

Electroweak Phase Transition, Scalar Dark Matter, & the LHC



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NPAC

Theoretical Nuclear, Particle, Astrophysics & Cosmology

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

ANL Seminar, February 2012

Recent Work

- *M. Gonderinger, Y. Li, H. Patel, & MRM, arXiv:1202.1316*
- *M. Buckley & MRM JHEP 1109 (2011) 094*
- *H. Patel & MRM, JHEP 1107 (2011) 029*
- *C. Wainwright, S. Profumo, MRM Phys Rev. D84 (2011) 023521*
- *M. Gonderinger, H. Lim, & MRM, arXiv:1202.1316*

Scalar Fields in Cosmology

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

Scalar Fields in Particle Physics

Scalar fields are a simple

Scalar fields are theoretically problematic

A diagram illustrating a scalar field loop. A dashed red circle labeled φ_{NEW} represents the scalar field. Two horizontal dashed blue lines, each labeled H^0 , represent Higgs bosons. The scalar field loop connects the two Higgs bosons.

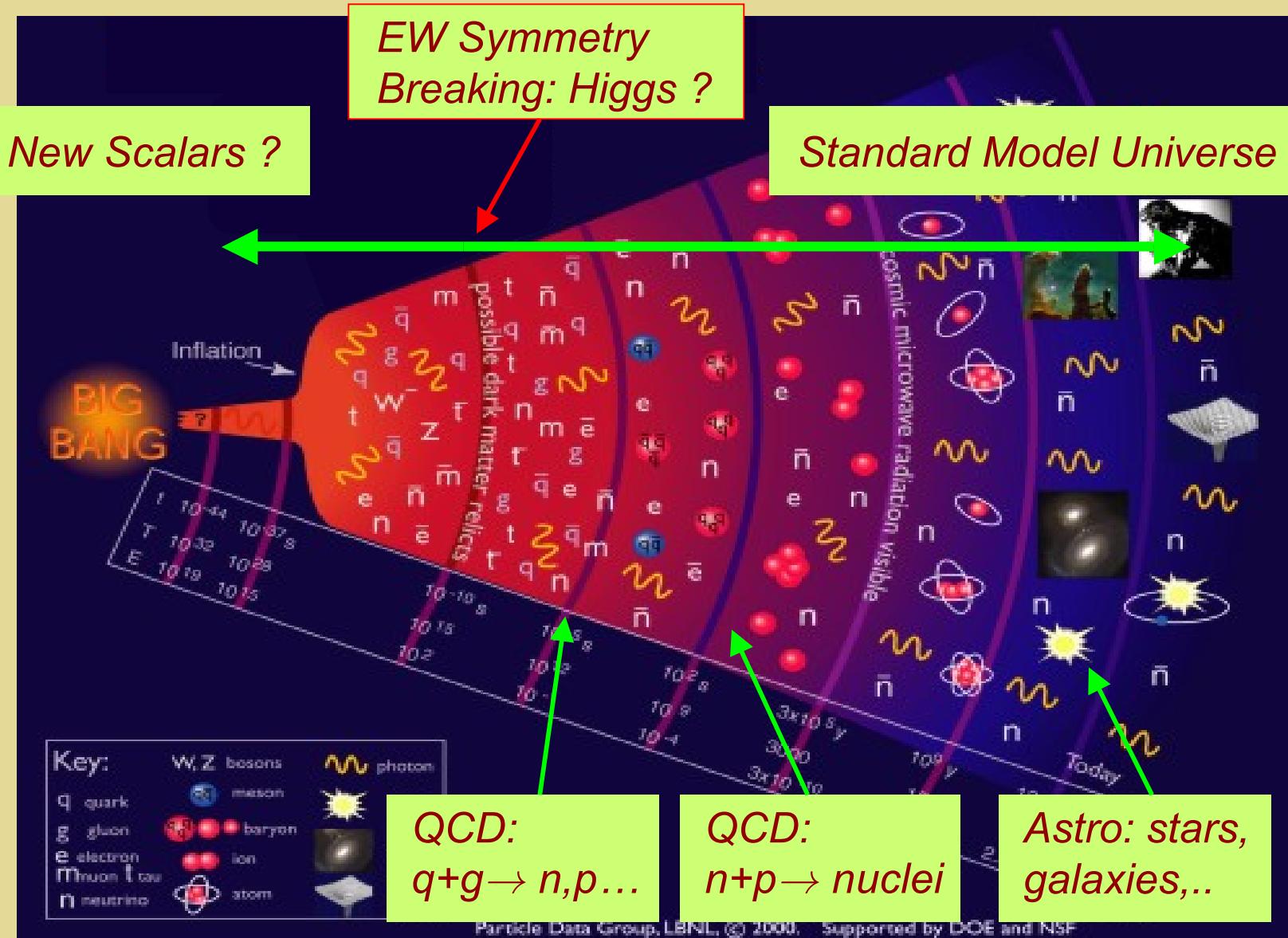
$$\Delta m^2 \sim \lambda \Lambda^2$$

Fundamental scalars have yet to be observed

Scalar Fields in Cosmology

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

Scalar Fields & Cosmic History



Scalar Fields & Inflation

*EW Symmetry
Breaking: Higgs ?*

New Scalars ?

Standard Model Universe

Scalar Field: Inflaton

*QCD:
 $n+p \rightarrow \text{nuclei}$*

*Astro: stars,
galaxies,..*

Reheat

“Slow roll”

V(φ)

φ

BOOMERANG

25°

Flatness

Isotropy

Homogeneity

Today

10⁻⁴⁴

3x10⁻¹⁰

10⁻³

10⁻²

10⁻¹

10⁰

10¹

10²

10³

10⁴

10⁵

10⁶

10⁷

10⁸

10⁹

10¹⁰

10¹¹

10¹²

10¹³

10¹⁴

10¹⁵

10¹⁶

10¹⁷

10¹⁸

10¹⁹

10²⁰

10²¹

10²²

10²³

10²⁴

10²⁵

10²⁶

10²⁷

10²⁸

10²⁹

10³⁰

10³¹

10³²

10³³

10³⁴

10³⁵

10³⁶

10³⁷

10³⁸

10³⁹

10⁴⁰

10⁴¹

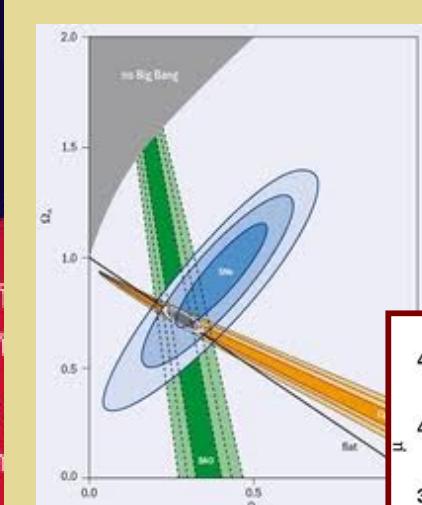
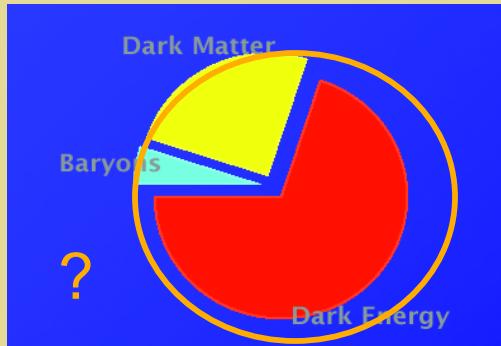
10⁴²

10⁴³

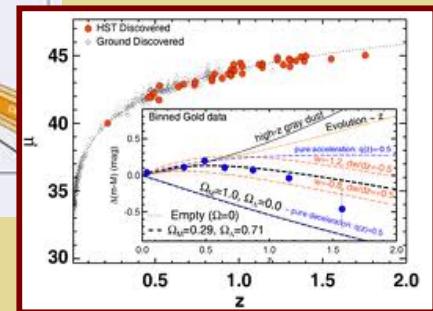
10⁴⁴

Particle Data Group, LBNL, © 1999. Supported by DOE and NSF

Scalar Fields & Dark Energy



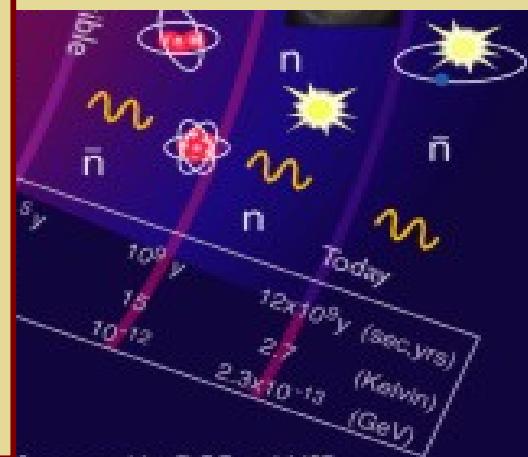
- Λ CDM
- Supernovae
- BAO



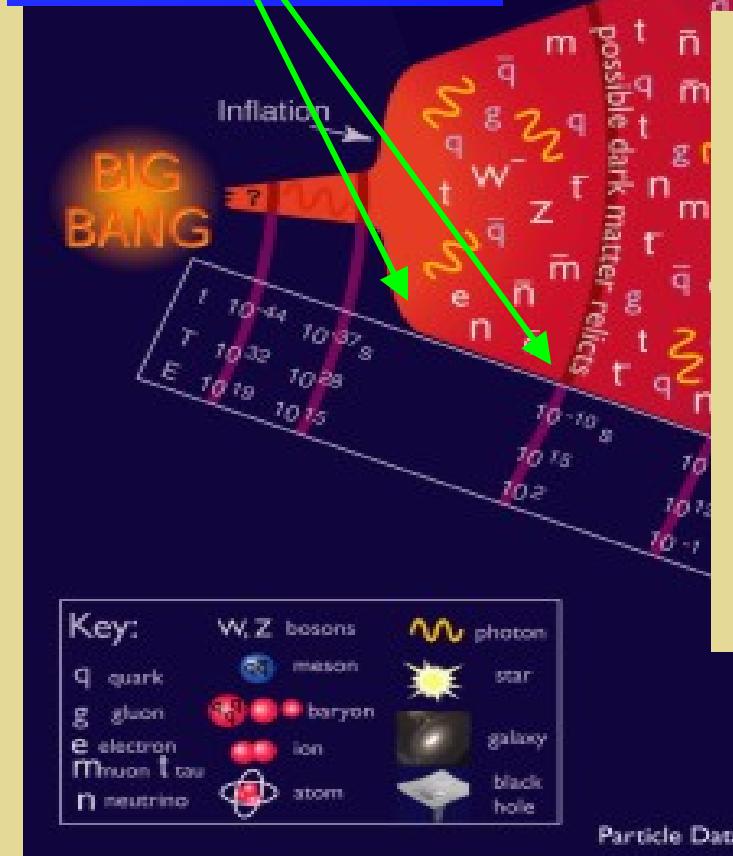
Cosmological constant ?

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left(\rho + \frac{3p}{c^2} \right) + \frac{\Lambda c^2}{3} > 0$$

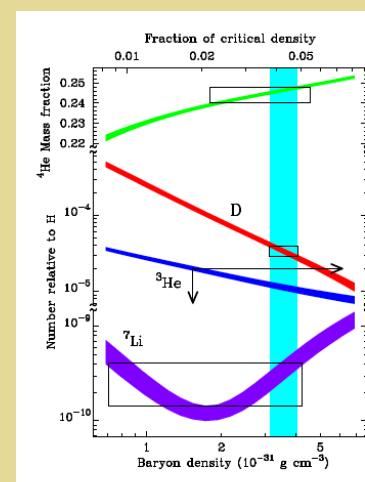
Scalar Field: Quintessence ?



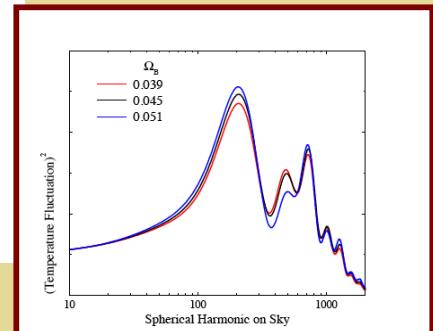
Scalar Fields & the Origin of Matter



*Baryogenesis: When?
CPV? SUSY? Neutrinos?
Non-equilibrium dynamics
or CPT violation?*



- BBN ($t \sim 100 \text{ s}$)
- CMB ($t \sim 10^5 \text{ y}$)



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

Scalar Fields & the Origin of Matter

Electroweak Phase Transition ? New Scalars

Baryogenesis: When?
CPV? SUSY? Neutrinos?
Non-equilibrium dynamics or CPT violation?

Dark Matter

Baryons

Dark Energy

?

Inflation

BIG BANG

Key:

- ψ, Z bosons
- q quark
- g gluon
- e electron
- μ muon
- ν neutrino
- meson
- baryon
- ion
- atom
- photon
- star
- galaxy
- black hole

Particle Data

Fraction of critical density

D

${}^3\text{He}$

${}^7\text{Li}$

Number relative to H

Baryon density ($10^{-31} \text{ g cm}^{-3}$)

$(\text{Temperature Fluctuation})^2$

Spherical Harmonic on Sky

Ω_B

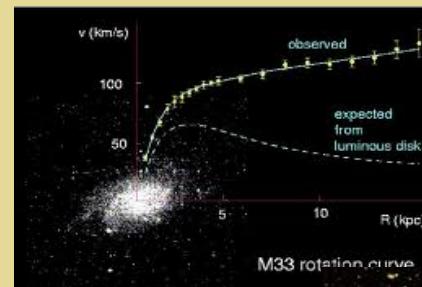
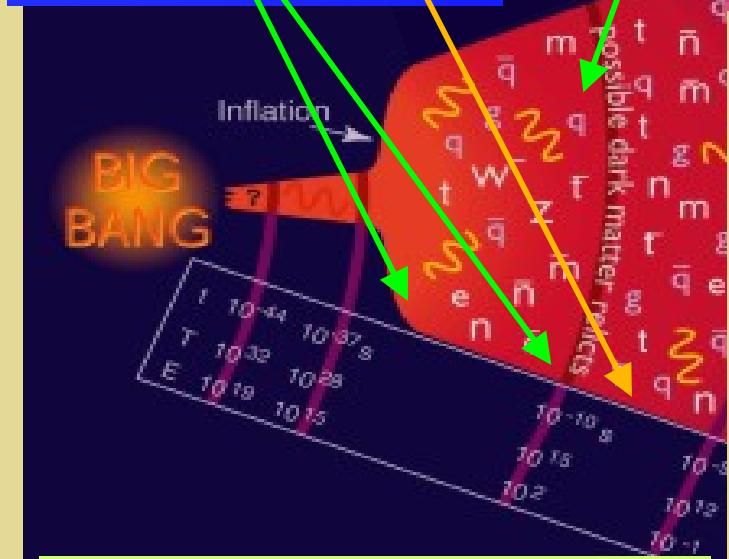
$Y_B = \frac{n_B}{s_\gamma} = (9.29 \pm 0.34) \times 10^{-11}$

Scalar Fields & the Origin of Matter



Electroweak Phase
Transition ? New
Scalars

Baryogenesis: When?
CPV? SUSY? Neutrinos?
Non-equilibrium dynamics
or CPT violation?



- Rotation curves
- Lensing
- Bullet clusters



Darkogenesis: When?
SUSY? Neutrinos?
Axions ? Y_B related ?

Particle Data

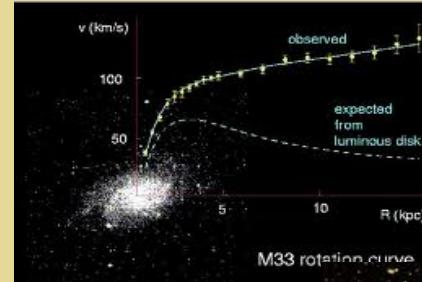
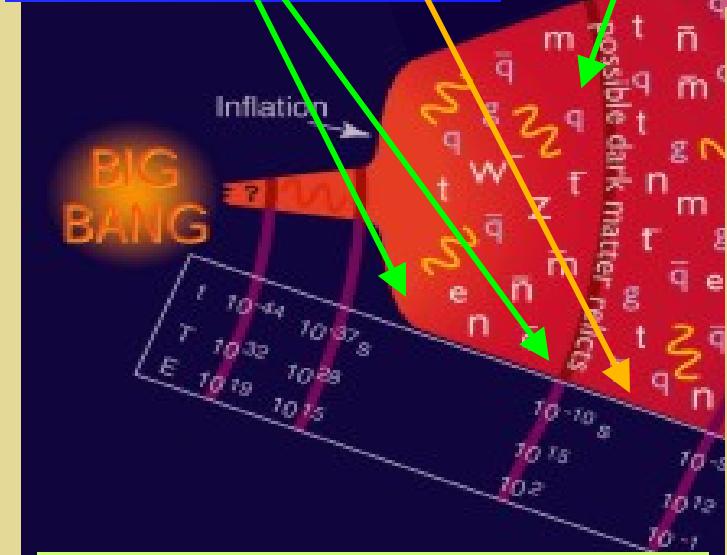
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Scalar Fields & the Origin of Matter

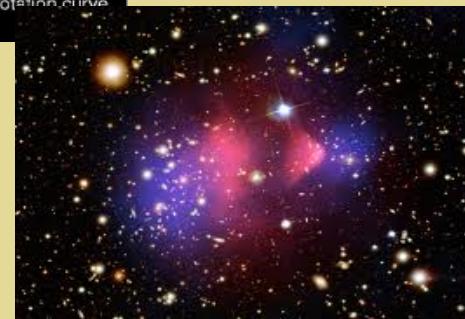


Electroweak Phase
Transition ? New
Scalars: CDM ?

Baryogenesis: When?
CPV? SUSY? Neutrinos?
Non-equilibrium dynamics
or CPT violation?



- Rotation curves
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Darkogenesis: When?
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Particle Data

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Scalar Fields in Cosmology

<i>Problem</i>	<i>Theory</i>	<i>Exp't</i>
• <i>Inflation</i>	✓	?
• <i>Dark Energy</i>	✓	?
• <i>Dark Matter</i>	✓	?
• <i>Phase transitions</i>	✓	?

Scalar Fields in Cosmology

<i>Problem</i>	<i>Theory</i>	<i>Exp't</i>
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• <i>Dark Matter</i>	✓	?
• <i>Phase transitions</i>	✓	?

Could experimental discovery of a fundamental scalar point to early universe scalar field dynamics?

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*

Questions for this Talk:

- *Was there a cosmic phase transition at $T \sim 100$ GeV ?*
- *Did it have the characteristics needed for successful electroweak baryogenesis and/or production of gravity waves?*
- *Are its dynamics coupled to dark matter ?*
- *What are the experimental signatures ?*
- *How robust is the underlying theory ?*

Outline

- I. *EWPT: General Features*
- II. *Three minimal extensions of the Standard Model scalar sector*
- III. *How will we know it's a scalar ?*
- IV. *Theoretical issues*

I. General Features

Effective Potential *

Tree level

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

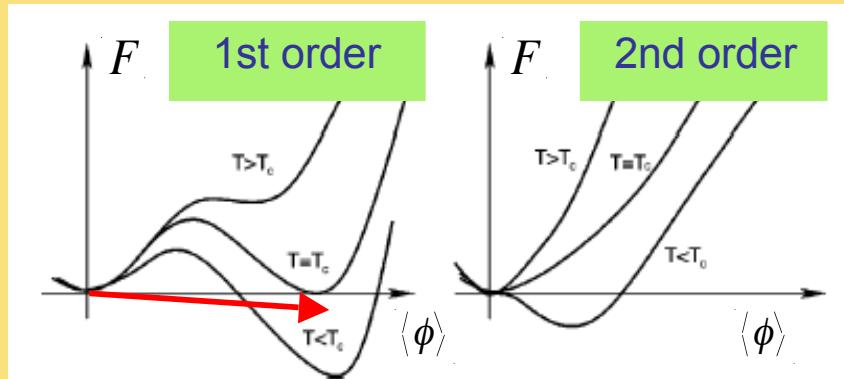
Quantum corrections

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

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

* Many applications: Effective action

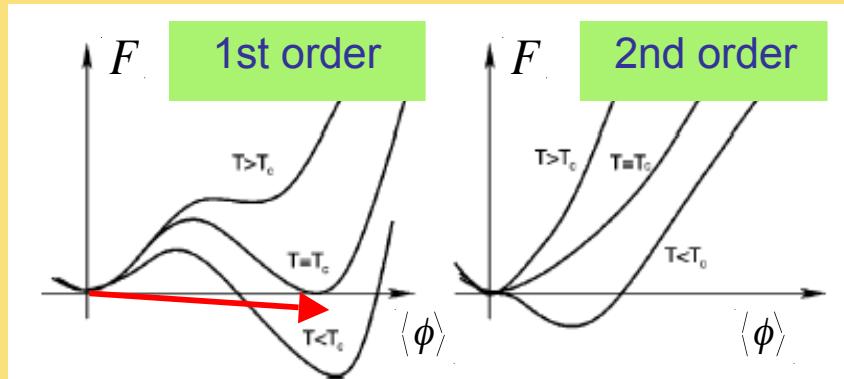
EW Phase Transition: New Scalars



Increasing m_h \longrightarrow

\longleftarrow *New scalars*

EW Phase Transition: New Scalars

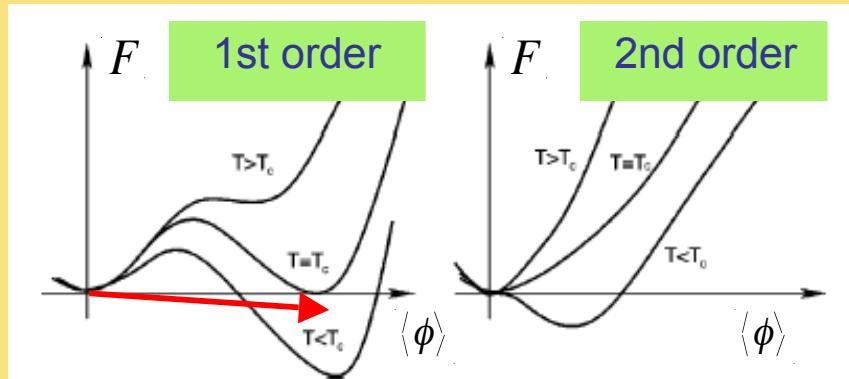


Increasing m_h \longrightarrow

\longleftarrow *New scalars*

*Baryogenesis
Gravity Waves
Scalar DM
LHC Searches*

EW Phase Transition: New Scalars



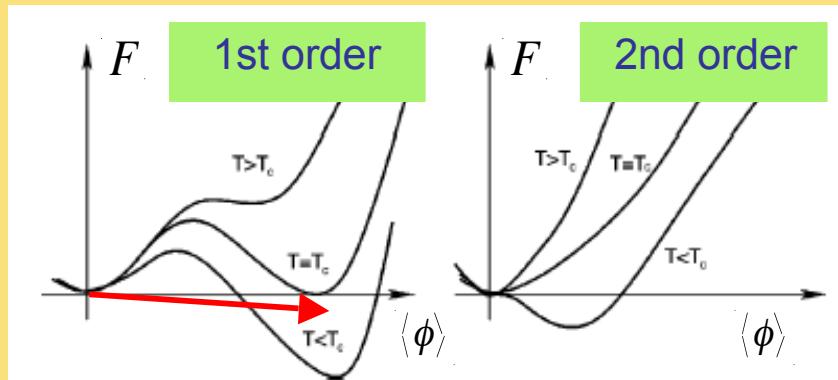
“Strong” 1st order EWPT

Increasing m_h \longrightarrow

\longleftarrow New scalars

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

EW Phase Transition: New Scalars

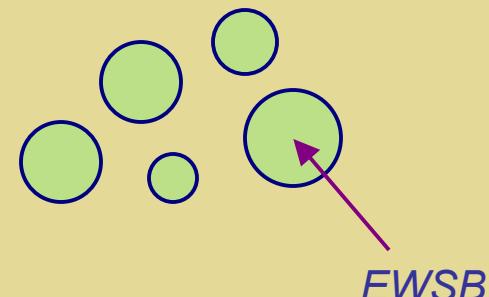


Increasing m_h \longrightarrow
 \longleftarrow New scalars

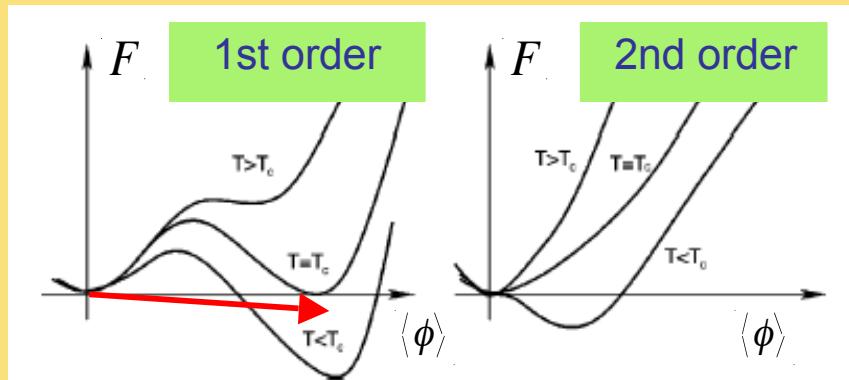
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

“Strong” **1st order EWPT**

Bubble nucleation



EW Phase Transition: New Scalars

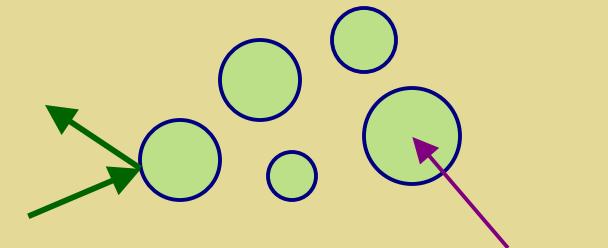


Increasing m_h →
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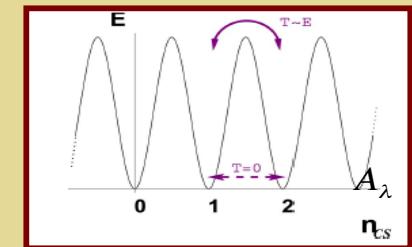
Baryogenesis
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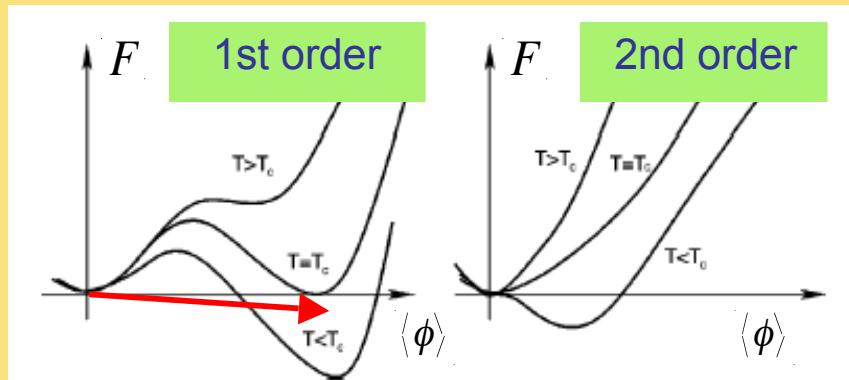
Bubble nucleation



Y_B : CPV & EW sphalerons EWSB



EW Phase Transition: New Scalars

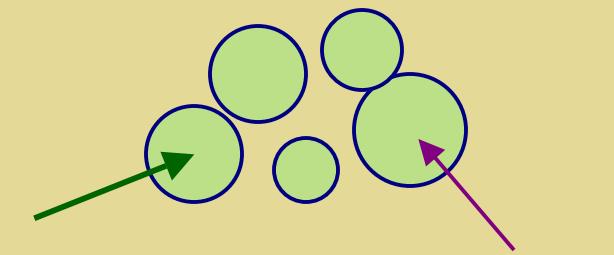


Increasing m_h →
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Baryogenesis
Gravity Waves
Scalar DM
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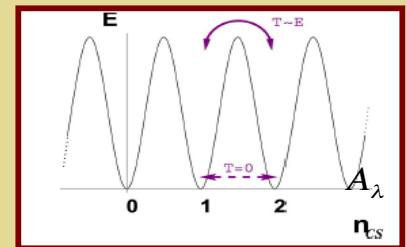
“Strong” **1st order EWPT**

Bubble nucleation

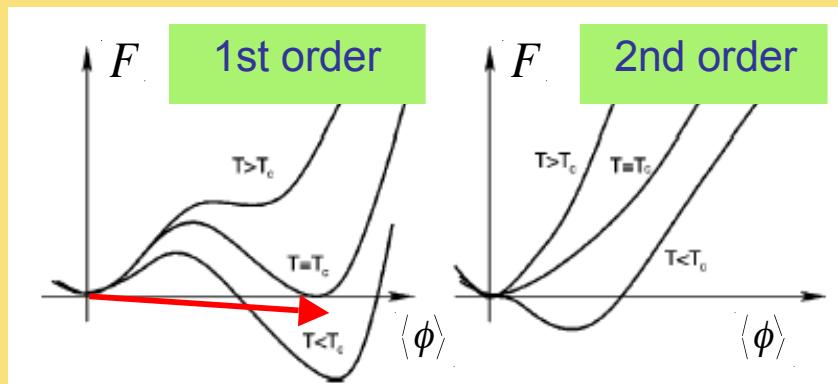


Y_B : diffuses
into interiors

EWSB

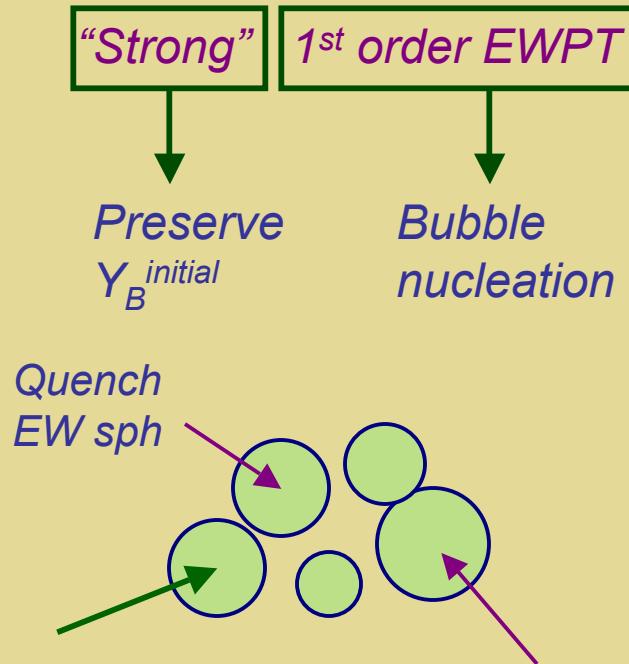


EW Phase Transition: New Scalars

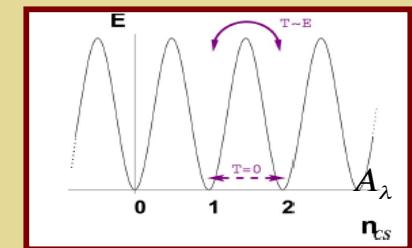


Increasing m_h \longrightarrow
 \longleftarrow *New scalars*

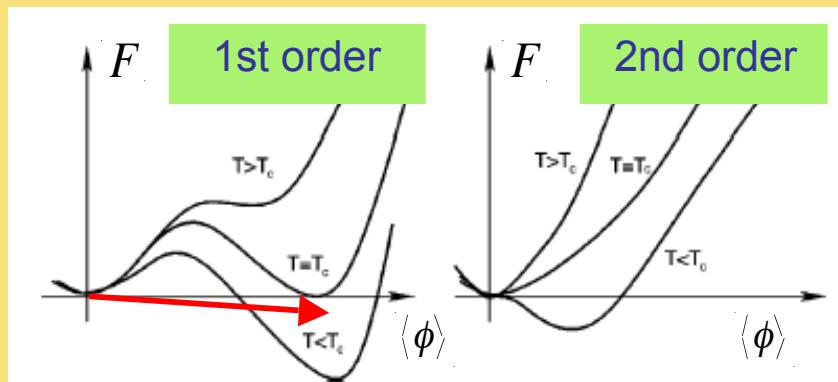
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches



Y_B : diffuses into interiors



EW Phase Transition: New Scalars



Increasing m_h →
← New scalars

Baryogenesis
Gravity Waves
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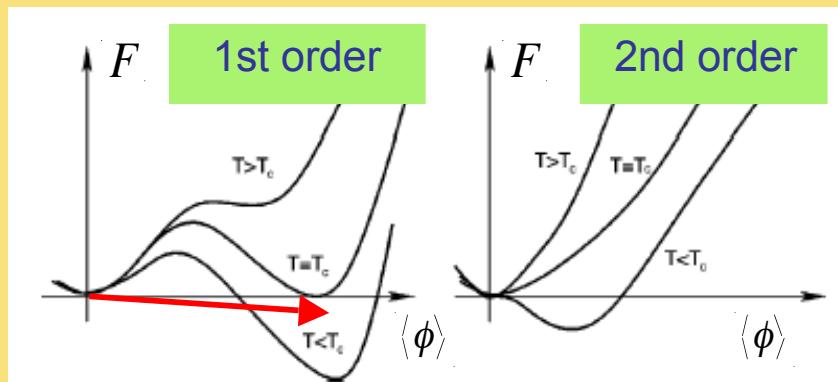
"Strong" \downarrow 1^{st} order EWPT \downarrow
Preserve Y_B^{initial} Bubble nucleation

Quench EW sph
 Y_B : diffuses into interiors

EWSB

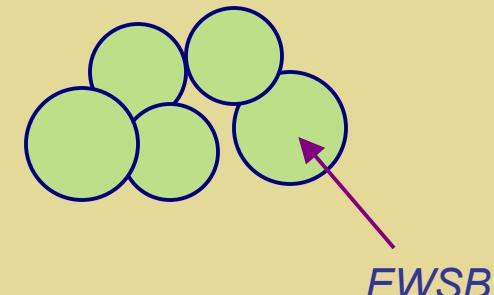
$T_C, E_{\text{sph}}, S_{\text{tunnel}} \longleftrightarrow F(\phi)$

EW Phase Transition: New Scalars

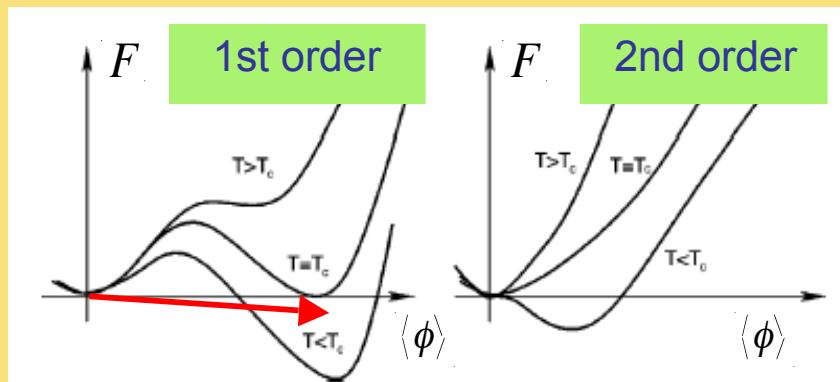


Increasing m_h \longrightarrow
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Baryogenesis
Gravity Waves
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LHC Searches

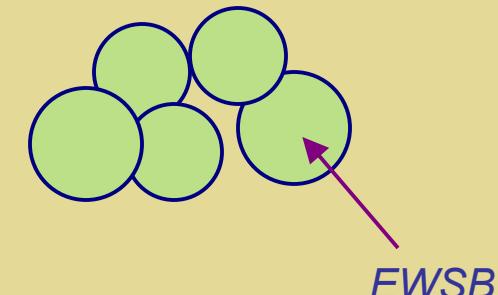
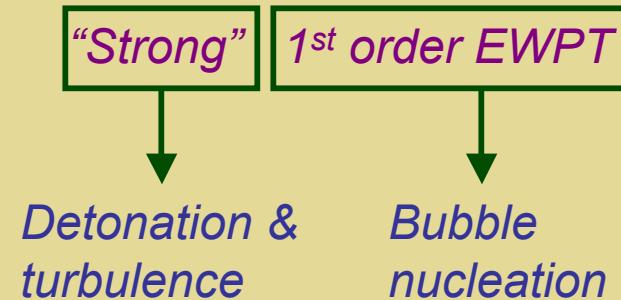


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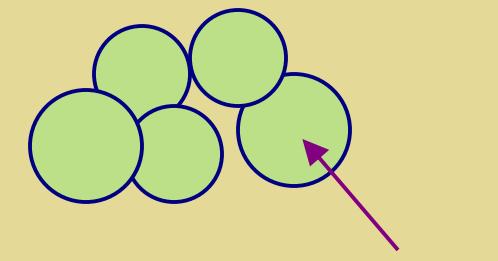
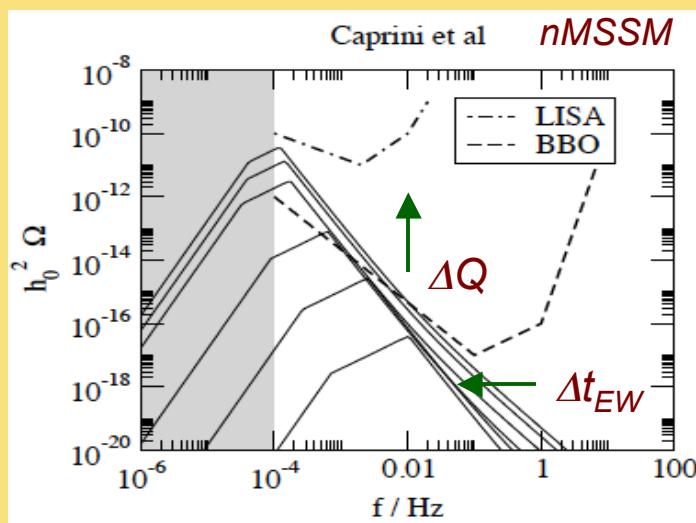
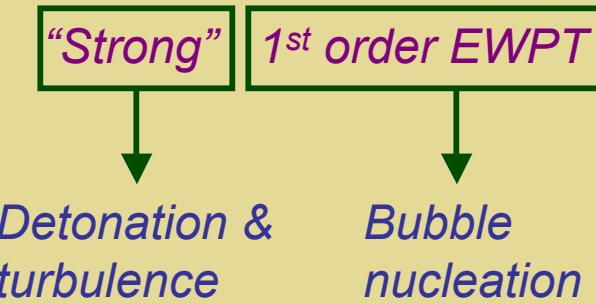
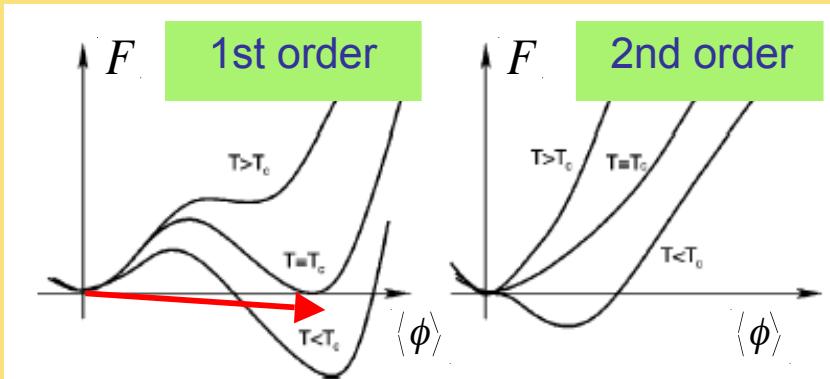
Increasing m_h \longrightarrow
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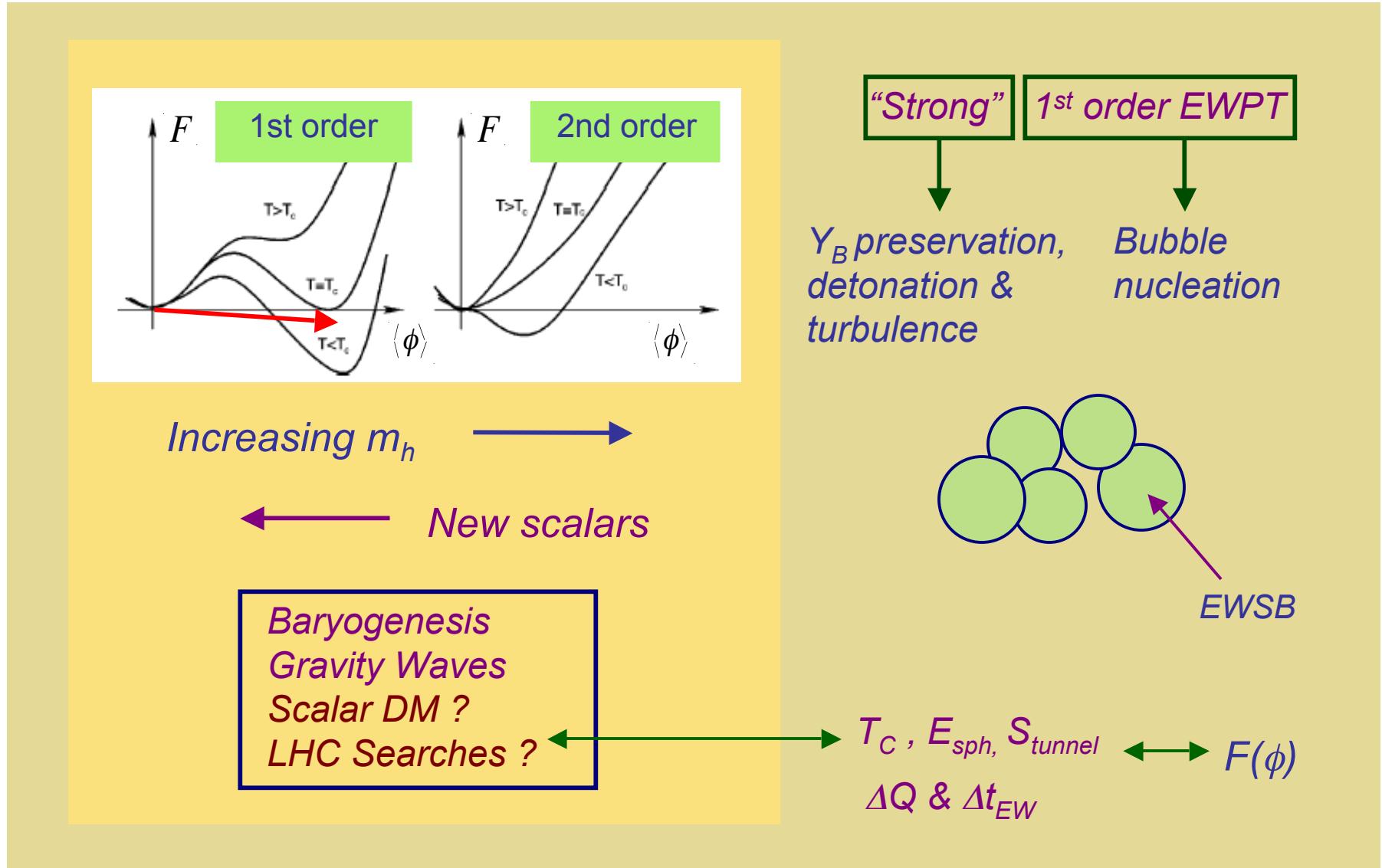
GW Spectra:
 ΔQ & Δt_{EW} $\longleftrightarrow F(\phi)$

EW Phase Transition: New Scalars

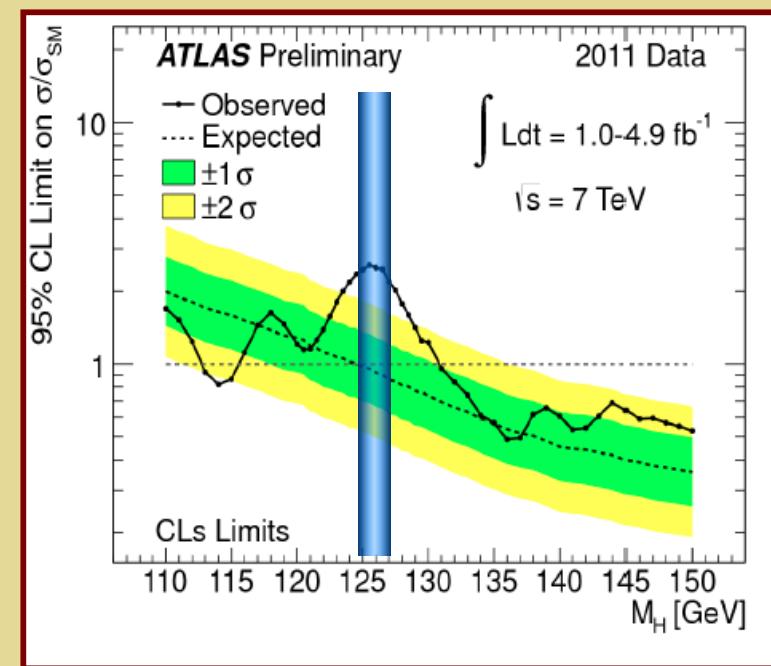
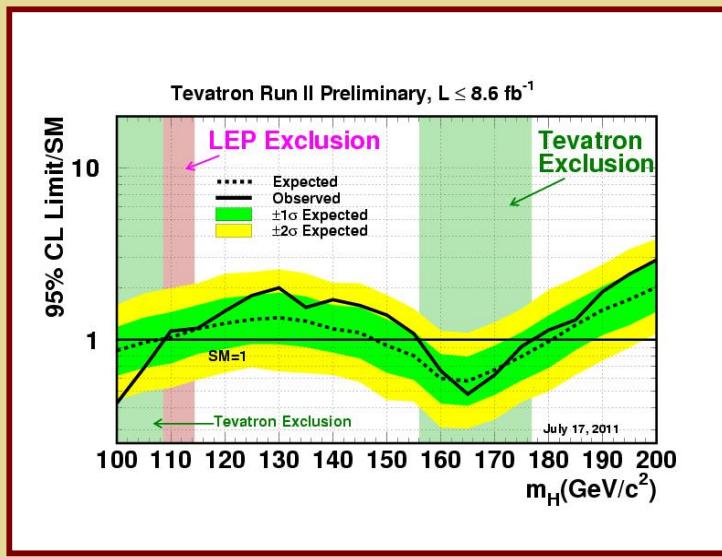
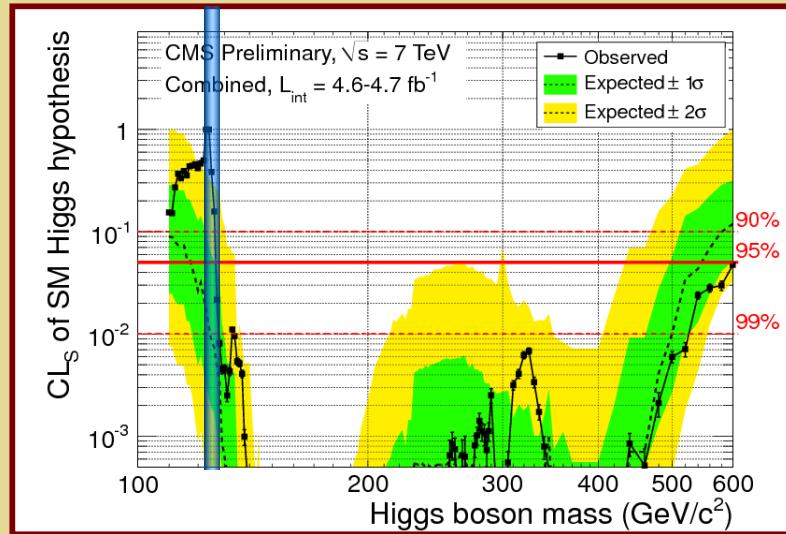


GW Spectra:
 ΔQ & Δt_{EW} $\longleftrightarrow F(\phi)$

EW Phase Transition: New Scalars



Higgs Boson Searches



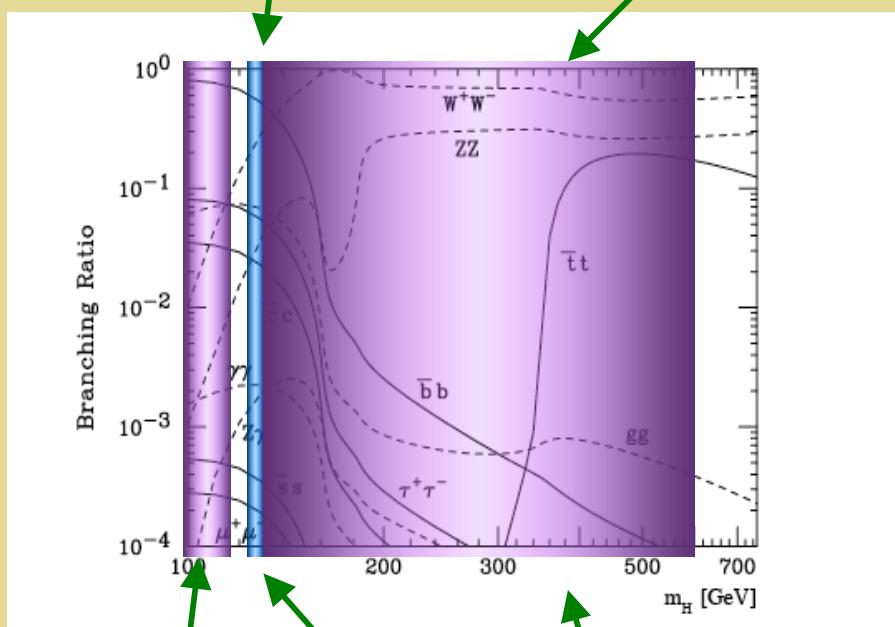
SM Higgs?

SM Higgs?

LHC Indications

LHC Exclusion

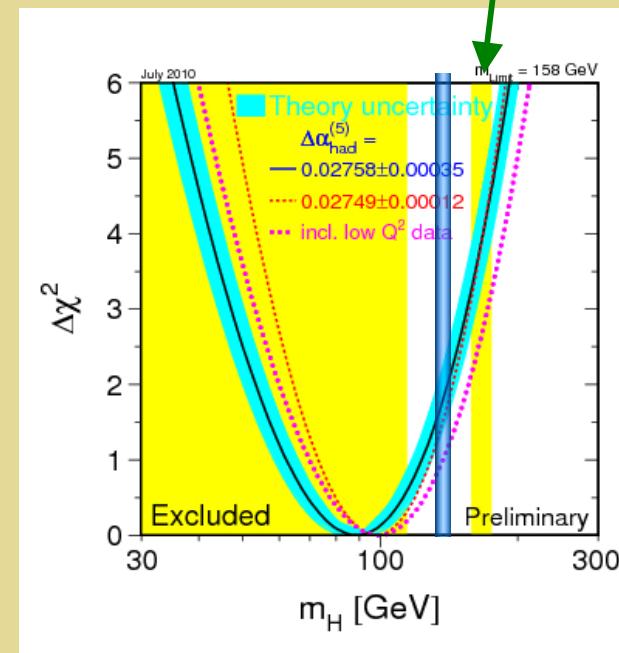
Tevatron Excl



LEP Exclusion

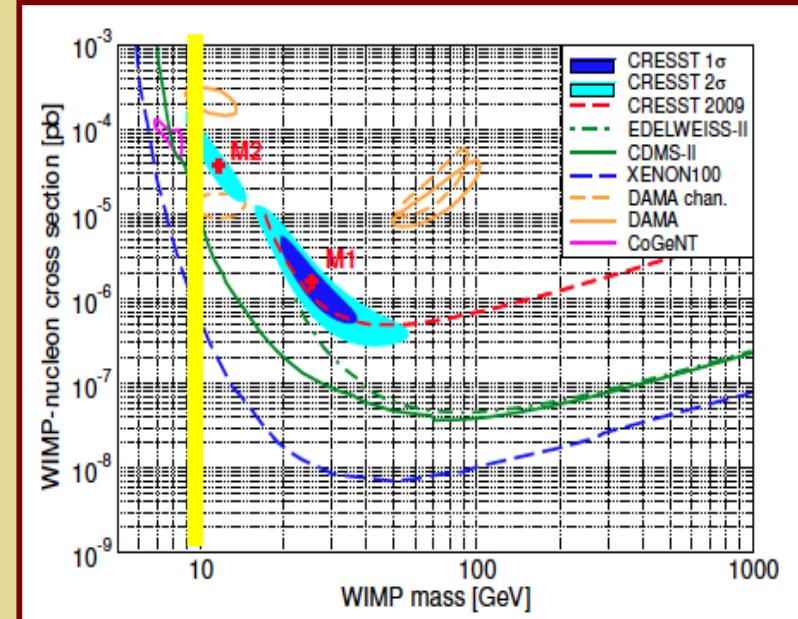
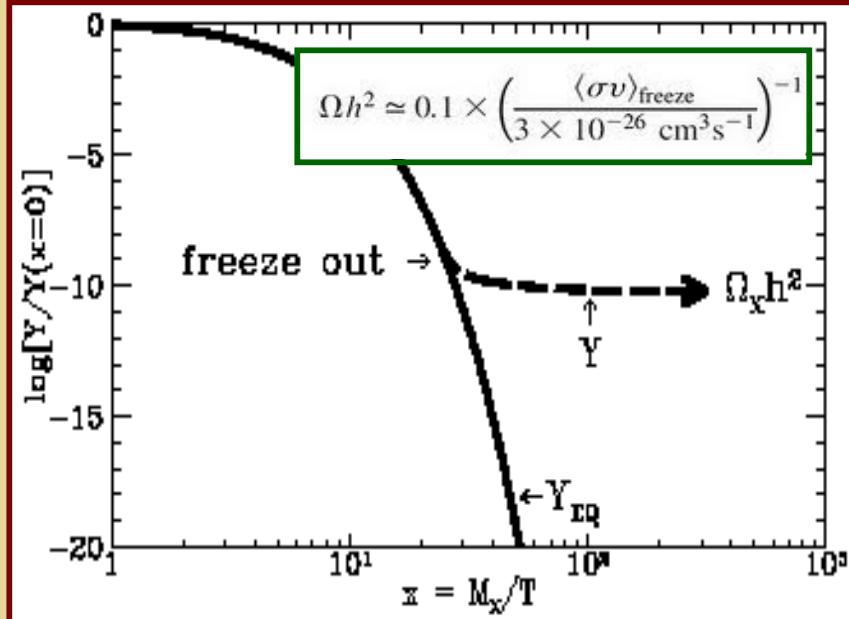
Non-SM Higgs(es) ?

SM Higgs properties ?

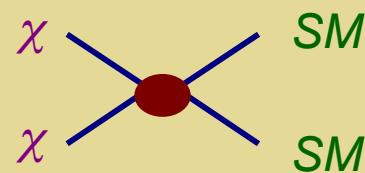


Precision Tests

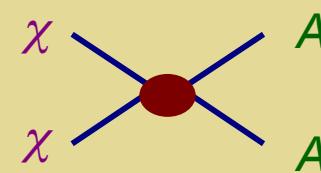
Dark Matter: Ω_χ & σ^{SI}



Thermal DM: WIMP



Direct detection: Spin-indep
DM-nucleus scattering



II. Simplest 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

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

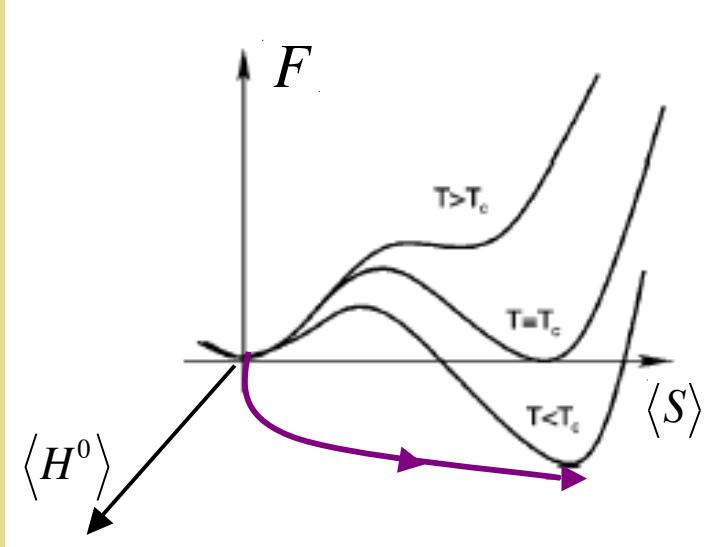
EWPT Scenario

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

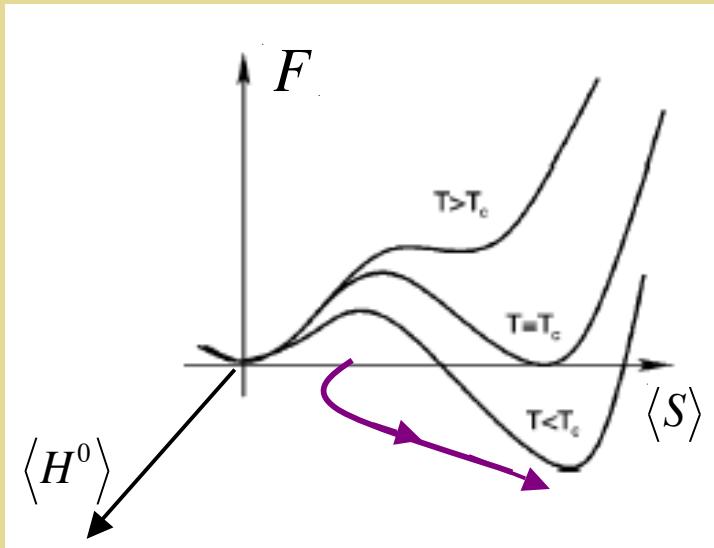
Raise barrier

Lower T_c :
 $a_2 < 0$

Finite Temperature Potential



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



The Simplest Extension

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

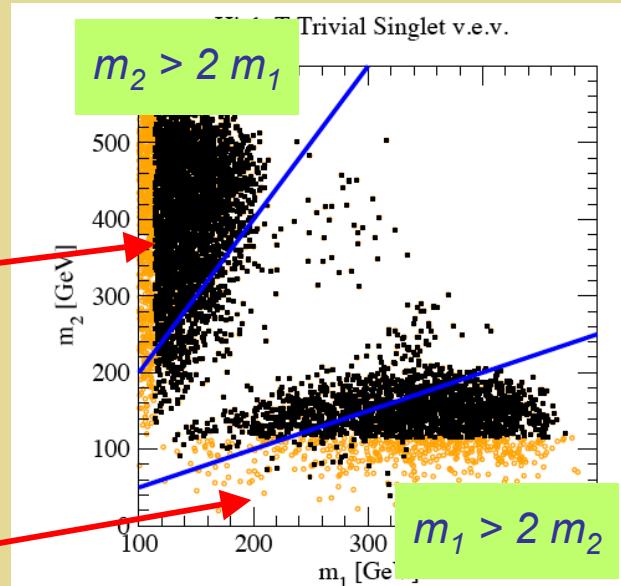
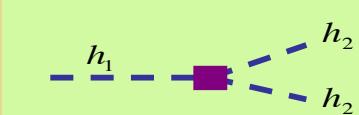
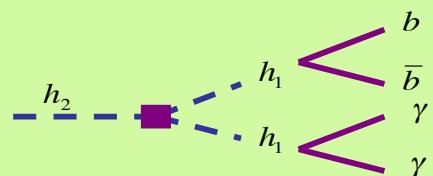
Lower T_c

Modified BRs

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

EWPT & LHC Phenomenology

Signatures



*Light: all models
Black: LEP allowed*

Signal Reduction Factor

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

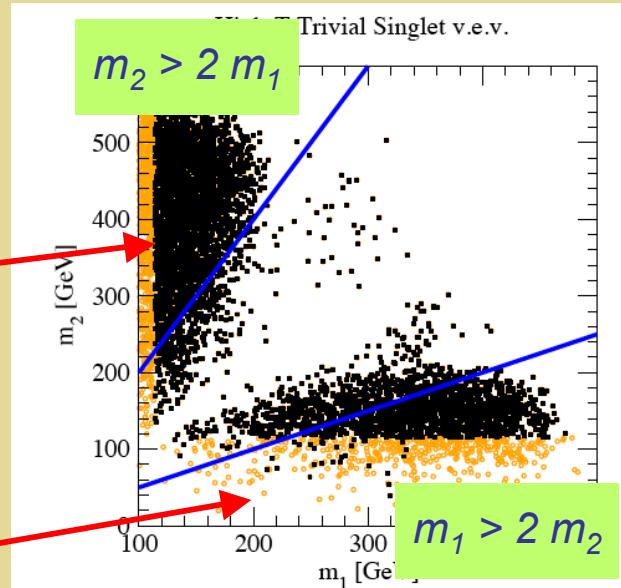
Production *Decay*

EWPT & LHC Phenomenology

Signatures

LHC exotic final states: 4b-jets, $\gamma\gamma + 2$ b-jets...

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



Signal Reduction Factor

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

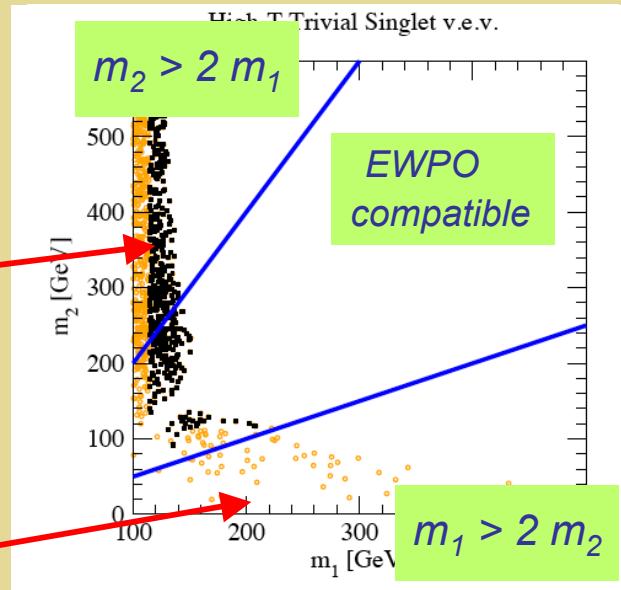
Production *Decay*

EWPT & LHC Phenomenology

Signatures

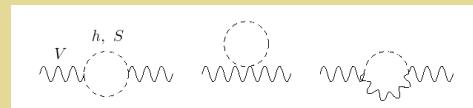
LHC exotic final states: 4b-jets, $\gamma + 2$ b-jets...

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



Scan: EWPT-viable model parameters

Light: all models
Black: LEP allowed



Signal Reduction Factor

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

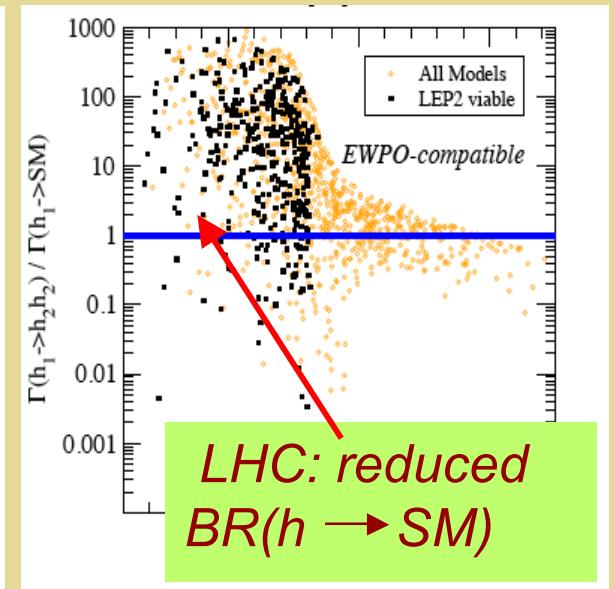
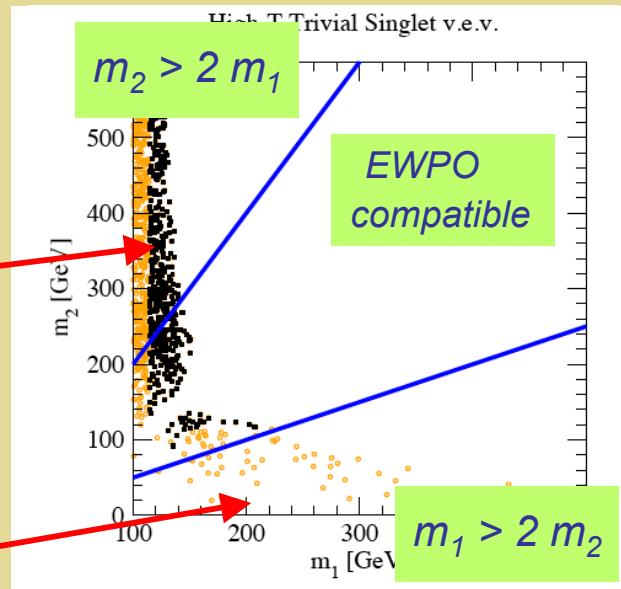
Production *Decay*

EWPT & LHC Phenomenology

Signatures

LHC exotic final states: 4b-jets, $\gamma + 2$ b-jets...

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Signal Reduction Factor

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

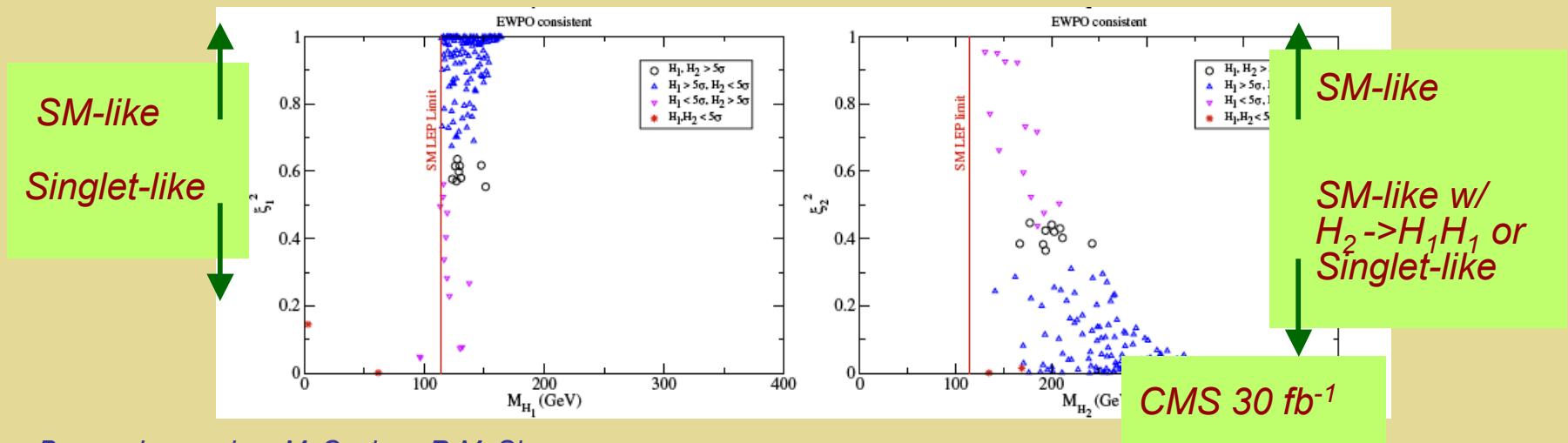
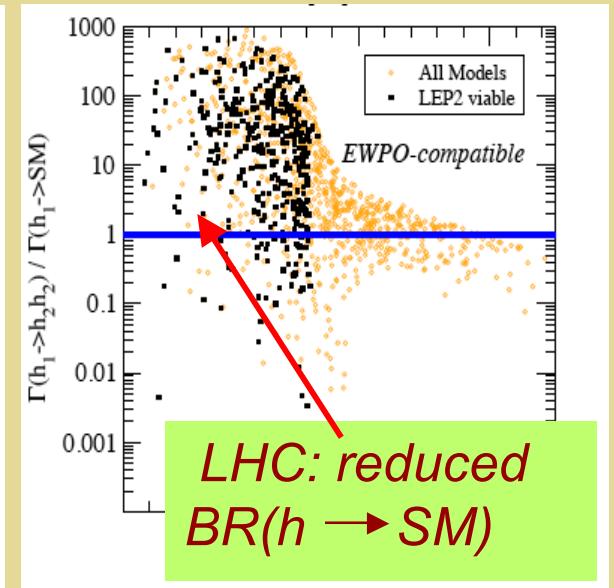
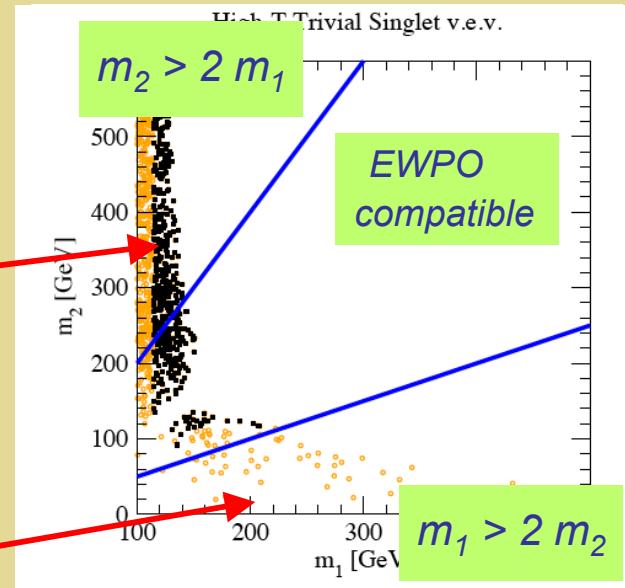
Production *Decay*

EWPT & LHC Phenomenology

Signatures

LHC exotic final states: 4b-jets, $\gamma + 2$ b-jets...

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

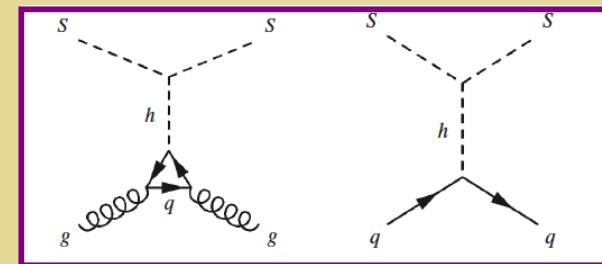
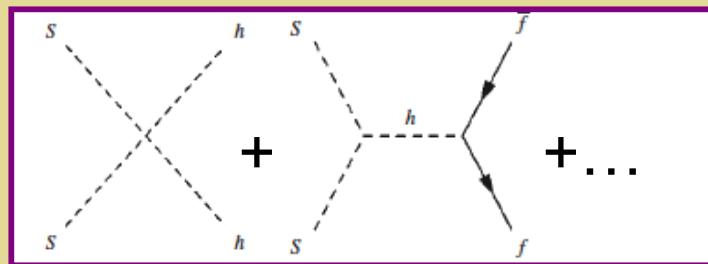


The Simplest Extension

DM Scenario

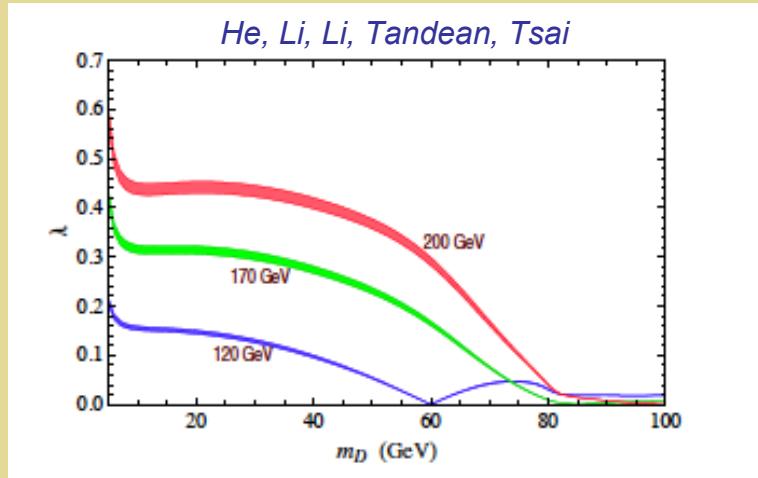
$$V_{\text{HS}} = + \frac{a_2}{2} \left(H^\dagger H \right) S^2$$

Ω_{DM} & σ_{SI}

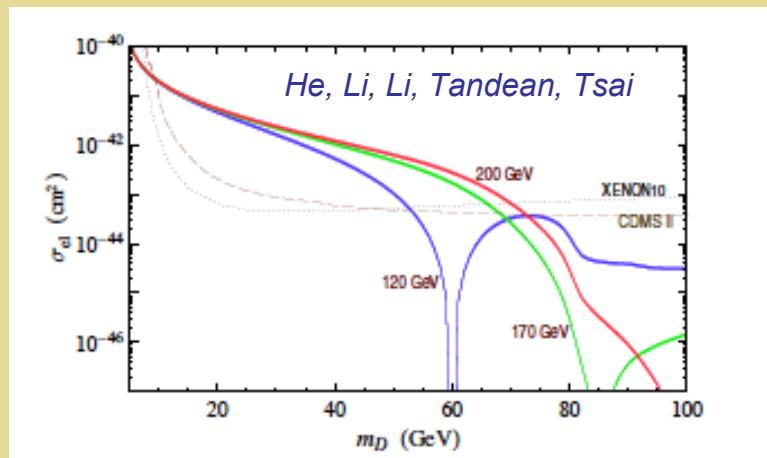


DM Phenomenology

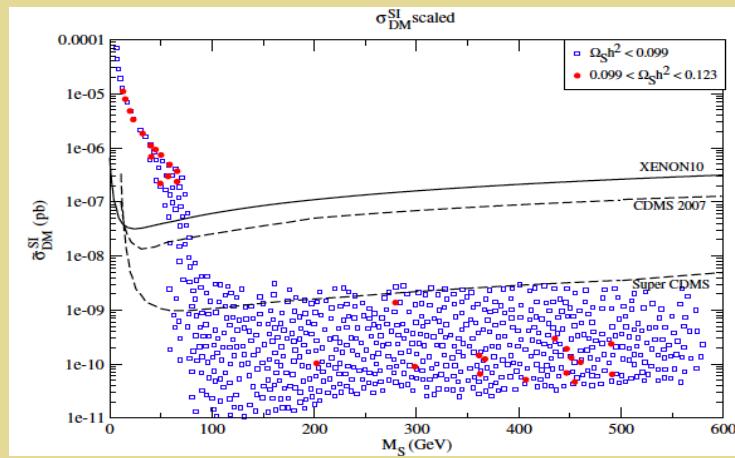
Relic Density



Direct Detection

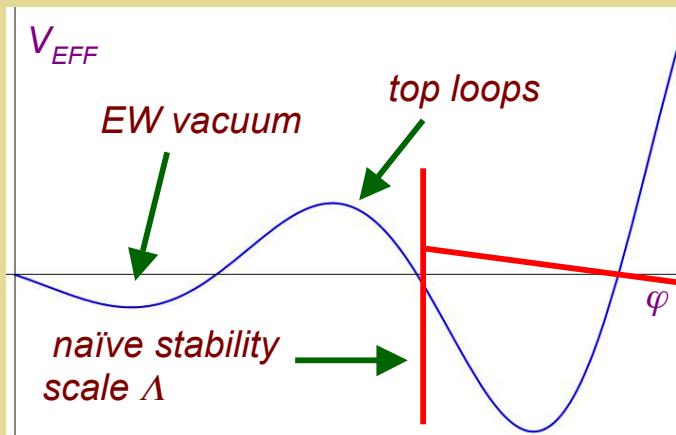


Barger, Langacker, McCaskey,
R-M, Shaugnessy

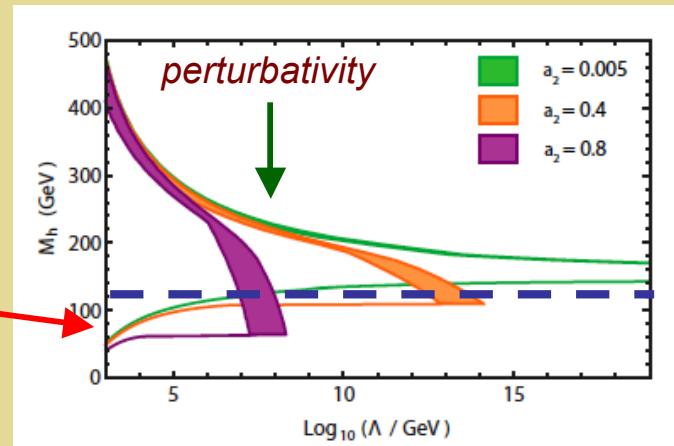


Vacuum Stability & Perturbativity

Preserving EW Min



“Funnel plot”



m_H ?

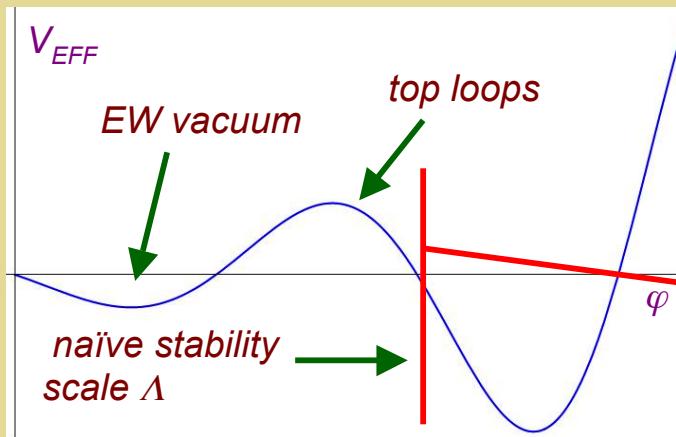
$$\beta_\lambda = \frac{1}{16\pi^2} \left(4\lambda^2 + 12a_2^2 - 36y_t^4 + 12\lambda y_t^2 - 9\lambda g^2 - 3\lambda g'^2 + \frac{9}{4}g'^4 + \frac{9}{2}g^2 g'^2 + \frac{27}{4}g^4 \right)$$

DM-H coupling

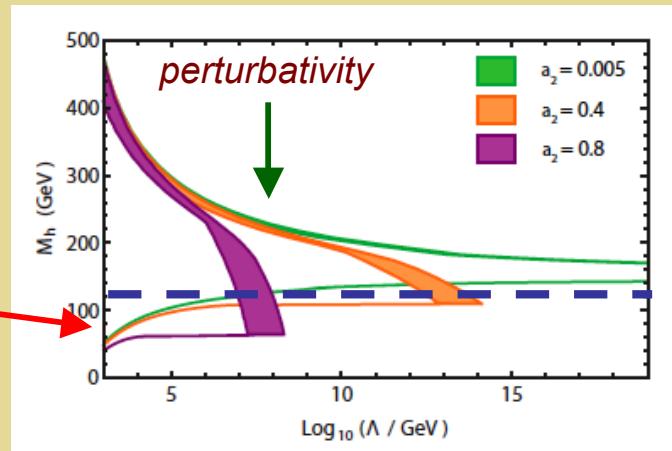
top loops

Vacuum Stability & Perturbativity

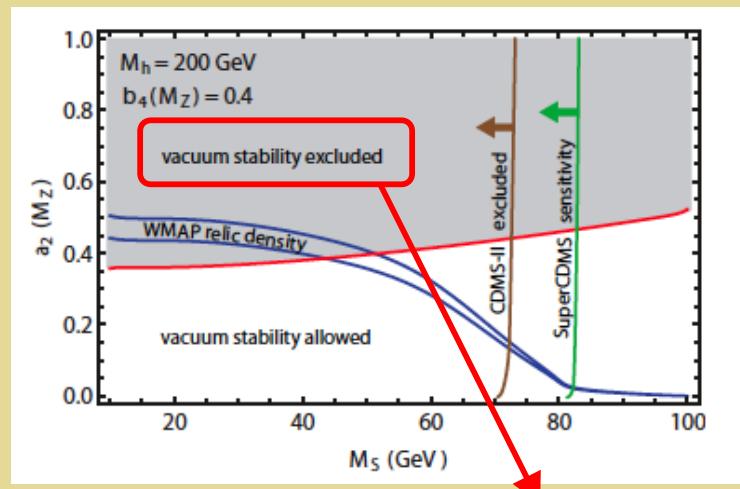
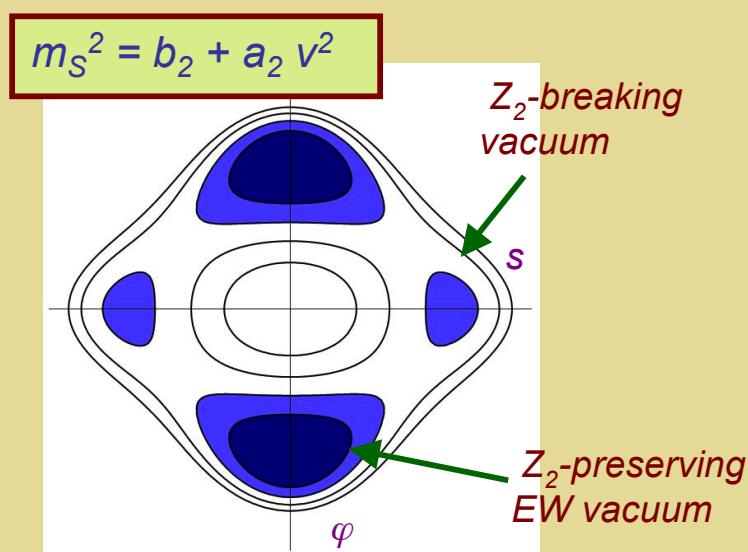
Preserving EW Min



"Funnel plot"



m_H ?

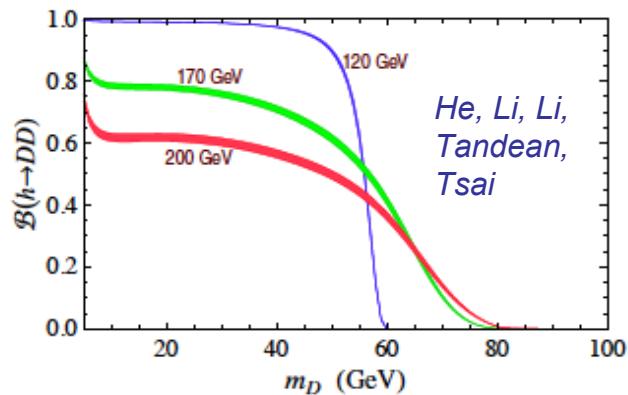


No DM: Z₂-breaking vac

Gonderinger, Li, Patel, R-M

LHC & Higgs Phenomenology

Invisible decays



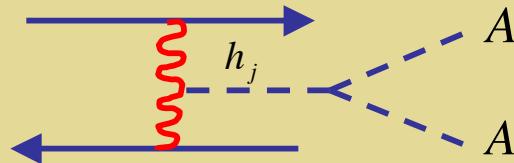
LHC discovery potential

Signal Reduction Factor

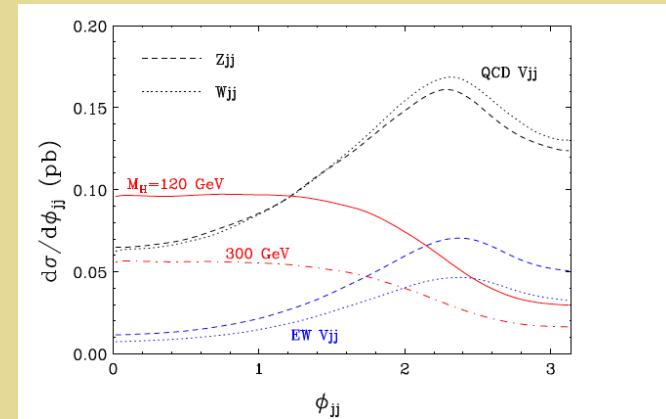
$$\xi_i^2 = V_{1j}^2 \frac{\text{BF}(H_j \rightarrow X_{SM})}{\text{BF}(h_{SM} \rightarrow X_{SM})}$$

Production *Decay*

Dijet azimuthal distribution

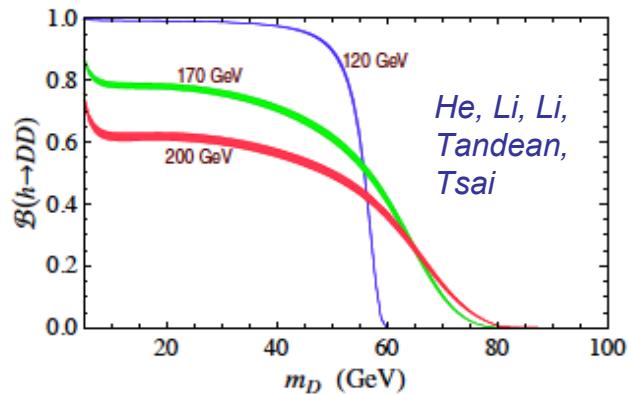


Look for azimuthal shape change of primary jets (Eboli & Zeppenfeld '00)



LHC & Higgs Phenomenology

Invisible decays

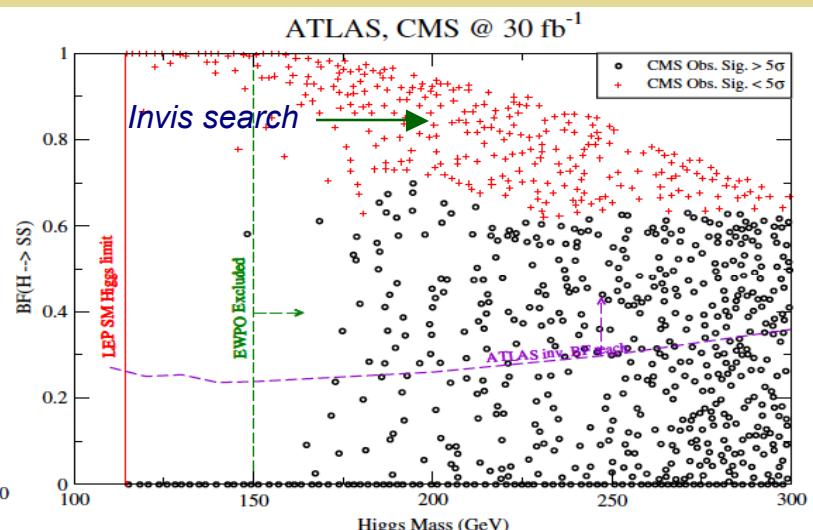
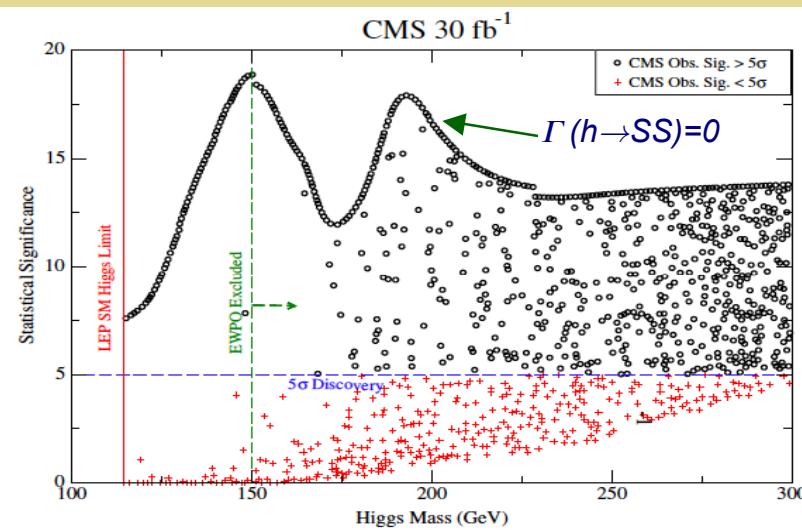


LHC discovery potential

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



Complex Singlet: EWB & DM?

Barger, Langacker, McCaskey, R-M Shaugnessy

Spontaneously & softly broken global U(1)

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



Controls Ω_{CDM} , T_c , & H-S mixing

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

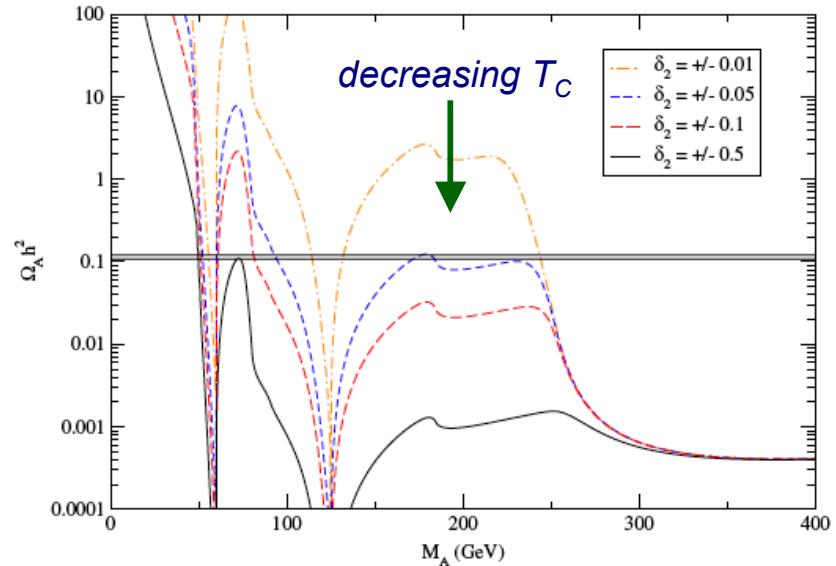
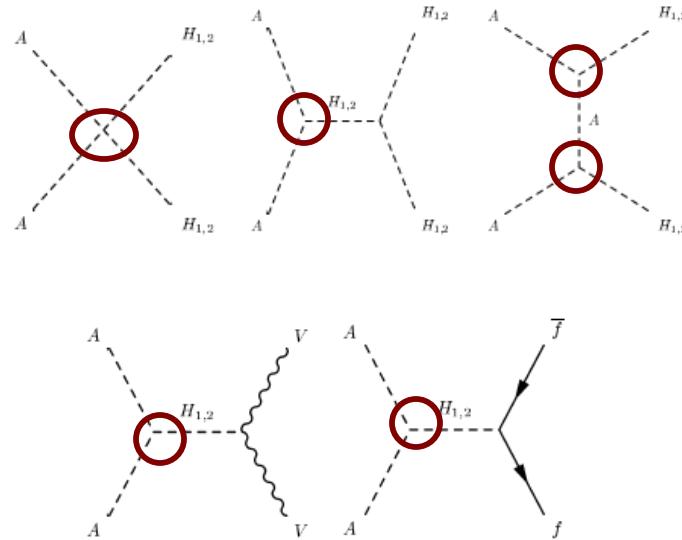


Gives non-zero M_A

Complex Singlet: EWB & DM

Barger, Langacker,
McCaskey, R-M, Shaugnessy

δ_2 controls Ω_{CDM} & EWPT

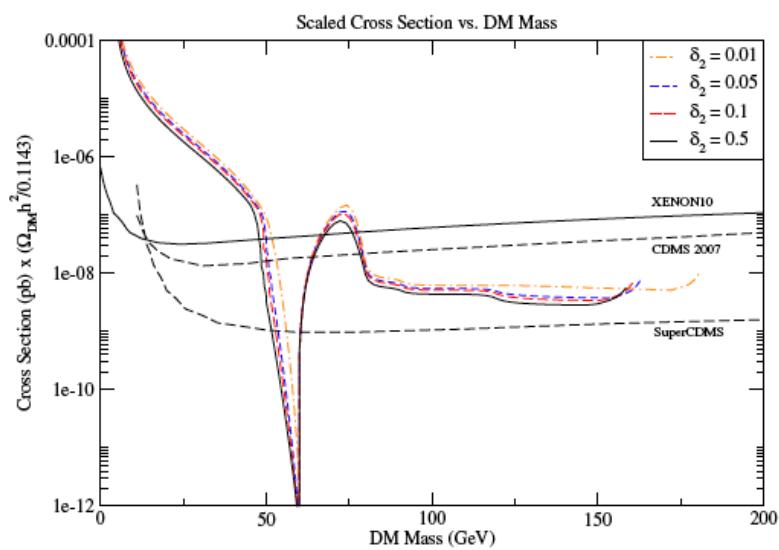
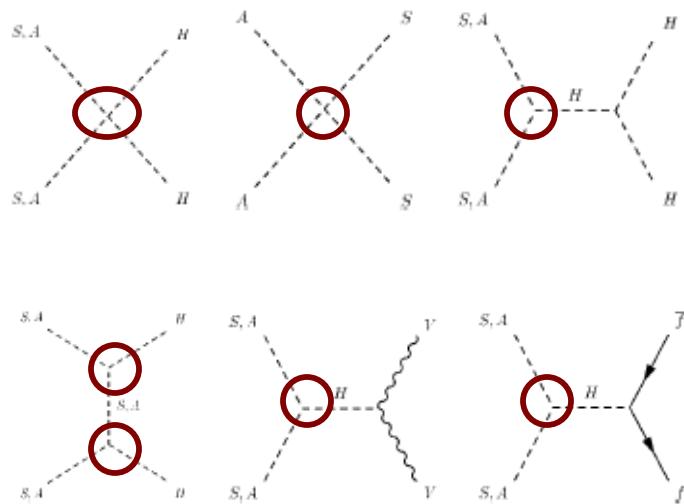


$$M_{H_1} = 120 \text{ GeV}, M_{H_2} = 250 \text{ GeV}, x_0 = 100 \text{ GeV}$$

Complex Singlet: Direct Detection

Barger, Langacker,
McCaskey, R-M, Shaugnessy

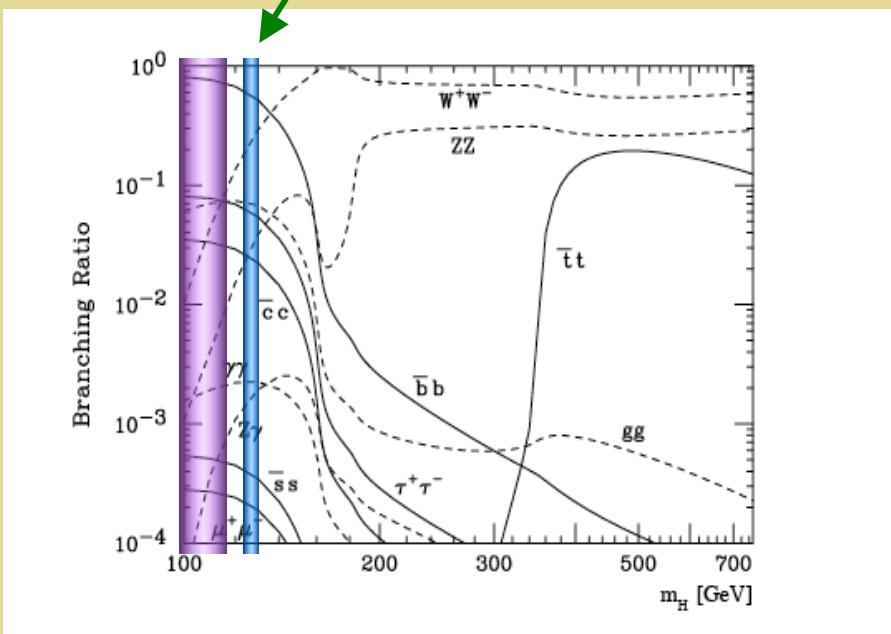
Two component case ($x_0=0$)



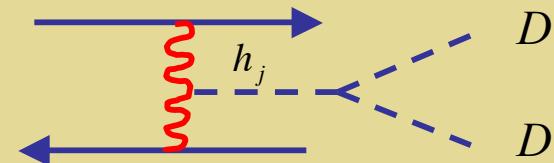
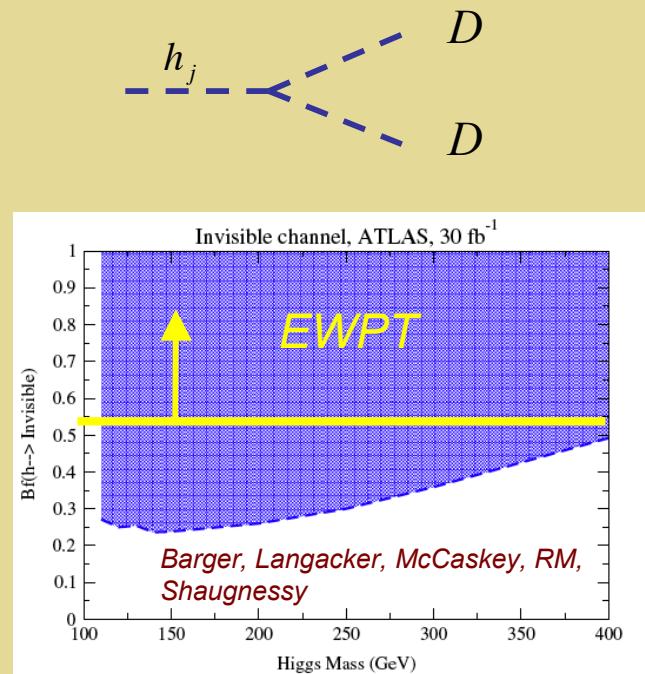
Little sensitivity of scaled σ_{SI} to δ_2

SM Higgs?

SM Branching Ratios ?



Three scalars: $h_{1,2}$ (Higgs-like)
 D (dark matter)



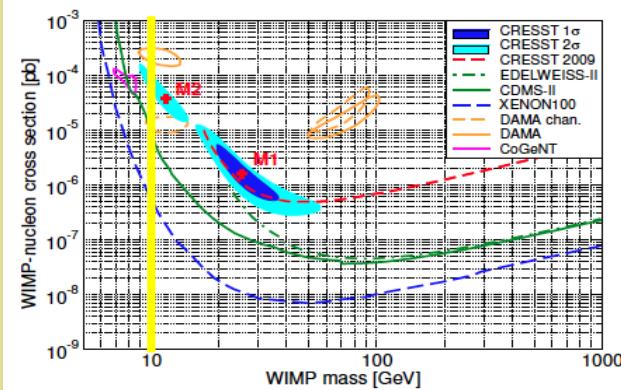
LHC: WBF "Invisible decay" search

SM Higgs?

SM Branching Ratios ?

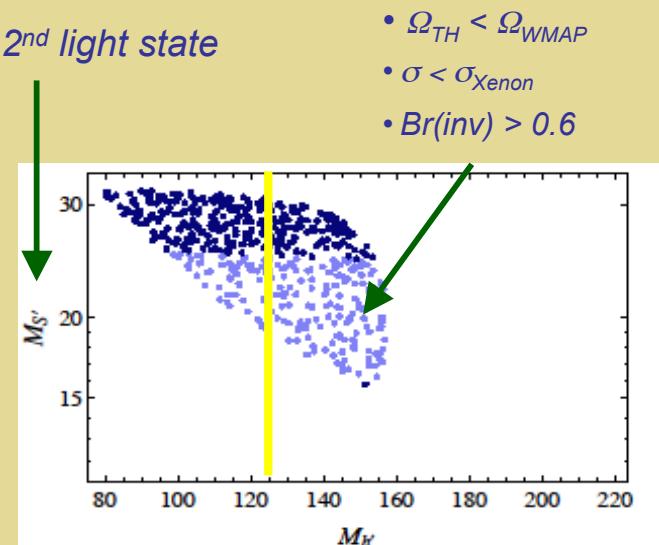


Viable Dark Matter ?



WIMP-Nucleus Scattering

2nd light state



Gonderinger, Lim, R-M

Three scalars: $h_{1,2}$ (Higgs-like)
D (dark matter)



LHC: WBF “Invisible decay” search

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]

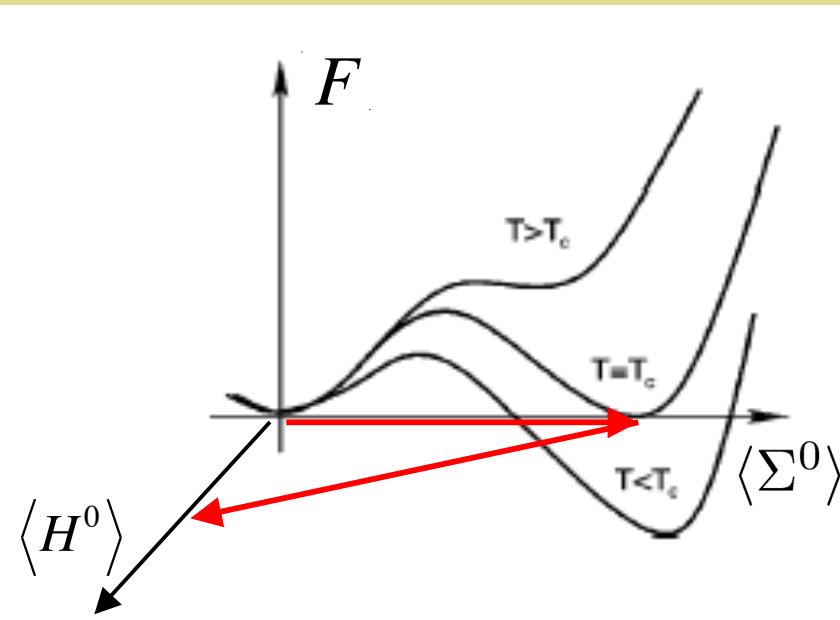
$$V_{H\Sigma} = \frac{a_1}{2} H^\dagger \Sigma H + \frac{a_2}{2} H^\dagger H \text{ Tr } \Sigma^2$$

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

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

Small: ρ -param

Finite Temperature Potential



Multi-step EWSB transition:

- Step 1: quench sphalerons
- Step 2: move to EW/DM vac

Real Triplet : DM Search

Basic signature:

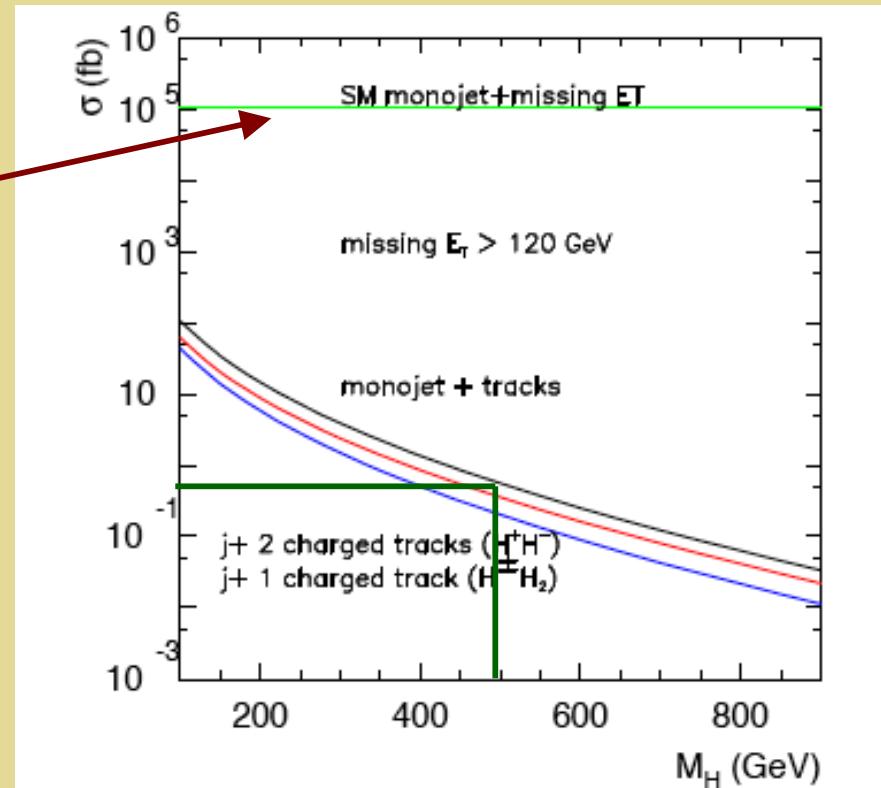
$$x_0 = 0 : H^\pm \rightarrow H_2 \pi^\pm$$

**Charged track disappearing
after ~ 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/
 $Z \rightarrow \nu\nu$ & $W \rightarrow l\nu$



Real Triplet : DM Search

Basic signature:

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

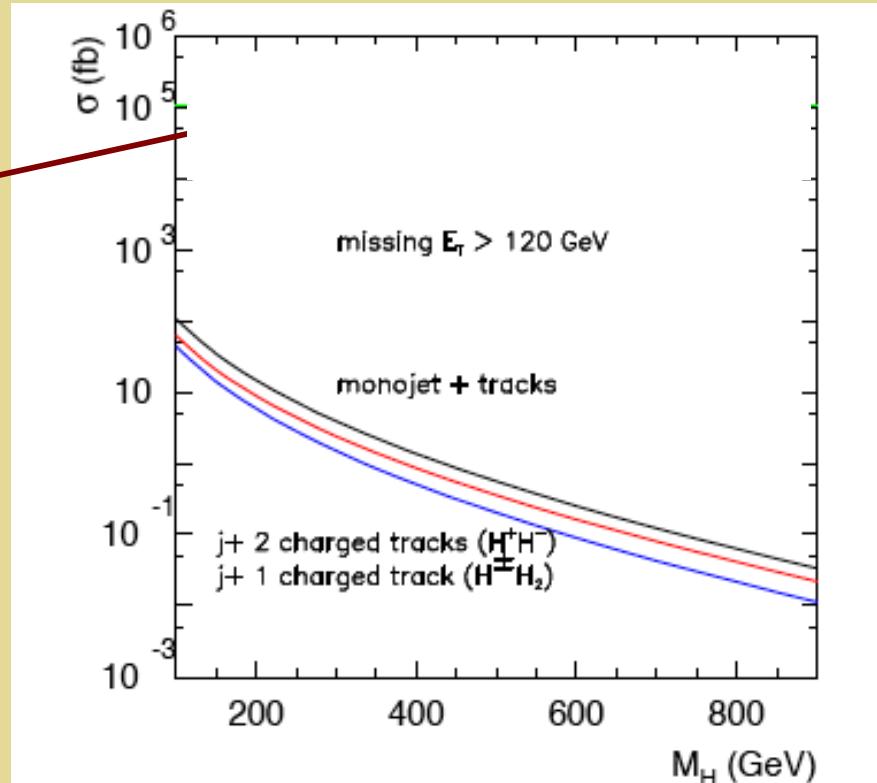
**Charged track disappearing
after ~ 5 cm**

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

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

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

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



Real Triplet : DM Search

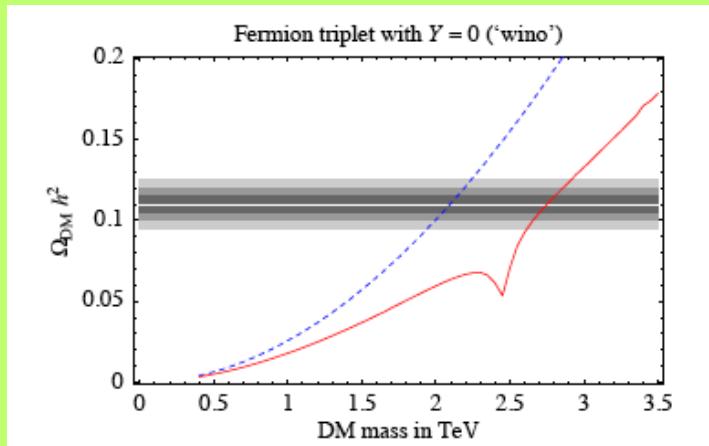
Basic signature:

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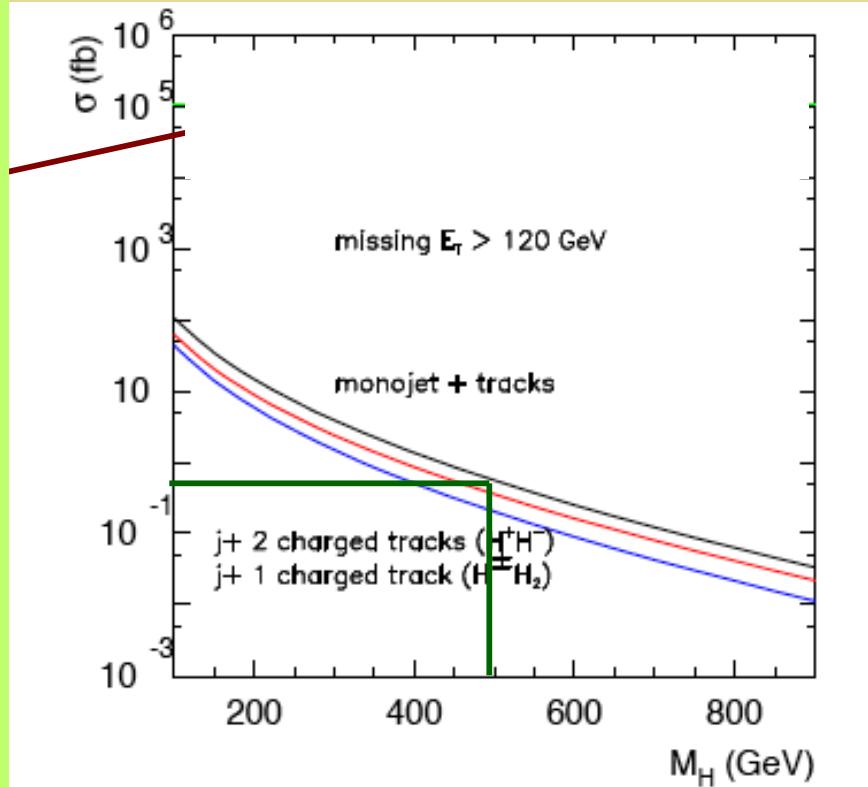
$$q\bar{q} \rightarrow W^{\pm*} \rightarrow H^\pm H_2 \quad q\bar{q} \rightarrow Z^*, \gamma^* \rightarrow H^+ H^-$$

Cirelli et al.:



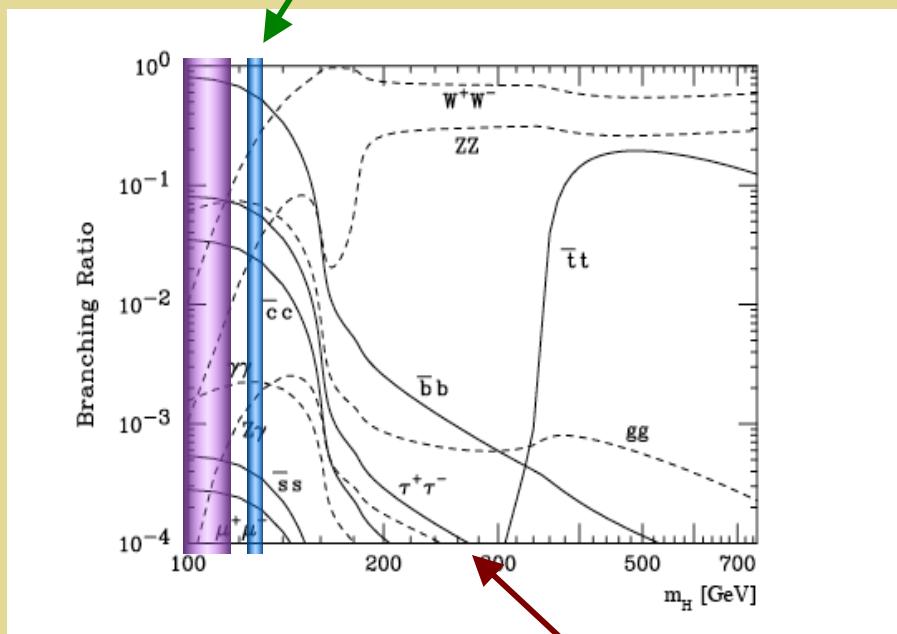
$M_\Sigma = 500$ GeV:

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

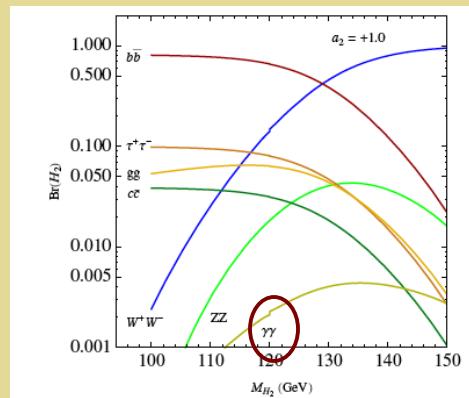
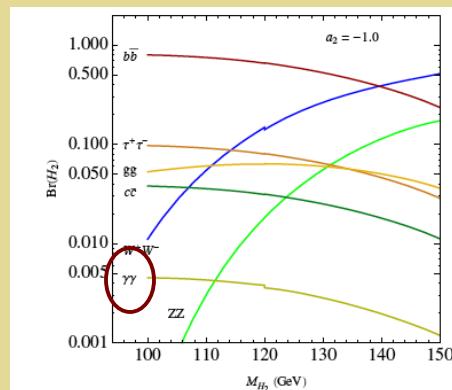
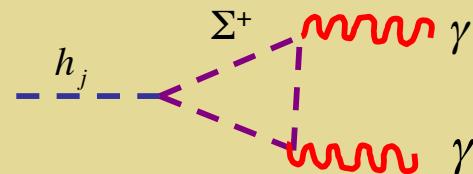


SM Higgs?

SM Branching Ratios ?



Four scalars: h_1 (Higgs-like)
 Σ^0 (dark matter)
 Σ^+, Σ^- (new states)



III. Is it a Scalar ?

<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	?	✓

III. Is it a Scalar ?

Extension	DOF	EWPT	DM
Real singlet	1	✓	✗
Real singlet	1	✗	✓
Complex Singlet	2	✓	✓
Real Triplet	3	?	✓

→ Mixed Higgs-like states and/or modified BRs:
signal reduction ξ , invisible search...

III. Is it a Scalar ?

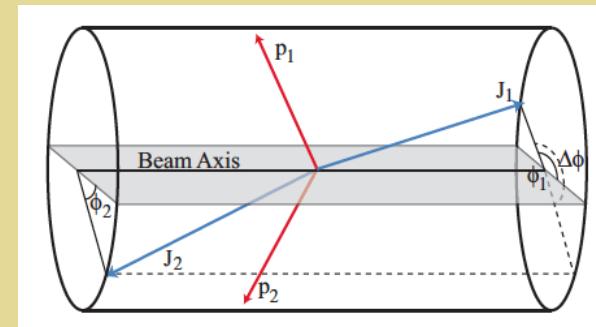
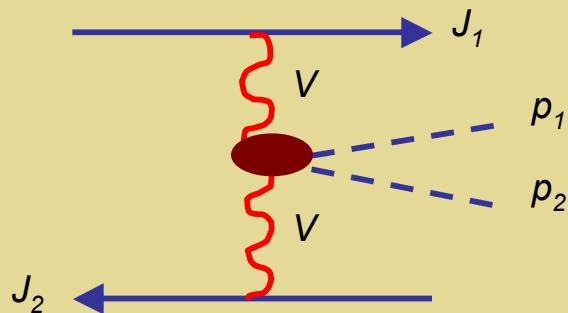
Extension	DOF	EWPT	DM
Real singlet	1	✓	✗
Real singlet	1	✗	✓
Complex Singlet	2	✓	✓
Real Triplet	3	?	✓



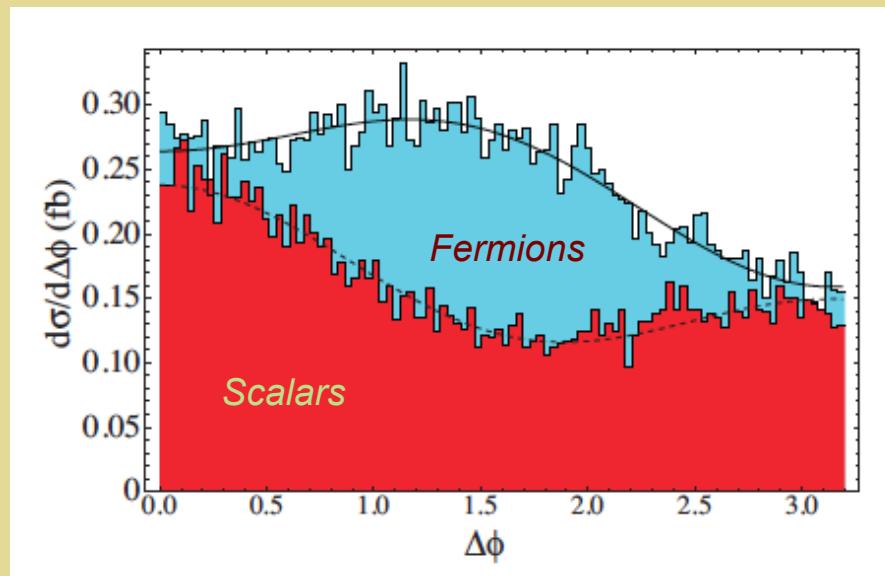
Could be fermionic triplet [e.g., Buckley, Randall, Shuve, JHEP 1105 (2011) 97]. How to distinguish?

Di-Jet Correlations

Buckley, R-M JHEP
1109 (2011) 094

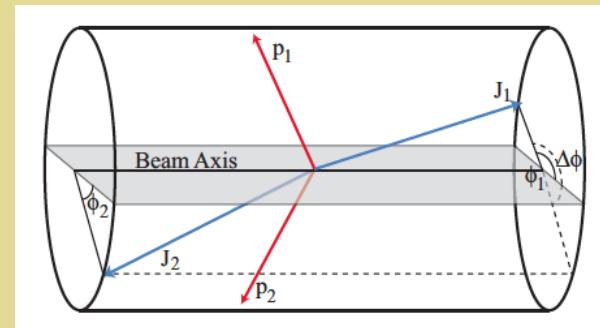
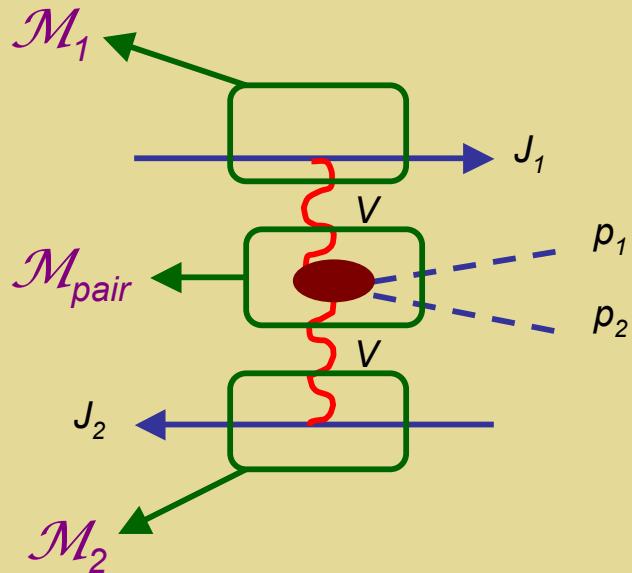


R-hadrons
from gg fusion



Di-Jet Correlations

Buckley, R-M JHEP
1109 (2011) 094



$$\frac{d\sigma}{d\Delta\phi} = A_0 + A_1 \cos \Delta\phi + A_3 \cos 2\Delta\phi$$

$$= (\mathcal{PS}) \mathcal{M}_1(+1) \mathcal{M}_1(-1)^* \mathcal{M}_2(-1) \mathcal{M}_2(+1)^* \\ \times \mathcal{M}_{\text{pair}}(+1, -1) \mathcal{M}_{\text{pair}}(-1, +1)^* + (1 \leftrightarrow -1)$$

Scalars: $A_3 \propto |\mathcal{M}_{\text{pair}}|^2 > 0$

Fermions: $A_3 < 0$

- Abelian
- Non-abelian
for large $\Delta\eta$

IV. 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. Gondleringer, H. Lim, & MRM, arXiv:1202.1316*

Origin of Gauge Dependence

Effective Action

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

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

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

Source term:

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

Not GI

Effective Potential

$$\phi_{\text{cl}}(x) \rightarrow \phi_{\text{cl}} \longrightarrow \Gamma(\phi_{\text{cl}}) = -(\text{vol}) V_{\text{eff}}(\phi_{\text{cl}})$$

Nielsen Identities

Identity:

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

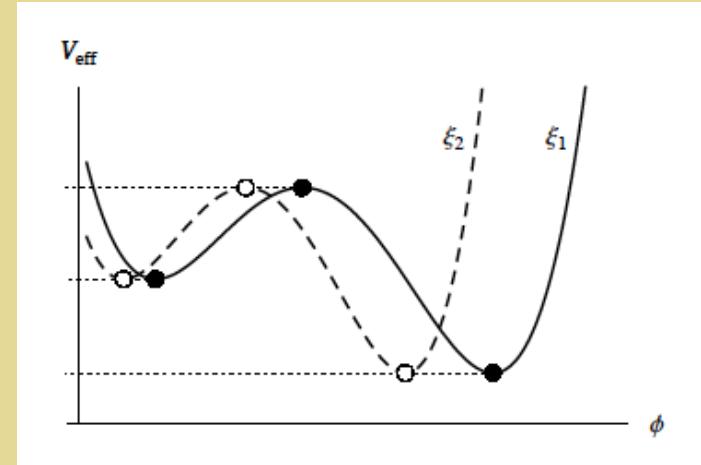
Extremal configurations:

$$\delta \Gamma / \delta \phi(x) = \delta \Gamma / \delta A_\mu^a(x) = 0 \quad \longrightarrow \quad \frac{\partial \Gamma}{\partial \xi} = 0$$

Effective potential:

$$\phi \rightarrow \phi_{\min}(\xi) \quad \longrightarrow$$

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



Baryon Number Preservation

“Washout factor”

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

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

$$\zeta = F(\varphi)$$

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

Two qtns of interest:

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

Baryon Number Preservation: Pert Theory

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

Conventional treatments

$$\frac{\varphi(T_C)}{T_C} \approx 1$$

Gauge Dep

$$\xi = F(\varphi)$$

- GI T_C from \hbar exp, $V_{\text{eff}}(\phi^*\phi)$, 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

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

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

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

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

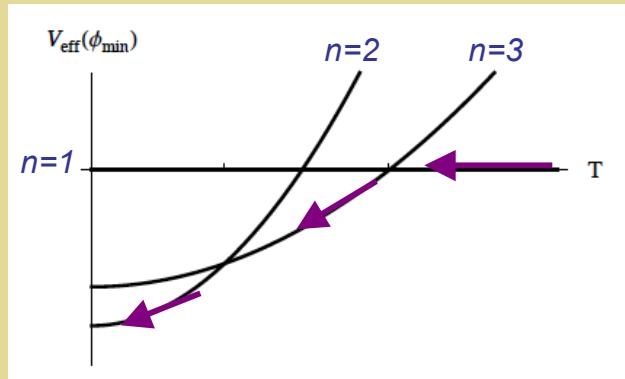
Implement minimization order-by-order (defines ϕ_n)

$$\begin{aligned} V_{\text{eff}}[\phi_{\min}(T), T] &= V_0(\phi_0) + \hbar V_1(\phi_0, T) \\ &\quad + \hbar^2 \left[V_2(\phi_0, T, \xi) - \frac{1}{2} \phi_1(T, \xi) \frac{\partial^2 V_0}{\partial \phi^2} \Big|_{\phi_0} \right] + \mathcal{O}(\hbar^3) \end{aligned}$$

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

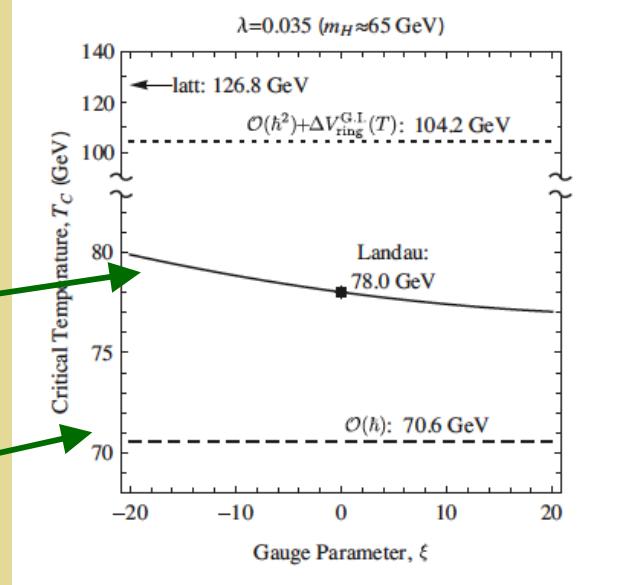
$$V_{\text{eff}}[\phi_{\min}^{(n)}(T), T] = V_0[\phi_0^{(n)}] + \hbar V_1[\phi_0(n), T]$$

Illustrative results in SM:

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

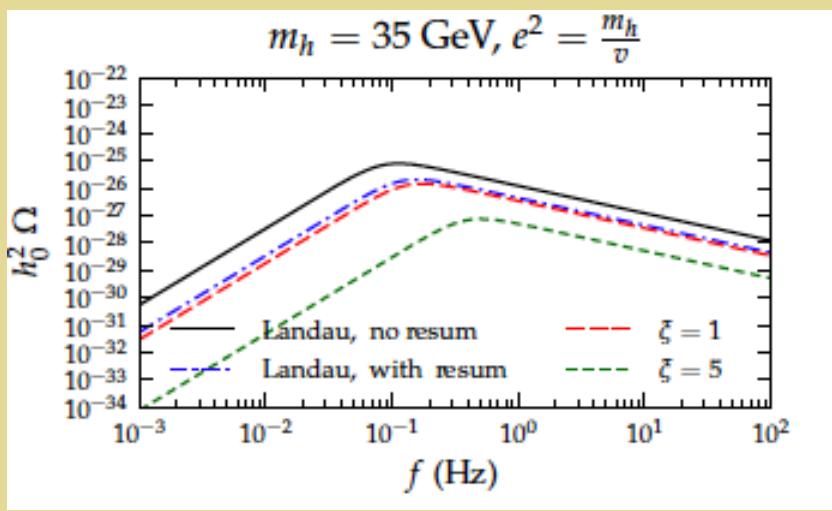
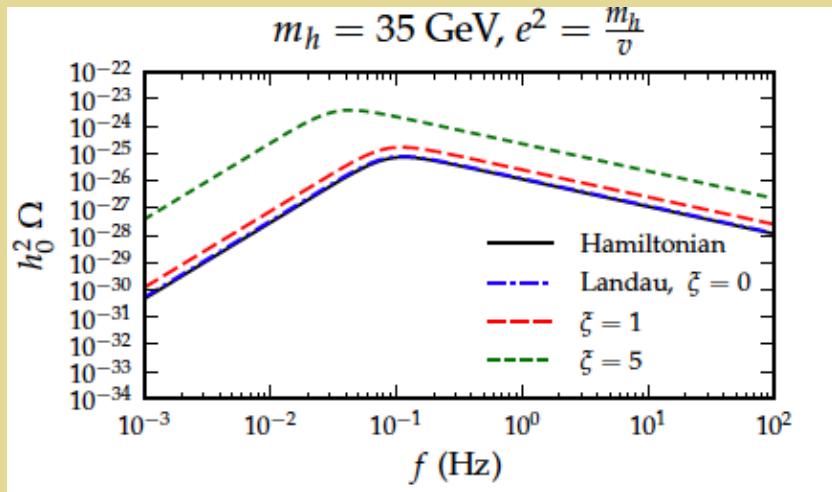
Full ϕ

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



Gravity Waves from EWPT: Pert Theory

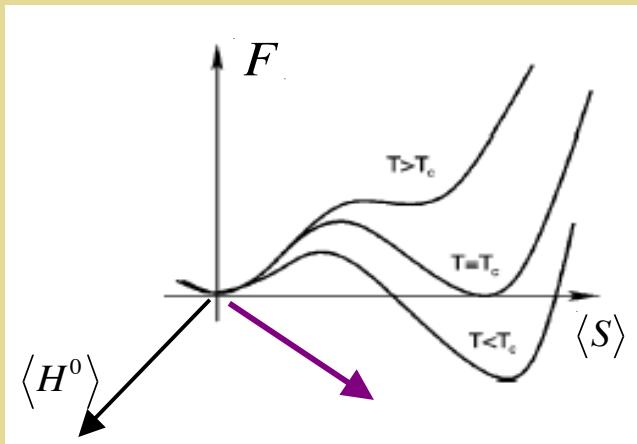
Abelian Higgs Model



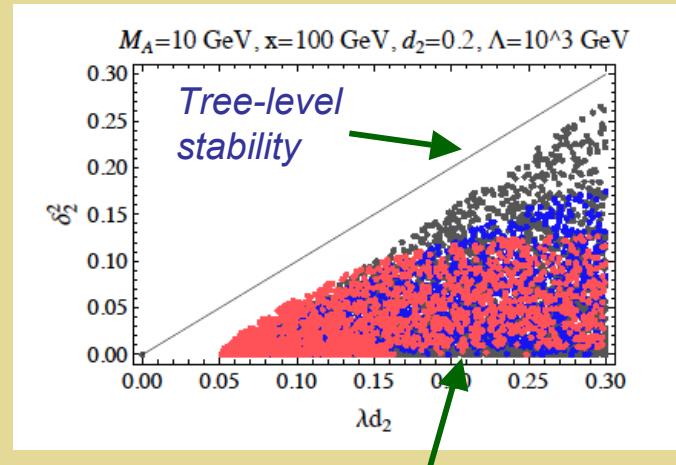
C. Wainwright, S. Profumo, R-M
Phys Rev. D84 (2011) 023521
arXiv:1104.5487[hep-ph]

Vacuum Stability & Gauge Dependence

Complex Singlet Model



Possible runaway direction
for $\delta_2 < 0$ (EWPT)



Full V_{EFF} (1-loop): ξ -dependence

GI Stability Condition

$$\left. \begin{array}{l} \delta_2^2(\mu) < \lambda(\mu) d_2(\mu) \\ \lambda(\mu) > 0 \\ d_2(\mu) > 0 \end{array} \right\} \forall \mu < \Lambda$$

Use β -fns

M. Gonderinger, H. Lim, M. R-M
arXiv:1202.1316 [hep-ph]

Conclusions

- *Cosmology loves scalar fields (inflation): although no fundamental scalar yet observed, perhaps scalar fields can address a number of questions about the early universe*
- *Simple extensions of the SM scalar sector and lead to observable (σ_{SI} , LHC) particle dark matter and/or EWPT with interesting implications: baryogenesis, GW, new Higgs states/modified Higgs properties....*
- *Perhaps observation of these scalars will point to a richer structure for scalar fields in the early universe involving both visible and dark physics*