Electroweak Phase Transition & Extended Scalar Sectors

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My pronouns: he/him/his

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Tsung-Dao Lee Institute
上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

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

http://tdli.sjtu.edu.cn/web/yjxy/5130001.htm

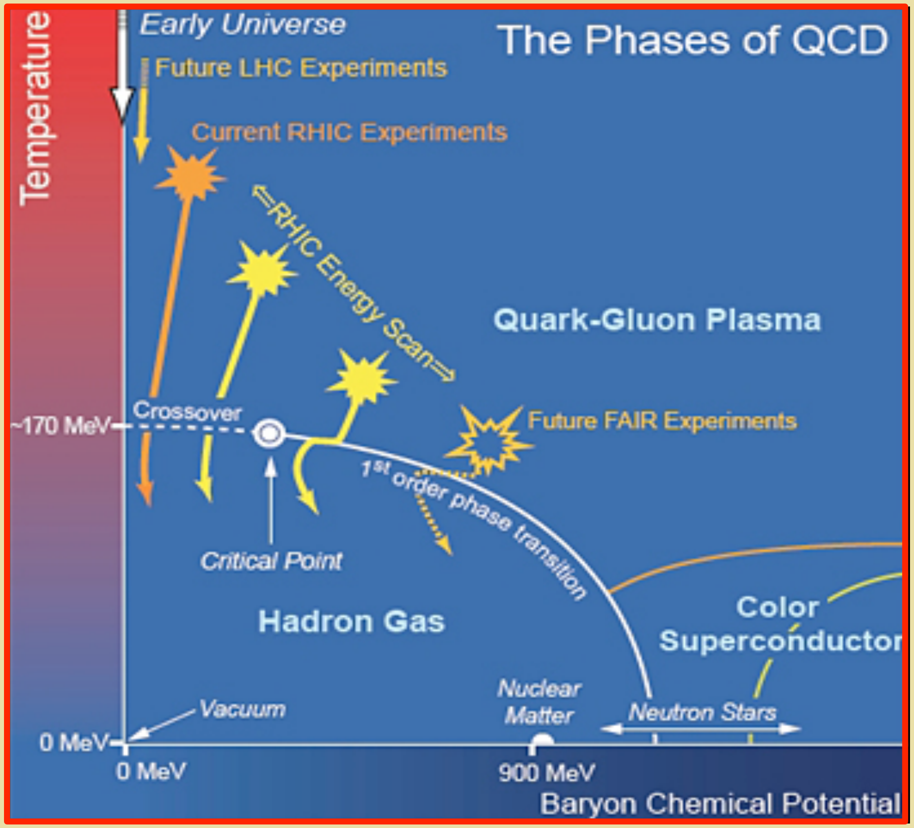
Collaborators: O. Gould, J. Kozaczuk, L. Niemi, H. Patel, T. Tenkanen, D. Weir

RISE Collaboration, Helsinki U
May 2019

Goals for This Talk

- *Discuss the implications of non-minimal Higgs sectors for the thermal history of electroweak symmetry breaking & illustrate experimental signatures*
- *Highlight the importance of carrying out non-perturbative studies of the EW symmetry-breaking transition & report on our recent work*

Thermal History of Symmetry Breaking



QCD Phase Diagram → EW Theory Analog?

Outline

I. Electroweak Phase Transition

II. Real Triplet: Perturbative Analysis

III. Theoretical Robustness: Lattice vs. PT

IV. Real Singlet: Non-pert study (time permitting)

V. Outlook

I. Electroweak Phase Transition

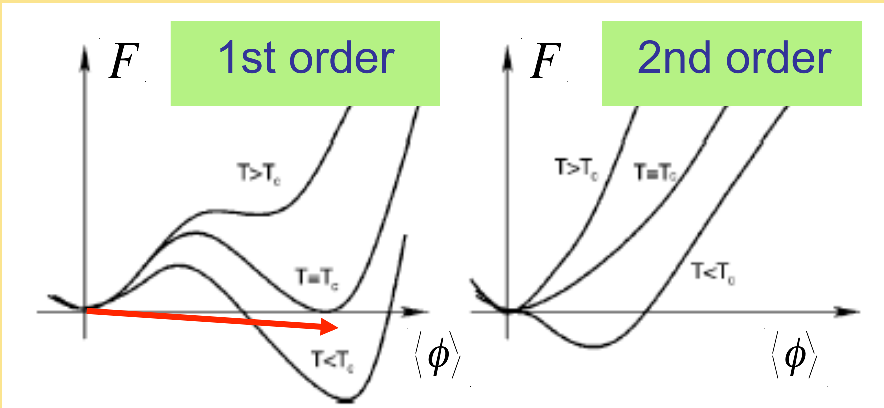
Electroweak Phase Transition

- *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 ?*

EWPT: Theory & Phenomenology

- *What models can lead to a (strong) first order electroweak phase transition (EW baryogenesis & gravitational waves) ?*
- *Can they also yield contributions to Ω_{DM} ?*
- *How can they be tested experimentally ?*
- *How reliably can we compute phase transition properties & make the connection with phenomenology ?*

EW Phase Transition: St'd Model



Increasing m_h →

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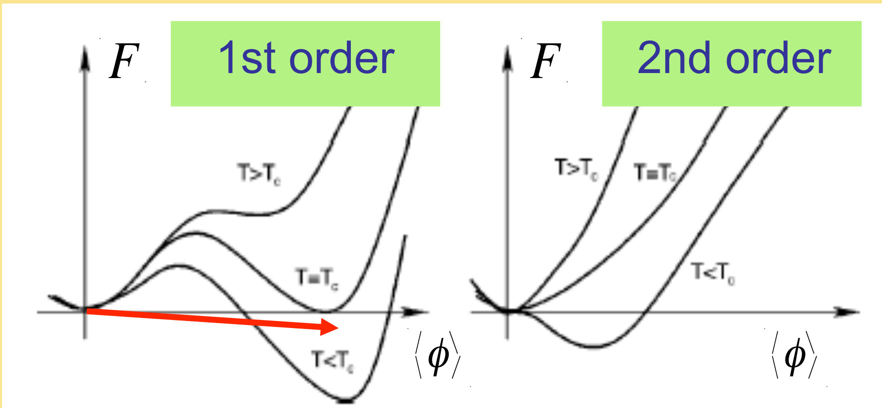
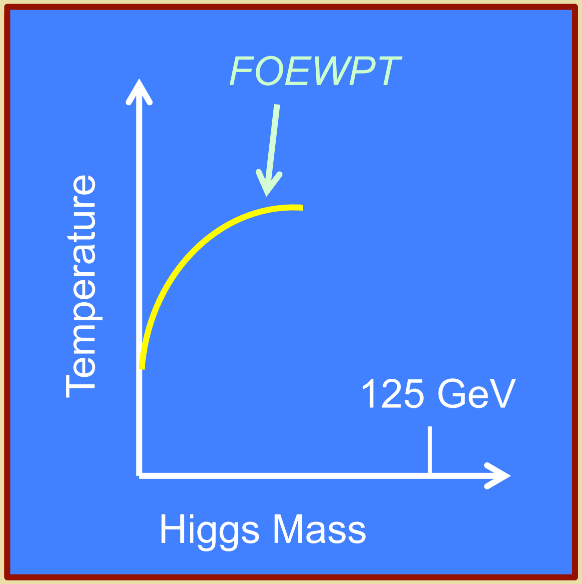


Increasing m_h →

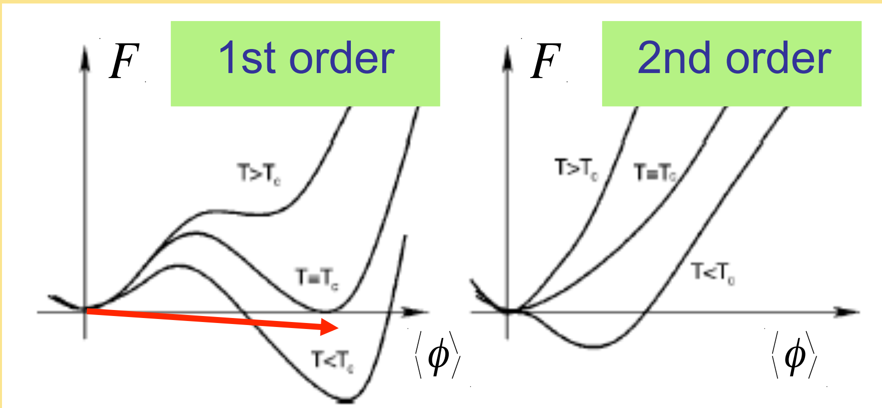
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

EW Phase Transition: St'd Model



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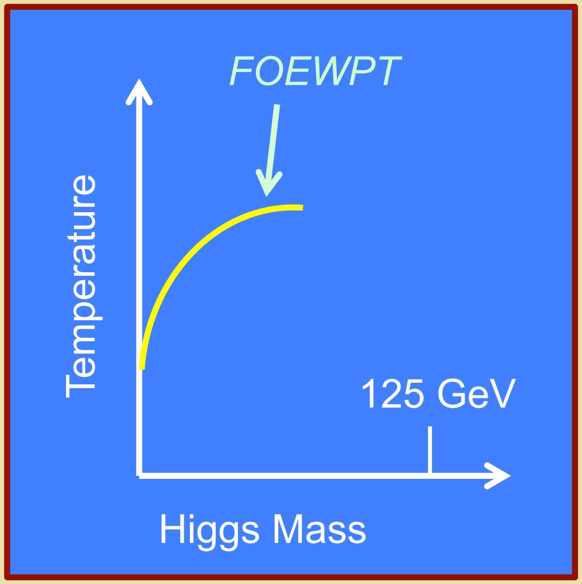

EW Phase Diagram

How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

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

Higgs Portal: Simple Scalar Extensions

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

II. Real Triplet: Perturbative Analysis

Real Triplet

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

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

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

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

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

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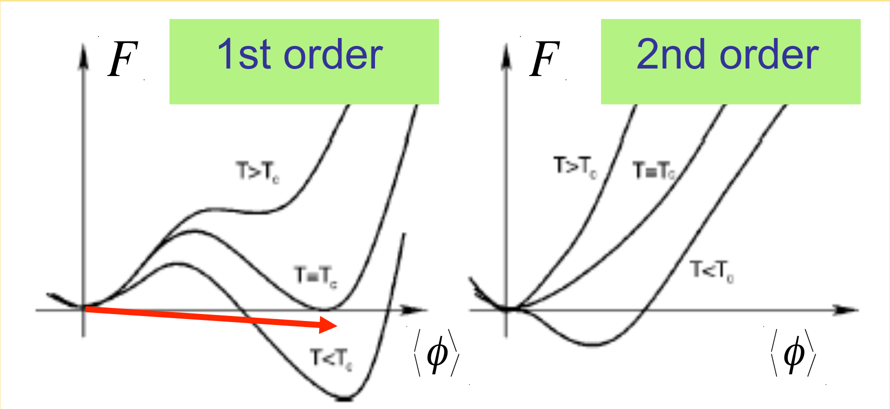
DM Stability

EW Multiplets: EWPT

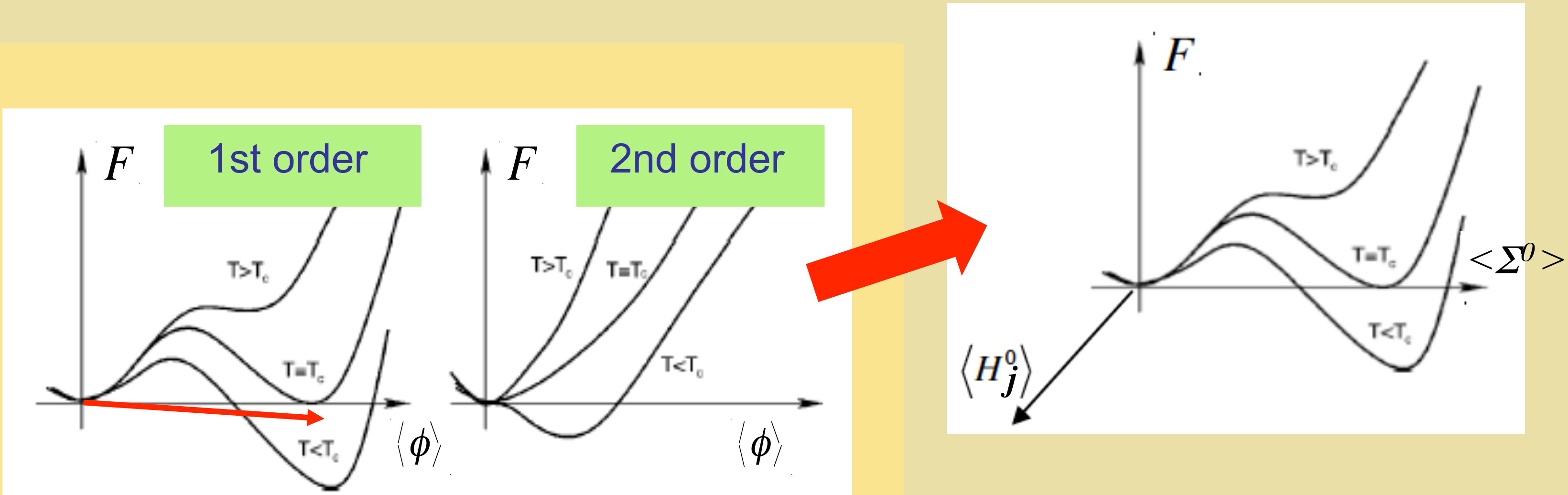


Increasing m_h ⟶

⟵ *New scalars*

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

EW Multiplets: EWPT



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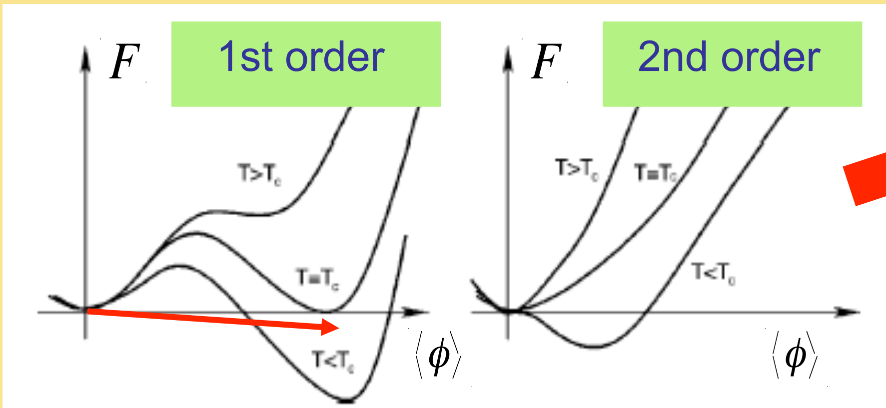
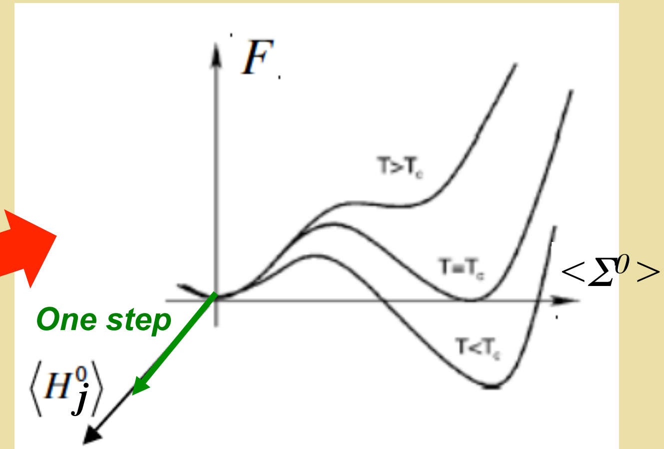
EW Multiplets: One-Step EWPT





Increasing m_h

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- *One-step: Sym pase → Higgs phase*

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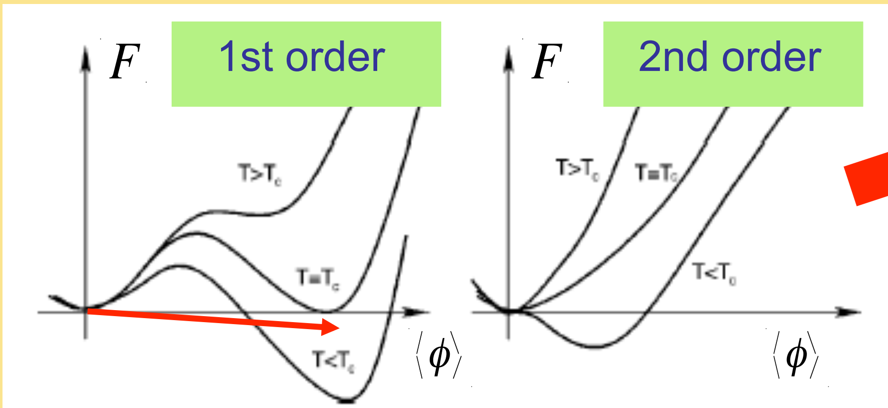
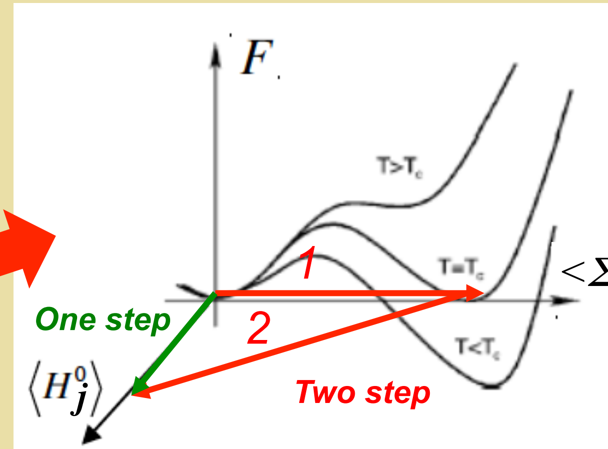
EW Multiplets: Two-Step EWPT





Increasing m_h →

← *New scalars*

- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

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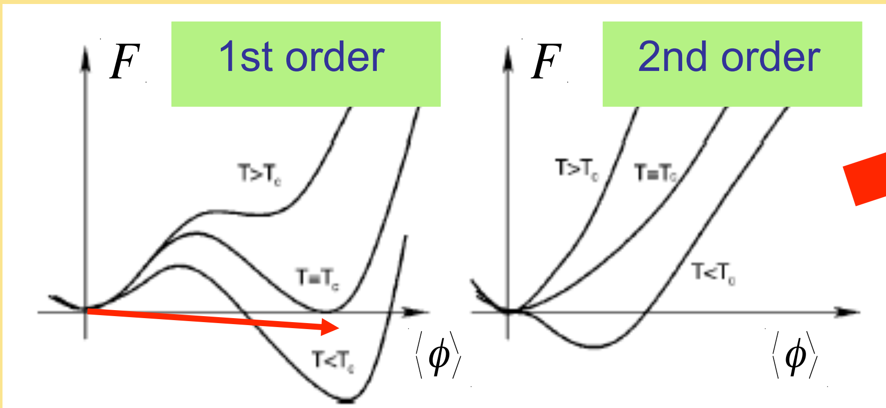
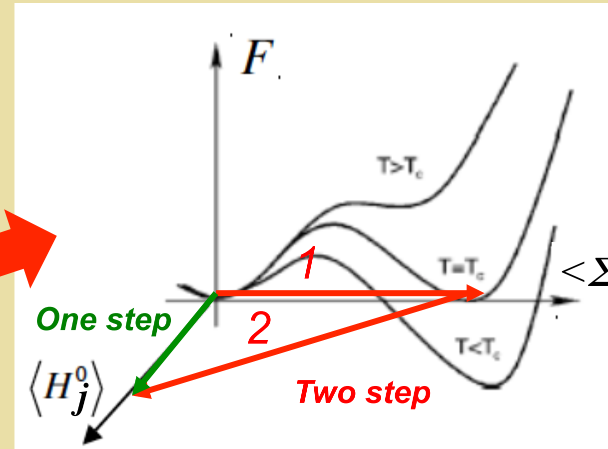
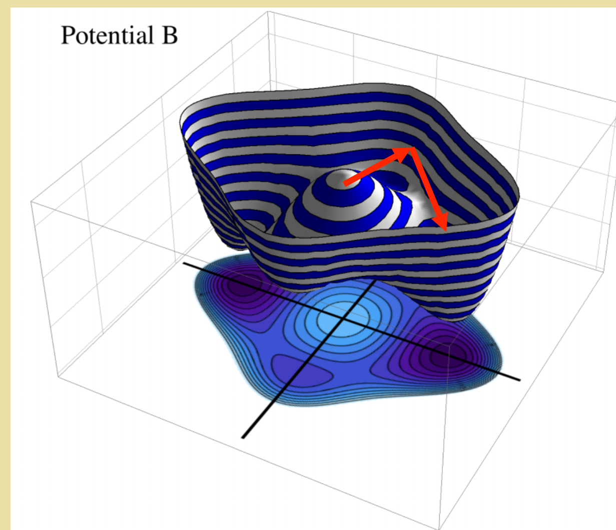
EW Multiplets: Two-Step EWPT







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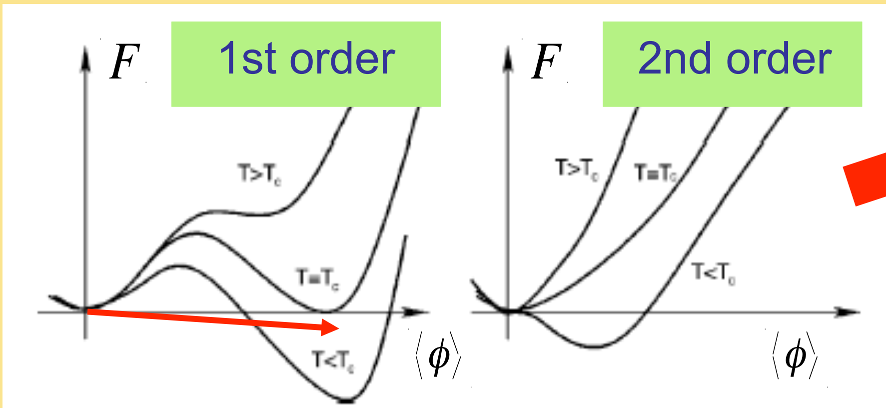
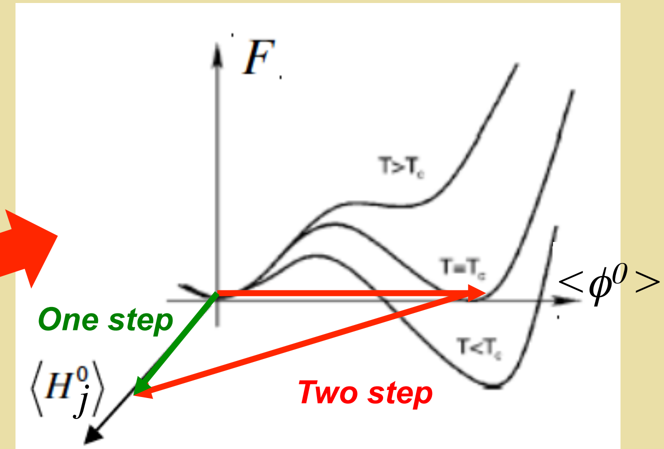
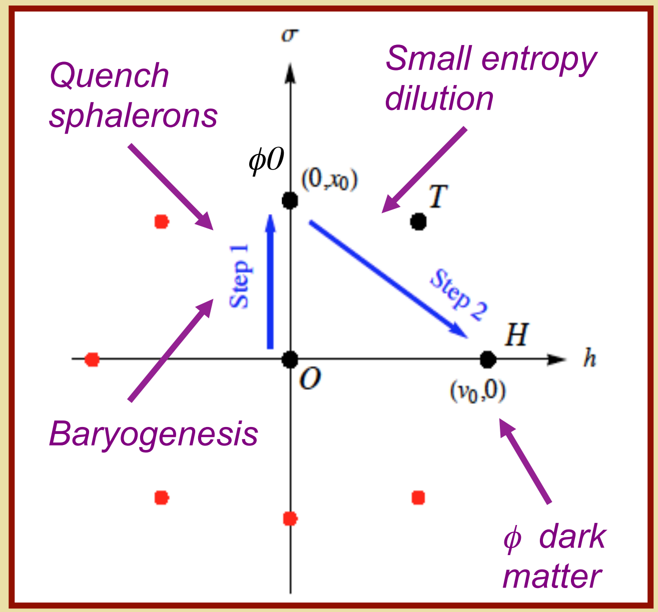




Increasing m_h

New scalars

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



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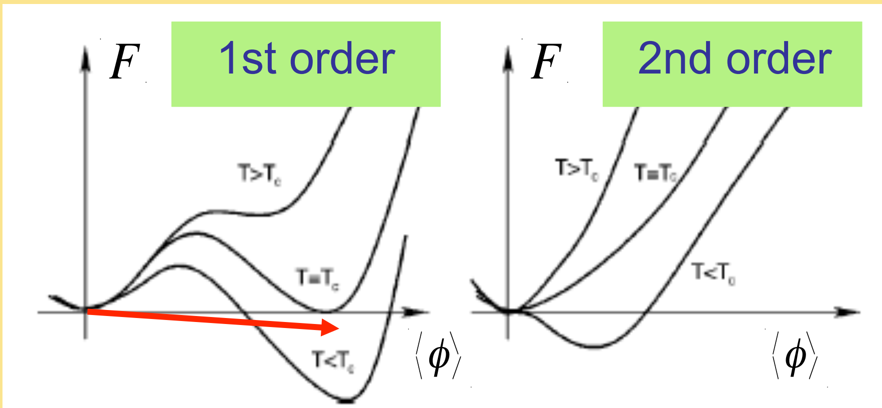
Perturbative Analysis

- *For what choices of parameters could a two-step transition occur ?*
- *What are the experimental signatures ?*

EW Multiplets: Two-Step EWPT



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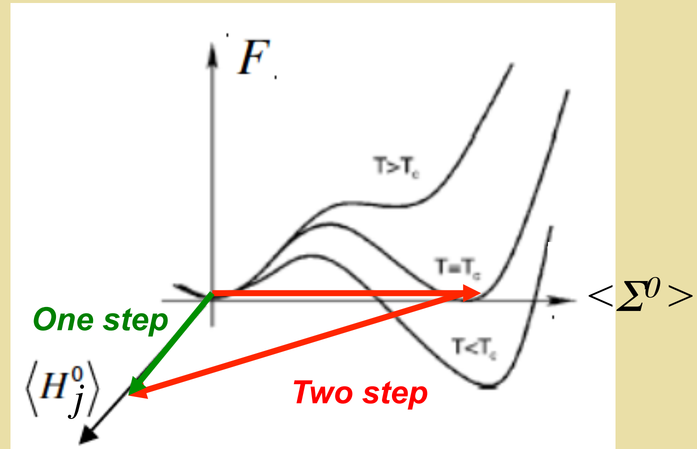

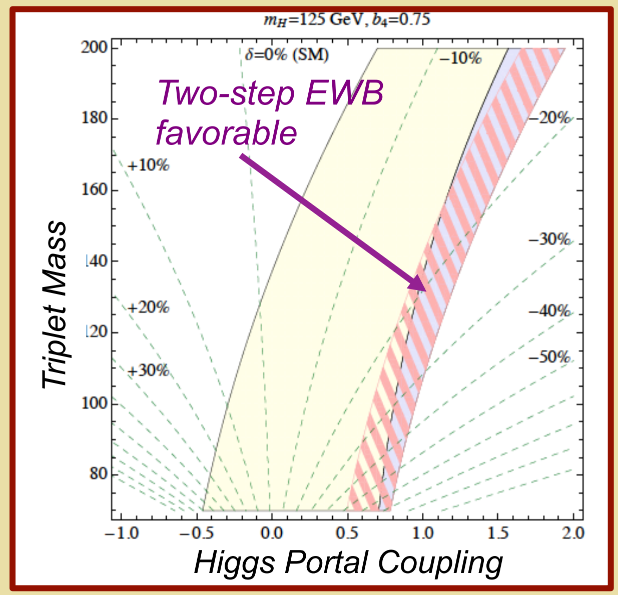

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III. EWPT: Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. Weir 1802.10500*
- *New work in progress*

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*

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Benchmark pert theory

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EWPT & Perturbation Theory

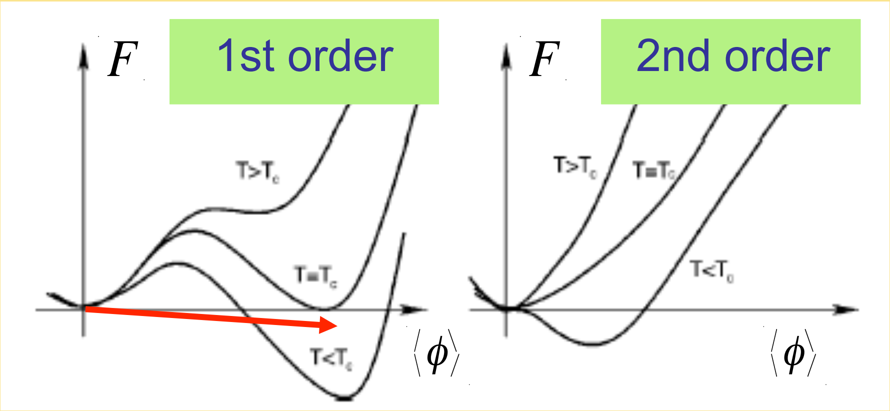
Expansion parameter

Gauge coupling in finite-T theory

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

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

EW Multiplets: One-Step EWPT ?



Increasing m_h →

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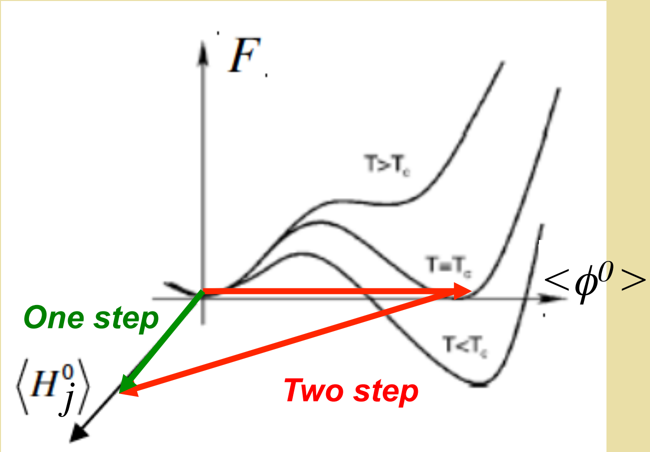
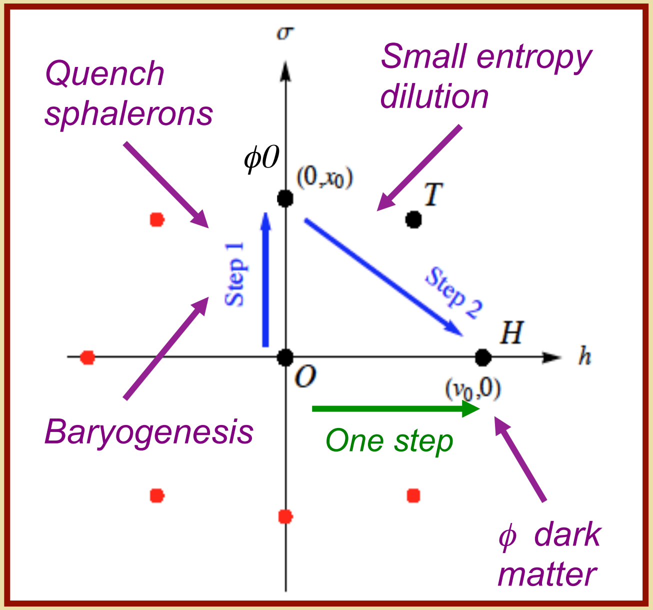
- *One-step: thermal loops*





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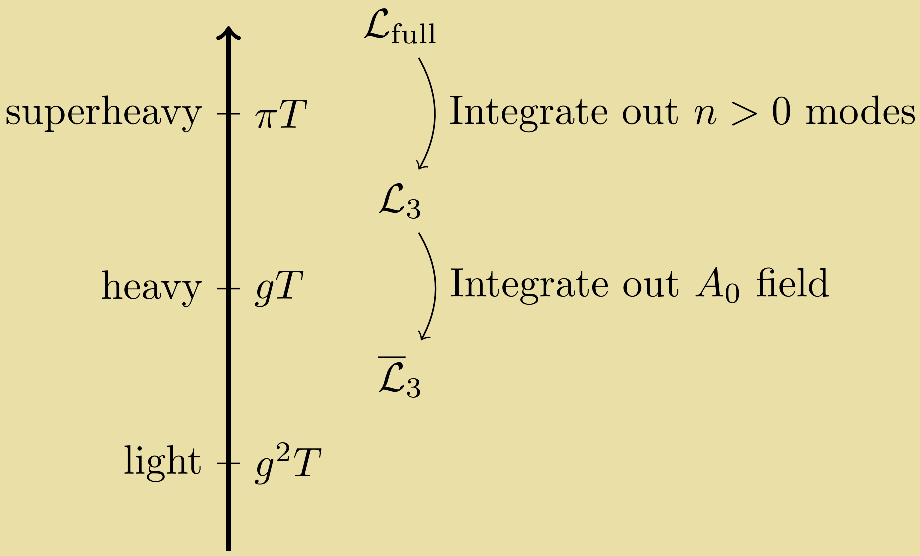
Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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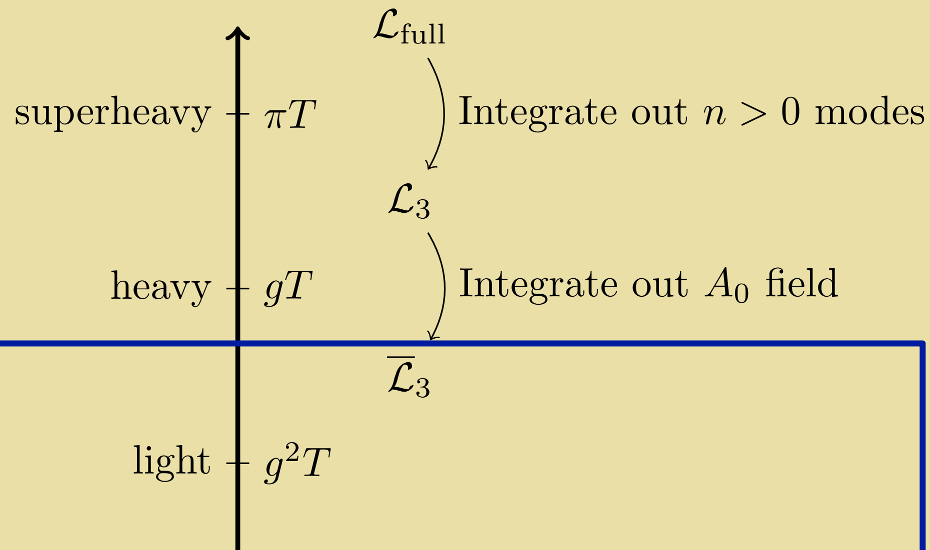

$$\boxed{V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2}$$

Lattice simulations exist

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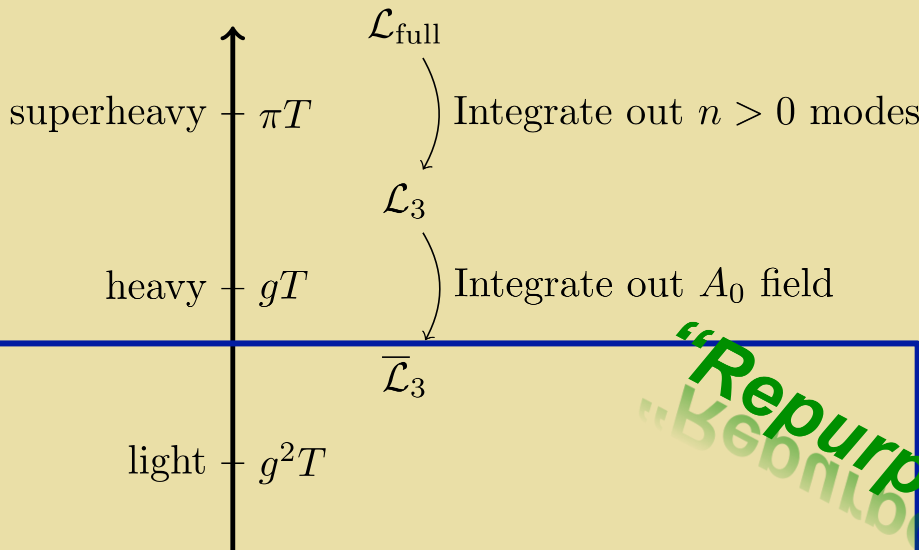

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"Repurpose" lattice results

Lattice simulations exist

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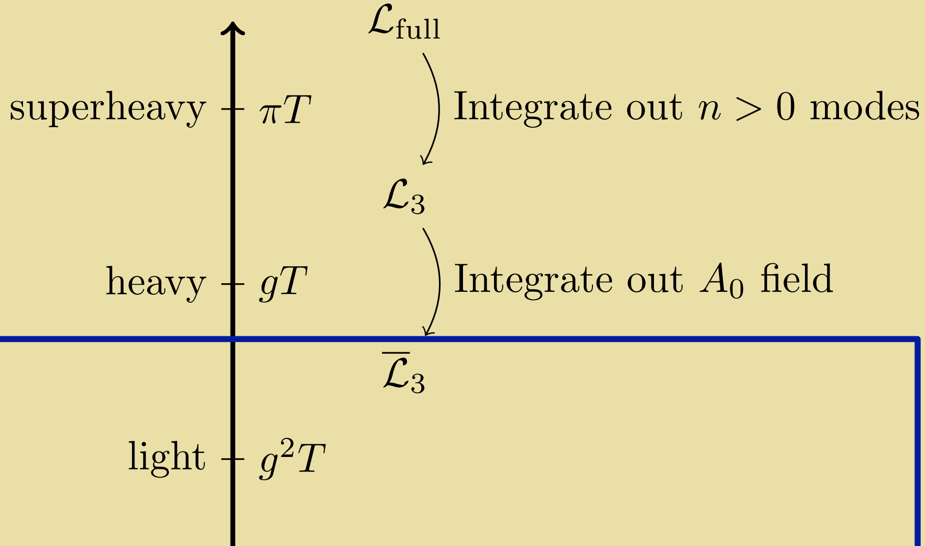

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Lattice simulations exist (e.g., Kajantie et al ‘95)

- *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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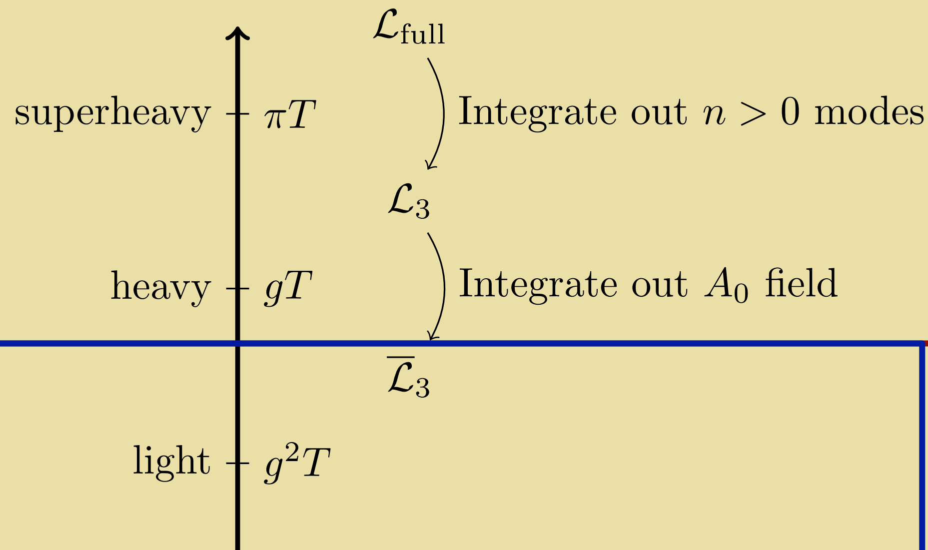

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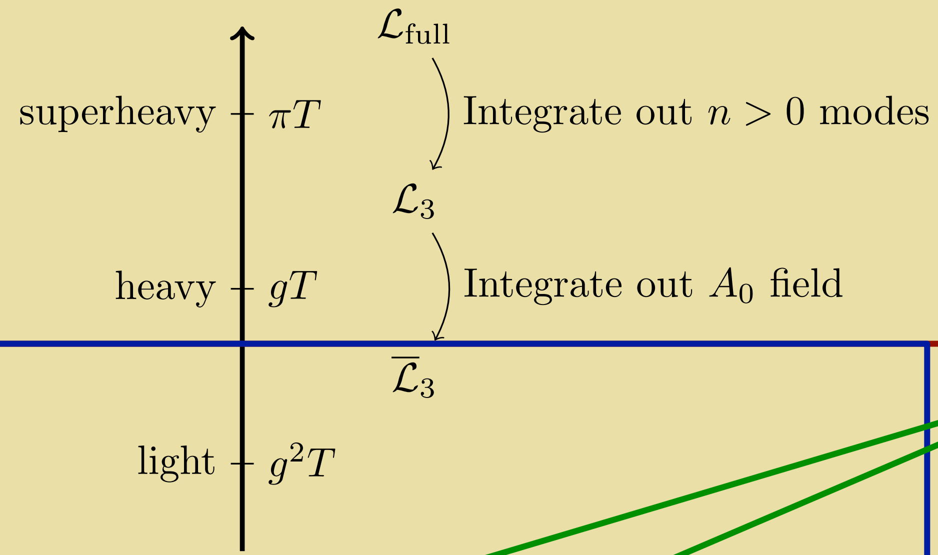

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Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory

$\mathcal{L}_{\rm full}$

superheavy — πT Integrate out $n > 0$ modes

$\mathcal{L}_3$

heavy — gT Integrate out A_0 field

$\overline{\mathcal{L}}_3$

light — $g^2 T$

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

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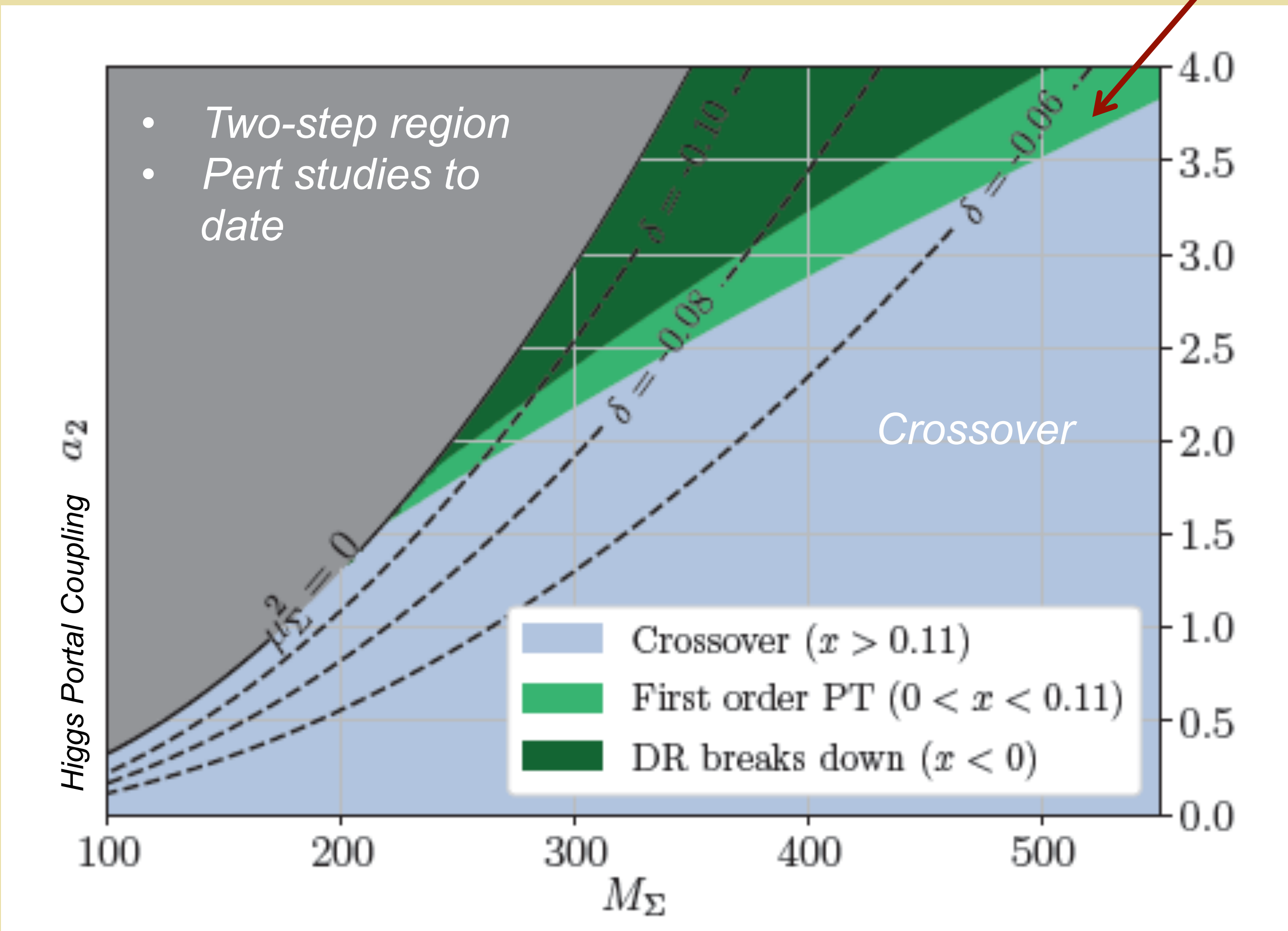
Real Triplet & EWPT

FOEWPT



- One-step
- Non-perturbative

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

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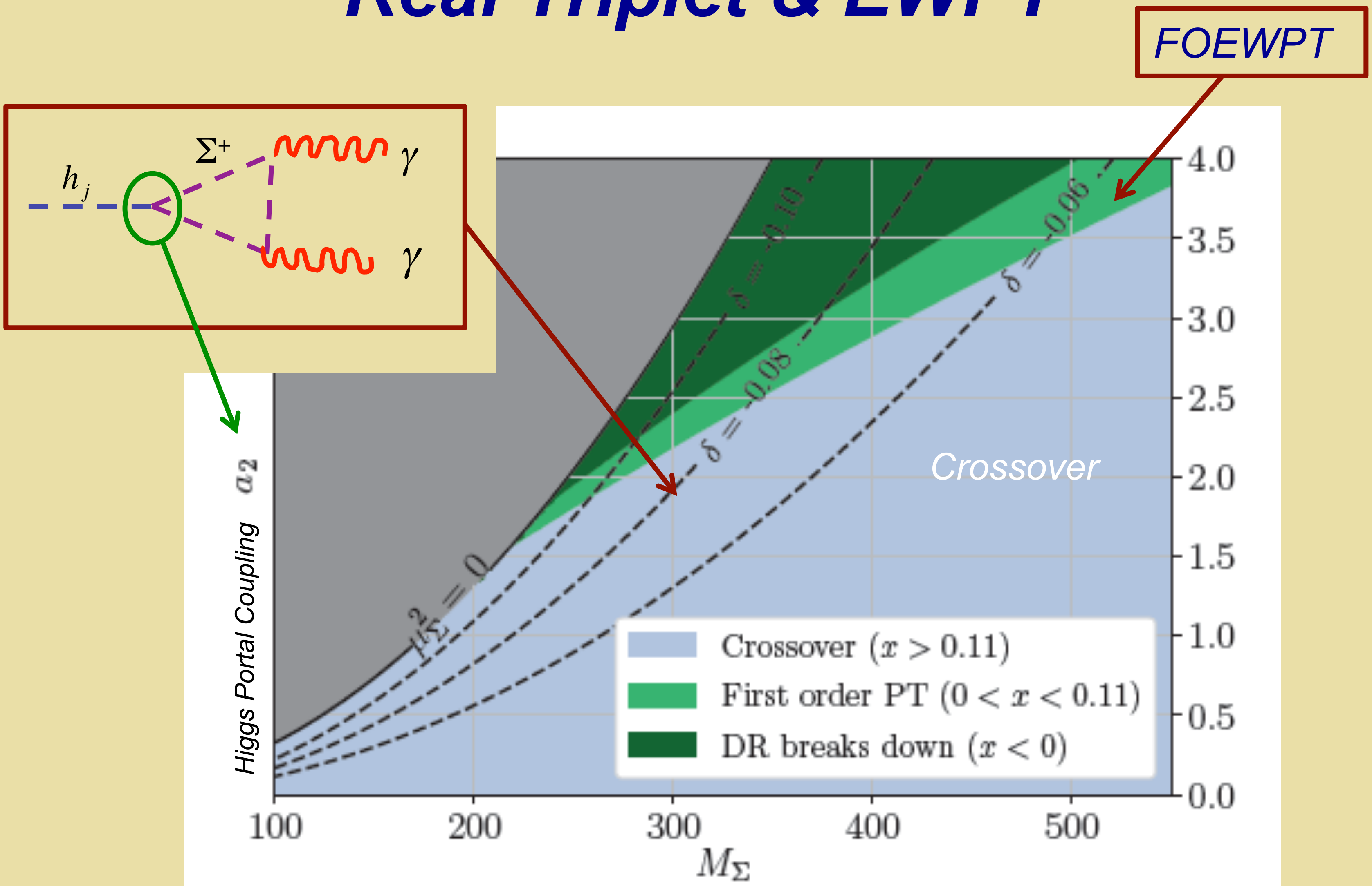

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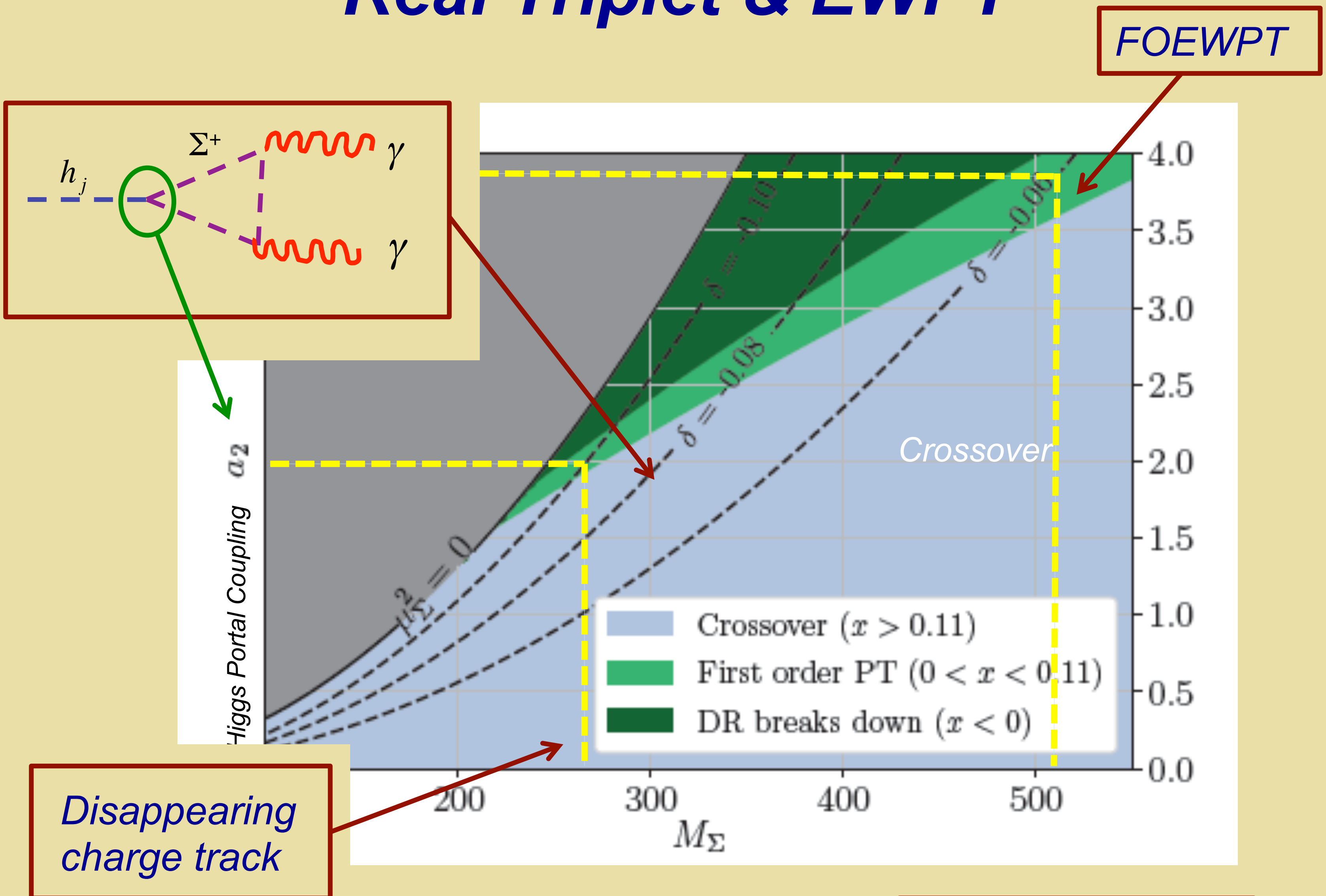

Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

- *One-step*
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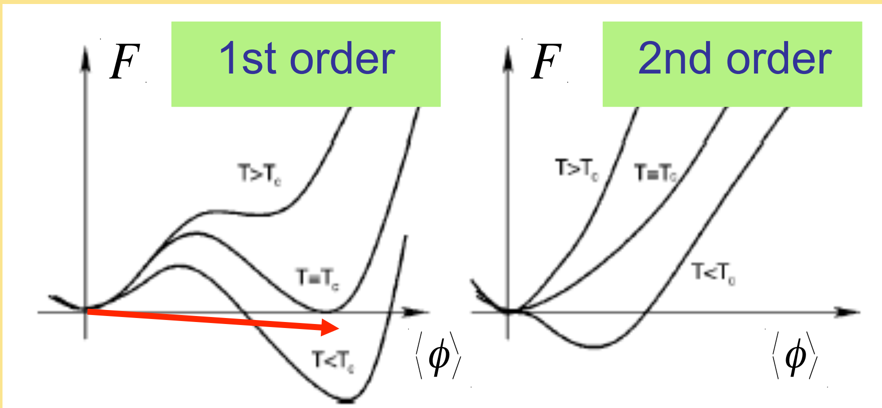
Real Triplet Example: Lessons

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

EW Multiplets: Two-Step EWPT



Increasing m_h →

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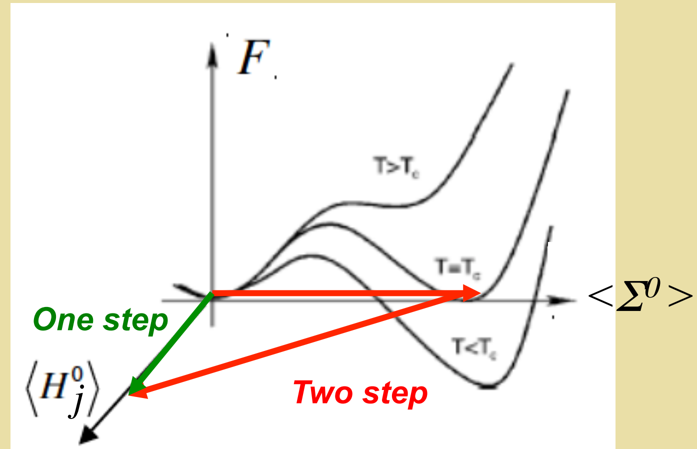
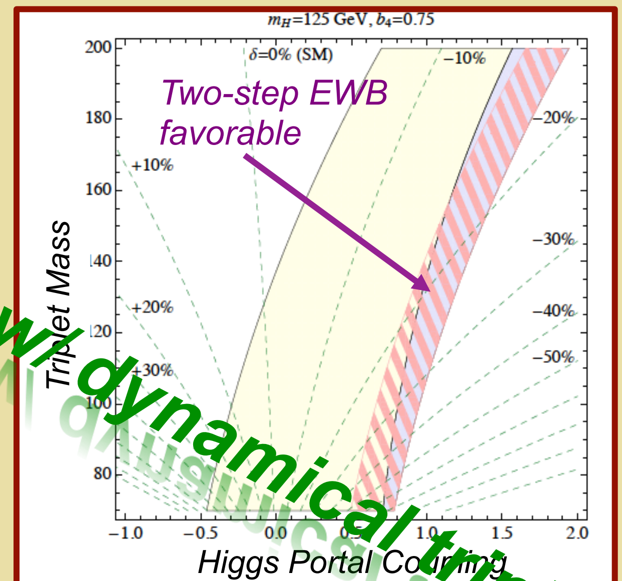


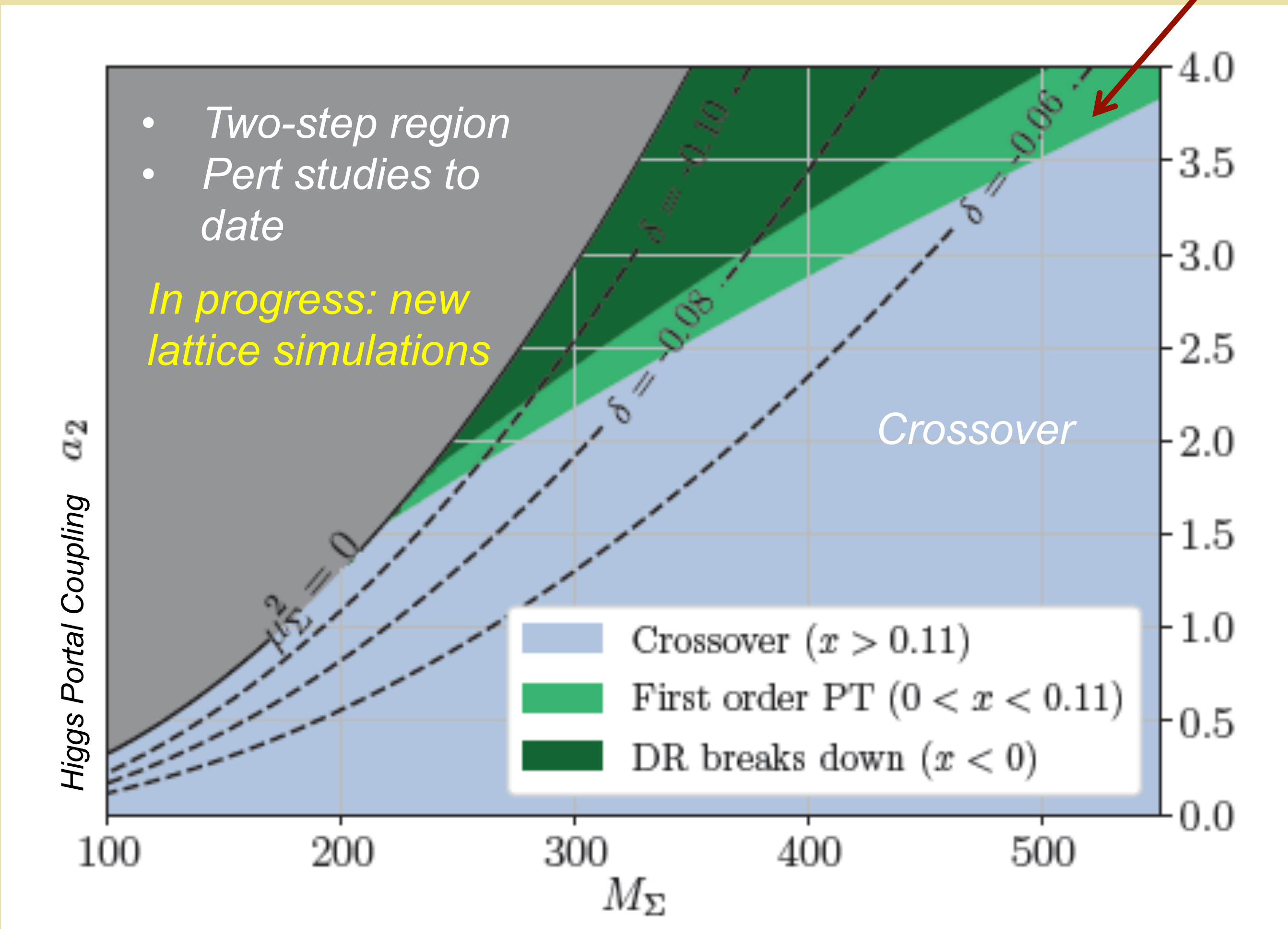


Lattice w/ dynamical triplet

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

Real Triplet & EWPT

FOEWPT



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

IV. Real Singlet: Non-Pert & GW

- *O. Gould, J. Kozaczuk, L. Niemi, MJRM, T. Tenkanen, D. Weir, arXiv:1903.11604 [hep-ph]*

Higgs Portal Interactions

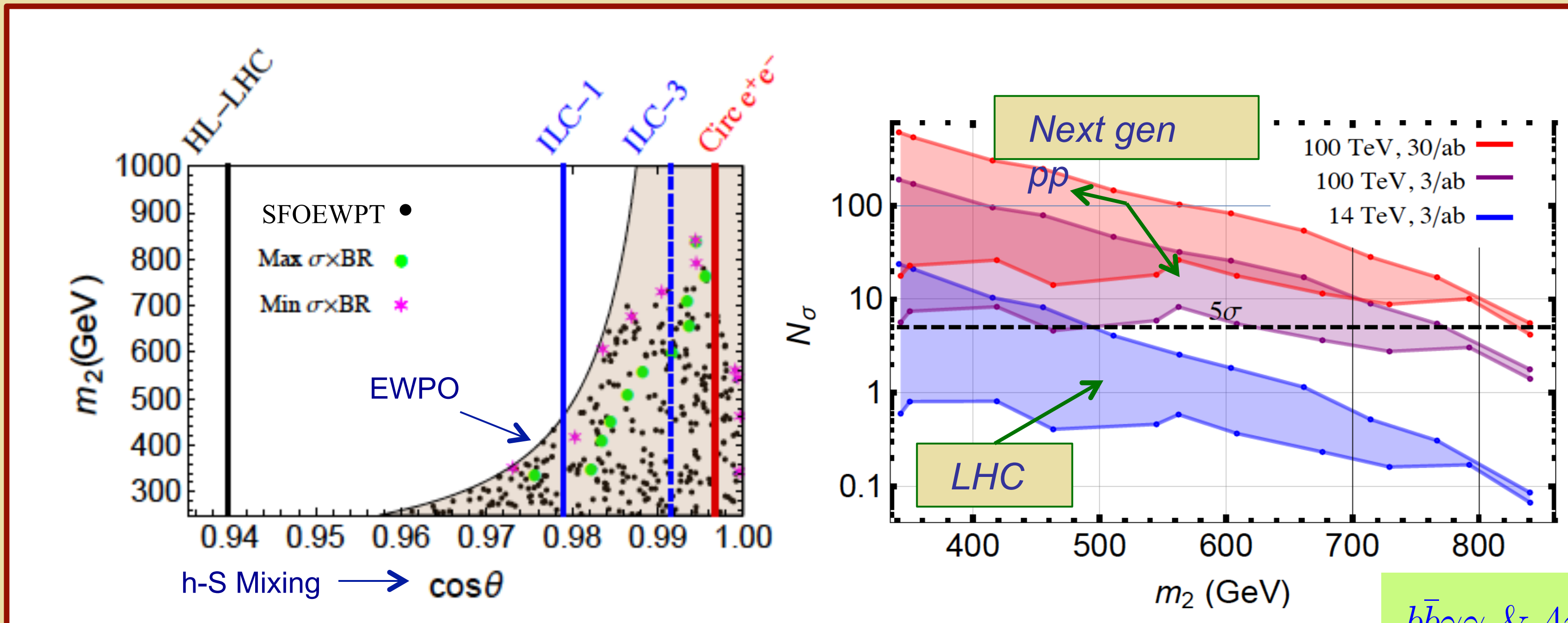
Standard Model + real singlet scalar

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

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

Scalar Singlets & EWPT: Collider Reach

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

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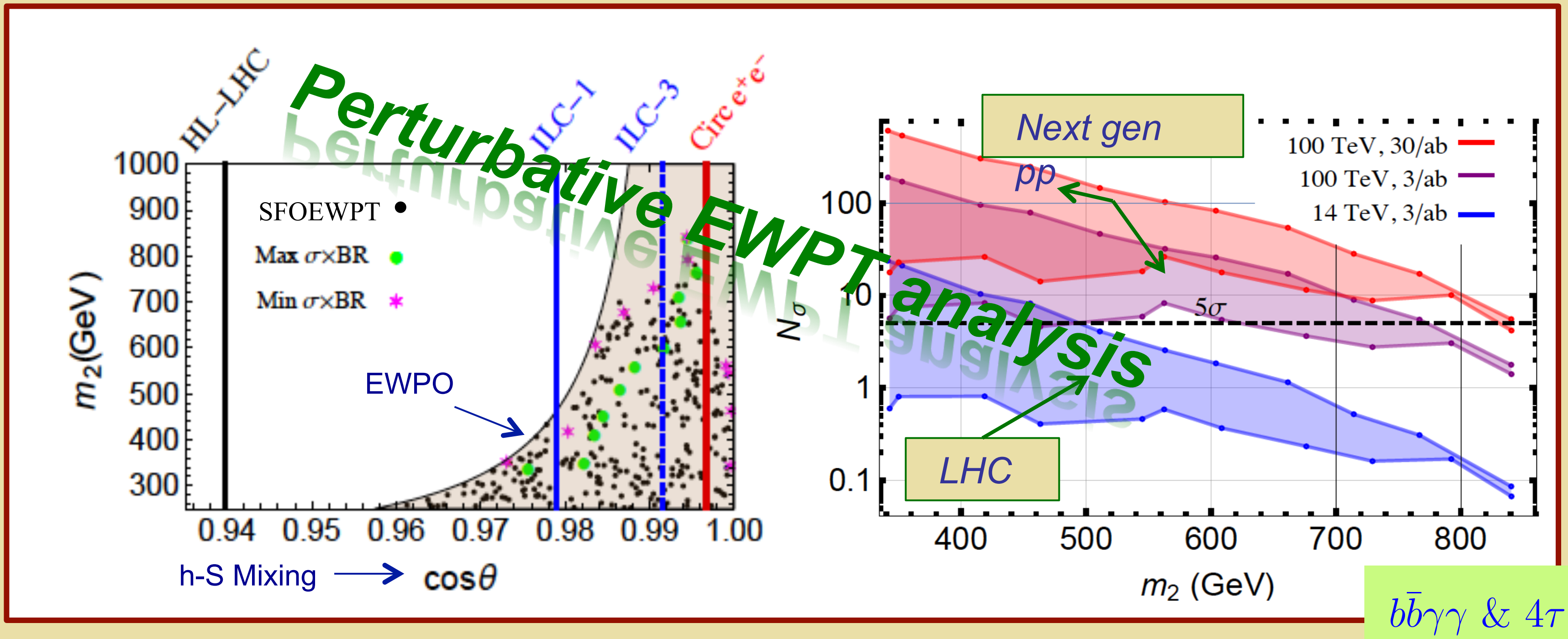

Kotwal, No, R-M, Winslow 1605.06123

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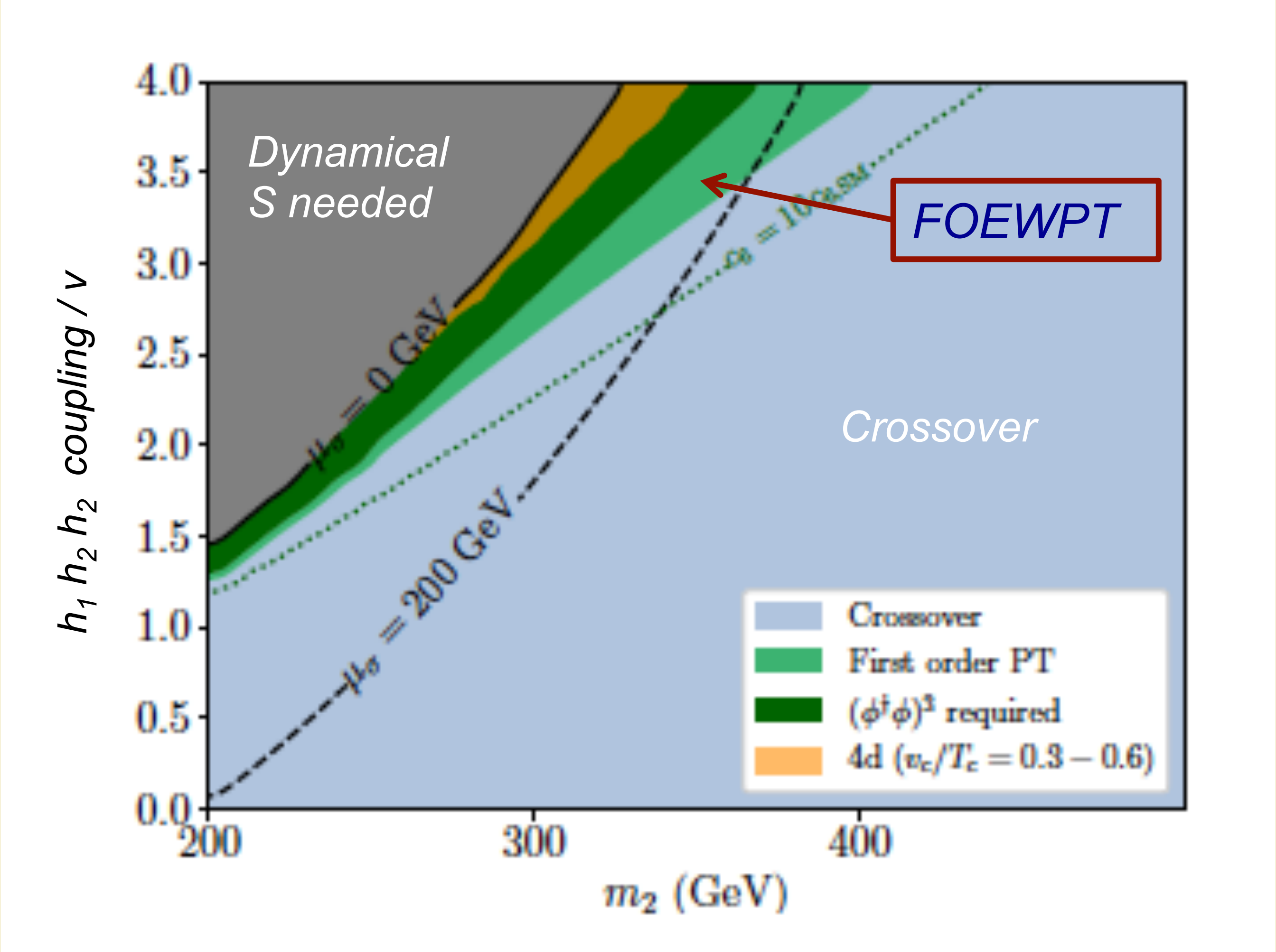
Real Singlet & EWPT: Lattice "Repurpose"



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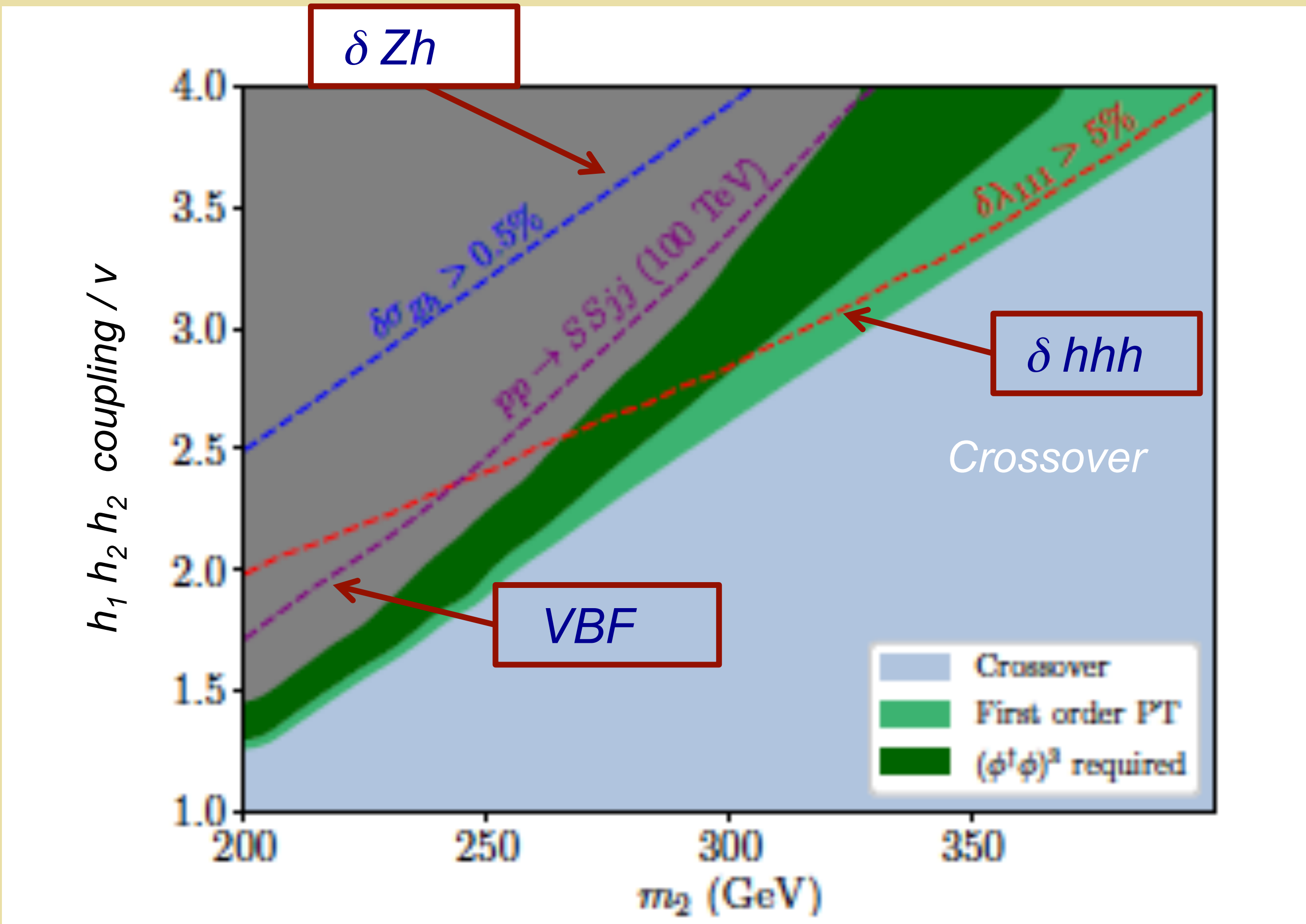
Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

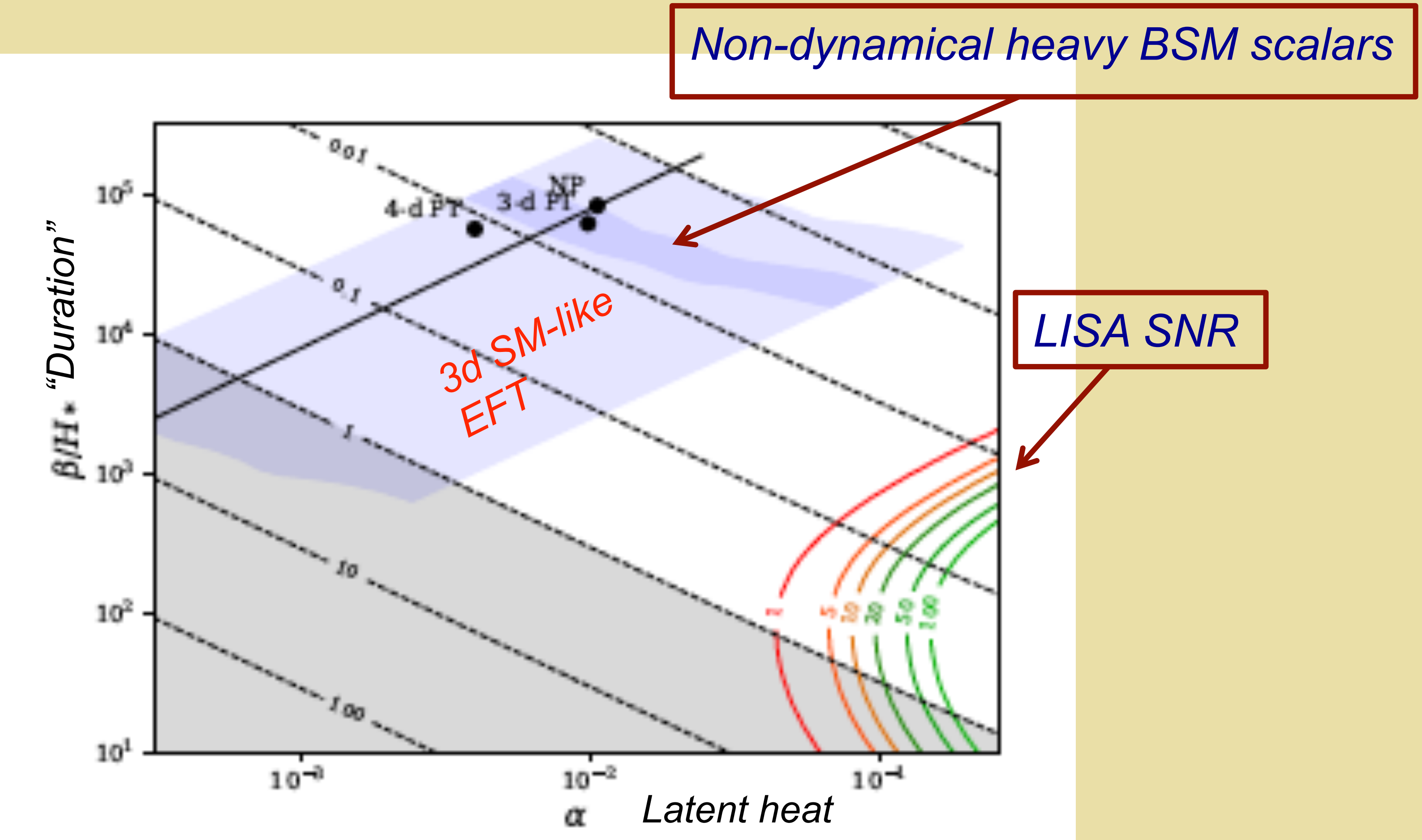
Heavy Real Singlet & EWPT: Probes



Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

- *One-step*
- *Non-perturbative*

Heavy Real Singlet: EWPT & GW



- One-step
- Non-perturbative

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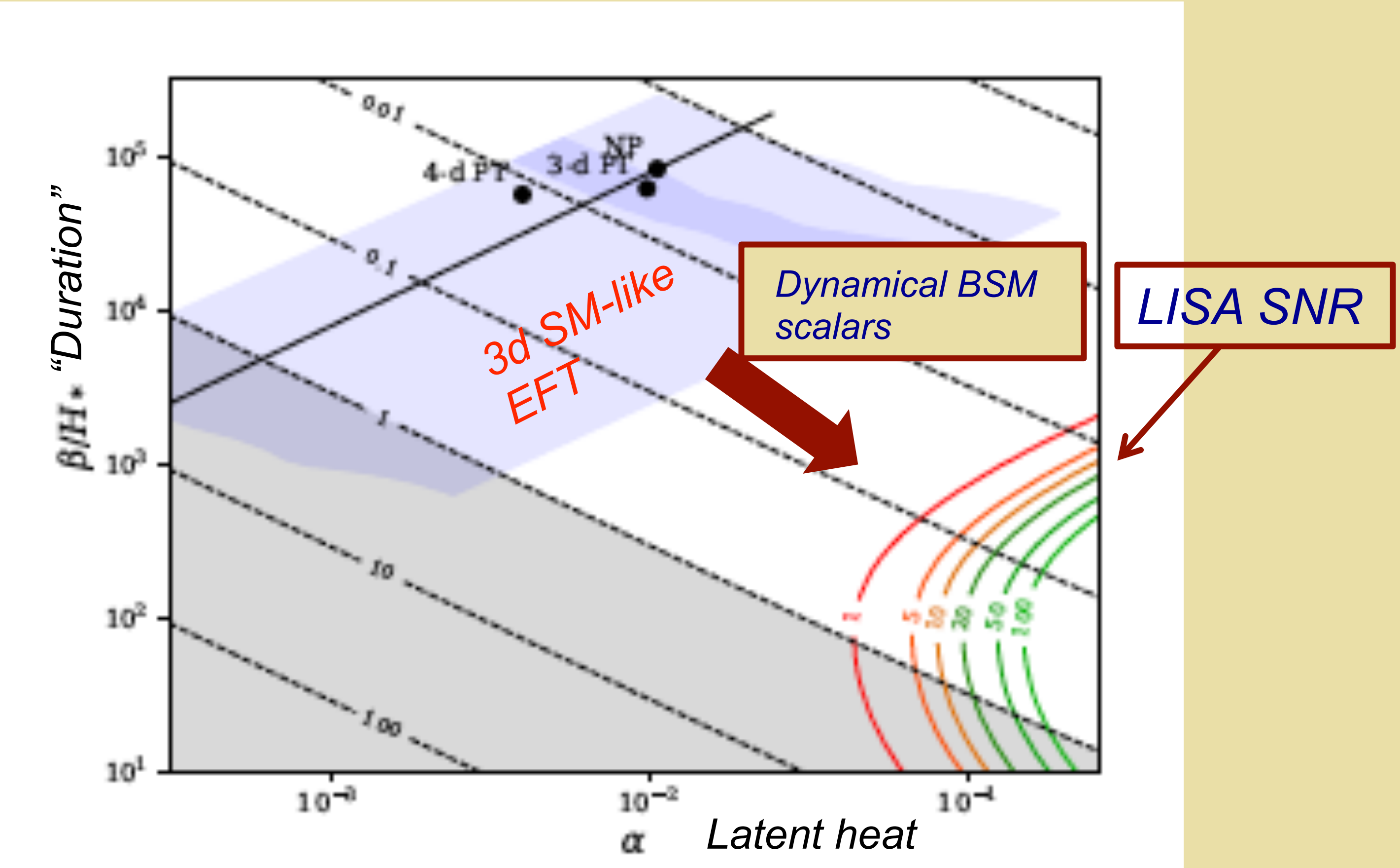
Heavy Real Singlet: EWPT & GW



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- One-step
- Non-perturbative

Heavy Real Singlet: Lattice vs PT

Benchmark pert theory

	T_c/GeV	T_n/GeV	$\alpha(T_c)$	β/H_*
NP	140.4	140.2	0.011	8.20×10^4
3-d PT	140.4	140.0	0.010	6.11×10^4
4-d PT	131.0	130.7	0.004	5.59×10^4

- *One-step*
- *Non-perturbative*

Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

IV. Outlook

- *Non-minimal Higgs sectors allow for novel patterns of EWSB at finite temperature and new paths to a SFOEWPT as needed for successful EWBG & gravitational wave generation*
- *There exists a rich array experimental probes of the nature of the EWSB transition that could extend well beyond the LHC and LISA eras*
- *A robust analysis of the EWPT dynamics requires non-perturbative computations that can reveal properties not accessible with perturbation theory and that are needed for phenomenological guidance*
- *The coming decade holds exciting opportunities for synergy between model building, collider phenomenology, astrophysics, and theory → it is an ideal time to get involved!*

Back Up Slides

Real Singlet Higgs Portal

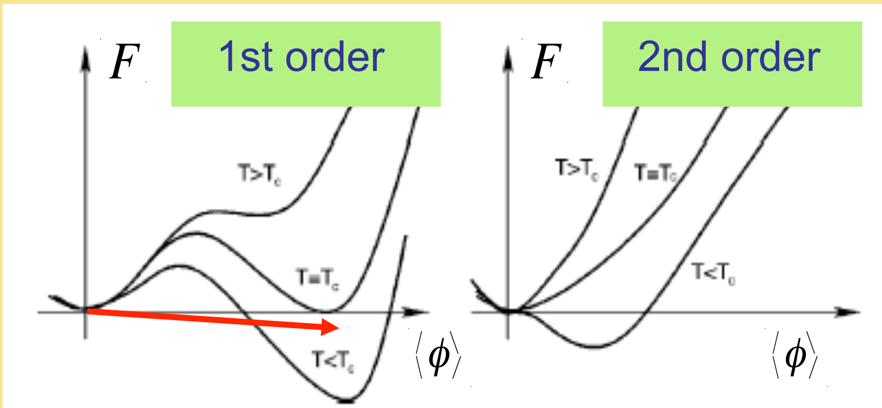
Standard Model + real singlet scalar

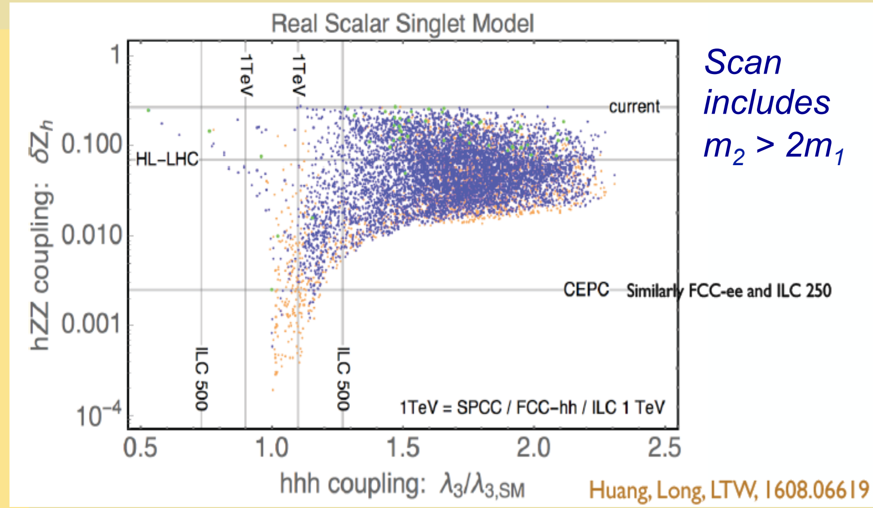
$$\boxed{V_{\mathrm{HS}} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2}$$

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

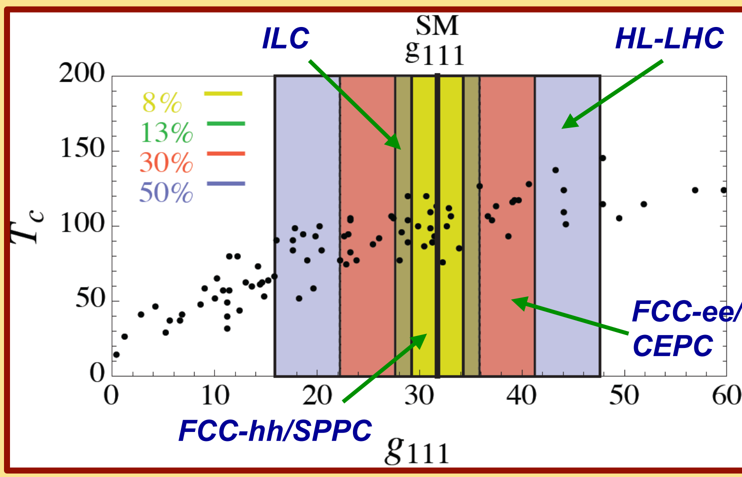
$h_1 = h \cos\theta + S \sin\theta \;,\; h_2 = S \cos\theta - h \sin\theta$

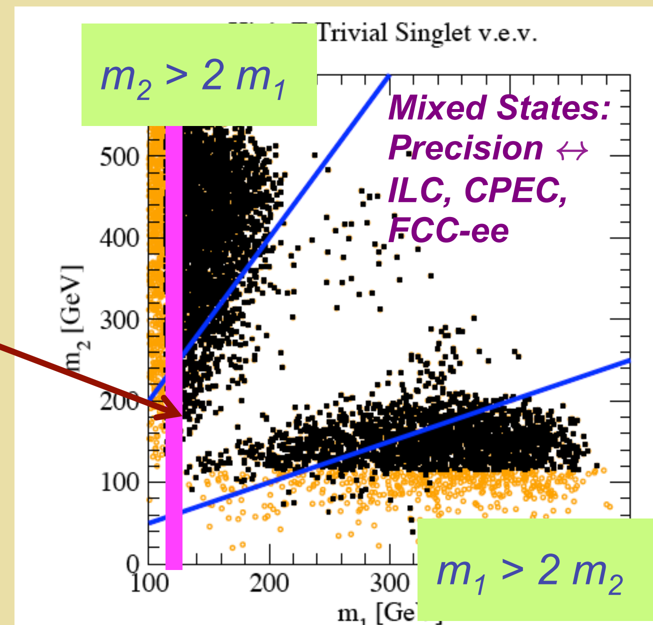
EW Phase Transition: Singlet Scalars





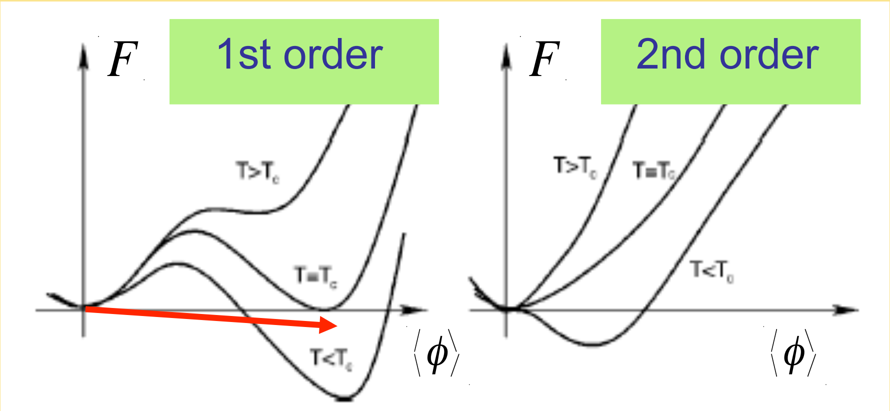
Modified Higgs Self-Coupling

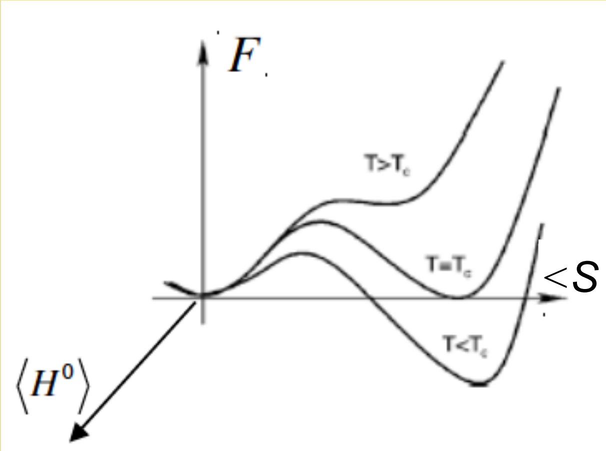




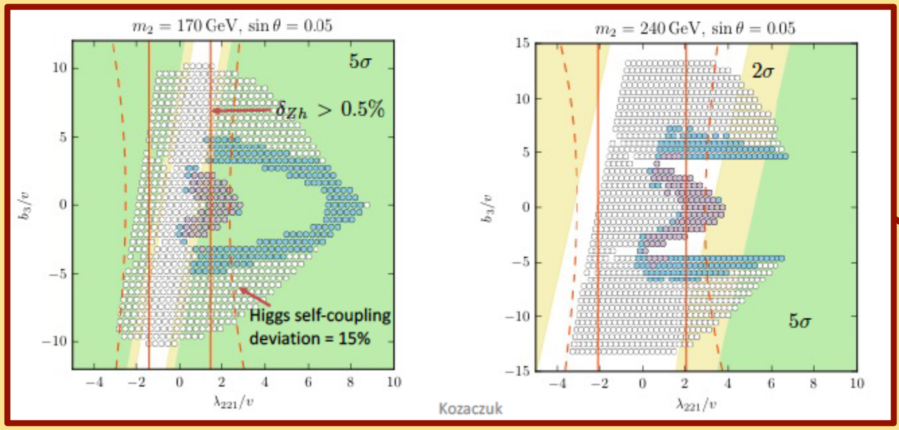
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

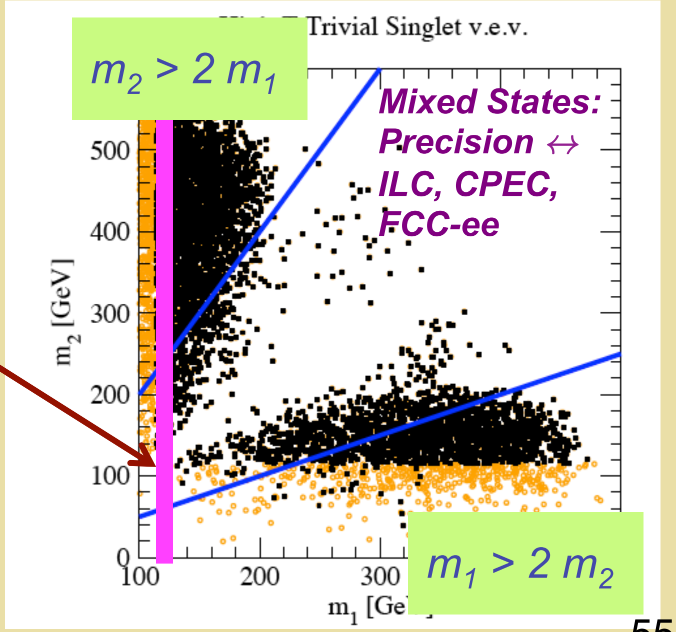
EW Phase Transition: Singlet Scalars





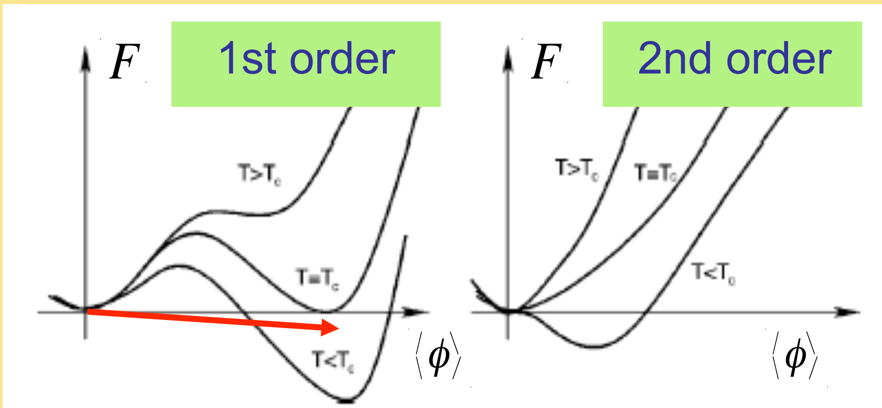
Non-resonant Di-Higgs

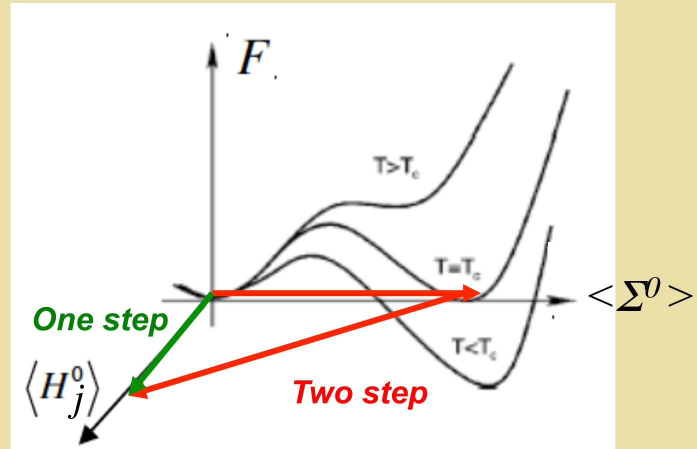




Chen, Kozaczuk, Lewis 2017

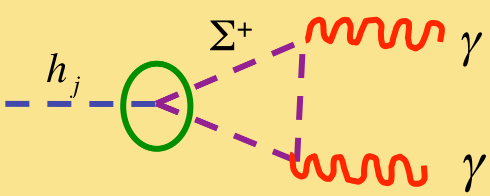
EW Multiplets: Two-Step EWPT

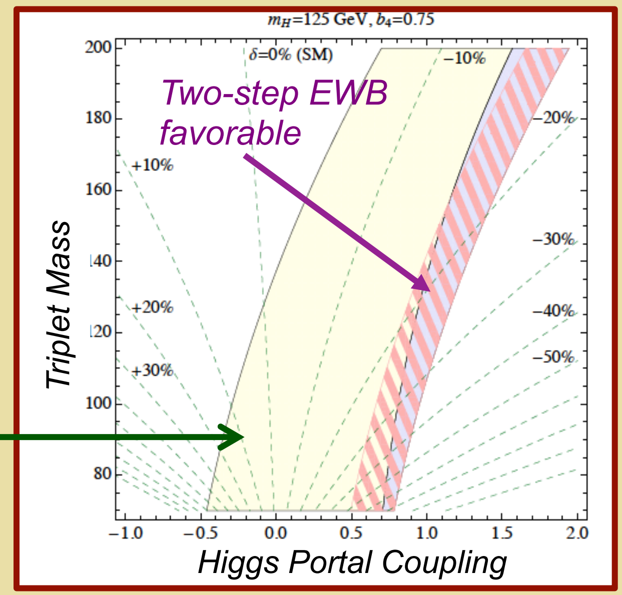




Increasing m_h

New scalars





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

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

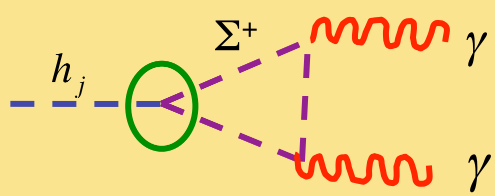
	γγ	Zγ	μμ
δ BR	~0.5%	~1%	~1%

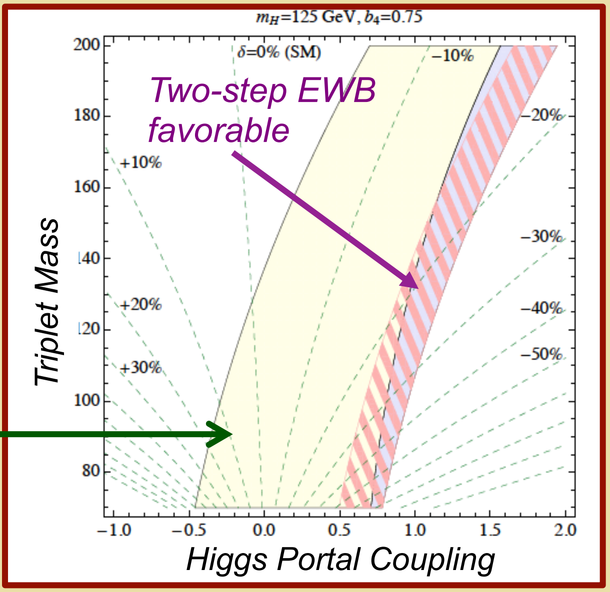
M. Mangano

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

Increasing m_h

New scalars





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