Higgs Portal & Cosmology: Theory Overview

M.J. Ramsey-Musolf

U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

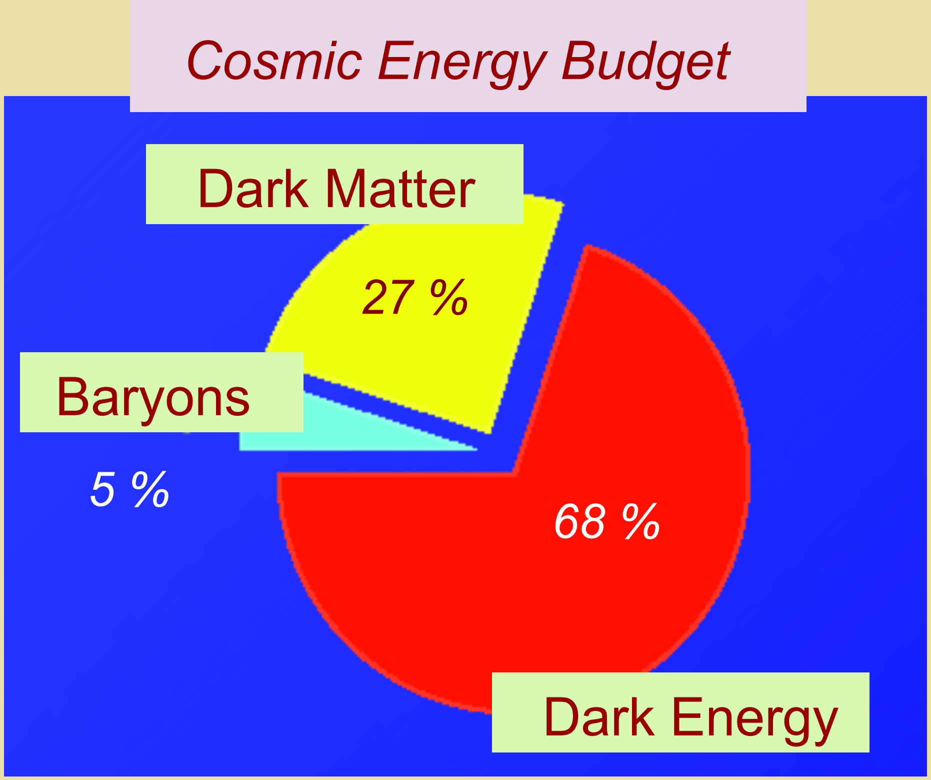
Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

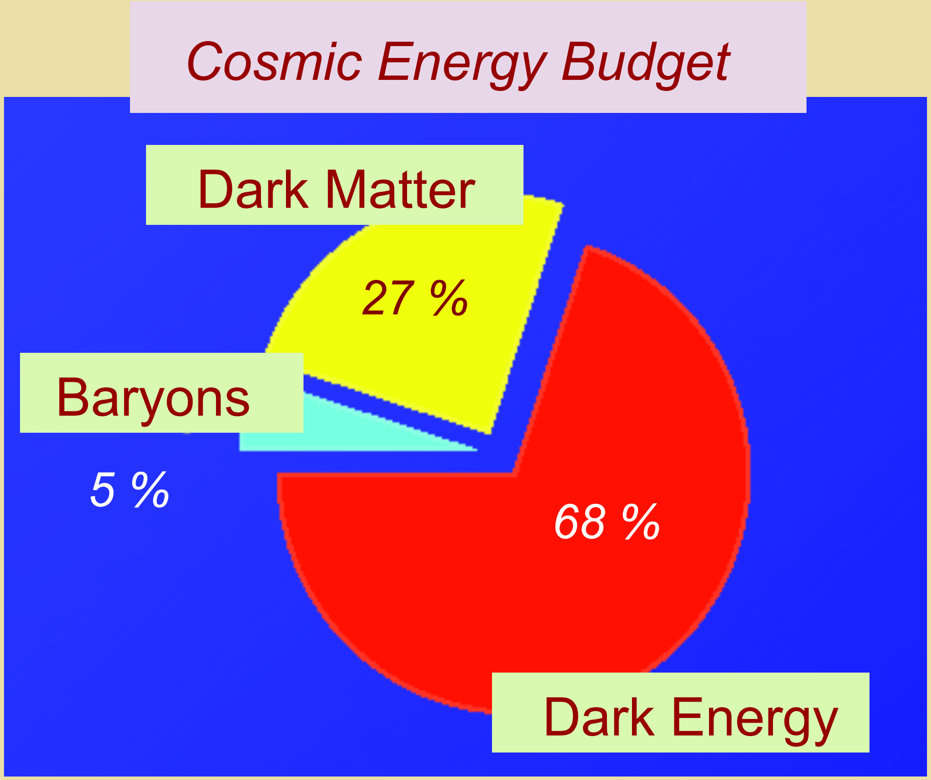
http://www.physics.umass.edu/acfi/

Higgs Portal WS May 2014

The Origin of Matter

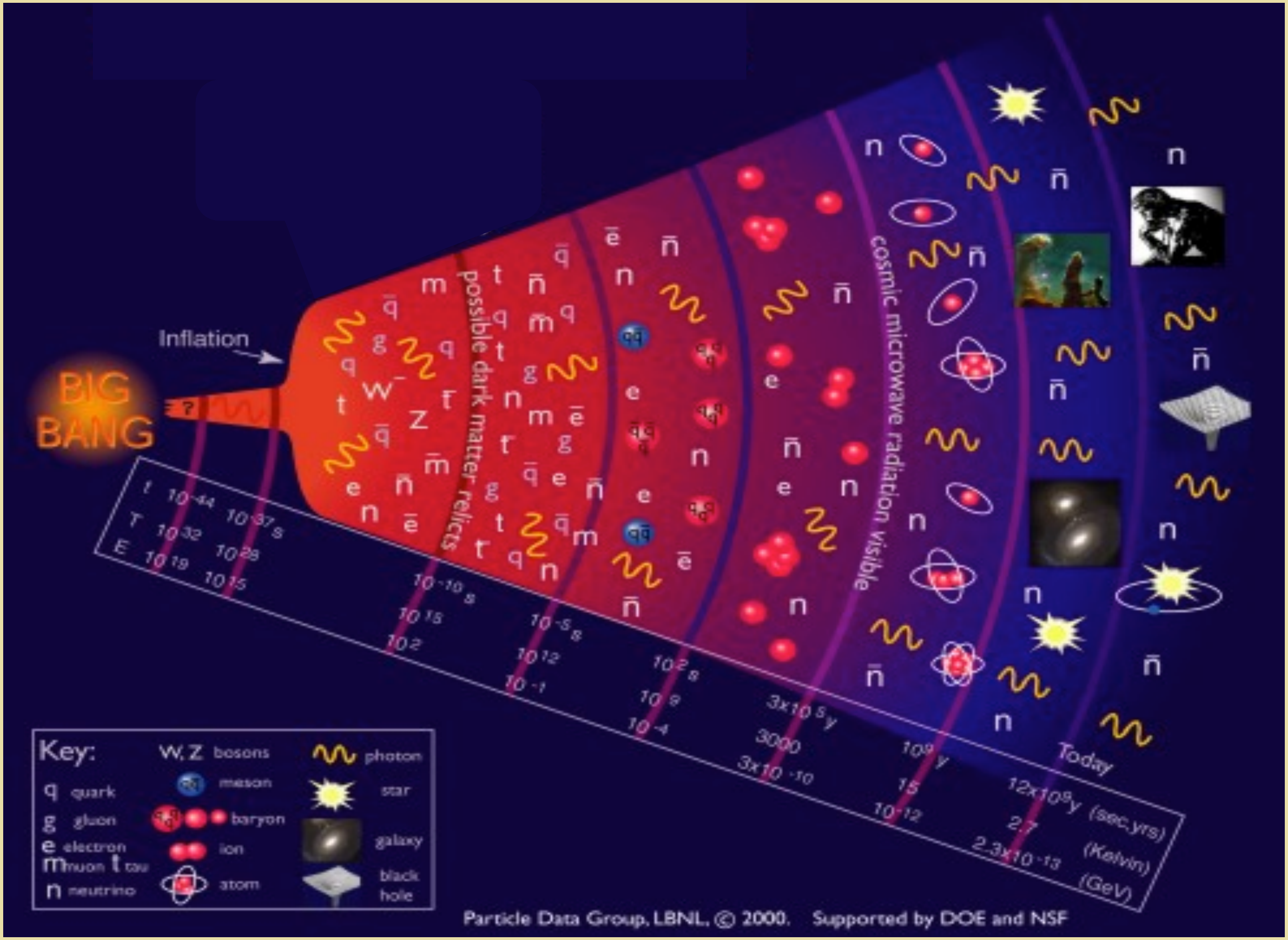


The Origin of Matter



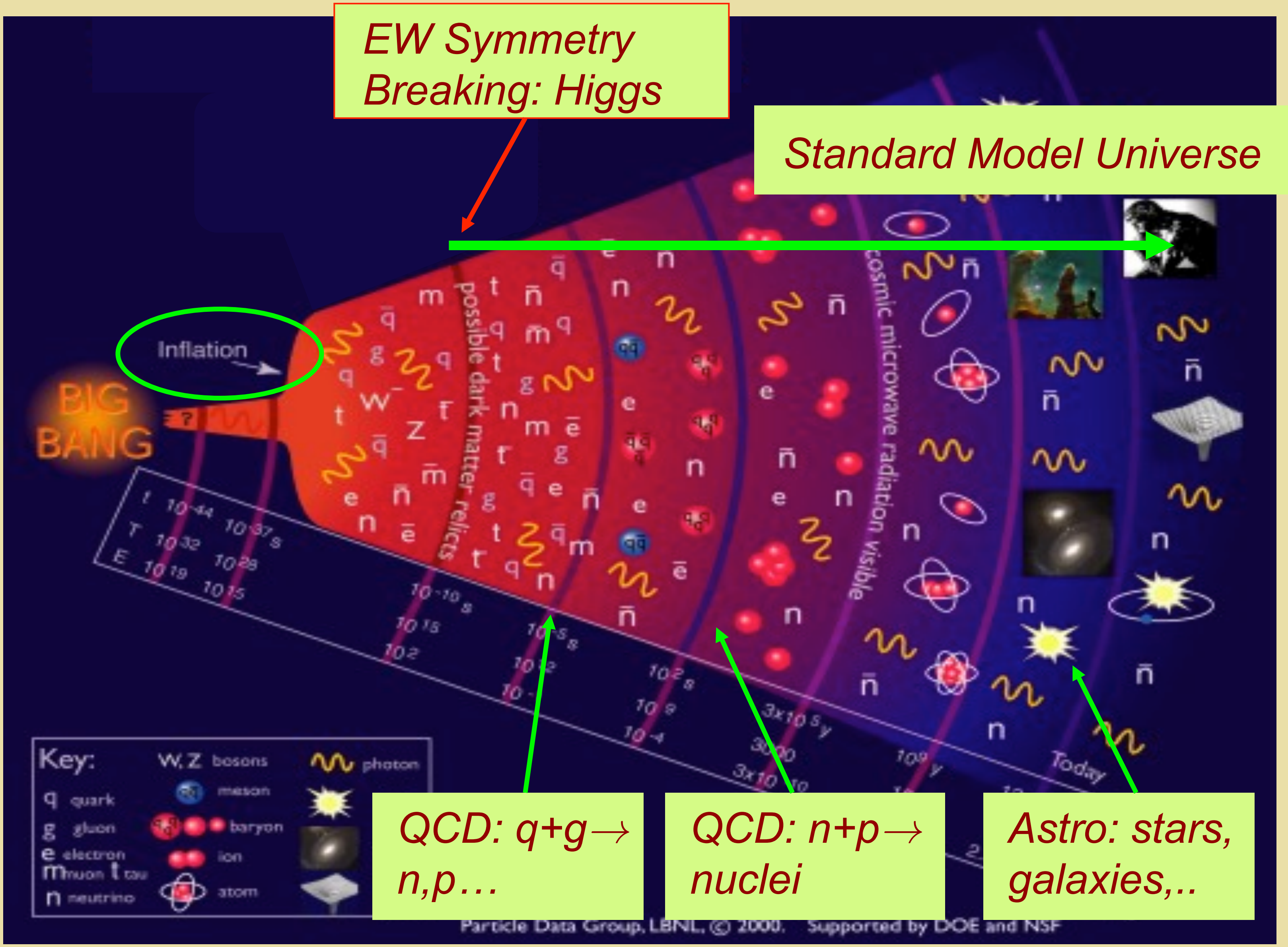
Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

Symmetries & Cosmic History



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs

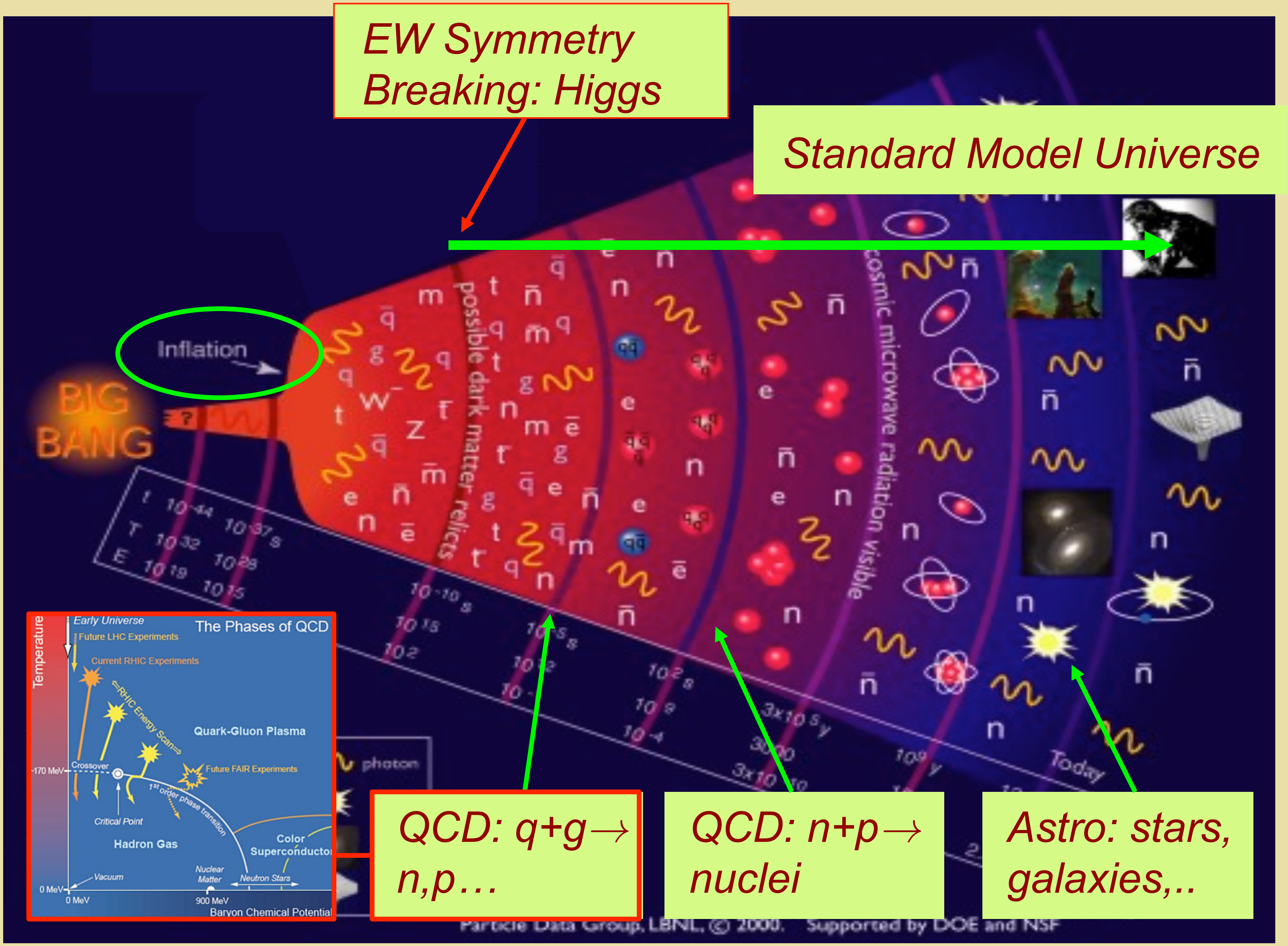
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs

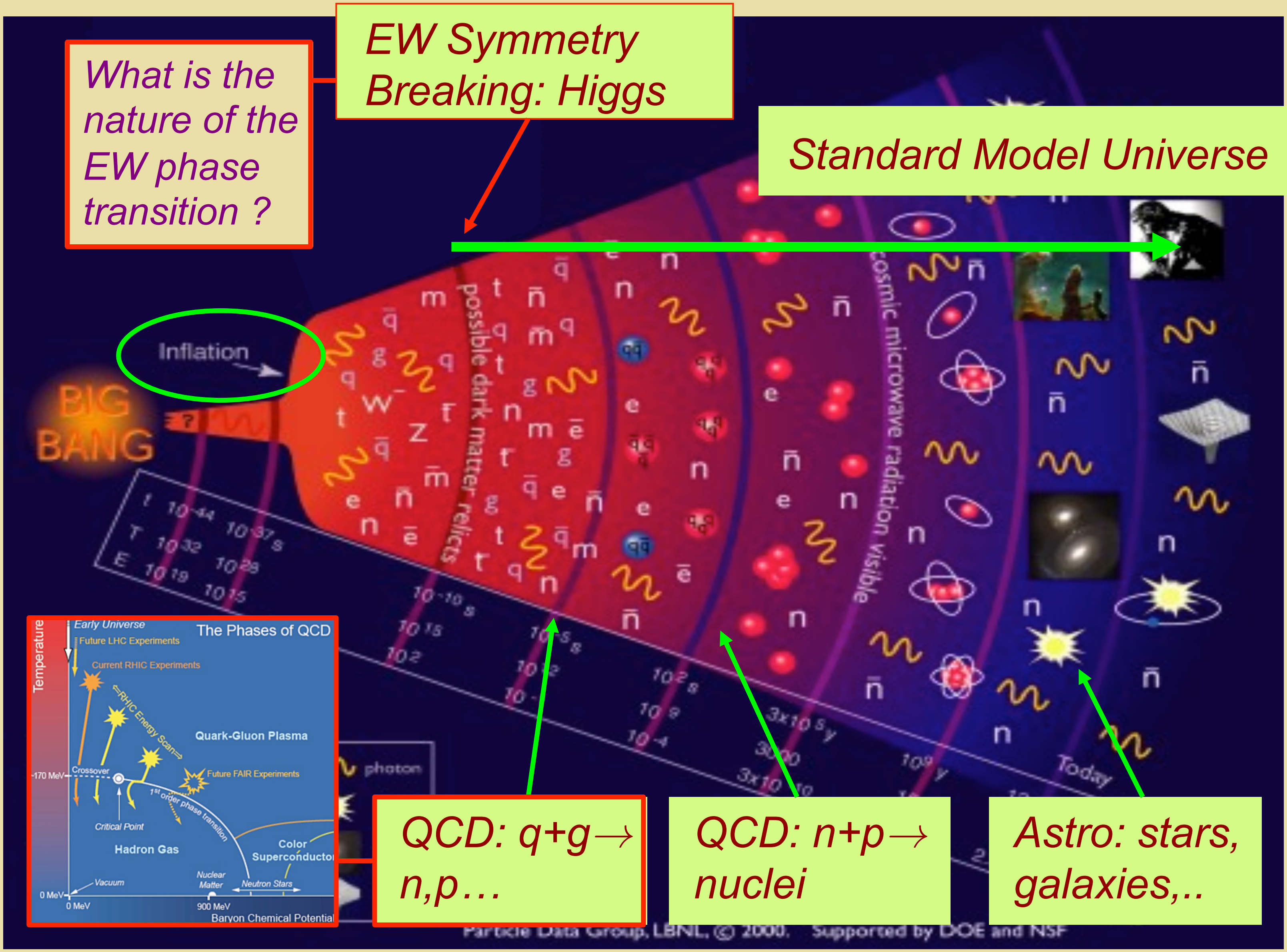
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



What is the nature of the EW phase transition ?

EW Symmetry Breaking: Higgs

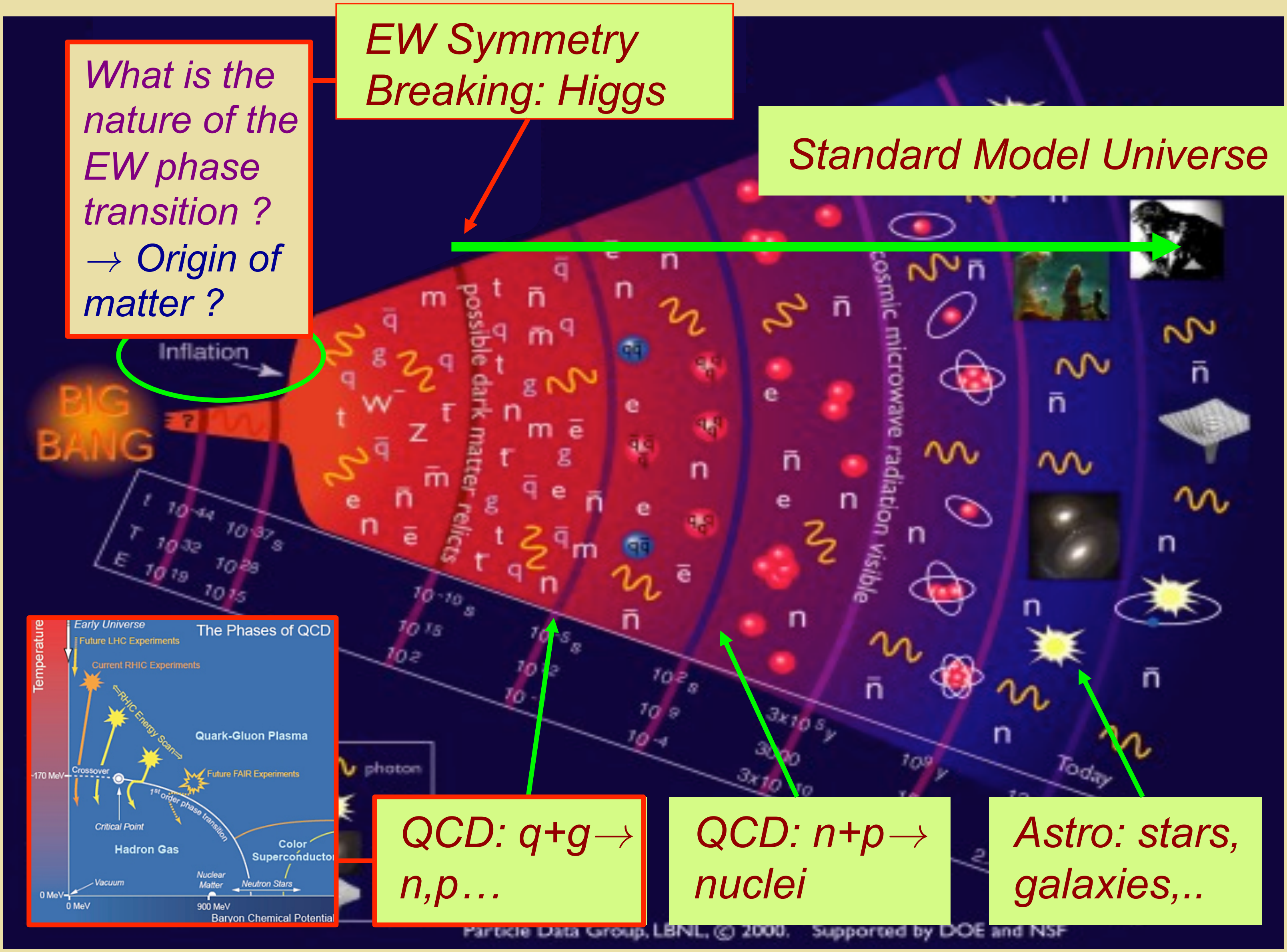
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



What is the nature of the EW phase transition ? → Origin of matter ?

EW Symmetry Breaking: Higgs

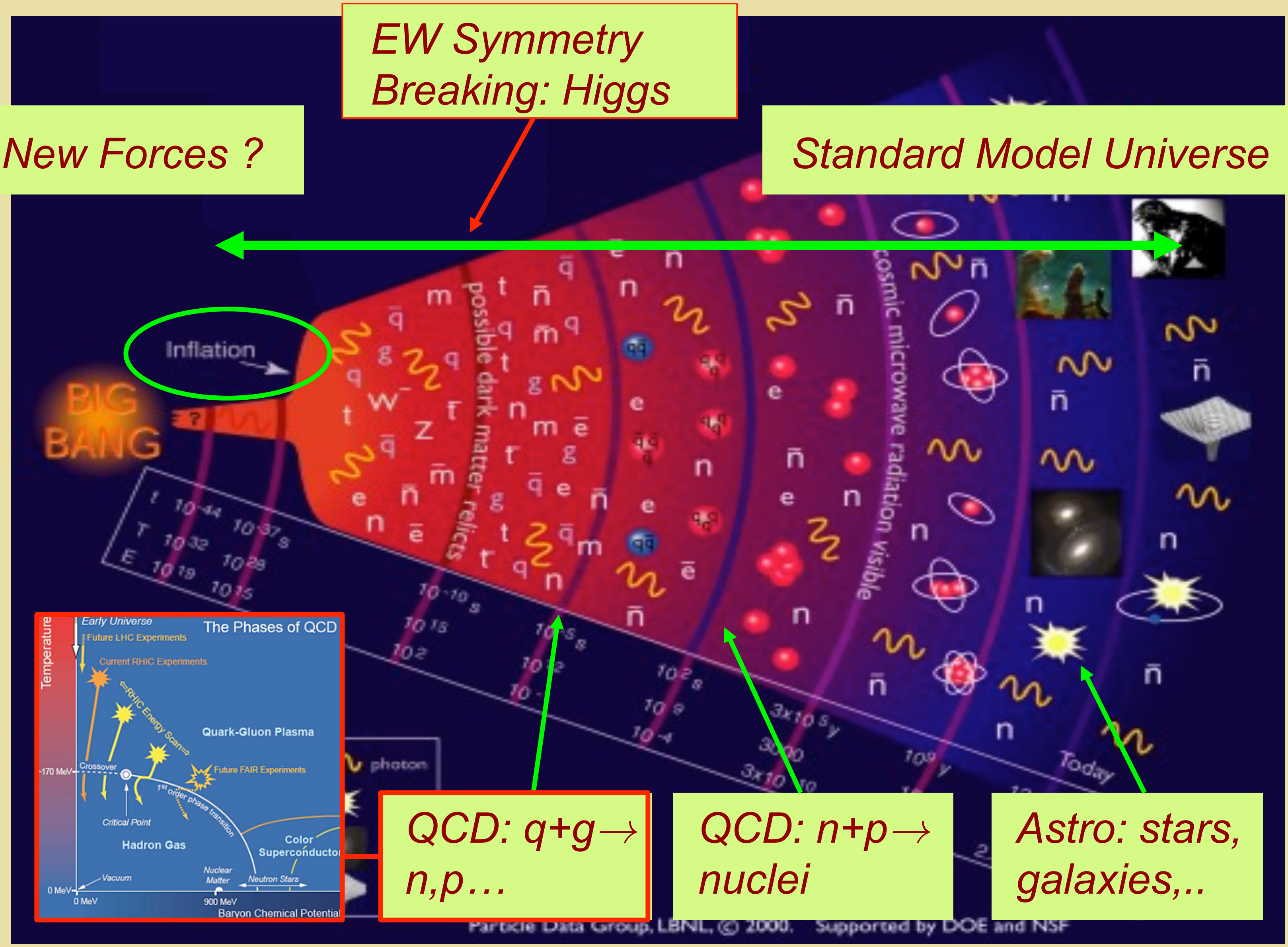
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs

New Forces ?

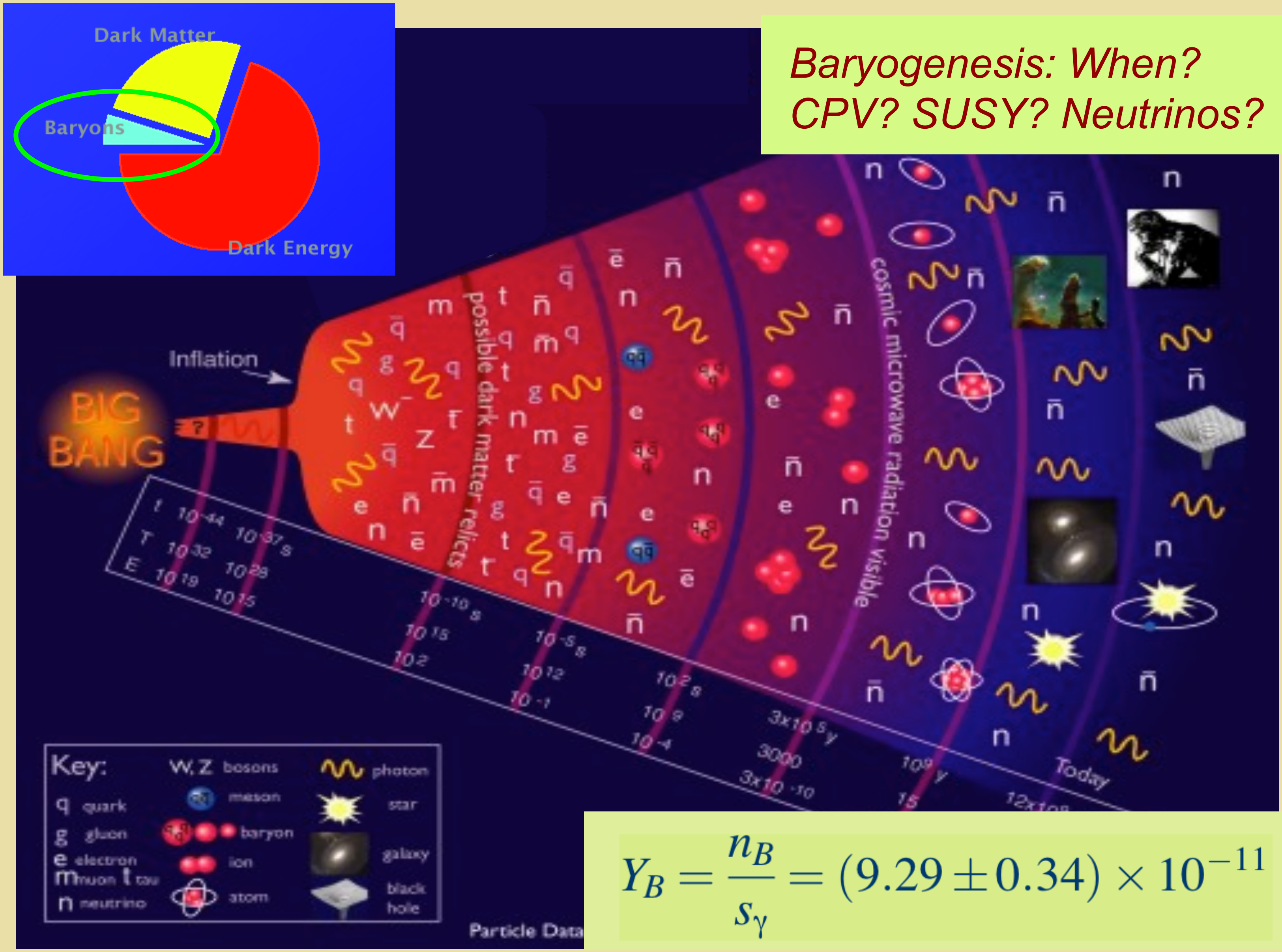
Standard Model Universe

QCD: q+g→ n,p…

QCD: n+p→ nuclei

Astro: stars, galaxies,..

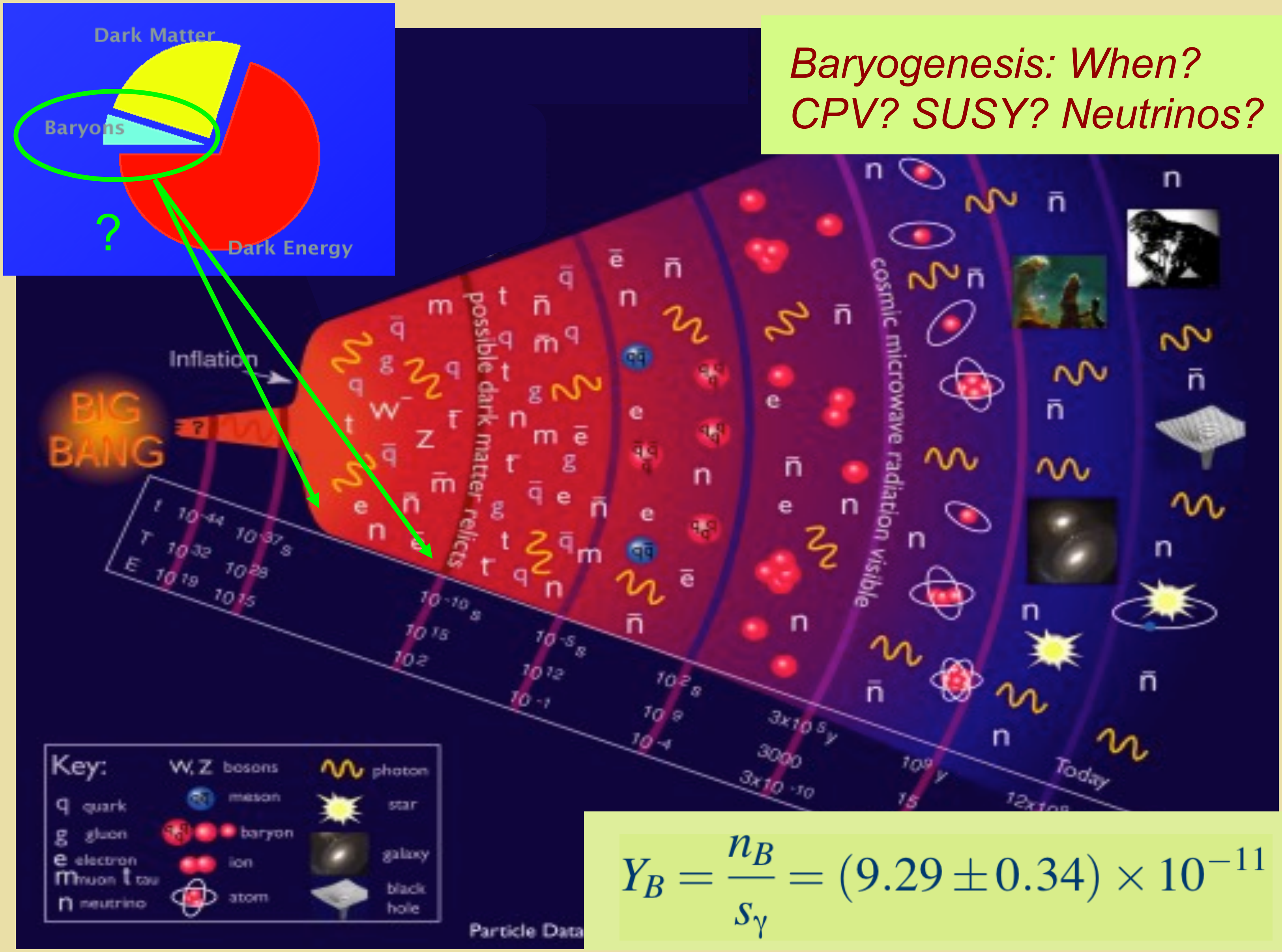
What is the Origin of Matter



Baryogenesis: When?
CPV? SUSY? Neutrinos?

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

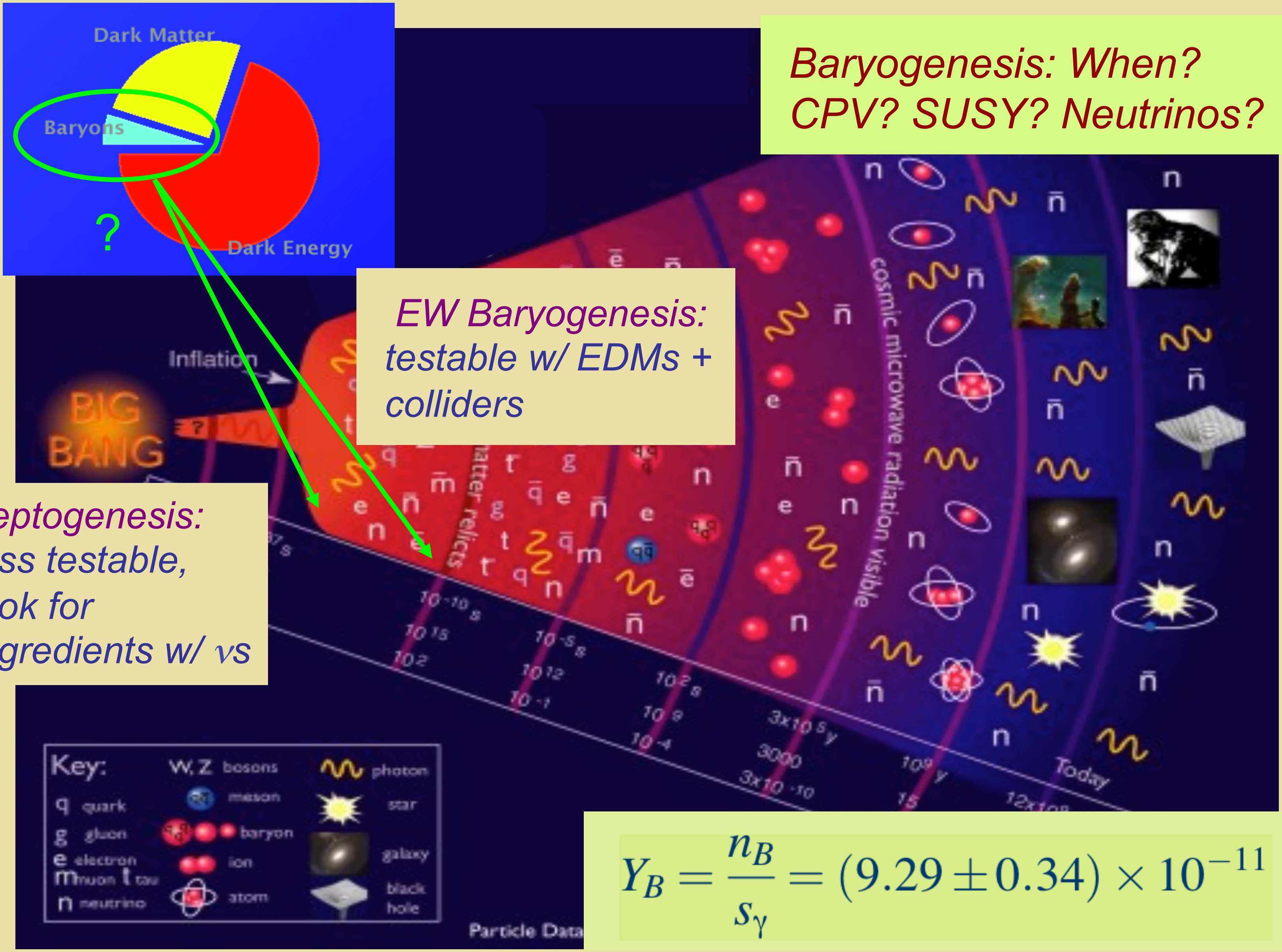
What is the Origin of Matter



Baryogenesis: When?
CPV? SUSY? Neutrinos?

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

What is the Origin of Matter



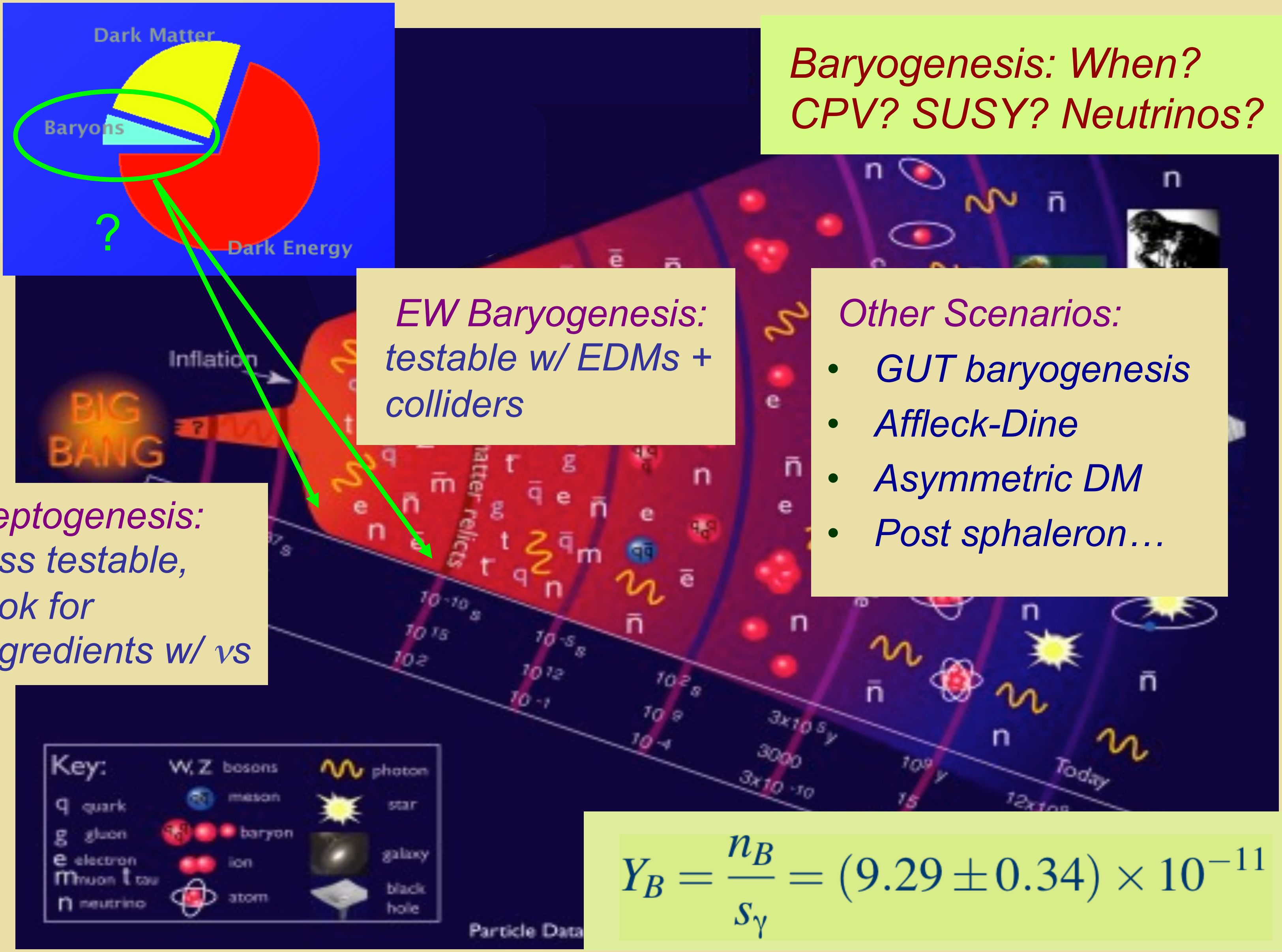
Baryogenesis: When? CPV? SUSY? Neutrinos?

EW Baryogenesis: testable w/ EDMs + colliders

Leptogenesis: less testable, look for ingredients w/ νs

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

What is the Origin of Matter



Baryogenesis: When?
CPV? SUSY? Neutrinos?

EW Baryogenesis:
testable w/ EDMs + colliders

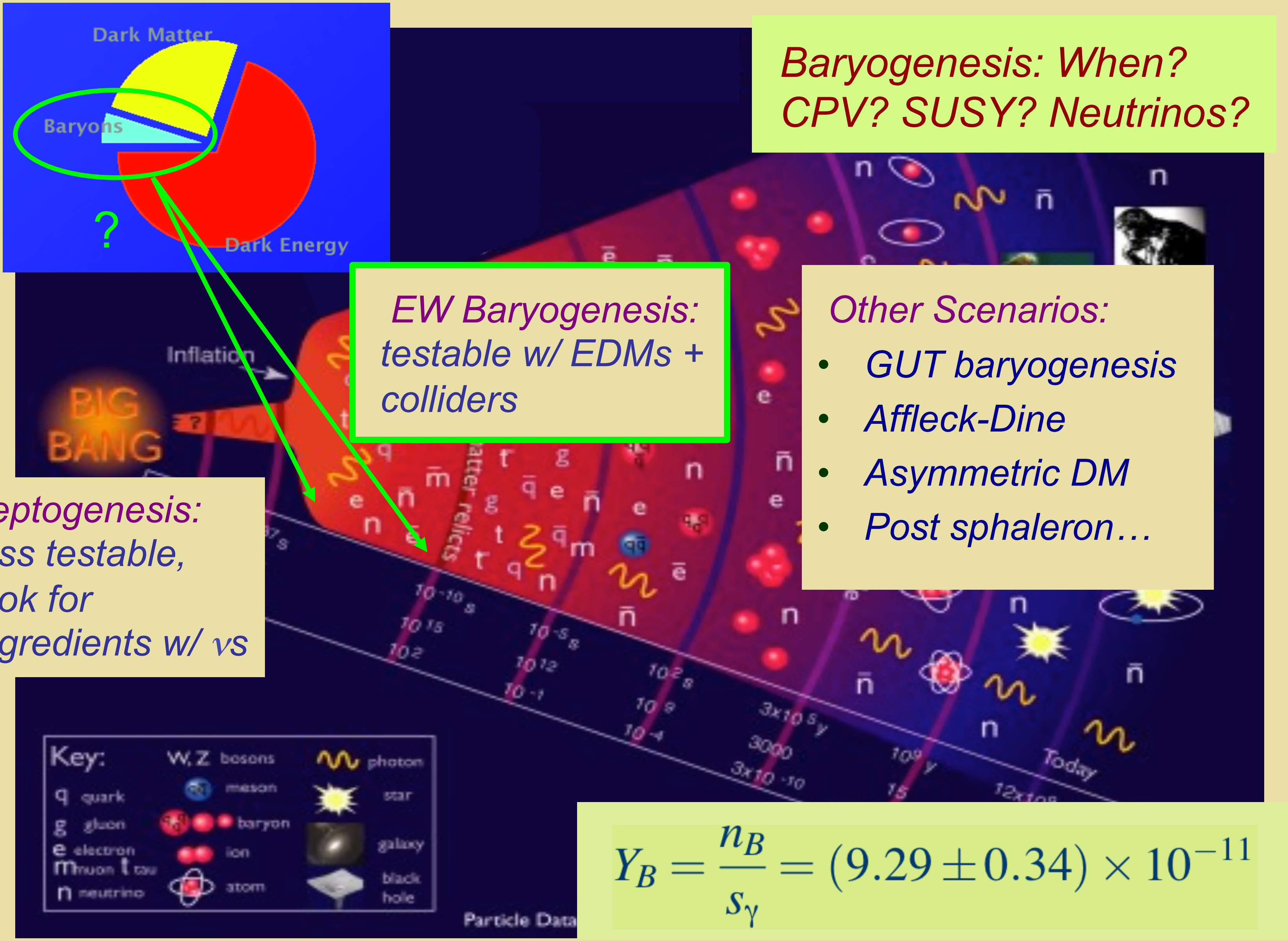
Other Scenarios:

- *GUT baryogenesis*
- *Affleck-Dine*
- *Asymmetric DM*
- *Post sphaleron…*

Leptogenesis:
less testable, look for ingredients w/ νs

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

What is the Origin of Matter



Baryogenesis: When?
CPV? SUSY? Neutrinos?

EW Baryogenesis:
testable w/ EDMs +
colliders

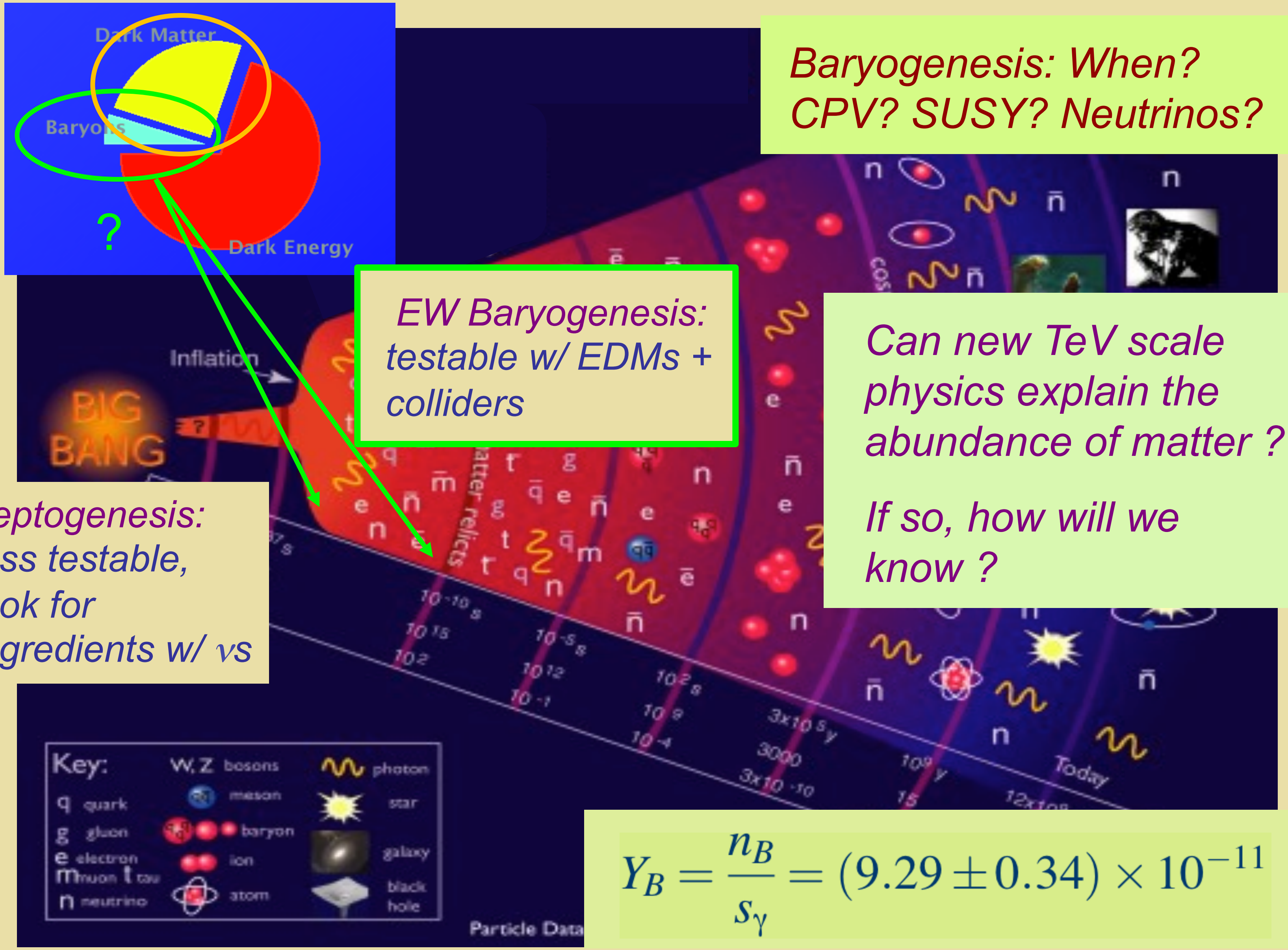
Other Scenarios:

- GUT baryogenesis
- Affleck-Dine
- Asymmetric DM
- Post sphaleron…

Leptogenesis:
less testable,
look for
ingredients w/ νs

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

Symmetries & the Origin of Matter



Baryogenesis: When?
CPV? SUSY? Neutrinos?

EW Baryogenesis: testable w/ EDMs + colliders

Can new TeV scale physics explain the abundance of matter ?

If so, how will we know ?

Leptogenesis: less testable, look for ingredients w/ νs

$$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$$

Questions for This Workshop

- *What happened ~ 10ps after the Big Bang?*

Questions for This Workshop

- *What happened ~ 10ps after the Big Bang?*
- *Single step (cross over) transition ?*
- *More d.o.f. with a richer pattern of EWSB?*
  - *Single or multiple steps ?*
  - *First or second order ?*
  - *Coupled to origin of matter ?*

Questions for This Workshop

- *What happened ~ 10ps after the Big Bang?*
- *Single step (cross over) transition ?*
- *More d.o.f. with a richer pattern of EWSB?*
    - *Single or multiple steps ?*
    - *First or second order ?*
    - *Coupled to origin of matter ?*
- *What are collider signatures that could provide clues?*
    - *Modified Higgs properties (production, decays)*
    - *New states*

Recent Developments:

- *BICEP2 CMB B-mode observation → Evidence for primordial gravitational radiation associated with inflation*
- *Discovery of BEH-like boson → Paradigm of symmetry-breaking in particle physics driven by a fundamental scalar likely correct*
- *Non-observation (so far) of physics beyond the Standard Model at the LHC*

Recent Results

- *Discovery of BEH-like scalar at the LHC*

- *Non-observation (so far) of sub-TeV particles at LHC*

Recent Results

- *Discovery of BEH-like scalar at the LHC*
  - *Idea of ϕ-driven spontaneous EW symmetry breaking is likely correct*
- *Non-observation (so far) of sub-TeV particles at LHC*

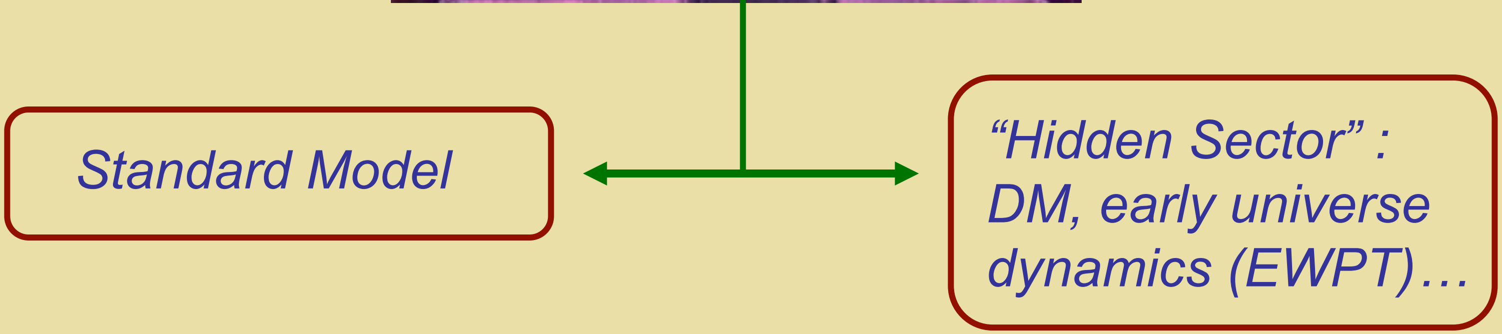
Recent Results

- *Discovery of BEH-like scalar at the LHC*
  - *Idea of ϕ-driven spontaneous EW symmetry breaking is likely correct*
- *Non-observation (so far) of sub-TeV particles at LHC*
  - *Sub-TeV BSM spectrum is compressed*
  - *Sub-TeV BSM is purely EW or Higgs portal*
  - *BSM physics lies at very different mass scale*

Outline

- *Portals & the Early Universe*
- *Why the Higgs Portal*
- *Scalar Fields in Particle Physics & Cosmology*
- *General Considerations*
- *Illustrative Higgs Portals: Simplest Extensions*

I. Portals & Early Universe



Standard Model

"Hidden Sector" : DM, early universe dynamics (EWPT)…

Portals

Two approaches:

- *Specific model (MSSM….)*
- *“Model independent”*

Model Independent Portals

- *Vector portal ("dark photons"…)*
- *Neutrino portal*
- *Axion portal*
- *Higgs portal*
- *Higher dimensional op's portal*

Model Independent Portals

- Vector portal (“dark photons”…)
- Neutrino portal
- Axion portal
- Higgs portal
- Higher dimensional op’s portal

Model Independent Portals

- *Vector portal (“dark photons”…)*
- *Neutrino portal*
- *Axion portal*
- *Higgs portal*
- *Higher dimensional op’s portal*

Higgs Portal: DM

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

- Renormalizable
- Z_2 symmetric
- Dimensionless coupling
- ϕ (DM): singlet or charged under $SU(2)_L$ x $U(1)_Y$

Higgs Portal: Phase Transitions

$$\boxed{\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H} \quad + \ldots$$

- *Renormalizable* ✓
- *Z_2 symmetric* ✖
- *Dimensionless coupling* ✖
- *ϕ (DM): singlet or charged under $SU(2)_L$ x $U(1)_Y$*

Higgs Portal: Higher Dim Op's

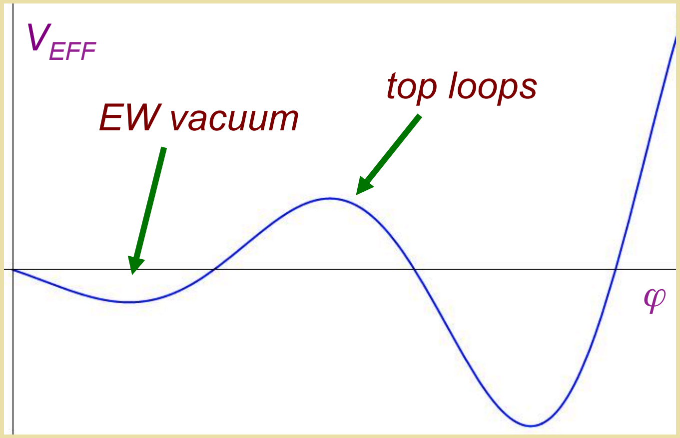
$$\boxed{\mathcal{O}_5 = \frac{\lambda_{\chi H}}{\Lambda}\,\bar{\chi}\chi\, H^\dagger H} \quad +\ldots$$

- Renormalizable ✘
- Z_2 symmetric ✓
- Dimensionless coupling ✘
- χ (DM): singlet or charged under $SU(2)_L \times U(1)_Y$

II. Why the Higgs Portal ?

Stable EW Vacuum ?

Preserving EW Min



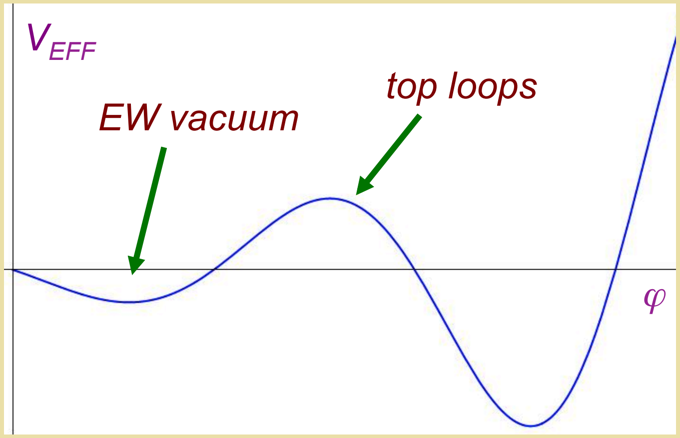
$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4\right)$$

sets m_H

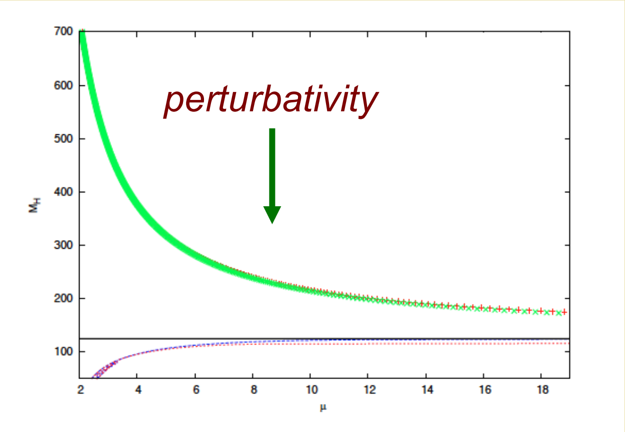
top loops

Stable EW Vacuum ?

Preserving EW Min



"Funnel plot"



$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

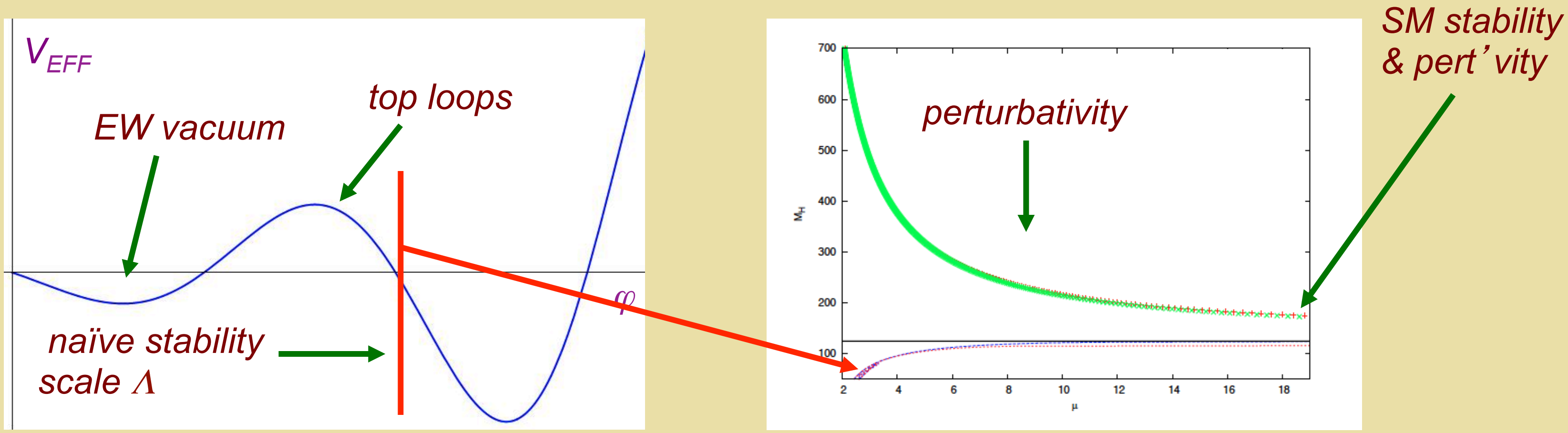
sets m_H

top loops

Stable EW Vacuum ?

Preserving EW Min

"Funnel plot"



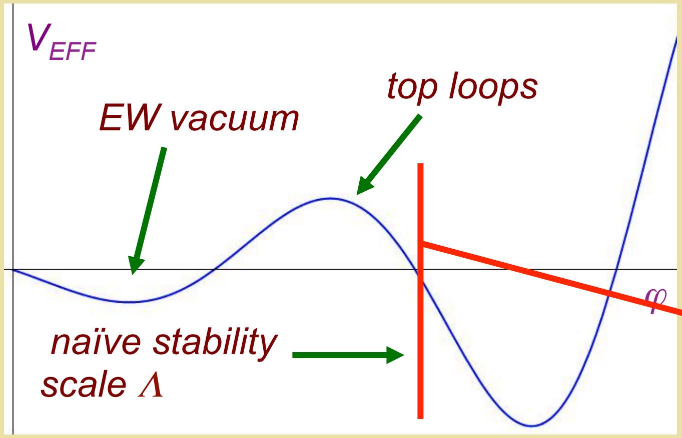
$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

sets m_H

top loops

Stable EW Vacuum ?

Preserving EW Min

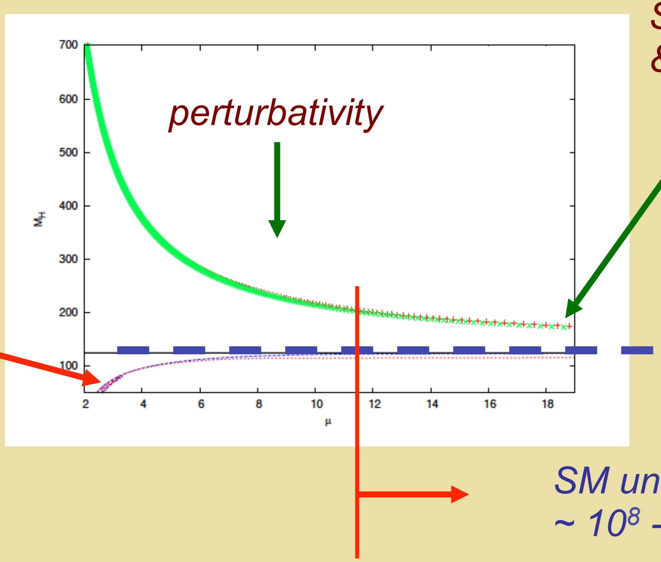


EW vacuum

top loops

naïve stability scale Λ

"Funnel plot"



perturbativity

SM stability & pert'vity

m_H

SM unstable above ~ 10^8 - 10^{15} TeV

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4\right)$$

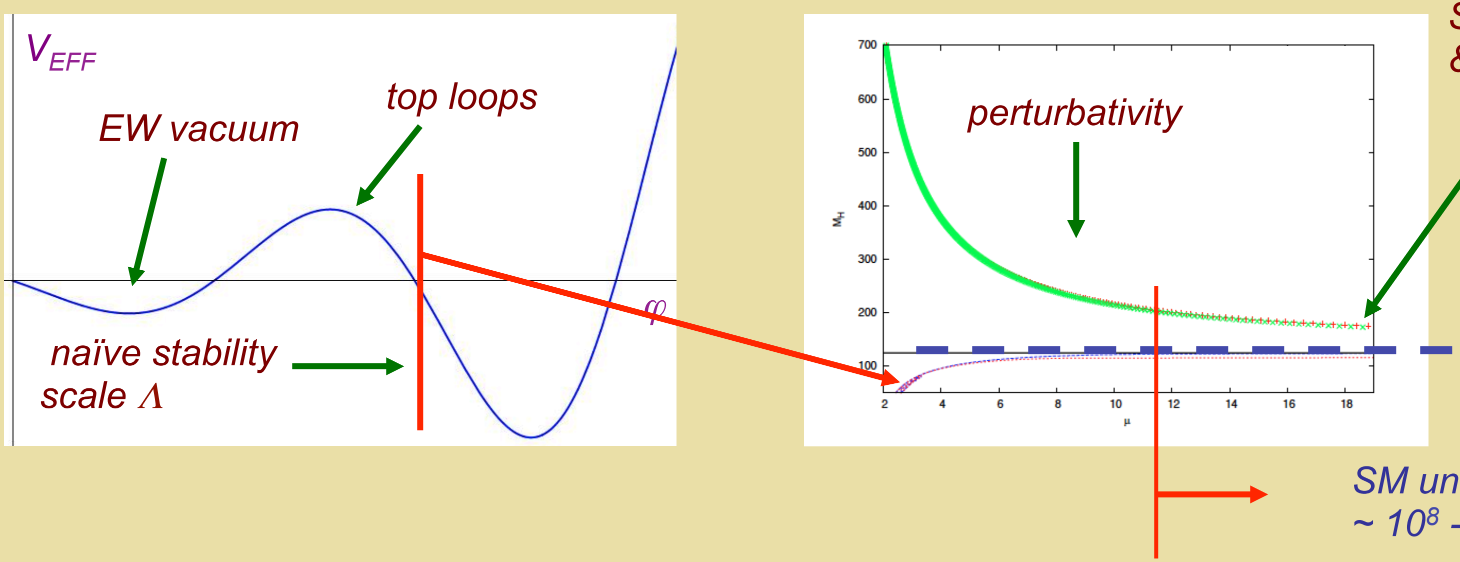
sets m_H

top loops

Stable EW Vacuum ?

Preserving EW Min

"Funnel plot"



EW vacuum

top loops

naïve stability scale Λ

perturbativity

SM stability & pert'vity

m_H

SM unstable above ~ 10^8 - 10^{13} TeV

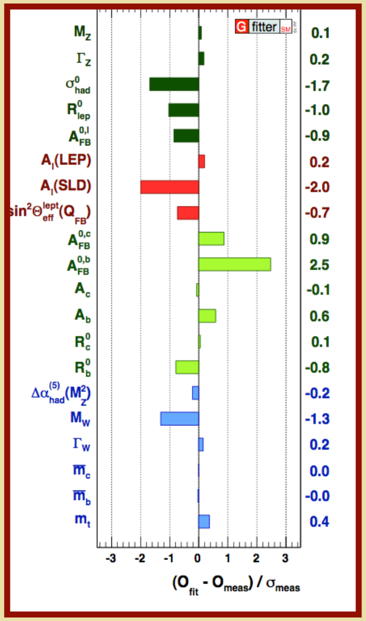
$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 \qquad - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4\right)$$

sets m_H

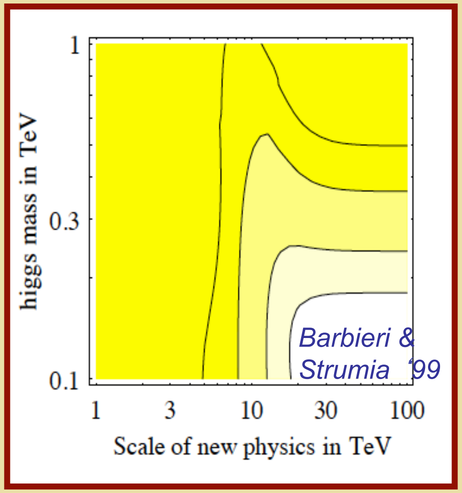
top loops

Higgs portal interactions → more robust stability ?

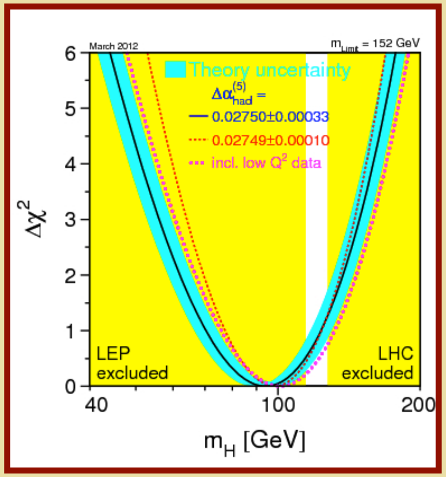
What is the BSM Energy Scale Λ ?



~ 10^{-3} agreement with EWPO



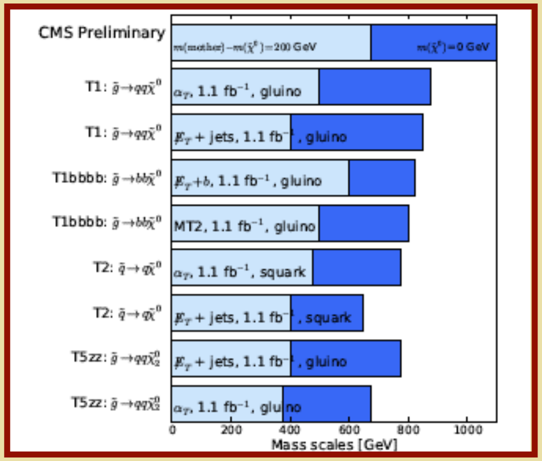
BSM: $\mathcal{O}_{BSM} = c / \Lambda^2 \rightarrow$ $\Lambda \sim 10$ TeV

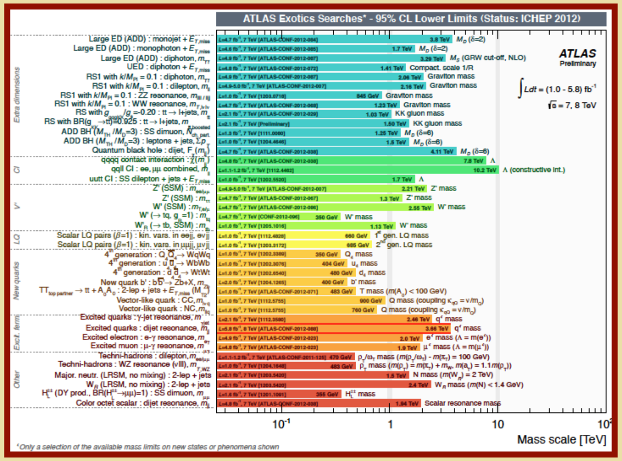


EWPO: data favor a "light" SM-like Higgs scalar

LHC: so far no sub-TeV BSM physics

Higgs Portal: new low scale d.o.f. ?





III. Scalar Fields in Particle Physics & Cosmology

φ ?

Scalar Fields in Cosmology

What role do scalar fields play (if any) in the physics of the early universe ?

Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation* • *Dark Energy* • *Dark Matter* • *Phase transitions*		

Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation*	✔	
• *Dark Energy*	✔	
• *Dark Matter*	✔	
• *Phase transitions*	✔	

Scalar Fields in Cosmology

Problem	Theory	Exp't
• *Inflation*	✔	?
• *Dark Energy*	✔	?
• *Dark Matter*	✔	?
• *Phase transitions*	✔	?

Scalar Fields in Cosmology

Problem	*Theory*	*Exp't*
• *Inflation*	✔	?
• *Dark Energy*	✔	?
• *Dark Matter*	✔	?
• *Phase transitions*	✔	?

- *Could experimental discovery of additional scalars point to early universe scalar field dynamics?*

- *Are there signatures in modified Higgs properties, new states, or EW precision tests ?*

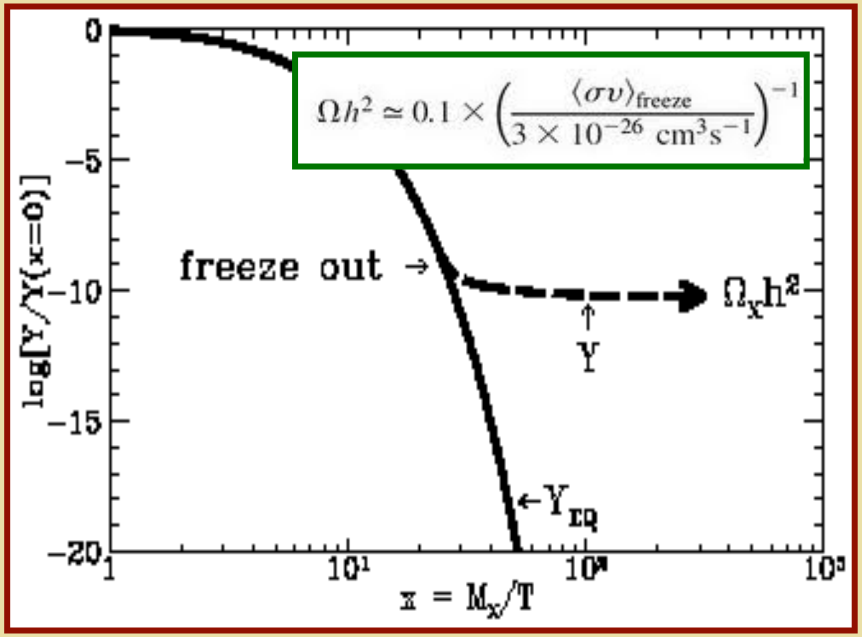
Scalar Fields in Cosmology

Problem	*Theory*	*Exp’t*
• *Inflation*	✔	?
• *Dark Energy*	✔	?
• *Dark Matter*	✔	?
• *Phase transitions*	✔	?

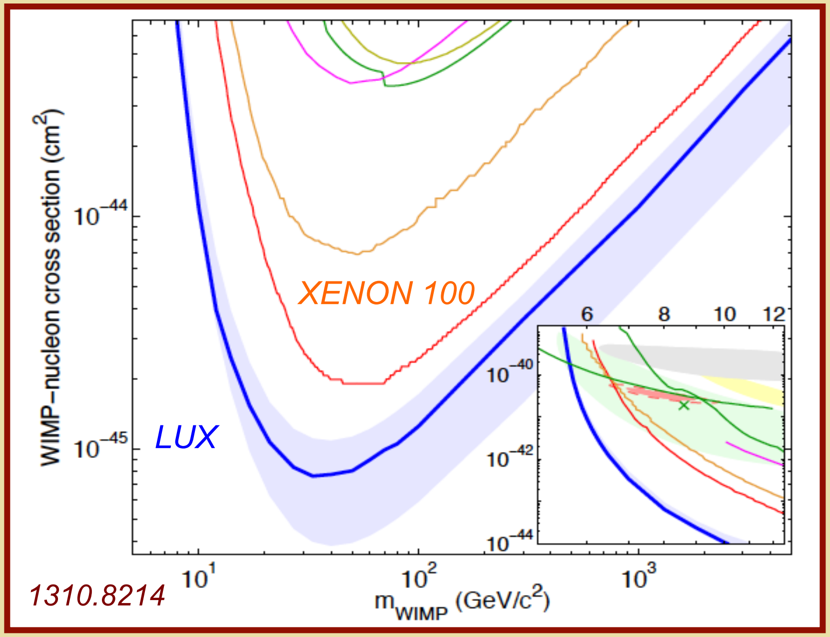
Focus of this talk, but perhaps part of larger role of scalar fields in early universe

IV. General Considerations

Thermal DM: Ω_{CDM} & σ_{SI}



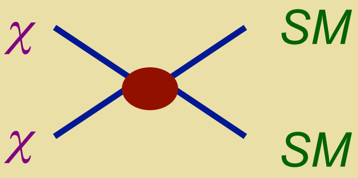
$$\Omega h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v\rangle_{\rm freeze}}{3\times10^{-26}\ {\rm cm^3 s^{-1}}}\right)^{-1}$$

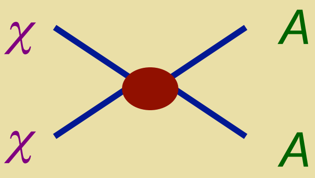


1310.8214

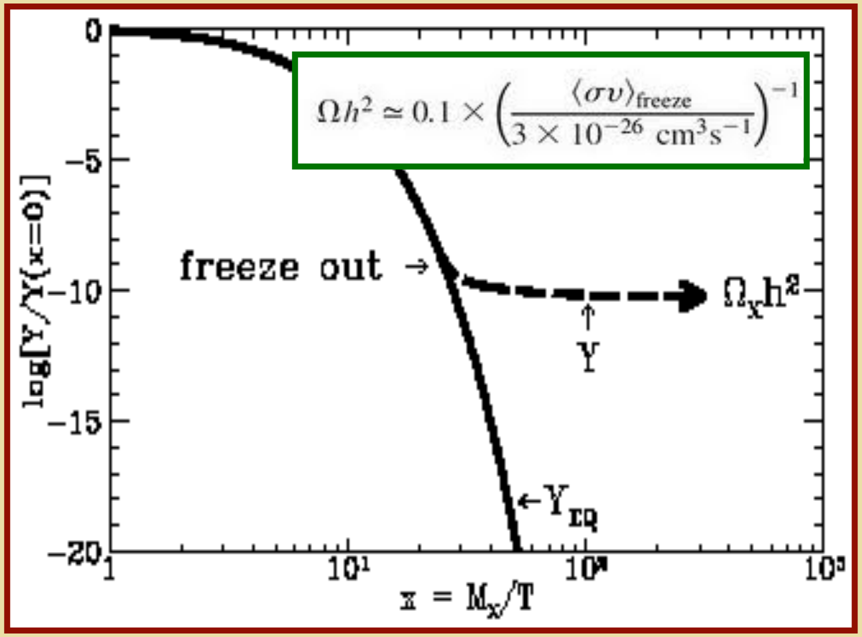
Thermal DM: WIMP

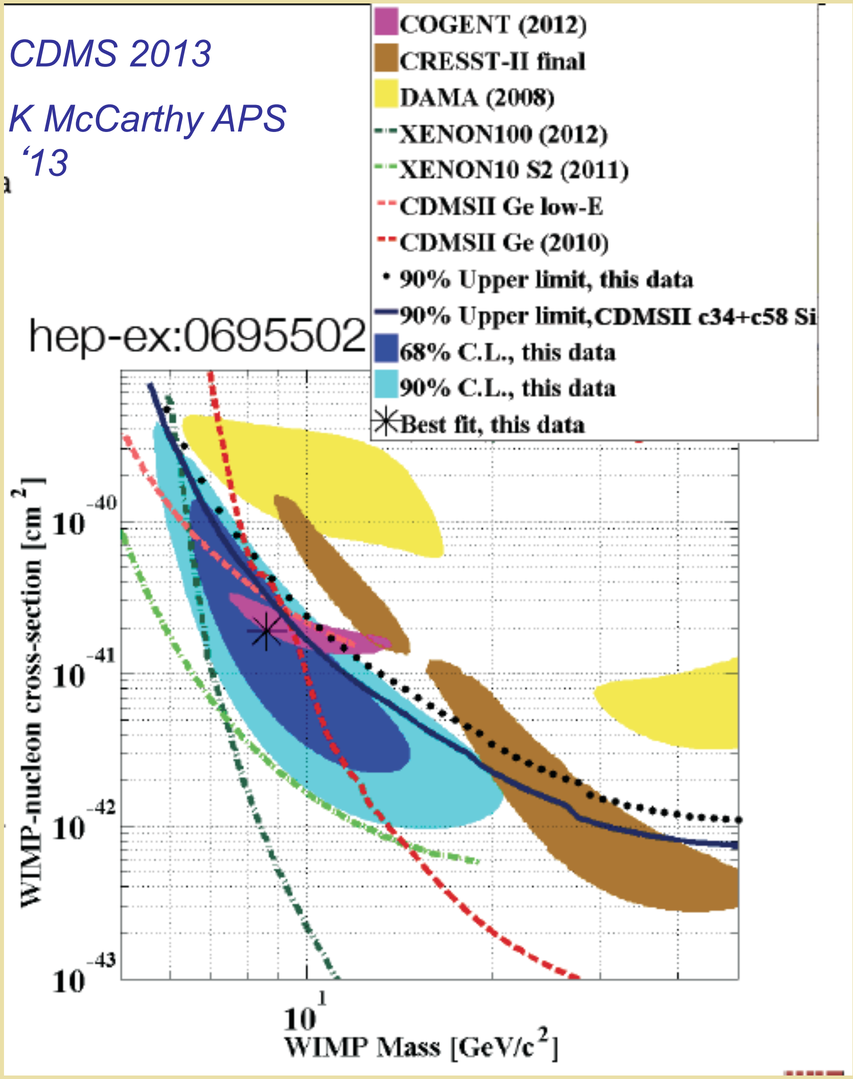
Direct detection: Spin-indep DM-nucleus scattering





Thermal DM: Ω_{CDM} & σ_{SI}

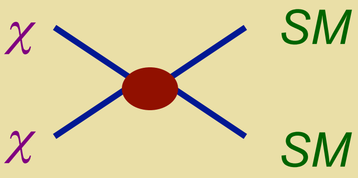



CDMS 2013

K McCarthy APS '13

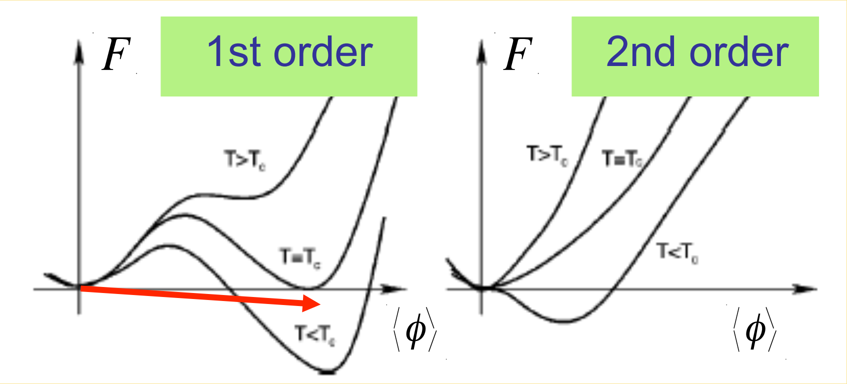
hep-ex:0695502

Thermal DM: WIMP

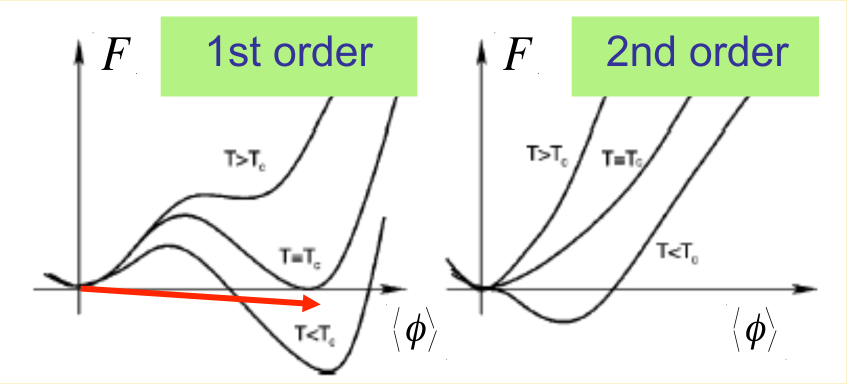


EWPT & EW Baryogenesis

EW Phase Transition: New Scalars & CPV

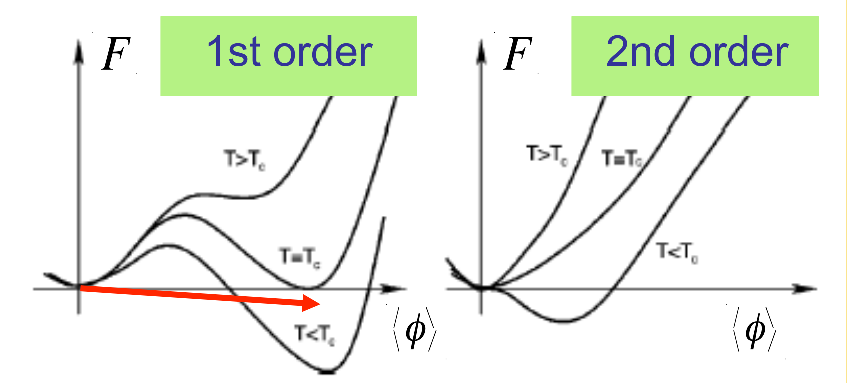


EW Phase Transition: New Scalars & CPV



Increasing m_h →

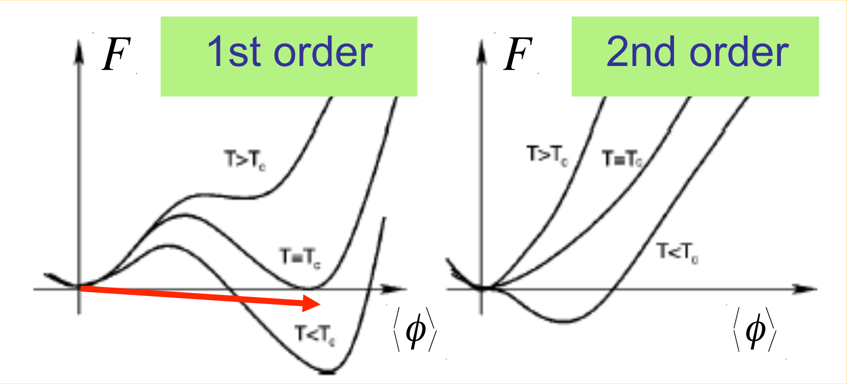
EW Phase Transition: New Scalars & CPV



Increasing m_h →

← *New scalars*

EW Phase Transition: New Scalars & CPV



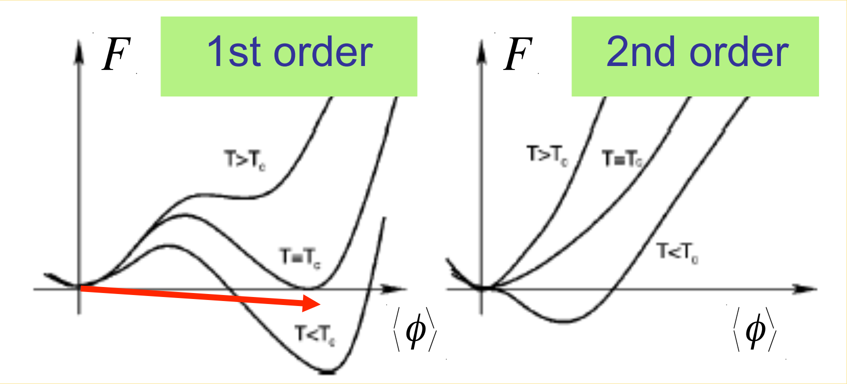
Increasing m_h →

← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

EW Phase Transition: New Scalars & CPV



Increasing m_h →

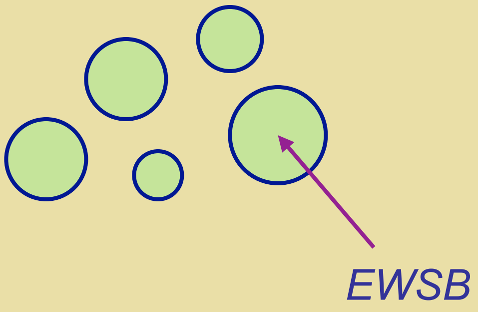
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

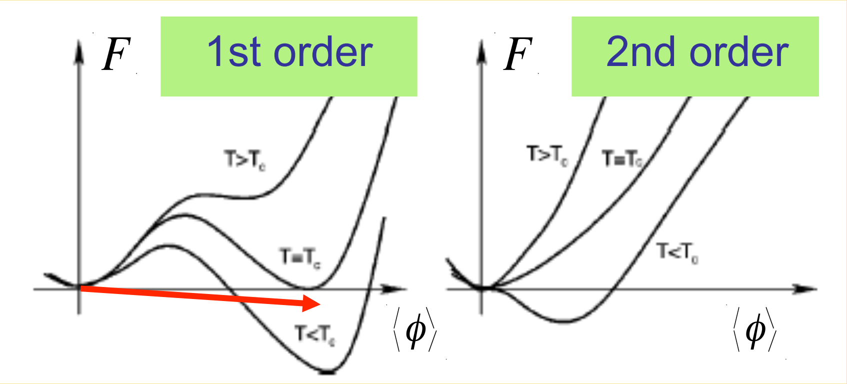
"Strong" 1st order EWPT

↓

Bubble nucleation



EW Phase Transition: New Scalars & CPV



Increasing m_h →

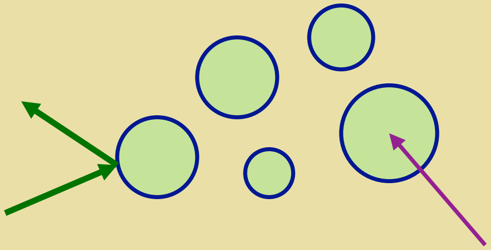
← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

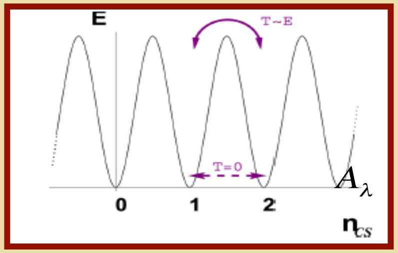
↓

Bubble nucleation

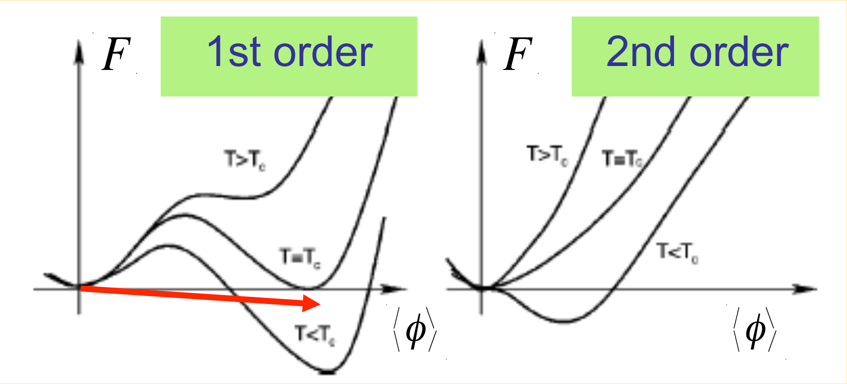


Y_B : CPV & EW sphalerons

EWSB



EW Phase Transition: New Scalars & CPV



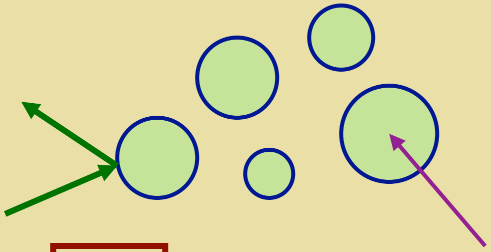
Increasing m_h →

← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

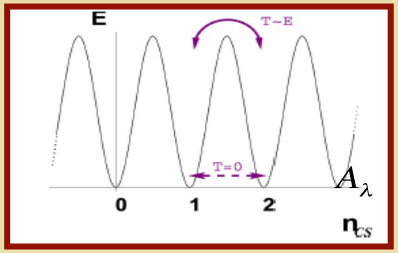
Bubble nucleation



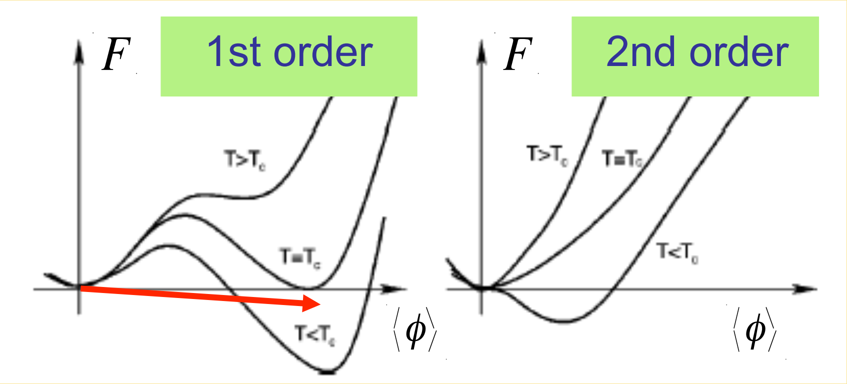
Y_B : CPV & EW sphalerons

EWSB

BSM



EW Phase Transition: New Scalars & CPV



Increasing m_h →

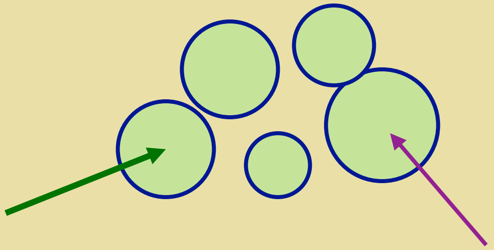
← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

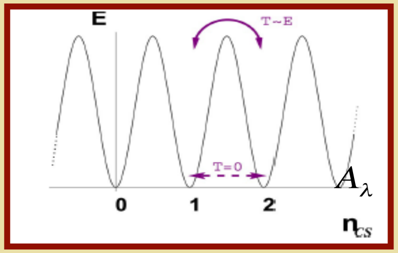
↓

Bubble nucleation

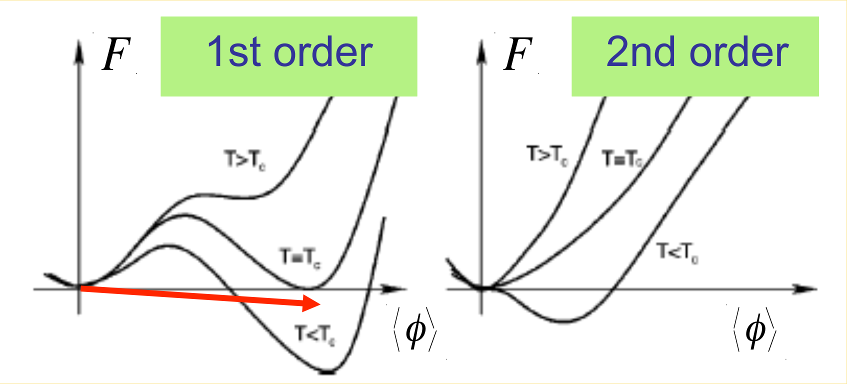


Y_B : diffuses into interiors

EWSB



EW Phase Transition: New Scalars & CPV



Increasing m_h →

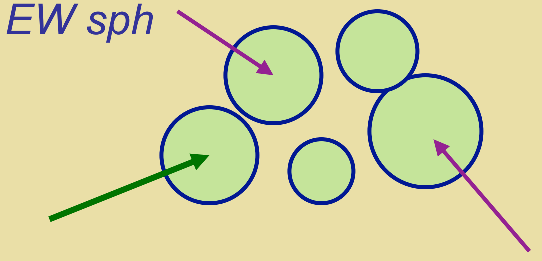
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation

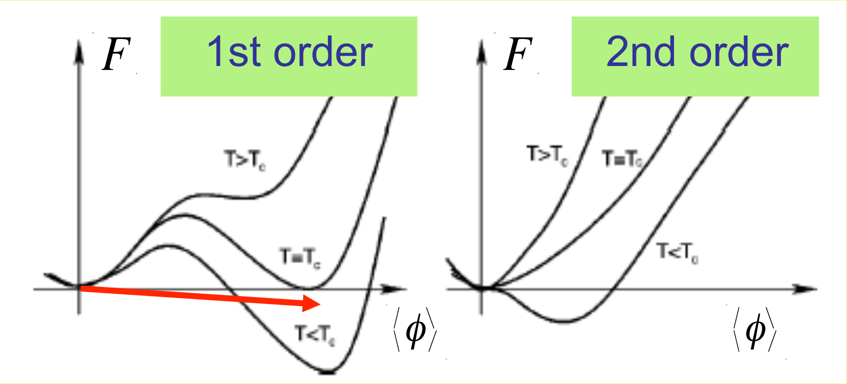


Quench EW sph

Y_B : diffuses into interiors

EWSB

EW Phase Transition: New Scalars & CPV



Increasing m_h →

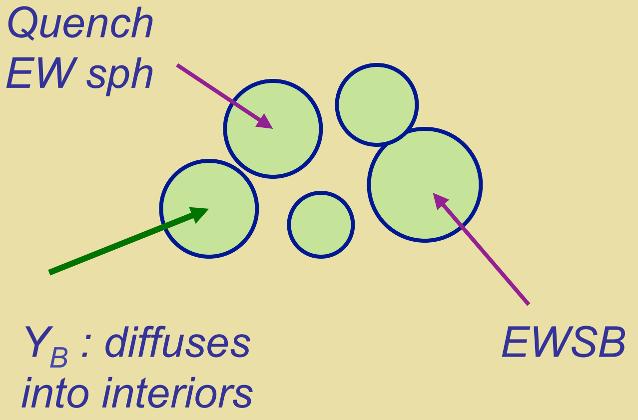
← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation

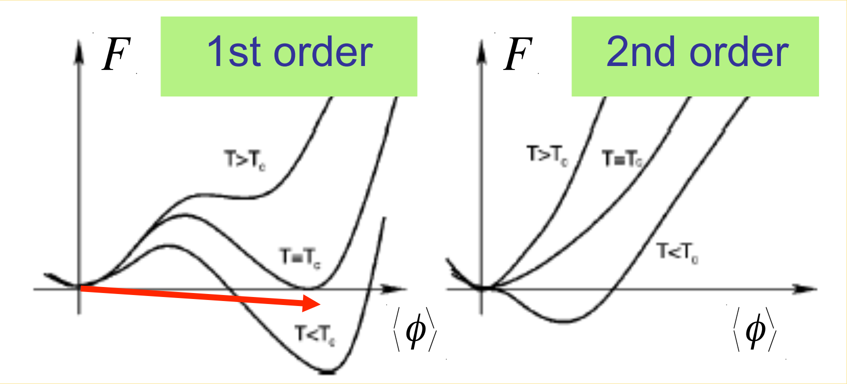


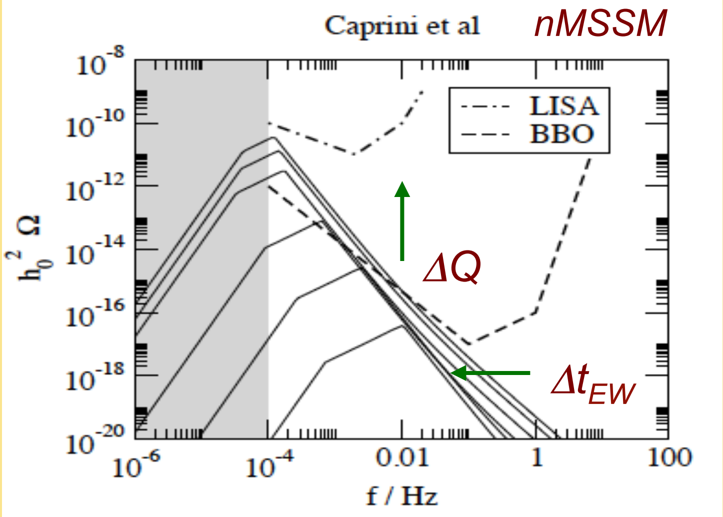
Quench EW sph

Y_B : diffuses into interiors

EWSB

EW Phase Transition: Gravity waves

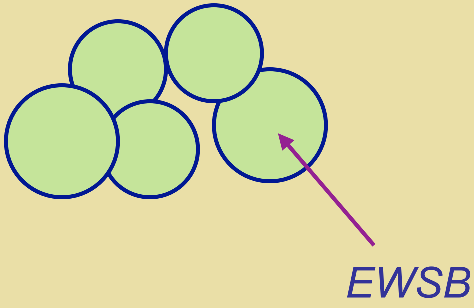




"Strong" *1^{st} order EWPT*

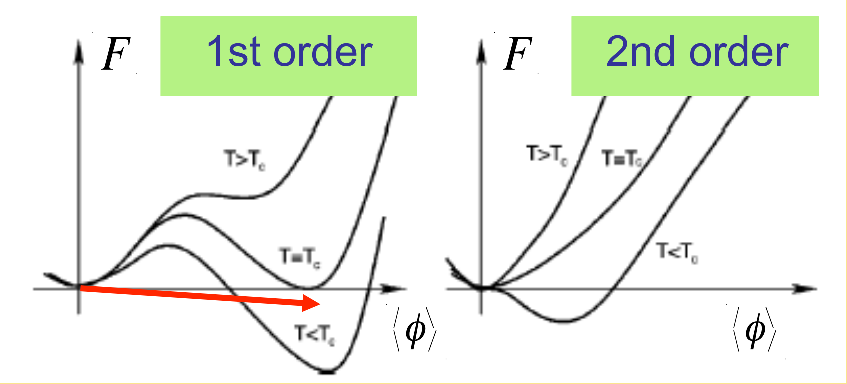
Detonation & turbulence

Bubble nucleation



GW Spectra: ΔQ & Δt_{EW} ↔ *$F(\phi)$*

EW Phase Transition: New Scalars & CPV



Increasing m_h →

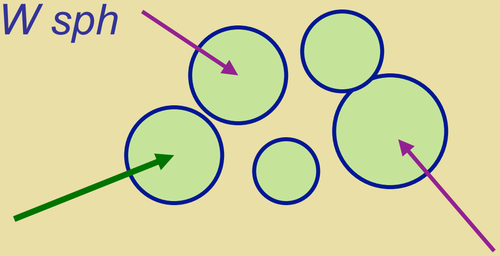
← New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation



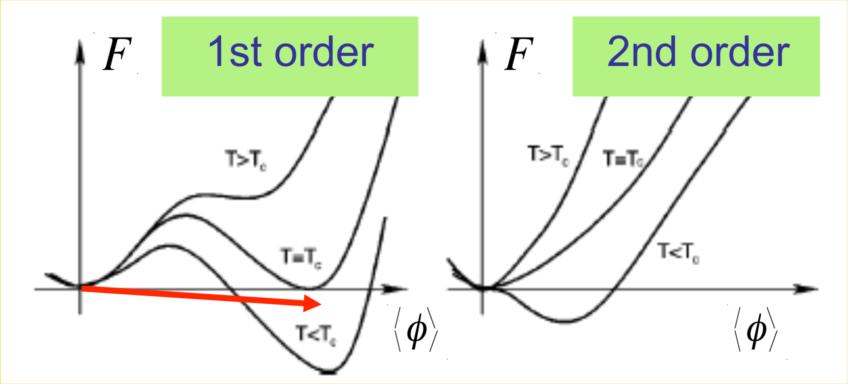
Quench EW sph

Y_B : diffuses into interiors

EWSB

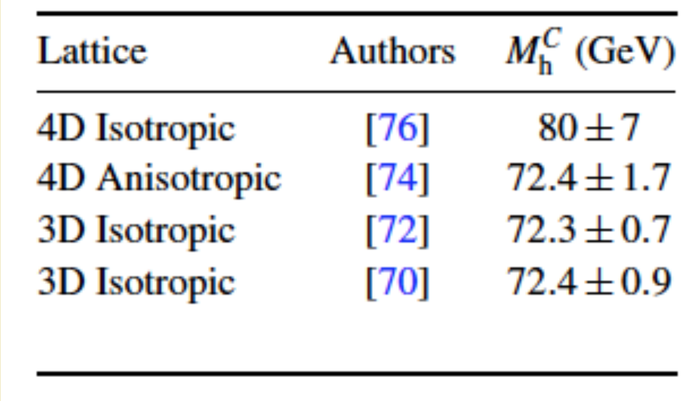
Electroweak Phase Transition

EW Phase Transition: St’d Model



Increasing m_h ⟶

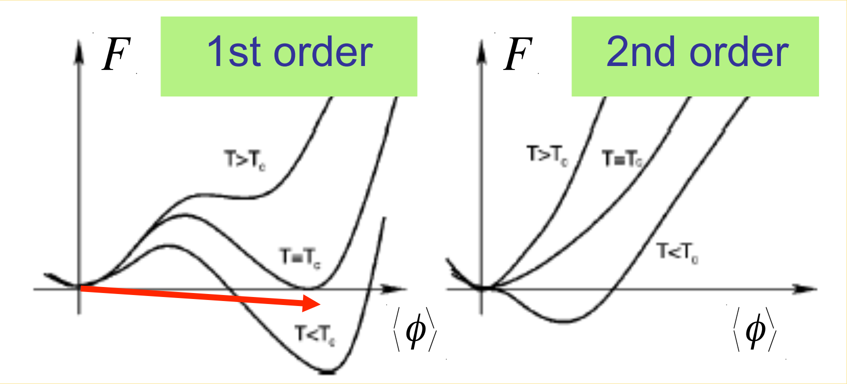
Lattice: Endpoint



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

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

EW Phase Transition: New Scalars



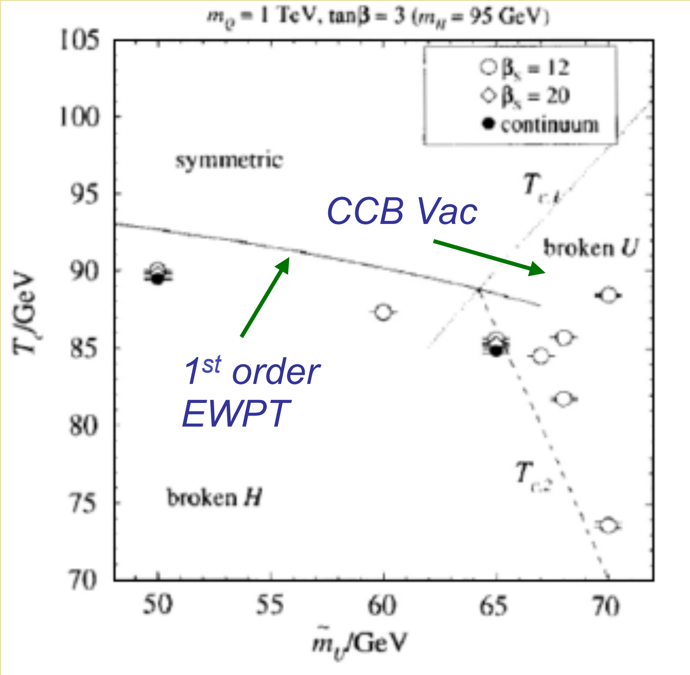
Increasing m_h →

← *New scalars*

MSSM: Light RH stops

PT: Carena et al,…

Lattice: Laine, Rummukainen

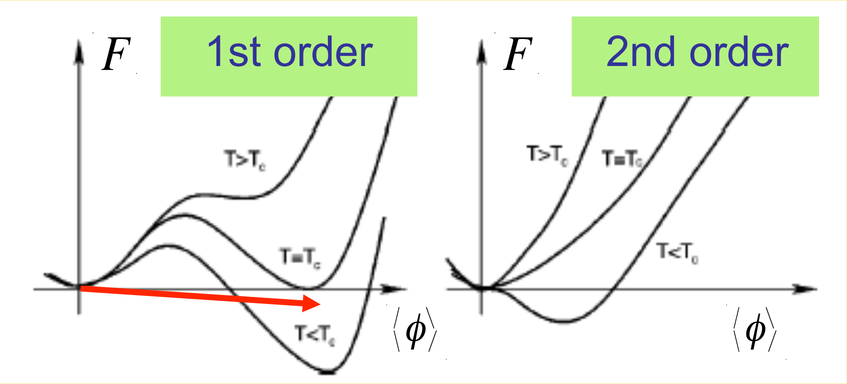


CCB Vac

1^{st} order
EWPT

Decreasing RH stop mass →

EW Phase Transition: MSSM

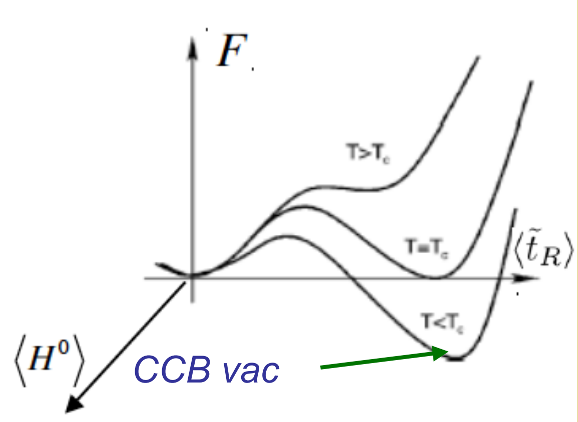


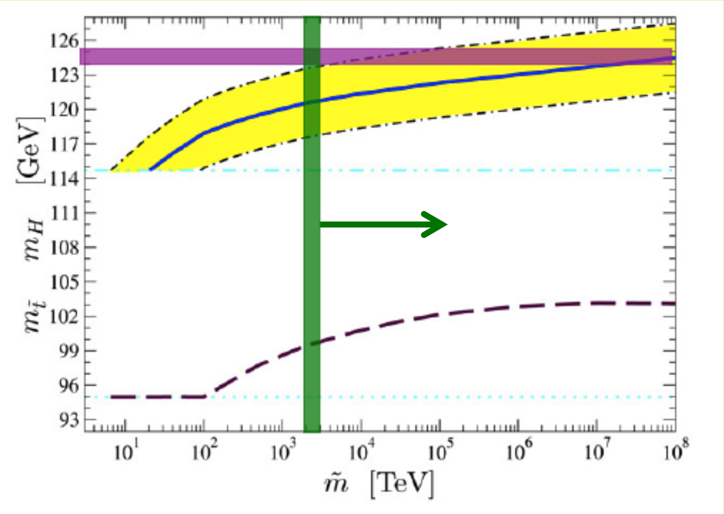
Increasing m_h →

← *New scalars*

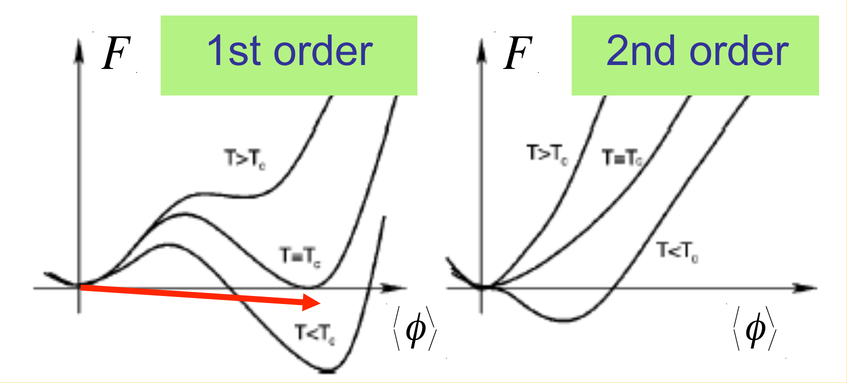
MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable





EW Phase Transition: MSSM

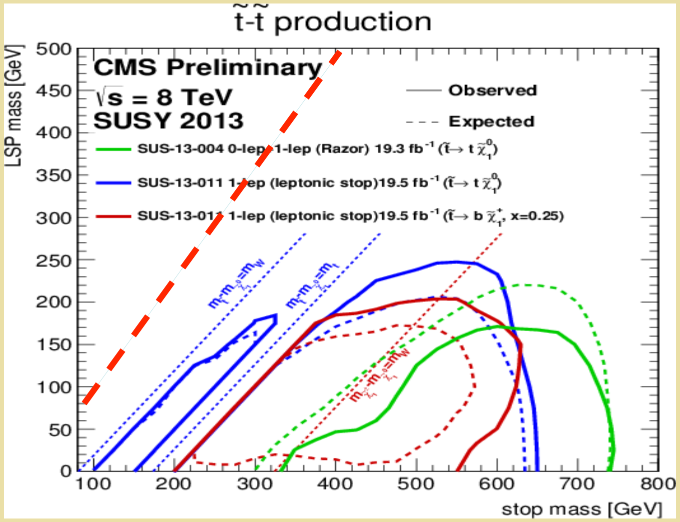


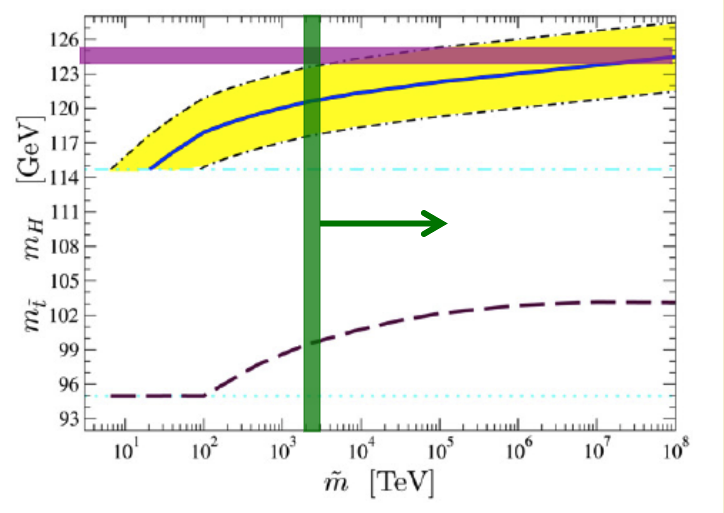
Increasing m_h ⟶

⟵ *New scalars*

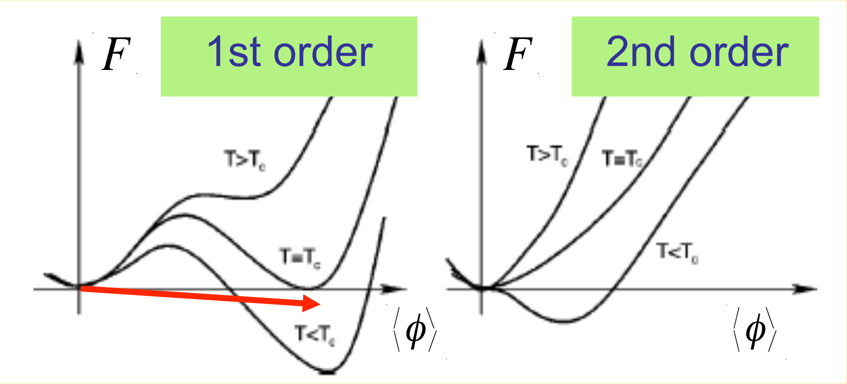
MSSM: Light RH stops

Carena et al 2008: Higgs phase metastable





EW Phase Transition: MSSM

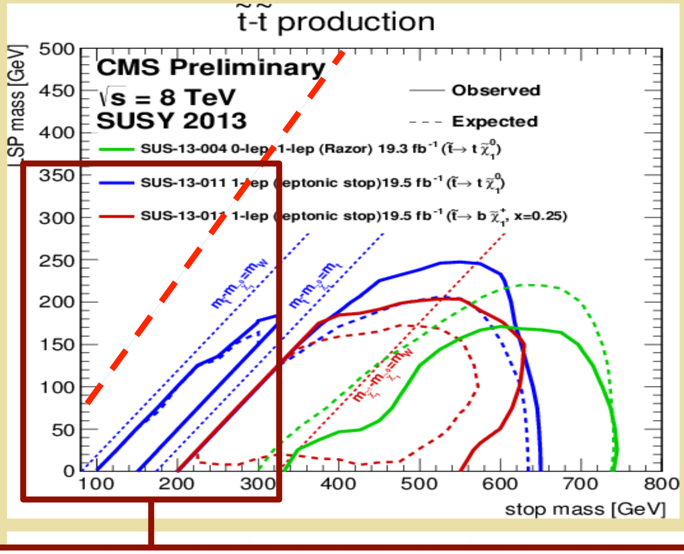


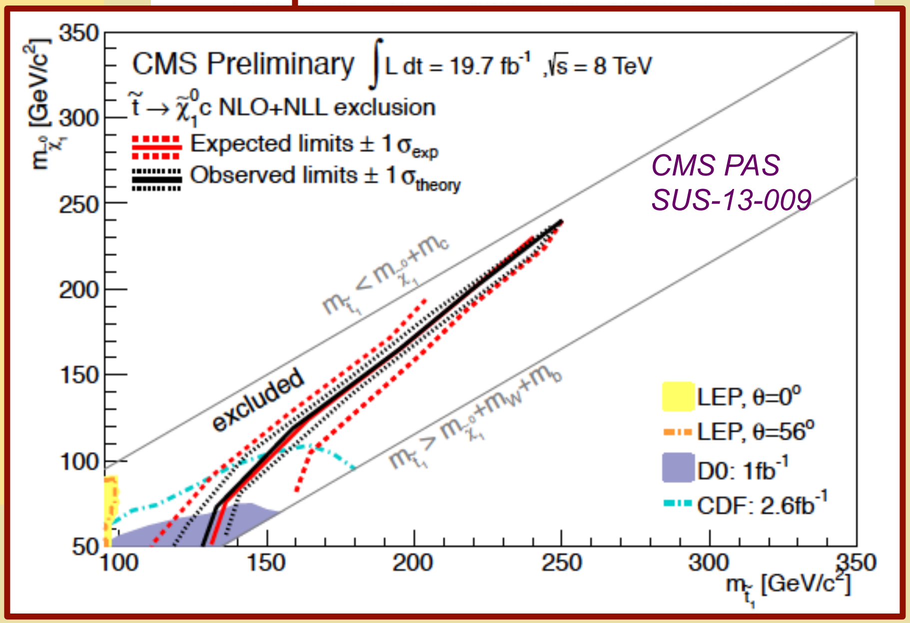
Increasing m_h →

← *New scalars*

MSSM: Light RH stops

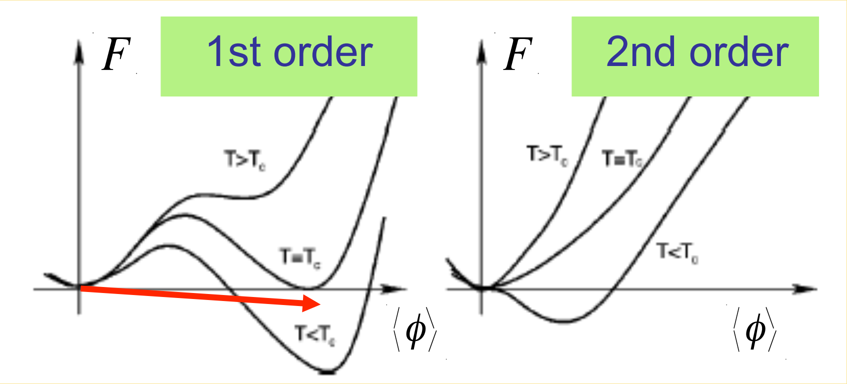
Carena et al 2008: Higgs phase metastable





CMS PAS SUS-13-009

EW Phase Transition: Higgs Portal

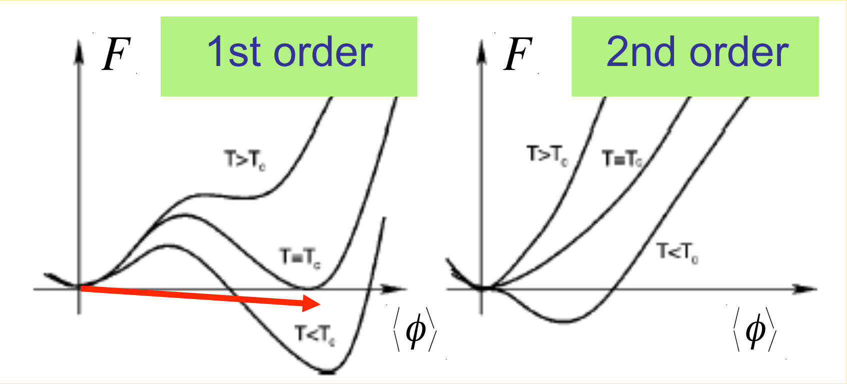


Increasing m_h →

← *New scalars*

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

EW Phase Transition: Higgs Portal



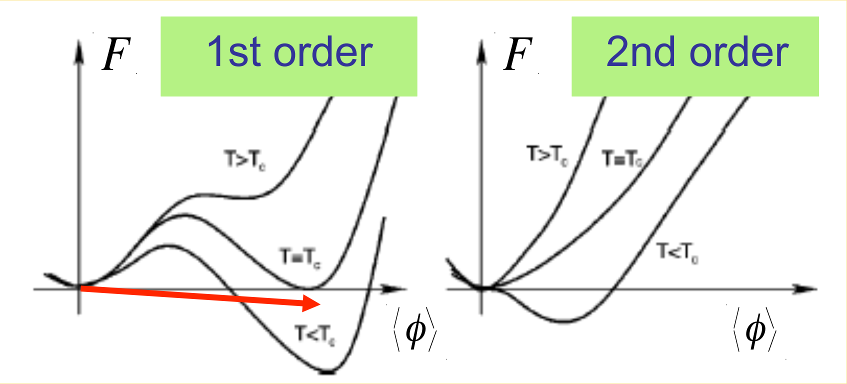
Increasing m_h →

← New scalars

$$\boxed{\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H} \quad + \ldots$$

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

EW Phase Transition: Higgs Portal

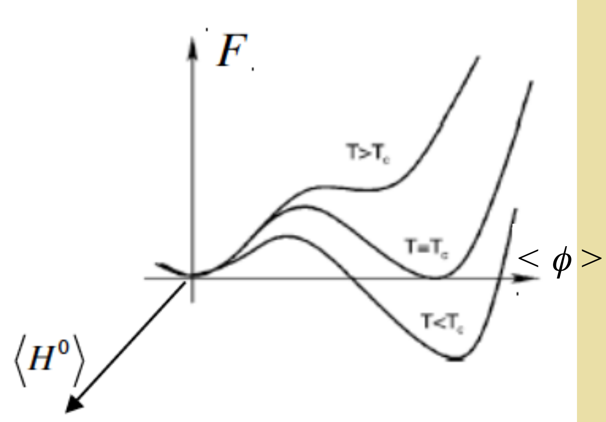


Increasing m_h →

← *New scalars*

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

+…



- *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	1	✓	✖
Real singlet	1	✖	✓
Complex Singlet	2	✓	✓
Real Triplet	3	✓	✓

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

Higgs Portal: Simple Scalar Extensions

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

May be low-energy remnants of UV complete theory & illustrative of generic features (NMSSM, GUTs, Hidden Valley….)

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 (NMSSM, GUTs, Hidden Valley….)

The Simplest Extension

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

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

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

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

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

The Simplest Extension, Cont'd

Mass matrix

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

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

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

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

x_0 = <S>

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

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

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

The Simplest Extension, Cont'd

Mass matrix

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

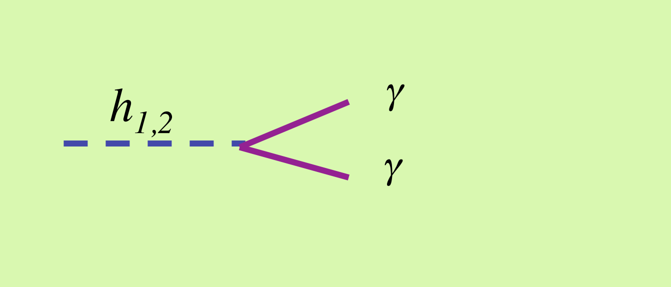
$$\mu_s^2 \equiv \frac{\partial^2 V}{\partial s^2} = b_3 x_0 + 2b_4 x_0^2 - \frac{a_1 v_0^2}{4x_0}$$

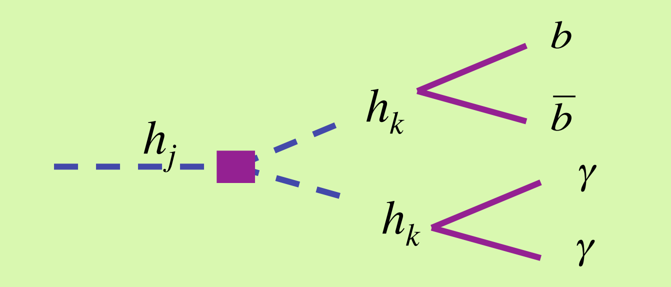
$$\mu_{hs}^2 \equiv \frac{\partial^2 V}{\partial h \partial s} = (\boxed{a_1} + 2a_2 \boxed{x_0})\, v_0$$

x_0 = <S>

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

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

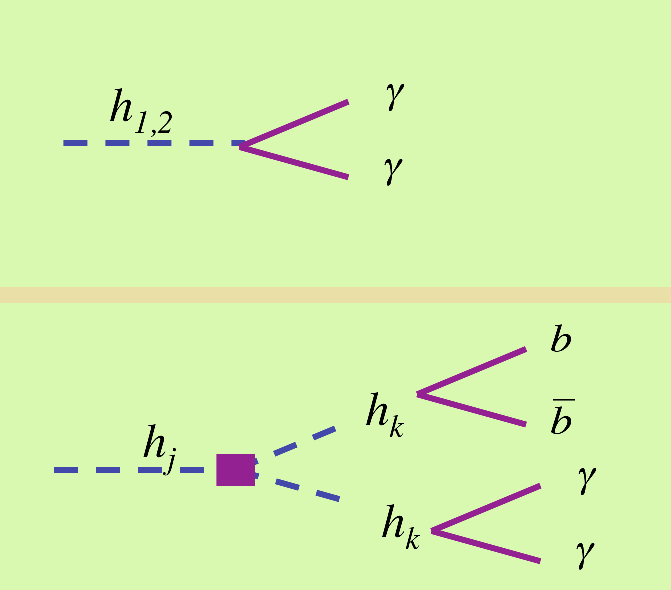




New topologies

The Simplest Extension, Cont'd

Mass matrix



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

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

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

$x_0 = \langle S \rangle$

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

Stable S (dark matter)

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

The Simplest Extension

DM Scenario

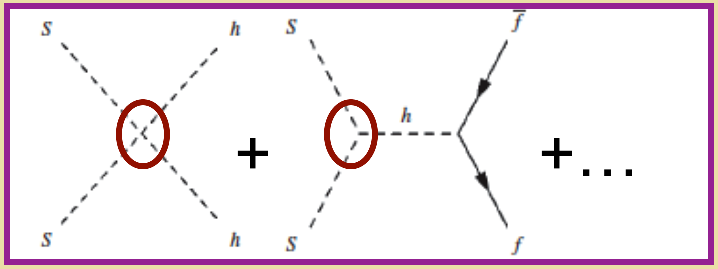
$$\boxed{V_{\rm HS} = \qquad\qquad\qquad + \frac{a_2}{2}\left(H^\dagger H\right)S^2}$$

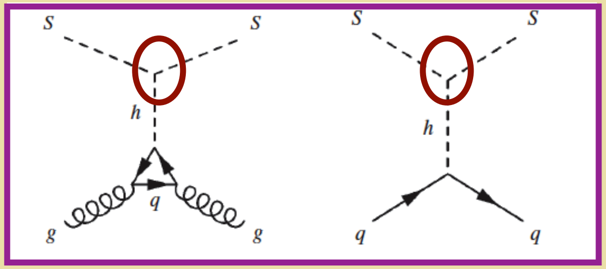
The Simplest Extension

DM Scenario

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

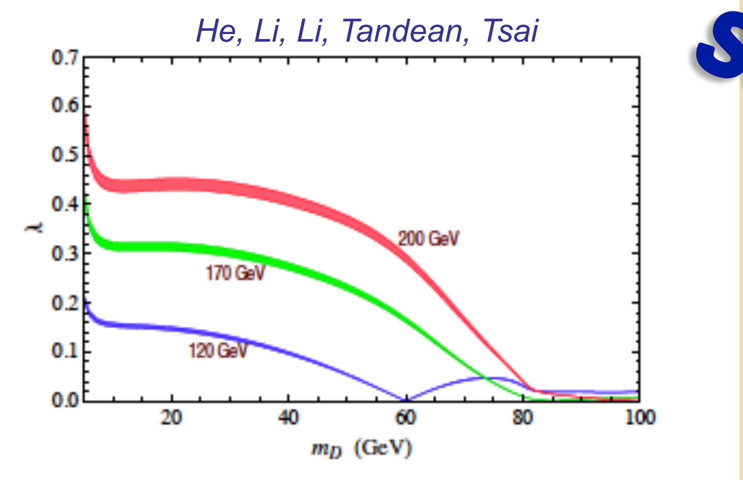
Ω_{DM} & σ_{SI}





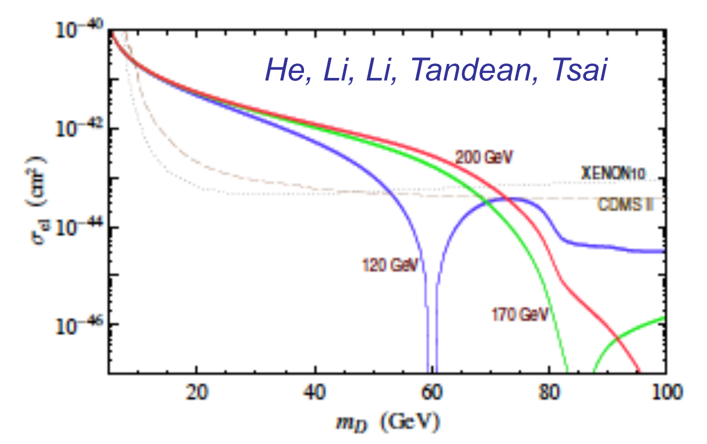
DM Phenomenology

Relic Density

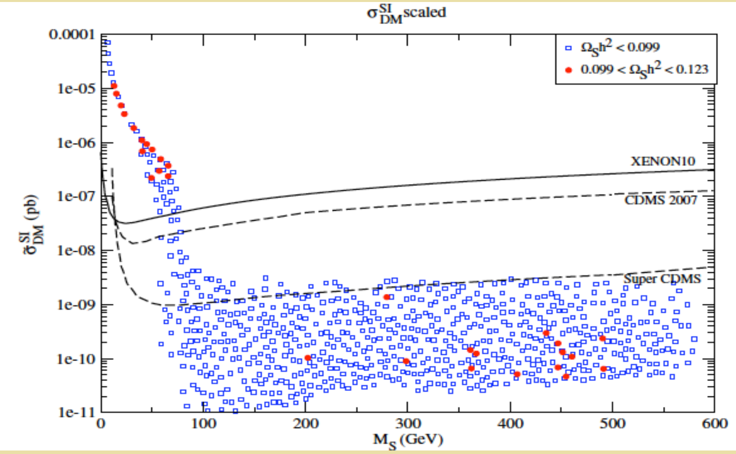

He, Li, Li, Tandean, Tsai

See Xiao-Gang He Talk

Direct Detection


He, Li, Li, Tandean, Tsai

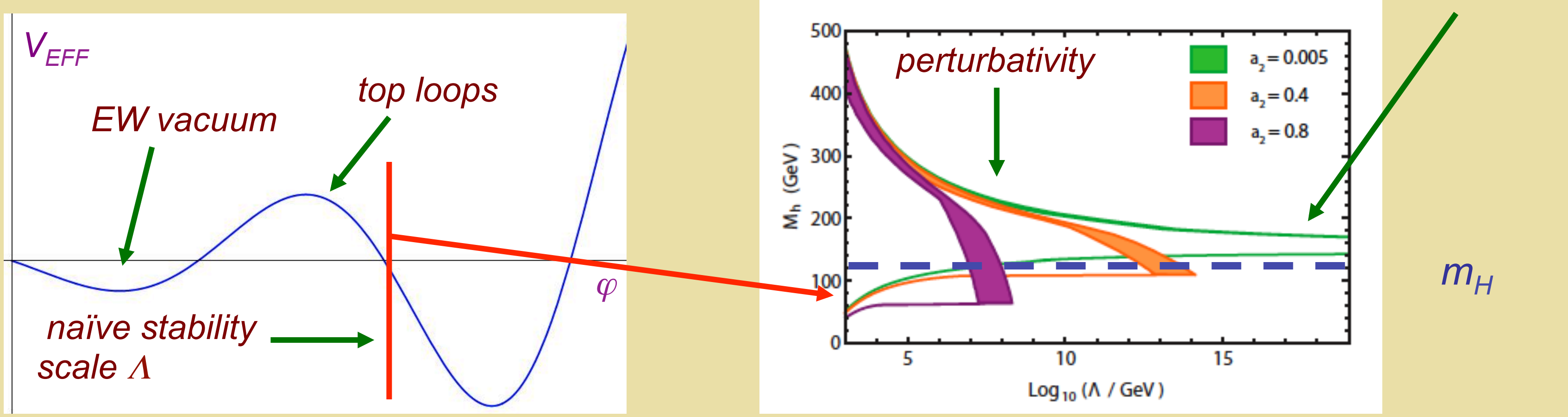
Barger, Langacker, McCaskey, R-M, Shaugnessy



New Scalars EW Vacuum Stability

Preserving EW Min

“Funnel plot”



$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4\right)$$

DM-H coupling

top loops

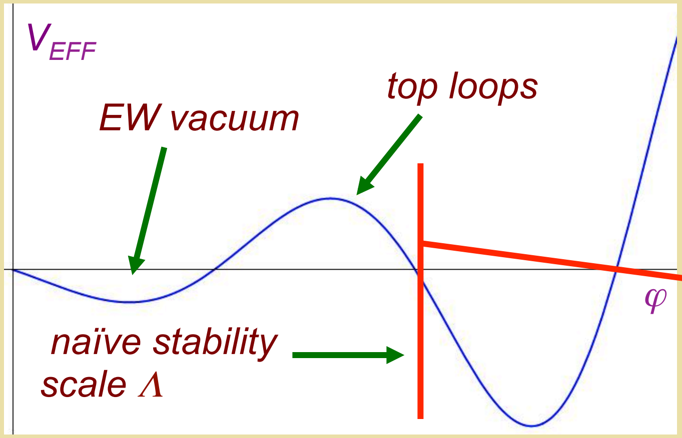
Gonderinger, Li, Patel, R-M; Gonderinger, Lim, R-M

New Scalars EW Vacuum Stability

Preserving EW Min

“Funnel plot”

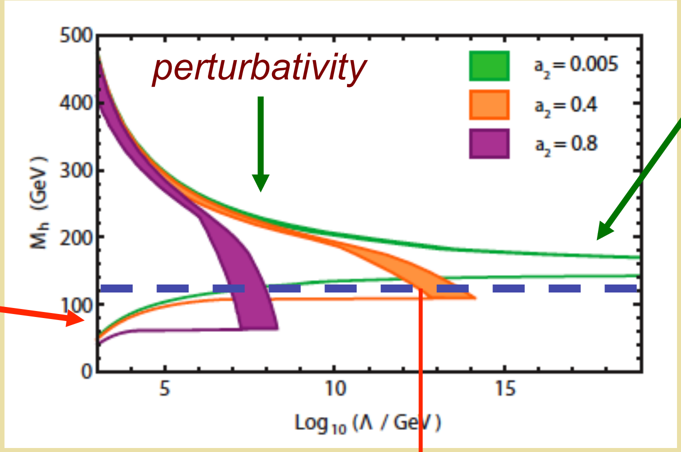
SM stability & pert’vity



EW vacuum

top loops

naïve stability scale Λ



perturbativity

m_H

SM + singlet: stable but non-pertur’tive

$$\beta_\lambda = \frac{1}{16\pi^2}\left(4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2g'^2 + \frac{27}{4}g^4\right)$$

DM-H coupling

top loops

Gonderinger, Li, Patel, R-M; Gonderinger, Lim, R-M

LHC & Higgs Phenomenology

LHC discovery potential

Signal Reduction Factor

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

Production

Decay

LHC & Higgs Phenomenology

LHC discovery potential

Signal Reduction Factor

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

Production

Decay

V_{1j} < 1: mixed states h_j

New decays: $h_2 \to h_1 h_1$

LHC & Higgs Phenomenology

LHC discovery potential

Signal Reduction Factor

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

Production

Decay

$V_{1j} < 1$: mixed states h_j

New decays: $h_2 \to h_1 h_1$

Dark matter: no mixing → states are h,S

New decays h→ SS (invisible!) possible

LHC & Higgs Phenomenology

LHC discovery potential

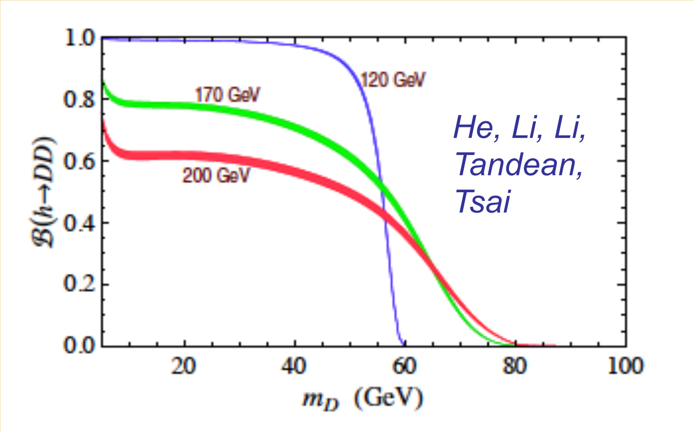
Signal Reduction Factor

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

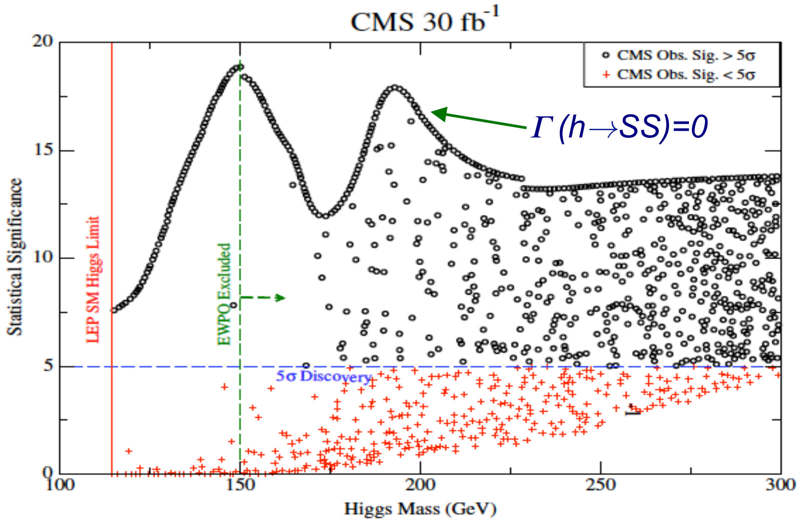
Production

Decay

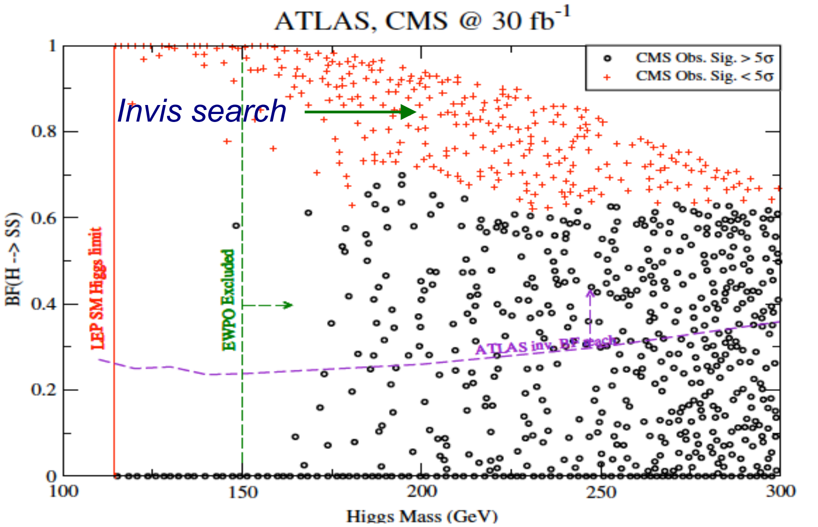
Invisible decays



He, Li, Li, Tandean, Tsai



Γ (h→SS)=0



Invis search

LHC & Higgs Phenomenology

LHC discovery potential

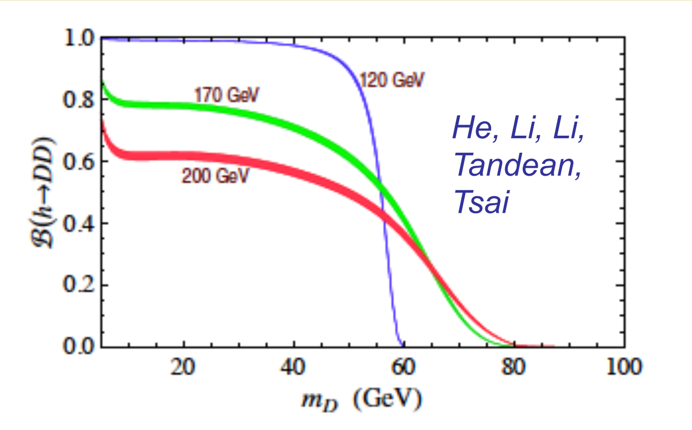
Signal Reduction Factor

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

Production

Decay

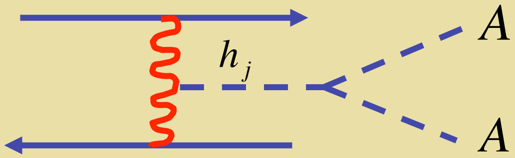
Invisible decays



He, Li, Li, Tandean, Tsai

Dijet azimuthal distribution

Jets + $\not{E}_T$



Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld ‘00)

LHC & Higgs Phenomenology

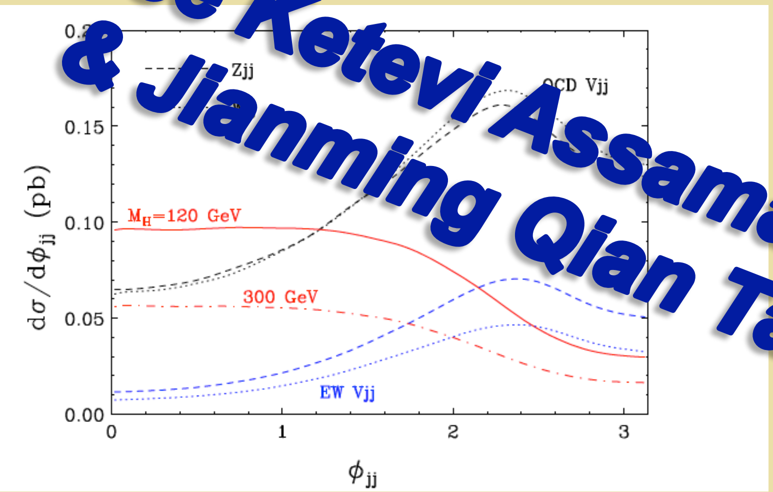
LHC discovery potential

Signal Reduction Factor

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

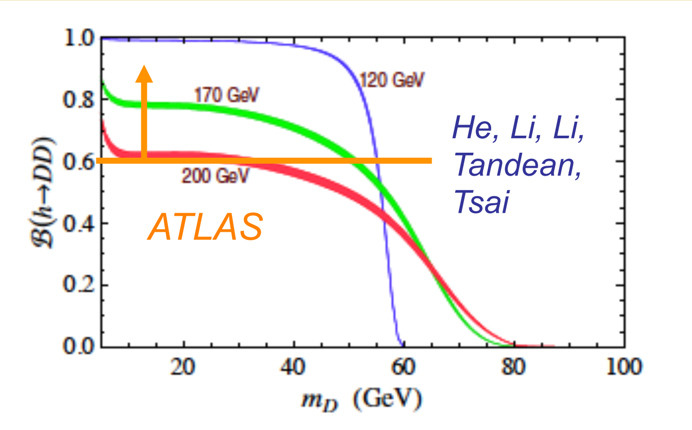
Production

Decay

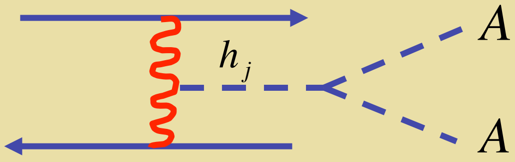


See Ketevi Assamagan & Jianming Qian Talks

Invisible decays



Dijet azimuthal distribution



Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld '00)

Real Singlet: EWPT

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

Real Singlet: EWPT

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

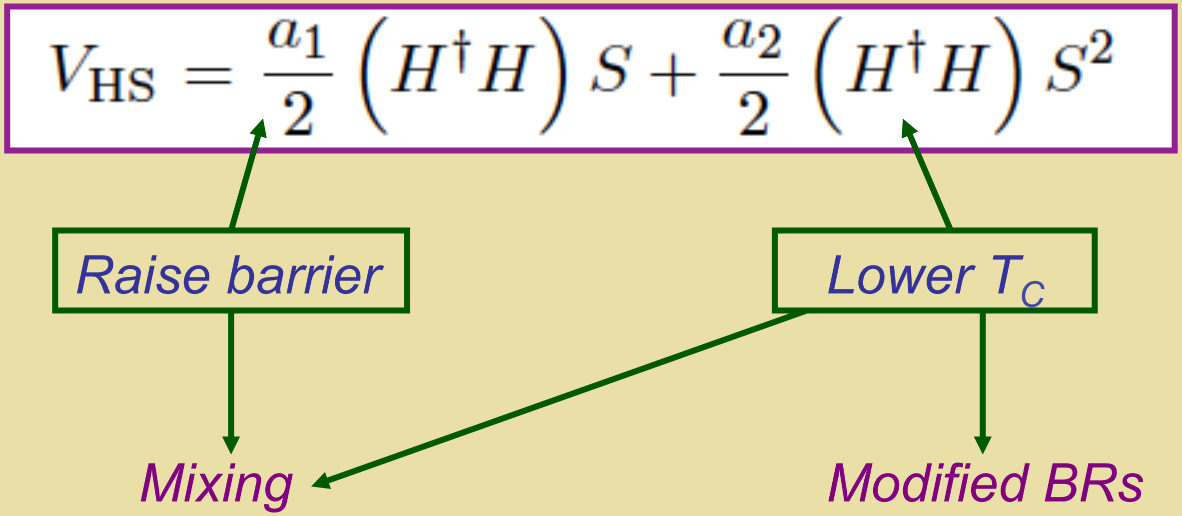
Raise barrier

Lower T_C

Real Singlet: EWPT

Low energy phenomenology

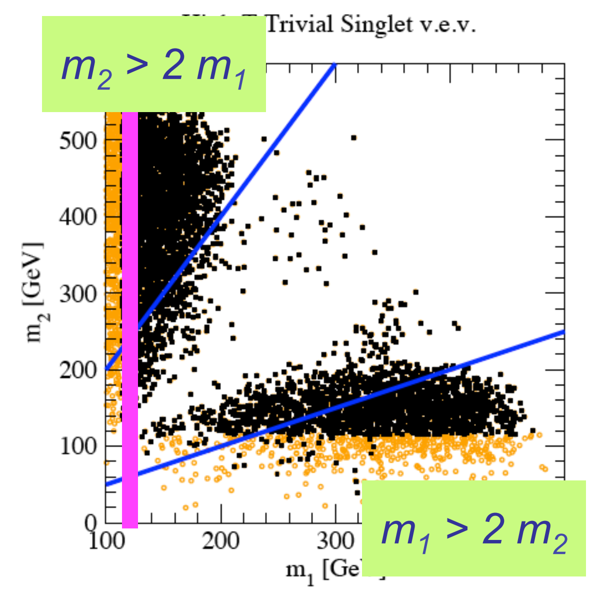
$$V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$



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

EWPT & LHC Phenomenology

Signatures



$m_2 > 2\, m_1$

$m_1 > 2\, m_2$

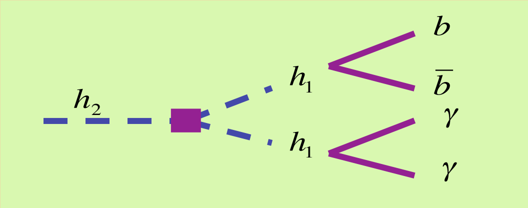
Scan: EWPT-viable model parameters

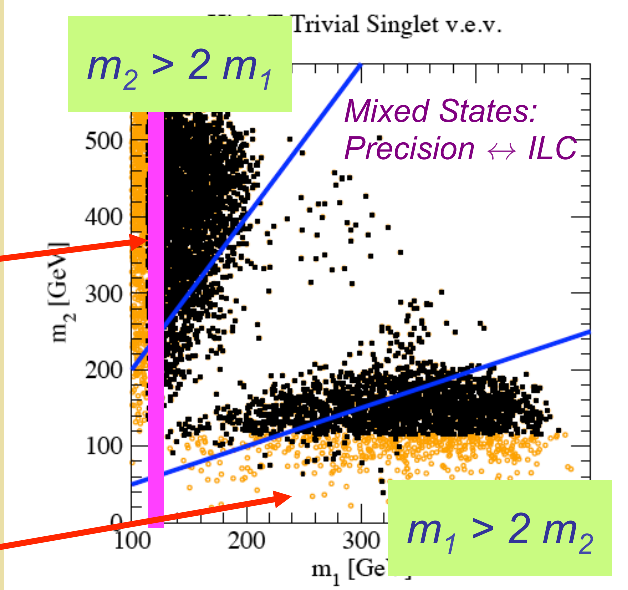
Light: all models
Black: LEP allowed

Profumo, R-M,
Shaugnessy ‘07

EWPT & LHC Phenomenology

Signatures

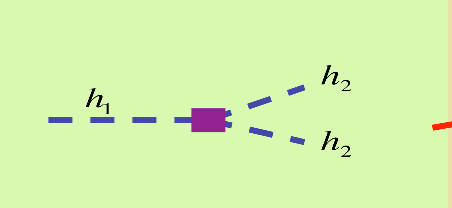




$m_2 > 2\ m_1$

Mixed States: Precision ↔ ILC

$m_1 > 2\ m_2$



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

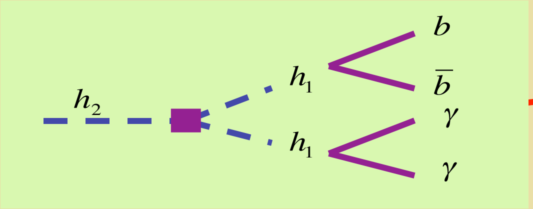
Scan: EWPT-viable model parameters

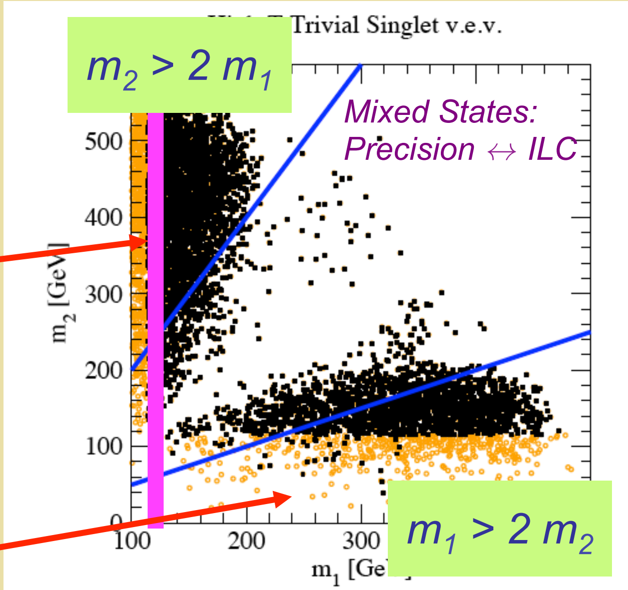
Light: all models
Black: LEP allowed

Profumo, R-M,
Shaugnessy '07

EWPT & LHC Phenomenology

Signatures





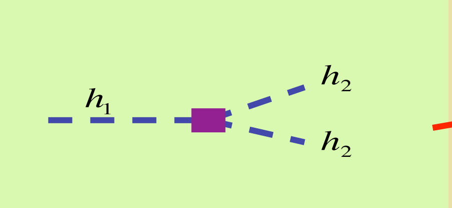
$m_2 > 2\, m_1$

Mixed States: Precision ↔ ILC

$m_1 > 2\, m_2$

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed



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

Signal Reduction Factor

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

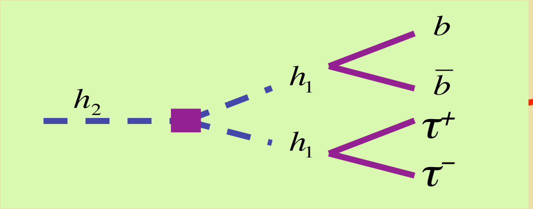
Production

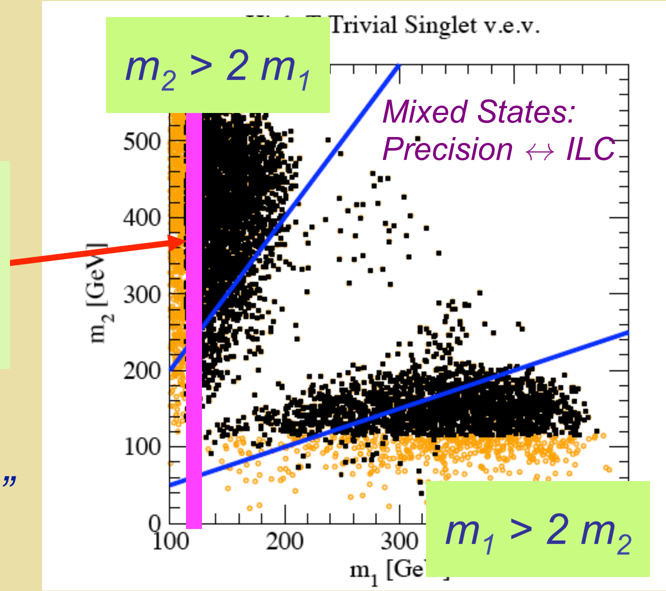
Decay

Profumo, R-M,
Shaugnessy '07

EWPT: Resonant Di-Higgs Production

Signatures





$m_2 > 2\, m_1$

Mixed States: Precision ↔ ILC

$m_1 > 2\, m_2$

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

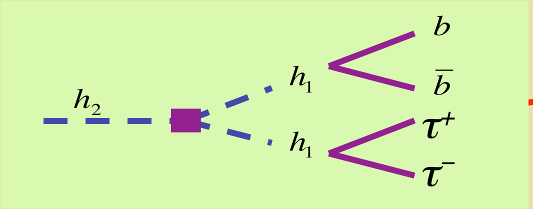
$m_2 = 270$ *GeV "un-boosted"*
$m_2 = 370$ *GeV "boosted"*

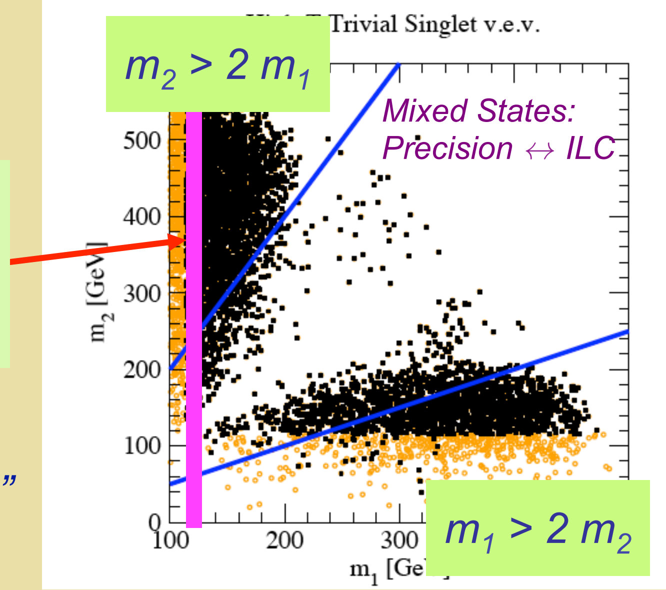
$bb\tau^+\tau^-$ *: discovery with ~ 100 fb*$^{-1}$ *in "*$\tau_{lep}\, \tau_{had}$*" channel*

R-M & No, arXiv:1310.6035

EWPT: Resonant Di-Higgs Production

Signatures





$m_2 > 2\ m_1$

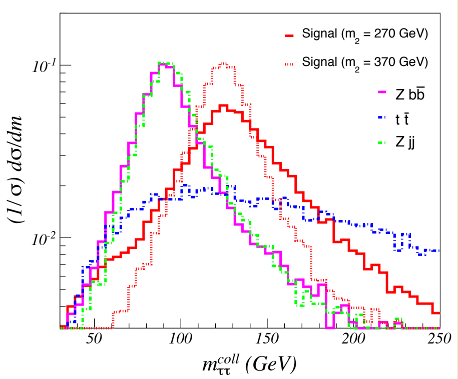
Mixed States: Precision ↔ ILC

$m_1 > 2\ m_2$

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

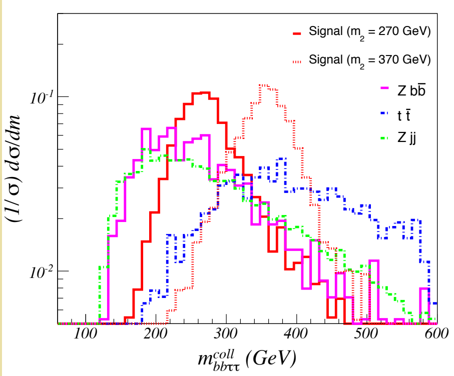
m_2 = 270 GeV "un-boosted"
m_2 = 370 GeV "boosted"



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

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

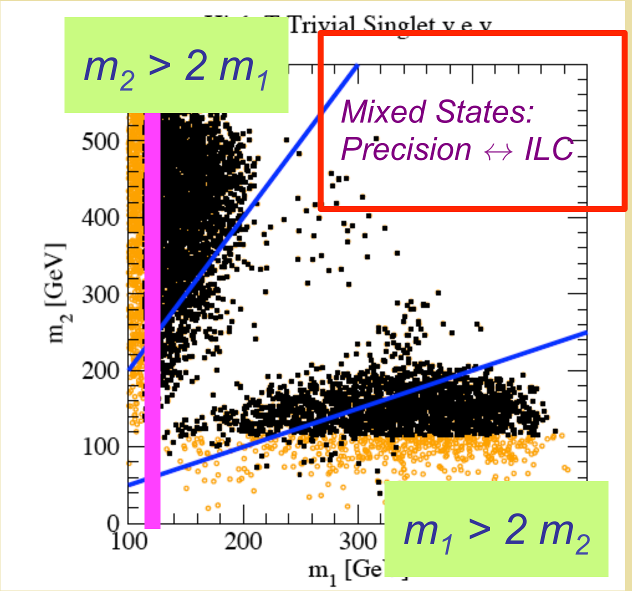
See Jose Miguel No Talk



R-M & No, arXiv:1310.6035

EWPT & LHC Phenomenology

Signatures



$m_2 > 2\ m_1$

Mixed States: Precision ↔ ILC

$m_1 > 2\ m_2$

Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed

See Peter Winslow Talk

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	✔	✔

Back up slides

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

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

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

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

↓

Controls Ω_{CDM}, T_C, & H-S mixing

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

↓

Gives non-zero M_A

Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Consequences:

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

A : *dark matter*

Phenomenology:

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

Higgs Portal: Simple Scalar Extensions

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

Simplest non-trivial EW multiplet

Real Triplet

Σ^0, Σ^+, Σ^- ~ (1, 3, 0)

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

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

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

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

Real Triplet

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

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

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

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

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

Small: ρ*-param*

Real Triplet: DM

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

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

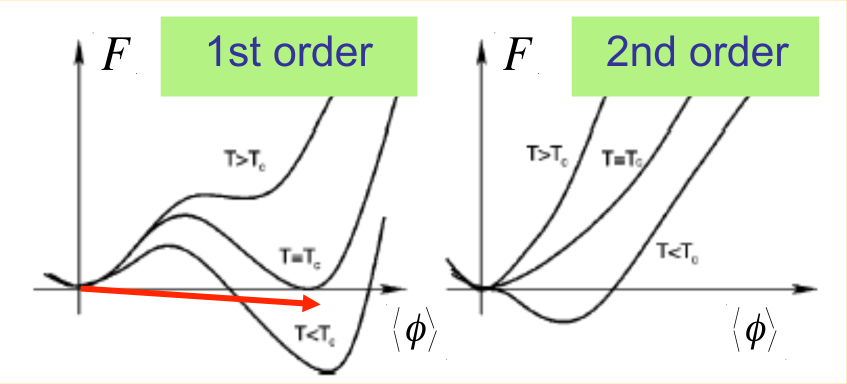
$$V_{H\Sigma} = \qquad \frac{a_2}{2} H^\dagger H \; \mathrm{Tr} \; \Sigma^2$$

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

DM & EWPT: $\boxed{a_1 = 0 \;\; \& \; \langle \Sigma^0 \rangle = 0}$

Small: ρ-param

EW Phase Transition: Higgs Portal



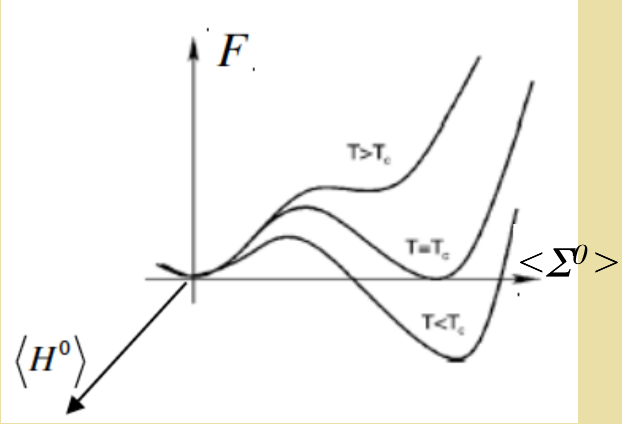
Increasing m_h →

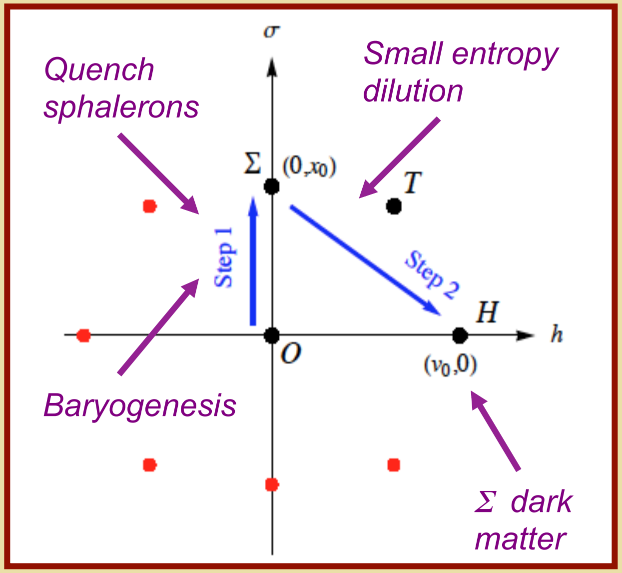
← New scalars

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

Two-step EWPT &
dark matter

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





Quench
sphalerons

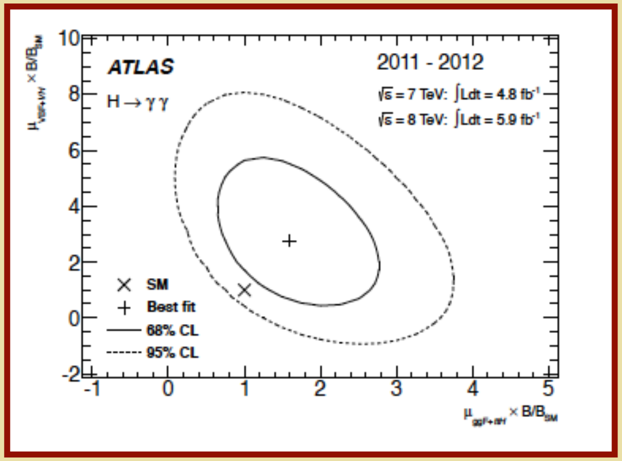
Small entropy
dilution

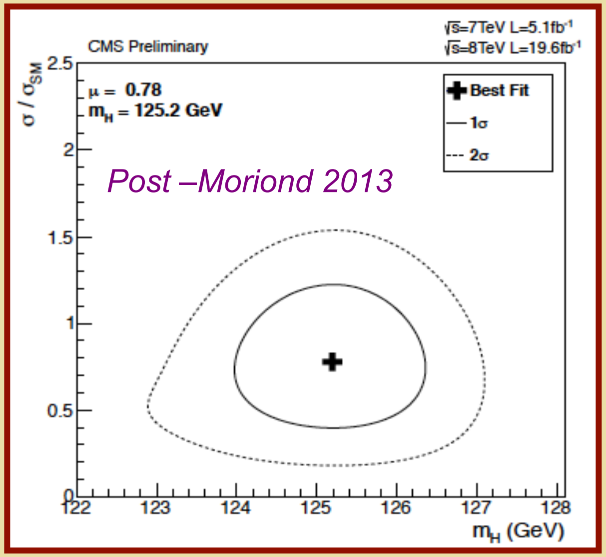
Baryogenesis

Σ dark
matter

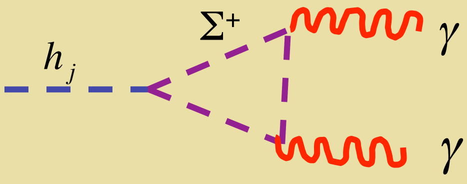
Higgs Diphoton Decays

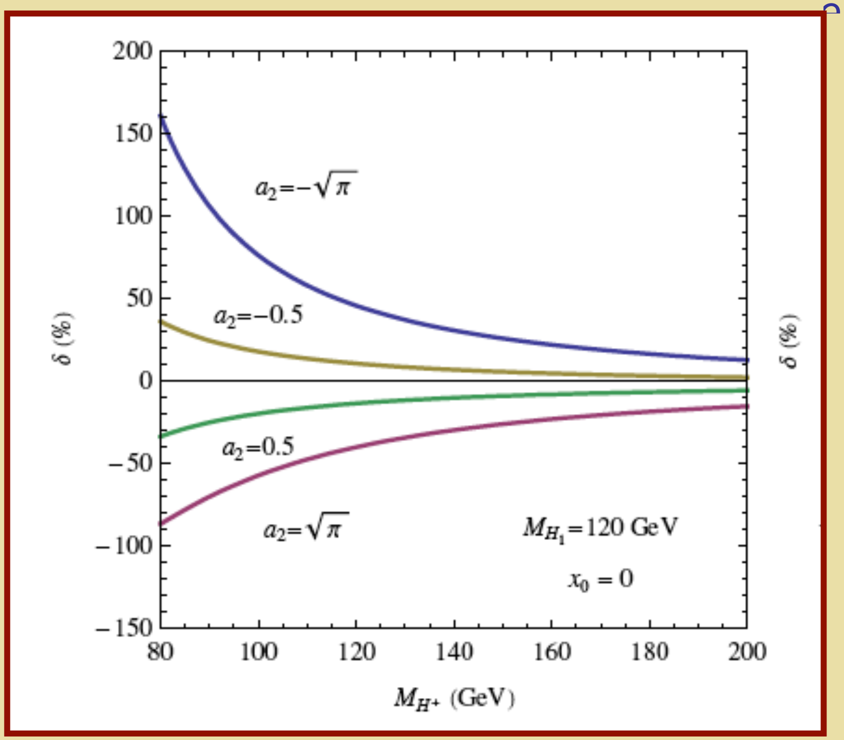
LHC: H $\rightarrow \gamma\gamma$





Post –Moriond 2013





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

Real Triplet: EWPT

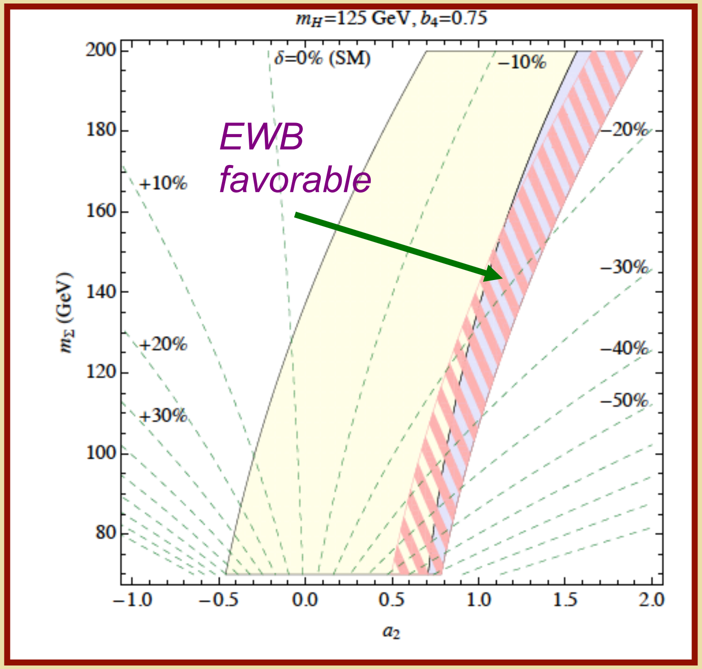
$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

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

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



Real Triplet: EWPT

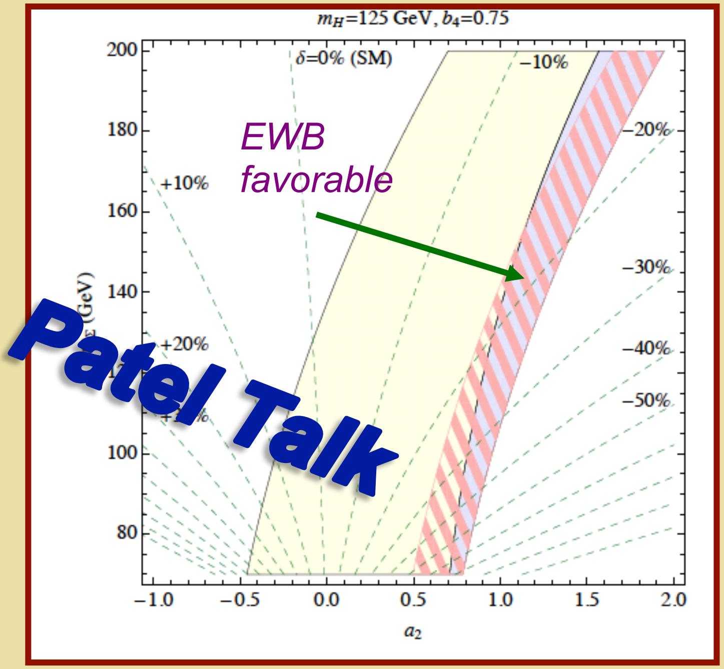
$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

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

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



EWB favorable

See Hiren Patel Talk

Real Triplet : DM Search

Mass splitting due to EW symmetry breaking:

$$\boxed{M_{\Sigma^\pm} - M_{\Sigma^0} \sim \frac{\alpha}{4\pi} M_W}$$

$\Sigma^+ \to \Sigma^0 + \pi^+$ ***(soft)***

Generalizes to higher dim EW multiplets

Real Triplet : DM Search

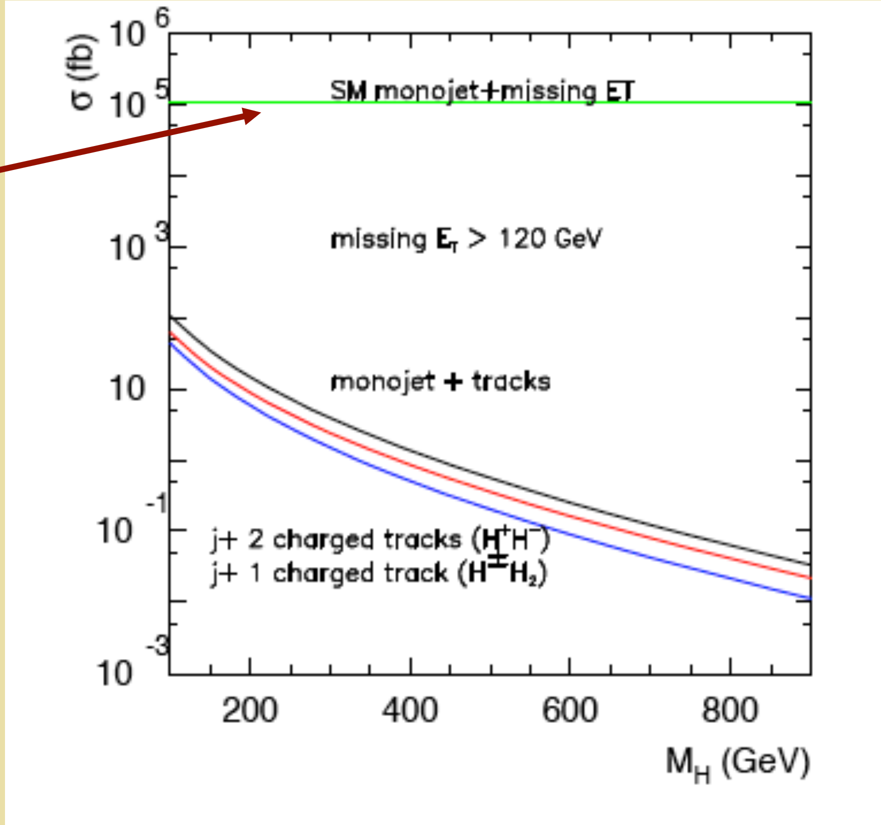
Basic signature: Charged track disappearing after ~ 5 cm

$x_0 = 0 : H^{\pm} \to H_2 \, \pi^{\pm}$

$q\bar{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\bar{q} \to Z^{*}, \gamma^{*} \to H^{+} H^{-}$

Trigger: Monojet (ISR) + large $\not{E}_T$

SM Background: QCD jZ and jW w/ $Z \to \nu\nu$ & $W \to l\nu$



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

Real Triplet : DM Search

Basic signature: **Charged track disappearing after ~ 5 cm**

$x_0 = 0 : H^{\pm} \to H_2\, \pi^{\pm}$

$q\overline{q} \to W^{\pm *} \to H^{\pm} H_2 \qquad q\overline{q} \to Z^{*}, \gamma^{*} \to H^{+} H^{-}$

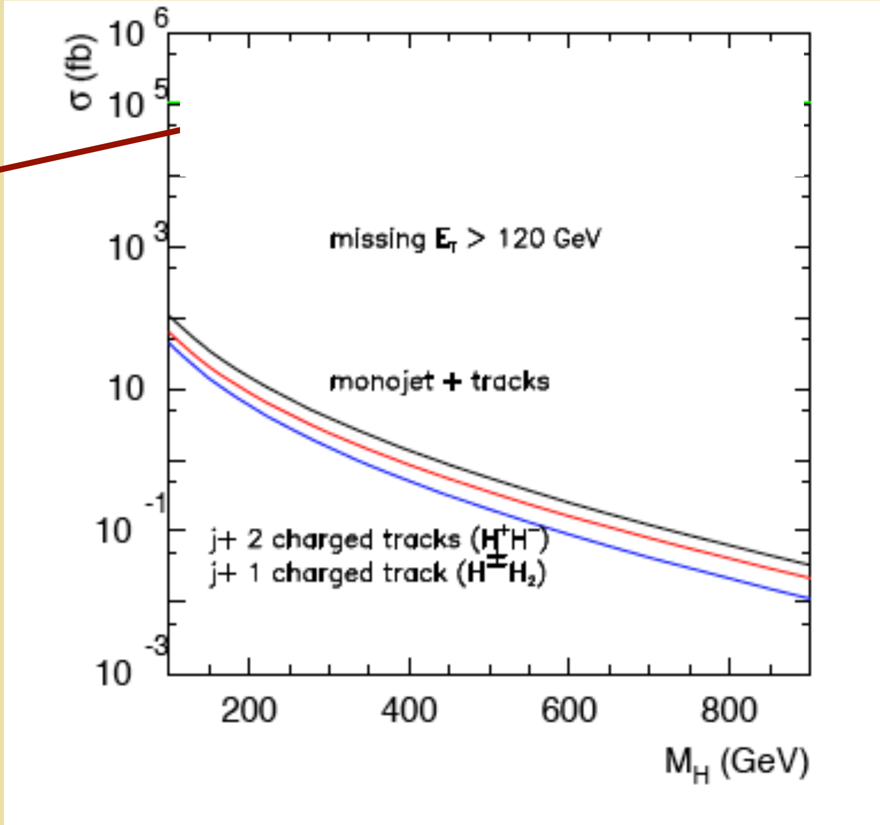
Trigger: Monojet (ISR) + large $\not{E}_T$

SM Background: QCD jZ and jW w/ $Z \to \nu\nu$ & $W \to l\nu$

Cuts: ***large $\not{E}_T$***

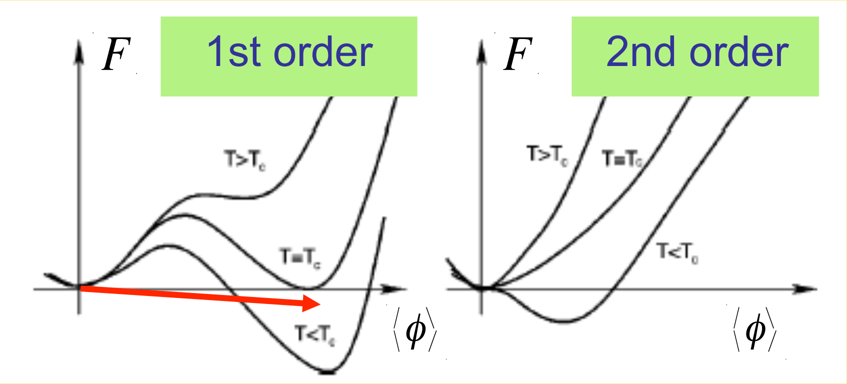
hard jet

One 5cm track



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

EW Phase Transition: Higgs Portal



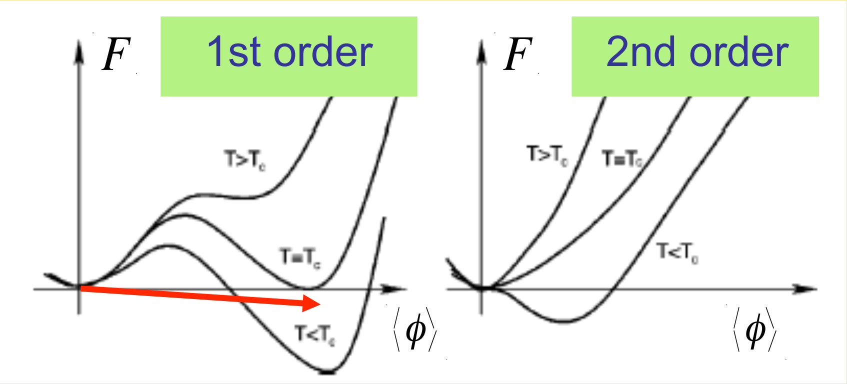
Increasing m_h →

← *New scalars*

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

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

Symmetry Breaking & Restoration

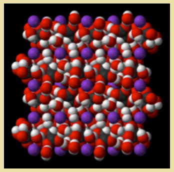


Increasing m_h →

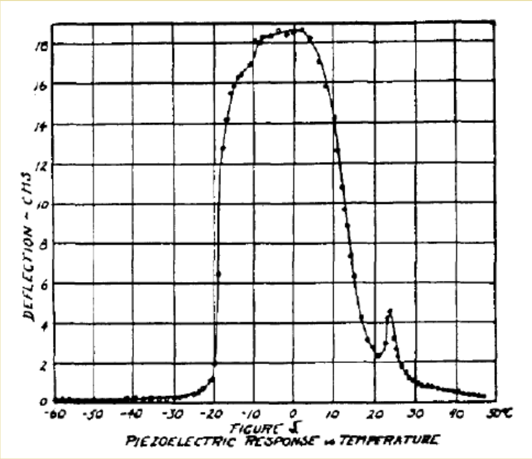
← New scalars

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

Rochelle salt:
$KNaC_4H_4O_6\ 4H_20$



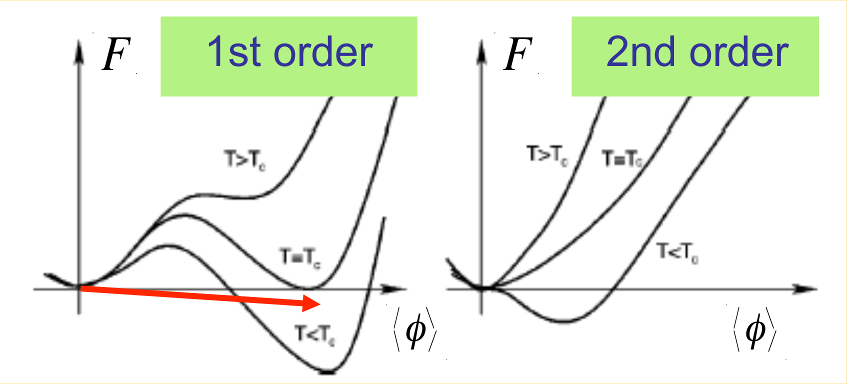
J. Valasek



Piezoelectricity

Increasing T $\rightarrow$

EW Phase Transition: Higgs Portal



Increasing m_h →

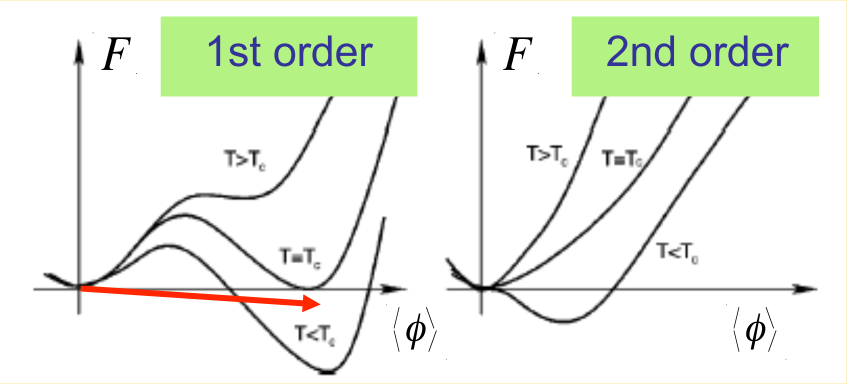
← *New scalars*

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

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

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

EW Phase Transition: Higgs Portal



Increasing m_h →

← New scalars

Colored Scalars

Color breaking & restoration

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

Color Breaking & Restoration

Two illustrative cases:

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

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

Color Breaking & Restoration

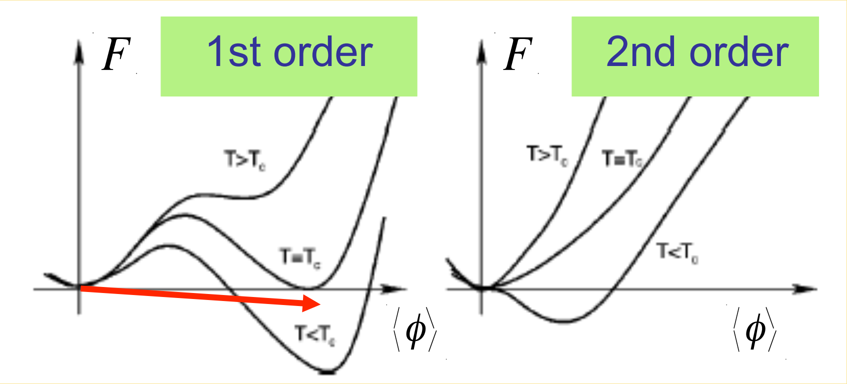
Two illustrative cases:

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

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

Spontaneous B violation

EW Phase Transition: Higgs Portal



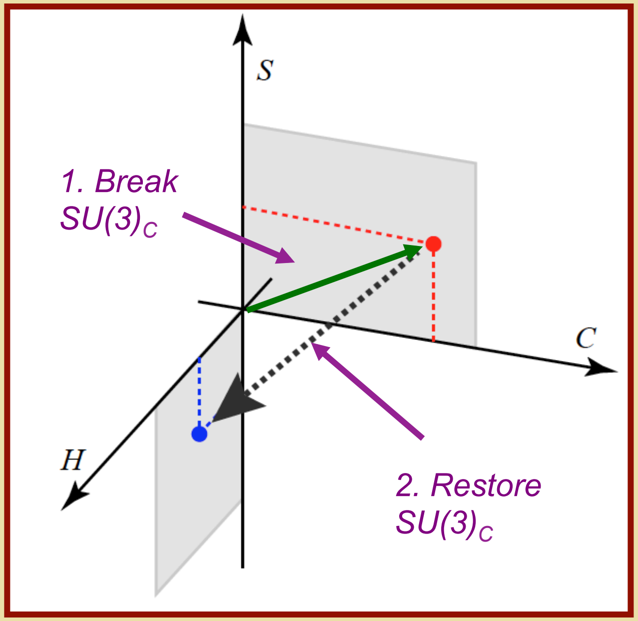
Increasing m_h →

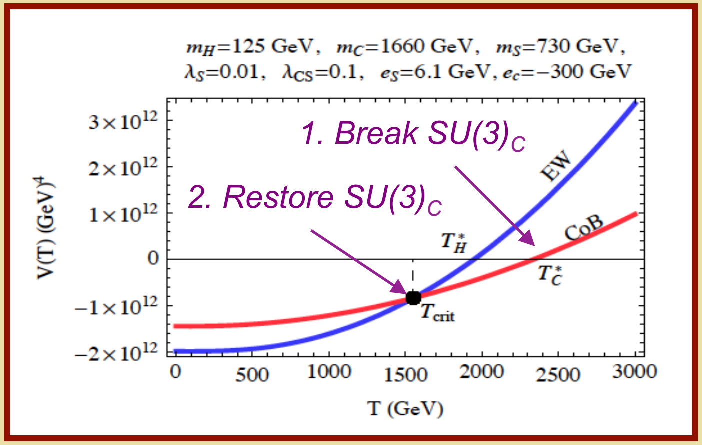
← *New scalars*

Colored Scalars (triplet)

Color breaking & restoration

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





Summary: Workshop Questions

- *What happened ~ 10ps after the Big Bang?*
- *Single step (cross over) transition ?*
- *More d.o.f. with a richer pattern of EWSB?*
  - *Single or multiple steps ?*
  - *First or second order ?*
  - *Coupled to origin of matter ?*
- *What are collider signatures that could provide clues?*
  - *Modified Higgs properties (production, decays)*
  - *New states*

Back Up Slides

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*	✖	✔

Ingredients for Baryogenesis

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

Testable

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

Baryon Number Preservation

“Washout factor”

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

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

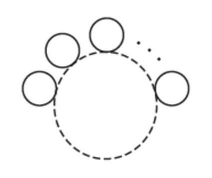
$$\zeta \equiv \left.\frac{\hat{E}_{\mathrm{sph}}}{T}\right|_{T=T_C}$$

$\boxed{\zeta = F(\varphi)}$

Two qtys of interest:

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

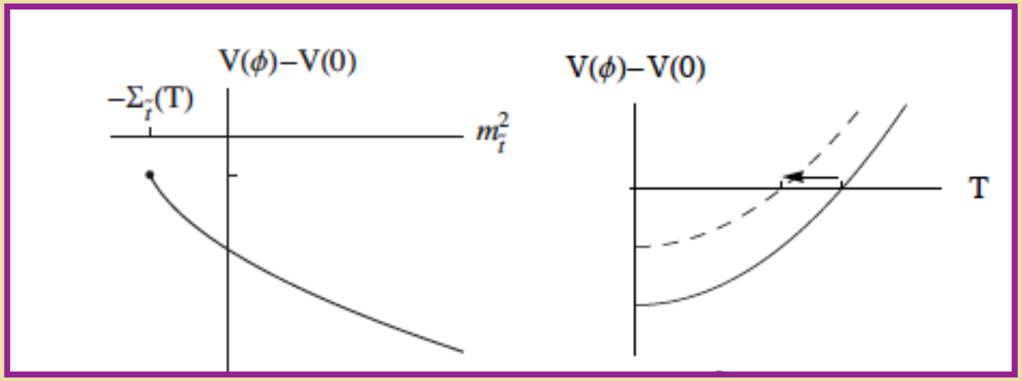
Daisy Resummation



Convergence of PT: going beyond $\hbar$ expansion

Light stop scenario

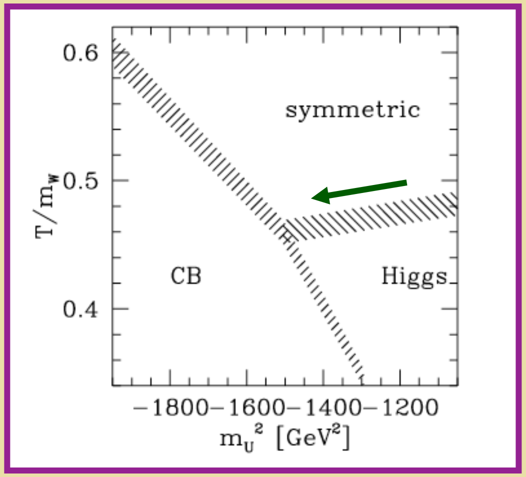
$$V_{\rm eff}(\phi_{\rm min},T) - V_{\rm eff}(0,T) \sim$$
$$-\hbar\frac{T}{12\pi}\left[\left(m_{\tilde t}^2 + y_{\tilde t}^2\phi^2 + \Sigma_{\tilde t}(T)\right)^{3/2} - \left(m_{\tilde t}^2+\Sigma_{\tilde t}(T)\right)^{3/2}\right].$$



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

Increased ΔV → Lowered T_C

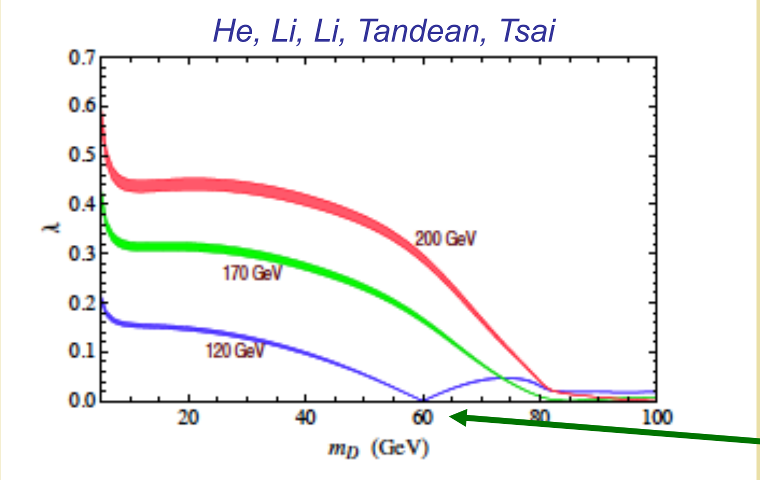
Patel & R-M '11



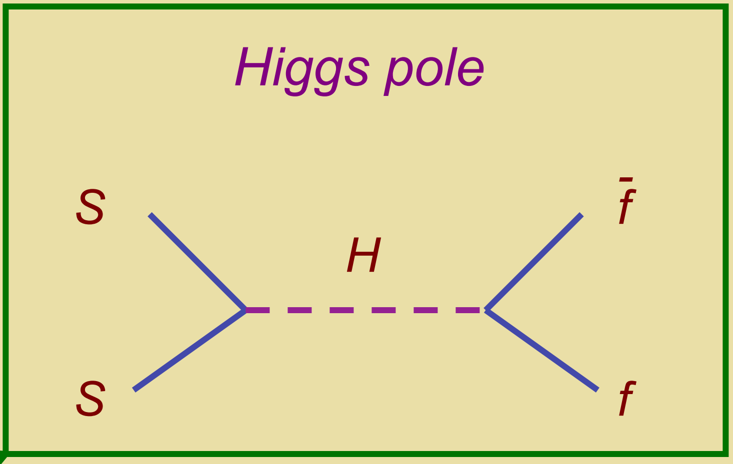
Csikor '00

DM Phenomenology

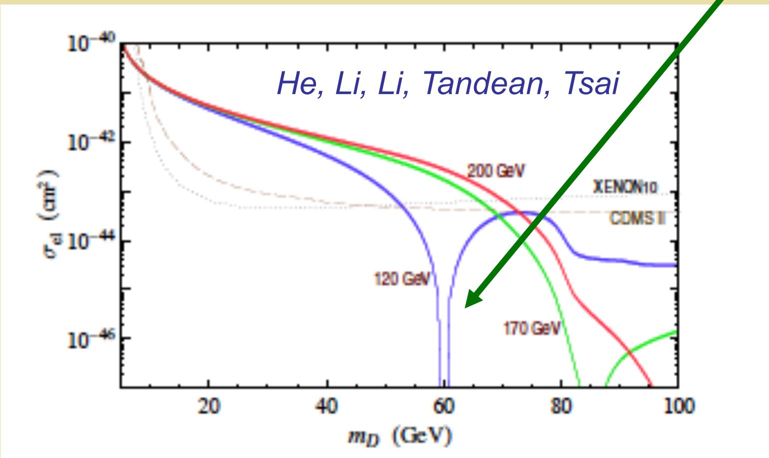
Relic Density


He, Li, Li, Tandean, Tsai

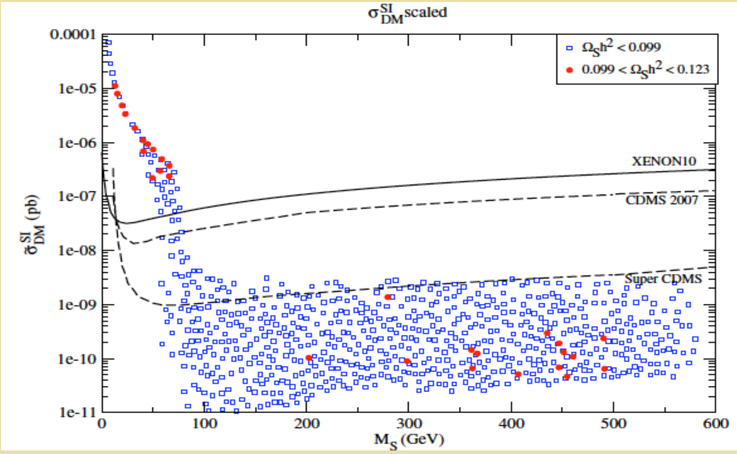
Higgs pole



Direct Detection


He, Li, Li, Tandean, Tsai

Barger, Langacker, McCaskey, R-M, Shaugnessy



Real Triplet: EWPT

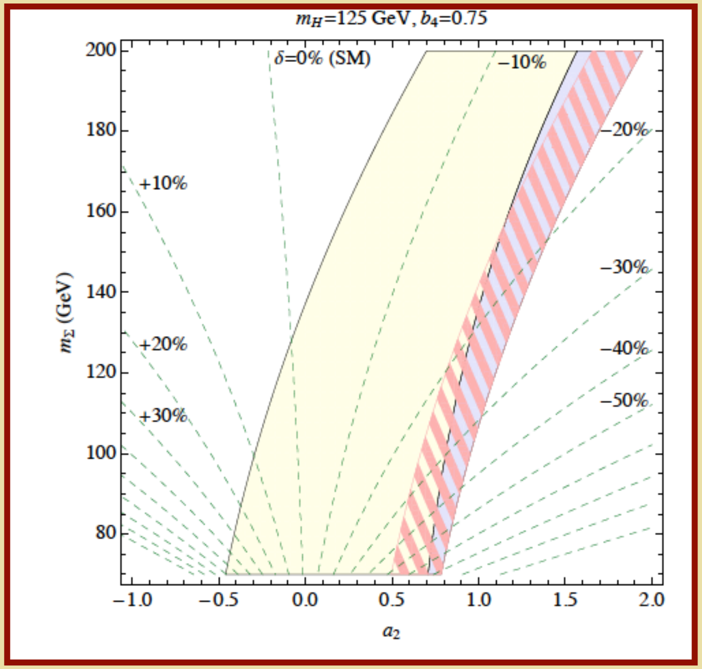
$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

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

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



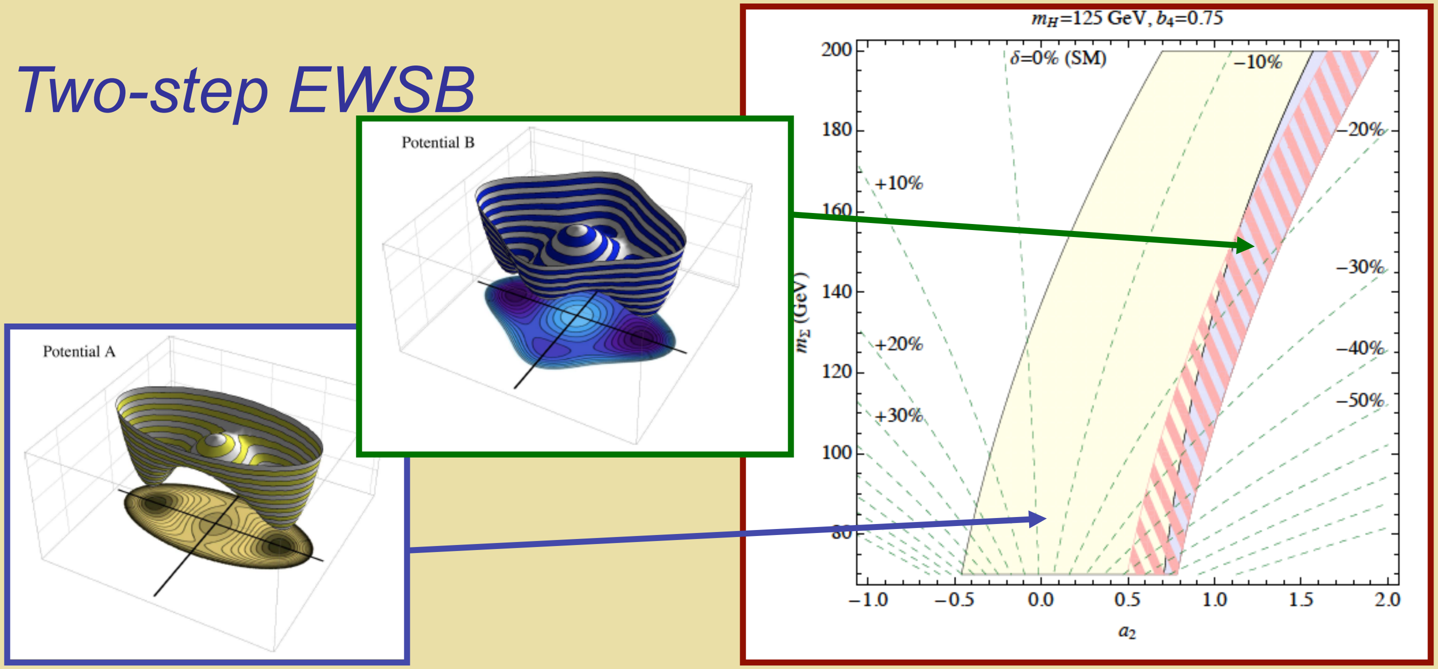
Real Triplet: EWPT

Σ^0, Σ^+, Σ^- ~ (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



Real Triplet: EWPT

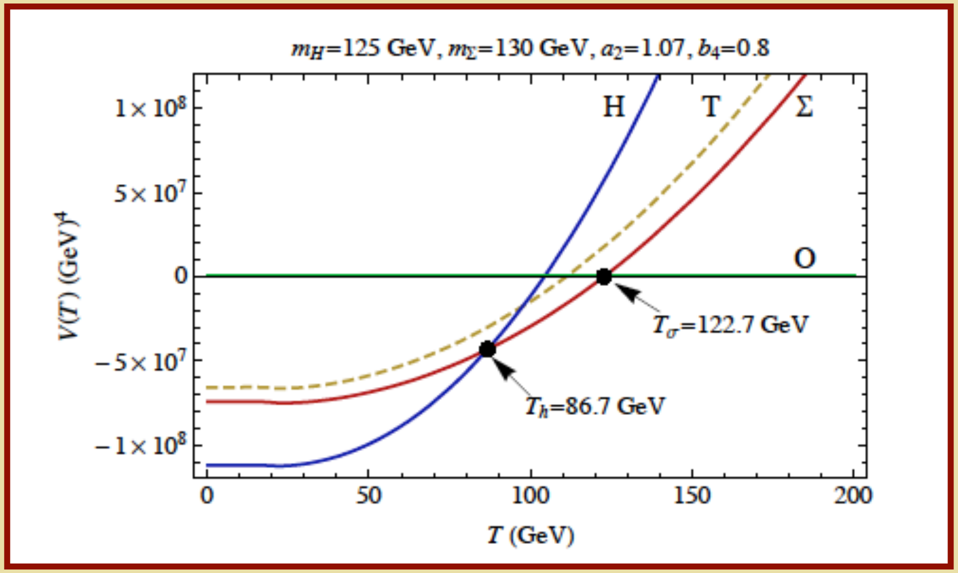
$\Sigma^0, \Sigma^+, \Sigma^-$ ~ (1, 3, 0)

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

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



Color Breaking & Restoration

Two illustrative cases:

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

Extension	DOF	EWPT	DM
Color triplet scalar	6	✓	✗
Color triplet + singlet	7	✓	✗
…..			

“Light”: special flavor structure

Spontaneous B violation

Color Breaking & Restoration

Two illustrative cases:

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

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

heavy: generic flavor structure

Spontaneous B violation

SM + Color Triplet

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

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

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

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

SM + Color Triplet

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

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

Upper bound on m$_C$:

$$\begin{aligned} m_h^2 &= 2\mu_H^2 = 2\lambda_H v_H^2 &> 0 \\ m_C^2 &= -\mu_C^2 + \lambda_{HC} v_H^2 &> 0 \end{aligned}$$

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

SM + Color Triplet + Singlet

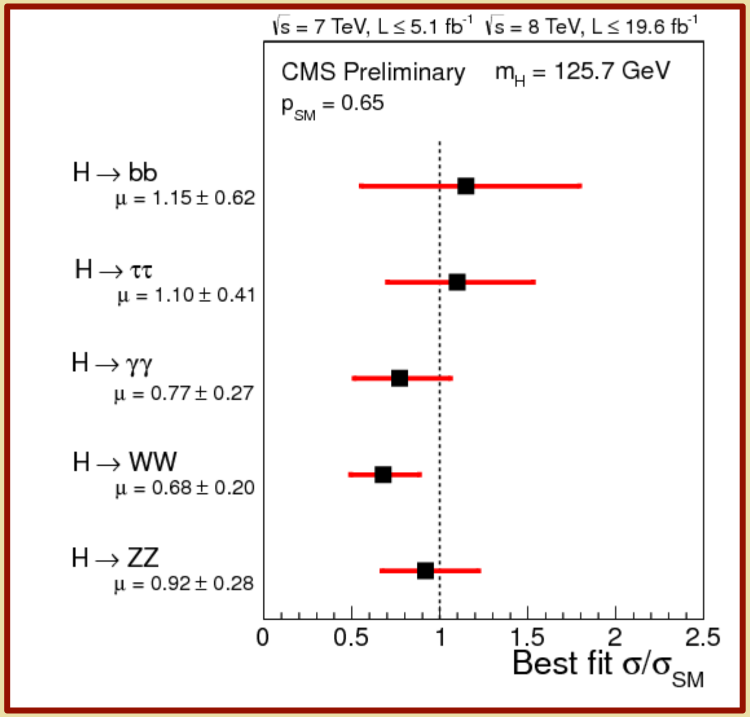
H. Patel, R-M, Wise 1303.1140 (2013)

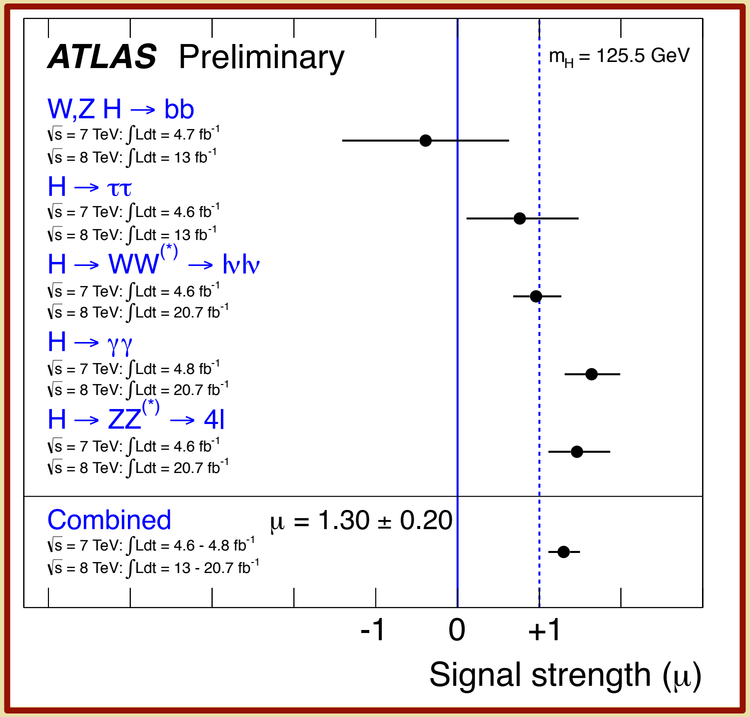
$$\begin{aligned}\Delta V = & -\frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{HC} (H^\dagger H)(C^\dagger C) \\ & + \frac{\lambda_{HS}}{2} (H^\dagger H) S^2 + \frac{\lambda_{CS}}{2} (C^\dagger C) S^2 \\ & + \frac{e_S}{3} S^3 + e_C C^\dagger C S + e_H H^\dagger H S \, .\end{aligned}$$

Heavier colored scalar

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

Higgs Decays: All Channels





Theoretical Issues

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

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

Ongoing research: approaches for carrying out tractable, GI computations

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

Origin of Gauge Dependence

Effective Action

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

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

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

Source term:

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

Not GI

Effective Potential

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

Nielsen Identities

Identity:

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

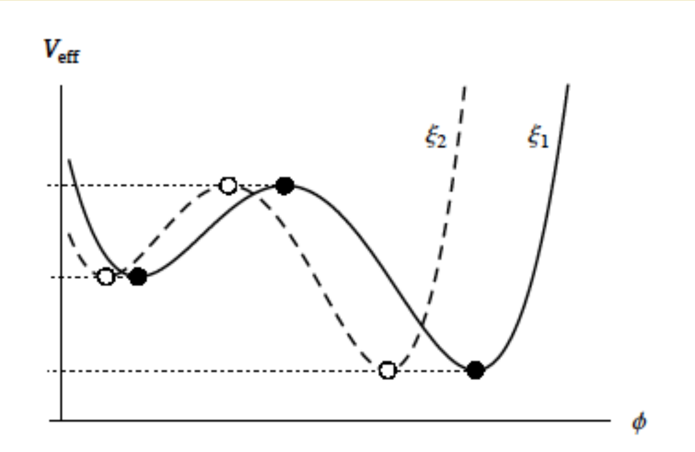
Extremal configurations:

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

Effective potential:

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

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



Baryon Number Preservation

"Washout factor"

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

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

$$\zeta \equiv \frac{\hat{E}_{\rm sph}}{T}\Bigg|_{T=T_C}$$

$$\boxed{\zeta = F(\varphi)}$$

Two qtys of interest:

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

Baryon Number Preservation: Pert Theory

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

$\zeta = F(\varphi)$

Conventional treatments

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

Gauge Dep

"Baryon number preservation criterion" (BNPC)

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

Baryon Number Preservation: Pert Theory

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

$\zeta = F(\varphi)$

Conventional treatments

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

Gauge Dep

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

"Baryon number preservation criterion" (BNPC)

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

Nielsen Identities: Application to T_C

Critical Temperature

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

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

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

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

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

Implement minimization order-by-order (defines ϕ_n)

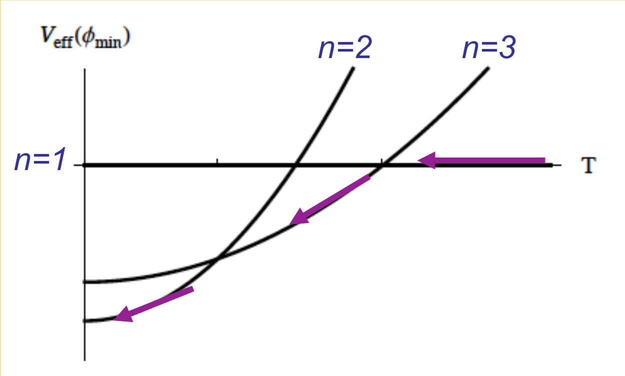
$$V_{\rm eff}[\phi_{\rm min}(T),\, T] = V_0(\phi_0) + \hbar V_1(\phi_0, T)$$

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

Obtaining a GI T_C

Patel & R-M '11

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



Track evolution of different minima with T using

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

Illustrative results in SM:

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

Full ϕ

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