Electroweak Phase Transition: Overview

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AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

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

University of Massachusetts Amherst

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

Next Gen PP Workshop, September 2015

Outline

- *Context & Motivation*
- *EWB in a Nutshell*
- *EW Phase Transition: Standard Model, BSM scenarios, novel EWSB patterns*
- *Outlook*

I. Context & Motivation

EWPT: Why Should We Care ?

- *Were there conditions favorable to generation of the matter-antimatter asymmetry during the era of EW symmetry breaking ?*

- *What was the detailed history and pattern of EW symmetry breaking ?*

  How is the EW symmetry-breaking transition affected by presence of new states & interactions introduced to solve other problems (naturalness, dark matter…) ?

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*	✖	✔

Ingredients for Baryogenesis

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Testable

	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
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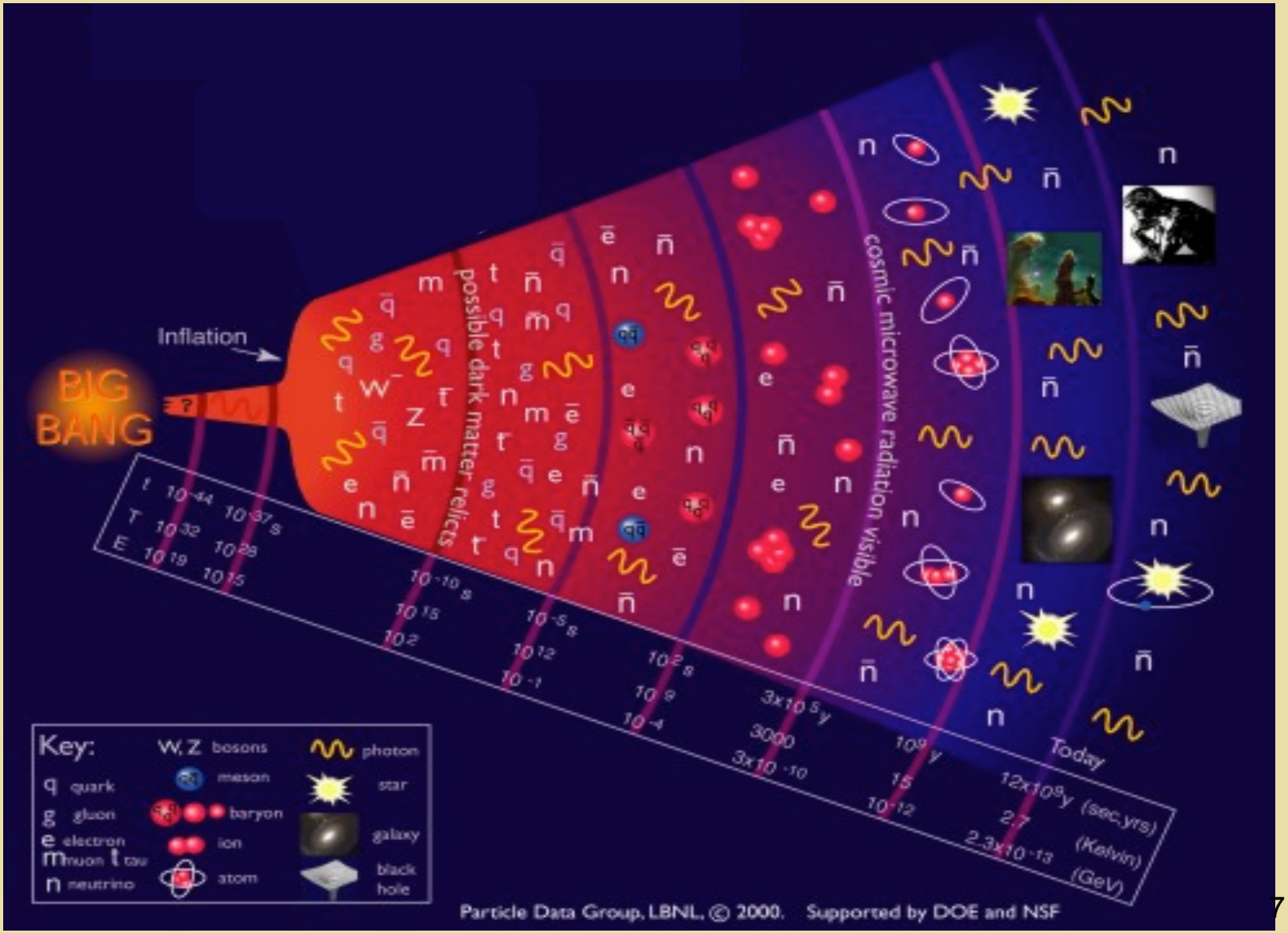
Symmetries & Cosmic History



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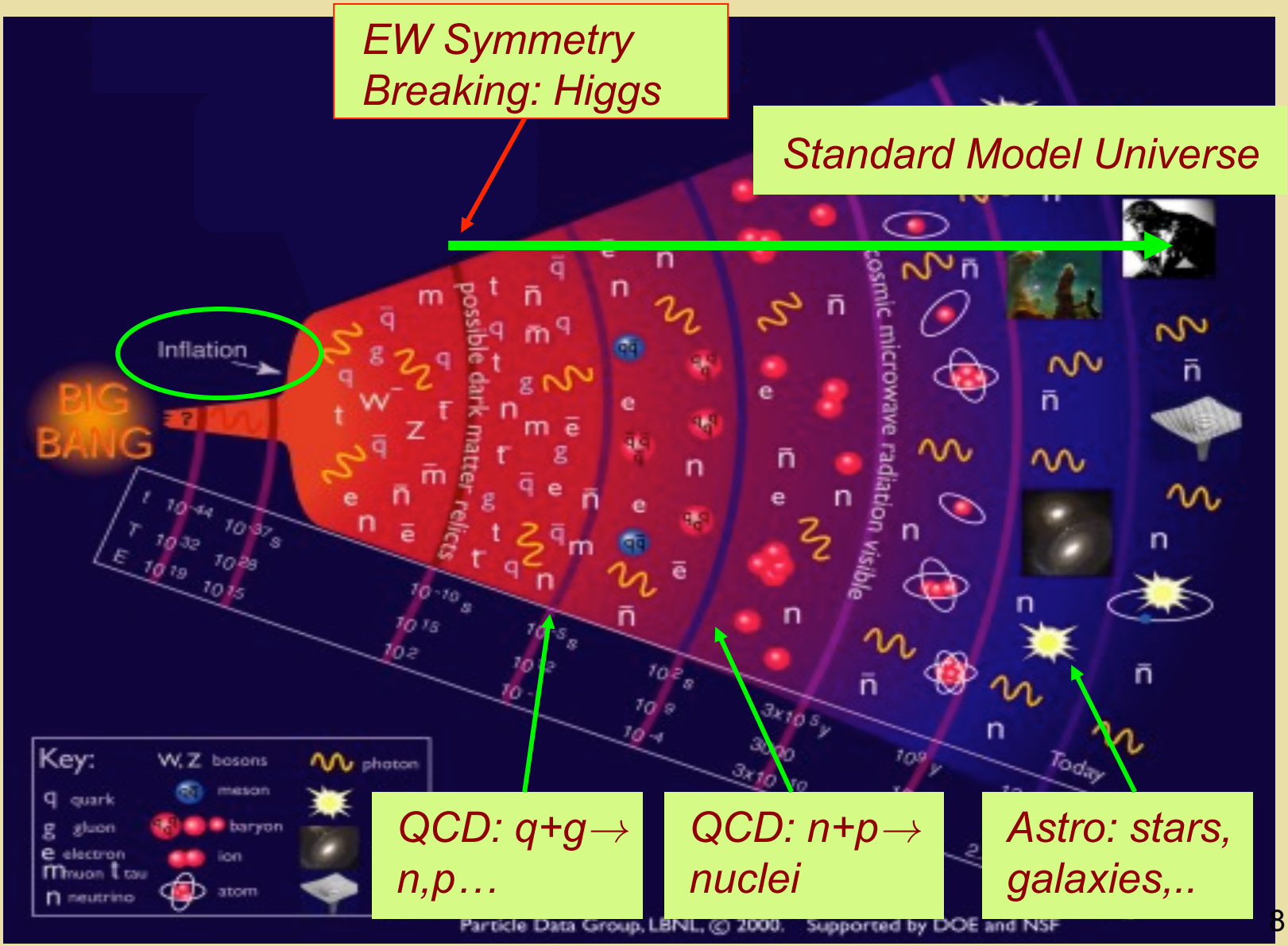

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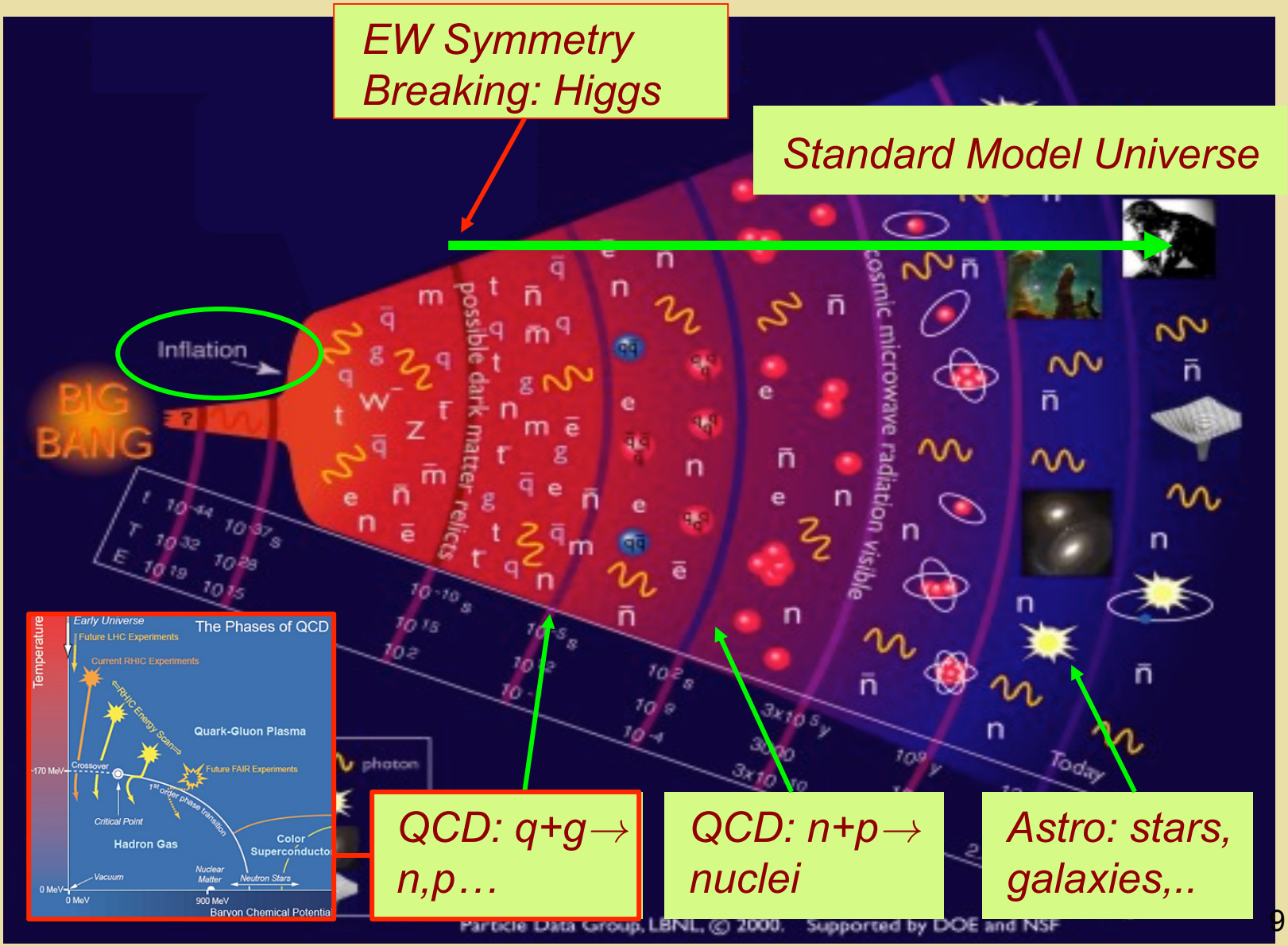

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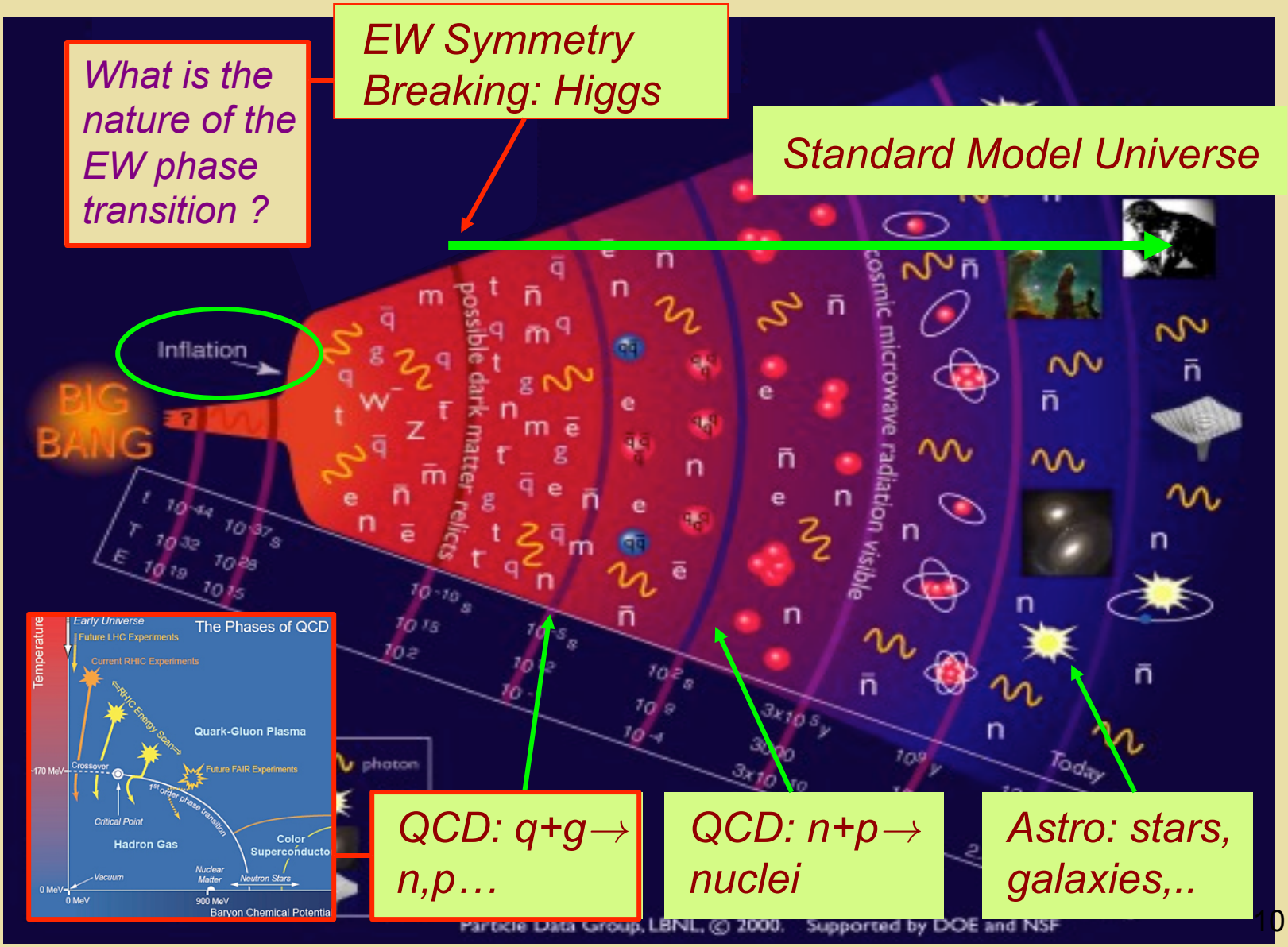

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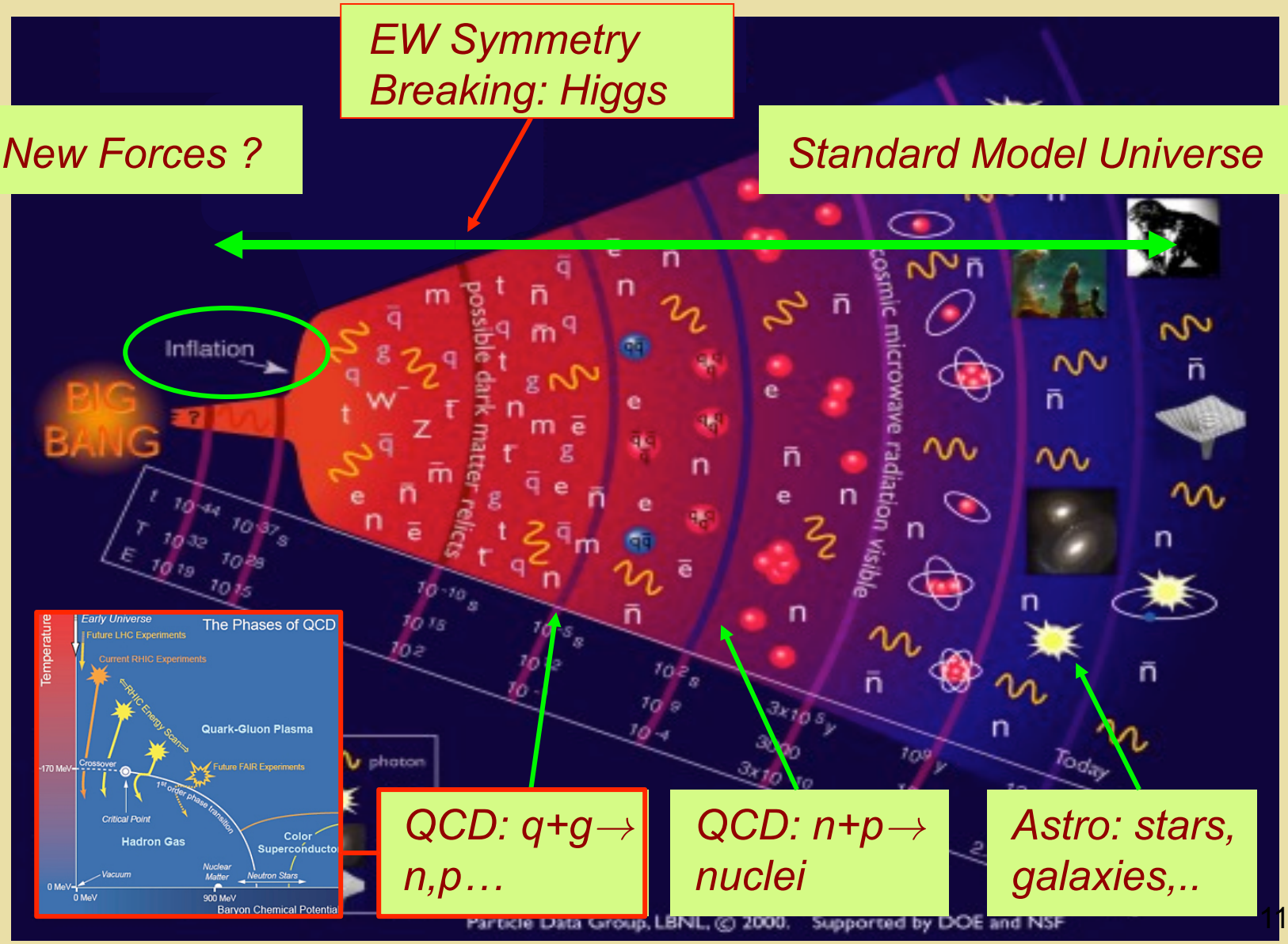

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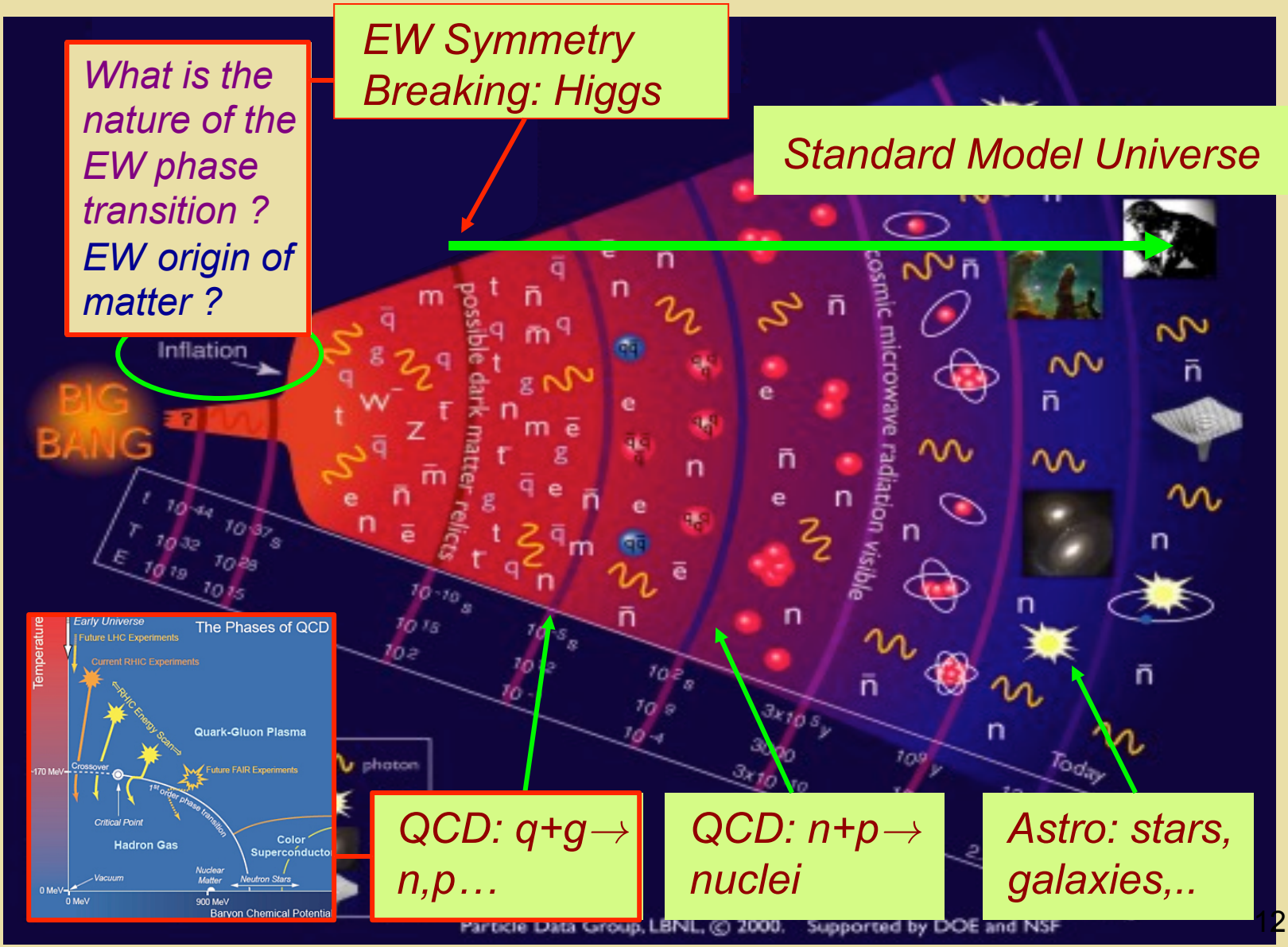


Questions for this Workshop

- *What are the implications for the EWPT of BSM scenarios that address other open problems (hierarchy/ naturalness, dark matter…) ?*

- *What BSM scenarios could lead to a 1st order EWPT as needed for electroweak baryogenesis ?*

- *What are the signatures of these scenarios at a next generation pp collider and how are they related to the character of the EWPT ?*

- *To what extent might these scenarios be probed at a next generation pp collider and how might this opportunity complement those at the LHC and a future e^+e^- collider ?*

Phenomenological Connections

- *What scenarios can be probed at the LHC and to what extent?*
- *What scenarios can be probed with a lepton collider ?*
- *What are the unique opportunities for a next gen pp collider ? (new states, higher masses, EW cross sections)*
- *What are the constraints from Higgs studies?*
- *What are the present & prospective probes from other observables ?*

Theoretical Connections

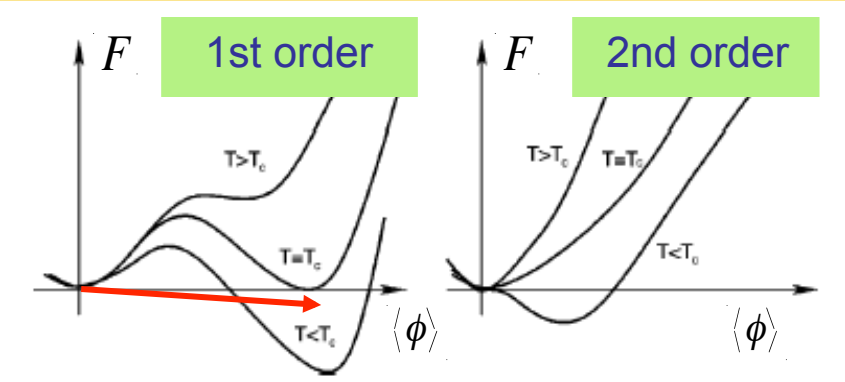
- *What are the patterns of EWSB & related thermal history for well-motivated BSM scenarios ?*
- *How robustly can we compute EWPT properties (order of transition, T_C , tunneling rate…) & relate them to experimental signatures ?*

Goals for the Workshop

- *Identify opportunities for a next gen pp collider*
- *Articulate complementarity with the LHC & prospective future lepton colliders*
- *Identify studies needed to flesh out the physics opportunities*
- *Provide input for the FCC-hh document*
- *Generate interest and activity among colleagues*

II. EWB in a Nutshell

EW Phase Transition: New Scalars & CPV



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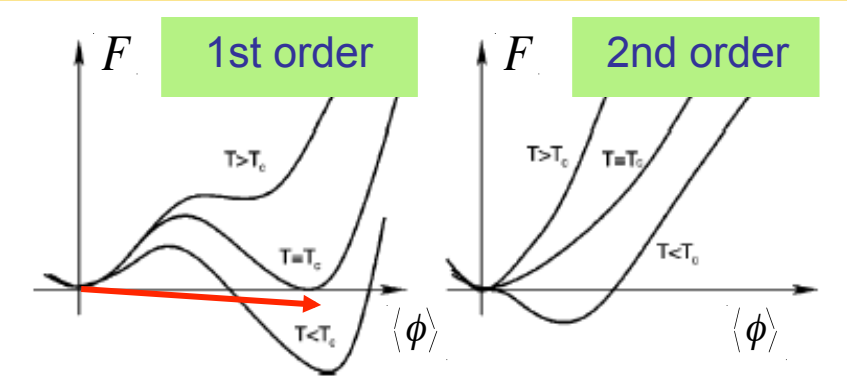
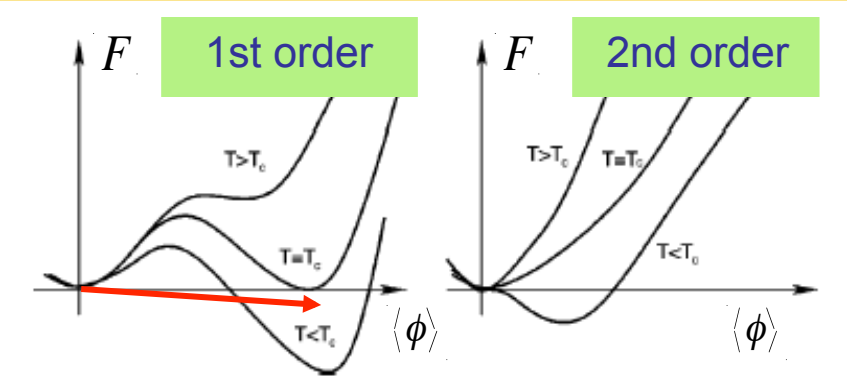


Increasing m_h →

EW Phase Transition: New Scalars & CPV



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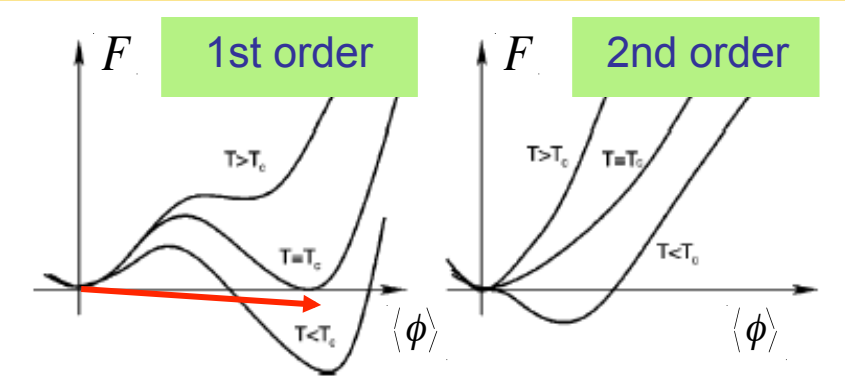

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Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

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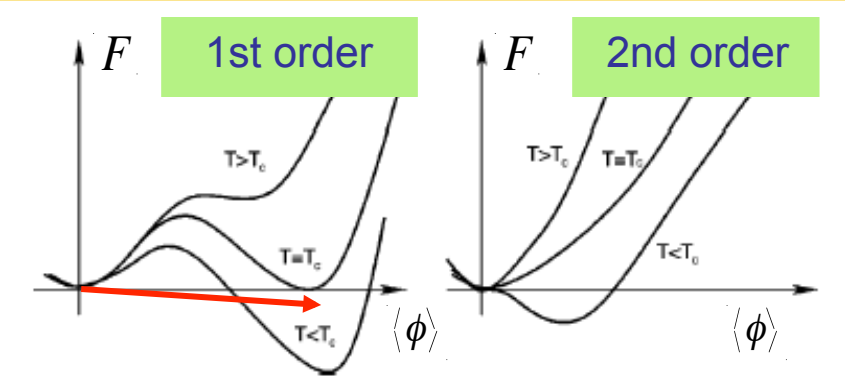

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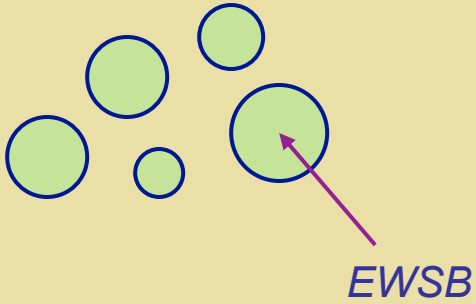
Bubble nucleation



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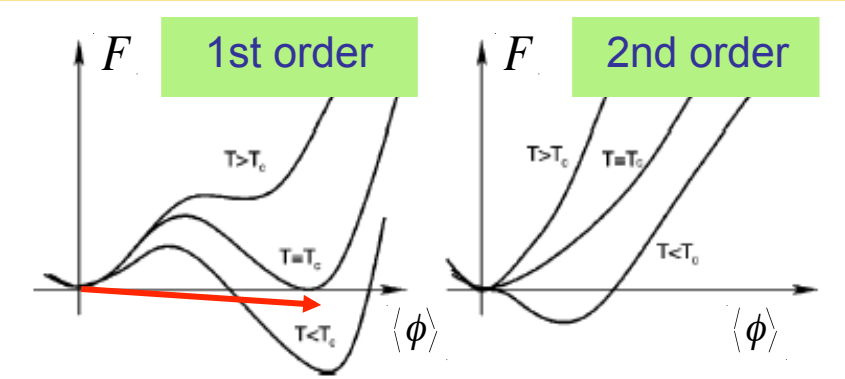

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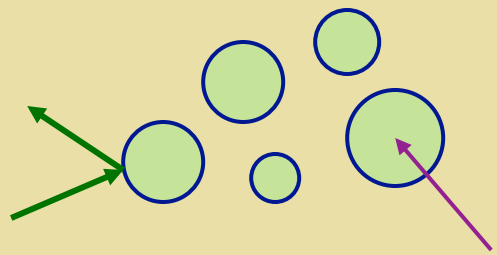
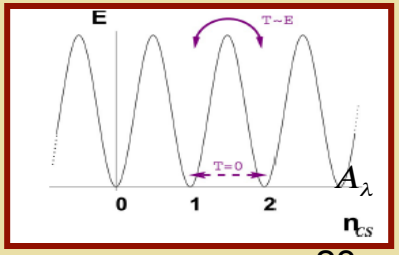


Y_B : CPV & EW sphalerons

EWSB



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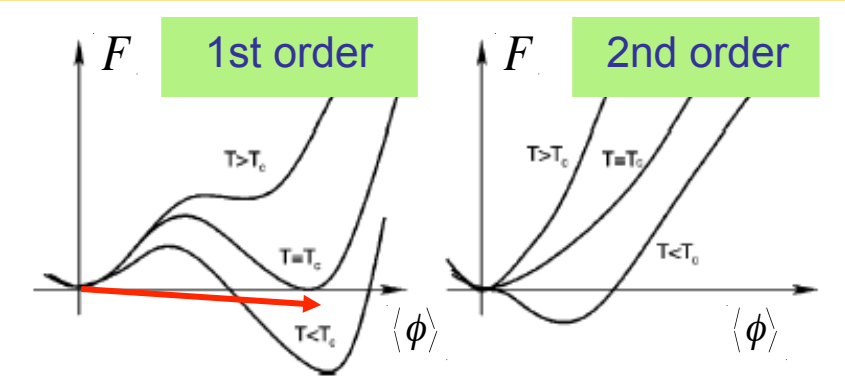

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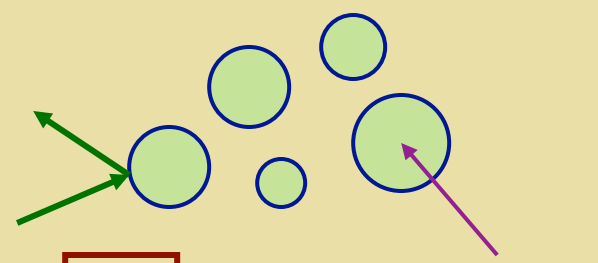
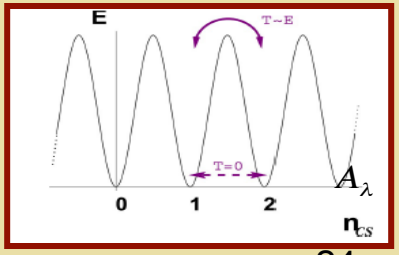


Y_B : CPV & EW sphalerons

EWSB

BSM



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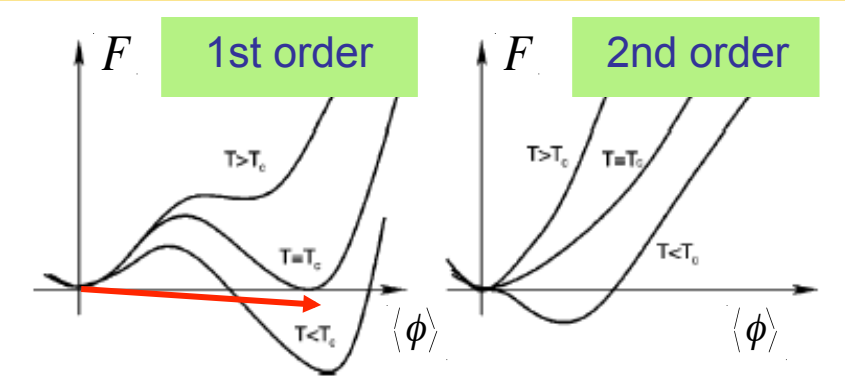

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Baryogenesis
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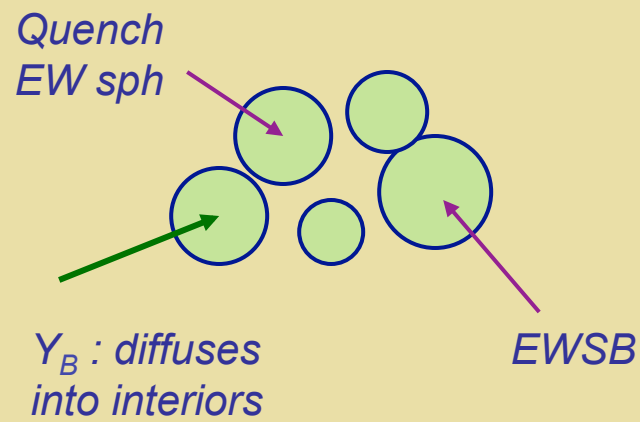
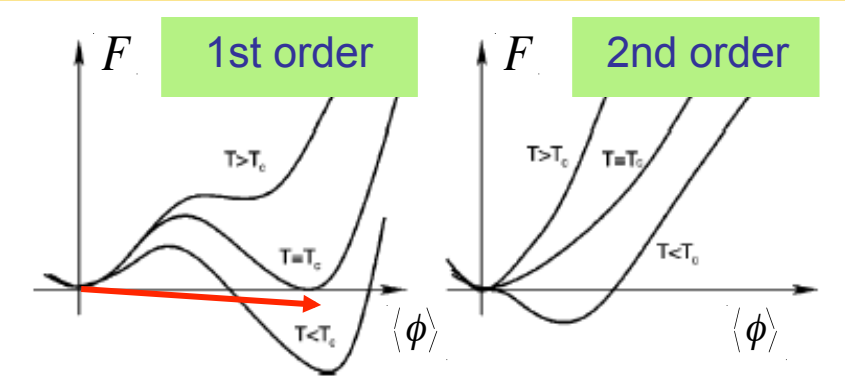
"Strong" → *Preserve $Y_B^{initial}$*

1st order EWPT → *Bubble nucleation*



III. Electroweak Phase Transition

EW Phase Transition: St'd Model



Increasing m_h →

Lattice: Endpoint

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
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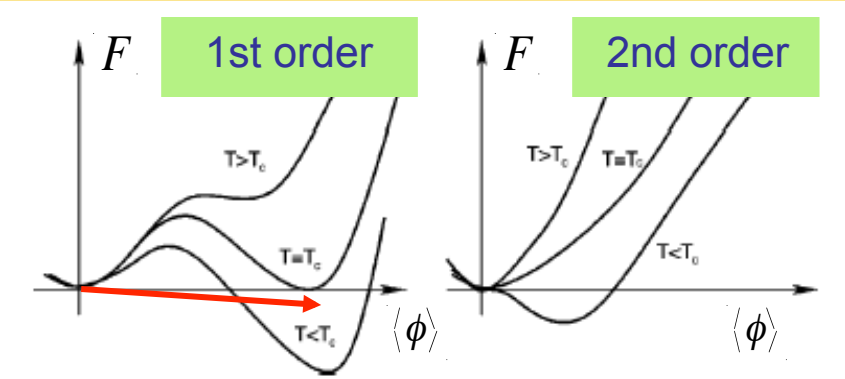
S'td Model: 1st order EWPT requires light Higgs

EW Phase Transition: St'd Model



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BSM induced 1st order EWPT:

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- *Tree level (Higgs portal, NMSSM…)*

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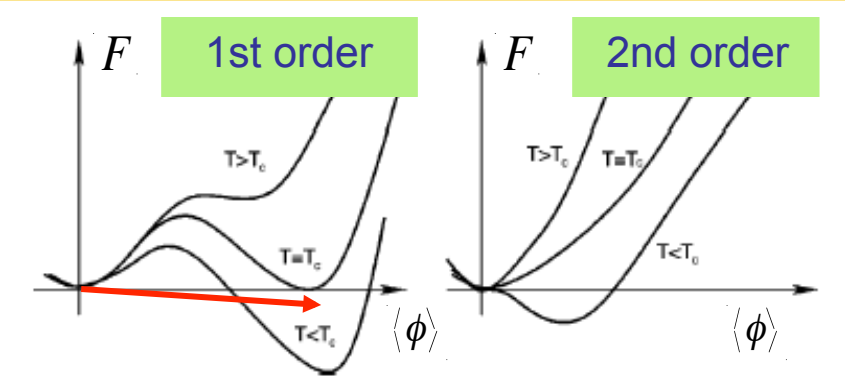

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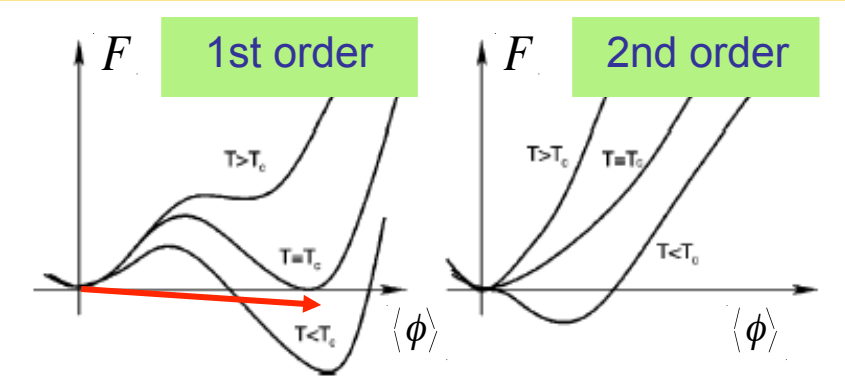

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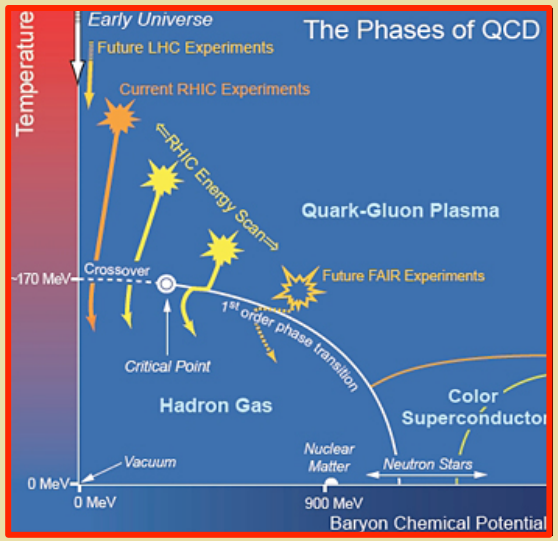
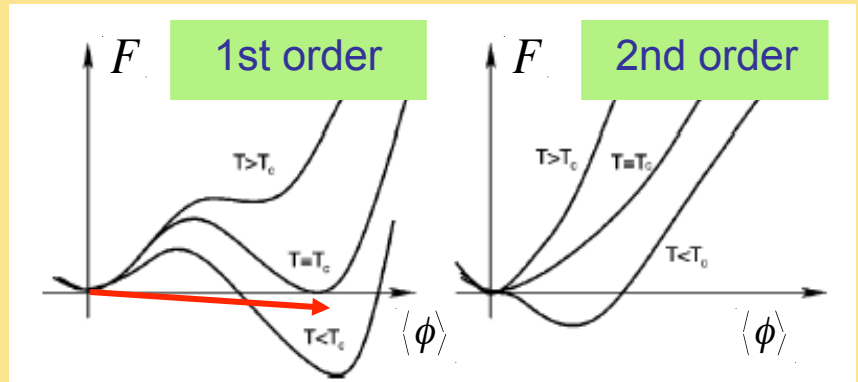
Other talks: Kotwal & Qian (expt), Cohen (models), Ren & Tweedie (collider pheno), Shuve (new baryo scenarios)

EWPT: Why Should We Care ?



QCD Phase Diagram



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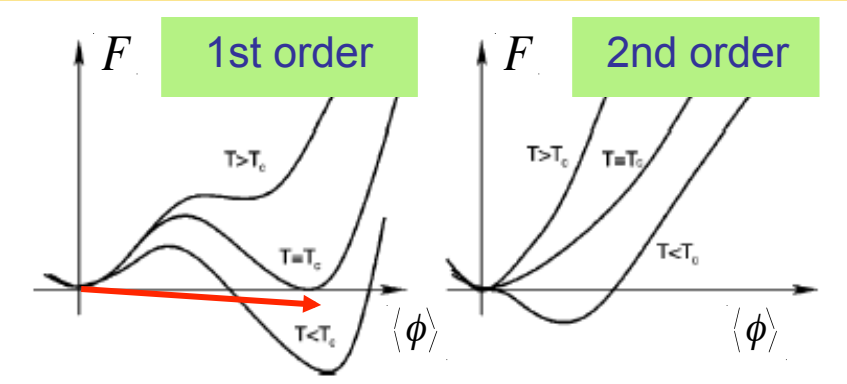
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ?

SM EW: Cross over transition

EW Phase Transition: New Scalars



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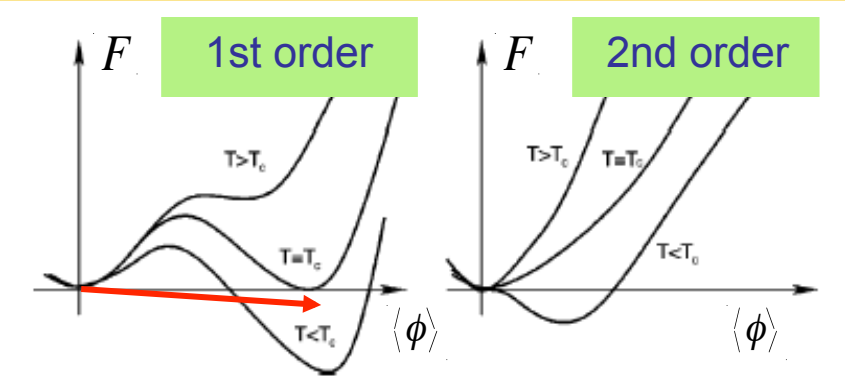
MSSM: Light RH stops

PT: Carena et al,…

EW Phase Transition: New Scalars



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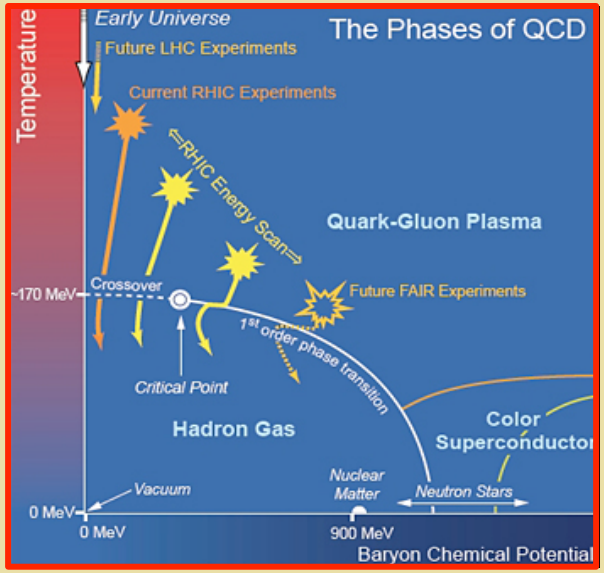
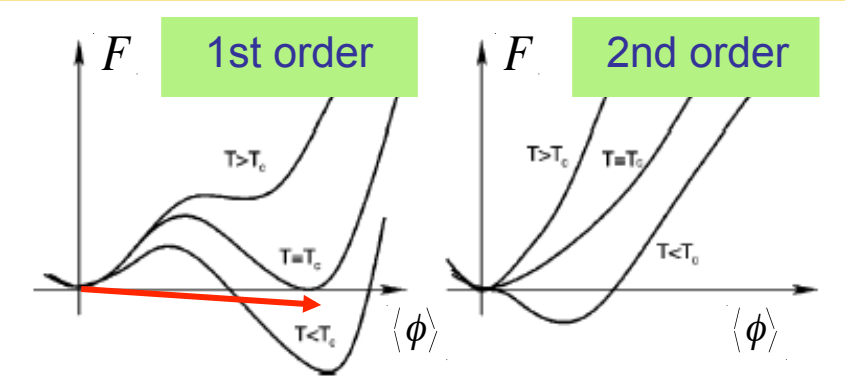
Recall: QCD phase diagram



What is the MSSM analog ?

EW Phase Transition: New Scalars



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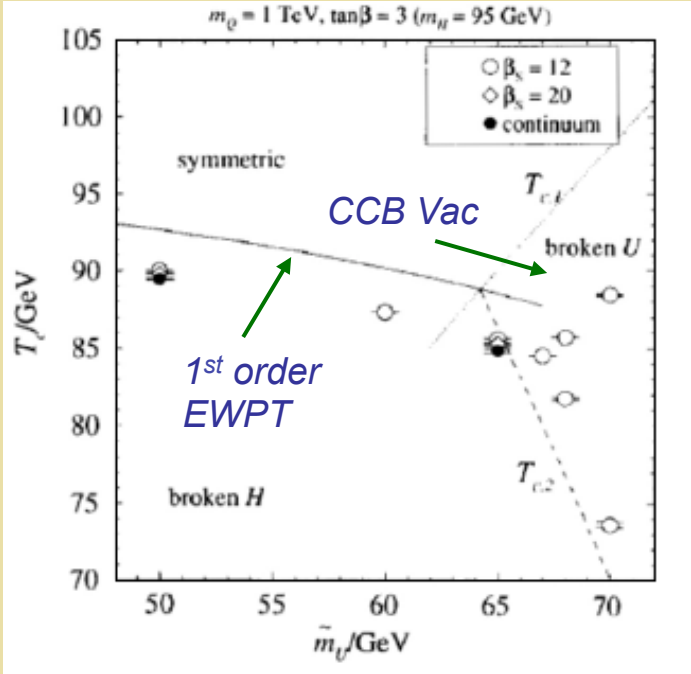
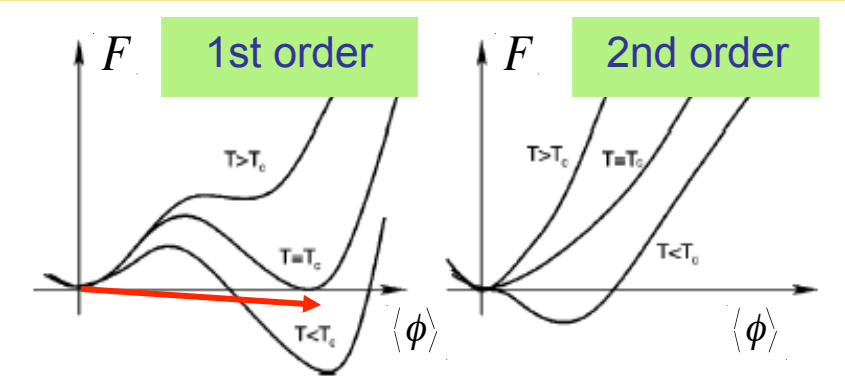
MSSM Phase Diagram

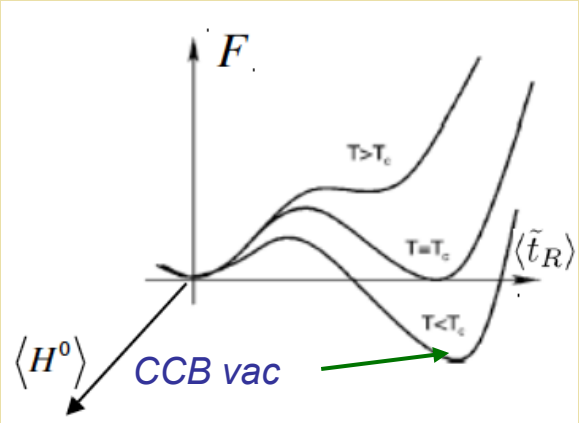
Lattice: Laine, Rummukainen



Decreasing RH stop mass →

EW Phase Transition: MSSM





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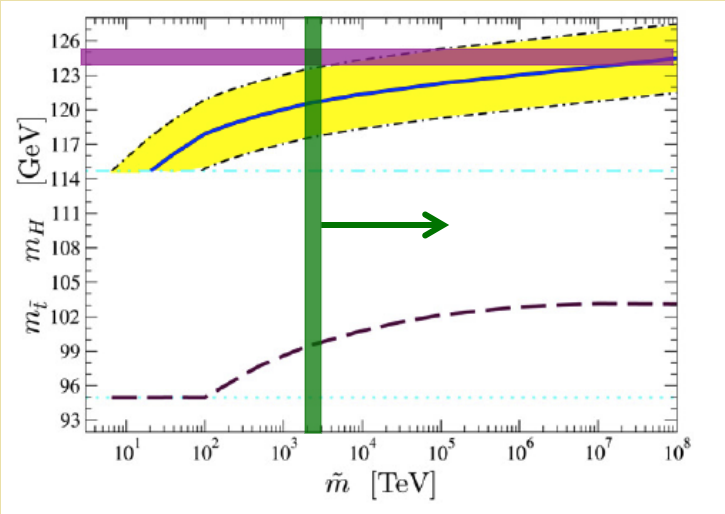
Carena et al 2008: Higgs phase metastable



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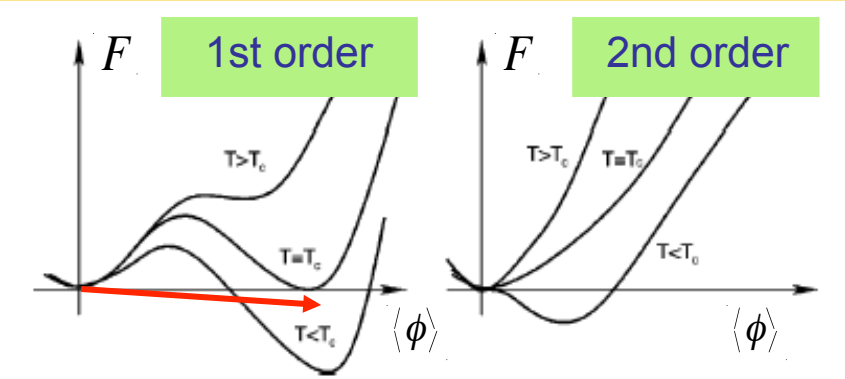

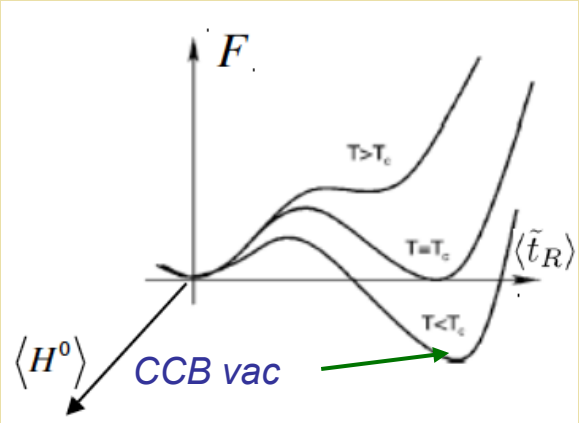

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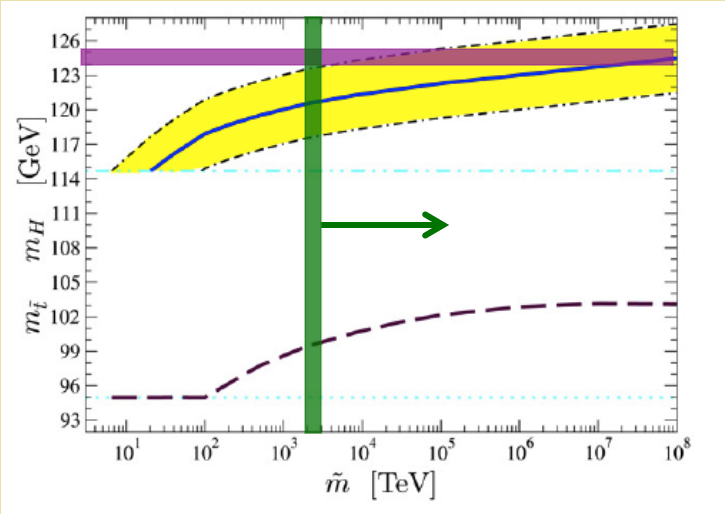
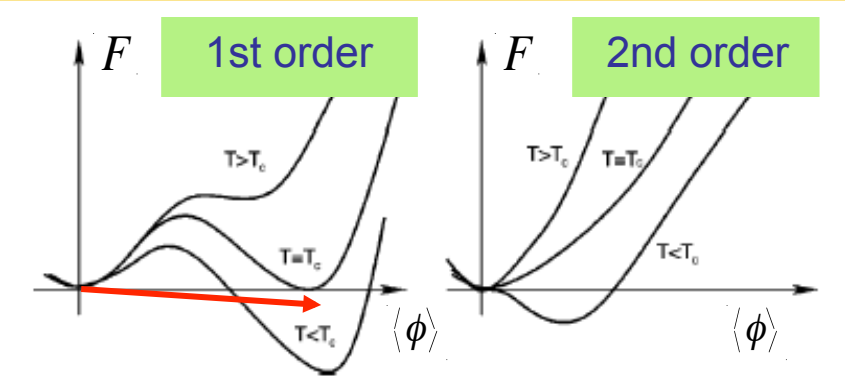


Viable? See talk by A. Katz

EW Phase Transition: Higgs Portal



Increasing m_h →

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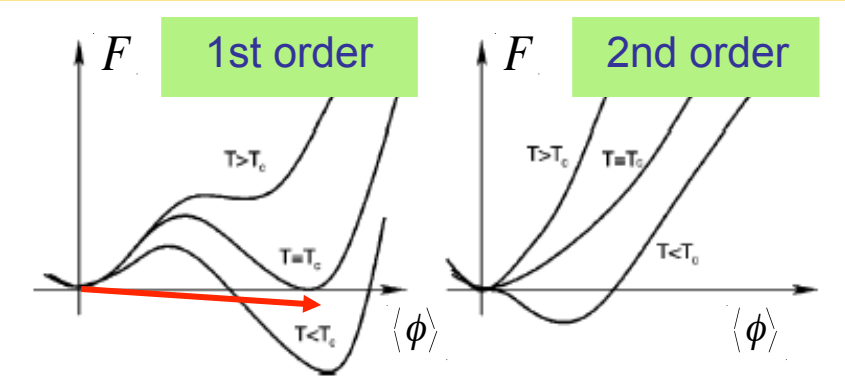
$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H$$

+...

EW Phase Transition: Higgs Portal



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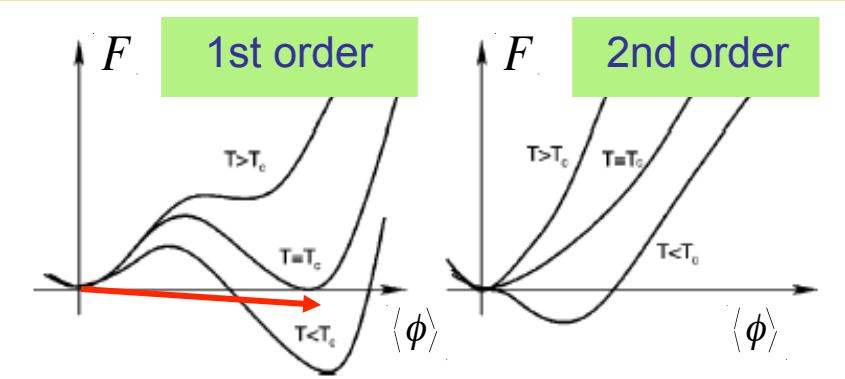
+…

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

EW Phase Transition: Higgs Portal



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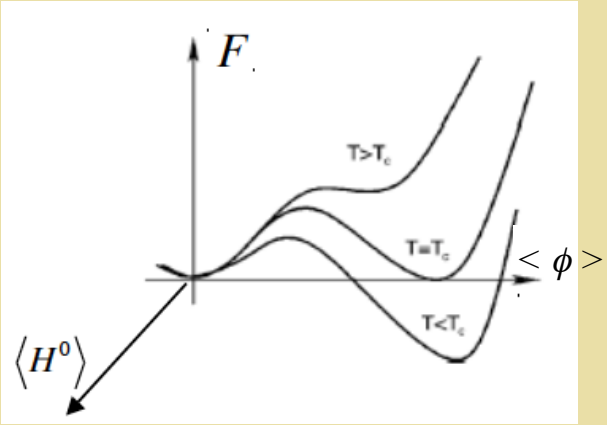

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Higgs Portal: Simple Scalar Extensions

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

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

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

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

The Simplest Extension

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

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

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

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

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

Real Singlet: EWPT

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

Real Singlet: EWPT

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

Raise barrier

Lower T_C

Real Singlet: EWPT

Low energy phenomenology

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

Raise barrier

Lower T_C

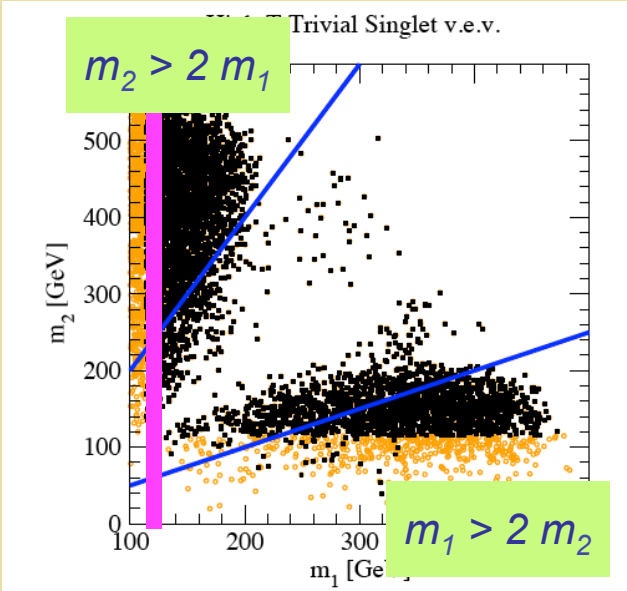
Mixing

Modified BRs

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

EWPT & LHC Phenomenology

Signatures



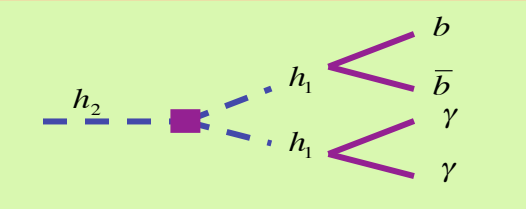
Scan: EWPT-viable model parameters

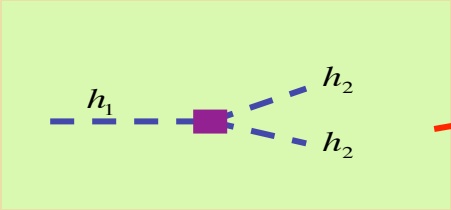
Light: all models
Black: LEP allowed

Profumo, R-M, Shaugnessy '07

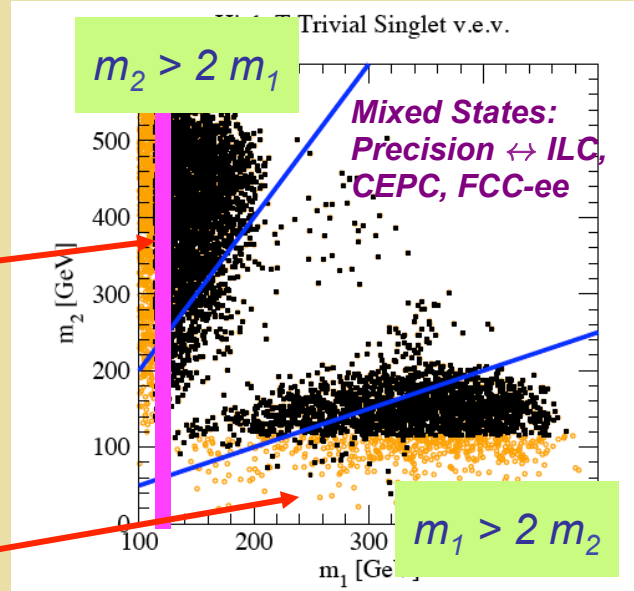
EWPT & LHC Phenomenology

Signatures





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



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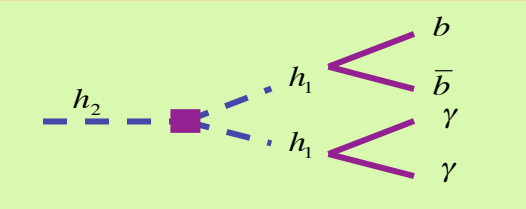
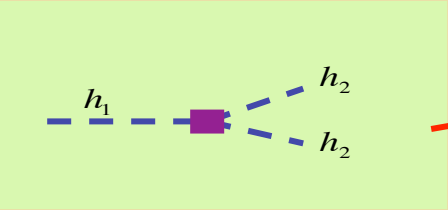
Profumo, R-M, Shaugnessy '07

EWPT & LHC Phenomenology

Signatures





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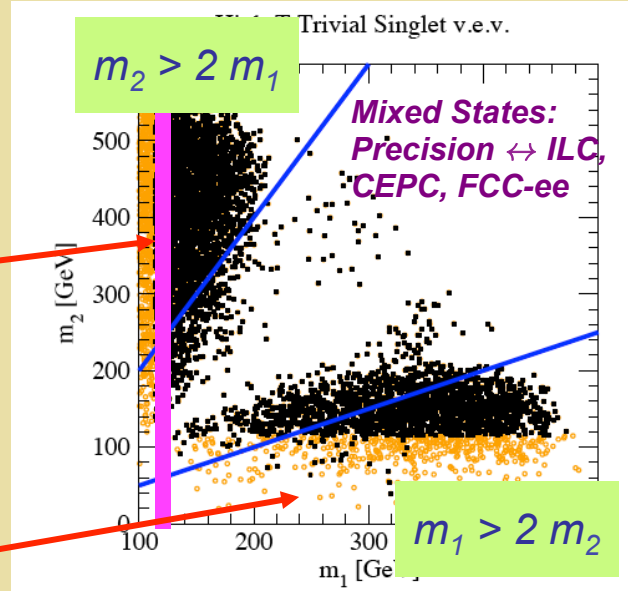


Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

See talks by C.-Y. Chen, D. Curtin, P. Winslow

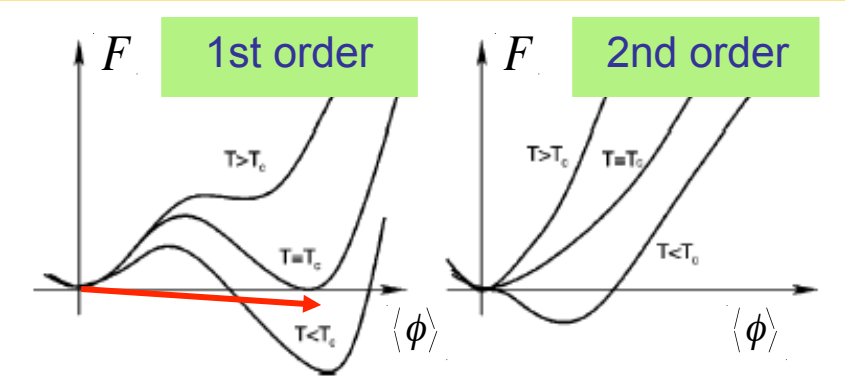
Profumo, R-M, Shaugnessy '07

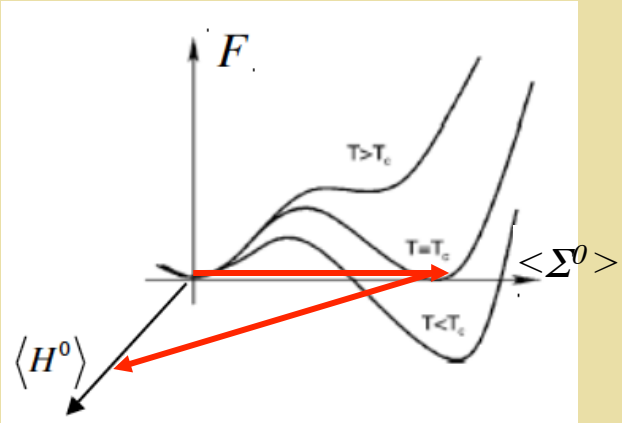
Higgs Portal: Simple Scalar Extensions

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

Simplest non-trivial EW multiplet

EW Phase Transition: Higgs Portal



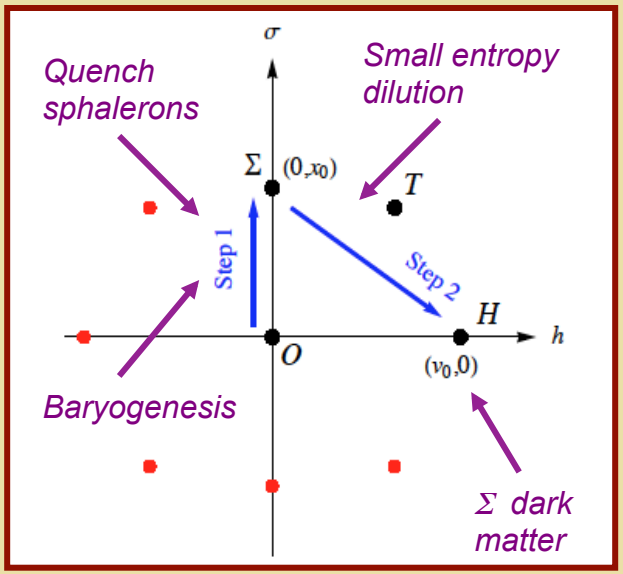


Increasing m_h →

← *New scalars*

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

Two-step EWPT & dark matter



Patel, R-M: arXiv 1212.5652 ; Fileviez-Perez, Patel, RM, Wang
Blinov, Kozaczuk, Morrissey, Tamarit arXiv: 1504.05195

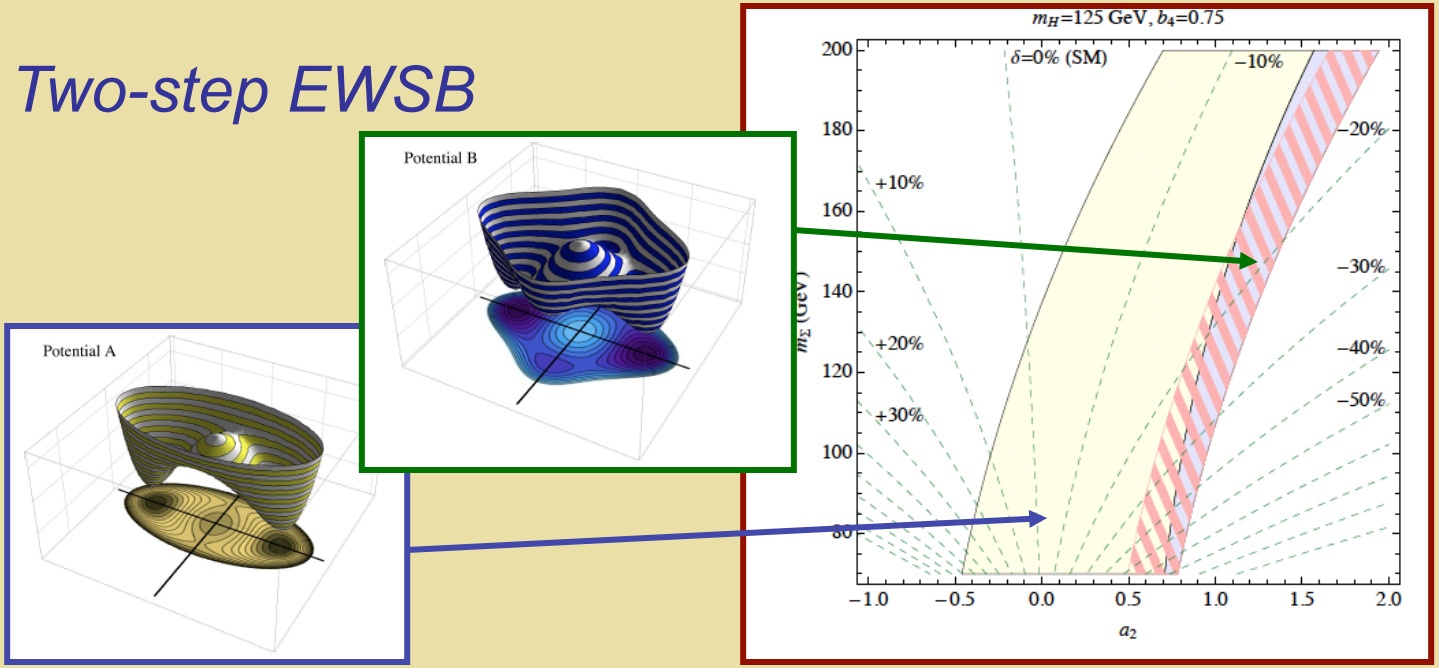
Real Triplet: EWPT

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

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

$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

Two-step EWSB



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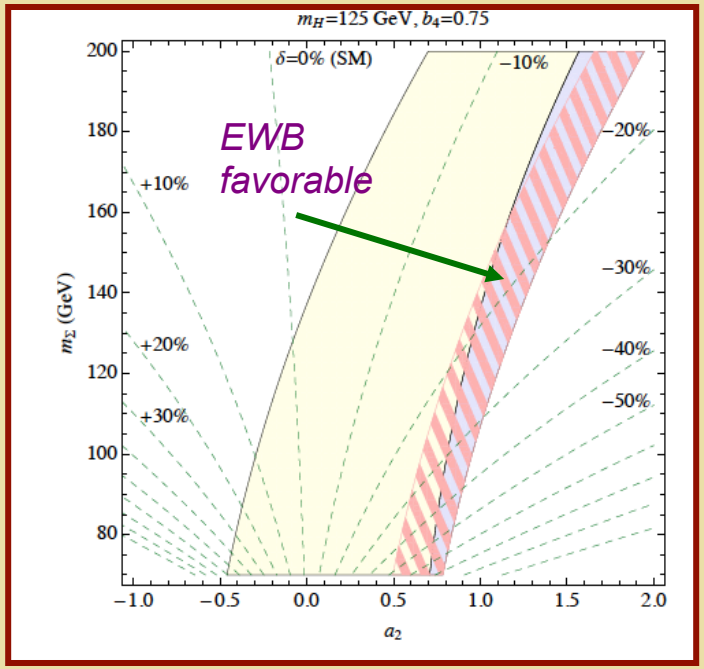
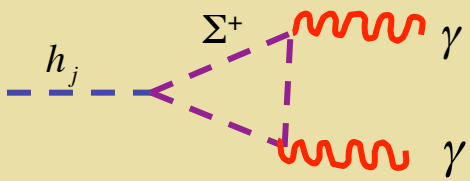
Two-step EWSB

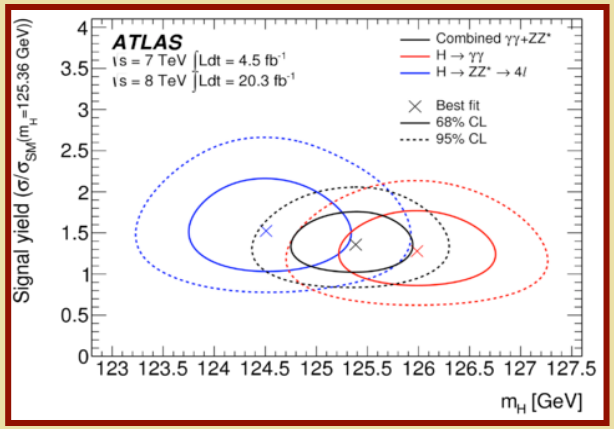
1. *Break $SU(2)_L$ x $U(1)_Y$ w/ Σ vev*
2. *Transition to Higgs phase w/ small or zero Σ vev*

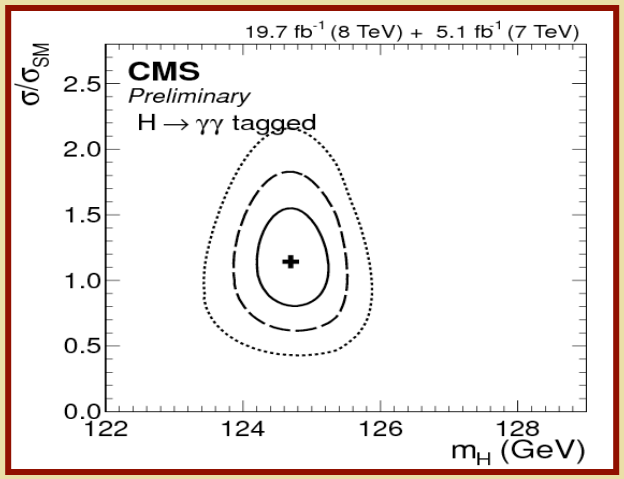


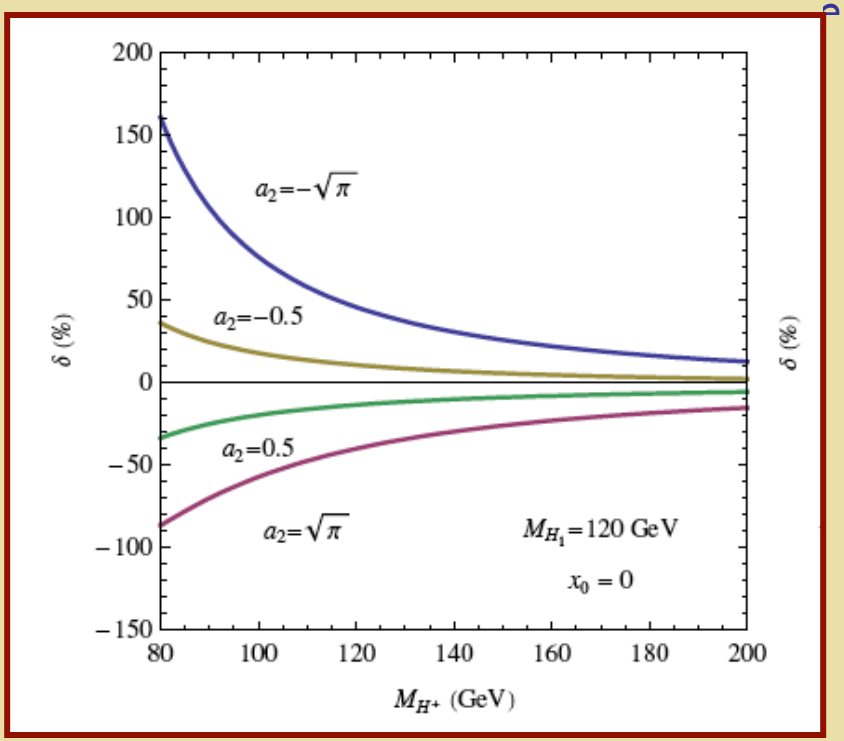
Higgs Diphoton Decays

LHC: H $\rightarrow \gamma\gamma$









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

Real Triplet: EWPT

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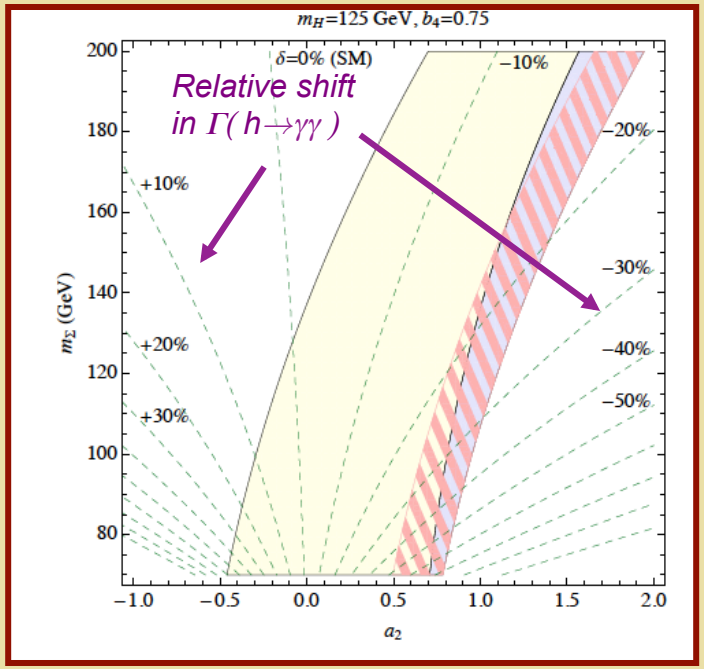

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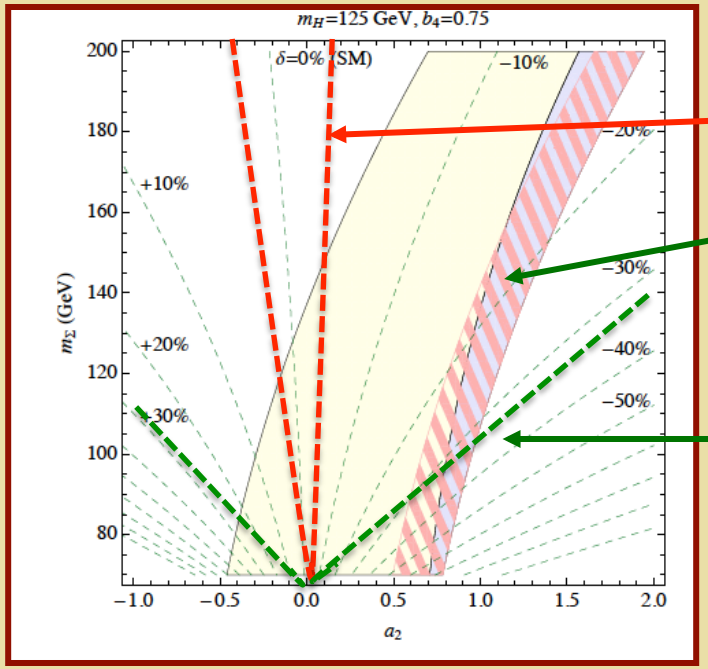


CEPC

EWB favorable

ILC 250

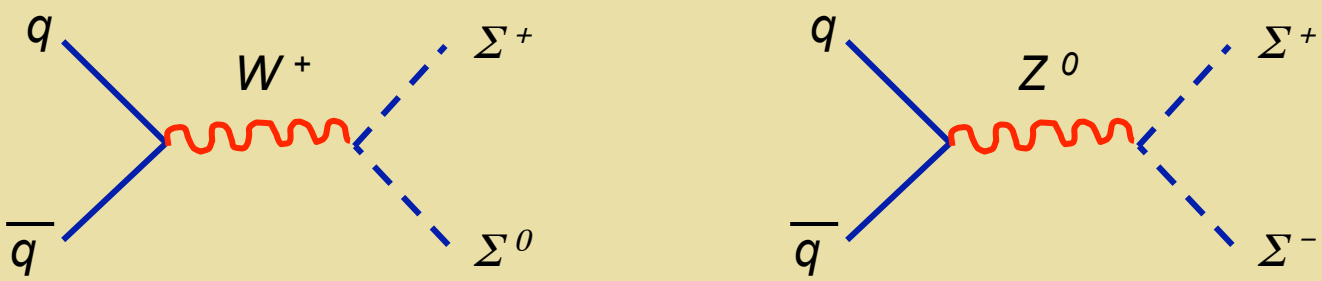
Observing New States: Production

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

Fileviez-Perez, Patel, Wang, R-M: 0811.3957 [hep-ph]

$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

New feature: gauge interactions & pp production



EW cross sections w/ charged states + $\not{E}_T$

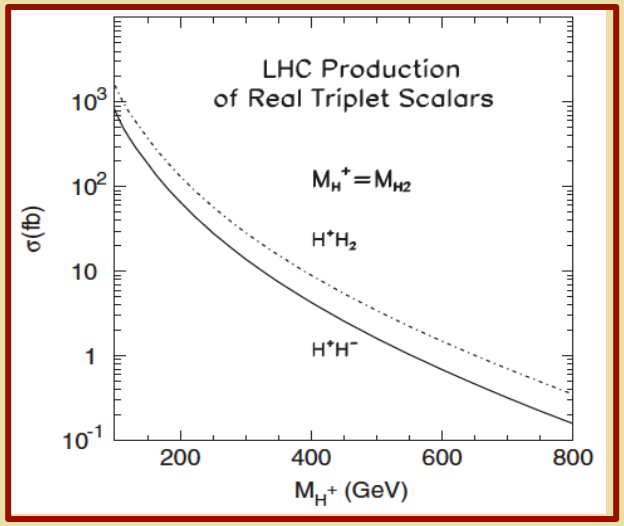
Observing New States: Production

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

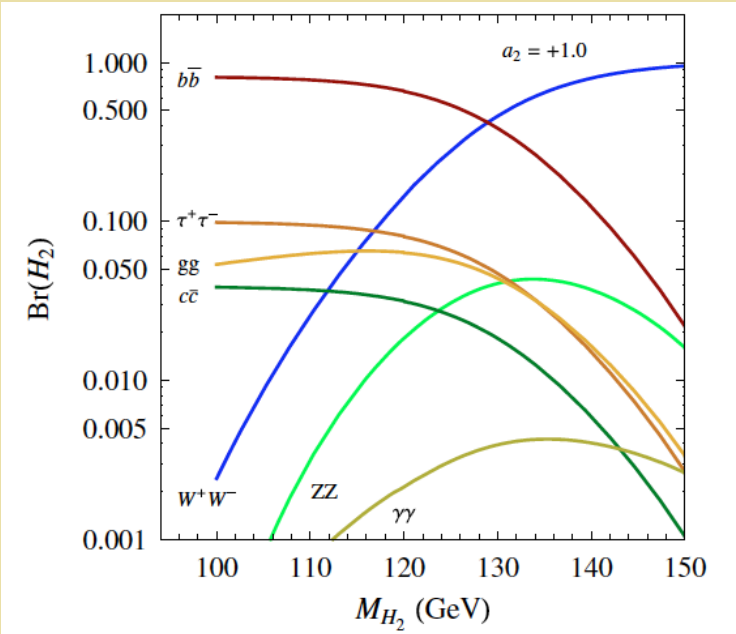
Fileviez-Perez, Patel, Wang, R-M: 0811.3957 [hep-ph]

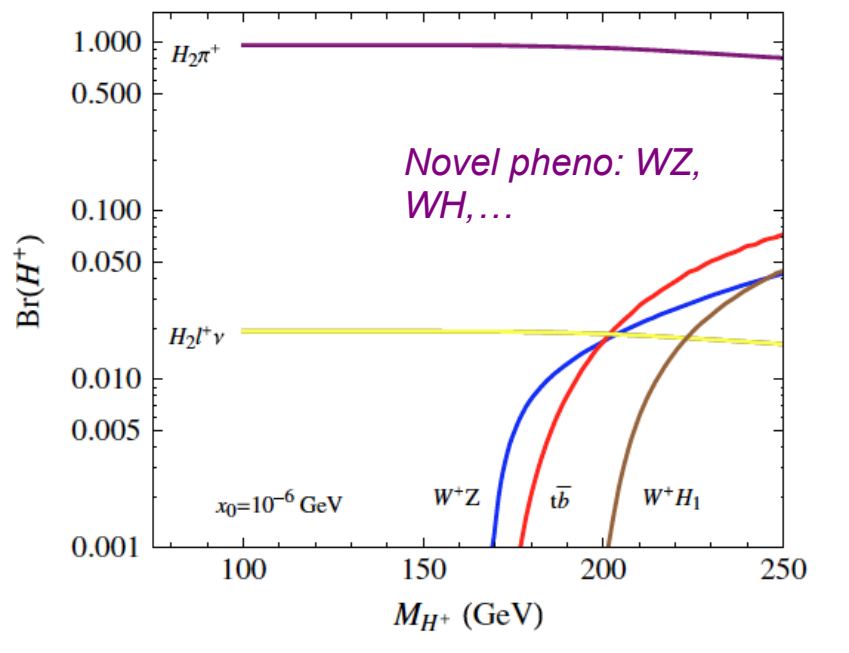
$$V_{H\Sigma} = \frac{a_2}{2} H^\dagger H \ \mathrm{Tr}\ \Sigma^2$$

New feature: gauge interactions & LHC production



EWPT: Heavier States ?



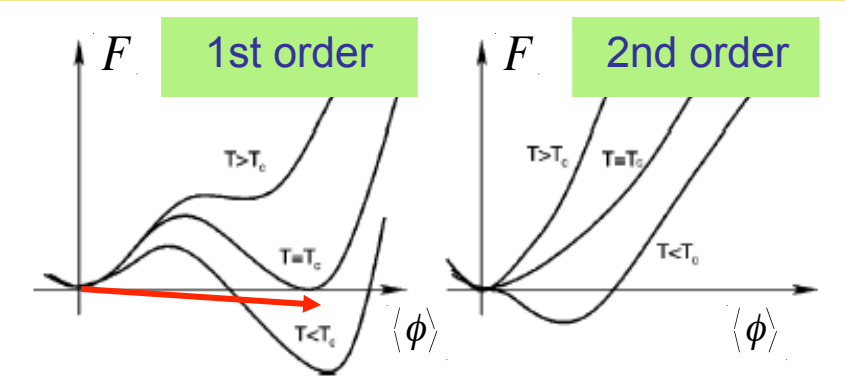


Four scalars: h_1 (Higgs-like)
$h_2 \sim \Sigma^0$ (unstable) *Σ^+ , Σ^-*
(new states)

Topologies:
bb $\tau\,\nu$
$\gamma\gamma\ \tau\nu$ ...

Fileviez-Perez, Patel, R-M, Wang

EW Phase Transition: Higgs Portal



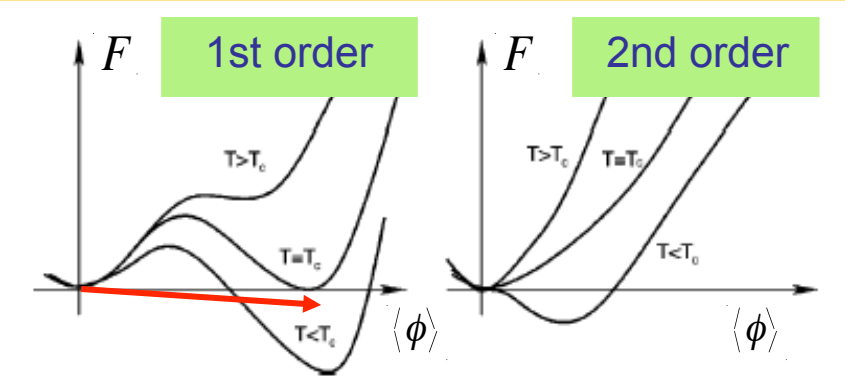
Increasing m_h →

← *New scalars*

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

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

Symmetry Breaking & Restoration



Increasing m_h →

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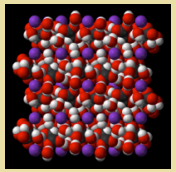
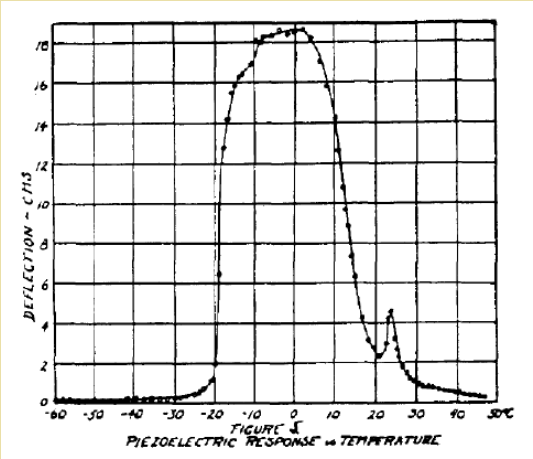
Do good symmetries today need to be good symmetries in the early Universe ?

Rochelle salt:
$KNaC_4H_4O_6\ 4H_20$



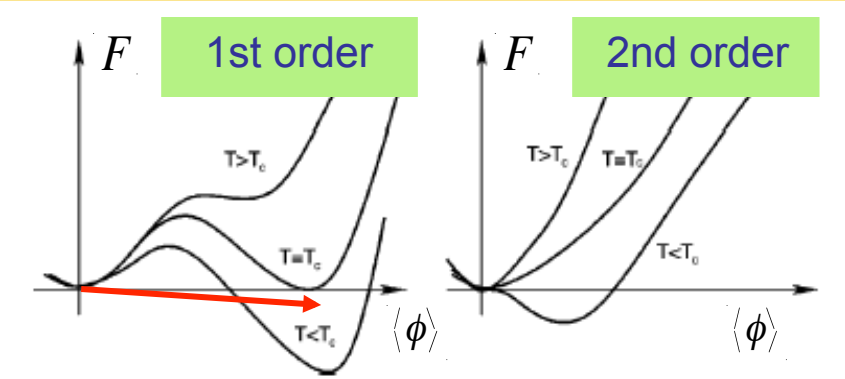
J. Valasek

Piezoelectricity



Increasing T →

EW Phase Transition: Higgs Portal



Increasing m_h →

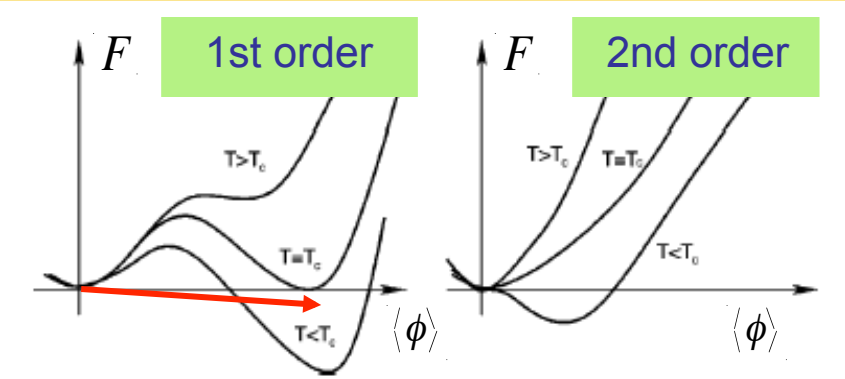
← *New scalars*

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

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

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

EW Phase Transition: Higgs Portal



Increasing m_h →

← *New scalars*

Colored Scalars

Color breaking & restoration

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

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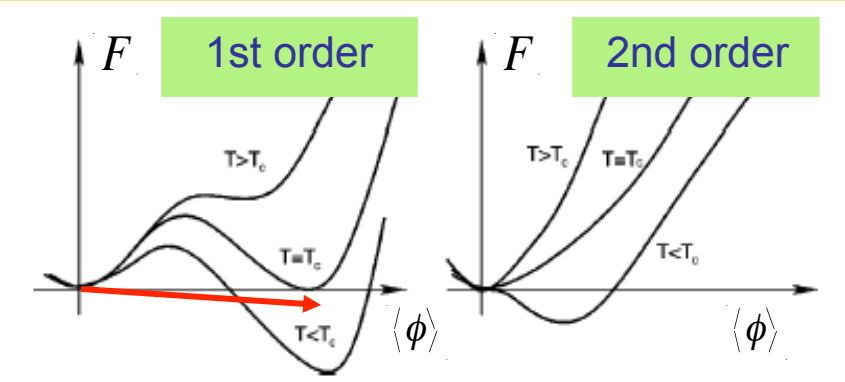
Patel, R-M, Wise: PRD 88 (2013) 015003

EW Phase Transition: Higgs Portal

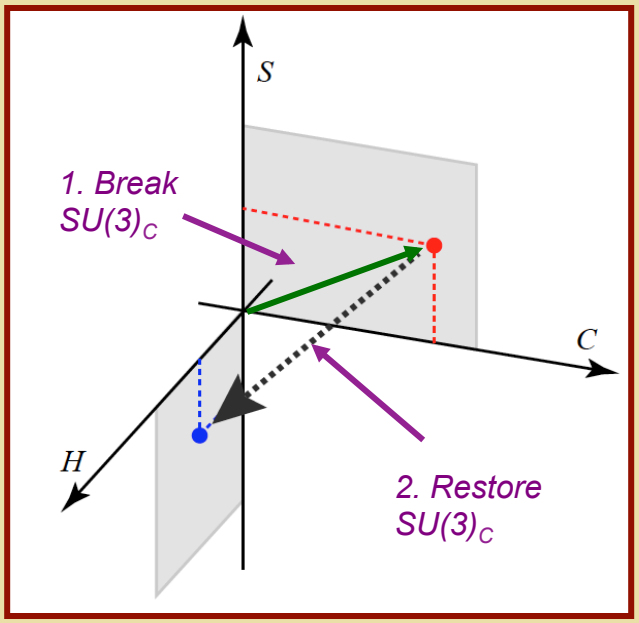


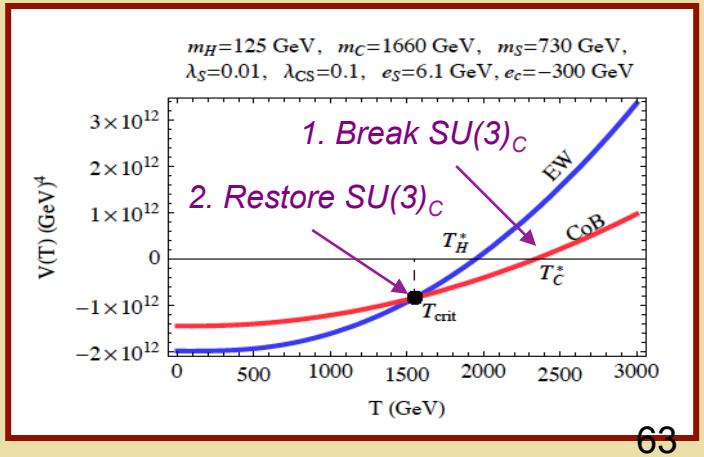
Increasing m_h →

← *New scalars*

Colored Scalars (triplet)

Color breaking & restoration





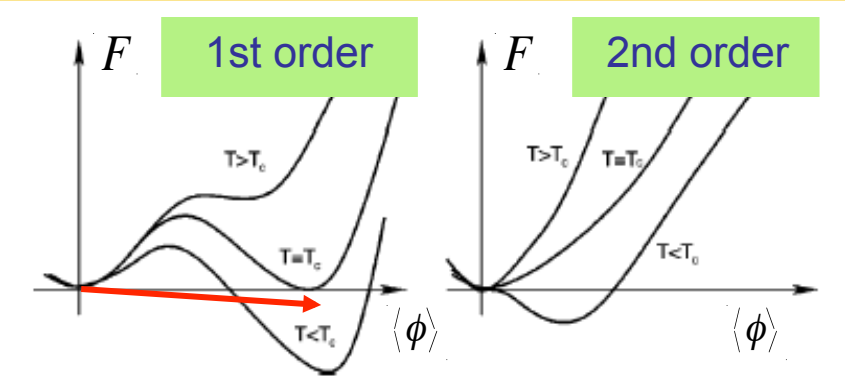
Patel, R-M, Wise: PRD 88 (2013) 015003

Outlook

- *Exploring the nature of the EWPT (a.k.a. thermal history of EWSB) is a forefront challenge for particle physics*
- *Discovering the ingredients for a 1st order EWPT would indicate that conditions for baryogenesis were present ~ 10ps after the Big Bang*
- *There exists a rich array of BSM scenarios that could admit a 1st order EWPT and novel patterns of EWSB*
- *Delineating the opportunities for addressing the nature of the EWPT with a next generation pp collider is important and exciting challenge for the HEP community*

Back Up Slides

EW Phase Transition: MSSM

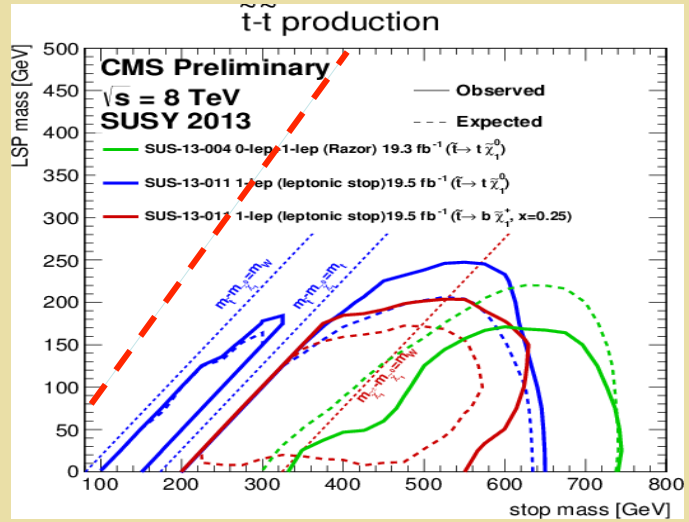


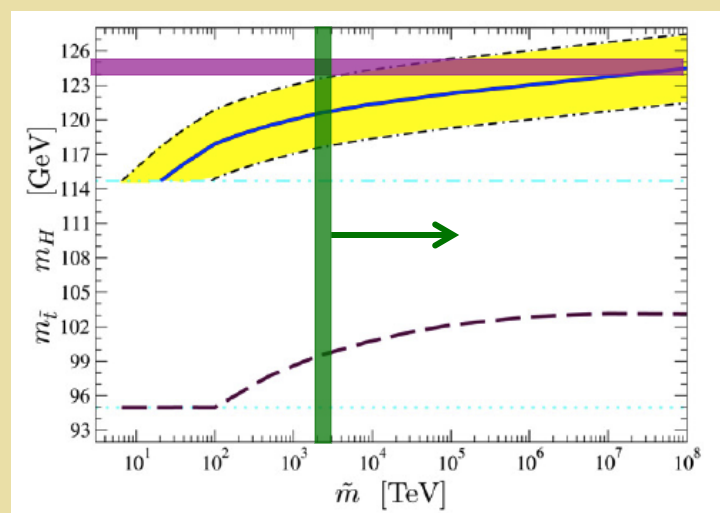
Increasing m_h →

← *New scalars*

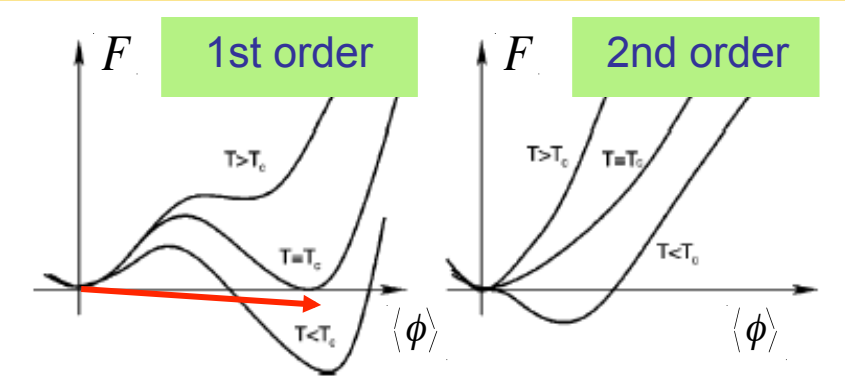
MSSM: Light RH stops

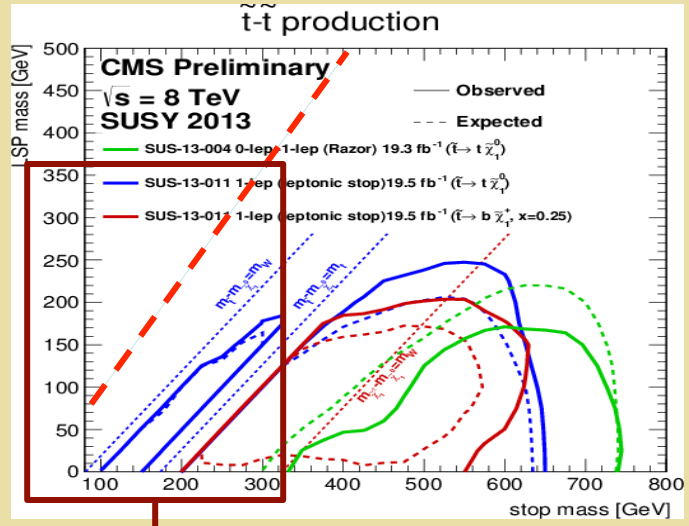
Carena et al 2008: Higgs phase metastable





EW Phase Transition: MSSM





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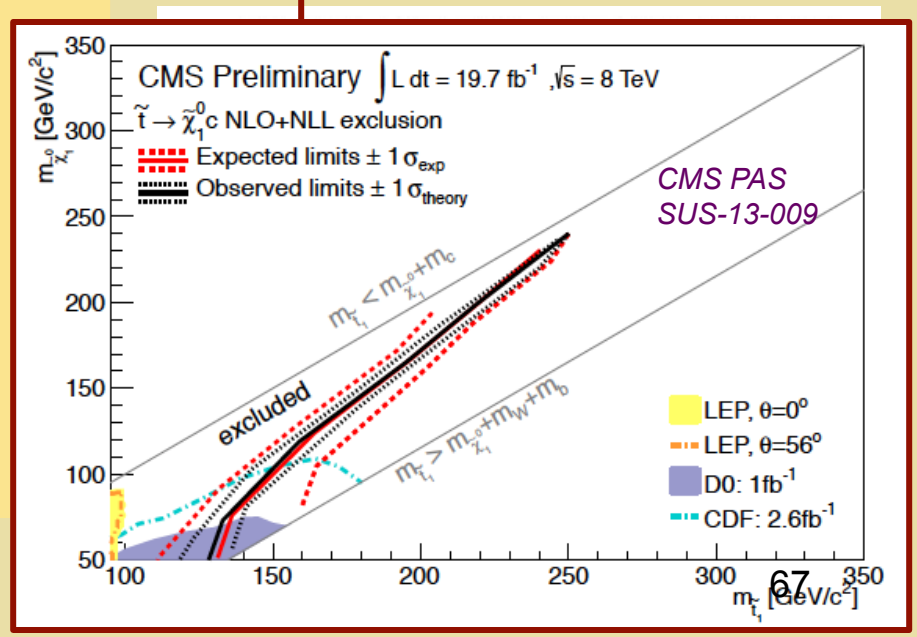

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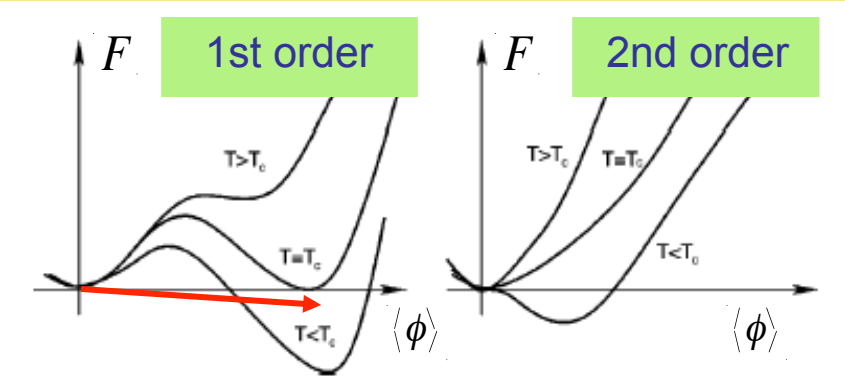

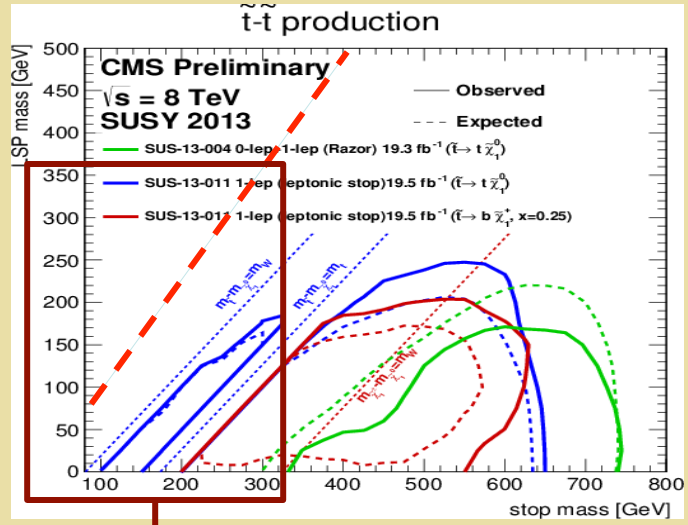

Increasing m_h →

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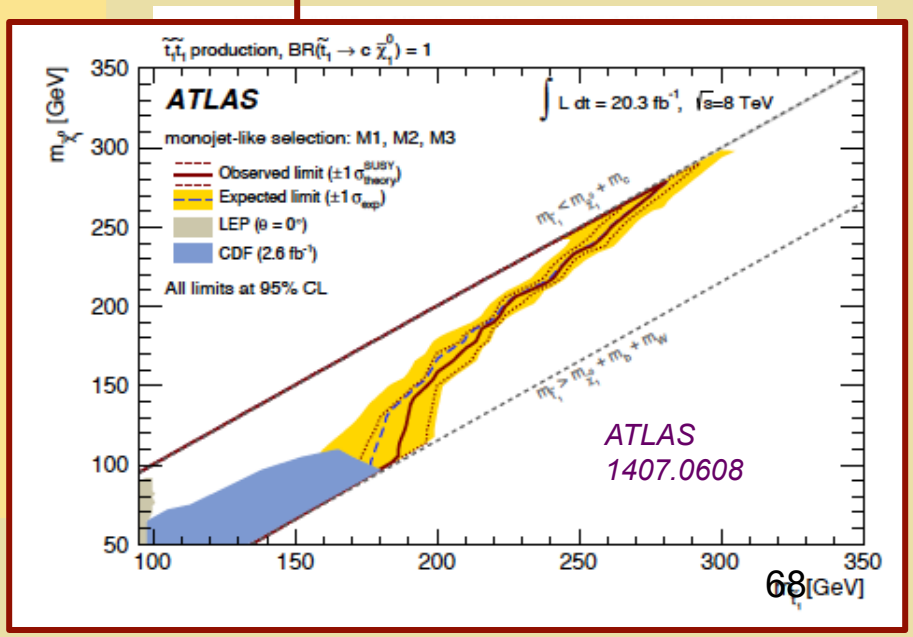

Real Triplet: EWPT

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

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