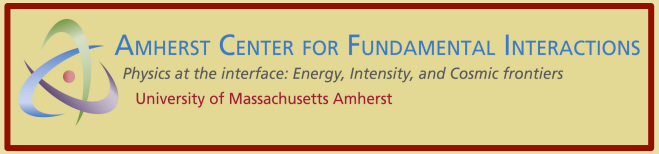
Baryogenesis

M.J. Ramsey-Musolf

U Mass Amherst



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

SUSY 16, Melbourne
July 2016

Cosmic Baryon Asymmetry

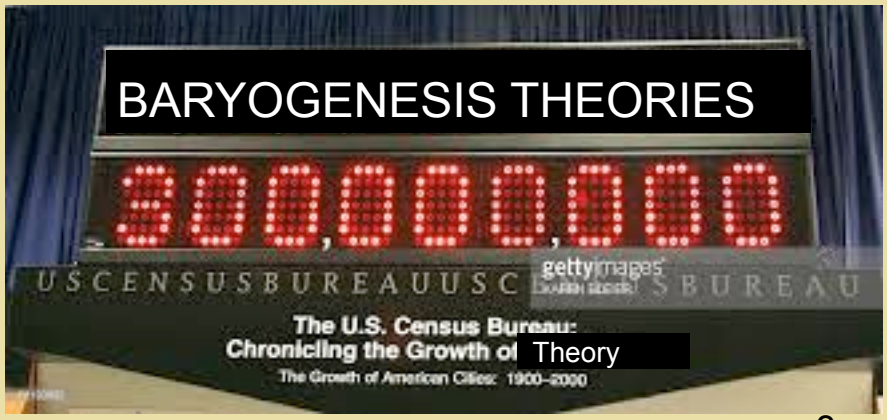
$$Y_B = \frac{n_B}{s} = (8.82 \pm 0.23) \times 10^{-11}$$

One number $\rightarrow$ BSM Physics

Cosmic Baryon Asymmetry

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

One number → ~~N~~ ~~N~~ ~~N~~ … Explanations



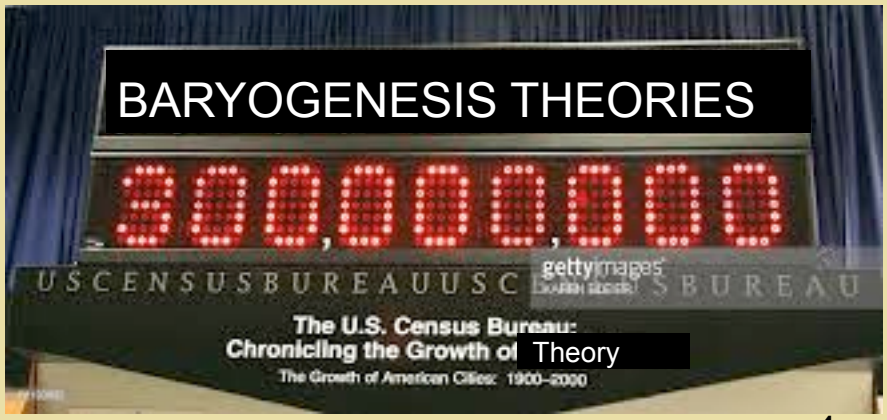
Cosmic Baryon Asymmetry

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

One number → ~~N~~ ~~N~~ ~~N~~ … Explanations

Experiment can help:

- *Discover ingredients*
- *Falsify candidates*



Ingredients for Baryogenesis

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

Ingredients for Baryogenesis

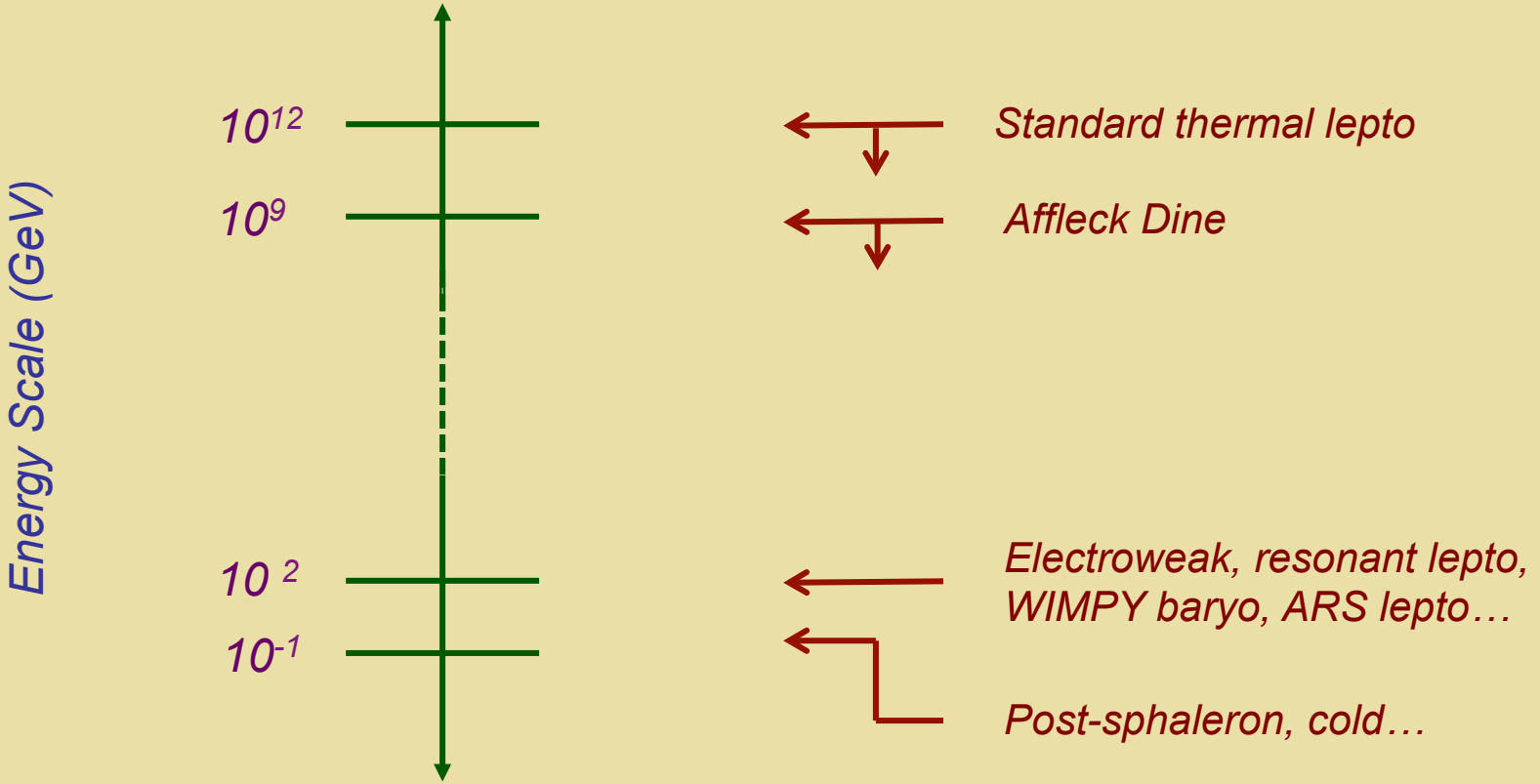
	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

Ingredients for Baryogenesis

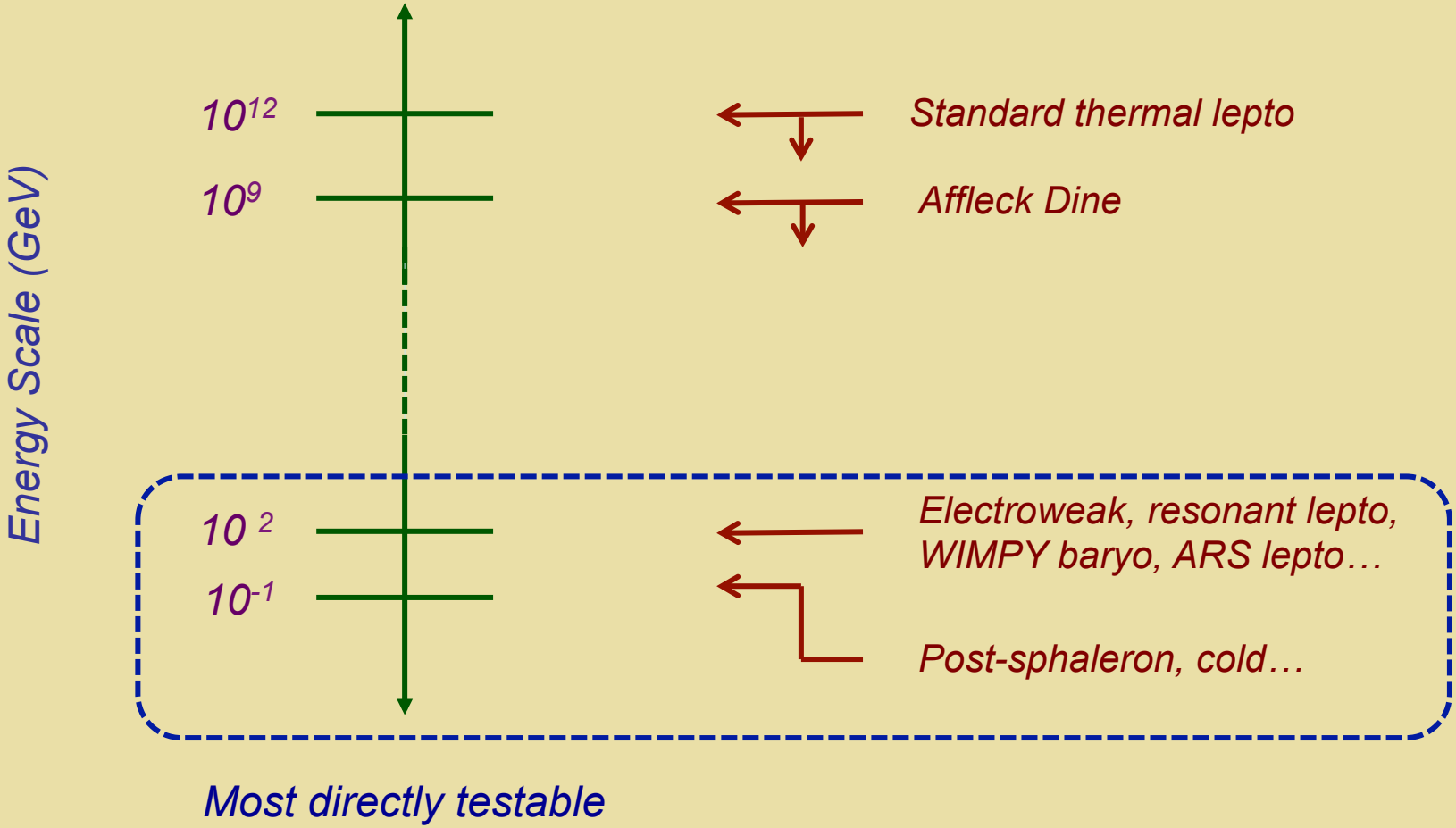
Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

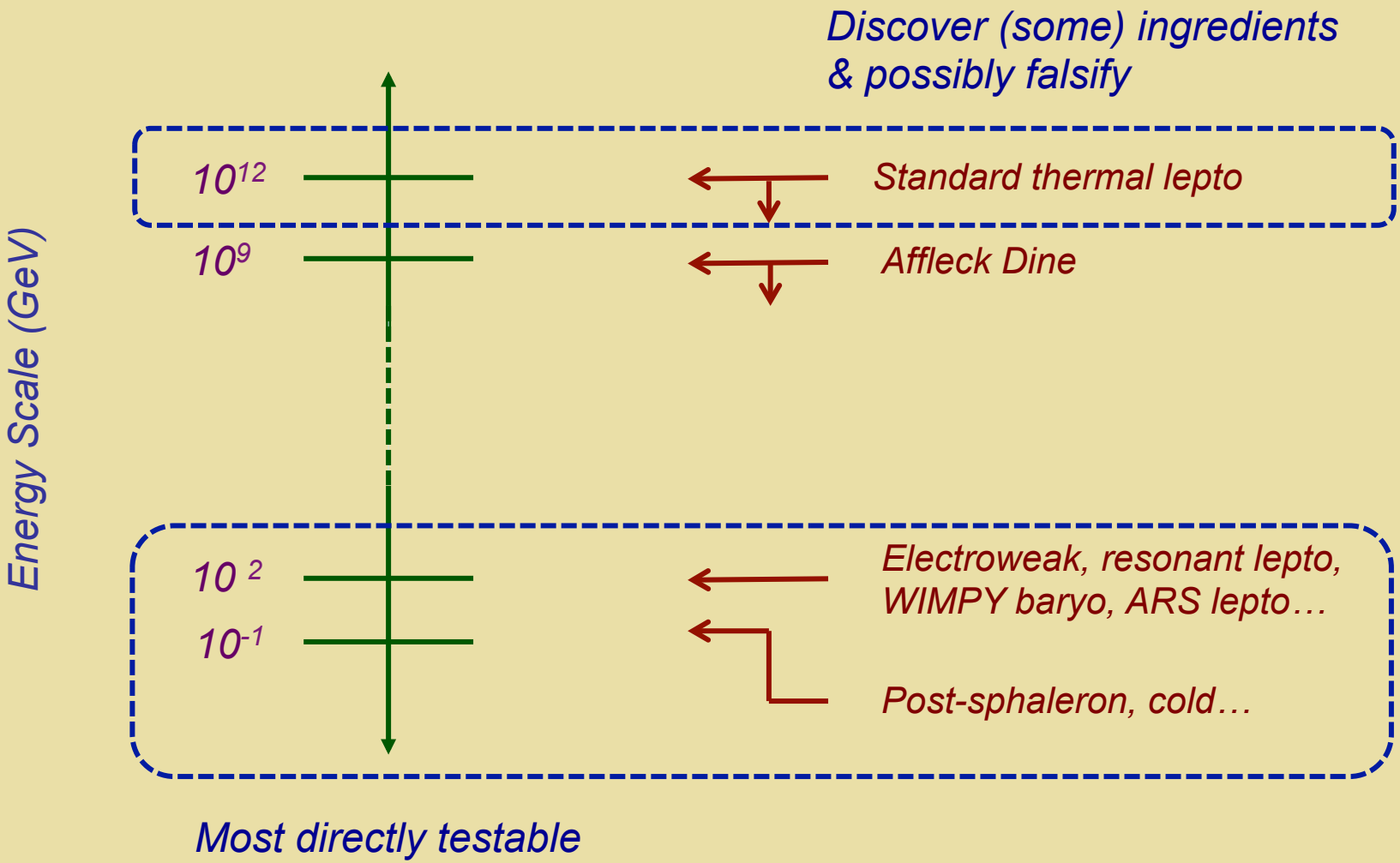
Baryogenesis Scenarios



Baryogenesis Scenarios



Baryogenesis Scenarios



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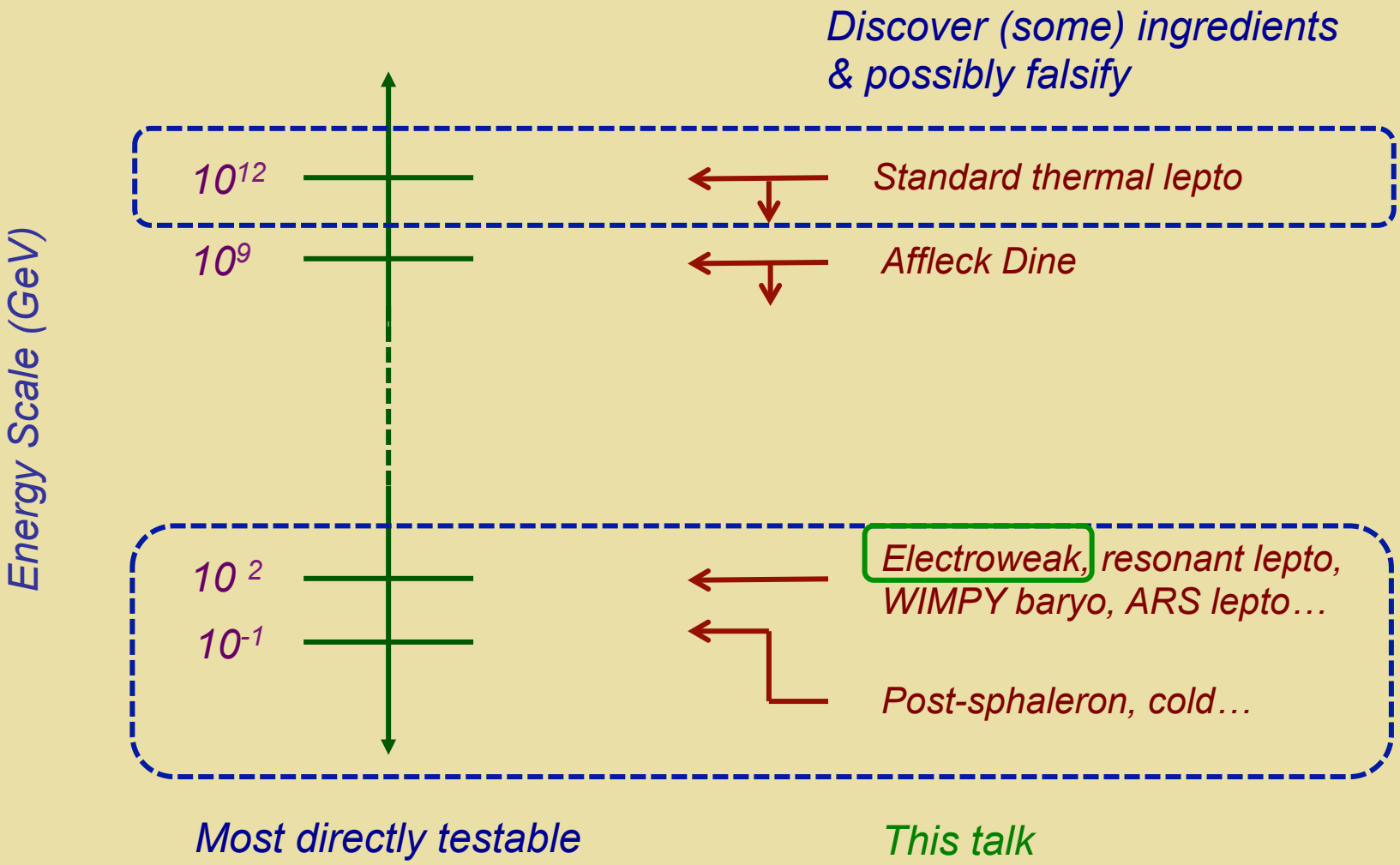


Electroweak Baryogenesis

Was Y_B generated in conjunction with electroweak symmetry-breaking?

Outline

I. Electroweak Baryogenesis in a Nutshell

II. Electroweak Phase Transition

III. CPV: the Baryon Asymmetry & EDMs

IV. Outlook

Outline

I. Electroweak Baryogenesis in a Nutshell

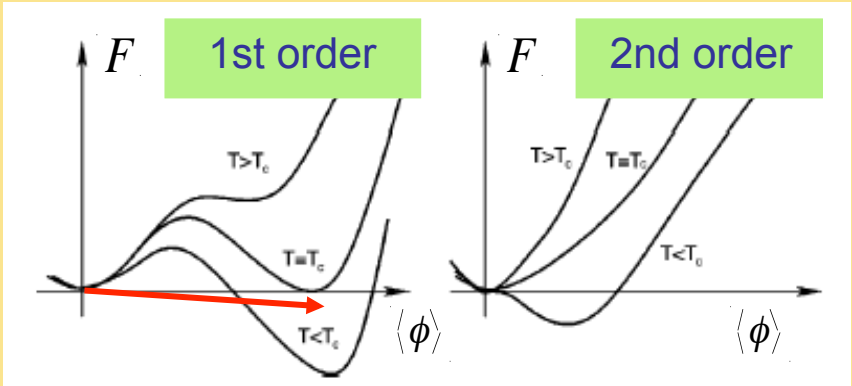
II. Electroweak Phase Transition *Time permitting*

III. CPV: the Baryon Asymmetry & EDMs

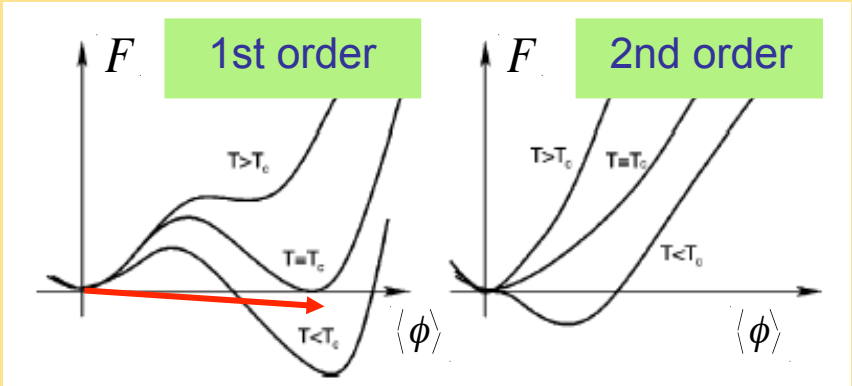
IV. Outlook

I. EWB in a Nutshell

EW Phase Transition: New Scalars & CPV

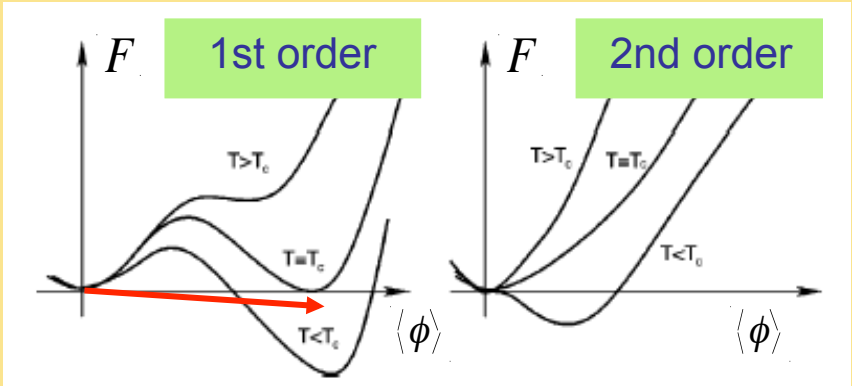


EW Phase Transition: New Scalars & CPV



Increasing m_h →

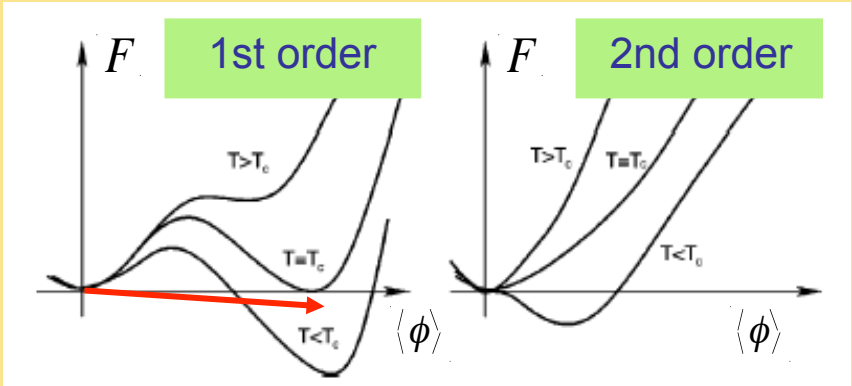
EW Phase Transition: New Scalars & CPV



Increasing m_h →

← *New scalars*

EW Phase Transition: New Scalars & CPV

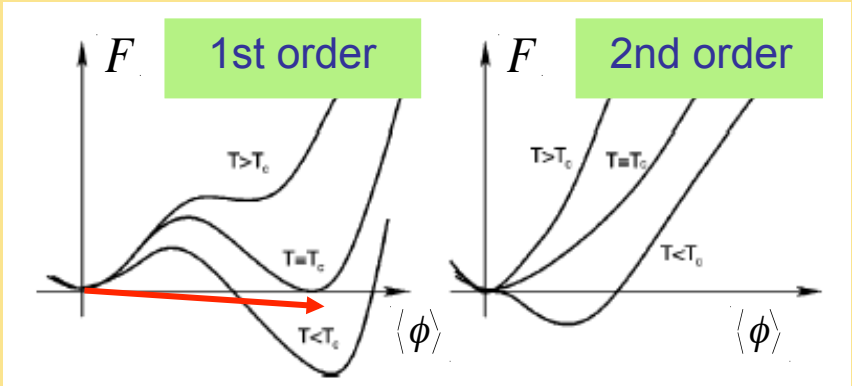


Increasing m_h →

← *New scalars*

- *Loop effects*
- *Tree-level barrier*

EW Phase Transition: New Scalars & CPV



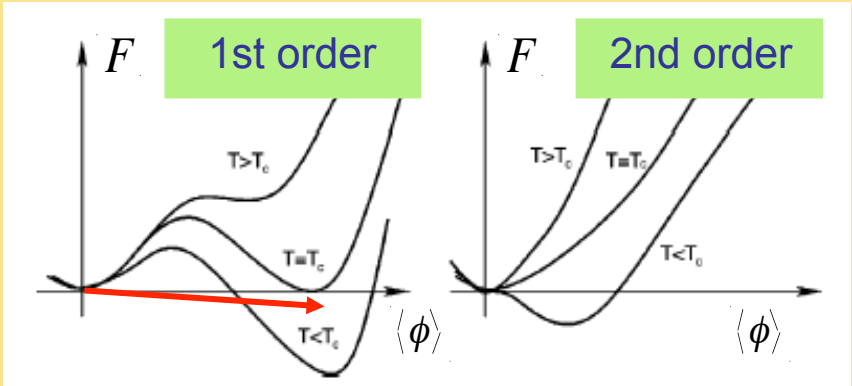
Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

EW Phase Transition: New Scalars & CPV

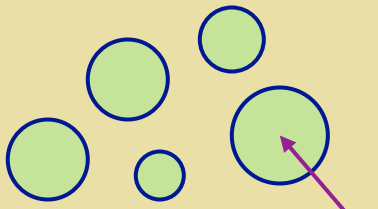


Increasing m_h →

← *New scalars*

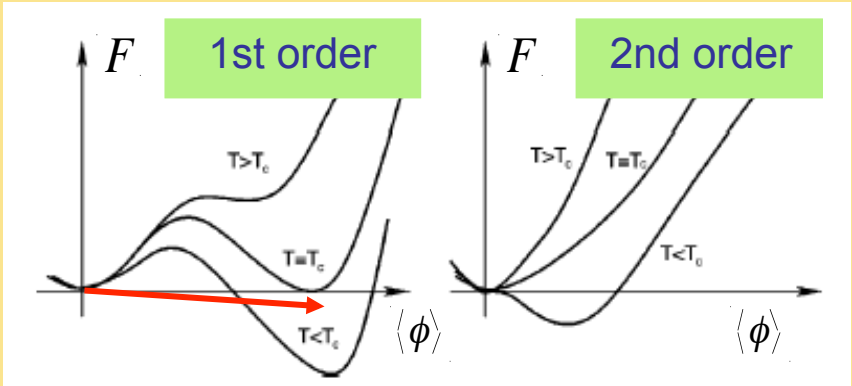
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1st order EWPT* → *Bubble nucleation*



EWSB

EW Phase Transition: New Scalars & CPV



Increasing m_h →

← *New scalars*

Baryogenesis
Gravity Waves
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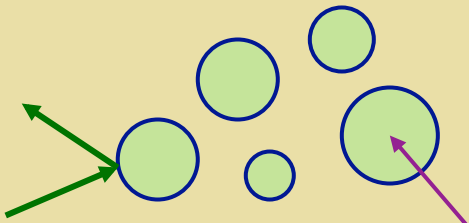
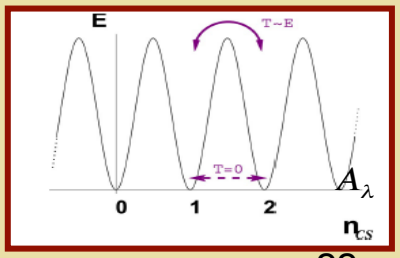
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*

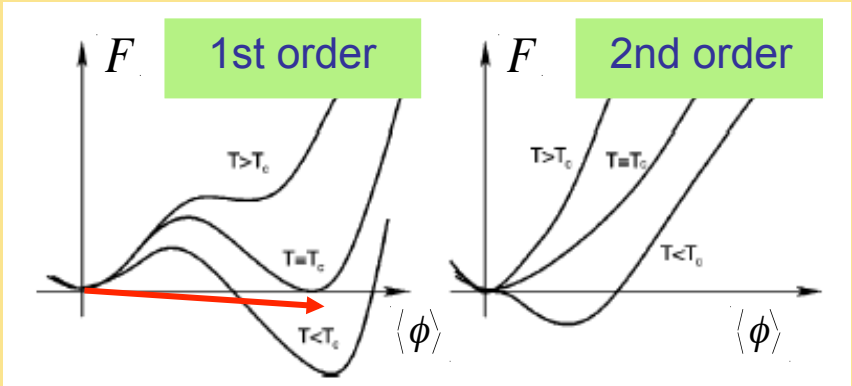


Y_B : CPV & EW sphalerons

EWSB



EW Phase Transition: New Scalars & CPV

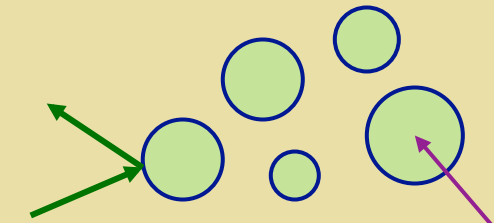


Increasing m_h →

← *New scalars*

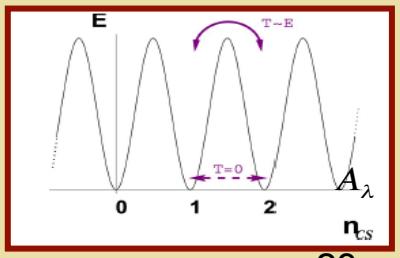
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*

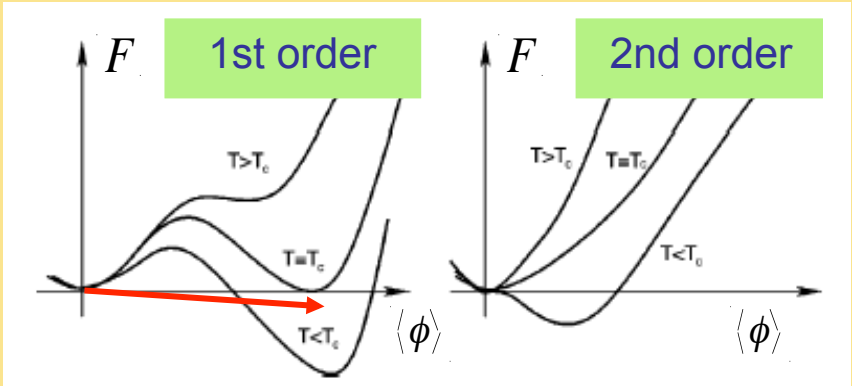


Y_B : CPV & EW sphalerons — **BSM**

EWSB



EW Phase Transition: New Scalars & CPV

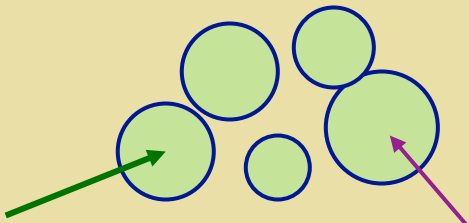


Increasing m_h →

← *New scalars*

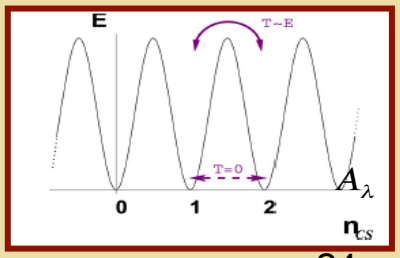
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*

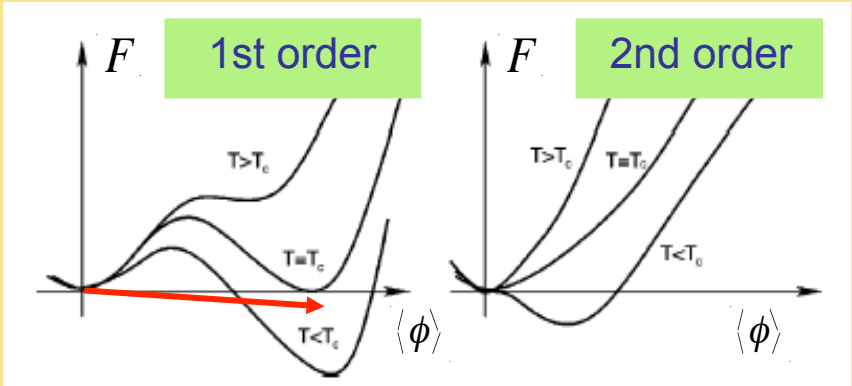


Y_B : diffuses into interiors

EWSB



EW Phase Transition: New Scalars & CPV



Increasing m_h →

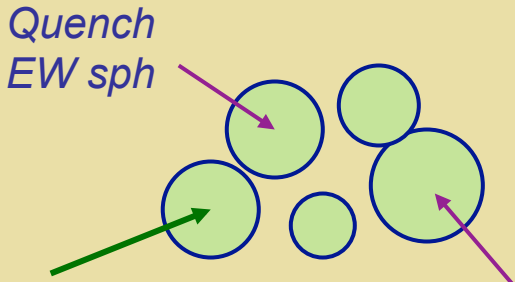
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" | *1st order EWPT*

Preserve $Y_B^{initial}$

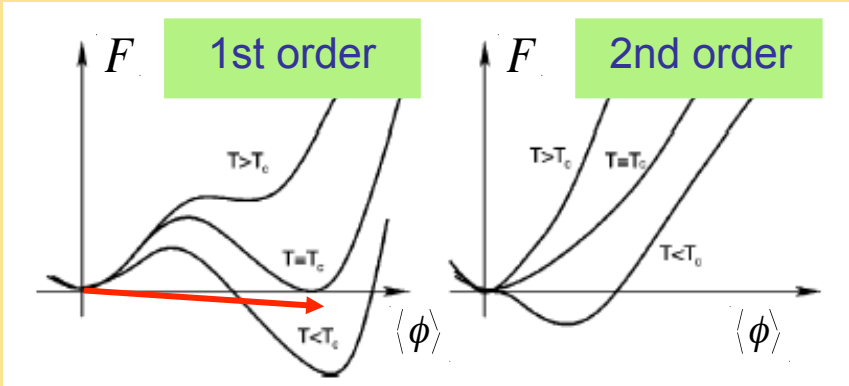
Bubble nucleation



II. Electroweak Phase Transition

Conditions for Electroweak Baryogenesis ?

EW Phase Transition: St'd Model



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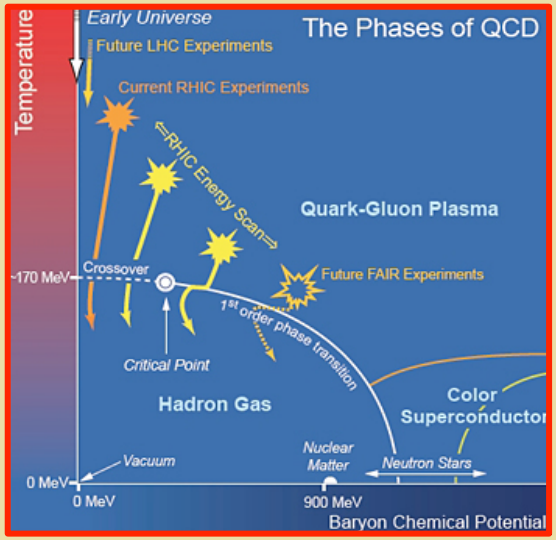
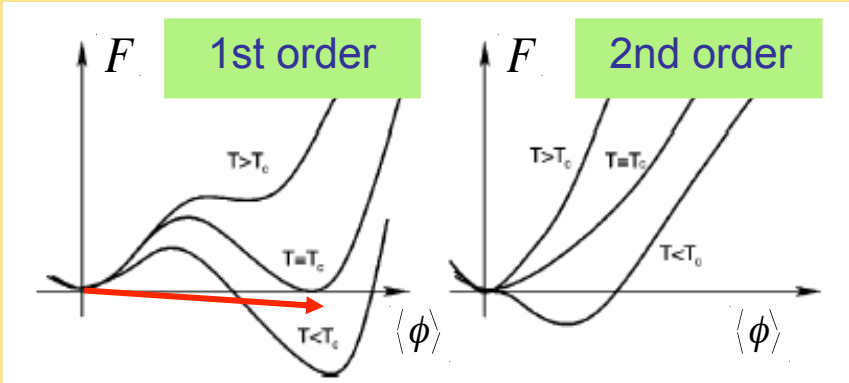


QCD Phase Diagram

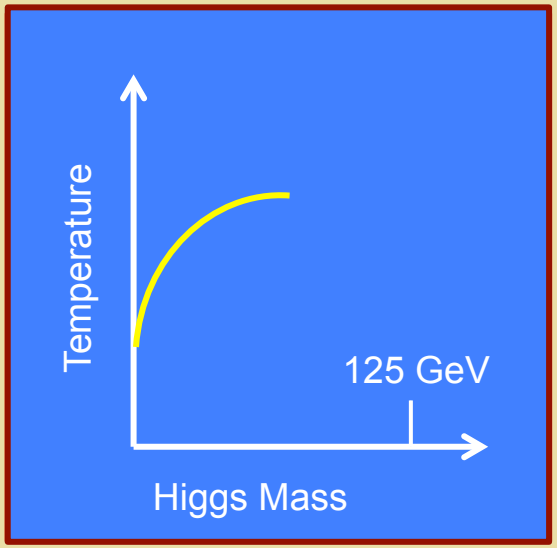
EW Phase Transition: St'd Model



Increasing m_h ⟶

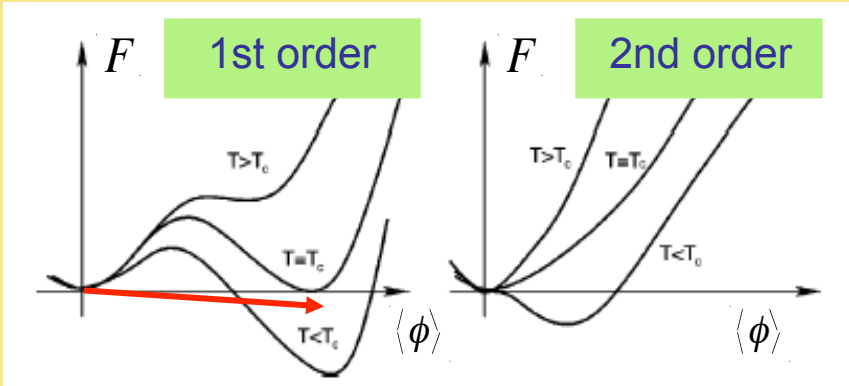
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

EW Phase Transition: St'd Model



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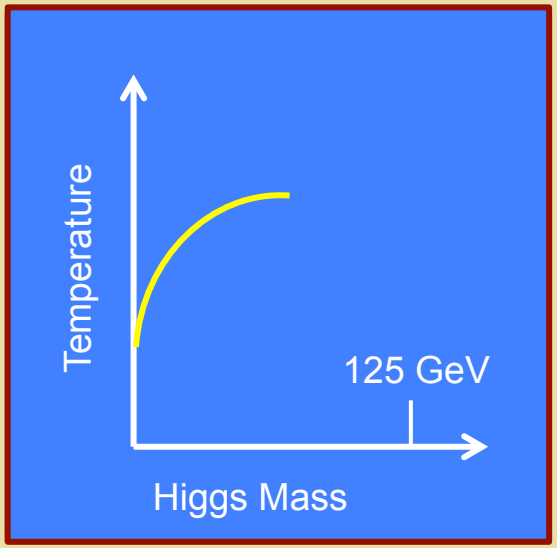
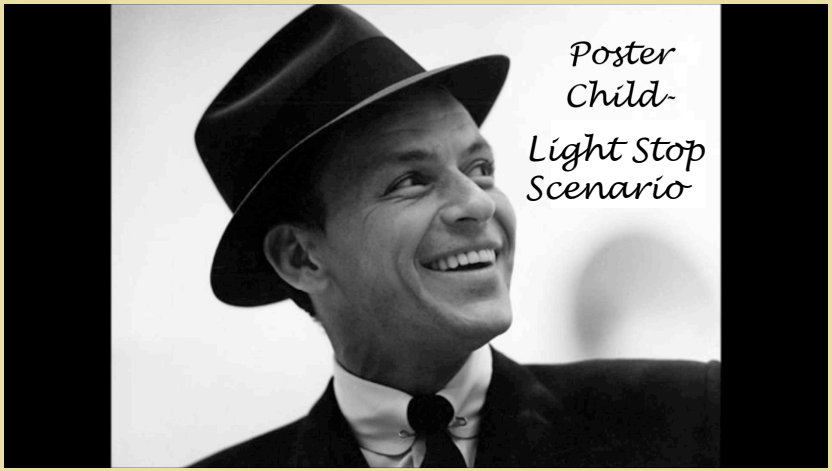


EW Phase Diagram

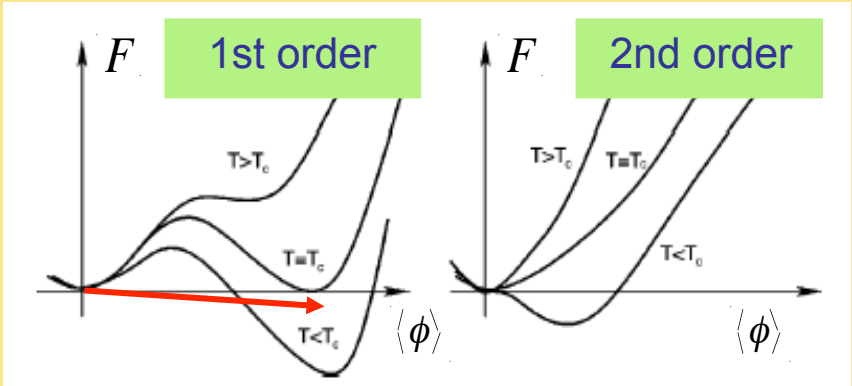
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ?

EWPT "Poster Child": MSSM Light Stop Scenario



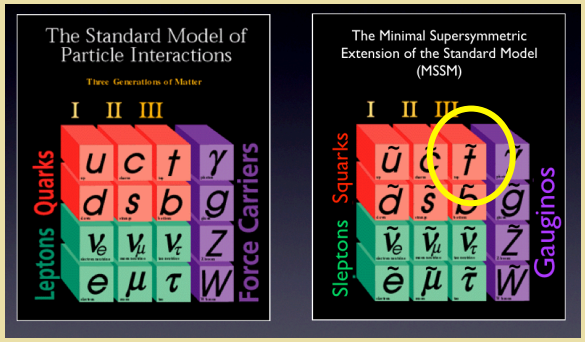
Thermal loops

EW Phase Transition: SUSY



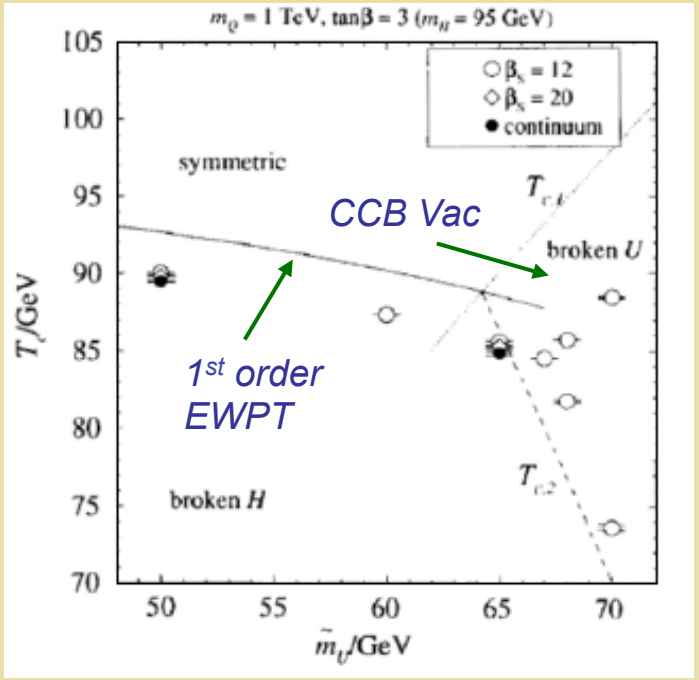
Increasing m_h →

← *New scalars*



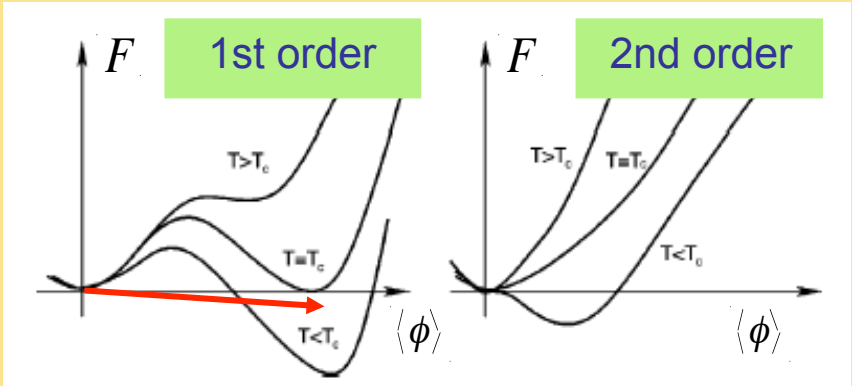
MSSM: Light Stop Scenario

Lattice: Laine, Rummukainen



Decreasing RH stop mass →

EW Phase Transition: SUSY



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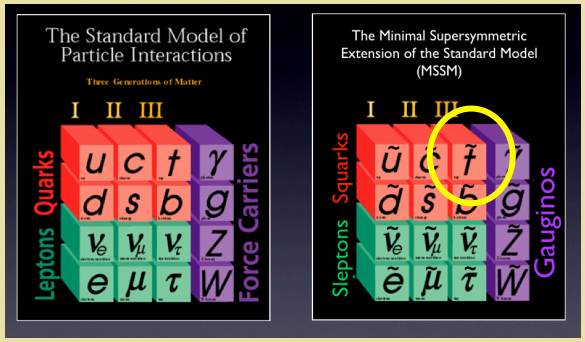

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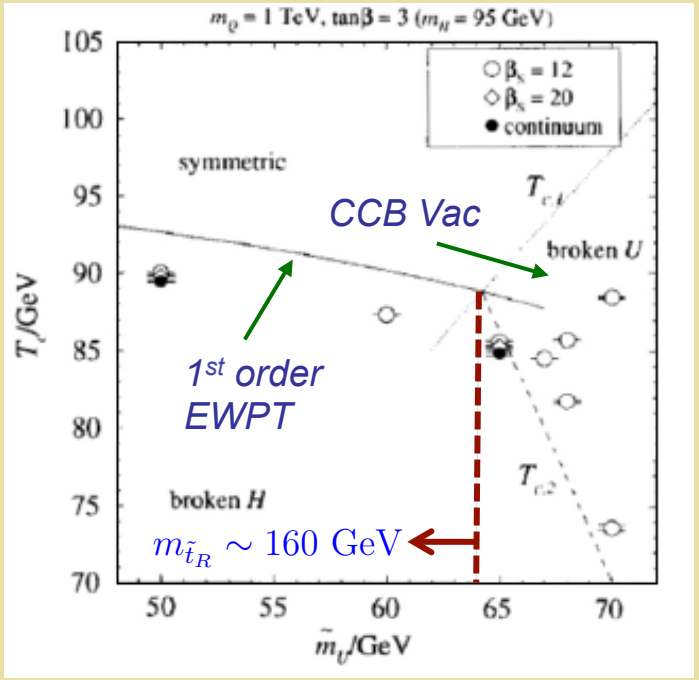

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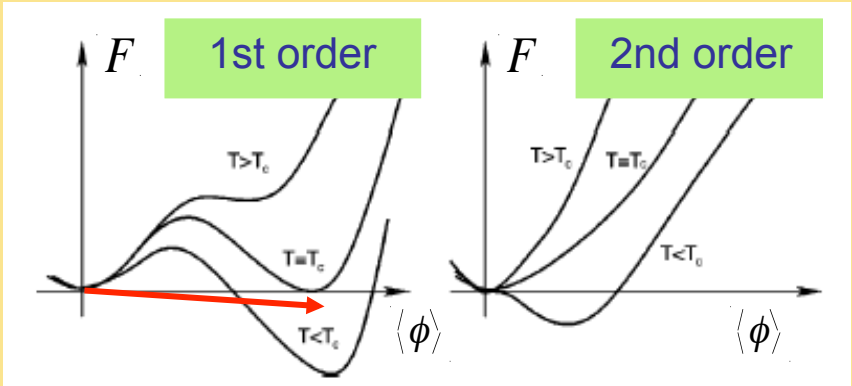
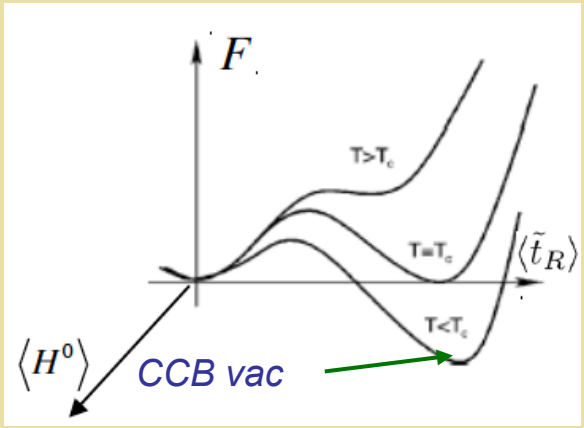


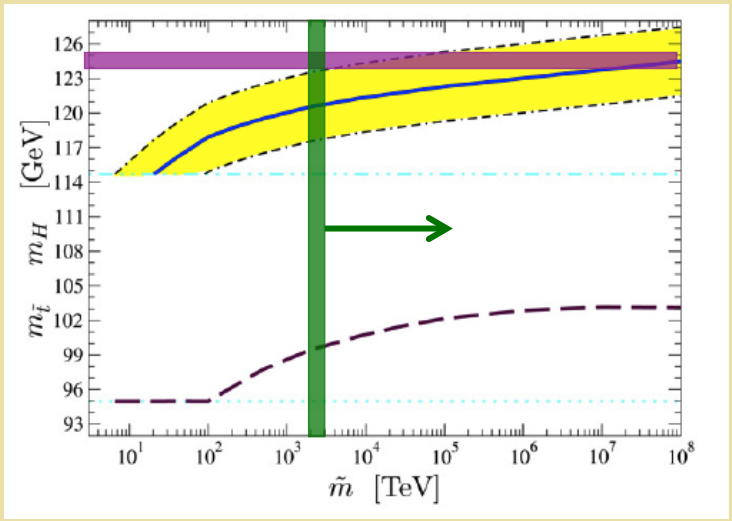


Increasing m_h →

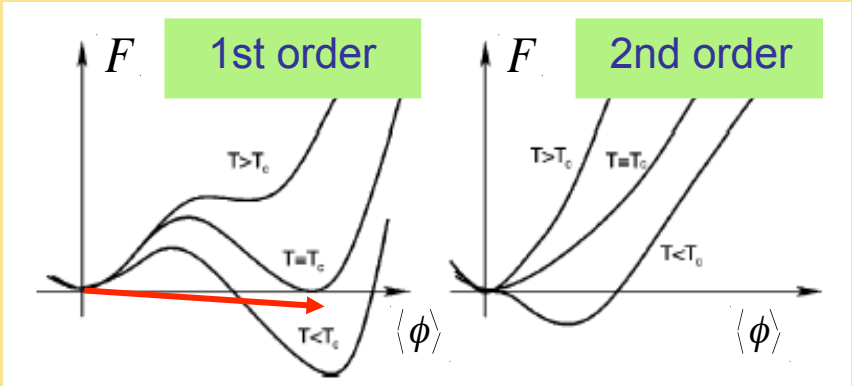
← *New scalars*

MSSM: Light RH stops

Carena et al 2008: MSSM strong 1st order EWPT: RH stop mass < 105 GeV



EW Phase Transition: MSSM



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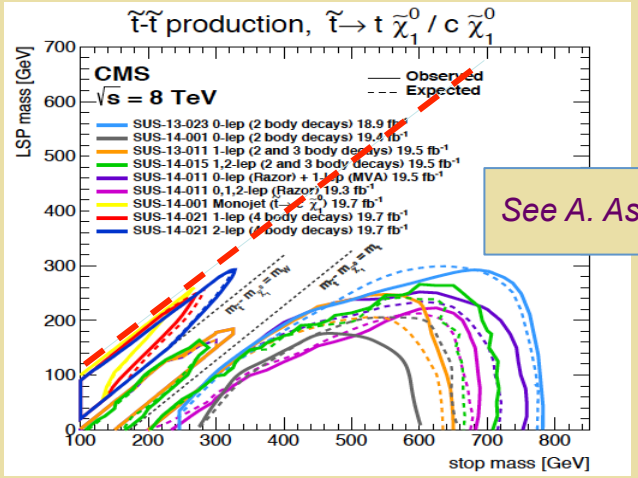
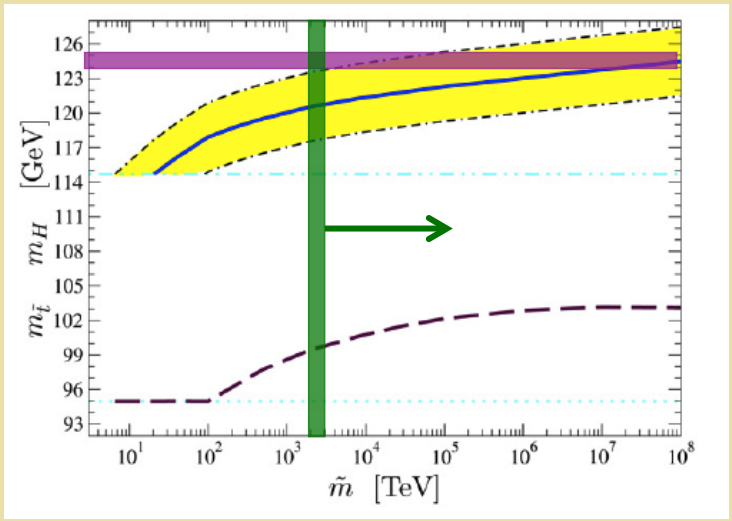
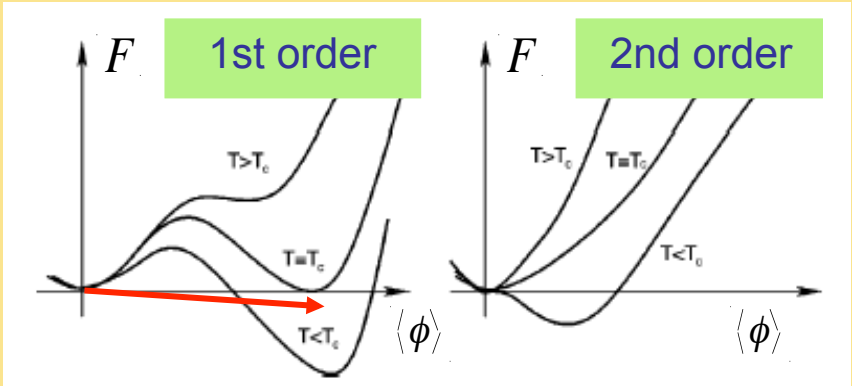


See A. Askew talk



EW Phase Transition: MSSM



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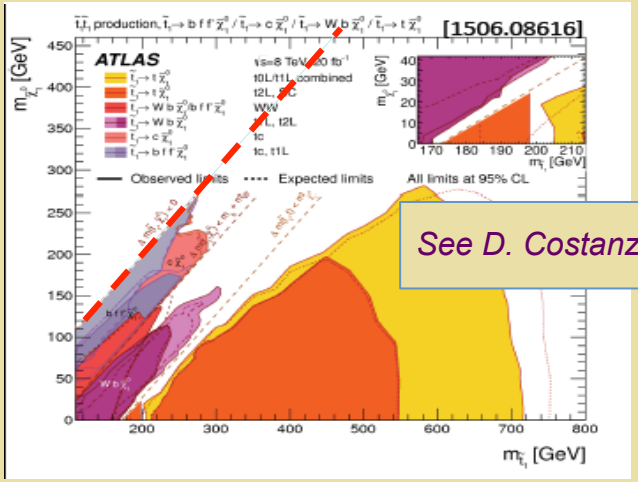
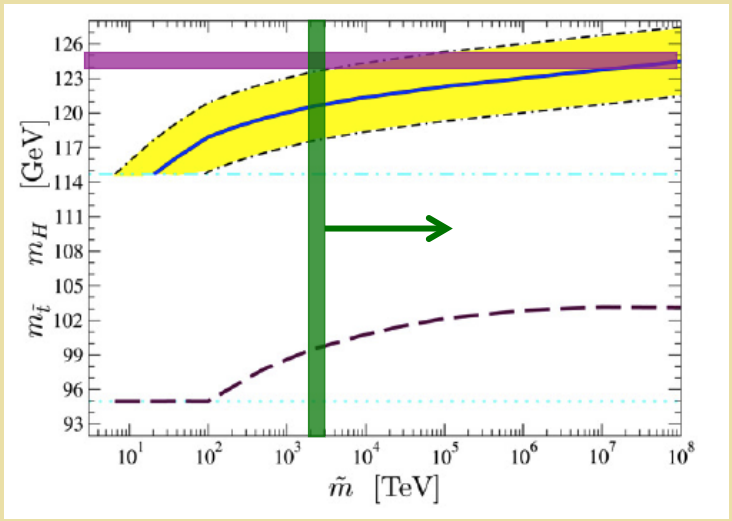
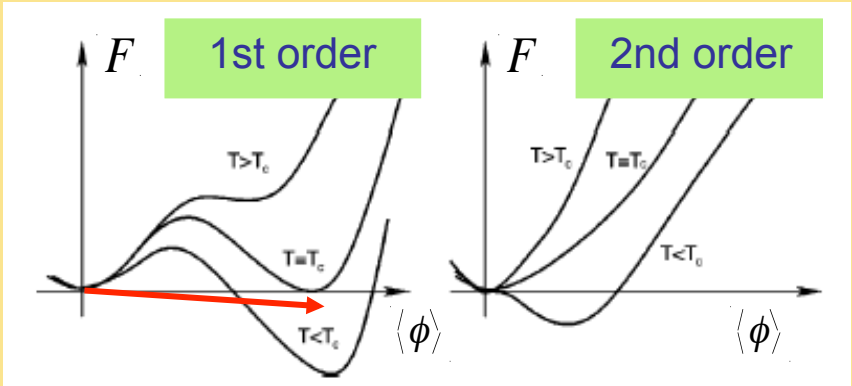


See D. Costanzo talk



EW Phase Transition: SUSY



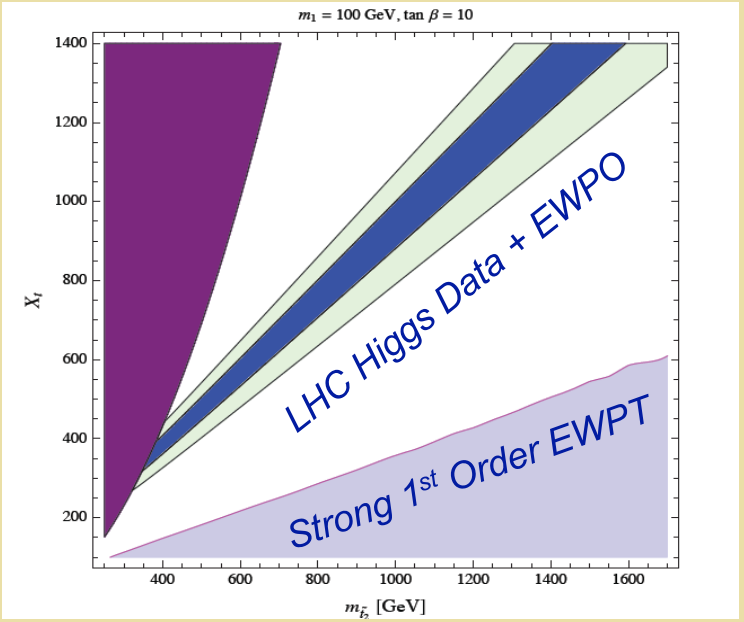
Increasing m_h →

← *New scalars*

Light RH stops also affect Higgs properties

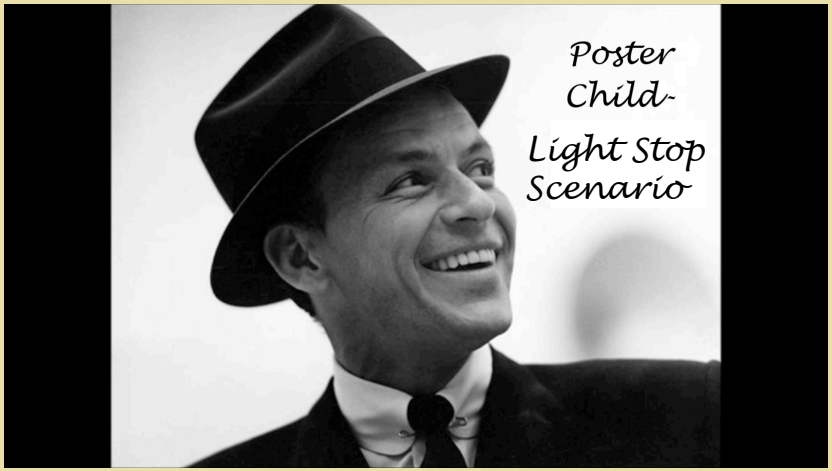
Curtin, Jaiswal, Meade 1203.2932

MSSM + $\delta\lambda_4 (H_u^\dagger H_u)^2$



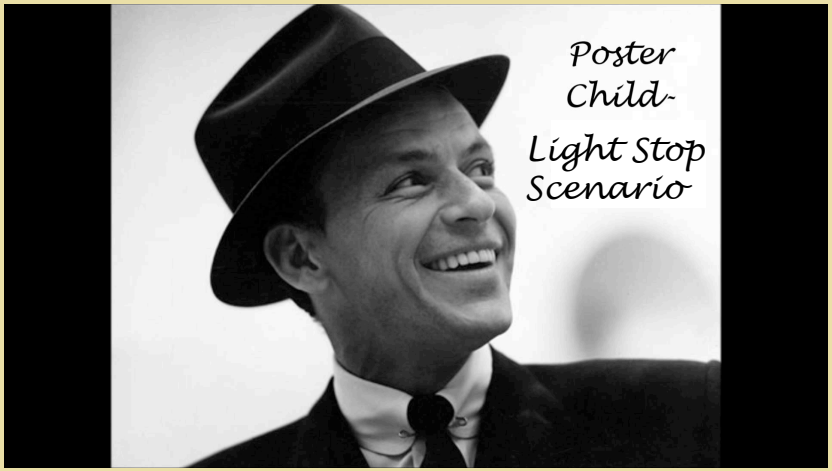
Katz, Perelstein, R-M, Winslow 1509.02934

Beyond the Poster Child



- *Gauge singlets (tree-level)*
- *EW multiplets (tree + loops)*

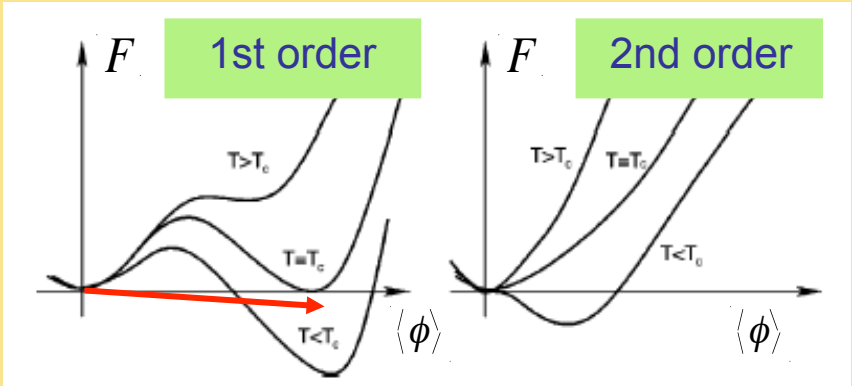
Beyond the Poster Child



- ***Gauge singlets (tree-level)***
- ***EW multiplets (tree + loops)***

Higgs portal:
SUSY or otherwise

EW Phase Transition: Higgs Portal



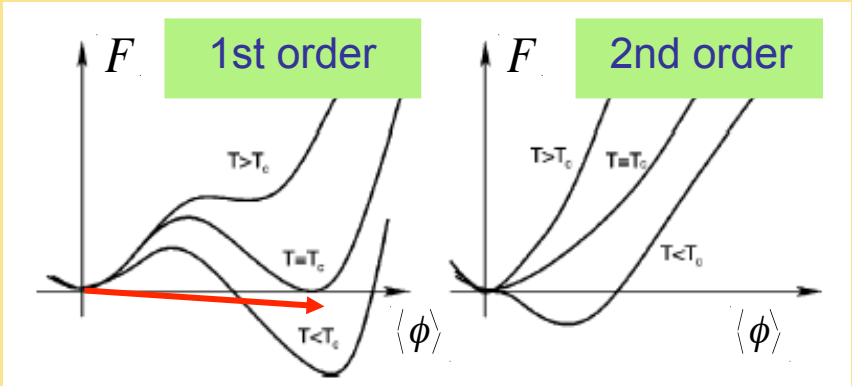
Increasing m_h →

← *New scalars*

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

+…

EW Phase Transition: Higgs Portal



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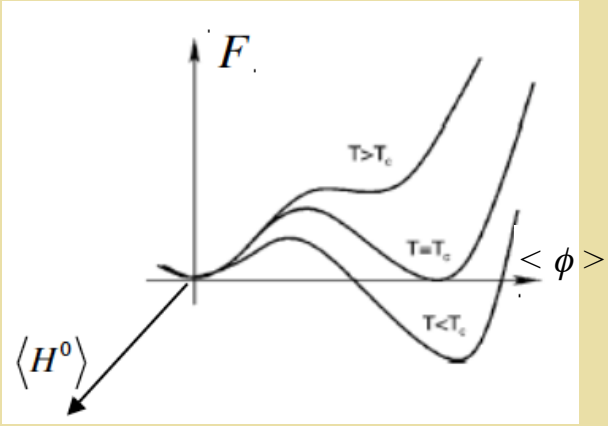
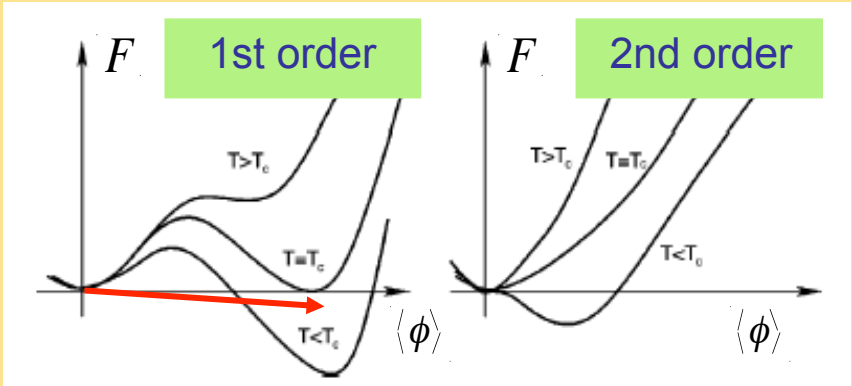
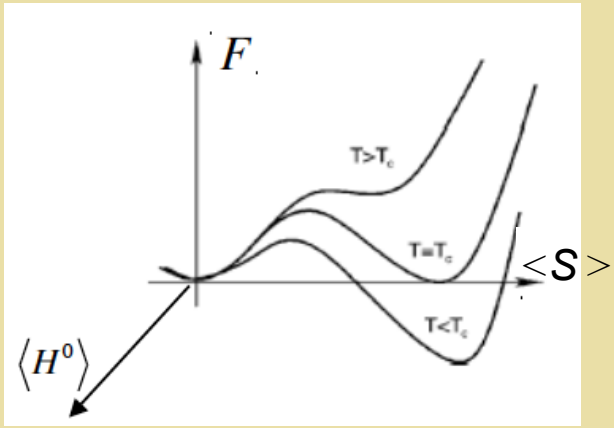


- *Renormalizable*
- *ϕ : singlet or charged under $SU(2)_L \times U(1)_Y$*
- *Generic features of full theory (NMSSM, GUTS…)*
- *More robust vacuum stability*
- *Novel patterns of SSB*

EW Phase Transition: New Scalars





Increasing m_h ⟶

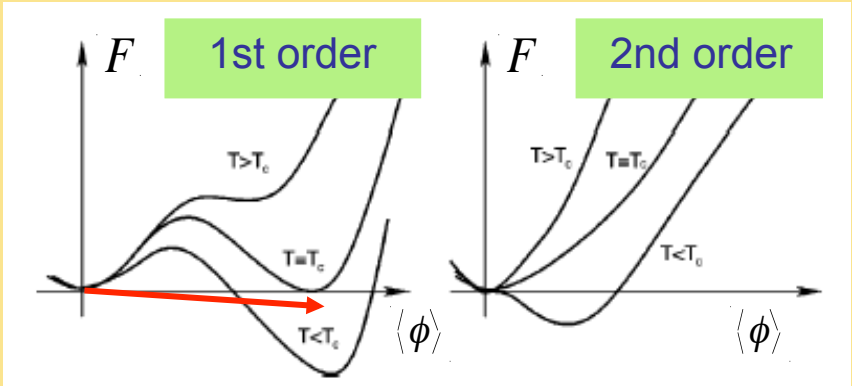
⟵ *New scalars*

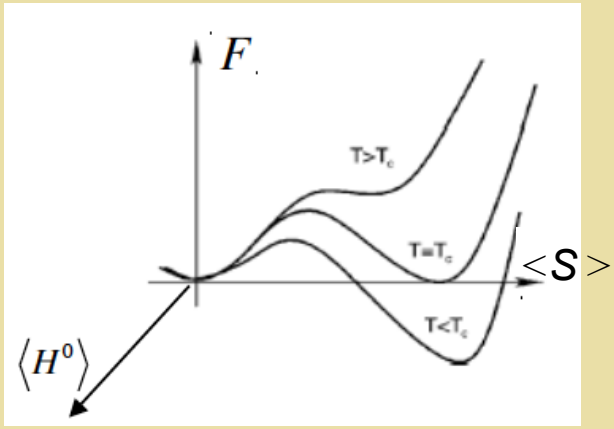
Real Singlet: $\phi \rightarrow S$

Simplest Extension:
two states h_1 & h_2

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

EW Phase Transition: New Scalars





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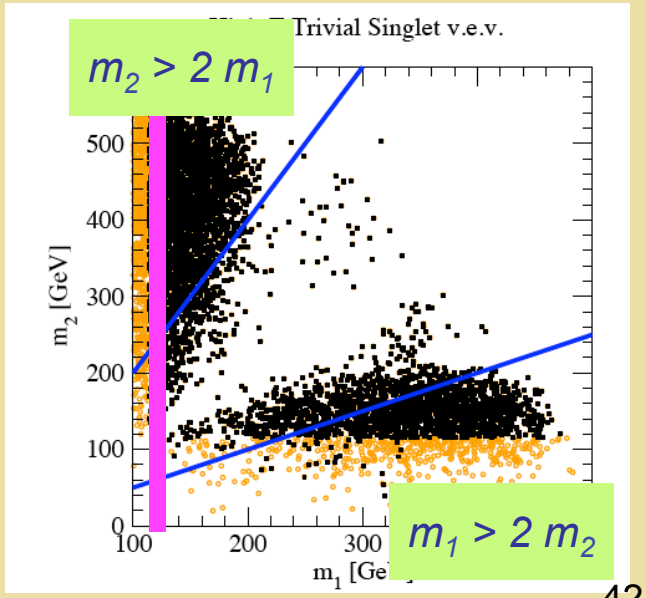

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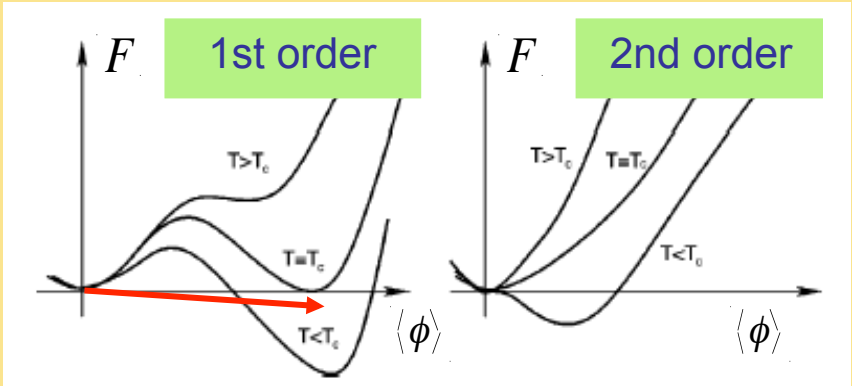
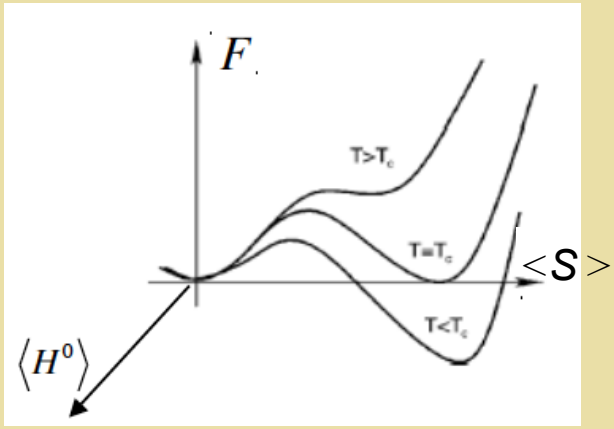
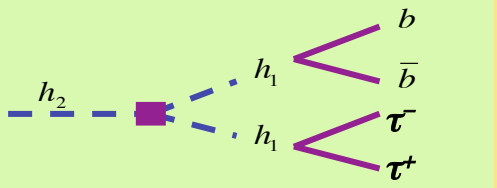


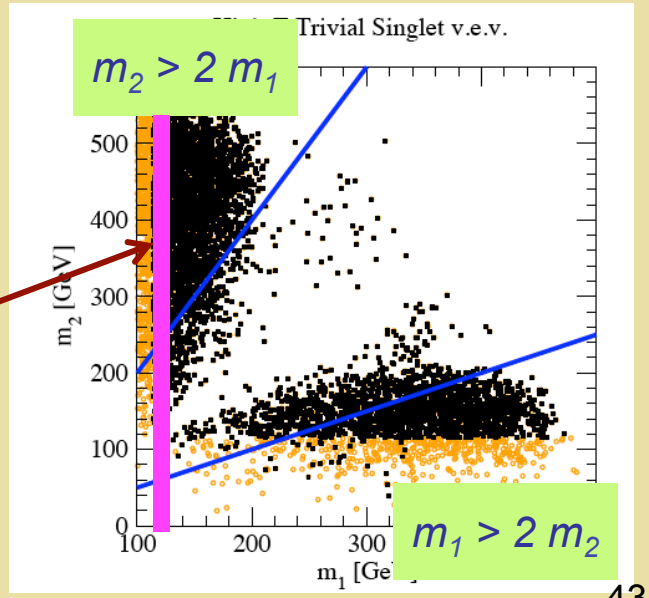


Increasing m_h →

← *New scalars*

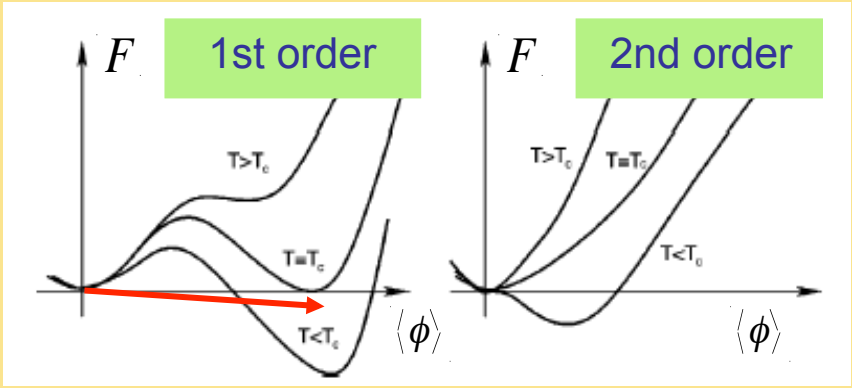
Resonant di-Higgs production:

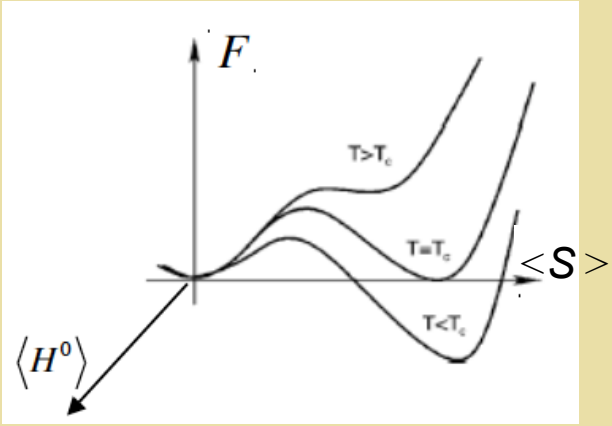


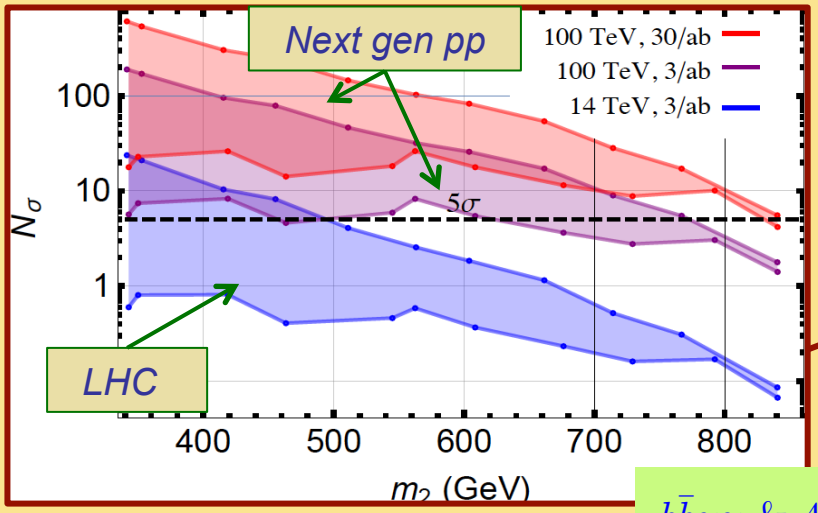


No & RM, arXiv:1310.6035 : ***LHC Discovery w/ 100 fb^{-1}***

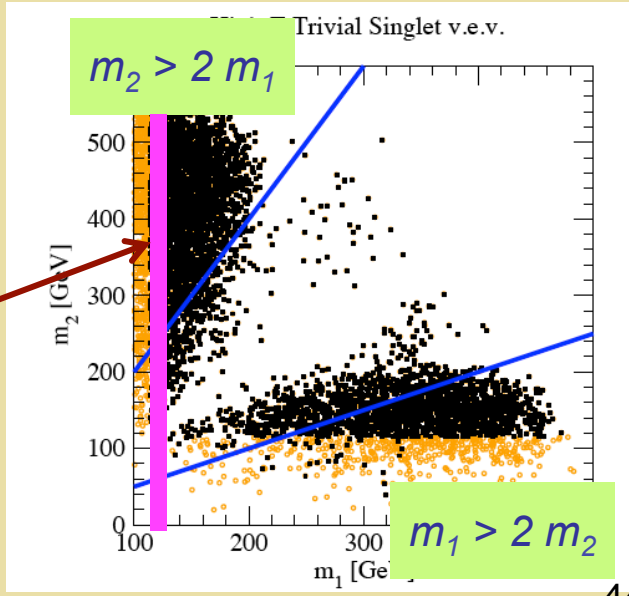
EW Phase Transition: New Scalars





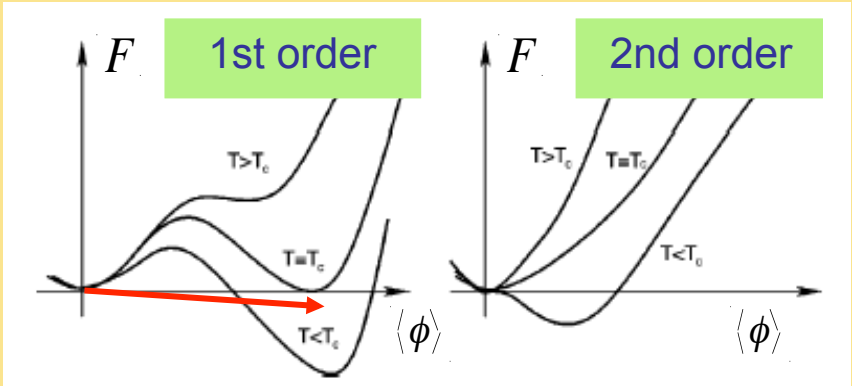


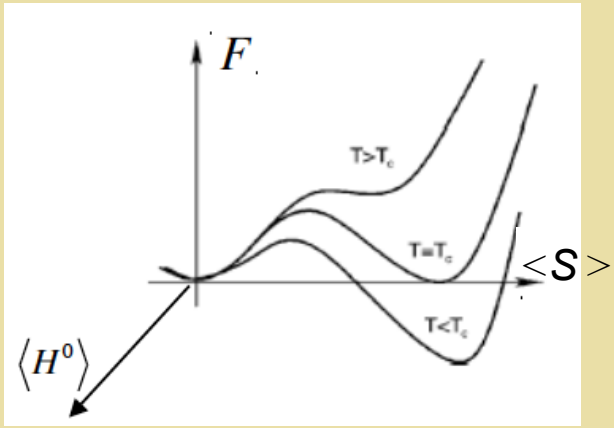
$b\bar{b}\gamma\gamma$ & 4τ

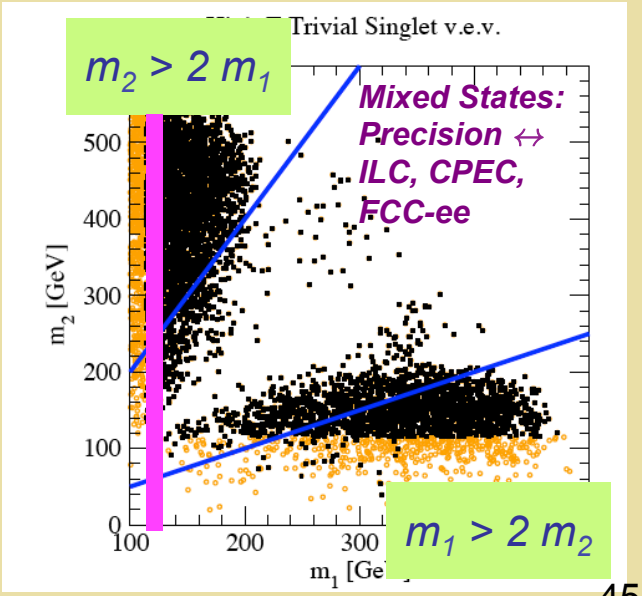


Next gen pp: Kotwal, No, R-M, Winslow 1605.06123

EW Phase Transition: New Scalars







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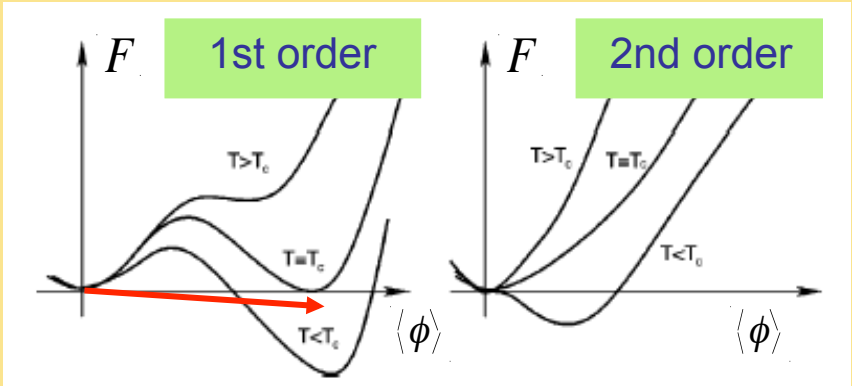
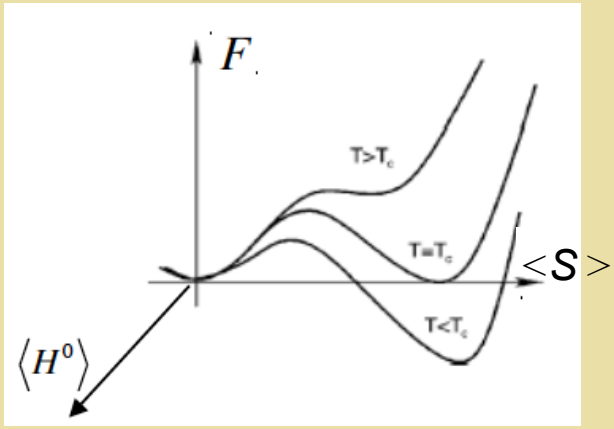
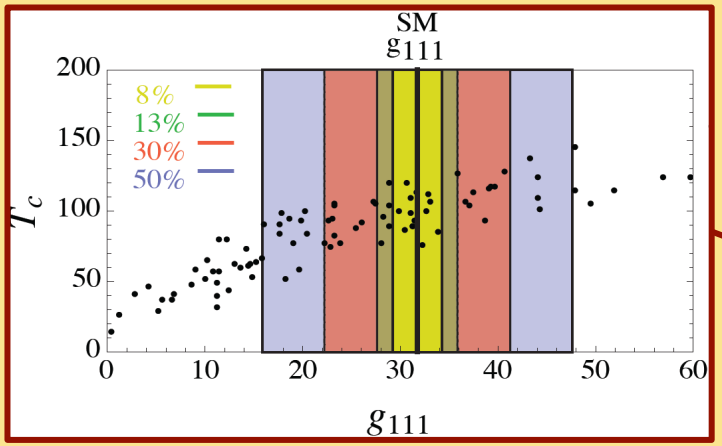
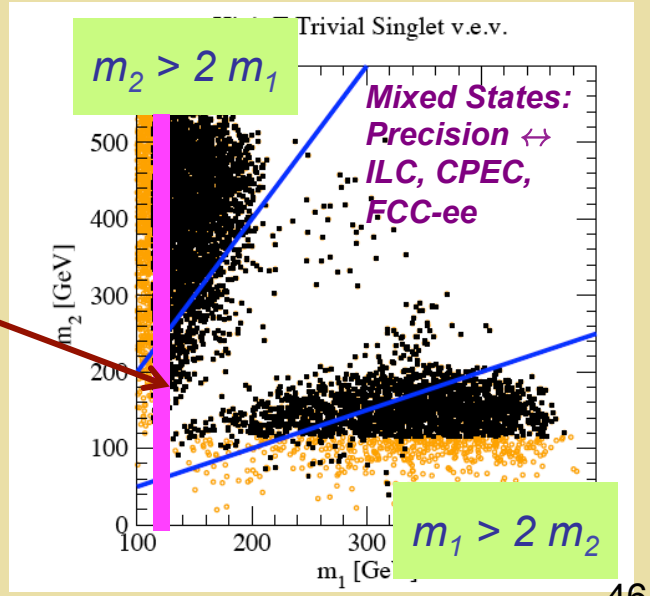




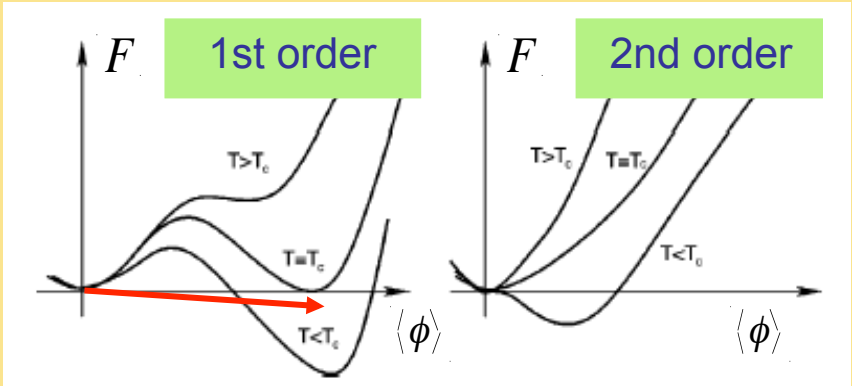
Modified Higgs Self-Coupling

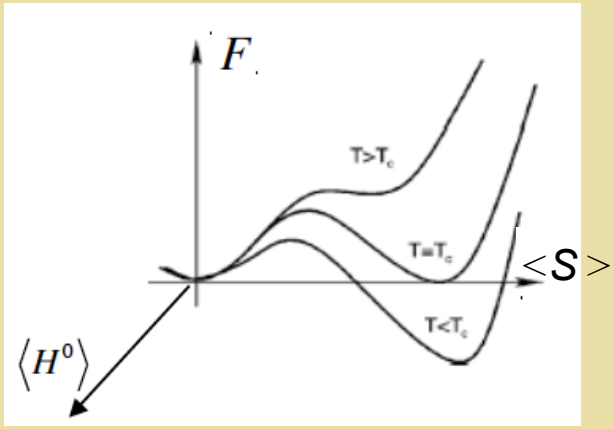




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: New Scalars





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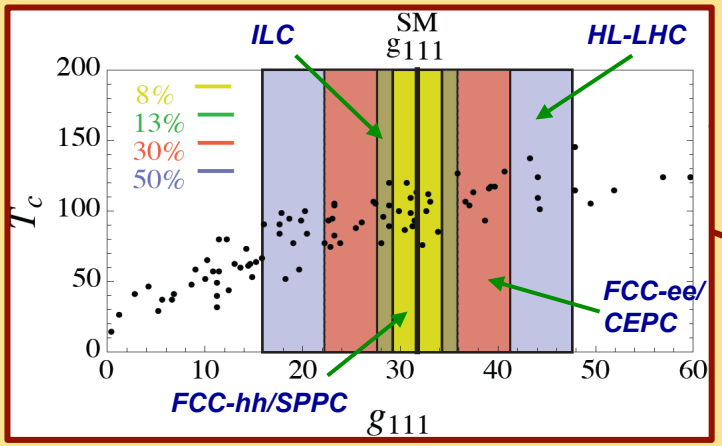

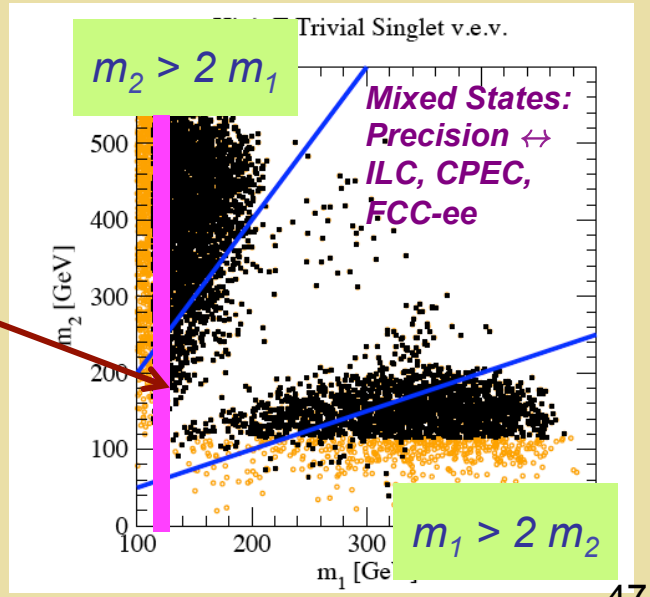

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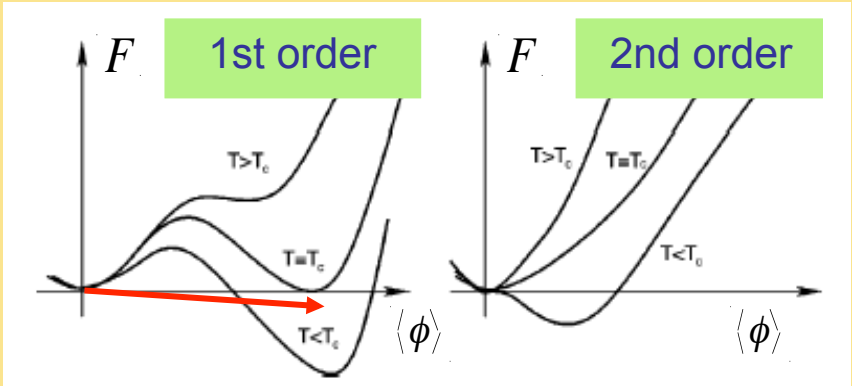
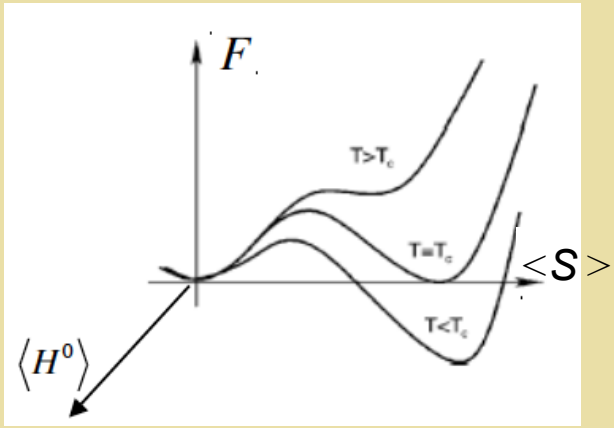
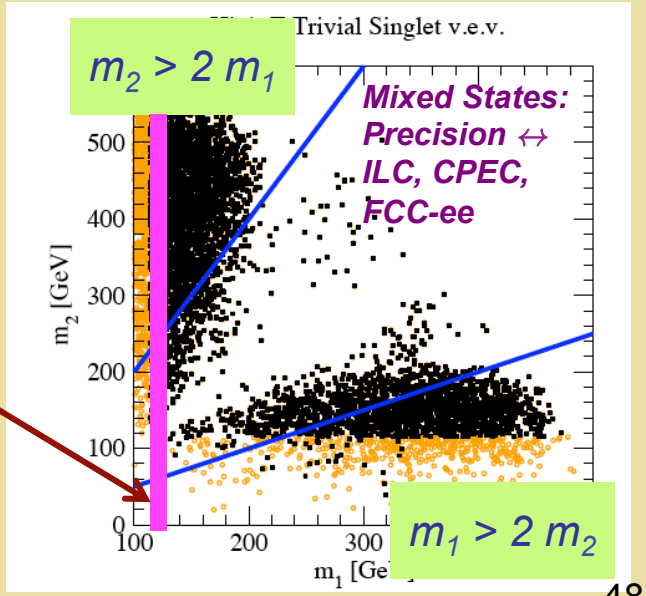


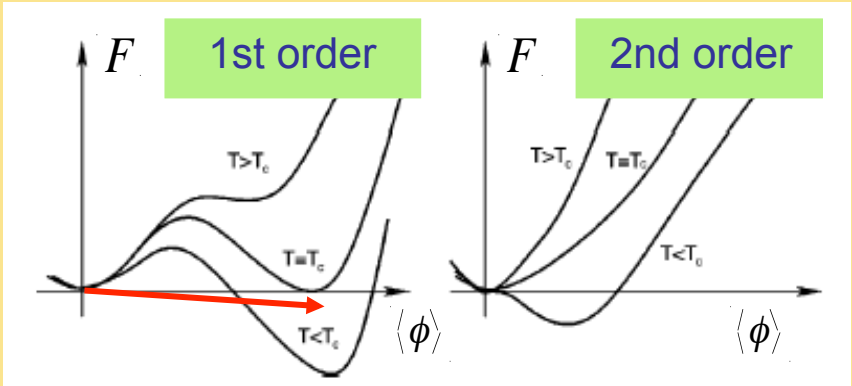


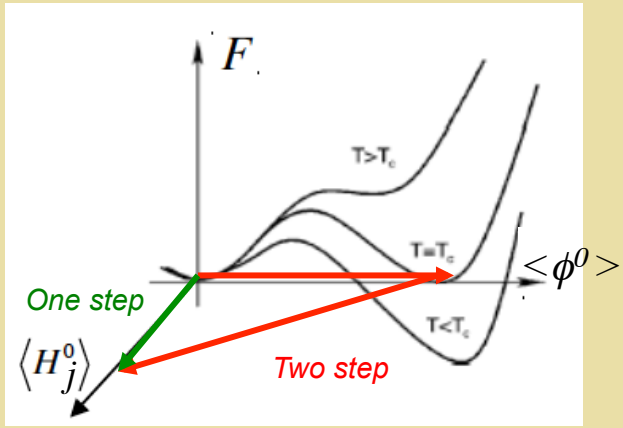
Exotic Higgs Decays

?



EW Multiplets: Two-Step EWPT

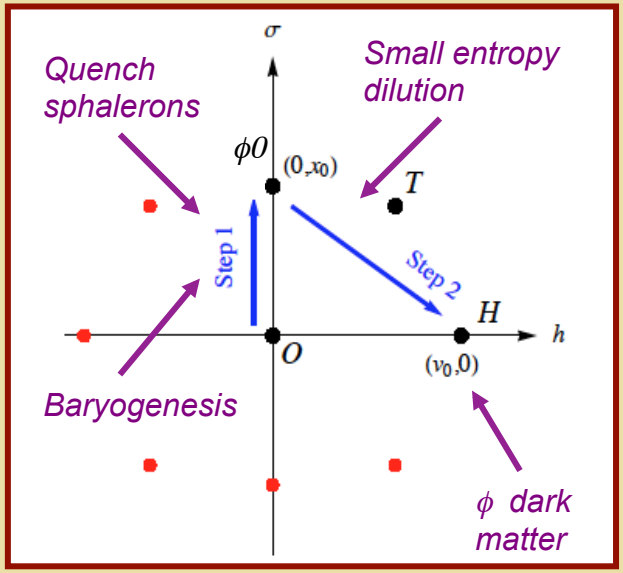




Increasing m_h →

← *New scalars*

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



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

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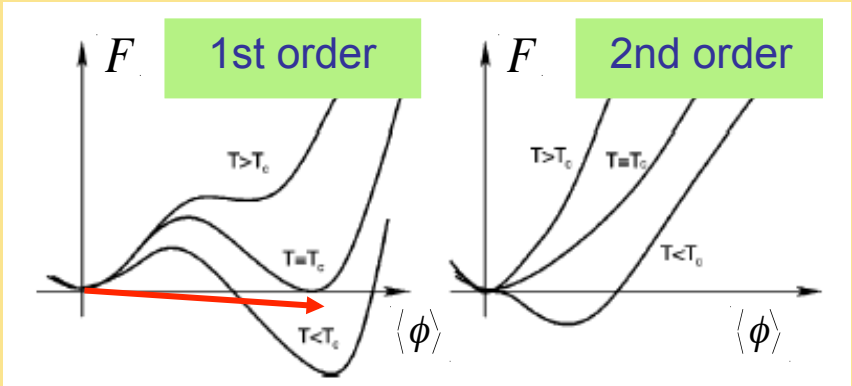
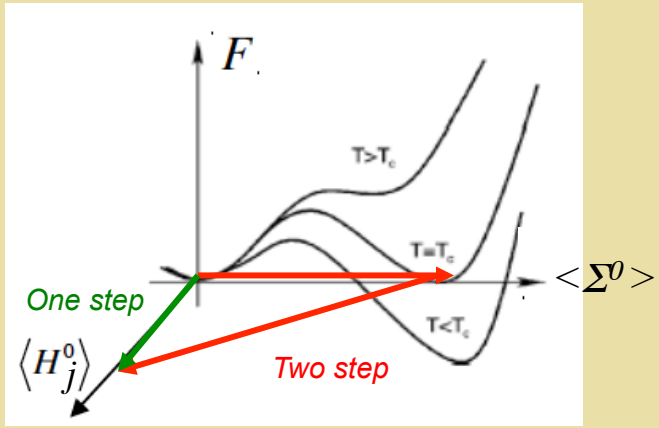


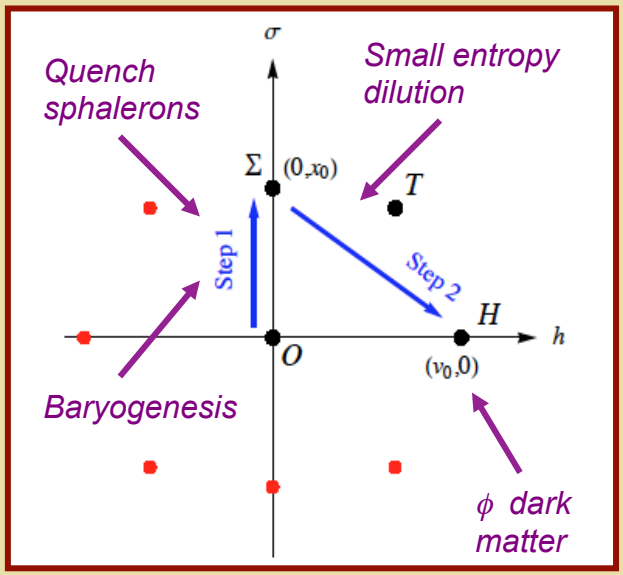


Increasing m_h →

← *New scalars*

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

Two-step EWPT & dark matter



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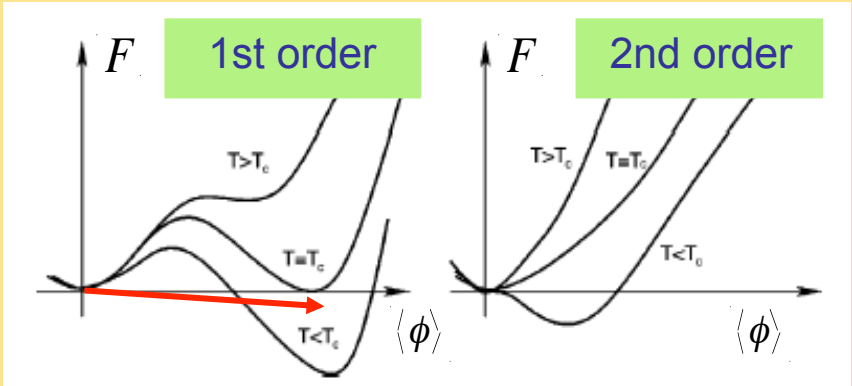

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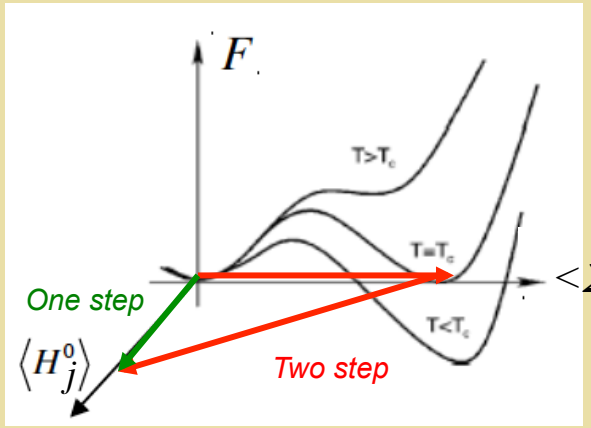

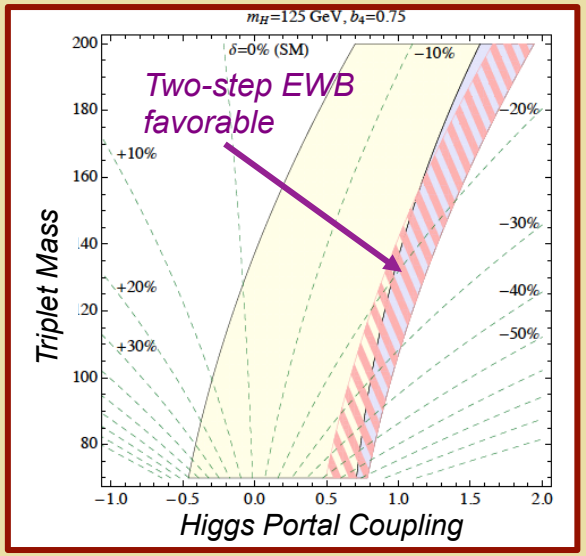

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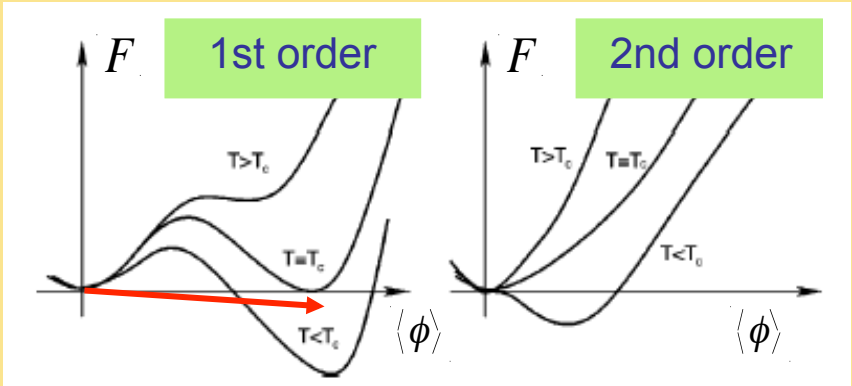

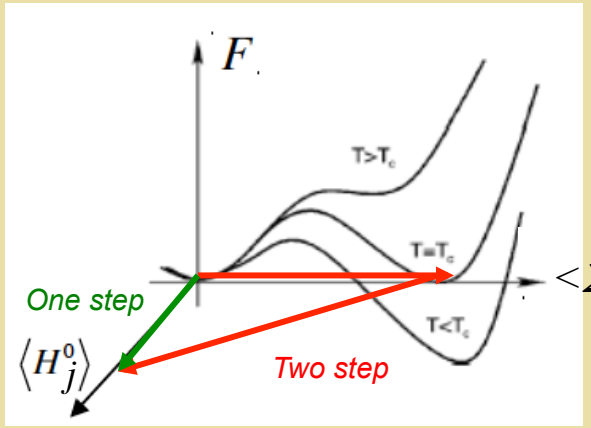

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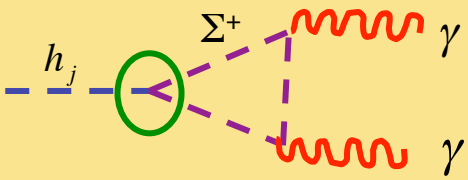

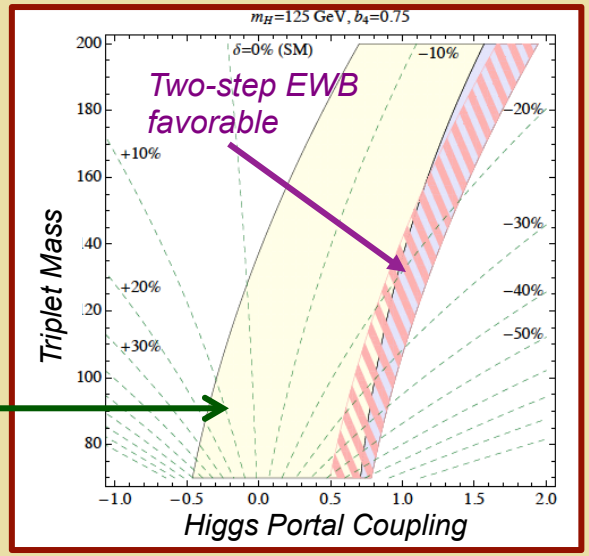

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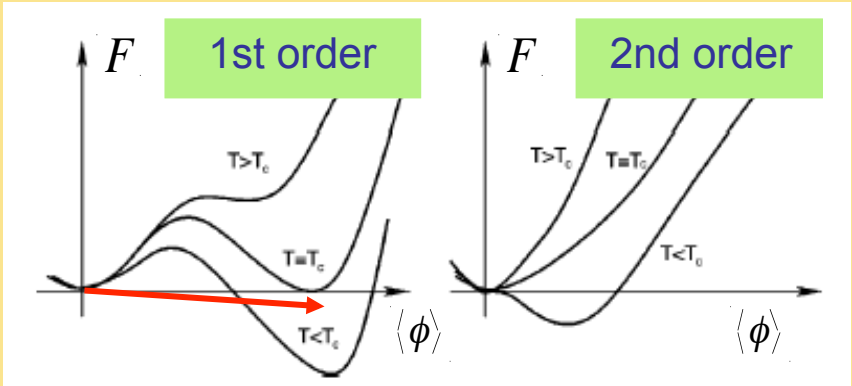
Strong 1st Order EWPT

Definitive probe of the possibilities →
LHC + next generation colliders

III. CPV: Baryon Asymmetry & EDMs

EW Phase Transition: New Scalars & CPV

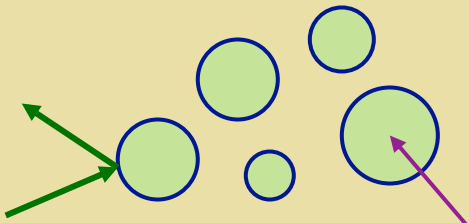


Increasing m_h →

← *New scalars*

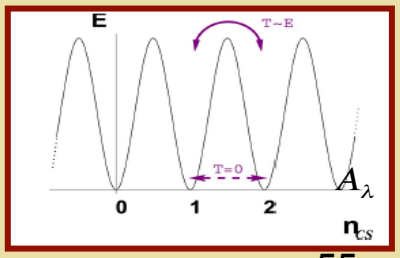
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" **1st order EWPT** → *Bubble nucleation*



Y_B : CPV & EW sphalerons — *EWSB*

BSM



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}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

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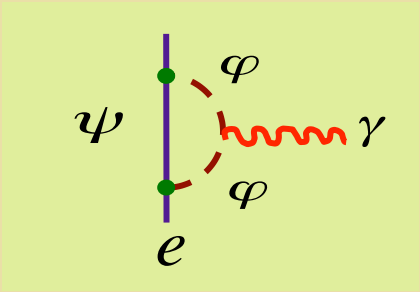
Mass Scale Sensitivity



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

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

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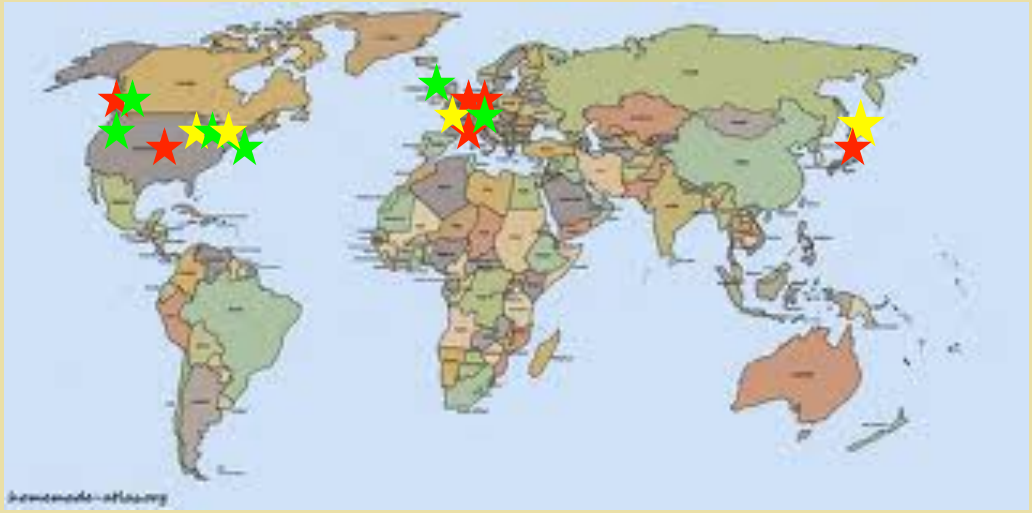

Not shown: muon

★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

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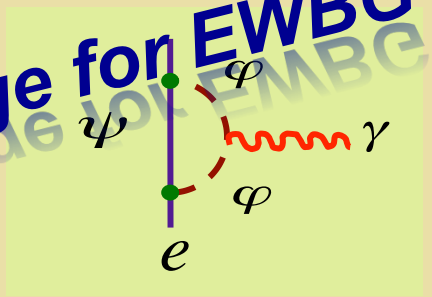
Mass Scale Sensitivity

Challenge for EWBG



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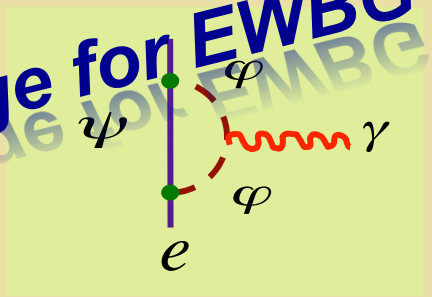
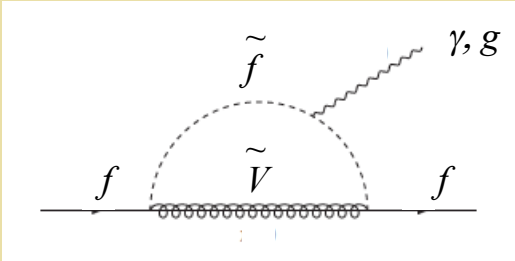
Mass Scale Sensitivity

Challenge for EWBG

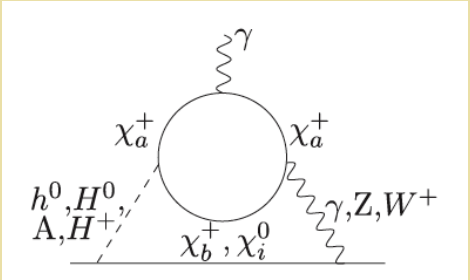


- *EDMs arise at > 1 loop*
- *CPV is flavor non-diagonal*
- *CPV is "partially secluded"*

EDMs & EWBG: MSSM & Beyond

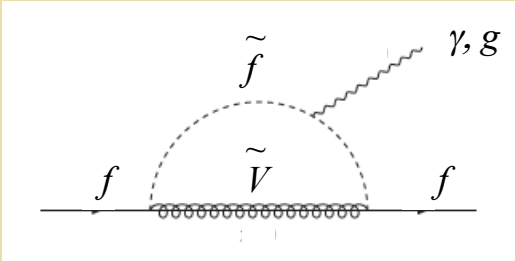


Heavy sfermions: LHC consistent & suppress 1-loop EDMs



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

EDMs & EWBG: MSSM & Beyond



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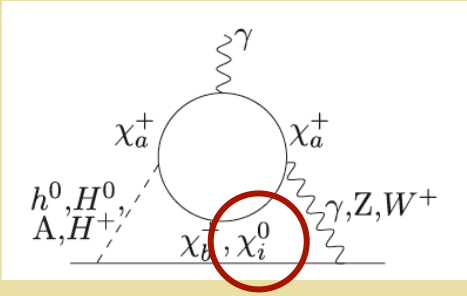
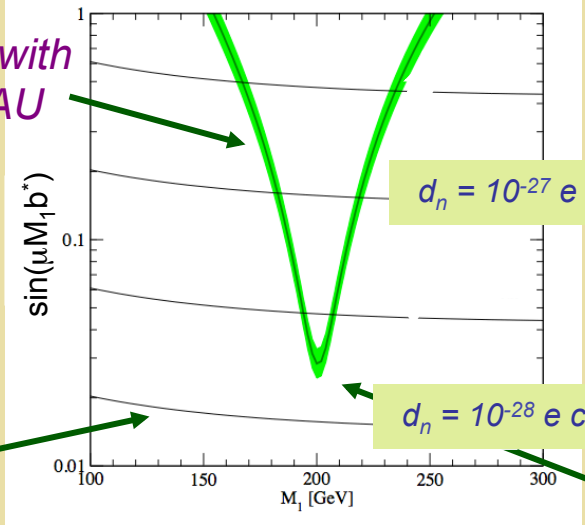


Sub-TeV EW-inos: LHC & EWB - viable but non-universal phases

Compatible with observed BAU

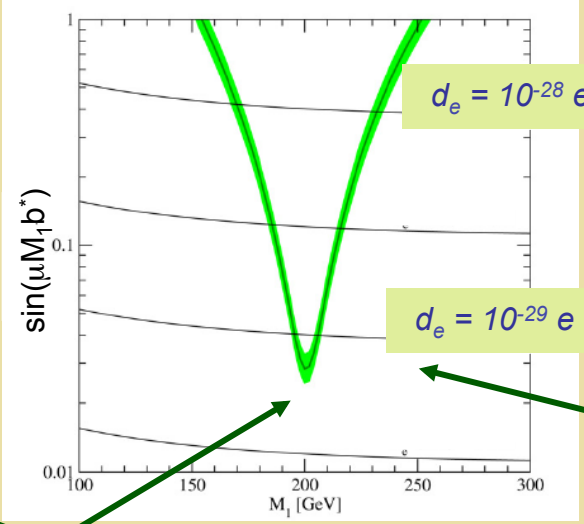


$d_n = 10^{-27}$ e cm

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

Next gen d_n

Li, Profumo, RM '09-'10



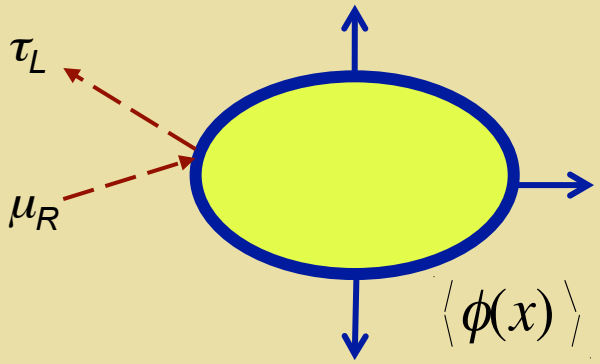
$d_e = 10^{-28}$ e cm *ACME: ThO*

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

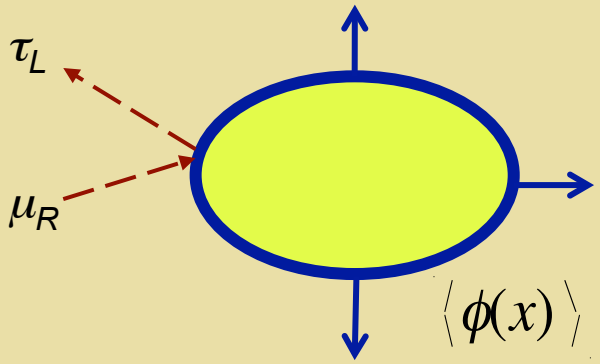
Next gen d_e

Compressed spectrum

Flavored EW Baryogenesis



Flavored EW Baryogenesis



Flavor basis (high T)

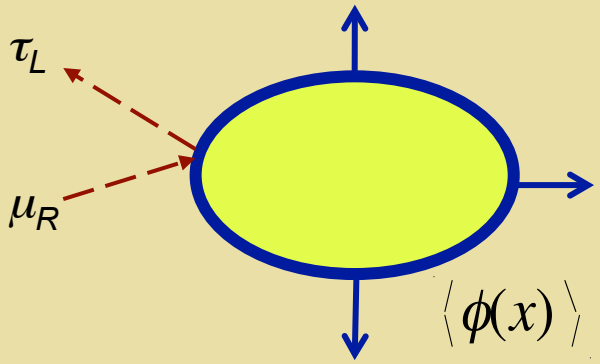
$$\mathscr{L}^{\text{Lepton}}_{\text{Yukawa}} = -\overline{E^i_L}\left[(Y^E_1)_{ij}\Phi_1 + (Y^E_2)_{ij}\Phi_2\right] e^j_R + h.c.$$

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 1607.XXXX

Flavored EW Baryogenesis



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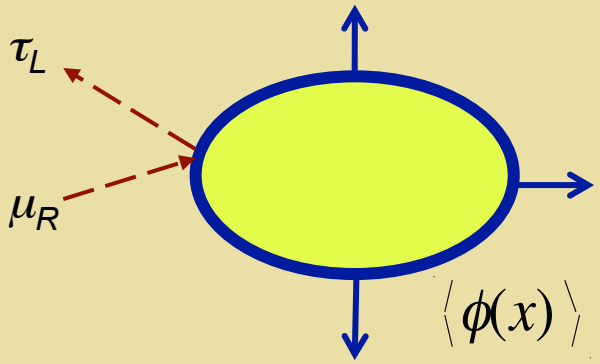
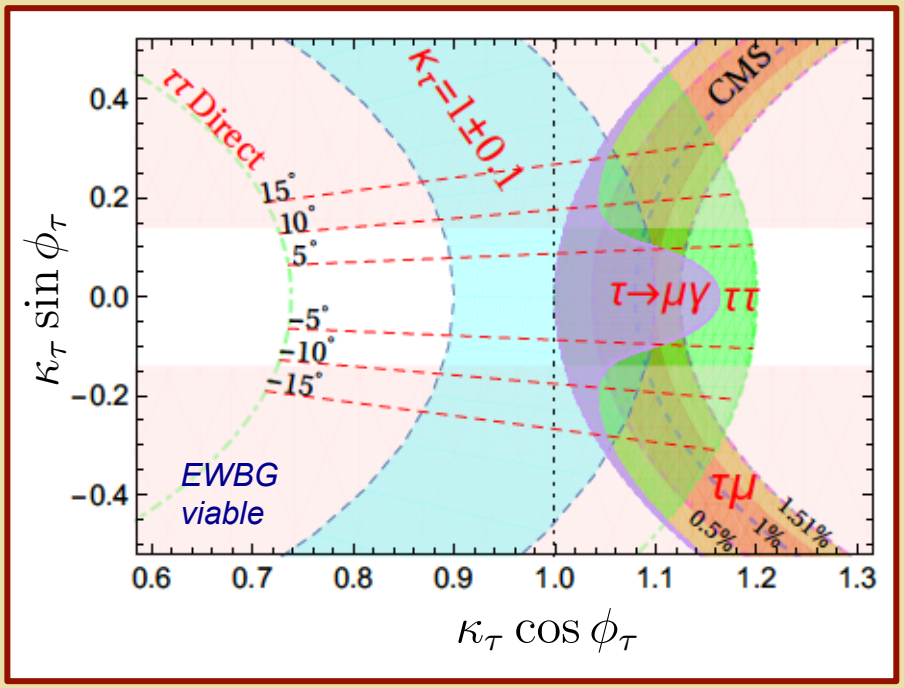
CPV $h \to \tau\tau$

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

Guo, Li, Liu, R-M, Shu 1607.XXXX

Flavored EW Baryogenesis





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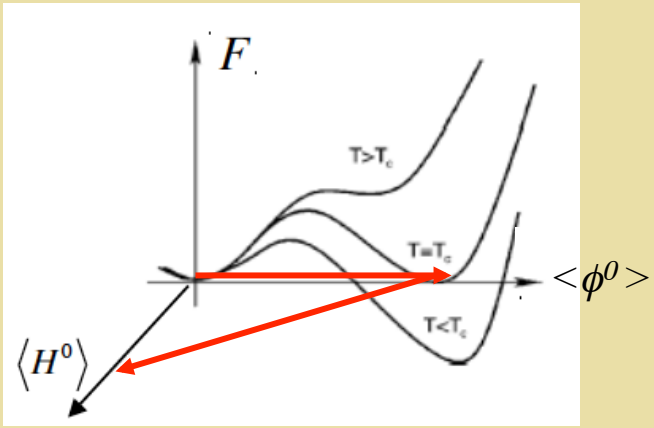
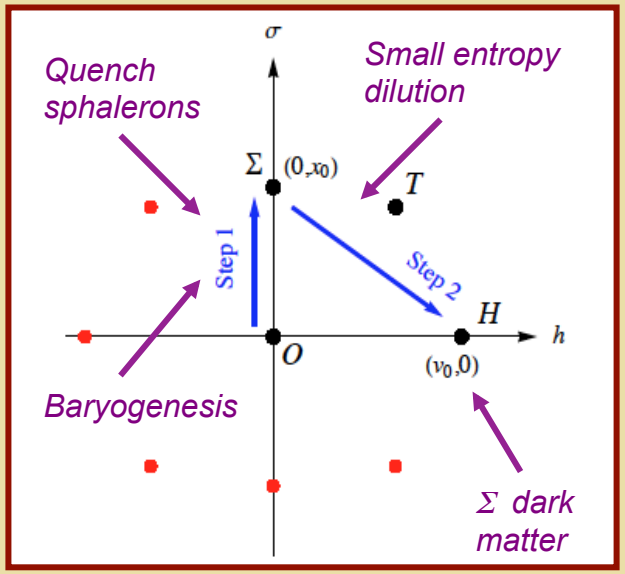
Guo, Li, Liu, R-M, Shu 1607.XXXX

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*

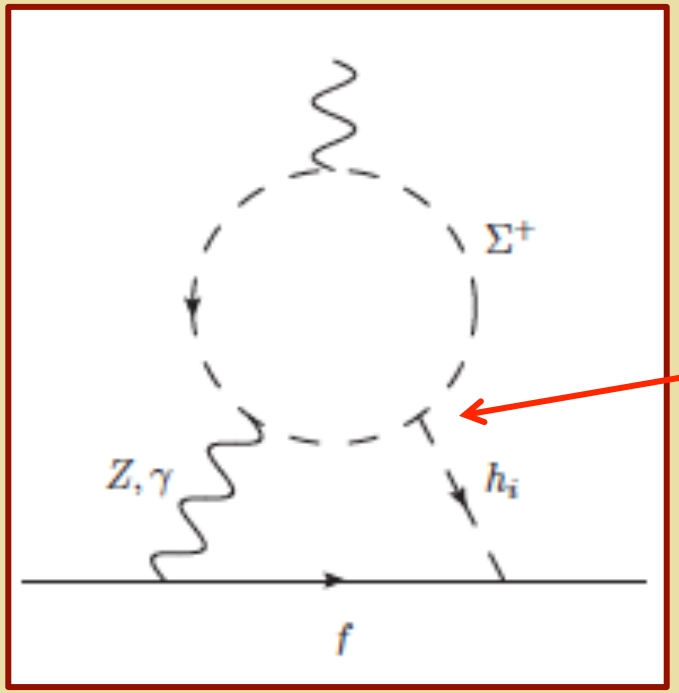
(SUSY: "TNMSSM", Coriano…)

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*

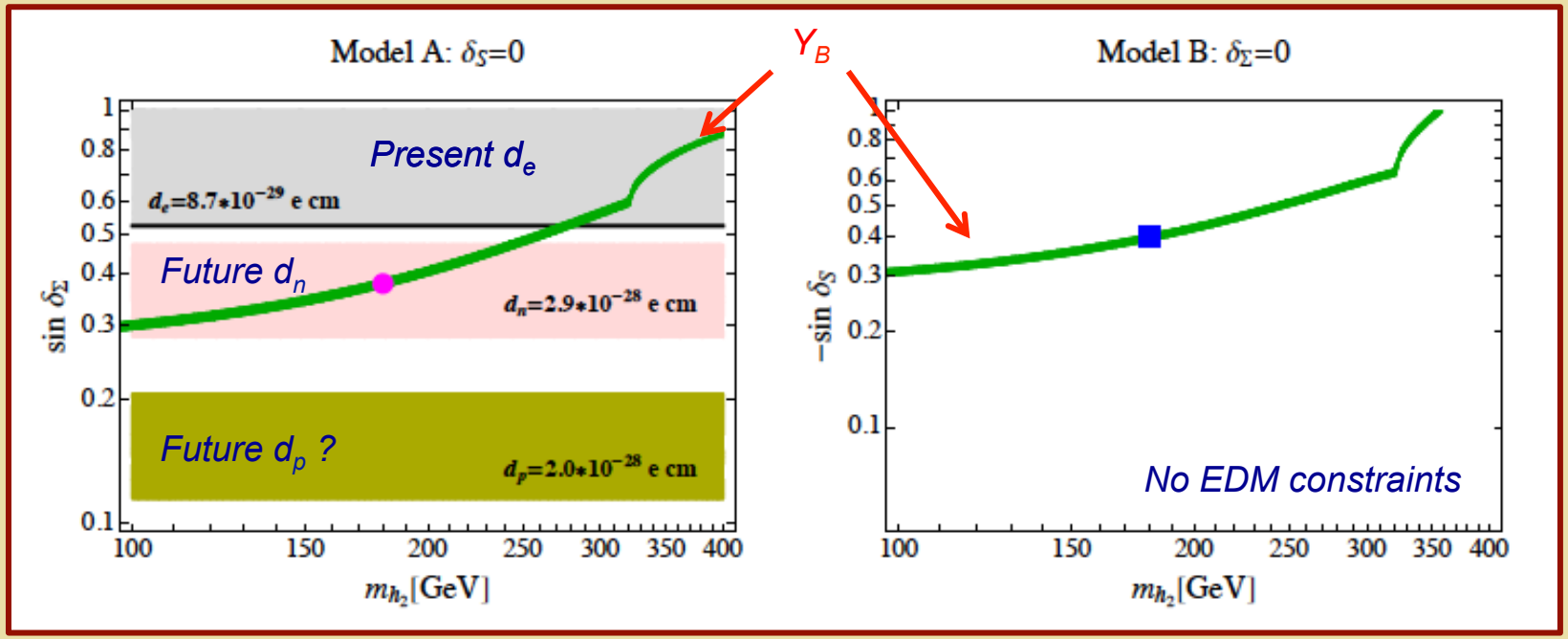
δ_S : *Singlet phase*

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

Inoue, Ovanesyan, R-M: 1508.05404

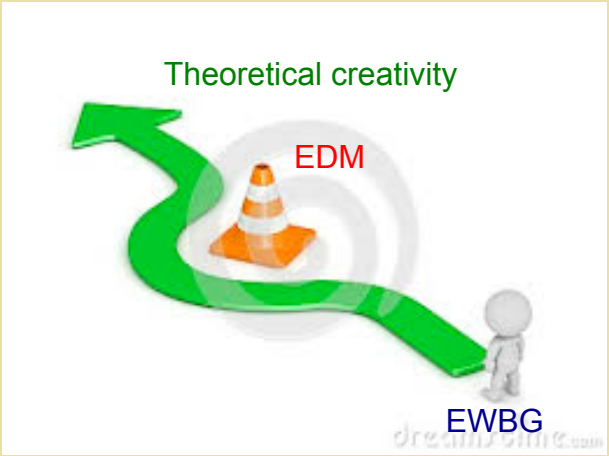
Two-Step EW Baryogenesis & EDMs

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



Inoue, Ovanesyan, R-M: 1508.05404

CPV for EWBG



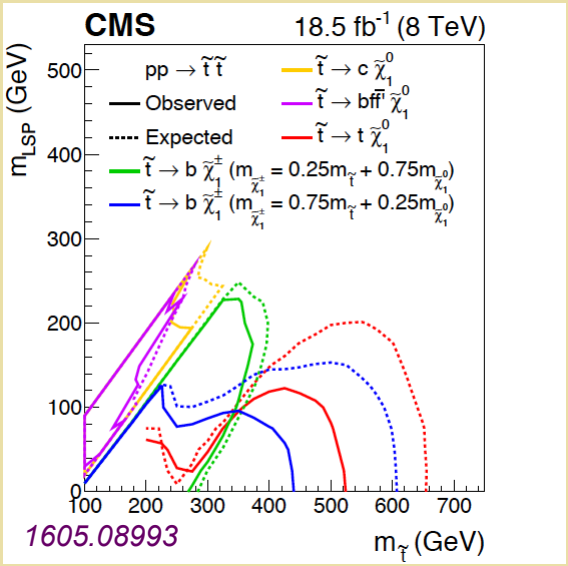
IV. Outlook

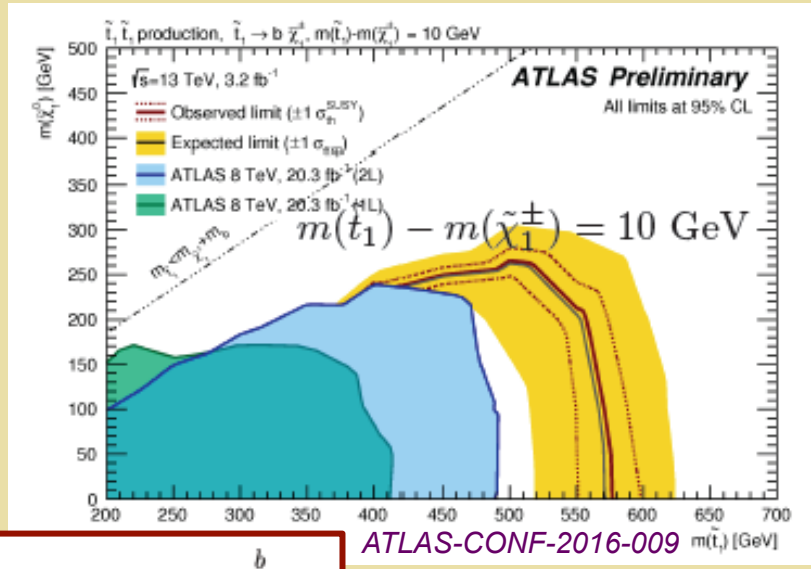
- *Explaining the origin of the matter-antimatter asymmetry is a forefront challenge for BSM physics*
- *Electroweak baryogenesis remains one of the most theoretically rich & experimentally accessible scenarios: "Was the baryon asymmetry produced in conjunction with electroweak symmetry-breaking ?"*
- *EDMs & collider studies (LHC & beyond) provide powerful probes of the ingredients & results to date challenge theoretical creativity*
- *Exciting array of possibilities to be explored*

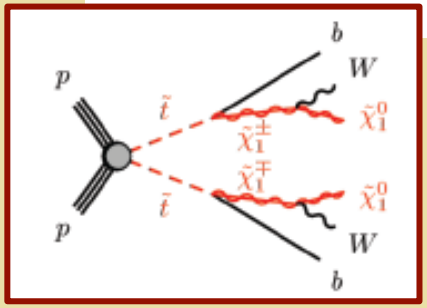
Refs: 1604.05324, 1206.2942

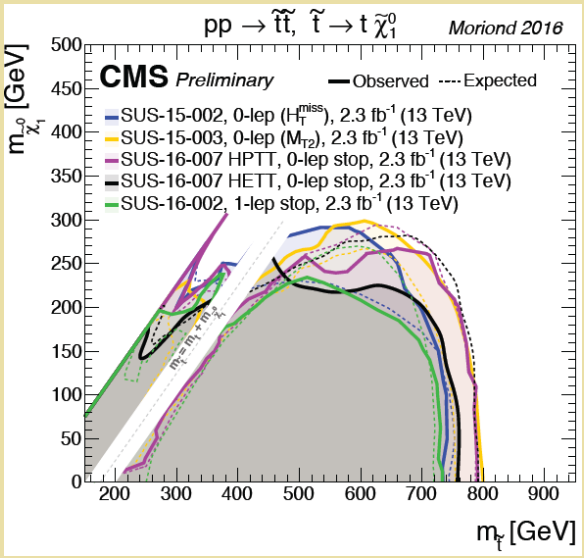
Back Up Slides

LHC Stop Searches

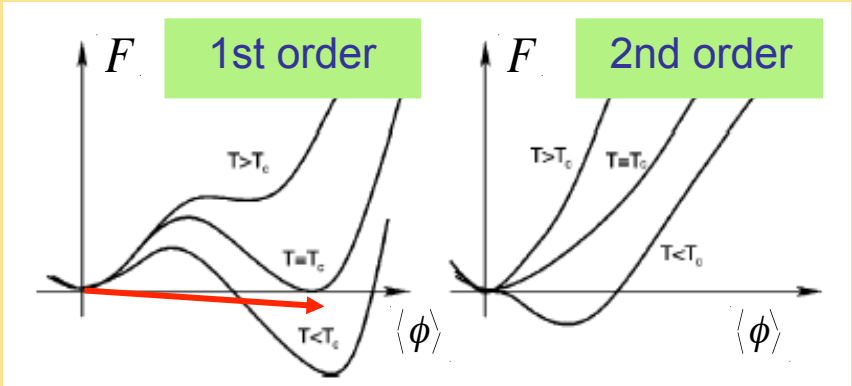


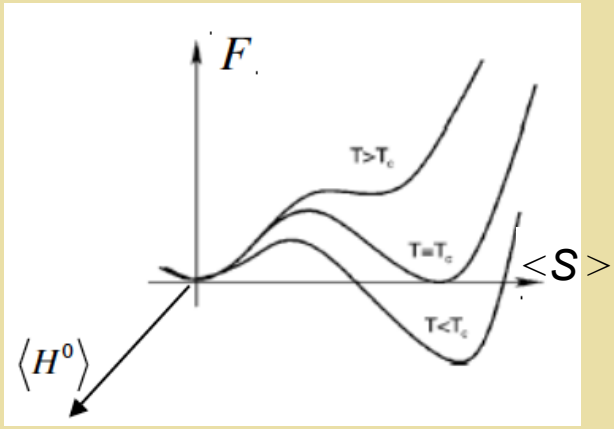




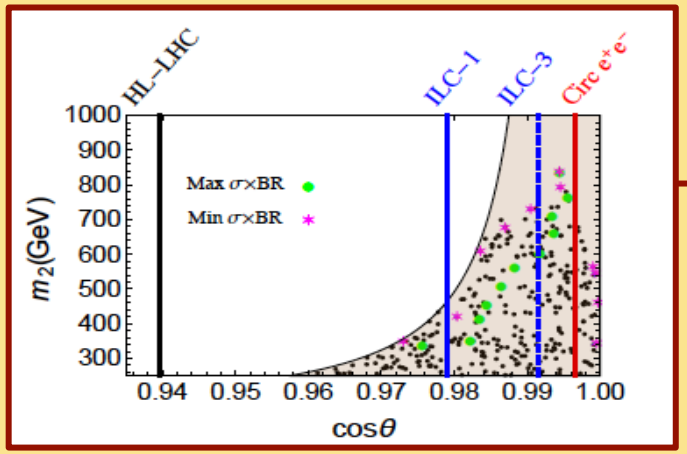


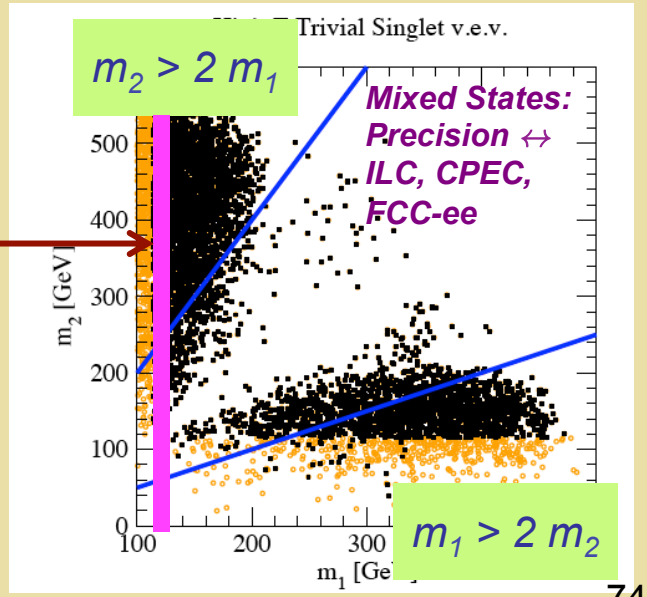
EW Phase Transition: New Scalars





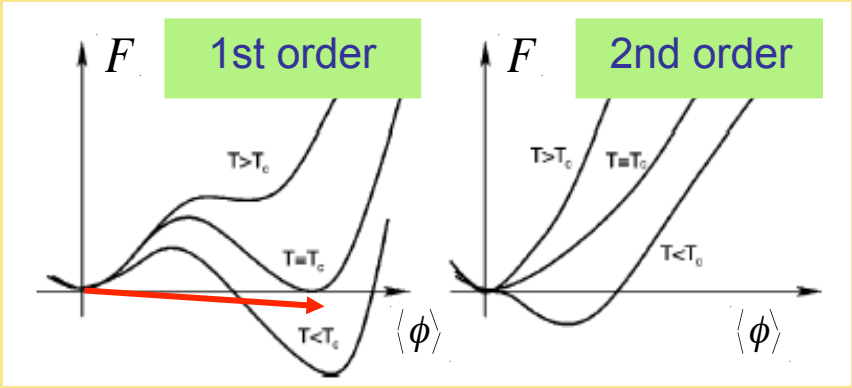
Mixing Angle

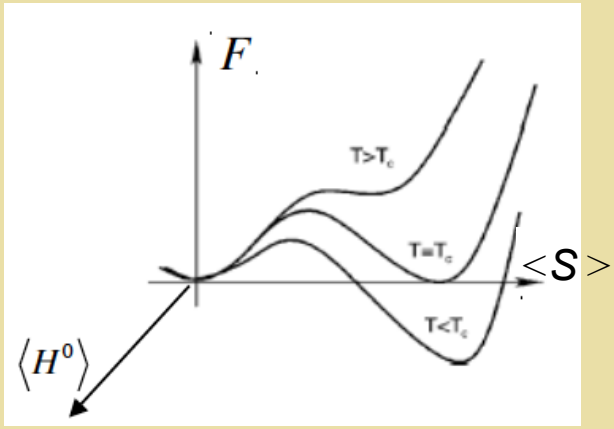


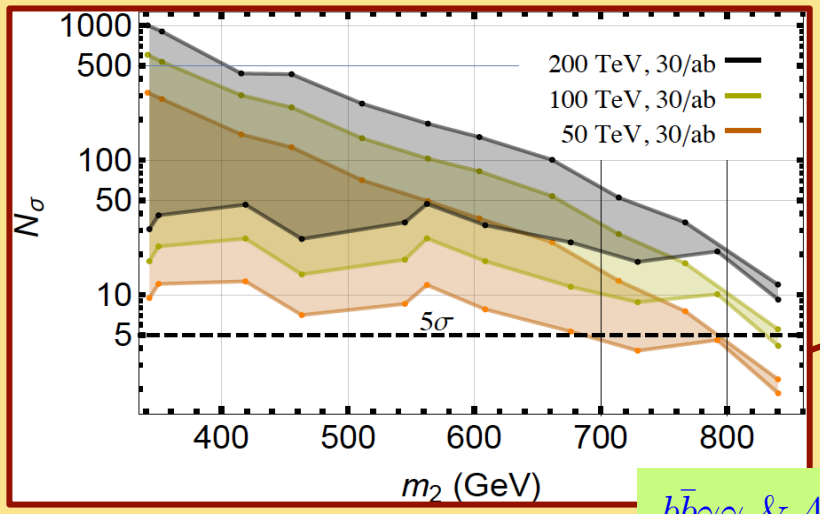


Profumo, R-M, Wainwright, Winslow: 1407.5342

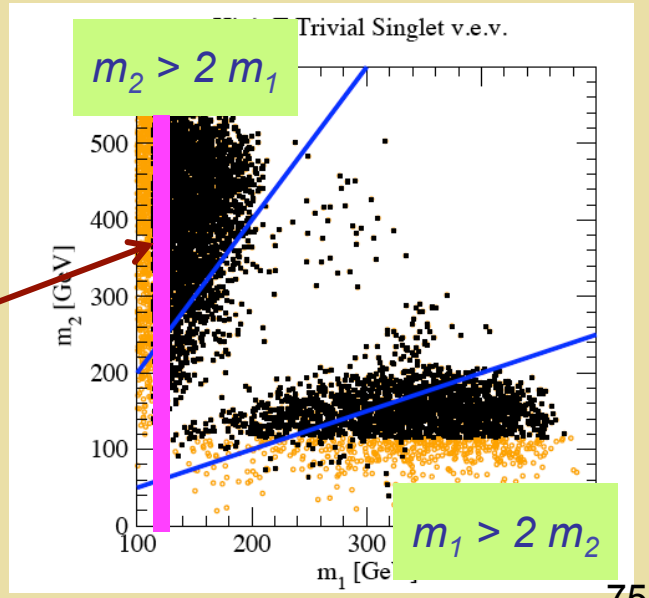
EW Phase Transition: New Scalars





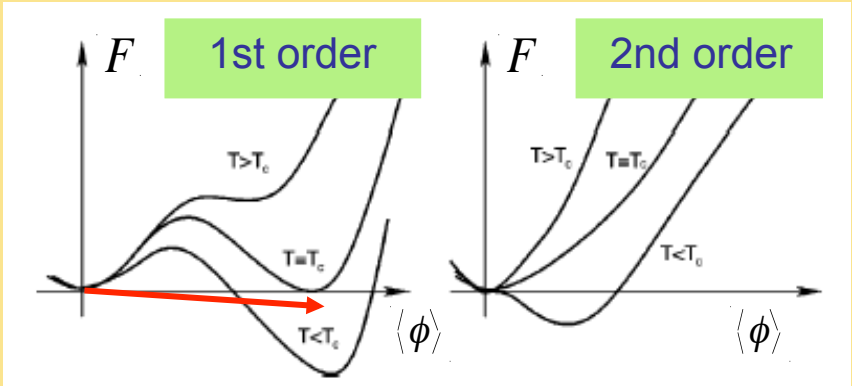


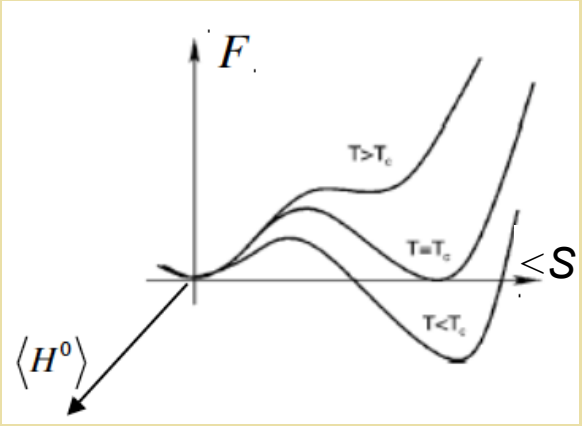
$b\bar{b}\gamma\gamma$ & 4τ



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

EW Phase Transition: 100 TeV pp





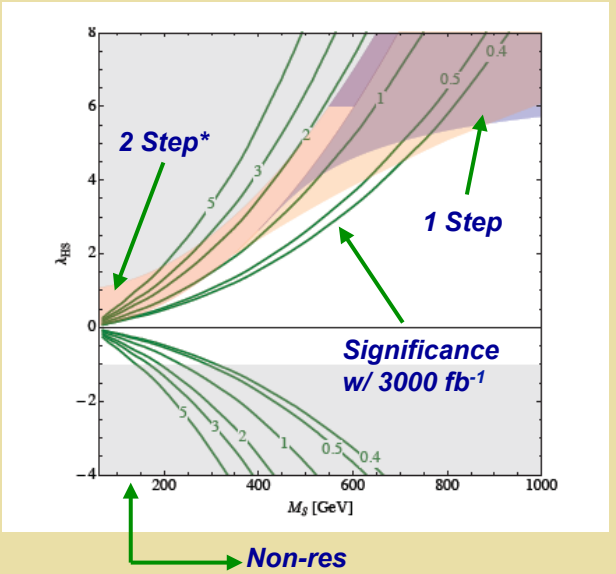
Curtain, Meade, Yu: arXiv: 1409.0005

Z_2 symmetric real singlet extension

- *Loop-induced 1-step transition*
- *2-step transition for $\mu_S^2 < 0$*

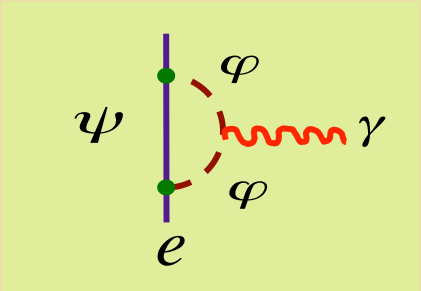
VBF @ 100 TeV pp:

$pp \rightarrow h\,jj\,,\ h \rightarrow$ invis



** Singlet two step: see also Profumo, R-M, Shaugnessy 2007*

EDMs & EWBG: MSSM & Beyond

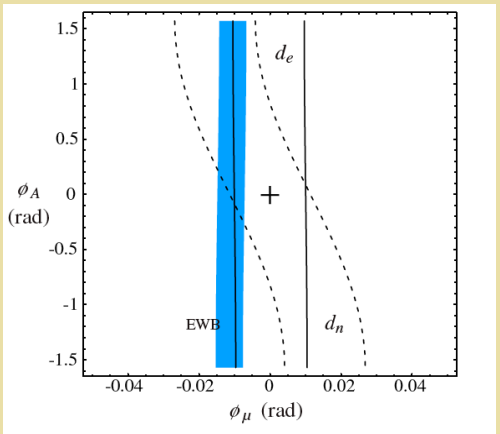


$\sin\phi_{CP} \sim 1 \rightarrow M > 5000$ GeV

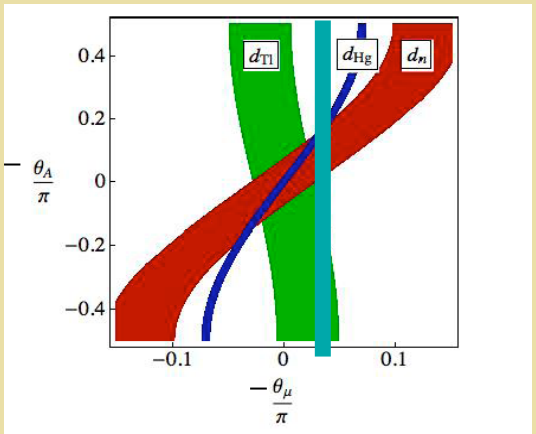
$M < 500$ GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

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