

BSM Higgs & Cosmology

M.J. Ramsey-Musolf

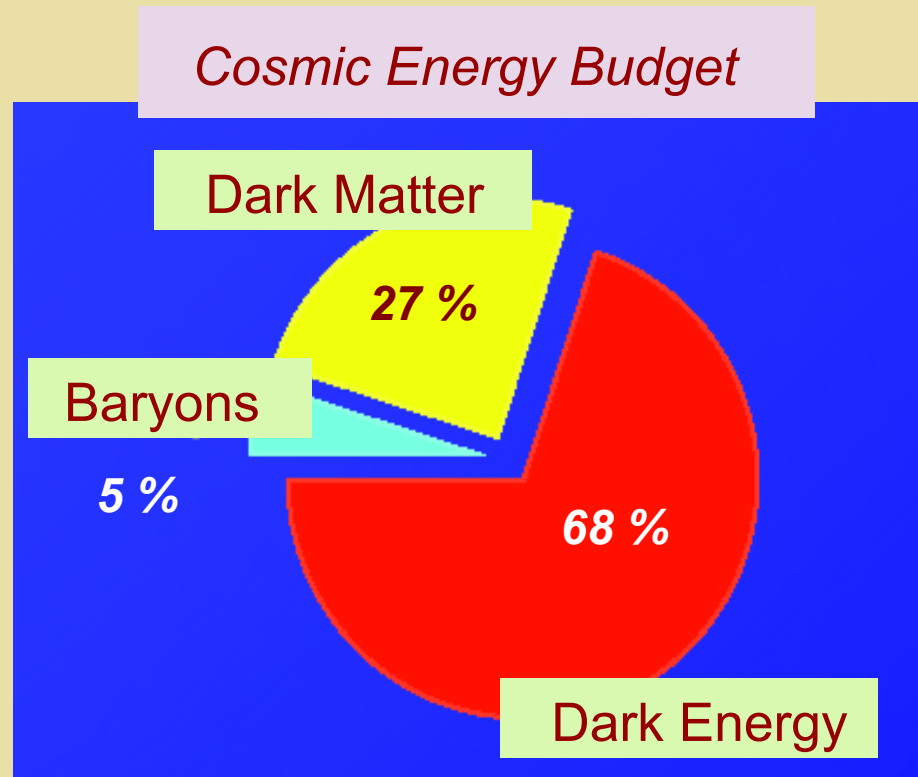
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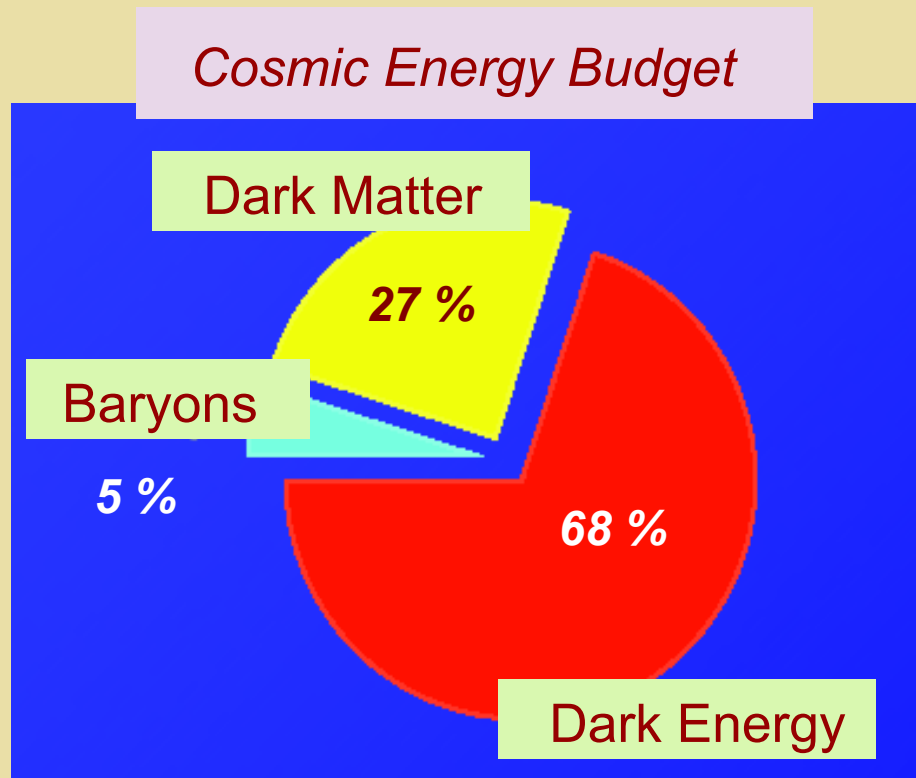
<http://www.physics.umass.edu/acfi/>

FCC Workshop,
CERN January 2017

BSM Higgs & Cosmology

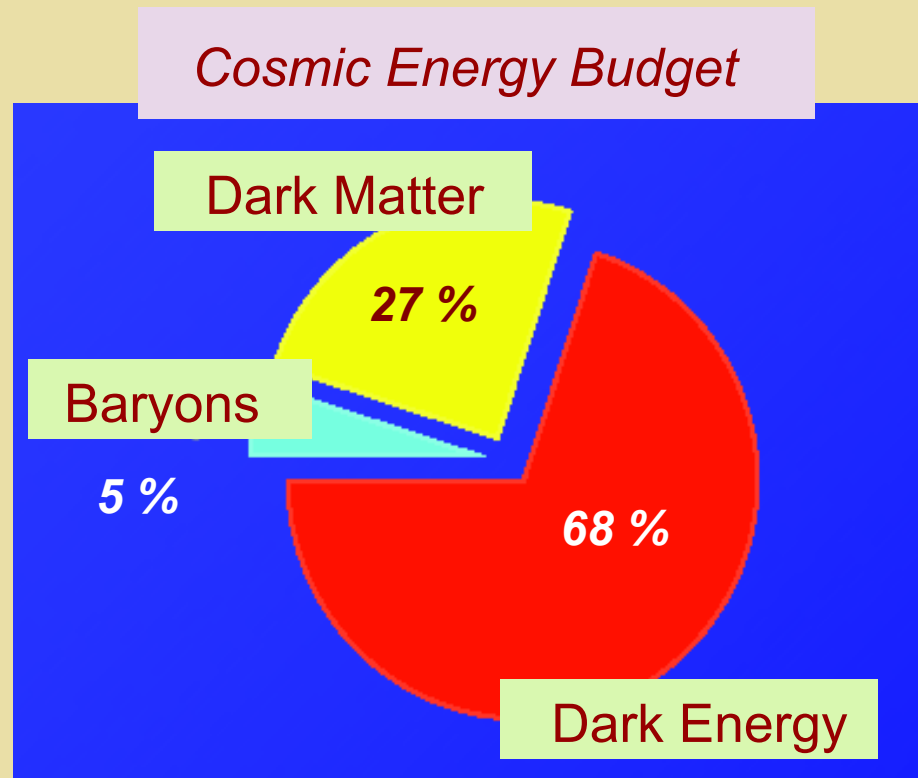


BSM Higgs & Cosmology



To what extent can extended Higgs sectors help explain this puzzle ?

BSM Higgs & Cosmology



This talk: focus primarily on matter-antimatter asymmetry (Y_B) & some dark matter implications

Matter-Antimatter Asymmetry

Was Y_B generated in conjunction with electroweak symmetry-breaking?

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** Electroweak baryogenesis...*

Matter-Antimatter Asymmetry

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- B violation: EW sphalerons*
- C & CP violation: BSM interactions*
- Out of equilibrium: EW phase transition*

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FCC opportunities

EWPT: Why Should We Care ?

- *Were there conditions favorable to generation of the matter-antimatter asymmetry during the era of EW symmetry breaking ?*
- *What was the detailed history and pattern of EW symmetry breaking ?*

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

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

FCC Opportunities

- *To what extent can the LHC and future e^+e^- and pp colliders probe the thermal history of EWSB ?*
- *If the universe underwent a strong first order EWPT, can the signatures be discovered in collider studies ?*
- *What are the necessary energies and integrated luminosities ?*

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- *What are the necessary energies and integrated luminosities ? **

** What will it take to comprehensively probe the landscape of possibilities ?*

FCC Opportunities



could you help us respond?

“There presently is no physics case for a 100-TeV hadron collider”

R. Brinkmann, M. Wing, DESY, 2016

“A 100 TeV p-p collider requires 50x luminosity of HL-LHC [i.e. $3 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$ or 140 ab^{-1}]” B. Richter, SLAC, 2014

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M. Harrison, BNL, 2015



First FCC Physics Workshop
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FCC Opportunities




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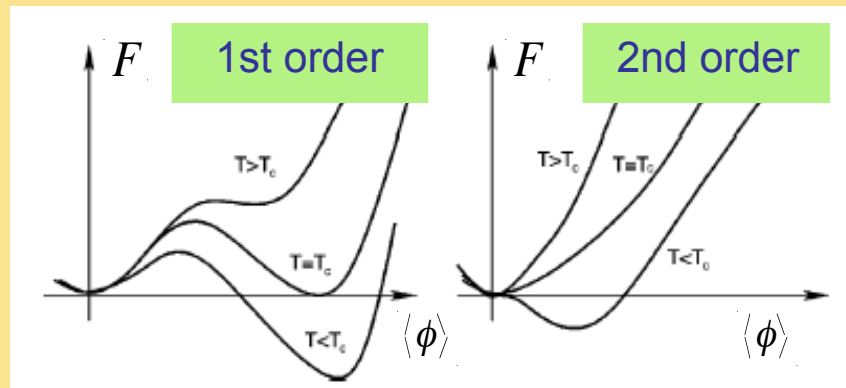
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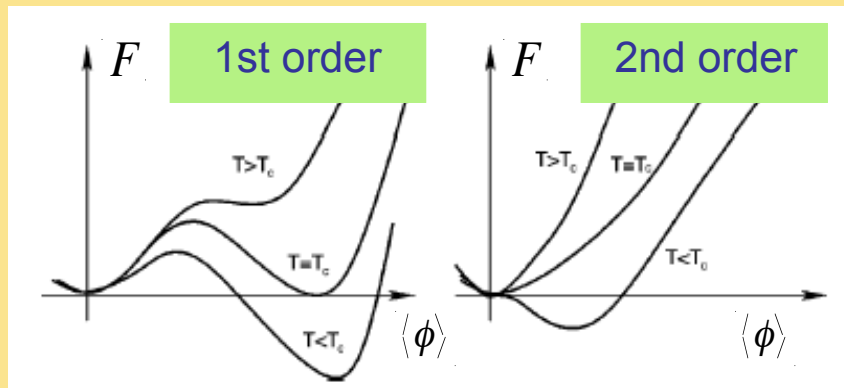
EW Phase Transition

Phase Transitions : St'd Model

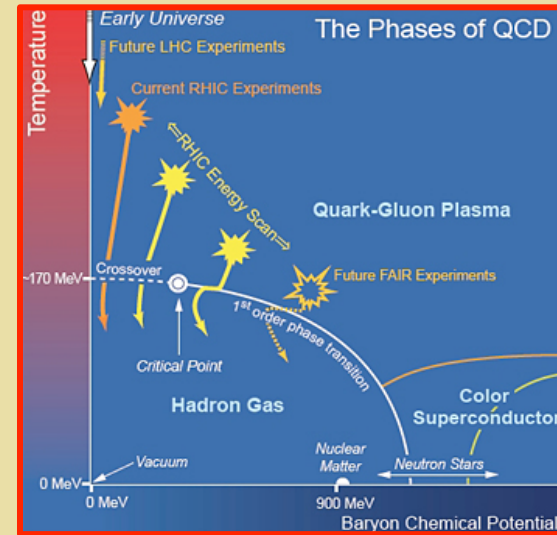


V_{EFF} & Phase Transitions

Phase Transitions : St'd Model

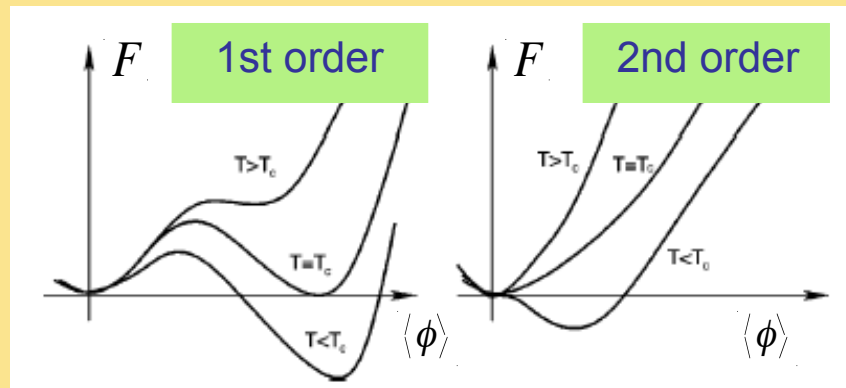


V_{EFF} & Phase Transitions



QCD Phase Diagram

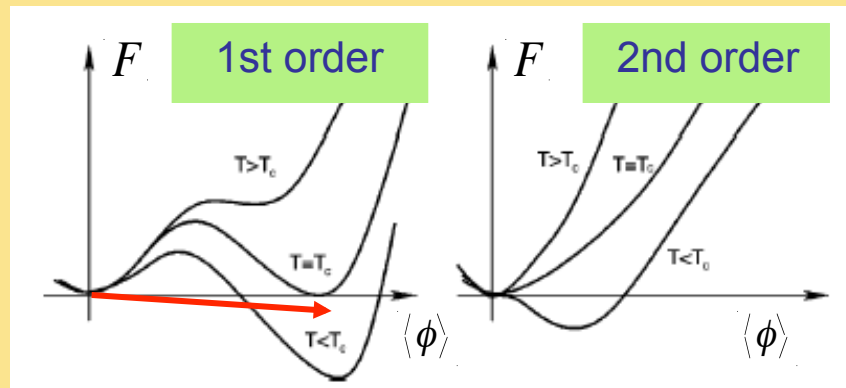
EW Phase Transition: St'd Model



Increasing m_h \longrightarrow

EW Theory: Phase Diagram & m_h

EW Phase Transition: St'd Model

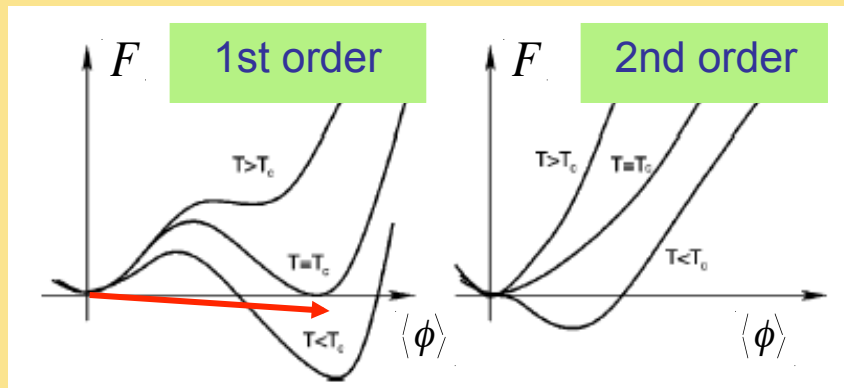


Increasing m_h \longrightarrow

EW Theory: Phase Diagram & m_h

- “Strong” 1st order EWPT needed for electroweak baryogenesis

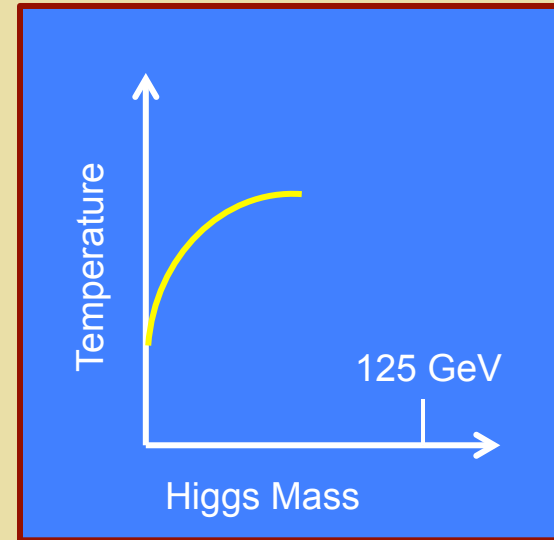
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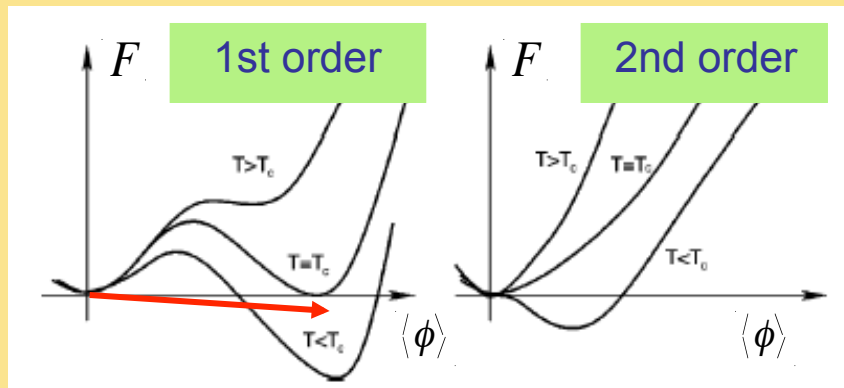
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SM EW: Cross over transition



EW Phase Diagram

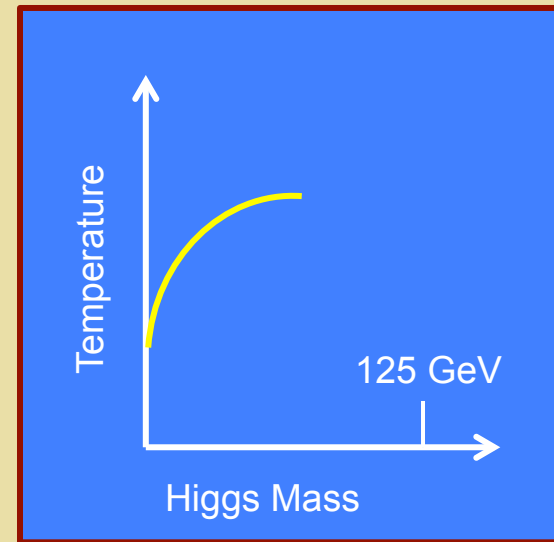
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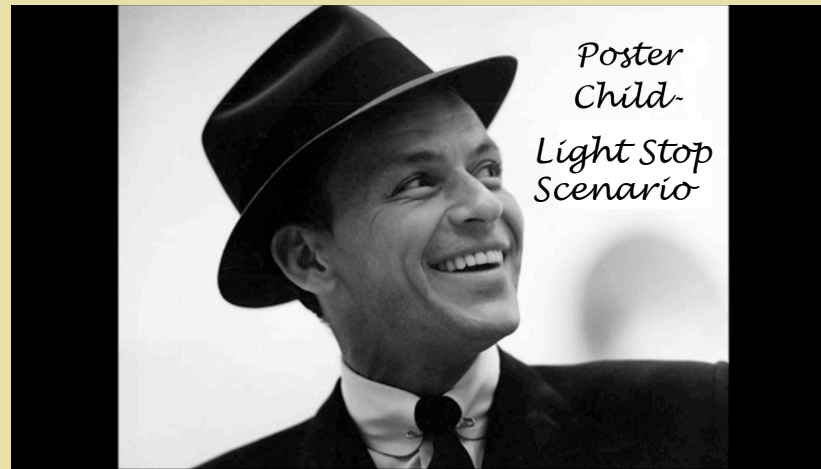
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EW Phase Diagram

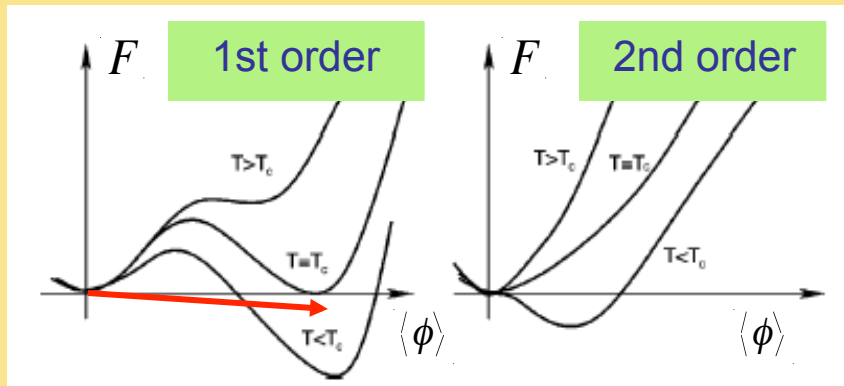
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EWPT “Poster Child”: MSSM Light Stop Scenario



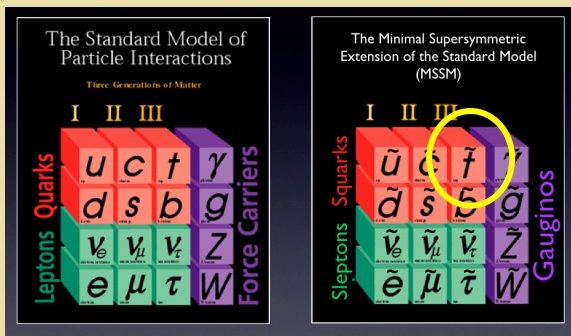
Thermal loops

EW Phase Transition: SUSY



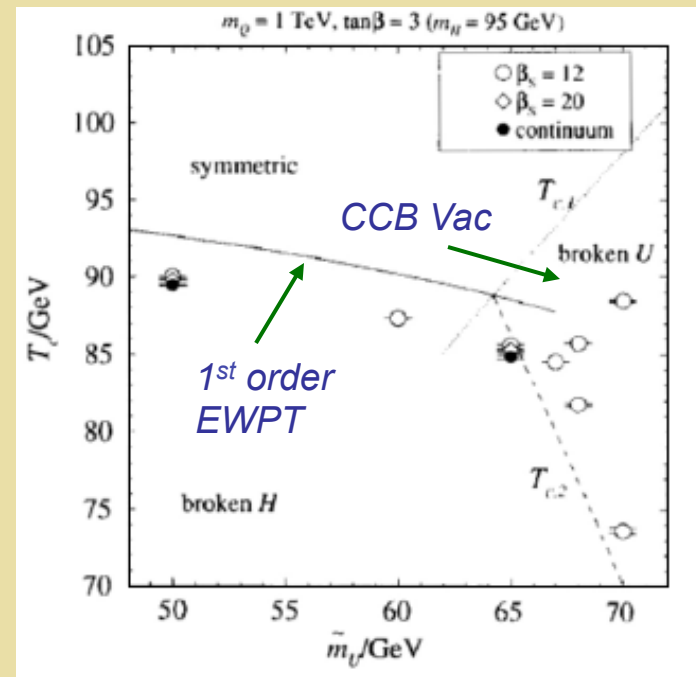
Increasing m_h \longrightarrow

\longleftarrow New scalars



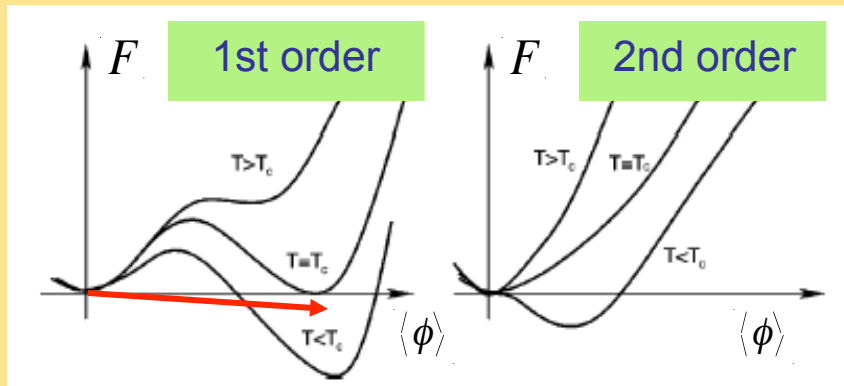
MSSM: Light Stop Scenario

Lattice: Laine, Rummukainen



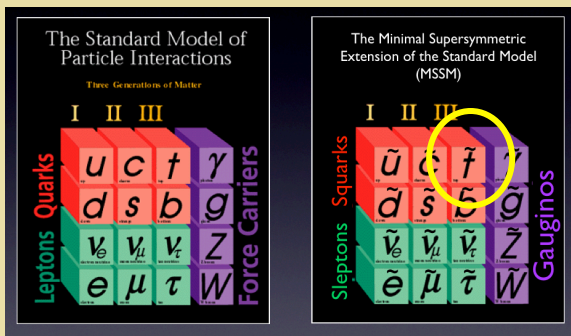
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EW Phase Transition: SUSY



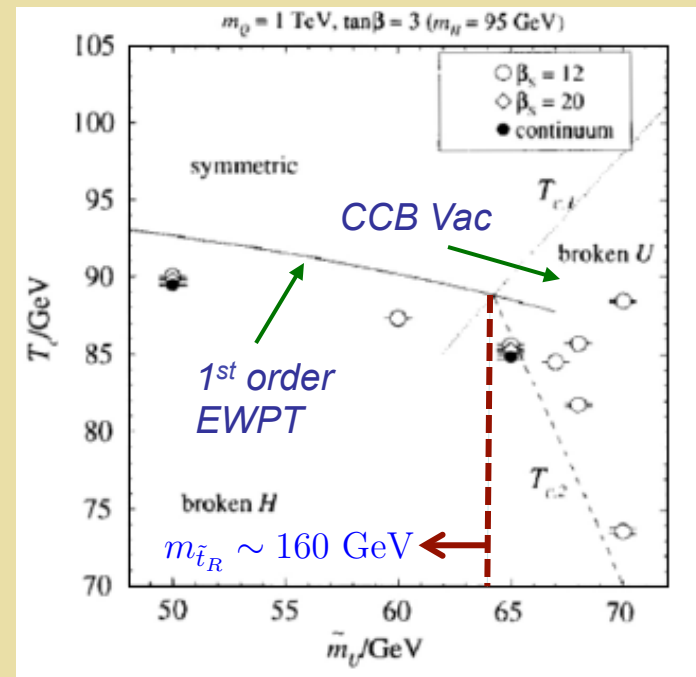
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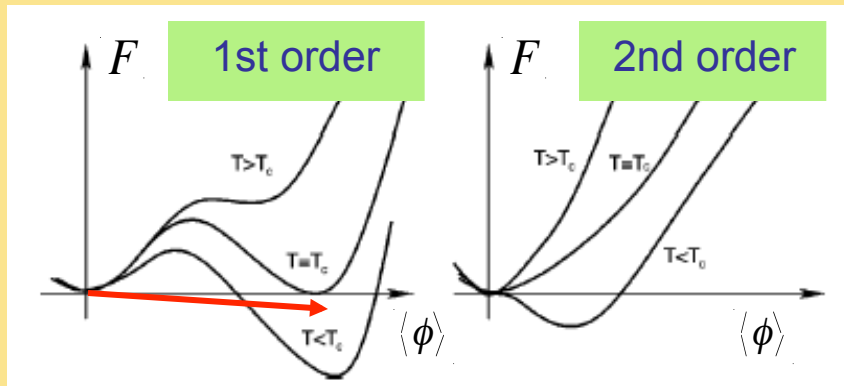
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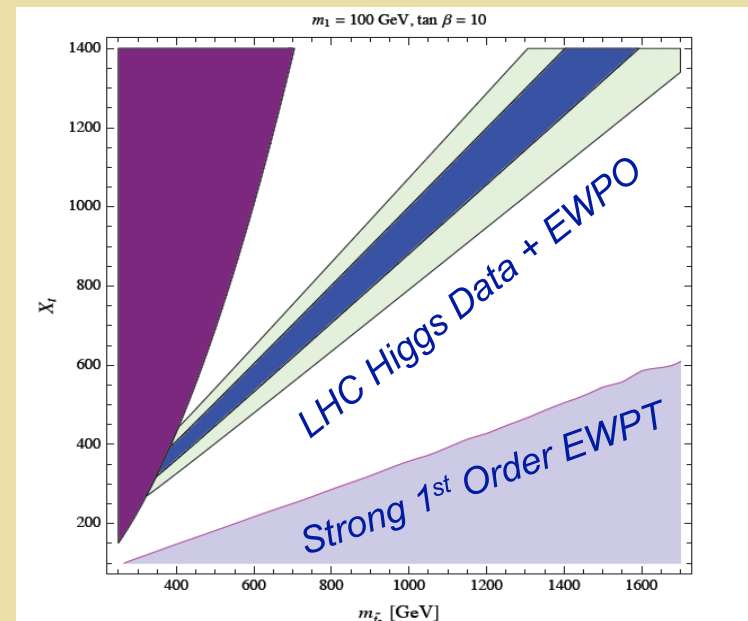
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Light RH stops also affect Higgs properties

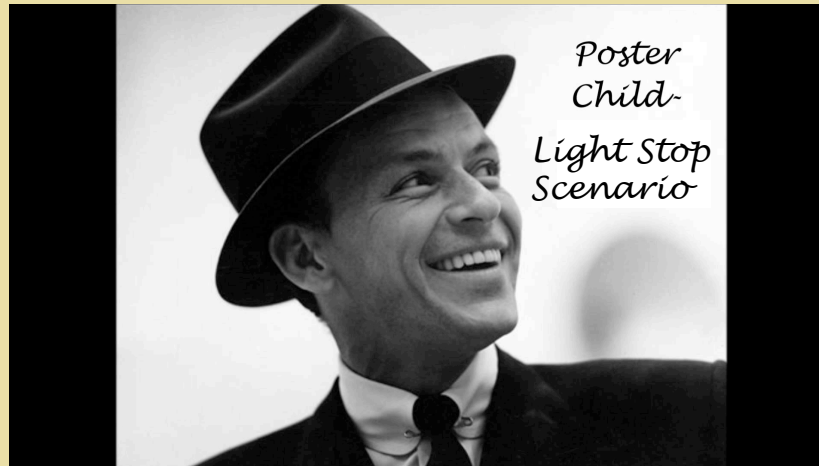
Curtin, Jaiswal, Meade 1203.2932

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



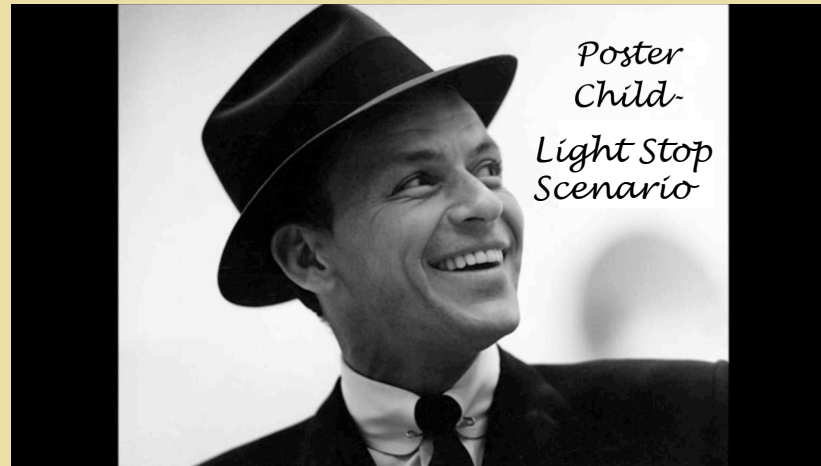
Katz, Perelstein, R-M,
Winslow 1509.02934

Beyond the Poster Child



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

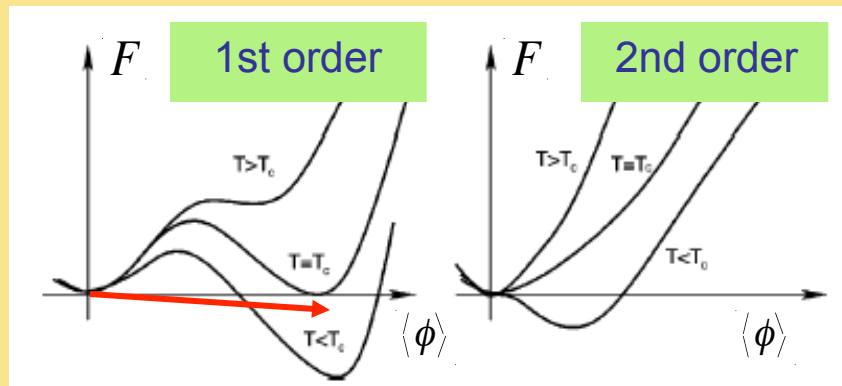
Beyond the Poster Child



- *Gauge singlets (tree-level)*
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*Higgs portal:
SUSY or otherwise*

EW Phase Transition: Higgs Portal

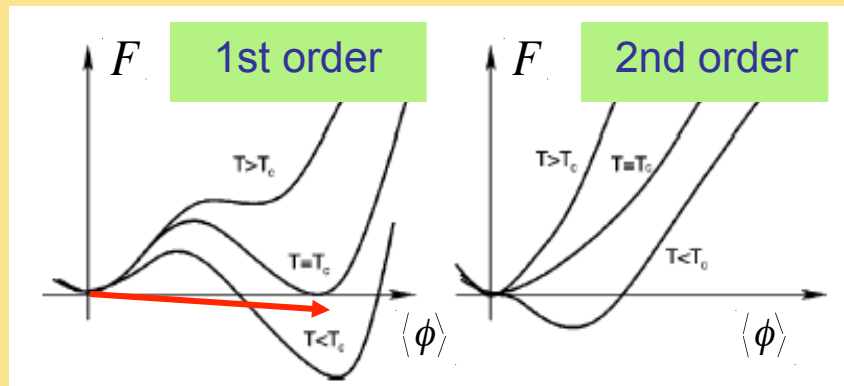


Increasing m_h \longrightarrow

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

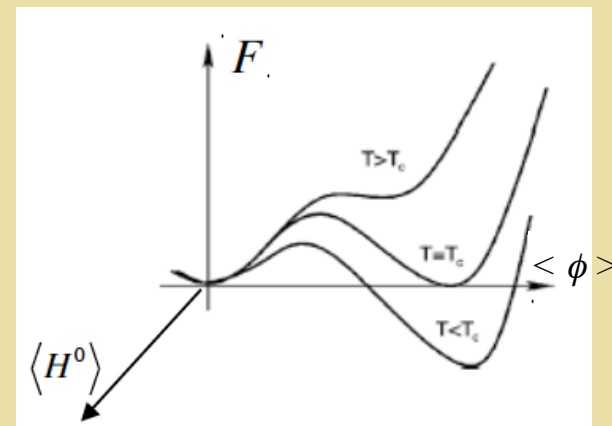
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- Renormalizable
- ϕ : singlet or charged under $SU(2)_L \times U(1)_Y$
- Generic features of full theory (NMSSM, GUTS...)
- More robust vacuum stability
- Novel patterns of SSB

Higgs Portal: Simple Scalar Extensions

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet: Z₂</i>	1	✓	✗
<i>Real singlet: Z₂</i>	1	✓	✓
<i>Complex Singlet</i>	2	✓	✓
<i>EW Multiplets</i>	3+	✓	✓

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

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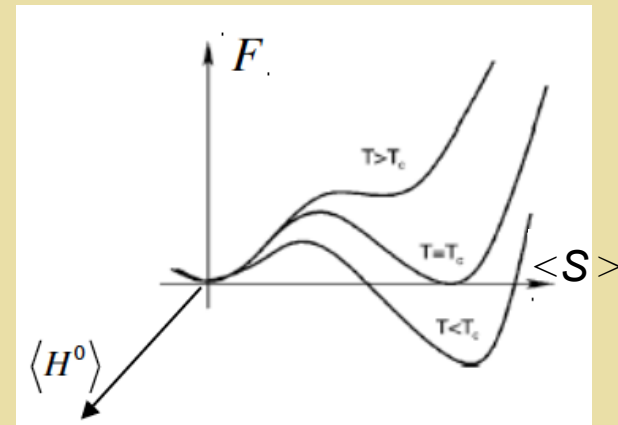
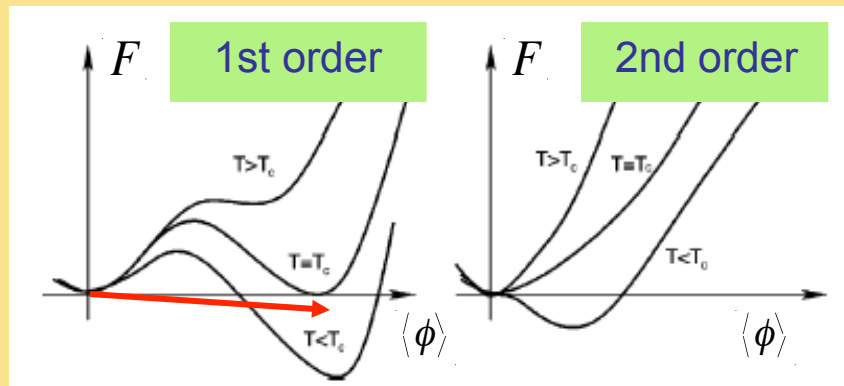
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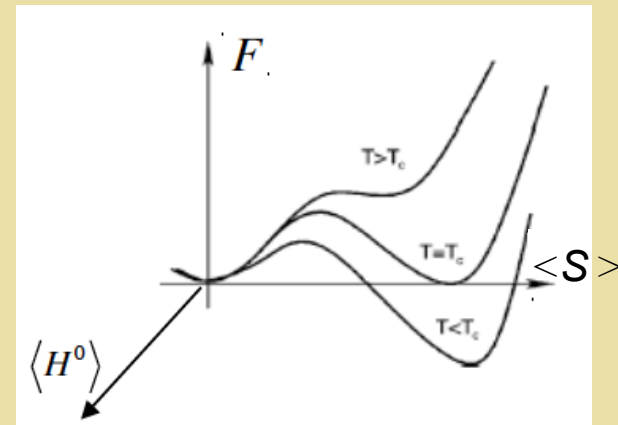
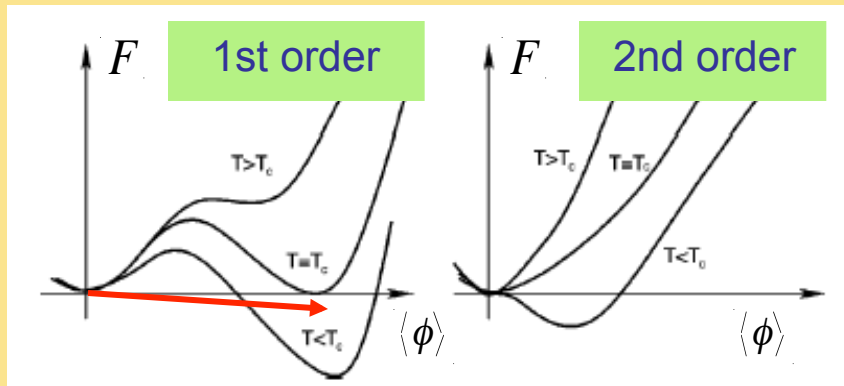
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Real Singlet: $\phi \rightarrow S$

Simplest Extension:
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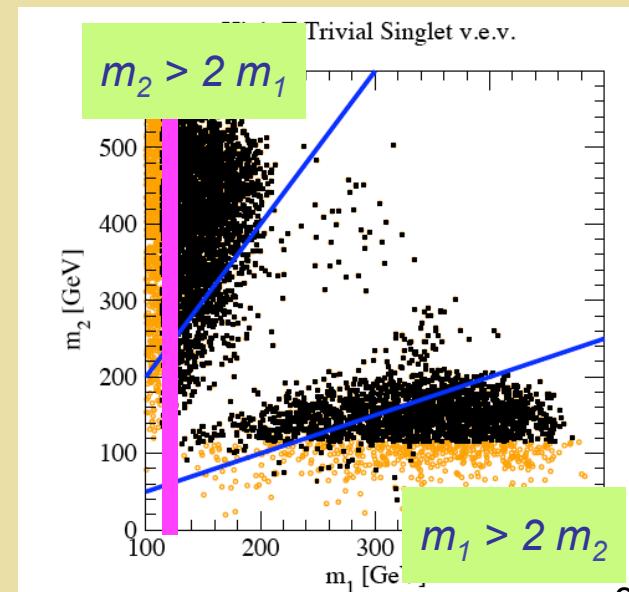


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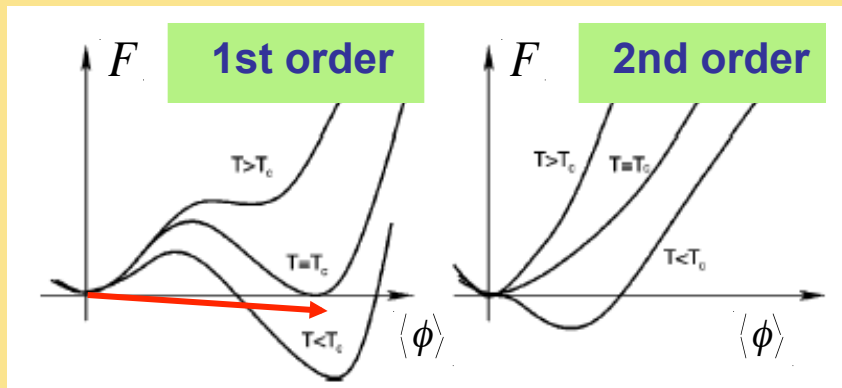
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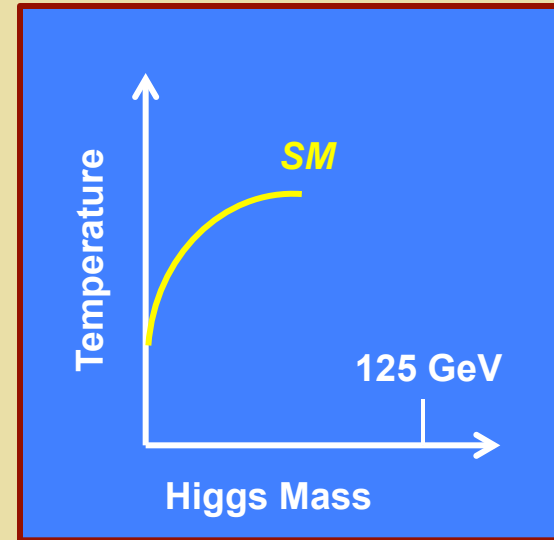
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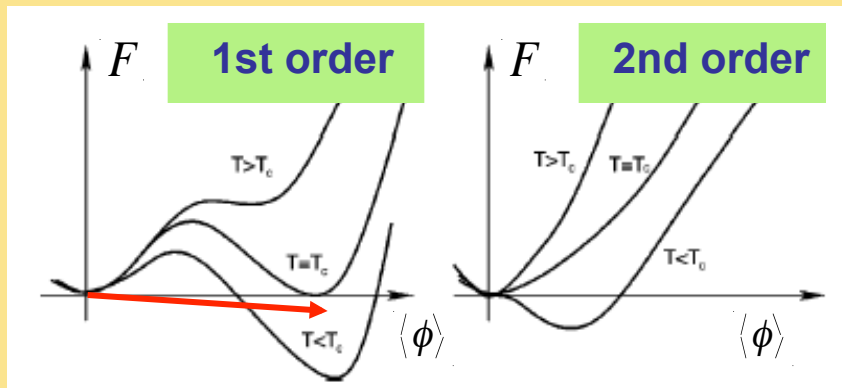
SM EW: Cross over transition



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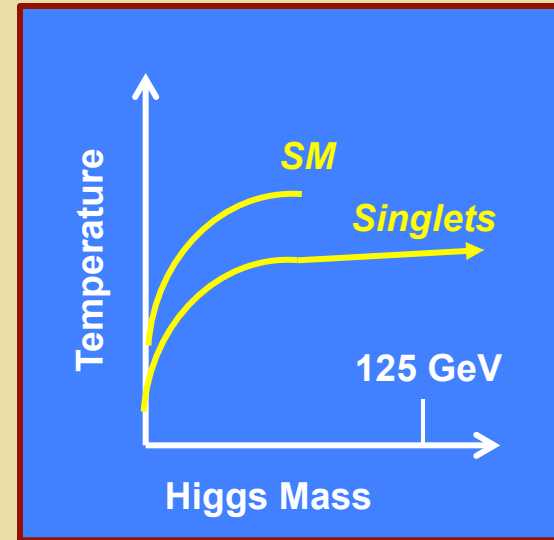
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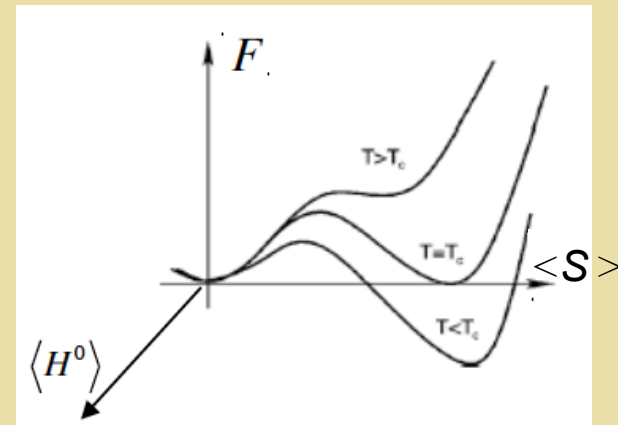
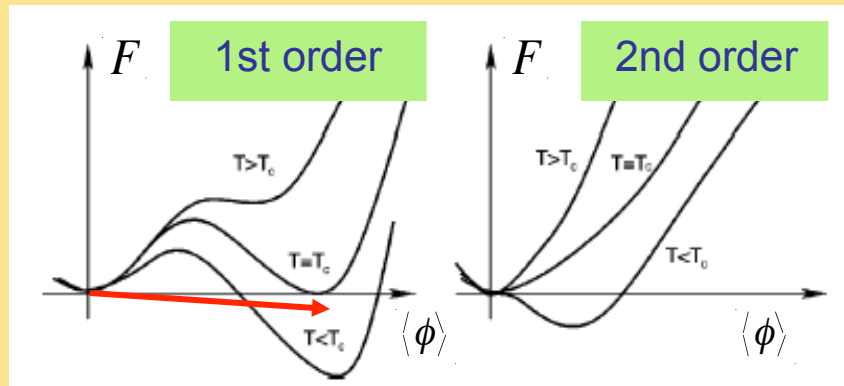
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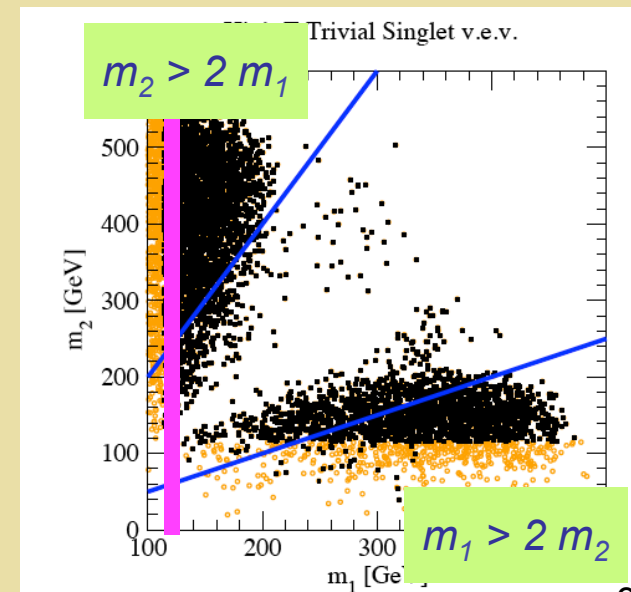
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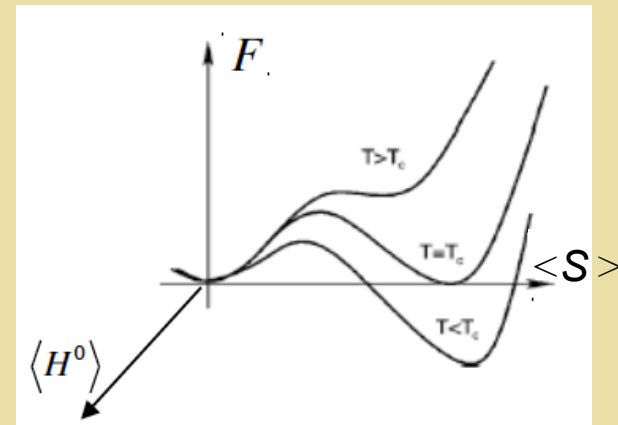
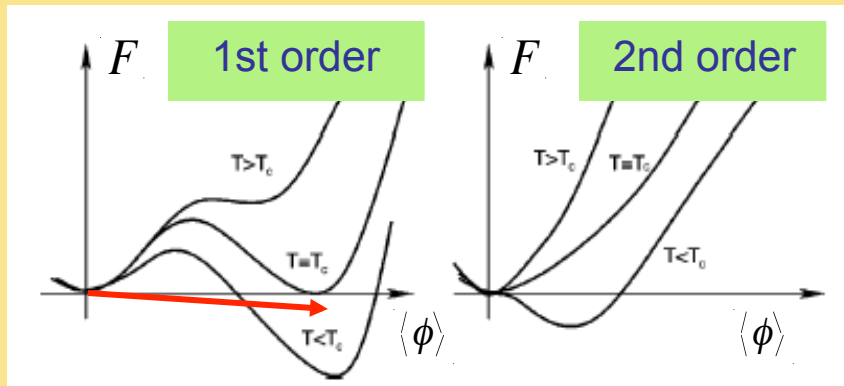
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Collider probes depend
on the spectrum



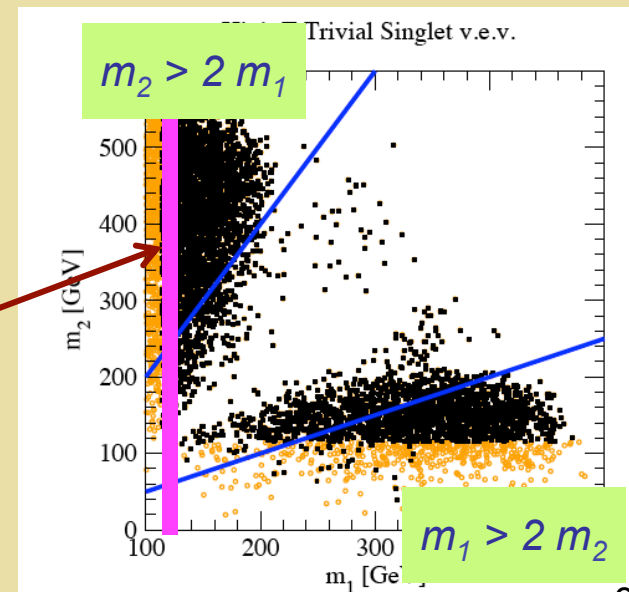
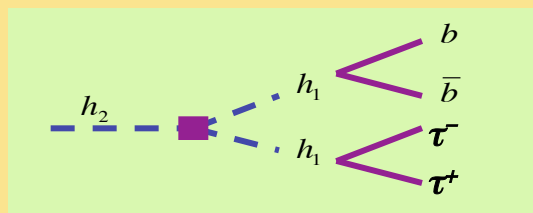
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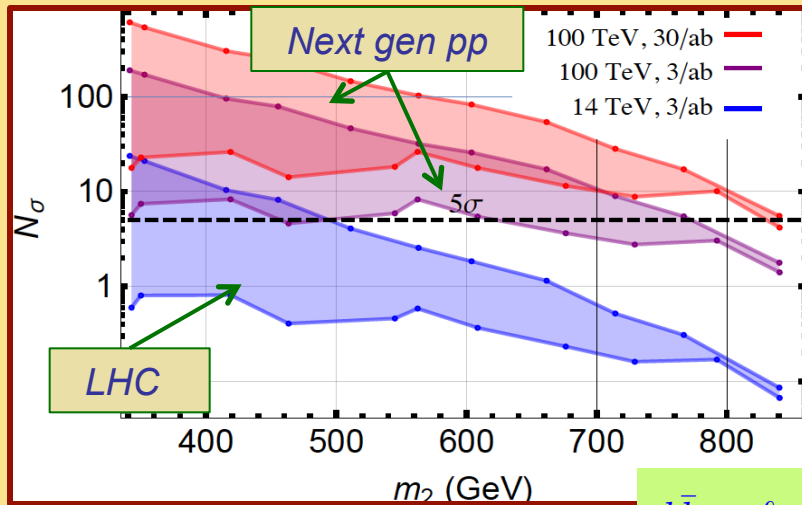
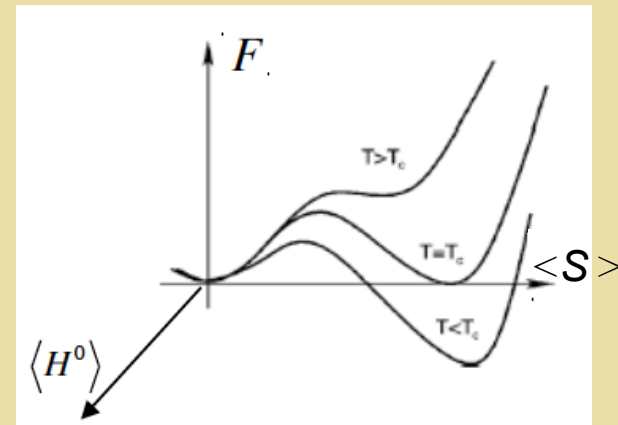
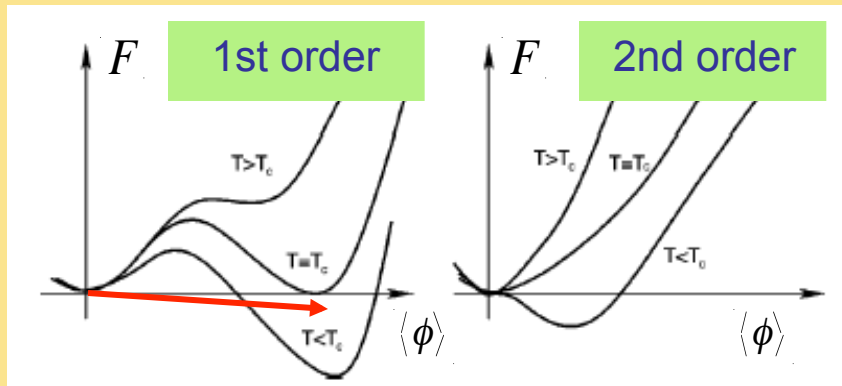
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Resonant di-Higgs production:

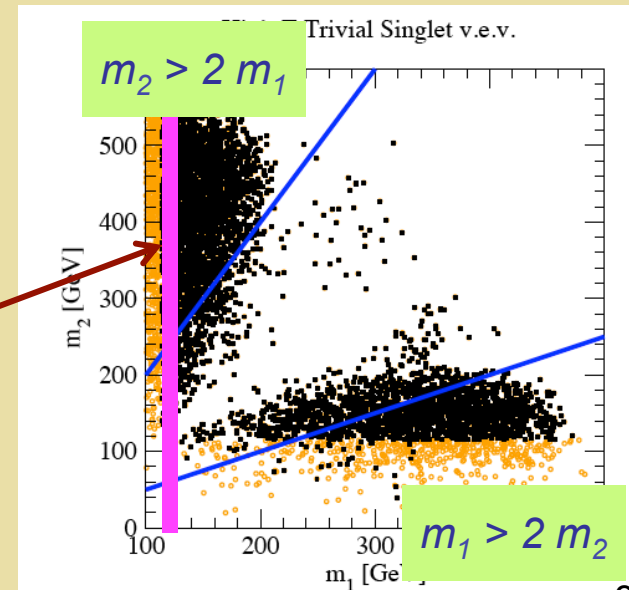


No & RM, arXiv:1310.6035 : LHC Discovery w/ 100 fb^{-1}

EW Phase Transition: Singlet Scalars



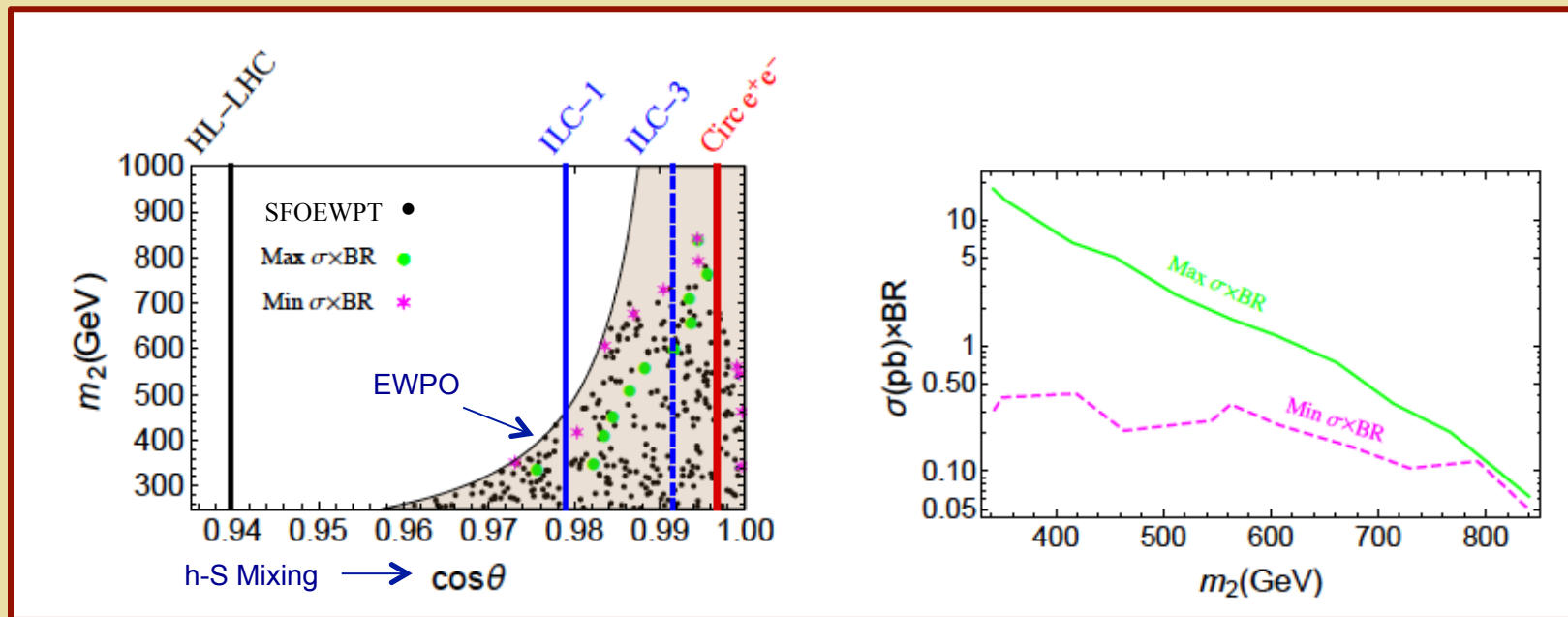
$b\bar{b}\gamma\gamma$ & 4τ



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

EW Phase Transition: Singlet Scalars

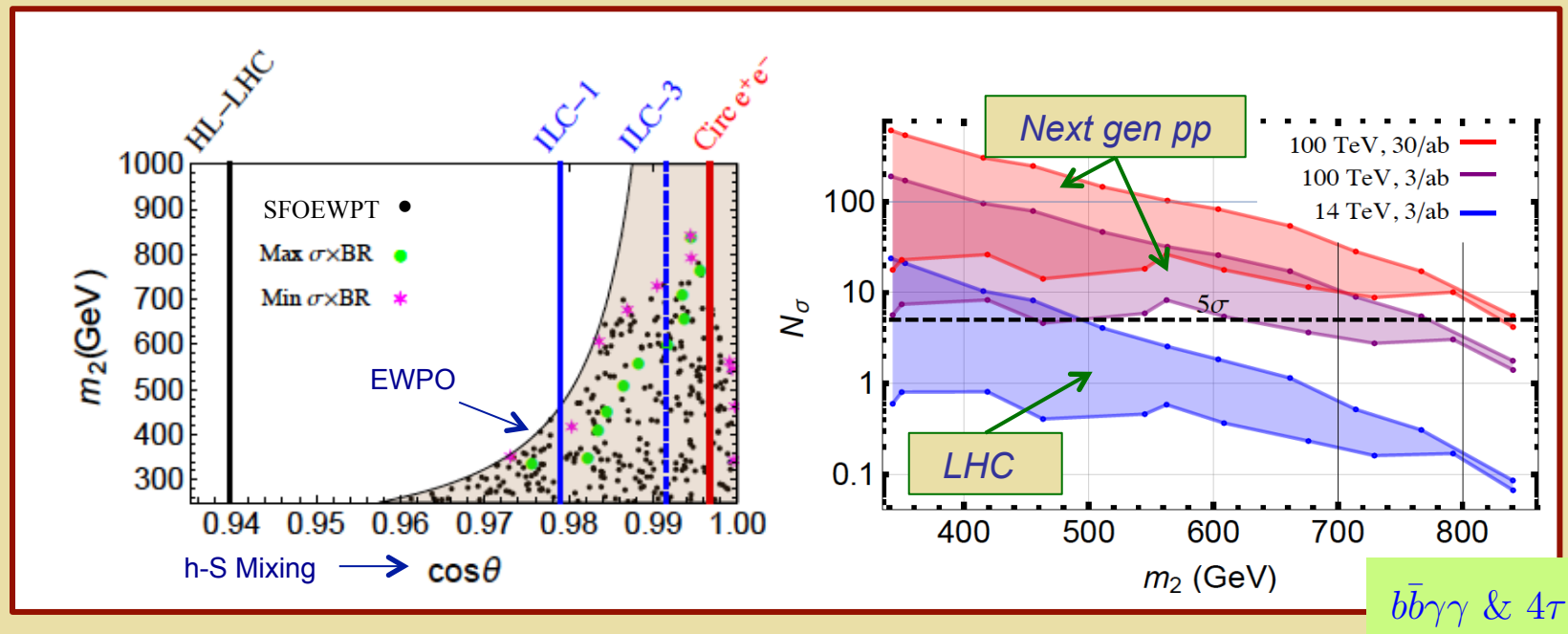
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



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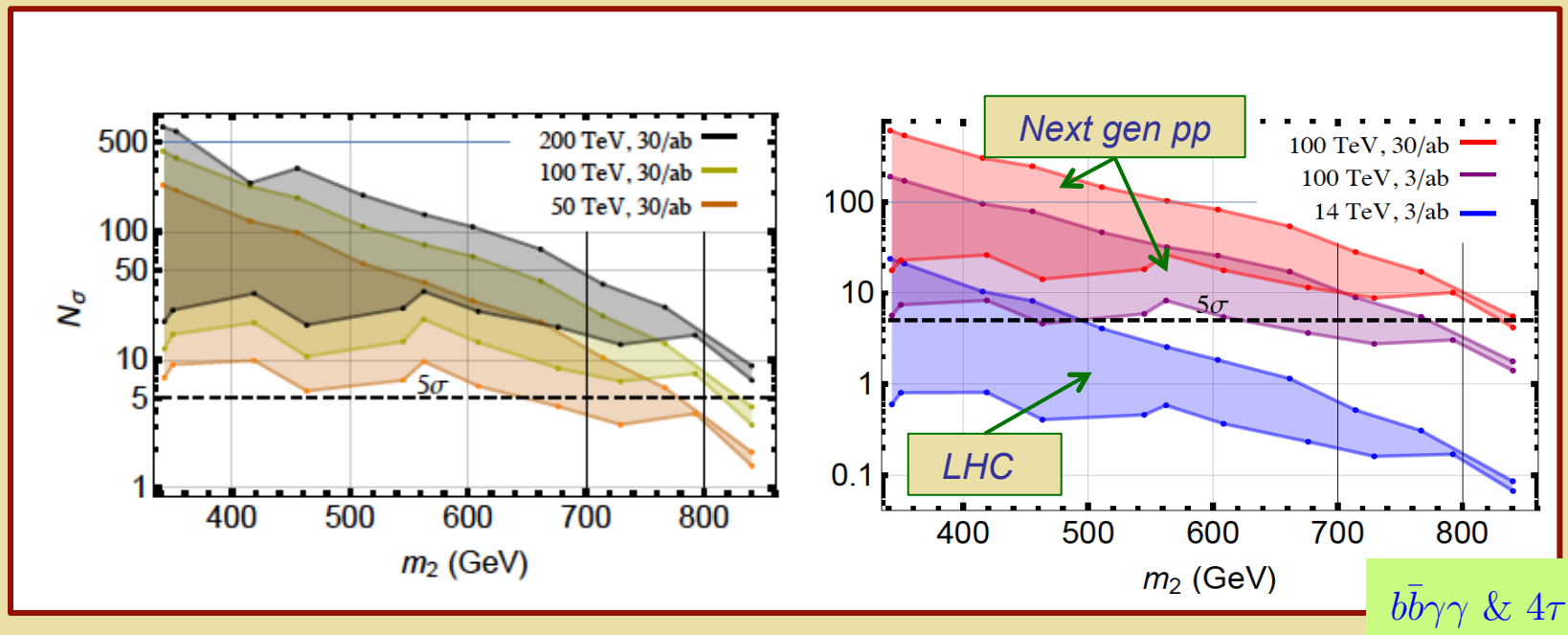
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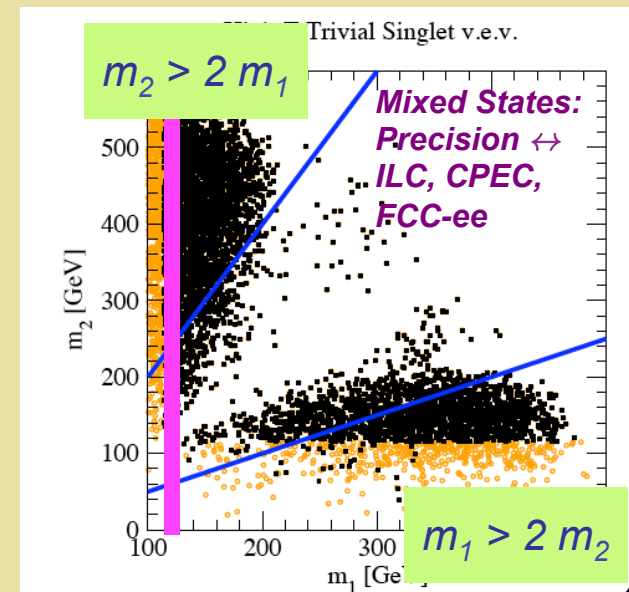
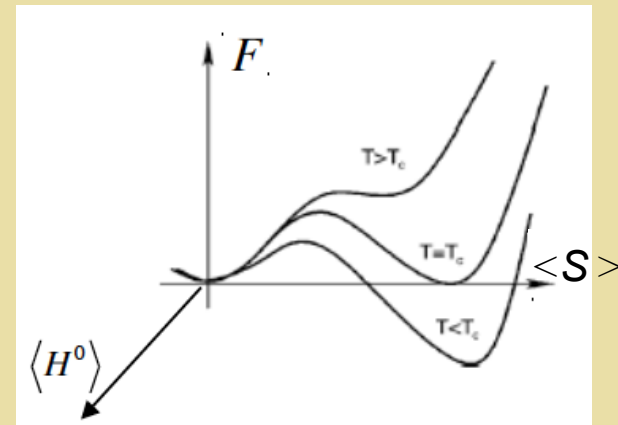
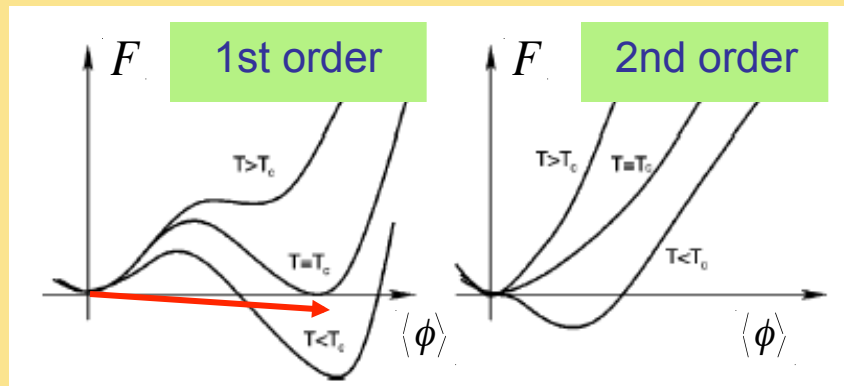
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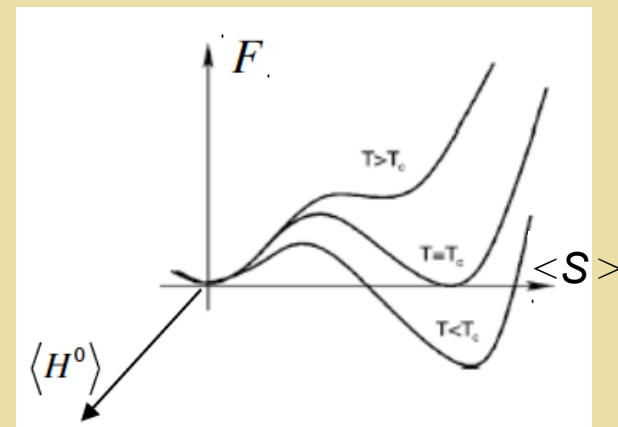
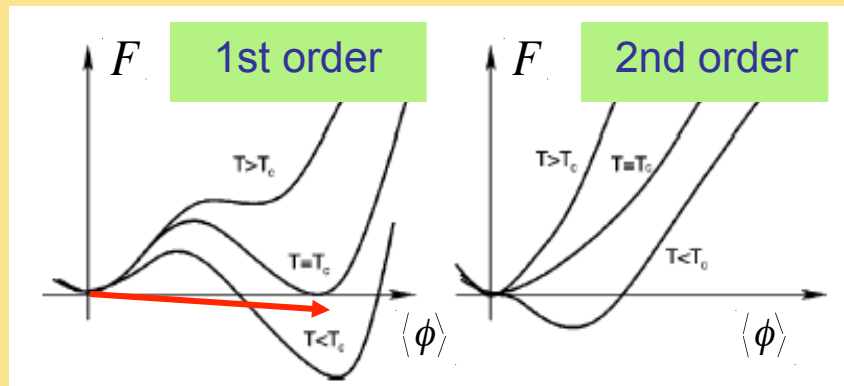


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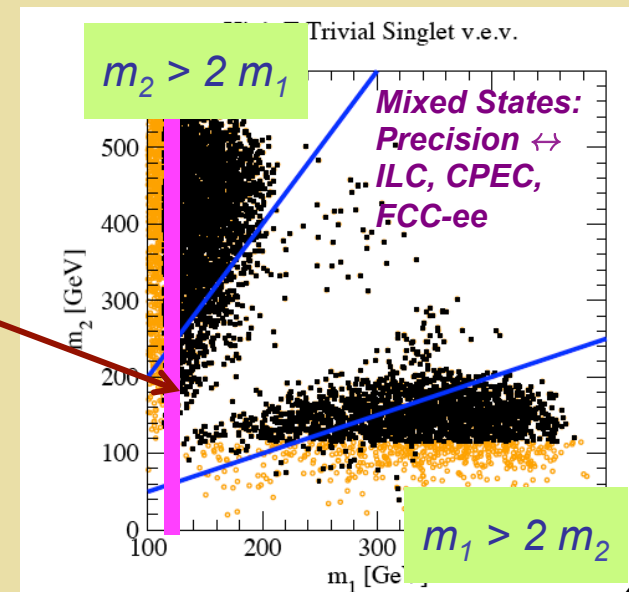
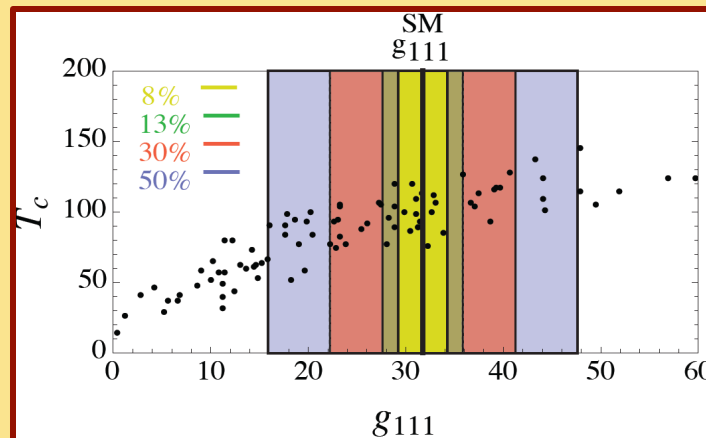
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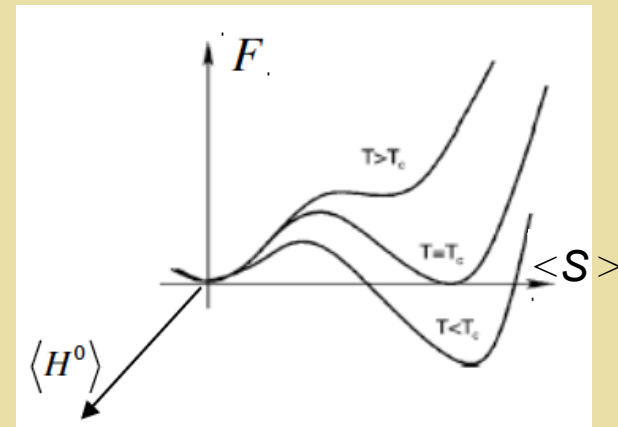
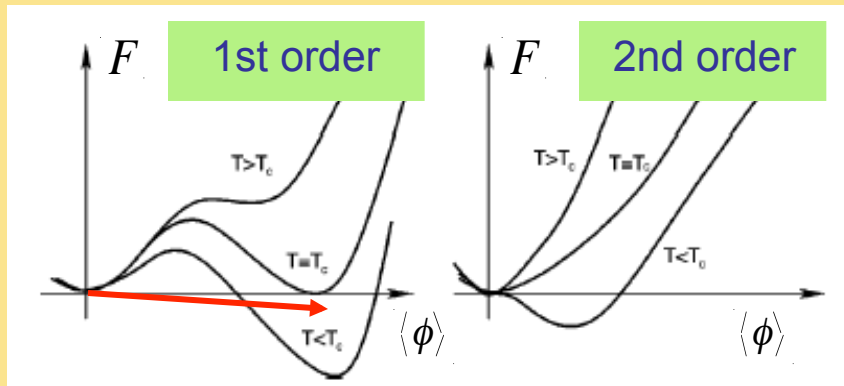


Modified Higgs Self-Coupling

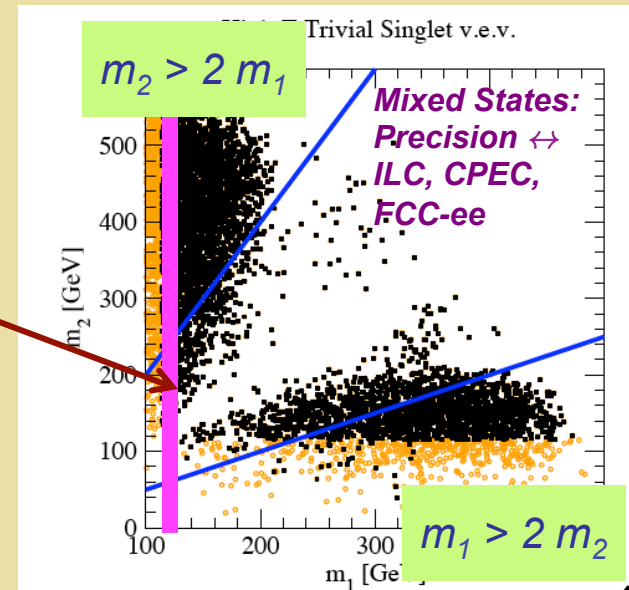
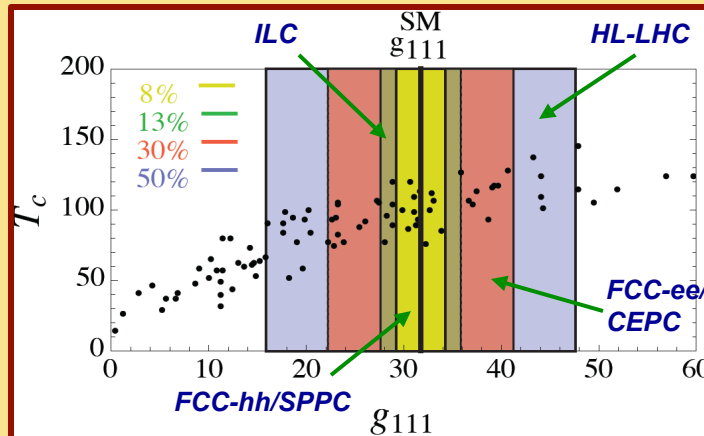


Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: Singlet Scalars

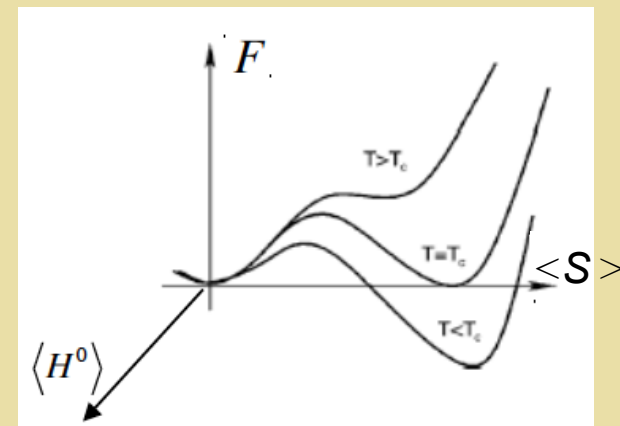
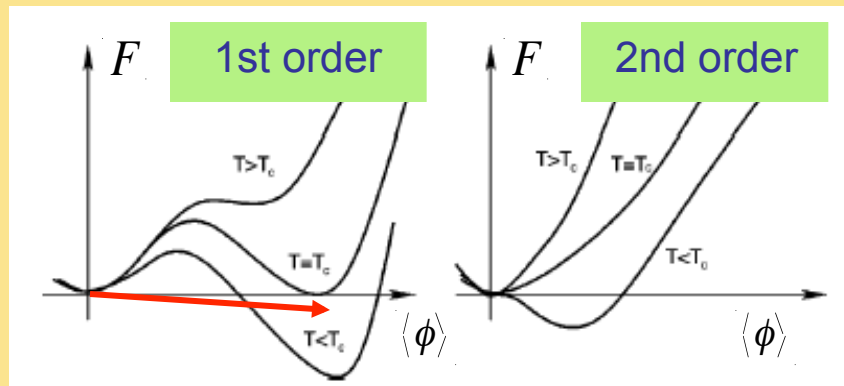


Modified Higgs Self-Coupling



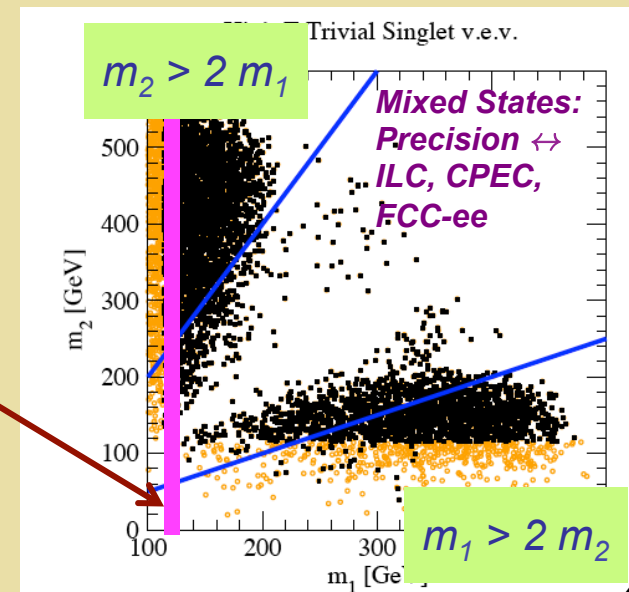
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

EW Phase Transition: Singlet Scalars



Exotic Higgs Decays

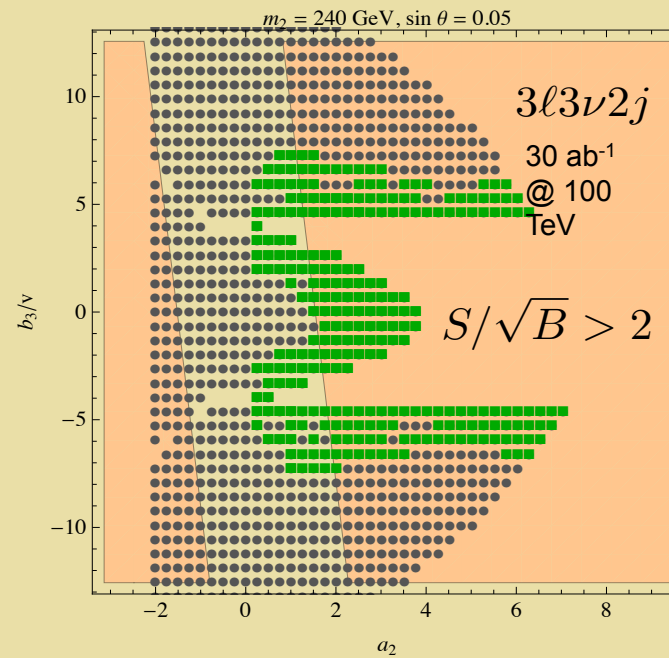
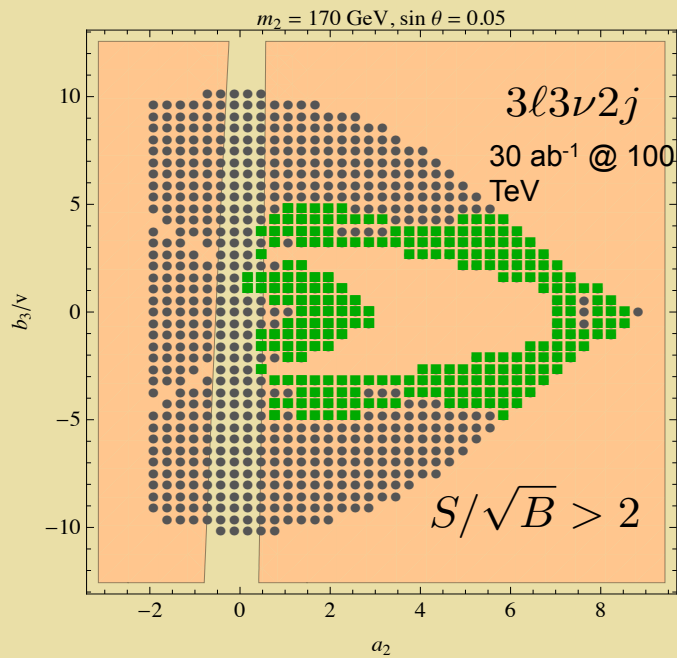
- $h_1^* \rightarrow h_2 h_2$
Chen, Kozaczuk, Lewis
- $h_1 \rightarrow h_2 h_2$ or $h_2 h_2^*$
Kozaczuk, RM, Shelton, Sajjad



EW Phase Transition: Singlet Scalars

Non-resonant: $h_1^* \rightarrow h_2 h_2$

$h_2 h_2 \rightarrow 4W \rightarrow 2j 2\ell^\pm \ell'^\mp 3\nu$, $\ell \neq \ell'$.



Vac stab & pert unitarity •

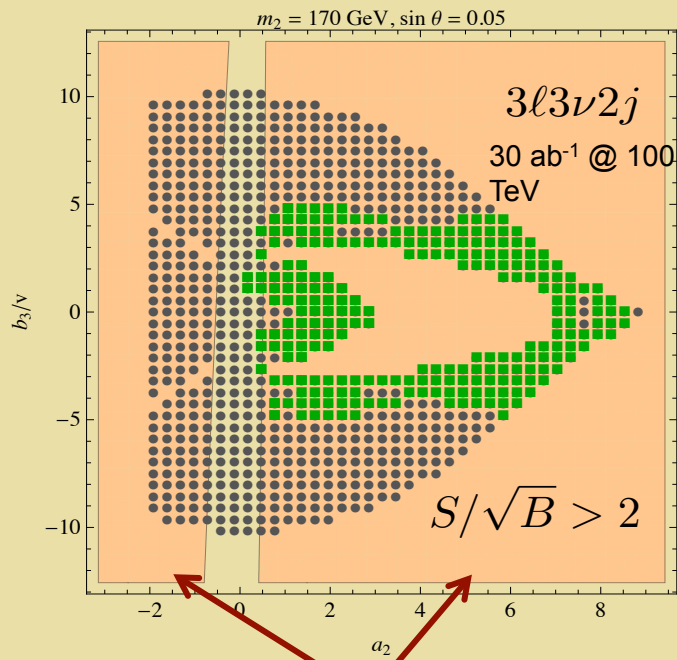
SFOEWPT •

Chen, Kozaczuk, Lewis to appear

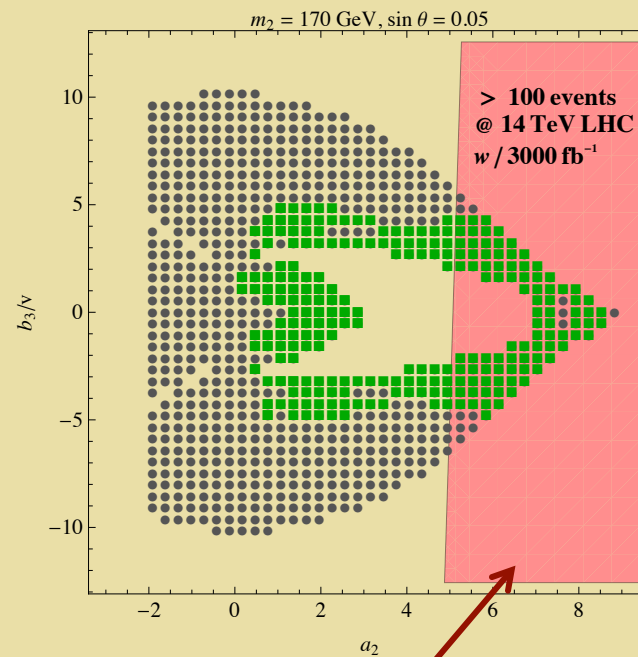
EW Phase Transition: Singlet Scalars

Non-resonant: $h_1^* \rightarrow h_2 h_2$

$h_2 h_2 \rightarrow 4W \rightarrow 2j 2\ell^\pm \ell'^\mp 3\nu$, $\ell \neq \ell'$.



100 TeV pp: 30 ab^{-1}



14 TeV pp: 3 ab^{-1}

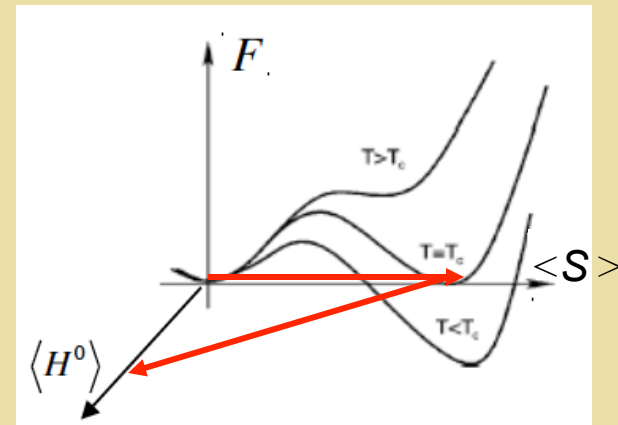
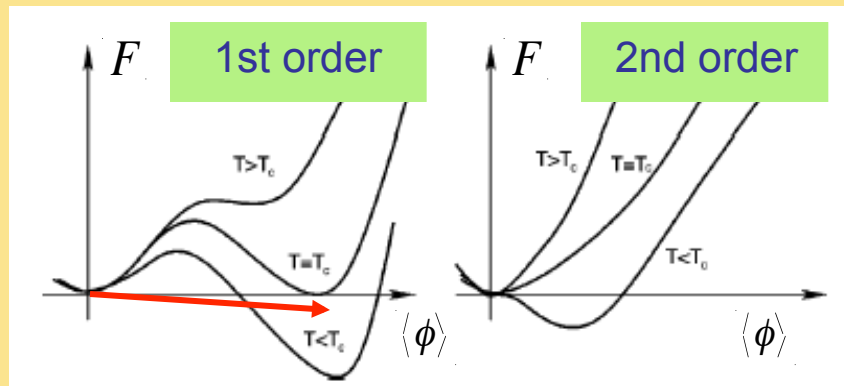
Chen, Kozaczuk, Lewis to appear

Higgs Portal: Simple Scalar Extensions

<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet: Z₂</i>	1	✓	✗
<i>Real singlet: Z₂</i>	1	✓	✓
<i>Complex Singlet</i>	2	✓	✓
<i>EW Multiplets</i>	3+	✓	✓

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

EW Phase Transition: Two-Step

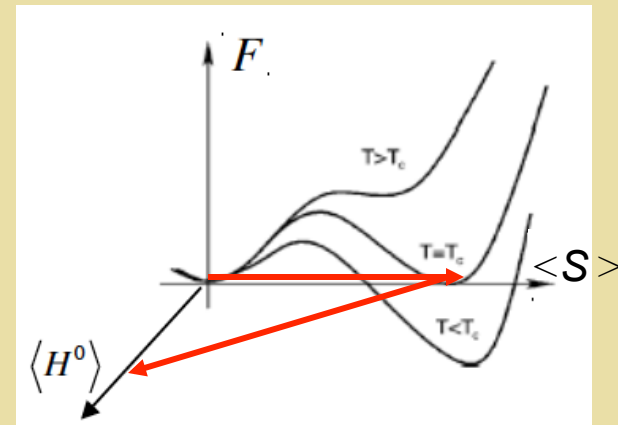
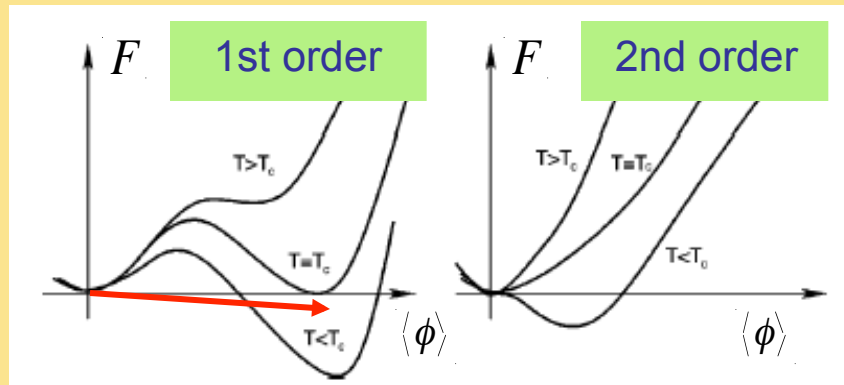


Profumo, R-M, Shaugnessy 2007

Curtain, Meade, Yu: arXiv: 1409.0005

Jiang, Bian, Huang, Shu 1502.07574

EW Phase Transition: Singlet Scalars



Curtain, Meade, Yu: arXiv: 1409.0005

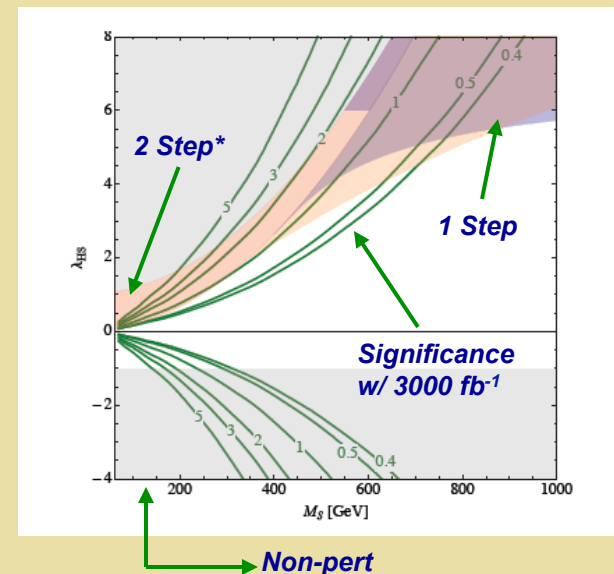
Z_2 symmetric real singlet extension

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

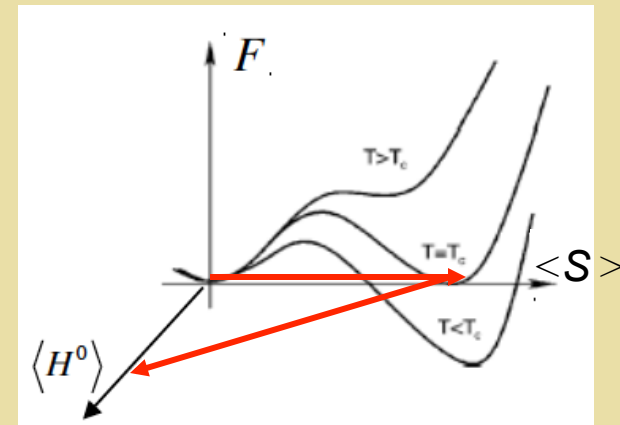
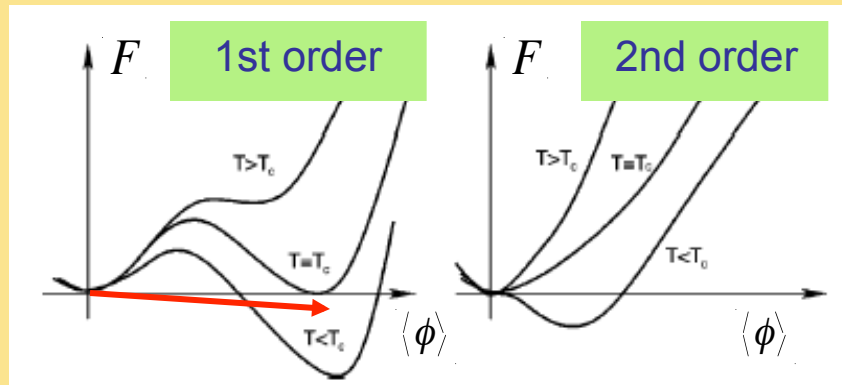
VBF @ 100 TeV pp:

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

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



EW Phase Transition: Singlet Scalars



Curtain, Meade, Yu: arXiv: 1409.0005

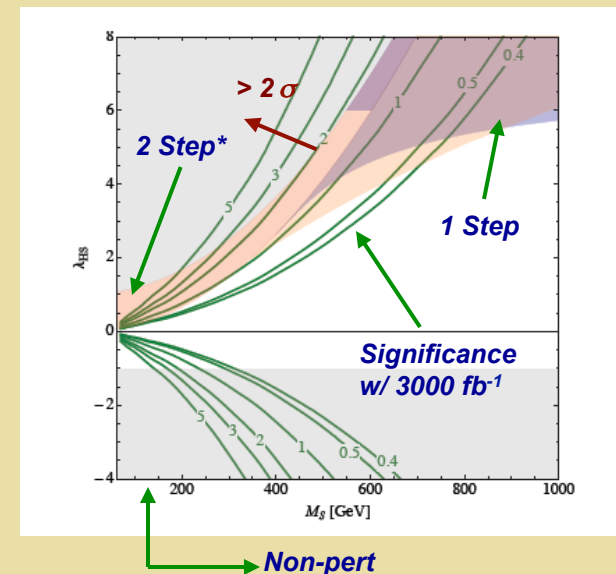
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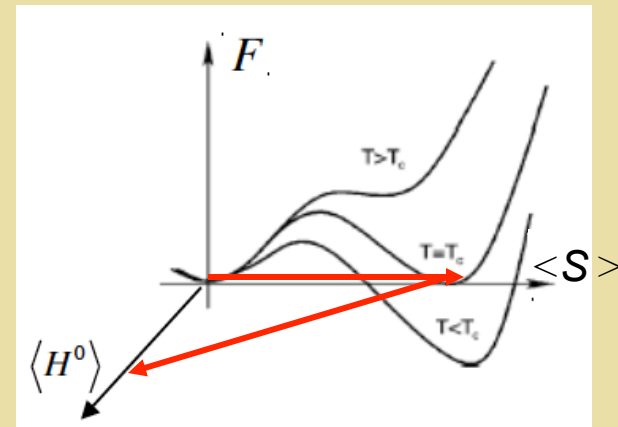
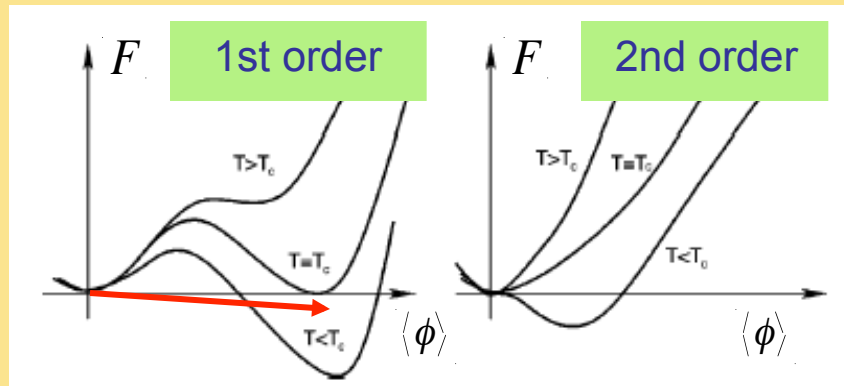
VBF @ 100 TeV pp:

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



EW Phase Transition: DM Direct Detection

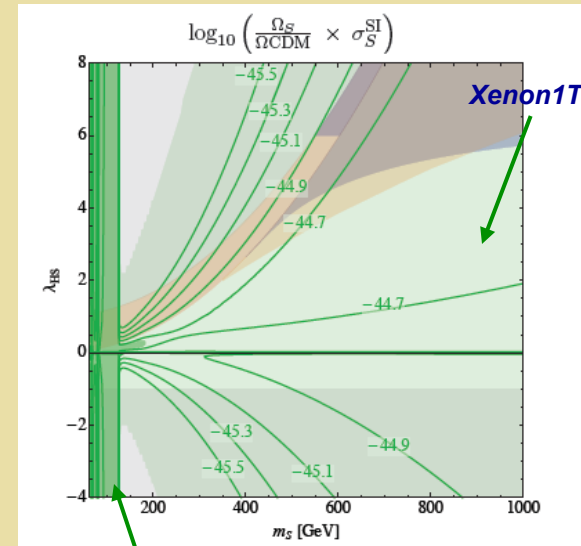


Curtain, Meade, Yu: arXiv: 1409.0005

Z_2 symmetric real singlet extension

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

Scalar singlet DM: direct detection



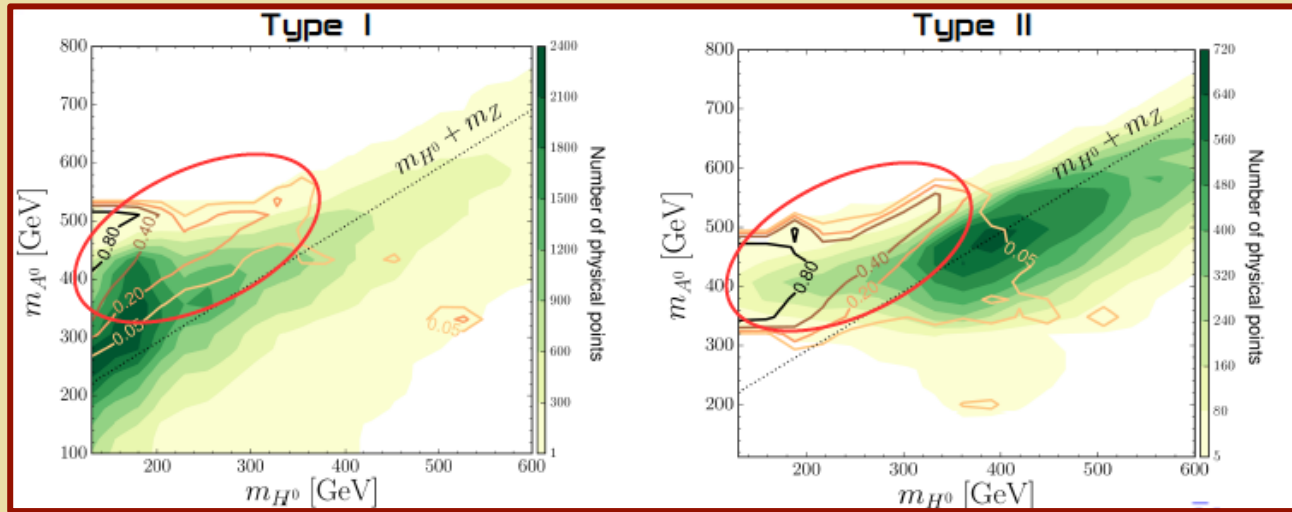
LUX Exclusion

Higgs Portal: Simple Scalar Extensions

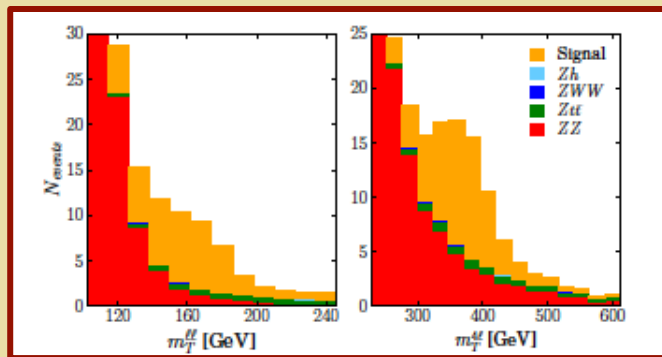
<i>Extension</i>	<i>DOF</i>	<i>EWPT</i>	<i>DM</i>
<i>Real singlet: Z₂</i>	1	✓	✗
<i>Real singlet: Z₂</i>	1	✓	✓
<i>Complex Singlet</i>	2	✓	✓
<i>EW Multiplets</i>	3+	✓	✓

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

EW Multiplets: 2HDM

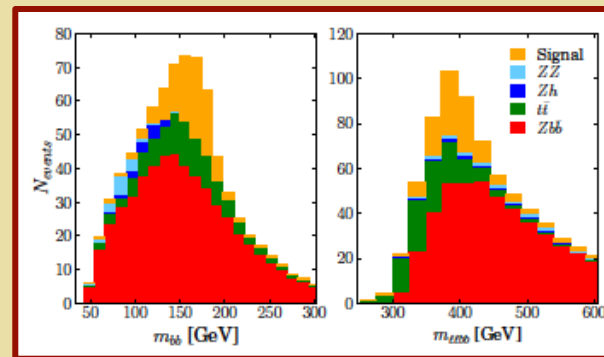


$A^0 \rightarrow Z H^0$
Signature



$bb \ell\ell : 5\sigma$ for 40 fb^{-1}

Dorsch et al

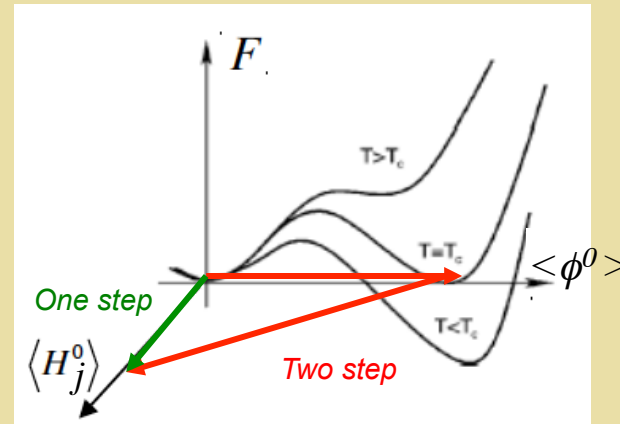
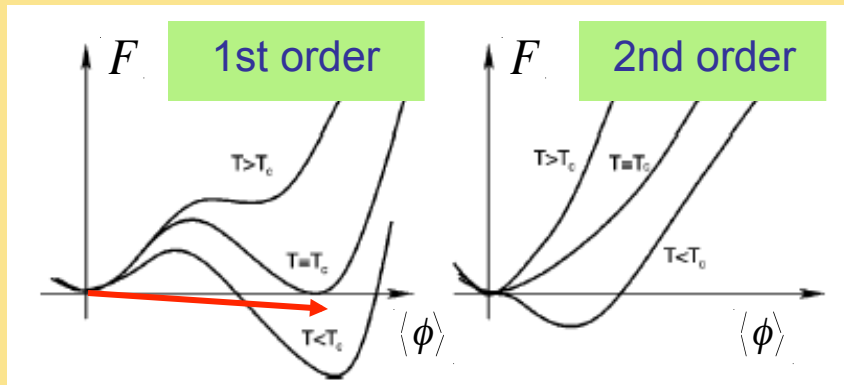


$4l + \text{MET} : 5\sigma$ for 60 fb^{-1}

See S. Su talk

$SFOEWPT$
testable w/
LHC

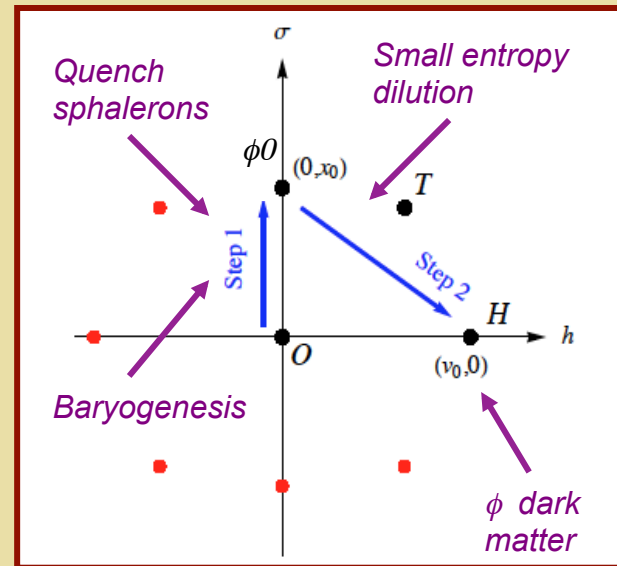
EW Multiplets: Two-Step EWPT



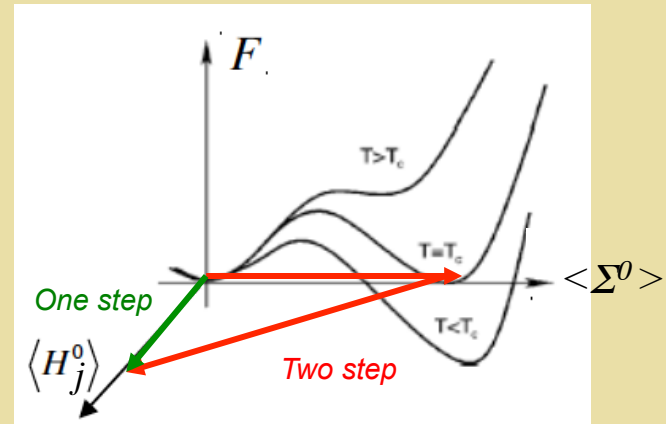
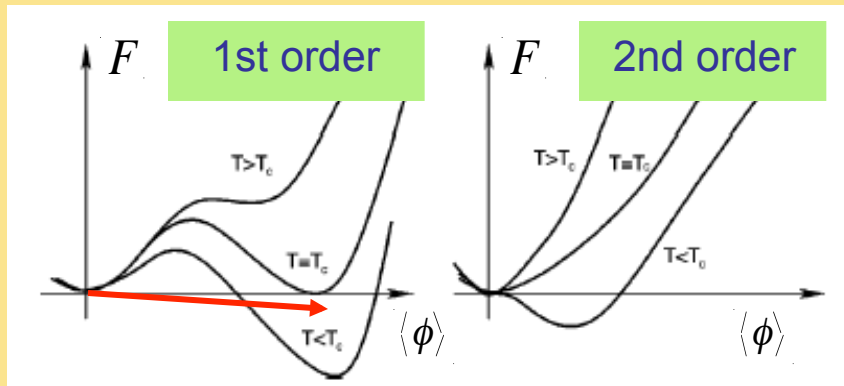
Increasing m_h \longrightarrow

\longleftarrow New scalars

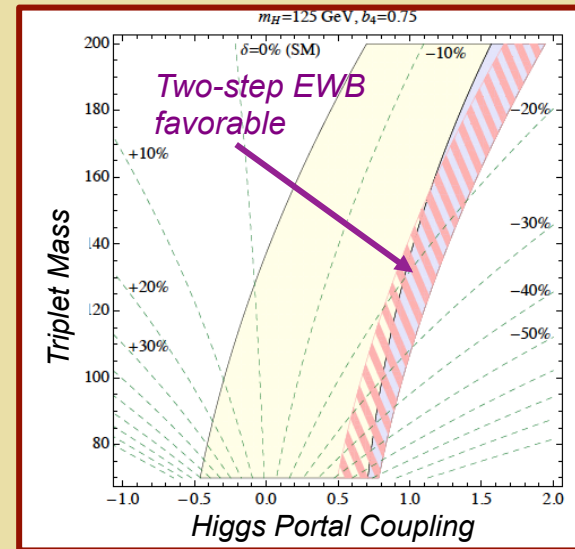
- Step 1: thermal loops
- Step 2: tree-level barrier



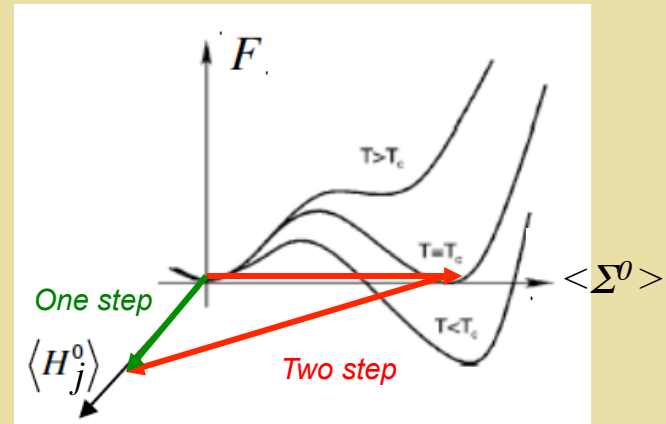
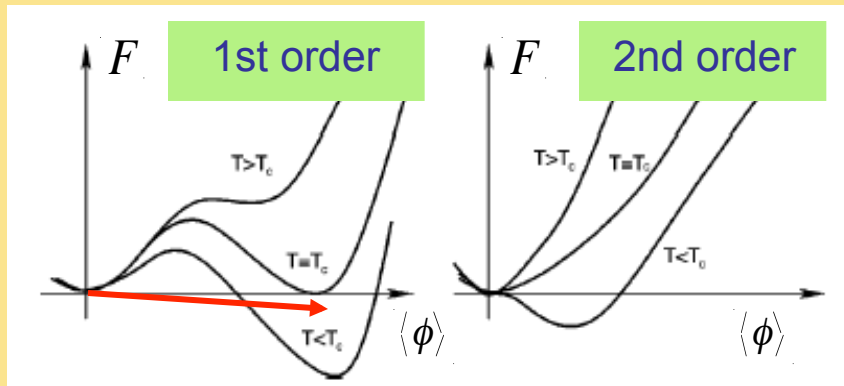
EW Multiplets: Two-Step EWPT



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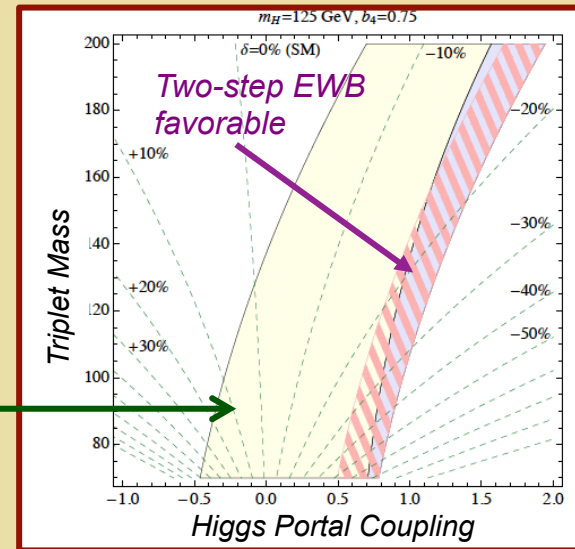
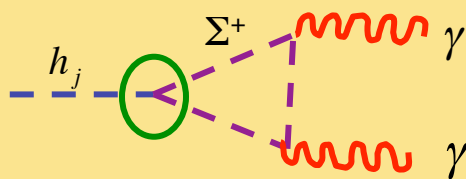


EW Multiplets: Two-Step EWPT



Increasing m_h \longrightarrow

\longleftarrow New scalars



Strong 1st Order EWPT



**Definitive probe of the possibilities →
Exciting opportunities for the FCC!**

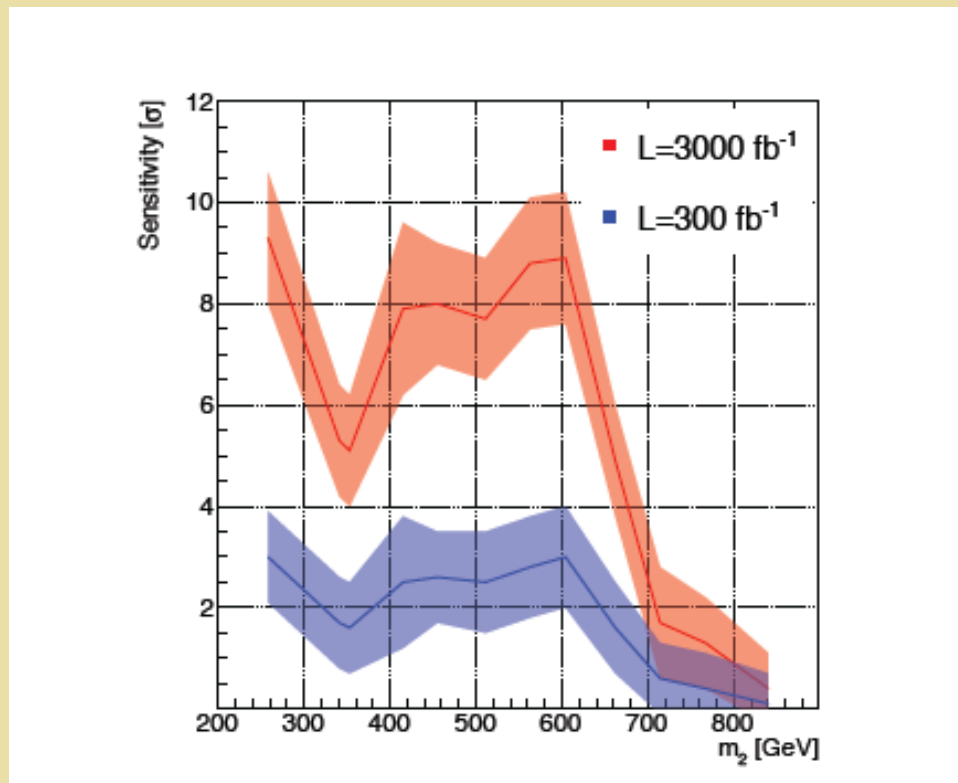
Outlook

- *Probing the thermal history of EWSB & determining whether conditions existed for generation of the matter-antimatter asymmetry (SFOEWPT) is a key opportunity for the FCC*
- *Simple BSM Higgs sectors (singlets, EW multiplets) can readily give rise to a SFOEWPT with a rich array of signatures*
- *A comprehensive probe of the EWSB thermal history will likely require the FCC-hh with $\sim \text{few} \times 10 \text{ ab}^{-1}$ & complementary precision e^+e^- Higgs factory studies*
- *On-going theoretical work underway: model building, collider pheno, & refined finite temperature field theory*
- *Ample opportunities for others to join the effort !*

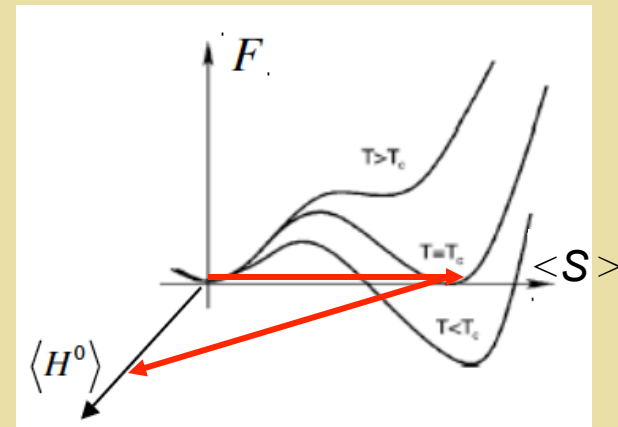
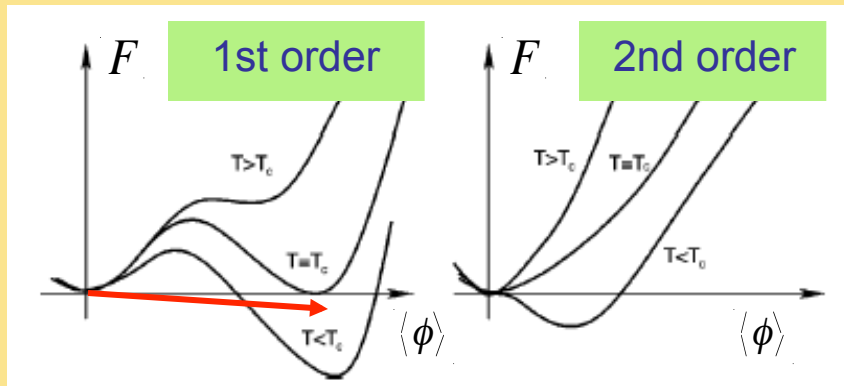
Back Up Slides

EW Phase Transition: Singlet Scalars

Resonant di-Higgs: bb WW channel @ LHC 13

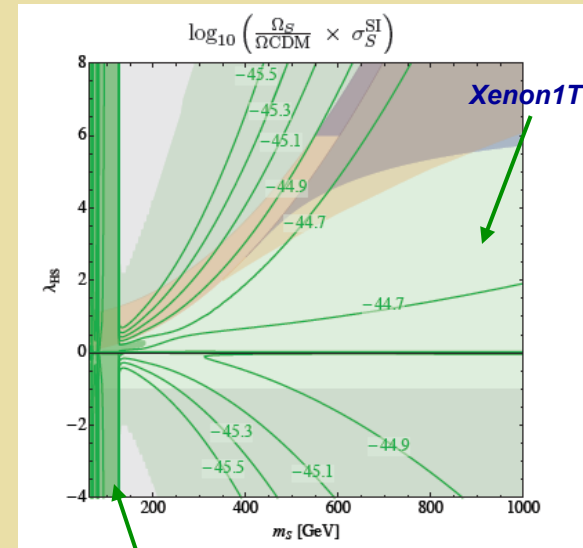
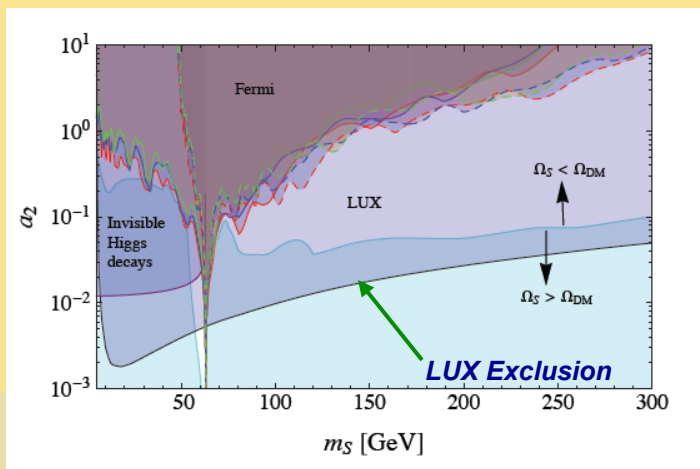


EW Phase Transition: DM Direct Detection



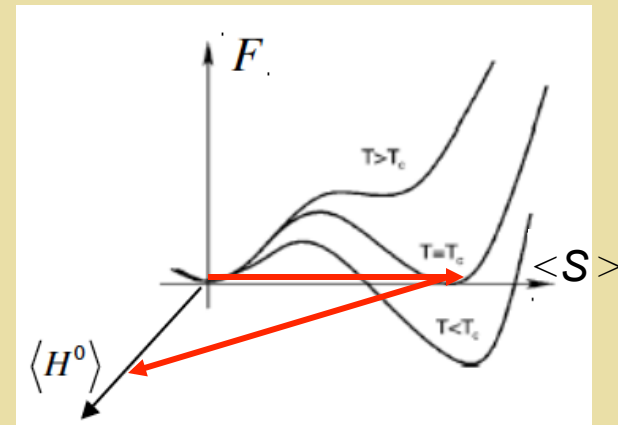
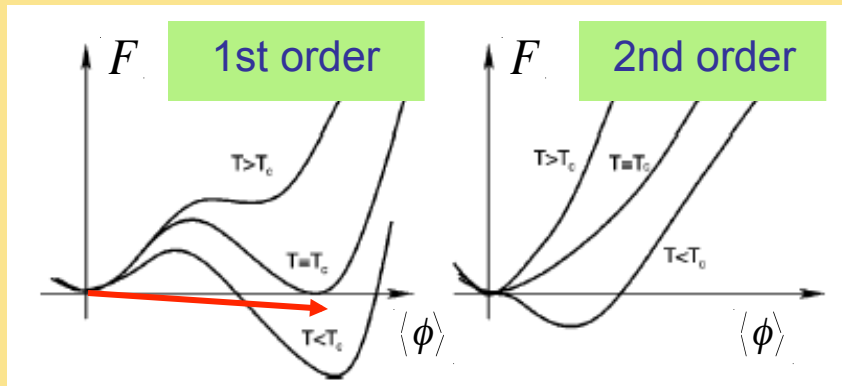
Feng, Profumo, Ubaldi 1412.1105

Z_2 symmetric real singlet extension



LUX Exclusion

EW Phase Transition: DM Direct Detection



Feng, Profumo, Ubaldi 1412.1105

Z_2 symmetric real singlet extension

