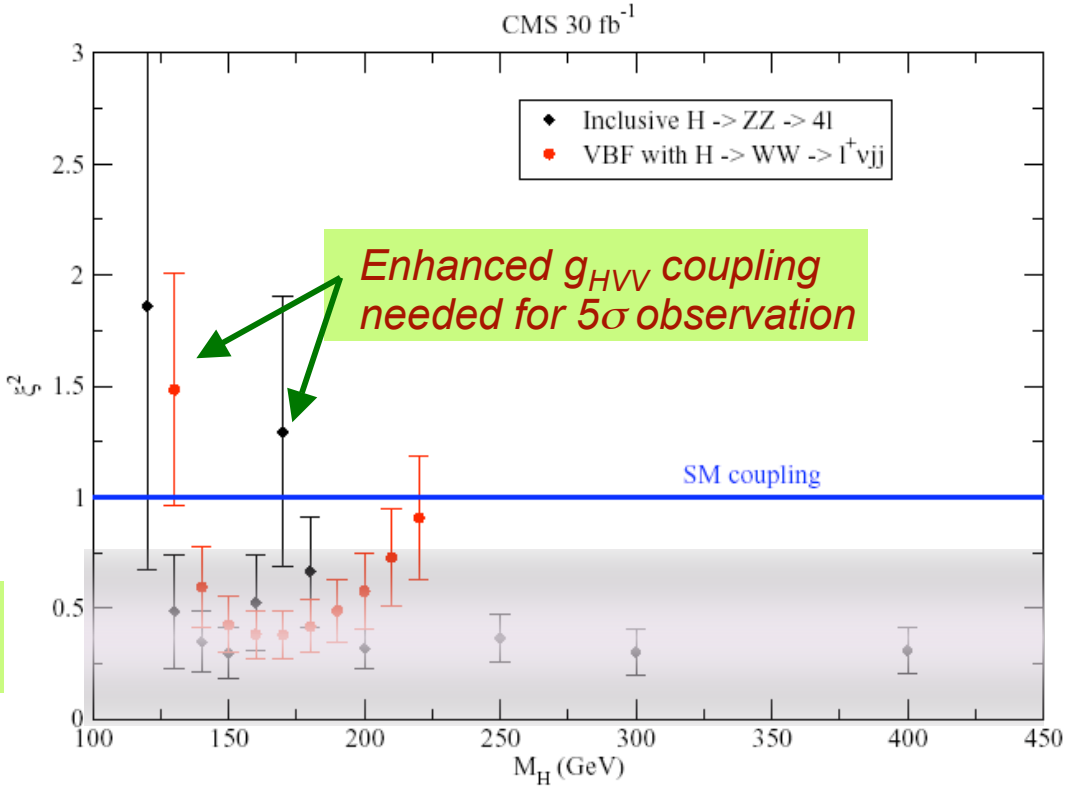
CMS 30 fb^{-1}

$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

LHC Phenomenology, cont'd

Determining ξ

Barger, Langacker, McKaskey, R-M, Shaughnessy



Enhanced g_{HVV} coupling needed for 5σ observation

~ EWB Viable

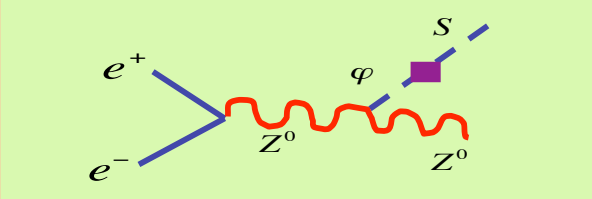
SM-like

SM-like w/ H_2!H_1H_1 or Singlet-like

$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

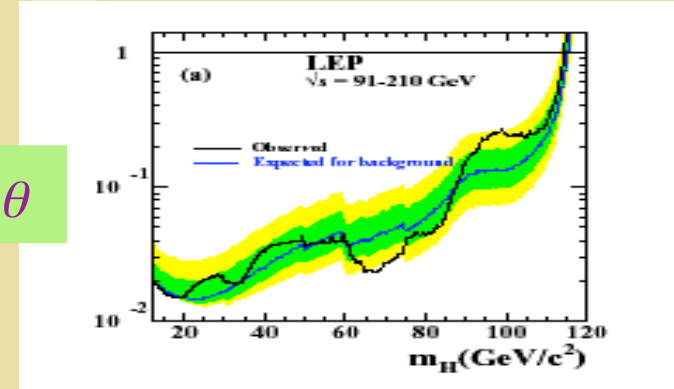
ILC Phenomenology

Colliders: $e^+e^- \rightarrow Z^* h$



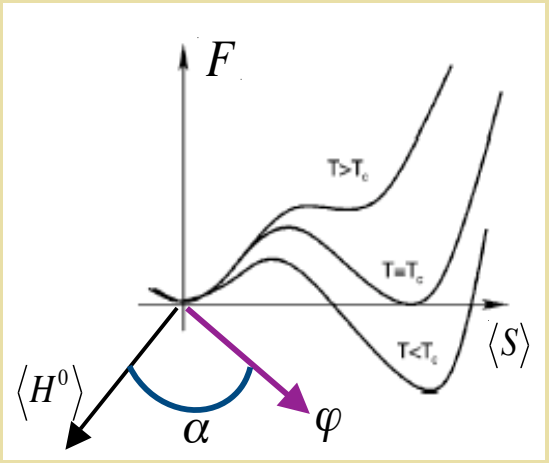
(also WWF, ZZF)

$sin^2\theta$

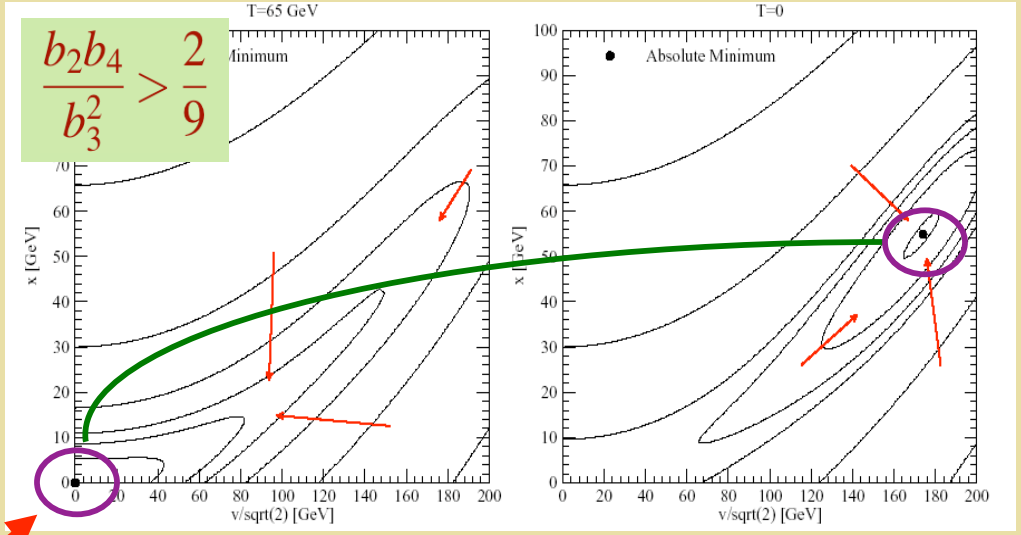


Scalar Sector & the EWPT

Symmetry Breaking



$$\frac{b_2 b_4}{b_3^2} > \frac{2}{9}$$



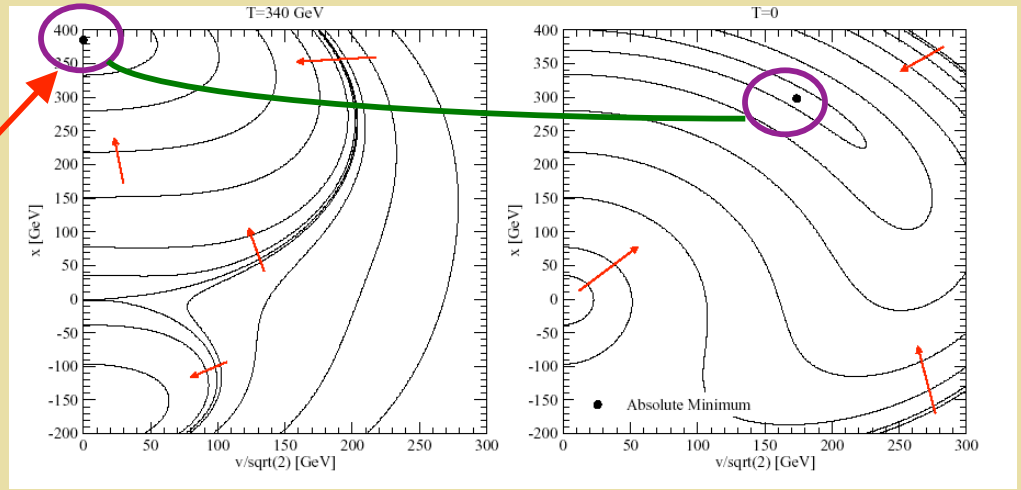
$$\langle S \rangle = x \equiv \varphi \sin\alpha$$

$$\langle H^0 \rangle = v/\sqrt{2} \equiv \varphi \cos\alpha$$

Two Cases for <S>at high T:

$V_{min} = 0$

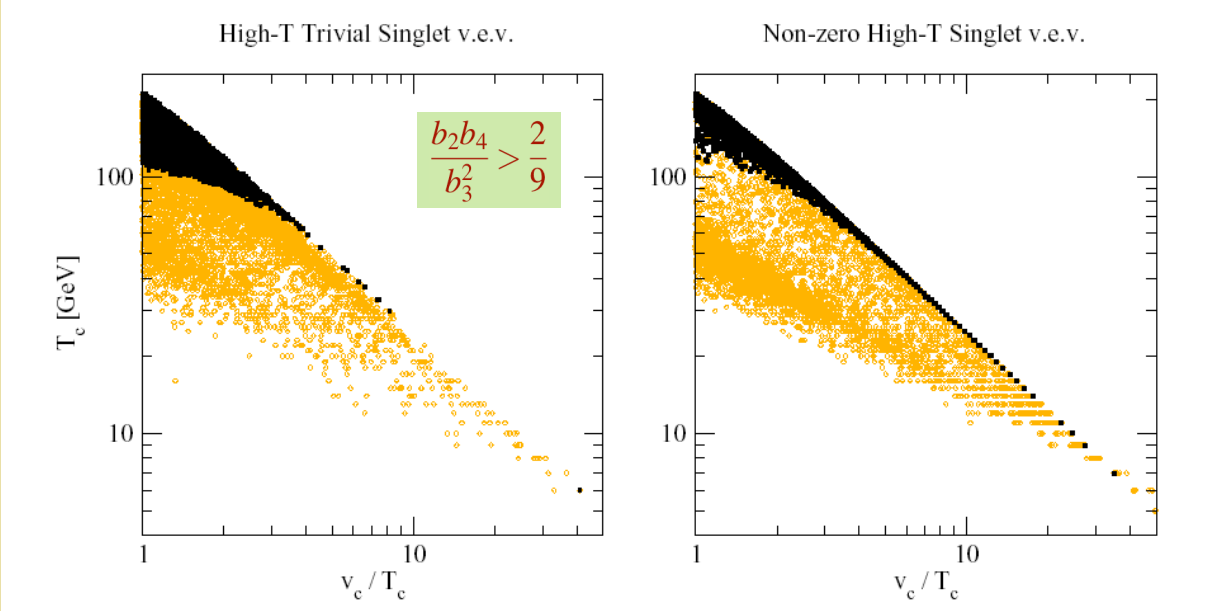
$V_{min} = V_0 < 0$



$$\langle S \rangle = x \equiv \varphi \sin\alpha$$

Electroweak Symmetry Breaking

Critical Temperature



LEP allowed models: $T_C \sim 100$ GeV

$$V_0 = -\frac{b_3^4}{12 b_4^3} F(b_2 b_4 / b_3^2)$$

$|V_0| / T_c^4 << 1$

Extending the Higgs Sector

SUSY Beyond the MSSM

Ando, Barger, Langacker, Profumo, R-M, Shaugnessy, Tulin

$$W = (\mu + \lambda S) H_u H_d + \alpha S + \frac{\kappa}{3} S^3$$

$$+ \mathcal{L}_{soft}$$

GUTs: SU(5) example

Σ^0 , Σ^+, Σ^-

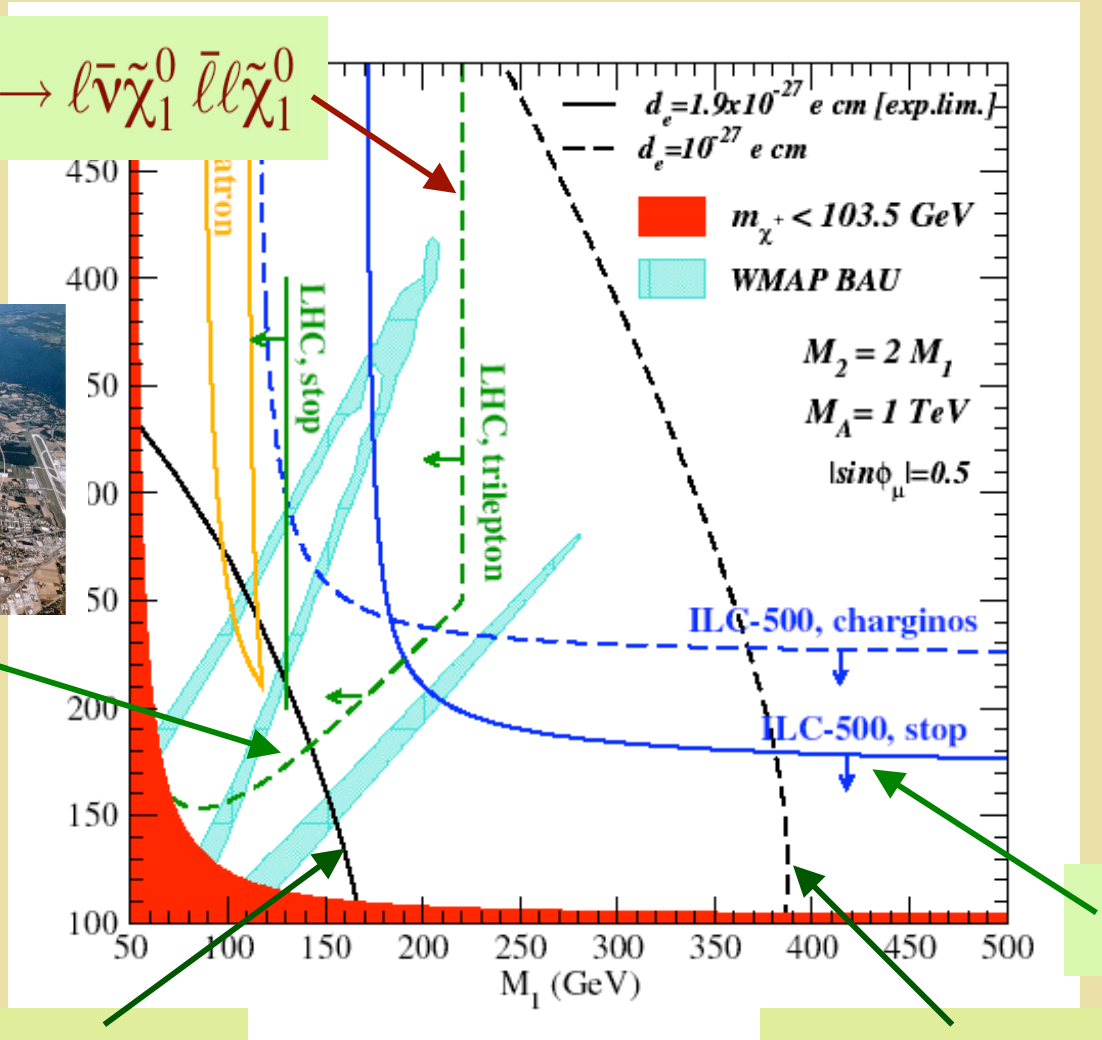
$$V(H, \Sigma_3, \Phi_a, \Phi_b) = V(H) + V(\Sigma_3) + V(\Phi_{a,b}) + V(H, \Sigma_3) + V(H, \Phi_{a,b}) + \cdots$$

$$V(H, \Sigma_3) = \gamma H^\dagger \Sigma_3 H + \alpha H^\dagger H \mathrm{Tr}\Sigma_3^2 + \beta H^\dagger \Sigma_3^2 H$$

Fileviez Perez, Patel, R-M

SUSY Baryogenesis & Colliders

LHC reach



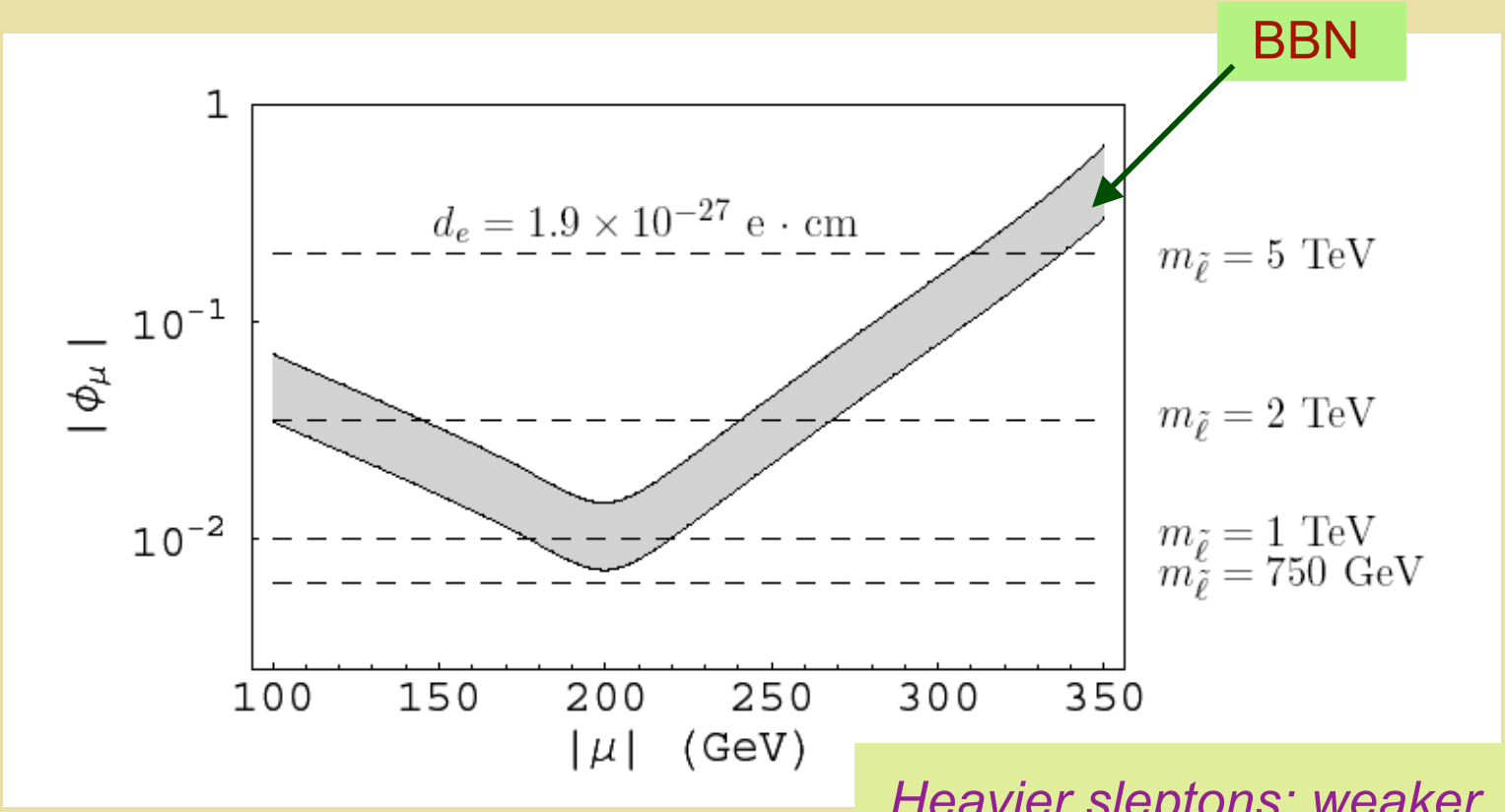
ILC reach

Present d_e

Prospective d_e

EDM constraints & SUSY CPV

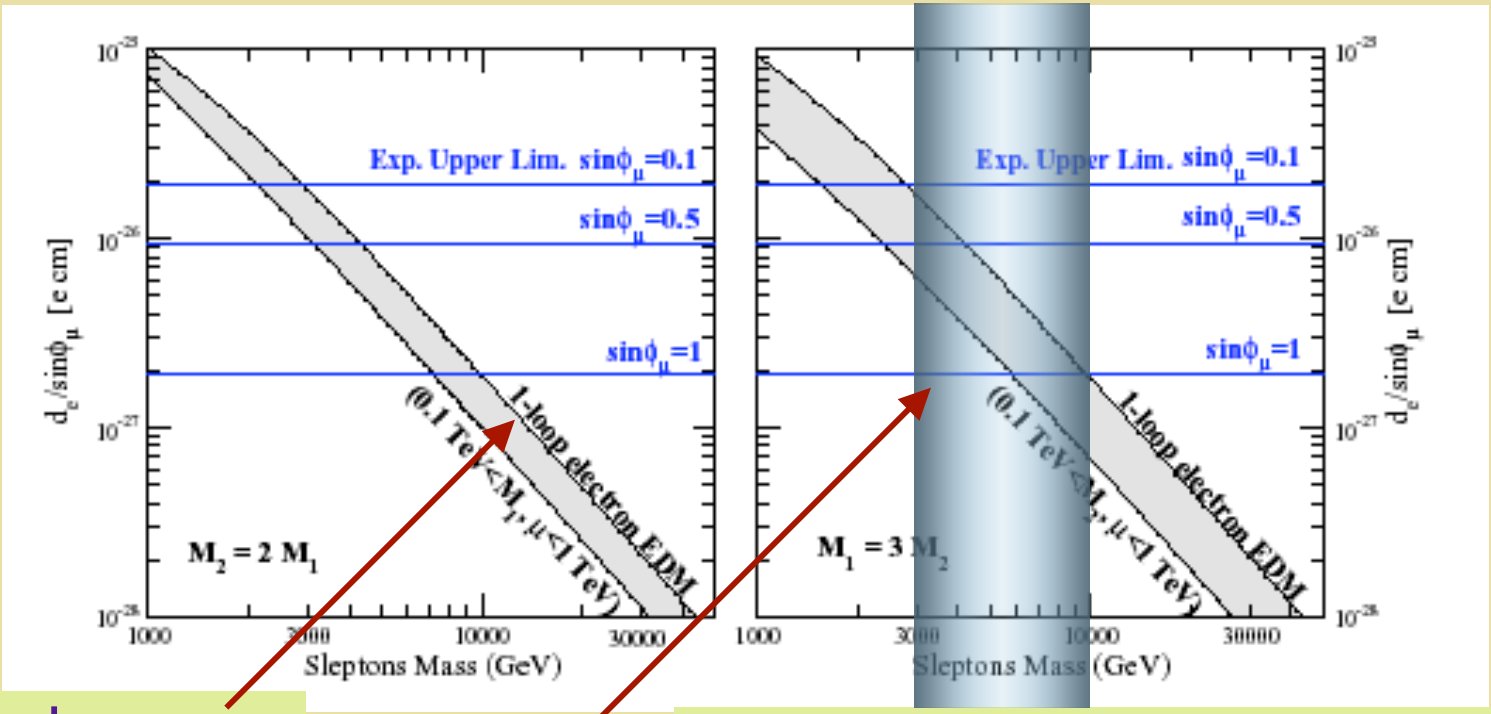
One-loop d_e & slepton mass

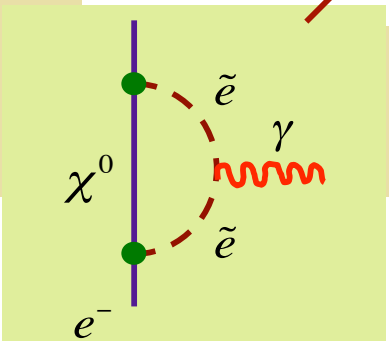


Heavier sleptons: weaker one-loop EDM constraints & less resonant baryogenesis

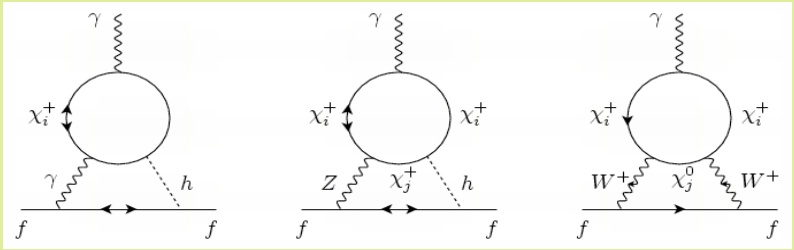
EDM constraints & SUSY CPV

One-loop vs. Two-loop EDMs





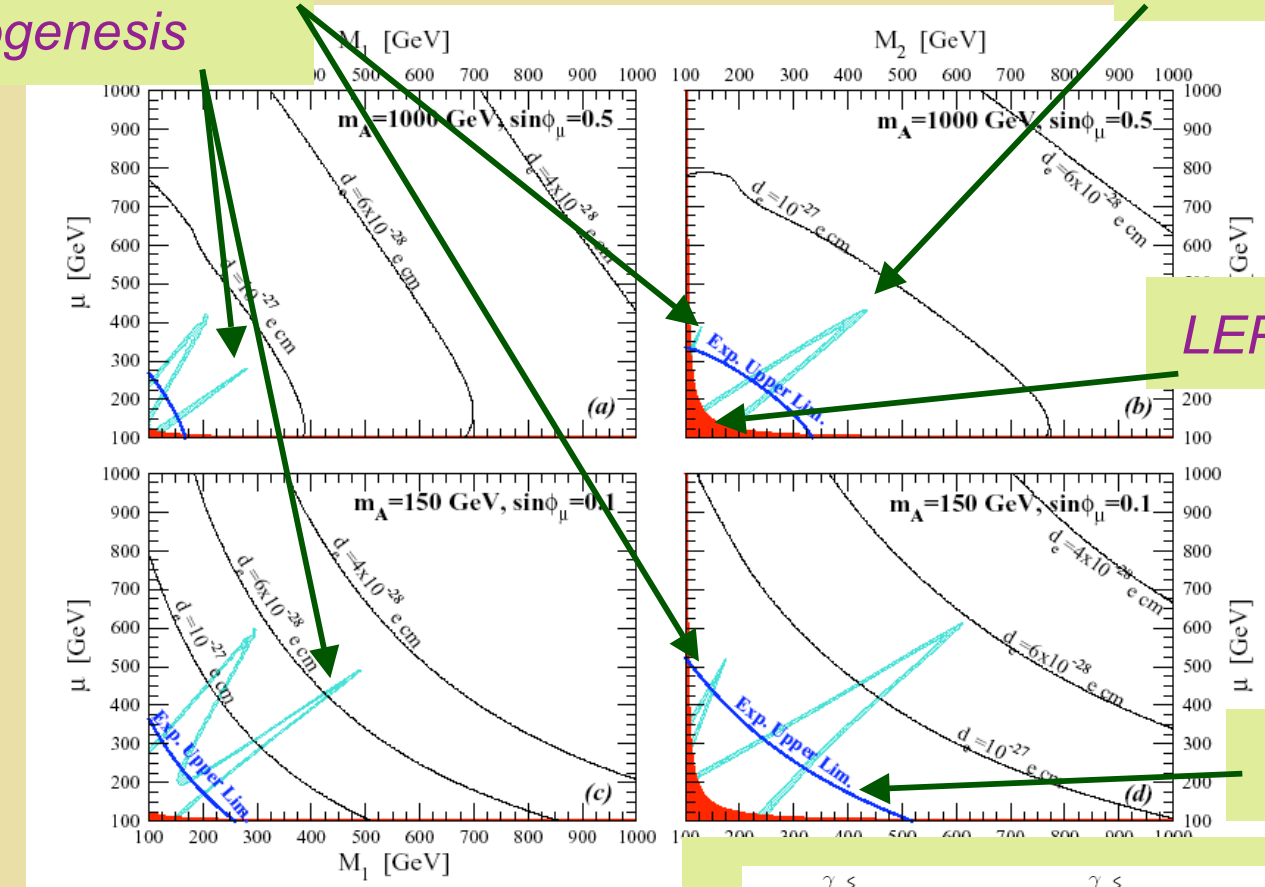
$d_e^{\,1\ loop} \sim d_e^{\,2\ loop}$



EDM constraints & SUSY CPV

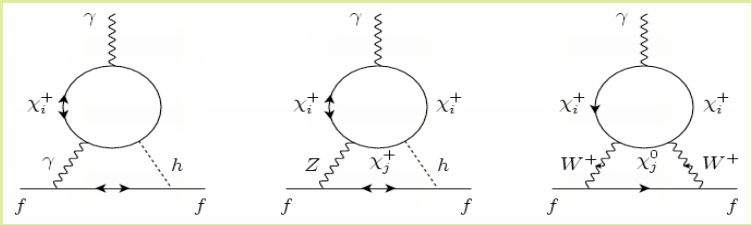
Neutralino-driven baryogenesis

Baryogenesis



LEP II Exclusion

Two loop d_e



Cirigliano, Profumo, R-M

SUGRA: $M_2 \sim 2M_1$

Extending the Higgs Sector: GUTs

SU(5) w/ extended Higgs sector

$\Sigma^0, \Sigma^+, \Sigma^-$

$$V(H, \Sigma_3, \Phi_a, \Phi_b) = V(H) + V(\Sigma_3) + V(\Phi_{a,b}) + V(H, \Sigma_3) + V(H, \Phi_{a,b}) + \cdots$$

$$V(H, \Sigma_3) = \gamma H^\dagger \Sigma_3 H + \alpha H^\dagger H \, \mathrm{Tr}\Sigma_3^2 + \beta H^\dagger \Sigma_3^2 H$$

Implications

- *Strong 1st order EWPT w/o SUSY ?*
- *New sources of CPV?*
- *Light triplet Higgs*
- *Light leptoquarks (unification)*

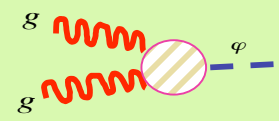
Perez, Patel, R-M

One-loop & Finite T Contributions

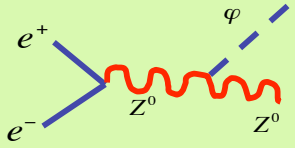
Cylindrical Co-ordinates

$$v/\sqrt{2} \equiv \varphi \cos\alpha \qquad x \equiv \varphi \sin\alpha$$

What is the origin of baryonic matter ?

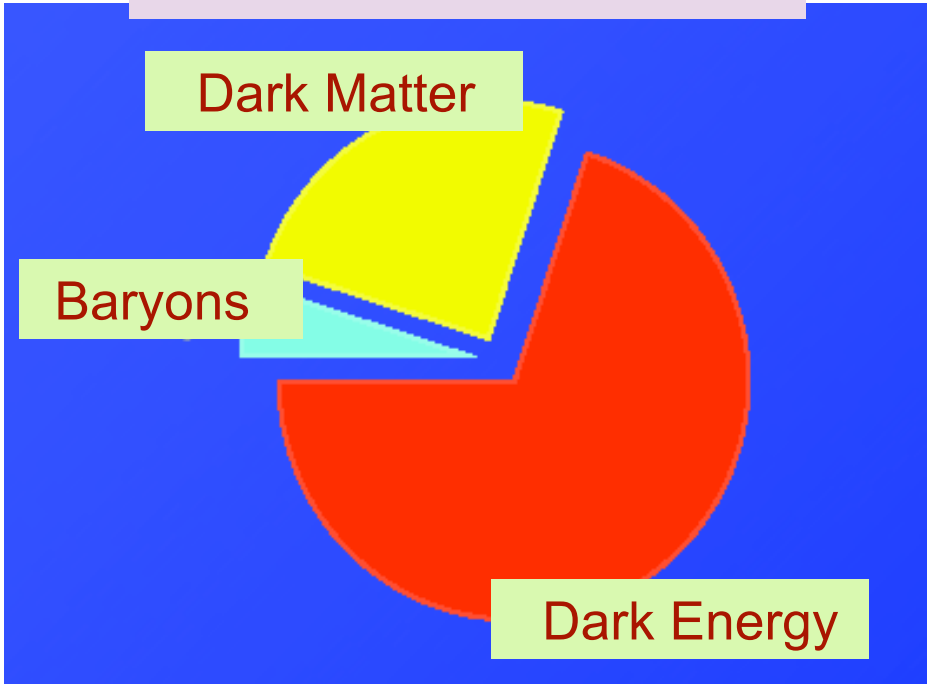


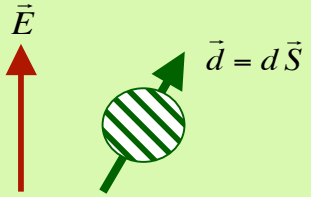
gg fusion at LHC



Higgsstrahlung at a linear collider

Cosmic Energy Budget





$$\nu_{EDM} = -\frac{d\vec{S}\cdot\vec{E}}{h}$$

T-odd , CP-odd by CPT theorem

What are the quantitative implications of new EDM experiments for explaining the origin of the baryonic component of the Universe ?

Can an augmented Higgs sector

- *Generate a strong 1st order EWPT ?*
- *Allow for a heavier SM-like Higgs than in the MSSM ?*
- *Alleviate the tension between direct Higgs search bounds and the EWPO ?*
- *Be discovered at the LHC ?*

Can its necessary characteristic probed at the LHC and a future e^+e^- collider ?

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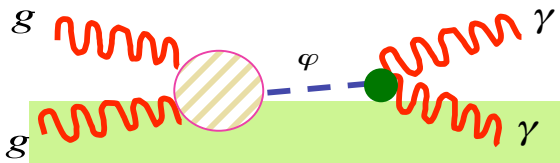
- Γ_Y!1? (No)
- Majorana fermions ? (densities decouple)
- Particle-sparticle eq?
- Density indep thermal widths?

- Fix m_H & fit S,T,U
- Require

$O(m_1, m_2, \sin\theta) - O_{SM}$

to lie inside 95% CL ellipse

Cosmic Energy Budget



From S-D Equations:

- S^{CPV}

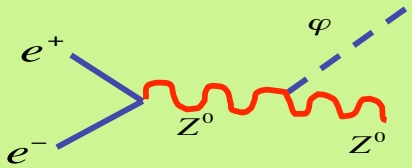
Riotto, Carena et al, Lee et al, Konstandin et al

- Γ_M, Γ_H, Γ_Y

Lee et al

Numerical work:

- Γ_{SS}



gg fusion at LHC