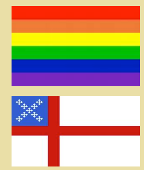
CPV: EDM's & Electroweak Baryogenesis

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 CPV Workshop
March 2018

Goals for This Talk

- *Illustrate the interplay of EDM searches with EW baryogenesis*
- *Introduce EDM physics*
- *Set the stage for remainder of the workshop*

Outline

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

II. *The Cosmic Matter-Antimatter Asymmetry*

III. *Electroweak Baryogenesis: Examples*

IV. *Outlook*

I. EDMs: The SM & BSM Context

EDMs & SM Physics

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

EDMs & SM Physics

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

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

C. Seng arXiv: 1411.1476

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

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

EDMs & BSM Physics

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

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

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

BSM mass scale: TeV ? Much higher ?

EDMs & BSM Physics

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

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

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"

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	8.7×10^{-29} **	10^{-38}	10^{-28}
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* 95% CL   ** e^- equivalent   *New Hf F^+ : 1.3×10^{-28} 1704.07928*

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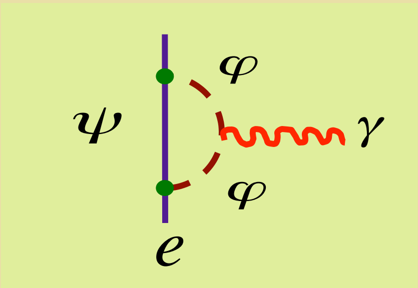
Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ 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

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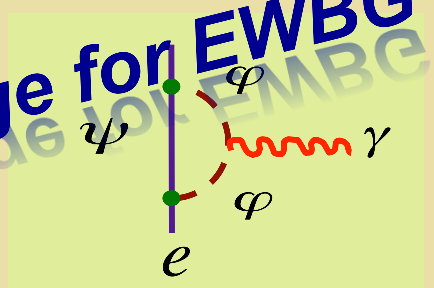
Mass Scale Sensitivity

Challenge for EWBG



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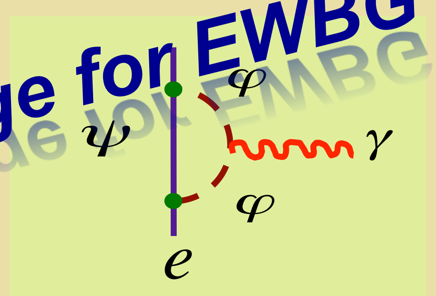

- *EDMs arise at > 1 loop*
- *CPV is flavor non-diagonal*
- *CPV is "partially secluded"*

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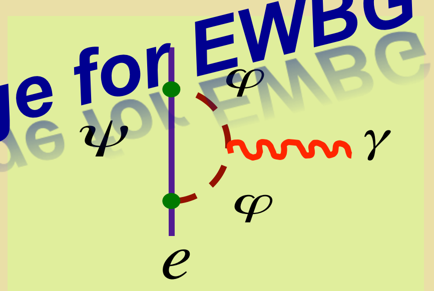


This talk

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

II. The Matter-Antimatter Asymmetry

Cosmic Baryon Asymmetry

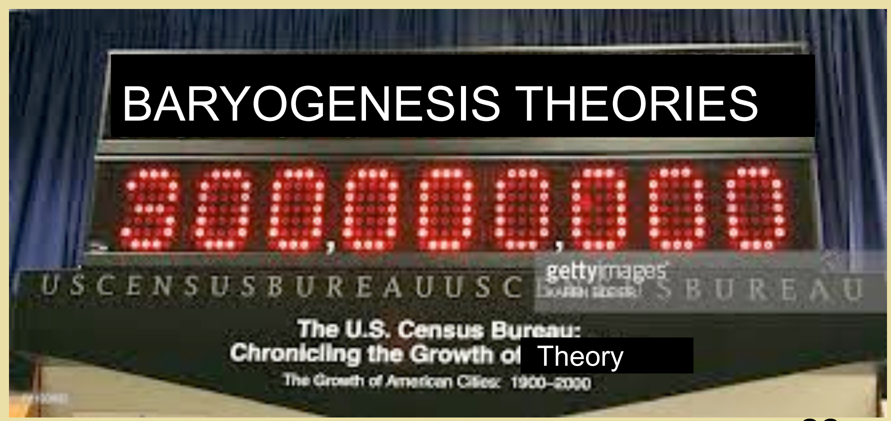
$$Y_B = \frac{n_B}{s} = (8.82 \pm 0.23) \times 10^{-11}$$

One number $\rightarrow$ BSM Physics

Cosmic Baryon Asymmetry

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

One number $\rightarrow$ ~~IIII~~ ~~IIII~~ ~~IIII~~ … ***Explanations***



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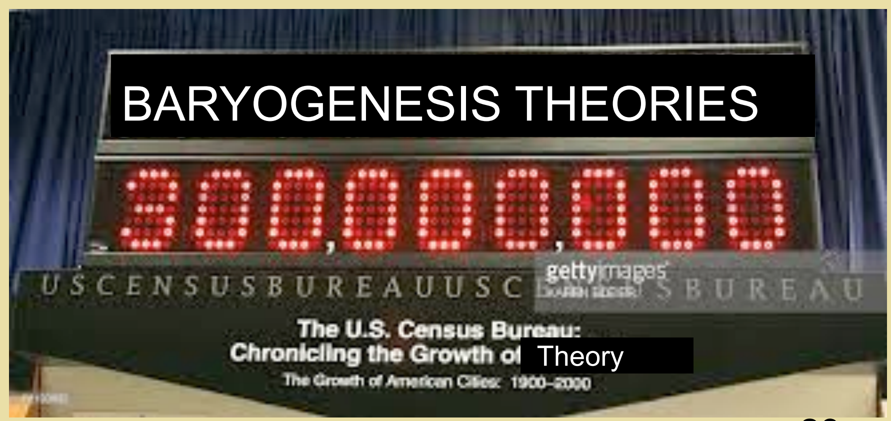
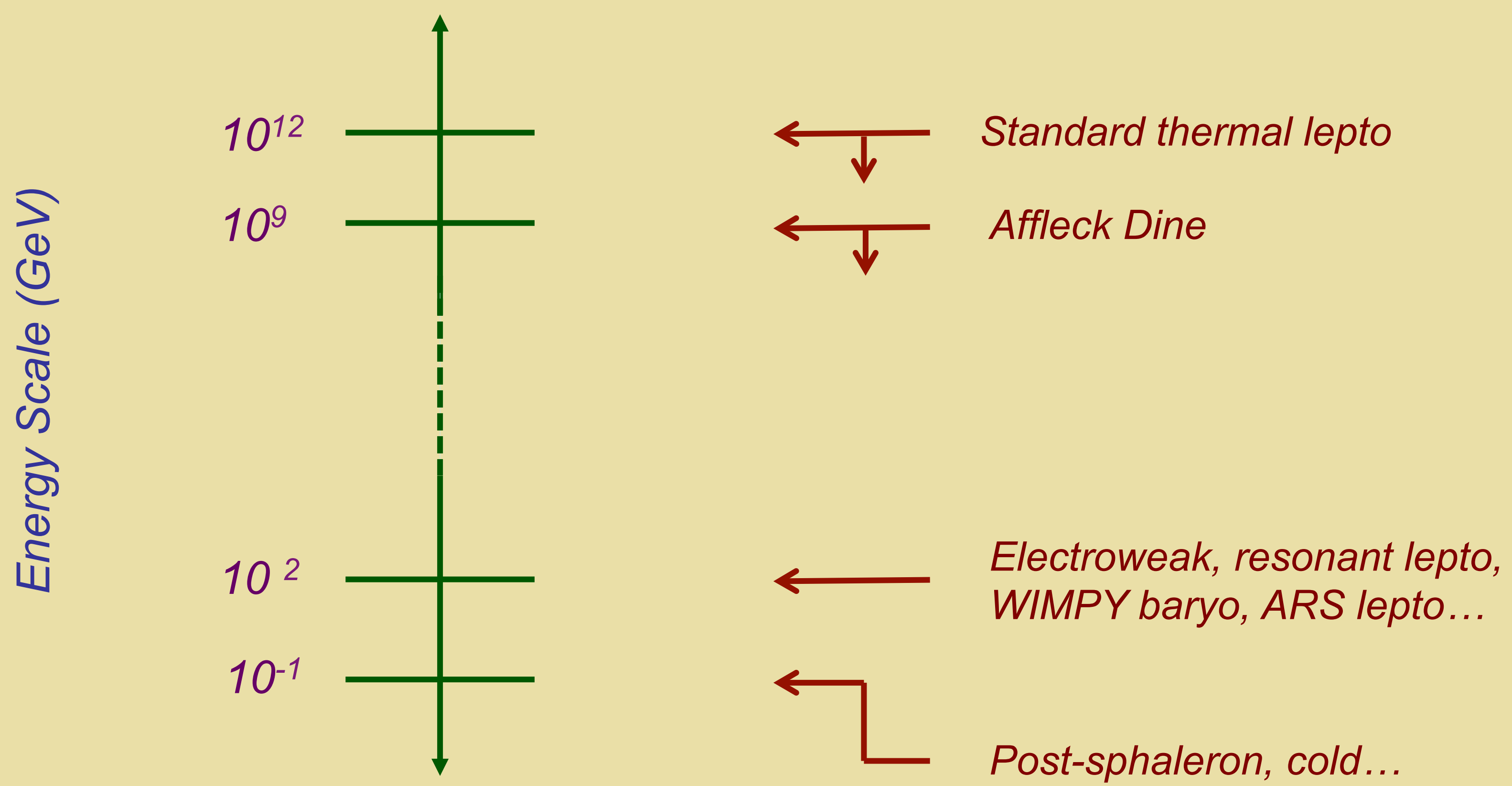
One number $\rightarrow$ ~~||||~~ ~~||||~~ ~~||||~~ … *Explanations*

Experiment can help:

- *Discover ingredients*
- *Falsify candidates*



Baryogenesis Scenarios



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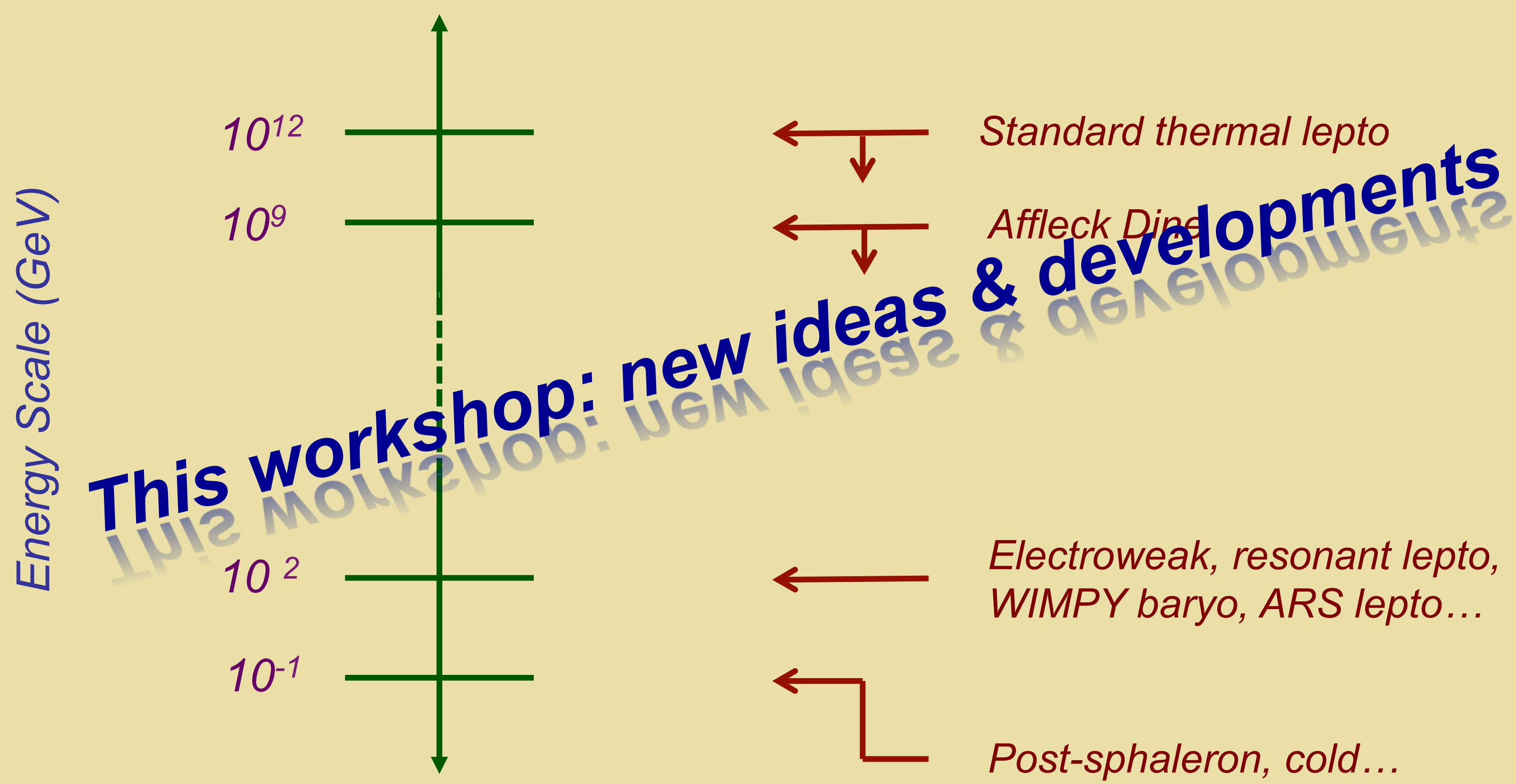

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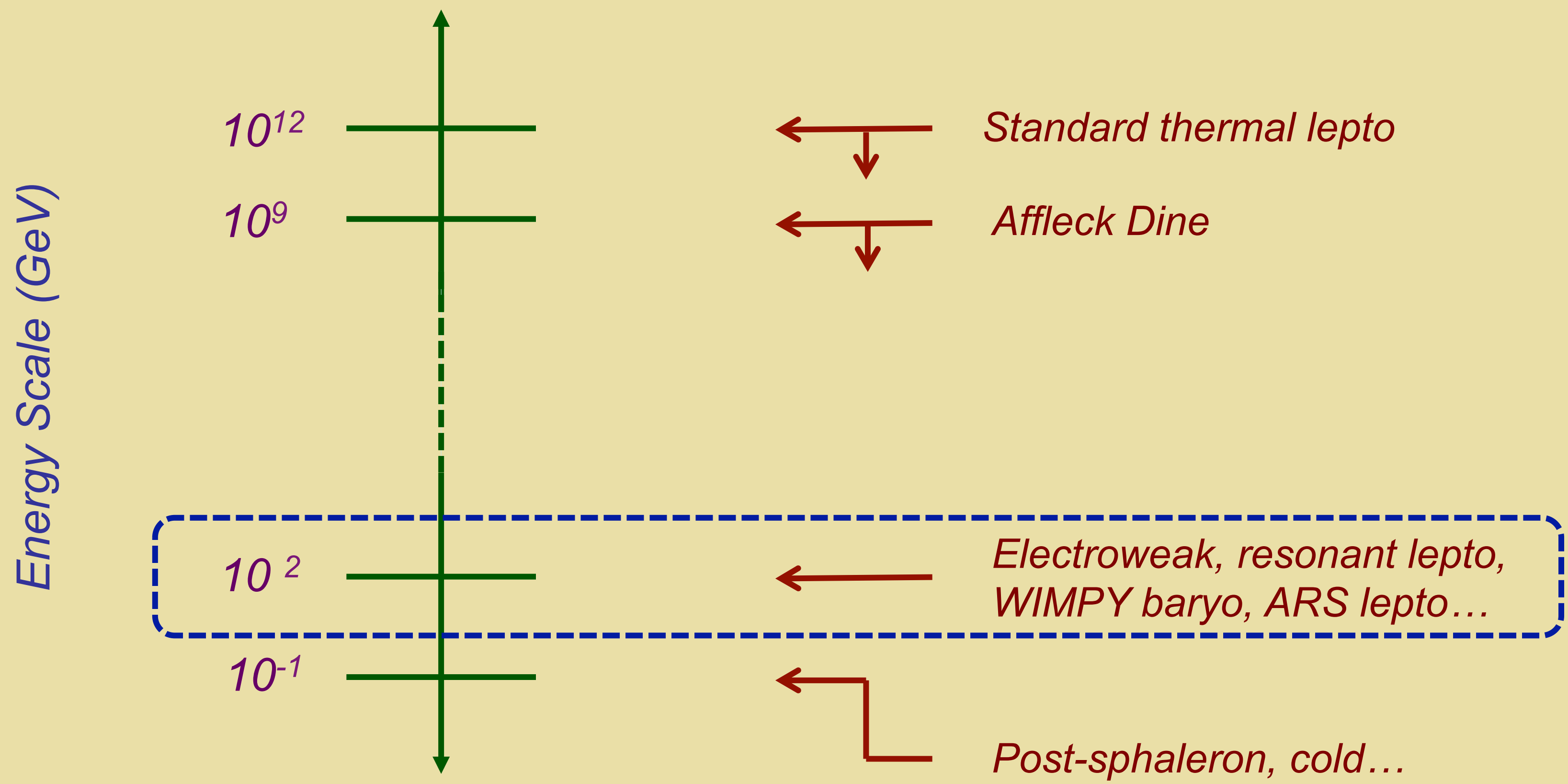


Era of EWSB: t_{univ} ~ 10 ps

Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

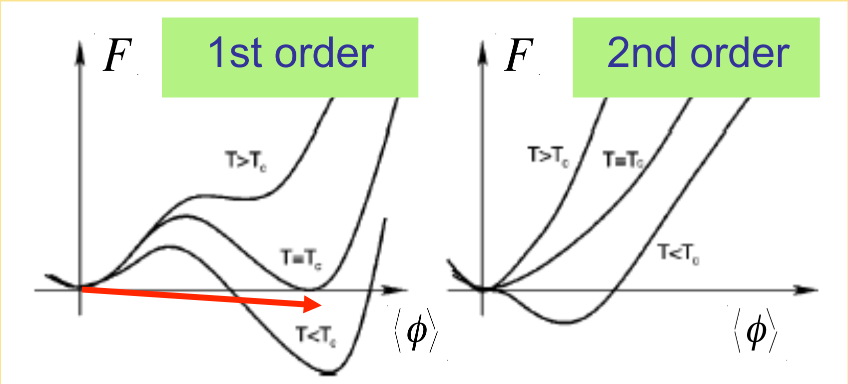
III. Electroweak Baryogenesis

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*

EW Phase Transition: Higgs Portal

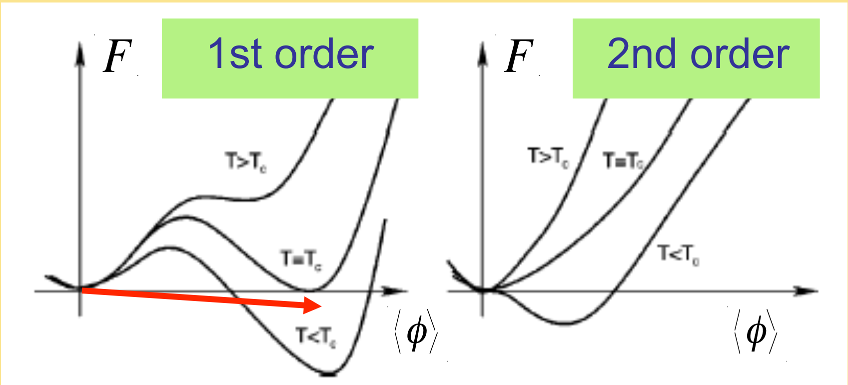


Increasing m_h →

← *New scalars*

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

EW Phase Transition: Higgs Portal



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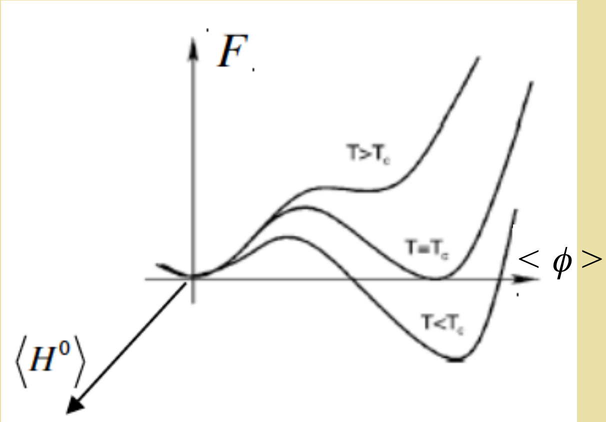

- *Renormalizable*
- *ϕ : singlet or charged under $SU(2)_L$ x $U(1)_Y$*
- *Generic features of full theory (NMSSM, GUTS…)*
- *More robust vacuum stability*
- *Novel patterns of SSB*

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: $\cancel{Z_2}$	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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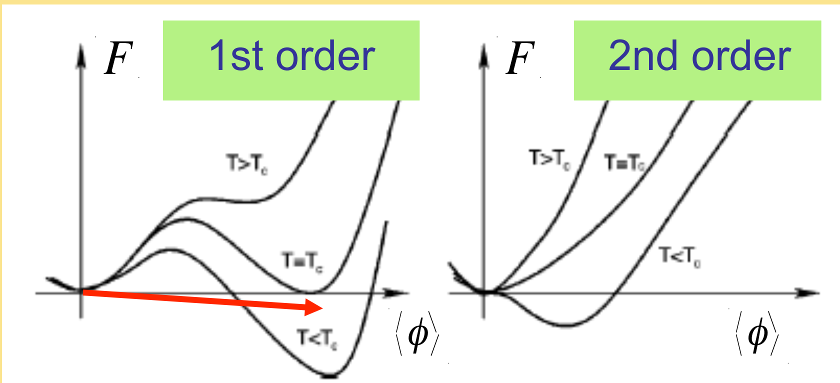
EW Phase Transition: Singlets

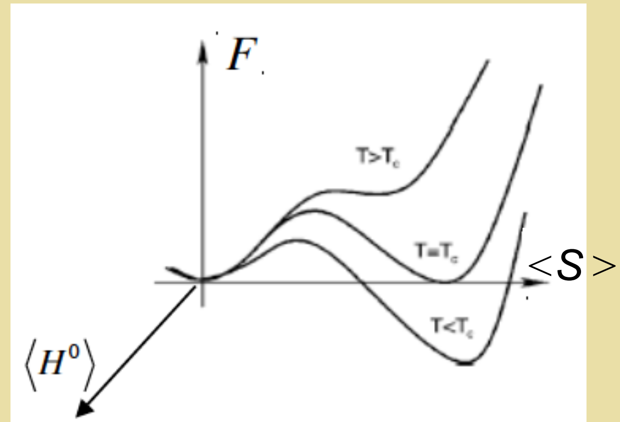


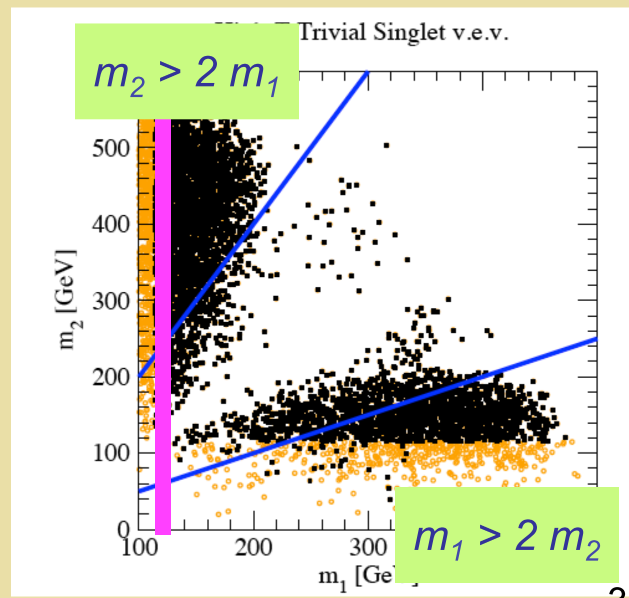
Increasing m_h ⟶

⟵ *New scalars*

Real Singlet: $\phi \to S$

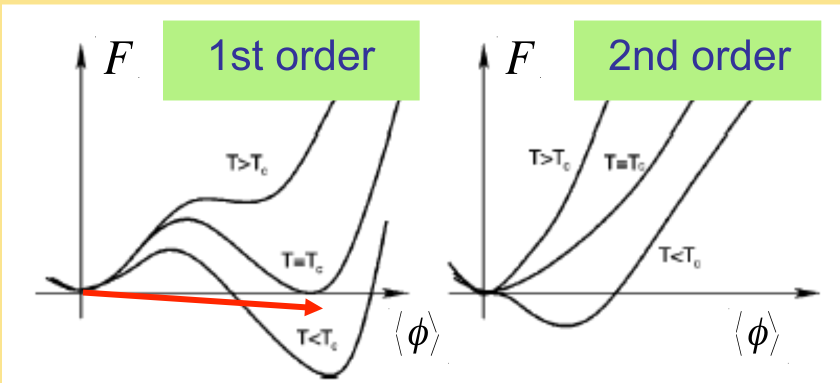
Simplest Extension:
two states h_1 & h_2

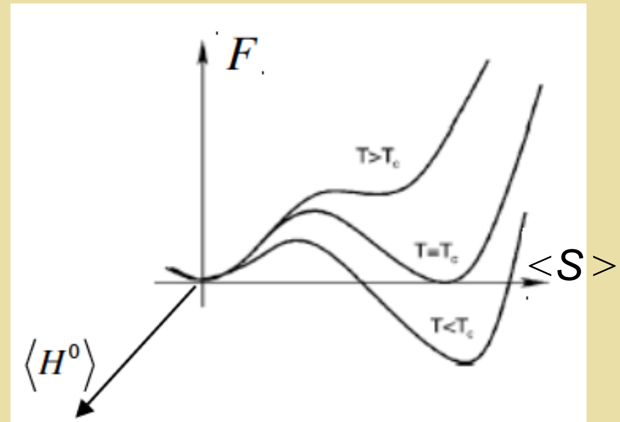




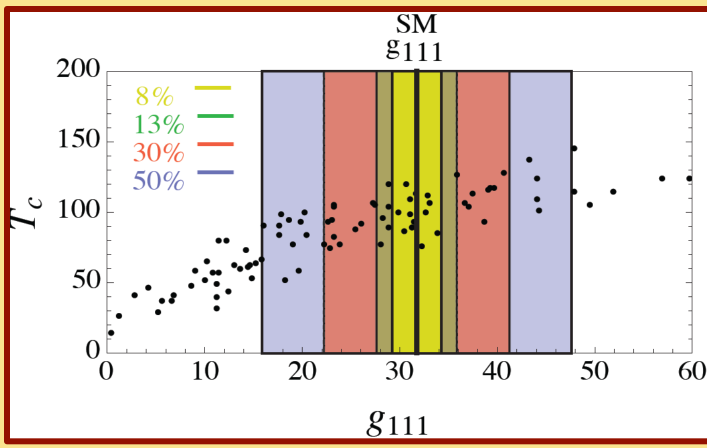
Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

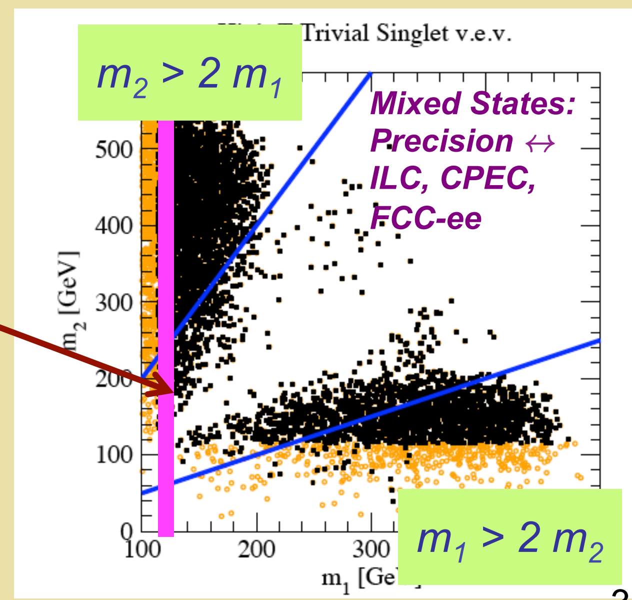
EW Phase Transition: Singlets





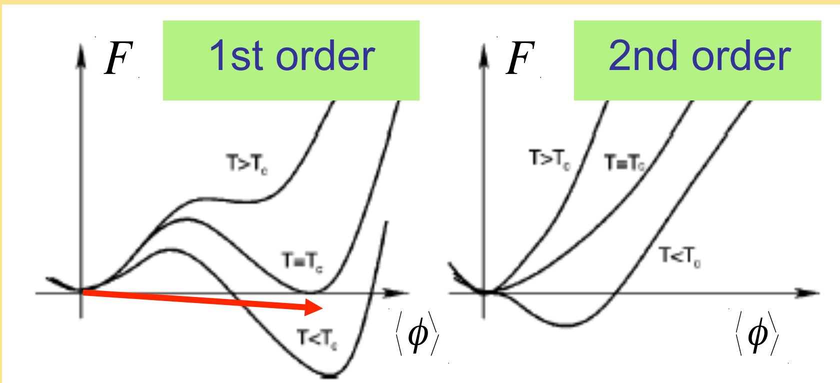
Modified Higgs Self-Coupling

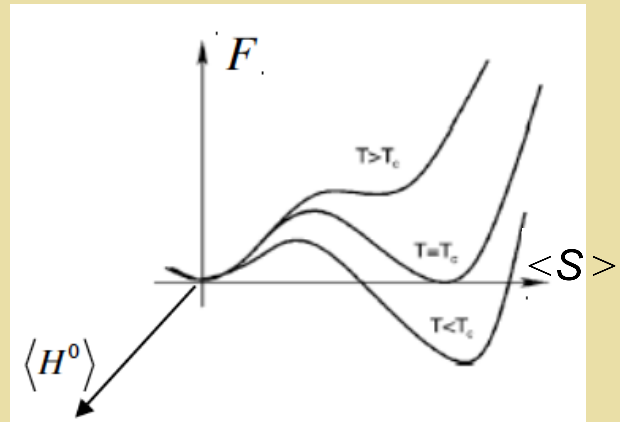




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: Singlets





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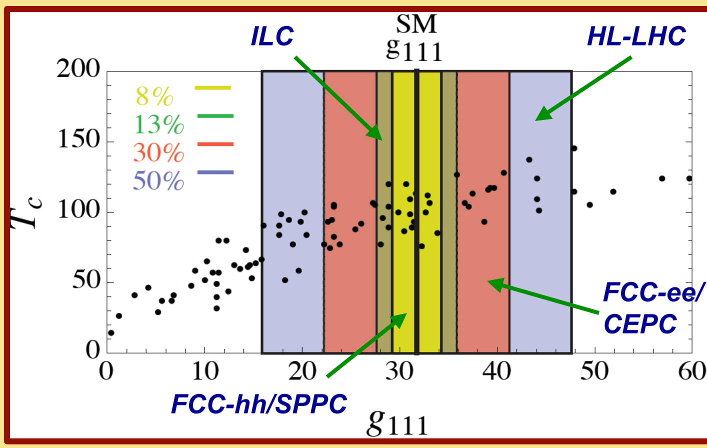

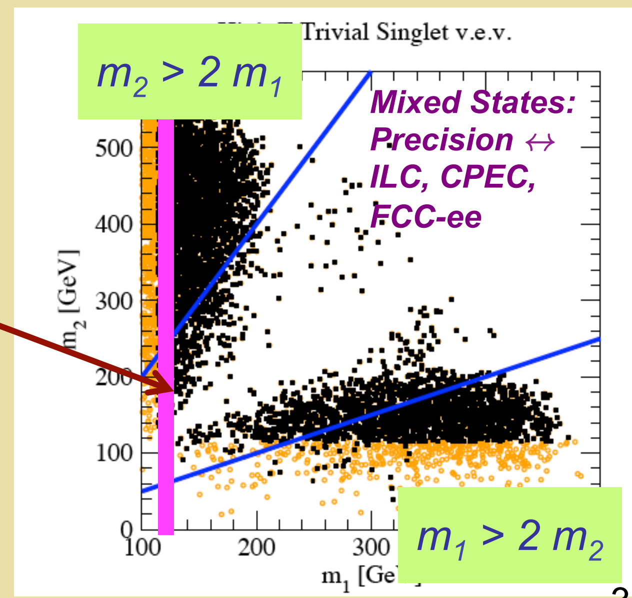

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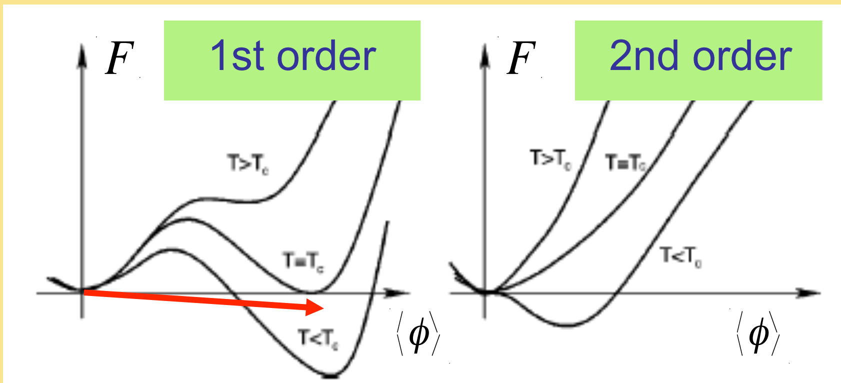
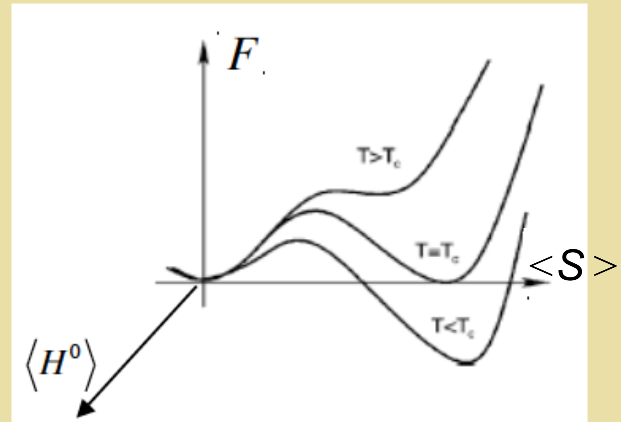
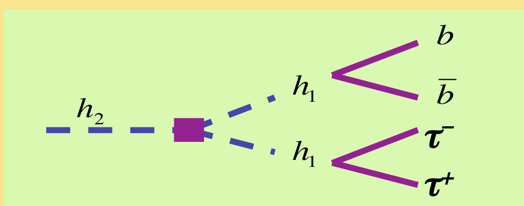


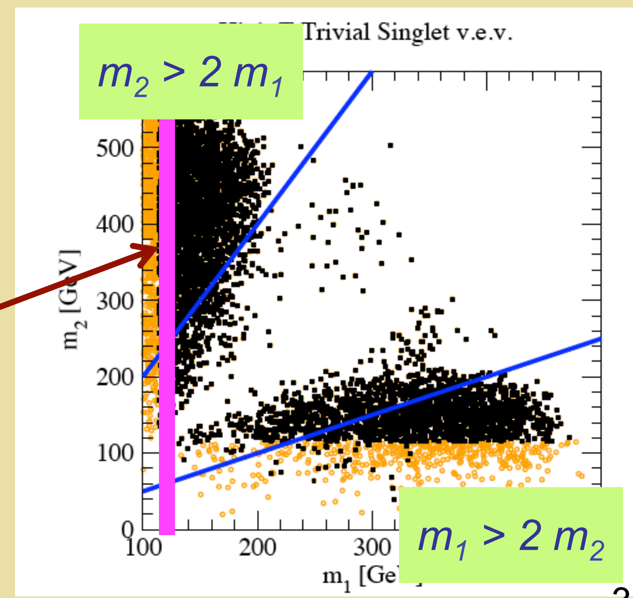


Increasing m_h

New scalars

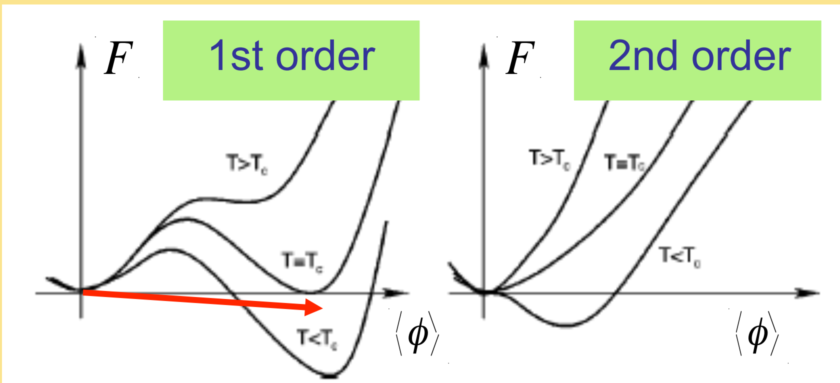
Resonant di-Higgs production:

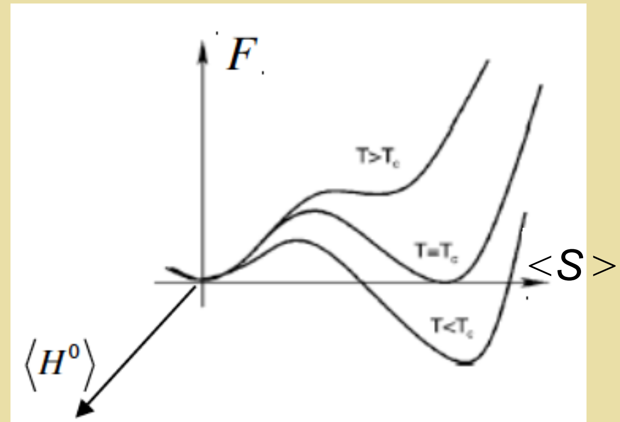


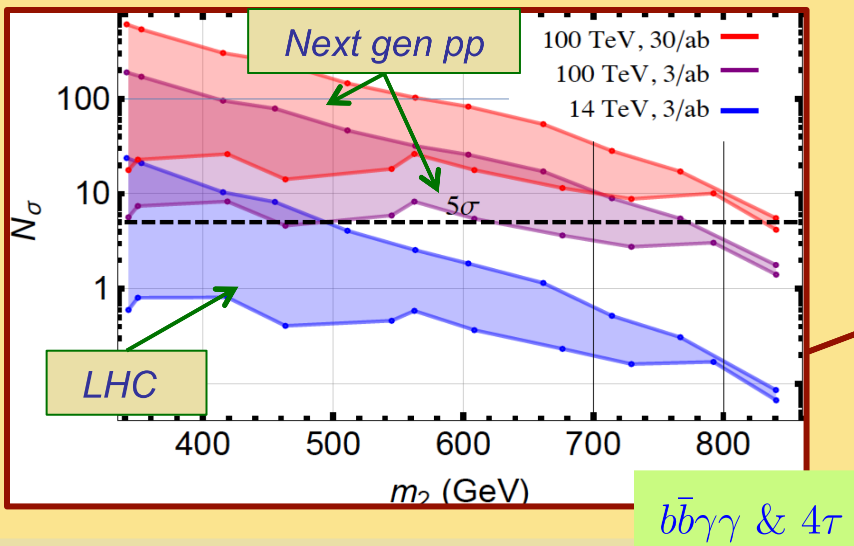


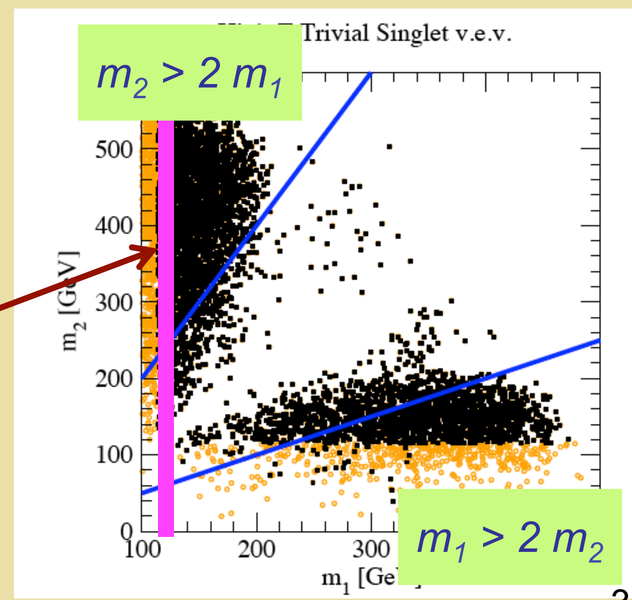
No & RM, arXiv:1310.6035 : ***LHC Discovery w/ 100 fb^{-1}***

EW Phase Transition: Singlets



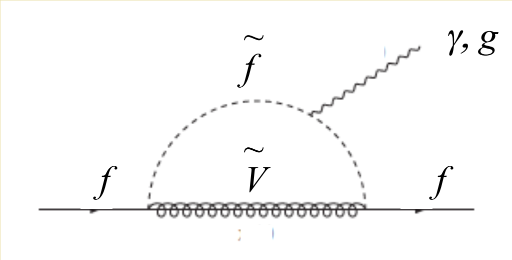




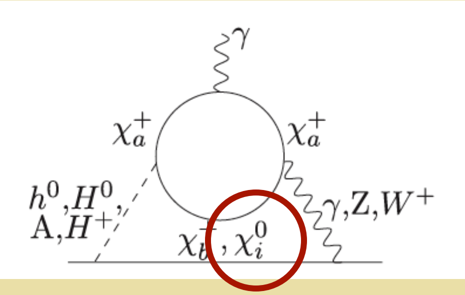


Next gen pp: Kotwal, No, R-M, Winslow 1605.06123

EDMs & EWBG: MSSM + Singlets



Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

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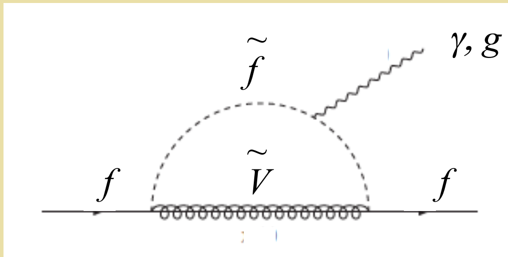

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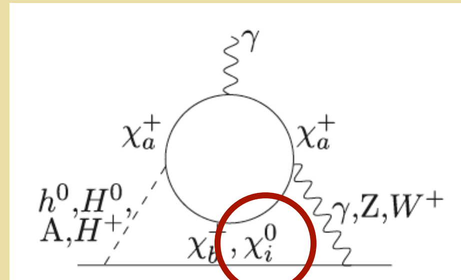

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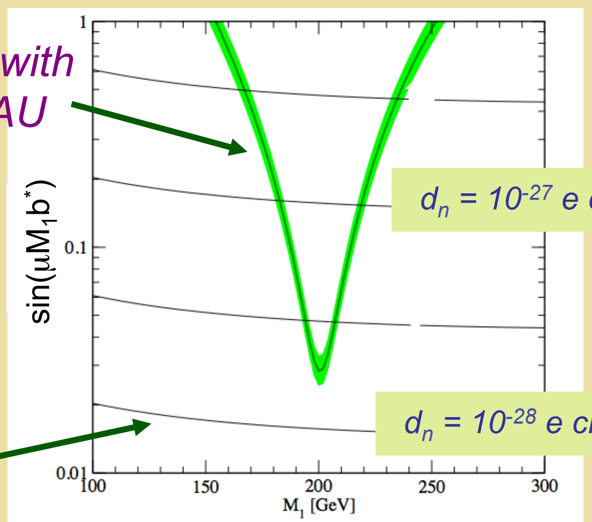
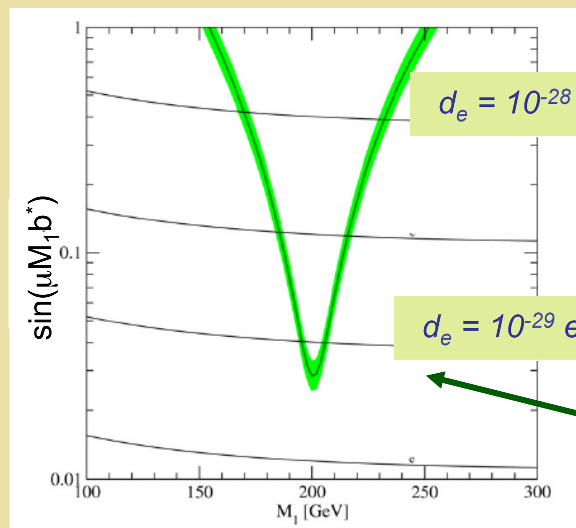
Compatible with observed BAU



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

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

Next gen d_n



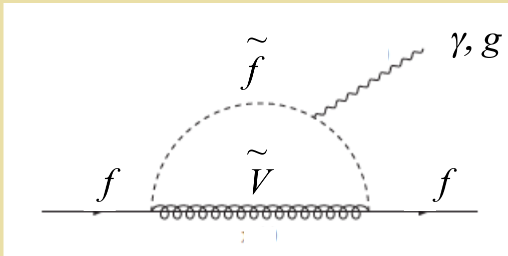
$d_e = 10^{-28}$ e cm *ACME: ThO*

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

Next gen d_e

Li, Profumo, RM '09-'10

EDMs & EWBG: MSSM + Singlets



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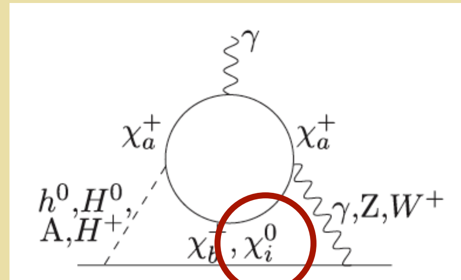

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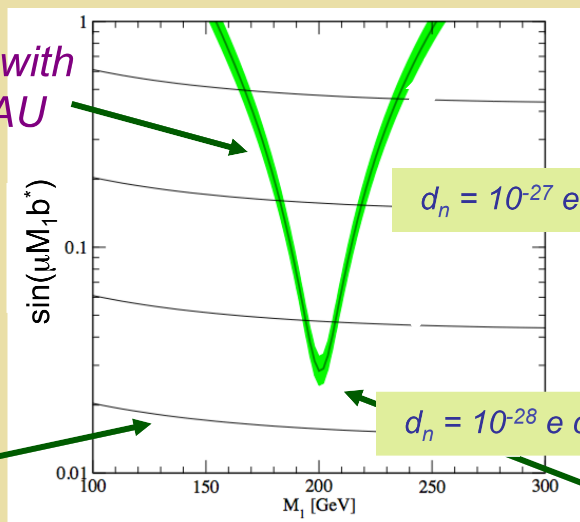
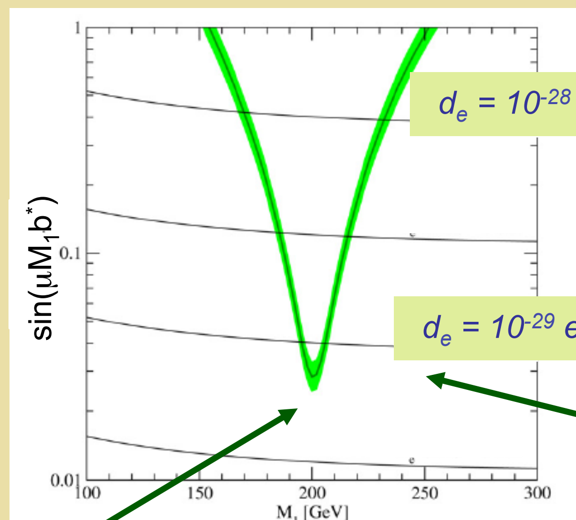


Next gen d_n



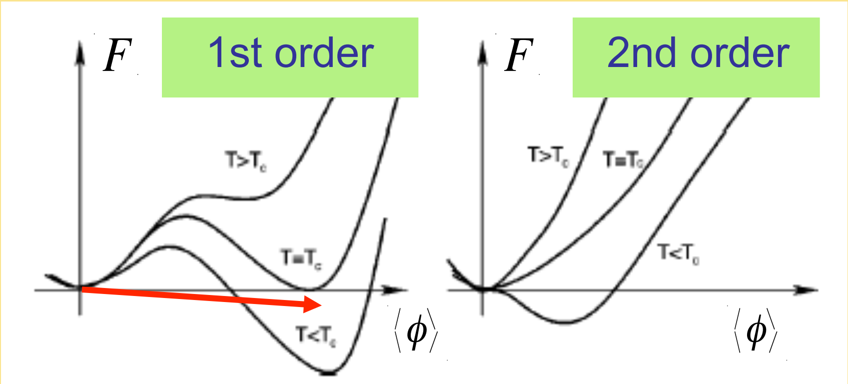
ACME: ThO

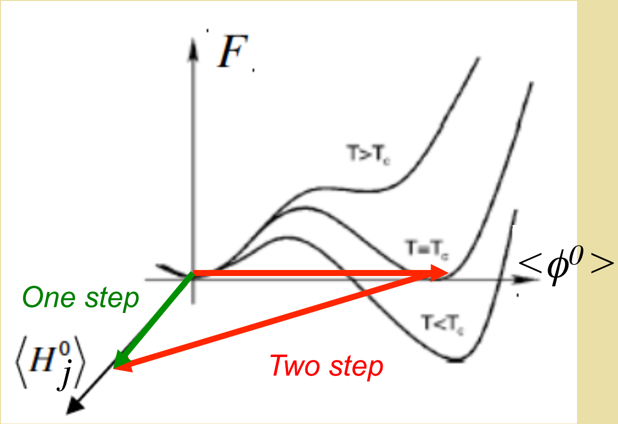
Next gen d_e

Li, Profumo, RM '09-'10

Compressed spectrum

EW Multiplets: Two-Step EWPT





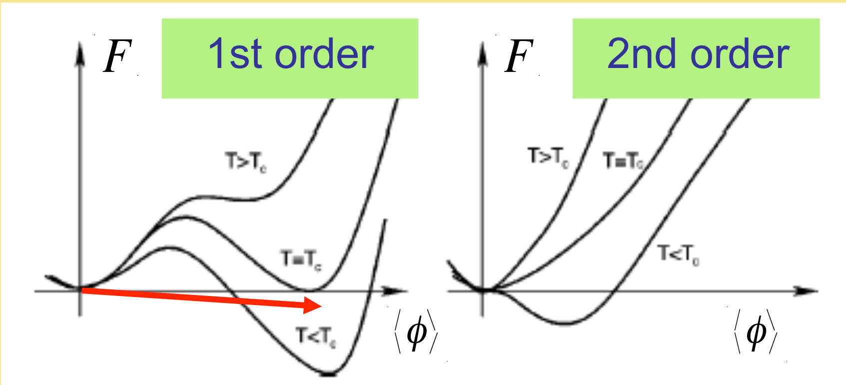
Increasing m_h →

← *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



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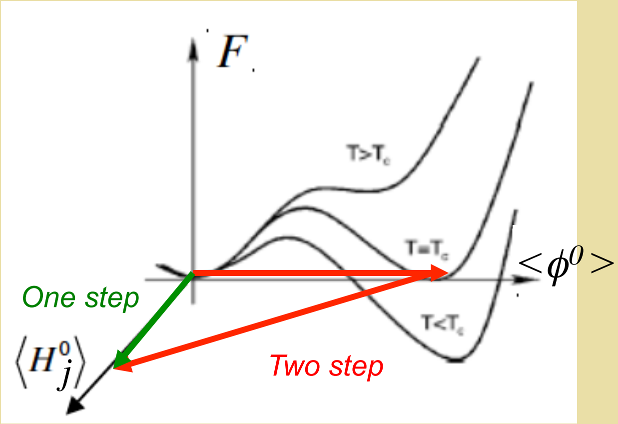
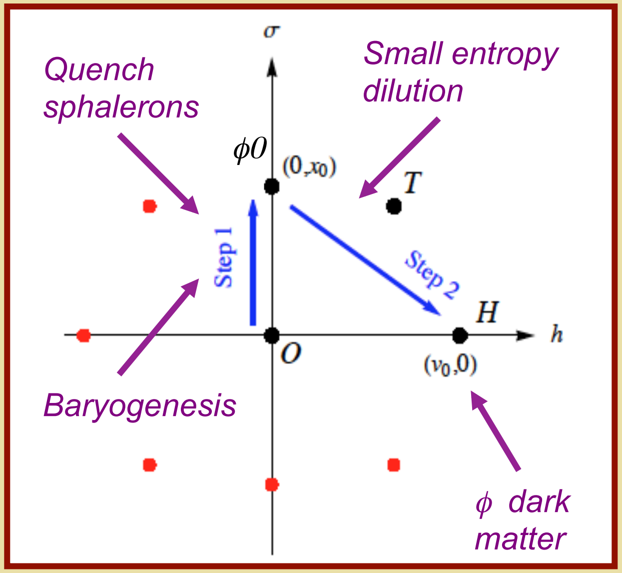
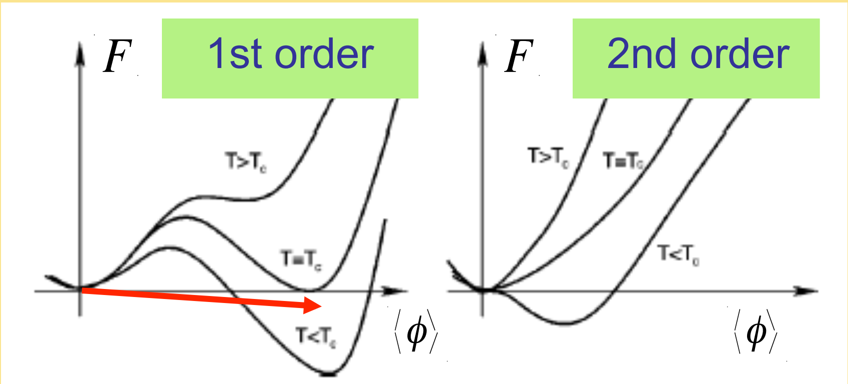
- *Step 1: thermal loops*
- *Step 2: tree-level barrier*





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

EW Multiplets: Two-Step EWPT

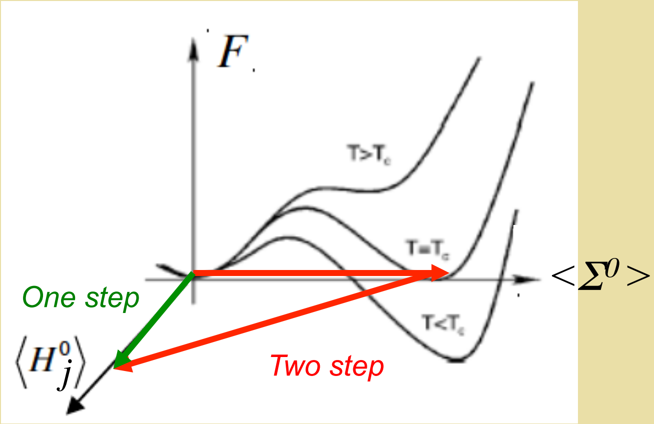


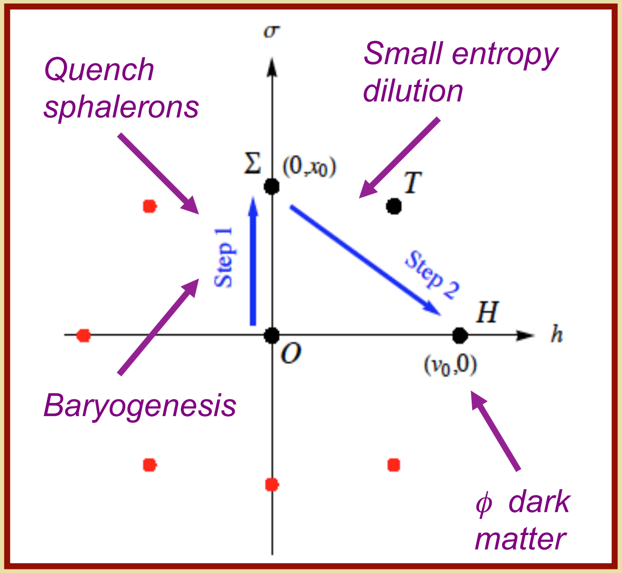
Increasing m_h →

← *New scalars*

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

Two-step EWPT & dark matter





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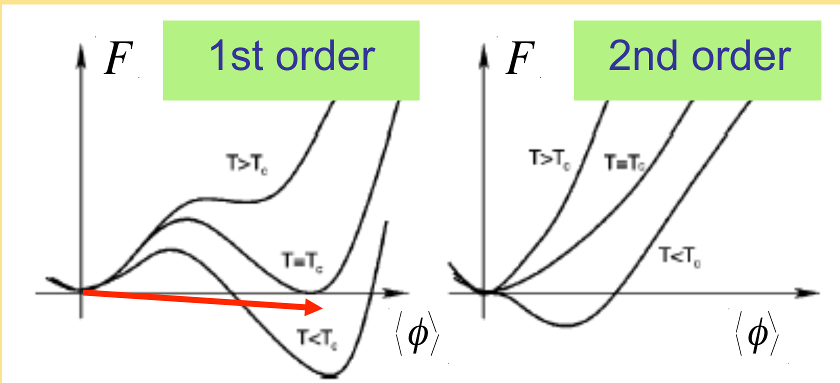
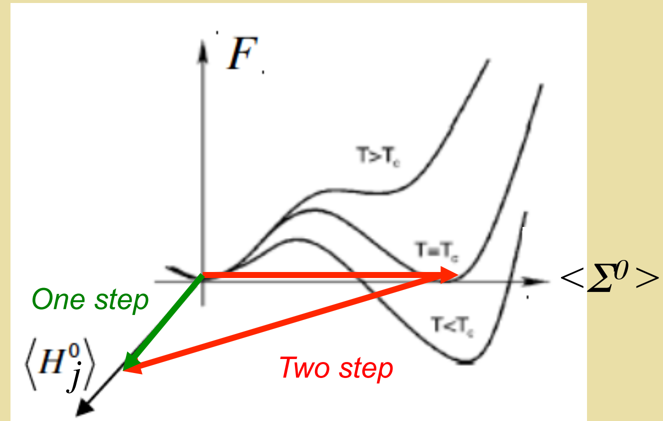
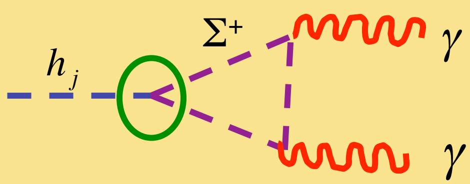
EW Multiplets: Two-Step EWPT

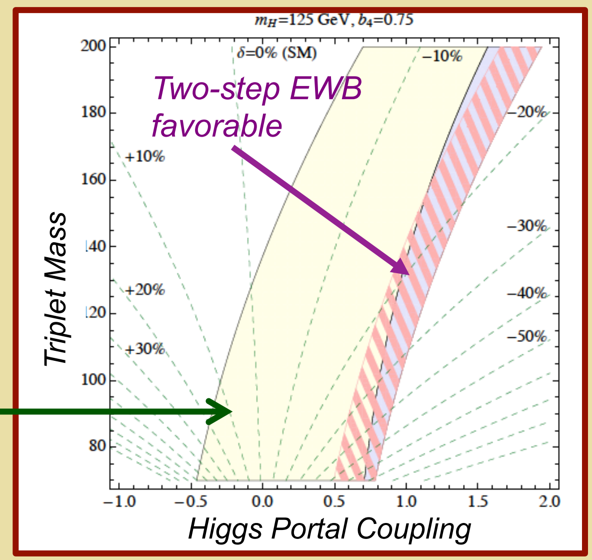




Increasing m_h

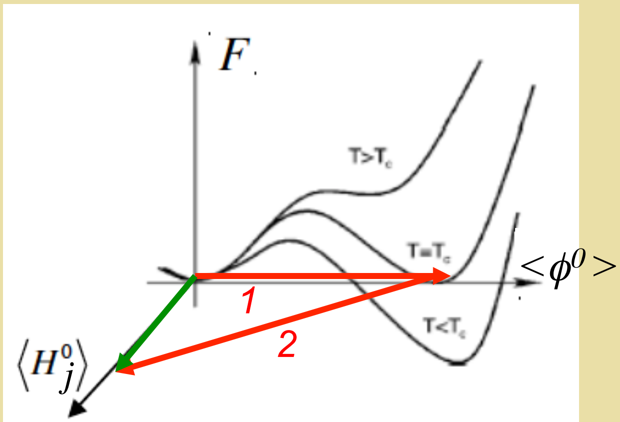
New scalars





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"*

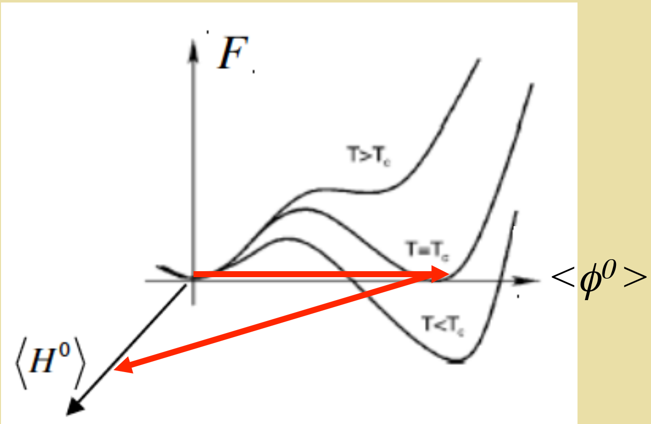
Conventional one step EWSB

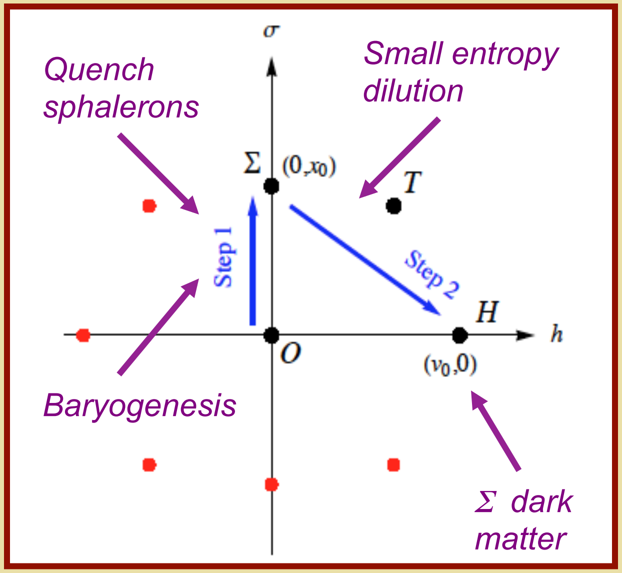
Two step EWSB

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

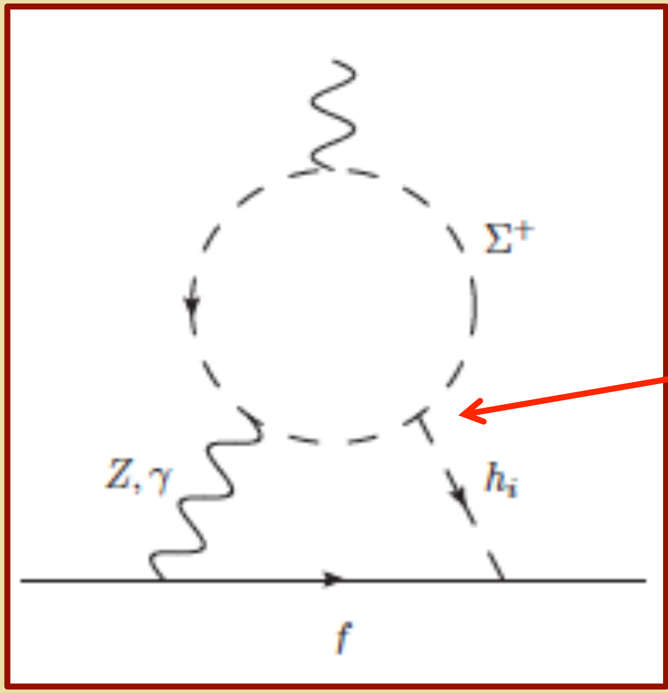
$H \to$ *Set of "SM" fields: 2 HDM*

(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

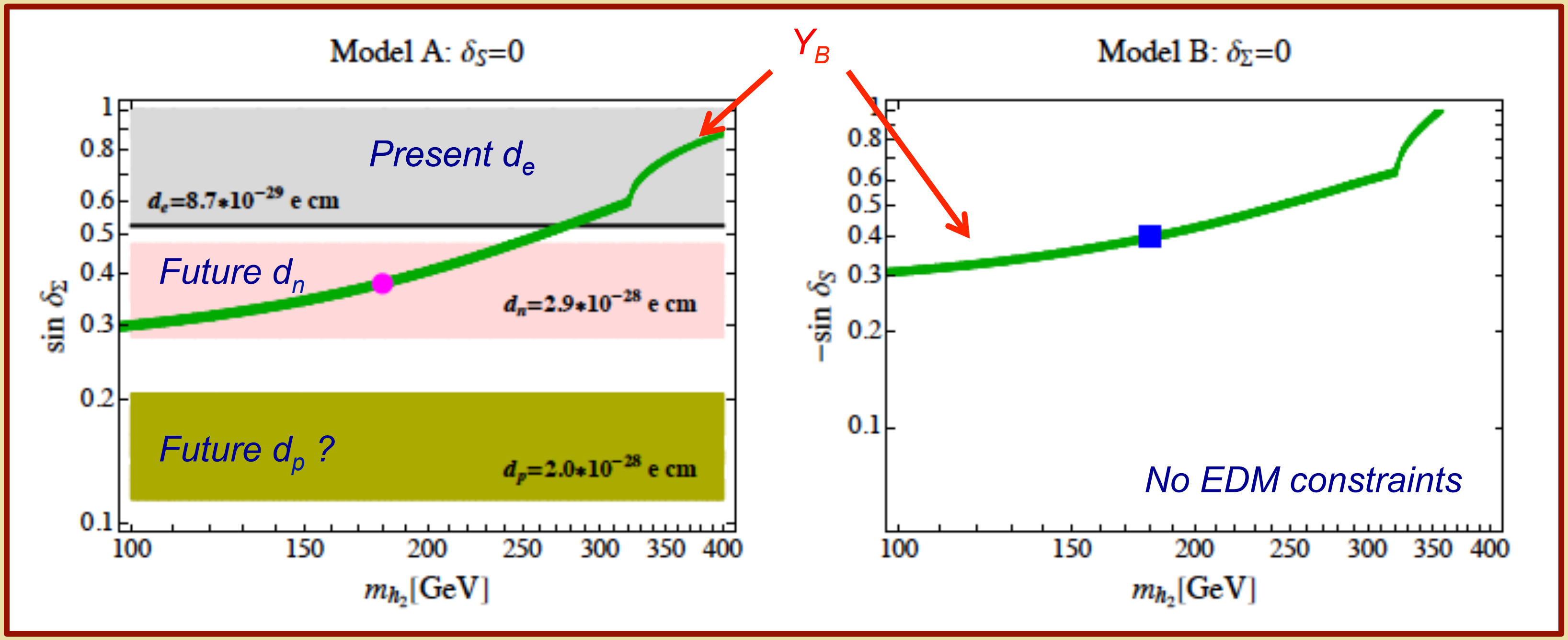
δ_S : Singlet phase

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

Inoue, Ovanesyan, R-M: 1508.05404

Two-Step EW Baryogenesis

Two cases: (A) δ_S = 0 (B) δ_Σ =0



Inoue, Ovanesyan, R-M: 1508.05404

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:*

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

What is the CP Nature of the Higgs Boson ?

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

- *New parameters:*

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

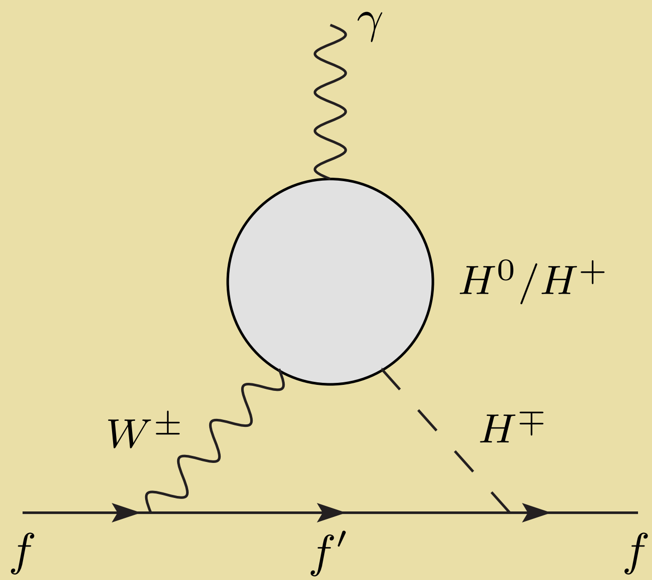
$$\boxed{\sin\alpha_b}$$

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

Higgs Portal CPV

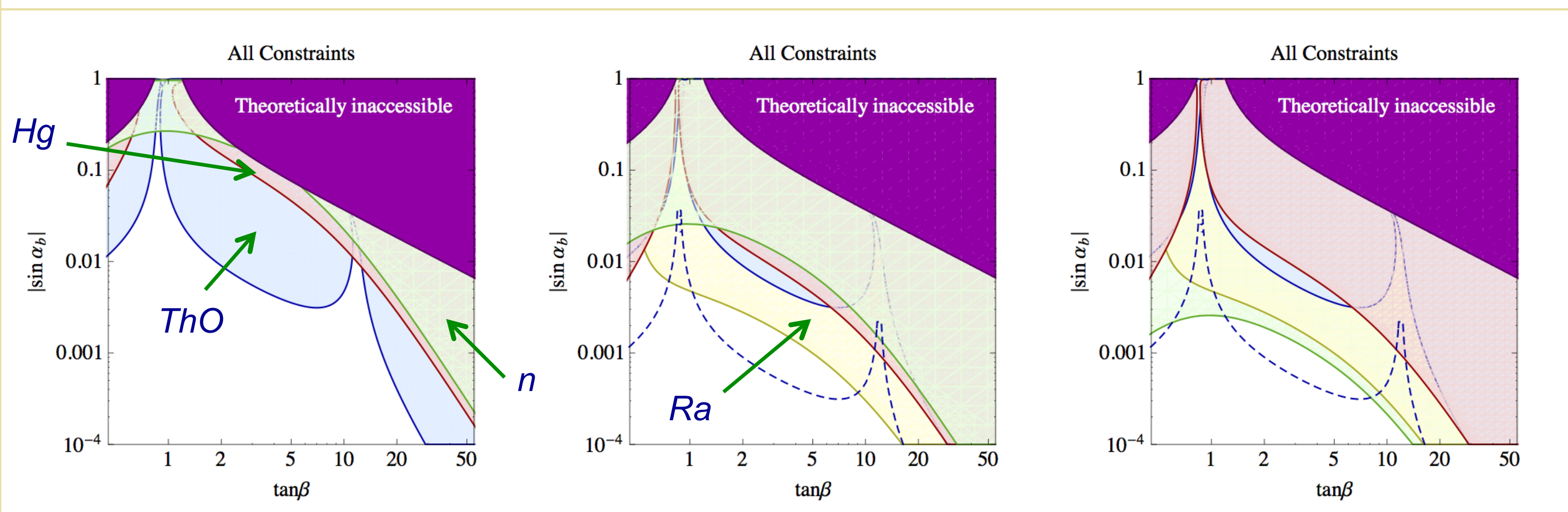
Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II



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)

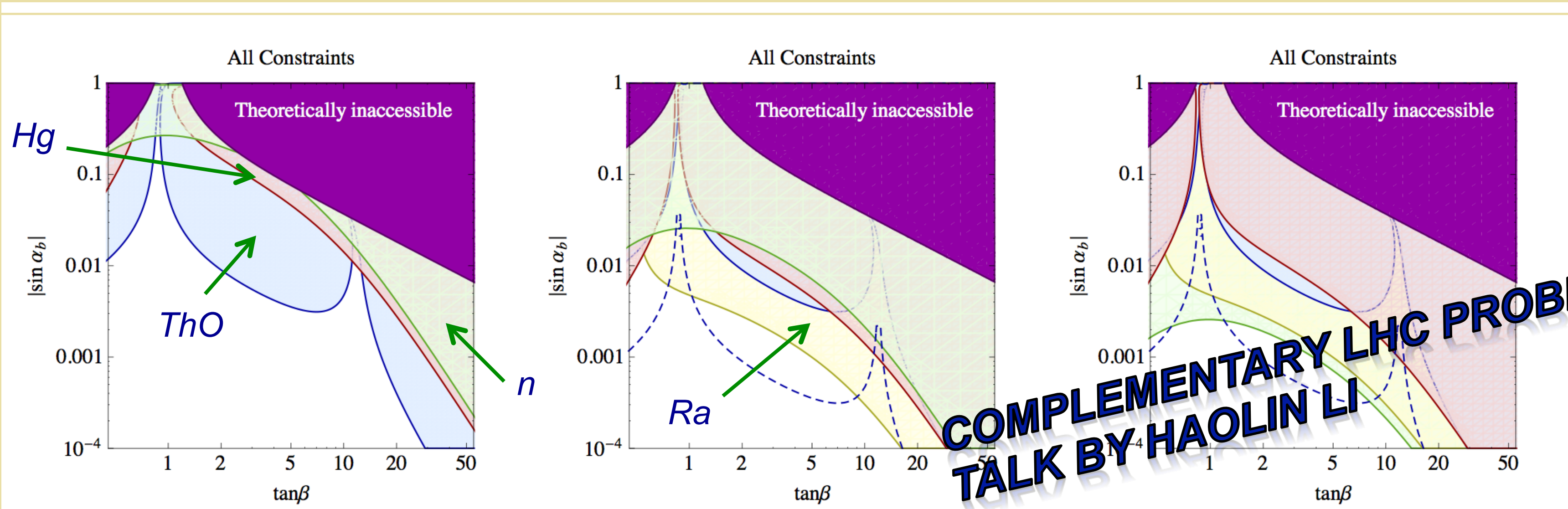
$\sin\alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs

CPV & 2HDM: Type II illustration

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



COMPLEMENTARY LHC PROBES: TALK BY HAOLIN LI

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)

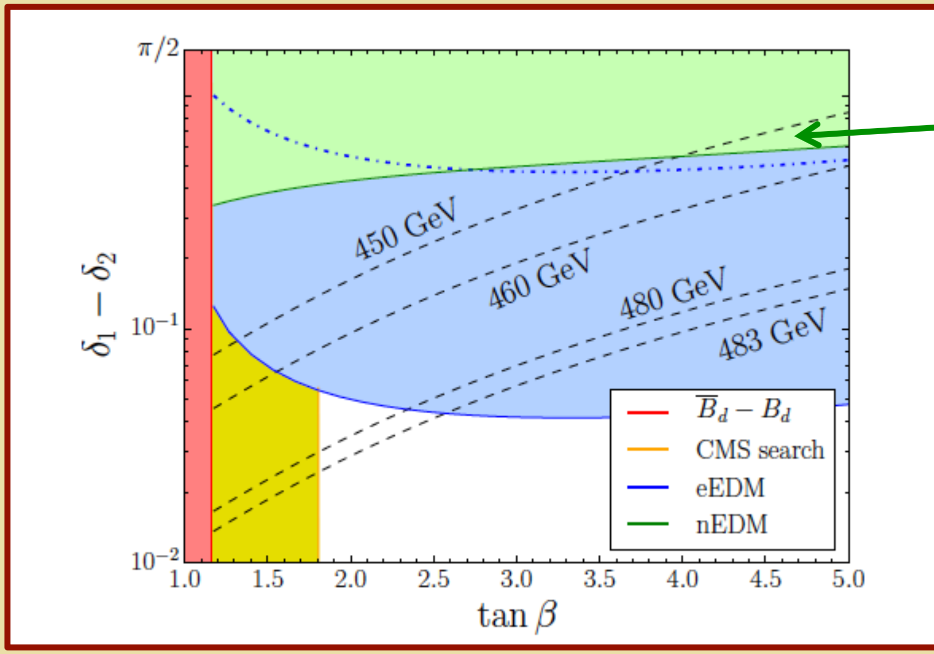
sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Low-Energy / High-Energy Interplay

Higgs Portal CPV: Source for EWBG?

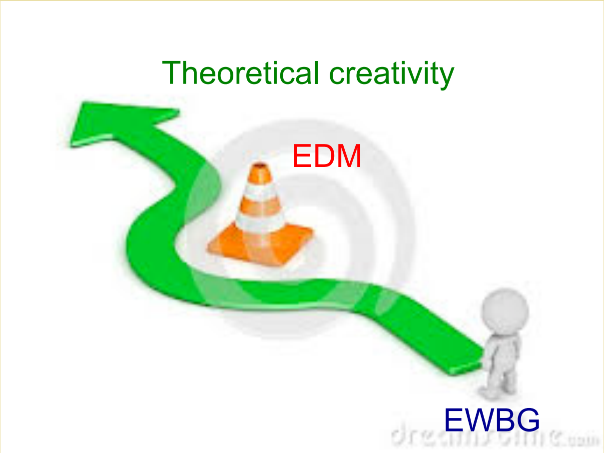
Dorsch et al, 1611.05874



EWBG viable

$$\alpha_b \propto \delta_1 - \delta_2$$

CPV for EWBG



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[**]*
- *Analysis of EDM implications of other baryogenesis scenarios is an important and interesting topic $\rightarrow$ Many interesting discussions during remainder of this WS*

*** + gravitational waves, flavor physics*

Back Up Slides

Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

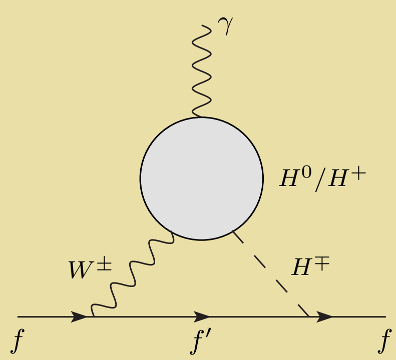
$\lambda_{6,7}$ = 0 for simplicity

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

$$
\begin{aligned}
\delta_1 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \ , \\
\delta_2 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right]
\end{aligned}
\quad \xrightarrow{\text{EWSB}} \quad
\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1
$$

h, H^0, A^0 $\rightarrow$ $h_{1,2,3}$

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



Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

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

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

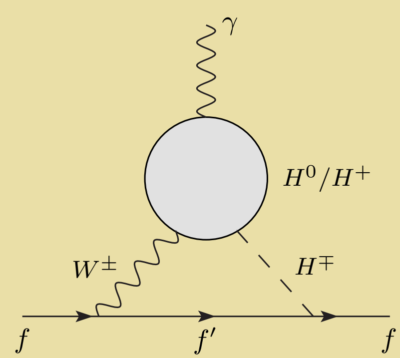
$$\begin{aligned} \delta_1 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \ , \\ \delta_2 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)v_1v_2^*\right] \end{aligned}$$

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 $\rightarrow$ $h_{1,2,3}$

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

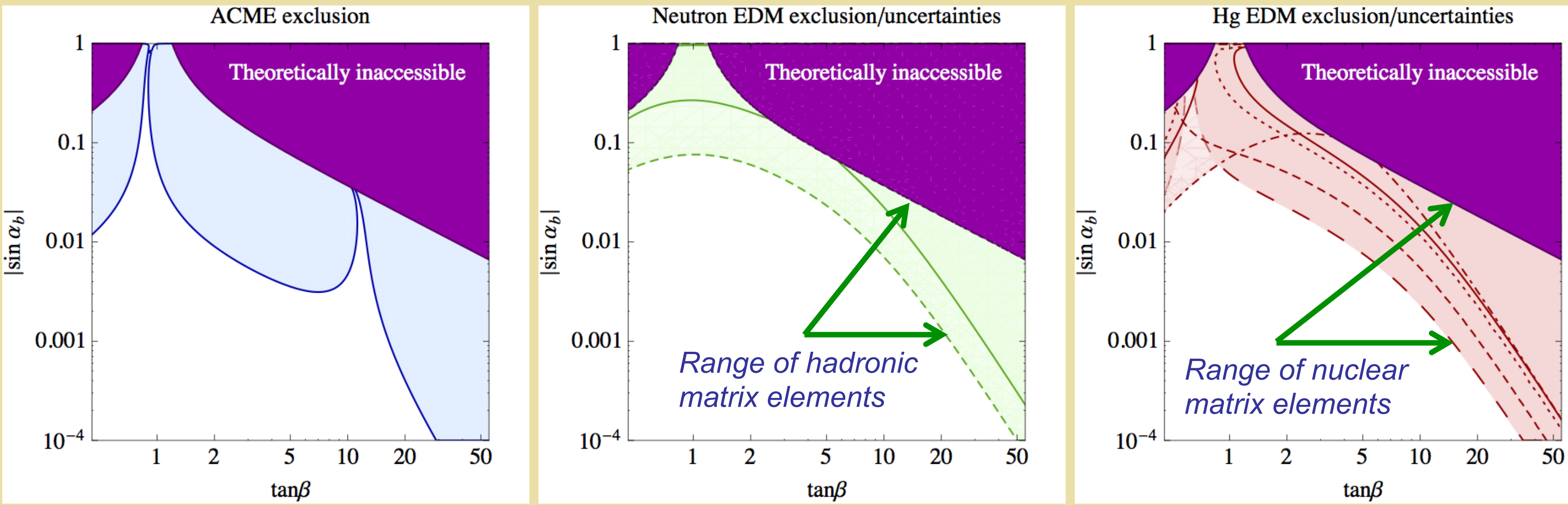


CP mixing: α_b & α_c not independent

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



Present

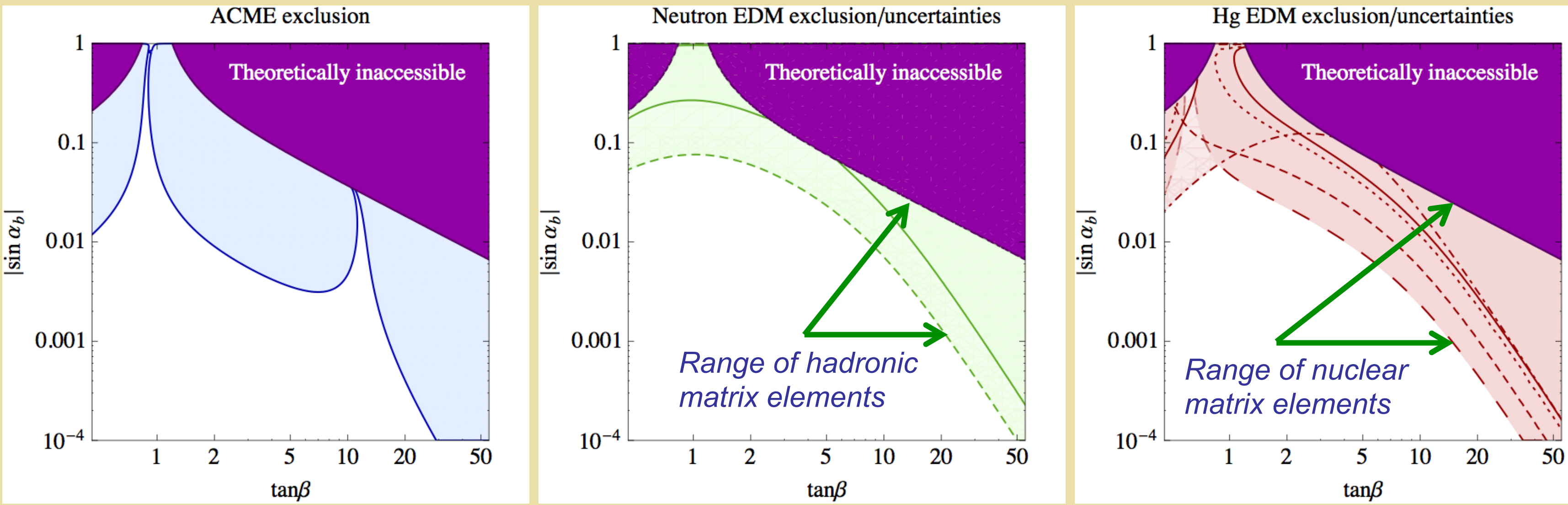
$\sin \alpha_b$: CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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



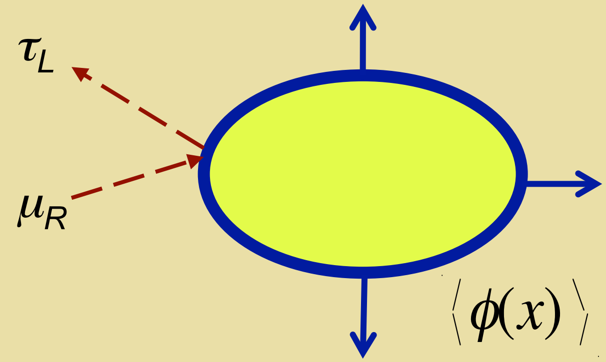
Present

Challenge

sin α_b : CPV scalar mixing

Inoue, R-M, Zhang: 1403.4257

Flavored EW Baryogenesis



Flavor basis (high T)

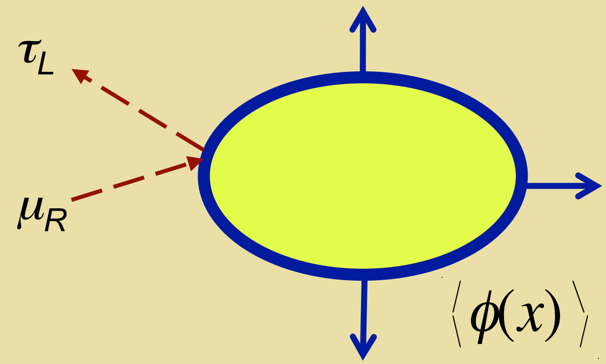
$$\mathscr{L}^{\rm Lepton}_{\rm Yukawa} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

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

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

T=0 Higgs couplings

Im (y_τ) ~ Im (J_A)

EWBG CPV Source

S^{CPV} ~ Im (J_A)

Flavor basis (high T)

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

Mass basis (T=0)

CPV $h \to \tau\tau$

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

Guo, Li, Liu, R-M, Shu 1609.09849
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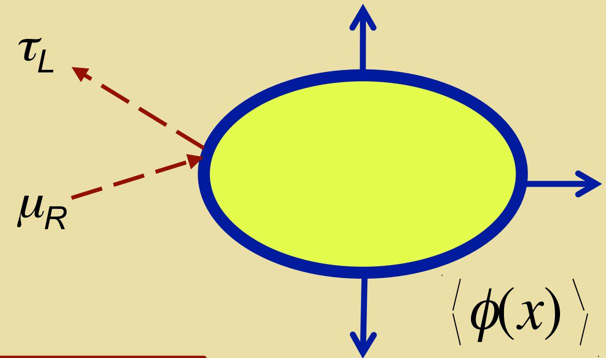
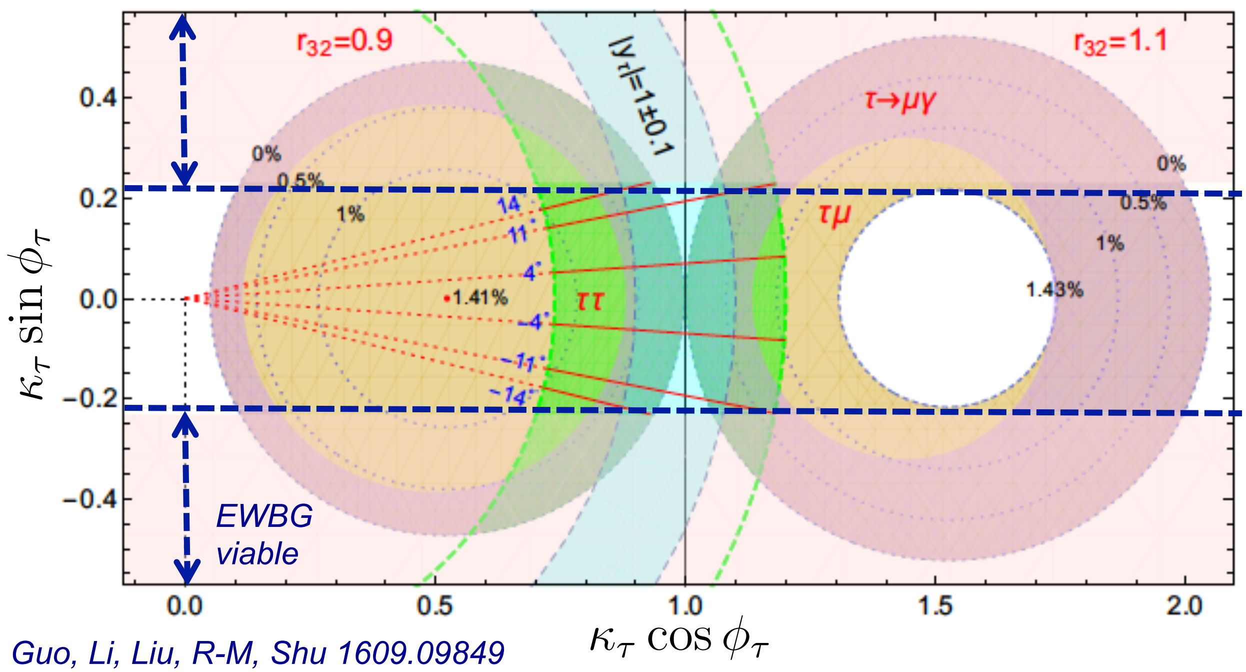
Flavored EW Baryogenesis





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

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

3 ab^{-1} @ LHC 14