EW Phase Transition: Di-Higgs & Higgs Precision

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April 2018

Electroweak Phase Transition

- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*
- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*
- *Gravitational waves $\rightarrow$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

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EW Baryogenesis & Gravitational Waves

Was Y_B generated in conjunction with electroweak symmetry-breaking?

- ***Was the EWSB transition first order ?***
- ***Was it sufficiently "strong" ?***

Themes for This Talk

I. Future collider opportunities

- *Phenomenological studies to date indicate high potential for probing the nature of the EWPT*

II. Complementarity

- *Di-Higgs + precision Higgs coupling measurements needed for a complete probe*

Outline

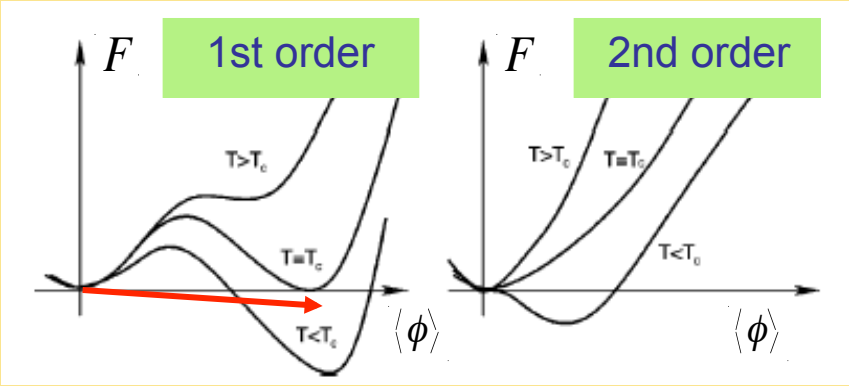
I. EWPT

II. Future collider discovery potential

III. Summary

I. Electroweak Phase Transition

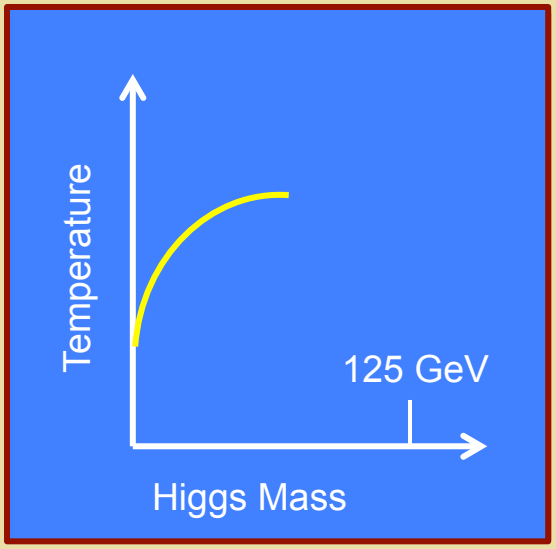
EW Phase Transition: St'd Model



Increasing m_h →

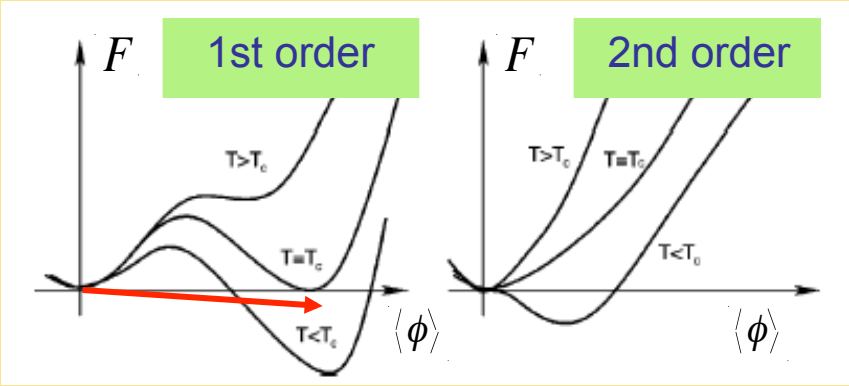
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

EW Phase Transition: St'd Model



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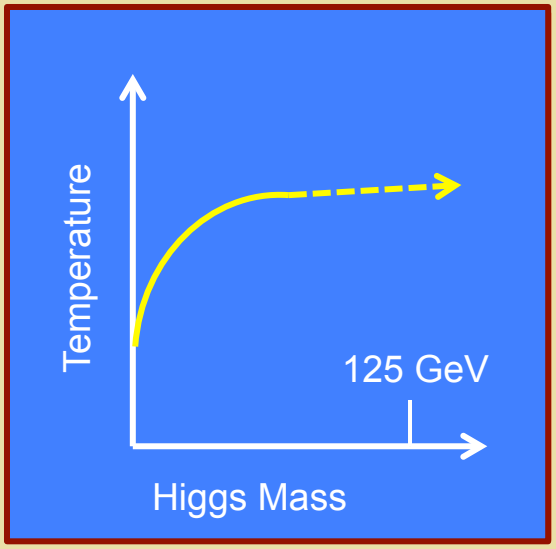

EW Phase Diagram

Extended scalar sector:
FOEWPT for m_h = 125 GeV

Higgs Portal: Simple Scalar Extensions

Extension	*DOF*	*EWPT*	*DM*
Real singlet: $\cancel{Z_2}$	***1***	✔	✖
Real singlet: Z_2	***1***	✔	✔
Complex Singlet	***2***	✔	✔
EW Multiplets	***3+***	✔	✔

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

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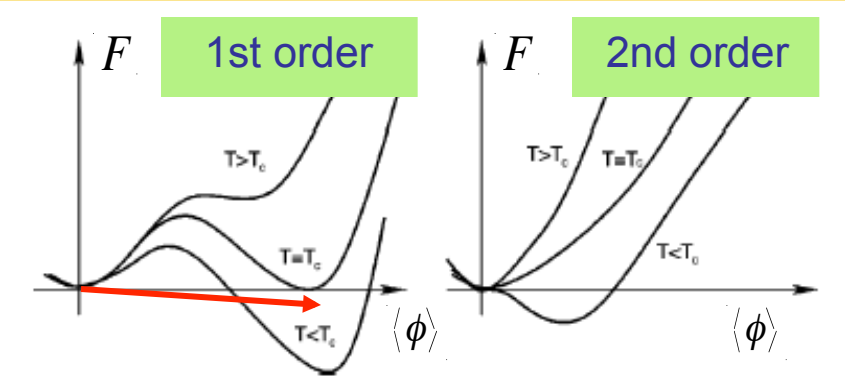
II. Discovery Potential

Standard Model + real singlet scalar

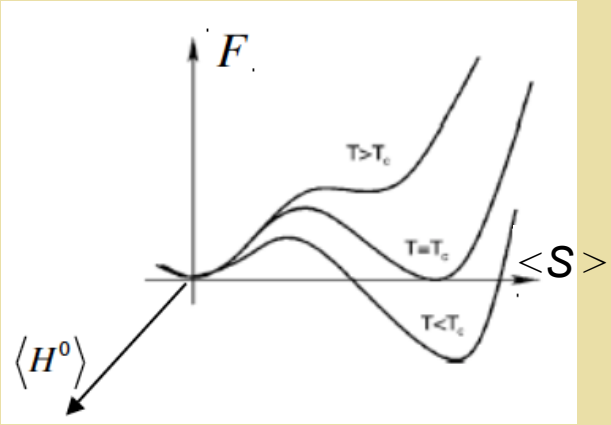
$$V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

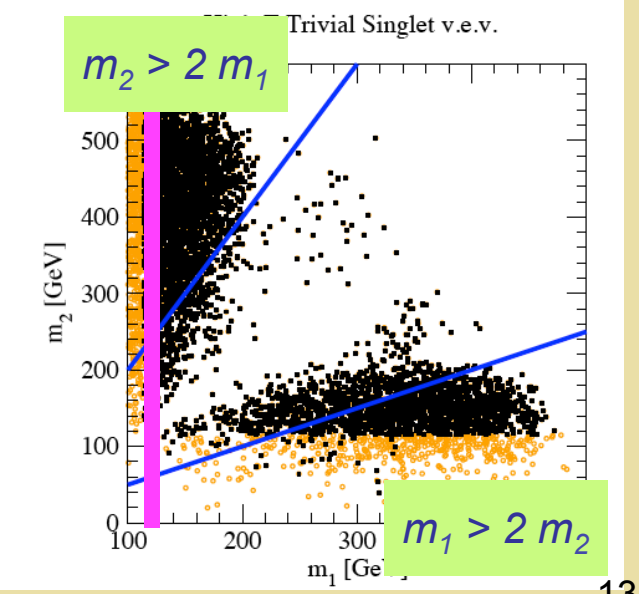
- *Strong first order EWPT*
- *Two mixed singlet-doublet states*

EW Phase Transition: Singlet Scalars



SFOEWPT-viable parameters





Profumo, MJRM, Shaugnessy '07

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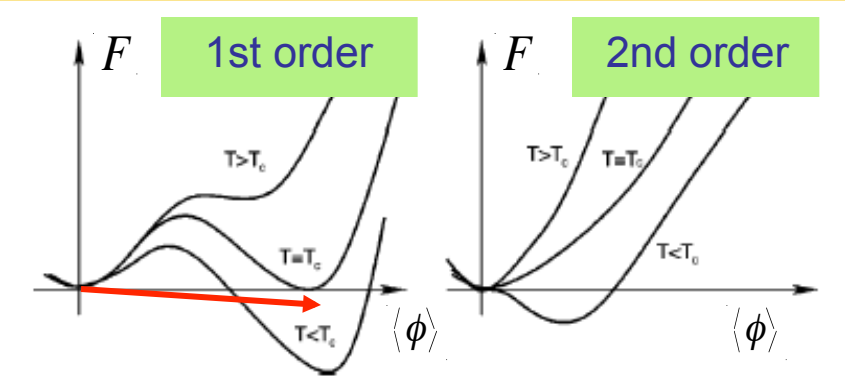
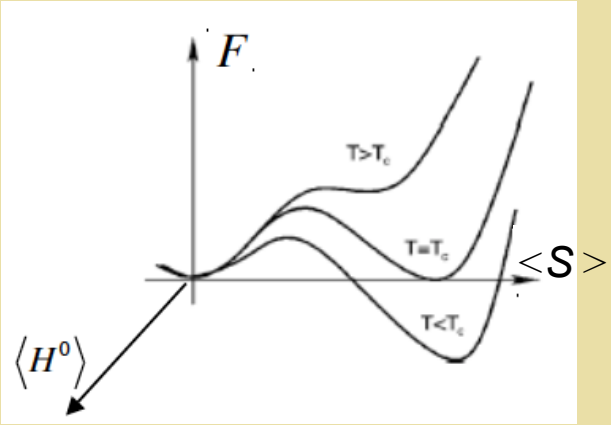
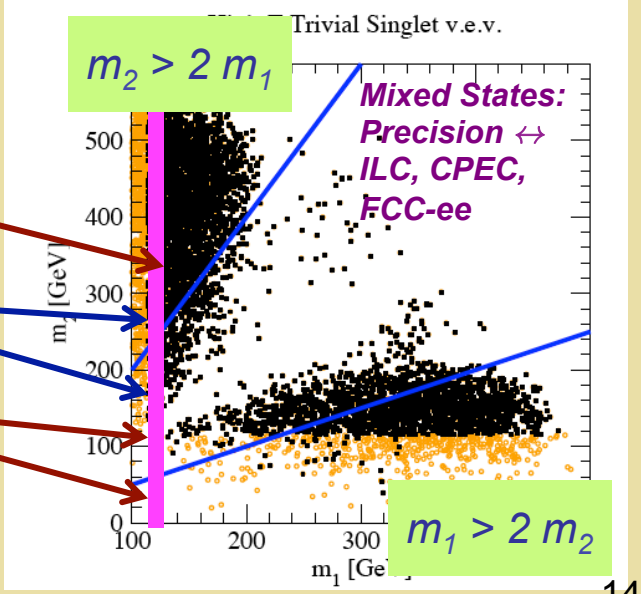




Collider probes

- *Resonant di-Higgs production*
- *Precision Higgs measurements*
- *Non-resonant di-Higgs & exotic Higgs decays*



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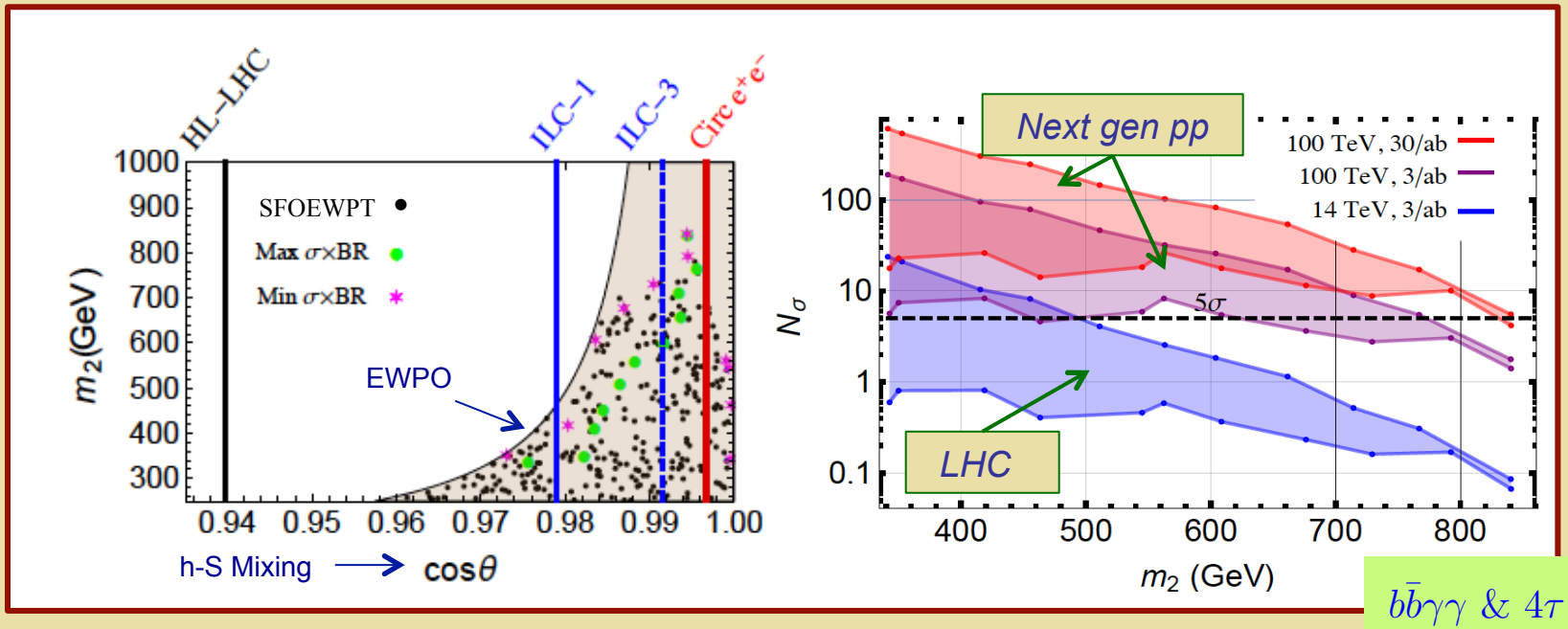
EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



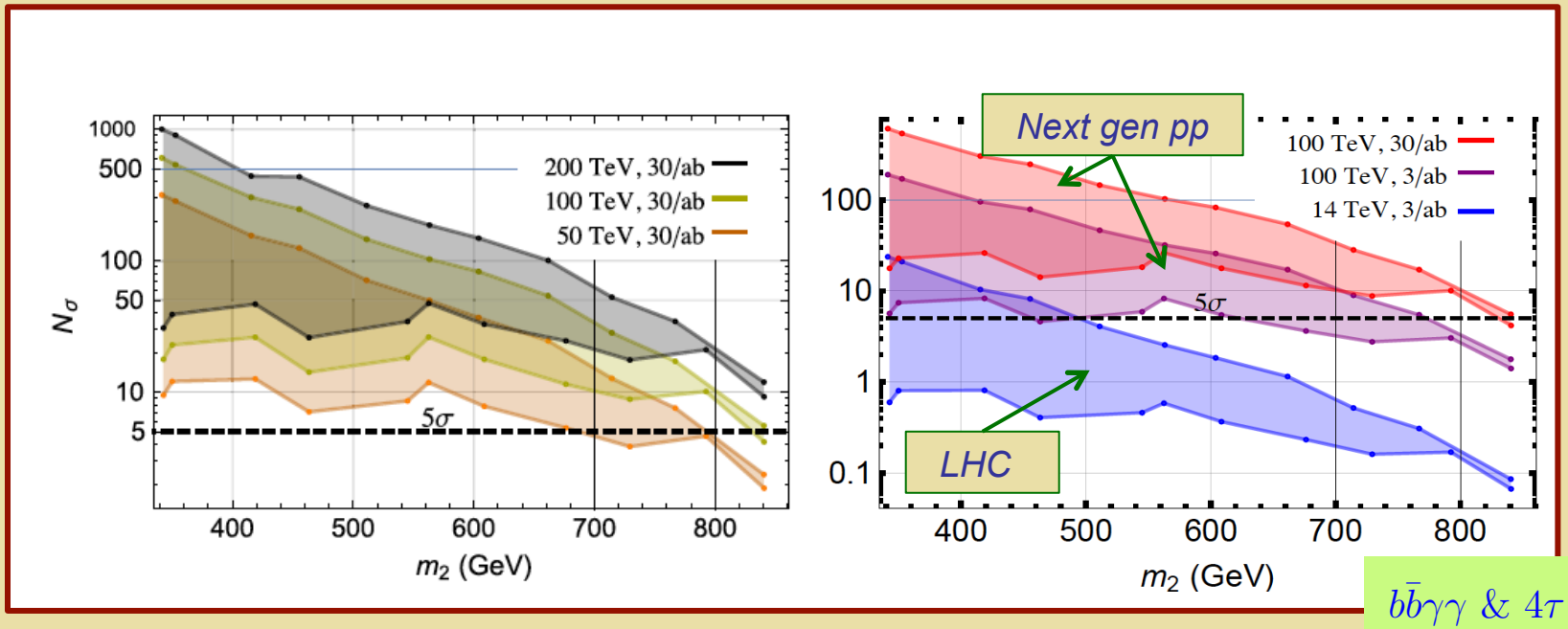
$b\bar{b}\gamma\gamma$ & 4τ

Kotwal, No, R-M, Winslow 1605.06123

See also: Huang et al, 1701.04442

EW Phase Transition: Singlet Scalars

SFOEWPT Benchmarks: Resonant di-Higgs



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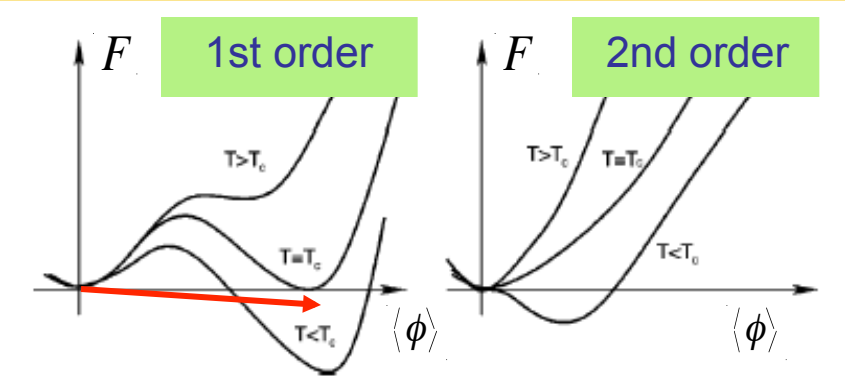
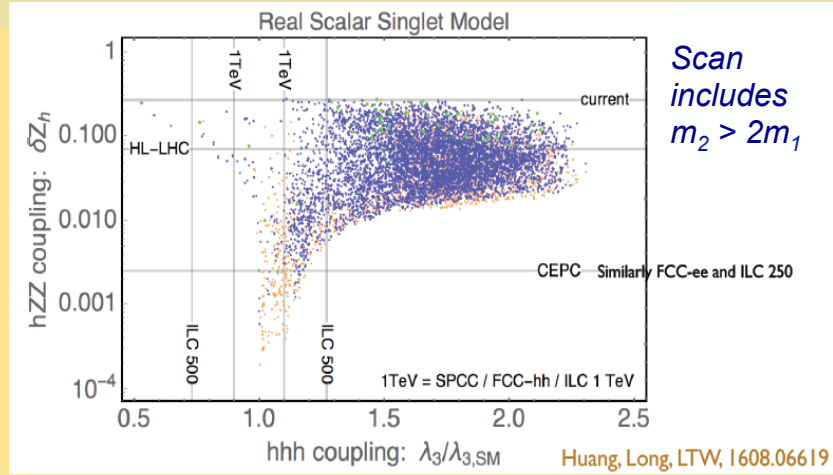
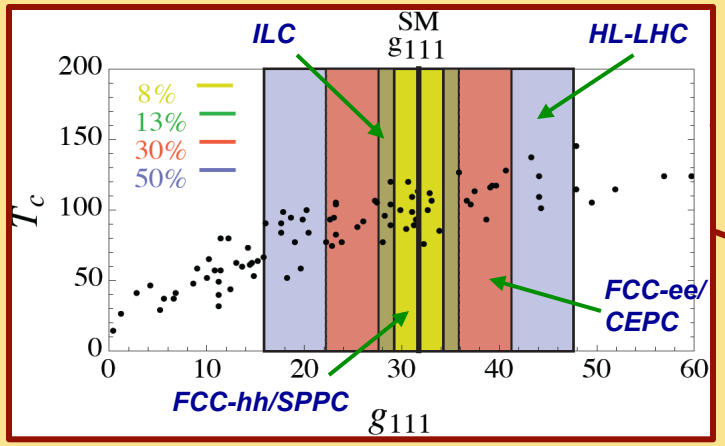
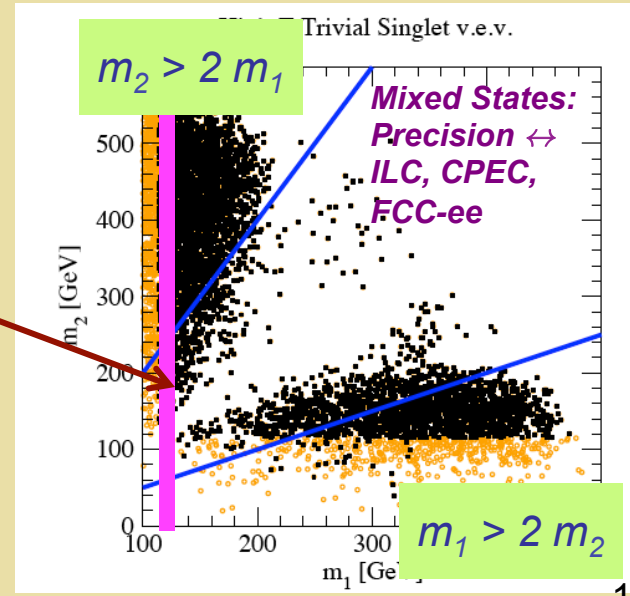




Scan includes $m_2 > 2m_1$

Modified Higgs Self-Coupling





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

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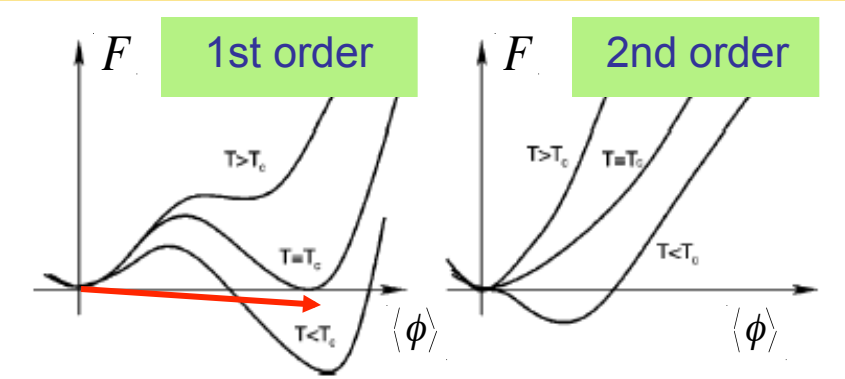

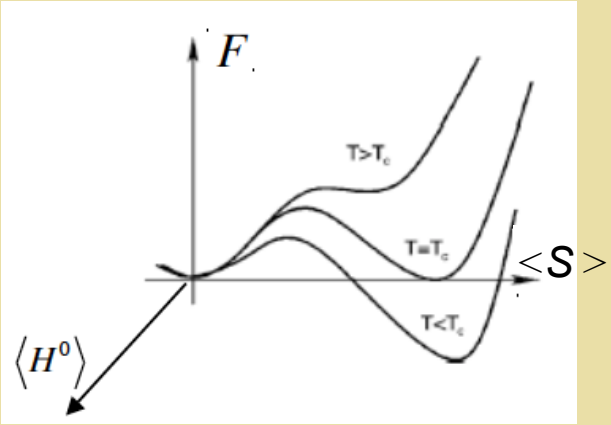

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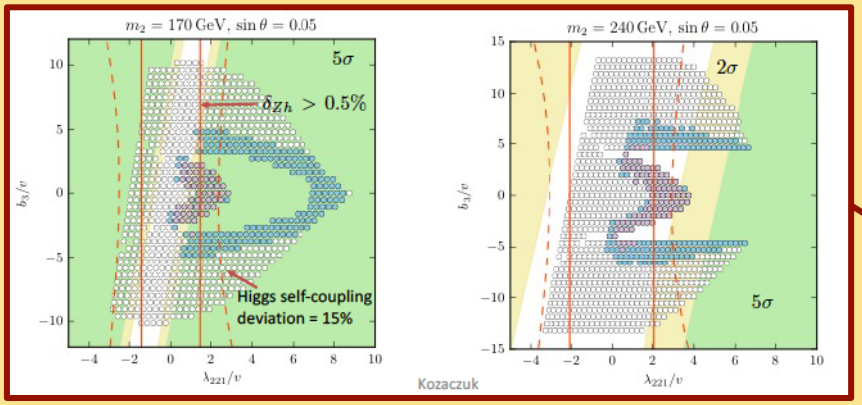

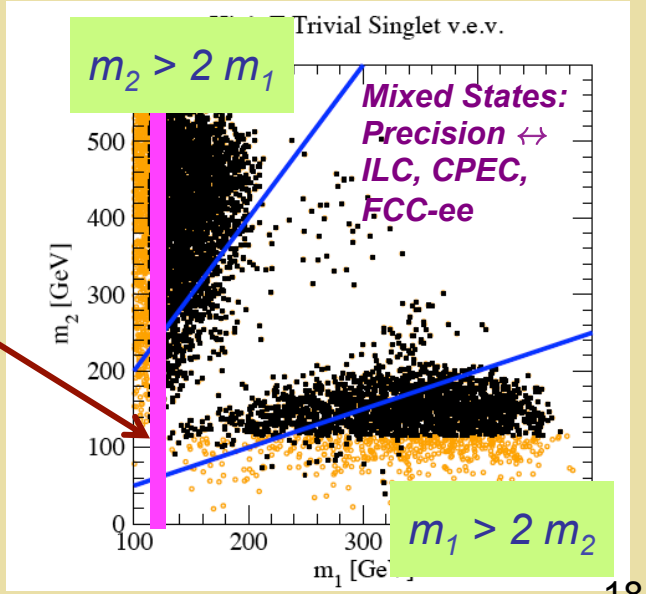

Chen, Kozaczuk, Lewis 1704.05844
100 TeV pp

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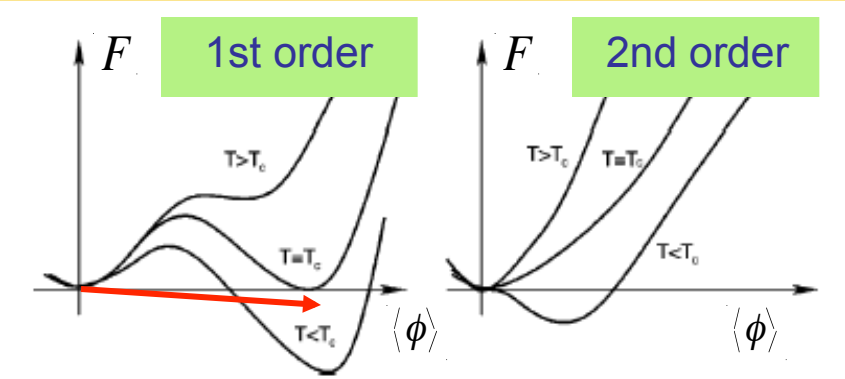
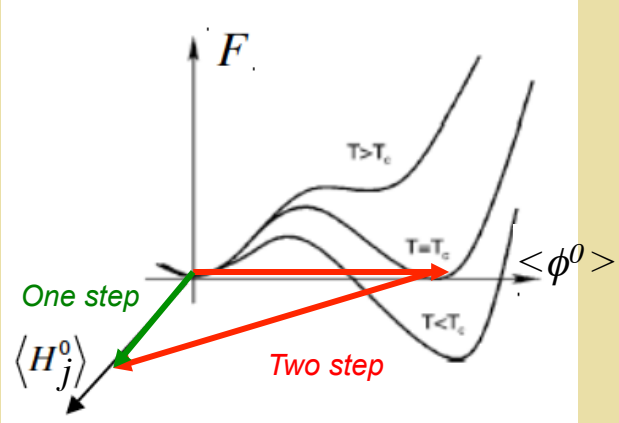
EW Multiplets: Two-Step EWPT

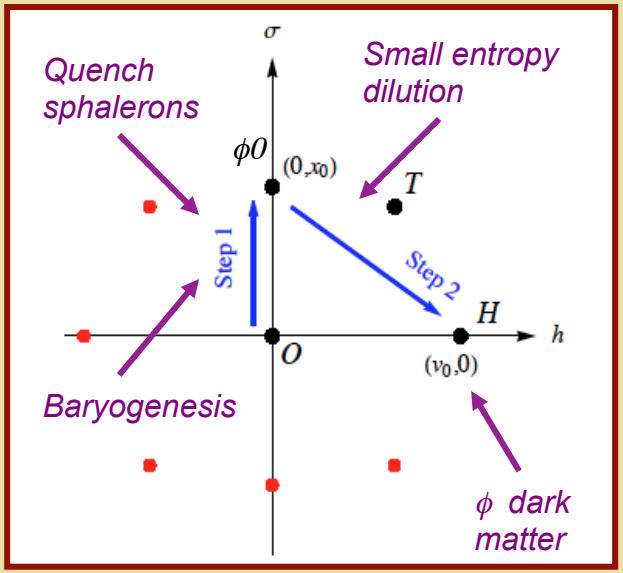




Increasing m_h →

← *New scalars*

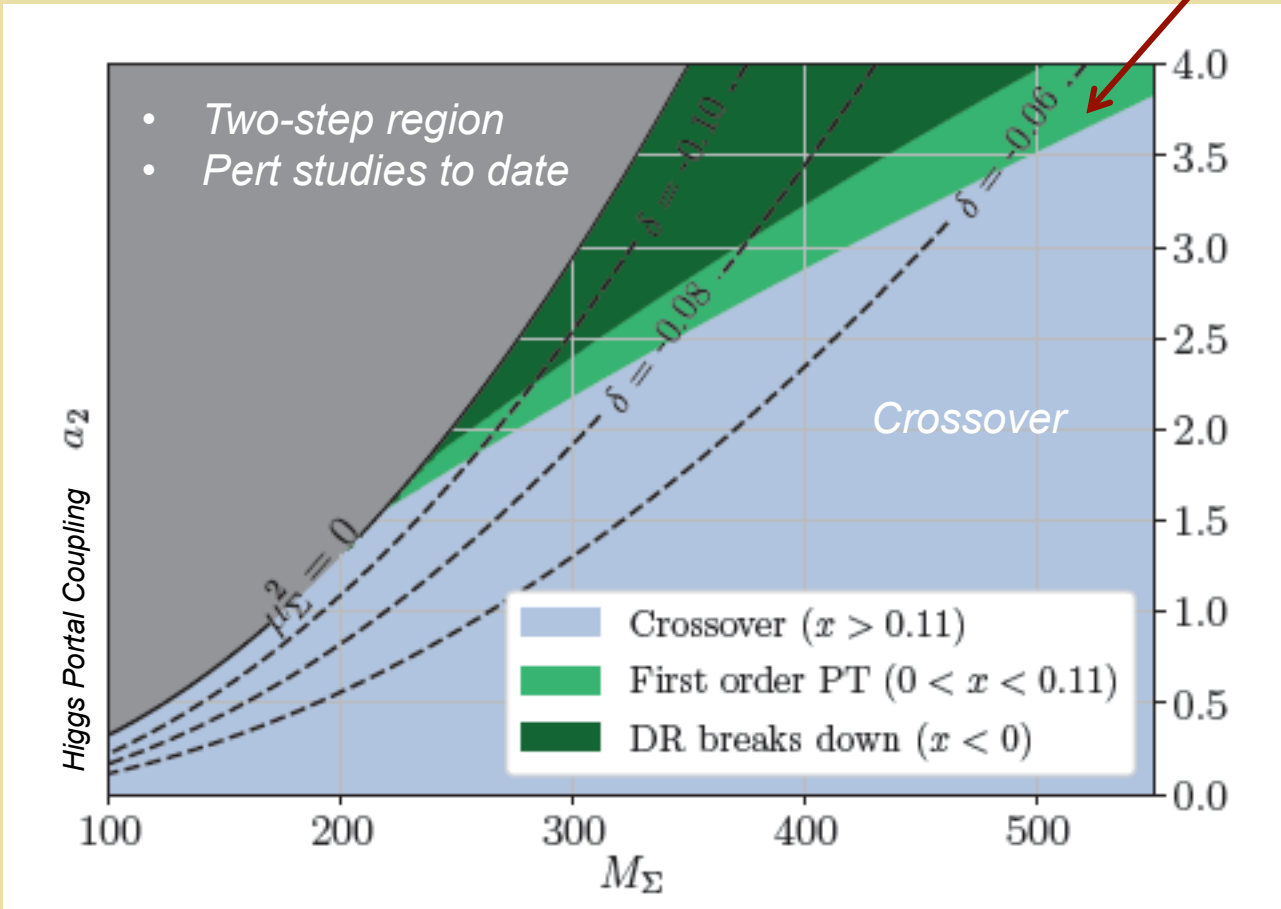
- *Step 1: thermal loops*
- *Step 2: tree-level barrier*



Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

Real Triplet & EWPT

FOEWPT



- One-step
- Non-perturbative

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

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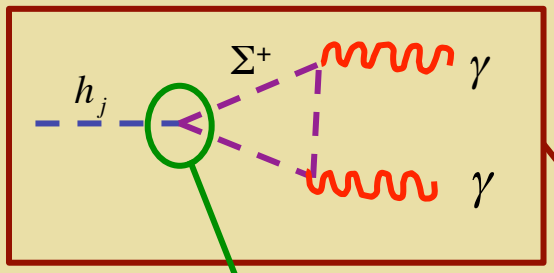

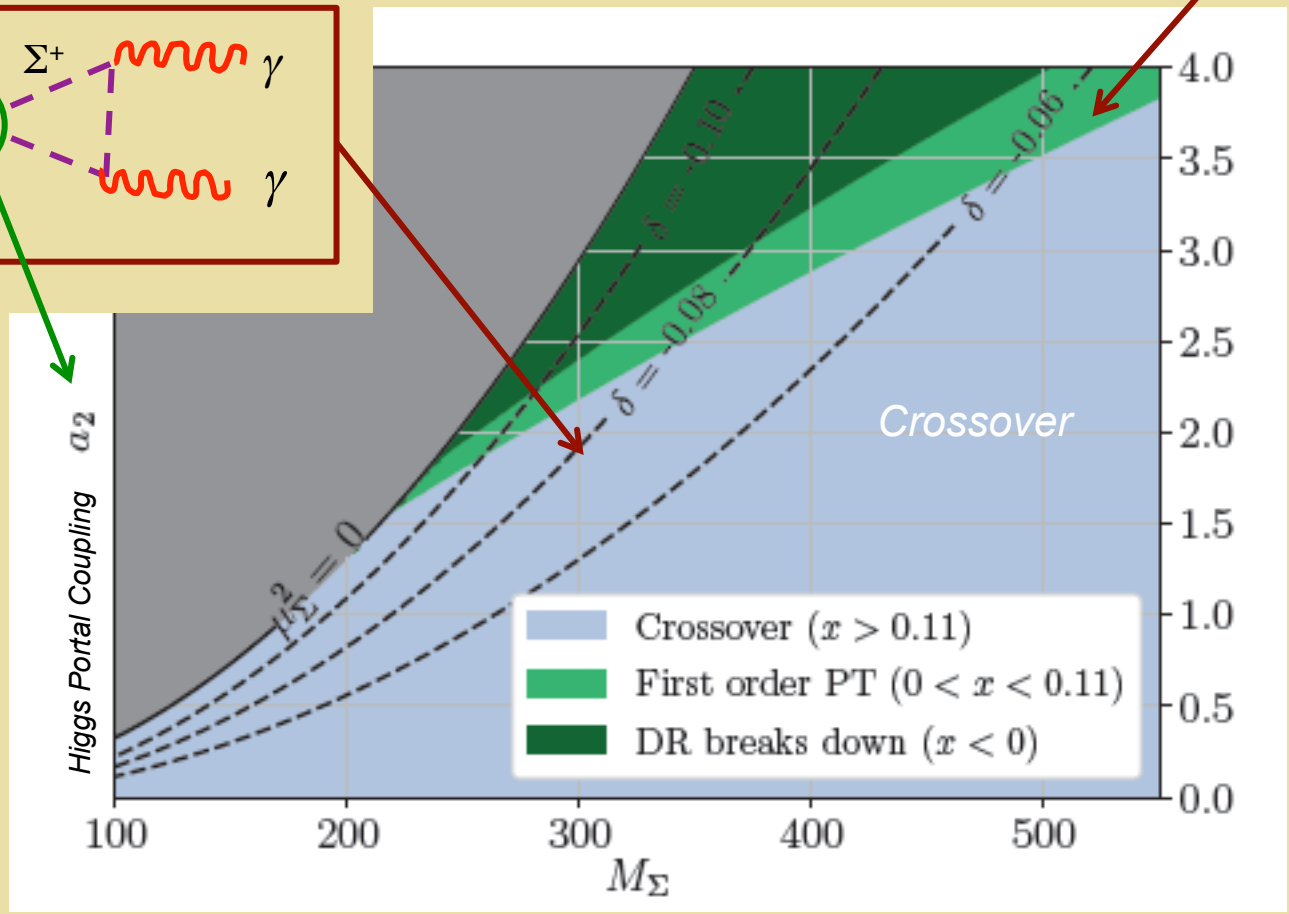

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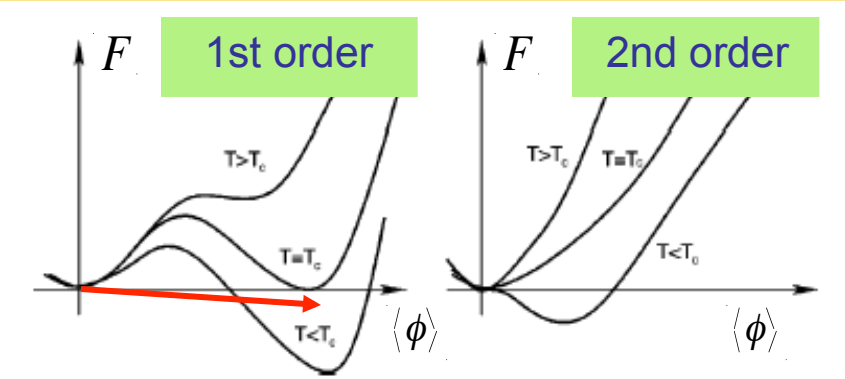
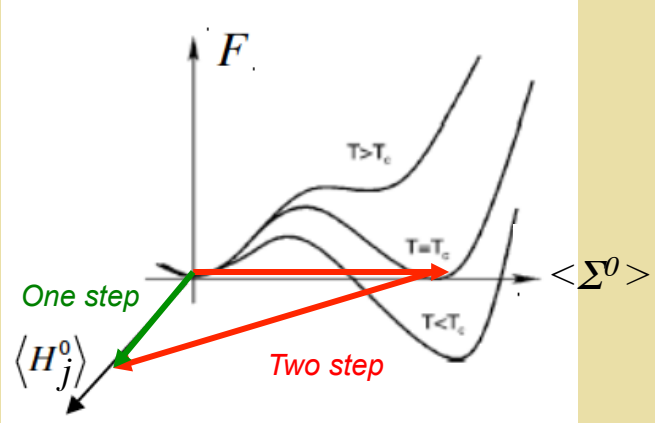
EW Multiplets: Real Triplet





Increasing m_h →

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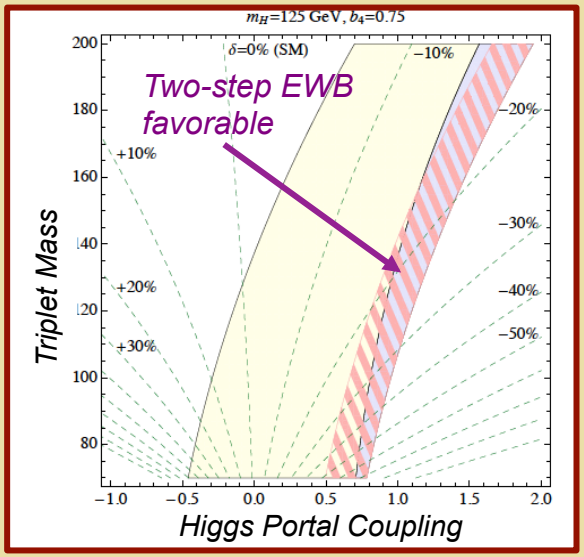
$$\mathcal{O}_4 = \lambda_{\phi H}\ \phi^\dagger\phi\ H^\dagger H$$



Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

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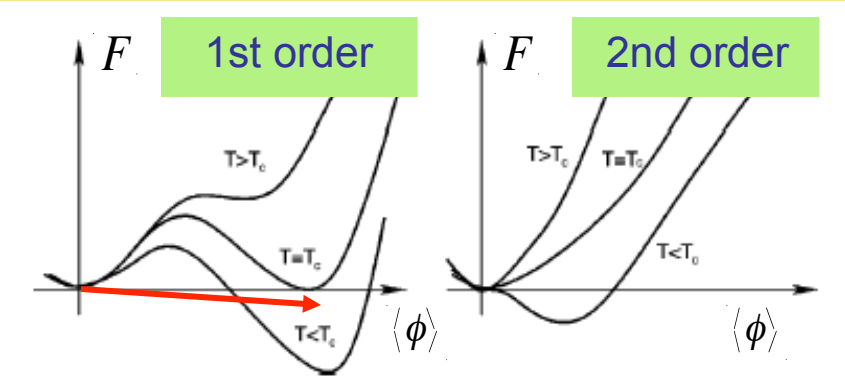

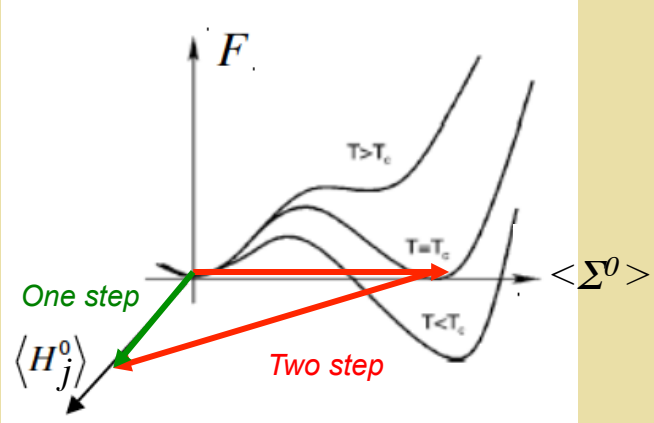

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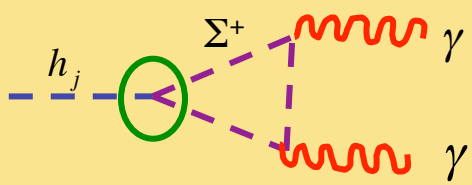

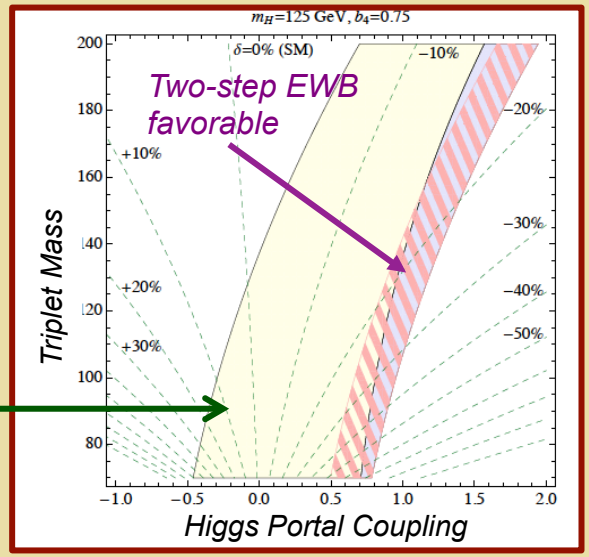

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EW Multiplets: Two-Step EWPT

Using BR(H→ZZ*) from FCC-ee (known at ~0.3% from δg_{HZZ}~0.15%), production ratios σ(H→XY)/σ(H→ZZ*) for p_T>100 GeV return the following stat precision on the **absolute value** of rare BRs

	γγ	Zγ	μμ
δ BR	~0.5%	~1%	~1%

M. Mangano

FCC-ee: < 2% on $\delta_{H\gamma\gamma}$

Increasing m_h →

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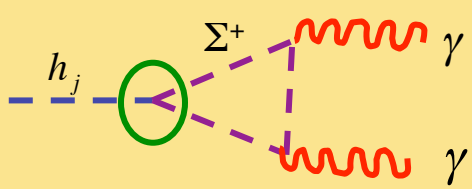

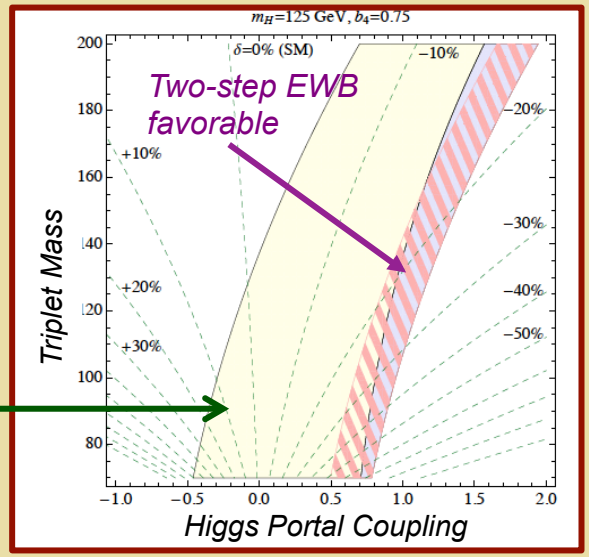

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Summary

- *Initial phenomenological studies indicate HL/HE LHC + other future colliders will have high potential for probing the nature of the EWSB transition & determining whether conditions existed for EW baryogenesis*
- *Resonant & non-resonant di-Higgs production and precision Higgs studies provide powerful, complementary probes*
- *Exciting opportunities exist for more theoretical & experimental investigation of the collider/EWPT interface*

Back Up

Higgs Portal: Simple Scalar Extensions

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EWPT & Dark Sector: EW Multiplets

Cirelli & Strumia '05

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM can decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Events at LHC $\int \mathcal{L}\, dt = 100/\text{fb}$	σ_{SI} in $10^{-45}\,\text{cm}^2$
2	1/2	0	EL	0.54 ± 0.01	350	$320 \div 510$	0.2
2	1/2	1/2	EH	1.1 ± 0.03	341	$160 \div 330$	0.2
3	0	0	HH^*	2.0 ± 0.05	166	$0.2 \div 1.0$	1.3
3	0	1/2	LH	2.4 ± 0.06	166	$0.8 \div 4.0$	1.3
3	1	0	HH, LL	1.6 ± 0.04	540	$3.0 \div 10$	1.7
3	1	1/2	LH	1.8 ± 0.05	525	$27 \div 90$	1.7
4	1/2	0	HHH^*	2.4 ± 0.06	353	$0.10 \div 0.6$	1.6
4	1/2	1/2	(LHH^*)	2.4 ± 0.06	347	$5.3 \div 25$	1.6
4	3/2	0	HHH	2.9 ± 0.07	729	$0.01 \div 0.10$	7.5
4	3/2	1/2	(LHH)	2.6 ± 0.07	712	$1.7 \div 9.5$	7.5
5	0	0	(HHH^*H^*)	5.0 ± 0.1	166	$\ll 1$	12
5	0	1/2	–	4.4 ± 0.1	166	$\ll 1$	12
7	0	0	–	8.5 ± 0.2	166	$\ll 1$	46

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Theory Meets Phenomenology

A. Non-perturbative

- *Most reliable determination of character of EWPT & dependence on parameters*
- *Broad survey of scenarios & parameter space not viable*

B. Perturbative

- *Most feasible approach to survey broad ranges of models, analyze parameter space, & predict experimental signatures*
- *Quantitative reliability needs to be verified*

EWPT & Perturbation Theory

Expansion parameter

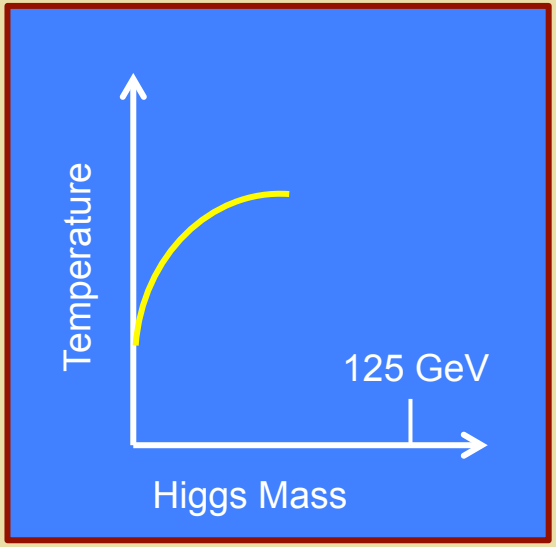
Gauge coupling in finite-T theory

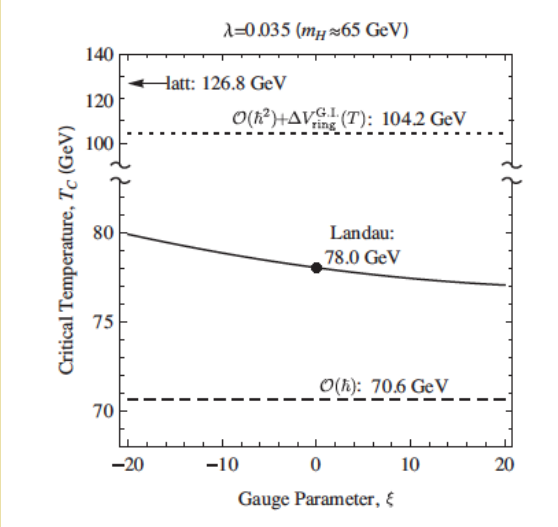
$$g_{\rm eff} \equiv \frac{g_3^2}{\pi m_T(\varphi)}$$

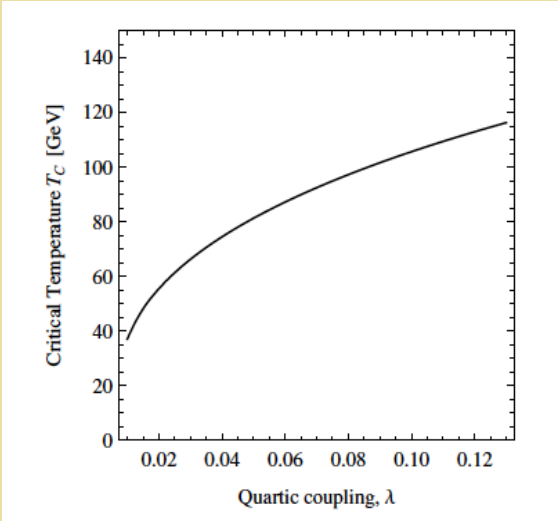
SM lattice studies: *g_{eff} ~ 0.8 in vicinity of EWPT for m_H ~ 70 GeV*

EWPT & Perturbation Theory (PT)

Lessons from St'd Model







- *No cross over transition or endpoint of FOEWPT seen in PT*
- *PT underestimates the critical temp*
- *PT seems to get trends with parameters correct*

EWPT & Perturbation Theory (PT)

Takeaways

- *Perturbative studies of EWPT properties may yield qualitatively realistic results but are not unlikely to be quantitatively reliable*

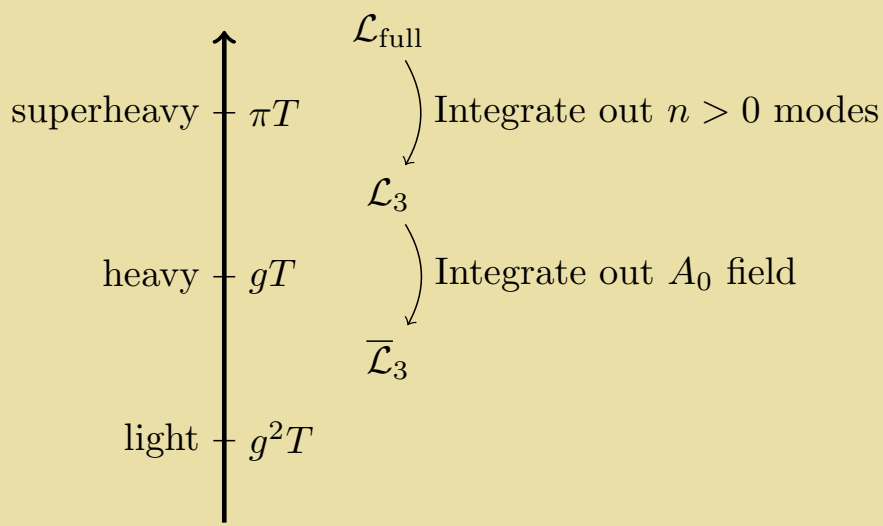
- *Non-perturbative studies also face limitations: challenging to study broad range of models & parameters, and (so far) limited information on whether or not FOEWPT is sufficiently strong for EWBG* **

- *Future theoretical work: interfacing PT w/ non-pert studies ("benchmarking") & improving PT*

** *However, see G. Moore '99 for non-pert SM sphaleron rate calc*

Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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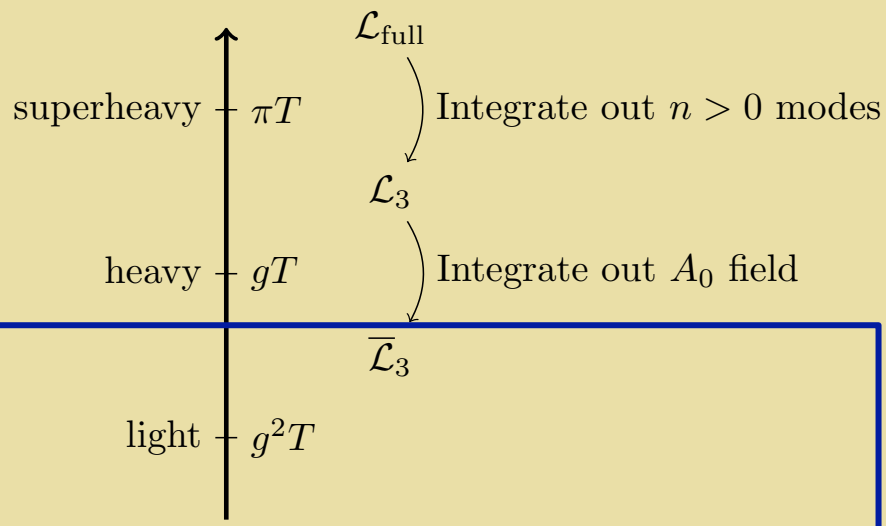

$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

Lattice simulations exist

- *Assume BSM fields are "heavy" or "supeheavy" : integrate out*
- *Effective "SM-like" theory parameters are functions of BSM parameters*
- *Use existing lattice computations for SM-like effective theory & matching onto full theory to determine FOEWPT-viable parameter space regions*

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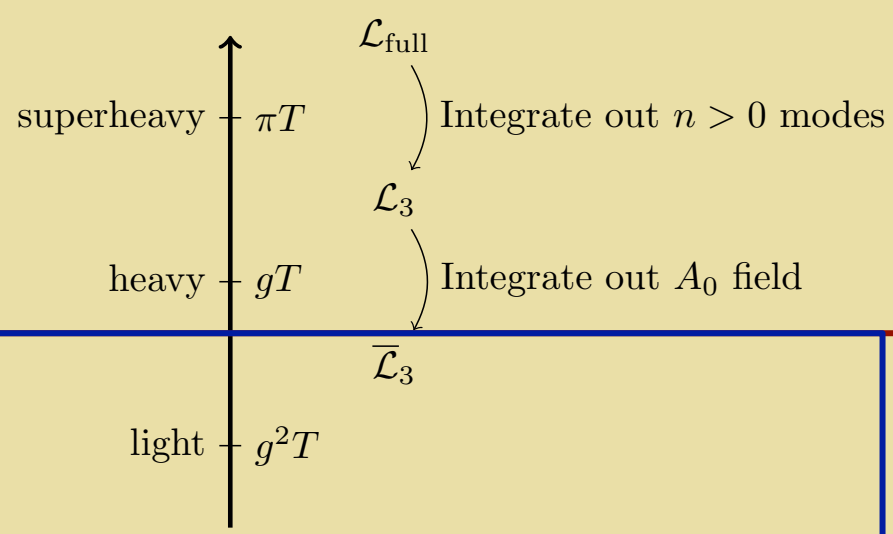

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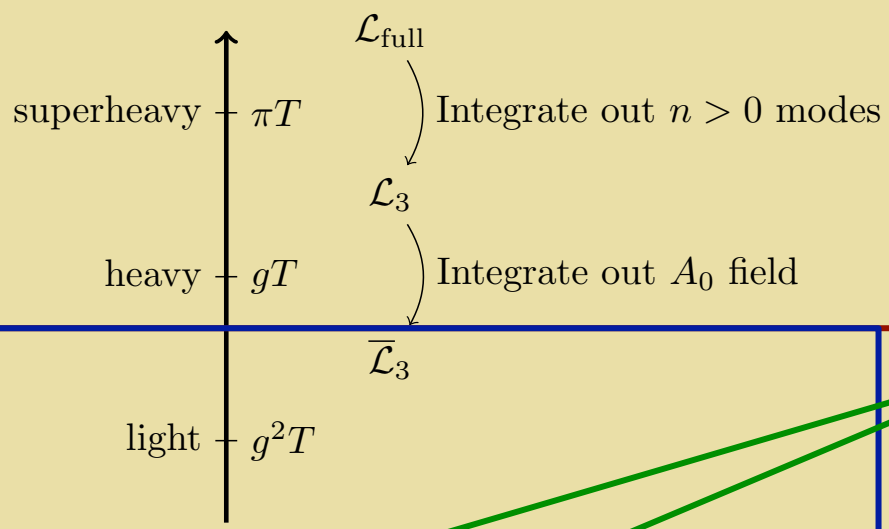

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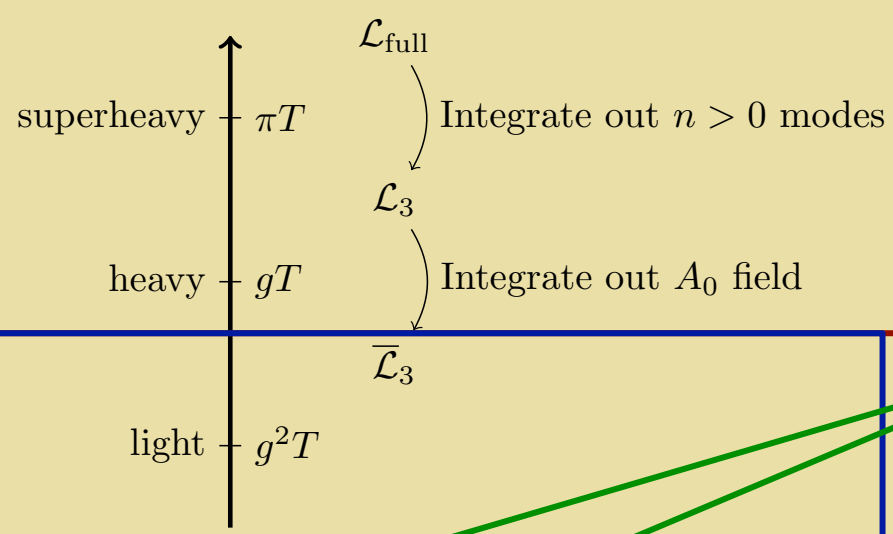

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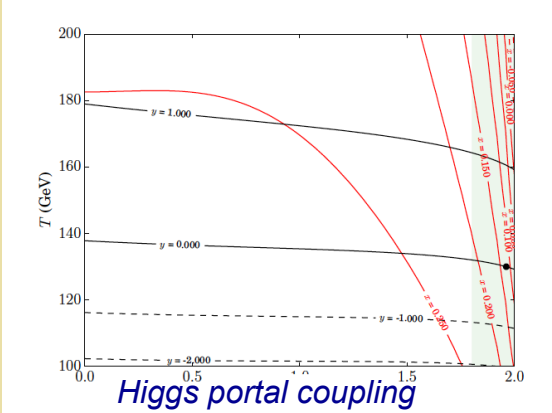
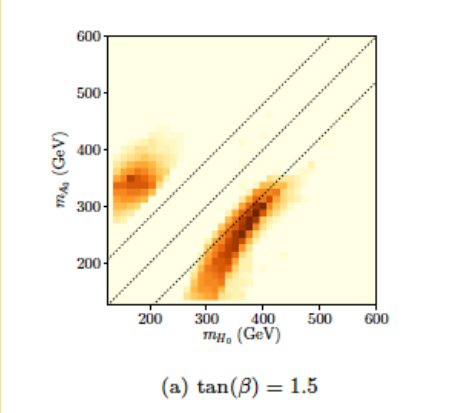
Benchmarking PT: Recent Progress

Z_2 Singlet: "superheavy"



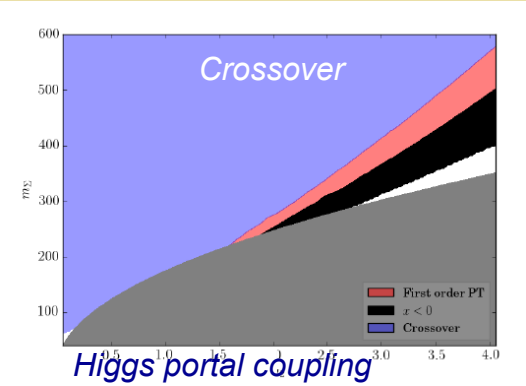
Brauner et al '16

2HDM: "heavy"



Andersen et al '17

Real triplet: "heavy"



Niemi et al '18 (preliminary)

$$x = \frac{\lambda}{g_3^3} \qquad y = \frac{\mu_3^2}{g_3^4}$$

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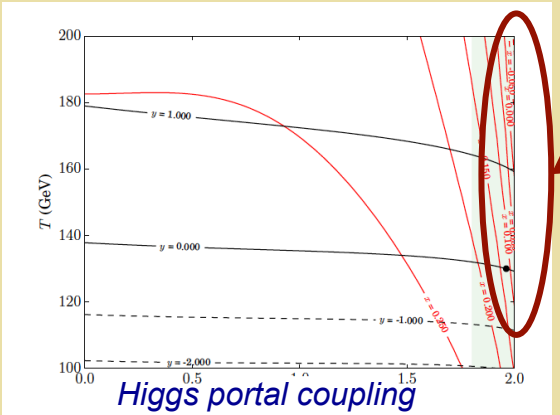

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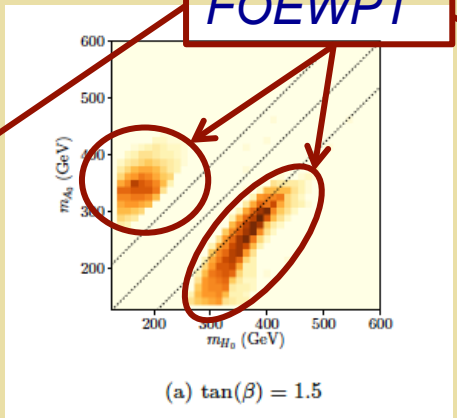
FOEWPT



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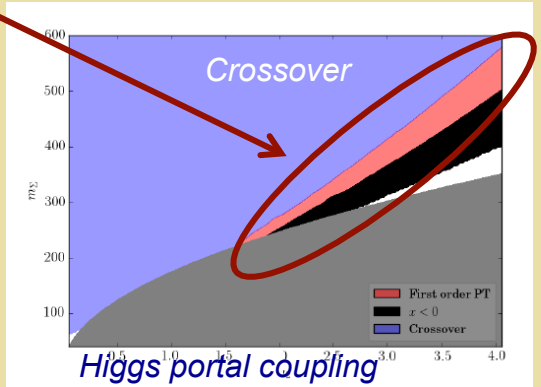

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Real Triplet Example: Lessons

- *Initial non-perturbative studies using 3d EFT reveals region of FOEWPT not evident in PT*
- *Next generation circular e+e- and pp colliders likely necessary to access this region: a first order transition* $\rightarrow$ *Observable shift in* $h \rightarrow \gamma\gamma$ *rate*
- *Next generation colliders will have needed sensitivity*

Benchmarking PT: Recent Progress

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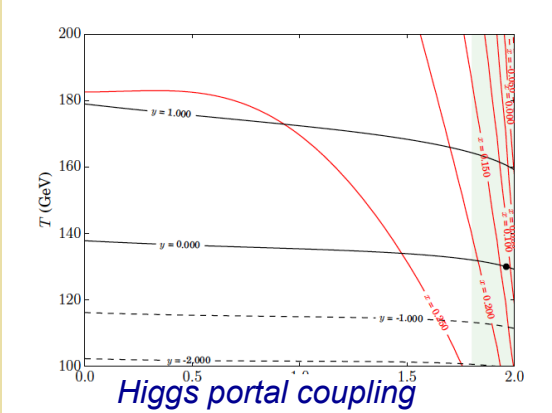

Higgs portal coupling

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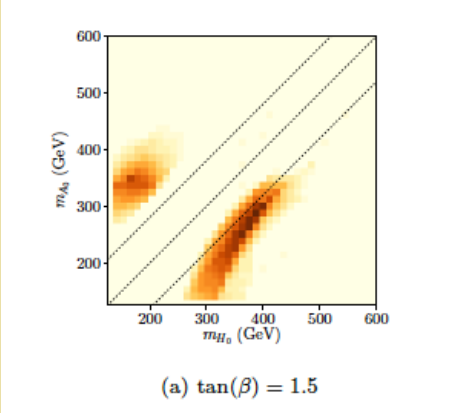

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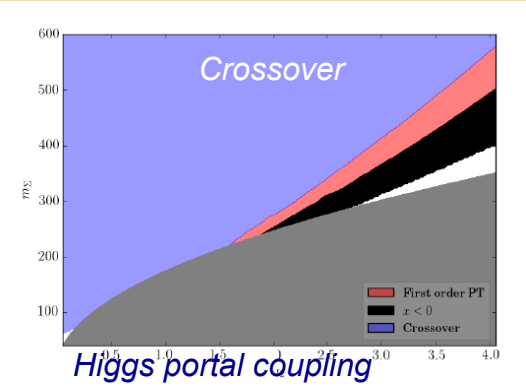

Higgs portal coupling

Niemi et al '18 (preliminary)

- *BSM fields fields do not play dynamical role in EWSB*
- *All transitions are single step – no multistep transitions occur*
- *Non-perturbative determination of strength of transition (sphaleron & tunneling rates) remain to be obtained*

→ ***Need lattice simulations w/ dynamical BSM scalars***