

# *The Higgs Portal: Phase Transitions, Dark Matter & the LHC*



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## NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

<http://www.physics.wisc.edu/groups/particle-theory/>

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# *Outline*

1. *Portals & early Universe*
2. *Why the Higgs portal?*
3. *Why scalar portals ?*
4. *General considerations*
5. *Simplest examples*
6. *Color-breaking & restoration*
7. *Summary*

## References

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- M. Gonderinger, H. Lim , and M. J. Ramsey-Musolf, *Phys. Rev.* **D86**:043511 (2012) [[arXiv:1202.1316](#)].
- C. W. Wainwright, S. Profumo, and M. J. Ramsey-Musolf, *Phys. Rev.* **D86**:083537 (2012) [[arXiv:1204.5464/hep-ph](#)].
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- W. Chao, M. Gonderinger, M. J. Ramsey-Musolf, *Phys. Rev. D86* (2012) 113017 [[ArXiv:1210.0409/hep-ph](#)]
- H. H. Patel and M. J. Ramsey-Musolf, [[ArXiv:1212.5652/hep-ph](#)]
- H. H. Patel, M. J. Ramsey-Musolf, and M. B. Wise, [[ArXiv:1303.1140/hep-ph](#)]

## *I. Portals & Early Universe*



# *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***

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## *Higgs Portal: DM*

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

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

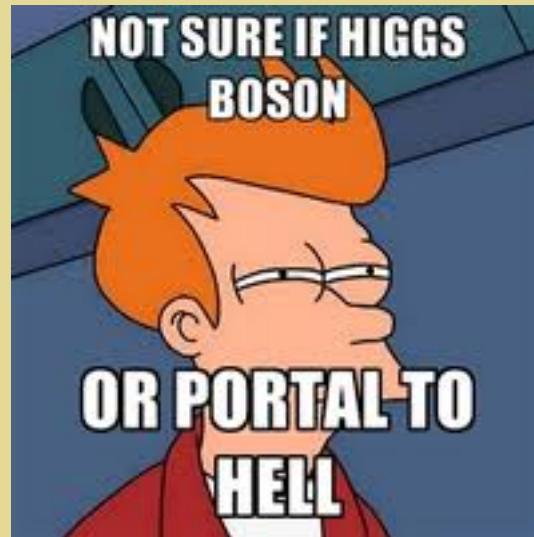
# *Higgs Portal: Phase Transitions*

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

+...

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

## *II. Why the Higgs Portal ?*



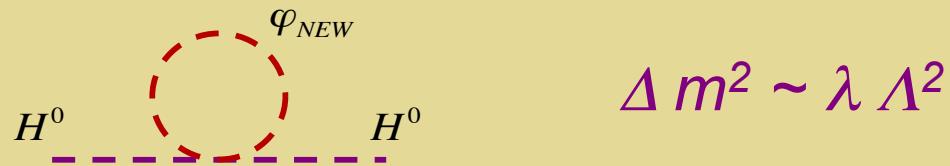
# ***Scalar Fields in Particle Physics***

*Scalar fields are a simple*

# **Scalar Fields in Particle Physics**

*Scalar fields are a simple*

*Scalar fields are theoretically problematic*

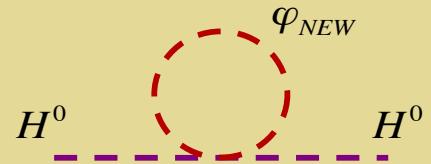


$$\Delta m^2 \sim \lambda \Lambda^2$$

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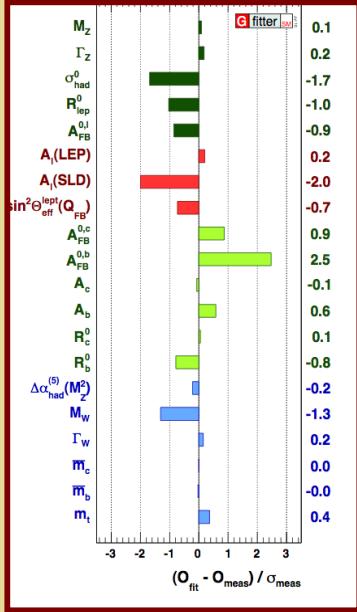
*Scalar fields are theoretically problematic*


$$\Delta m^2 \sim \lambda \Lambda^2$$

*Has a fundamental scalar finally been discovered ?*

*If so, is it telling us anything about  $\Lambda$  ?*

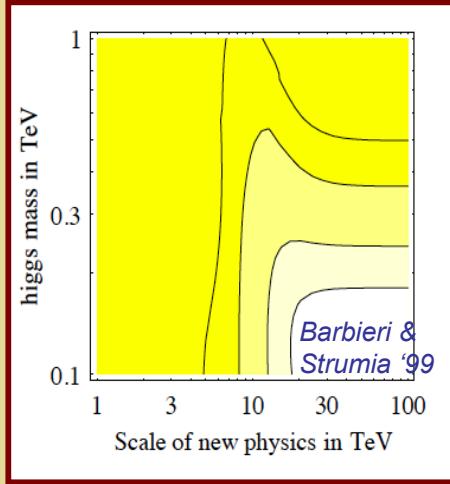
# What is the BSM Energy Scale $\Lambda$ ?



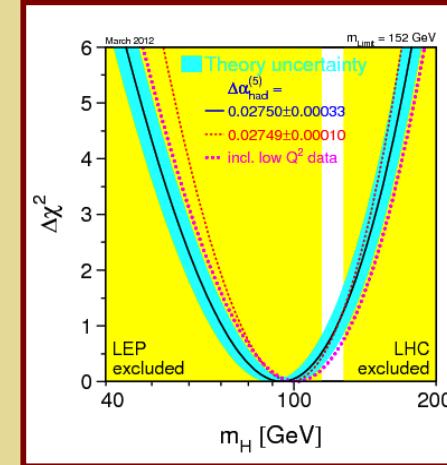
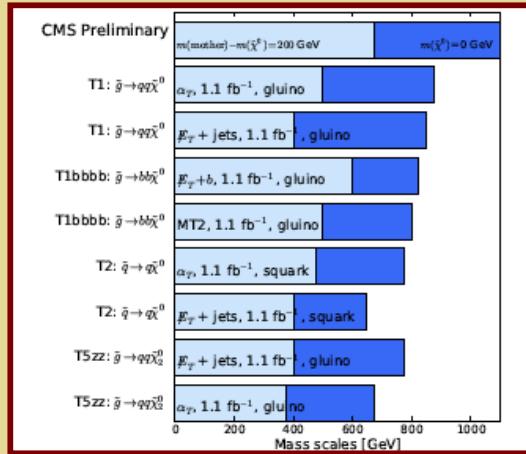
$\sim 10^{-3}$  agreement  
with EWPO

LHC: so far no sub-  
TeV BSM physics

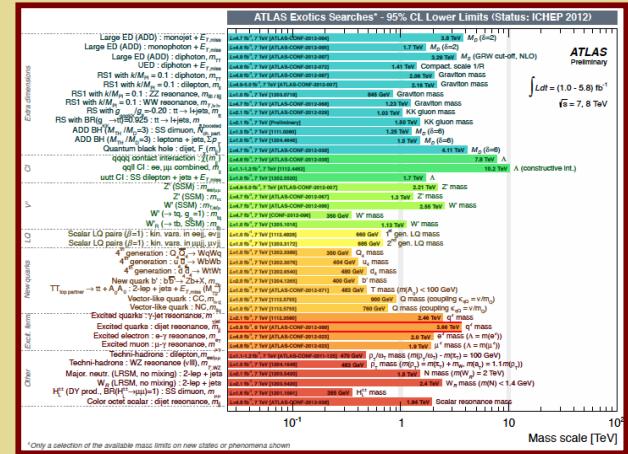
Hierarchy problem(s) ?



BSM:  $O_{BSM} = c / \Lambda^2 \rightarrow \Lambda \sim 10 \text{ TeV}$  generically



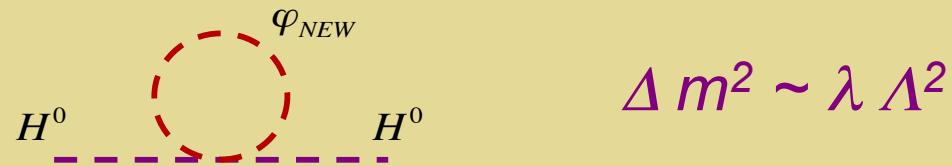
EWPO: data favor a “light”  
SM-like Higgs scalar



# **Scalar Fields in Particle Physics**

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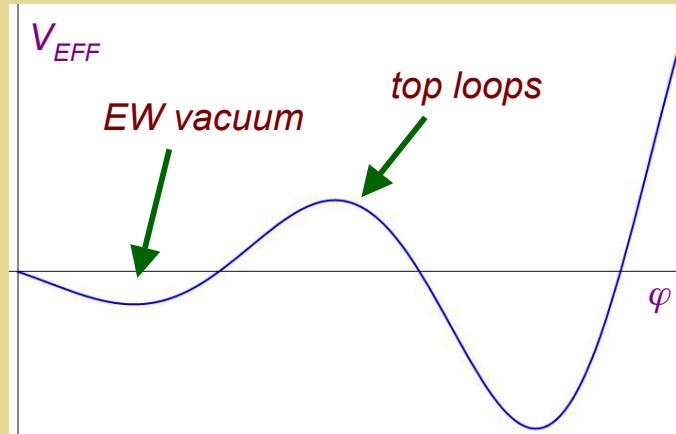
$$\Delta m^2 \sim \lambda \Lambda^2$$

*Must  $\Lambda_{BSM} \sim \text{TeV}$  to maintain a weak scale scalar ?*

*Perhaps new weak scale physics couples only to scalar sector: “Higgs portal”*

# Stable EW Vacuum ?

Preserving EW Min



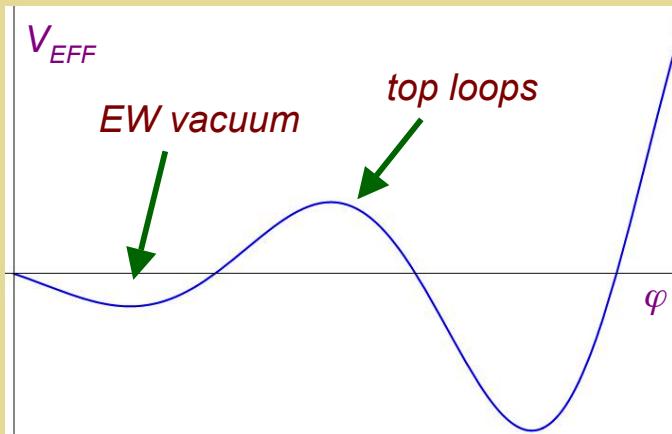
$$\beta_\lambda = \frac{1}{16\pi^2} \left( 4\lambda^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4 \right)$$

sets  $m_H$

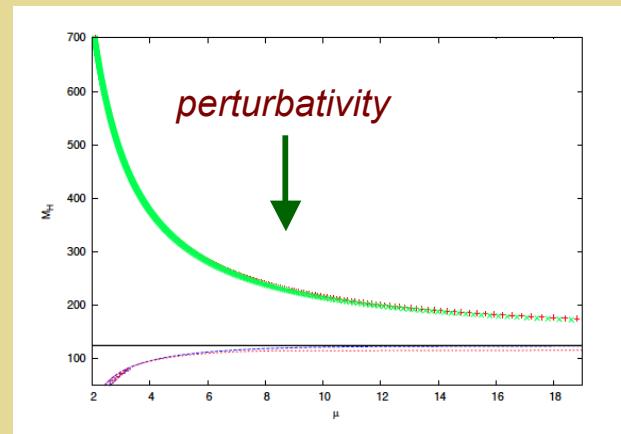
top loops

# Stable EW Vacuum ?

Preserving EW Min



“Funnel plot”



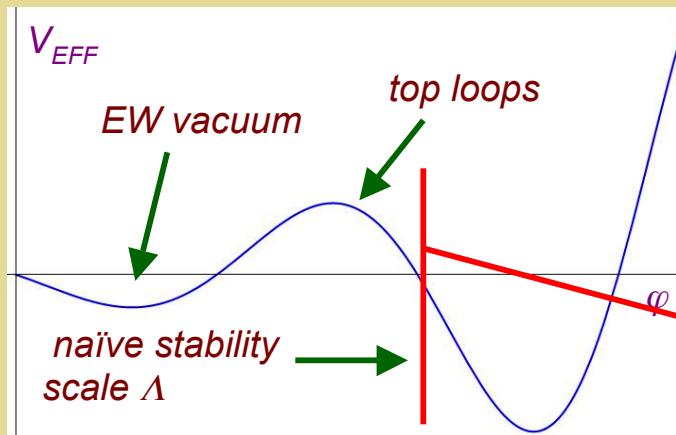
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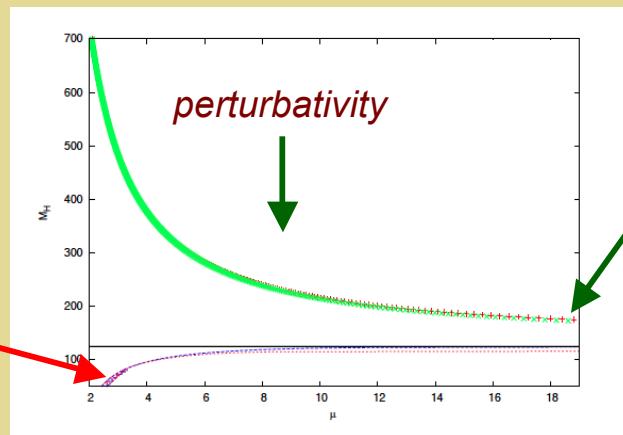
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SM stability  
& pert'vity

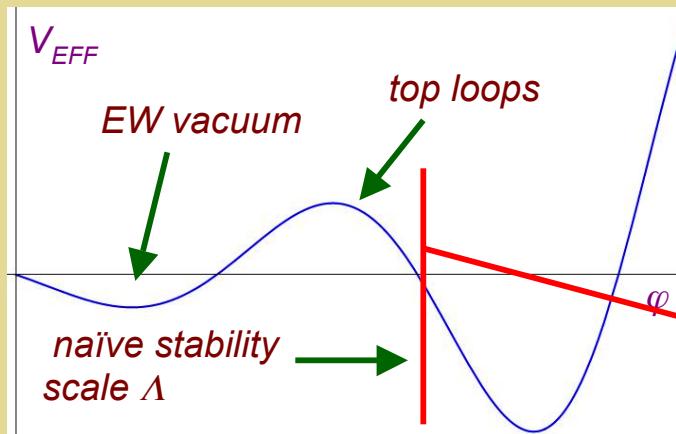
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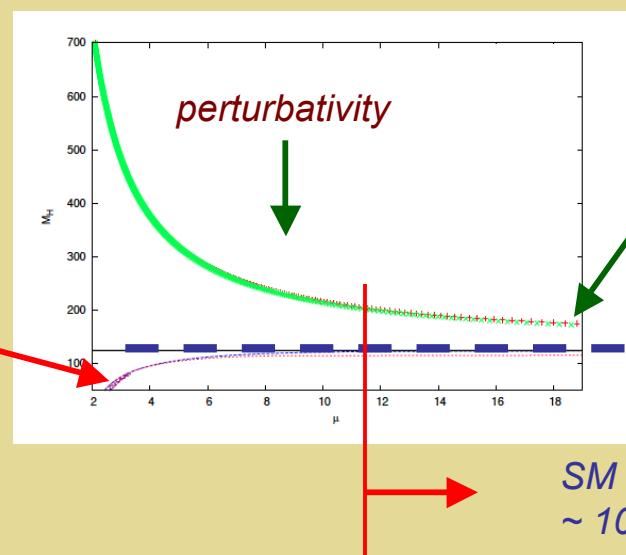
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# Stable EW Vacuum ?

Preserving EW Min



“Funnel plot”



SM stability & pert'vity

$m_H$

SM unstable above  
 $\sim 10^8 - 10^{13}$  TeV

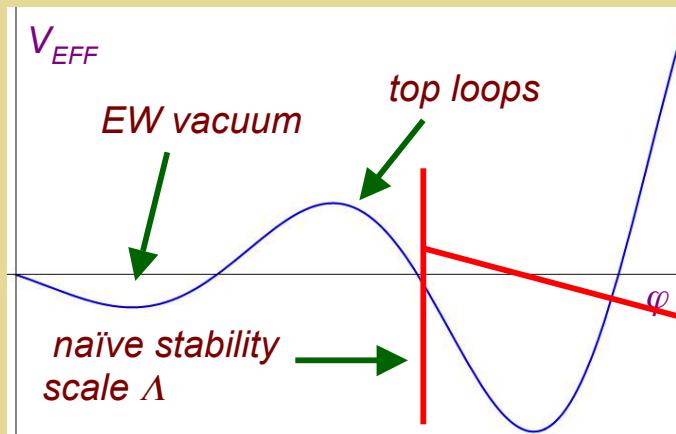
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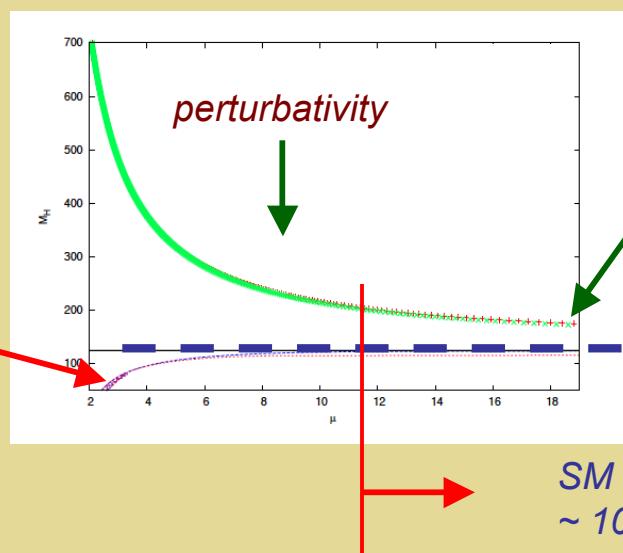
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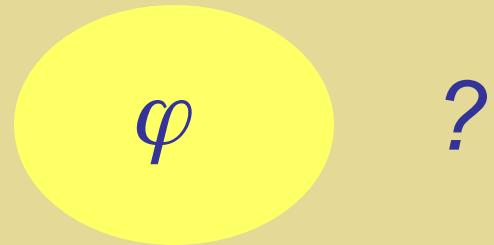
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sets  $m_H$

top loops

Higgs portal interactions  $\rightarrow$   
more robust stability

### *III. Why scalar portals ?*



# **Scalar Fields in Cosmology**

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

# **Scalar Fields in Cosmology**

<i>Problem</i>	<i>Theory</i>	<i>Exp't</i>
<ul style="list-style-type: none"><li>• <i>Inflation</i></li><li>• <i>Dark Energy</i></li><li>• <i>Dark Matter</i></li><li>• <i>Phase transitions</i></li></ul>		

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# Scalar Fields in Cosmology

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• <i>Phase transitions</i>	✓	?

- Could experimental discovery of a fundamental scalar 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
• <i>Inflation</i>	✓	?
• <i>Dark Energy</i>	✓	?
• <i>Dark Matter</i>	✓	?
• <i>Phase transitions</i>	✓	?



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

# Scalar Fields in Cosmology

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

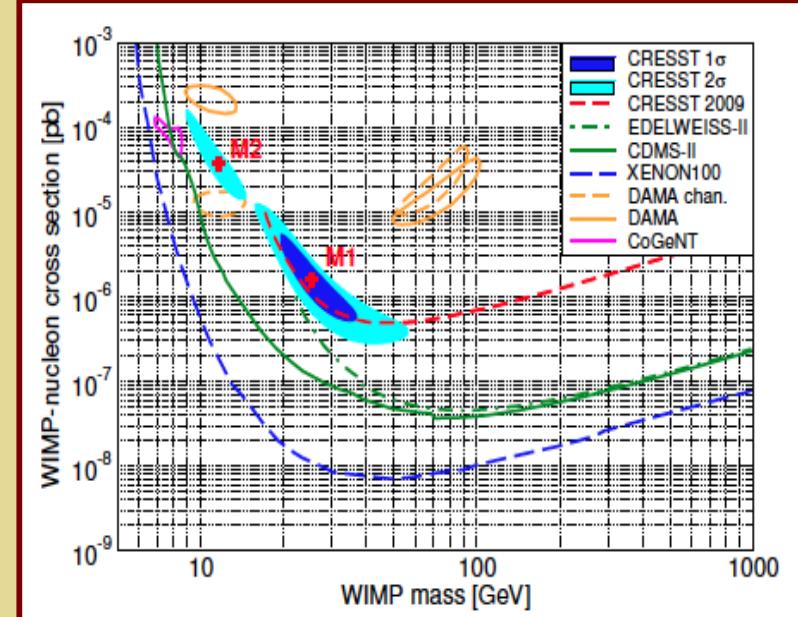
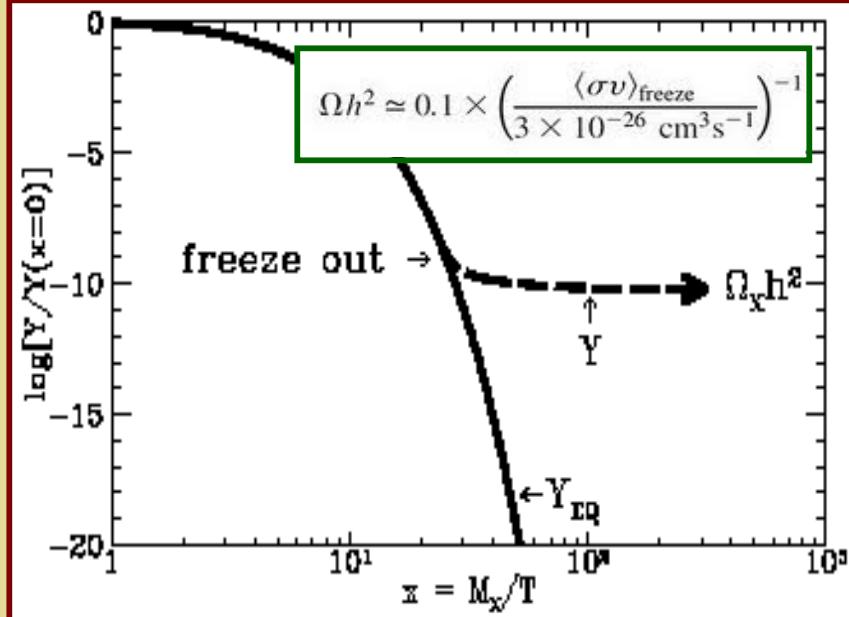


*What was the pattern of EWSB ?*

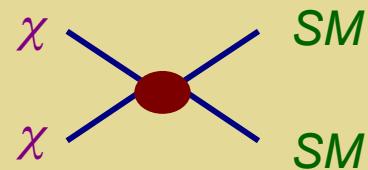
- Single step? Multi-step?
- Symmetry breaking & restoration ?

## *IV. General Considerations*

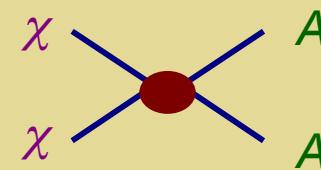
# Thermal DM: $\Omega_{CDM}$ & $\sigma_{SI}$



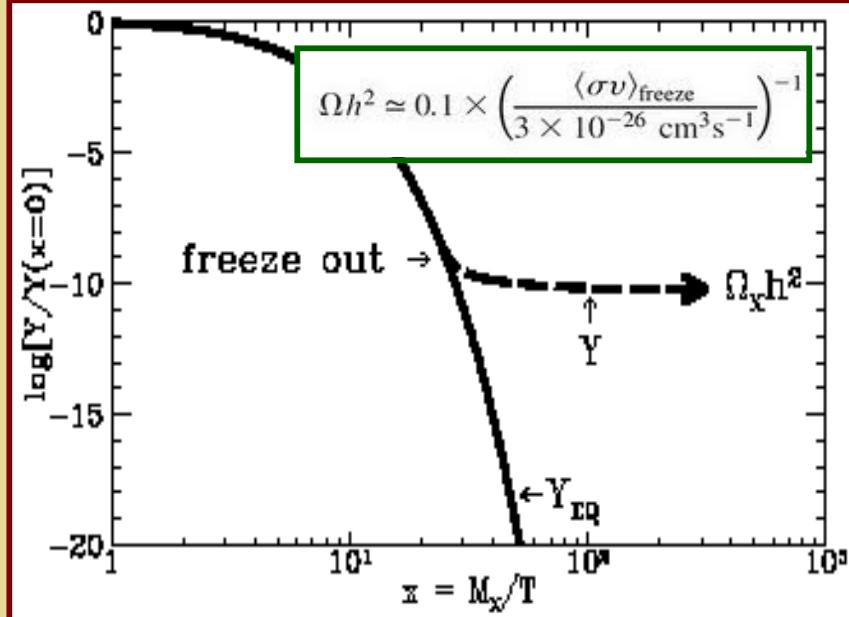
Thermal DM: WIMP



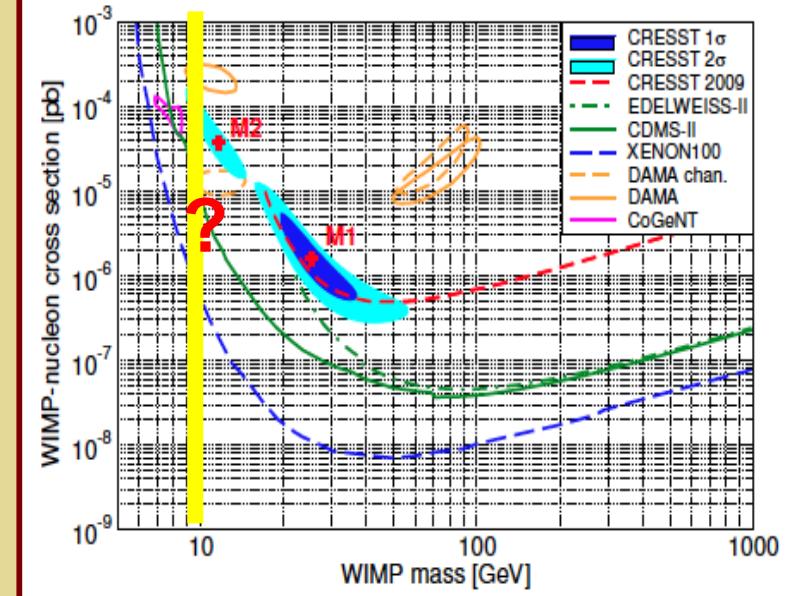
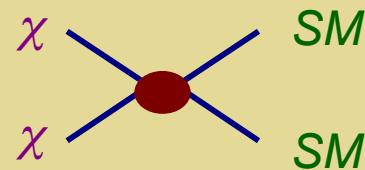
Direct detection: Spin-indep  
DM-nucleus scattering



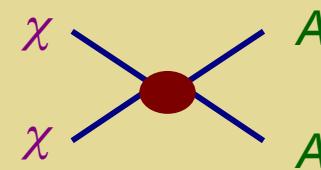
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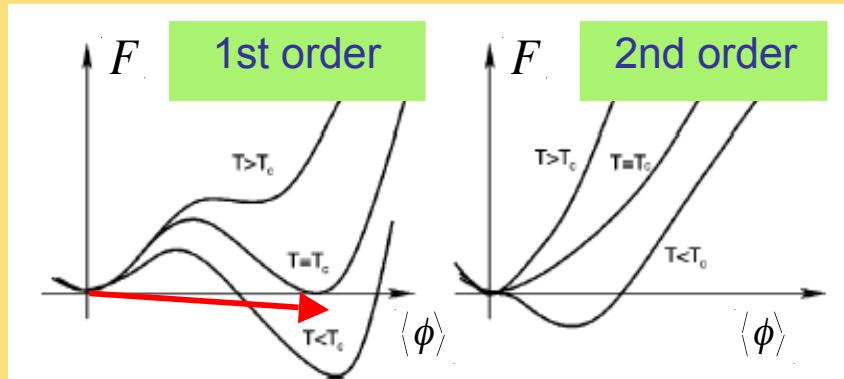
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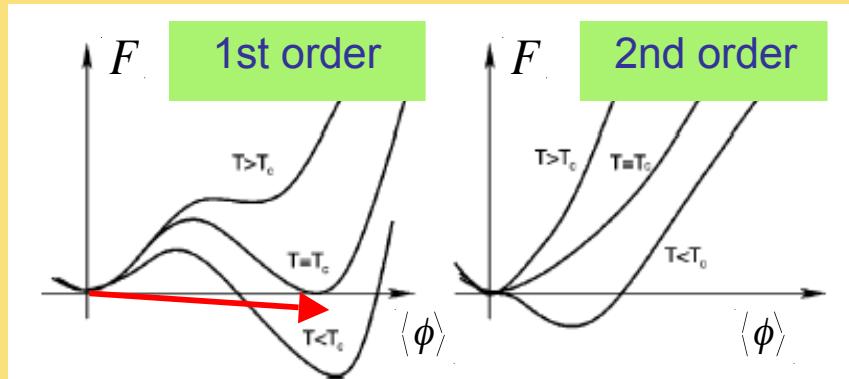
# *EW Phase Transition: New Scalars*



*Increasing  $m_h$*   $\longrightarrow$

$\longleftarrow$  *New scalars*

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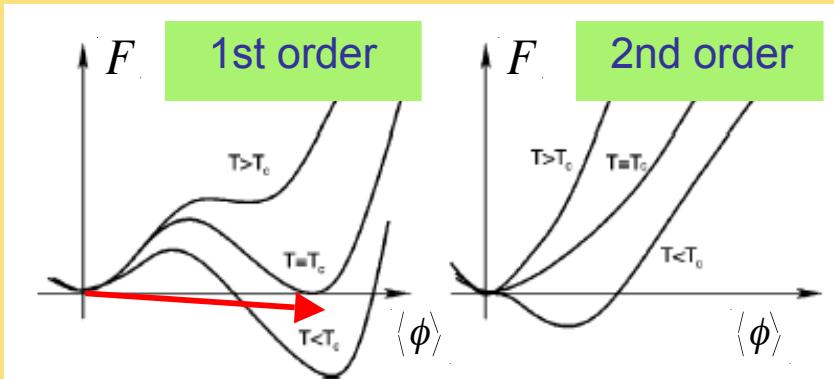
“Strong” 1<sup>st</sup> order EWPT

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$\longleftarrow$  New scalars

Baryogenesis  
Gravity Waves  
Scalar DM  
LHC Searches

# EW Phase Transition: New Scalars

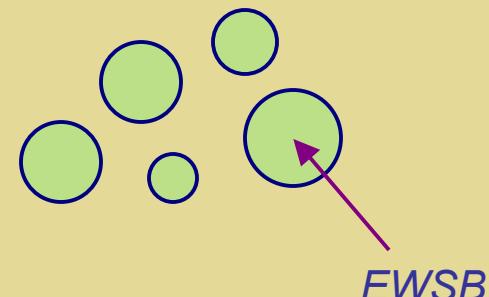


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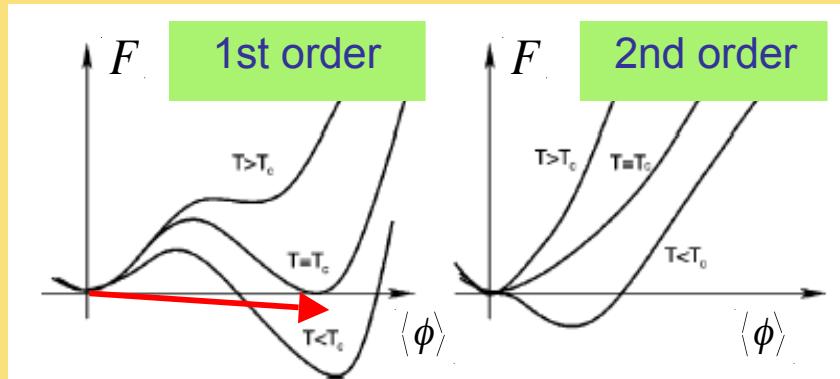
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Bubble nucleation



# EW Phase Transition: New Scalars

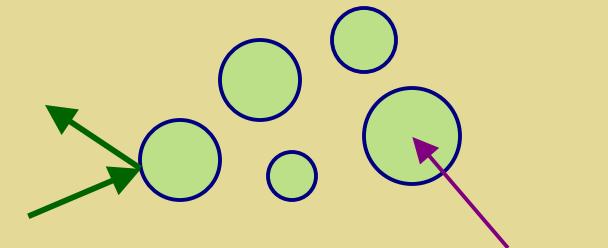


*Increasing  $m_h$*  →  
← *New scalars*

*Baryogenesis*  
*Gravity Waves*  
*Scalar DM*  
*LHC Searches*

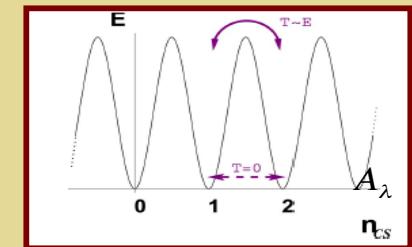
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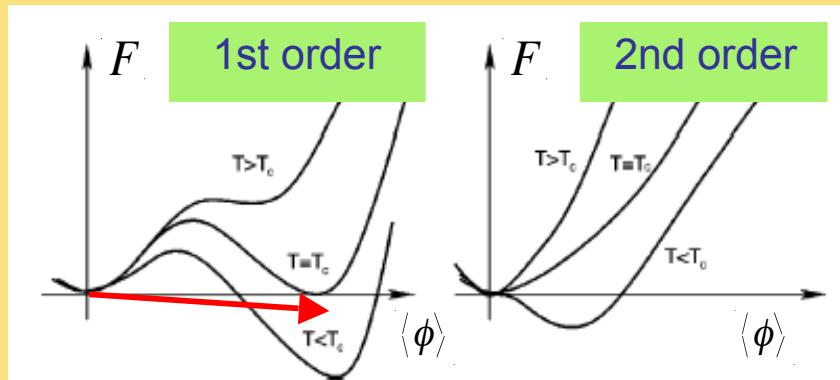


$Y_B$  : CPV & EW sphalerons

EWSB



# EW Phase Transition: New Scalars

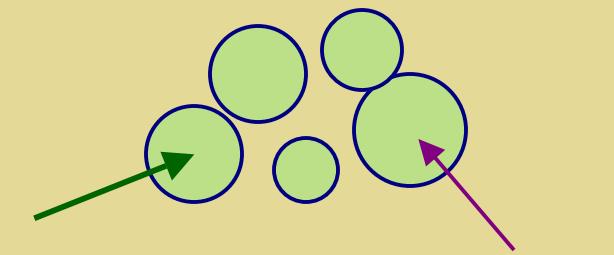


*Increasing  $m_h$*  →  
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*Scalar DM*  
*LHC Searches*

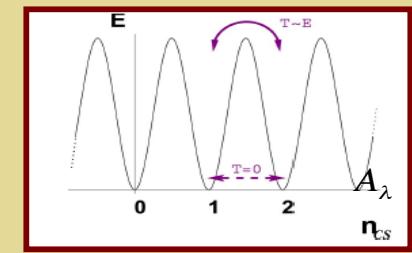
“Strong” **1<sup>st</sup> order EWPT**

*Bubble nucleation*

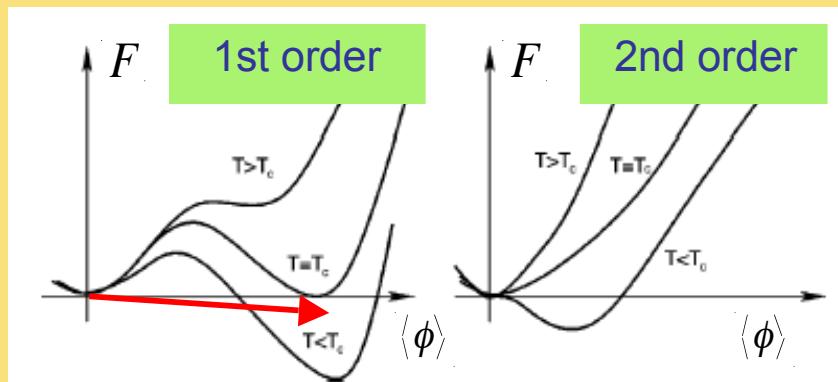


$Y_B$  : diffuses  
into interiors

EWSB



# EW Phase Transition: New Scalars



Increasing  $m_h$  →  
← New scalars

Baryogenesis  
Gravity Waves  
Scalar DM  
LHC Searches

"Strong"  $\downarrow$   $1^{\text{st}}$  order EWPT  $\downarrow$   
Preserve  $Y_B^{\text{initial}}$  Bubble nucleation

Quench EW sph  
 $Y_B$  : diffuses into interiors  
EWSB

$T_C, E_{\text{sph}}, S_{\text{tunnel}} \longleftrightarrow F(\phi)$

## *V. Simple examples*

# *Higgs Portal: Simple Scalar Extensions*

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet</i>	1	✓	✗
<i>Real singlet</i>	1	✗	✓
<i>Complex Singlet</i>	2	✓	✓
<i>Real Triplet</i>	3	✓	✓

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

# *Higgs Portal: Simple Scalar Extensions*

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
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<i>Real Triplet</i>	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)*

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

*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

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

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

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

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

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

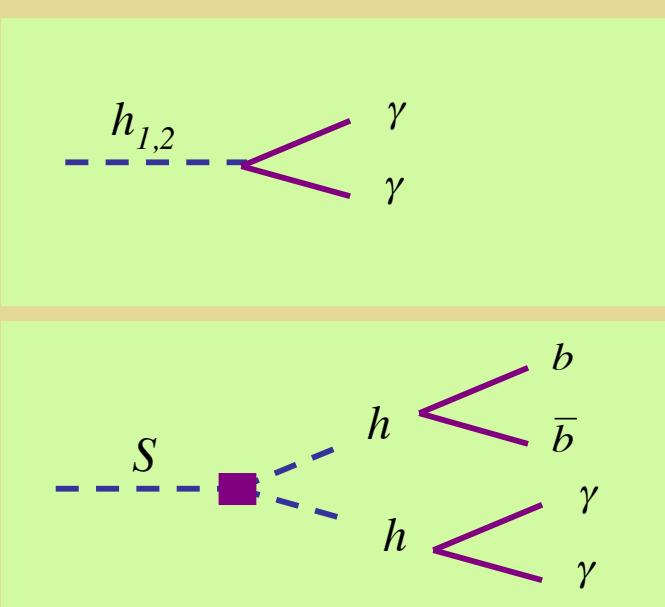
$x_0 = \langle S \rangle$

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

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

# The Simplest Extension, Cont'd

## Mass matrix



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

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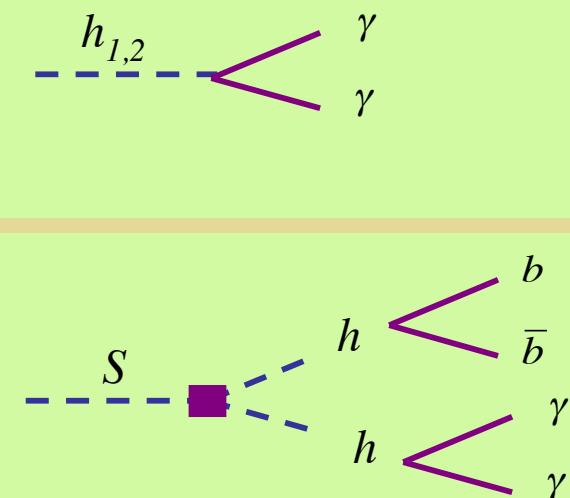
$$\tan \theta = \frac{y}{1 + \sqrt{1 + y^2}}, \quad y \equiv \frac{\mu_{hs}^2}{\mu_h^2 - \mu_s^2}$$

New topologies

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

# The Simplest Extension, Cont'd

## Mass matrix



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

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

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

$x_0 = \langle S \rangle$

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

*Stable S (dark matter)*

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

# *The Simplest Extension*

*DM Scenario*

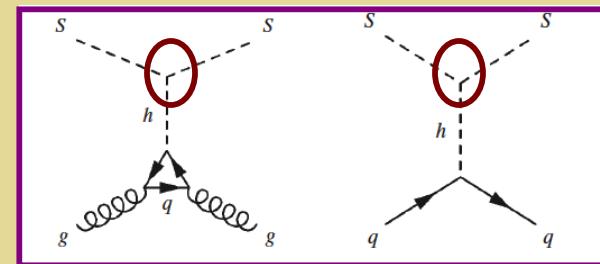
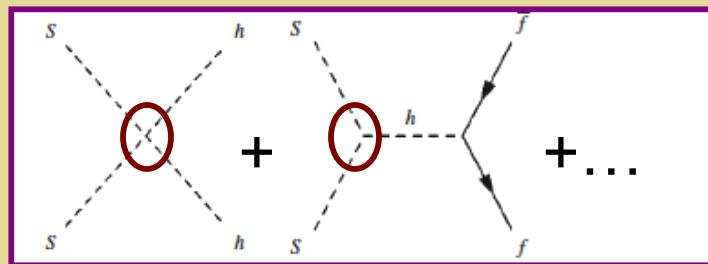
$$V_{\text{HS}} = \dots + \frac{a_2}{2} \left( H^\dagger H \right) S^2$$

# *The Simplest Extension*

*DM Scenario*

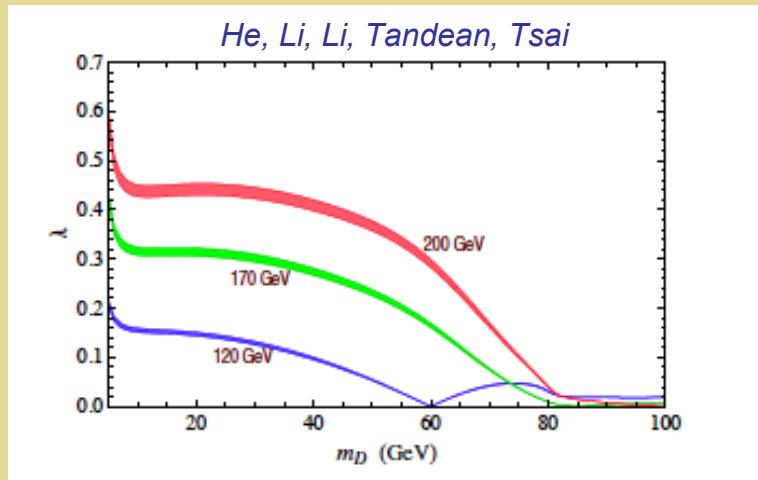
$$V_{\text{HS}} = + \frac{a_2}{2} \left( H^\dagger H \right) S^2$$

$\Omega_{\text{DM}}$  &  $\sigma_{\text{SI}}$

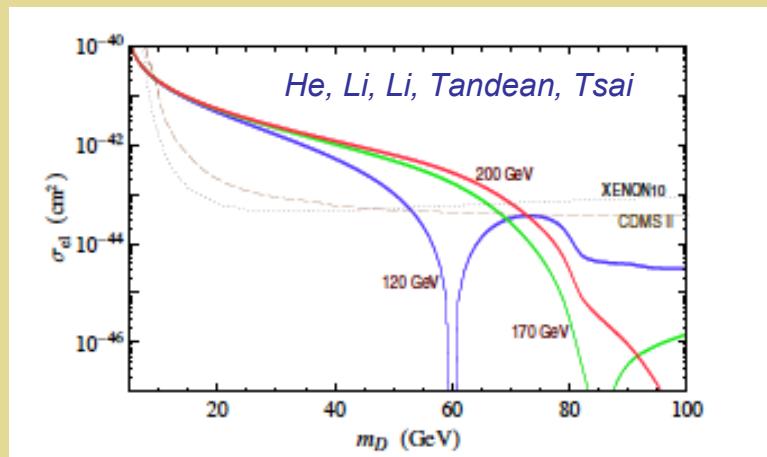


# DM Phenomenology

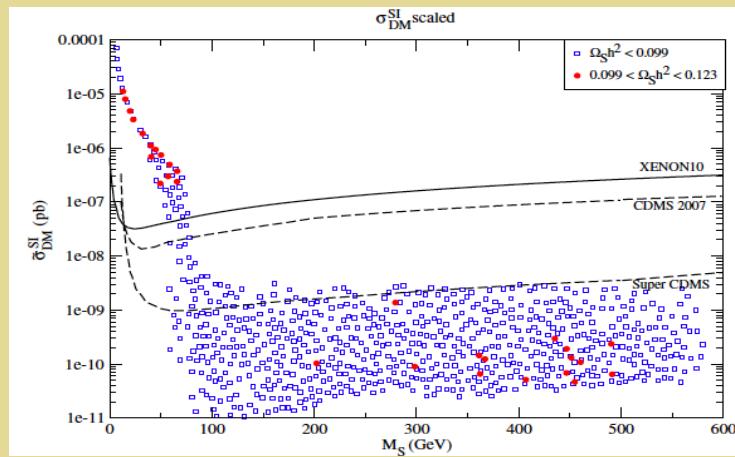
## Relic Density



## Direct Detection

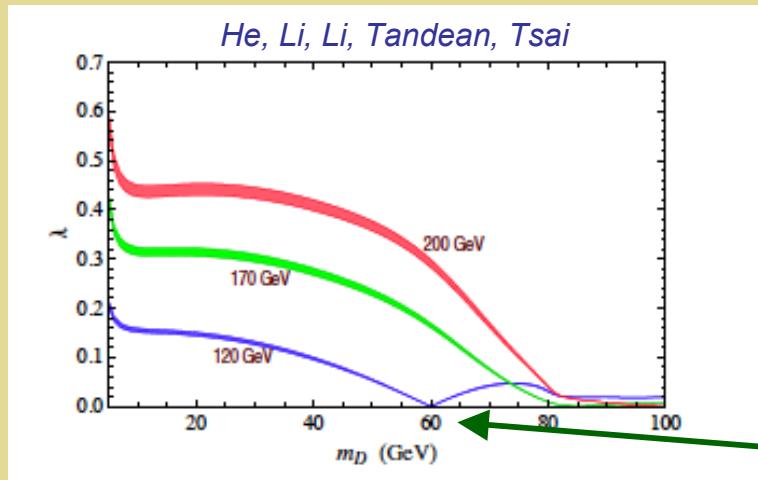


Barger, Langacker, McCaskey,  
R-M, Shaugnessy

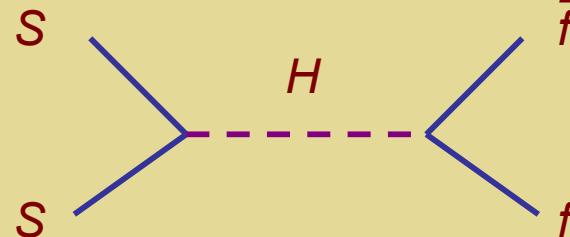


# DM Phenomenology

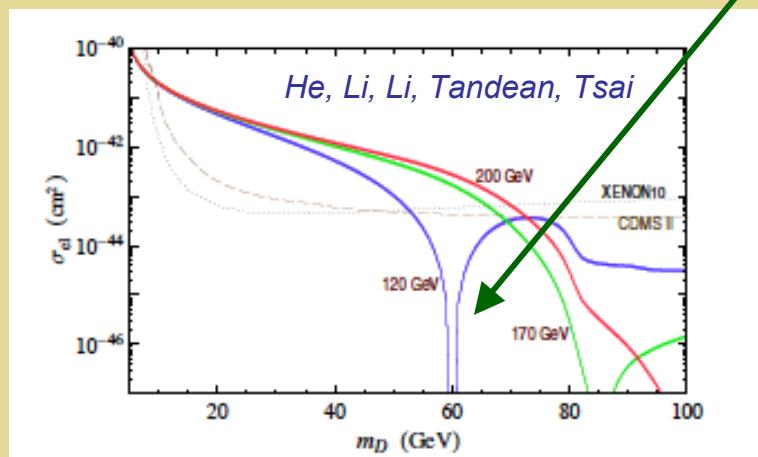
## Relic Density



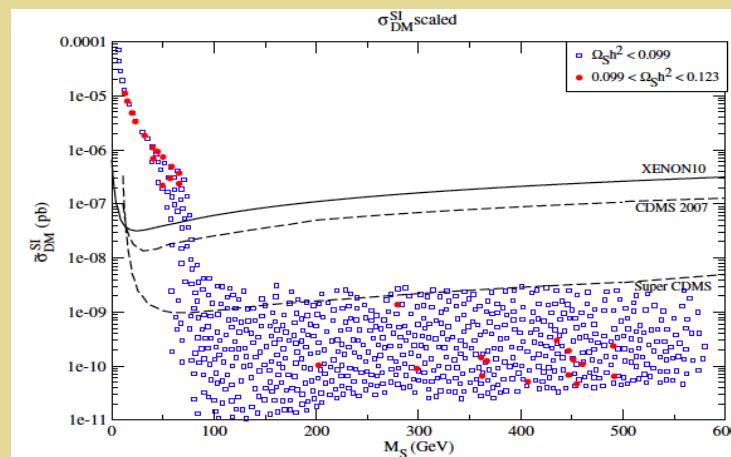
Higgs pole



## Direct Detection

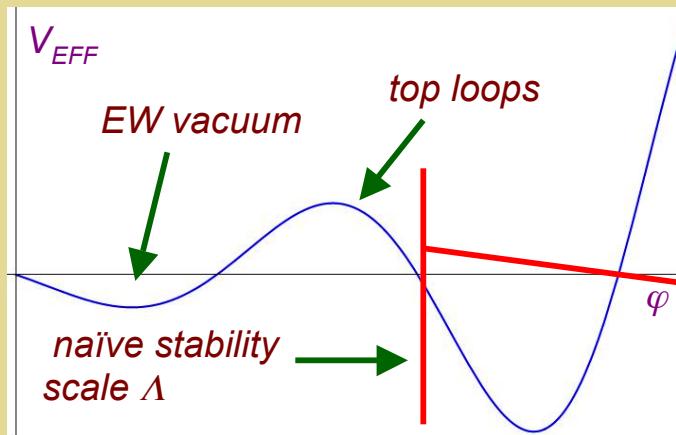


Barger, Langacker, McCaskey,  
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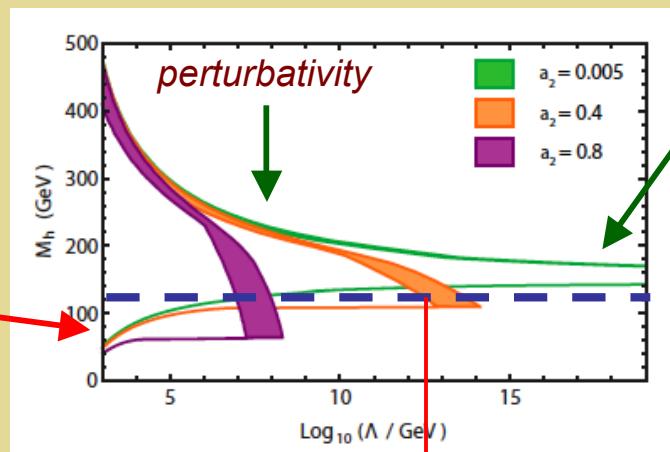


# New Scalars EW Vacuum Stability

Preserving EW Min



"Funnel plot"



SM stability  
& pert'vity

$m_H$

SM + singlet: stable  
but non-pertur'tive

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

DM-H coupling

top loops

# LHC & Higgs Phenomenology

*LHC discovery potential*

## Signal Reduction Factor

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

Production                      Decay

$V_{1j} < 1$ : mixed states  $h_j$       New decays:  $h_2 \rightarrow h_1 h_1$

*Dark matter: no mixing  $\rightarrow$  states are  $h, S$*

*New decays  $h \rightarrow SS$  (invisible!) possible*

# LHC & Higgs Phenomenology

*LHC discovery potential*

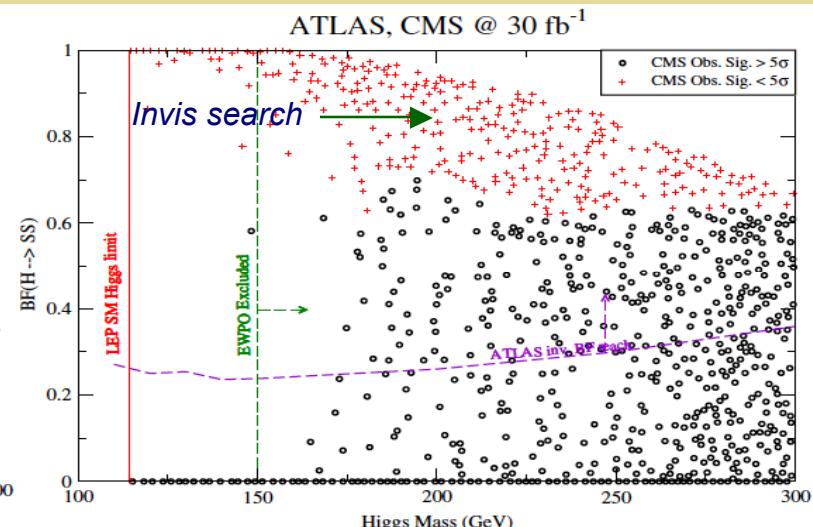
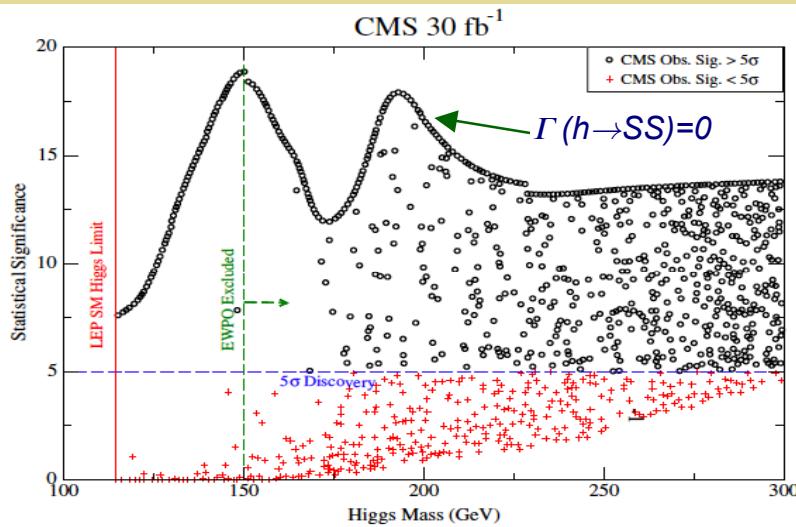
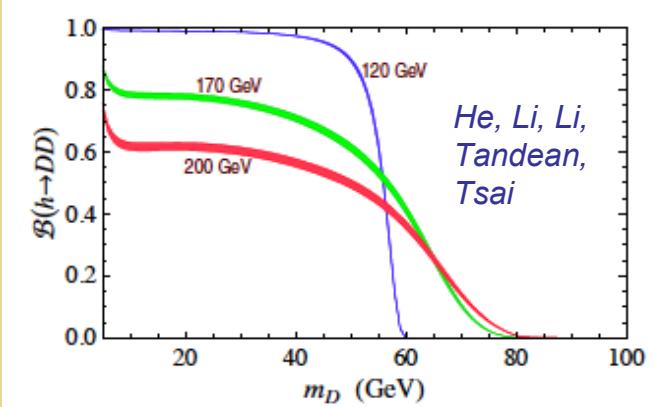
## Signal Reduction Factor

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

Production

Decay

*Invisible decays*



# LHC & Higgs Phenomenology

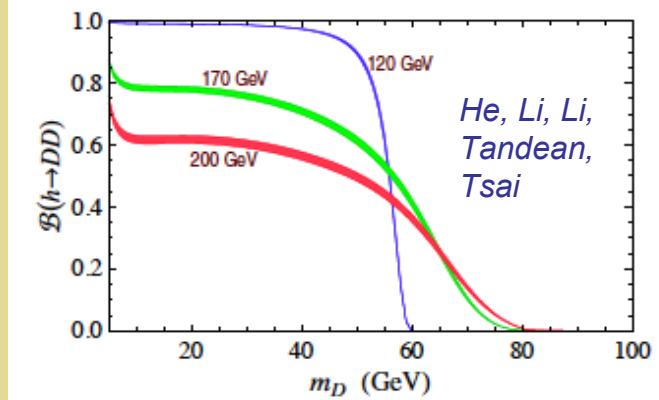
*LHC discovery potential*

## *Signal Reduction Factor*

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

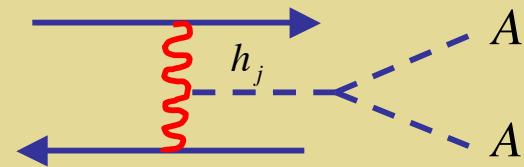
*Production*      *Decay*

*Invisible decays*



## *Dijet azimuthal distribution*

Jets +  $E_T$



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

# LHC & Higgs Phenomenology

*LHC discovery potential*

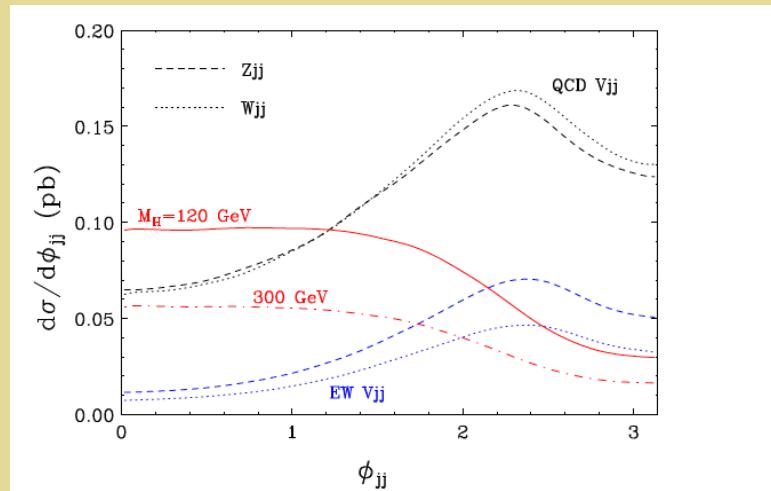
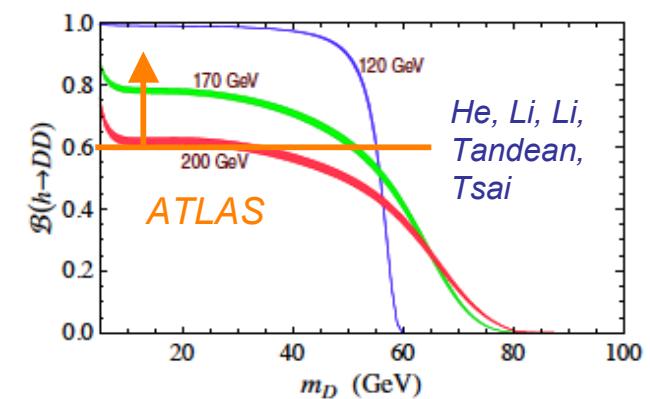
## Signal Reduction Factor

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

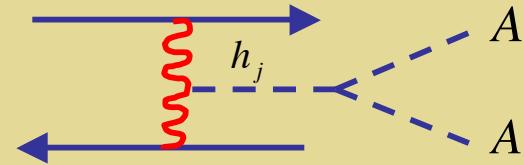
Production

Decay

*Invisible decays*

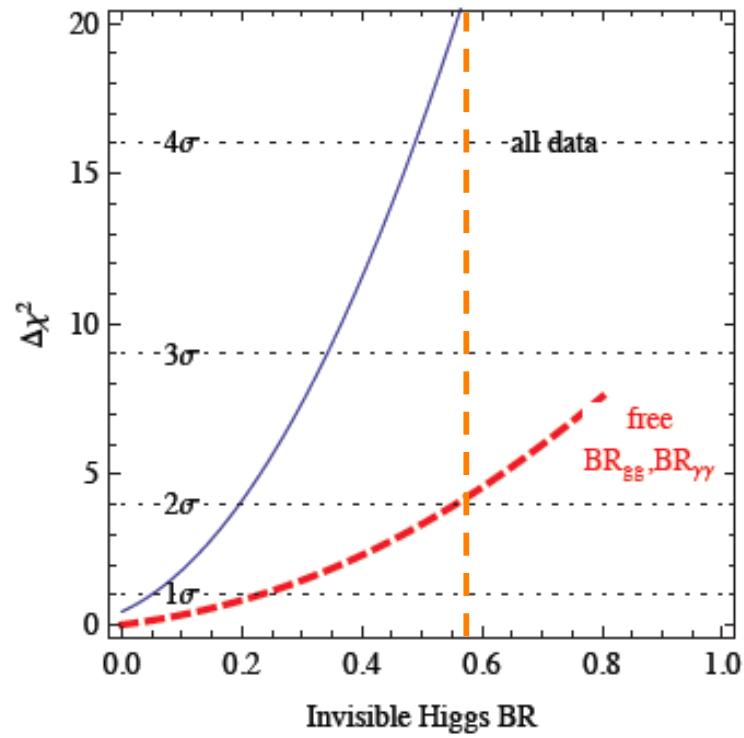
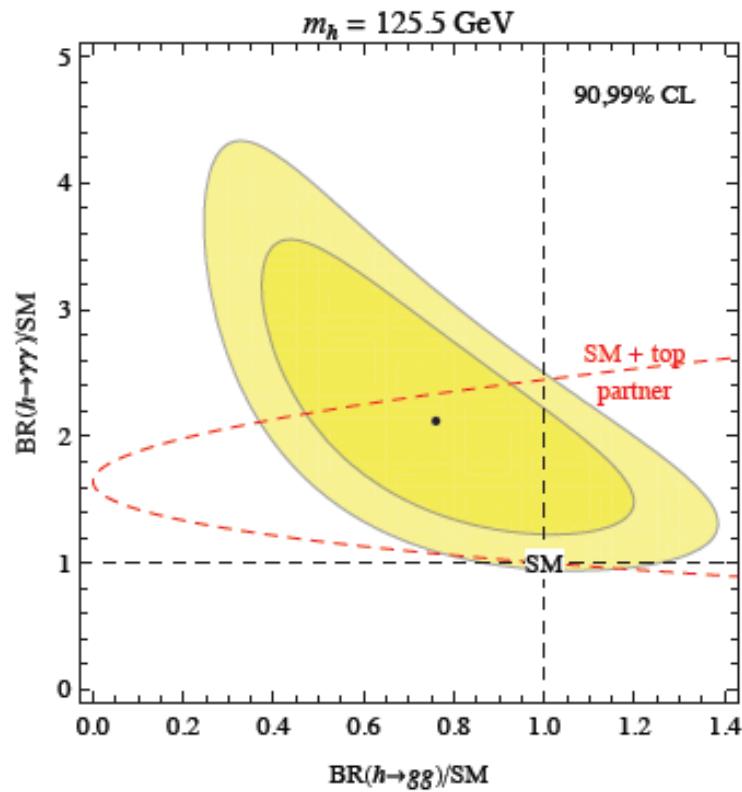


## Dijet azimuthal distribution



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

# LHC & Higgs Phenomenology

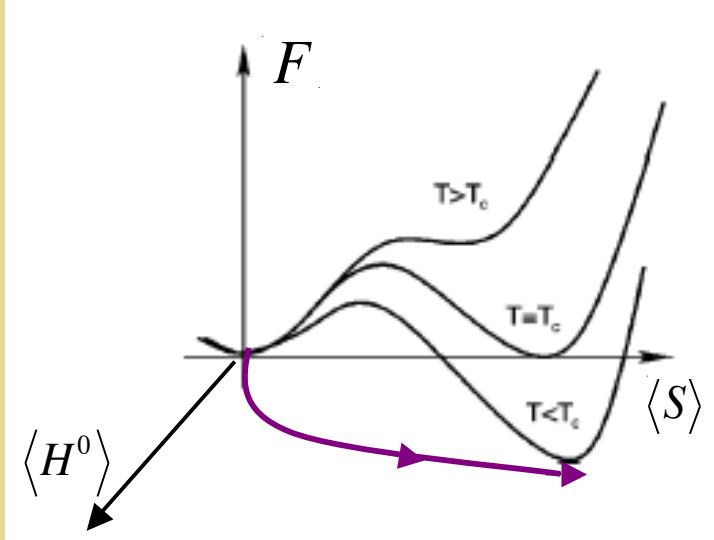


Giardino et al:  
arXiv 1207:1347

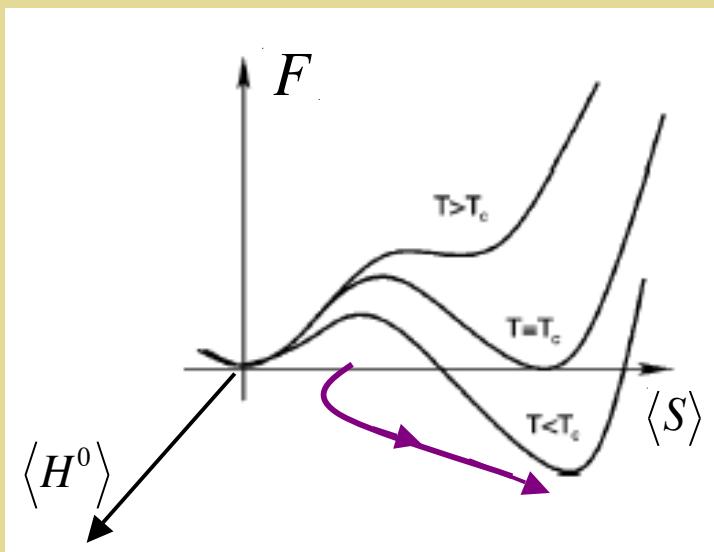
## *Real Singlet: EWPT*

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

# New Patterns of EWSB



Multiple fields & new interactions: novel patterns of symmetry breaking, lower  $T_c$ , greater super-cooling, “stronger 1<sup>st</sup> order EWPT”



## *Real Singlet: EWPT*

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

*Raise barrier*

*Lower  $T_c$*

# *Real Singlet: EWPT*

*Low energy phenomenology*

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

*Raise barrier*

*Mixing*

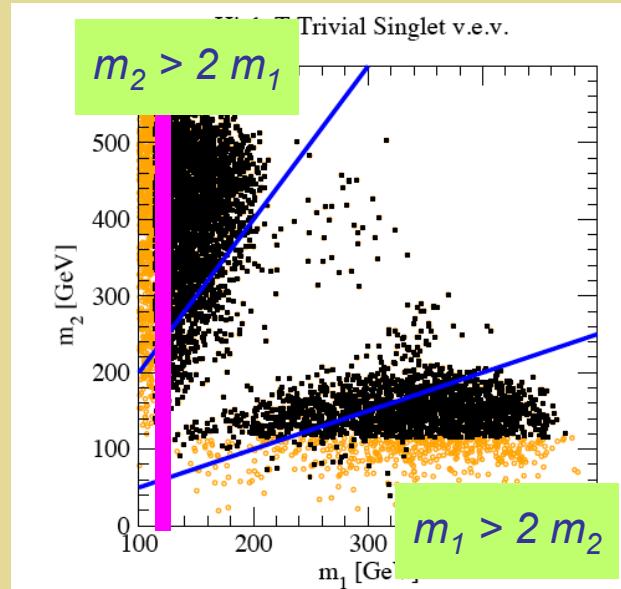
*Lower  $T_c$*

*Modified BRs*

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

# ***EWPT & LHC Phenomenology***

## ***Signatures***

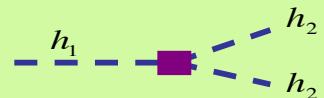
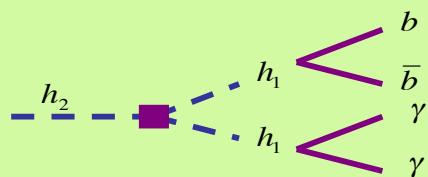


*Scan: EWPT-viable  
model parameters*

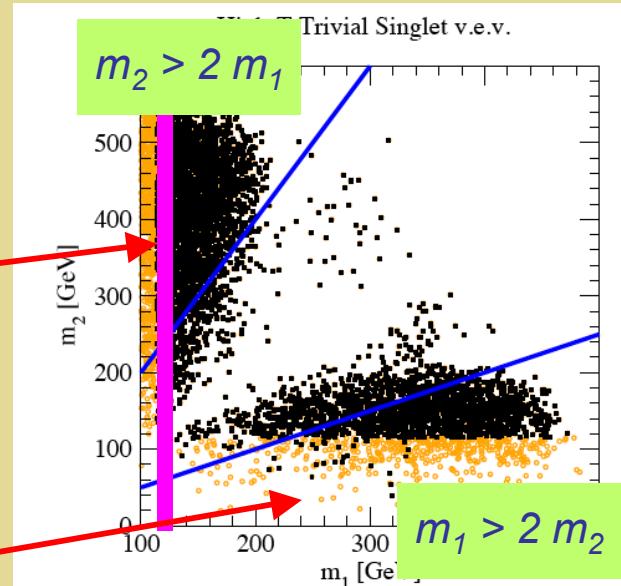
*Light: all models  
Black: LEP allowed*

# *EWPT & LHC Phenomenology*

## *Signatures*



*LHC: reduced  
 $BR(h \rightarrow SM)$*

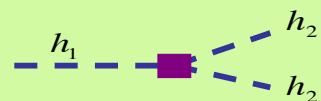
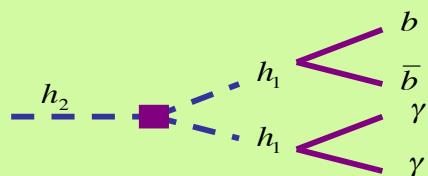


*Scan: EWPT-viable  
model parameters*

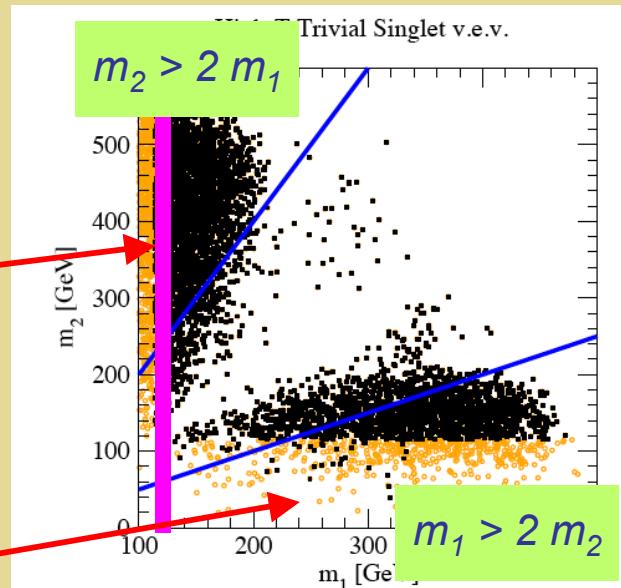
*Light: all models  
Black: LEP allowed*

# EWPT & LHC Phenomenology

## Signatures



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



Scan: EWPT-viable  
model parameters

Light: all models  
Black: LEP allowed

## Signal Reduction Factor

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

*Production*                           *Decay*

# *Higgs Portal: Simple Scalar Extensions*

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet</i>	1	✓	✗
<i>Real singlet</i>	1	✗	✓
<i>Complex Singlet</i>	2	✓	✓
<i>Real Triplet</i>	3	✓	✓

*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  $U(1)$        $\langle S \rangle \neq 0$

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



Controls  $\Omega_{CDM}$ ,  $T_c$ , & H-S mixing

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



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  $\sigma$
- Reduce BR ( $h_j \rightarrow \text{SM}$ )
- Observation of BR (invis)
- Possible obs of  $\sigma^{SI}$

# *Higgs Portal: Simple Scalar Extensions*

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet</i>	1	✓	✗
<i>Real singlet</i>	1	✗	✓
<i>Complex Singlet</i>	2	✓	✓
<i>Real Triplet</i>	3	✓	✓

*Simplest non-trivial EW multiplet*

# *Real Triplet*

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

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

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

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

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

# *Real Triplet*

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

*Small:  $\rho$ -param*

# *Real Triplet: DM*

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

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79: 055024 (2009); 0811.3957 [hep-ph]

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

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*DM & EWPT:*  $a_1 = 0 \text{ & } \langle \Sigma^0 \rangle = 0$

*Small:  $\rho$ -param*

# Real Triplet: $DM$

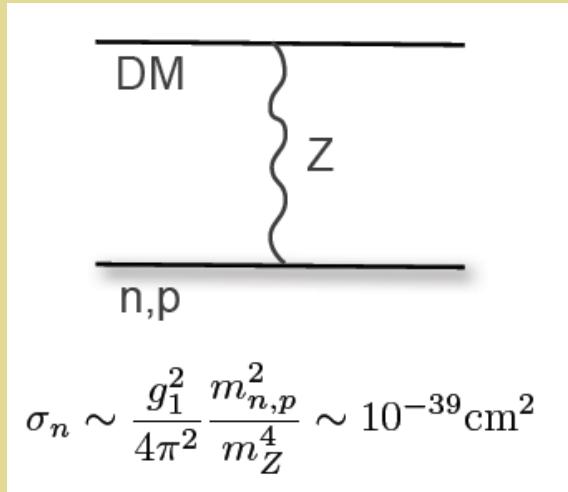
$$\Sigma^0, \Sigma^+, \Sigma^-$$

$$\sim (1, 3, 0)$$

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

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

New feature: gauge interactions & direct detection



$$g_{\chi\chi Z} \propto 2 I_3 - 4 Q \sin^2 \theta_W$$

$$Y = 2 (Q - I_3)$$



Want  $Y = 0$

# Real Triplet: DM

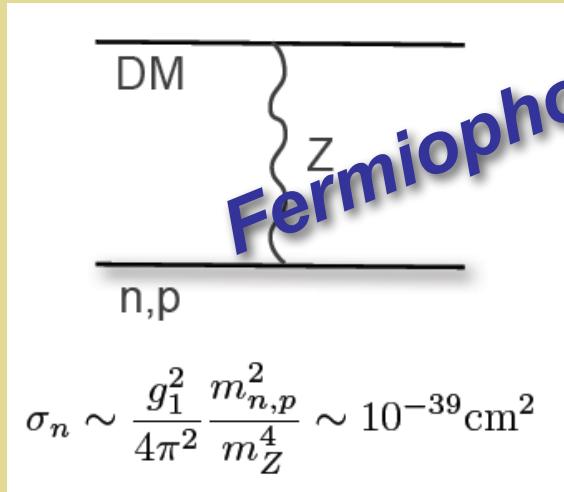
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Want  $Y = 0$

# Real Triplet: EWPT

$$\Sigma^0, \Sigma^+, \Sigma^-$$

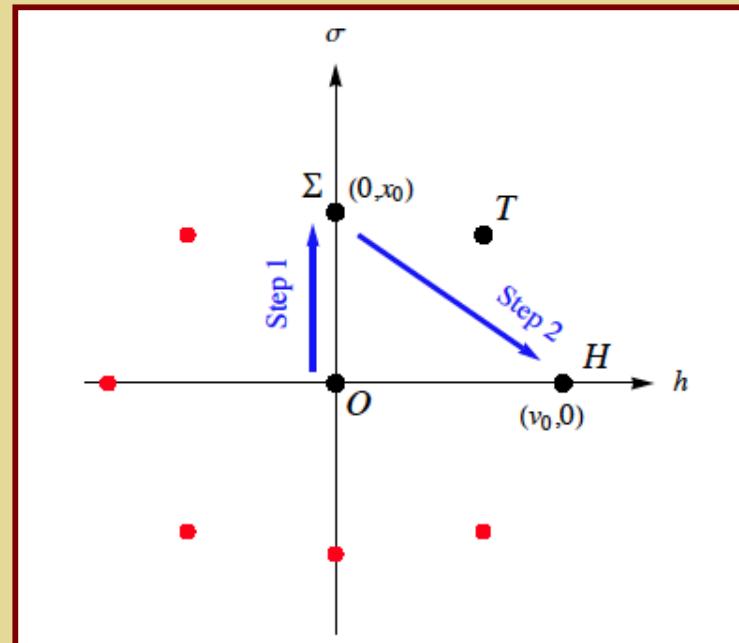
$$\sim (1, 3, 0)$$

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

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

## Two-step EWSB

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



# Real Triplet: EWPT

$$\Sigma^0, \Sigma^+, \Sigma^-$$

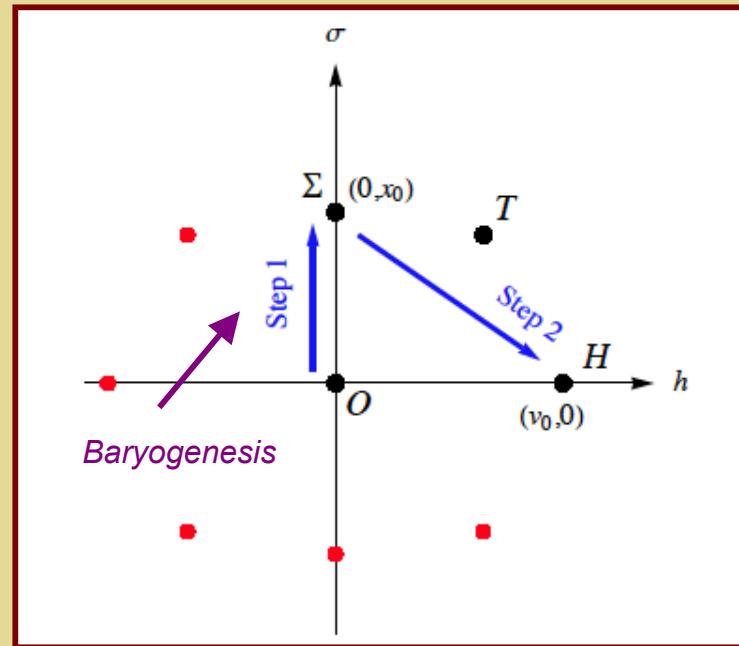
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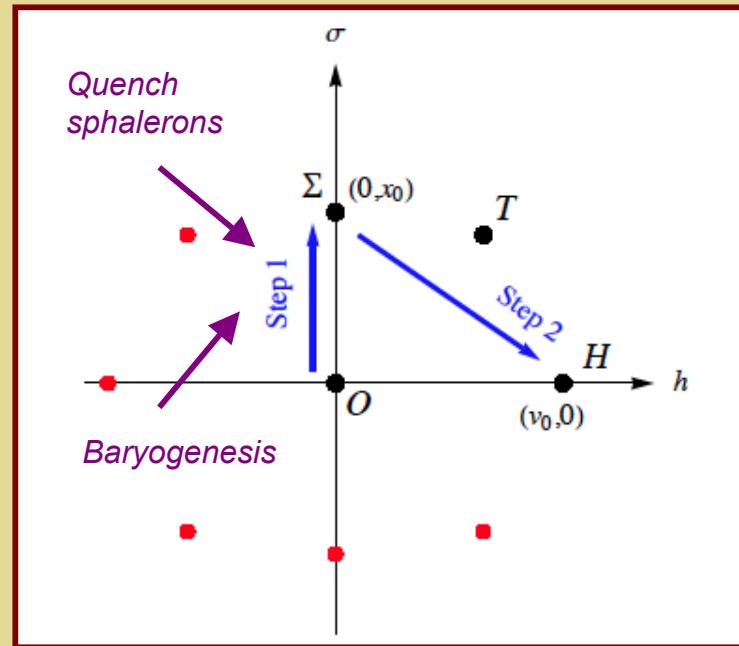
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# Real Triplet: EWPT

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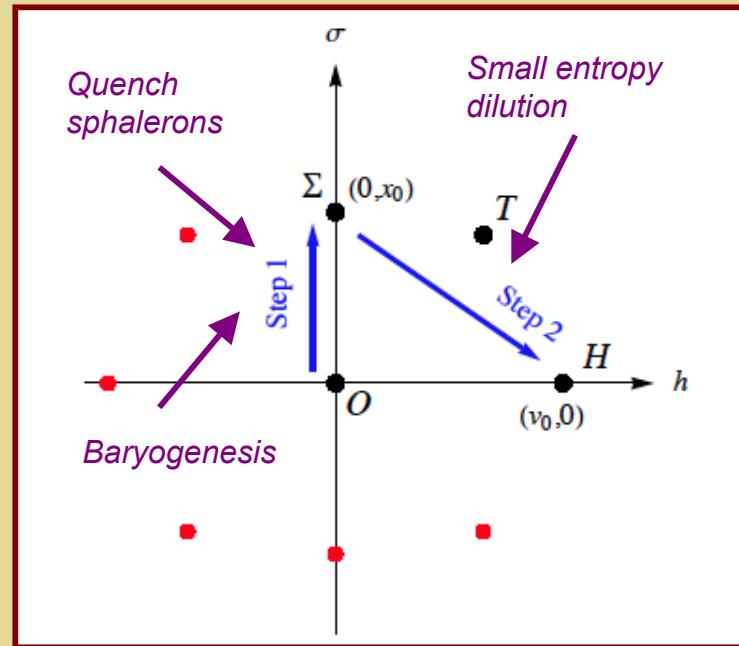
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## Two-step EWSB

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# Real Triplet: EWPT

$$\Sigma^0, \Sigma^+, \Sigma^-$$

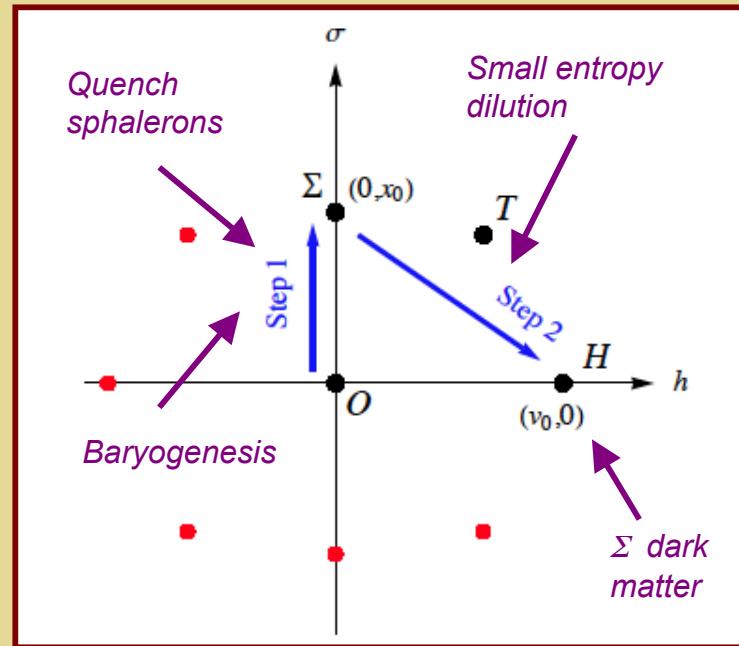
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H. Patel & R-M, 1212.5652/hep-ph (2012)

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

## Two-step EWSB

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# Real Triplet: EWPT

$$\Sigma^0, \Sigma^+, \Sigma^-$$

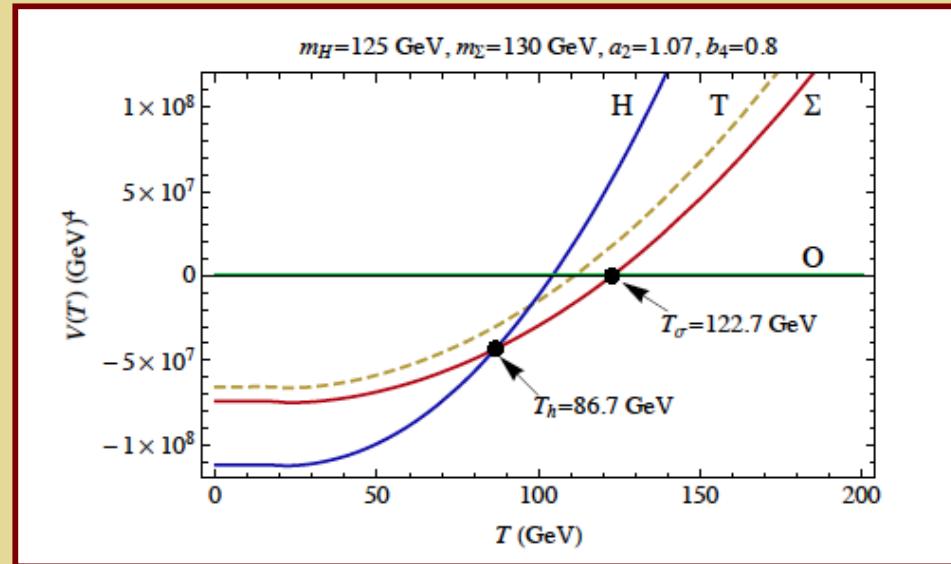
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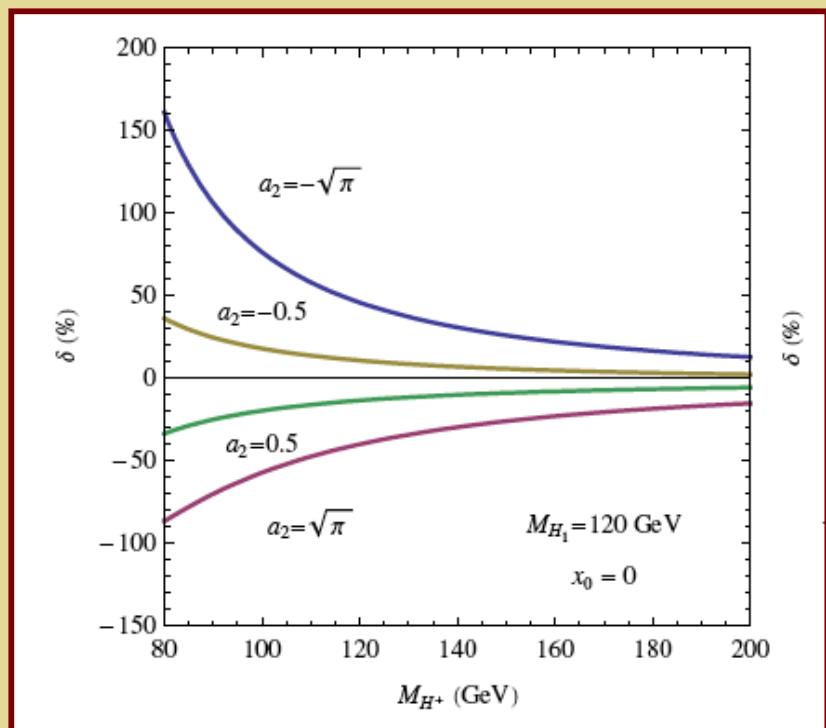
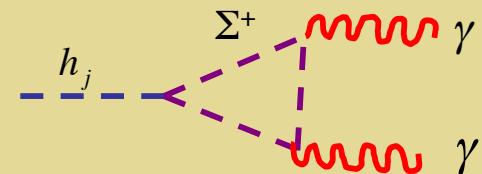
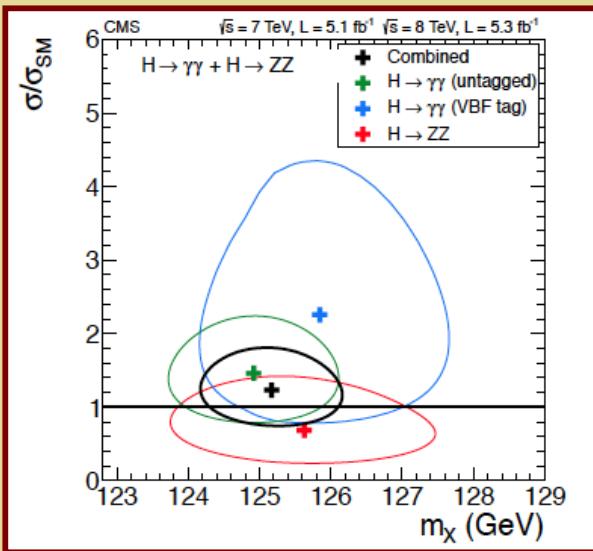
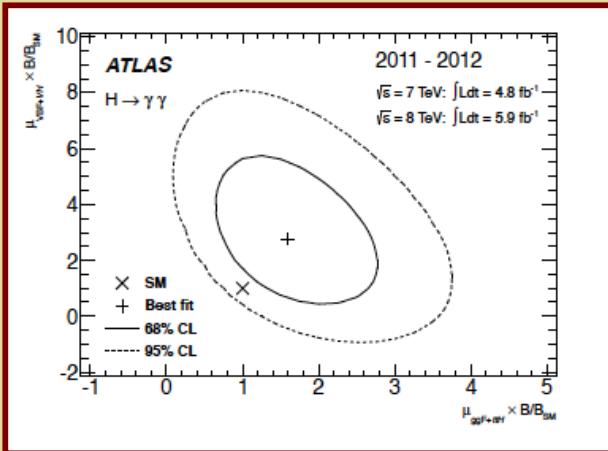
## Two-step EWSB

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



# Higgs Diphoton Decays

LHC:  $H \rightarrow \gamma\gamma$



# Real Triplet: EWPT

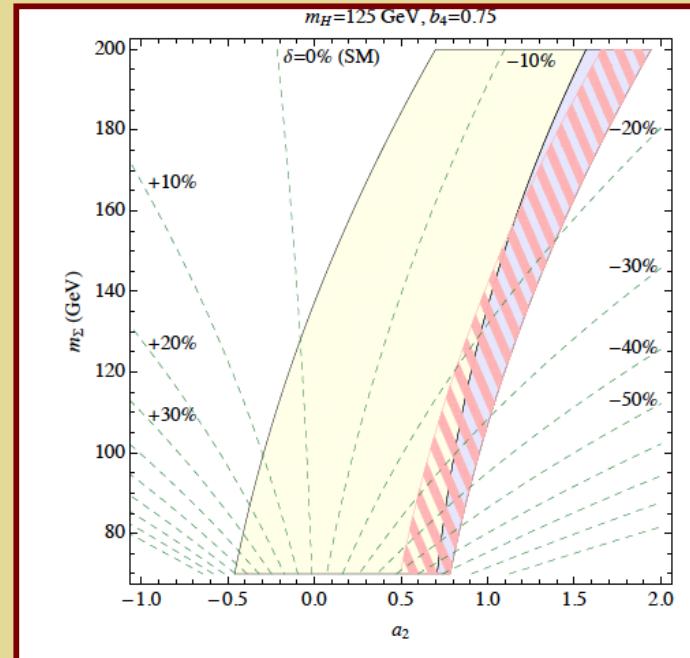
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# Real Triplet: EWPT

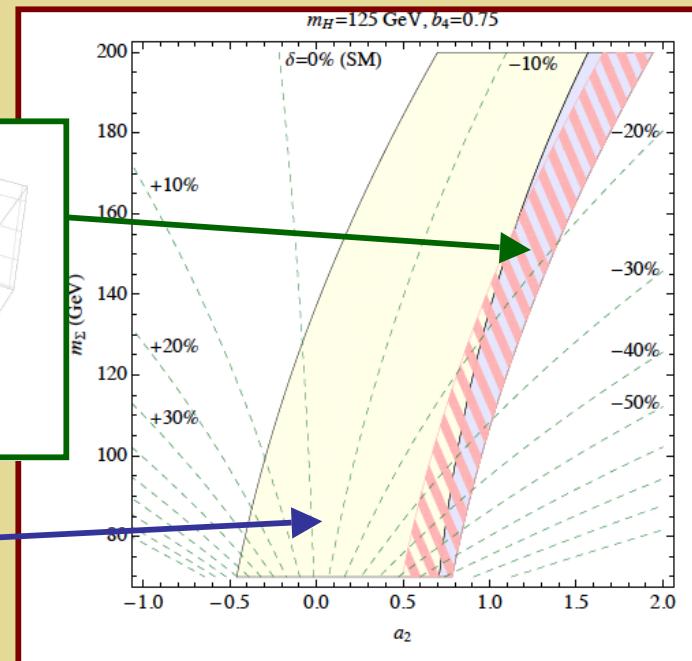
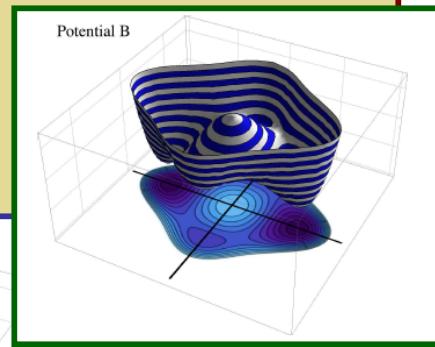
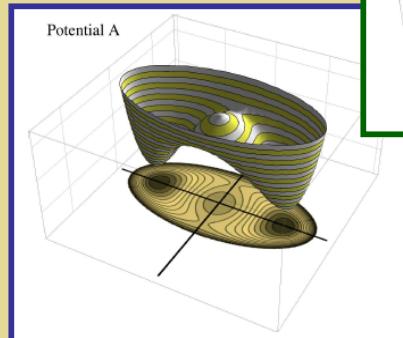
$$\Sigma^0, \Sigma^+, \Sigma^-$$

$\sim (1, 3, 0)$

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

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

Two-step EWSB



# Real Triplet: EWPT

$$\Sigma^0, \Sigma^+, \Sigma^-$$

$$\sim (1, 3, 0)$$

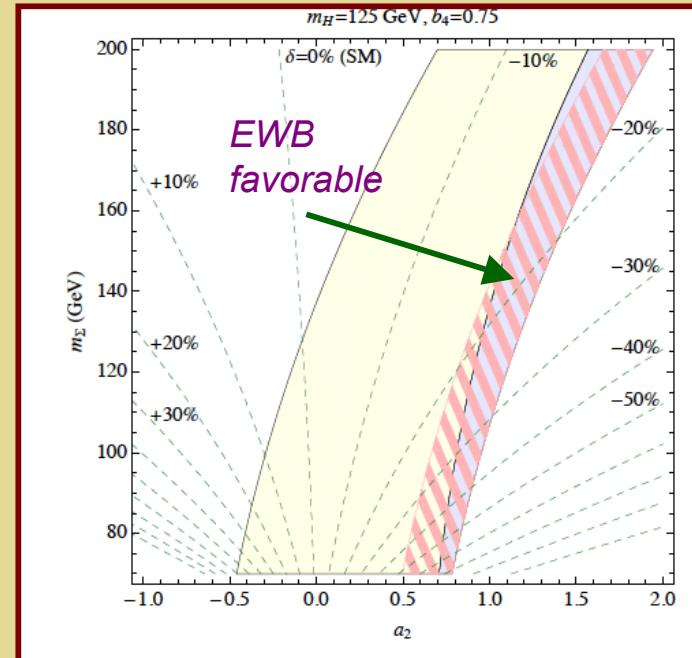
H. Patel & R-M, 1212.5652/hep-ph (2012)

$$V_{H\Sigma} =$$

$$\frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2$$

## Two-step EWSB

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



## *VI. Color Breaking & Restoration*

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

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

- $O(n) \times O(n)$ : Weinberg (1974)
- $SU(5)$ ,  $CP\dots$ : 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: ArXiv 1303.1140

# *Color Breaking & Restoration*

*Two illustrative cases:*

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

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Color triplet scalar</i>	6	✓	✗
<i>Color triplet + singlet</i>	7	✓	✗
.....			

# *Color Breaking & Restoration*

*Two illustrative cases:*

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1303.1140 (2013)*

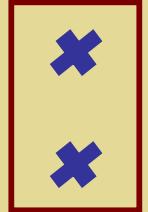
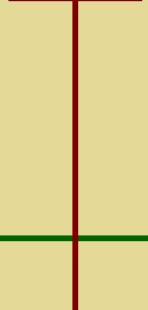
<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
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.....			

*Spontaneous  $B$  violation*

# *Color Breaking & Restoration*

*Two illustrative cases:*

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<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Color triplet scalar</i>	6	✓	
<i>Color triplet + singlet</i> .....	7	✓	
<i>“Light”: special flavor structure</i>		<i>Spontaneous B violation</i>	

# *Color Breaking & Restoration*

*Two illustrative cases:*

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

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Color triplet scalar</i>	6	✓	
<i>Color triplet + singlet</i>	7	✓	
.....			
<i>heavy: generic flavor structure</i>			
		<i>Spontaneous B violation</i>	

# **SM + Color Triplet**

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

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

*Decays:*  $C \rightarrow \langle C \rangle = v_C$  :  $B$  violation

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

# **SM + Color Triplet**

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

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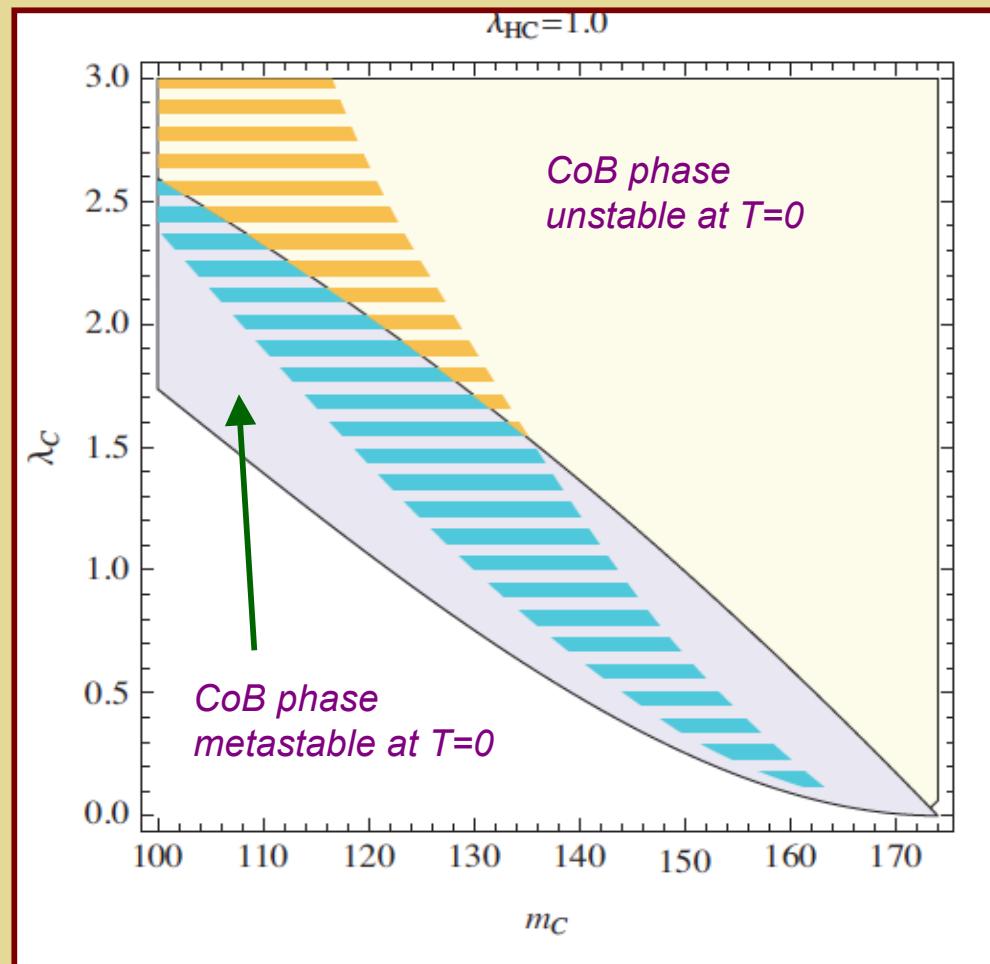
*Upper bound on  $m_C$ :*

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

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

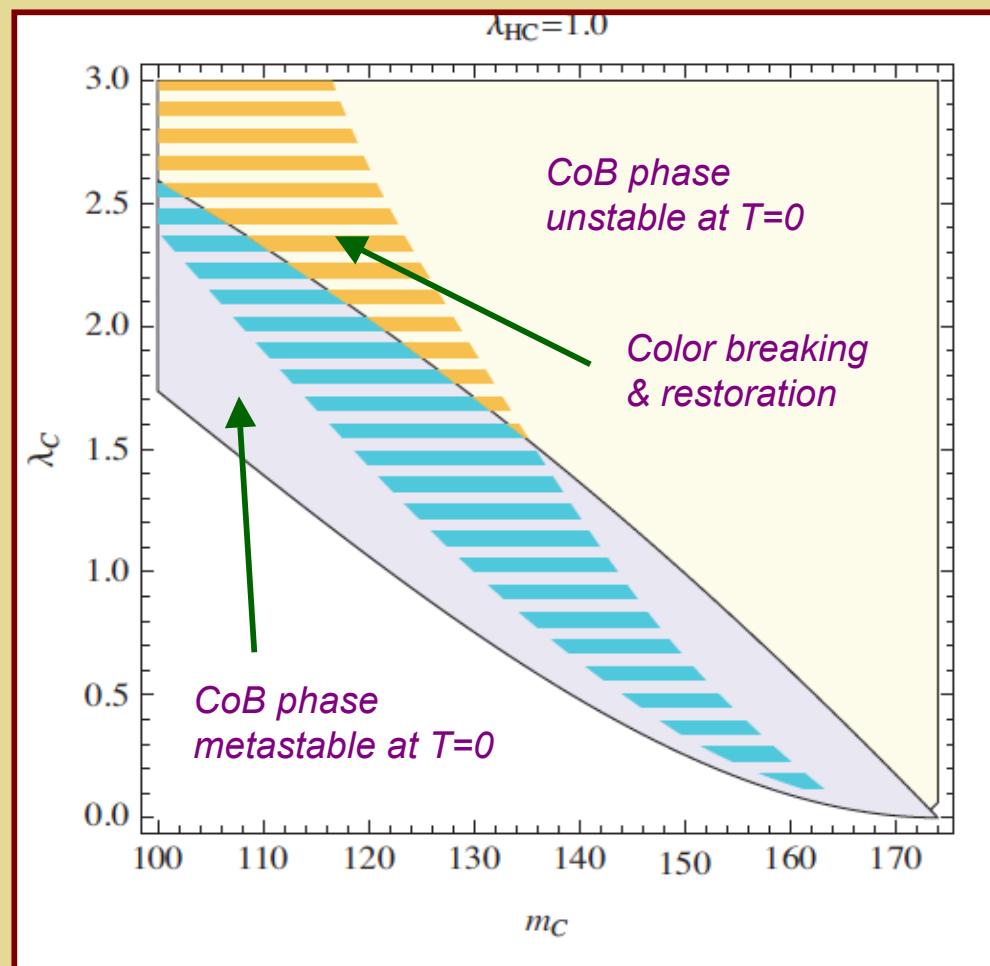
# ***SM + Color Triplet***

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



# ***SM + Color Triplet***

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



# ***SM + Color Triplet + Singlet***

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

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

*Heavier colored scalar*

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

# ***SM + Color Triplet + Singlet***

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

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

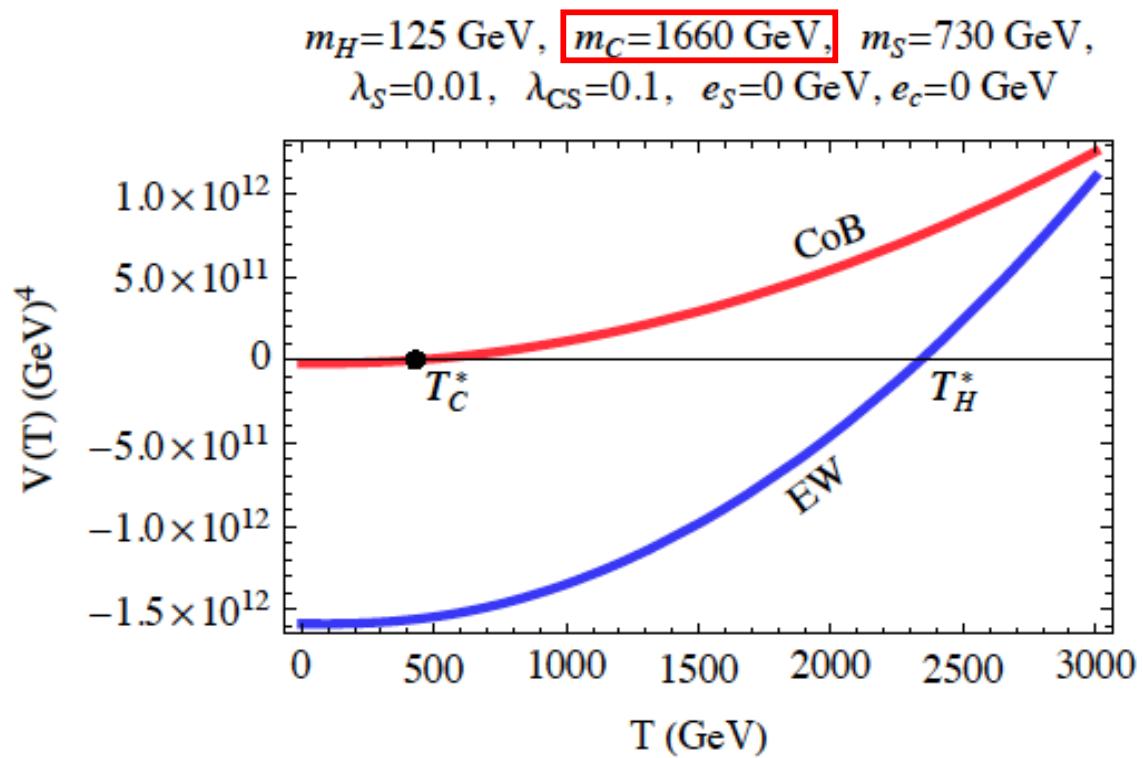
*But  $SU(3)_C$  restored more quickly*

$$\begin{aligned}\mu_C^2(T) &= \mu_C^2 - T^2 \left( \frac{\lambda_C}{3} + \frac{\lambda_{HC}}{6} + \frac{\lambda_{CS}}{24} + \frac{g_3^2}{3} \right) \\ \mu_S^2(T) &= \mu_S^2 - T^2 \left( \frac{\lambda_S}{8} + \frac{\lambda_{HS}}{12} + \frac{\lambda_{CS}}{8} \right).\end{aligned}$$

# ***SM + Color Triplet + Singlet***

$Z_2$  Symmetric

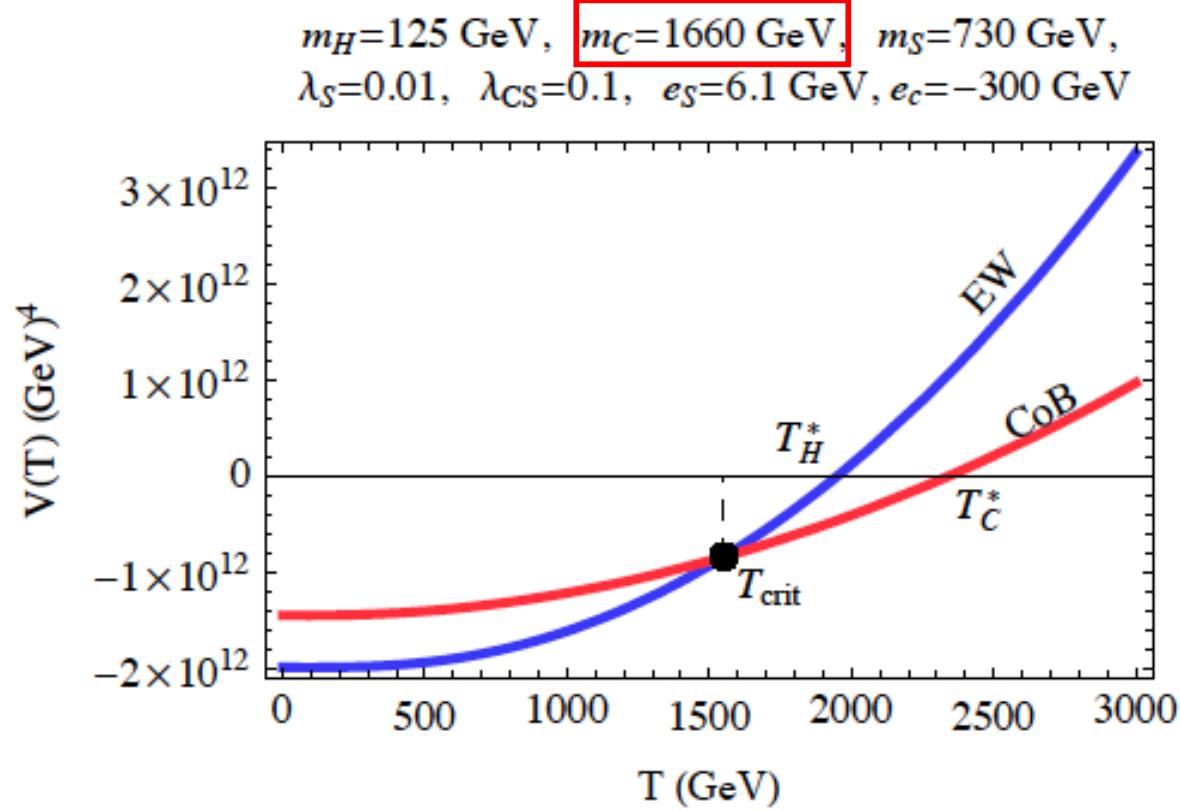
*H. Patel, R-M, Wise 1303.1140 (2013)*



# ***SM + Color Triplet + Singlet***

*Z<sub>2</sub> Symmetric*

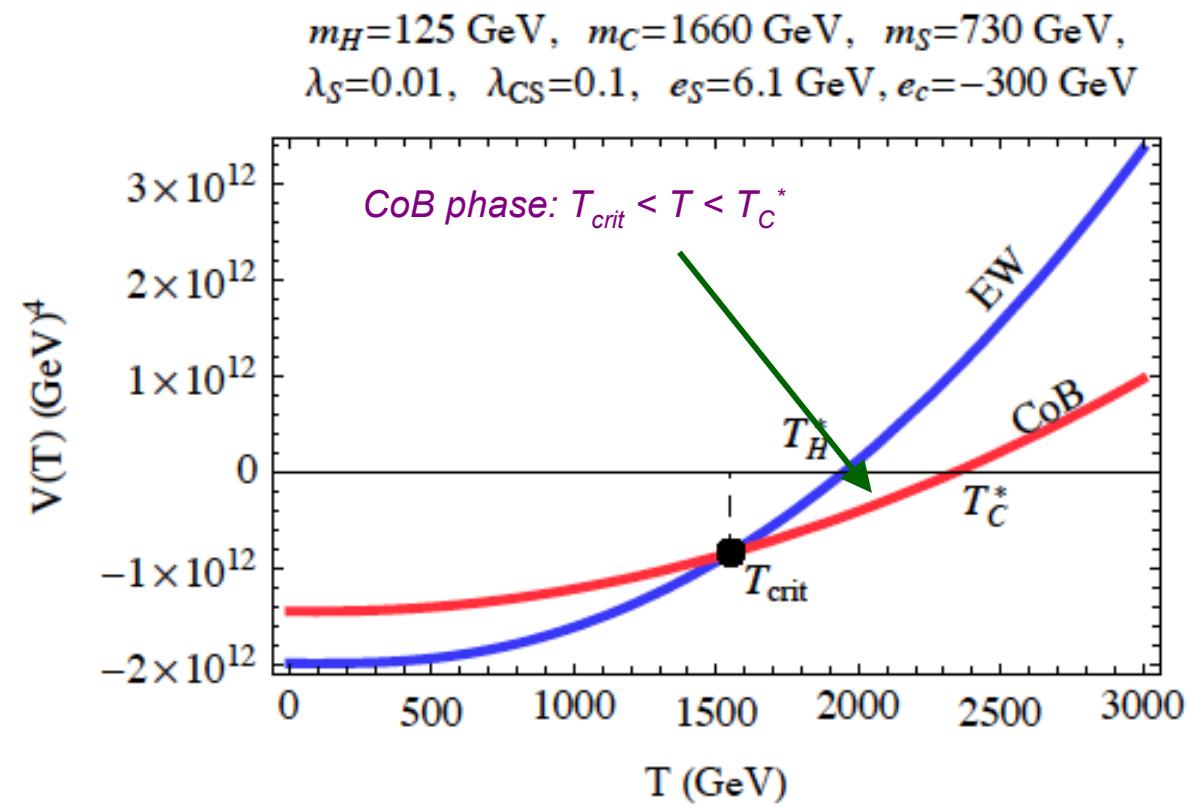
*H. Patel, R-M, Wise 1303.1140 (2013)*



# ***SM + Color Triplet + Singlet***

*Z<sub>2</sub> Symmetric*

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

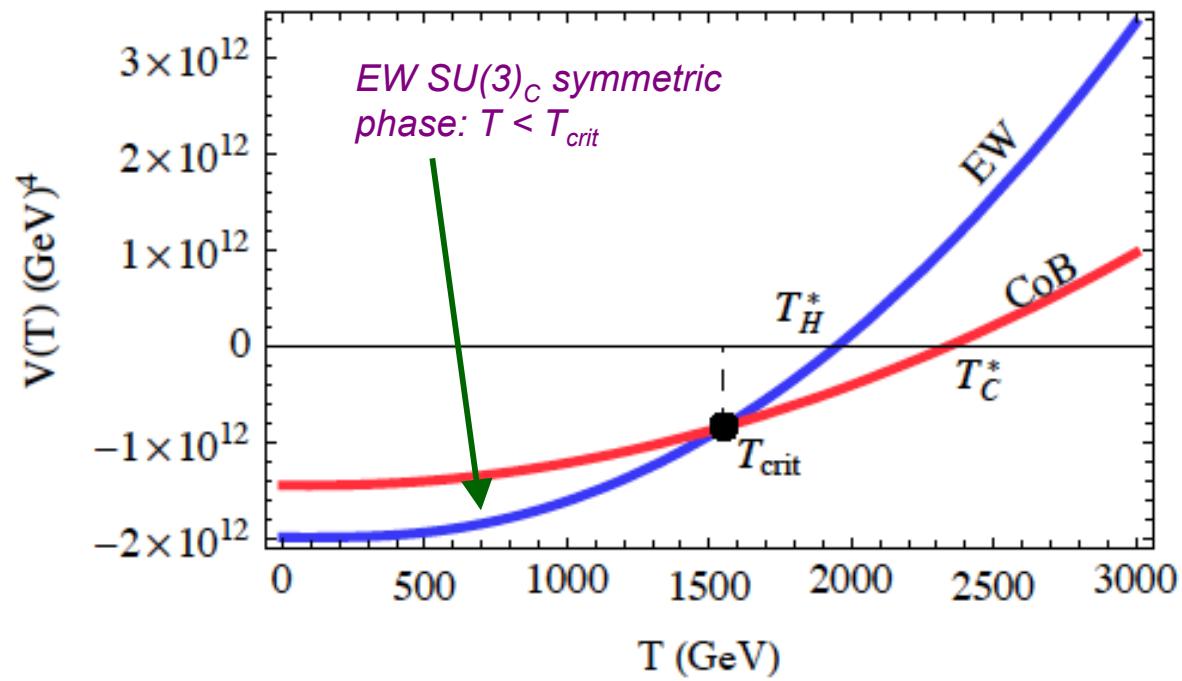


# ***SM + Color Triplet + Singlet***

$Z_2$  Symmetric

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

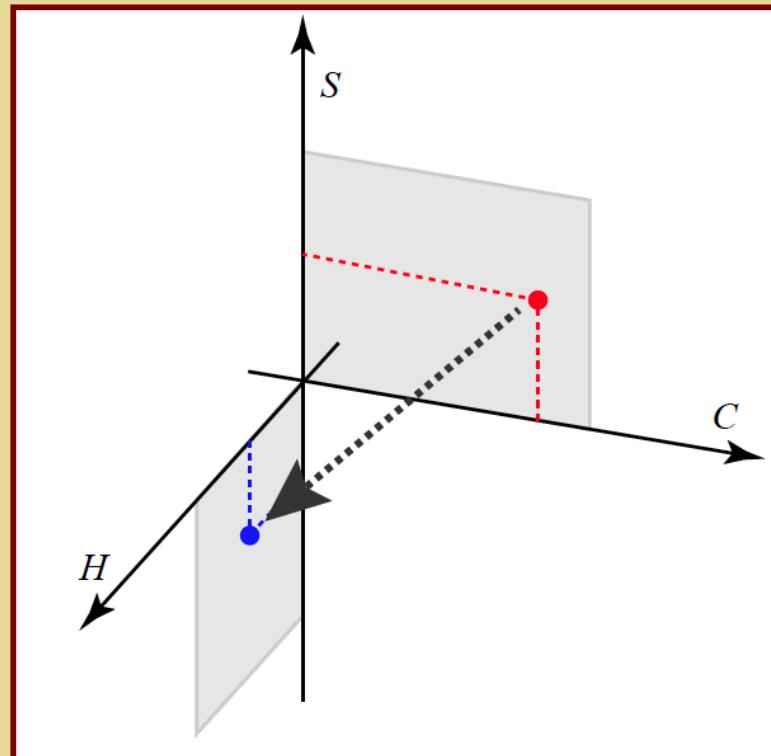
$m_H = 125 \text{ GeV}$ ,  $m_C = 1660 \text{ GeV}$ ,  $m_S = 730 \text{ GeV}$ ,  
 $\lambda_S = 0.01$ ,  $\lambda_{CS} = 0.1$ ,  $e_S = 6.1 \text{ GeV}$ ,  $e_c = -300 \text{ GeV}$



# ***SM + Color Triplet + Singlet***

$Z_2$  Symmetric

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



# **Summary**

- *Observation of ~125 GeV Higgs-like scalar makes Higgs portal particularly interesting window on a number of questions: EW vacuum stability, gauge hierarchy, dark matter, EW phase transition...*
- *Higgs portal offers possibility of new early Universe dynamics: novel patterns of symmetry-breaking (multi-step, color-breaking & restoration) & “economic” mechanism for DM and EWPT*
- *Higgs portal presents a rich array of possible signatures: modified Higgs properties, new (heavy) states, new event topologies associated w/ mixing and/or EW cross sections*

# *Back Up Slides*

# **Effective Potential \***

*Tree level*

$$\mathcal{L} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - V(\varphi)$$

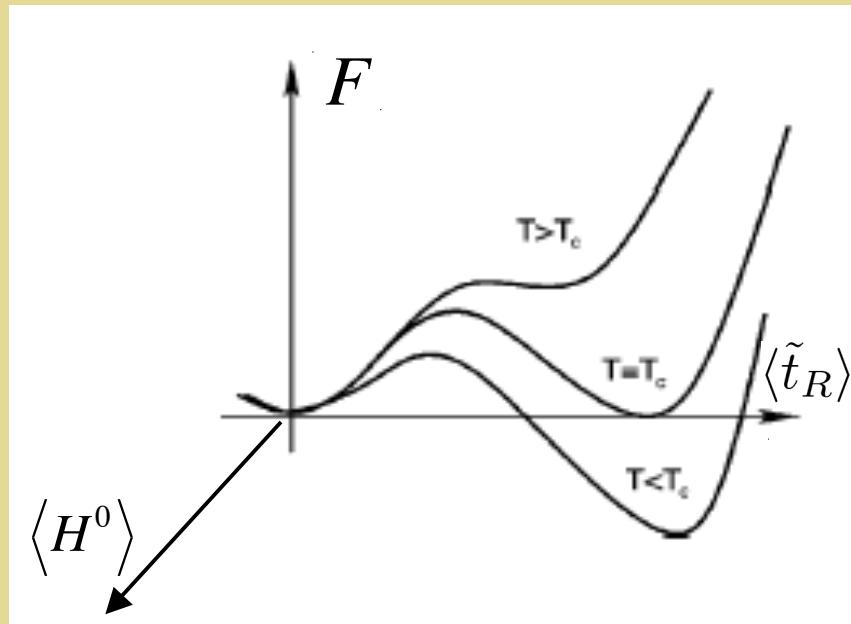
*Quantum corrections*

$$V(\varphi) \Rightarrow V_{EFF}(\varphi, T)$$

- $T=0$  : Coleman-Weinberg (RG improved)
- $T>0$  : Finite- $T$  effective potential

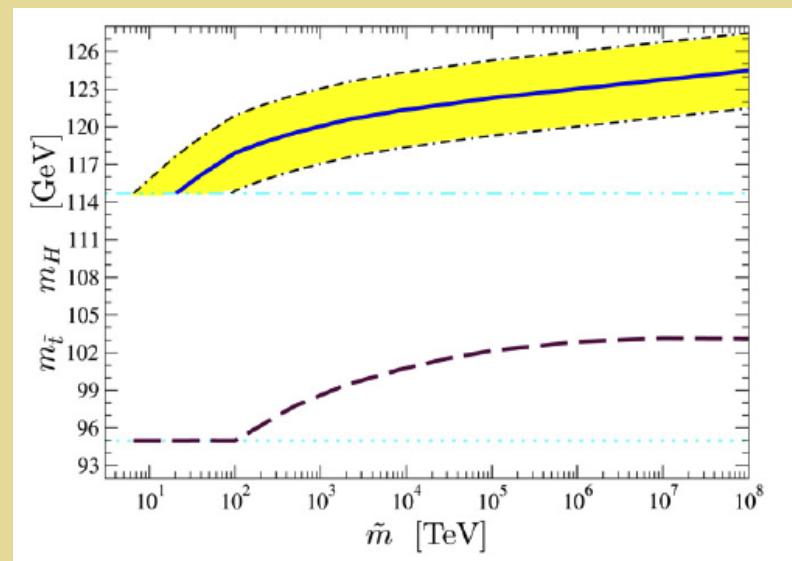
\* Many applications: Effective action

# MSSM: Color Breaking Vacua



Two-loop analysis of  $V_{EFF}$   
in effective theory

- Deeper minima may develop along stop direction
- Carena et al (2008): color-neutral EW vacuum is metastable for appropriate MSSM parameters



# Real Triplet : DM Search

**Basic signature:**

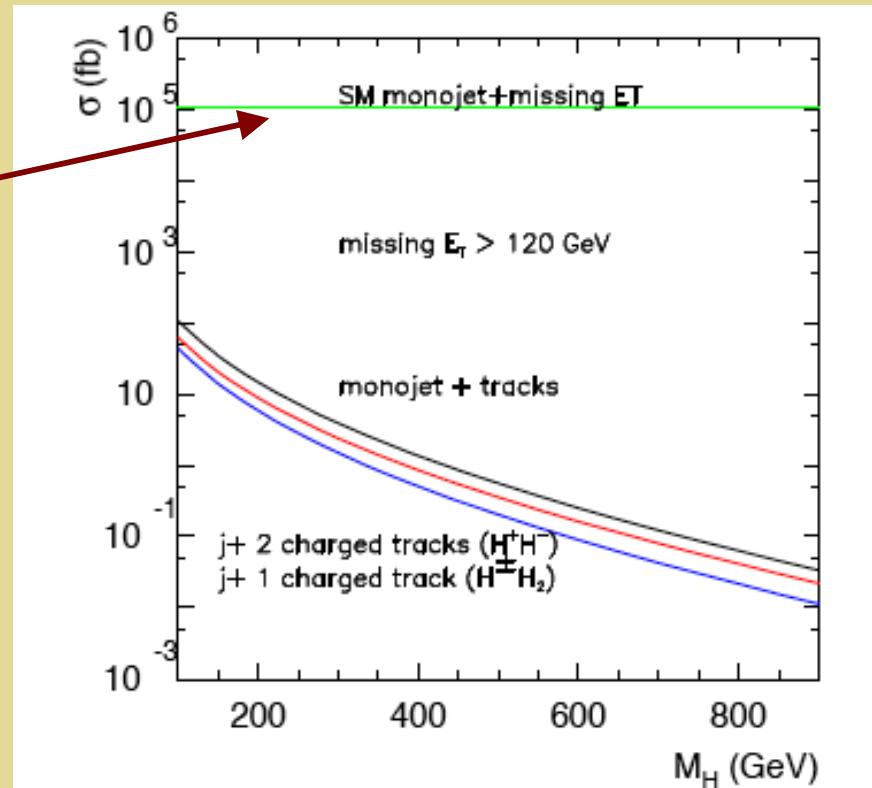
$$x_0 = 0 : H^\pm \rightarrow H_2 \pi^\pm$$

**Charged track disappearing  
after  $\sim 5$  cm**

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

Trigger: Monojet  
(ISR) + large  $\cancel{E}_T$

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



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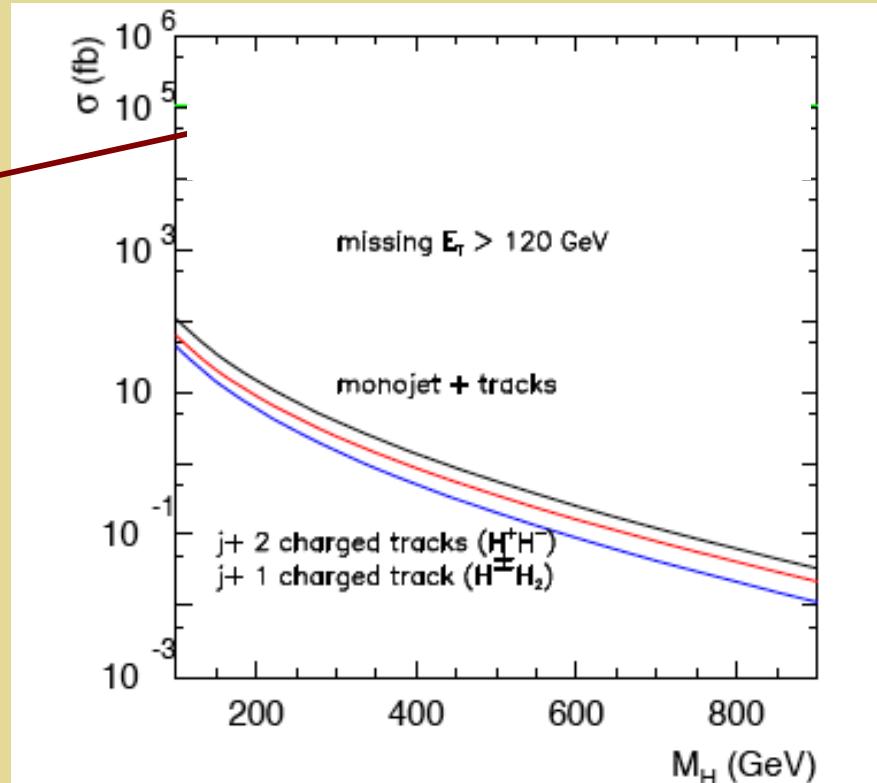
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**SM Background:**  
QCD  $jZ$  and  $jW$  w/  
 $Z \rightarrow \nu\nu$  &  $W \rightarrow l\nu$

**Cuts:**  
large  $\cancel{E}_T$   
hard jet  
One 5cm track



# Real Triplet : DM Search

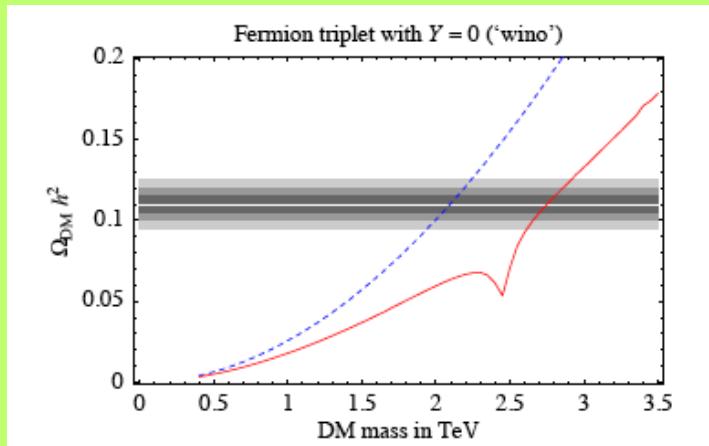
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*Cirelli et al.:*



$M_\Sigma = 500$  GeV:

$$\Omega_\Sigma / \Omega_{CDM} \sim 0.1$$

