T-Violation & Baryogenesis

M.J. Ramsey-Musolf

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/

ACFI TRV Workshop
December 2018

Themes for This Talk

- *So far, connecting tests of TR invariance in neutron physics with the baryon asymmetry has focused on the neutron EDM*
- *In this context, the neutron EDM provides an important probe that complements information from paramagnetic systems and diamagnetic atoms*
- *Non-observations of EDMs place severe – but not fatal – constraints on baryogenesis scenarios at the TeV scale & below*
- *There is room for more thought about connections with other neutron TR tests*

Goals for This Talk

- *Provide a general context for interpreting EDM experiments*
- *Illustrate the interplay of EDM searches with TeV scale & below baryogenesis scenarios*
- *Invite discussion*

Outline

I. *EDM's: The SM & BSM context*

II. *The Cosmic Matter-Antimatter Asymmetry*

III. *Electroweak Baryogenesis: Examples*

IV. *Post-sphaleron Baryogenesis*

V. *Outlook*

I. EDMs: The SM & BSM Context

EDMs & SM Physics

$$d_n^{SM} \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + d_n^{CKM}$$

EDMs & SM Physics

$$d_n^{SM} \sim (10^{-16}\ e\ cm)\ x\ \ \theta_{QCD} + d_n^{CKM}$$

$$d_n^{CKM} = (1 - 6)\ x\ 10^{-32}\ e\ cm$$

C. Seng arXiv: 1411.1476

EDMs & SM Physics

$$d_n^{SM} \sim (10^{-16}\ e\ cm)\ \times\ \theta_{QCD} + d_n^{CKM}$$

$$d_n^{CKM} = (1 - 6) \times 10^{-32}\ e\ cm^{*}$$

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* $3.3 \times 10^{-33}\ e\ cm < d_p < 3.3 \times 10^{-32}\ e\ cm$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f\, F$$

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \boxed{\sin\phi}\ \times\ y_f\ F$$

CPV Phase: large enough for baryogenesis ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f\ F$$

BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \times\ (\upsilon / \Lambda)^2\ \times\ \sin\phi\ \times\ y_f F$$

BSM dynamics: perturbative? Strongly coupled?
Dependence on other parameters ?

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm) \times \boxed{(\upsilon / \Lambda)^2} \times \boxed{\sin\phi} \times \boxed{y_f F}$$

Need information from at least three "frontiers"

EDMs & BSM Physics

$$d \sim (10^{-16}\ e\ cm)\ \ x\ \boxed{(\upsilon / \Lambda)^2}\ x\ \boxed{\sin\phi}\ x\ \boxed{y_f F}$$

Need information from at least three "frontiers"

- *Baryon asymmetry* — *Cosmic Frontier*
- *High energy collisions* — *Energy Frontier*
- *EDMs* — *Intensity Frontier*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-33}	10^{-29}
ThO	1.1×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

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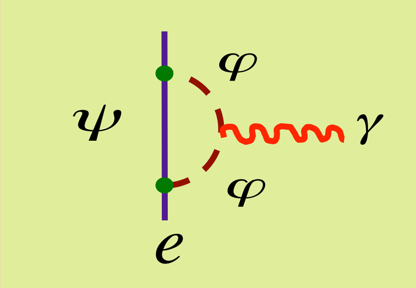
Mass Scale Sensitivity



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

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

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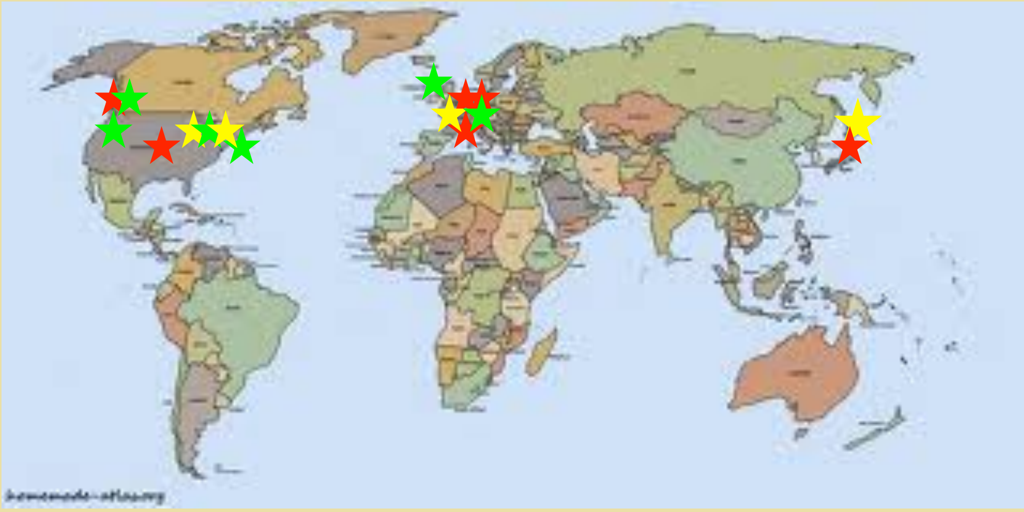

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

Not shown: muon

EDMs: New CPV?

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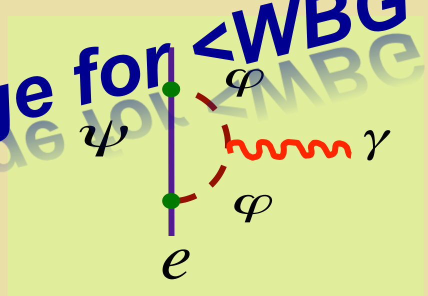
Mass Scale Sensitivity

Challenge for <WBG



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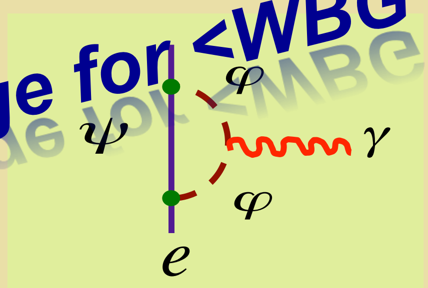

- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
- ***CPV is "partially secluded"***
- ***CPV is vector-like***

EDMs: New CPV?

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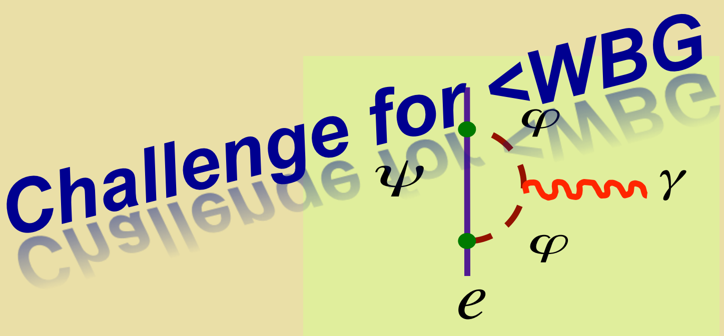

This talk

- ***EDMs arise at > 1 loop***
- ***CPV is flavor non-diagonal***
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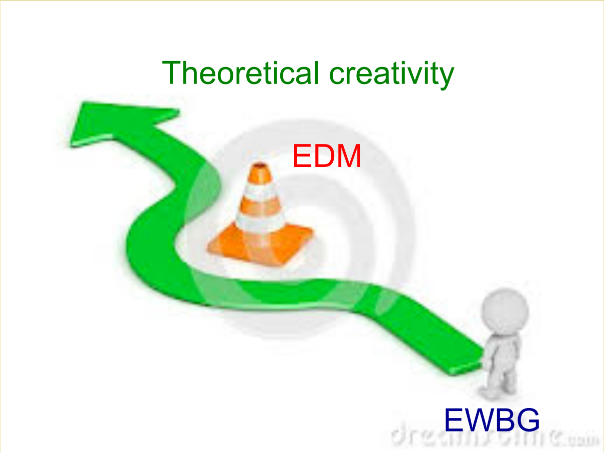
- ***CPV is vector-like***

CPV for <WBG



II. The Matter-Antimatter Asymmetry

Cosmic Baryon Asymmetry

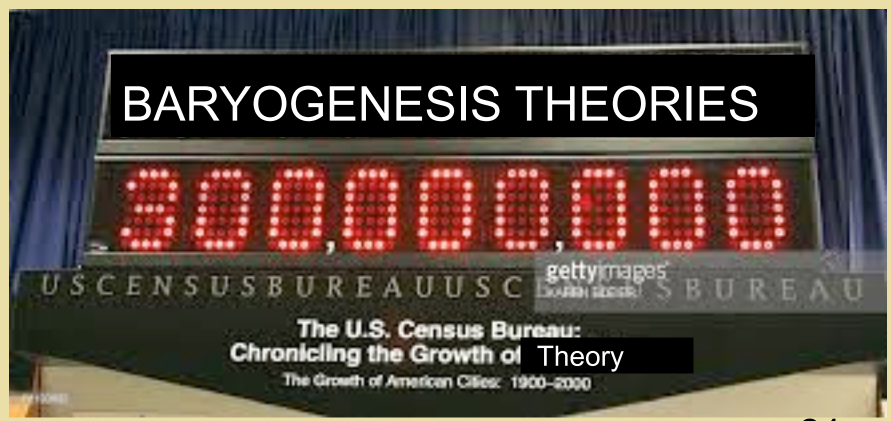
$$Y_B = \frac{n_B}{s} = (8.82 \pm 0.23) \times 10^{-11}$$

One number $\rightarrow$ BSM Physics

Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.82 \pm 0.23) \times 10^{-11}$$

One number** $\rightarrow$ 𝍸 𝍸 𝍸 … **Explanations



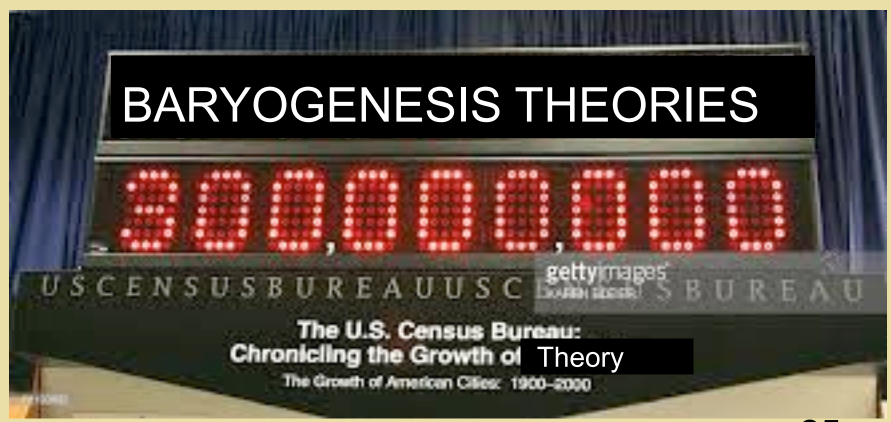
Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.82 \pm 0.23) \times 10^{-11}$$

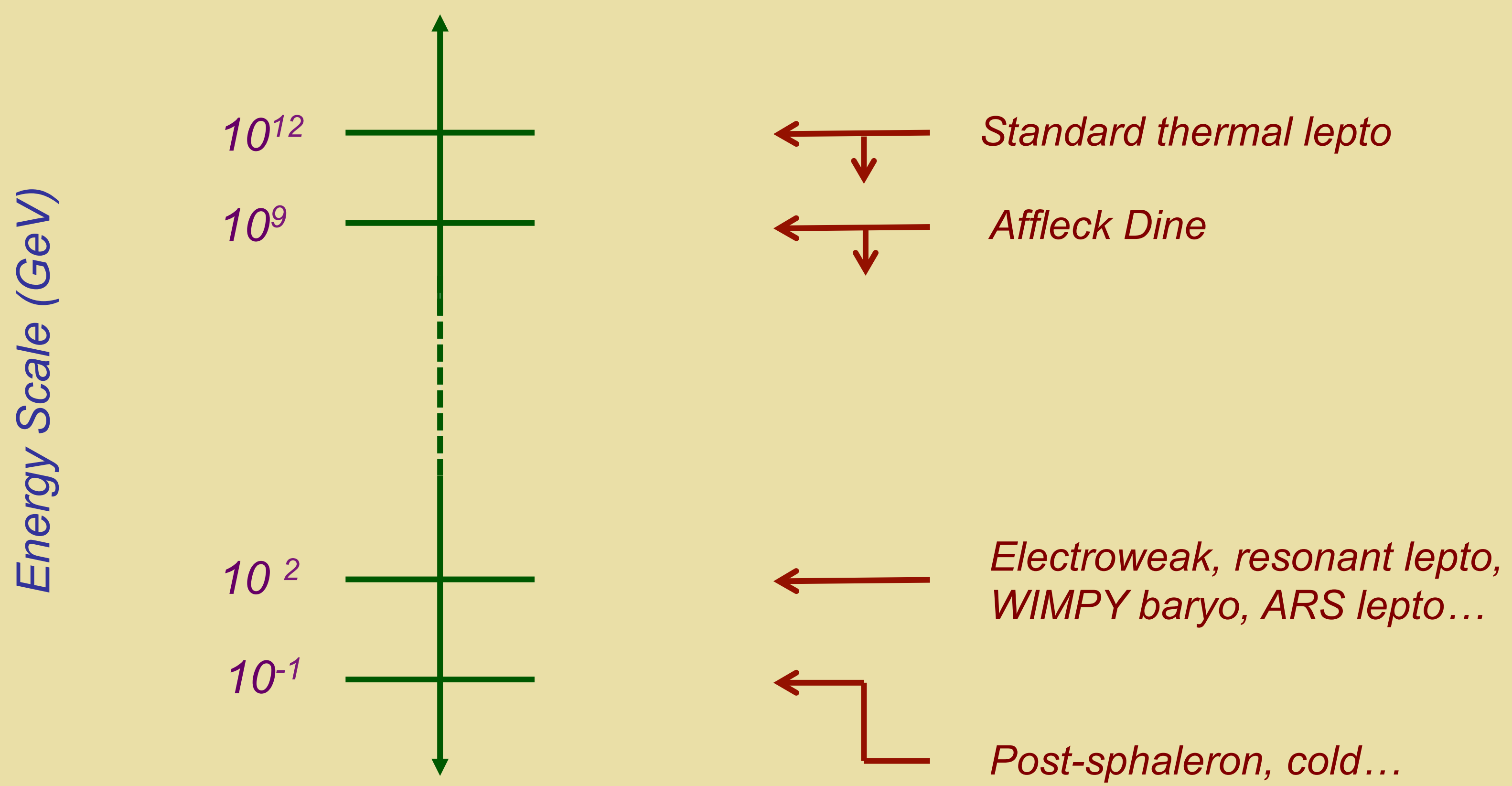
One number $\rightarrow$ 𝍸 𝍸 𝍸 … *Explanations*

Experiment can help:

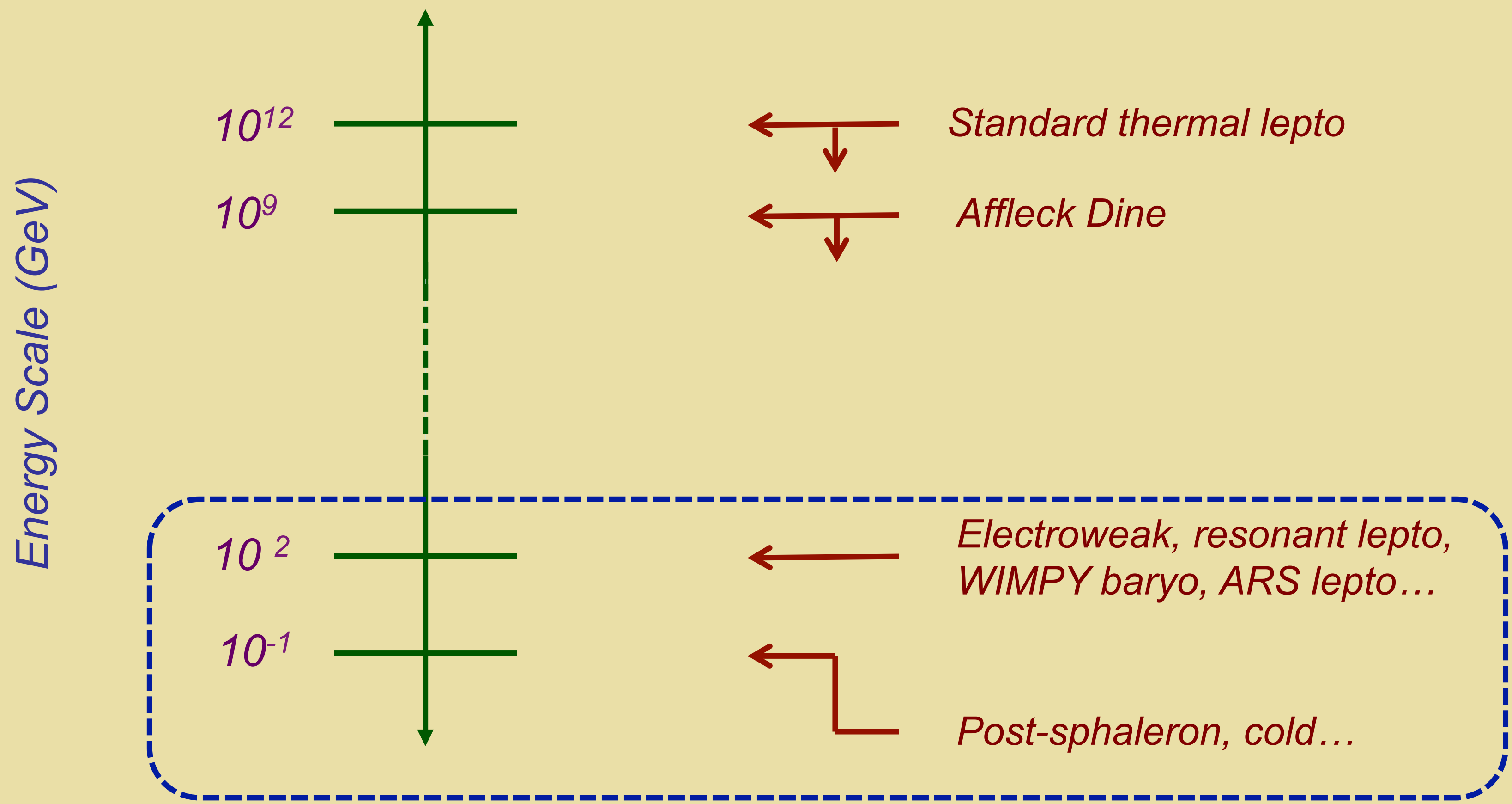
- *Discover ingredients*
- *Falsify candidates*



Baryogenesis Scenarios



Baryogenesis Scenarios



Era of EWSB: t_{univ} ~ 10 ps

Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

III. Electroweak Baryogenesis

- ***SUSY***
- ***Non-SUSY***

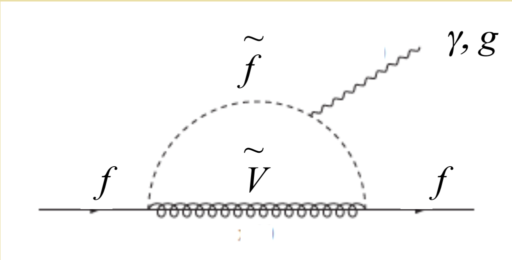
EWBG: Ingredients

- ***Strong first order EWPT:*** *LHC $\rightarrow$ Excluded for the MSSM $\rightarrow$ Possible w/ extensions (e.g., NMSSM)*
- ***CPV:*** *SUSY: Sources same as in MSSM + possible additional; non-SUSY*

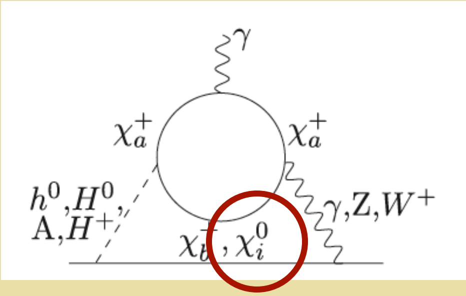
Strong 1st Order EWPT

Definitive probe of the possibilities → LHC + next generation colliders

EDMs & EWBG: MSSM + Singlets

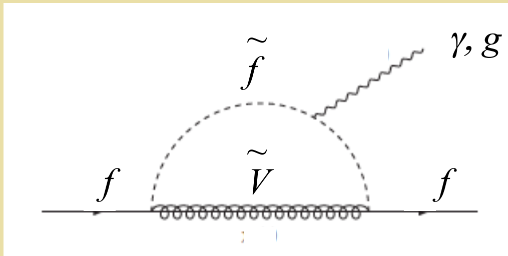


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

EDMs & EWBG: MSSM + Singlets



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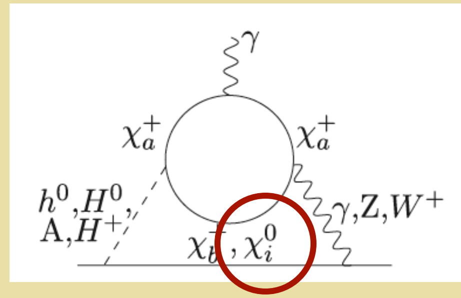
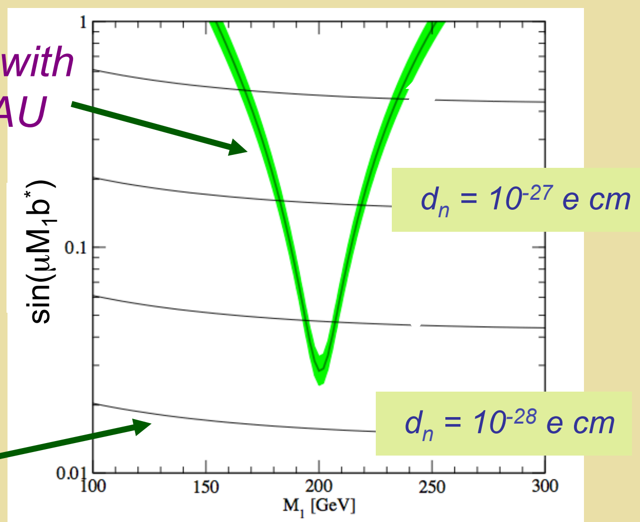
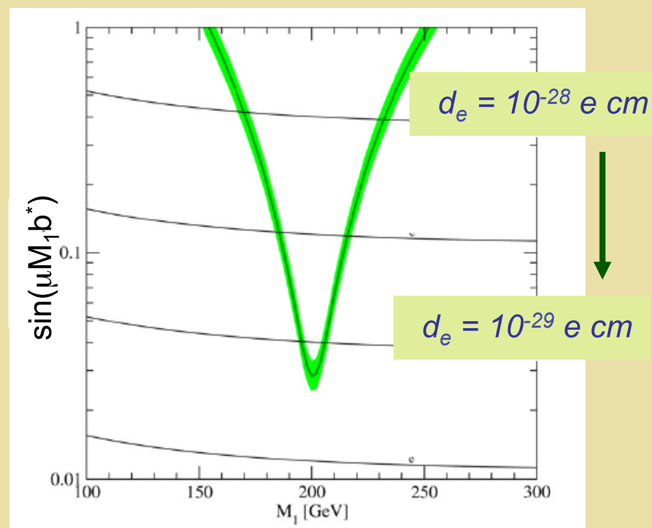


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU



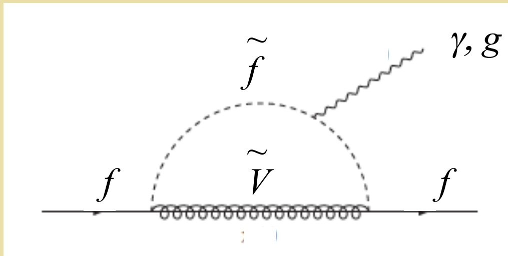
Next gen d_n



ACME: ThO

Li, Profumo, RM ‘09-’10

EDMs & EWBG: MSSM + Singlets



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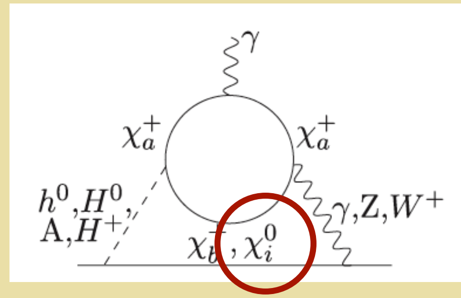

Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

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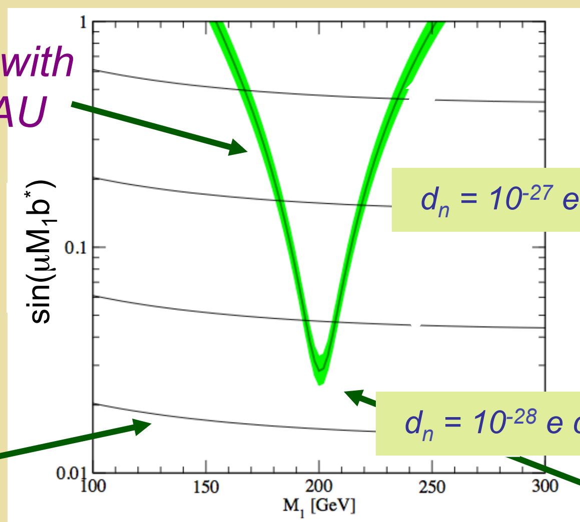
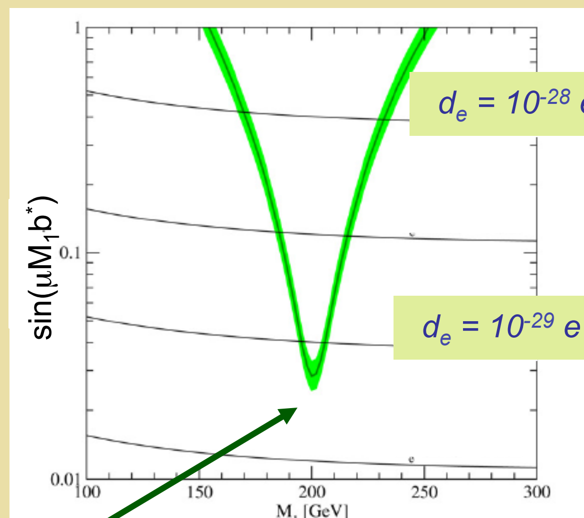


$d_n = 10^{-27}$ e cm

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

Next gen d_n



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

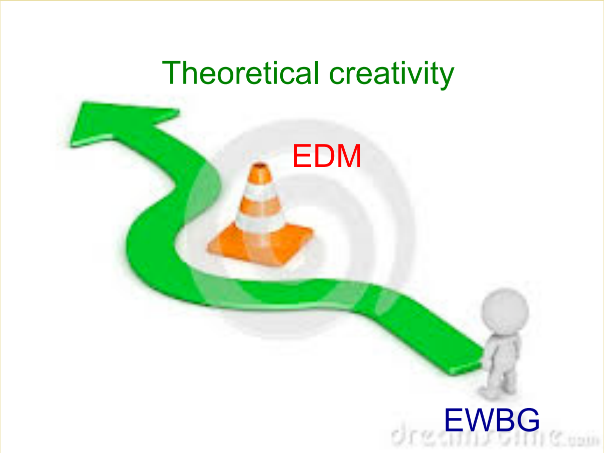
ACME: ThO

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

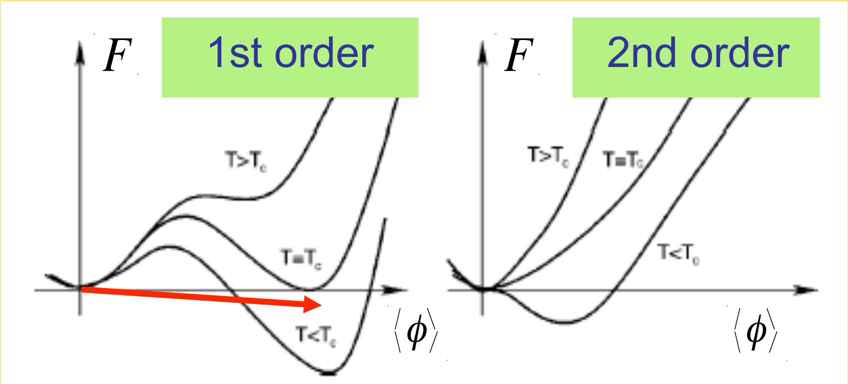
Li, Profumo, RM '09-'10

Compressed spectrum

CPV for <WBG



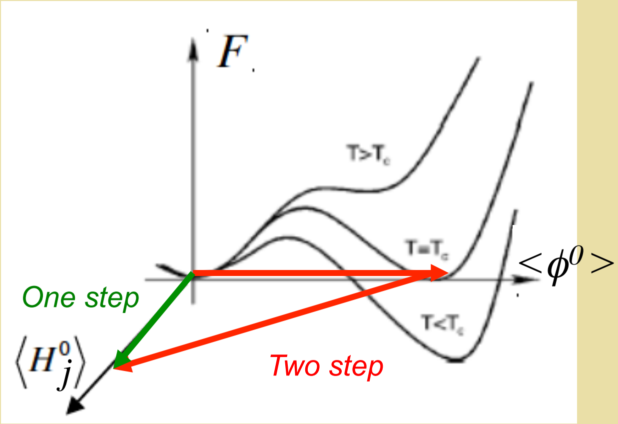
EW Multiplets: Two-Step EWPT



Increasing m_h →

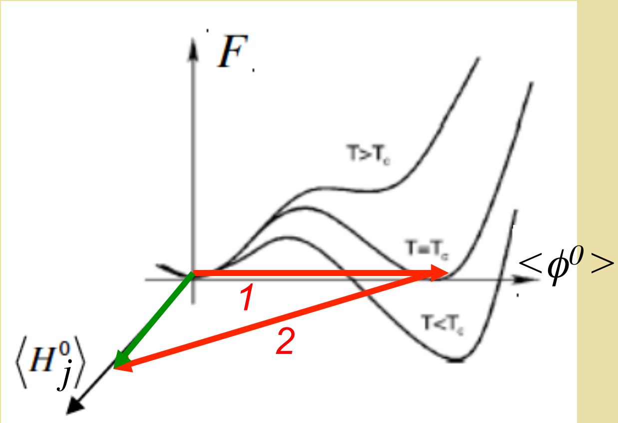
← *New scalars*

- *Step 1: EWSB along ϕ*
- *Step 2: EWSB along H*



Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1505.05195

Two-Step EW Baryogenesis



H_j — St'd Model Scalar Sector

ϕ — BSM Scalar Sector: at least one $SU(2)_L$ non-singlet plus possibly gauge singlets: "partially secluded sector CPV"

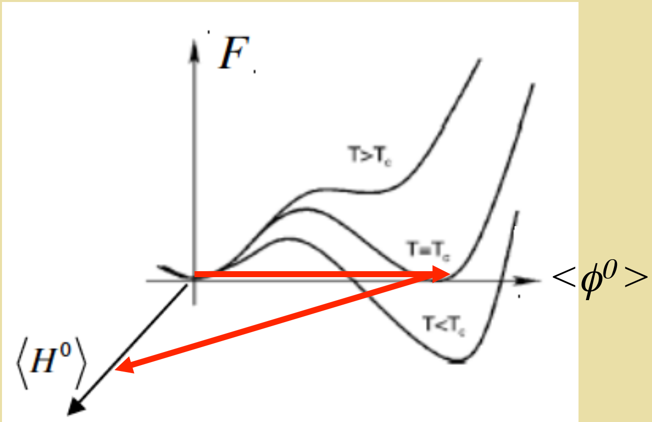
 Conventional one step EWSB

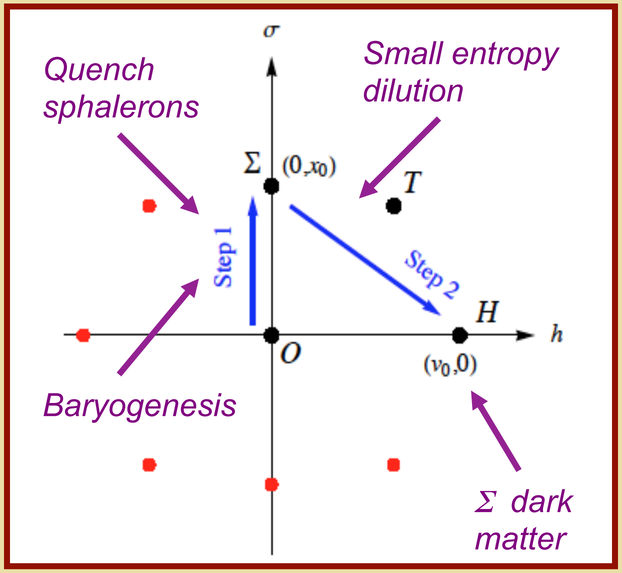
 Two step EWSB

BSM CPV in ϕ H interactions: baryogenesis during step 1

Inoue, Ovanesyan, R-M: 1508.05404;
Patel & R-M: 1212.5652; Blinov, Kozaczuk, Morrissey: 1504.05195

Two-Step EW Baryogenesis





Inoue, Ovanesyan, R-M: 1508.05404

Illustrative Model:

New sector: "Real Triplet" Σ
Gauge singlet *S*

H $\rightarrow$ *Set of "SM" fields: 2 HDM*

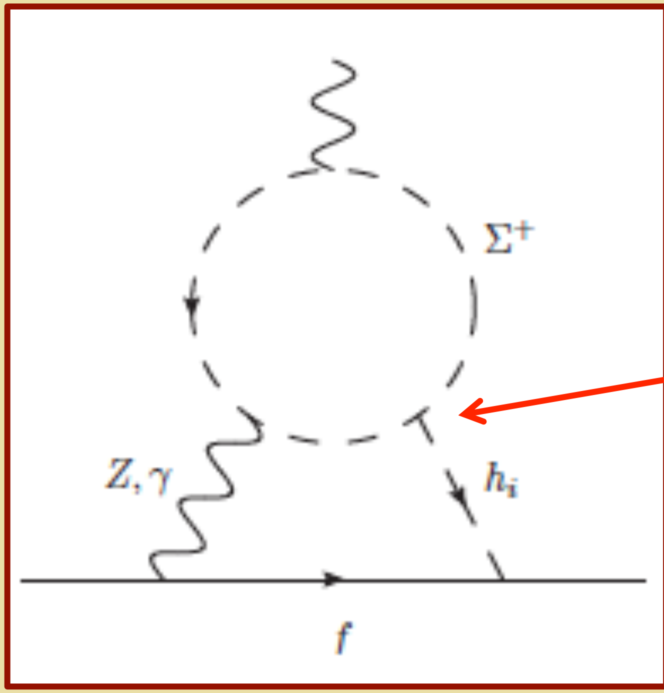
(SUSY: "TNMSSM", Coriano…)

Two CPV Phases:

δ_Σ : *Triplet phase*

δ_S : *Singlet phase*

Two-Step EW Baryogenesis & EDMs



EDMs are Two Loop

Two CPV Phases:

δ_Σ : Triplet phase

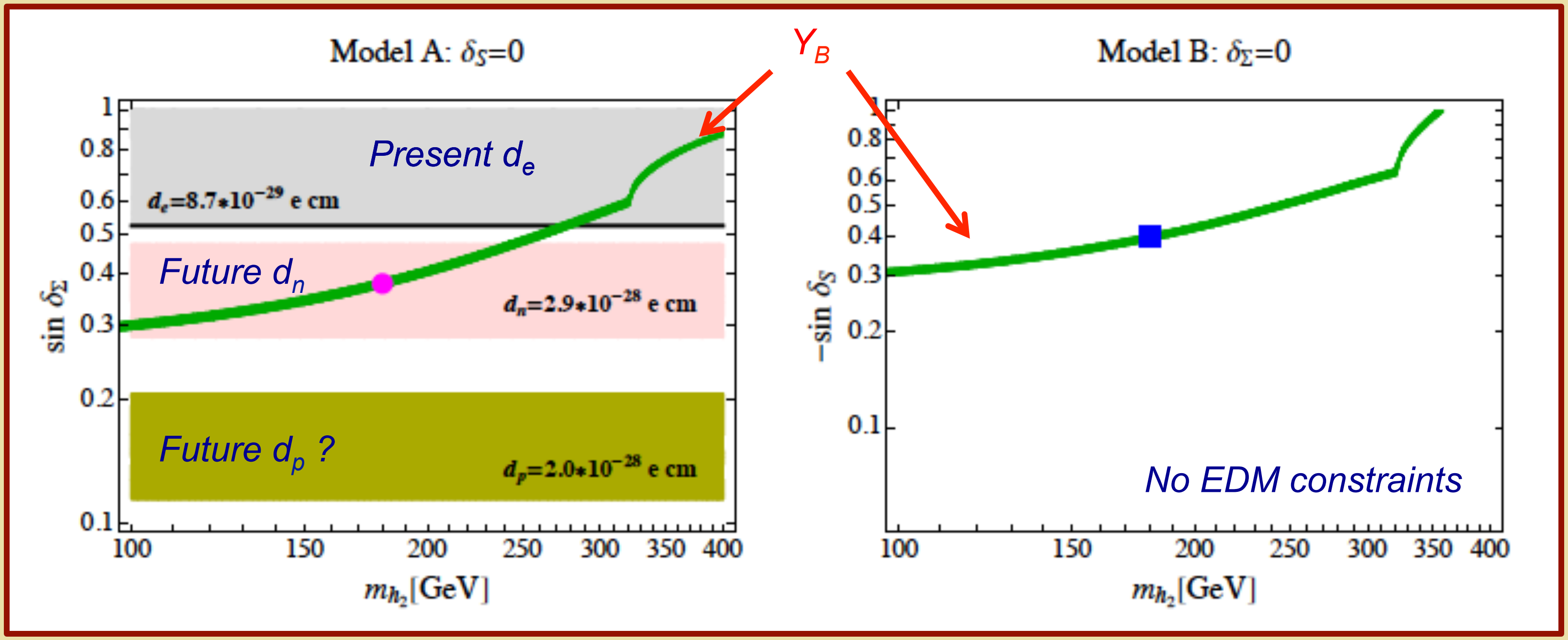
δ_S : Singlet phase

Insensitive to δ_S : electrically neutral $\rightarrow$ "partially secluded"

Inoue, Ovanesyan, R-M: 1508.05404

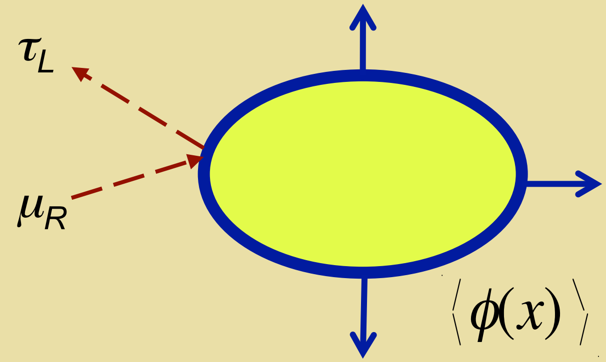
Two-Step EW Baryogenesis

Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$



Inoue, Ovanesyan, R-M: 1508.05404

Flavored EW Baryogenesis



Flavor basis (high T)

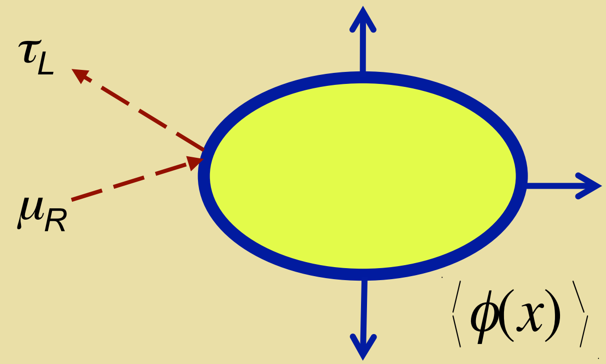
$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

Mass basis (T=0)

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis



Jarlskog invariant

$$J_A = \frac{1}{v^2 \mu_{12}^{\rm HB}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} \, \mathrm{Tr}\left[Y_c Y_a^\dagger \right]$$

T=0 Higgs couplings

Im (y_τ) ~ Im (J_A)

EWBG CPV Source

S^{CPV} ~ Im (J_A)

Flavor basis (high T)

$$\mathscr{L}_{\rm Yukawa}^{\rm Lepton} = -\overline{E_L^i}\left[(Y_1^E)_{ij} \Phi_1 + (Y_2^E)_{ij} \Phi_2 \right] e_R^j + h.c.$$

Mass basis (T=0)

CPV $h \to \tau\tau$

$$\frac{m_f}{v} \kappa_\tau (\cos\phi_\tau \bar{\tau}\tau + \boxed{\sin\phi_\tau \bar{\tau} i \gamma_5 \tau) h}$$

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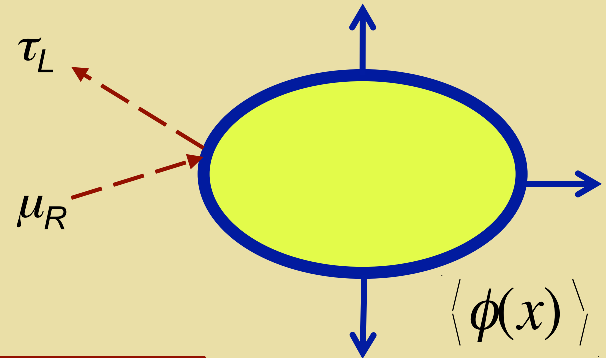
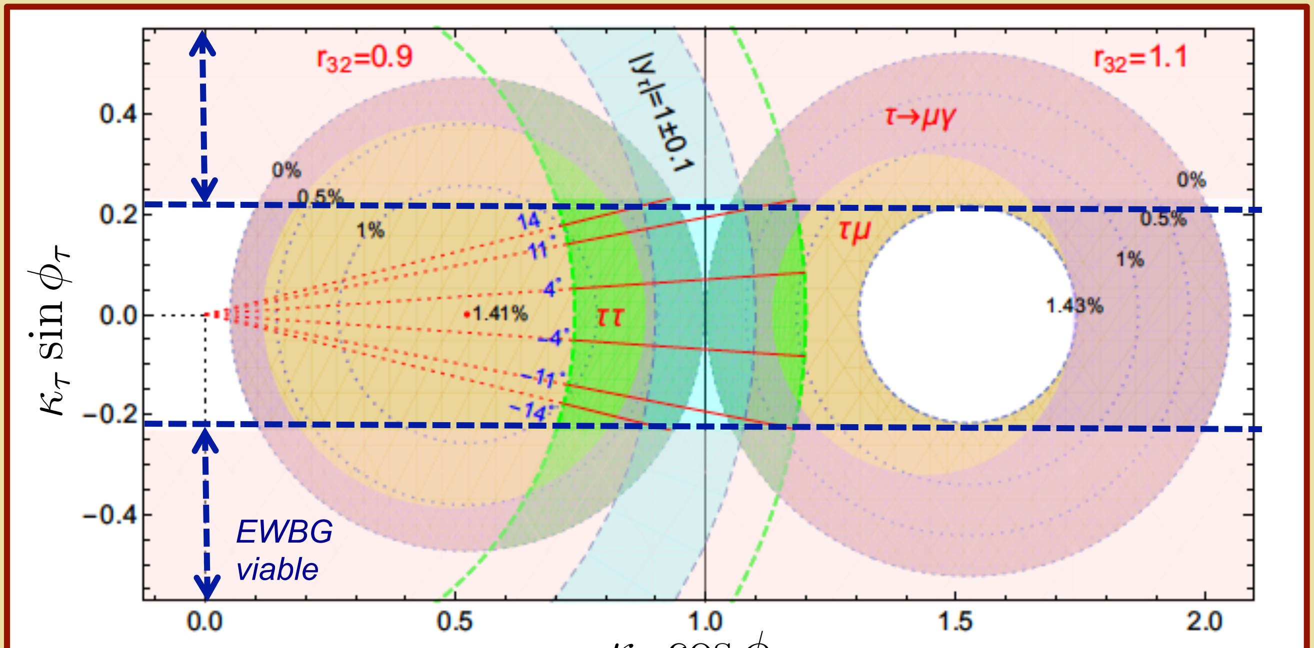




Guo, Li, Liu, R-M, Shu 1609.09849

$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14

IV. Post-Sphaleron Baryogenesis

- ***Babu, Mohapatra, Nasri '06***
- ***Babu, Dev, Fortes, Mohapatra '13***
- ***Bell, Corbett, Nee, R-M '18***

Model

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	couplings
Δ_{dd}	6	1	-2/3	$d_R d_R$
Δ_{uu}	6	1	4/3	$u_R u_R$
Δ_{ud}	6	1	1/3	$u_R d_R$
Φ	1	1	0	$\Delta_{dd}\Delta_{ud}^2,\ \Delta_{uu}\Delta_{dd}^2$

Field Content: New Scalars

$$V \supset \frac{\lambda}{2}\Phi\Delta_{dd}\Delta_{ud}^2 + \frac{\lambda'}{2}\Phi\Delta_{uu}\Delta_{dd}^2 \,.$$

Scalar Interactions

BMN original

$$\mathcal{L}_{\rm Yukawa} = \frac{h_{\alpha\beta}}{2}\bar{K}\Delta_{dd}(\bar{d}_R)_\alpha(d_R)^c_\beta + \frac{f_{\alpha\beta}}{2}\bar{K}\Delta_{uu}(\bar{u}_R)_\alpha(u_R)^c_\beta + g_{\alpha\beta}\bar{K}\Delta_{ud}(\bar{u}_R)_\alpha(d_R)^c_\beta$$

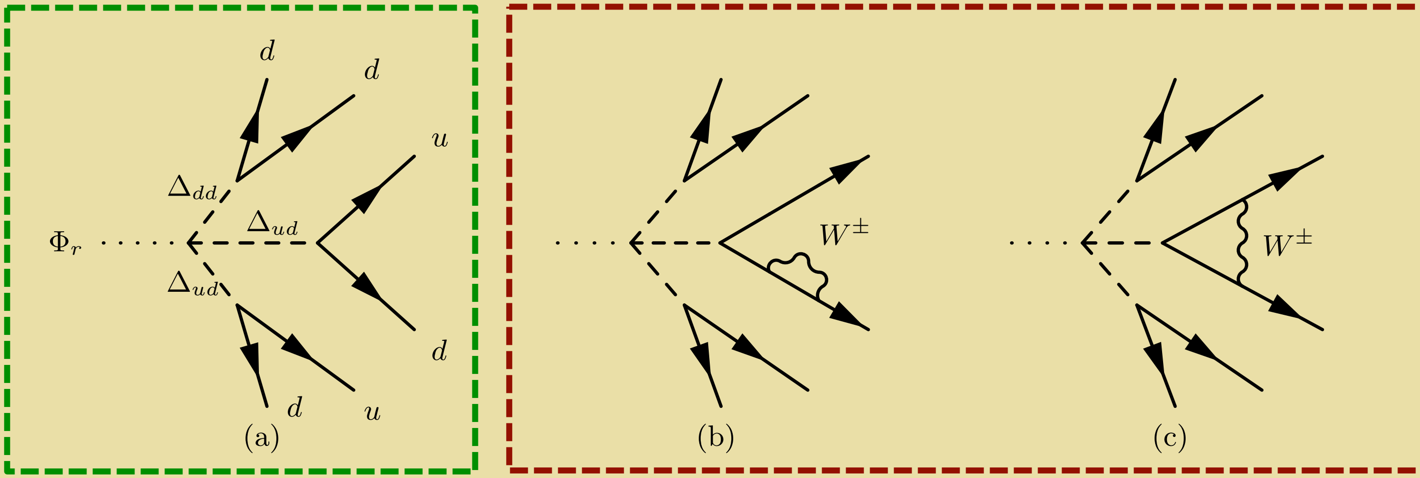
$$+ g'_{\alpha\beta}\bar{K}\Delta_{ud}\epsilon_{ij}(\bar{Q}_i)_\alpha(Q_j)^c_\beta + h.c.\,,$$

BCNR-M

Yukawa Interactions

Baryogenesis

ΔB = 2 decays



Tree-level ***X*** ***Loops: absorptive part***

Decay Asymmetry:

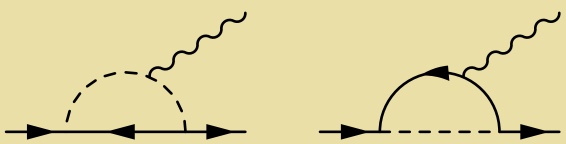
$$\epsilon = \frac{\Gamma(\Phi \to 6q) - \Gamma(\Phi \to 6\bar{q})}{\Gamma(\Phi \to 6q) + \Gamma(\Phi \to 6\bar{q})}$$

Constraints

EDMs

$$d_n = \sum_{q=u,d} \frac{v^2}{M^2_{\Delta_{ud}}} \left(\beta_n^{q\gamma}\, \mathrm{Im}[c_{q\gamma}] + \beta_n^{qG}\, \mathrm{Im}[c_{uG}] \right)$$

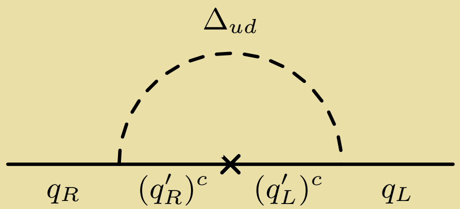
d_q



$$\bar{g}_\pi^{(i)} = \frac{v^2}{M^2_{\Delta_{ud}}} \gamma_{(i)}^{\pm G} \left(\mathrm{Im}[c_{uG}] \pm \mathrm{Im}[c_{dG}] \right)$$

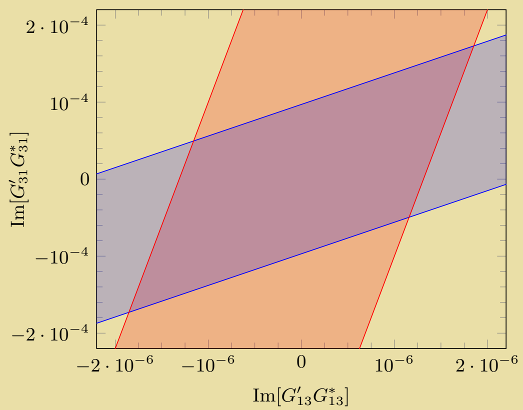
$\tilde{d}_q$

Quark mass



Baryon Asymmetry

EDM Constraints



- ***Original BMN: G' = 0 (RH quarks only)***
- ***Non-zero EDMs: G, G' non-vanishing***
- ***Largest BAU: G = 0, G' non-vanishing, EDM compatible***

BAU

	$\epsilon_{\mathrm{wave}}(M_\Phi = 8\ \mathrm{TeV})$	$\epsilon_{\mathrm{vertex}}(M_\Phi = 8\ \mathrm{TeV})$	Dilution Factor $(M_\Phi = 8\ \mathrm{TeV})$
$G_{\alpha\beta}\sim 1,\ G'_{\alpha\beta}=0$	10^{-9}	10^{-14}	10^{-2}
$G'_{\alpha\beta}\sim 1,\ G_{\alpha\beta}=0$	10^{-7}	10^{-8}	10^{-2}
$G_{\alpha\beta}\sim G'_{\alpha\beta}\sim 10^{-3}$	10^{-7}	10^{-6}	10^{-5}

IV. Outlook

- *Searches for permanent EDMs of atoms, molecules, hadrons and nuclei provide powerful probes of BSM physics at the TeV scale and above and constitute important tests of < weak scale baryogenesis*
- *Studies on complementary systems is essential for first finding and then disentangling new CPV & testing EWBG*
- *EWBG remains an important baryogenesis scenario for which definitive tests will likely require next generation EDM & collider studies***

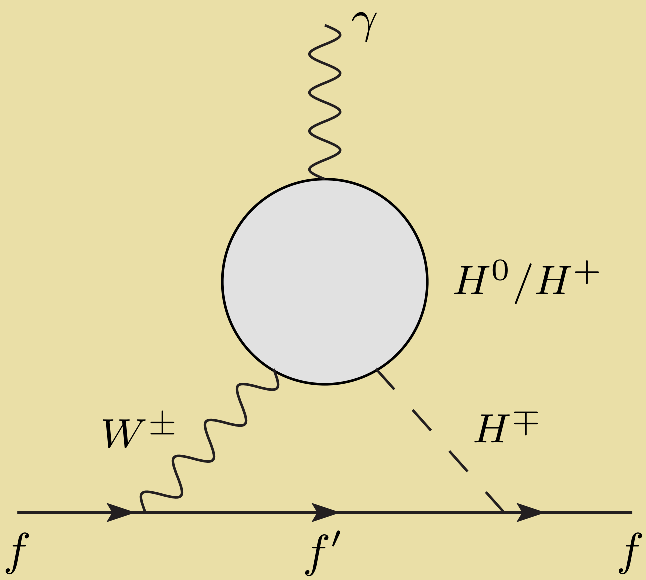
*** + gravitational waves, flavor physics*

Back Up Slides

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II



What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

- *Two Higgs doublets ?*

$$H \rightarrow H_1 \, , \, H_2$$

- *New parameters:*

$$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$$
$$\sin \alpha_b$$

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- *New parameters:*

$\tan \beta = \langle H_1 \rangle / \langle H_2 \rangle$

$\sin \alpha_b$

CPV : scalar-pseudoscalar mixing from $V(H_1, H_2)$

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

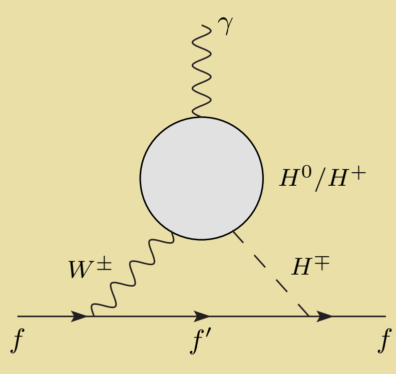
$$\delta_1 = \text{Arg}\left[\lambda_5^*(m_{12}^2)^2\right],$$
$$\delta_2 = \text{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]$$

EWSB →

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

h, H^0, A^0 → $h_{1,2,3}$

$$\begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$



Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

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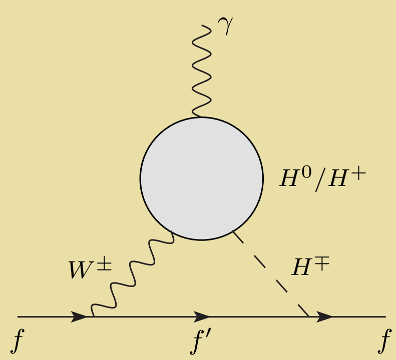
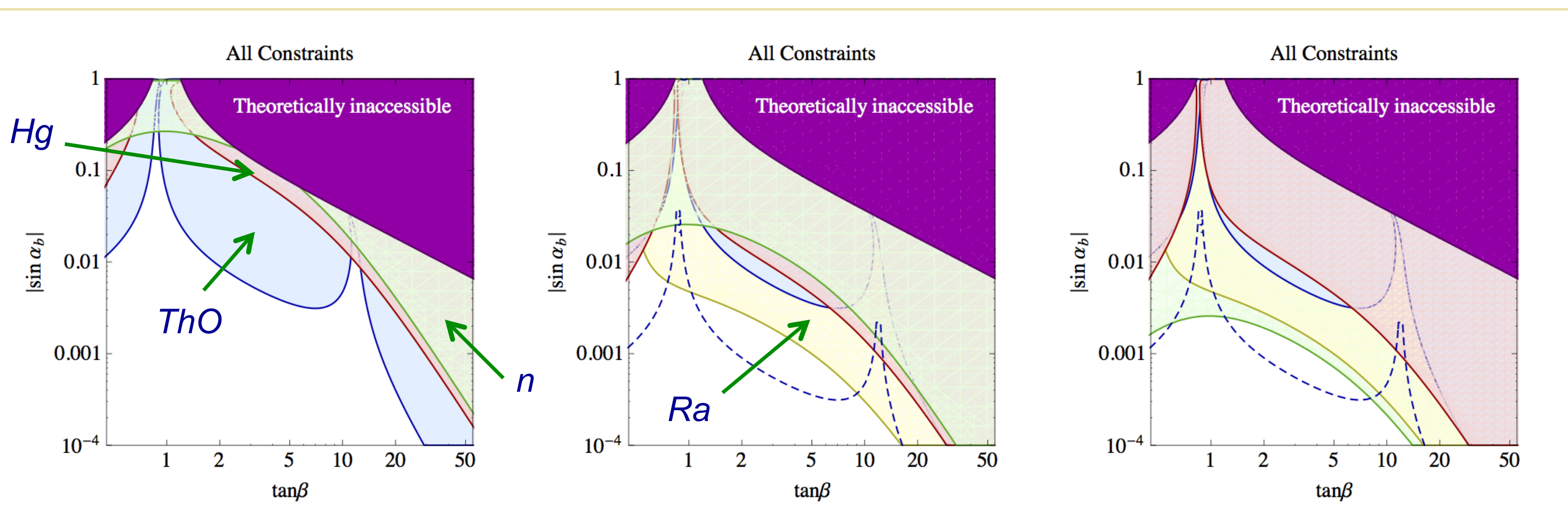


CP mixing: α_b & α_c not independent

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



Present

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra) [10^{-27} e cm]

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

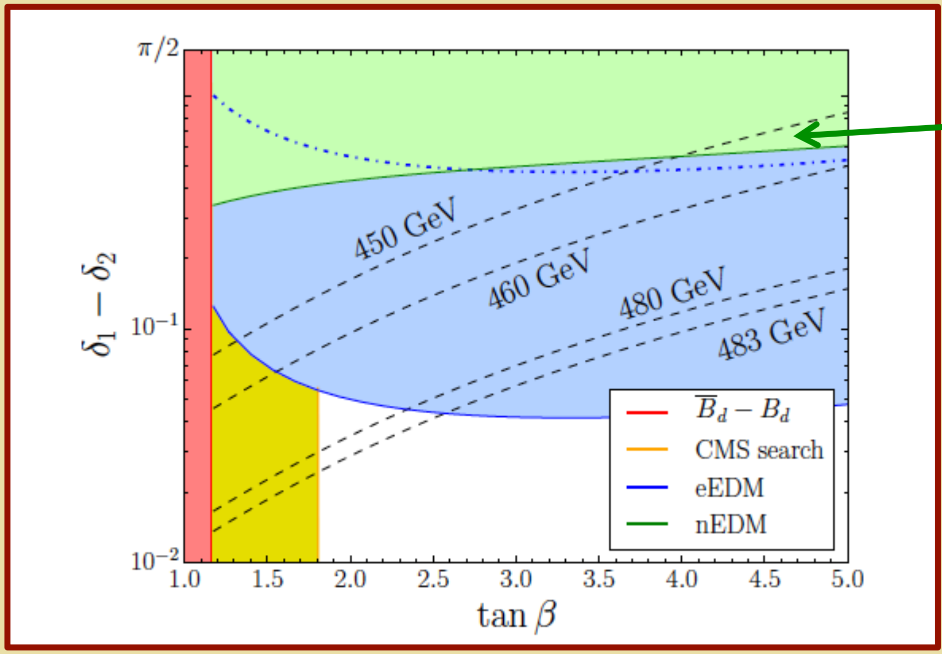
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Low-Energy / High-Energy Interplay

Higgs Portal CPV: Source for EWBG?

Dorsch et al, 1611.05874

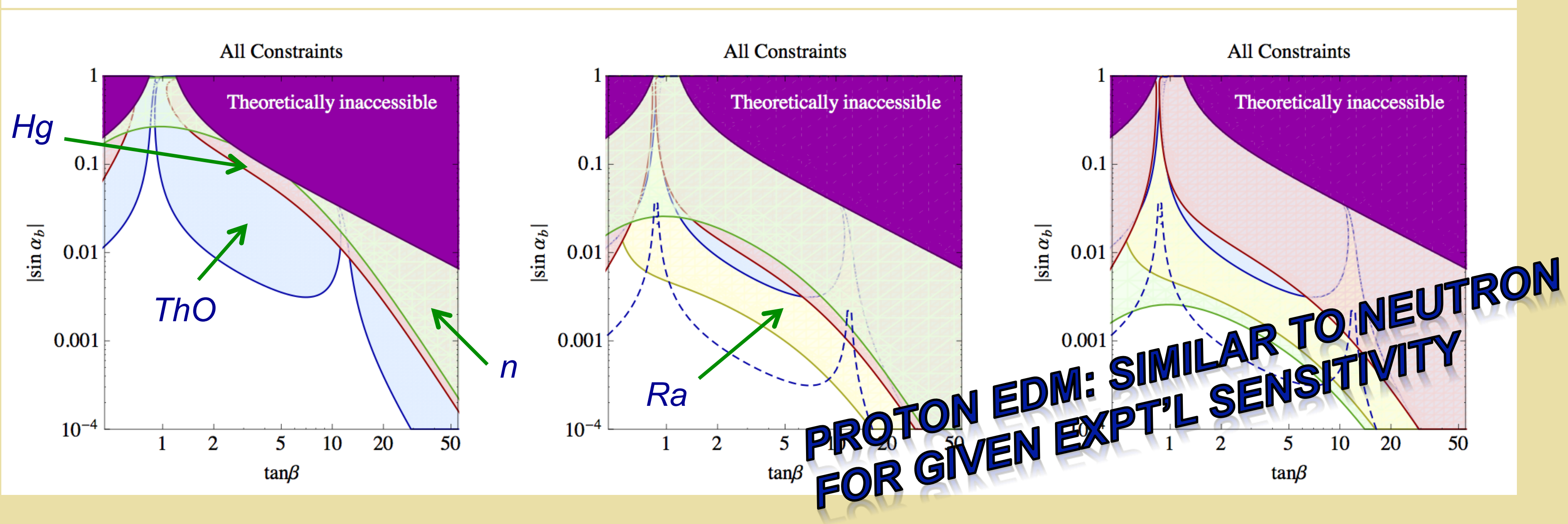


EWBG viable

$\alpha_b \propto \delta_1 - \delta_2$

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



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Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

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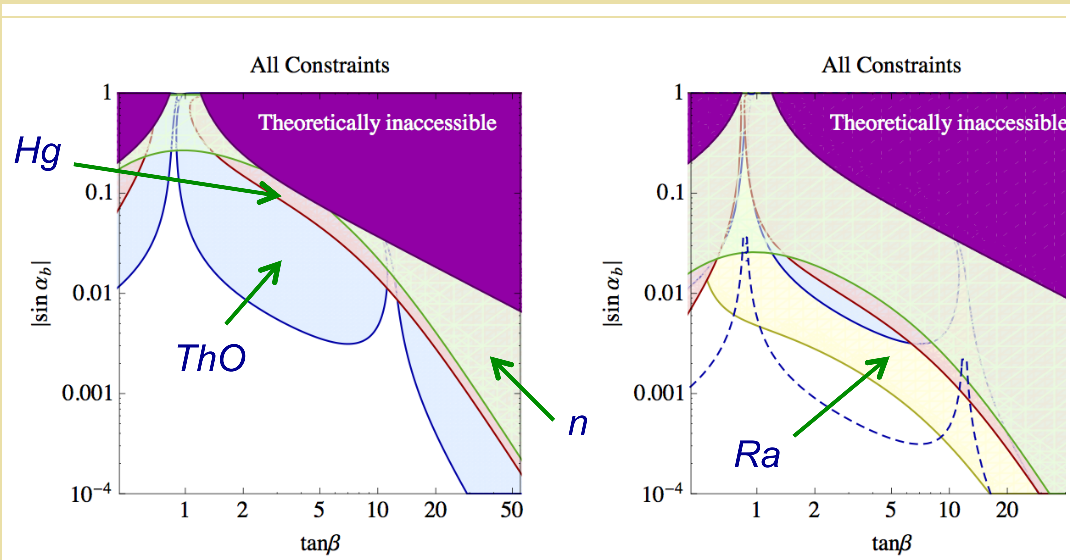

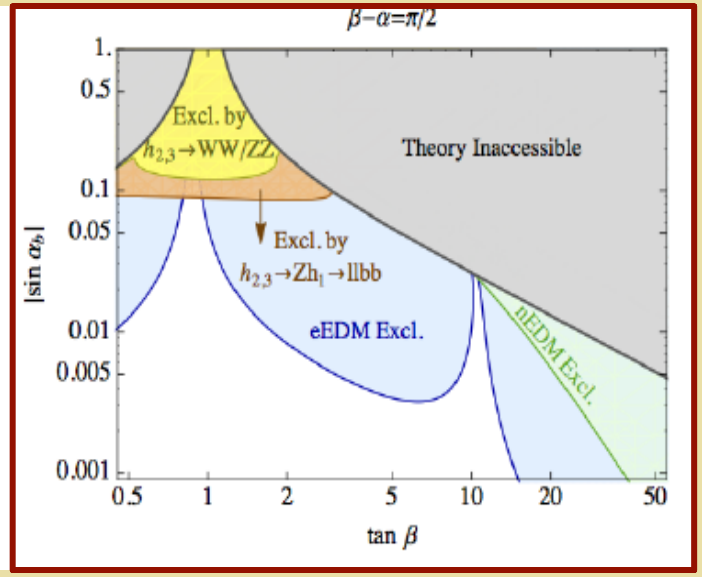

Chen, Lewis, Dawson: 1503.01114

Present	Future:	Future:
	d_n x 0.1	d_n x 0.01
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Inoue, R-M, Zhang: 1403.4257

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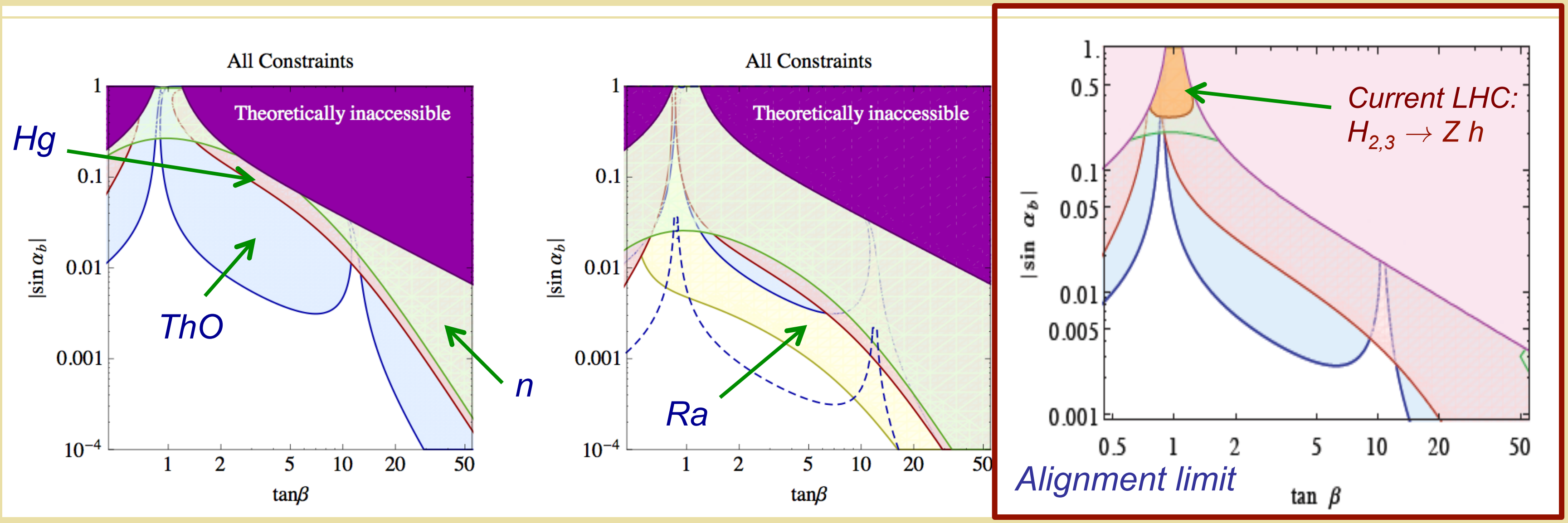

Chen, Li, R-M: 1708.00435

Present

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Inoue, R-M, Zhang: 1403.4257

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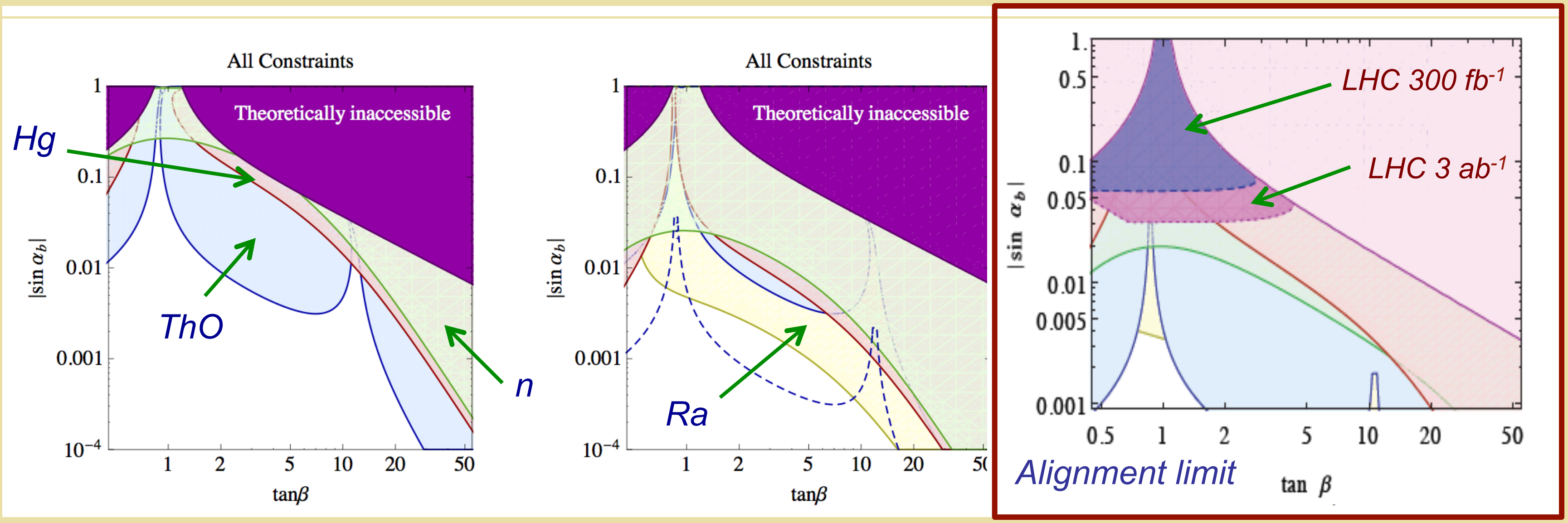

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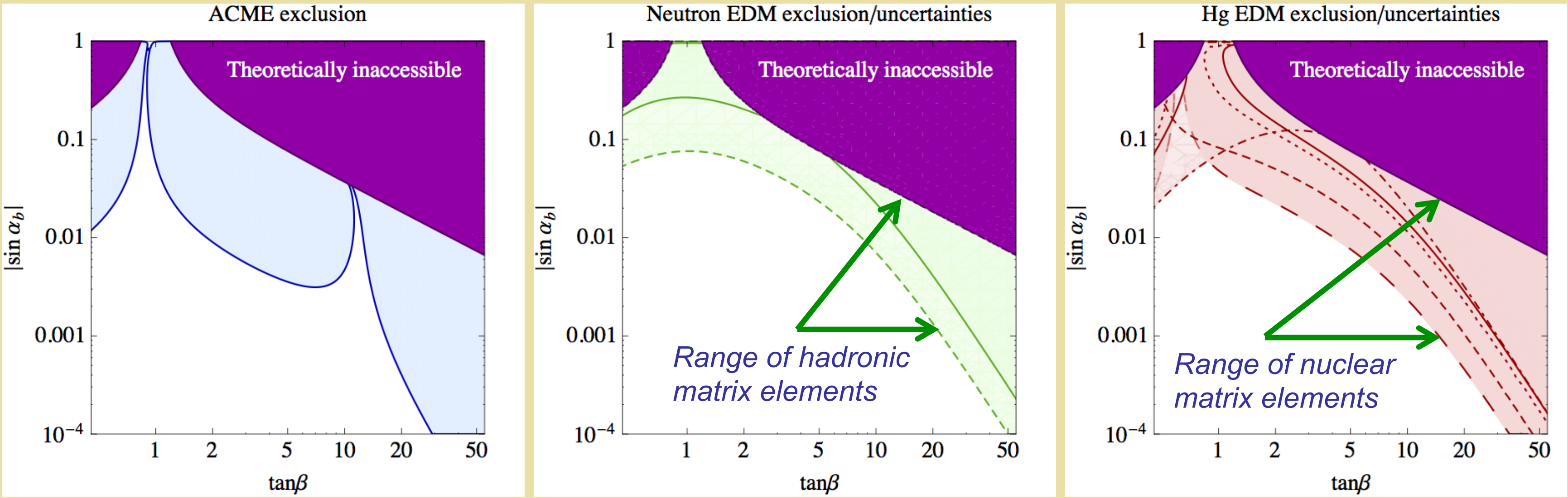
Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*



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sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

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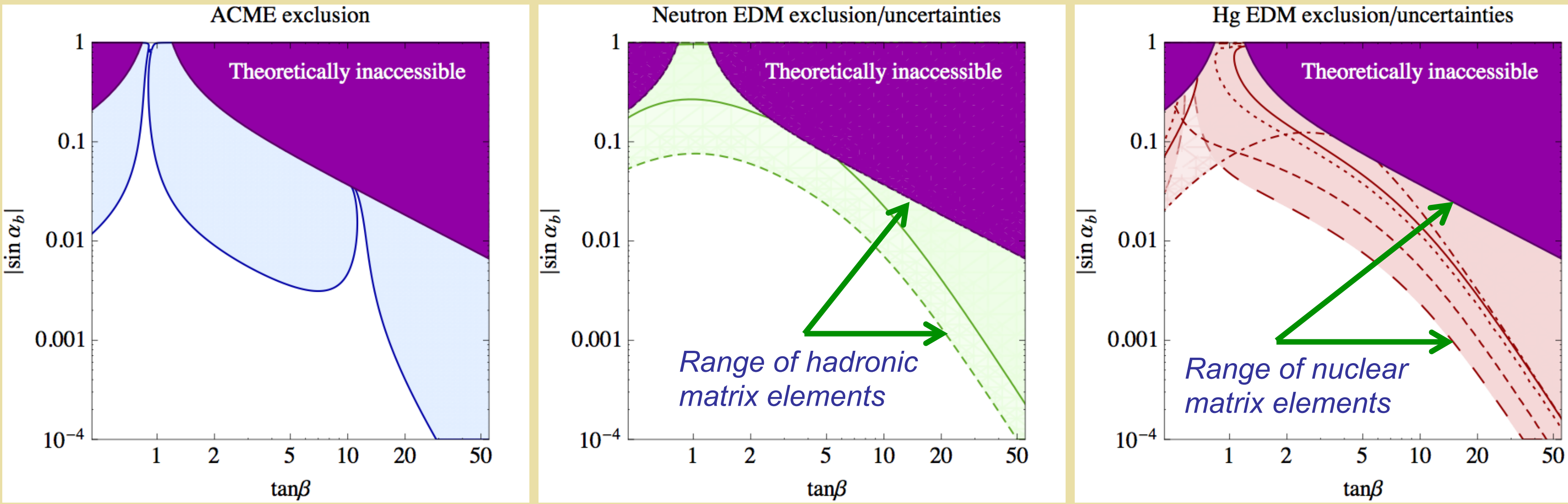


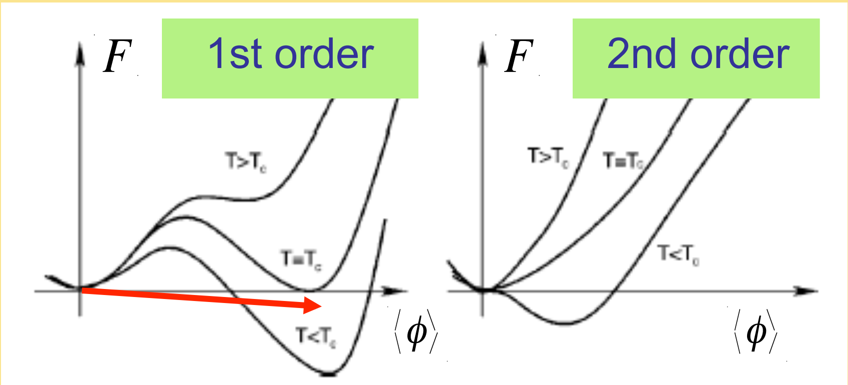
Present

Challenge

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

EW Phase Transition: Higgs Portal

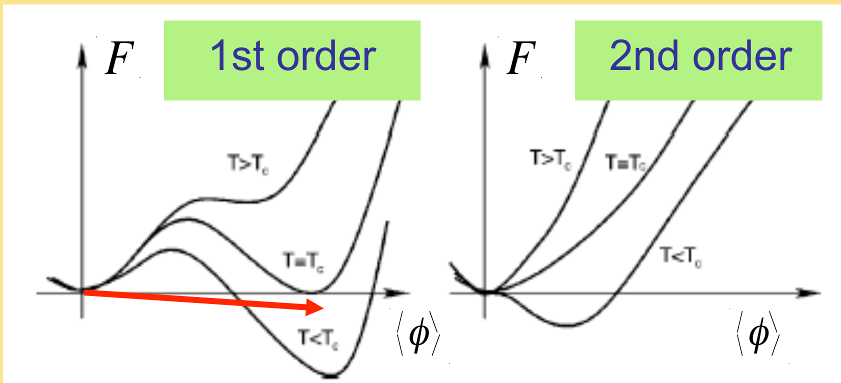


Increasing m_h →

← *New scalars*

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

EW Phase Transition: Higgs Portal



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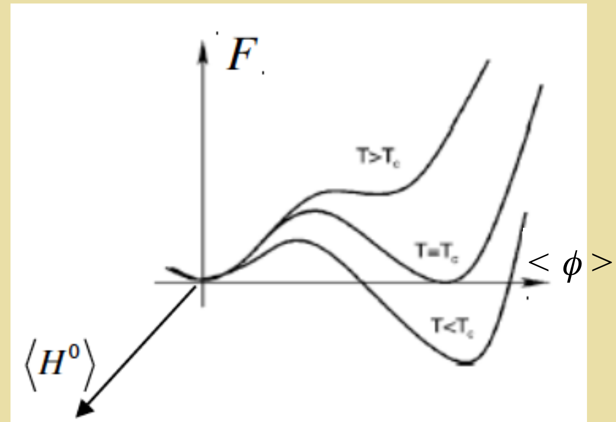

- *Renormalizable*
- *ϕ : singlet or charged under $SU(2)_L$ x $U(1)_Y$*
- *Generic features of full theory (NMSSM, GUTS…)*
- *More robust vacuum stability*
- *Novel patterns of SSB*

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: ~~Z_2~~	1	✔	✖
Real singlet: Z_2	1	✔	✔
Complex Singlet	2	✔	✔
EW Multiplets	3+	✔	✔

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

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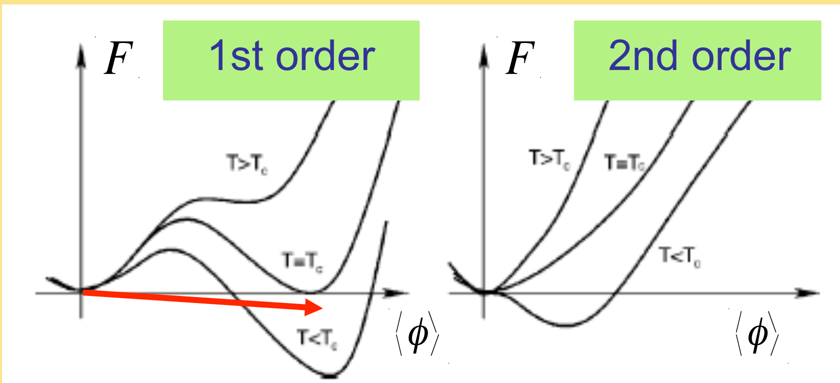
EW Phase Transition: Singlets

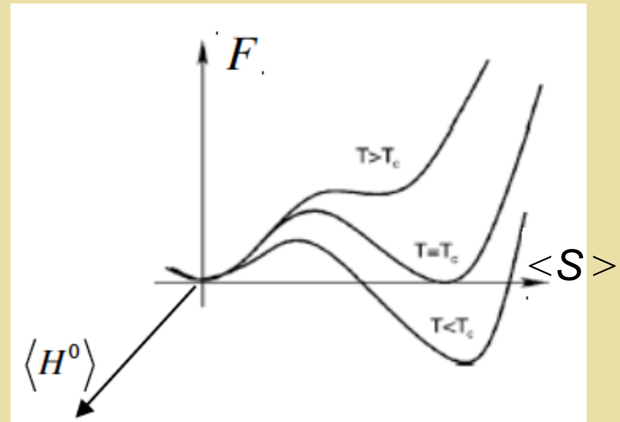


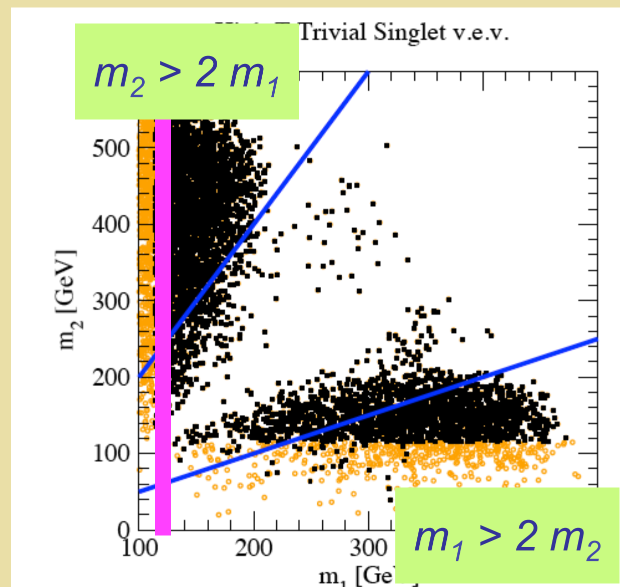
Increasing m_h →

← *New scalars*

Real Singlet: $\phi \to S$

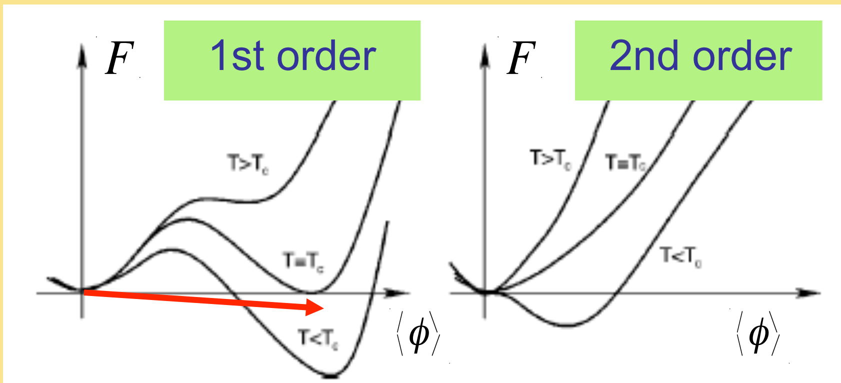
Simplest Extension:
two states h_1 & h_2

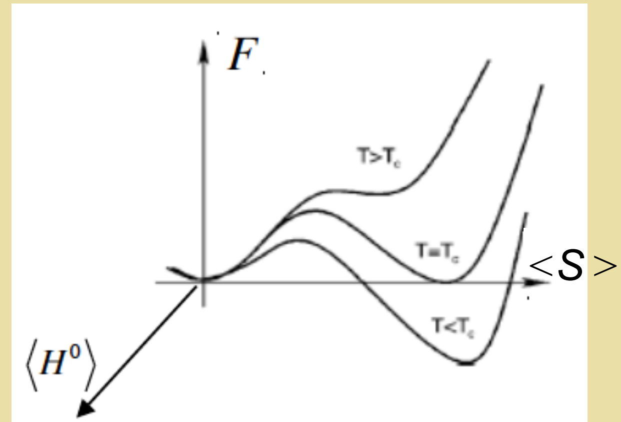




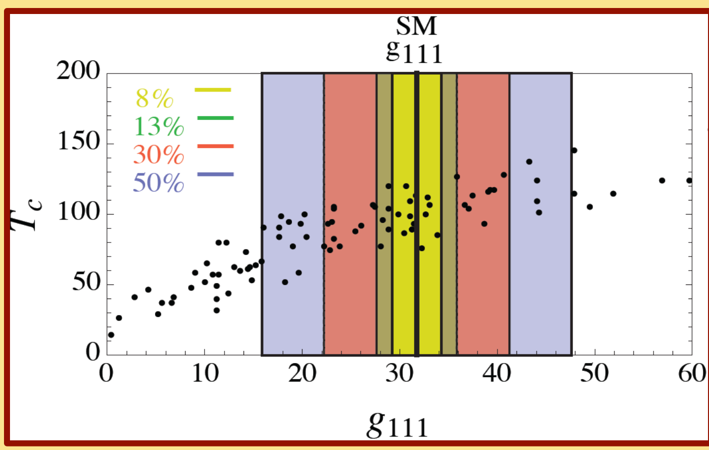
Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

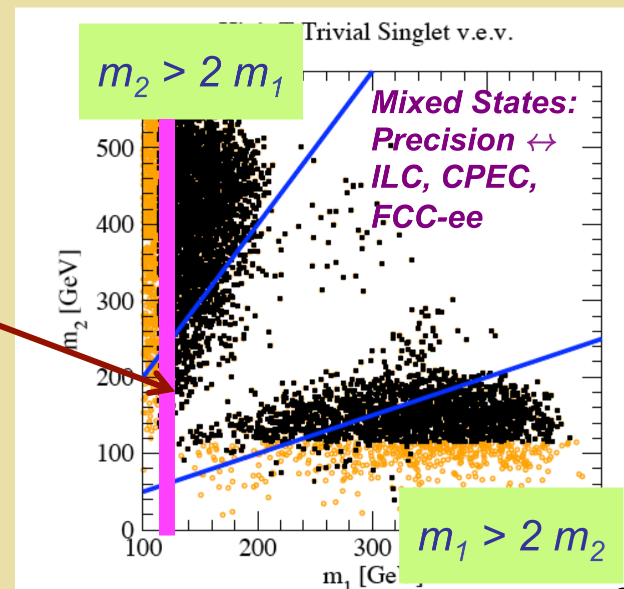
EW Phase Transition: Singlets





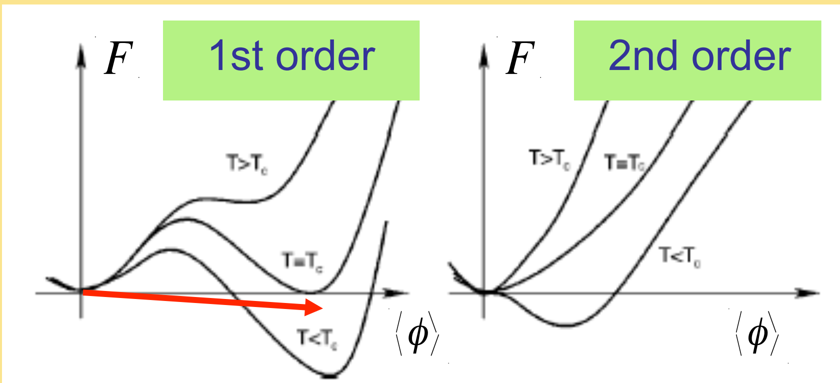
Modified Higgs Self-Coupling

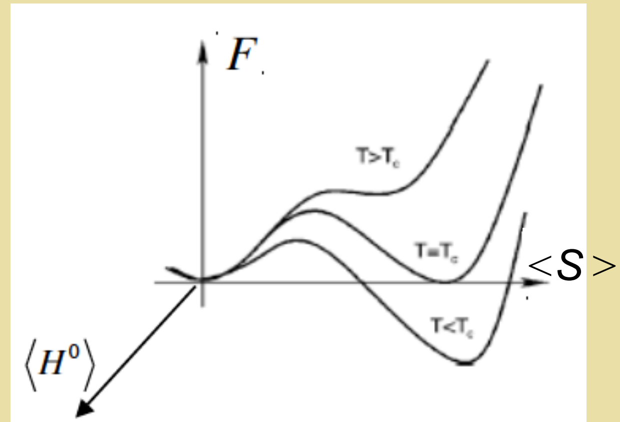




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: Singlets





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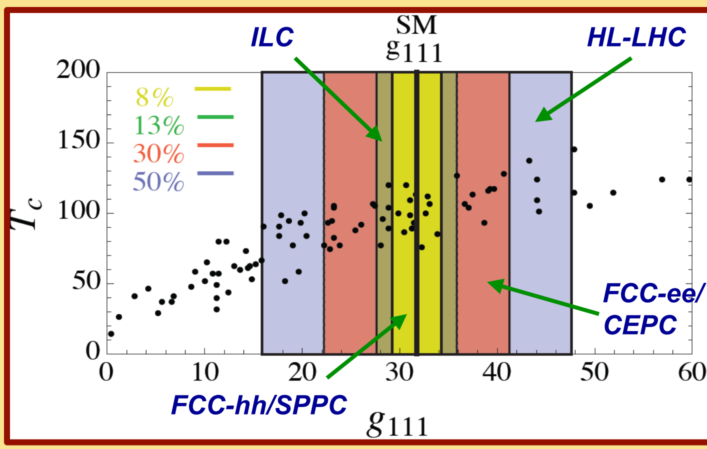

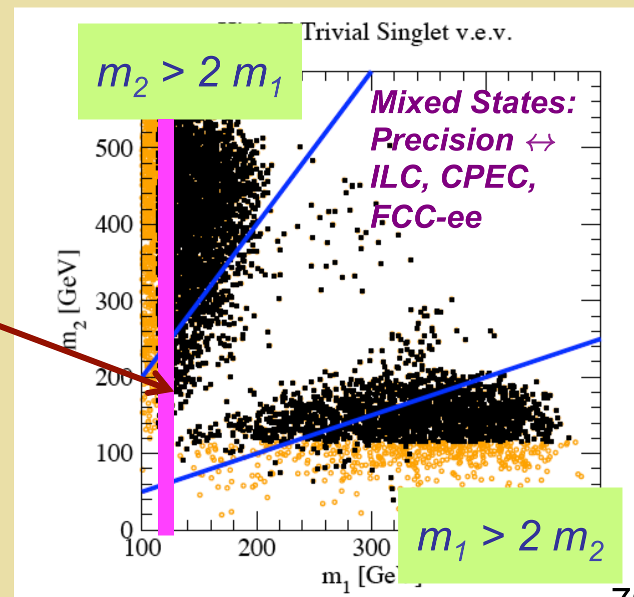

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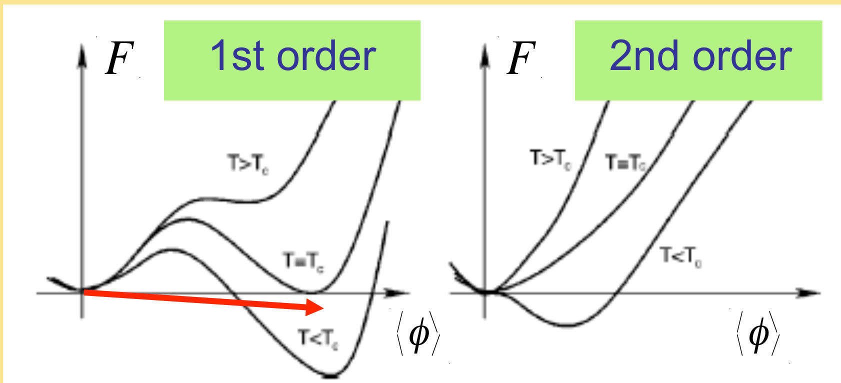
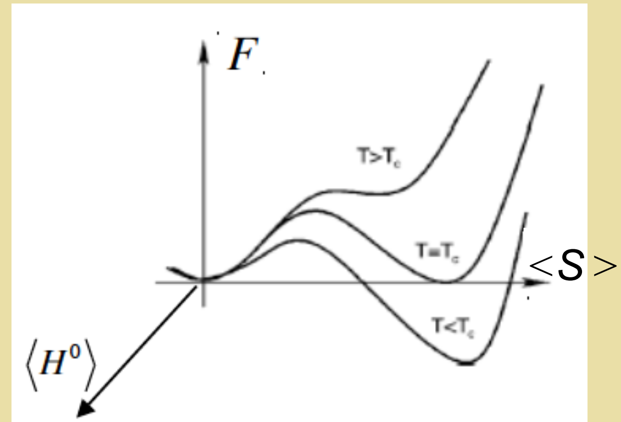
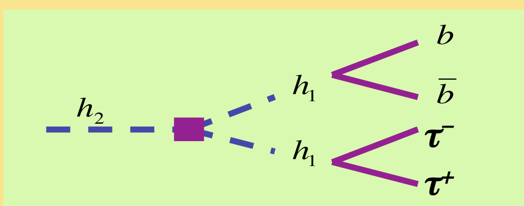


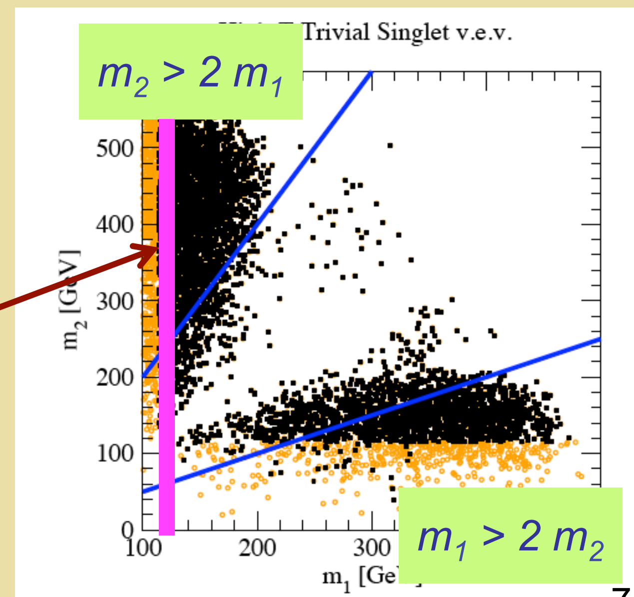


Increasing m_h

New scalars

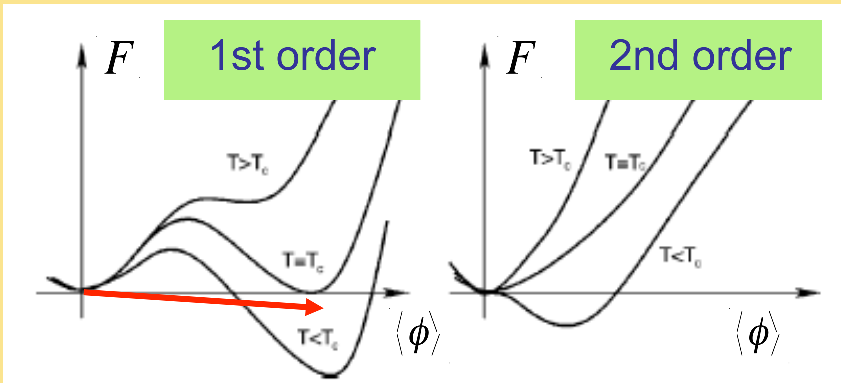
Resonant di-Higgs production:

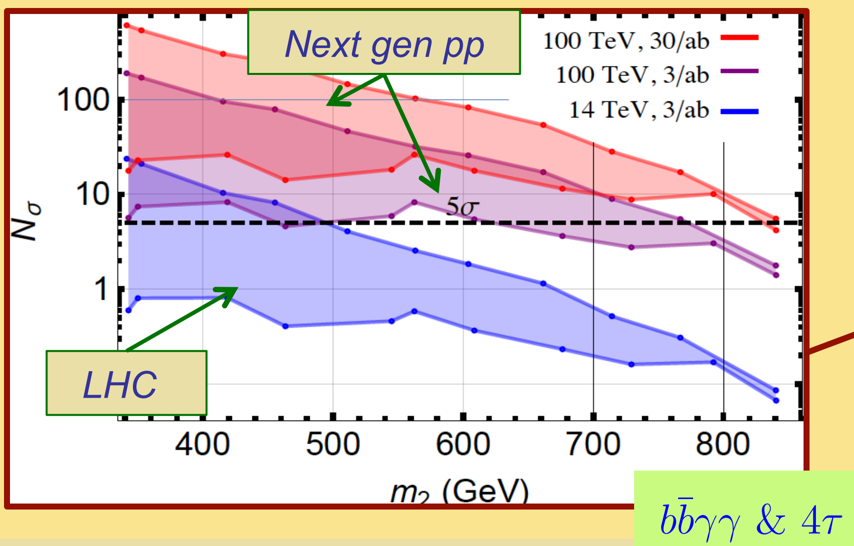


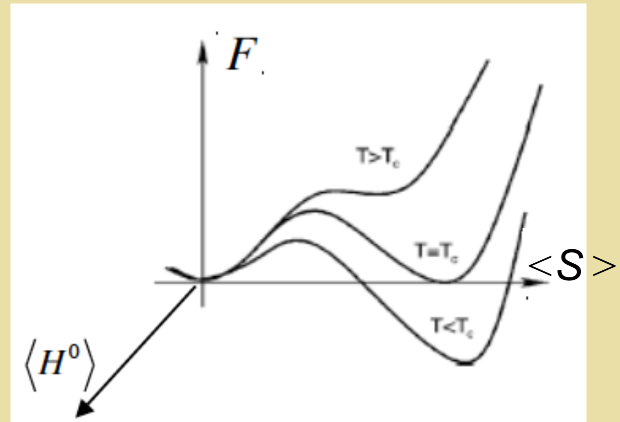


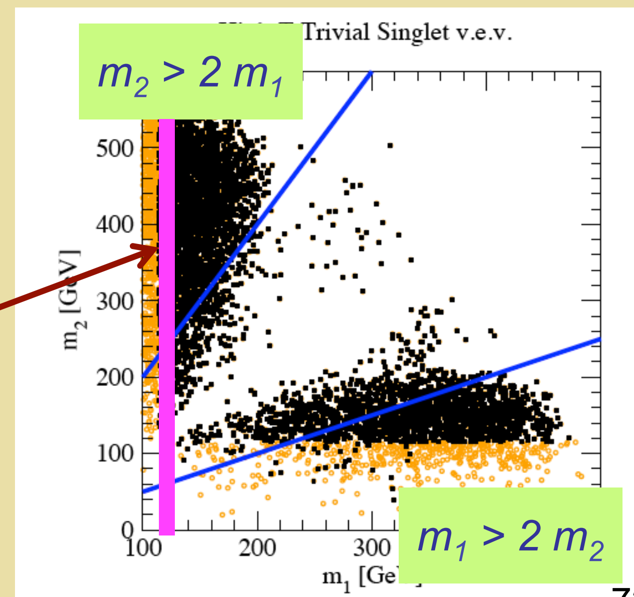
No & RM, arXiv:1310.6035 : ***LHC Discovery w/ 100 fb^{-1}***

EW Phase Transition: Singlets



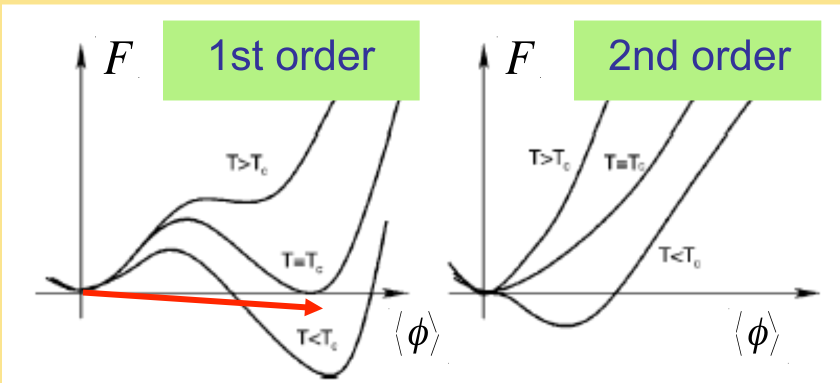






Next gen pp: Kotwal, No, R-M, Winslow *1605.06123*

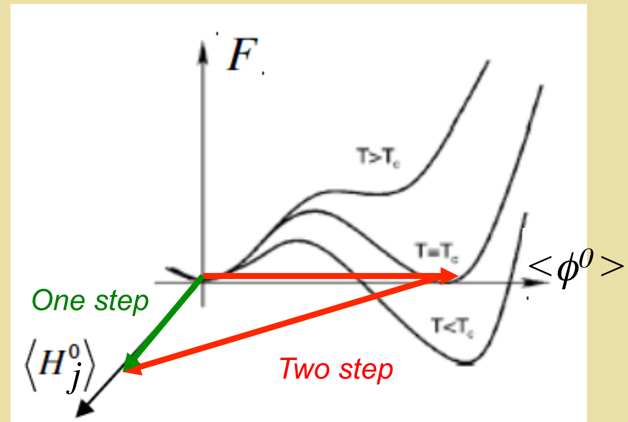
EW Multiplets: Two-Step EWPT

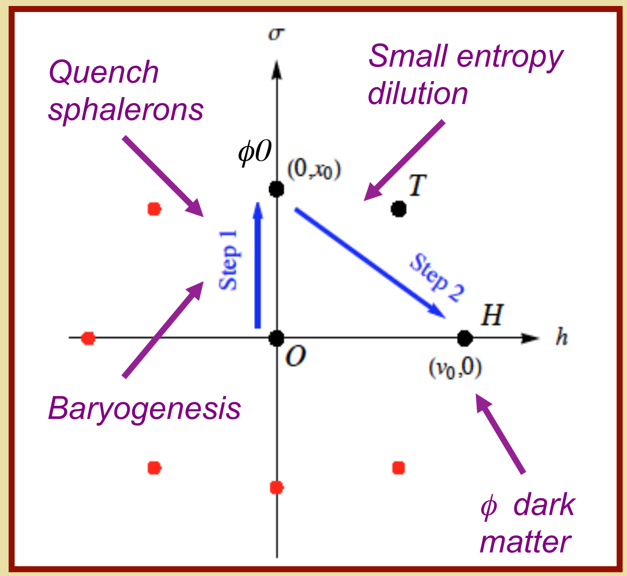


Increasing m_h →

← *New scalars*

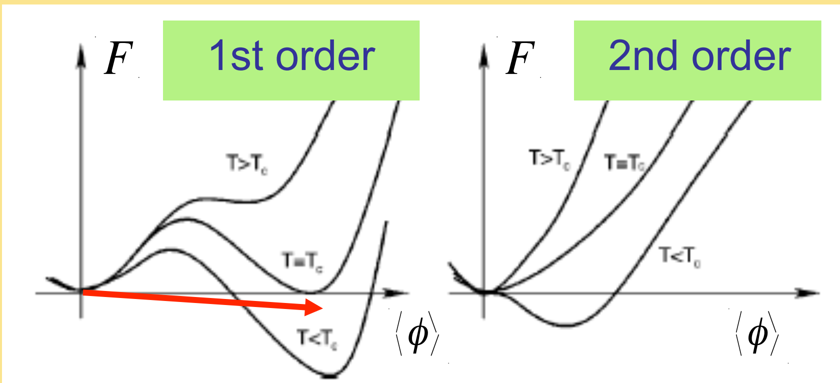
- *Step 1: thermal loops*
- *Step 2: tree-level barrier*





Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1505.05195

EW Multiplets: Two-Step EWPT

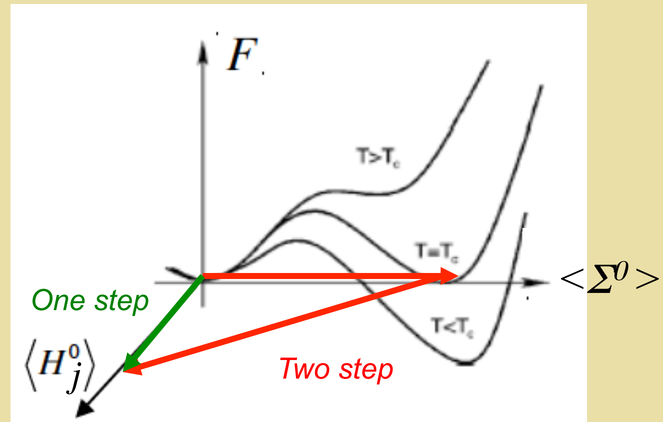


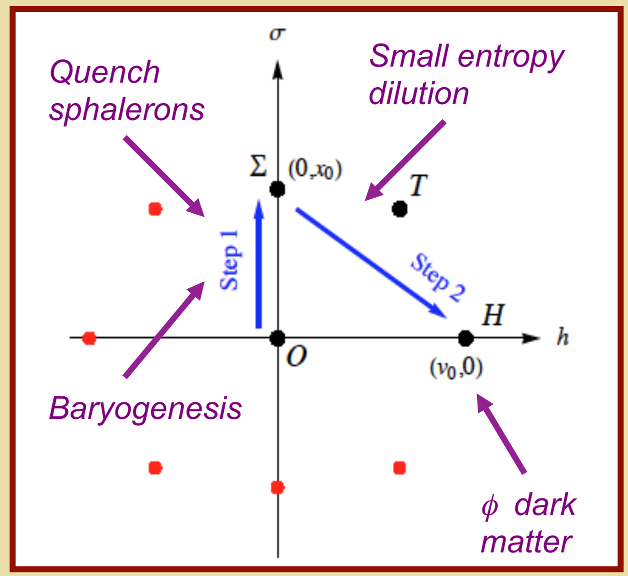
Increasing m_h ⟶

⟵ *New scalars*

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

Two-step EWPT & dark matter





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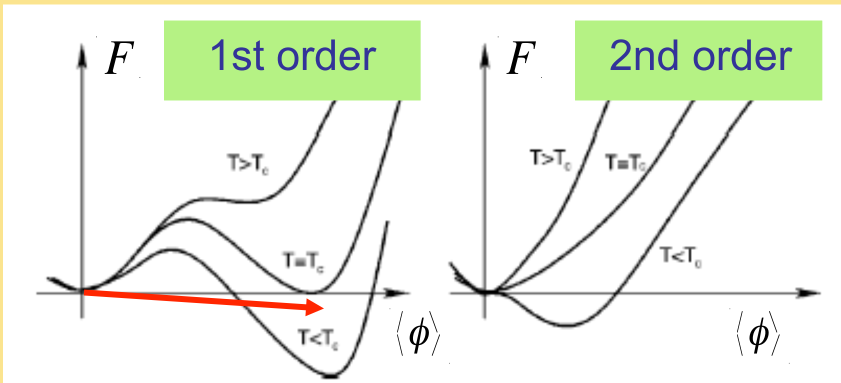

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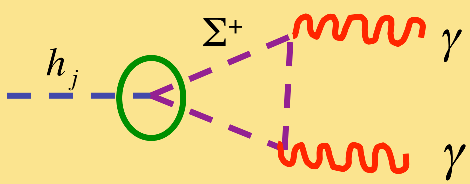

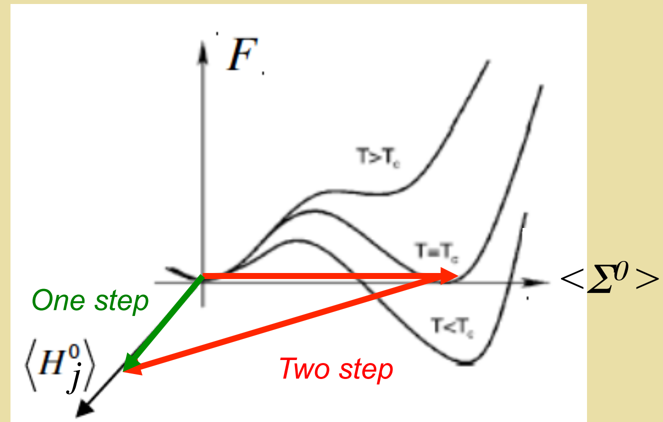

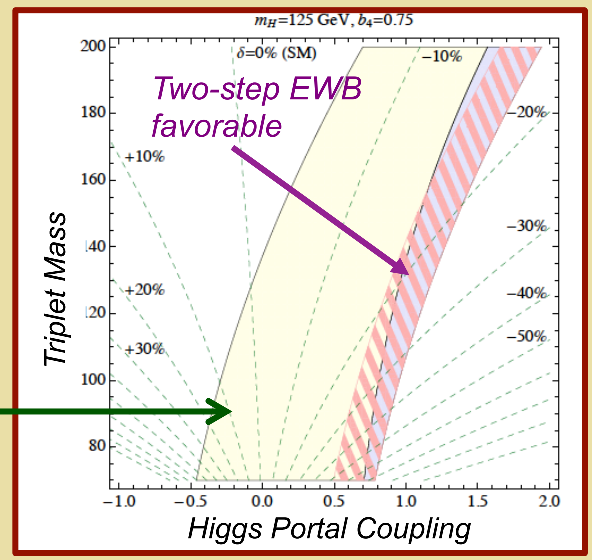

Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1505.05195