BSM Higgs & SFOEWPT @ CEPC

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- *UMass Amherst*
- *Caltech*

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

CEPC International Conference, Nanjing, October 23, 2023

Outline

I. Context & Questions

II. Theoretical Developments

III. Collider Pheno Developments

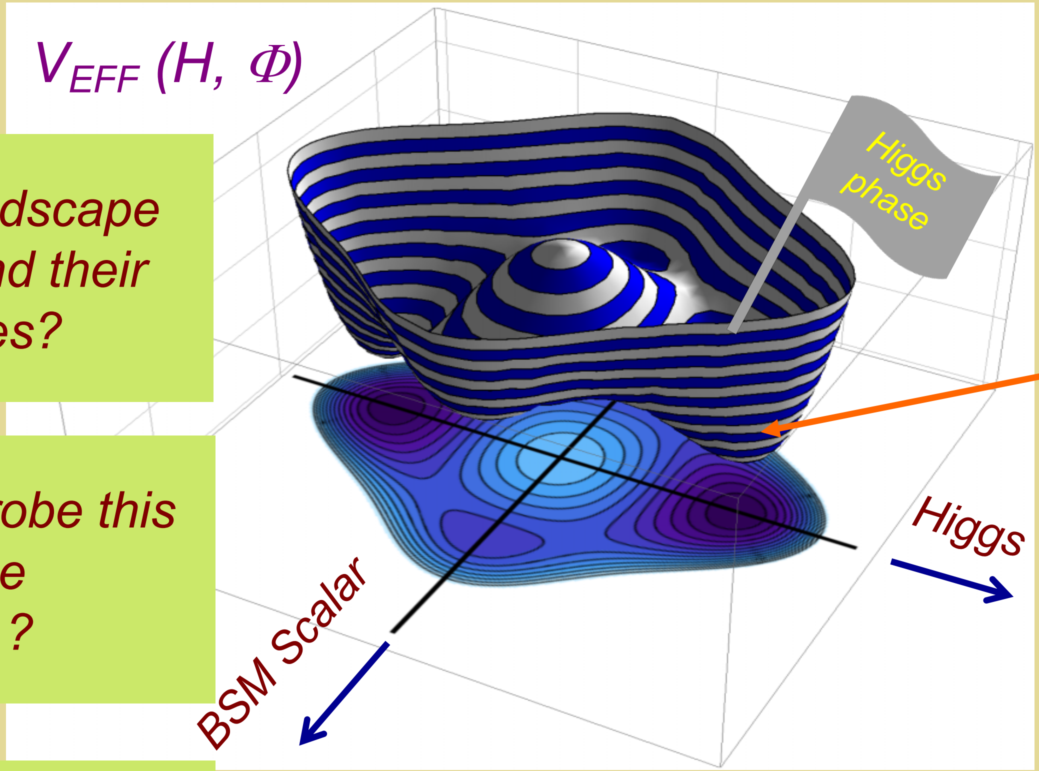
IV. Outlook

I. Context & Questions

Was There an Electroweak Phase Transition ?

- *Interesting in its own right*
- *Key ingredient for EW baryogenesis*
- *Source of gravitational radiation*

Was There an EW Phase Transition?



How did we end up here ?

- *What is the landscape of potentials and their thermal histories?*
- *How can we probe this T > 0 landscape experimentally ?*
- *How reliably can we compute the thermodynamics ?*

n evolve differently as T evolves →
ilities for symmetry breaking

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

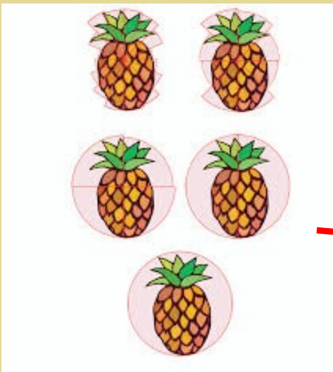
High-T SM Effective Potential

$$\boxed{V(h,T)_{\rm SM} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \ + \ldots}$$

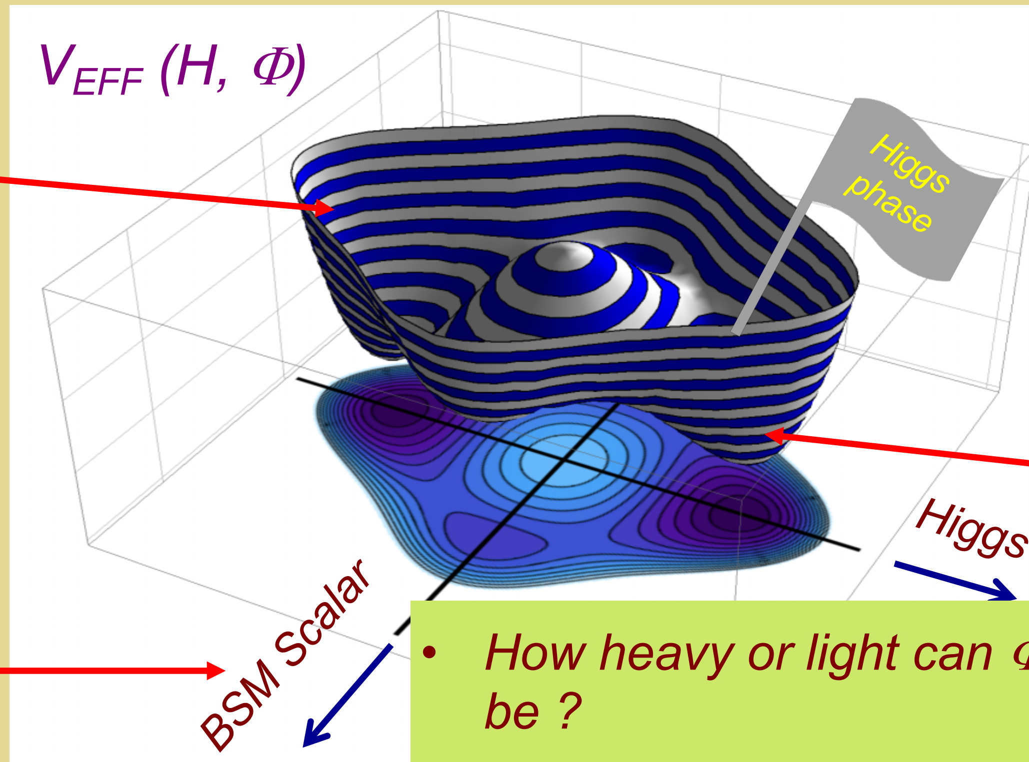
$\boxed{T_0 \sim 140 \text{ GeV}}$ $\boxed{\equiv \ T_{EW}}$

Was There an EW Phase Transition?

Bubble Collisions

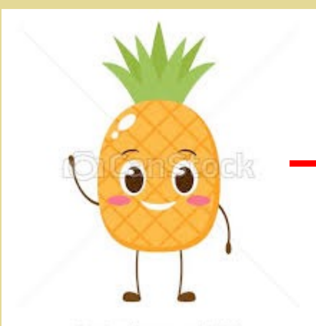


Grav Radiation



Higgs precision tests

Direct Production



BSM Higgs

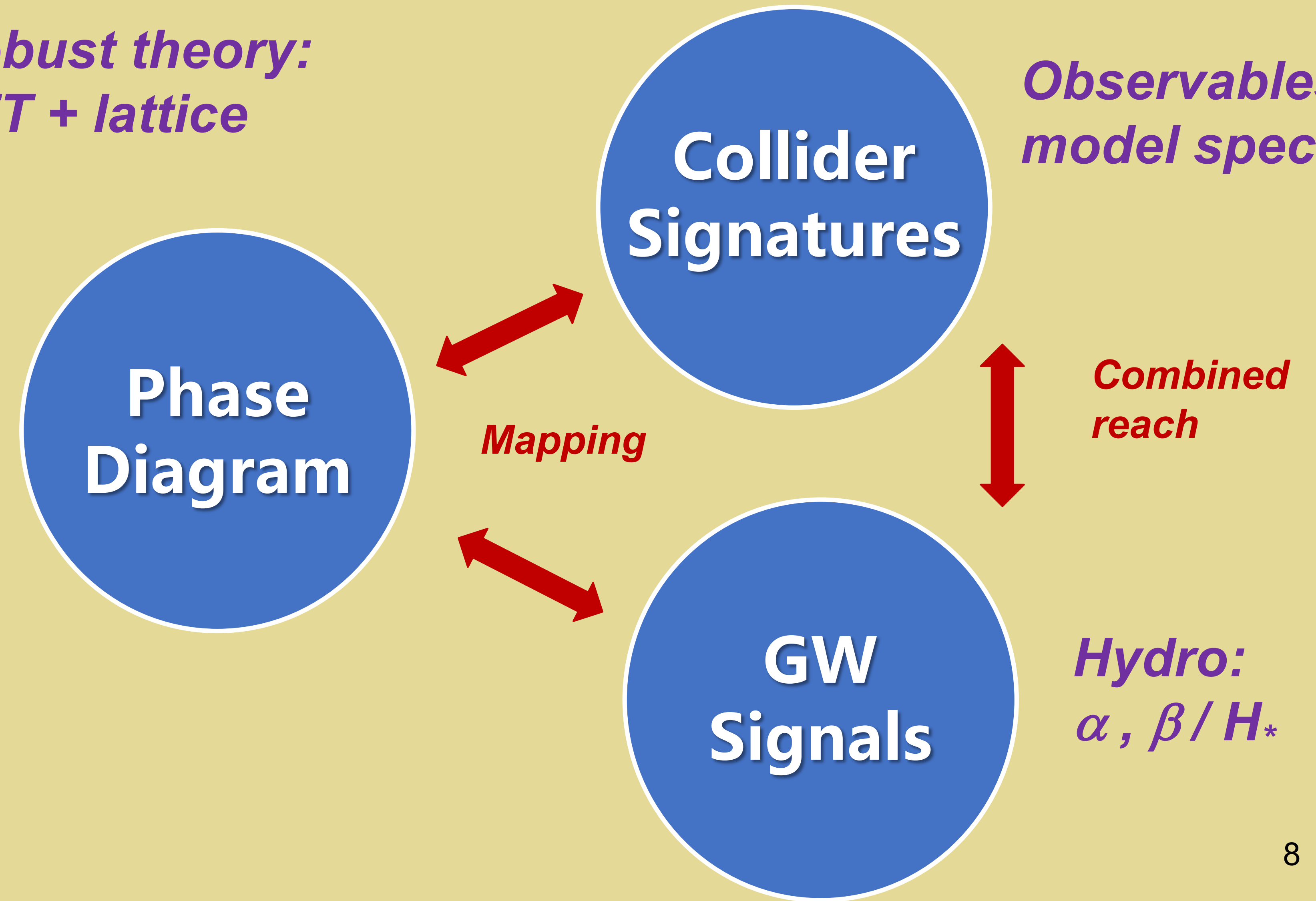
- *How heavy or light can Φ be ?*
- *How coupled to H ?*
- *Can it be discovered at the LHC or beyond ?*

Extrema can evolv →
rich possibilities fc

BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

Observables:
model specific



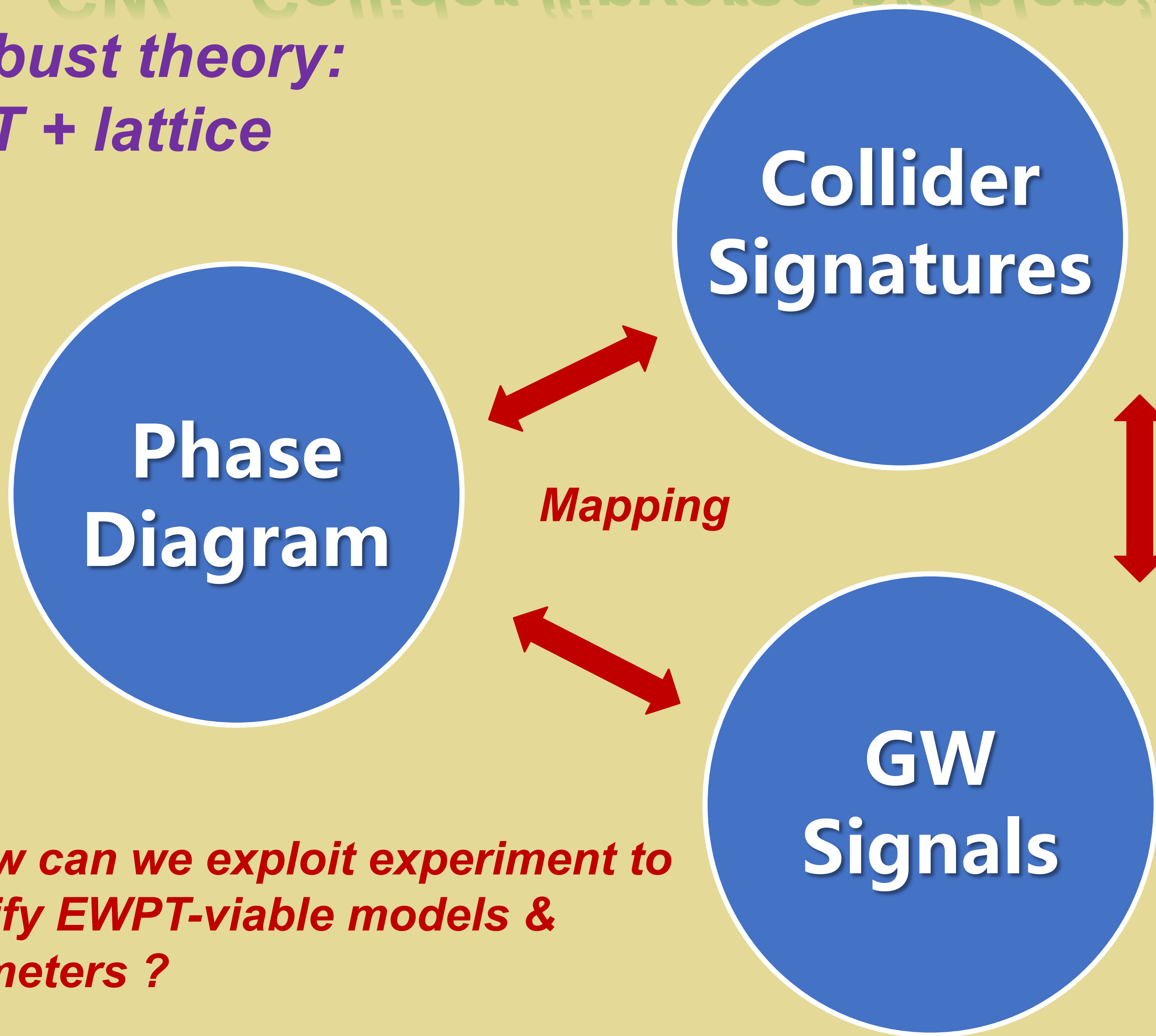
Hydro:
α , β / H_*

BSM EWPT: Inter-frontier Connections

GW – Collider "inverse problem" **

Robust theory:
EFT + lattice

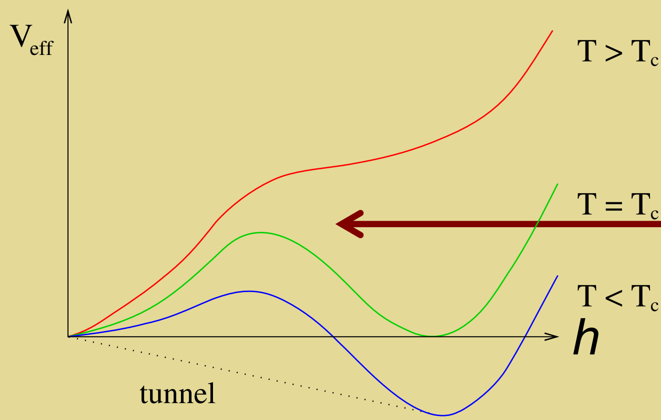
Observables:
model specific



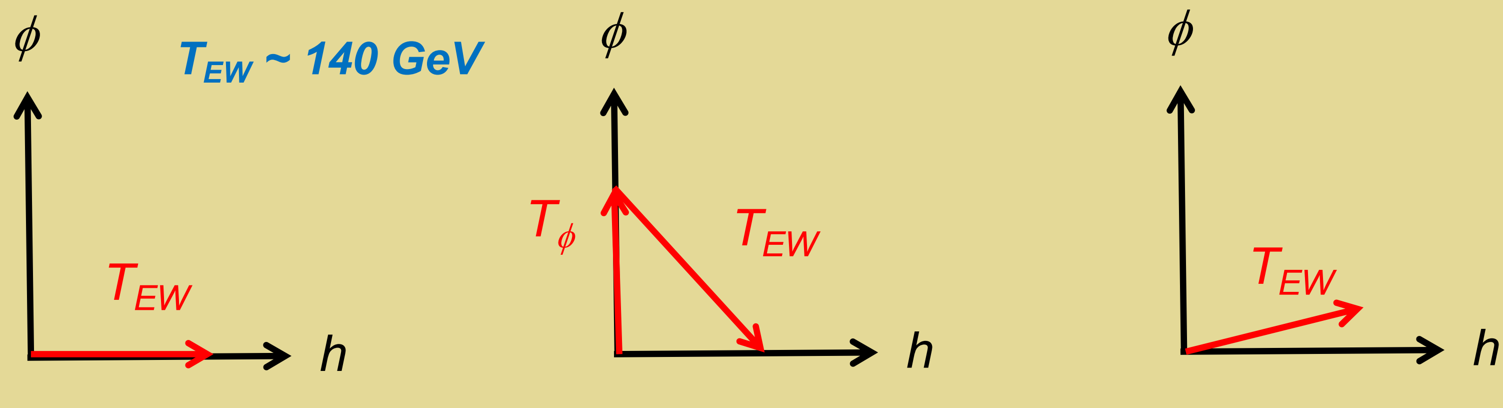
Hydro:
$\alpha\,,\ \beta\,/\,H_*$

*** How can we exploit experiment to identify EWPT-viable models & parameters ?*

First Order EWPT from BSM Physics



Representative thermal histories → barrier for SFOEWPT



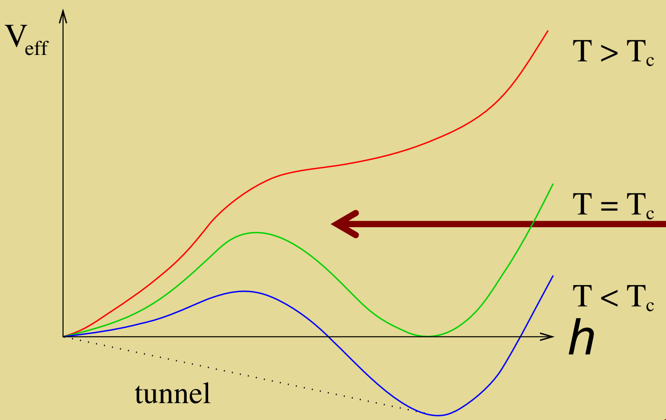
$a_2\, H^2\phi^2$: $T > 0$
loop effect

$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

$a_1\, H^2\phi$: $T = 0$
tree-level effect

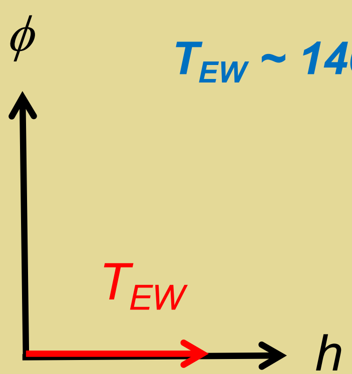
MJRM: 1912.07189

First Order EWPT from BSM Physics



Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

T_{EW} ~ 140 GeV



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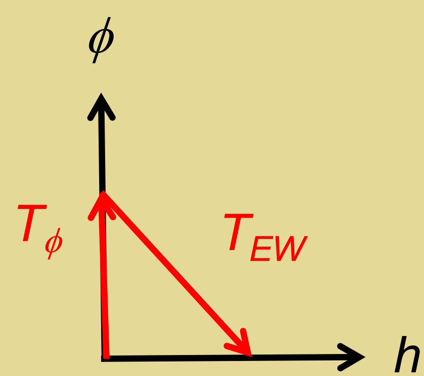
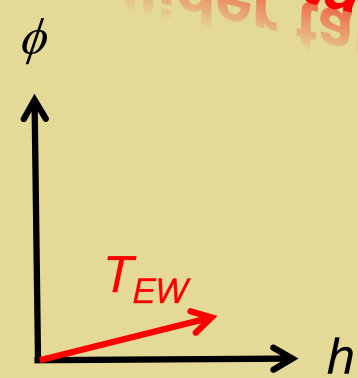


$a_2\, H^2\phi^2$: $T = 0$
tree-level effect

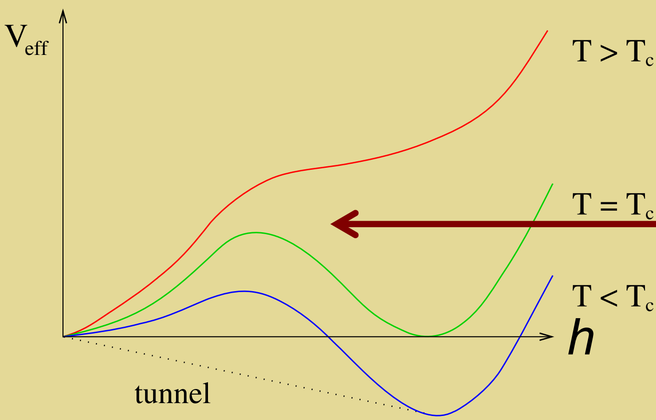
Collider target



$a_1\, H^2\phi$: $T = 0$
tree-level effect

MJRM: 1912.07189

First Order EWPT from BSM Physics

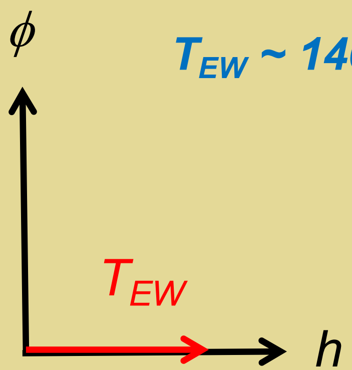


$|\sin\theta| \gtrsim 0.01$ $|\Delta\lambda / \lambda| \gtrsim 0.003$

$\boxed{\text{Higgs} - \phi^0 \text{ Mixing}}$

Collider target

$T_{EW} \sim 140$ GeV



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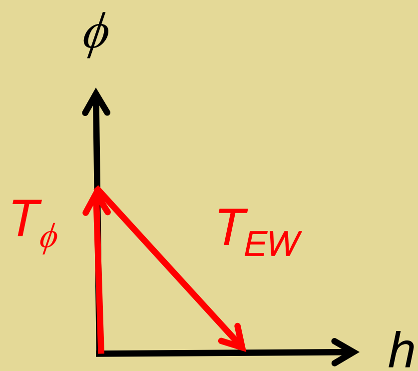
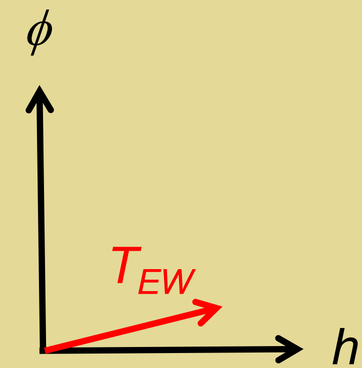
loop effect

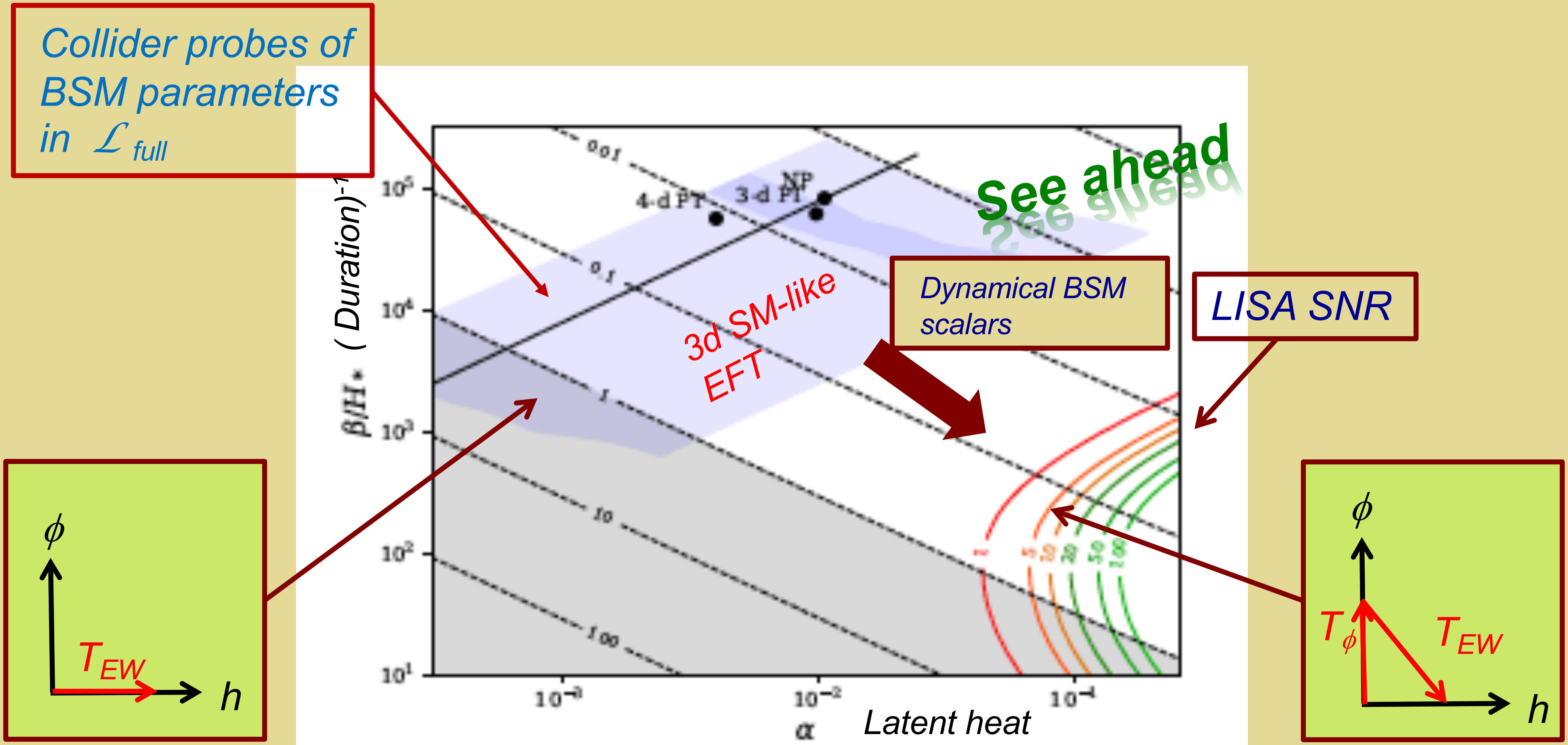


$a_2 H^2\phi^2$: $T = 0$
tree-level effect



$a_1 H^2\phi$: $T = 0$
tree-level effect

BSM Scalar: EWPT & GW



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

- One-step
- Non-perturbative

II. Theoretical Developments

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet	Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...
SM + Scalar Doublet (2HDM)	Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Fromme, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...
NMSSM...	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Models & pheno: how reliable ?

Thanks: J. M. No *Extensive references in MJRM: 1912.07189*

Challenges for Theory

Perturbation theory

- I.R. problem: poor convergence
- Thermal resummations
- Gauge Invariance (radiative barriers)
- RG invariance at T>0

BSM proposals

Non-perturbative (I.R.)

- Computationally and labor intensive

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*

Benchmark pert theory

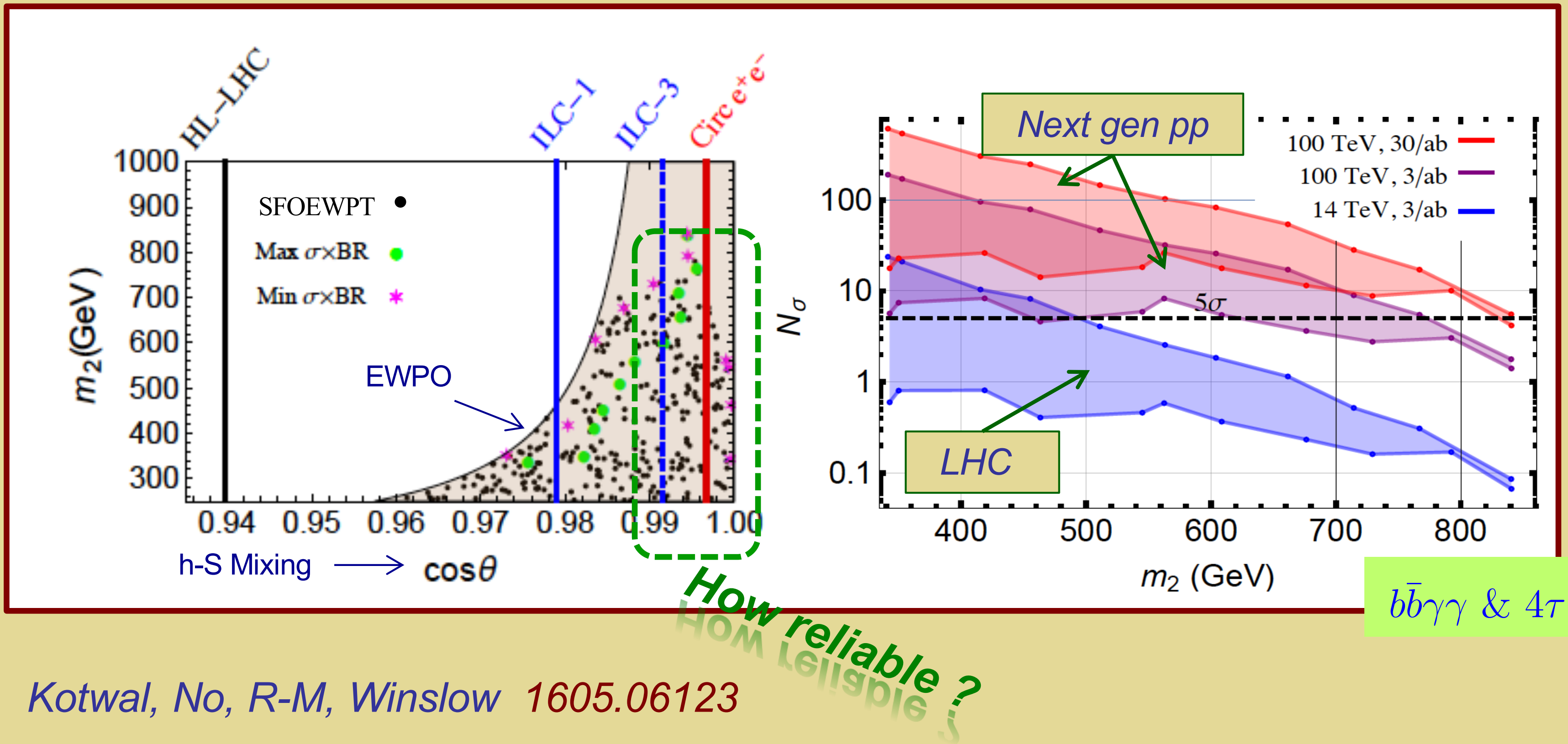
Model Illustrations

Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***Real EW triplet (SM + 3)***

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Kotwal, No, R-M, Winslow 1605.06123

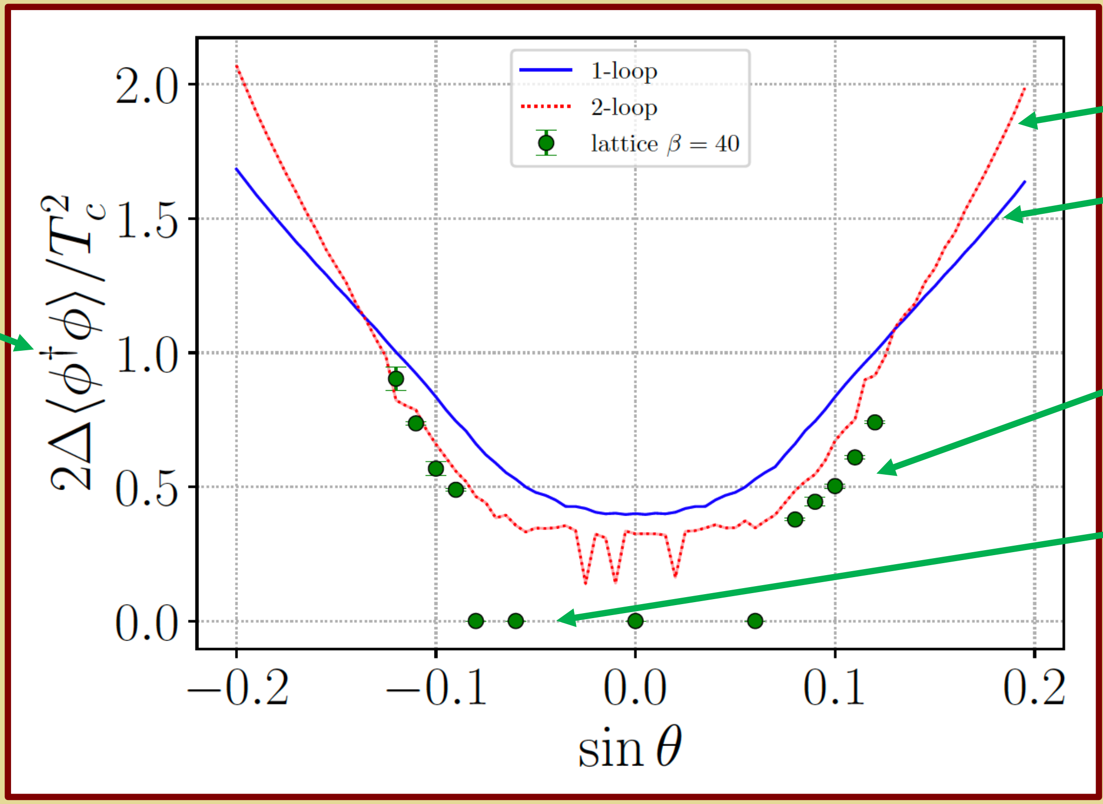
See also: Huang et al, 1701.04442;
Li et al, 1906.05289

Lattice Benchmarking

L. Niemi, MRM, G. Xia in prog

M_{h2} = 350 GeV

Change in condensate at T_C



2 loop PT

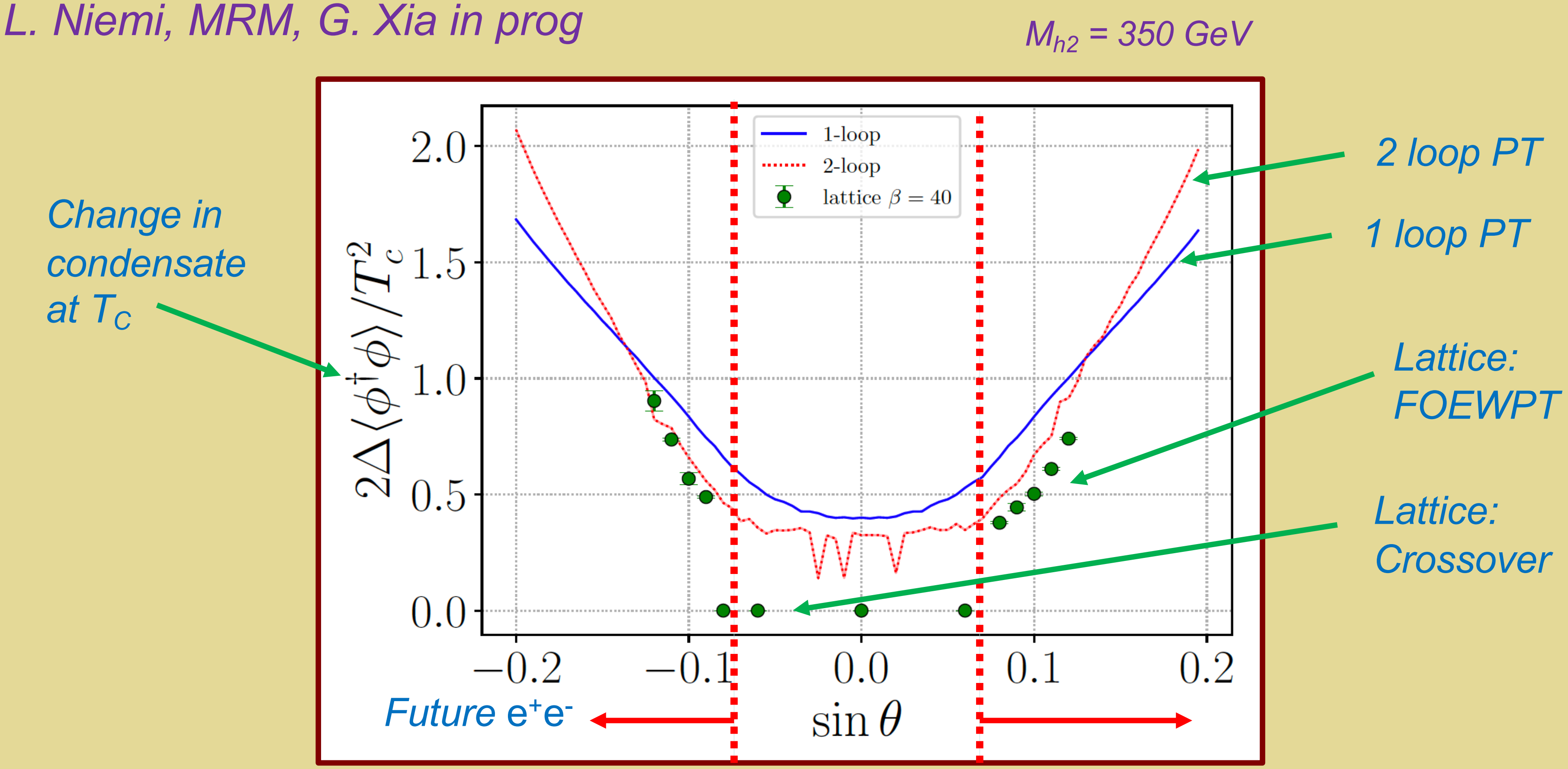
1 loop PT

Lattice: FOEWPT

Lattice: Crossover

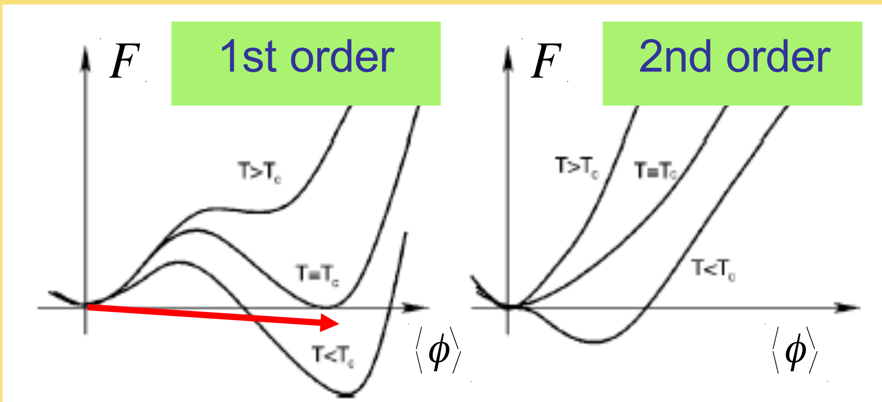
Lattice Benchmarking

L. Niemi, MRM, G. Xia in prog

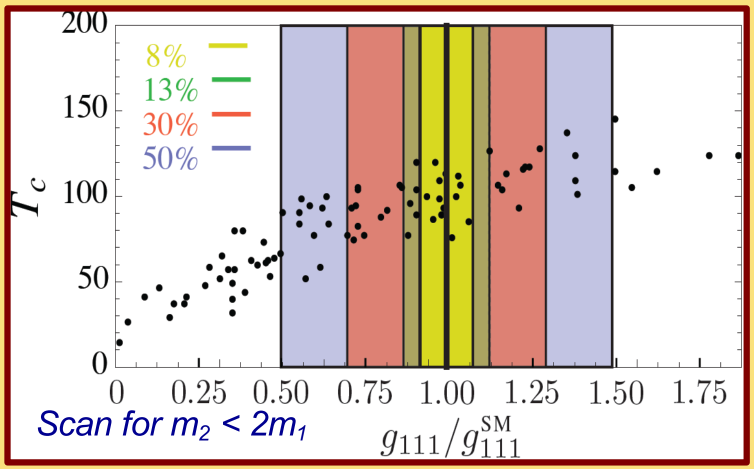


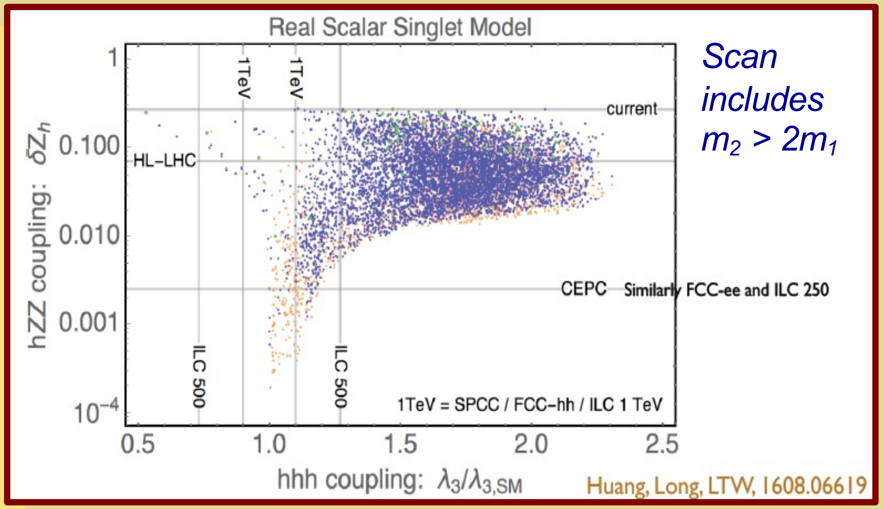
- *When a FOEWPT occurs, 2 loop PT gives a good description*
- *Lattice needed to determine when onset of FOEWPT occurs*
- *Future precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

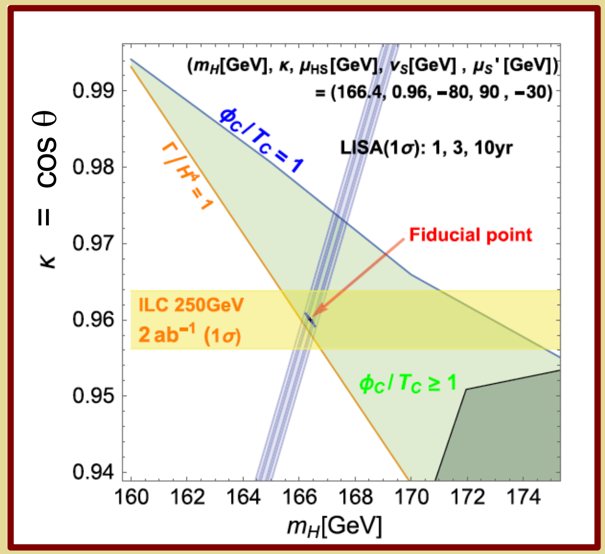
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling



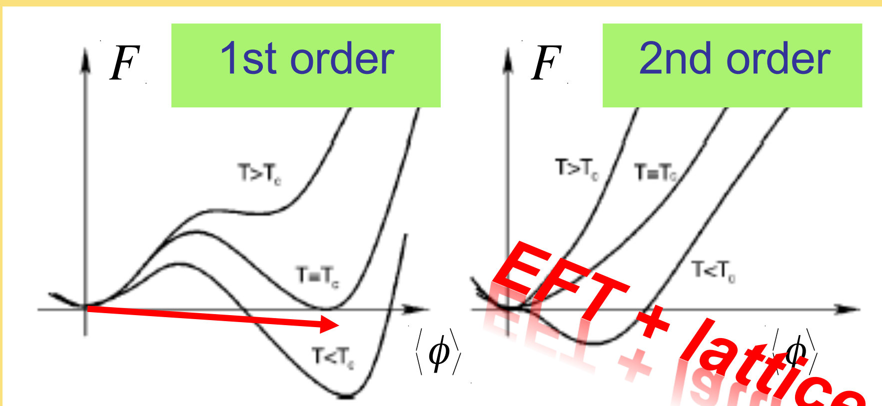




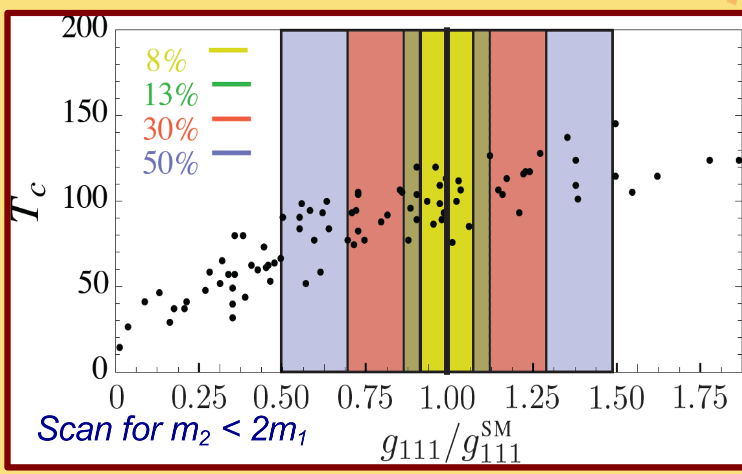
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

K. Hasino et al, PRD 99 (2019) 075011

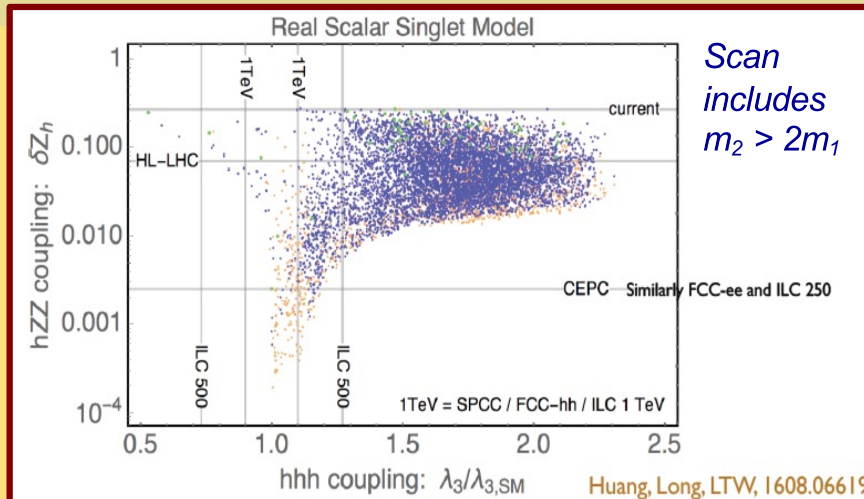
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling

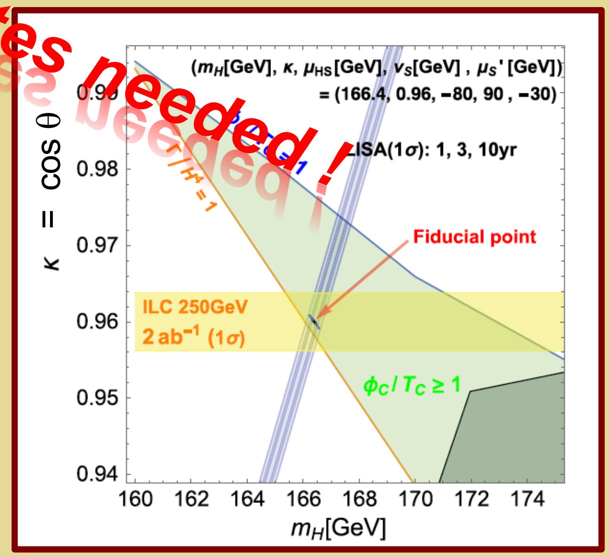


Scan for $m_2 < 2m_1$



Scan includes $m_2 > 2m_1$

EFT + lattice updates needed !



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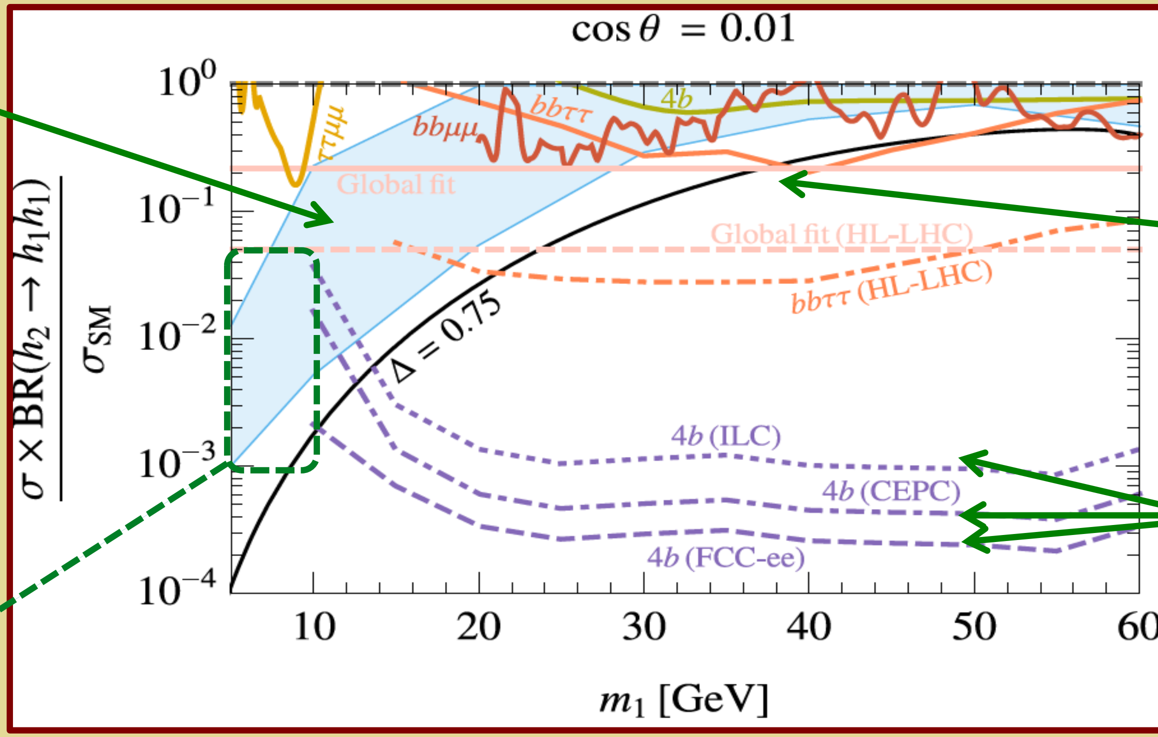
Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

Future e^+e^-

Other probes?

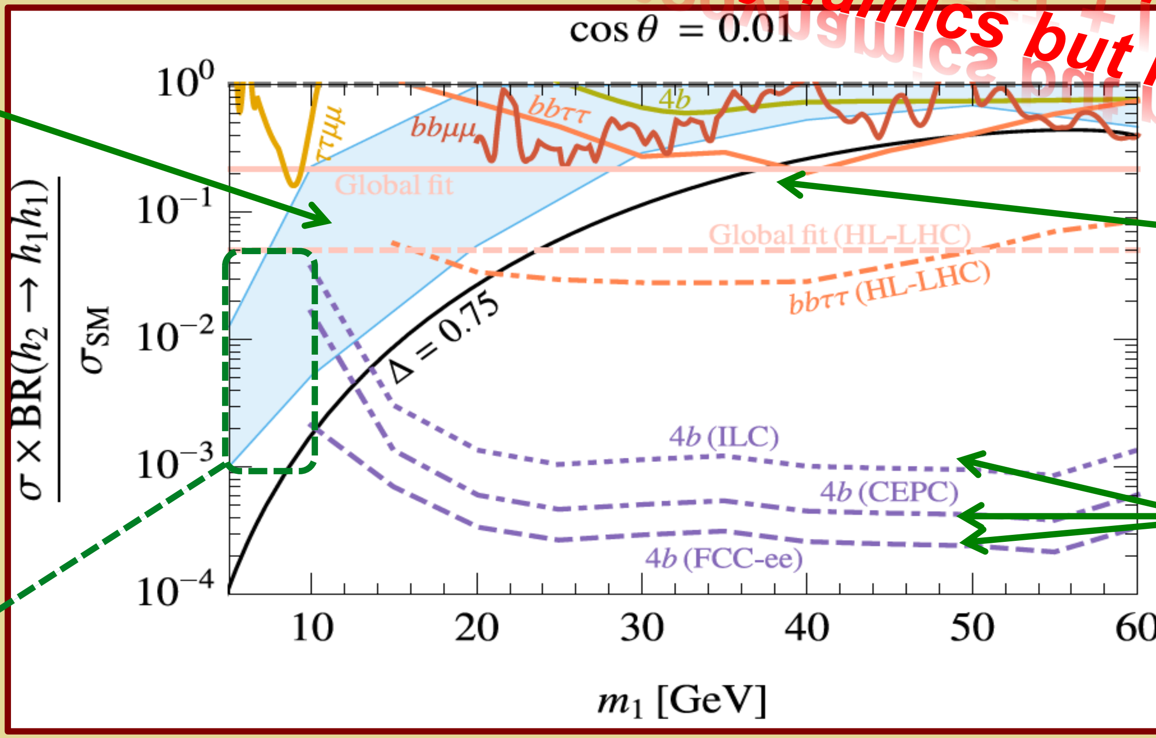
J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206, Carena et al 2203.08206, Wang et al 2203.10184,

Light Singlets: Exotic Higgs Decays

Consistent w/ EFT + lattice thermodynamics but nucleation ?

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



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Model Illustrations

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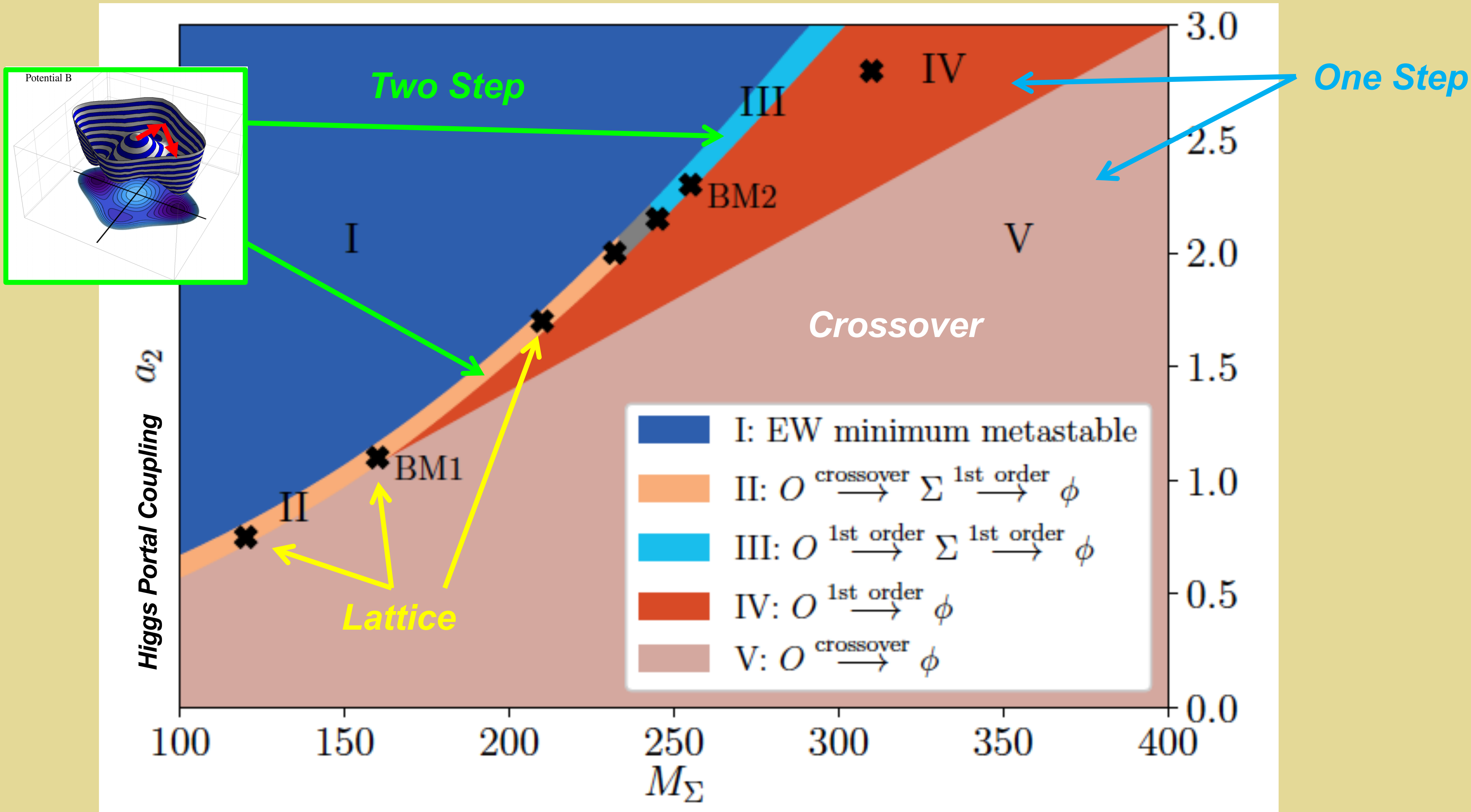
- ***Real EW triplet (SM + 3)***

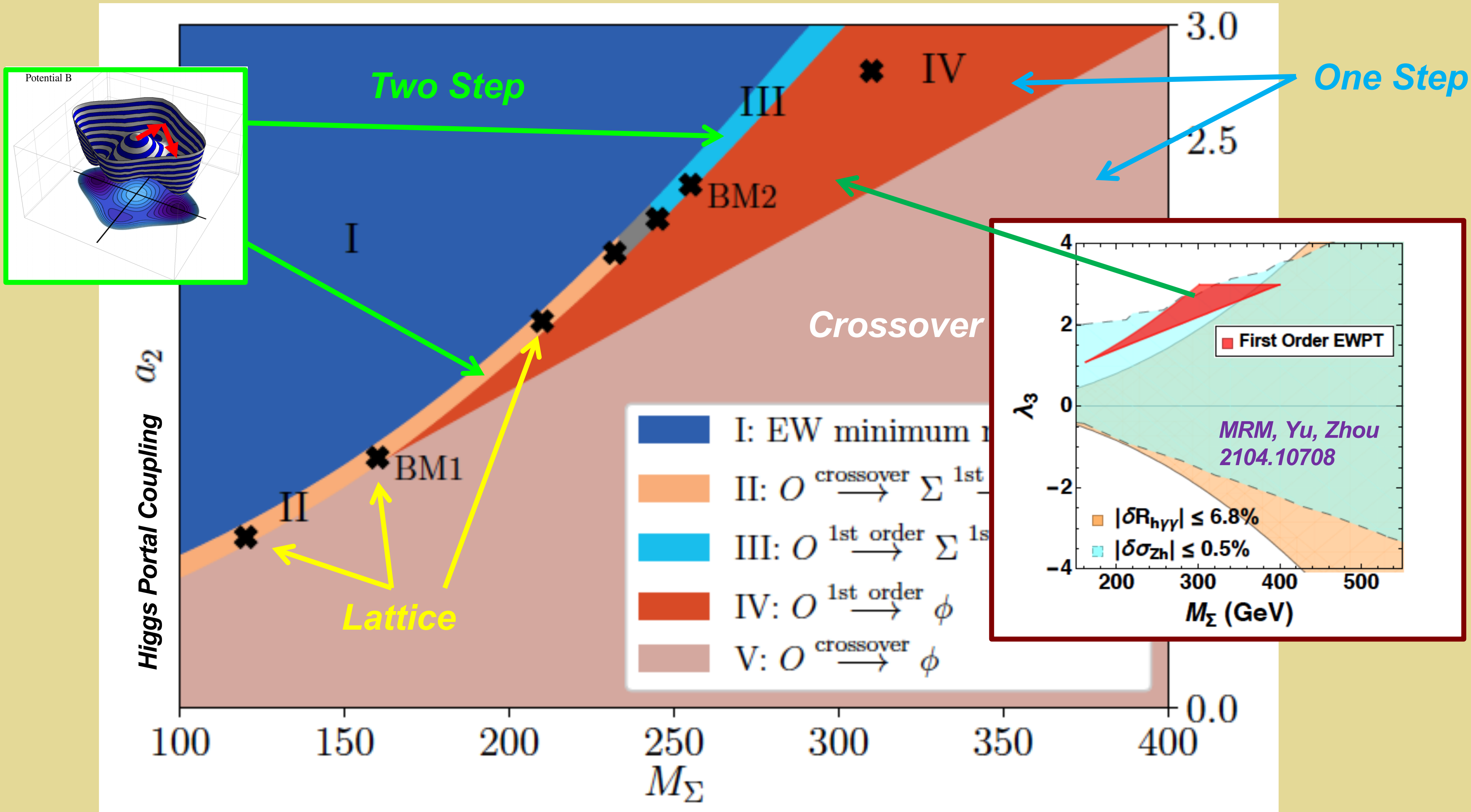
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

- *1 or 2 step*
- *Non-perturbative*

Real Triplet & EWPT: Novel EWSB



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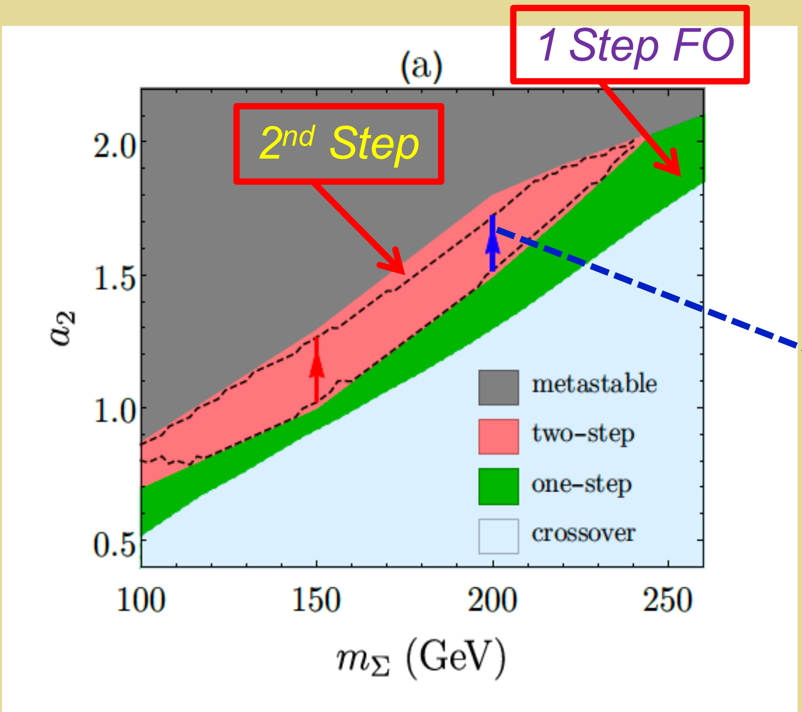
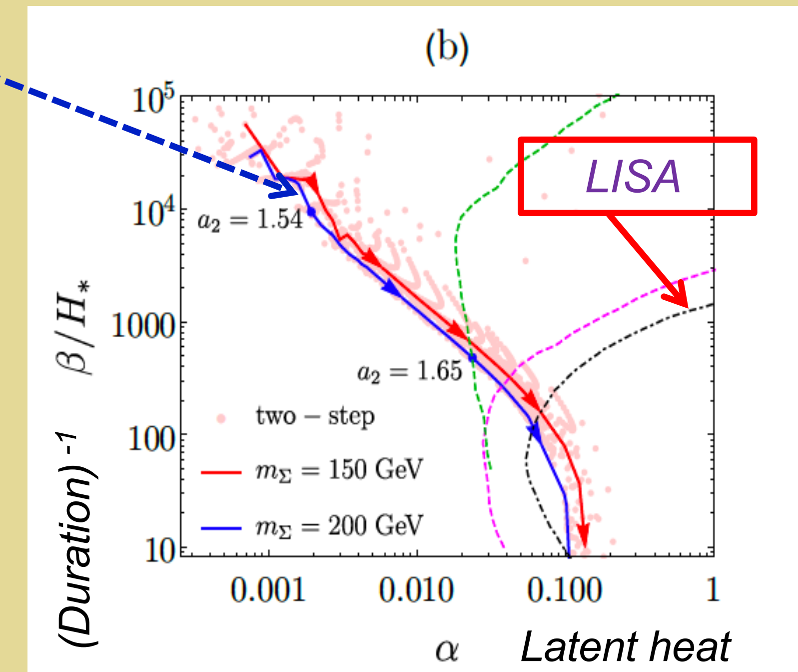
Niemi, R-M, Tenkanen, Weir 2005.11332

GW & EWPT Phase Diagram

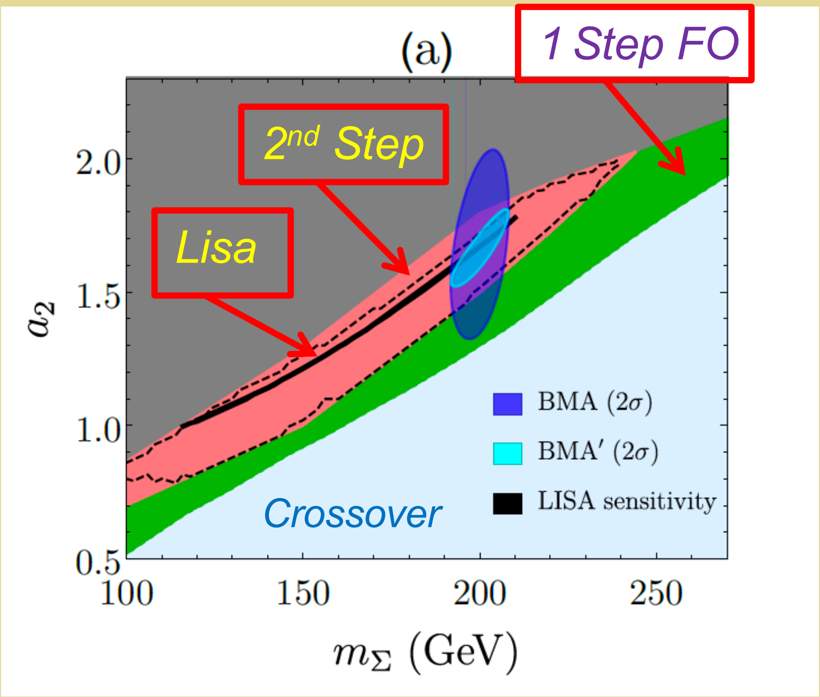


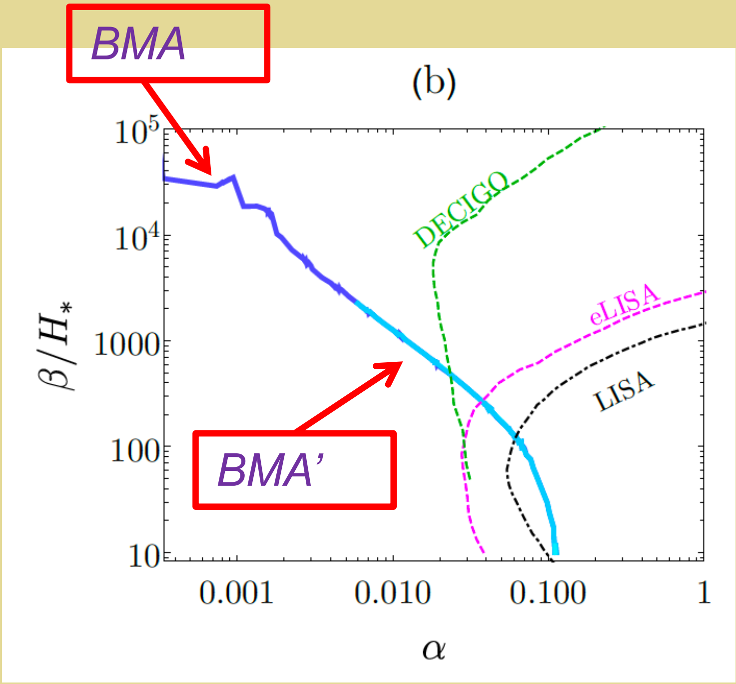


- ***Single step transition: GW well outside LISA sensitivity***
- ***Second step of 2-step transition can be observable***

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





BMA: m_Σ + $h \rightarrow \gamma\gamma$

BMA' : BMA + $\Sigma^0 \rightarrow ZZ$

- *Two-step*
- *EFT+ Non-perturbative*

Friedrich, MJRM, Tenkanen, Tran 2203.05889

Nucleation

Tunneling @ T>0: Gravitational Waves

Amplitude & frequency: latent heat & intrinsic time scale

Normalized latent heat

$$\boxed{\begin{aligned} \Delta Q &= \Delta F + T\Delta S \\ S &= -\partial F/\partial T \\ F &\approx V \end{aligned}}$$

$$\boxed{\Delta Q \approx \Delta V - T\partial\Delta V/\partial T}$$

$$\boxed{\alpha = \frac{30\Delta q}{\pi^2 g_* T^4}}$$

Time scale

$$\boxed{\frac{\beta}{H_*} = T\frac{d}{dT}\frac{S_3}{T}}$$

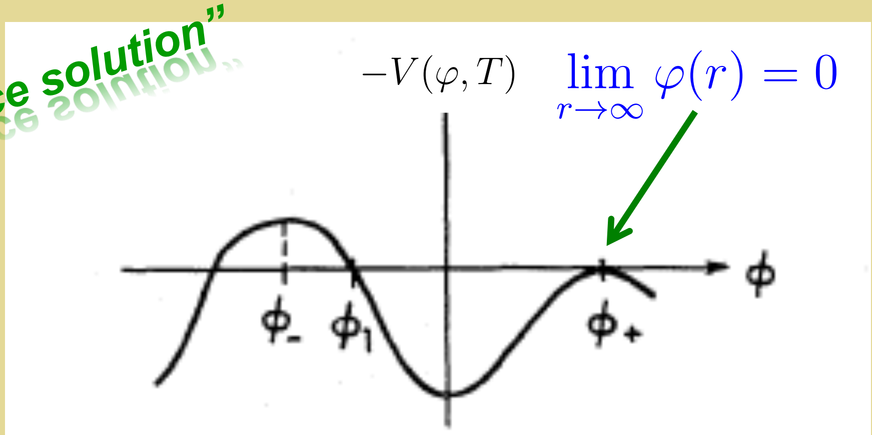
How Reliable?

T=0: S. Coleman, PRD 15 (1977) 2929

Tunneling @ T>0

Scalar Quantum Field Theory

"Bounce solution"



Tunneling rate / unit volume:

$$\Gamma = A e^{-\beta S_3/\hbar}\,[1 + \mathcal{O}(\hbar)]$$

$$\frac{d^2\varphi}{dr^2} + \frac{2}{r}\frac{d\varphi}{dr} = V'(\varphi, T)$$

Friction term

Exponent in Γ

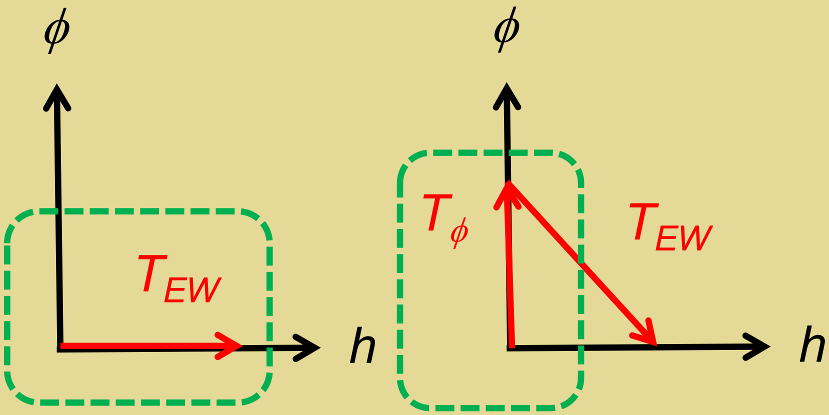
Path: minimize S_E

$$S_3 = \int d^3x \left\{ \frac{1}{2}(\vec{\nabla}\varphi)^2 + V(\varphi, T) \right\}$$

$$A \sim \mathcal{O}(1) \times T^4$$

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



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Tunneling @ T>0

Theoretical issues:

- *Radiatively-induced barrier (St'd Model) → gauge dependence*
    - *T = 0 Abelian Higgs: E. Weinberg & D. Metaxas: hep-ph/9507381*
    - *T=0 St'd Model: A. Andreassen, W. Frost, M. Schwartz 1408.0287*
    - *T > 0 Gauge theories:* ***recently solved in 2112.07452 (→ PRL) and 2112.08912***
- *Multi-field problem (still gauge invar issue)*
    - *Cosmotransitions: C. Wainwright 1109.4189*
    - *Espinosa method: J. R. Espinosa 1805.03680*

(Re) Organize the Perturbative Expansion

Illustrate w/ Abelian Higgs

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F_{\mu\nu} + (D_\mu\Phi)^*(D_\mu\Phi) + \mu^2\Phi^*\Phi + \lambda(\Phi^*\Phi)^2 + \mathcal{L}_{\text{GF}} + \mathcal{L}_{\text{FP}}$$

- *Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL*
- *Hirvonen, Lofgren, MRM, Tenkanen, Schicho 2112.08912*

Full 3D effective action

$$S_3 = \int \mathrm{d}^3x \left[V^{\text{eff}}(\phi, T) + \frac{1}{2}Z(\phi, T)\,(\partial_i\phi)^2 + \ldots\right]$$

Adopt appropriate power-counting in couplings

$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

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G.I. pertubative expansion only valid up to NLO → Δ: higher order contributions only via other methods

G.I. pertubative expansion

Tunneling @ T>0: Take Aways

- *For a radiatively-induced barrier, a gauge-invariant perturbative computation of nucleation rate can be performed for S_3 to $\mathcal{O}(g^{-1/2})$ by adopting an appropriate power counting for T in the vicinity of T_{nuc}*

- *Abelian Higgs example generalizes to non-Abelian theories as well as other early universe phase transitions*

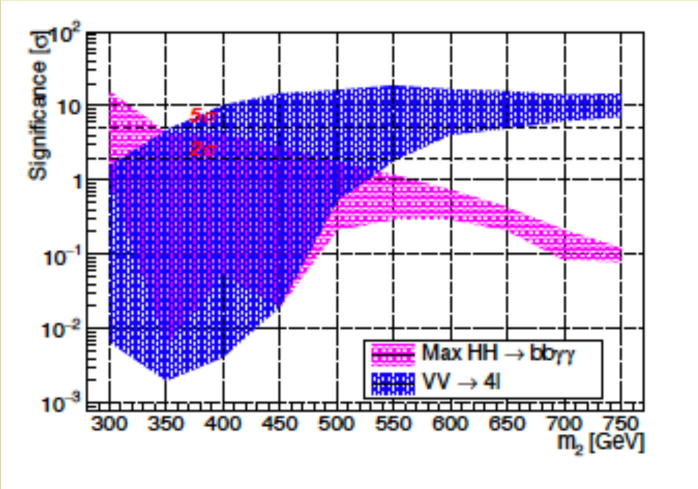
- *Remaining contributions to Γ_{nuc} beyond $\mathcal{O}(g^{-1/2})$ in S_3 and including long-distance (nucleation scale) contributions require other methods*

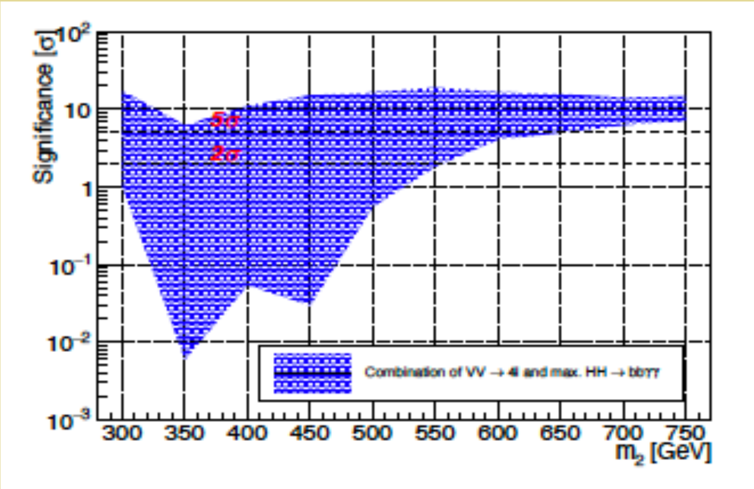
- *Assessing numerical reliability will require benchmarking with non-perturbative computations*

III. Collider Pheno Developments

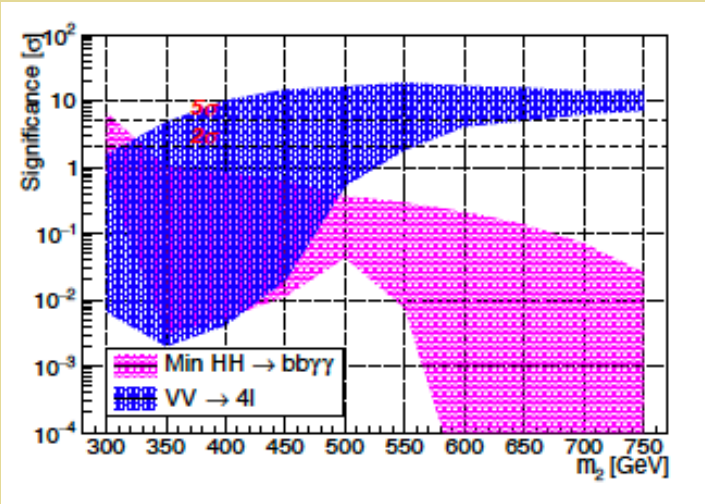
Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

SFOEWPT Max Benchmarks: HL LHC Combination $bb\gamma\gamma$ & 4 lepton





SFOEWPT Min Benchmarks:



S. Arunasalam, Hao-Lin Li, Kun Liu, MJRM, Yongchao Zeng, Wenxing Zhang 2211.0303612

Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

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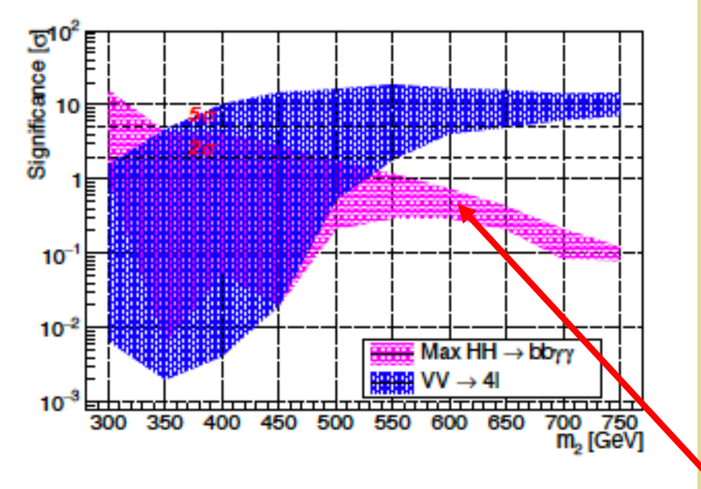
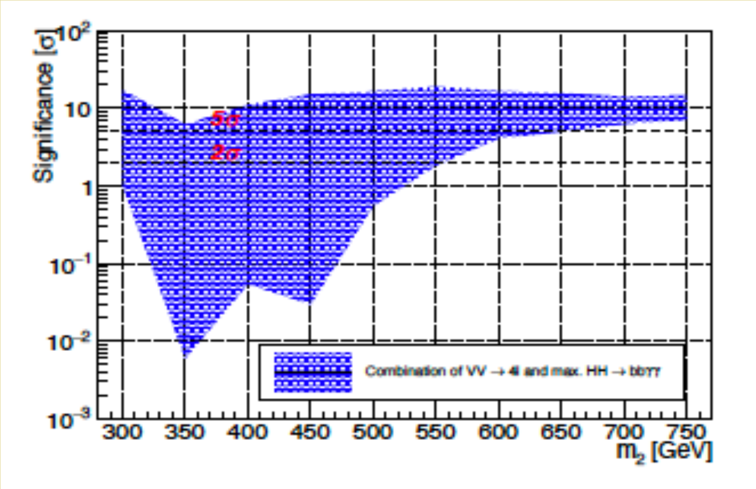
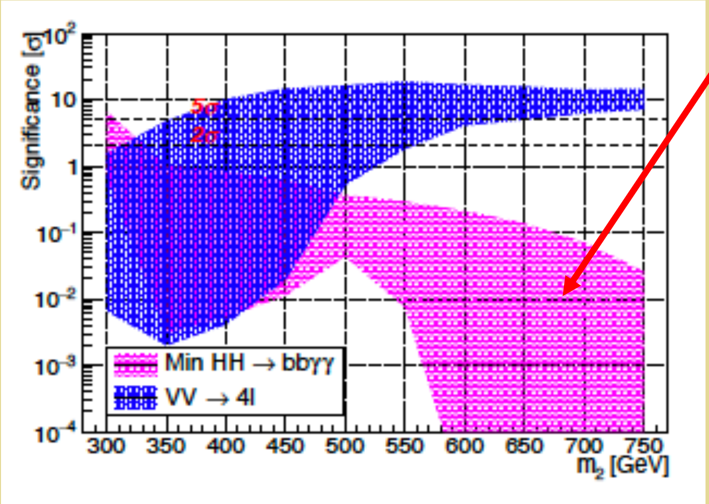




100 TeV accessible

SFOEWPT Min Benchmarks:



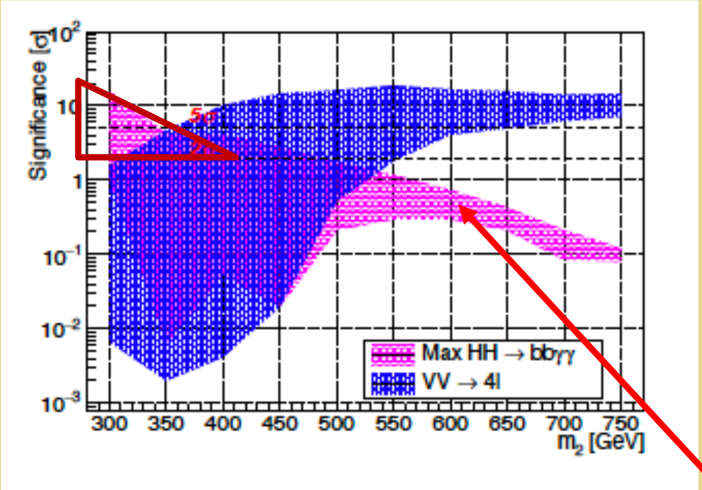
S. Arunasalam, Hao-Lin Li, Kun Liu, MJRM, Yongchao Zeng, Wenxing Zhang 2211.0303612

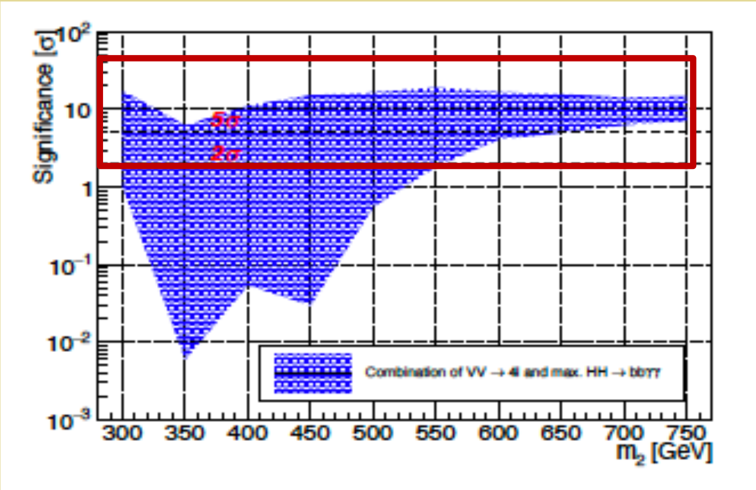
Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

SFOEWPT Max Benchmarks: HL LHC Combination bb$\gamma\gamma$ & 4 lepton

"Smoking gun" region

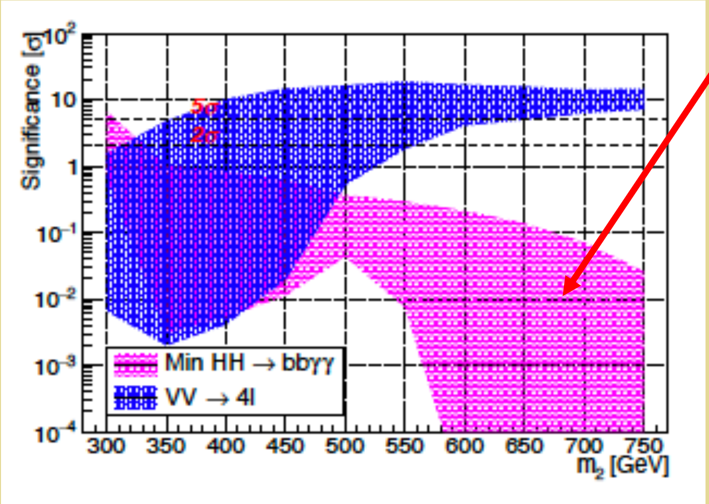
Parameter exclusion region





100 TeV accessible

SFOEWPT Min Benchmarks:



- *Observation of 4l channel would indicate existence of heavy resonance consistent with xSM SFOEWPT*
- *"Smoking gun" region would provide nearly definitive evidence & narrow down model parameter space*
- *Exclusion would leave ample room for 100 TeV pp discovery*

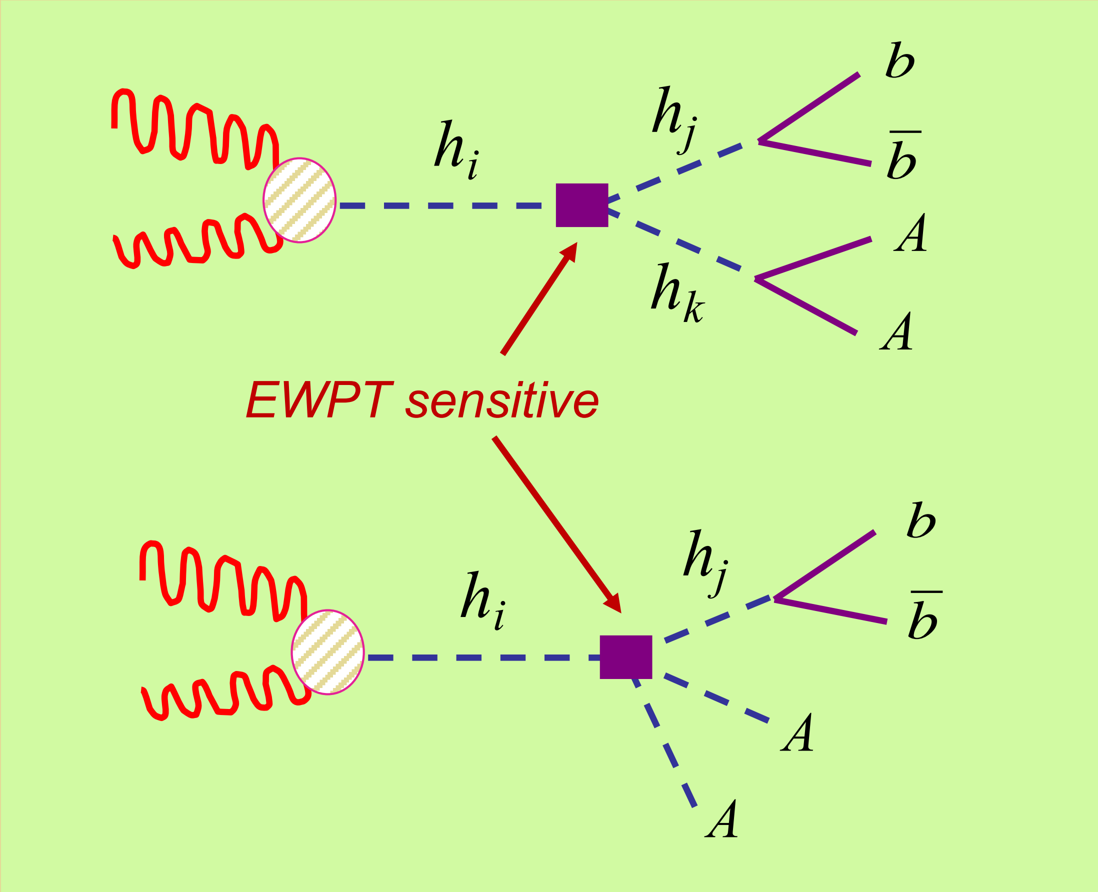
S. Arunasalam, Hao-Lin Li, Kun Liu, MJRM, Yongchao Zeng, Wenxing Zhang 2211.0303612

Complex Singlet: DM + EWPT

Original Model:

- SM + complex scalar singlet
- Global U(1): broken spontaneously & softly
- Particle spectrum
  - Mixed doublet-singlet scalars $h_{1,2}$
  - Scalar dark matter A

Search for bb + MET: example sub-processes



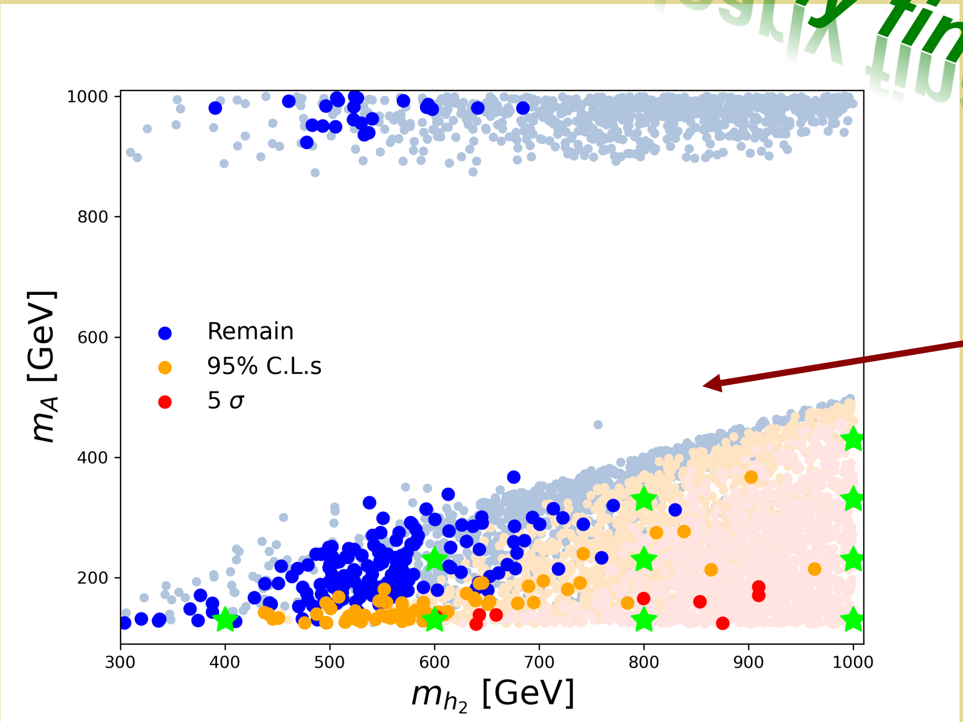
V. Barger, P. Langacker, M. McCaskey, MJRM, G. Shaugnessy 0811.0393

Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang 2311.NNNNN

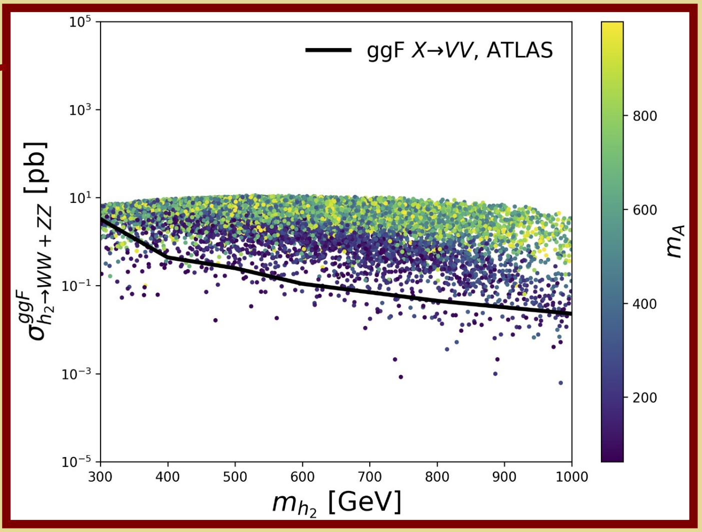
Complex Singlet: DM + EWPT

Search for bb + MET

Nearly final



Heavy Higgs → VV exclusion: BR (h_2→VV) larger when m_{h2} < 2 m_A



Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang 2311.NNNNN

IV. Outlook

Was There an Electroweak Phase Transition ?

- *Answering this question is an important and exciting challenge for Higgs Physics at the CEPC/FCC-ee/ILC*
- *The relevant scale T_{EW} makes this physics a prime target for collider and gravitational wave probes*
- *The EWPT question entails a rich interplay of model building, thermal QFT, phenomenology & experiment*
- *The collider – gravitational wave "inverse problem" has emerged as a particularly compelling arena for further exploration and opportunity for the CEPC community and beyond*

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谢谢！

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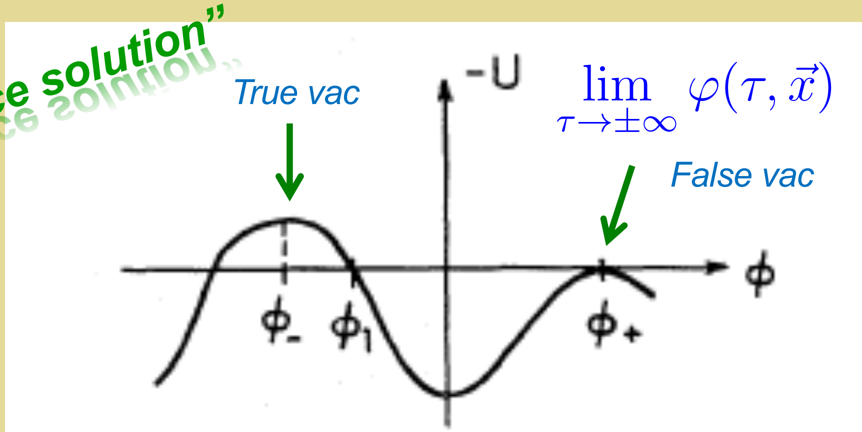
Back Up Slides

S. Coleman, PRD 15 (1977) 2929

Tunneling @ T=0: Coleman

Scalar Quantum Field Theory

"Bounce solution"



Rotational symmetry

$$\boxed{\rho^2 \equiv \tau^2 + |\vec{x}|^2}$$

$$\boxed{\frac{d^2\varphi}{d\rho^2} + \frac{3}{\rho}\frac{d\varphi}{d\rho} = U'(\varphi)}$$

Friction term

Ln Γ

Path: minimize S_E

$$\boxed{S_E = \int d\tau d^3x \left\{ \frac{1}{2}(\partial_\tau \varphi)^2 + \frac{1}{2}(\vec{\nabla}\varphi)^2 + U(\varphi) \right\}}$$

Inputs from Thermal QFT

Thermodynamics

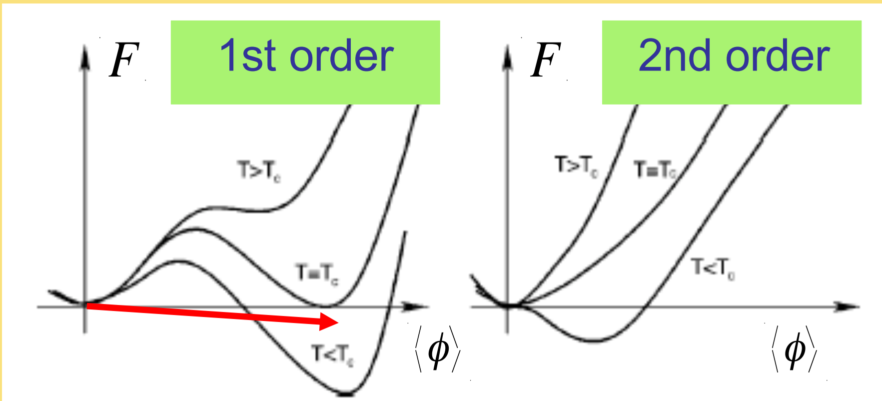
- Phase diagram: first order EWPT?
- Latent heat: GW

Dynamics

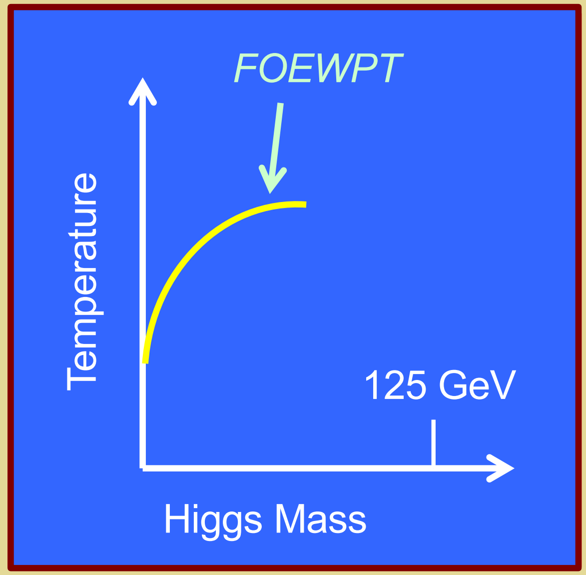
- Nucleation rate: transition occurs? T_N ? Transition duration (GW) ?
- EW sphaleron rate: baryon number preserved?

How reliable is the theory ?

Was There an EW Phase Transition?



Increasing m_h



EW Phase Diagram

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

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

EWPT & Perturbation Theory: IR Problem

Bosonic loop at T>0

Bose dist fn

$$I(T) = g^2 \int \frac{d^3p}{(2\pi)^3}\, f_B(E,T)\, \frac{1}{(p^2+m^2)^n} \longrightarrow \boxed{\frac{g^2 T}{m}} \int_{\text{I.R.}} \frac{d^3p}{(2\pi)^3} \frac{1}{(p^2+m^2)^n}$$

Effective expansion parameter

Small p regime

$$f_B(E,T) \longrightarrow \frac{T}{m}$$

Field-dependent thermal mass

$$m^2(\varphi,T) \sim C_1\, g^2\varphi^2 + C_2\, g^2 T^2 \equiv m_T^2(\varphi)$$

- *Near phase transition: $\varphi \sim 0$*
- *$m_T(\varphi) < g\, T$*

EWPT & Perturbation Theory

Expansion parameter

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

Infrared sensitive near phase trans

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

* *Kajantie et al, NPB 466 (1996) 189; hep/lat 9510020 [see sec 10.1]*

(Re) Organize the Perturbative Expansion

Illustrate w/ Abelian Higgs

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F_{\mu\nu} + (D_\mu\Phi)^*(D_\mu\Phi) + \mu^2\Phi^*\Phi + \lambda(\Phi^*\Phi)^2 + \mathcal{L}_{\mathrm{GF}} + \mathcal{L}_{\mathrm{FP}}$$

- *Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL*
- *Hirvonen, Lofgren, MRM, Tenkanen, Schicho 2112.08912*

Full 3D effective action

$$S_3 = \int \mathrm{d}^3x \left[V^{\mathrm{eff}}(\phi, T) + \frac{1}{2}Z(\phi, T)\,(\partial_i\phi)^2 + \ldots \right]$$

Adopt appropriate power-counting in couplings

$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

G.I. pertubative expansion only valid up to NLO → Δ: higher order contributions only via other methods

SSB @ T>0 : Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

$$\mu^2_{\rm eff} \equiv \mu^2 + (4\lambda + 3g^2)\frac{T^2}{12}$$

T=0 parameter < 0

Thermal corrections > 0

Near cancellation for $T \sim T_C$

For a range of $T \sim T_{nuc}$: N = 1

$$\boxed{\mu^2_{\rm eff} \sim \mathcal{O}(g^{2+N}\, T^2) < \mathcal{O}(g^2\, T^2)}$$

Power Counting

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

ϕ	~	T
λ	~	g^3
μ^2	~	$g^2 T^2$
$\mu_{\rm eff}^2$	~	$g^3 T^2$

→

$$V_{\rm LO}^{\rm eff} = \frac{1}{2}\mu_{\rm eff}^2\phi^2 + \frac{1}{4}\lambda\phi^4$$
$$\boxed{-\frac{g^3 T}{12\pi}\left[2\phi^3 + \left(\frac{1}{3}T^2 + \phi^2\right)^{\frac{3}{2}}\right]}$$

Radiative barrier:
ξ-independent

Tunneling @ T>0: G.I. & Nielsen Identities

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

Adopt appropriate power-counting in couplings

$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

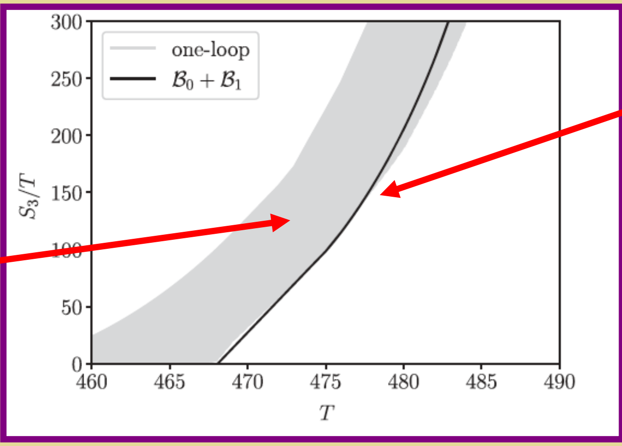
Order-by-order consistent with Nielsen Identities

$$\xi \frac{\partial S^{\mathrm{eff}}}{\partial \xi} = -\int \mathrm{d}^d \mathbf{x} \frac{\delta S^{\mathrm{eff}}}{\delta \phi(x)} \mathcal{C}(x)$$

$$\mathcal{C}(x) = \frac{ig}{2} \int \mathrm{d}^d \mathbf{y} \Big\langle \chi(x) c(x) \bar{c}(y) \times \left[\partial_i B_i(y) + \sqrt{2} g \xi \phi \chi(y)\right] \Big\rangle$$

Numerical comparison with conventional approach

Conventional: $0 < \xi < 4$



S_3 to $\mathcal{O}(g^{-1/2})$: $0 < \xi < 4$

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

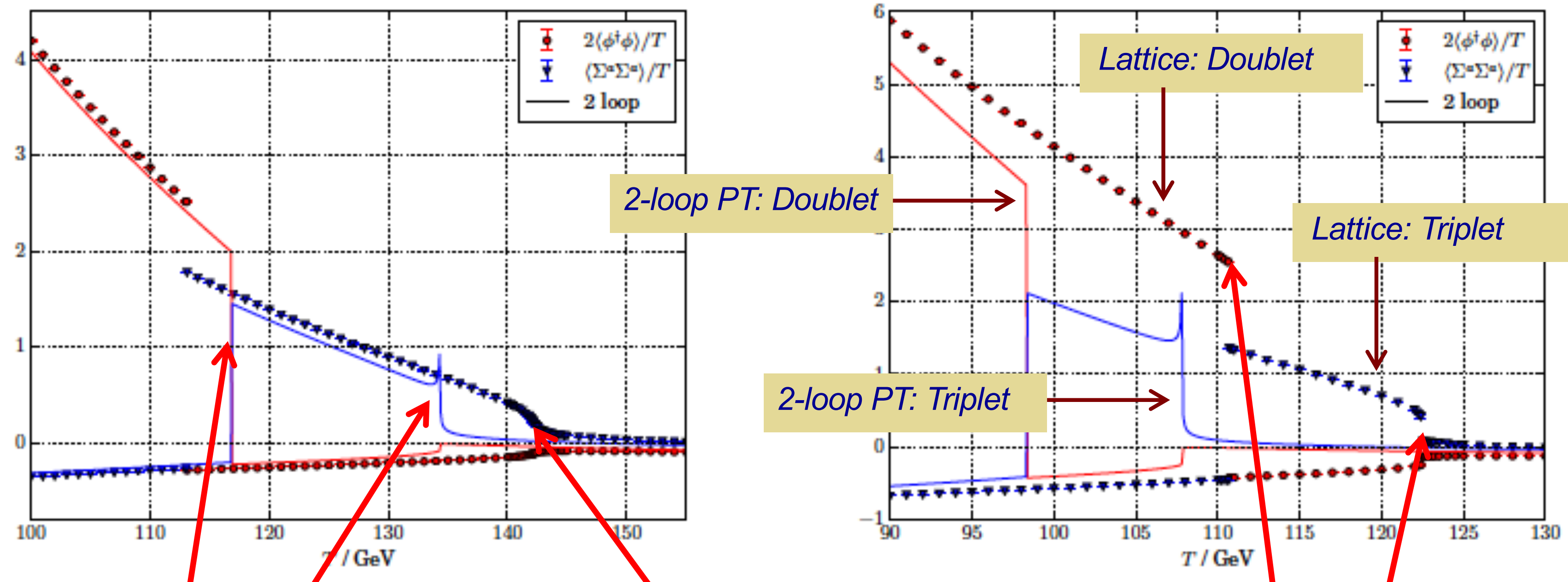
High-T SM Effective Potential

$$V(h,T)_{\mathrm{SM}} = D(T^2 - T_0^2)\, h^2 + \lambda\, h^4 \ + \ldots$$

$$T_0^2 = (8\lambda + \ \mathrm{loops}) \left(4\lambda + \frac{3}{2} g^2 + \frac{1}{2} g'^{\,2} + 2 y_t^2 + \cdots \right)^{-1} \ v^2$$

$T_0 \sim$ 140 GeV $\equiv$ **T_{EW}**

Real Triplet & EWPT: Benchmark PT



(a) BM1: $(M_\Sigma, a_2, b_4) = (160\ \text{GeV}, 1.1, 0.25)$

(b) BM2: $(M_\Sigma, a_2, b_4) = (265\ \text{GeV}, 2.3, 0.25)$

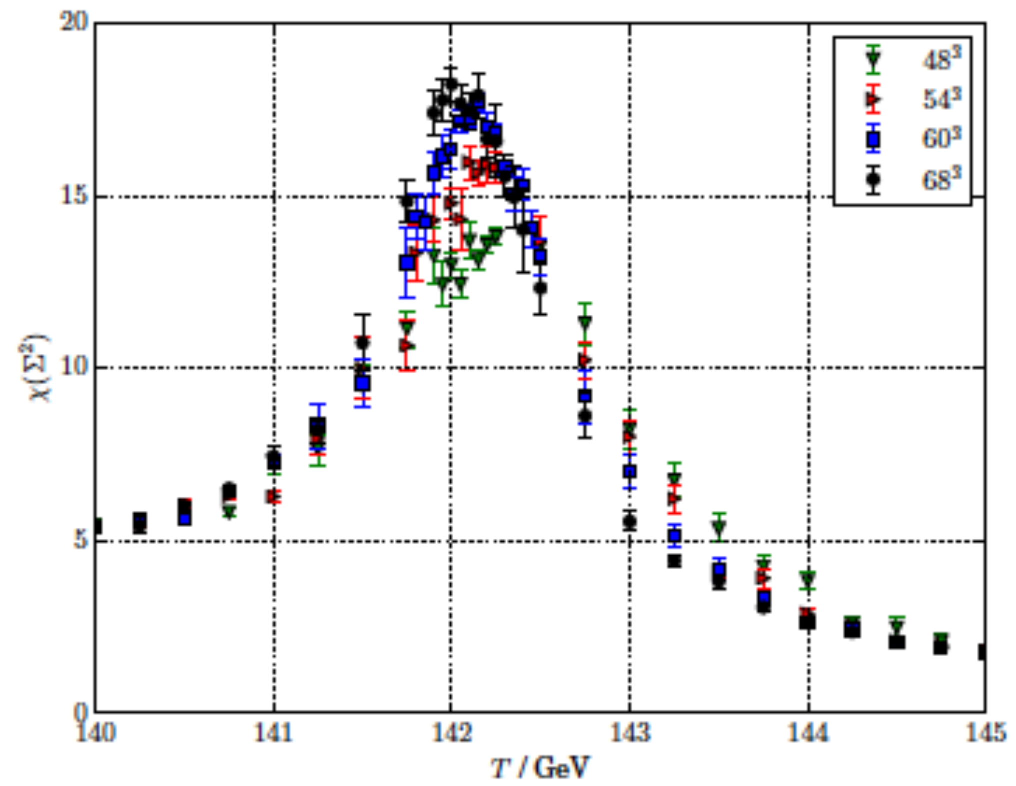
PT Discontinuities:
First order EWPT

Lattice: Smooth Crossover:
No phase transition

Discontinuities:
First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet: Crossover vs 2nd Order



$$\chi(\Sigma^2) = \frac{1}{4}VT\left[\langle(\Sigma^a\Sigma^a)_V^2\rangle - \langle(\Sigma^a\Sigma^a)_V\rangle^2\right]$$

Niemi, R-M, Tenkanen, Weir 2005.11332

Challenges for Theory

Perturbation theory

- *I.R. problem: poor convergence*
- *Thermal resummations*
- *Gauge Invariance (radiative barriers)*
- *RG invariance at T>0*

Non-perturbative (I.R.)

- *Computationally and labor intensive*

Dimensionally reduced 3D EFT at T > 0

BSM proposals

Inputs from Thermal QFT: EFTs

Thermodynamics

- *Phase diagram: first order EWPT?*
- *Latent heat: GW*

EFT 1

Dynamics

EFT 2

- *Nucleation rate: transition occurs? T_N ? Transition duration (GW) ?*

- *EW sphaleron rate: baryon number preserved?*

EFT 3

High-T EFT: Dimensional Reduction

DR 3dEFT: Scales

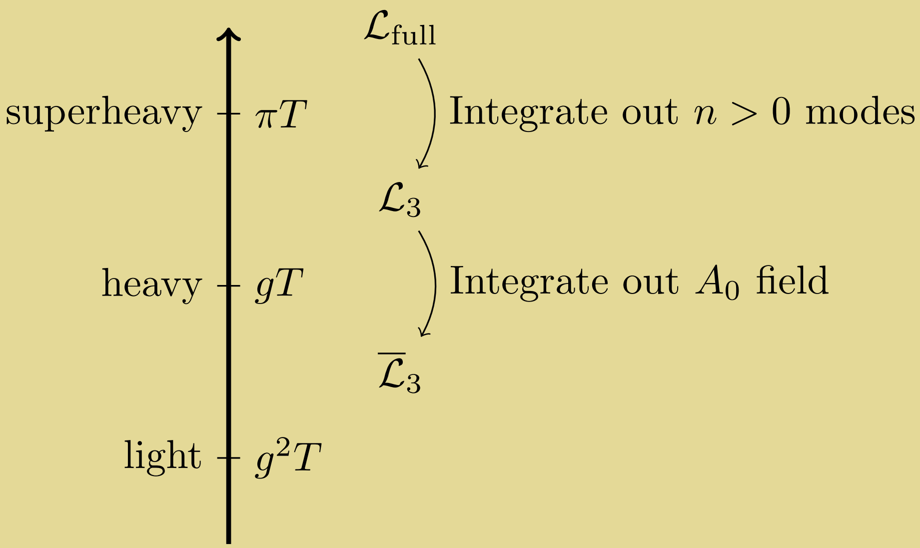
• πT	*Non-zero Matsubara modes*
• M_{BSM}	*BSM mass scale: can be > or < πT*
• $g\,T$	*Thermal masses*
• M_{NUC}	*Nucleation scale ~ $1/r_{bubble}$*
• $g^2\,T$	*Light scale*

EFT 2

EFT 1

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



EFT 1: Thermodynamics

Matching: Two Elements

Dimensional Reduction

All integrals are 3D with prefactor T → Rescale fields, couplings…

$$\int \frac{d^4k}{(2\pi)^4} \longrightarrow \frac{1}{\beta}\sum_n \int \frac{d^3k}{(2\pi)^3}$$

- $\varphi^2_{4d} = T\,\varphi^2_{3d}$
- $T\,\lambda_{4d} = \lambda_{3d}$

Thermal Loops

Equate Greens functions

$$\phi^2_{\mathrm{3d}} = \frac{1}{T}\left[1 + \hat{\Pi}'_\phi(0,0)\right]\phi^2$$

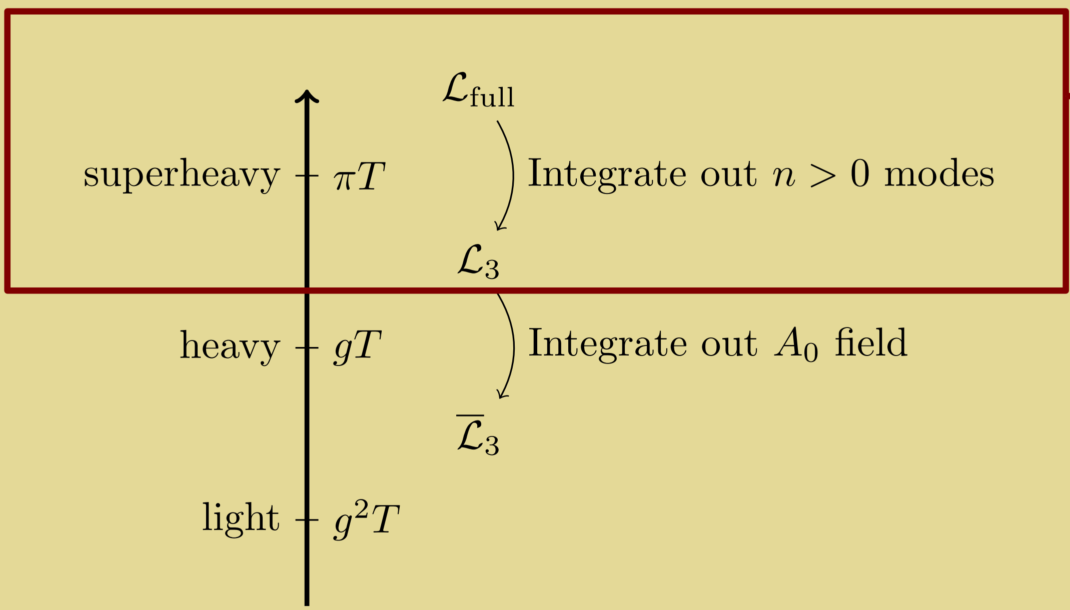
Field

$$a_{2,3} = T\left[a_2 - a_2(\hat{\Pi}'_H(0) + \hat{\Pi}'_\Sigma(0)) + \hat{\Gamma}(0)\right]$$

Quartic coupling

EFT 1: Thermodynamics

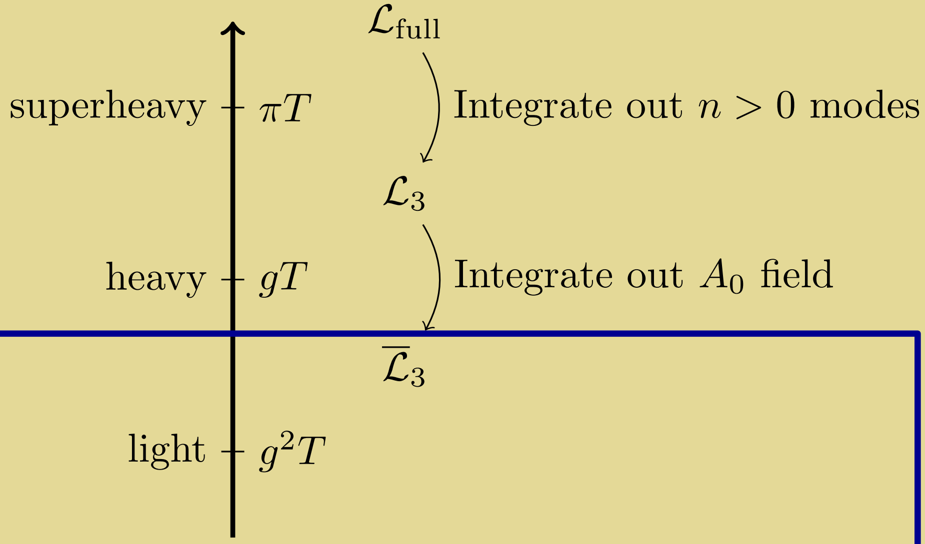
Meeting ground: 3-D high-T effective theory



Thermal resummations: systematically implemented

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



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

When $\mathcal{L}_{full}$ contains BSM interactions, λ_3 and $\mu_{\phi,3}$ can accommodate first order EWPT and m_h =125 GeV

Lattice simulations exist

EFT 1: Thermodynamics

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 — $g^2 T$

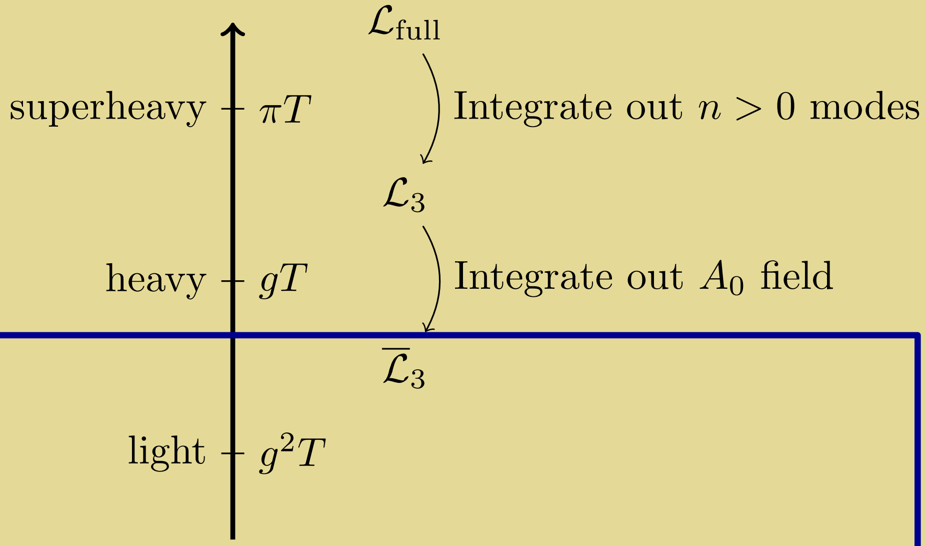
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

"Repurpose" lattice results

Lattice simulations exist

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



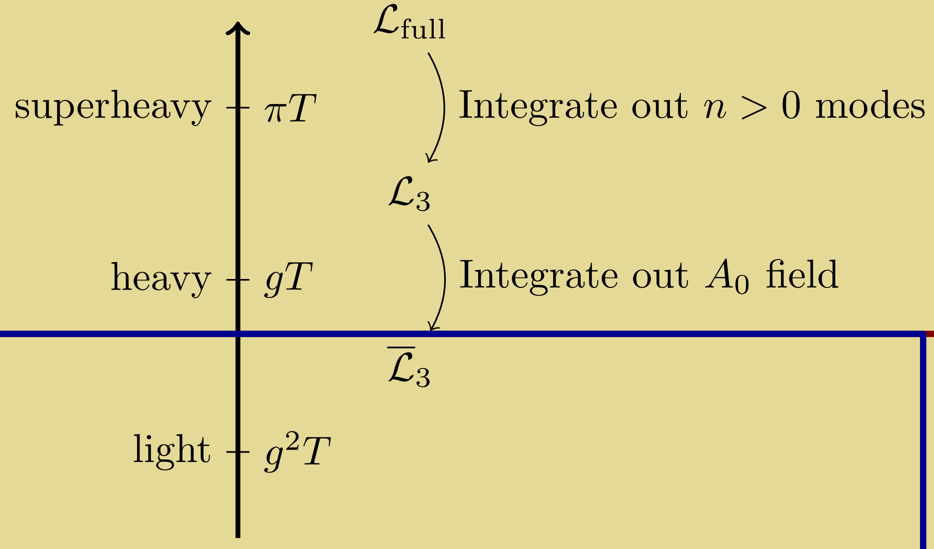
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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*

EFT 1: Thermodynamics

Meeting ground: 3-D high-T effective theory



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Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory

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

superheavy — πT — Integrate out $n > 0$ modes

$\mathcal{L}_3$

heavy — gT — Integrate out A_0 field

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

light — $g^2 T$

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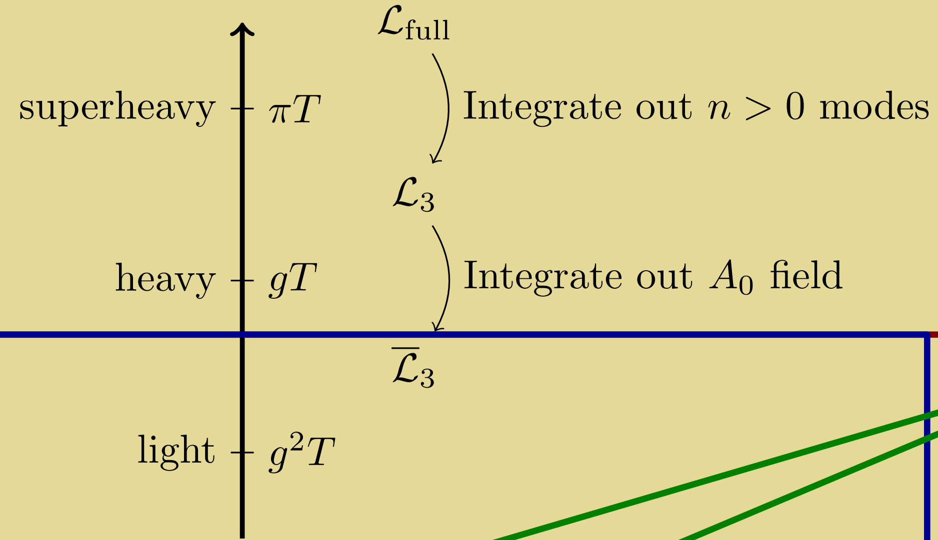

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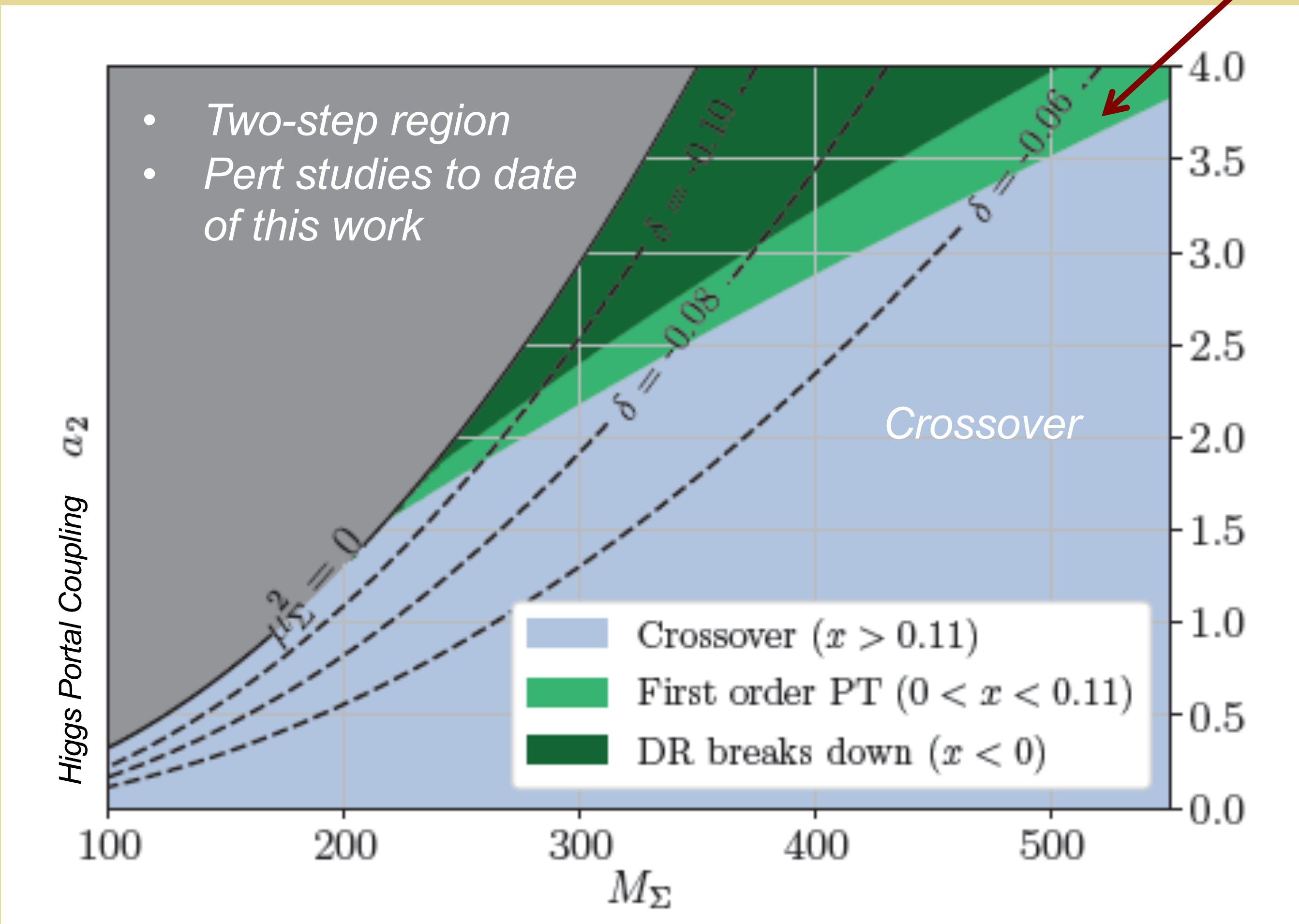
Lattice simulations exist (e.g., Kajantie et al '95)

Real Triplet: One-Step EWPT

FOEWPT

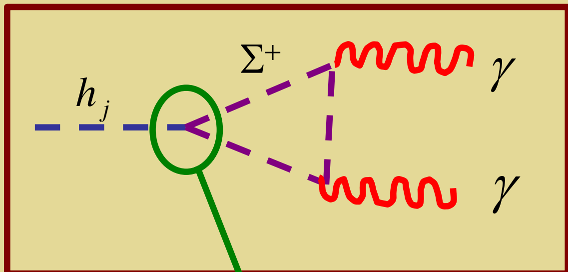


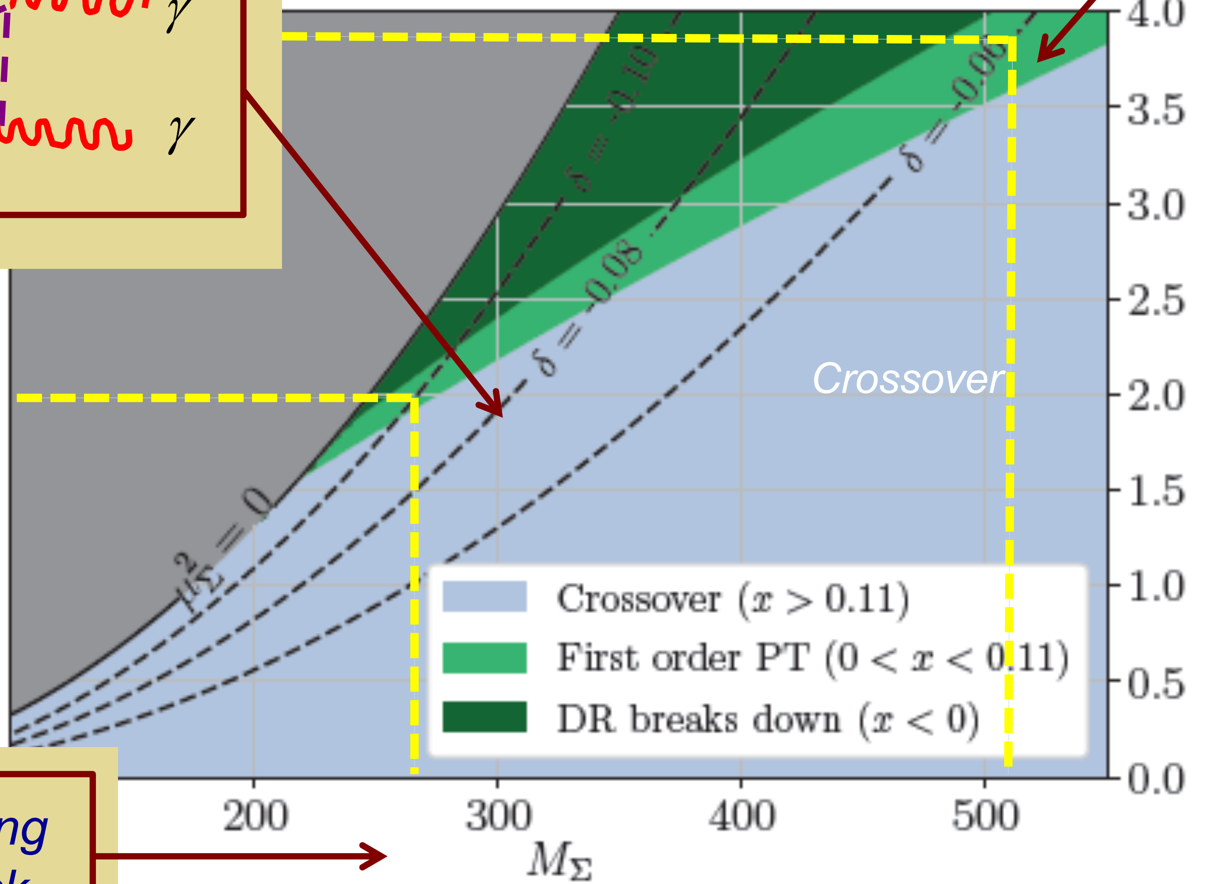
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

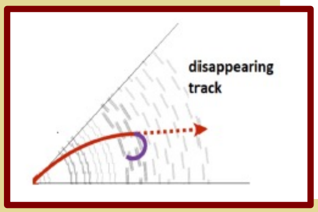
- One-step
- Non-perturbative

Real Triplet & EWPT

FOEWPT







Disappearing charge track

- One-step
- Non-perturbative

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