Electroweak Baryogenesis: Searching for New Scalars and New CPV

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U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

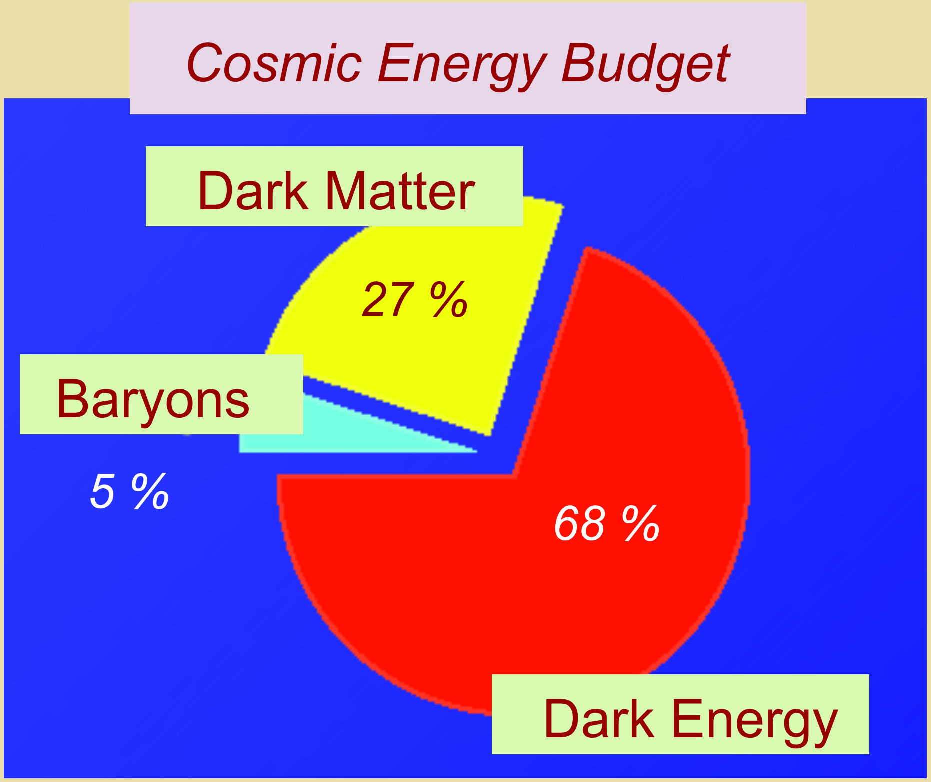
Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

UC Irvine Seminar January 2015

The Origin of Matter



Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

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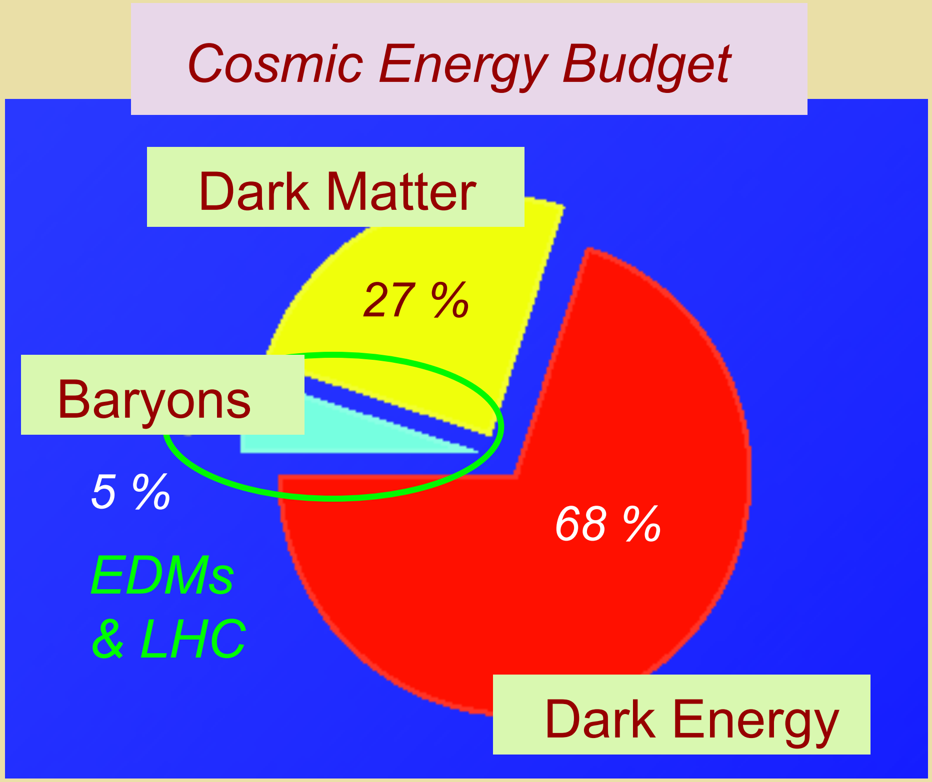

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Ingredients for Baryogenesis

- *B violation (sphalerons)*
- *C & CP violation*
- *Out-of-equilibrium or CPT violation*

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	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
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Testable

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• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
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Recent Developments:

- *Discovery of BEH-like boson $\rightarrow$ Paradigm of symmetry-breaking in particle physics driven by a fundamental scalar likely correct*
- *Non-observation (so far) of physics beyond the Standard Model at the LHC*
- *New stringent limits on permanent electric dipole moments*

Recent Results

- *Discovery of BEH-like scalar at the LHC*
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  - *BSM physics lies at very different mass scale*
- *New stringent limits on EDMs*
  - *BSM CPV lies at high mass scale*
  - *BSM CPV doesn't talk directly to SM fermions*
  - *BSM CPV is flavor non-diagonal*

Outline

- *EWB in a Nutshell*
- *EW Phase Transition: new scalars, new patterns of symmetry-breaking & LHC phenomenology*
- *BSM CPV: unflavored CPV & EDMs, flavored CPV & heavy flavors*

Focus on Higgs Portal

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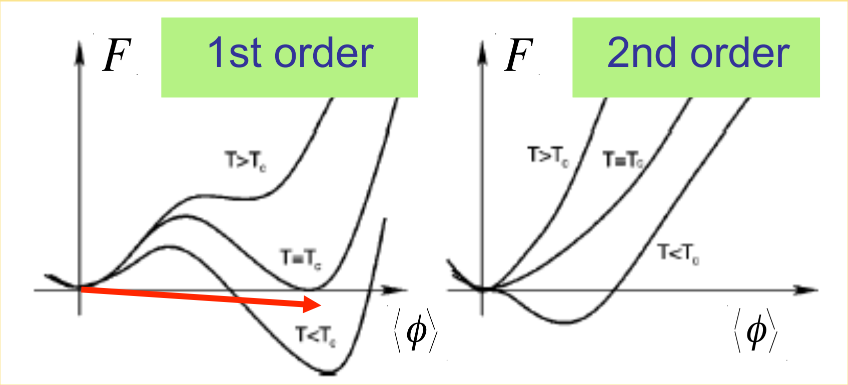
Formal issues: back up slides

I. EWB in a Nutshell

EW Phase Transition: New Scalars & CPV



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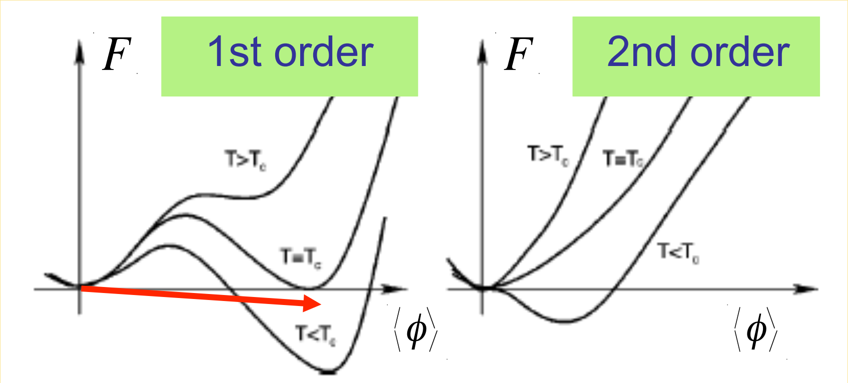

Increasing m_h →

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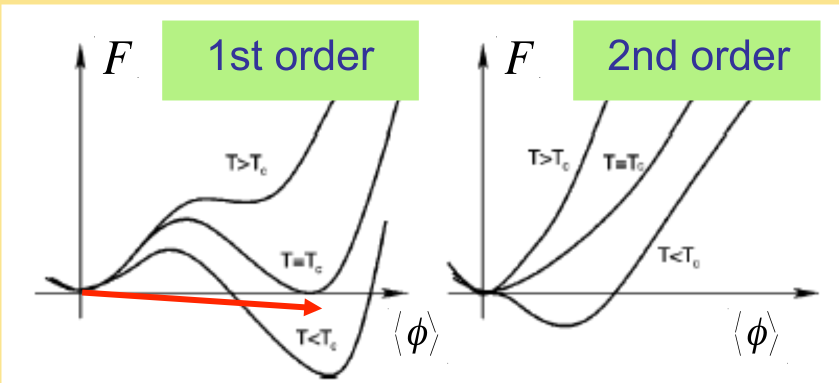

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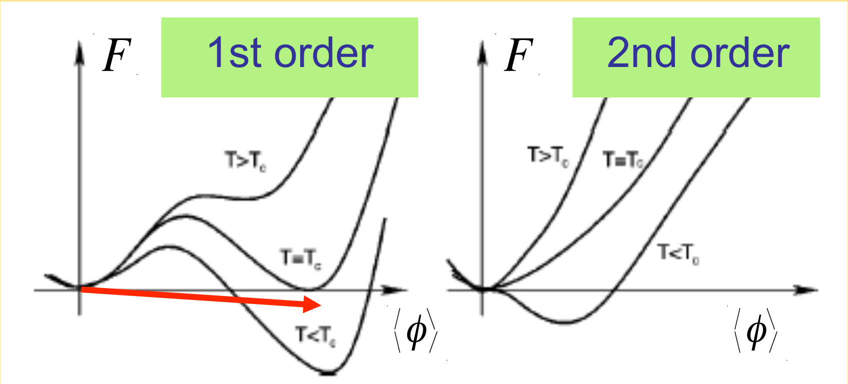

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Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

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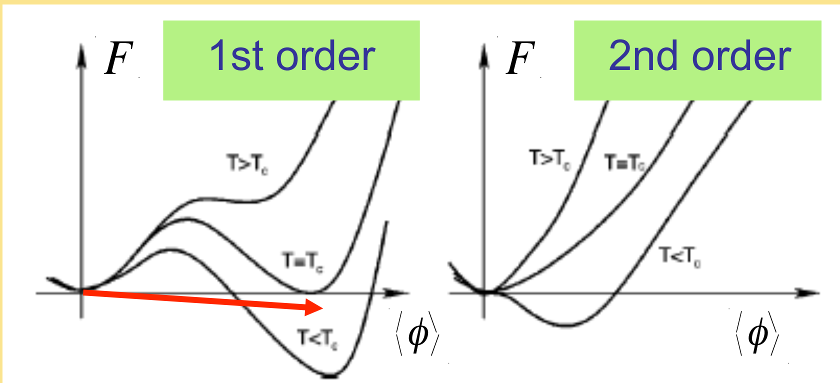

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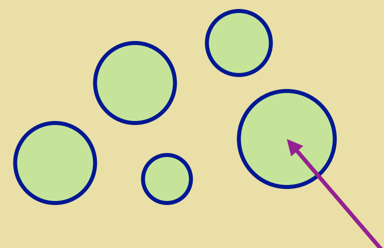

EWSB

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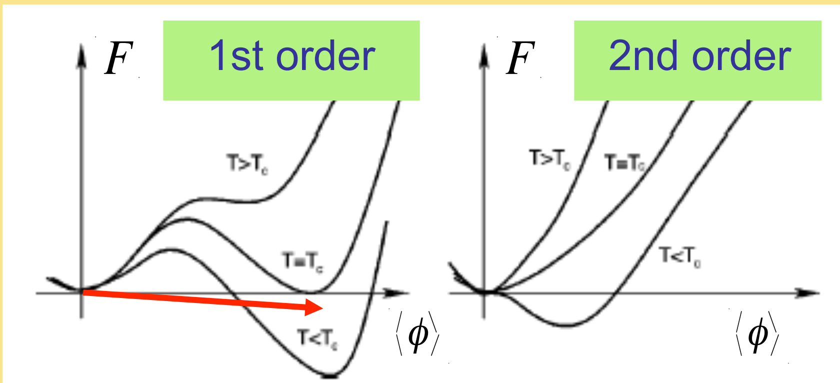

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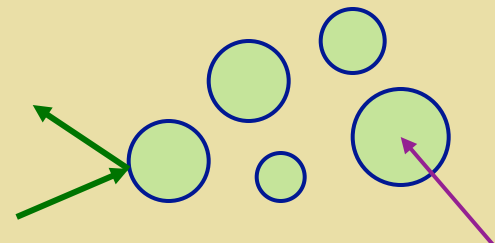
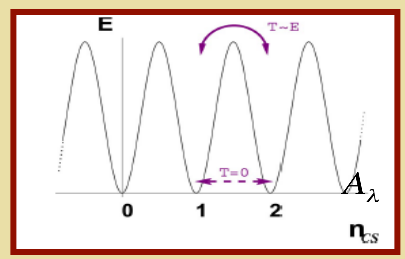


Y_B : CPV & EW sphalerons

EWSB



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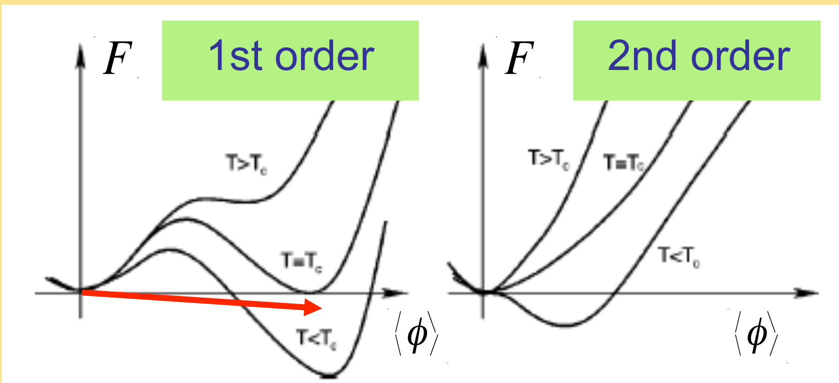

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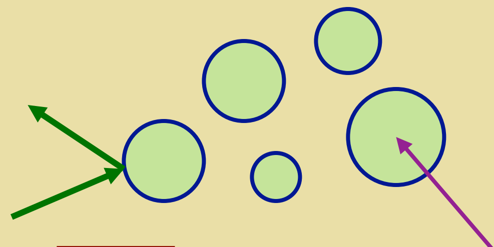

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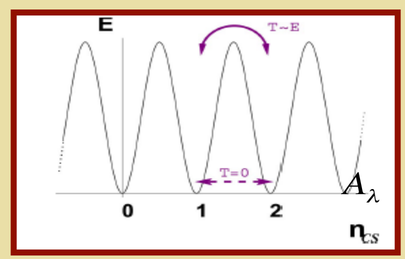
EWSB

BSM



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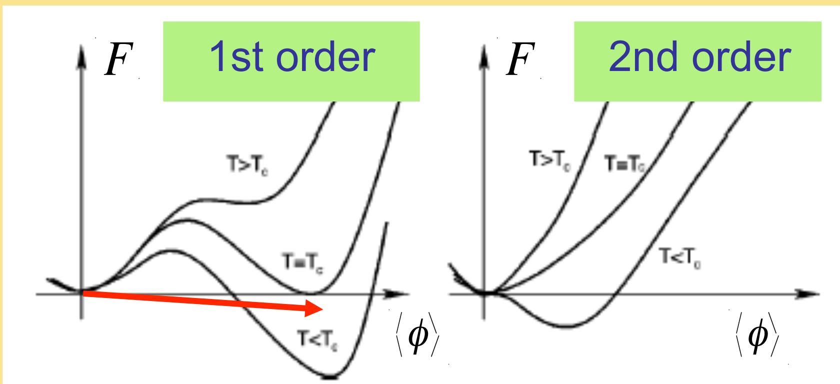

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↓

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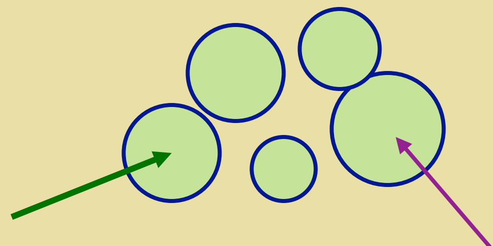
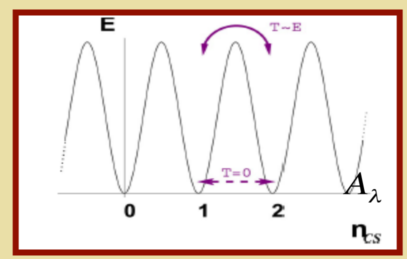


Y_B : diffuses into interiors

EWSB



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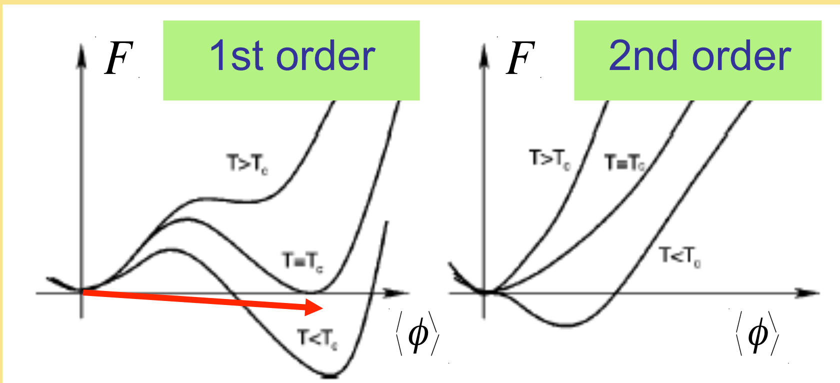


Increasing m_h →

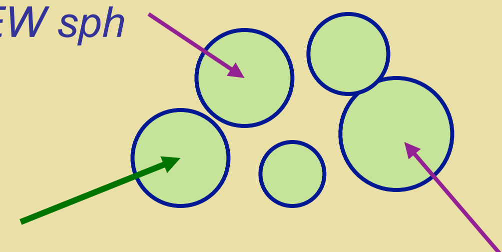
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

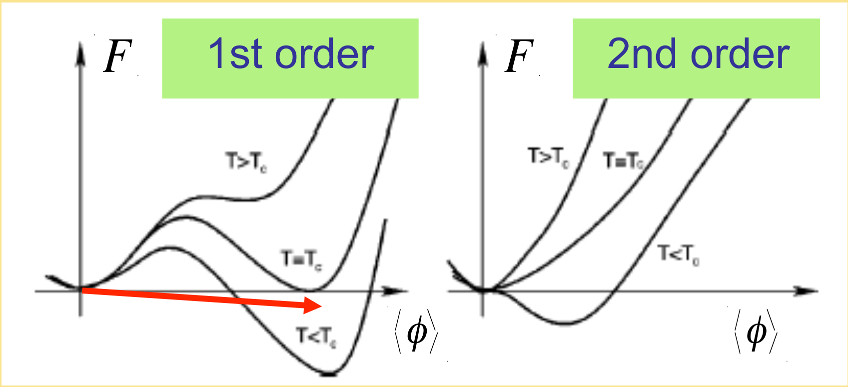
Preserve $Y_B^{initial}$ ← "Strong"

Bubble nucleation ← 1st order EWPT



II. Electroweak Phase Transition

EW Phase Transition: St'd Model



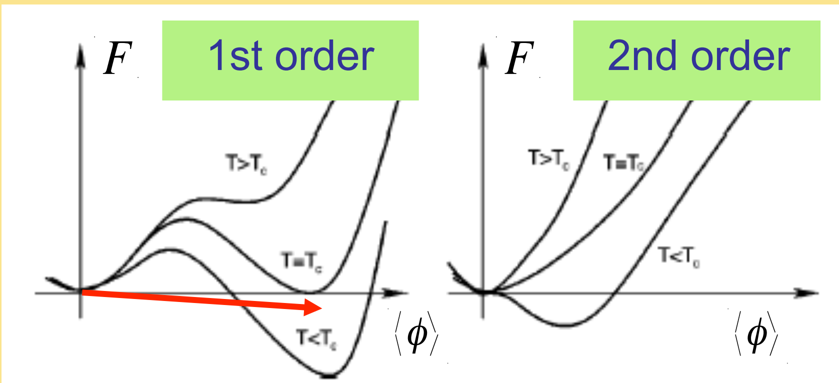
Increasing m_h →

Lattice: Endpoint

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

S'td Model: 1st order EWPT requires light Higgs

EW Phase Transition: New Scalars



Increasing m_h →

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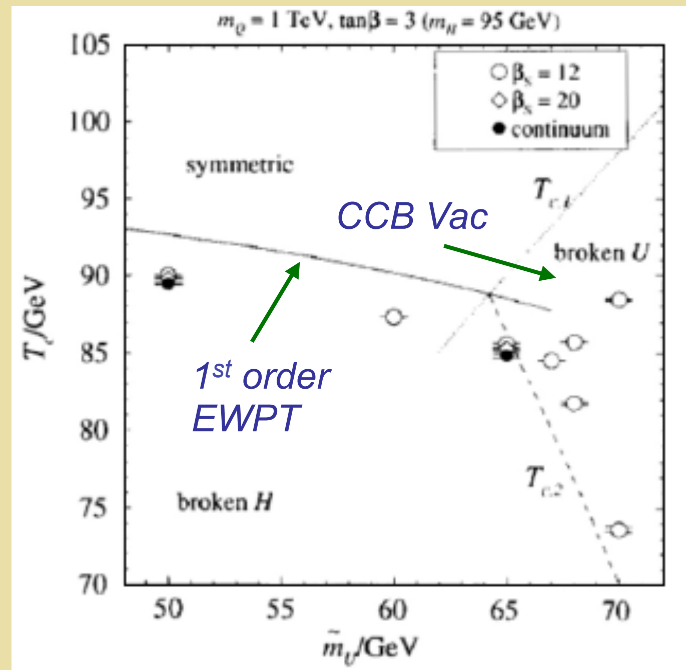
MSSM: Light RH stops

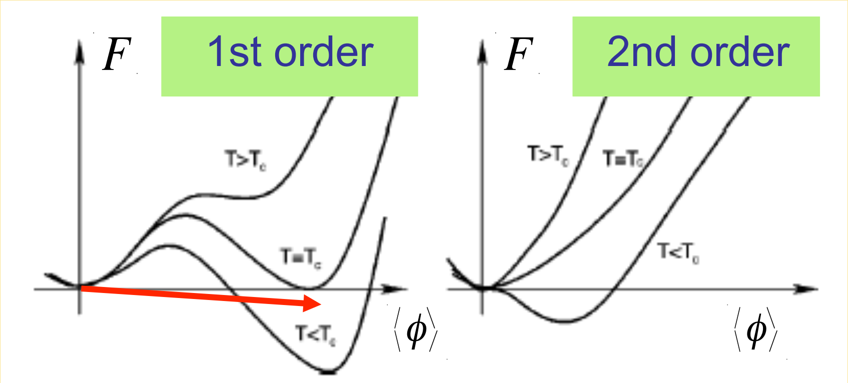
PT: Carena et al,…

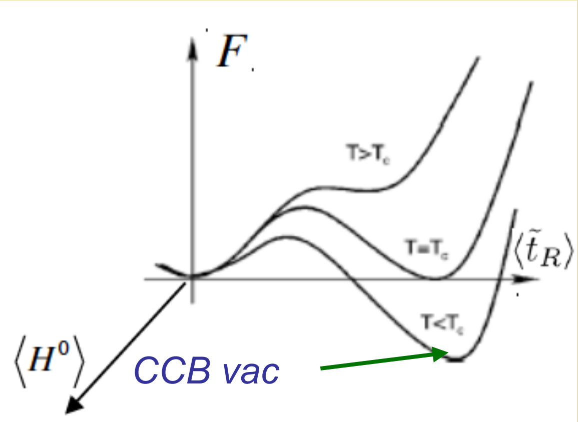
Lattice: Laine, Rummukainen



Decreasing RH stop mass →

EW Phase Transition: MSSM





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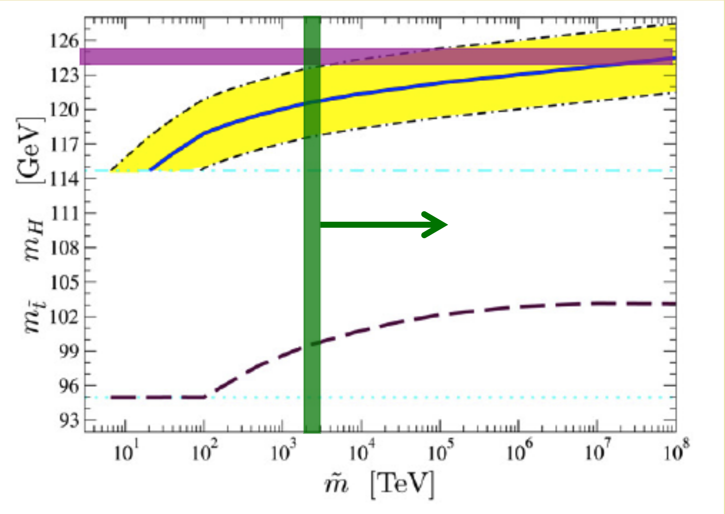

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Carena et al 2008: Higgs phase metastable

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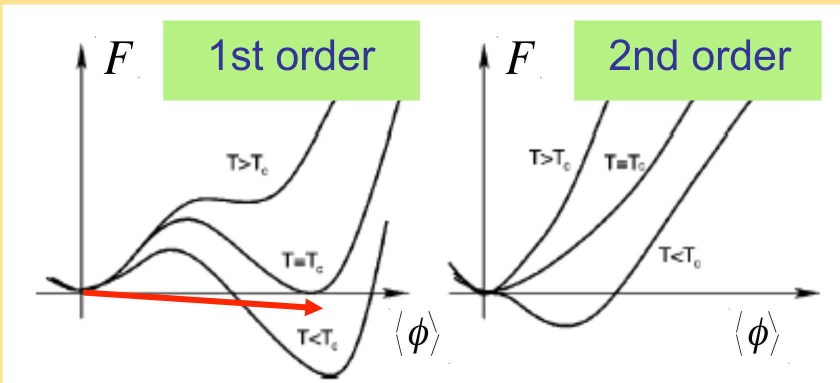

Increasing m_h ⟶

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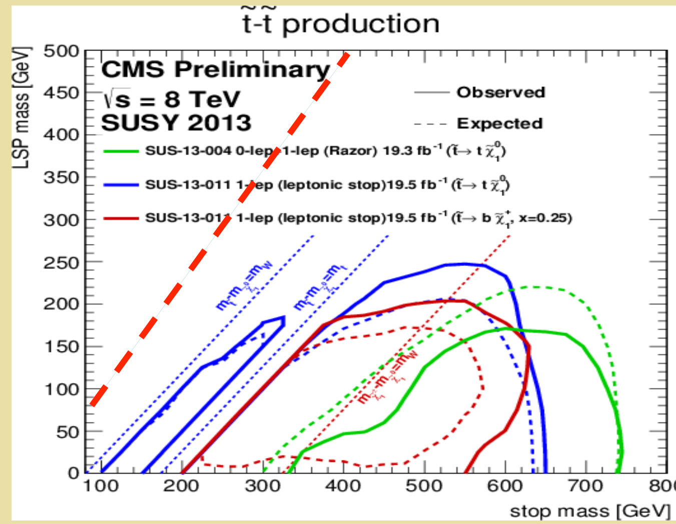

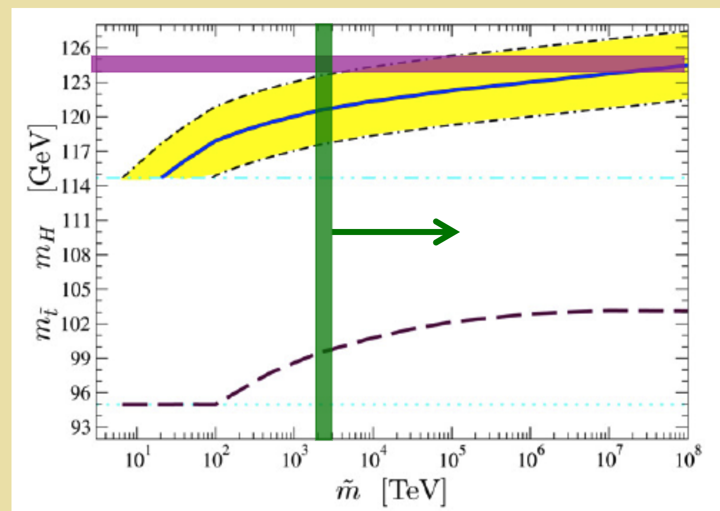

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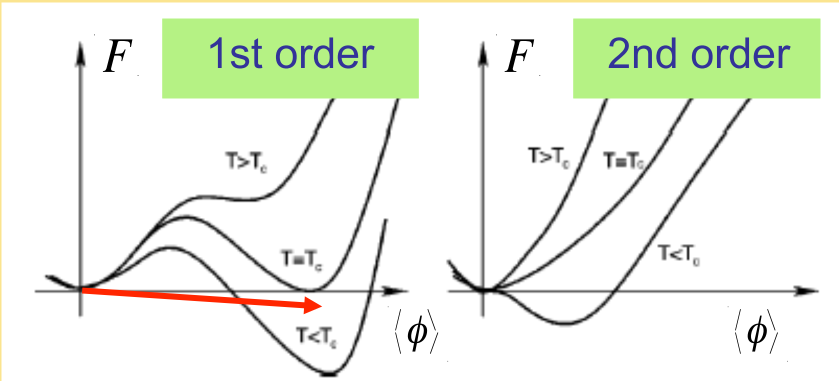

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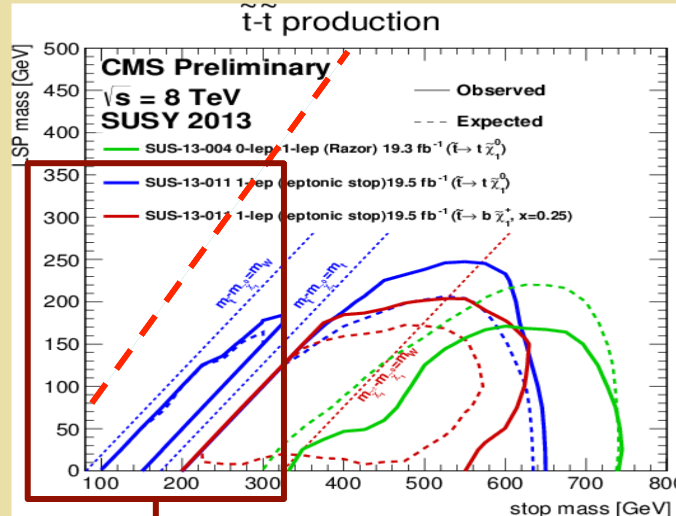

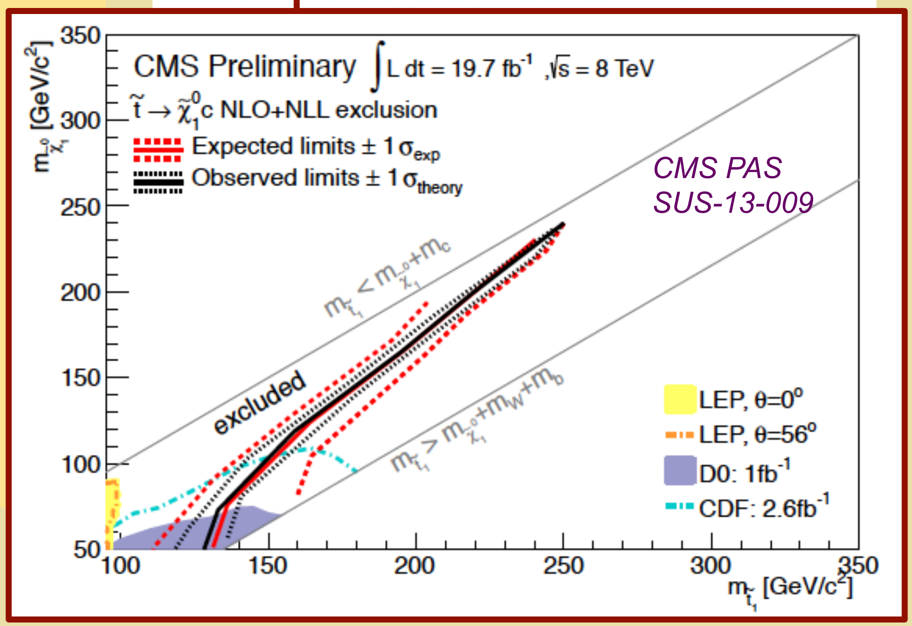

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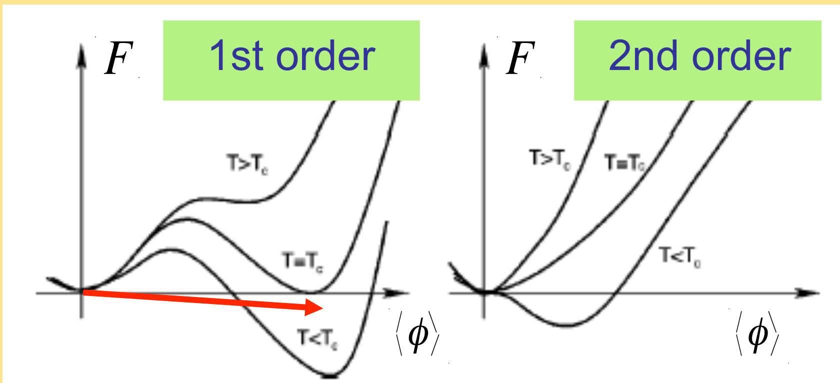

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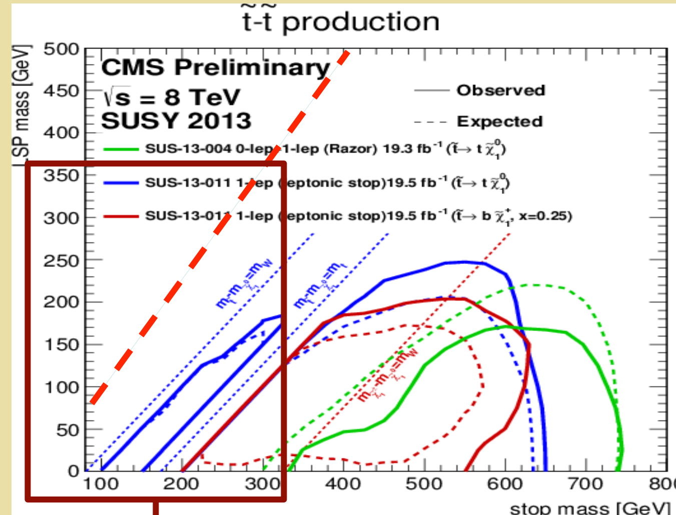
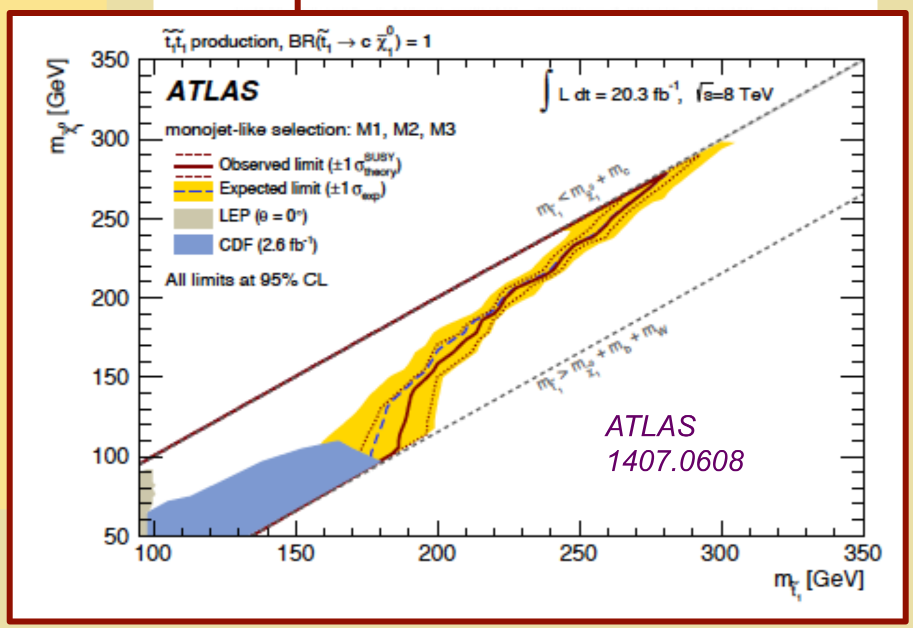
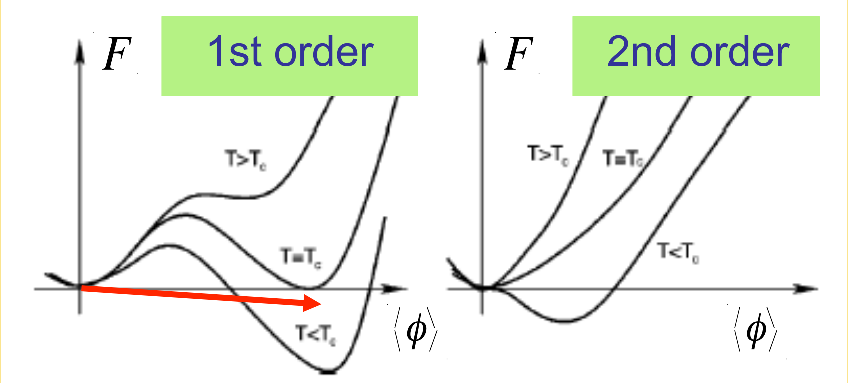




EW Phase Transition: Higgs Portal



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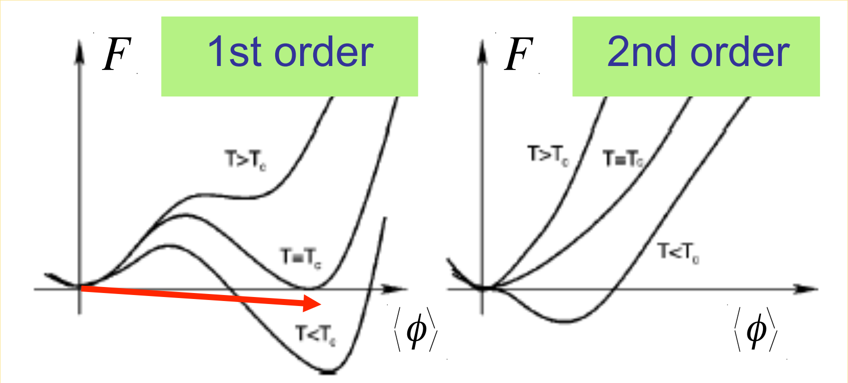
$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger \phi\ H^\dagger H$$

+…

EW Phase Transition: Higgs Portal



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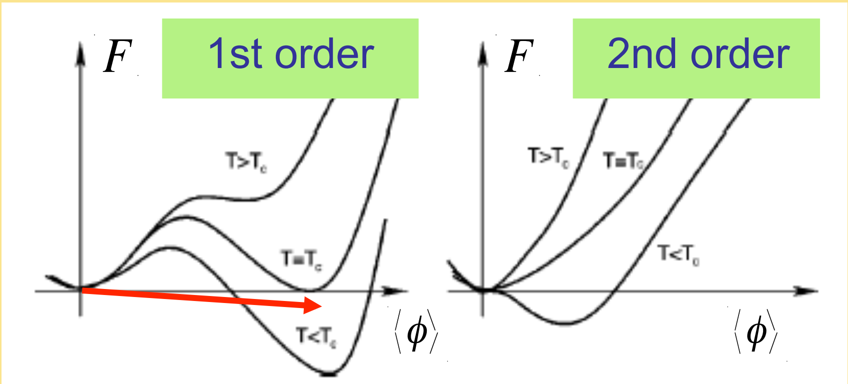
- Renormalizable
- ϕ : singlet or charged under $SU(2)_L$ x $U(1)_Y$
- Generic features of full theory (NMSSM, GUTS…)
- More robust vacuum stability
- Novel patterns of SSB

EW Phase Transition: Higgs Portal



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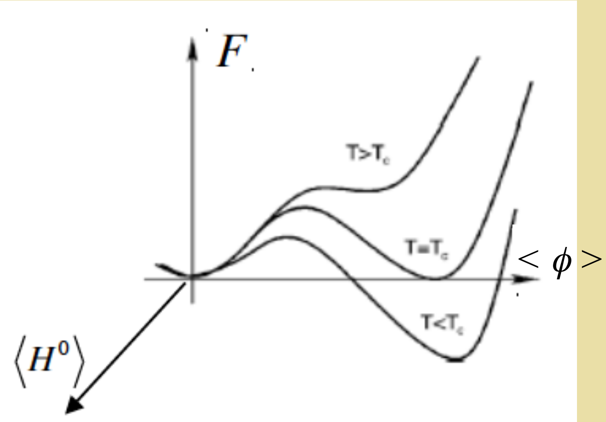

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Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet	1	✔	✖
Real singlet	1	✖	✔
Complex Singlet	2	✔	✔
Real Triplet	3	✔	✔

May be low-energy remnants of UV complete theory & illustrative of generic features

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The Simplest Extension

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

$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

EWPT: $a_{1,2} \neq 0$ & $\langle S \rangle \neq 0$

DM: $a_1 = 0$ & $\langle S \rangle = 0$

O'Connel, R-M, Wise; Profumo, R-M, Shaugnessy; Barger, Langacker, McCaskey, R-M Shaugnessy; He, Li, Li, Tandean, Tsai; Petraki & Kusenko; Gonderinger, Li, Patel, R-M; Cline, Laporte, Yamashita; Ham, Jeong, Oh; Espinosa, Quiros; Konstandin & Ashoorioon…

The Simplest Extension, Cont'd

Mass matrix

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

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

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

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

x_0 = <S>

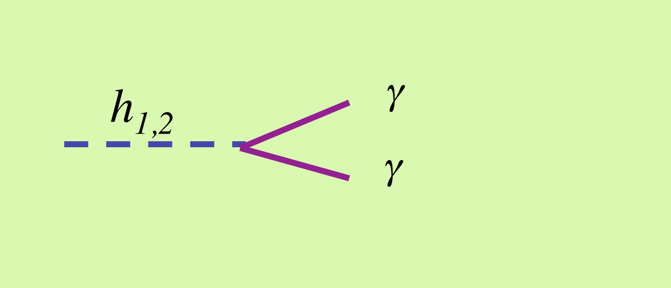
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

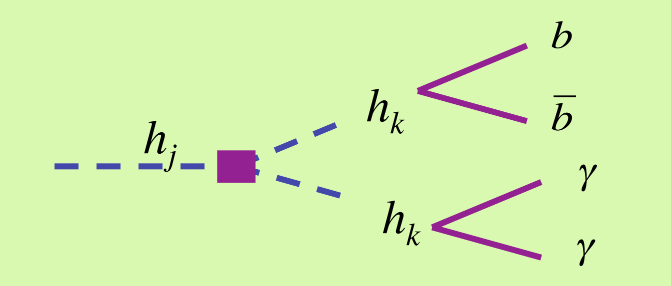
$$\tan\theta = \frac{y}{1+\sqrt{1+y^2}}, \qquad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}$$

$$m_{1,2}^2 = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2}\sqrt{1+y^2}$$

The Simplest Extension, Cont'd

Mass matrix





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New topologies

$$m_{1,2}^2 = \frac{\mu_h^2 + \mu_s^2}{2} \pm \frac{\mu_h^2 - \mu_s^2}{2}\sqrt{1+y^2}$$

The Simplest Extension, Cont'd

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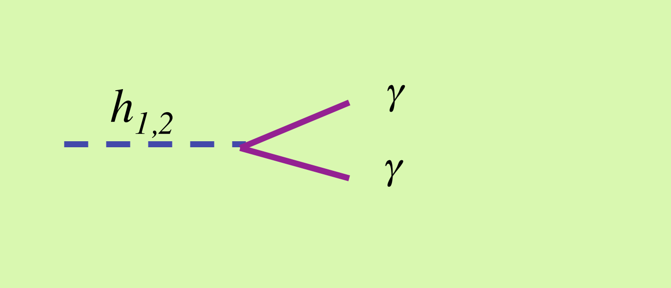

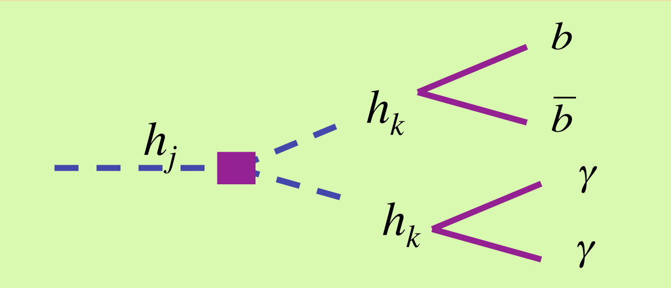

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x_0 = <S>

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

Stable S (dark matter)

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

Real Singlet: EWPT

$$V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

Real Singlet: EWPT

$$V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

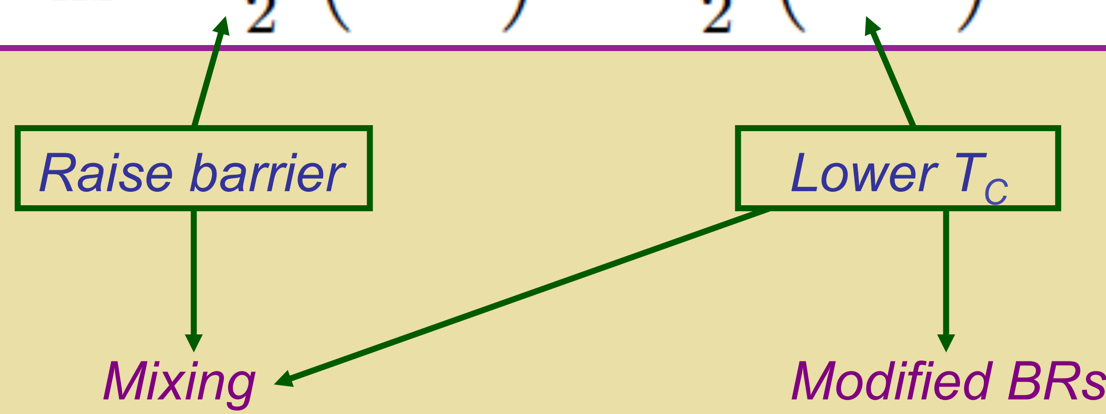
Raise barrier

Lower T_C

Real Singlet: EWPT

Low energy phenomenology

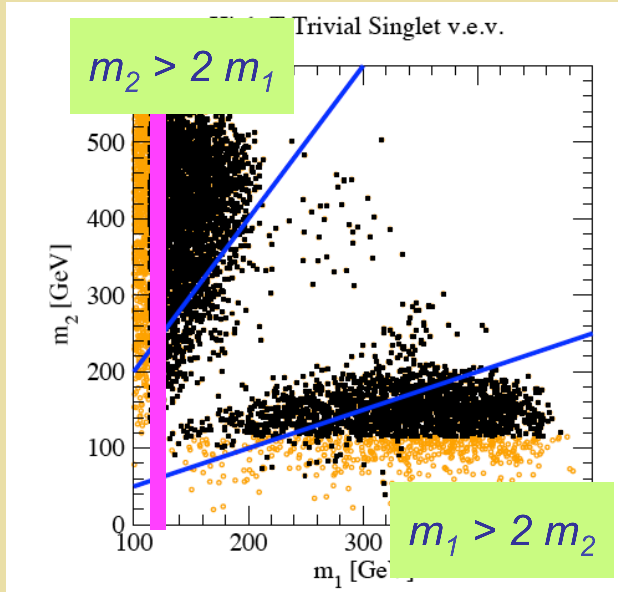
$$V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$



Two mixed (singlet-doublet) states w/ reduced SM branching ratios

EWPT & LHC Phenomenology

Signatures



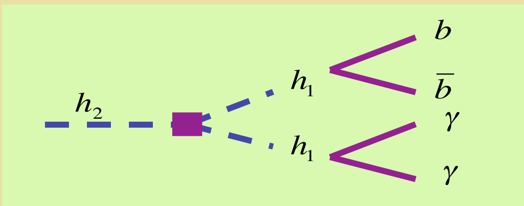
Scan: EWPT-viable model parameters

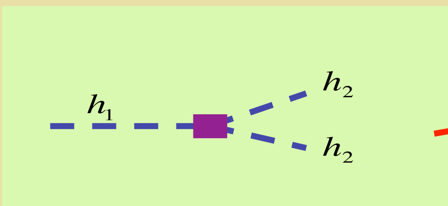
Light: all models
Black: LEP allowed

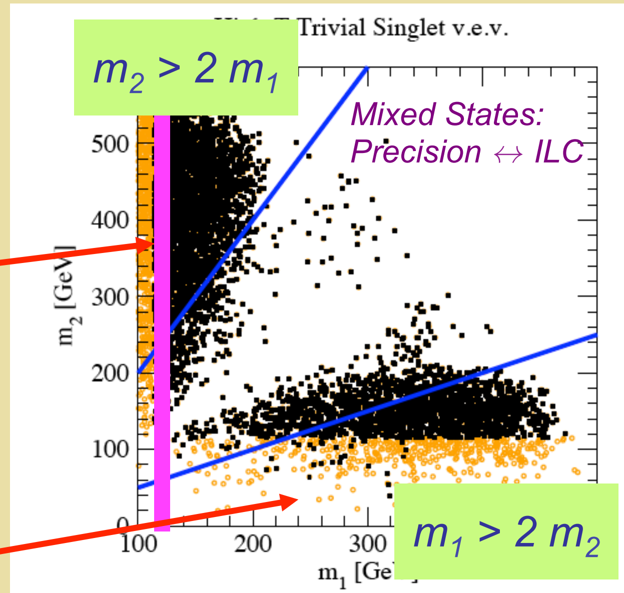
Profumo, R-M, Shaugnessy '07

EWPT & LHC Phenomenology

Signatures







Scan: EWPT-viable model parameters

Light: all models
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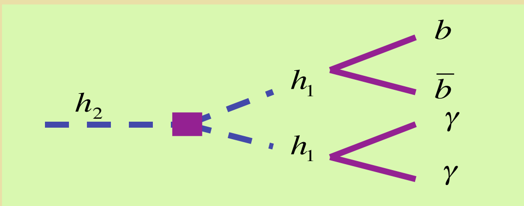
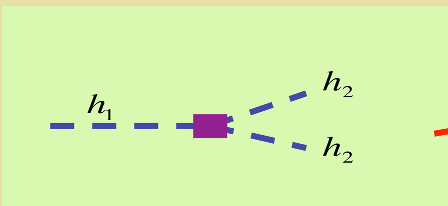
LHC: reduced BR(h ⟶ SM)

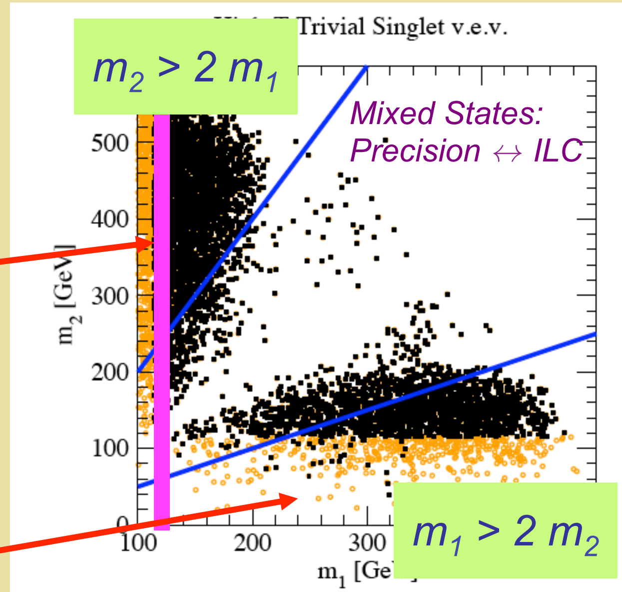
Profumo, R-M, Shaugnessy '07

EWPT & LHC Phenomenology

Signatures







Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

LHC: reduced $BR(h \longrightarrow SM)$

Signal Reduction Factor

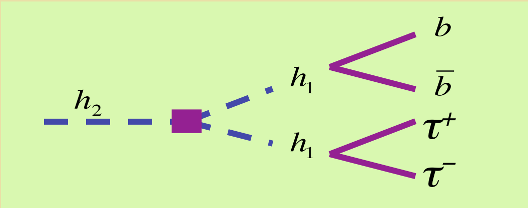
$$\xi_i^2 = V_{1j}^2 \frac{\mathrm{BF}(H_j \to X_{SM})}{\mathrm{BF}(h_{SM} \to X_{SM})}$$

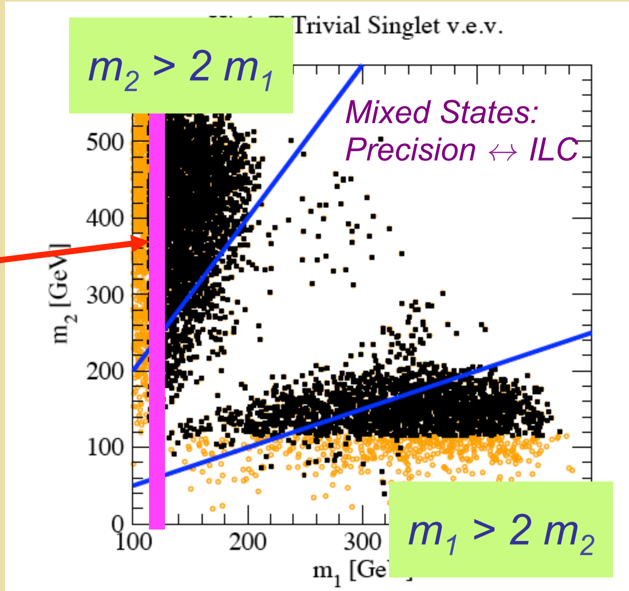
Production — Decay

Profumo, R-M, Shaugnessy ‘07

EWPT: Resonant Di-Higgs Production

Signatures





Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

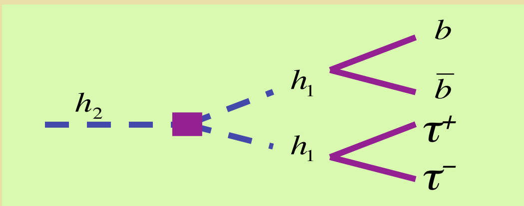
m_2 = 270 GeV "un-boosted"
m_2 = 370 GeV "boosted"

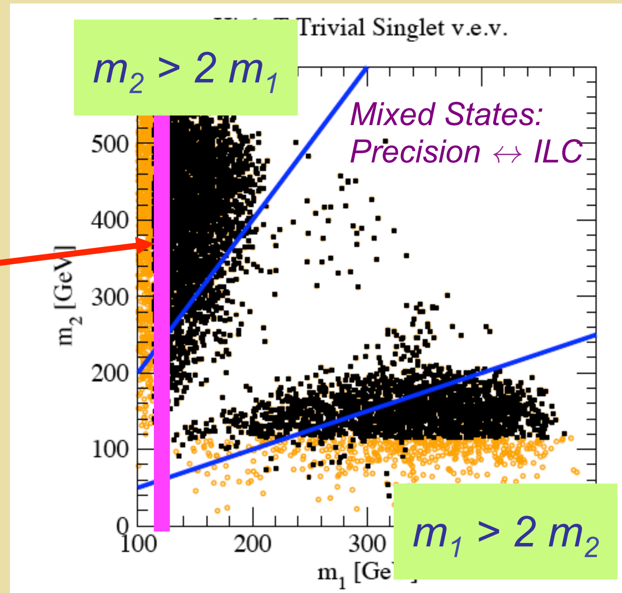
$bb\tau^+\tau^-$: discovery with ~ 100 fb^{-1} in "$\tau_{lep}\,\tau_{had}$" channel

R-M & No, arXiv:1310.6035

EWPT: Resonant Di-Higgs Production

Signatures





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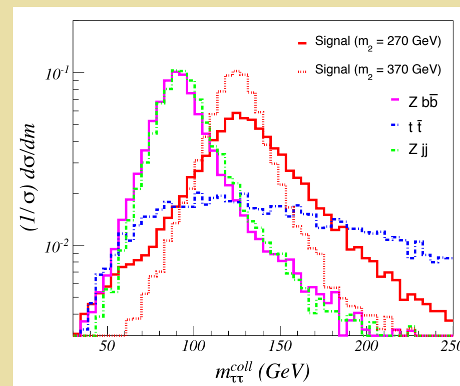
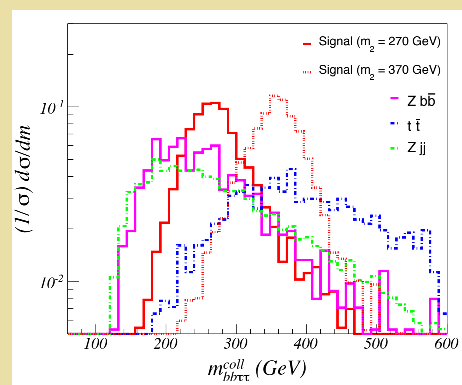
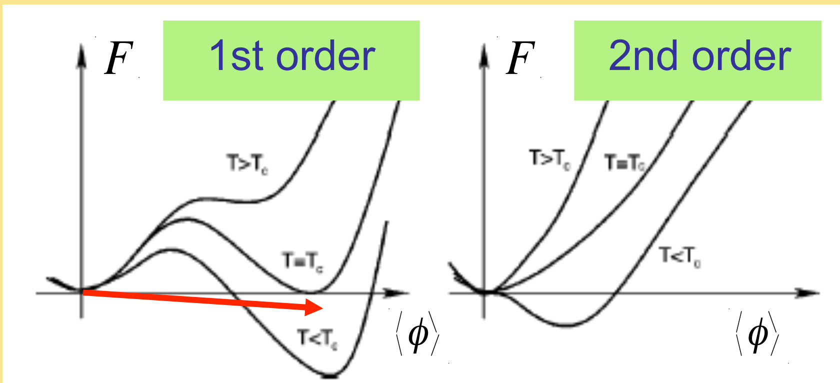
	$h_2 \to h_1 h_1$	$t\bar{t}$		$Z\,b\bar{b}$	$Z\,jj$
	$bb\tau_{\rm lep}\tau_{\rm had}$	$bb\ell\tau_{\rm had}$	$bb\tau_{\rm lep}\tau_{\rm had}$	$bb\tau_{\rm lep}\tau_{\rm had}$	$jj\tau_{\rm lep}\tau_{\rm had}$
Event selection (see section V.C)	19.17	5249	762	601	98
$\Delta R_{bb} > 2.1$, $P_{T,b_1} > 45$ GeV, $P_{T,b_2} > 30$ GeV	11.45	2639	384	188	10.8
h_1-mass: 90 GeV $< m_{bb} <$ 140 GeV	8.00	531	80	69	3.68
Collinear x_1, x_2 Cuts	4.81	209	36.4	41.6	2.41
$\Delta R_{\ell\tau} > 2$	4.10	129	23.1	26.5	2.03
$m_T^\ell < 30$ GeV	3.44	30.9	11.1	24.4	1.90
h_1-mass: 110 GeV $< m_{\tau\tau}^{\rm coll} <$ 150 GeV	1.56	4.97	2.05	4.92	0.38
$E_T^{\rm miss} < 50$ GeV	1.37	3.31	0.87	4.29	0.36
h_2-mass: 230 GeV $< m_{bb\tau\tau}^{\rm coll} <$ 300 GeV	1.29	0.39	0.17	1.21	0.13



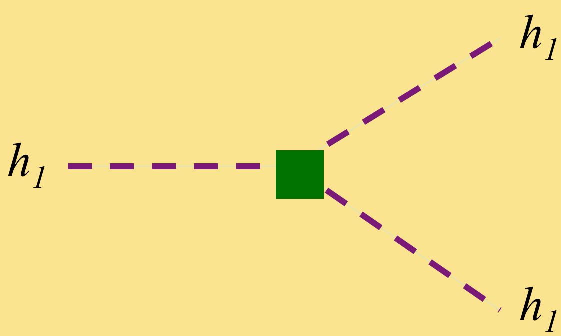


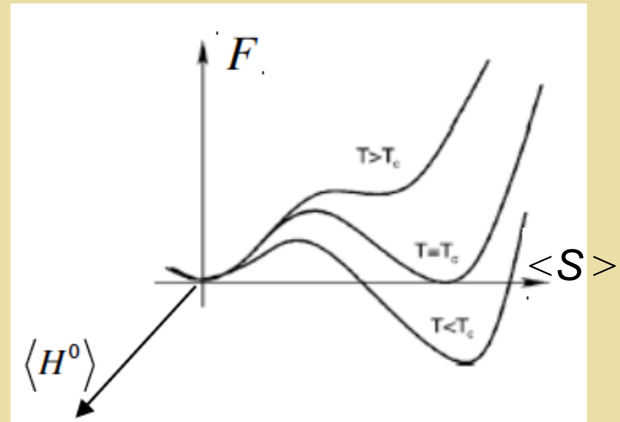
R-M & No, arXiv:1310.6035

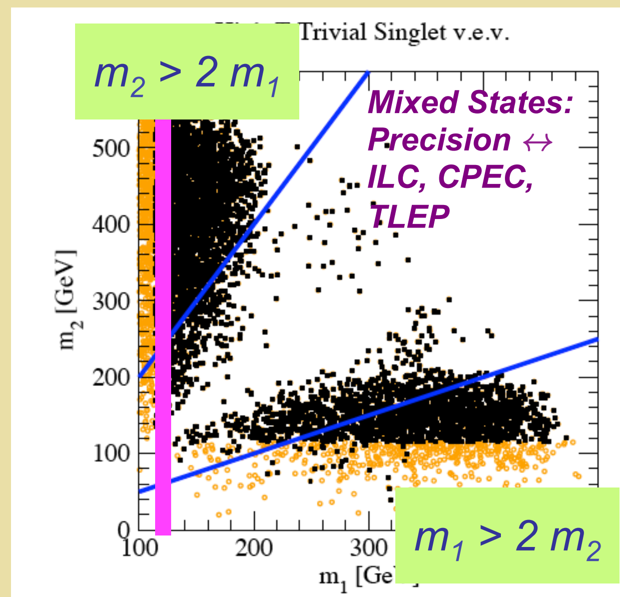
EW Phase Transition: New Scalars



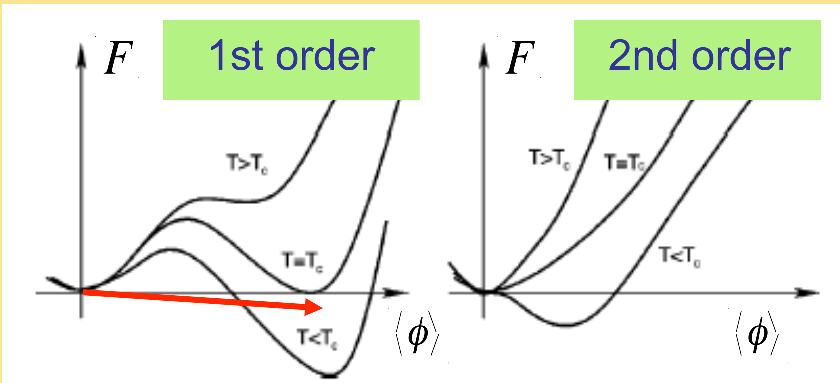
Modified Higgs Self-Coupling

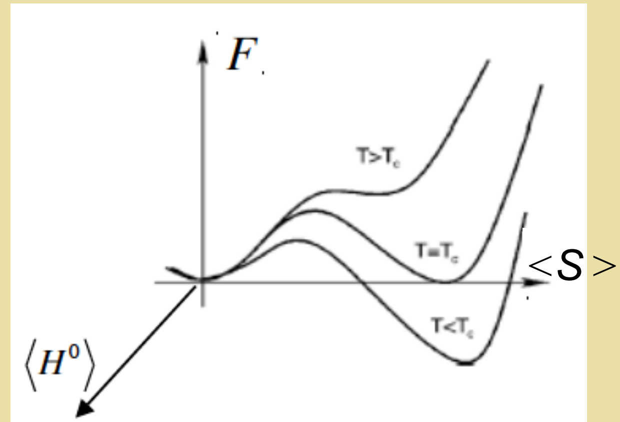




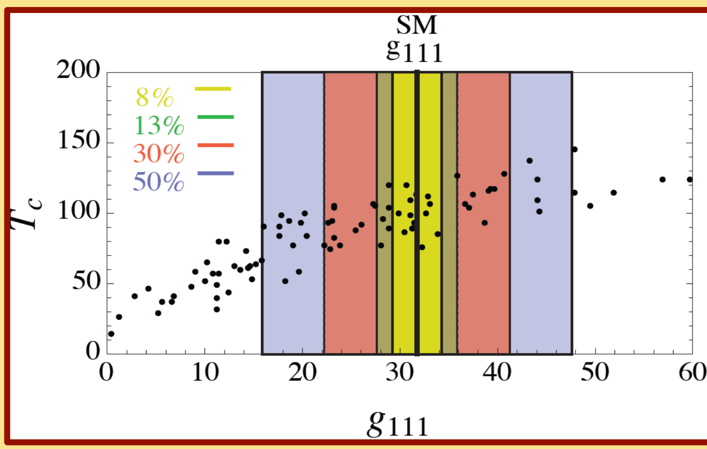


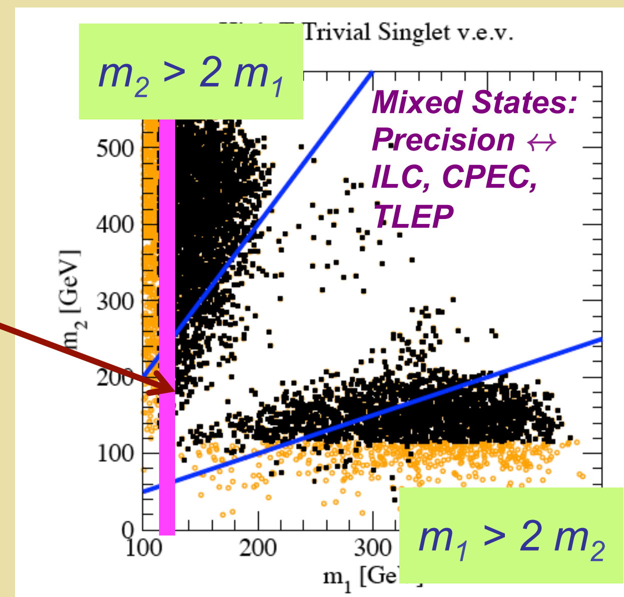
EW Phase Transition: New Scalars





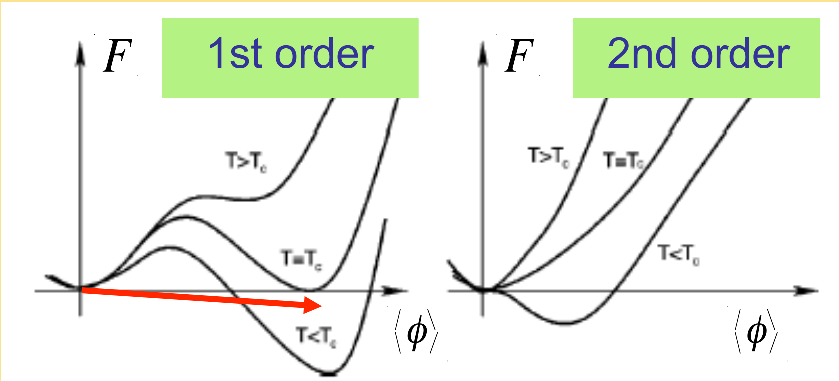
Modified Higgs Self-Coupling

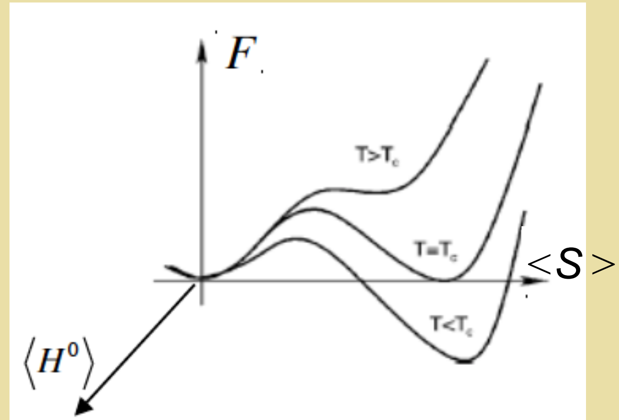




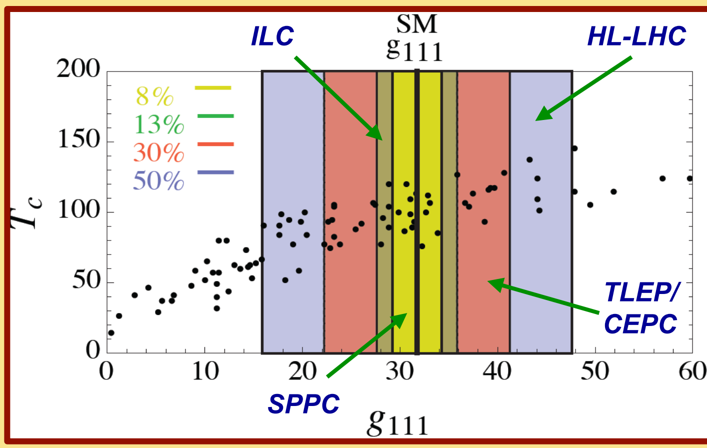
Profumo, R-M, Wainwright, Winslow: 1407.5342

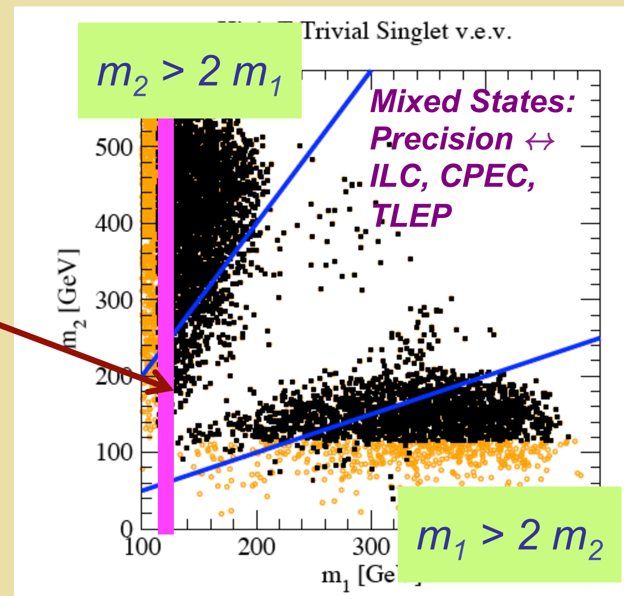
EW Phase Transition: New Scalars





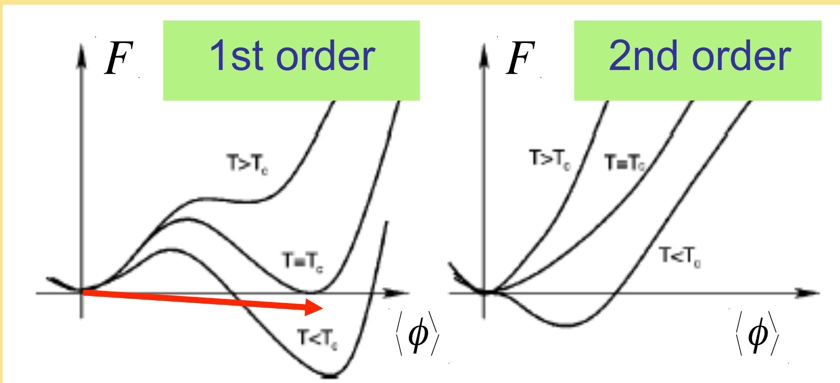
Modified Higgs Self-Coupling



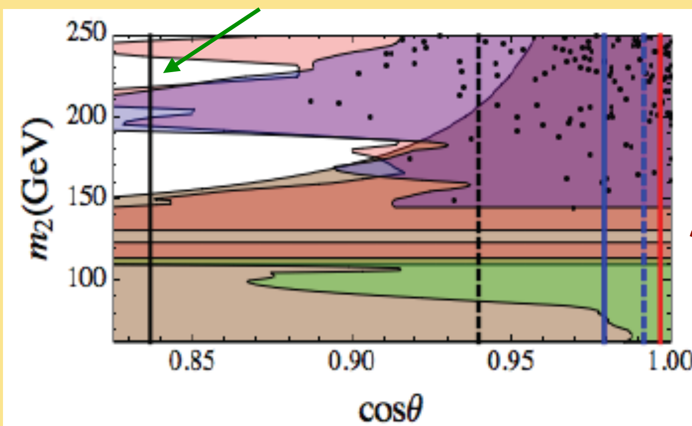


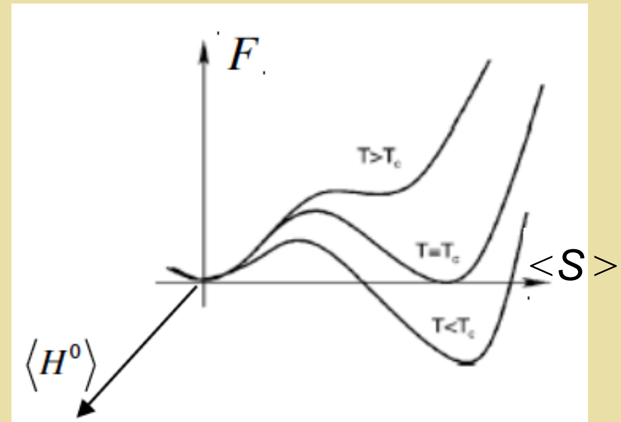
Profumo, R-M, Wainwright, Winslow: 1407.5342

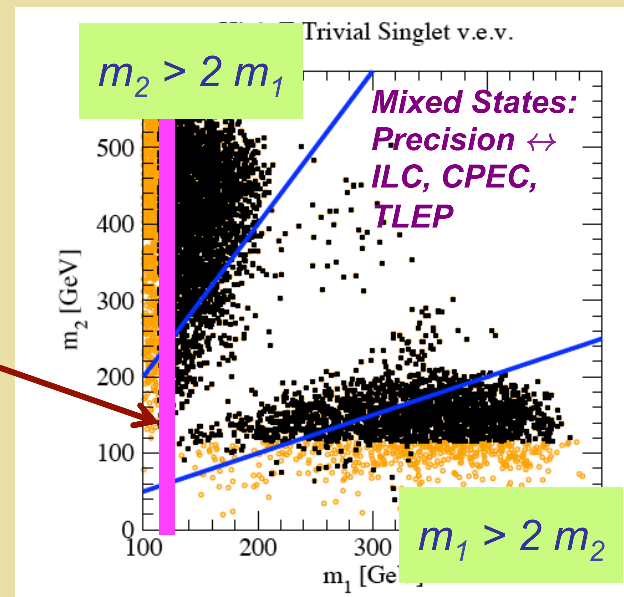
EW Phase Transition: New Scalars



Higgs Mixing

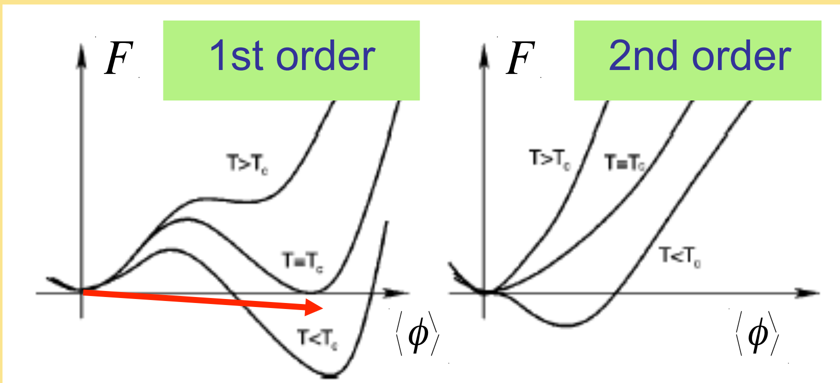


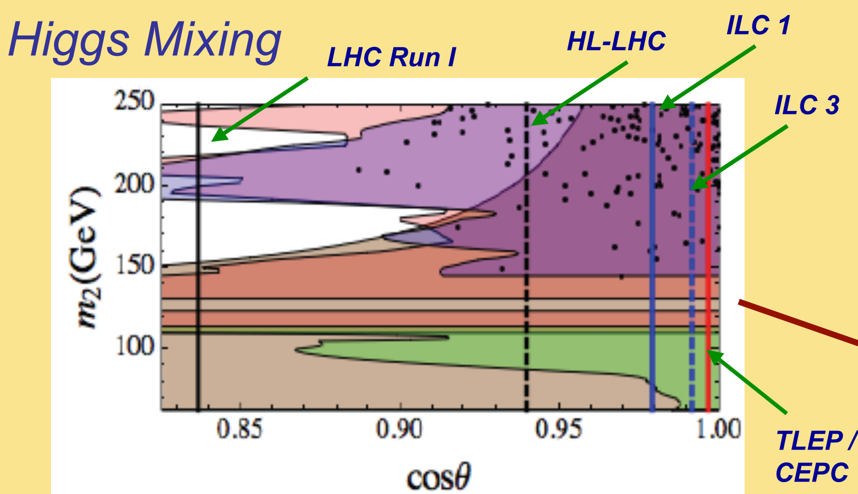


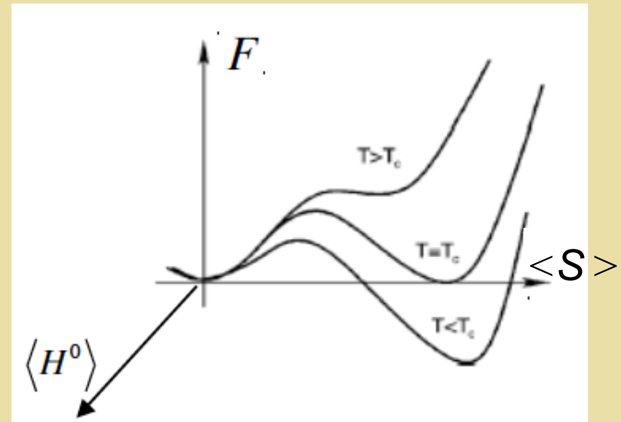


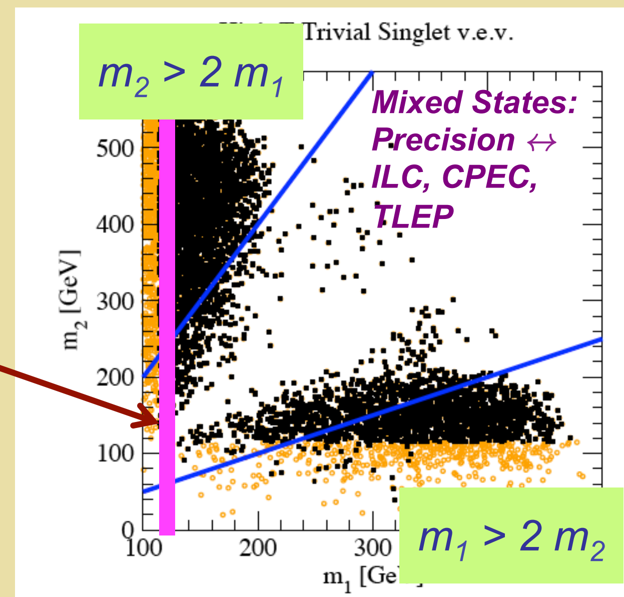
Profumo, R-M, Wainwright, Winslow: 1407.5342

EW Phase Transition: New Scalars









Profumo, R-M, Wainwright, Winslow: 1407.5342

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet	1	✔	✖
Real singlet	1	✖	✔
Complex Singlet	2	✔	✔
Real Triplet	3	✔	✔

Back up slides

May be low-energy remnants of UV complete theory & illustrative of generic features

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet	1	✔	✖
Real singlet	1	✖	✔
Complex Singlet	2	✔	✔
Real Triplet	3	✔	✔

Simplest non-trivial EW multiplet

Real Triplet

$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \; \mathrm{Tr}\, \Sigma^2$$

EWPT: $a_{1,2} \neq 0$ & $\langle\Sigma^0\rangle \neq 0$

DM & EWPT: $a_1 = 0$ & $\langle\Sigma^0\rangle = 0$

Real Triplet

Σ^0, Σ^+, Σ^- ~ (1, 3, 0)

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DM & EWPT: $a_1 = 0$ & $\langle\Sigma^0\rangle = 0$

Small: ρ-param

Real Triplet: DM

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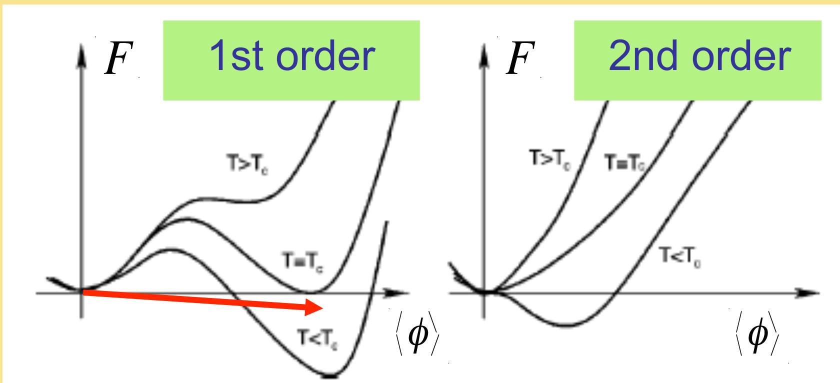
Small: ρ*-param*

EW Phase Transition: Higgs Portal

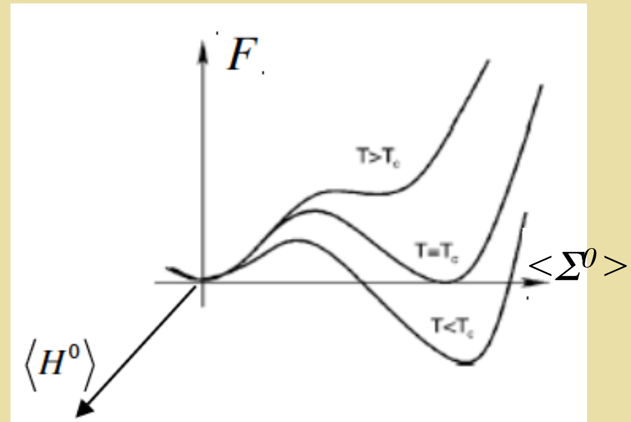


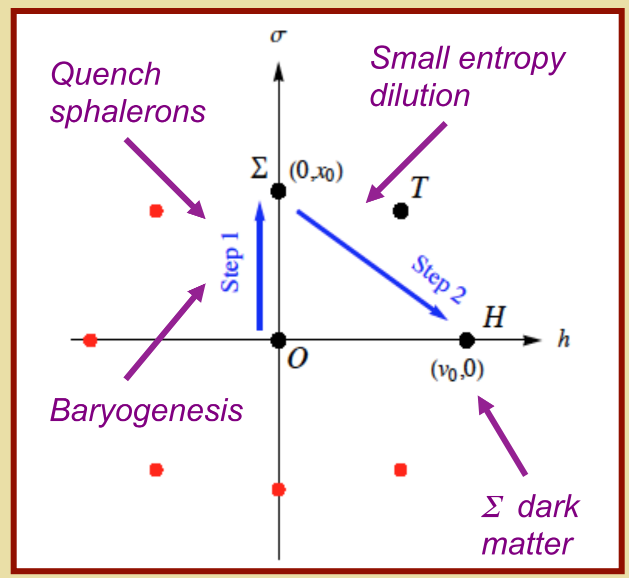
Increasing m_h →

← *New scalars*

Real Triplet *$\Sigma \sim (1,3,0)$*

Two-step EWPT & dark matter





Patel, R-M: arXiv 1212.5652 ; Fileviez-Perez, Patel, RM, Wang

Real Triplet: EWPT

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H. Patel & R-M, 1212.5652/hep-ph (2012)

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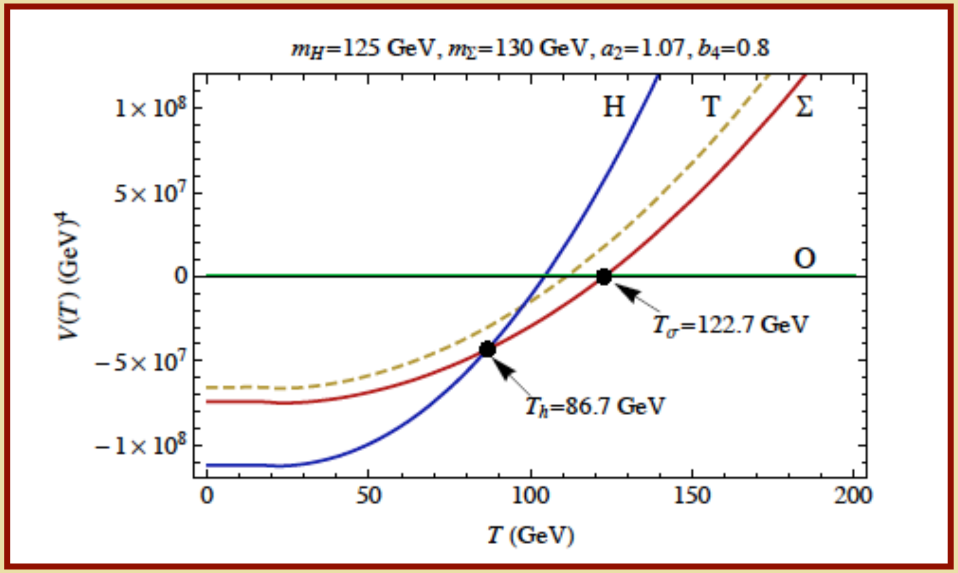
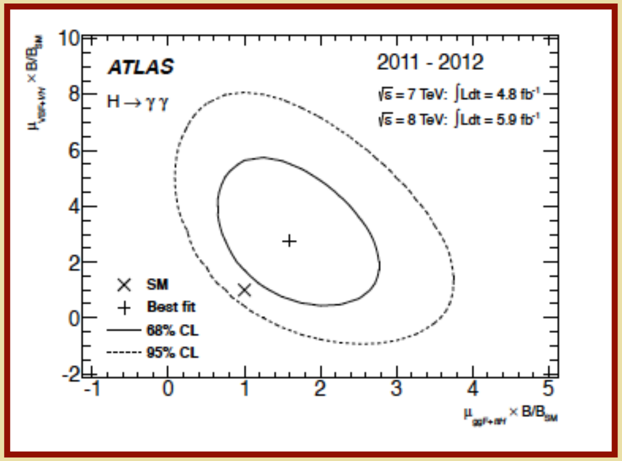
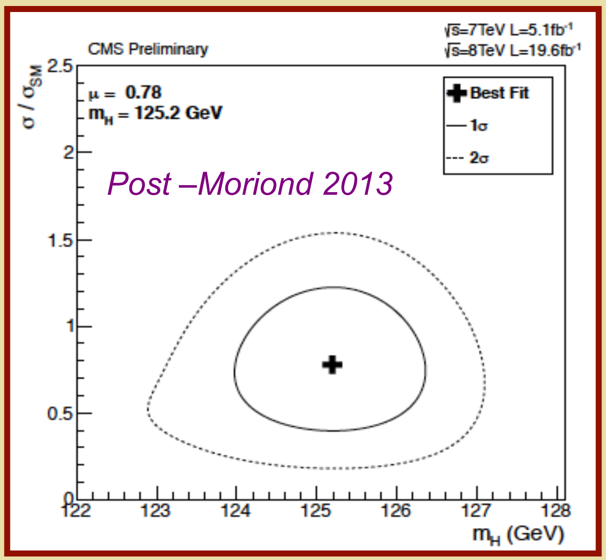
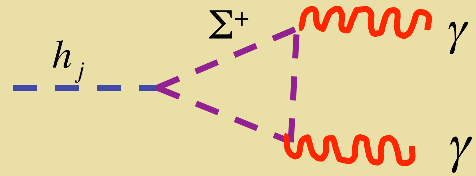


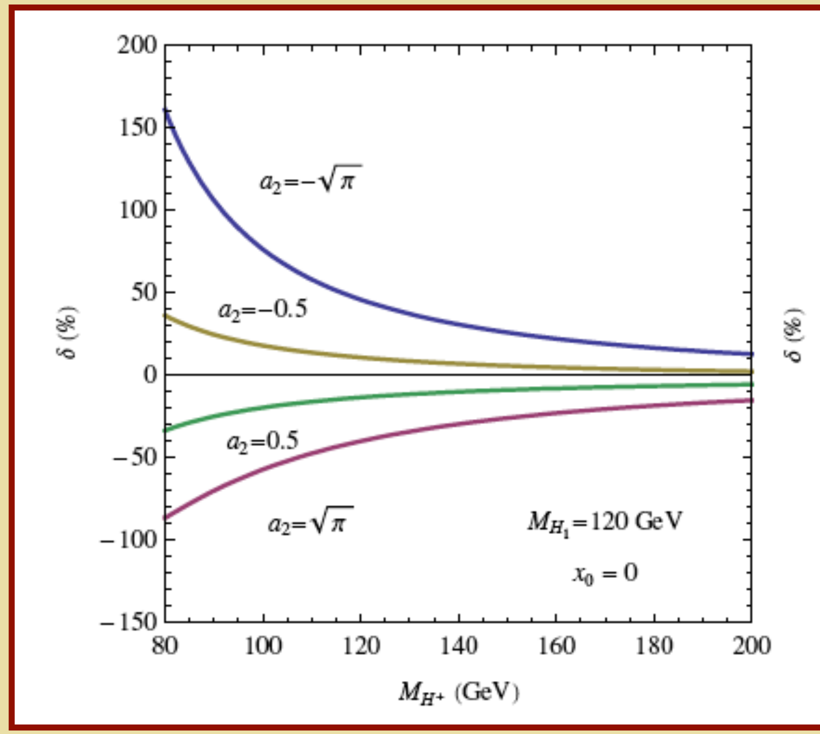
Higgs Diphoton Decays

LHC: $H \to \gamma\gamma$



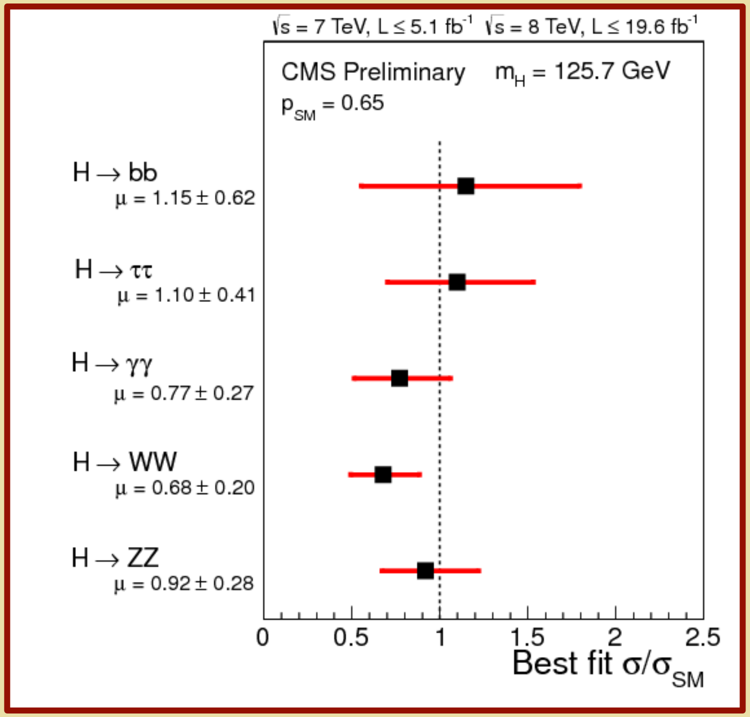


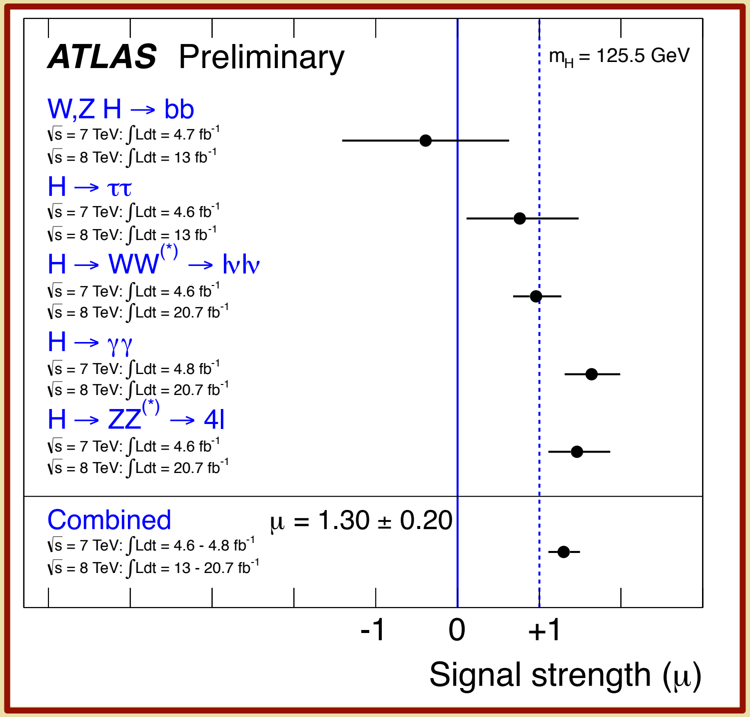




Fileviez-Perez, Patel, Wang, R-M: PRD 79: 055024 (2009); 0811.3957 [hep-ph]

Higgs Decays: All Channels





Real Triplet: EWPT

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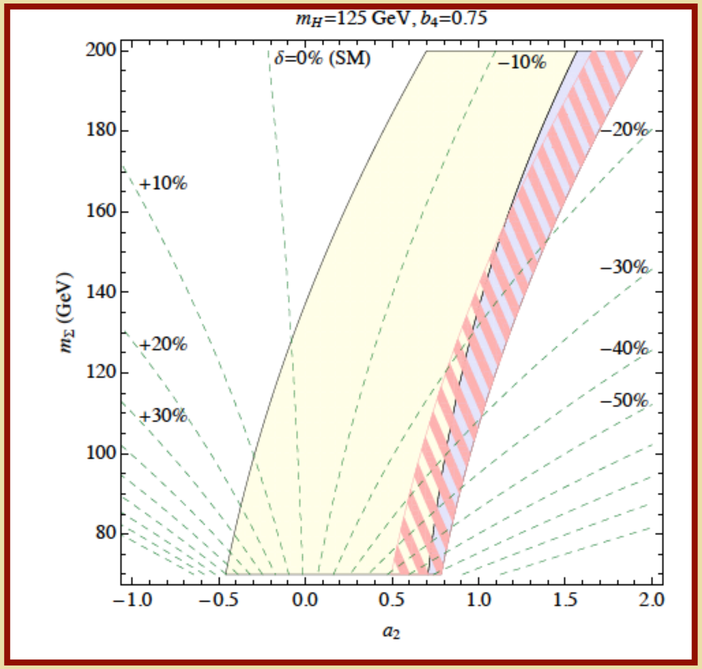

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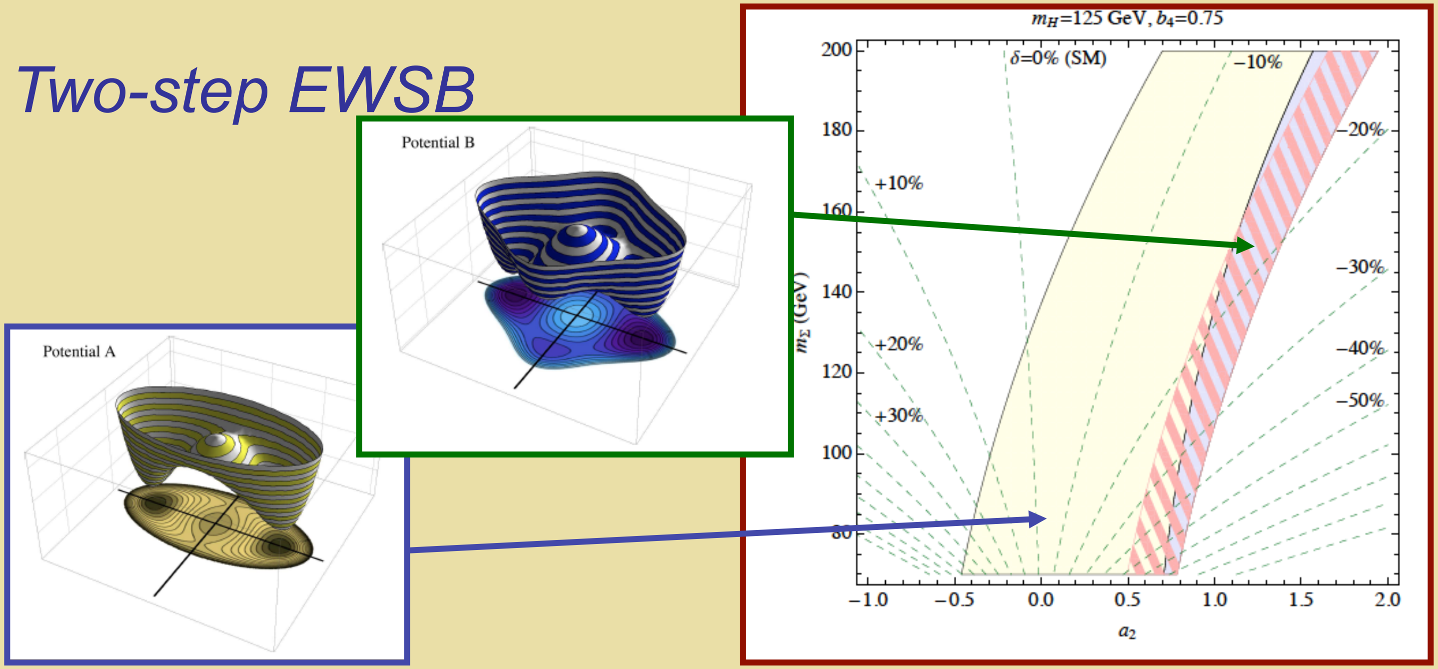

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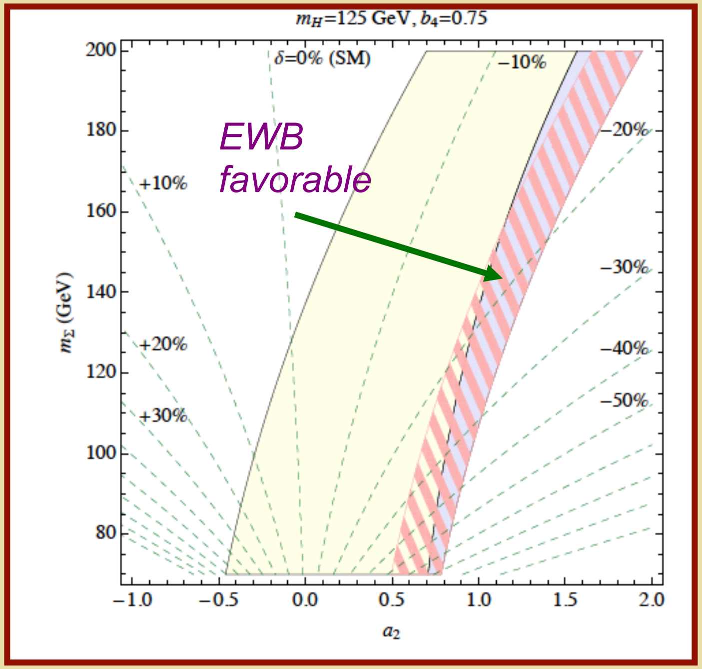

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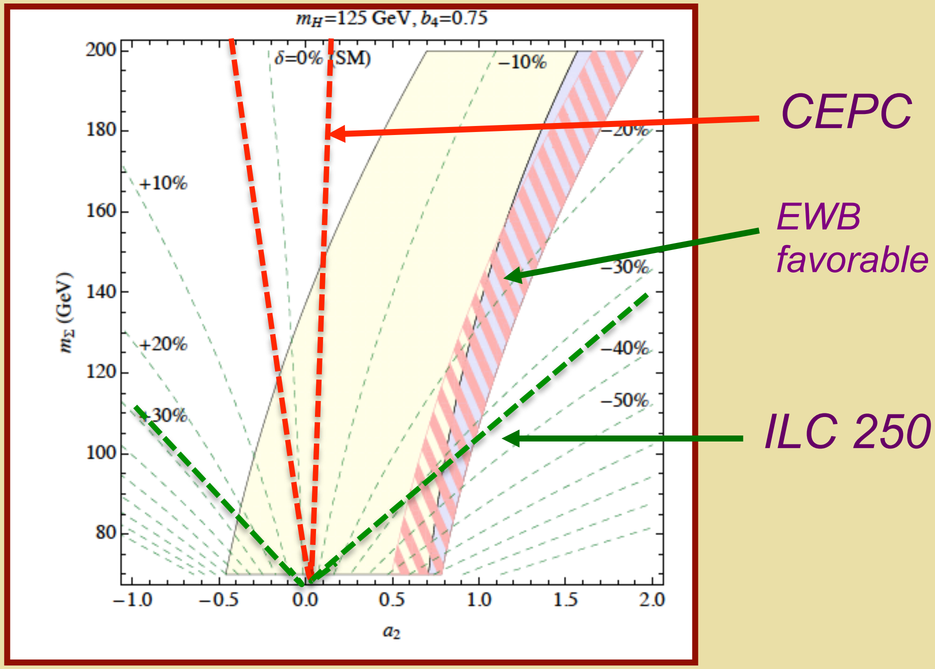
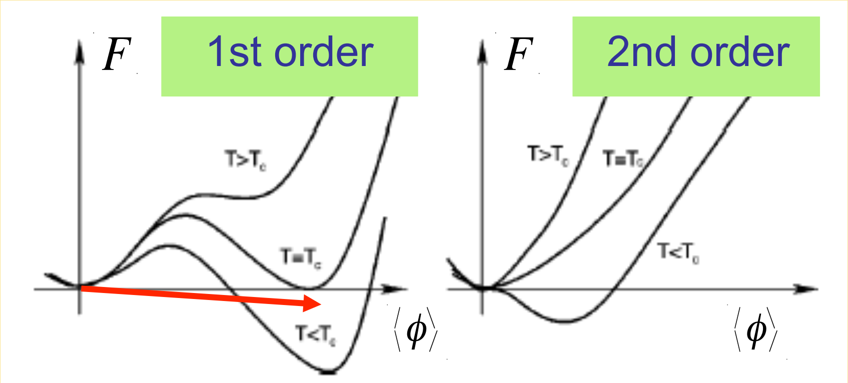


EW Phase Transition: Higgs Portal



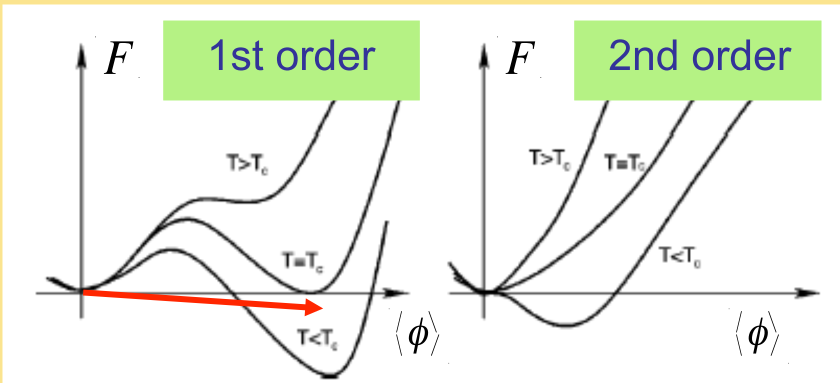
Increasing m_h →

← *New scalars*

Do good symmetries today need to be good symmetries in the early Universe ?

Patel, R-M, Wise: PRD 88 (2013) 015003

Symmetry Breaking & Restoration



Increasing m_h →

← New scalars

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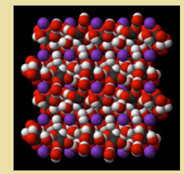
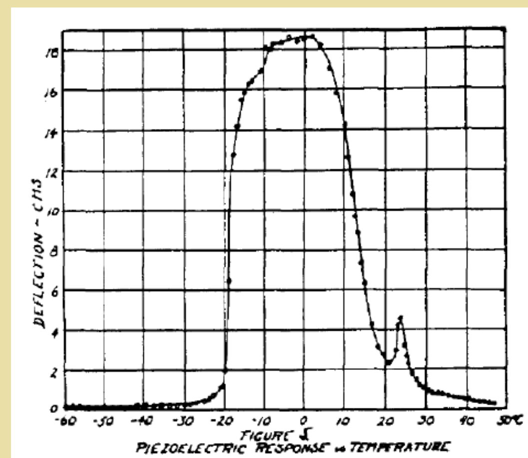
Rochelle salt:
$KNaC_4H_4O_6\ 4H_20$



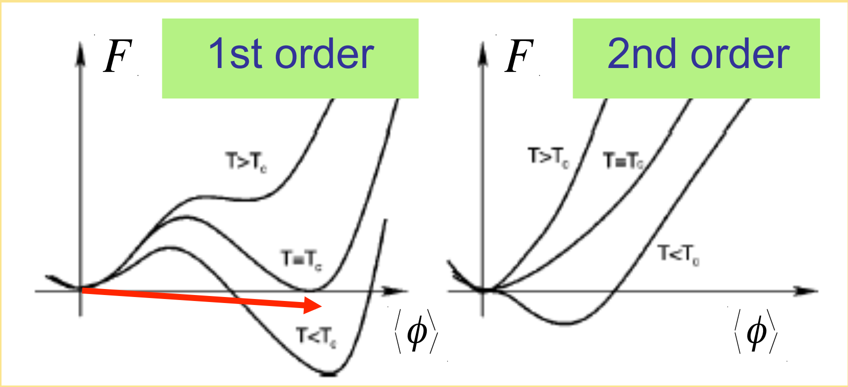
J. Valasek

Piezoelectricity



Increasing T $\rightarrow$

EW Phase Transition: Higgs Portal



Increasing m_h →

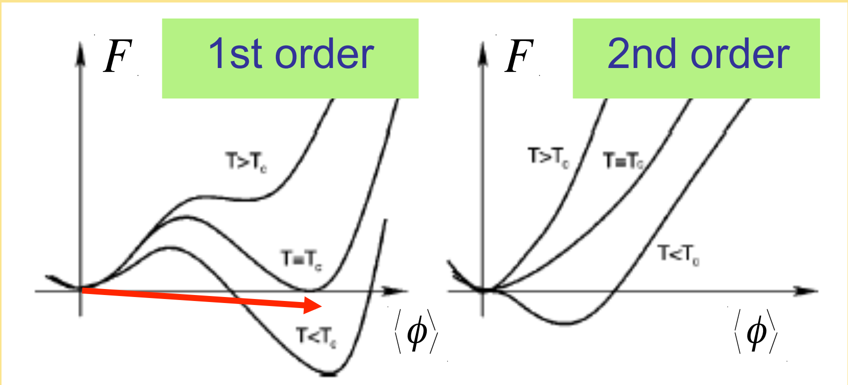
← New scalars

Do good symmetries today need to be good symmetries in the early Universe ? *No*

- *O(n) x O(n): Weinberg (1974)*
- *SU(5), CP….: Dvali, Mohapatra, Senjanovic ('79, 80's, 90's)*
- *Cline, Moore, Servant et al (1999)*
- *EM: Langacker & Pi (1980)*
- *$SU(3)_C$: Patel, R-M, Wise: PRD 88 (2013) 015003*

Patel, R-M, Wise: PRD 88 (2013) 015003

EW Phase Transition: Higgs Portal



Increasing m_h →

← New scalars

Colored Scalars

Color breaking & restoration

Patel, R-M, Wise: PRD 88 (2013) 015003

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Color Breaking & Restoration

Two illustrative cases:

H. Patel, R-M, Wise
1303.1140 (2013)

Extension	DOF	EWPT	DM
Color triplet scalar	6	✔	✖
Color triplet + singlet	7	✔	✖
…..			

Color Breaking & Restoration

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…..			

Spontaneous B violation

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H. Patel, R-M, Wise 1303.1140 (2013)

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Color triplet scalar	6	✔	✖
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…..			

"Light": special flavor structure

Spontaneous B violation

Color Breaking & Restoration

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H. Patel, R-M, Wise
1303.1140 (2013)

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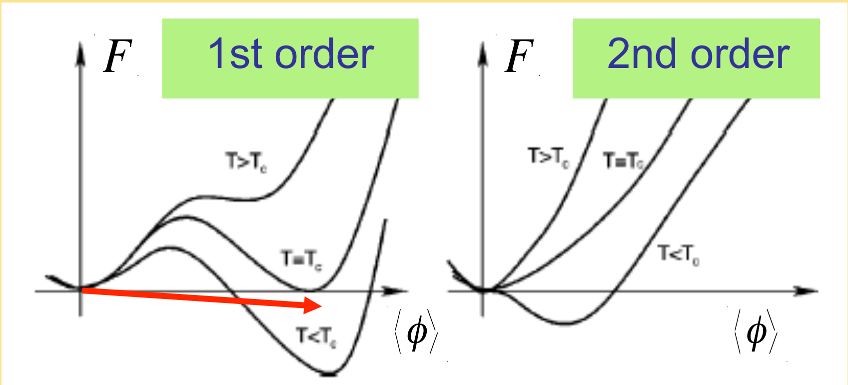
Color triplet scalar	6	✔	✖
Color triplet + singlet	7	✔	✖
…..			

heavy: generic flavor structure

Spontaneous B violation

EW Phase Transition: Higgs Portal

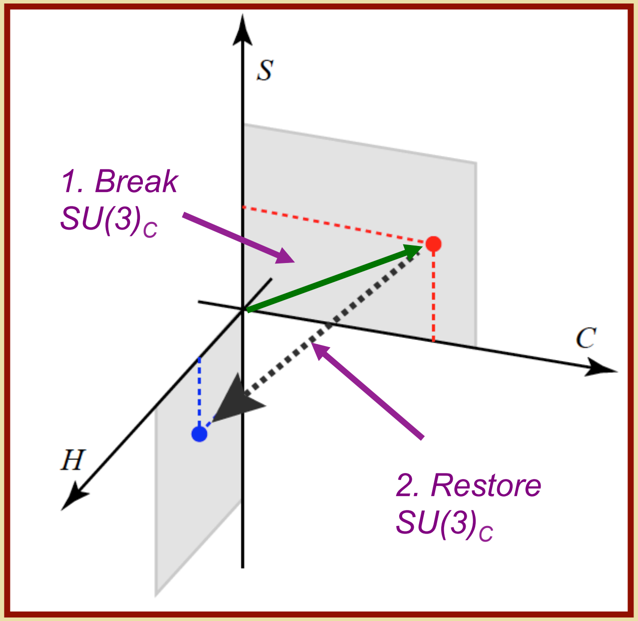


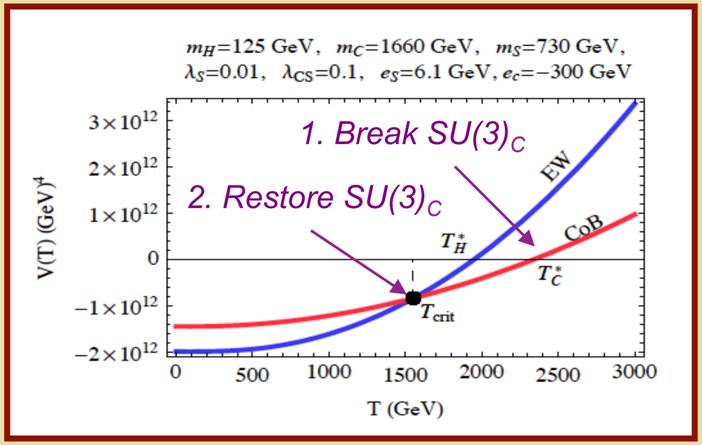
Increasing m_h →

← *New scalars*

Colored Scalars (triplet)

Color breaking & restoration

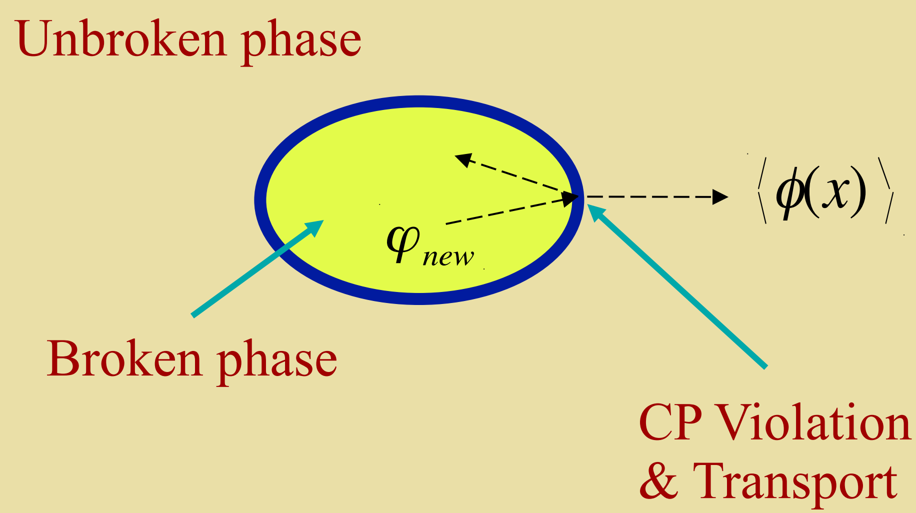




Patel, R-M, Wise: PRD 88 (2013) 015003

III. CPV: EDMs & Scalar Sector

CPV in EW Baryogenesis



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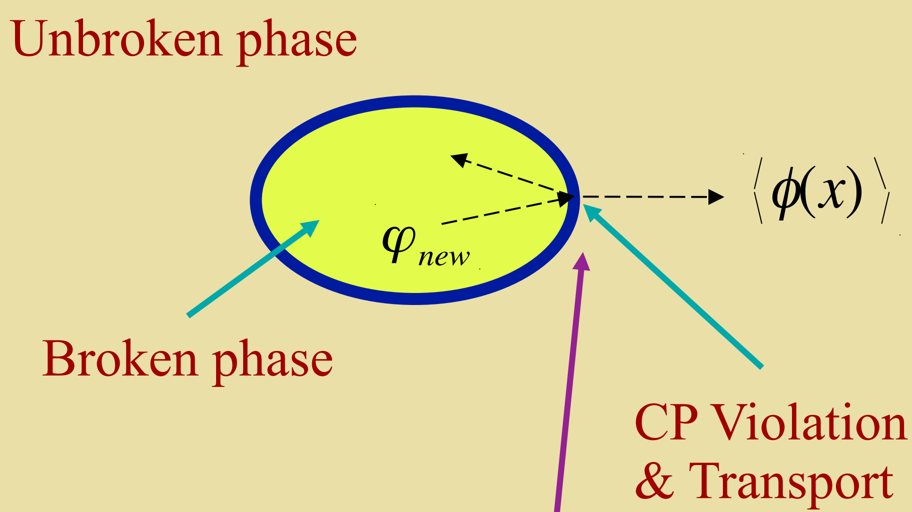


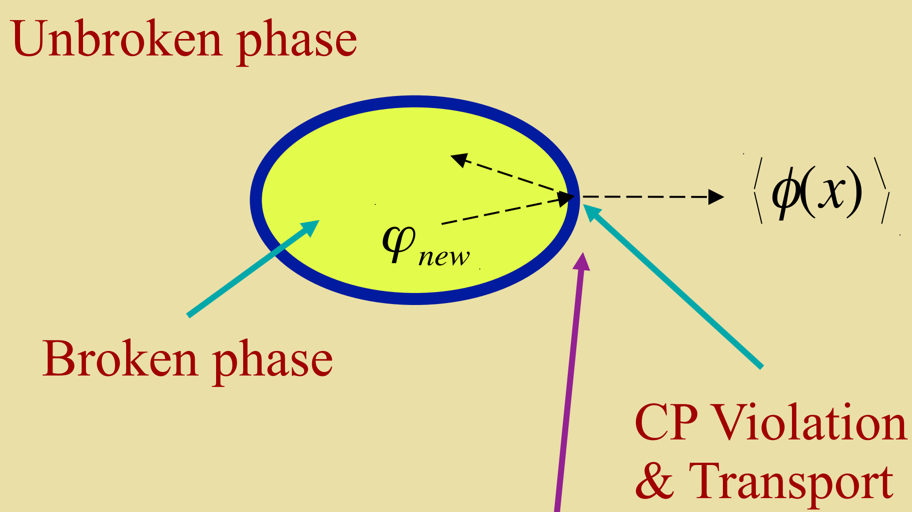
Transport: A Competition *R-M et al*

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

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

$\Gamma(A+B \leftrightarrow A+B)$ *Diffusion*

CPV in EW Baryogenesis: MSSM



CP Conserving Interactions

$\Gamma_Y(\tilde{Q} \to t\tilde{H})$ — $A^{CP}{}_{BSM} \to A^{CP}{}_{SM}$

$\Gamma_V(\tilde{Q} \to Q\tilde{V})$ — *"Superequilibrium"*

$\Gamma_D(\tilde{Q} + q \to \tilde{Q} + q)$ — *Diffusion*

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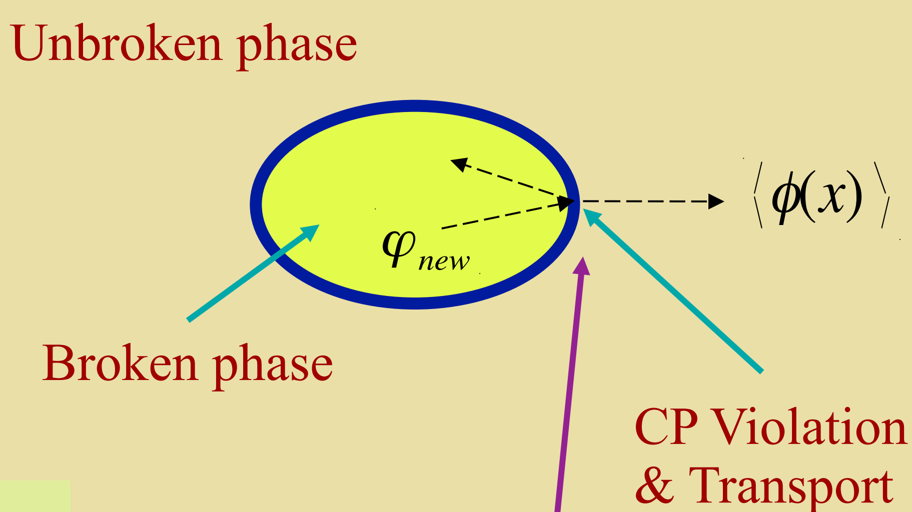

CP Violating Sources

$$W_{\rm MSSM} = \bar{u}\mathbf{y_u} Q H_u - \bar{d}\mathbf{y_d} Q H_d - \bar{e}\mathbf{y_e} L H_d + \mu H_u H_d$$

$$\mathcal{L}_{\rm soft} = -\frac{1}{2}(M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}\tilde{W} + M_1 \tilde{B}\tilde{B}) + c.c.$$
$$- (\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d) + c.c.$$
$$- \tilde{Q}^\dagger \mathbf{m^2_Q}\tilde{Q} - \tilde{L}^\dagger \mathbf{m^2_L}\tilde{L} - \tilde{\bar{u}}\mathbf{m^2_{\bar{u}}}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m^2_{\bar{d}}}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m^2_{\bar{e}}}\tilde{\bar{e}}^\dagger$$
$$- m^2_{H_u} H_u^* H_u - m^2_{H_d} H_d^* H_d - (b H_u H_d + c.c.)$$

$\phi_j = \arg(\mu M_j b^*)$ $\phi_A = \arg(A_f M_j)$

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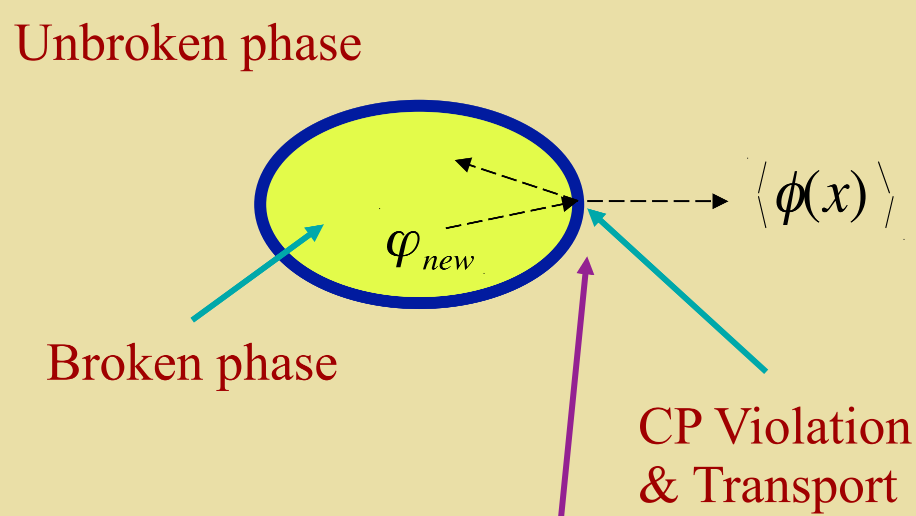

MSSM: ~ 30 Coupled Eqns

$$
\begin{aligned}
\partial_\mu \widetilde{t}^\mu = & -\Gamma_Y^{(\widetilde{t},\widetilde{q},H_1)} \left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}} - \frac{H_1}{k_{H_1}} \right) - \Gamma_Y^{(\widetilde{t},\widetilde{q},H_2)} \left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}} - \frac{H_2}{k_{H_2}} \right) + S_{\widetilde{t}}^{\not{CP}} \\
& - \Gamma_Y^{(\widetilde{t},q,\widetilde{H})} \left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{q}{k_q} - \frac{\widetilde{H}}{k_{\widetilde{H}}} \right) - \Gamma_{\widetilde{V}}^{(t,\widetilde{t})} \left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{t}{k_t} \right) - \Gamma_M^{(\widetilde{t},\widetilde{q})} \left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}} \right)
\end{aligned}
$$

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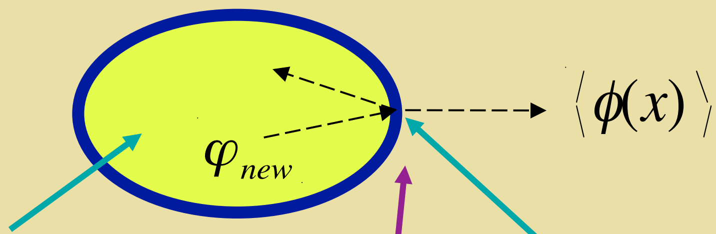
CPV in EW Baryogenesis: MSSM

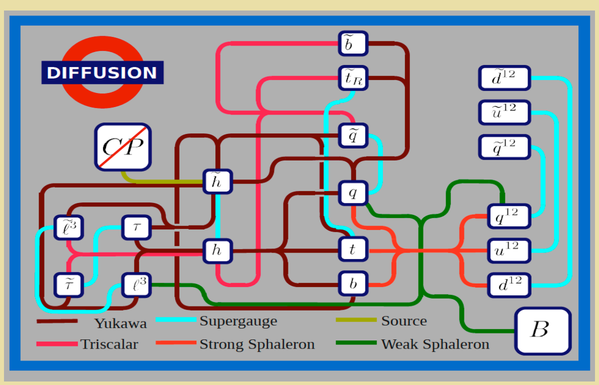
Unbroken phase



Broken phase

CP Violation
& Transport

MSSM: ~ 30 Coupled Eqns



Thanks: B. Garbrecht

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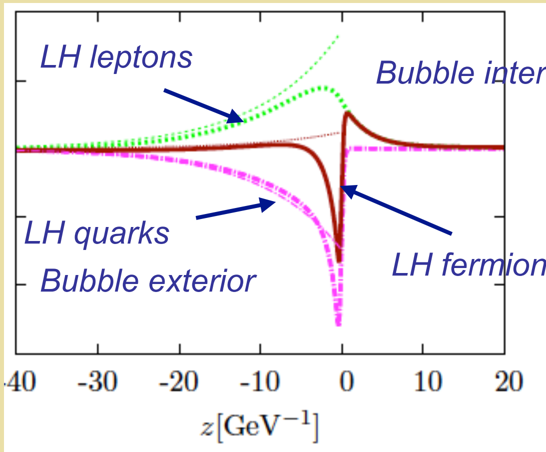

MSSM: Chung, Garbrecht, R-M, Tulin '09

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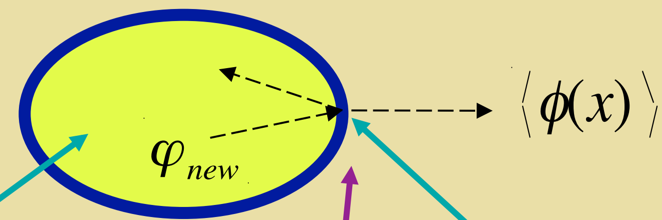

Broken phase

CP Violation
& Transport

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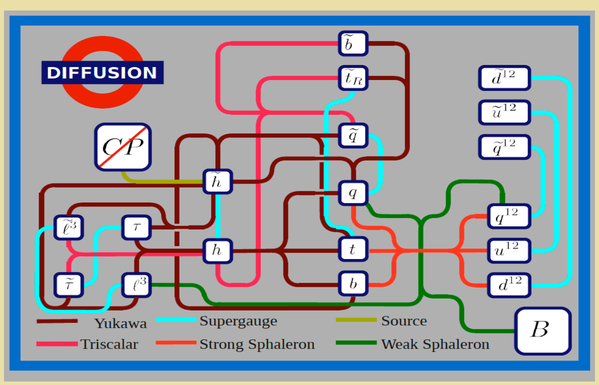

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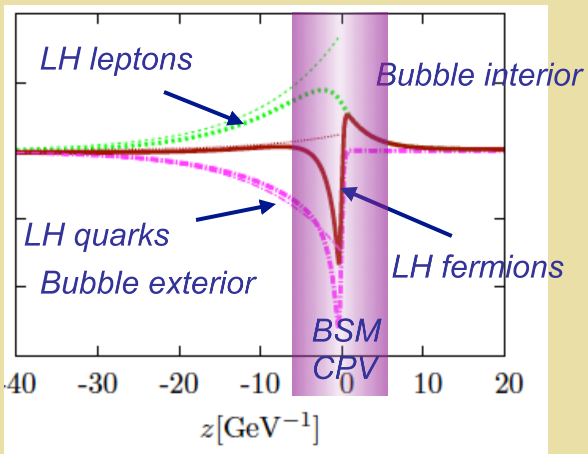

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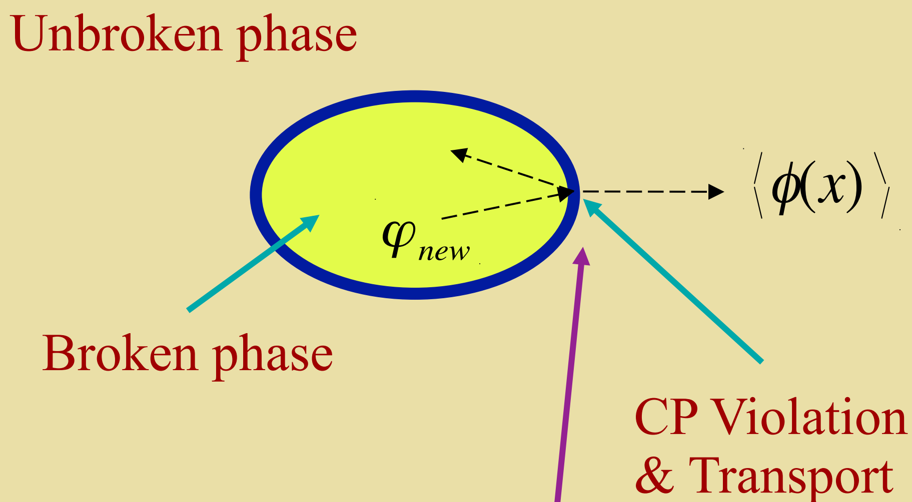

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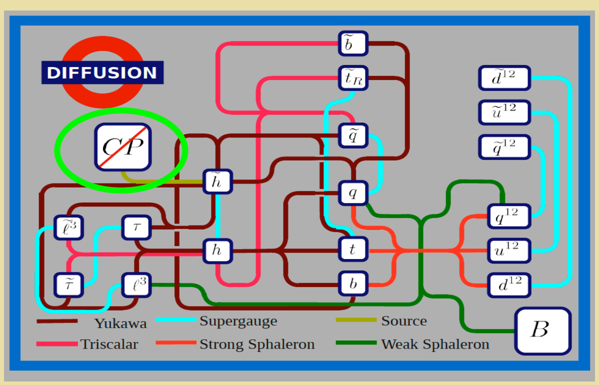

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EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^- equivalent

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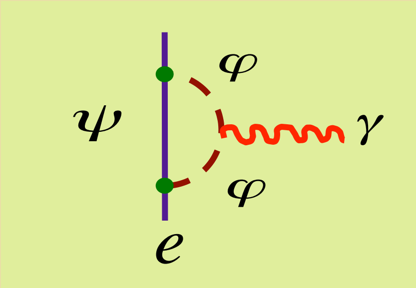
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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* 95% CL   ** e^{-} equivalent

★ neutron

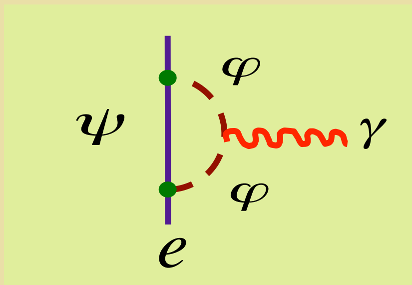
★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

EDM Probes: EWB Implications



$\sin\phi_{CP} \sim 1 \;\; \rightarrow M > 5000$ GeV

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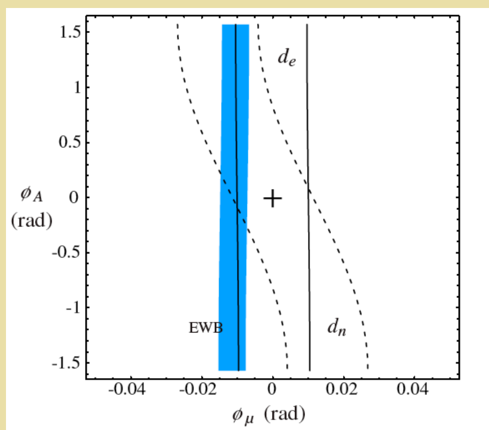
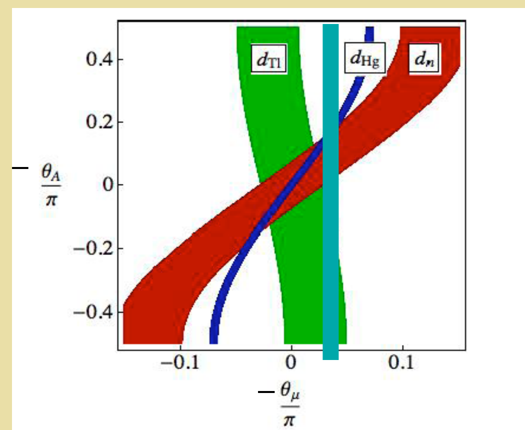
Universal gaugino phases

$Arg(\mu M_i b^*)$ =

$Arg(\mu M_j b^*)$



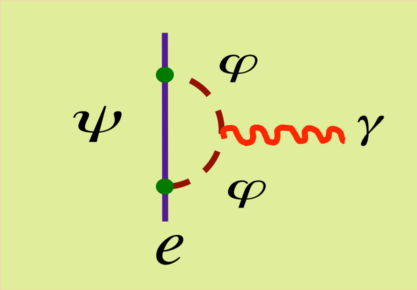
Cirigliano, R-M, Tulin, Lee '06



Ritz CIPANP 09 +

Cirigliano, R-M, Tulin, Lee '06

EDM Probes: EWB Implications



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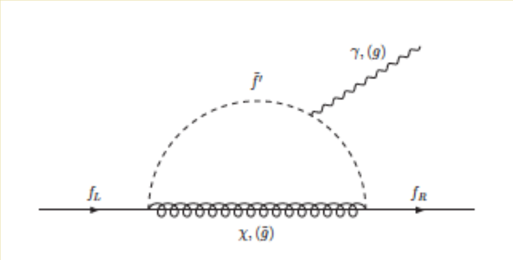
Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

EDM Probes: EWB Implications



Heavy sfermions: LHC consistent & suppress 1-loop EDMs

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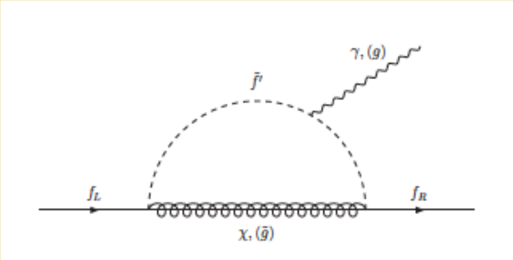

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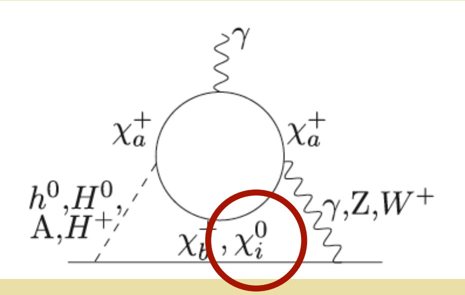

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

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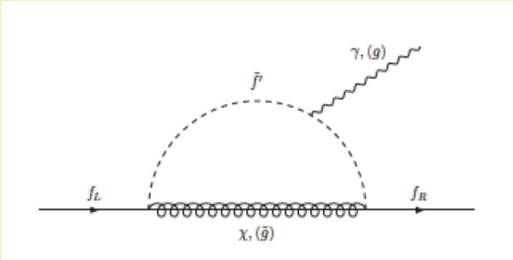
EDM Probes: EWB Implications



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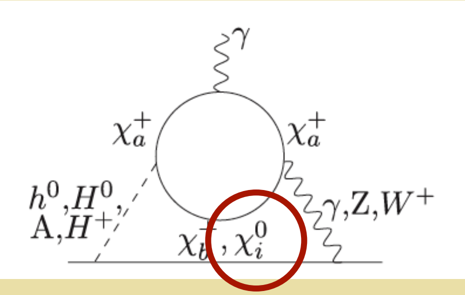

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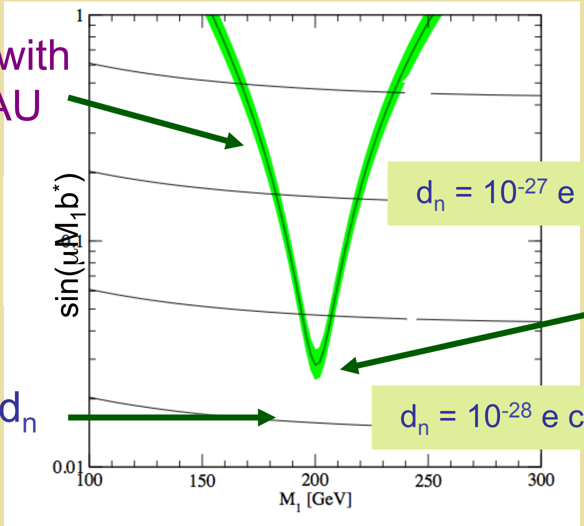

Li, Profumo, RM '09-' 10

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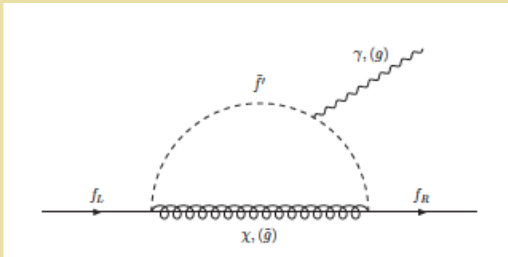

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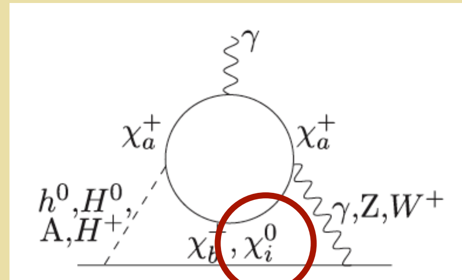
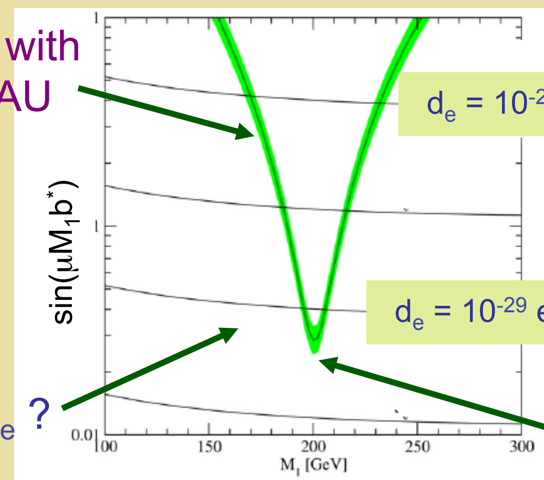


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



$d_e = 10^{-28}$ e cm

$d_e = 10^{-29}$ e cm

Next gen d_e ?

Compressed spectrum (stealthy SUSY)

Li, Profumo, RM '09-' 10

Viable EWB & CPV:

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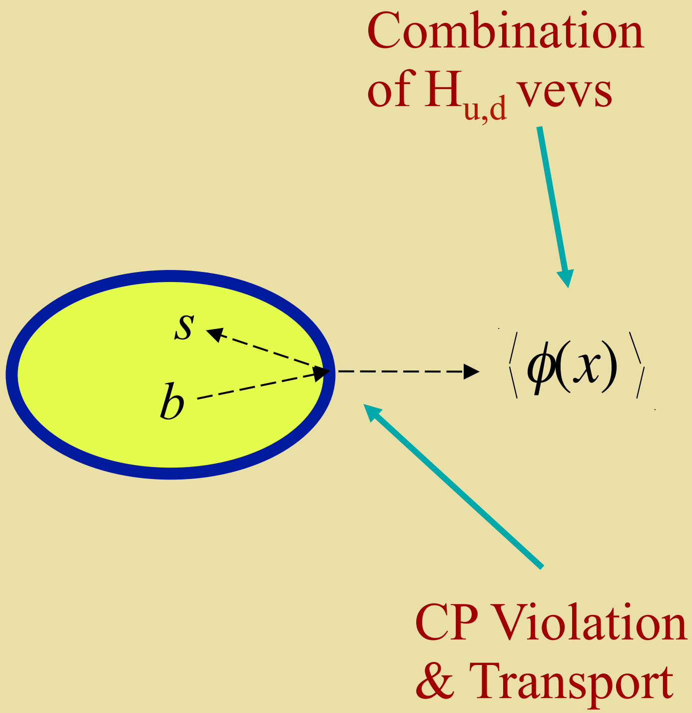
New Direction: Flavored CPV & EWB

CPV & 2HDM

$$\mathcal{L} = -y_{ij}^u \bar{Q}^i (\epsilon H_u^\dagger) u_R^j - y_{ij}^d \bar{Q}^i H_u d_R^j$$
$$-\lambda_{ij}^u \bar{Q}^i H_d u_R^j - \lambda_{ij}^d \bar{Q}^i (\epsilon H_d^\dagger) d_R^j + h.c..$$

Liu, R-M, Shu ‘11; see also Tulin & Winslow ‘11; Cline et al ‘11

Update in progress



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Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

$\lambda_{6,7}$ = 0 for simplicity

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right] - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \mathrm{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

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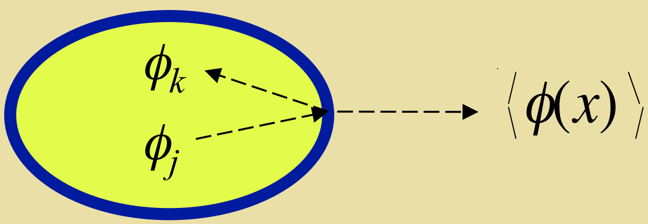

Scalar asym $\rightarrow n_L$ via Yukawa int

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

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$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right] - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

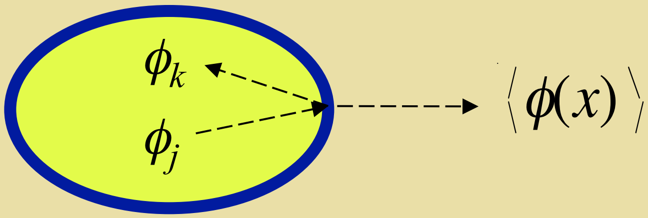
$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] ,$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]$$

EWSB →

$$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$

Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*



Scalar asym → n_L via Yukawa int

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

$\lambda_{6,7}$ = 0 for simplicity

$$V = \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}\right]$$
$$-\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \text{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.$$

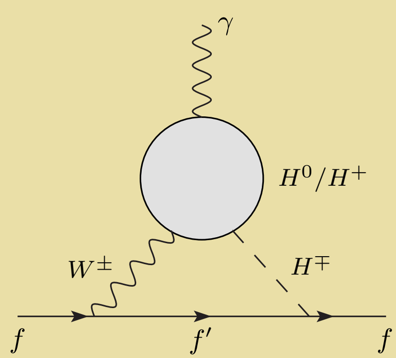
$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] ,$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right]$$

EWSB →

$$\delta_2 \approx \frac{1-\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1-2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$

Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

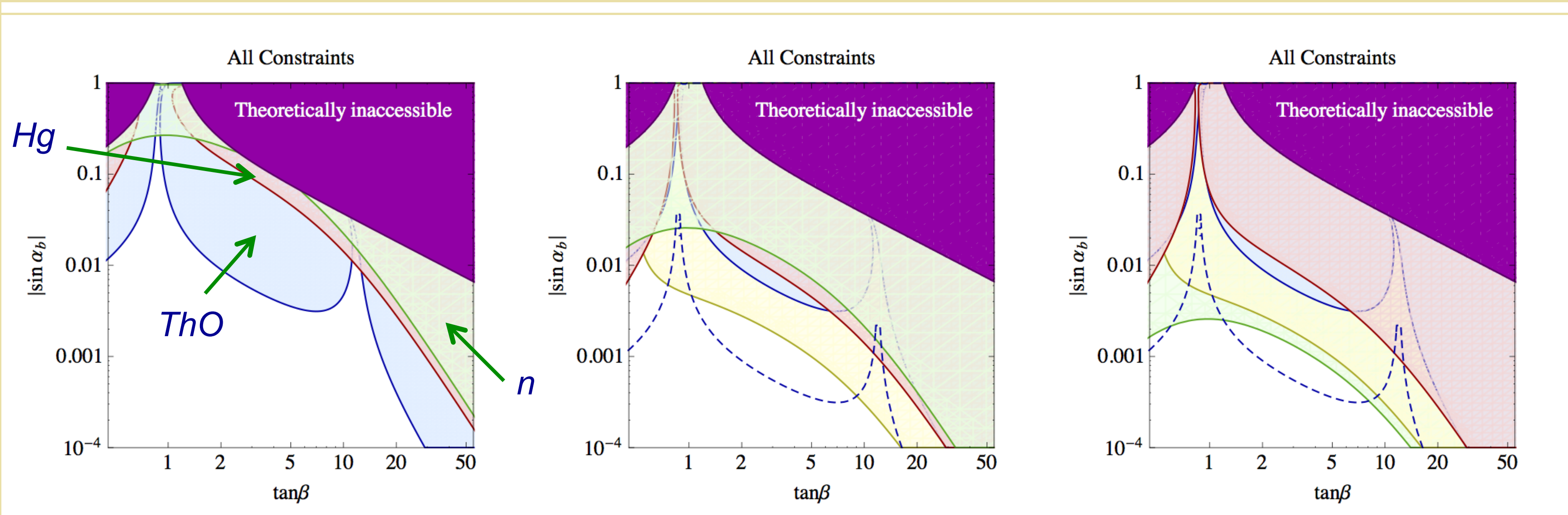


Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type II illustration

$\Lambda_{6,7}$ = 0 for simplicity



Present

sin α_b : CPV scalar mixing

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Summary

- *Origin of visible matter remains a key unsolved problem at interface of particle & nuclear physics with cosmology*

- *Weak scale baryogenesis is a viable and testable scenario: EDM/LHC meeting ground*

- *EDM & LHC results inspire us to think more creatively about history of SSB & its interplay with CPV & flavor*

Back Up Slides

Baryon Number Preservation

"Washout factor"

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

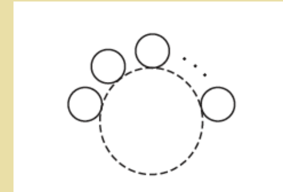
$\ln S \sim A(T_C)\, e^{\zeta}$

$\zeta = F(\varphi)$ ← $\zeta \equiv \left.\frac{\hat{E}_{\mathrm{sph}}}{T}\right|_{T=T_C}$

Two qtys of interest:

- T_C from V_{eff}
- E_{sph} from Γ_{eff}

Daisy Resummation

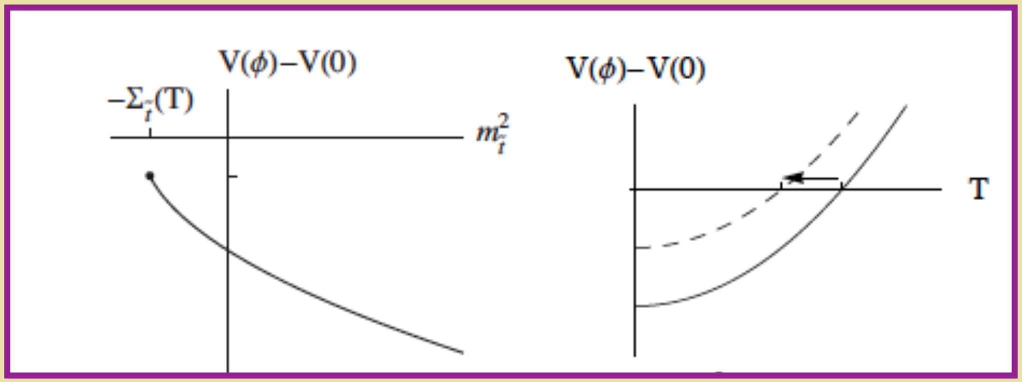


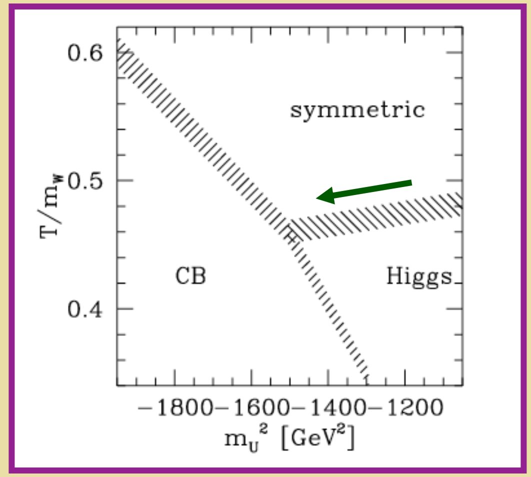
Convergence of PT: going beyond $\hbar$ expansion

Light stop scenario

Patel & R-M '11

$$V_{\rm eff}(\phi_{\rm min},T) - V_{\rm eff}(0,T) \sim -\hbar \frac{T}{12\pi}\left[\left(m_{\tilde t}^2 + y_{\tilde t}^2\phi^2 + \Sigma_{\tilde t}(T)\right)^{3/2} - \left(m_{\tilde t}^2 + \Sigma_{\tilde t}(T)\right)^{3/2}\right].$$





Csikor '00

For given T, increasingly negative $m_{\tilde t}^2$ increases difference between two minima

Increased $\Delta V \rightarrow$ Lowered T_C

SM + Color Triplet

H. Patel, R-M, Wise
1303.1140 (2013)

$$V = -\mu_H^2(H^\dagger H) - \mu_C^2(C^\dagger C) + \frac{\lambda_H}{2}(H^\dagger H)^2 + \frac{\lambda_C}{2}(C^\dagger C)^2 + \lambda_{HC}(H^\dagger H)(C^\dagger C)\,.$$

Decays: C $\rightarrow$ <C> = v_C : *B violation*

$$L_Y = C\bar{u}_R g_{uL} L_L + C\bar{Q}_L g_{Qe} e_R + \text{h.c.}\,.$$

SM + Color Triplet

H. Patel, R-M, Wise 1303.1140 (2013)

$$V = -\mu_H^2(H^\dagger H) - \mu_C^2(C^\dagger C) + \frac{\lambda_H}{2}(H^\dagger H)^2 + \frac{\lambda_C}{2}(C^\dagger C)^2 + \lambda_{HC}(H^\dagger H)(C^\dagger C)\,.$$

Upper bound on m_C:

$$m_h^2 = 2\mu_H^2 = 2\lambda_H v_H^2 \;>\; 0$$
$$m_C^2 = -\mu_C^2 + \lambda_{HC} v_H^2 \;>\; 0$$

$$m_C < \left(\sqrt{\lambda_{HC}}\right) v_H \simeq (174\,\mathrm{GeV})\sqrt{\lambda_{HC}}$$

SM + Color Triplet + Singlet

H. Patel, R-M, Wise 1303.1140 (2013)

$$\Delta V = -\frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{HC} (H^\dagger H)(C^\dagger C) + \frac{\lambda_{HS}}{2} (H^\dagger H) S^2 + \frac{\lambda_{CS}}{2} (C^\dagger C) S^2 + \frac{e_S}{3} S^3 + e_C C^\dagger C S + e_H H^\dagger H S\,.$$

Heavier colored scalar

$$m_C^2 = -\mu_C^2 + \lambda_{HC} v_H^2 + \frac{\lambda_{CS}}{2} v_S^2 + e_C v_S$$

New Direction: Flavored CPV & EWB

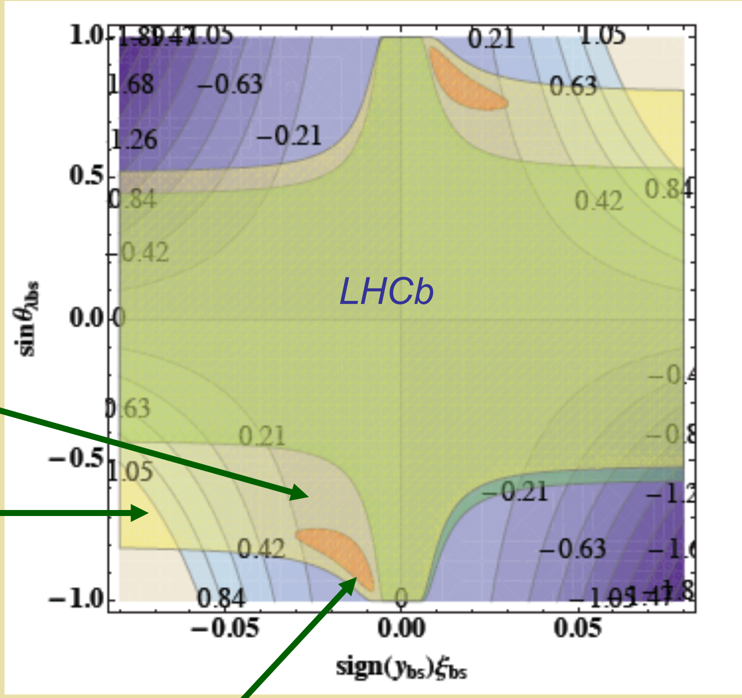
CPV & 2HDM

$$\mathcal{L} = -y^u_{ij}\bar{Q}^i(\epsilon H_u^\dagger)u^j_R - y^d_{ij}\bar{Q}^i H_u d^j_R$$
$$-\lambda^u_{ij}\bar{Q}^i H_d u^j_R - \lambda^d_{ij}\bar{Q}^i(\epsilon H_d^\dagger)d^j_R + h.c..$$

Liu, R-M, Shu ‘11; see also Tulin & Winslow ‘11; Cline et al ‘11

Tevatron w/o same-sign $A^{\mu\mu}$

constant n_B / s



Tevatron: same-sign $A^{\mu\mu}$ included

Viable EWB & CPV:

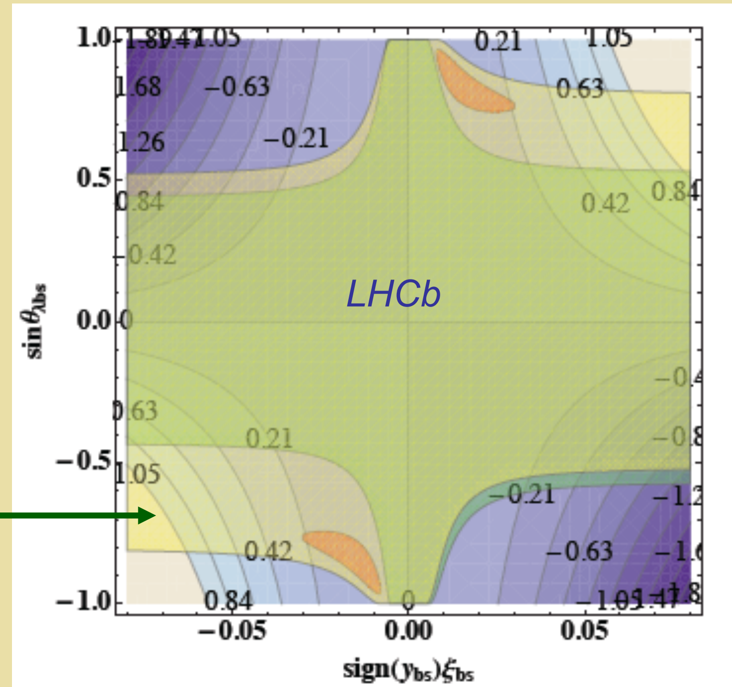
- *EDMs are 2-loop*
- *CPV is flavor non-diag*

New Direction: Flavored CPV & EWB

CPV & 2HDM

$$\mathcal{L} = -y^u_{ij}\bar{Q}^i(\epsilon H_u^\dagger)u_R^j - y^d_{ij}\bar{Q}^i H_u d_R^j$$
$$-\lambda^u_{ij}\bar{Q}^i H_d u_R^j - \lambda^d_{ij}\bar{Q}^i(\epsilon H_d^\dagger)d_R^j + h.c..$$

Liu, R-M, Shu ‘11; see also Tulin & Winslow ‘11; Cline et al ‘11



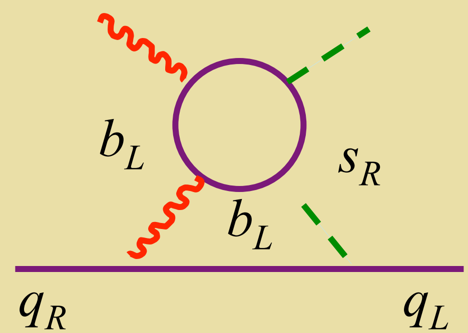
constant n_B / s →

Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

Wrong flavor & chiral structure for EDM

$$\frac{\zeta^2_{bs}}{\Lambda^2_{bs}}(\bar{b}_L s_R)(\bar{b}_L s_R)$$



Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Spontaneously & softly broken global U(1) $< S > \neq 0$

$$V_{HS} = \frac{\delta_2}{2} H^\dagger H |\tilde{S}|^2 = \frac{\delta_2}{2} H^\dagger H (S^2 + A^2)$$

Controls Ω_{CDM}, T_C, & H-S mixing

$$V_{\tilde{S}} = \frac{b_2}{2} |\tilde{S}|^2 + \frac{b_1}{2} \tilde{S}^2 + \mathrm{c.c.} + \cdots$$

Gives non-zero M_A

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Consequences:

Three scalars: h_1 , h_2 : *mixtures of h & S*

A : dark matter

Phenomenology:

- *Produce* h_1 , h_2 *w/ reduced* σ
- *Reduce BR* ($h_j \rightarrow$ *SM*)
- *Observation of BR (invis)*
- *Possible obs of* σ^{SI}

Collision Terms: Transfer Reactions

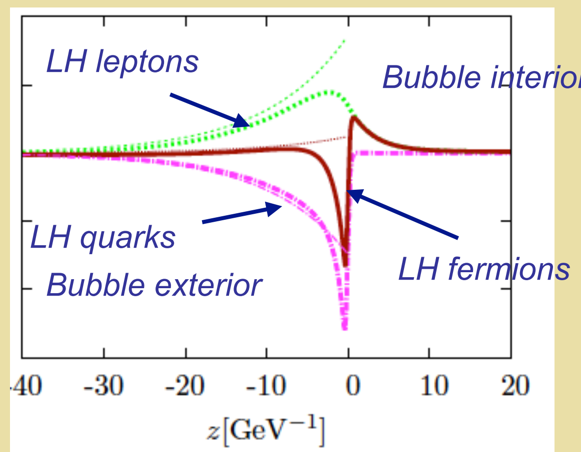
Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2\,k\cdot\partial_X\,G^{<}(k,X) = -i\left[M^2(X), G^{<}(k,X)\right] - 2\left[k\cdot\Sigma, G^{<}(k,X)\right] + \Lambda\left[G(k,X)\right]$$

MSSM: ~ 30 Coupled Eqns

$$\partial_\mu \tilde{t}^\mu = -\Gamma_Y^{(\tilde{t},\tilde{q},H_1)}\left(\frac{\tilde{t}}{k_{\tilde{t}}} - \frac{\tilde{q}}{k_{\tilde{q}}} - \frac{H_1}{k_{H_1}}\right) - \Gamma_Y^{(\tilde{t},\tilde{q},H_2)}\left(\frac{\tilde{t}}{k_{\tilde{t}}} - \frac{\tilde{q}}{k_{\tilde{q}}} - \frac{H_2}{k_{H_2}}\right) + S_{\tilde{t}}^{\not{CP}}$$
$$- \Gamma_Y^{(\tilde{t},q,\tilde{H})}\left(\frac{\tilde{t}}{k_{\tilde{t}}} - \frac{q}{k_q} - \frac{\tilde{H}}{k_{\tilde{H}}}\right) - \Gamma_{\tilde{V}}^{(t,\tilde{t})}\left(\frac{\tilde{t}}{k_{\tilde{t}}} - \frac{t}{k_t}\right) - \Gamma_M^{(\tilde{t},\tilde{q})}\left(\frac{\tilde{t}}{k_{\tilde{t}}} - \frac{\tilde{q}}{k_{\tilde{q}}}\right)$$



MSSM: Chung, Garbrecht, R-M, Tulin '09

Higgs Portal CPV

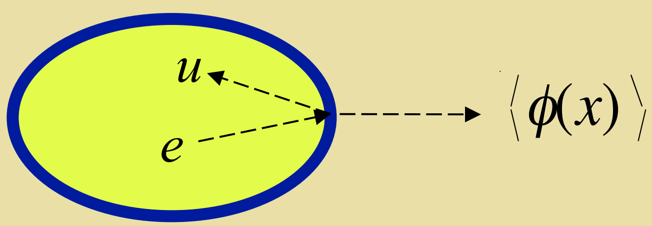
R-M, White, Winslow in progress

Color breaking

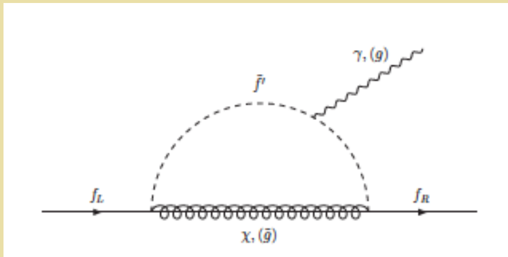
Decays: C $\to$ <C> = υ_C *: B violation*

$$L_Y = C \bar{u}_R g_{uL} L_L + C \bar{Q}_L g_{Qe} e_R + \mathrm{h.c.}\,.$$

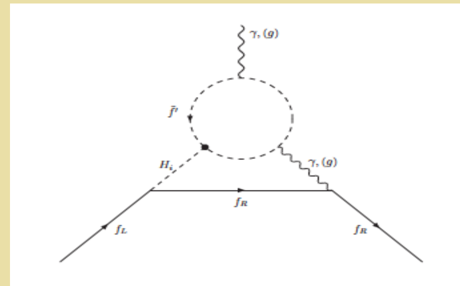
CPV phases



EDM Probes: EWB Implications



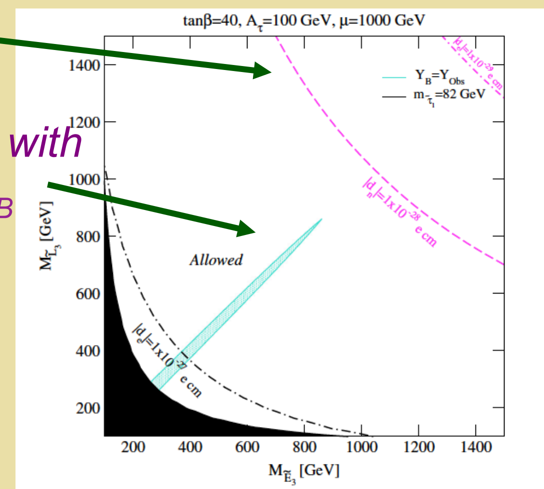
Light staus: LHC consistent & suppress 1-loop EDMs



No CEDM (^{199} Hg): EWB-viable but $m_H \rightarrow$ New scalars for EWPT

Next gen d_n

Compatible with observed Y_B



Viable EWB & CPV:

- *EDMs are 2-loop*
- *CPV is flavor non-diag*

Kozaczuk, Wainwright, Profumo, RM

Theoretical Issues

Gauge-dependence in $V_{EFF}(\varphi , T)$

$$V_{EFF}(\varphi , T) \rightarrow V_{EFF}(\varphi , T ; \xi)$$

Ongoing research: approaches for carrying out tractable, GI computations

- *H. Patel & MRM, JHEP 1107 (2011) 029*
- *C. Wainwright, S. Profumo, MRM Phys Rev. D84 (2011) 023521*
- *H. Gonderinger, H. Lim, & MRM, arXiv:1202.1316*

Origin of Gauge Dependence

Effective Action

$$\Gamma[\phi_{\rm cl}(x)] = W[j] - \int d^4x\, j(x)\phi_{\rm cl}(x)$$

$$W[j] = -i \ln Z[j]$$

$$Z[j] = \int \mathcal{D}\phi\, \mathcal{D}A\, \mathcal{D}\eta\, \mathcal{D}\eta^\dagger e^{i\int d^dx\left[\mathcal{L}(x;j,\xi)\right]}$$

Source term:

$$\int\ d^dx\ j(x)\phi(x)$$

Not GI

Effective Potential

$$\phi_{\rm cl}(x) \to \phi_{\rm cl} \quad \longrightarrow \quad \Gamma(\phi_{\rm cl}) = -({\rm vol})\, V_{\rm eff}(\phi_{\rm cl})$$

Nielsen Identities

Identity:

$$\frac{\partial\Gamma}{\partial\xi} = \int d^d x\, d^d y \Big[C(\phi, A;\, x, y) \frac{\delta\Gamma}{\delta\phi(x)} + E^a_\mu(\phi, A;\, x, y) \frac{\delta\Gamma}{\delta A^a_\mu(x)} \Big]$$

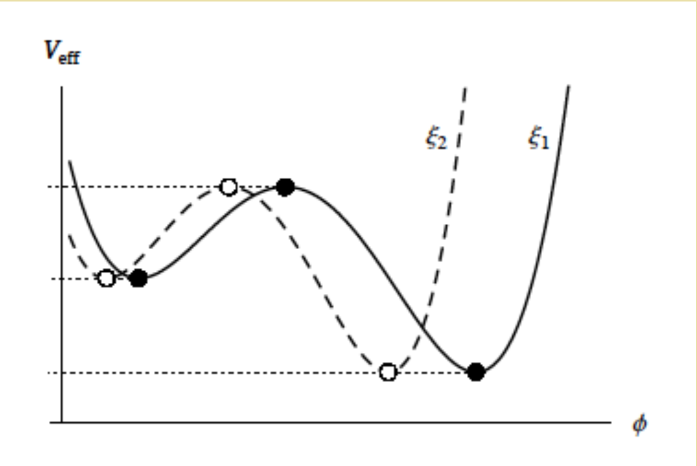
Extremal configurations:

$$\delta\Gamma/\delta\phi(x) = \delta\Gamma/\delta A^a_\mu(x) = 0 \longrightarrow \frac{\partial\Gamma}{\partial\xi} = 0$$

Effective potential:

$$\phi \to \phi_{\min}(\xi) \longrightarrow$$

$$\frac{\partial V_{\rm eff}}{\partial\xi} = -\tilde{C}(\phi,\xi) \frac{\partial V_{\rm eff}}{\partial\phi} = 0$$



Baryon Number Preservation

"Washout factor"

$$S \equiv \rho_B(\Delta t_{\rm EW})/\rho_B(0) > e^{-N}$$

ln S ~ A(T$_C$) e $^{\zeta}$

$$\zeta = F(\varphi) \longleftarrow \zeta \equiv \frac{\hat{E}_{\rm sph}}{T}\Big|_{T=T_C}$$

Two qtys of interest:

- T_C from V_{eff}
- E_{sph} from Γ_{eff}

Baryon Number Preservation: Pert Theory

$$S \equiv \rho_B(\Delta t_{\mathrm{EW}})/\rho_B(0) > e^{-N}$$

$\zeta = F(\varphi)$

Conventional treatments

$$\frac{\varphi(T_C)}{T_C} \gtrsim 1$$

Gauge Dep

"Baryon number preservation criterion" (BNPC)

H. Patel & MRM, JHEP 1107 (2011) 029

Baryon Number Preservation: Pert Theory

$$S \equiv \rho_B(\Delta t_{\rm EW})/\rho_B(0) > e^{-N}$$

$\zeta = F(\varphi)$

Conventional treatments

~~$\frac{\varphi(T_C)}{T_C} \gtrsim 1$~~

Gauge Dep

- GI T_C from hbar exp, $V_{eff}(\phi^+\phi)$, or Hamiltonian formulation
- Use GI scale in E_{sph} computation

"Baryon number preservation criterion" (BNPC)

H. Patel & MRM, JHEP 1107 (2011) 029

Nielsen Identities: Application to T_C

Critical Temperature

$$V_{eff}(\varphi_{min}, T_C) = V_{eff}(0, T_C)$$

Fukuda & Kugo '74: T=0 V_{EFF}
Laine '95 : 3D high-T Eff Theory
Patel & R-M '11: Full high T Theory

Apply consistently order-by-order in $\hbar$

$$V_{\rm eff}(\phi, T) = V_0(\phi) + \hbar\, V_1(\phi, T) + \hbar^2\, V_2(\phi, T) + \ldots$$

$$\phi_{\rm min} = \phi_0 + \hbar\, \phi_1(T, \xi) + \hbar^2\, \phi_2(T, \xi) + \ldots$$

Implement minimization order-by-order (defines ϕ_n)

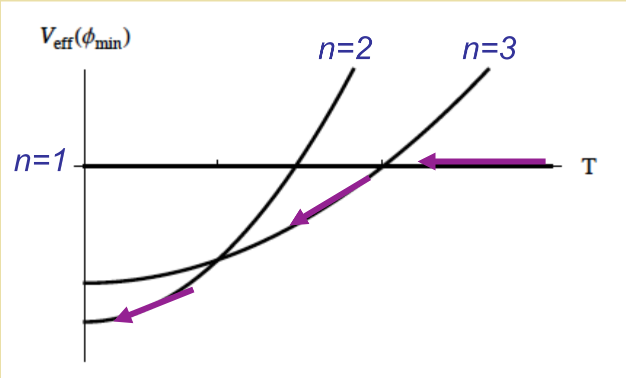
$$V_{\rm eff}[\phi_{\rm min}(T),\, T] = V_0(\phi_0) + \hbar V_1(\phi_0, T)$$

$$+\ \hbar^2 \left[V_2(\phi_0, T, \xi) - \tfrac{1}{2}\phi_1(T, \xi)\, \frac{\partial^2 V_0}{\partial \phi^2}|_{\phi_0} \right] + \mathcal{O}(\hbar^3)$$

Obtaining a GI T_C

Patel & R-M '11

Track evolution of minima with T using $\hbar$ expansion



Track evolution of different minima with T using

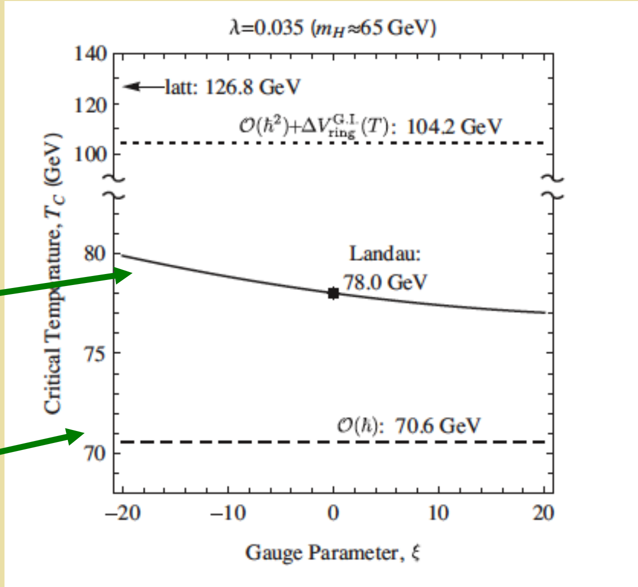
$$V_{\rm eff}\left[\phi_{\rm min}^{(n)}(T),\, T\right] = V_0\left[\phi_0^{(n)}\right] + \hbar V_1\left[\phi_0(n), T\right]$$

Illustrative results in SM:

$$V_{\rm eff}(\phi_{\rm min}(T),\, T) = V_0(\phi) + \hbar V_1(\phi, T)$$

Full ϕ

$$V_{\rm eff}[\phi_{\rm min}(T),\, T] = V_0(\phi_0) + \hbar V_1(\phi_0, T)$$



Theoretical Issues

Systematic Transport Theory

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

CTP or Schwinger-Keldysh Green's functions

$$\tilde{G}(x,y) = \left\langle P\varphi_a(x)\varphi_b^*(y)\right\rangle \boldsymbol{\tau}_{ab} = \begin{bmatrix} G^t(x,y) & -G^<(x,y) \\ G^>(x,y) & -G^{\bar{t}}(x,y) \end{bmatrix}$$

- *Appropriate for evolution of "in-in" matrix elements*
- *Contain full info on number densities: $n_{\alpha\beta}$*
- *Matrices in flavor space: (e,μ,τ) , $(\tilde{t}_L, \tilde{t}_R)$, …*

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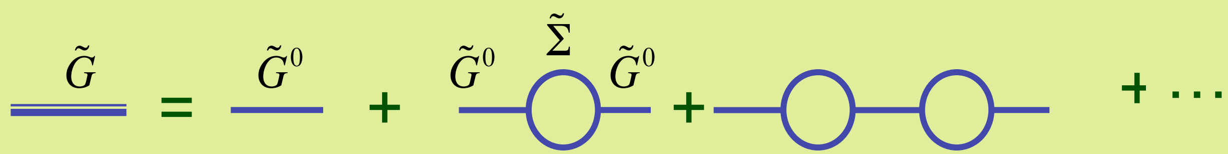

Systematic Baryo/leptogenesis:

Scale Hierarchies $\rightarrow$ *power counting*

EW Baryogenesis

Gradient expansion

$\varepsilon_w = v_w (k_w / \omega) << 1$

Quasiparticle description

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

Thermal, but not too dissipative

$\varepsilon_{coll} = \Gamma_{coll} / \omega << 1$

Plural, but not too flavored

$\varepsilon_{osc} = \Delta\omega / T << 1$

Leptogenesis

Gradient expansion

$\varepsilon_{LNV} = \Gamma_{LNV} / \Gamma_H < 1$

Quasiparticle description

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

Thermal, but not too dissipative

$\varepsilon_{coll} = \Gamma_{coll} / \omega << 1$

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

Lowest non-trivial order in grad's

$$2k\cdot\partial_X\ G^{<}(k,X) = -i\left[M^2(X), G^{<}(k,X)\right] - 2\left[k\cdot\Sigma, G^{<}(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

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$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k\cdot\Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Diagonal after rotation to local mass basis:

$$M^2(X) = U^+\, m^2(X)\, U$$

$$\Sigma_\mu(X) = U^+\, \partial_\mu\, U$$

$(\tilde{t}_L, \tilde{t}_R) \to (\tilde{t}_1, \tilde{t}_2)$

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2\,k\cdot\partial_X\;G^<(k,X) = -i\left[M^2(X),G^<(k,X)\right] - 2\left[k\cdot\Sigma,G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

Flavor oscillations: flavor off-diag densities

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k \cdot \partial_X \, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k \cdot \Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

Systematic Baryo/leptogenesis:

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields

How large is CPV source ? Riotto; Carena et al; Prokopec et al; Cline et al; Konstandin et al; Cirigliano et al; Kainulainen….

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

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CPV in $m^2(X)$: for EWB, arises from spacetime varying complex phase(s) generated by interaction of background field(s) (Higgs vevs) with quantum fields ✔

Resonant enhancement of CPV sources for small ε_{osc}

✔ *= recent progress*

Cirigliano et al

CPV Sources: EW Baryogenesis

CPV Sources: how large a $\sin\phi_{CPV}$ necessary ?

Kinetic eq (approx) in Wigner space:

$$2k \cdot \partial_X G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - \boxed{2\left[k \cdot \Sigma, G^<(k,X)\right]} + \Lambda\left[G(k,X)\right]$$

VEV insert approx

- *Riotto*
- *Carena et al*
- *Cirigliano et al*

Large resonant enhancement but not realistic in small ε_{osc} regime

Resummed vevs

- *Konstandin, Prokpec, Schmidt*

Small resonant effect but neglected diffusion and off-diag $\Sigma_{ii}\, G_{ij}$ terms

Resummed vevs

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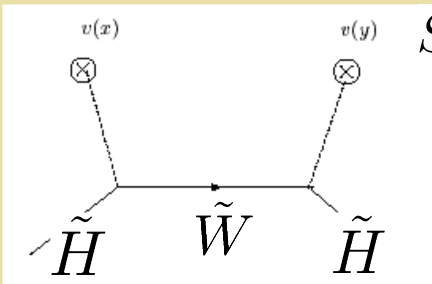
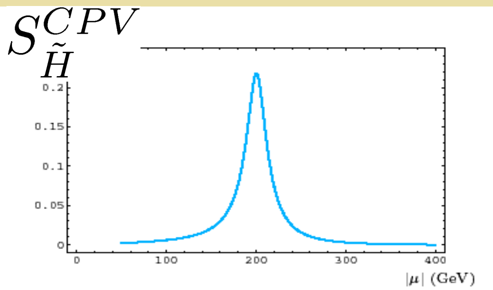
Exact solution in two-flavor toy model: large resonant enhancement

CPV Sources: EW Baryogenesis

CPV Sources: how large a sinϕ_{CPV} necessary ?





$$\Sigma, G^{<}(k,X)\Big] + \Lambda\big[G(k,X)\big]$$

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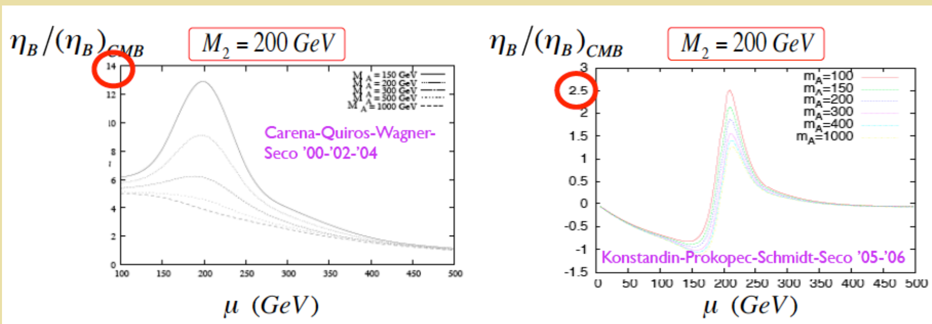

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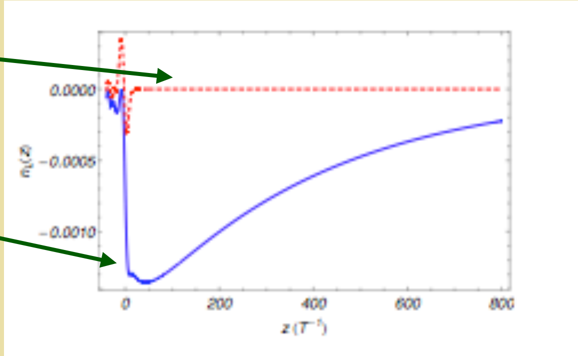
Neglect o-d $\Sigma_{ii}\, G_{ij}$ terms & approx Λ

Full solution



VEV insert approx

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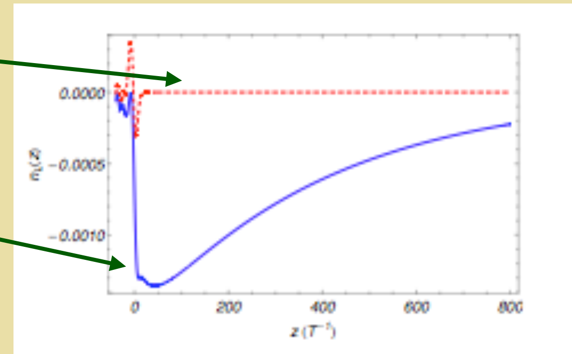

Next steps:

1. *Apply to realistic model (MSSM)*
2. *Fermions*

ed vevs

Resummed vevs

- *Riotto*
- *Carena et al*
- *Cirigliano et al*

- *Konstandin, Prokpec, Schmidt*

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Small resonant effect but neglected diffusion and off-diag Σ_{ii} G_{ij} terms

Exact solution in two-flavor toy model: large resonant enhancement

Systematic Baryo/leptogenesis:

Formalism: Kadanoff-Baym to Boltzmann

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EW Baryogenesis

$\Gamma_Y(\tilde{Q} \to t\tilde{H})$ — $A^{CP}{}_{BSM} \to A^{CP}{}_{SM}$

$\Gamma_V(\tilde{Q} \to Q\tilde{V})$ — *"Superequilibrium"*

$\Gamma_D(\tilde{Q} + q \to \tilde{Q} + q)$ — *Diffusion*

Collision Terms: Transfer Reactions

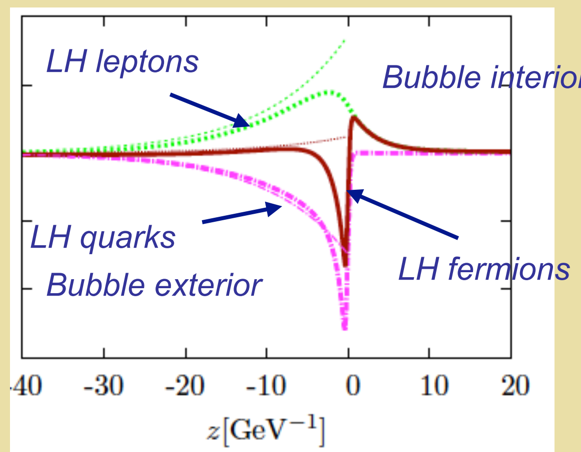
Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k \cdot \partial_X \, G^<(k,X) = -i\left[M^2(X), G^<(k,X)\right] - 2\left[k \cdot \Sigma, G^<(k,X)\right] + \Lambda\left[G(k,X)\right]$$

MSSM: ~ 30 Coupled Eqns

$$\partial_\mu \widetilde{t}^\mu = -\Gamma_Y^{(\widetilde{t},\widetilde{q},H_1)}\left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}} - \frac{H_1}{k_{H_1}}\right) - \Gamma_Y^{(\widetilde{t},\widetilde{q},H_2)}\left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}} - \frac{H_2}{k_{H_2}}\right) + S_{\widetilde{t}}^{\not{CP}}$$
$$- \Gamma_Y^{(\widetilde{t},q,\widetilde{H})}\left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{q}{k_q} - \frac{\widetilde{H}}{k_{\widetilde{H}}}\right) - \Gamma_{\widetilde{V}}^{(t,\widetilde{t})}\left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{t}{k_t}\right) - \Gamma_M^{(\widetilde{t},\widetilde{q})}\left(\frac{\widetilde{t}}{k_{\widetilde{t}}} - \frac{\widetilde{q}}{k_{\widetilde{q}}}\right)$$



MSSM: Chung, Garbrecht, R-M, Tulin '09

Collision Terms: Transfer Reactions

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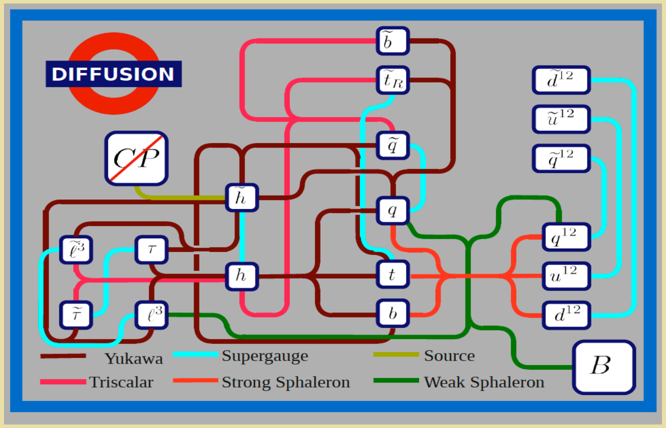
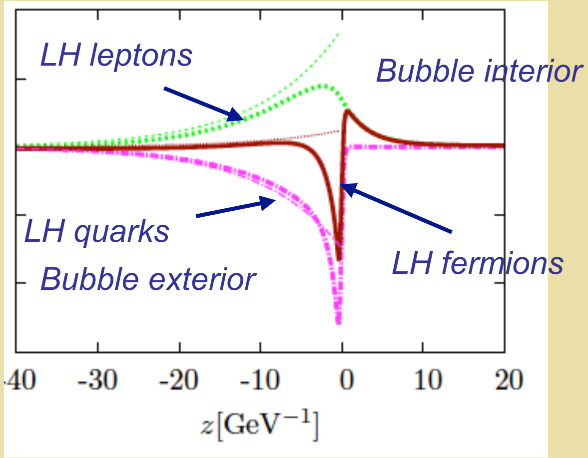


Thanks: B. Garbrecht



MSSM: Chung, Garbrecht, R-M, Tulin '09

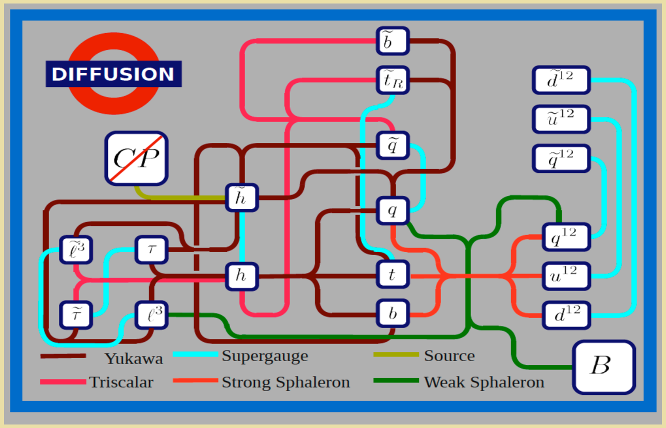
Solving the Transport Equations: MSSM

Formalism: Kadanoff-Baym to Boltzmann

Kinetic eq (approx) in Wigner space:

$$2k\cdot\partial_X\, G^<(k,X) = -i\left[M^2(X),G^<(k,X)\right] - 2\left[k\cdot\Sigma,G^<(k,X)\right] + \boxed{\Lambda\left[G(k,X)\right]}$$

MSSM: ~ 30 Coupled Eqns



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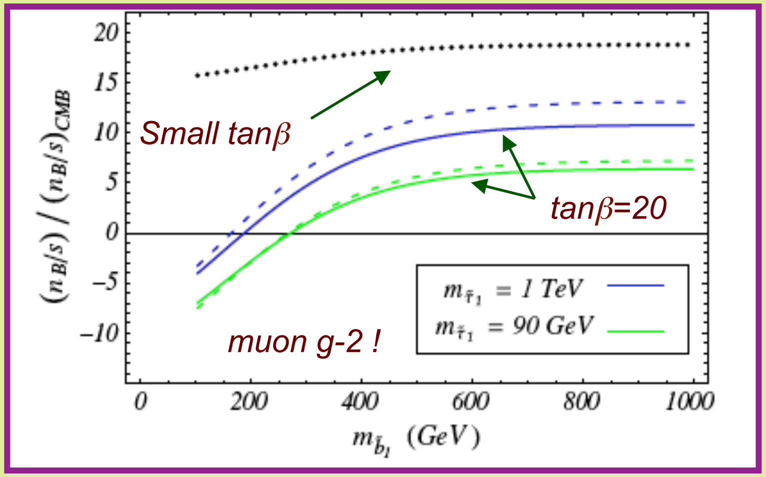

Chung, Garbrecht, R-M, Tulin