Was There an Electroweak Phase Transition ?

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- 微信：mjrm-china
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About MJRM:

Science

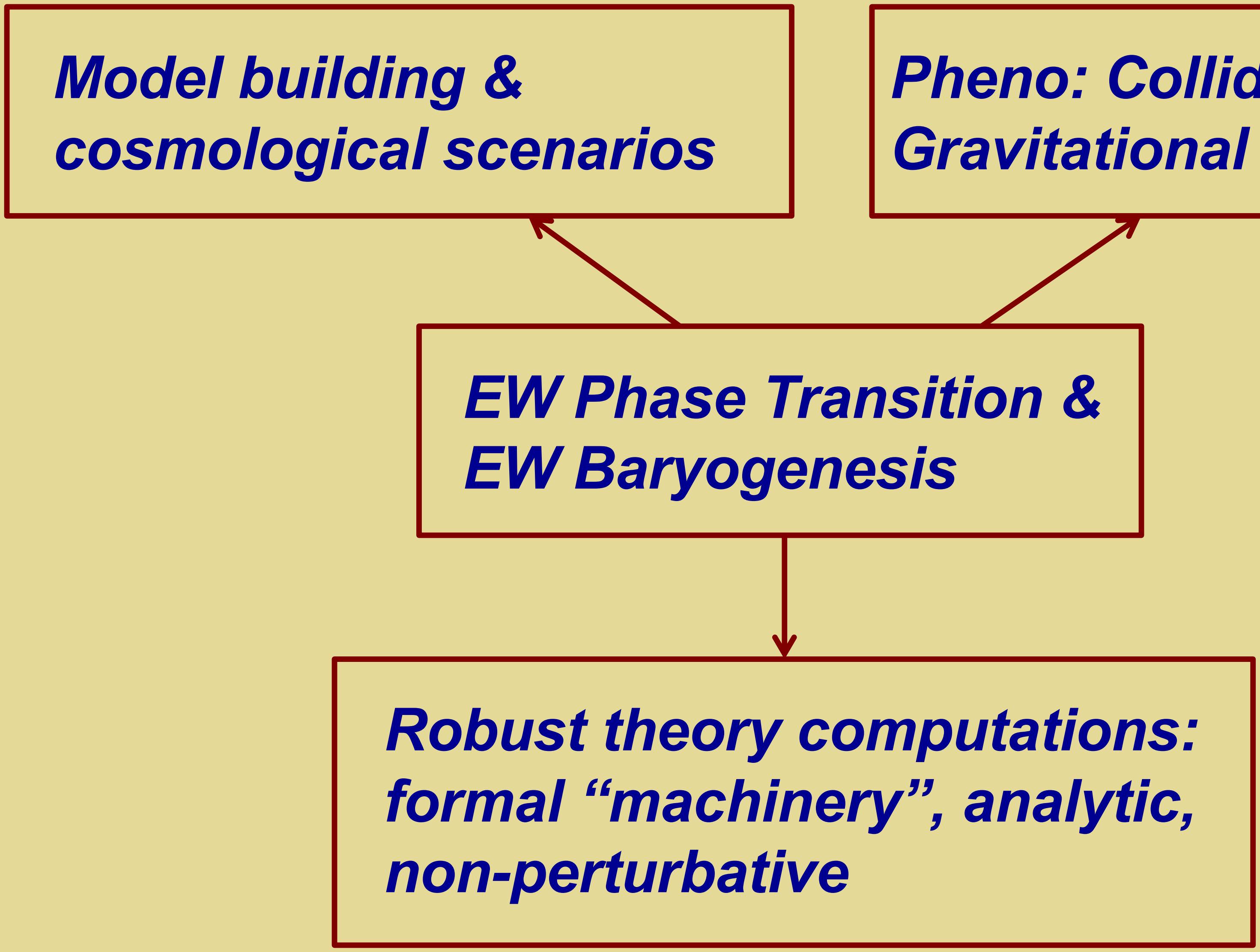
Family

Friends

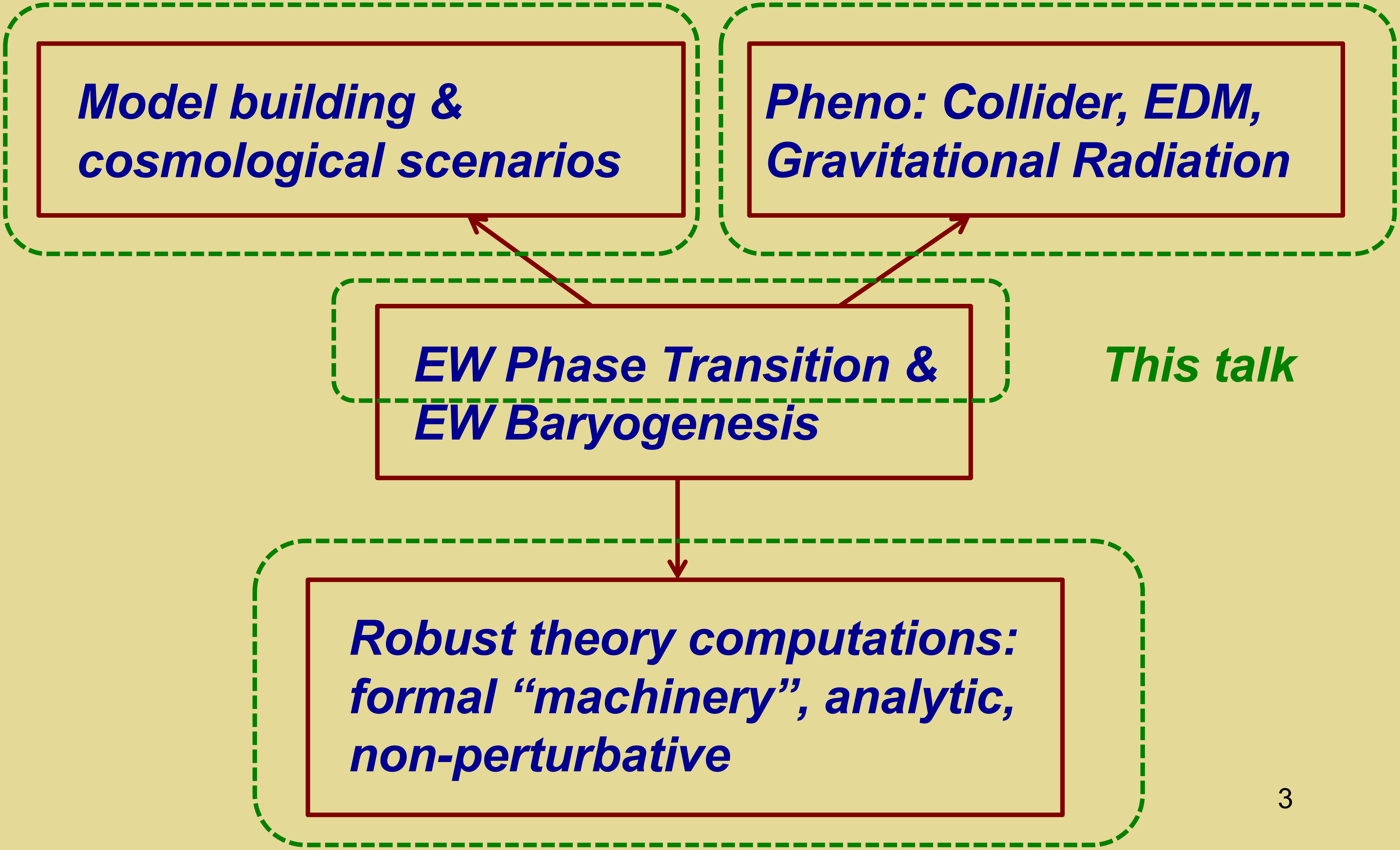
My pronouns: he/him/his
MeToo

USTC Lectures June 4-6, 2024

MJRM TDLI/SJTU Program



MJRM TDLI/SJTU Program



Goals for this Talk

- *Motivate the scientific opportunity associated with a possible EWPT in BSM scenarios*
- *Introduce the rich array of phenomenological probes & inter-frontier connections*
- *Discuss recent theoretical developments and their implications for phenomenology*
- *Inspire discussion and further involvement !*

Key Ideas for this Talk

- ***The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders & GW probes***
- ***Simple arguments → BSM physics that changes the thermal history of EWSB cannot be too heavy or too feebly coupled to the SM***
- ***Robust test of theory requires a new era of EFT & non-perturbative computations → new results highlight this theoretical frontier***

Key Ideas for this Talk

- ***MJRM: 1912.07189***

- ***Recent EFT + Non-perturbative:***

  - ***L. Niemi, H.H. Patel, MJRM, T.V.I. Tenkanen, D. J. Weir: 1802.10500***
  - ***O. Gould, J. Kozaczuk, L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 1903.11604***
  - ***L. Niemi, MJRM, T.V.I. Tenkanen, D.J. Weir: 2005.11332***
  - ***L. Friedrich, MJRM, T.V.I. Tenkanen, V.Q. Tran: 2203.05889***

- ***Nucleation & gauge invariance***

  - ***J. Lofgren, MJRM, P. Schicho, T.V.I. Tenkanen:2112.05472***
  - ***J. Hirvonen, J. Lofgren, MJRM, P. Schicho, T.V.I. Tenkanen: 2112.08912***

Acknowledgments

- *Apologies for omissions of references to other important work*

- *Collaborators (this talk):*

  - *T. V. I. Tenkanen* *
  - *L. Niemi* *
  - *L. Friedrich* *
  - *V.Q. Tran* *
  - *G. Xia* *
  - *D. J. Weir*
  - *O. Gould*
  - *J. Kozaczuk*
  - *P. Schicho*
  - *J. Hirvonen*
  - *J. Lofgren*
  - *H. Patel*
  - *S. Arunasalam* *

* TDLI / SJTU

Outline

I. Context & Questions

II. EWPT: A Collider & GW Target

III. Collider Phenomenology

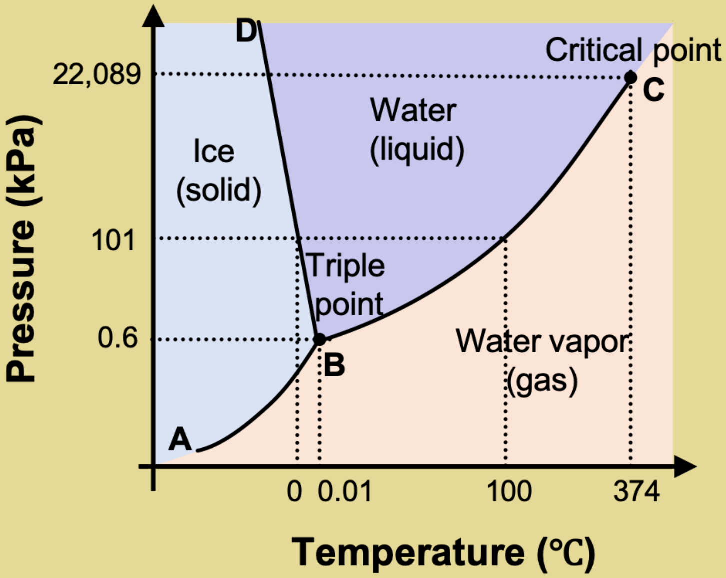
IV. Gravitational Wave-Collider-Theory Interface

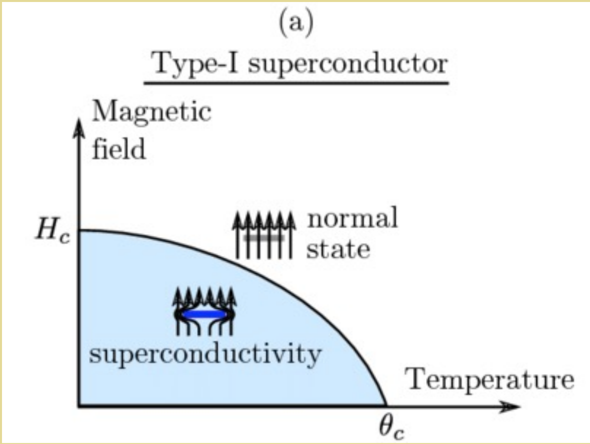
V. Theoretical Robustness

VI. Outlook

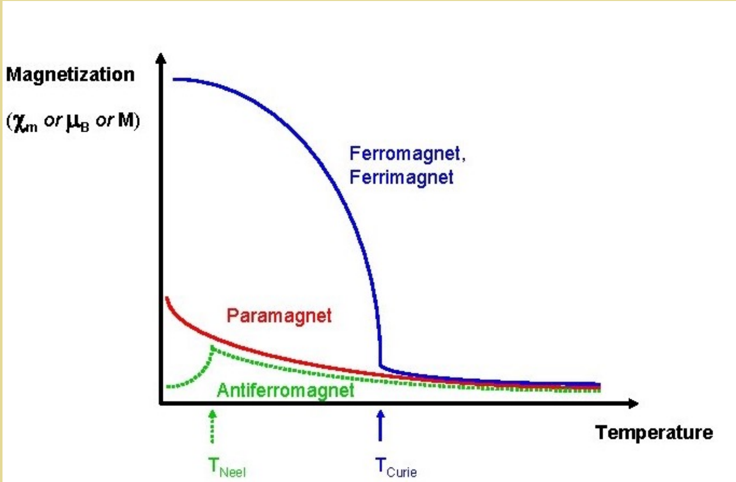
I. Context & Questions

Phase Transitions





Order parameter



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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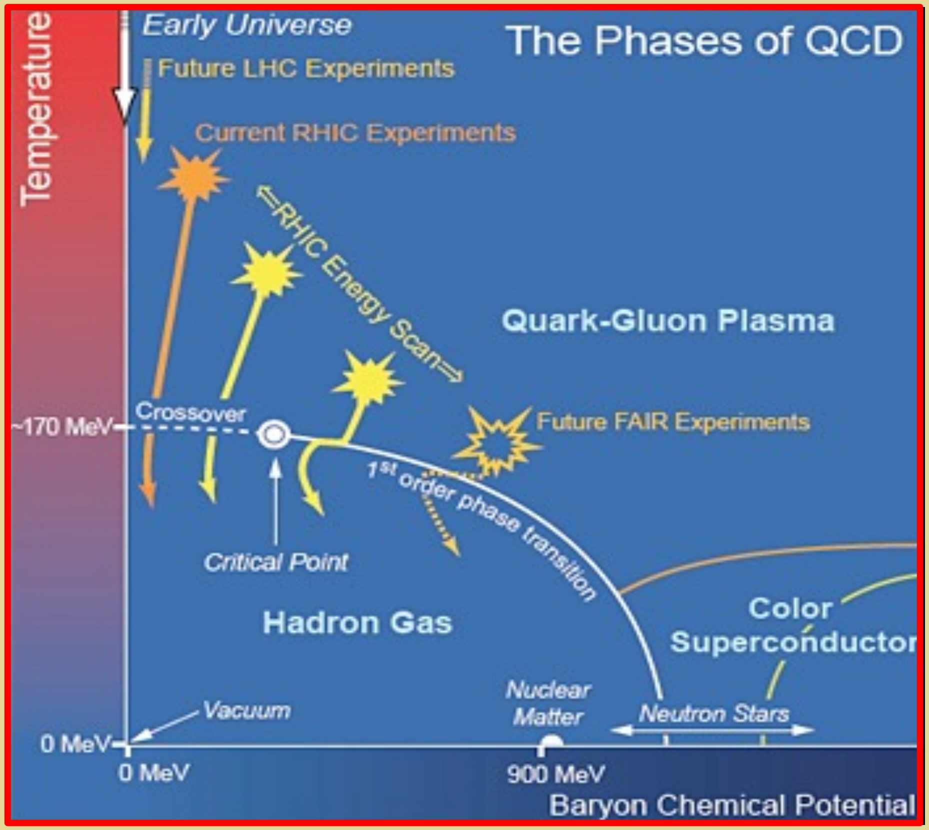
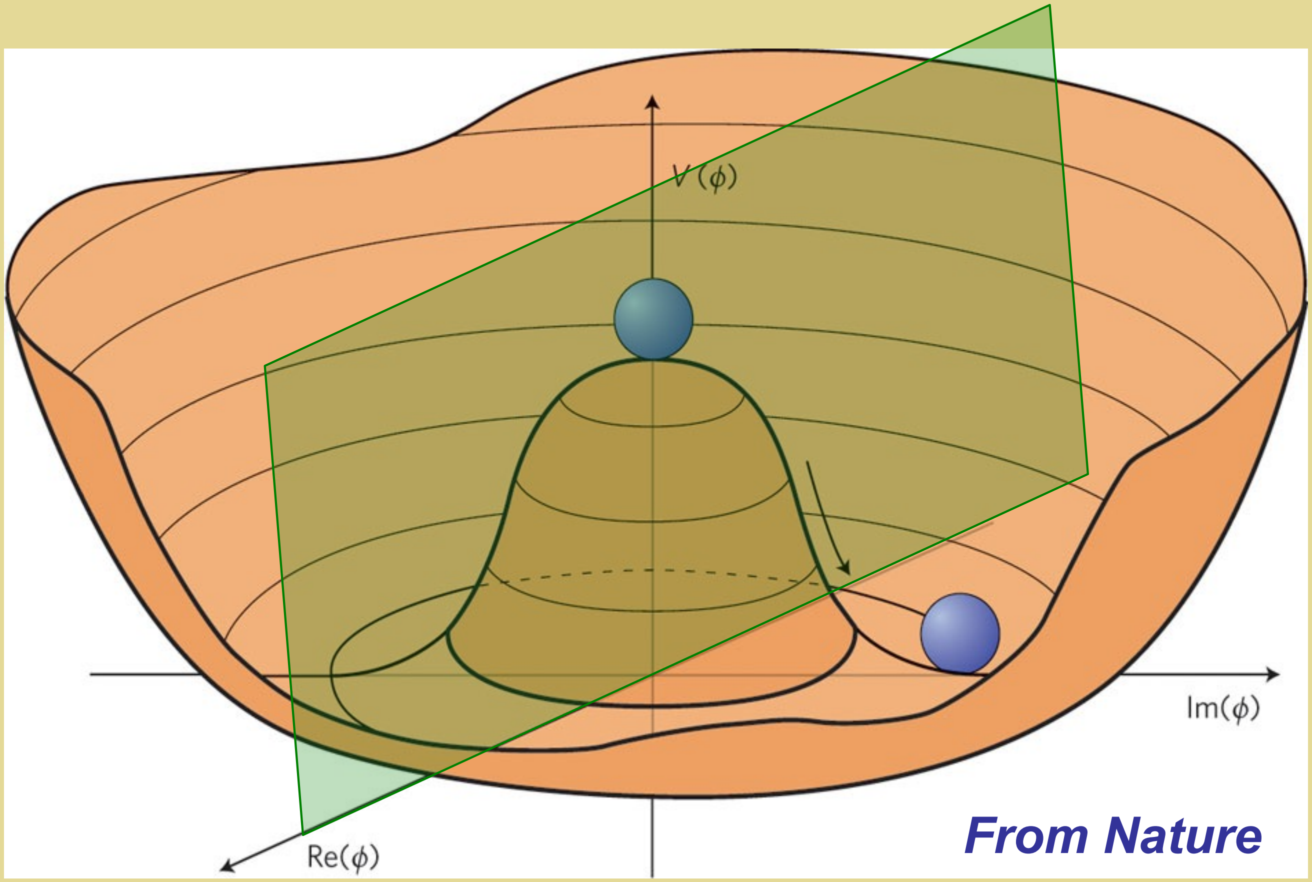
Thermal History of Symmetry Breaking



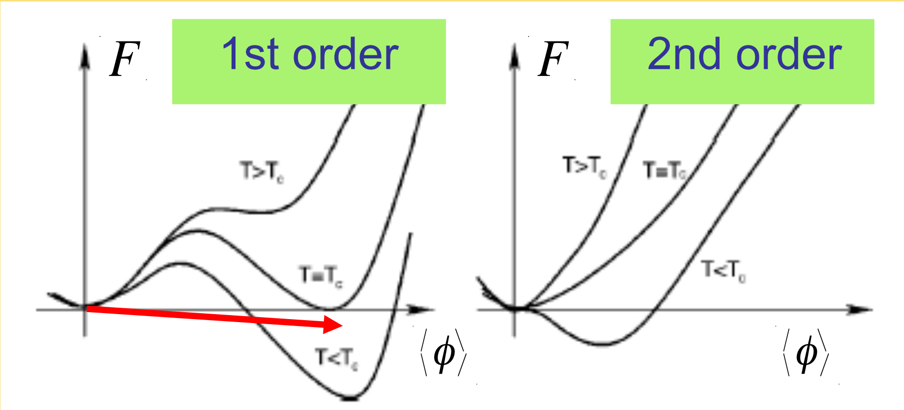
QCD Phase Diagram → EW Theory Analog?

EWSB: The Scalar Potential



What was the thermal history of EWSB ?

EWSB Transition: St'd Model



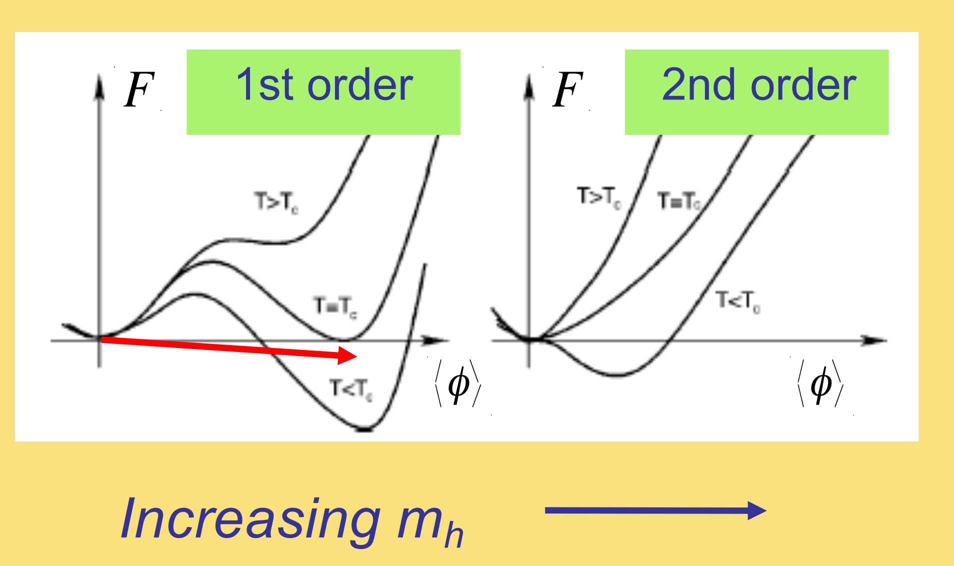
Increasing m_h →

Higgs potential: T=0

$$V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

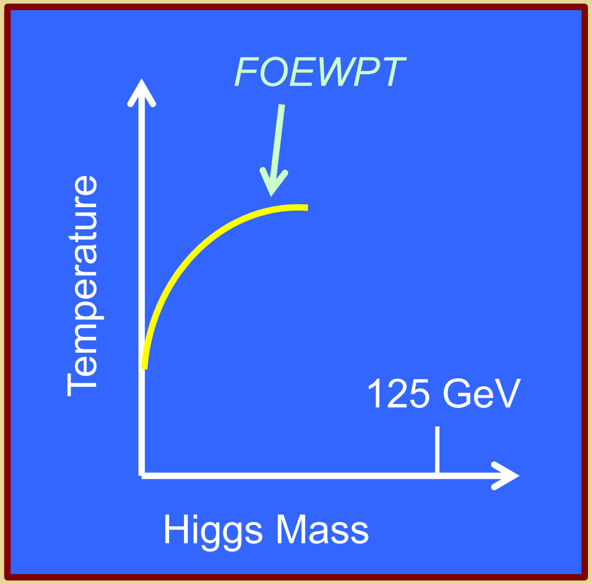
$$m_h^2 = 2\lambda\, v^2$$

EWSB Transition: St'd Model



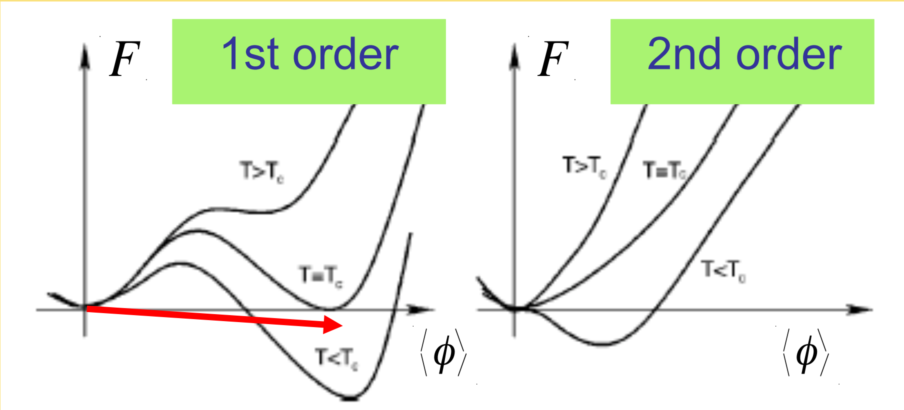
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

EWSB Transition: St'd Model



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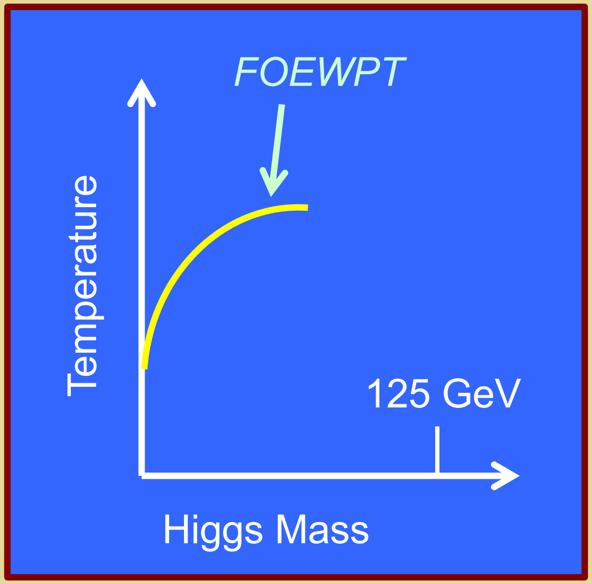
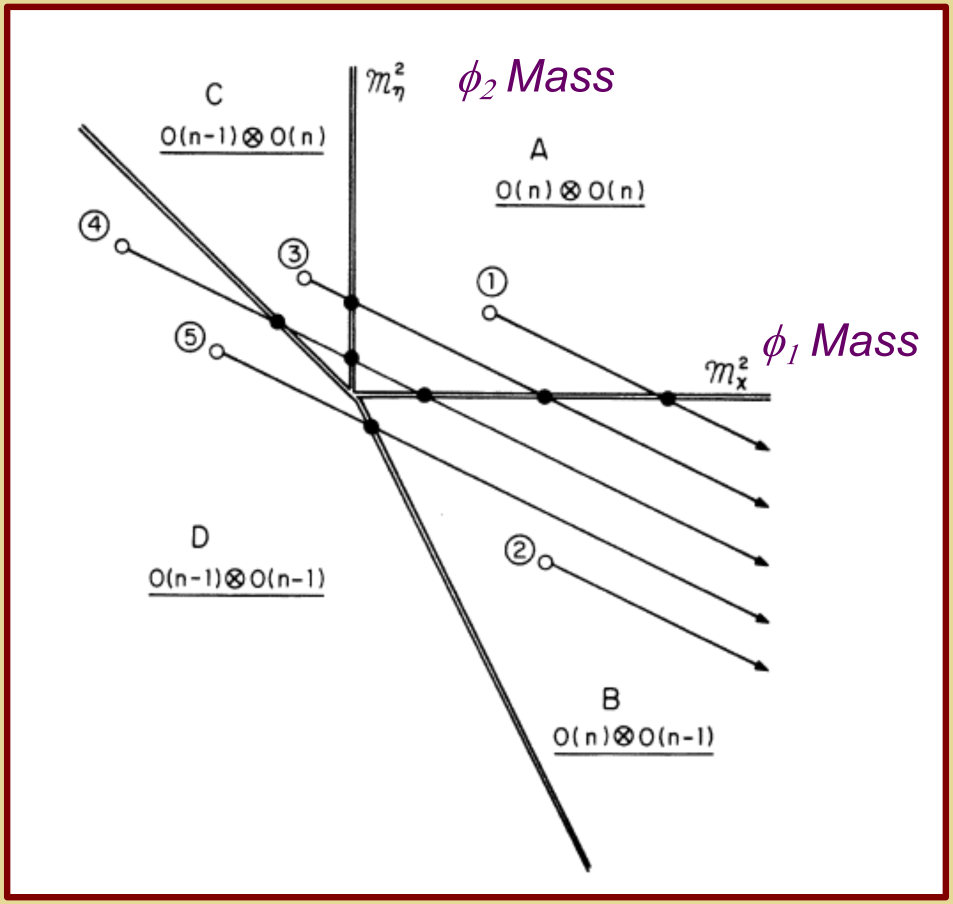


EW Phase Diagram

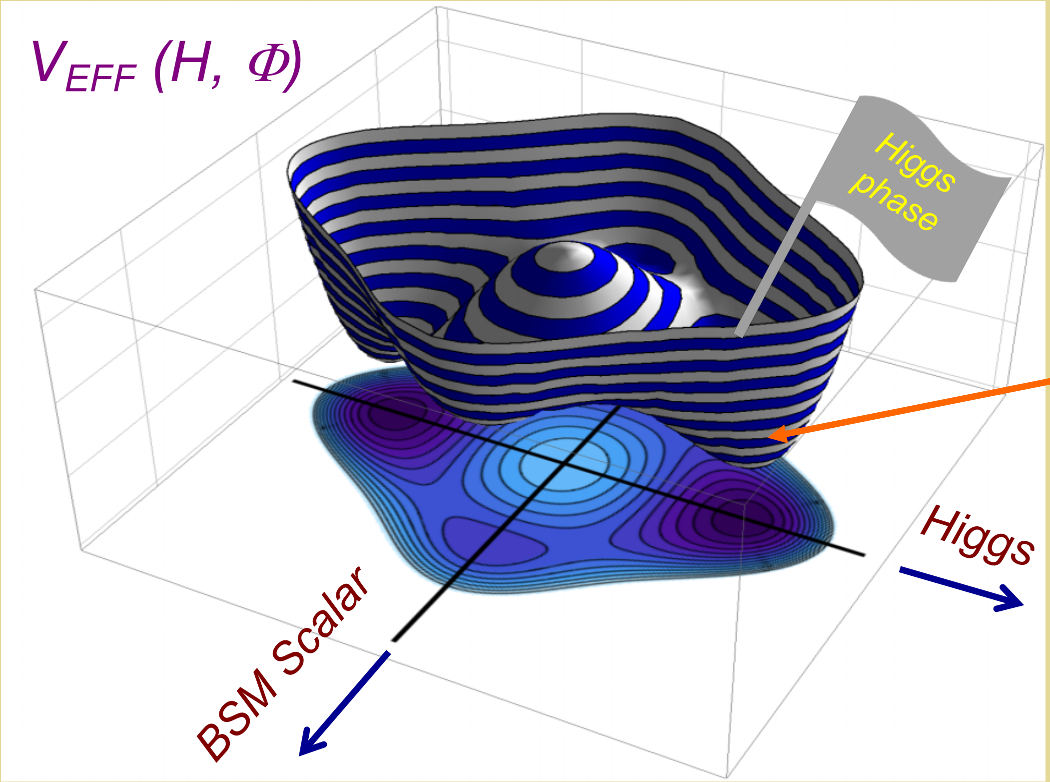
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ? SFOEWPT ?

Patterns of Symmetry Breaking



S. Weinberg, PRD 9 (1974) 3357

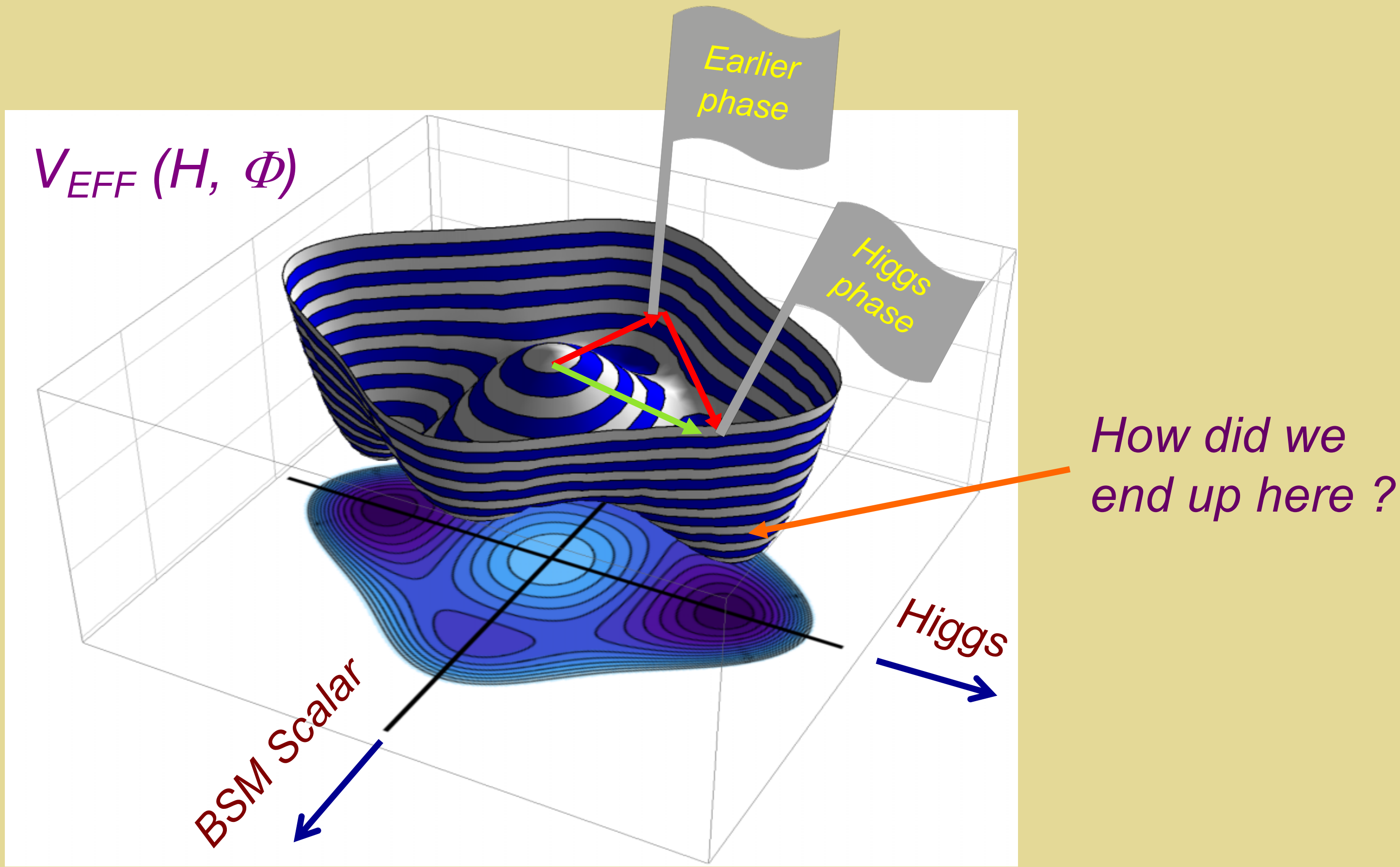
Patterns of Symmetry Breaking



How did we end up here ?

Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

Patterns of Symmetry Breaking



Extrema can evolve differently as T evolves →
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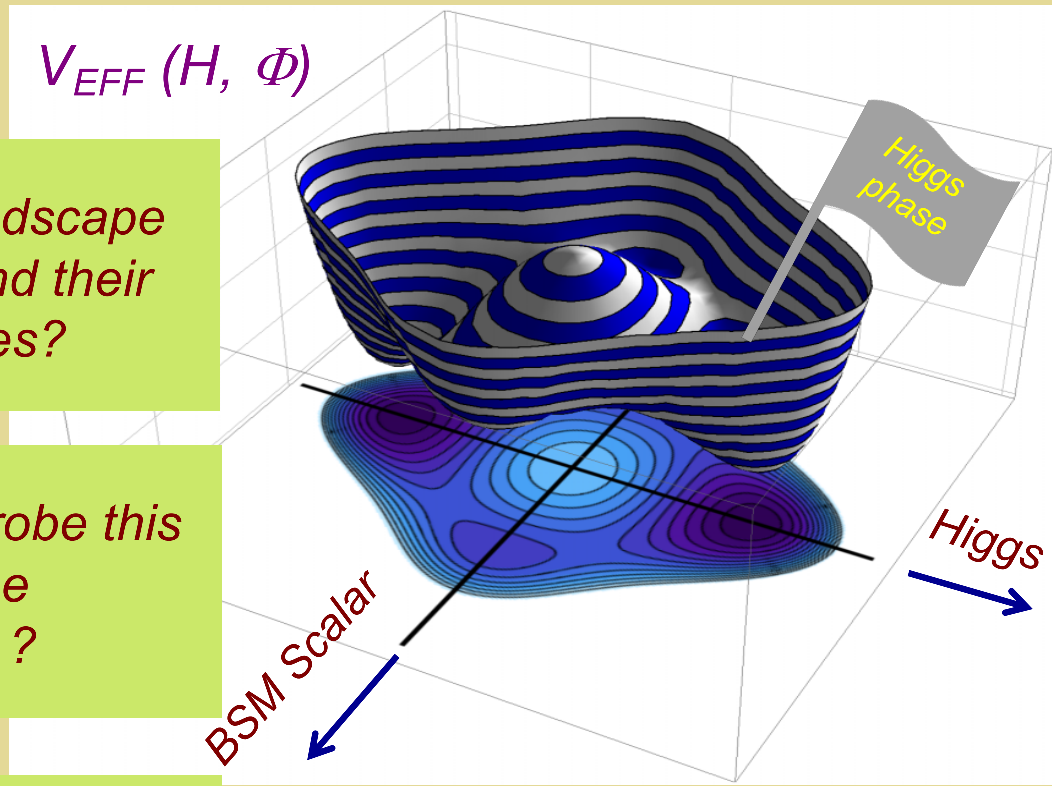
Thermal History of EWSB



- *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

Electroweak Phase Transition

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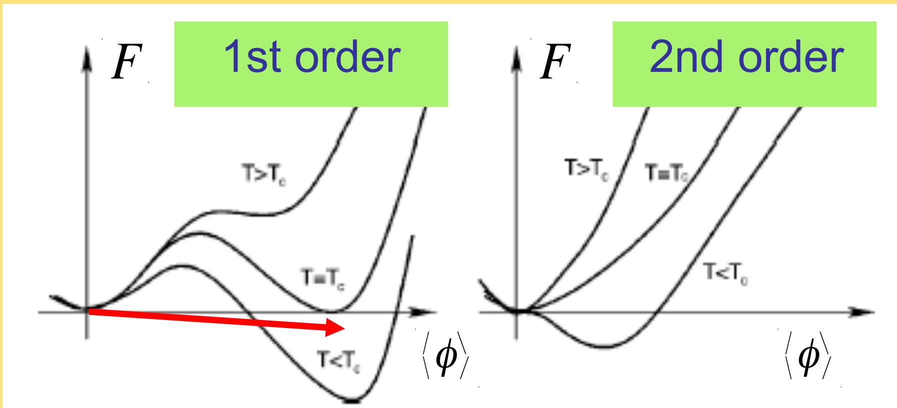
EW Phase Transition: Baryogen & GW



Increasing m_h →

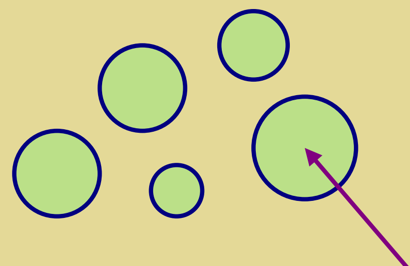
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

- *Baryogen**
- *GW*

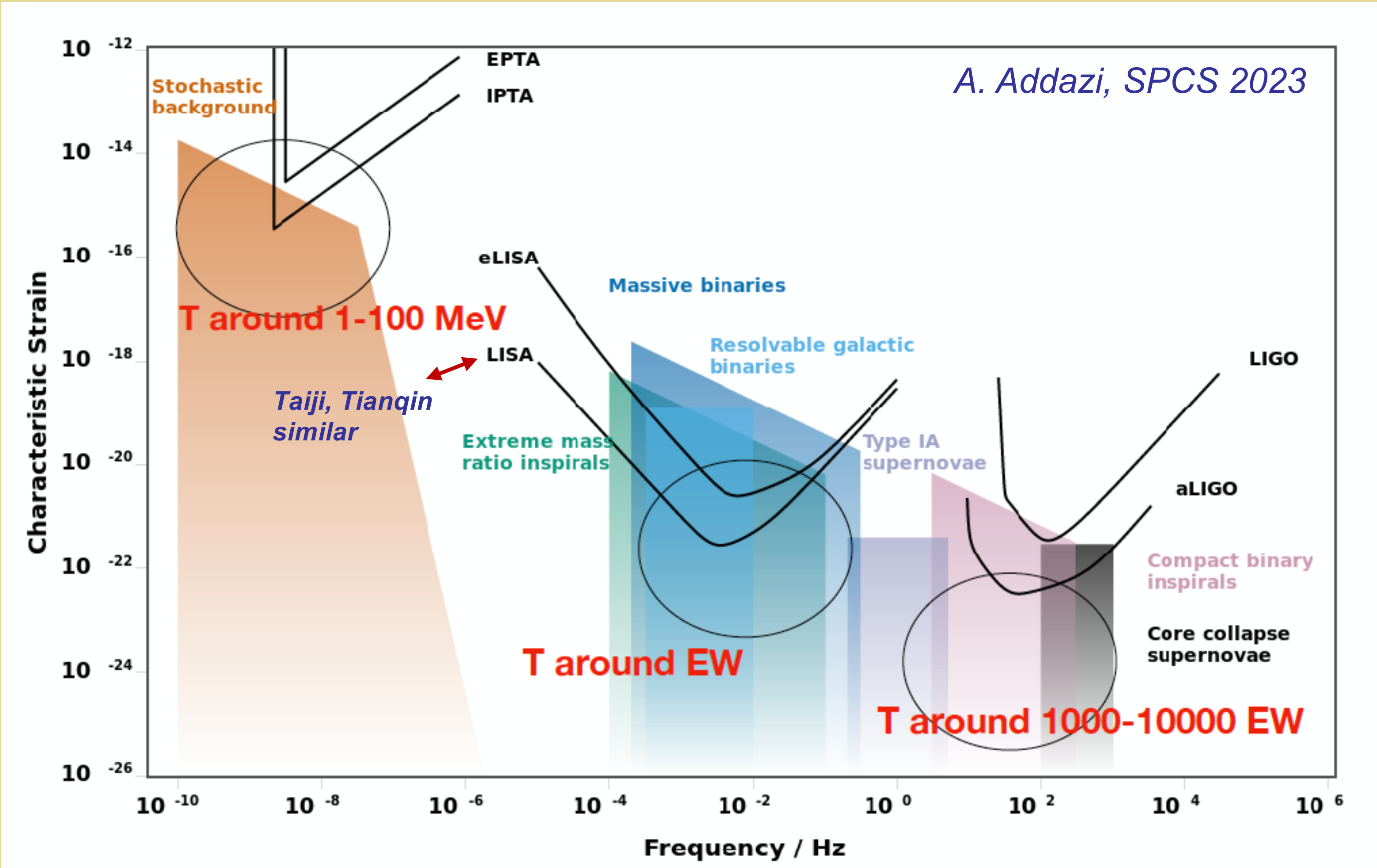
Bubble nucleation



EWSB

** Need BSM CPV*

Gravitational Waves



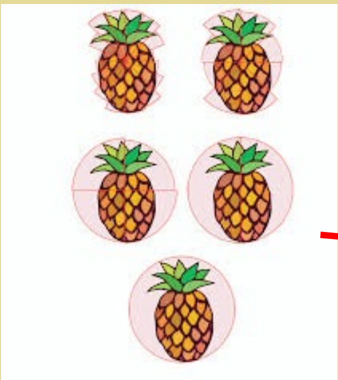
II. EWPT: A Collider Target

MJRM 1912.07189

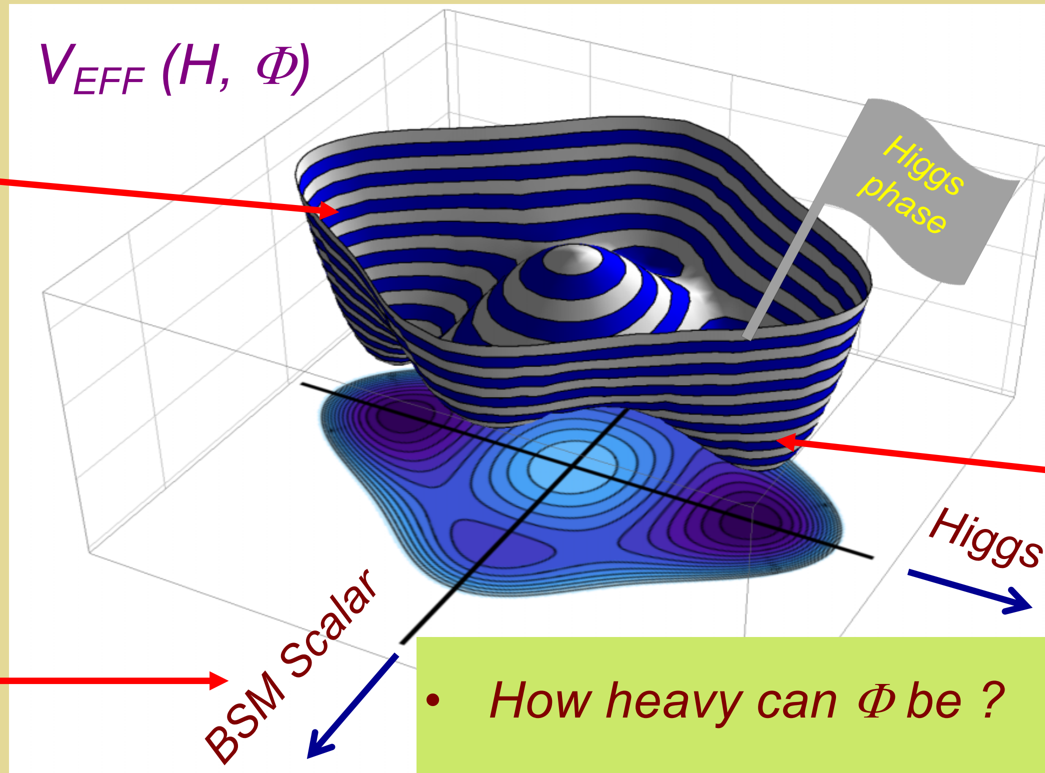
- ***Mass scale***
- ***Precision***

Experimental Probes

Bubble Collisions



Grav Radiation



Higgs precision tests

Direct Production

BSM Higgs

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

Extrema can evolv
rich possibilities fo
→

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T_{EW} Sets a Scale for Colliders

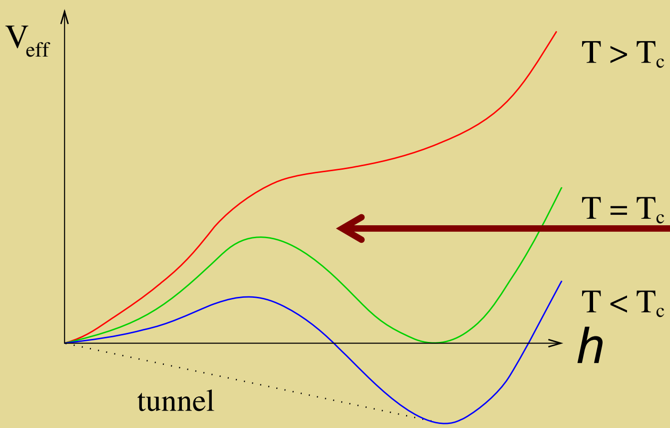
High-T SM Effective Potential

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

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

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

First Order EWPT from BSM Physics



Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

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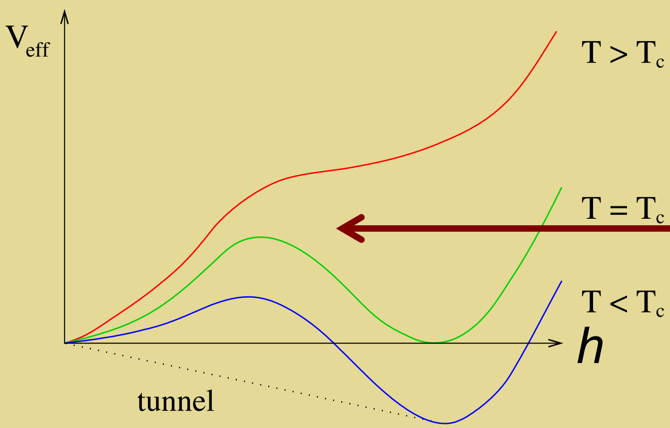
First Order EWPT from BSM Physics



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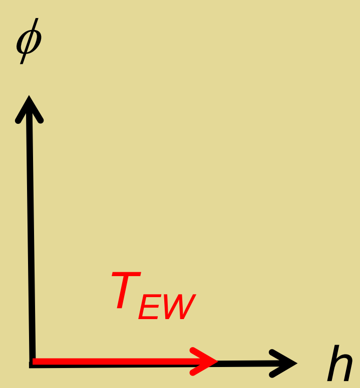
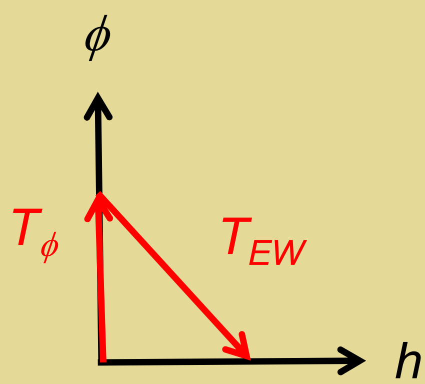


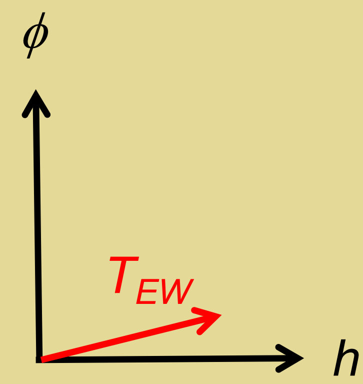
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

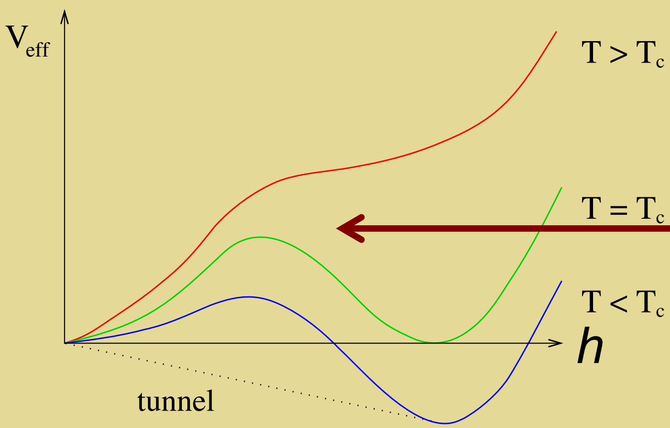
tree-level effect



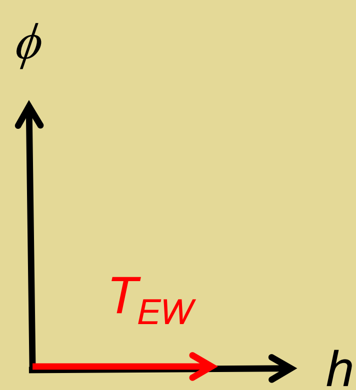
$a_1\, H^2\phi$: $T = 0$

tree-level effect

First Order EWPT from BSM Physics



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



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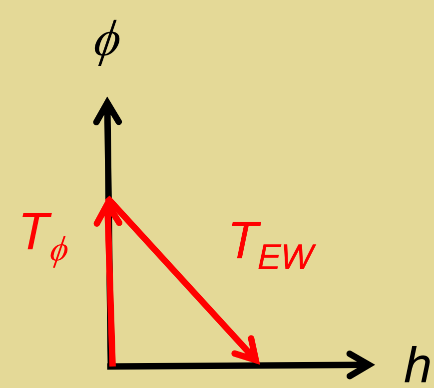

$a_2 H^2\phi^2$: $T = 0$

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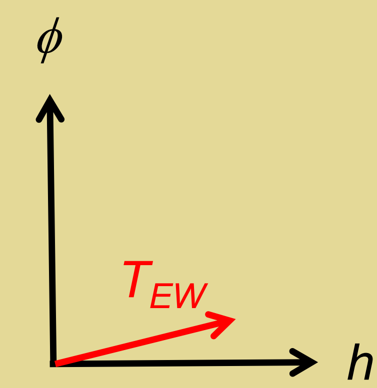

$a_1 H^2\phi$: $T = 0$

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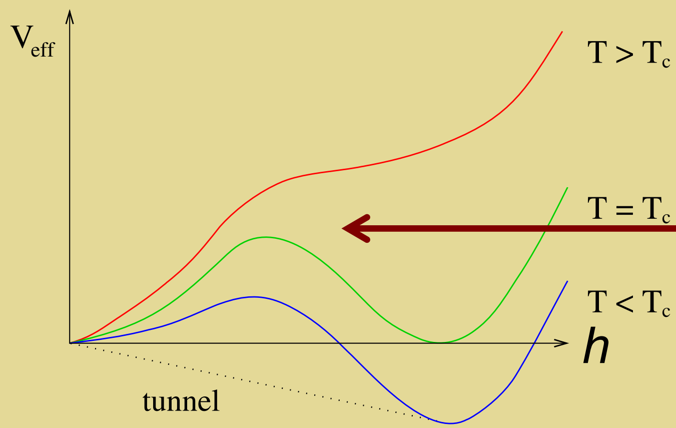
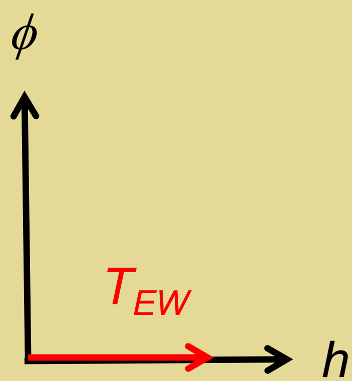
First Order EWPT from BSM Physics



Higgs – ϕ^0 Mixing



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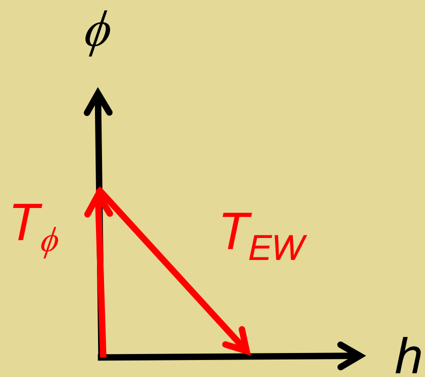
loop effect



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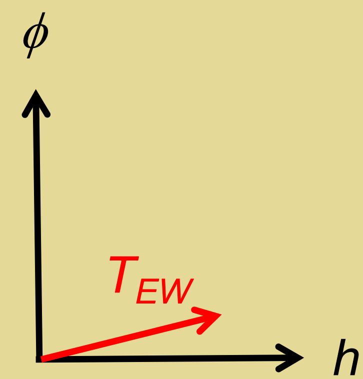

$a_1\, H^2 \phi$: $T = 0$

tree-level effect

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Strong First Order EWPT

- ***Prevent baryon number washout***

- ***Observable GW***

Collider Target: Precision and single ϕ production

$$\frac{|a_1|}{2\lambda T_{\rm EW}} \gtrsim 1$$

→

$| \sin\theta | \gtrsim 0.01$

$| \Delta\lambda / \lambda | \gtrsim 0.003$

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...

Models & pheno: how reliable ?

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...

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

Theory Meets Phenomenology

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

A. **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

III. Collider Phenomenology

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM
Real singlet: ~~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

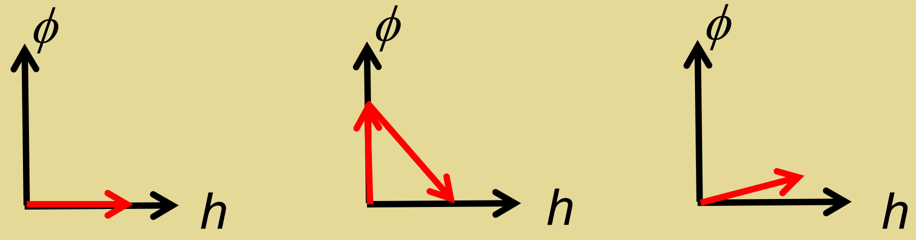
May be low-energy remnants of UV complete theory & illustrative of generic features

Theory-Pheno Interface

Simple Higgs portal models:

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

$$V \subset a_1 H^2\phi + a_2 H^2\phi^2$$



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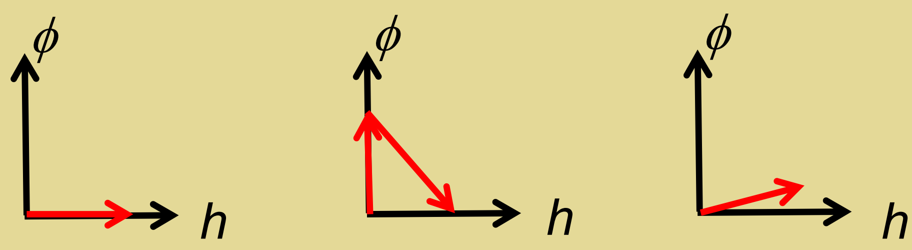


Phenomenology

$$h_1 = \sin\theta\ s + \cos\theta\ h$$
$$h_2 = \cos\theta\ s - \sin\theta\ h$$

$m_{1,2}$; θ ; $h_i\, h_j\, h_k$ couplings

Collider Probes

- *Resonant di-Higgs (h_1 h_1) production* *
- *Heavy h_2 production* *
- *Associated production (Z h_1) and non-resonant di-Higgs production* *
- *Exotic Higgs decays* **

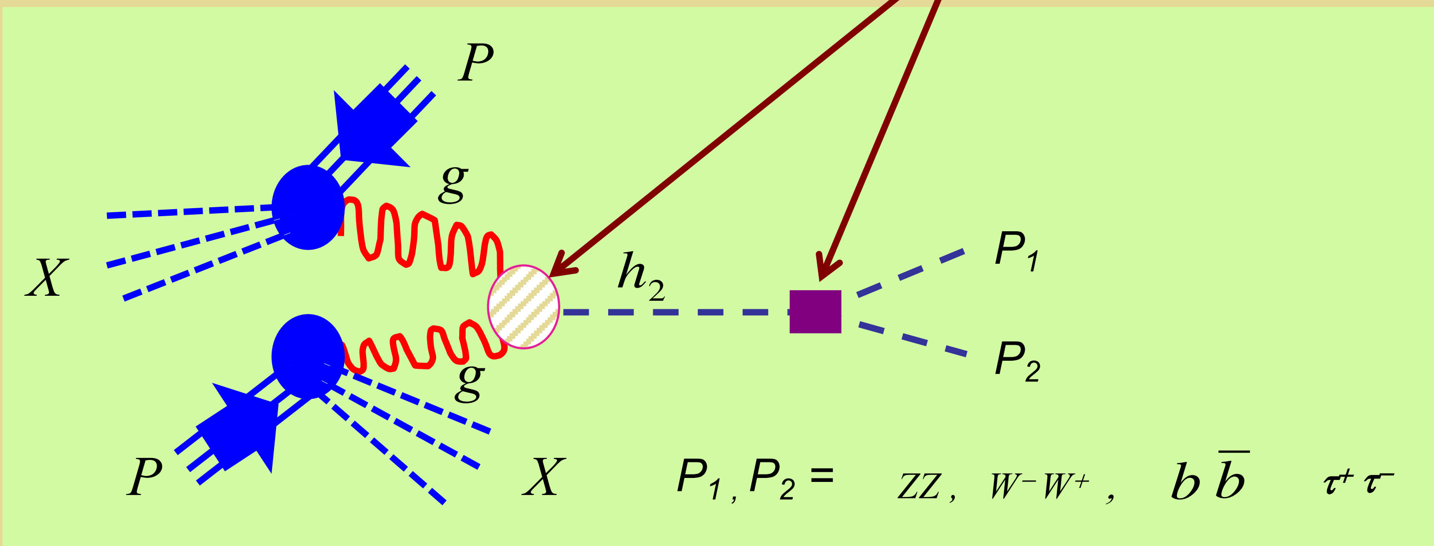
* *Heavy h_2*

** *Light h_2*

Experimental Probes: Energy Frontier

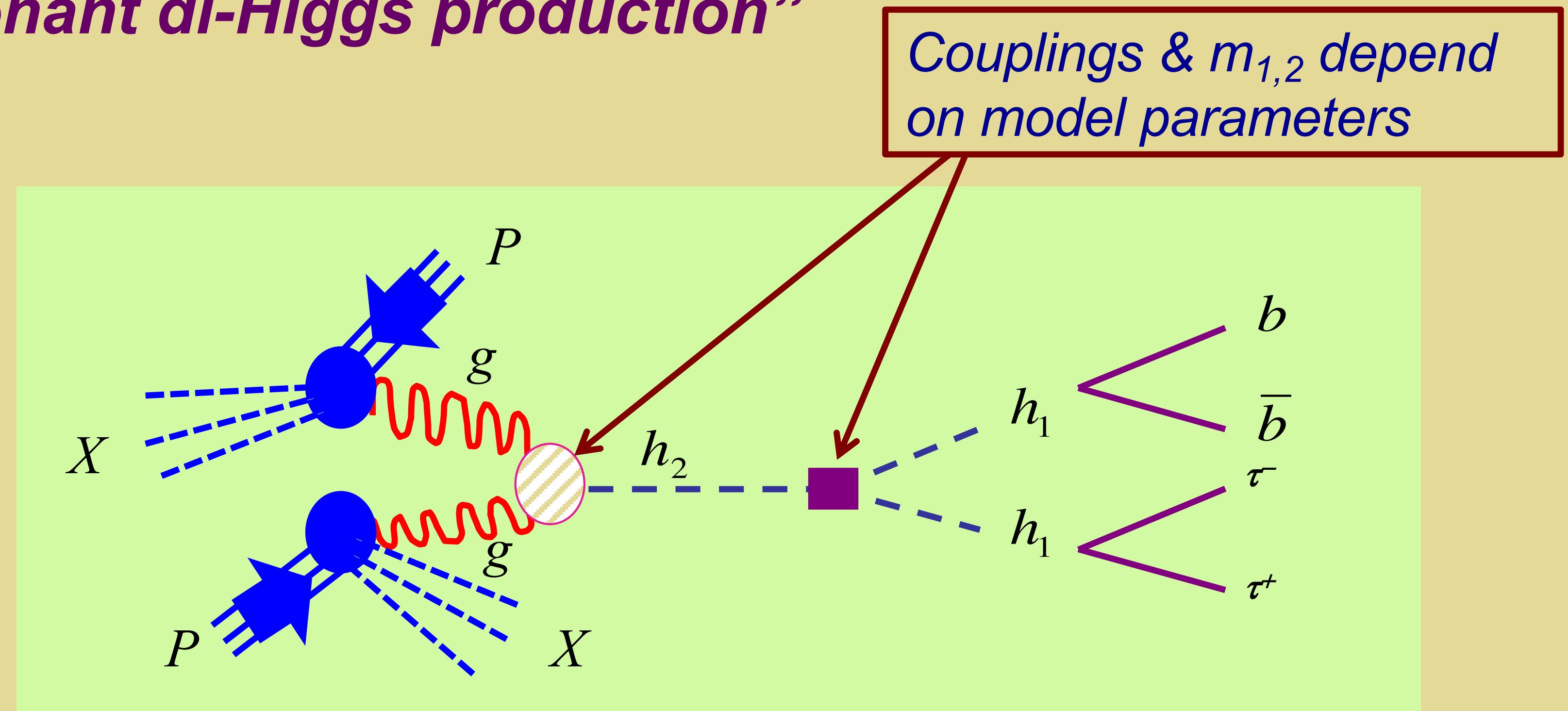
"Heavy Higgs Production"

Couplings & $m_{1,2}$ depend on model parameters



Experimental Probes: Energy Frontier

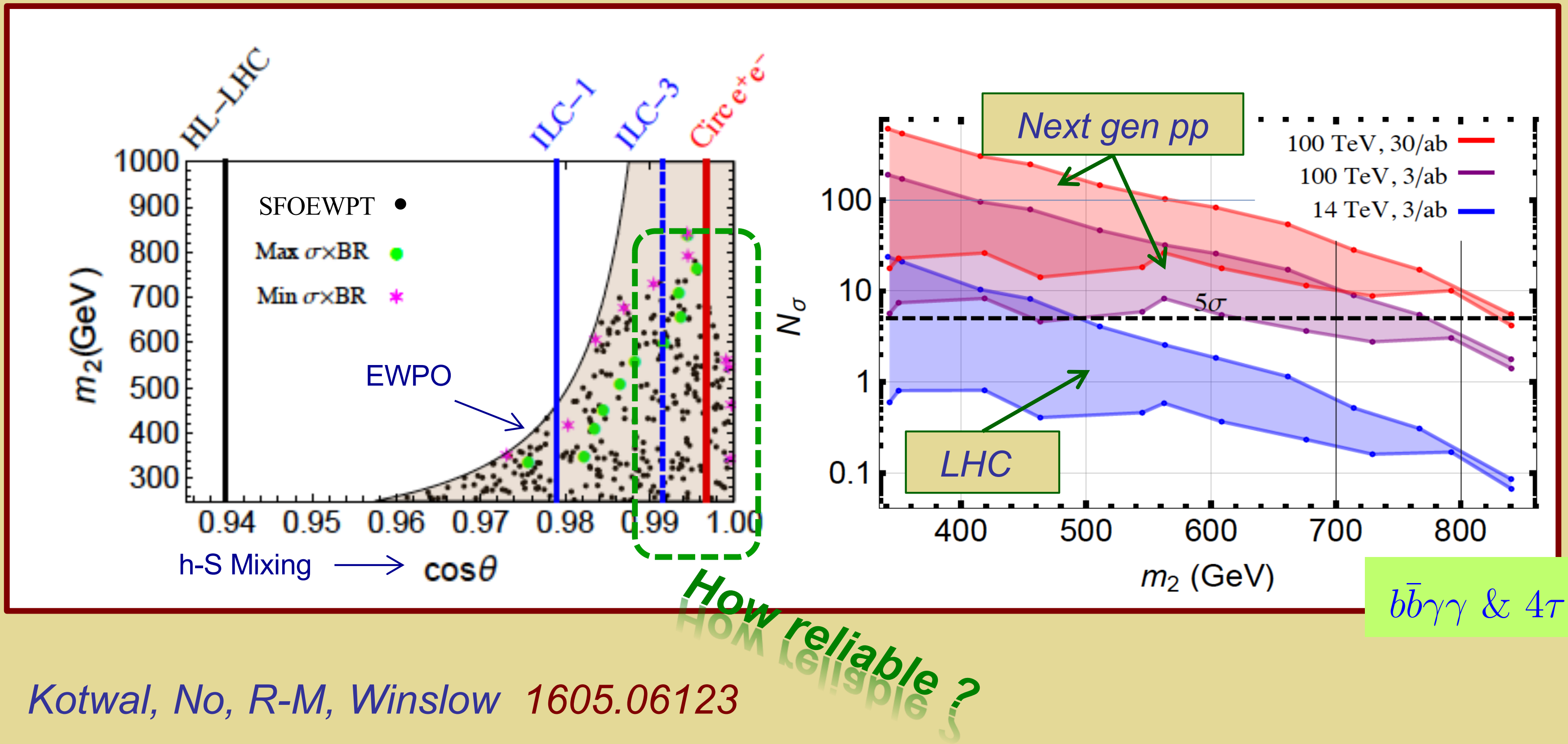
"Resonant di-Higgs production"



+…   Other final states: bb $\gamma\gamma$, bb WW, …

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

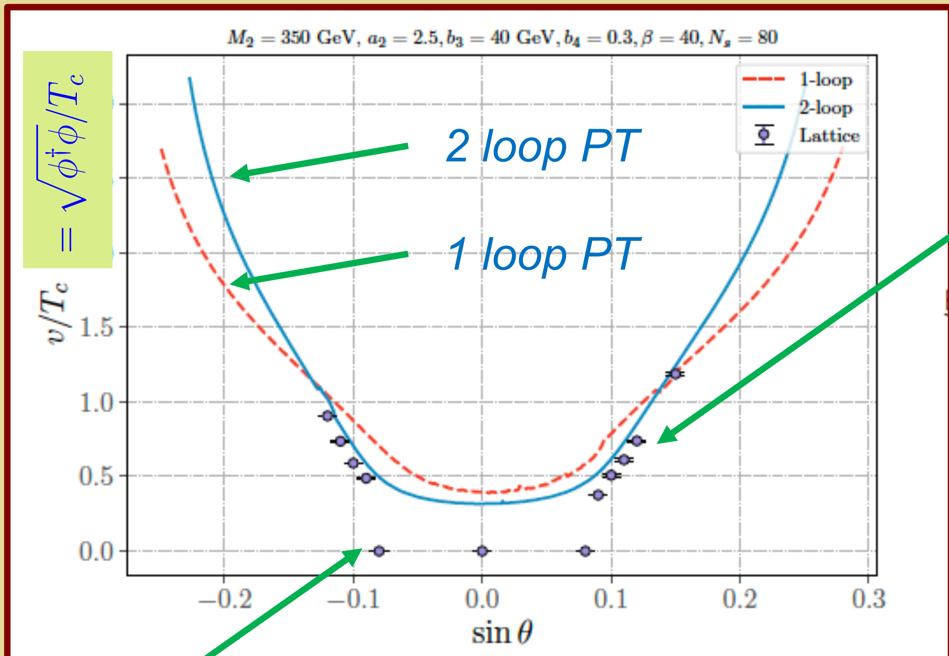


Kotwal, No, R-M, Winslow 1605.06123

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

Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory

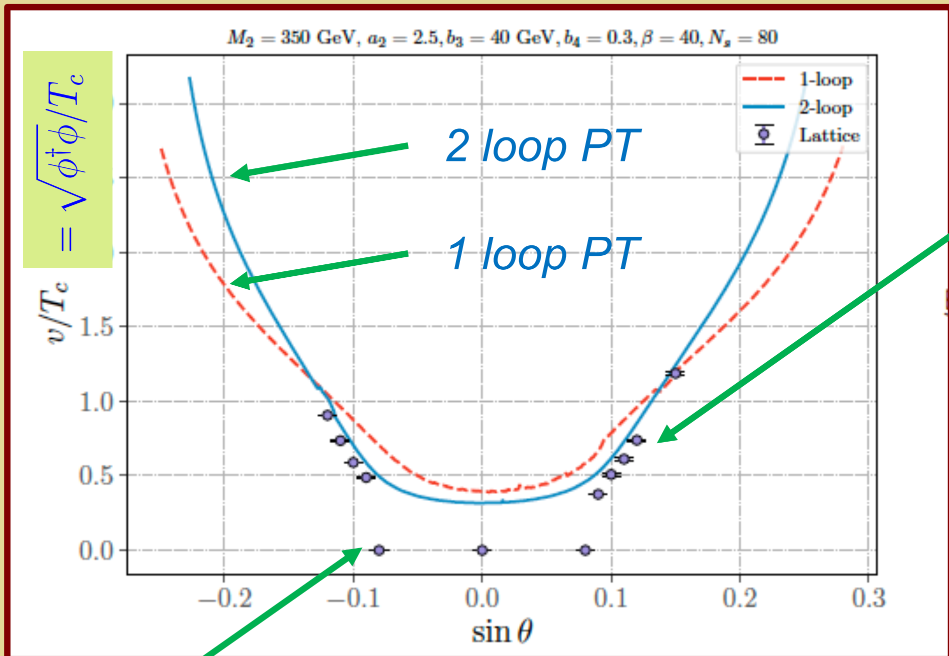


Lattice:
FOEWPT

Lattice:
Crossover

Lauri Niemi, MJRM, Gutao Xia, 2405.01191

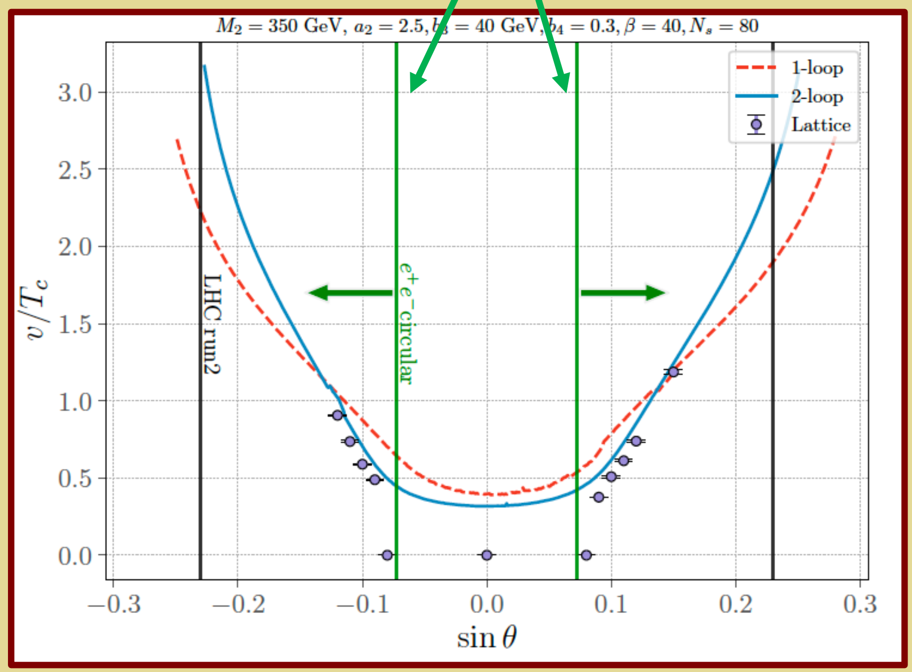
Singlets: Lattice vs. Pert Theory



Lattice:
FOEWPT

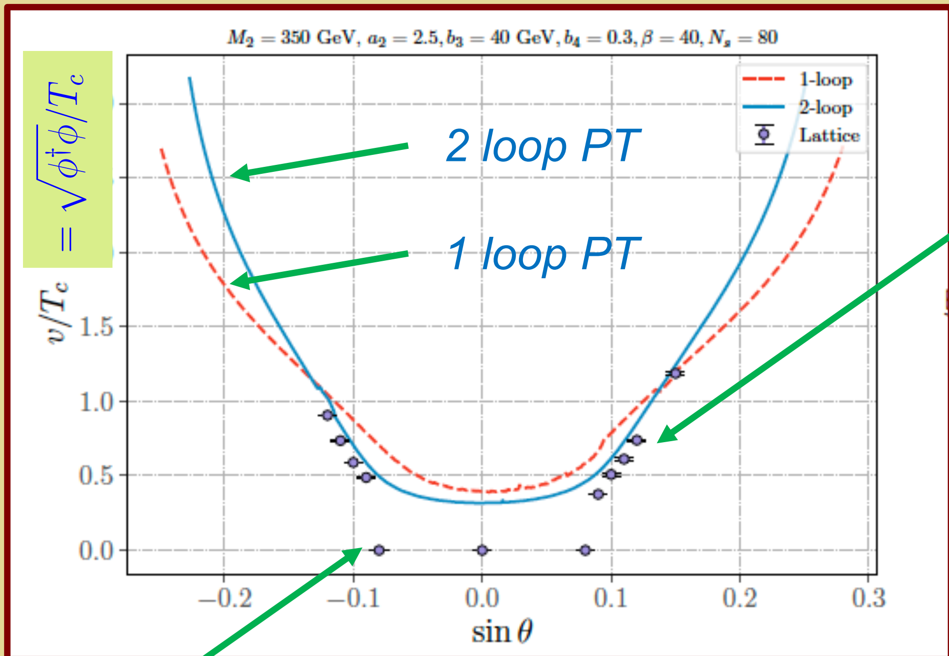
Future e⁺e⁻

Lattice:
Crossover



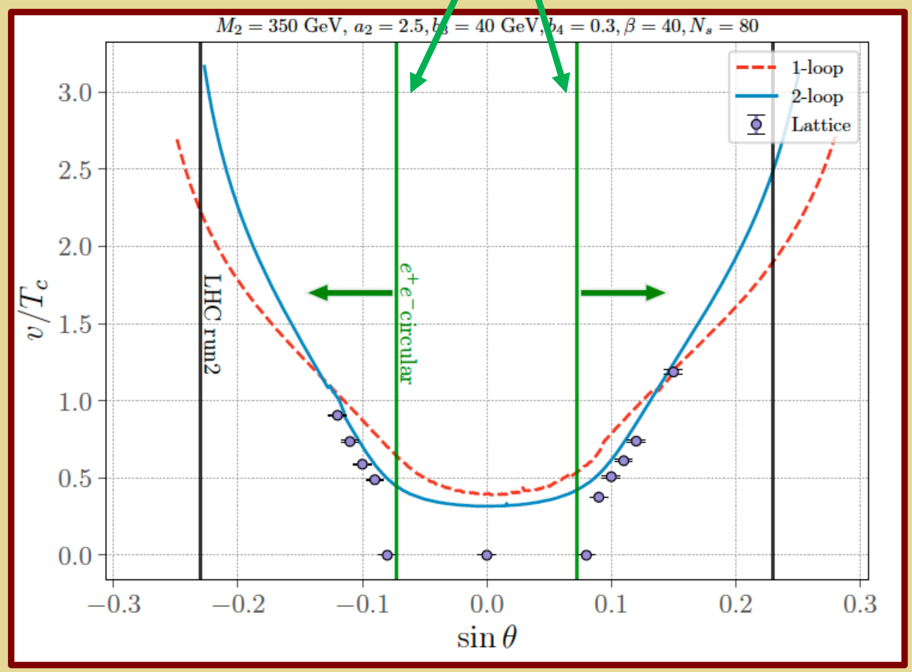
Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



Lattice: FOEWPT

Future e^+e^-



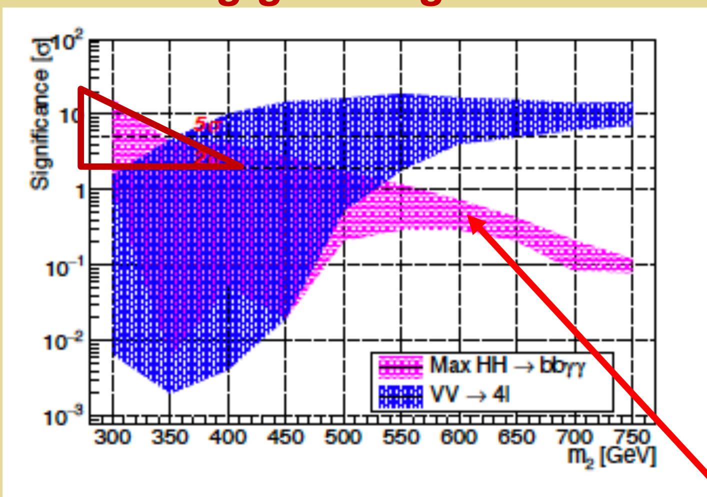
Lattice: Crossover

- *Lattice: crossover-FOEWPT boundary*
- *FOEWPT region: PT-lattice agreement*
- *Pheno: precision Higgs studies may be sensitive to a greater portion of FOEWPT-viable param space than earlier realized*

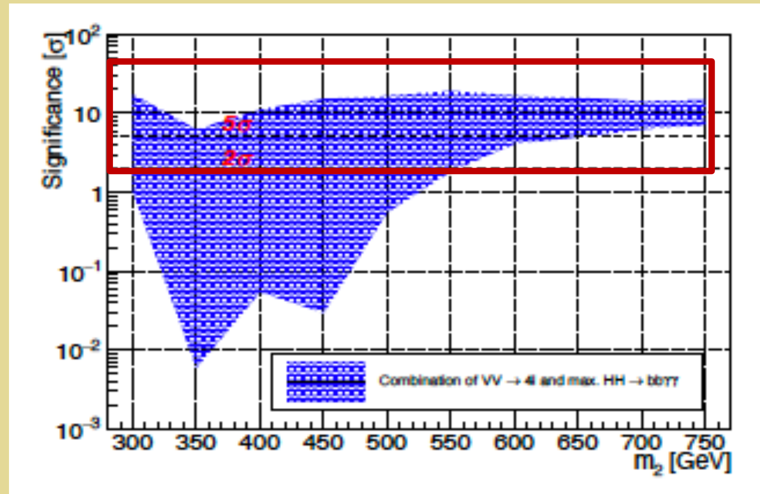
Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

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

"Smoking gun" region

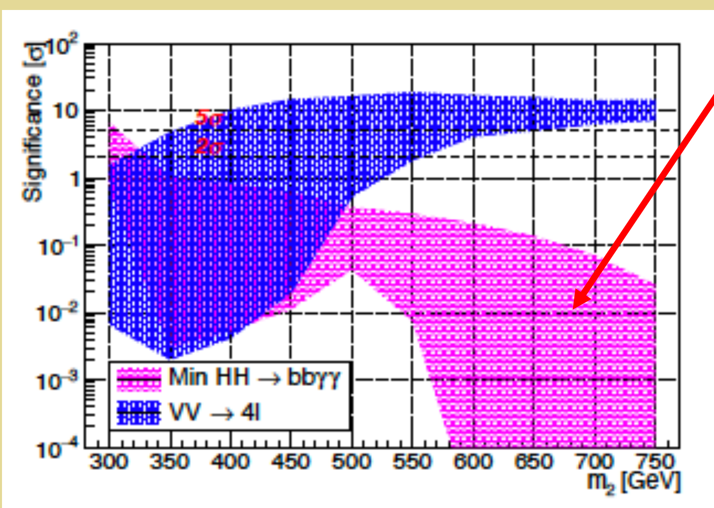


Parameter exclusion region



100 TeV accessible

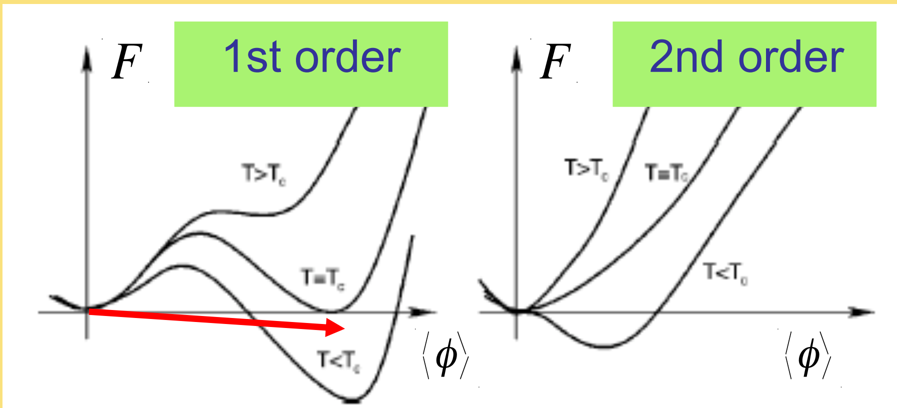
SFOEWPT Min Benchmarks:



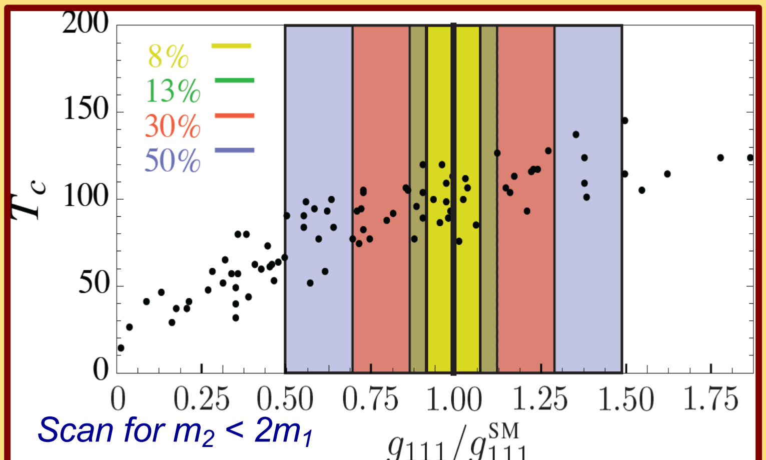
- *Observation of 4l channel would indicate existence of heavy resonance consistent with xSM SFOEWPT*
- *"Smoking gun" region would provide nearly definitive evidence & narrow down model parameter space*
- *Exclusion would leave ample room for 100 TeV pp discovery*

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

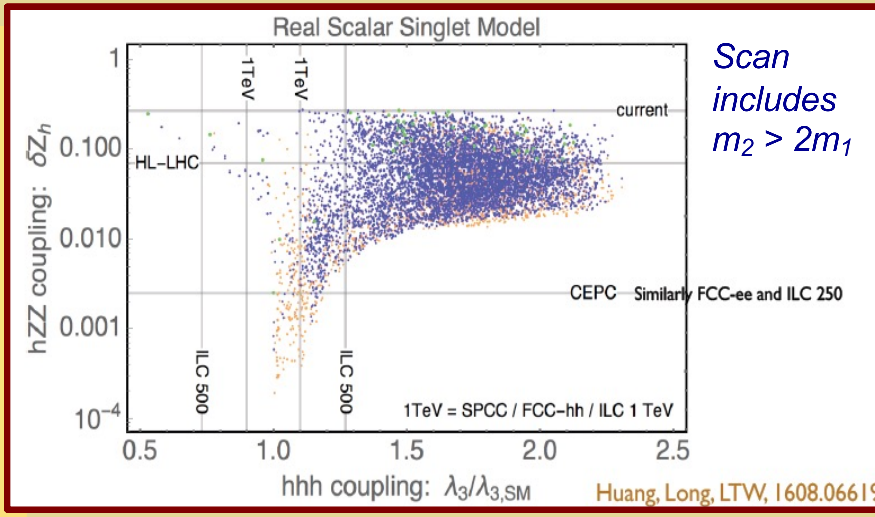
EWPT: Higgs Self-Coupling



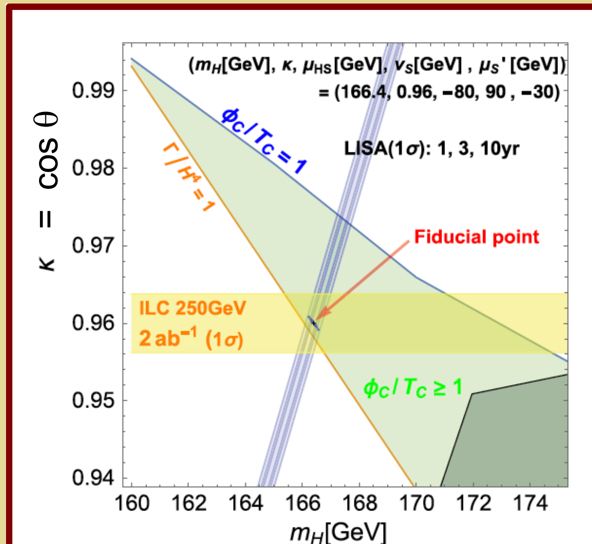
Modified Higgs Self-Coupling



Scan for $m_2 < 2m_1$



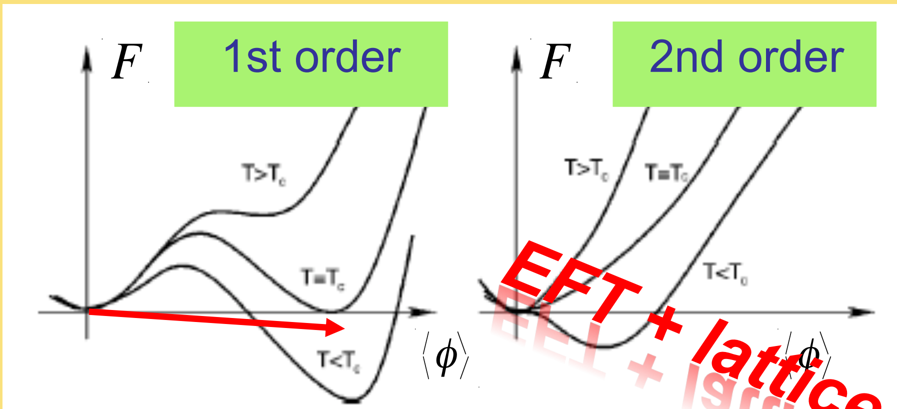
Scan includes $m_2 > 2m_1$

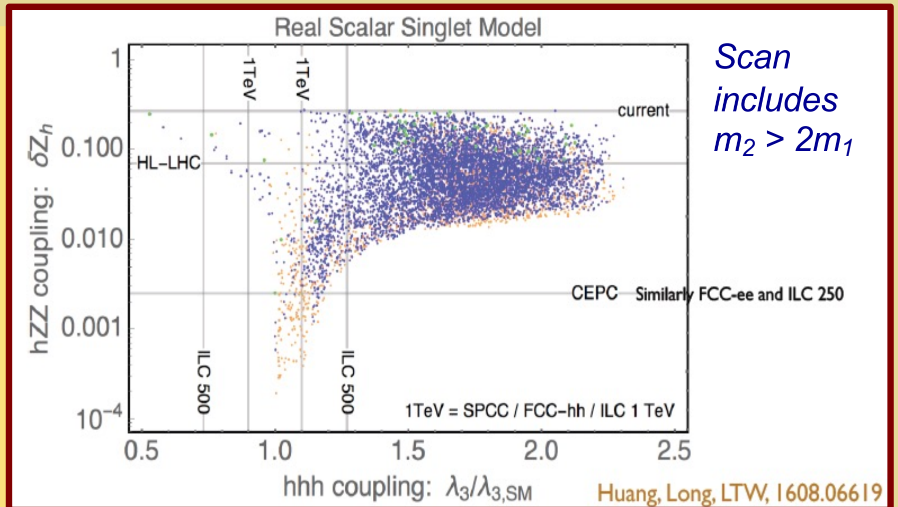


Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

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

EW Phase Transition: Singlet Scalars

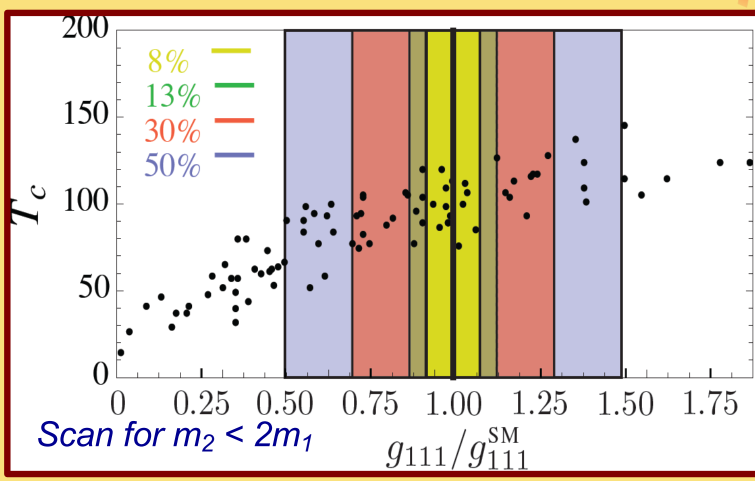




Scan includes $m_2 > 2m_1$

EFT + lattice updates needed !

Modified Higgs Self-Coupling



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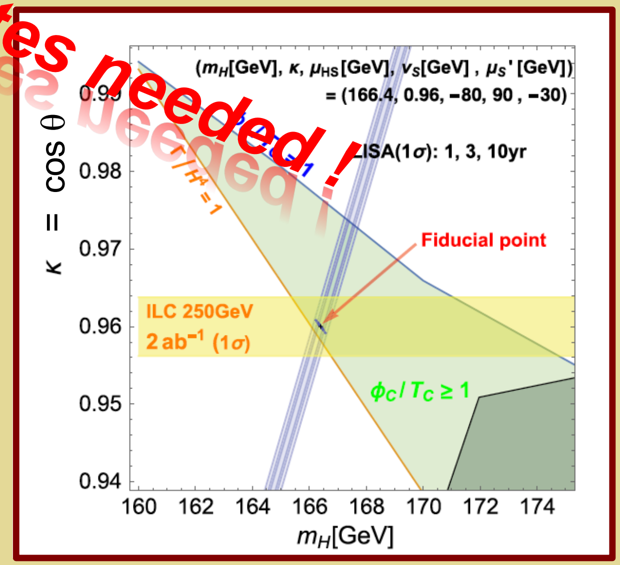
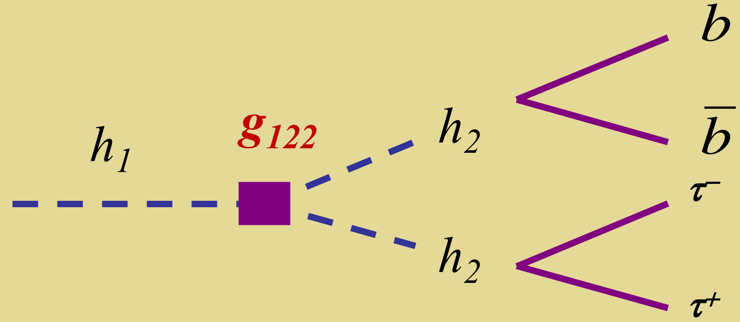


Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

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

Collider Probes

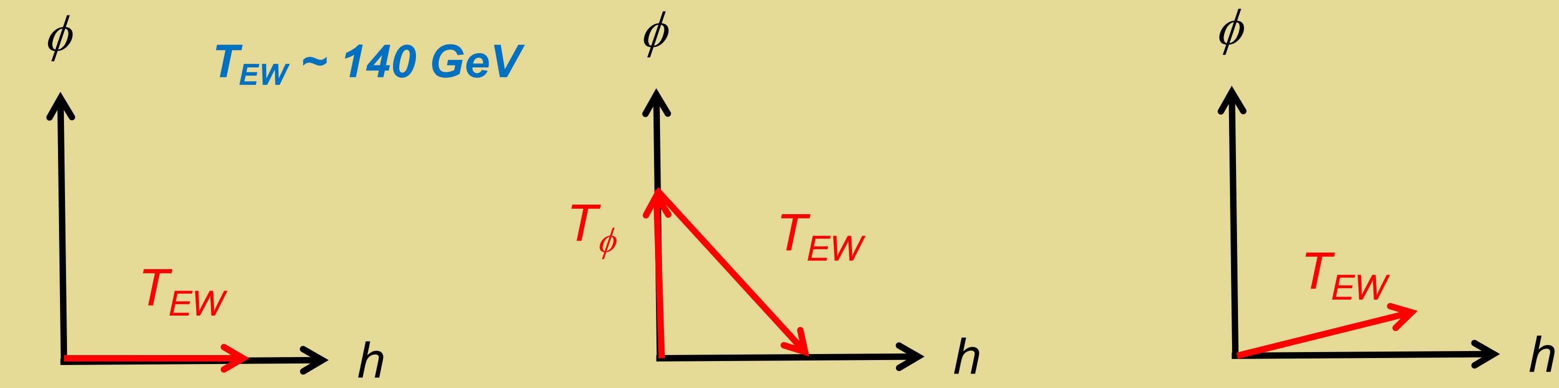
- *Resonant di-Higgs (h_1 h_1) production* *
- *Heavy h_2 production* *
- *Associated production (Z h_1) and non-resonant di-Higgs production* *
- *Exotic Higgs decays* **



* *Heavy h_2*

** *Light h_2*

Exotic Higgs Decays & EWPT



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

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

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

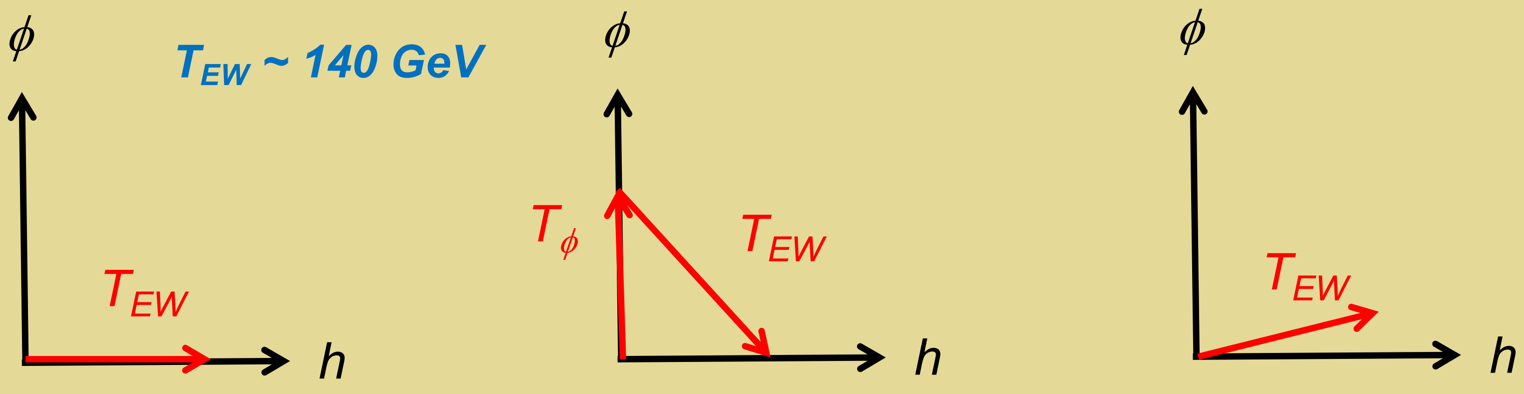
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

Exotic decays

$h_1 \rightarrow h_2 h_2$

$$\Gamma(h_2, m_2) = \sin^2\theta\, \Gamma(h_{\rm SM}, m_2)$$

Exotic Higgs Decays & EWPT



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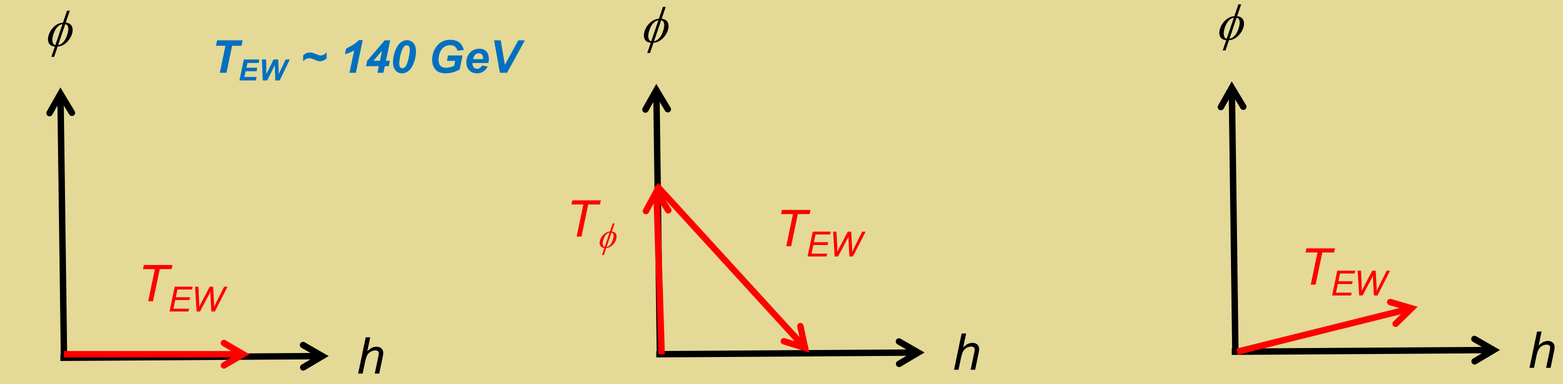

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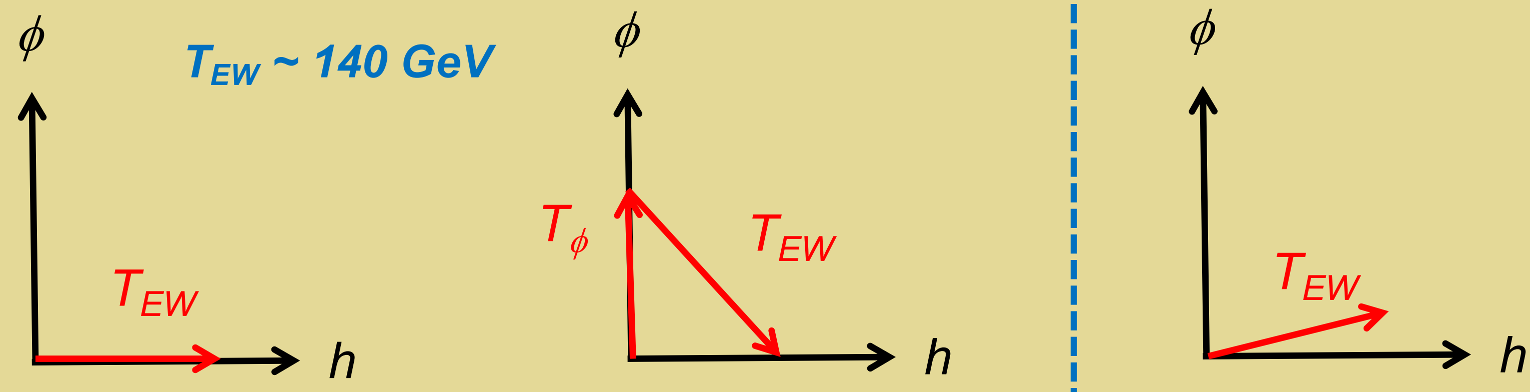

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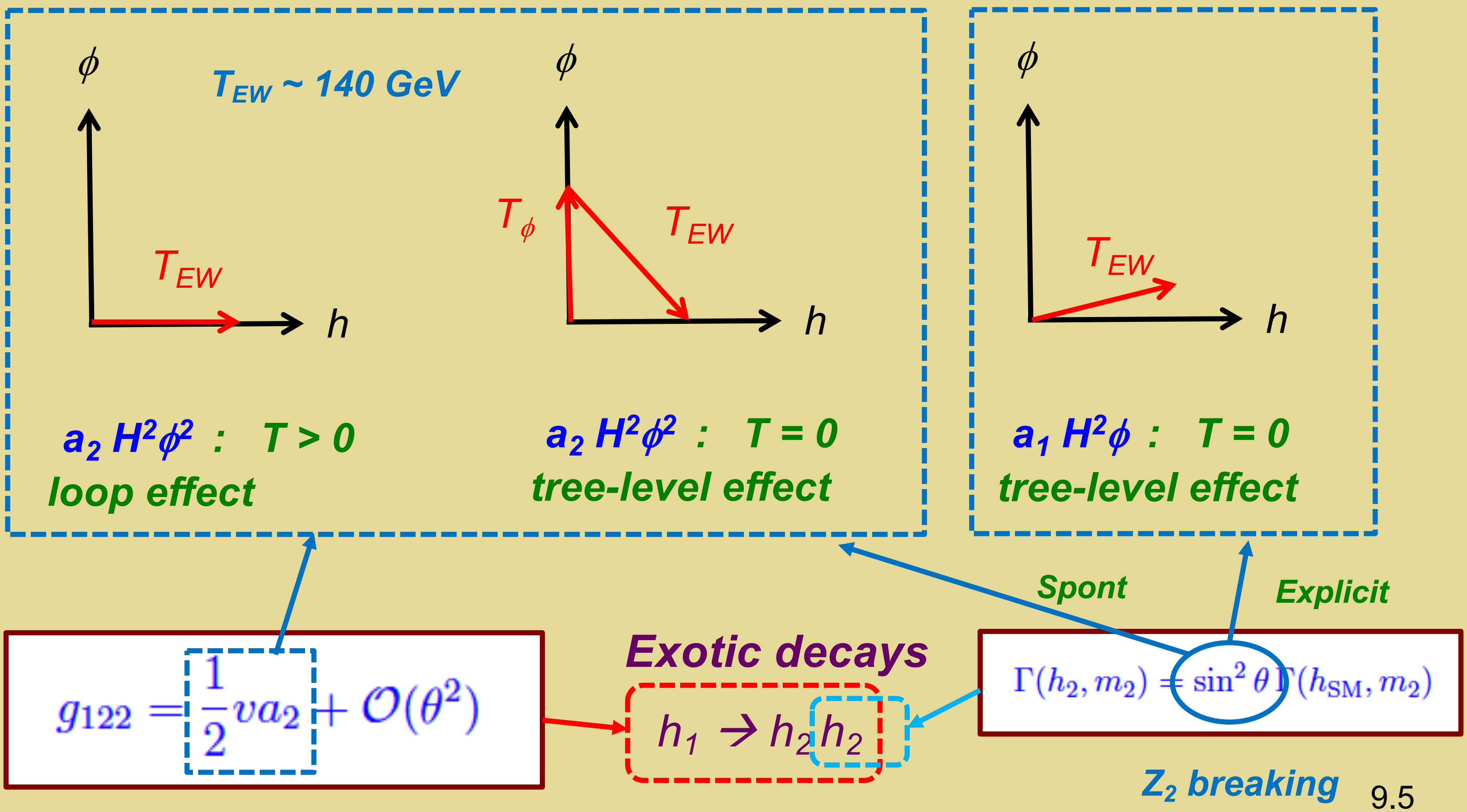


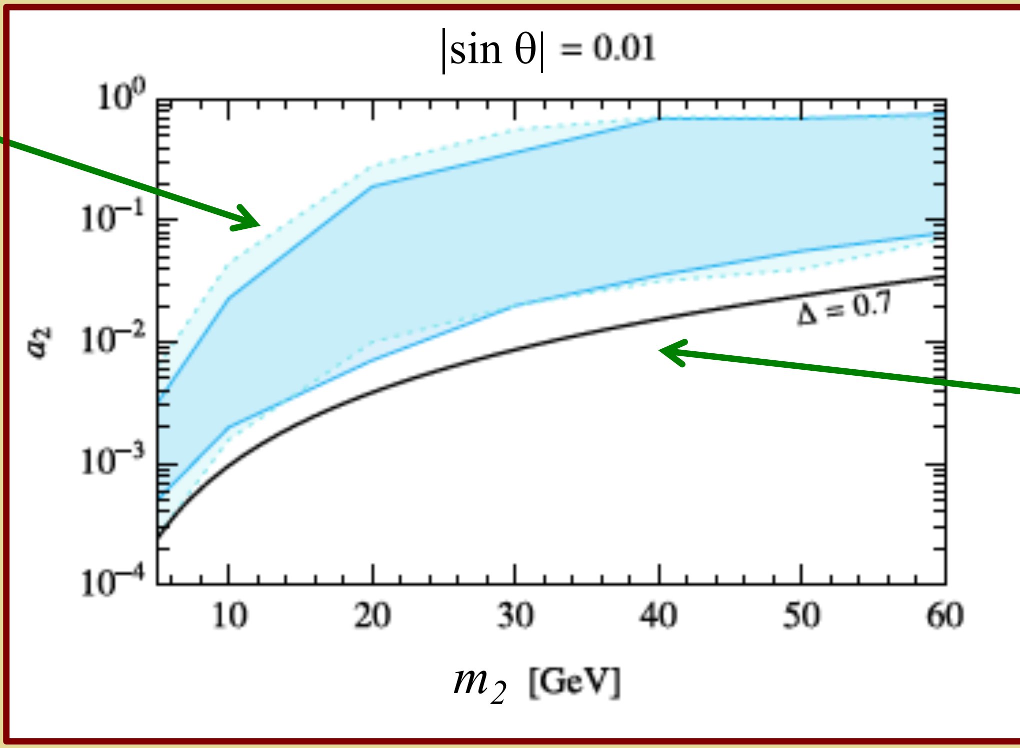
Theoretical Developments

- ***Perturbative study***
- ***Lattice benchmark (new)***

Light Singlets: Exotic Higgs Decays

One loop perturbation theory

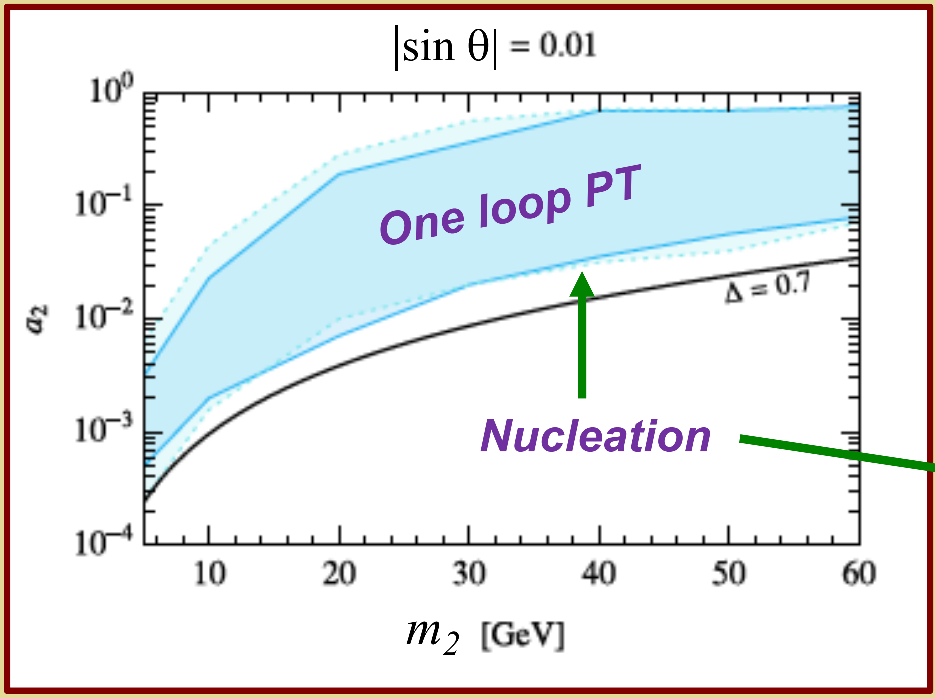
EWPT viable: numerical

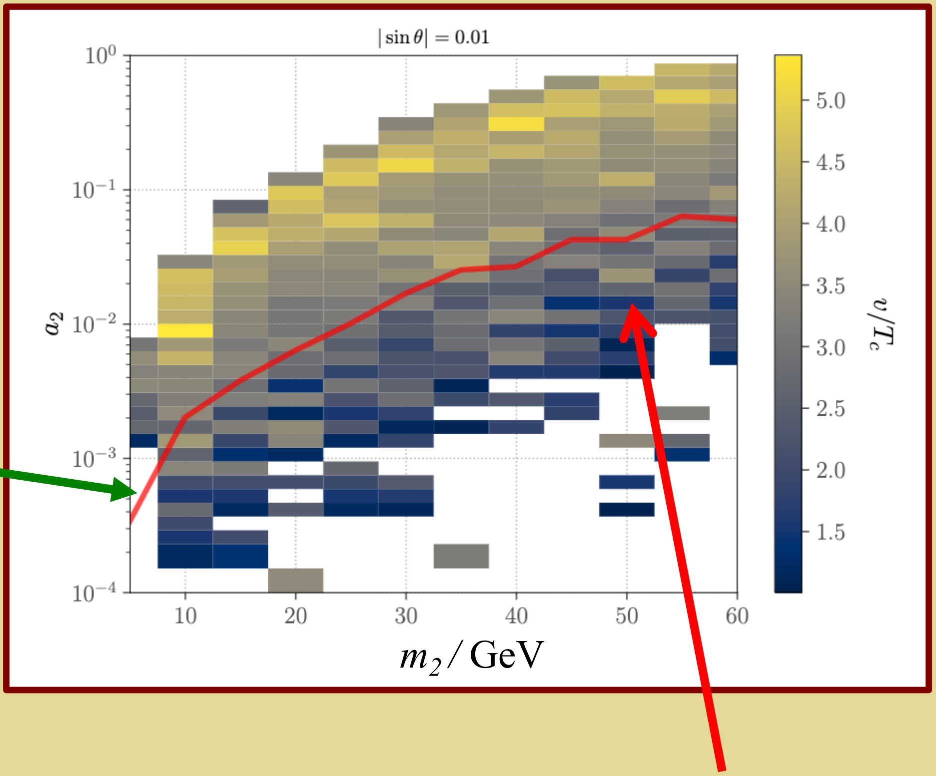


EWPT viable: Semi analytic
→ nucleation decisive

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,

New: Lattice + EFT @ T > 0





J. Kozaczuk, MR-M, J. Shelton 1911.10210

L. Niemi, MJRM, G. Xia 2405.01191

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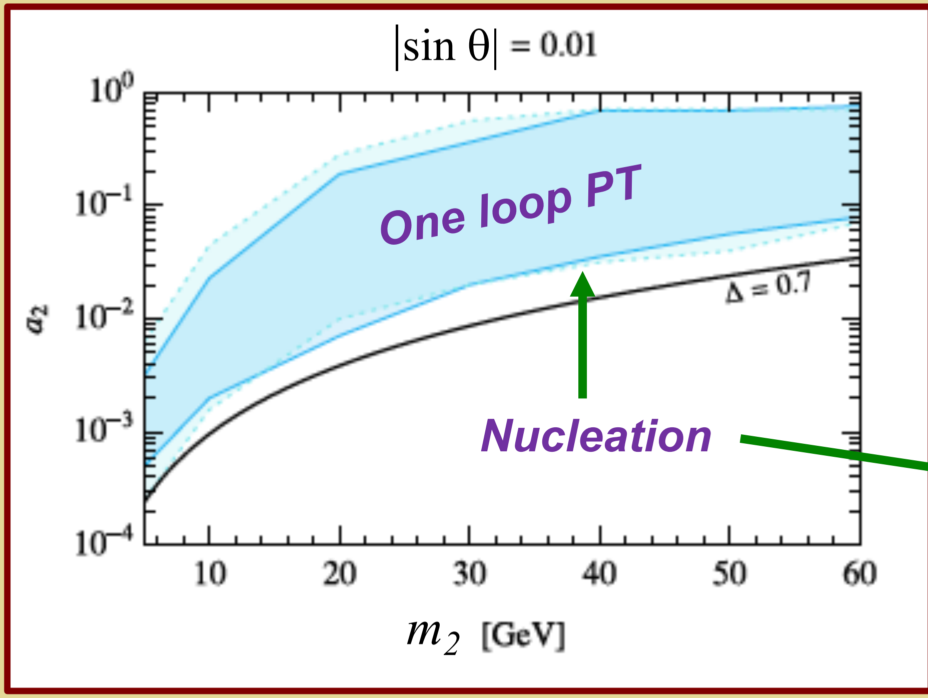
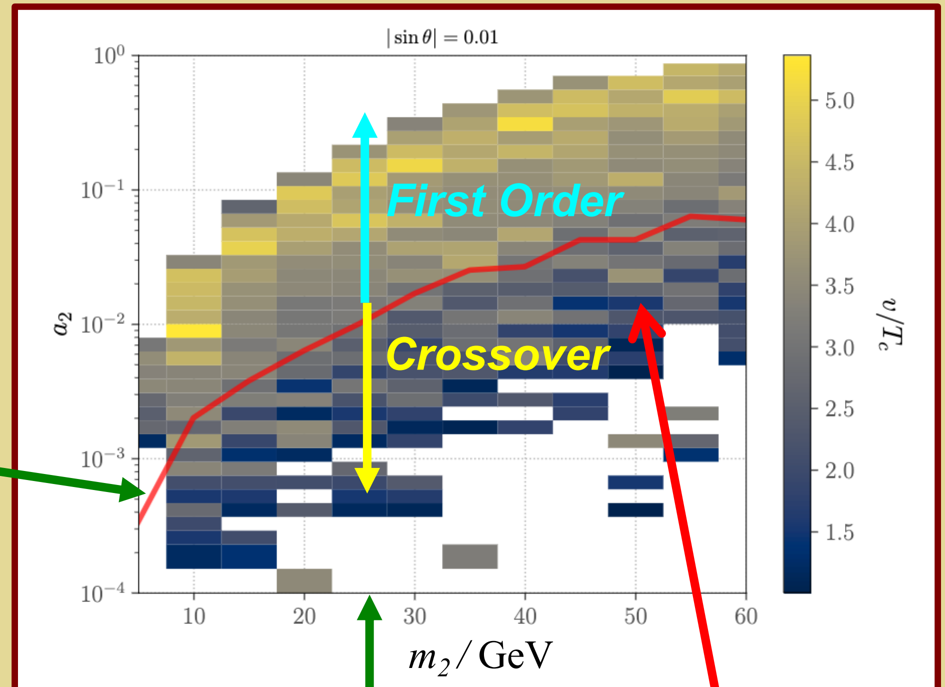




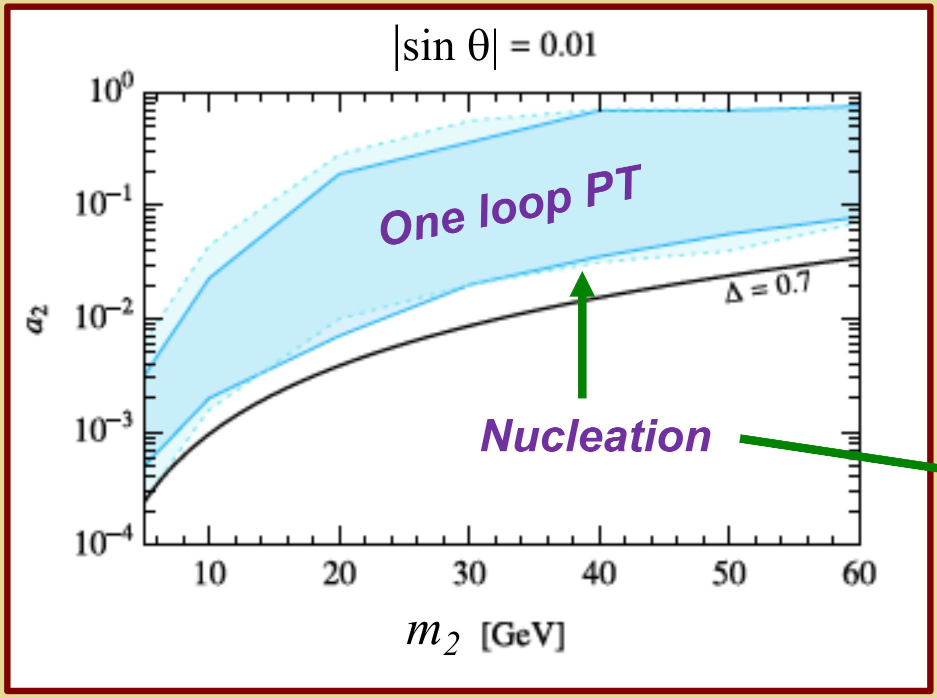
J. Kozaczuk, MR-M, J. Shelton 1911.10210

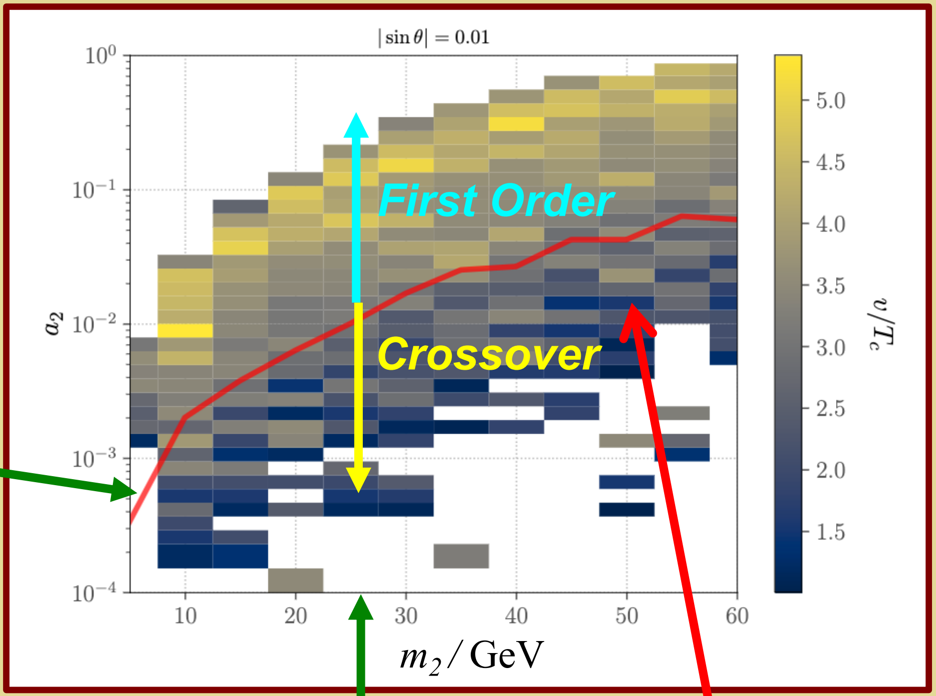
Lattice study

Two-loop PT:
3d EFT

L. Niemi, MJRM, G. Xia 2405.01191

New: Lattice + EFT @ T > 0





J. Kozaczuk, MR-M, J. Shelton 1911.10210

Lattice study

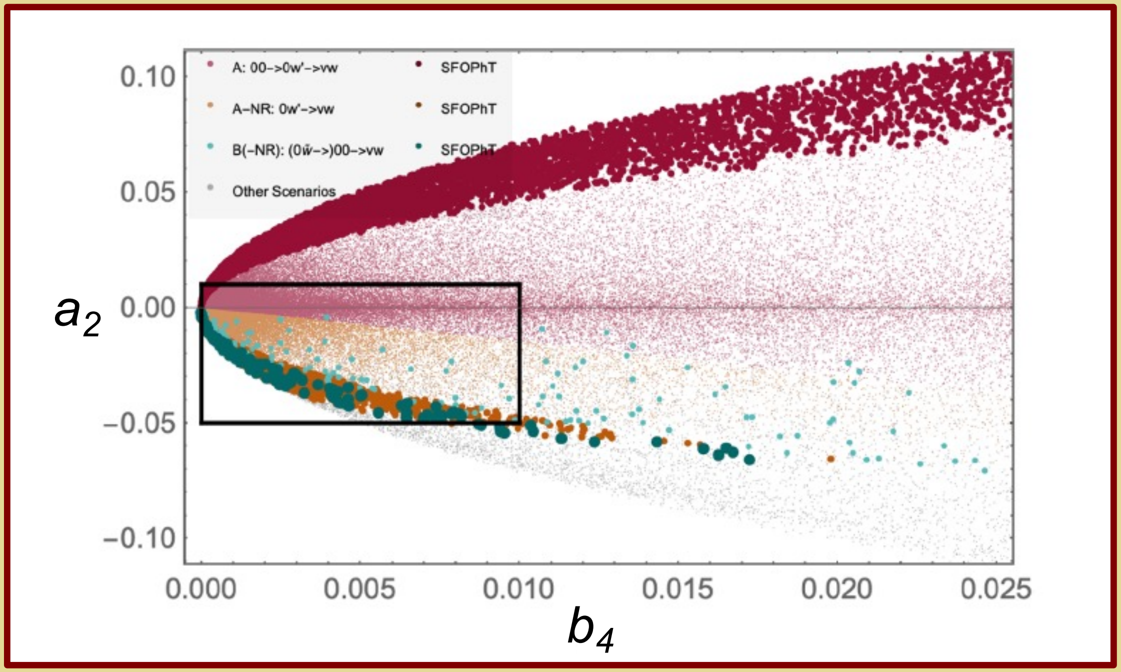
Two-loop PT: 3d EFT

Small portal couplings → FO EWPT unlikely

L. Niemi, MJRM, G. Xia 2405.01191

Light Singlets: Exotic Higgs Decays

Z_2 breaking ***One loop perturbation theory***



Carena et al 1911.10206

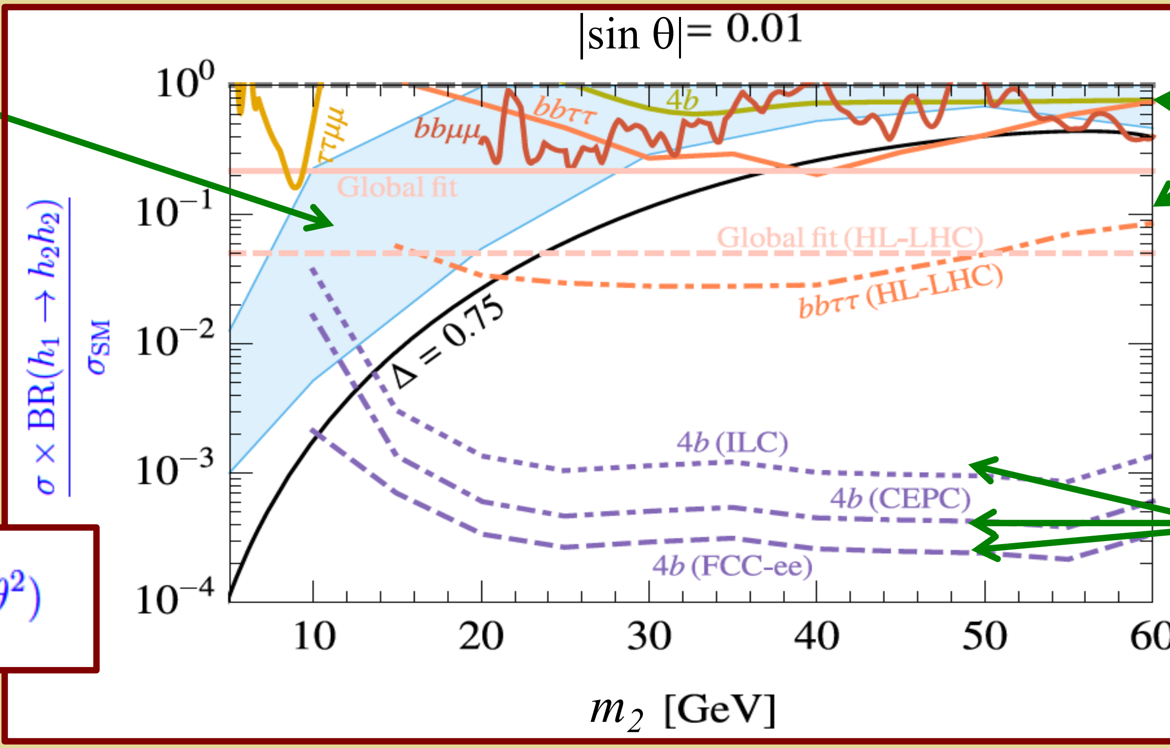
Exotic Higgs Decay Phenomenology

- *Prompt h_2 decays*
- *Displaced h_2 decays*
- *Invisible h_1 decays*

Light Singlets: Exotic Higgs Decays

Prompt decays: $h_2 \rightarrow h_1 h_1 \rightarrow AA\ BB$

EWPT viable: numerical



LHC: 2019 & HL

Future e^+e^-

$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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

Prompt decays: $h_2 \rightarrow h_1 h_1 \rightarrow AA\ BB$

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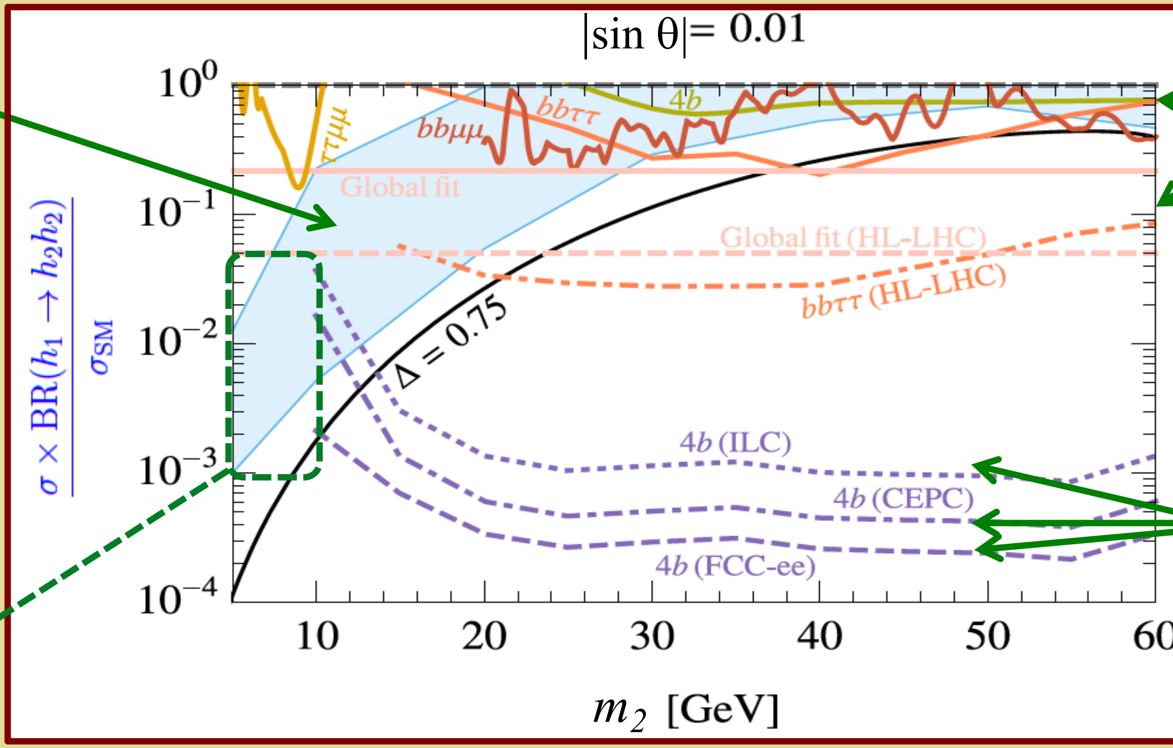


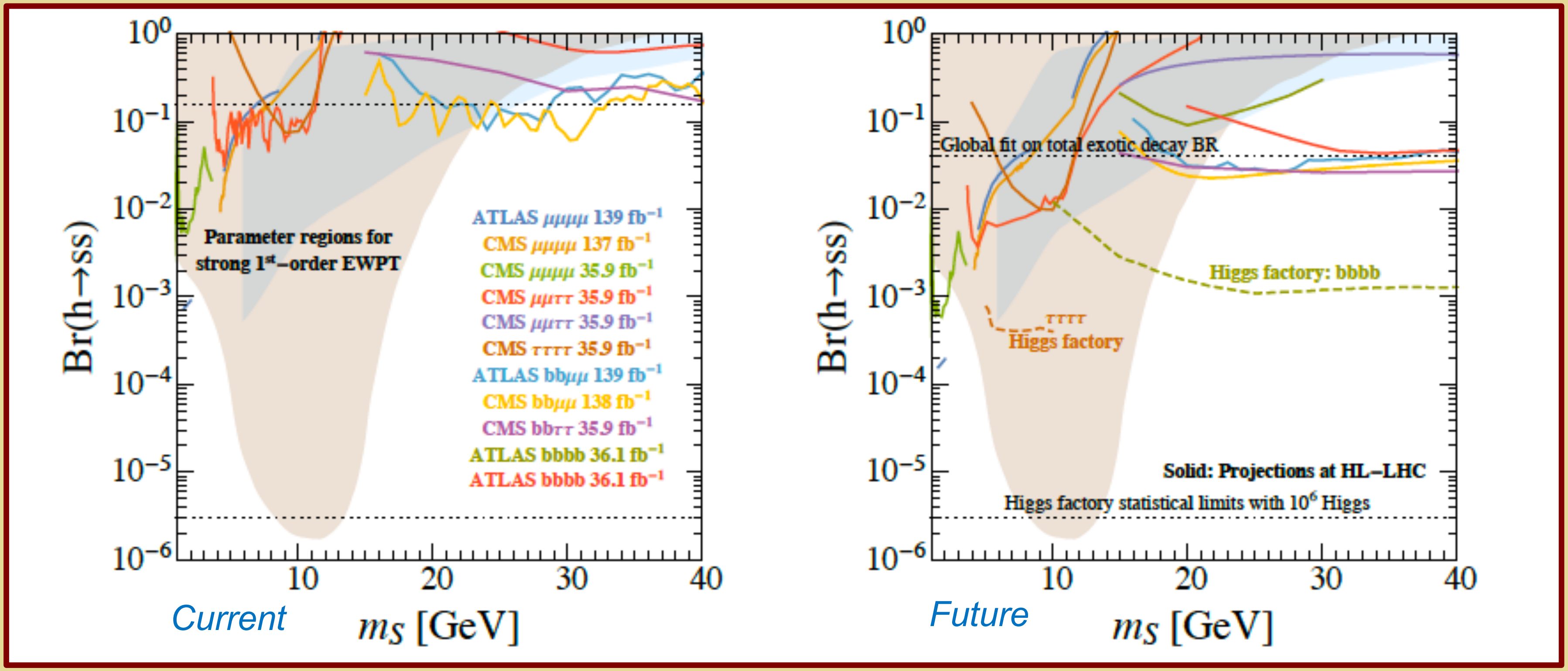
Future e^+e^-

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

Z_2 breaking: prompt h_2 decays

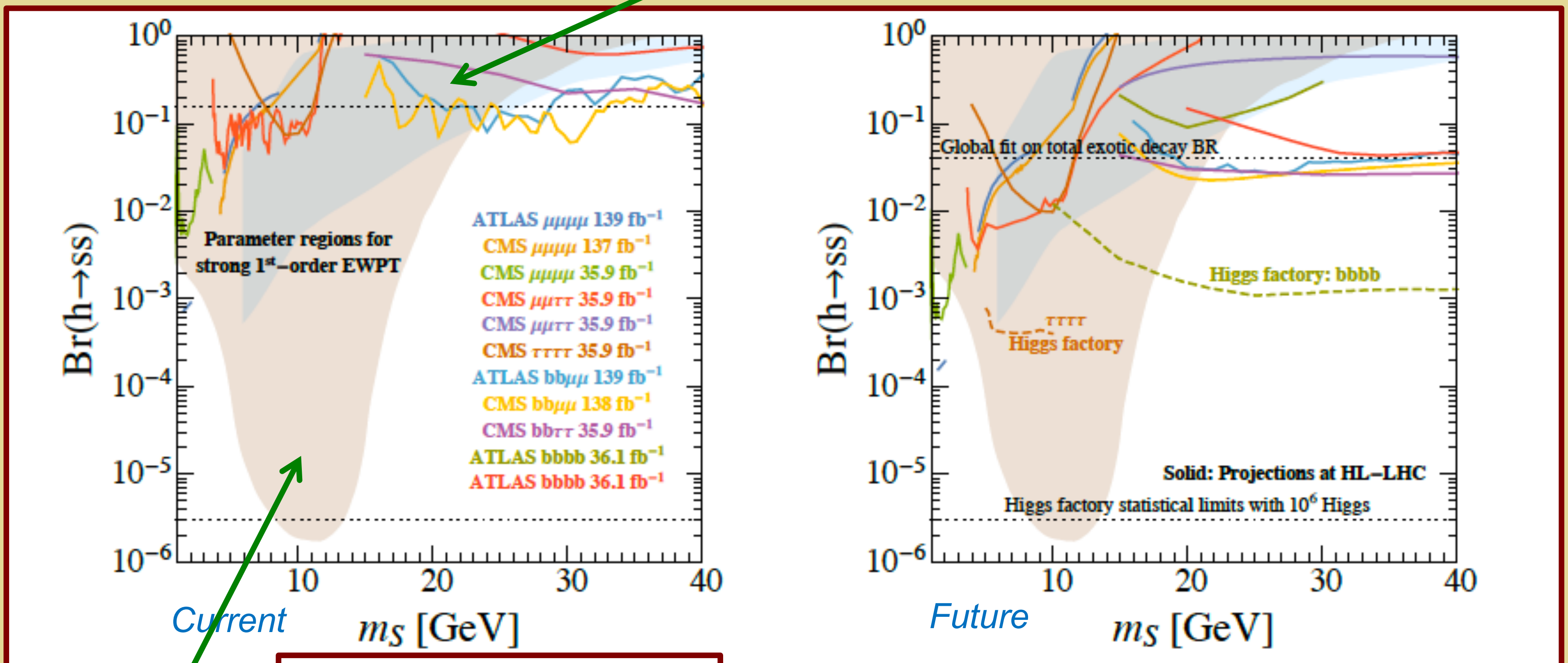


Carena et al (Snowmass) 2203.08206

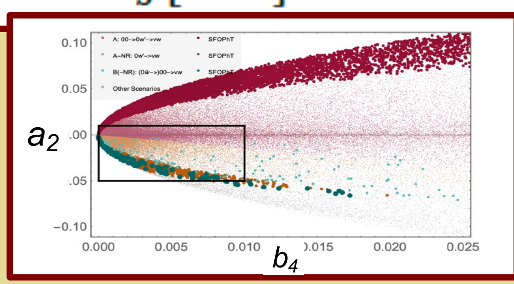
Light Singlets: Exotic Higgs Decays

Z_2 breaking: prompt h_2 decays

Explicit Z_2 breaking



Spont Z_2 breaking



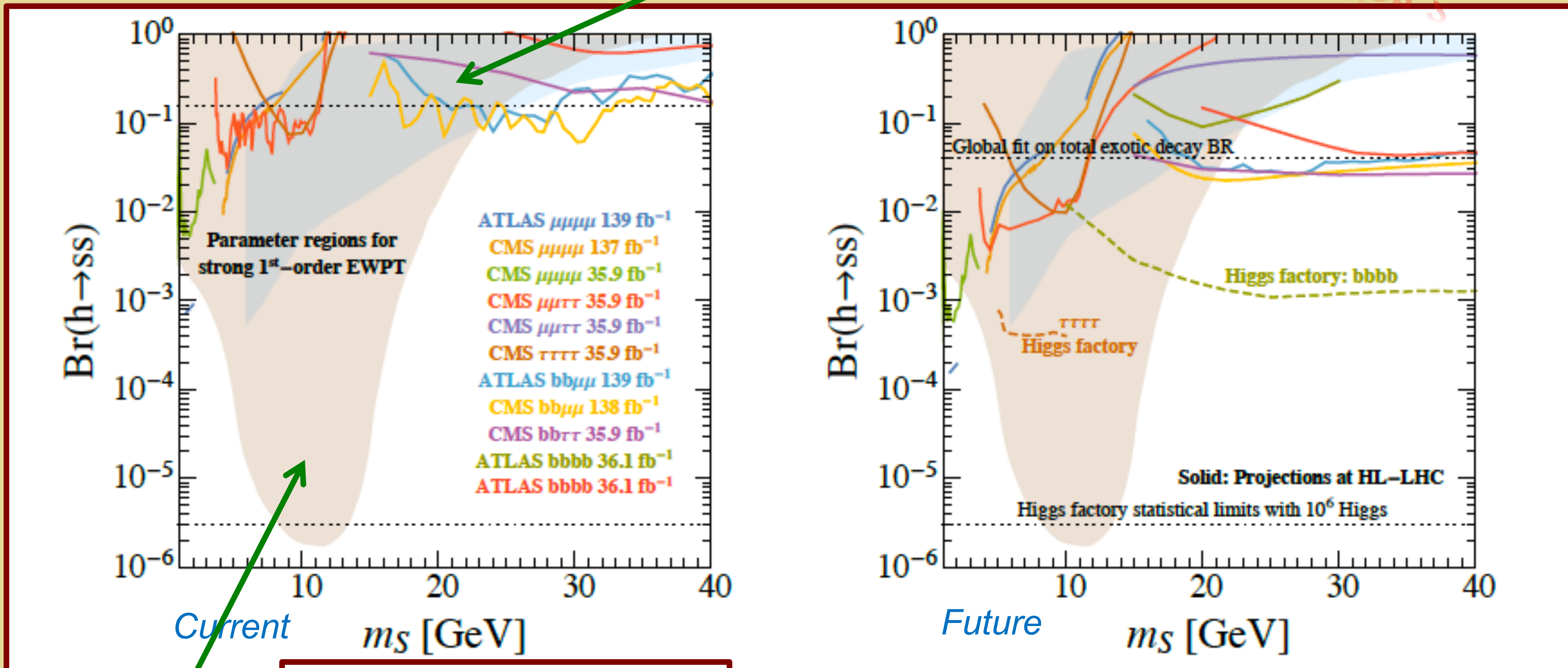
Carena et al (Snowmass) 2203.08206

Light Singlets: Exotic Higgs Decays

Z_2 breaking: prompt h_2 decays

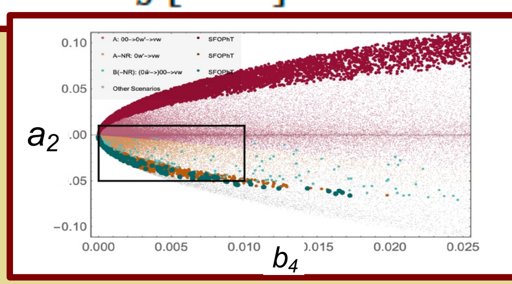
Explicit Z_2 breaking

Consistent w/ EFT + lattice thermo but nucleation ?



Spont Z_2 breaking

Consistent w/ EFT + lattice ? Tiny a_2



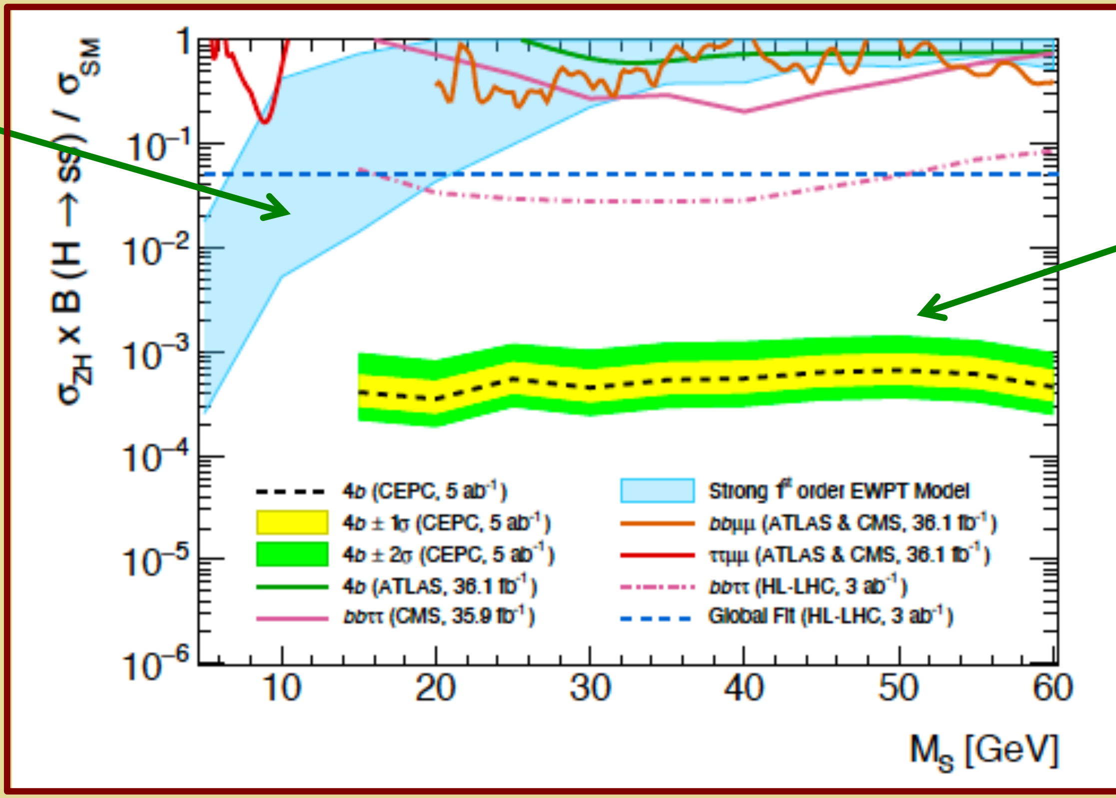
Carena et al (Snowmass) 2203.08206

Light Singlets: Exotic Higgs Decays

$h_1 \rightarrow h_2\, h_2 \rightarrow 4b$ (prompt)

EWPT viable: numerical

CEPC 4b

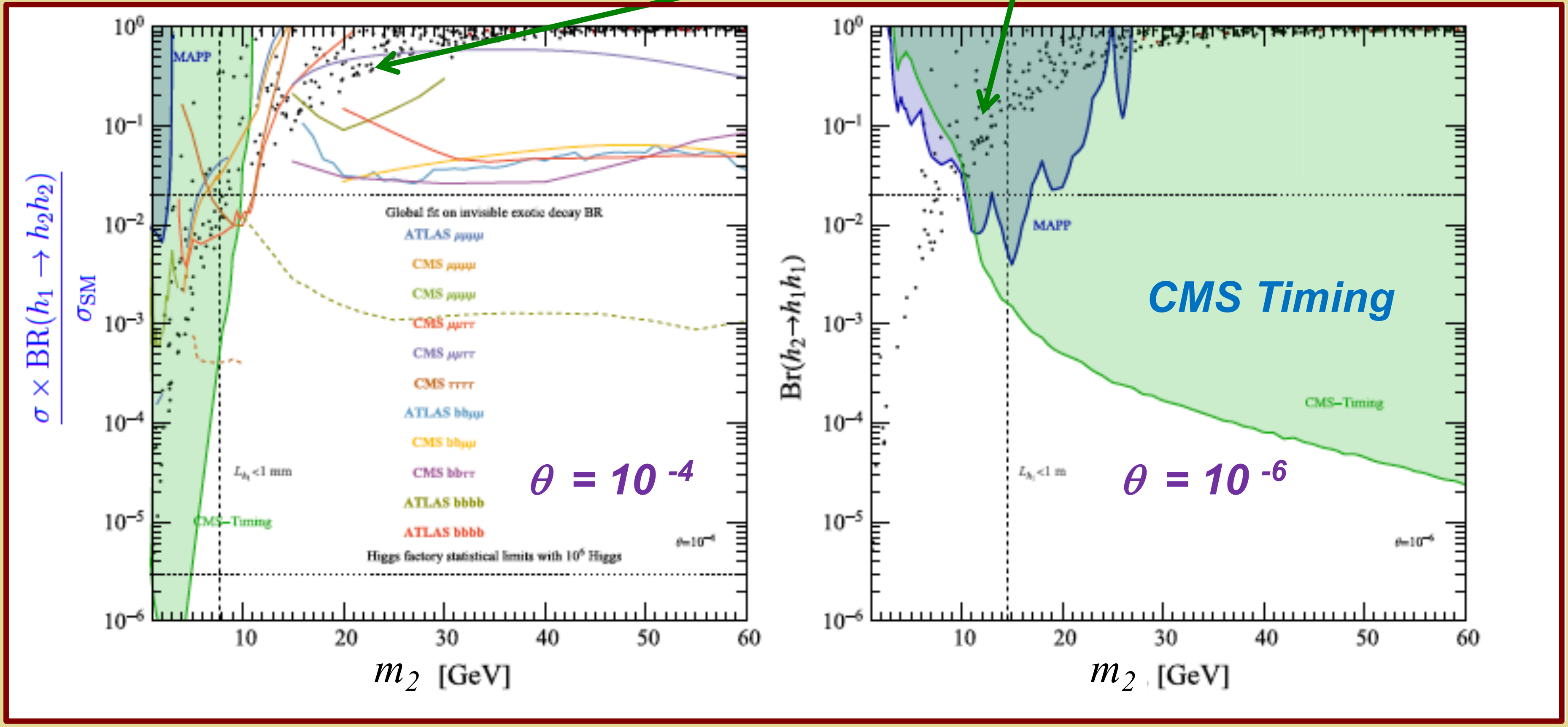


J. Wang et al (Snowmass) 2203.10184

Light Singlets: Exotic Higgs Decays

$h_1 \rightarrow h_2\, h_2 \rightarrow 4j$ Displaced (LLP)

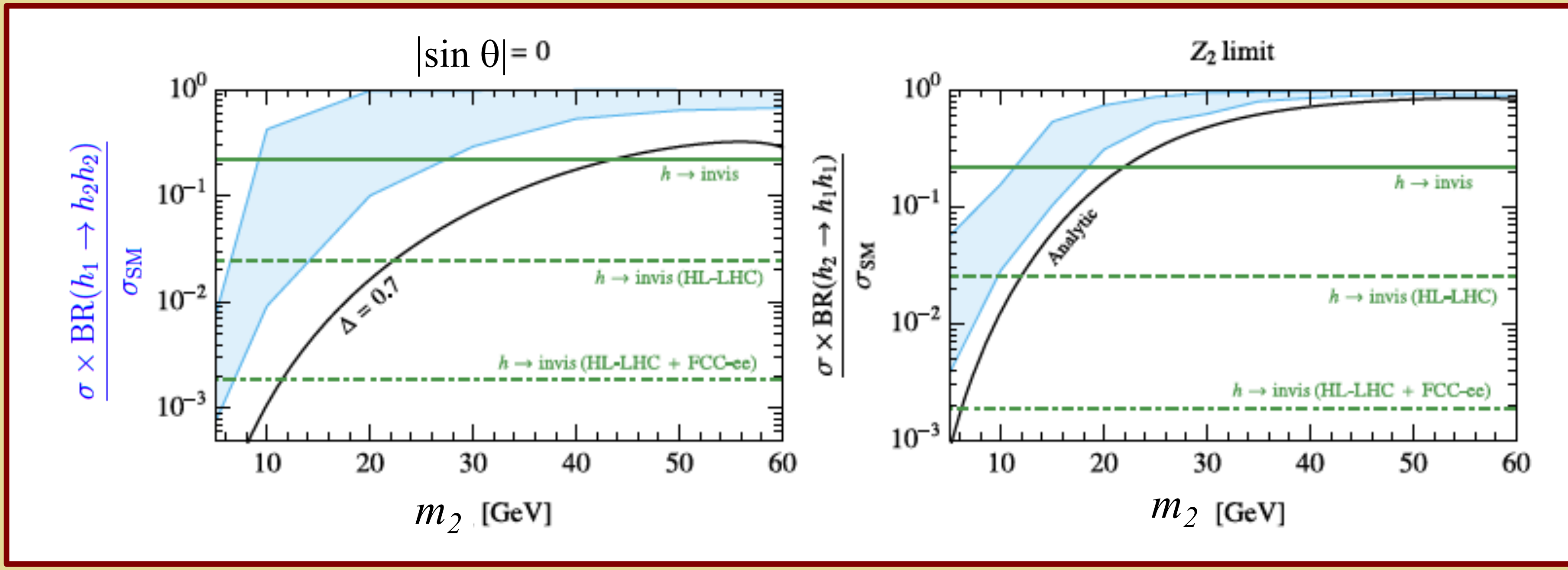
EWPT viable: numerical



W. Liu, A. Yang, H. Sun, PRD 105 (2022) 115040

Light Singlets: Exotic Higgs Decays

Invisible decays



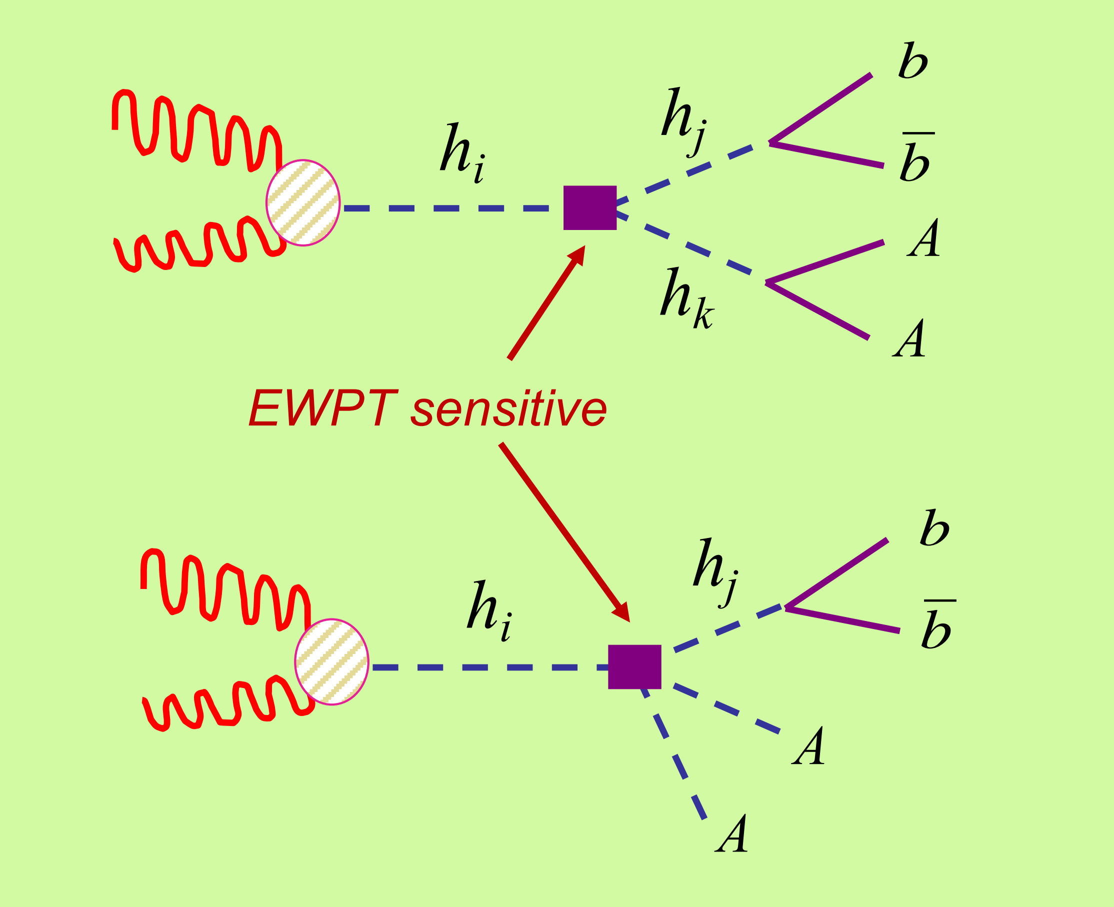
J. Kozaczuk, MR-M, J. Shelton 1911.10210

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

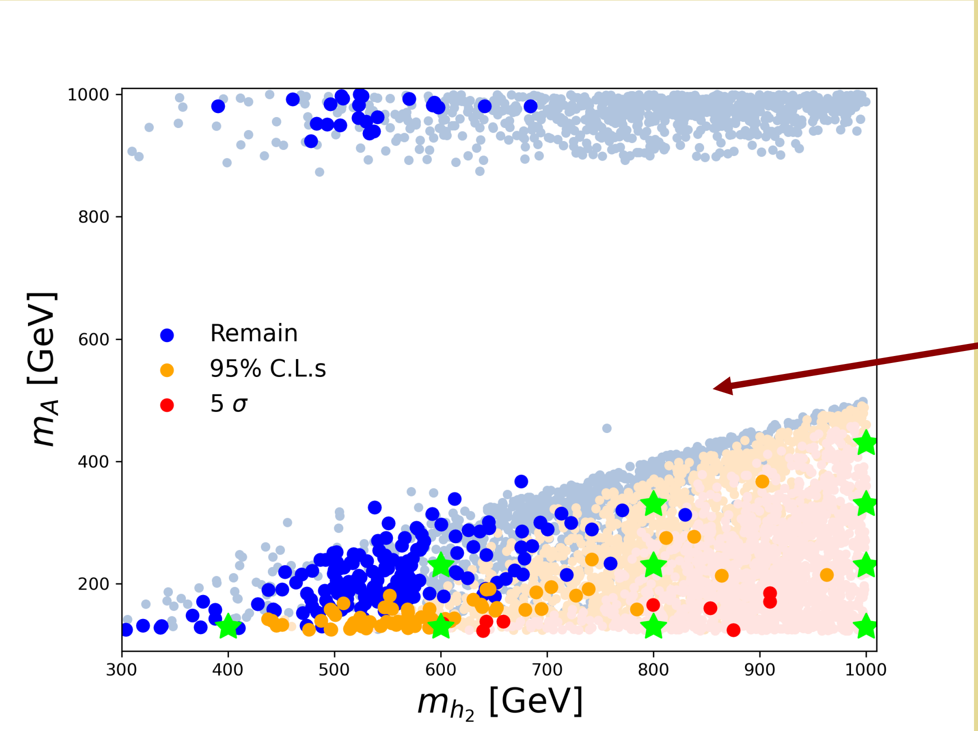


V. Barger, P. Langacker, M. McCaskey, MJRM, G. Shaugnessy 0811.0393

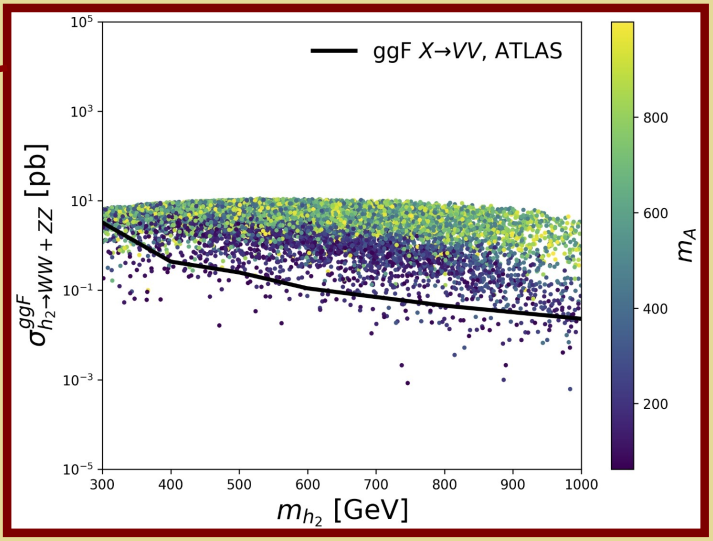
Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang 2311.NNNNN

Complex Singlet: DM + EWPT

Search for bb + MET



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



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

Model Illustrations

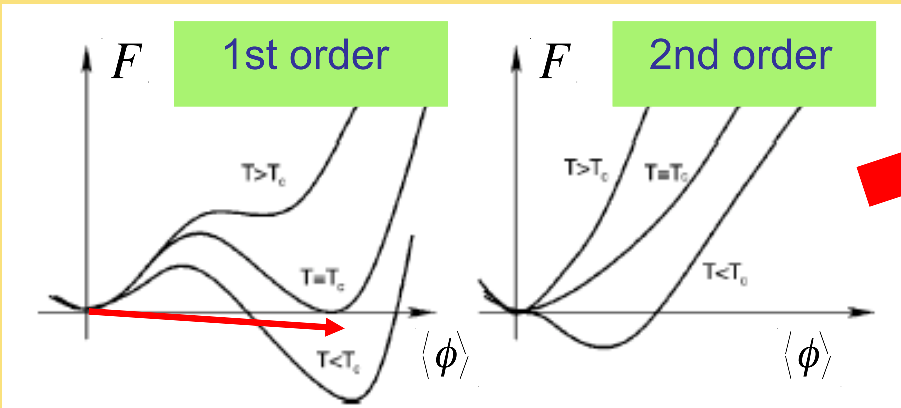
Simple Higgs portal models:

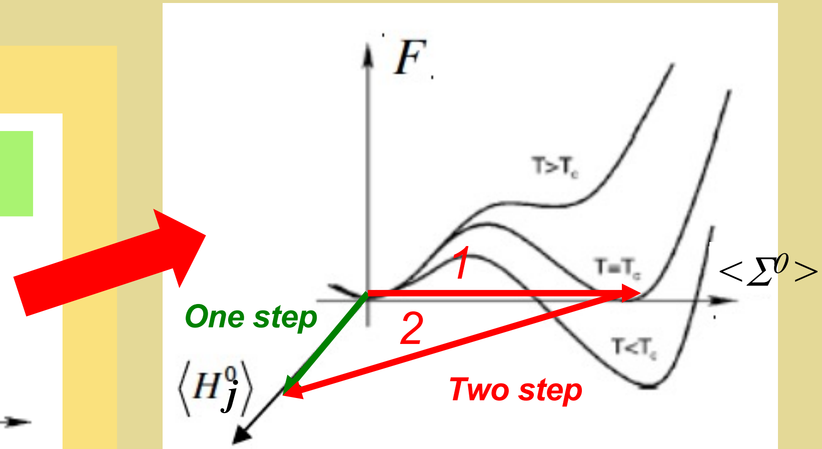
- *Real gauge singlet (SM + 1)*
- *Real EW triplet (SM + 3)*

Illustrate with real triplet: $\Sigma \sim (1,3,0)$

$H^2\phi^2$ Barrier

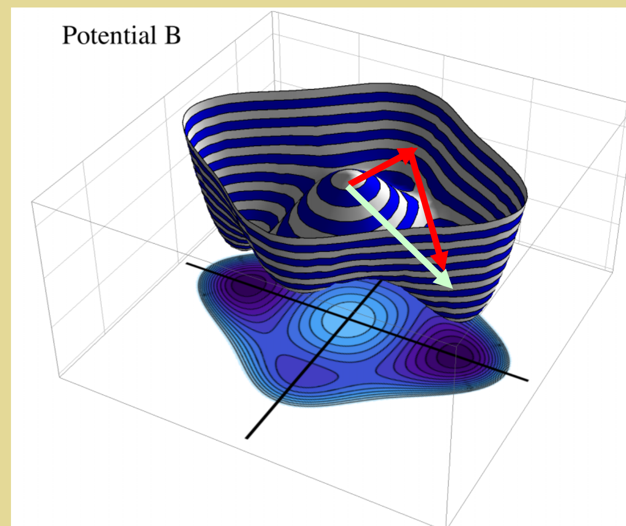
EW Multiplets: Two-Step EWPT





Increasing m_h →

← *New scalars*



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

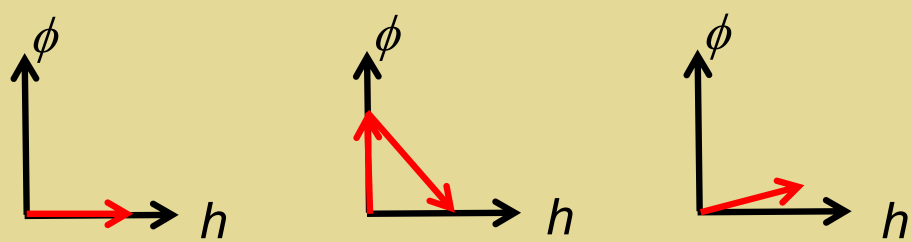
Patel, R-M: arXiv 1212.5652 ; Blinov et al: 1504.05195

Theory-Pheno Interface

Simple Higgs portal models:

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

$$V \supset a_1 H^2\phi + a_2 H^2\phi^2$$



Theory-Pheno Interface

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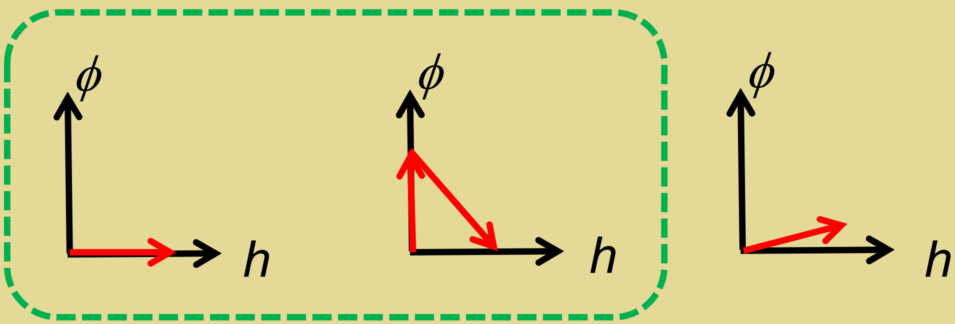

Theory-Pheno Interface

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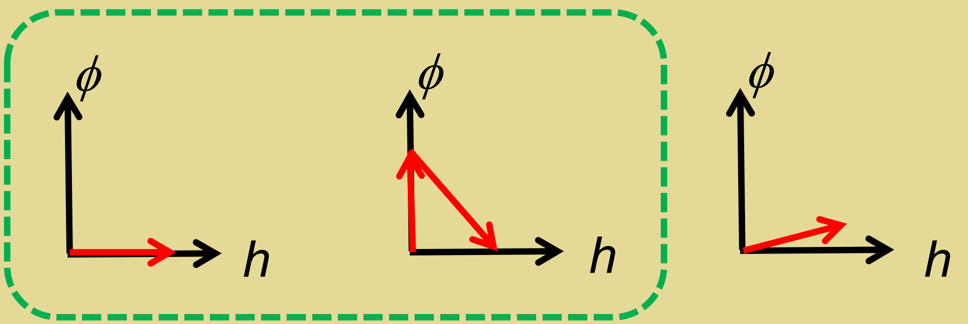


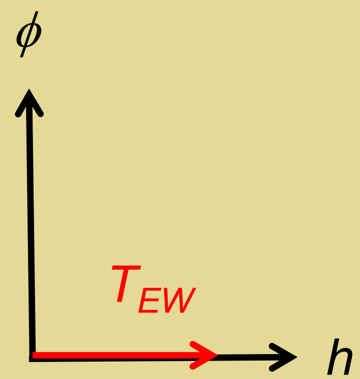
Phenomenology

- *Gravitational waves*
- *Collider: $h \rightarrow \gamma\gamma$, dis charged track, NLO $e^+e^- \rightarrow Zh$…*

Strategy

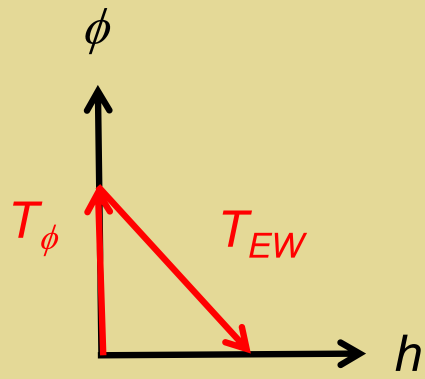
- *Employ dimensionally-reduced 3D EFT in two regimes:*
  - *Heavy BSM scalars → integrate out and "repurpose" existing lattice computations* **Non-dynamical BSM scalar**
  - *Light BSM scalars → perform new lattice simulations* **Dynamical BSM scalar**
- *Compare with perturbative computations at benchmark parameter points in selected models*

Real Triplet: Non-Dynamical Regime



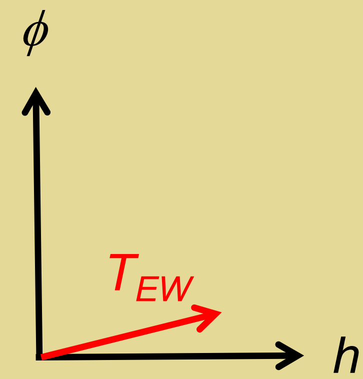
$a_2 H^2\phi^2$: $T > 0$

loop effect



$a_2 H^2\phi^2$: $T = 0$

tree-level effect



$a_1 H^2\phi$: $T = 0$

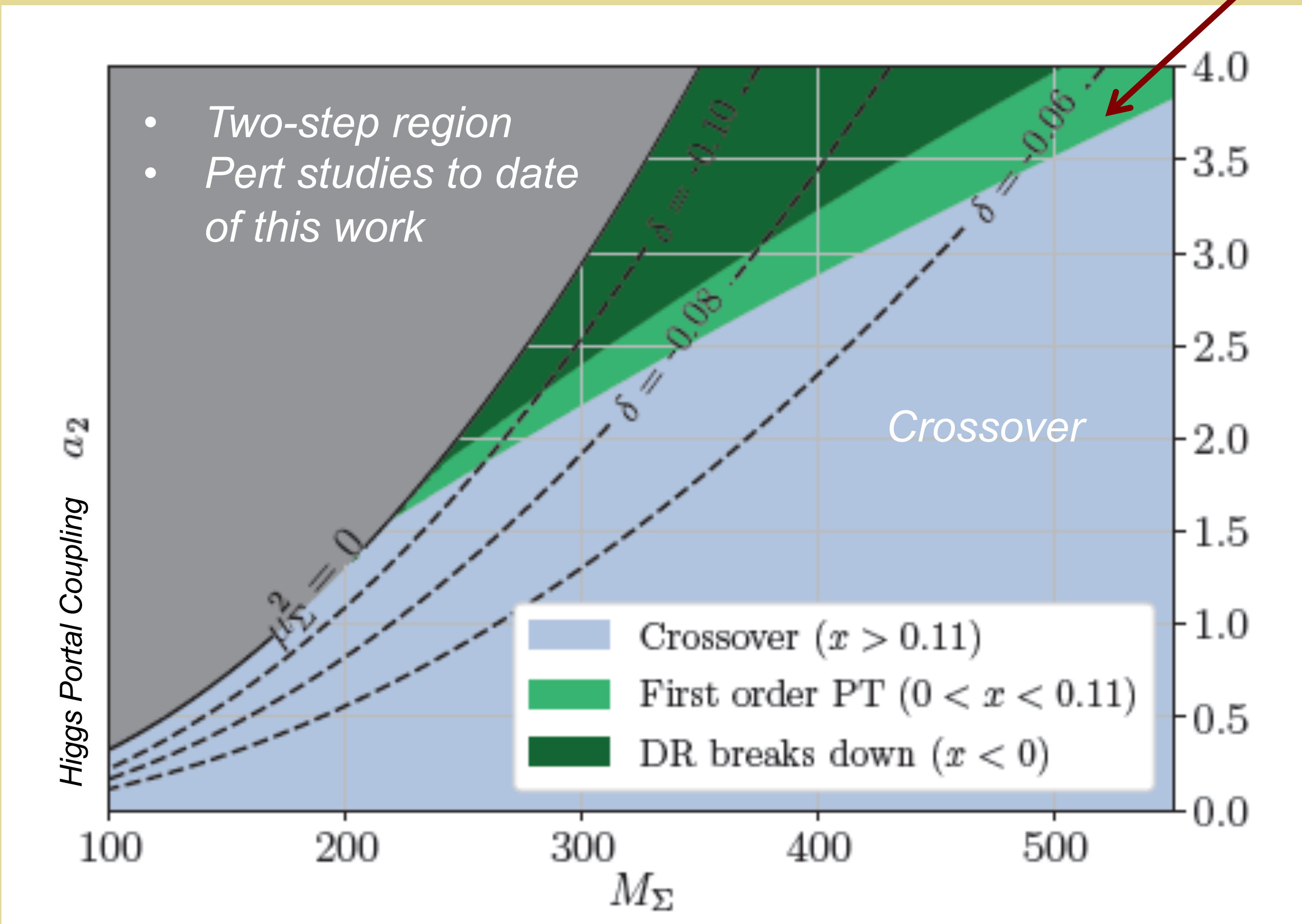
tree-level effect

Non-perturbative results:
Heavy triplet

EW precision tests → too tiny

Non-Dynamical Real Triplet: One-Step EWPT

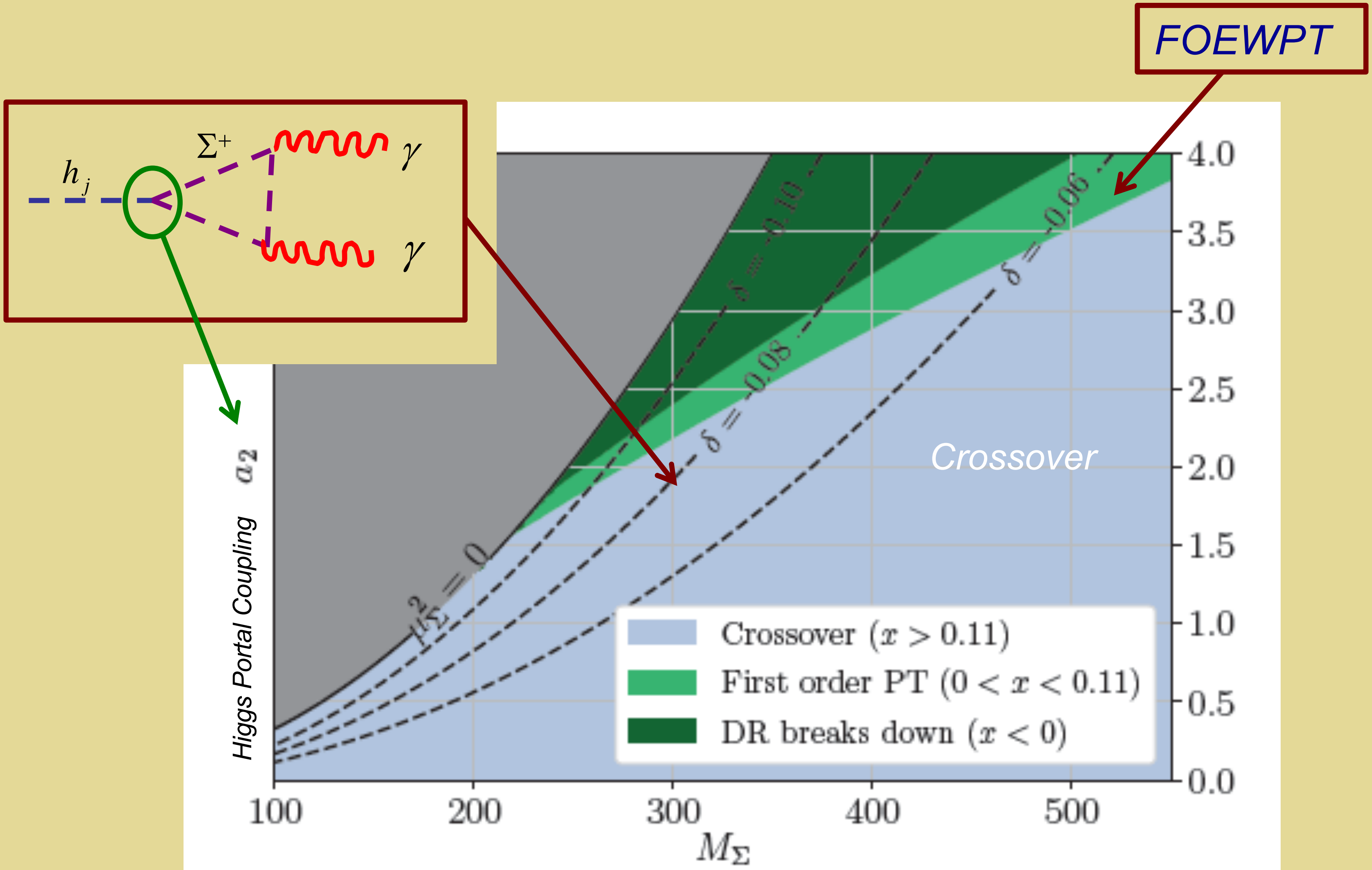
FOEWPT



- One-step
- Non-perturbative

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

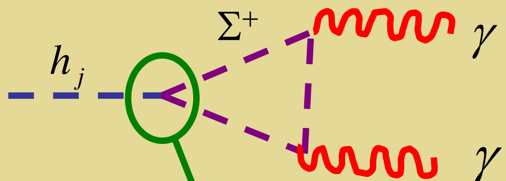
Non-Dynamical Real Triplet: One-Step EWPT

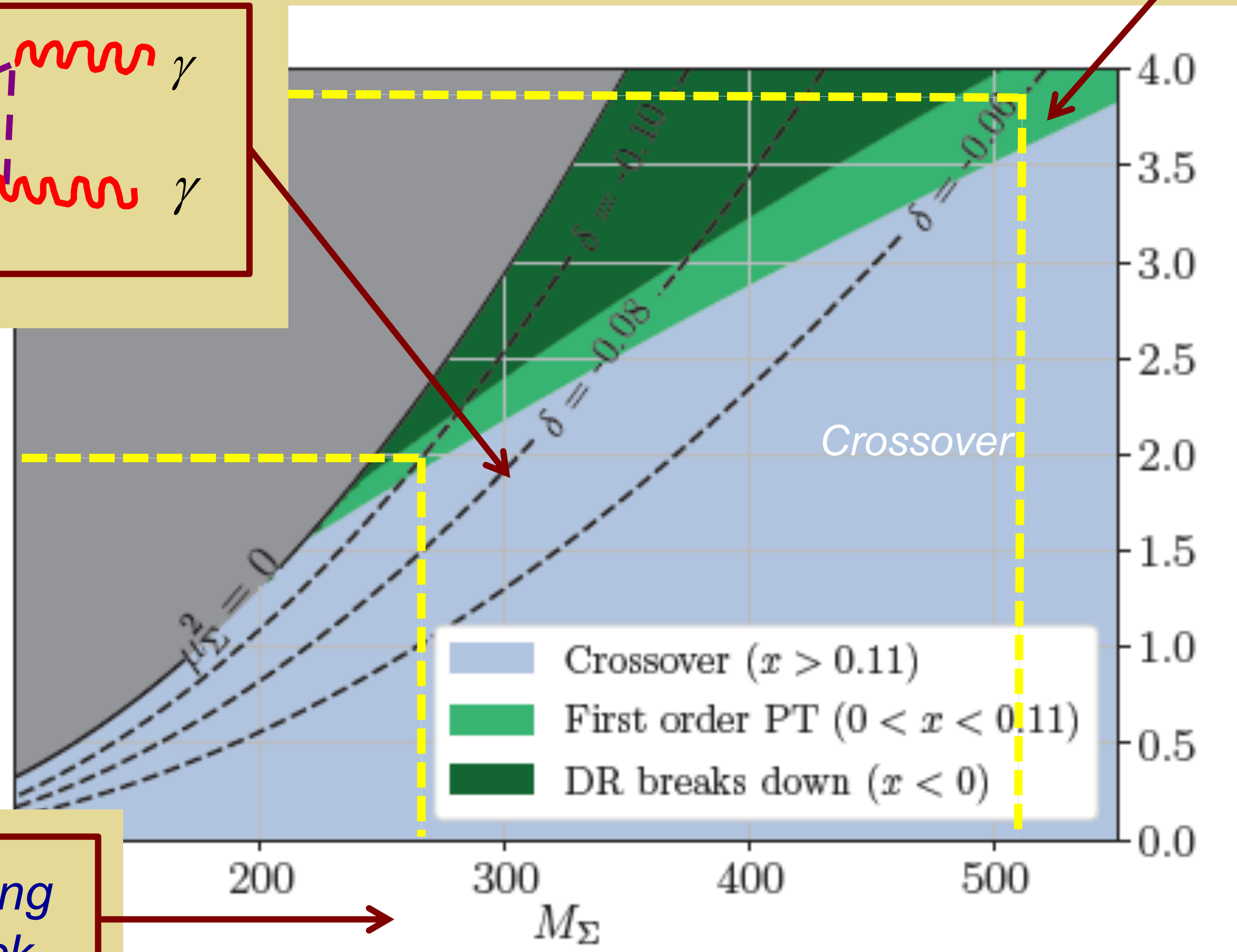


- *One-step*
- *Non-perturbative*

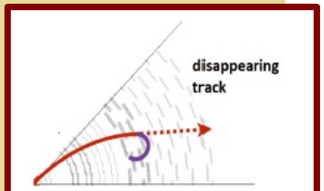
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Non-Dynamical Real Triplet: One-Step EWPT





FOEWPT

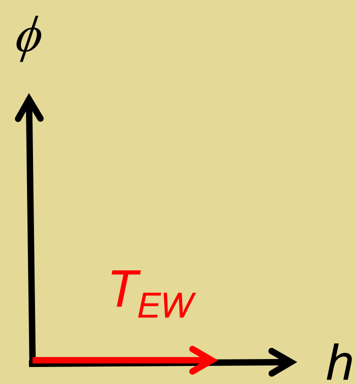


Disappearing charge track

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

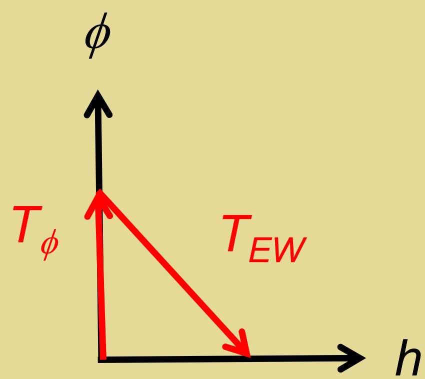
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Dynamical Real Triplet



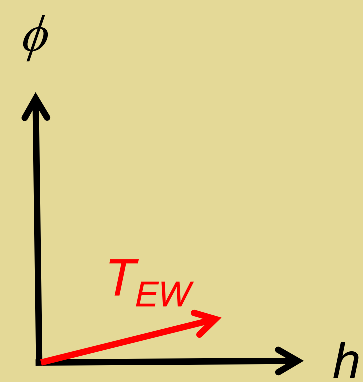
$a_2\, H^2\phi^2$: $T > 0$

loop effect



$a_2\, H^2\phi^2$: $T = 0$

tree-level effect



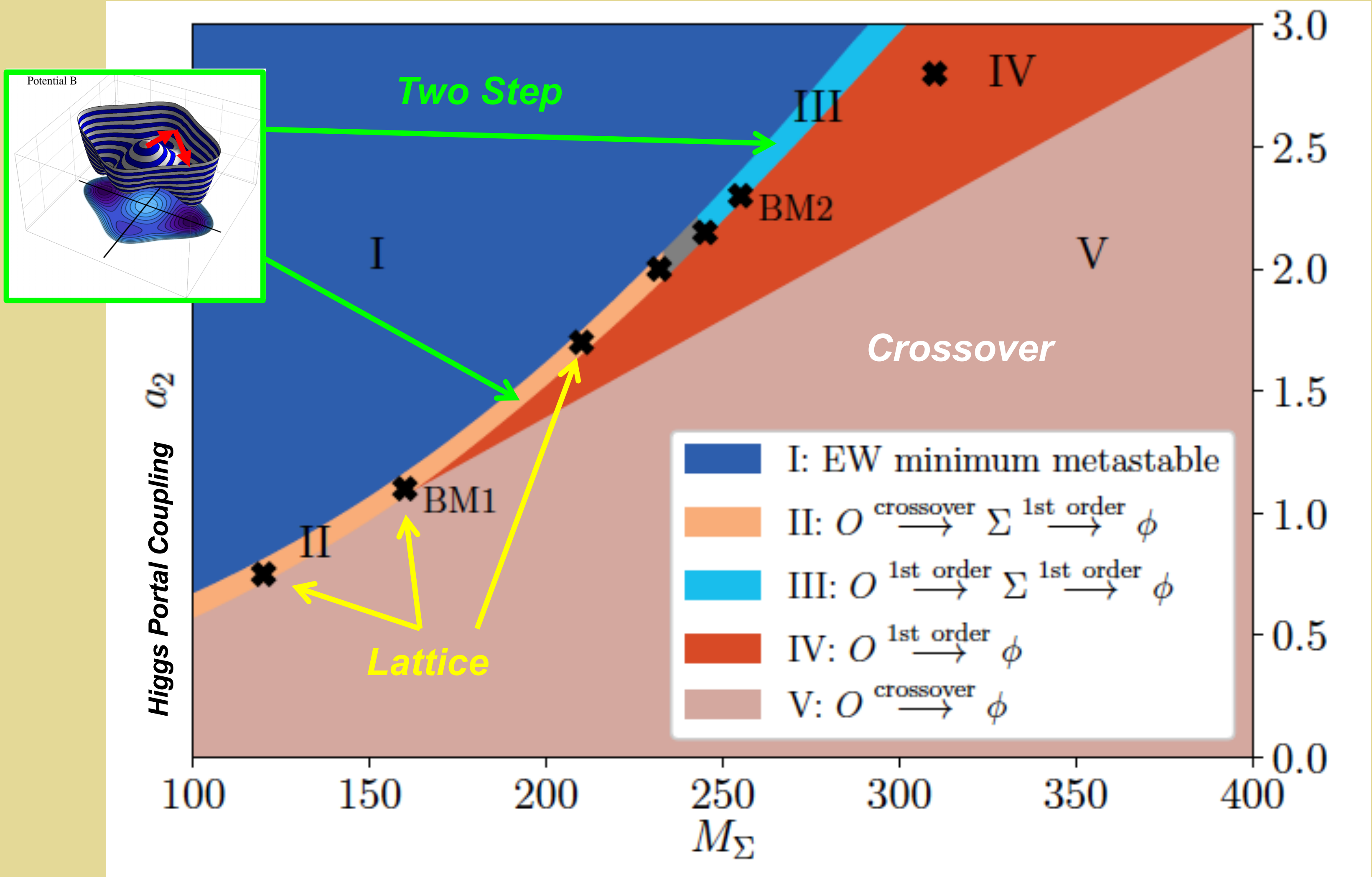
$a_1\, H^2\phi$: $T = 0$

tree-level effect

Non-perturbative results

EW precision tests → too tiny

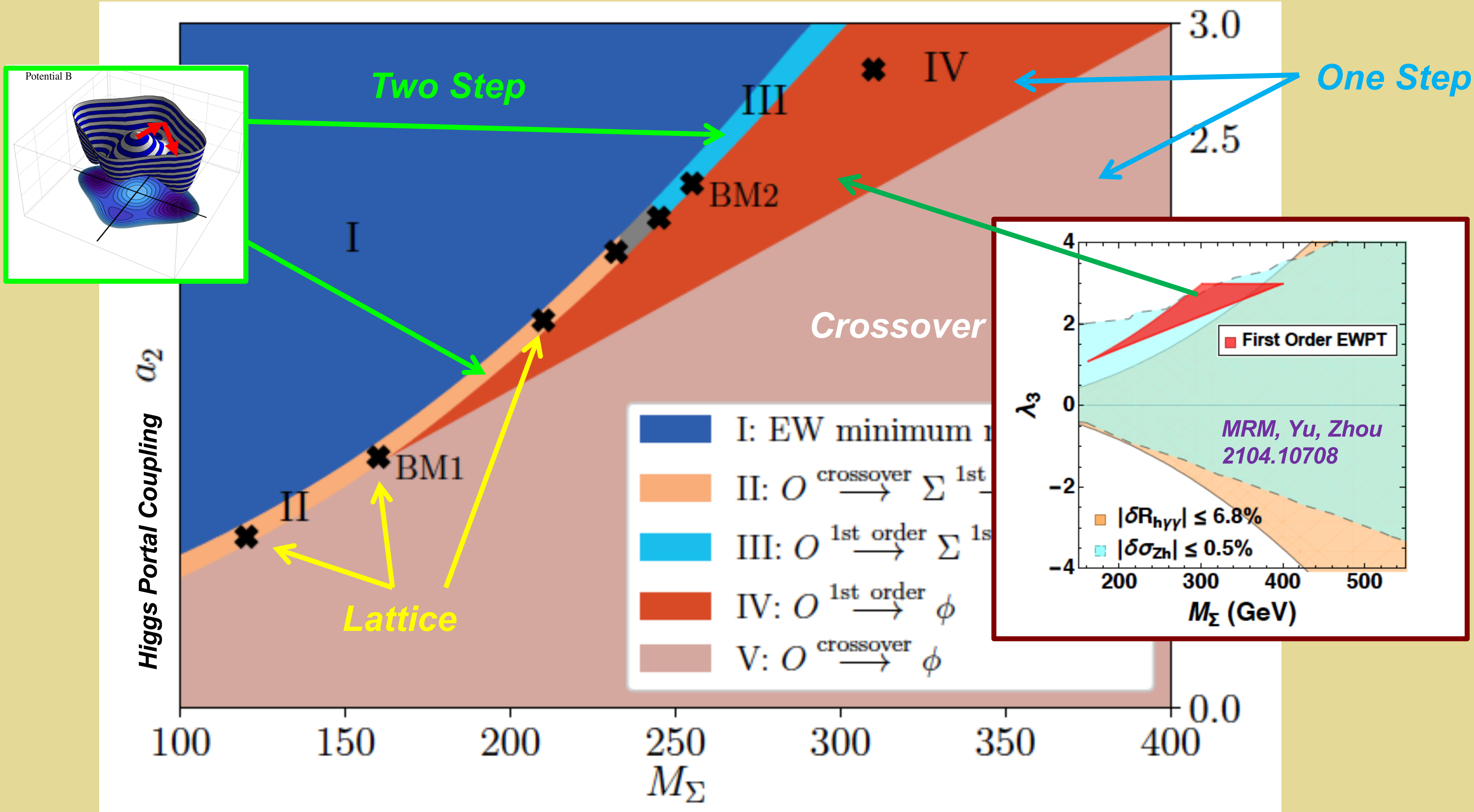
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

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

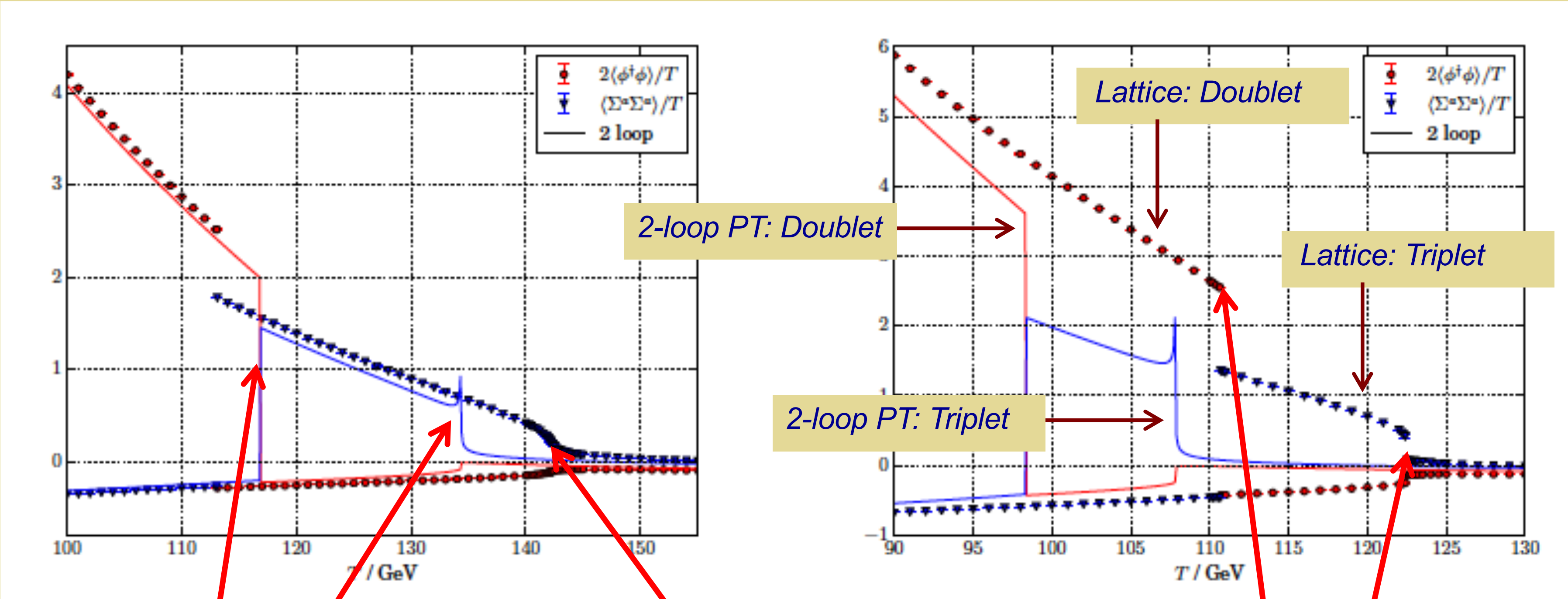
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

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

Real Triplet & EWPT: Benchmark PT



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

(b) BM2: $(M_\Sigma, a_2, b_4) = (255\ \text{GeV}, 2.3, 0.25)$

PT Discontinuities: First order EWPT

Lattice: Smooth Crossover: No phase transition

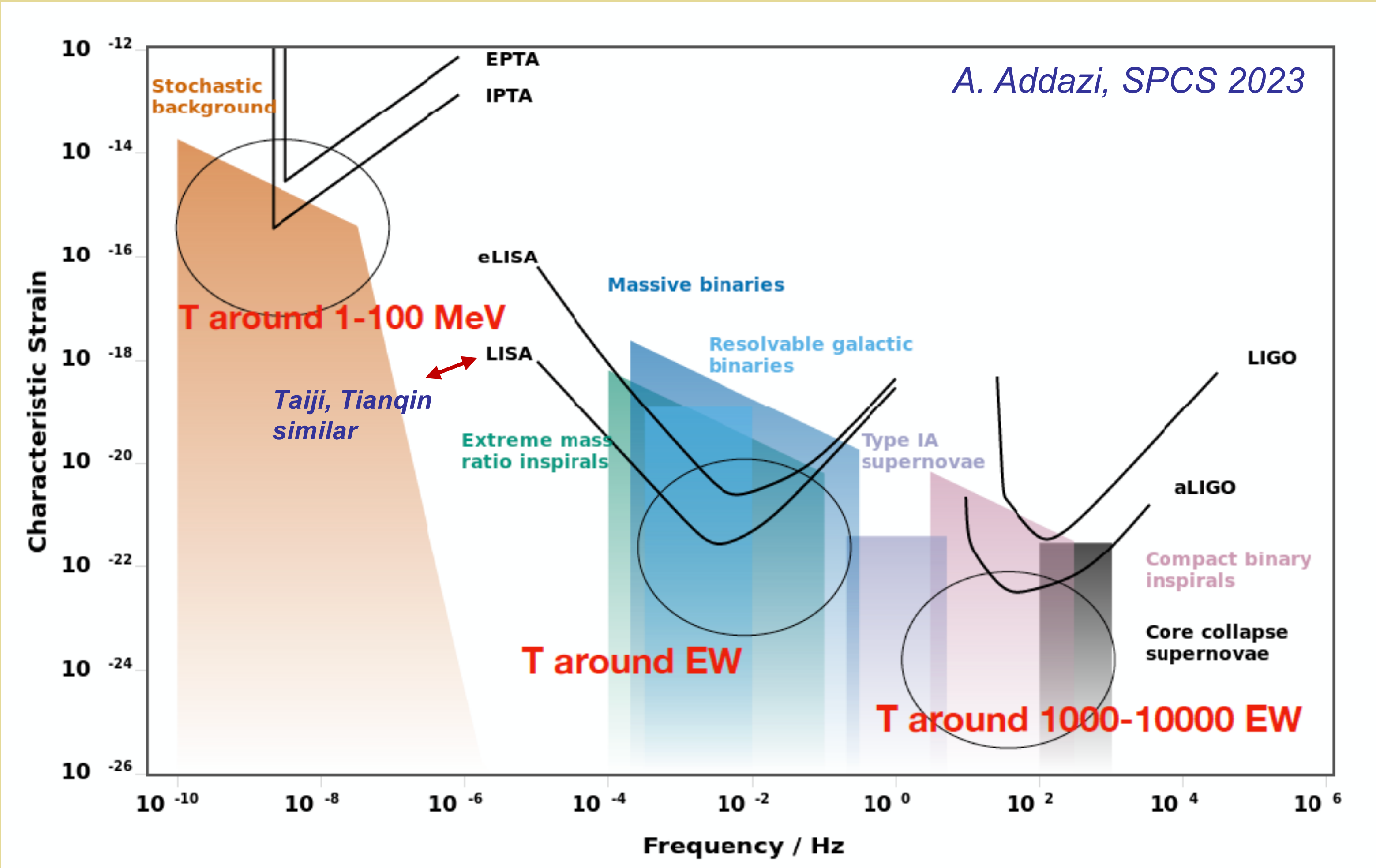
Discontinuities: First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332

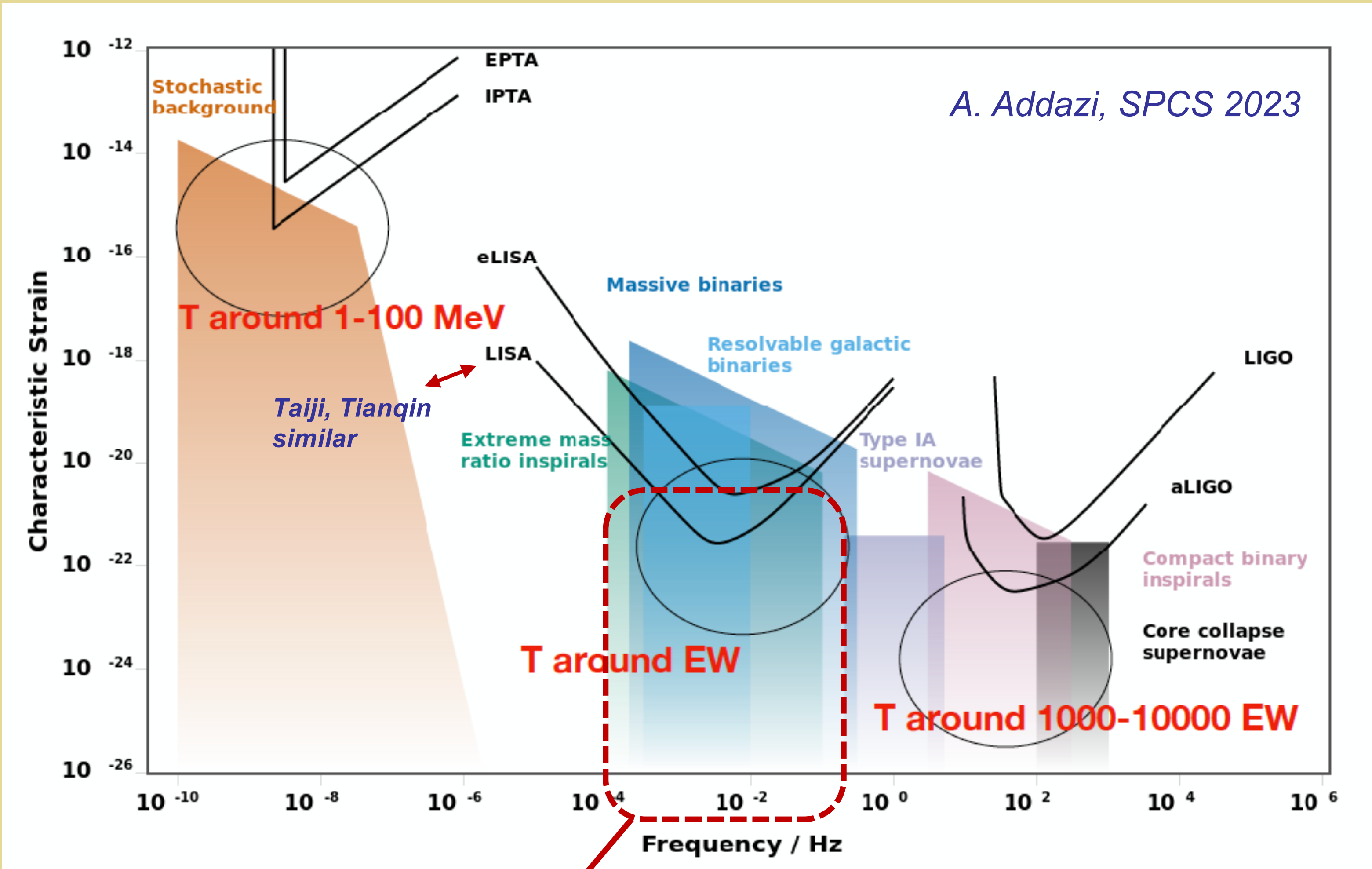
IV. GW-Collider Interface: Theory+ Phenomenology

- ***How robustly can we map the phase diagram onto experimental observables ?***
- ***How can we exploit experiment to identify EWPT-viable models & parameters ?***

Gravitational Waves



Gravitational Waves



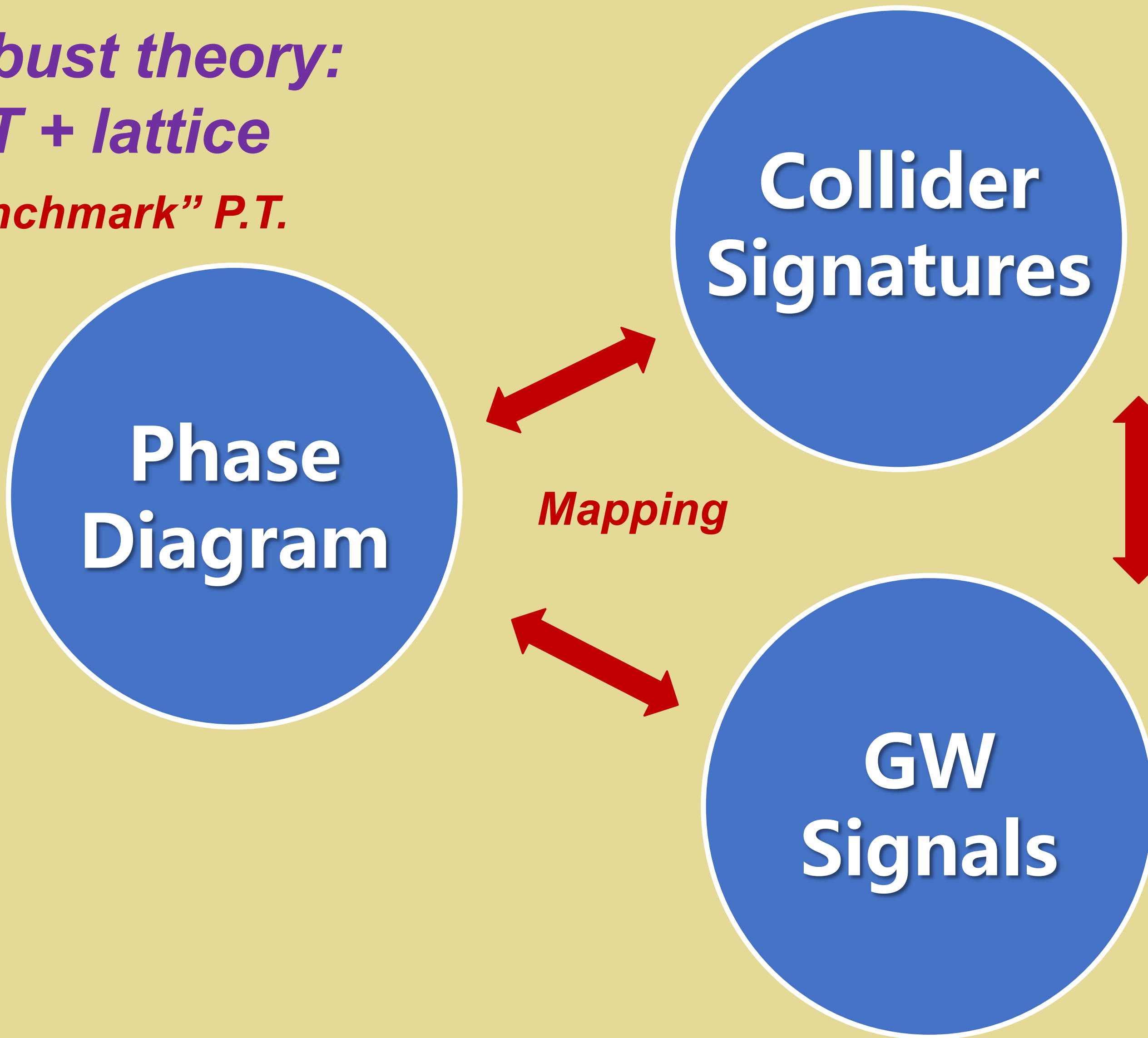
EWPT laboratory for GW micro-physics: colliders can probe particle physics responsible for non-astro GW sources → test our framework for GW microphysics at other scales

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.

Observables:
model specific



Combined reach: N_σ vs S/N

Hydro:
α , β / H_*

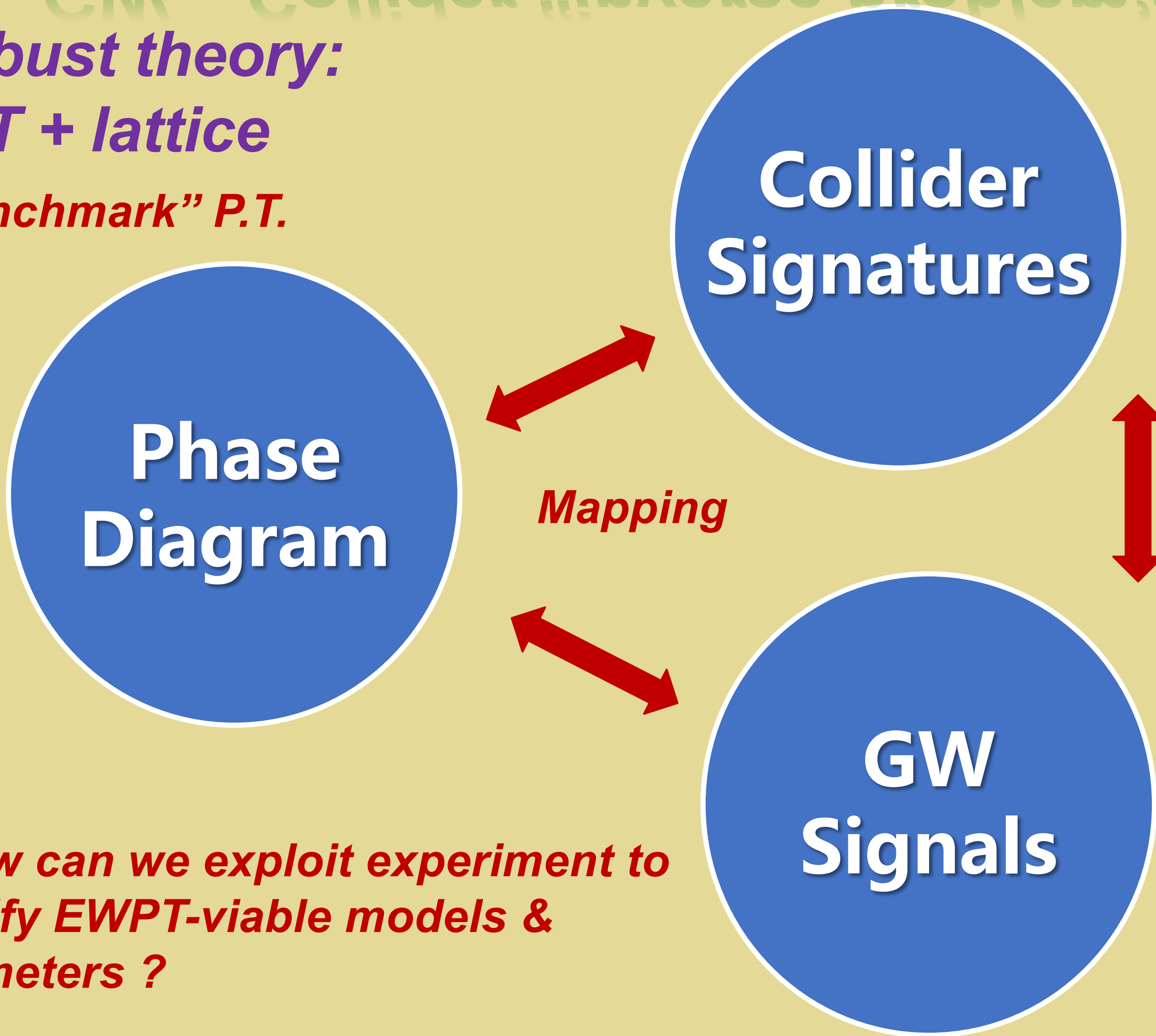
BSM EWPT: Inter-frontier Connections

GW – Collider "inverse problem" **

Robust theory: EFT + lattice

"Benchmark" P.T.

Observables: model specific



Combined reach: N_σ vs S/N

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

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

Tunneling @ T>0: Gravitational Waves

Amplitude & frequency: latent heat & intrinsic time scale

Normalized latent heat

$$\Delta Q = \Delta F + T\Delta S$$
$$S = -\partial F/\partial T$$
$$F \approx V$$

$$\Delta Q \approx \Delta V - T\partial\Delta V/\partial T$$

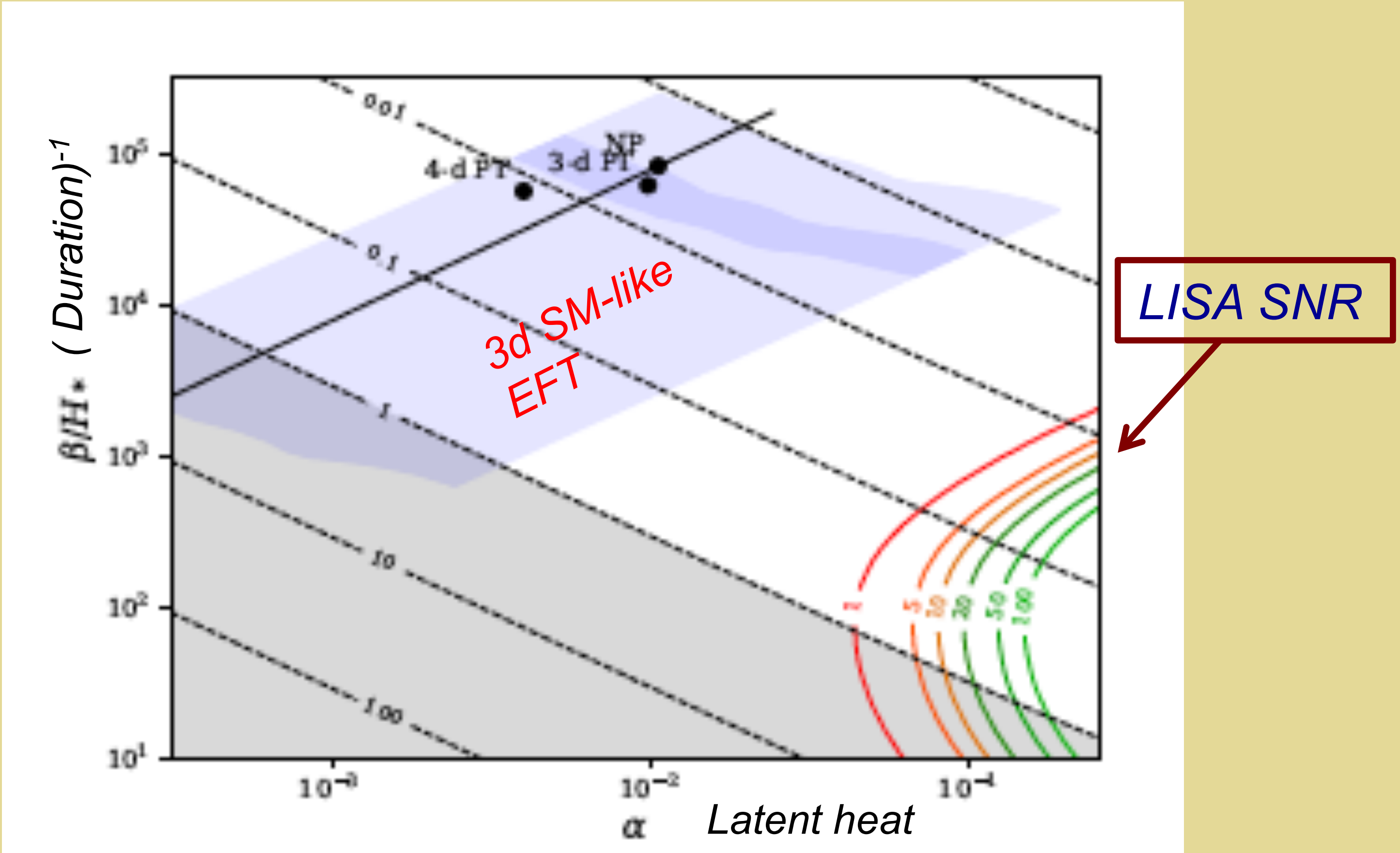
$$\alpha = \frac{30\Delta q}{\pi^2 g_* T^4}$$

Time scale

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

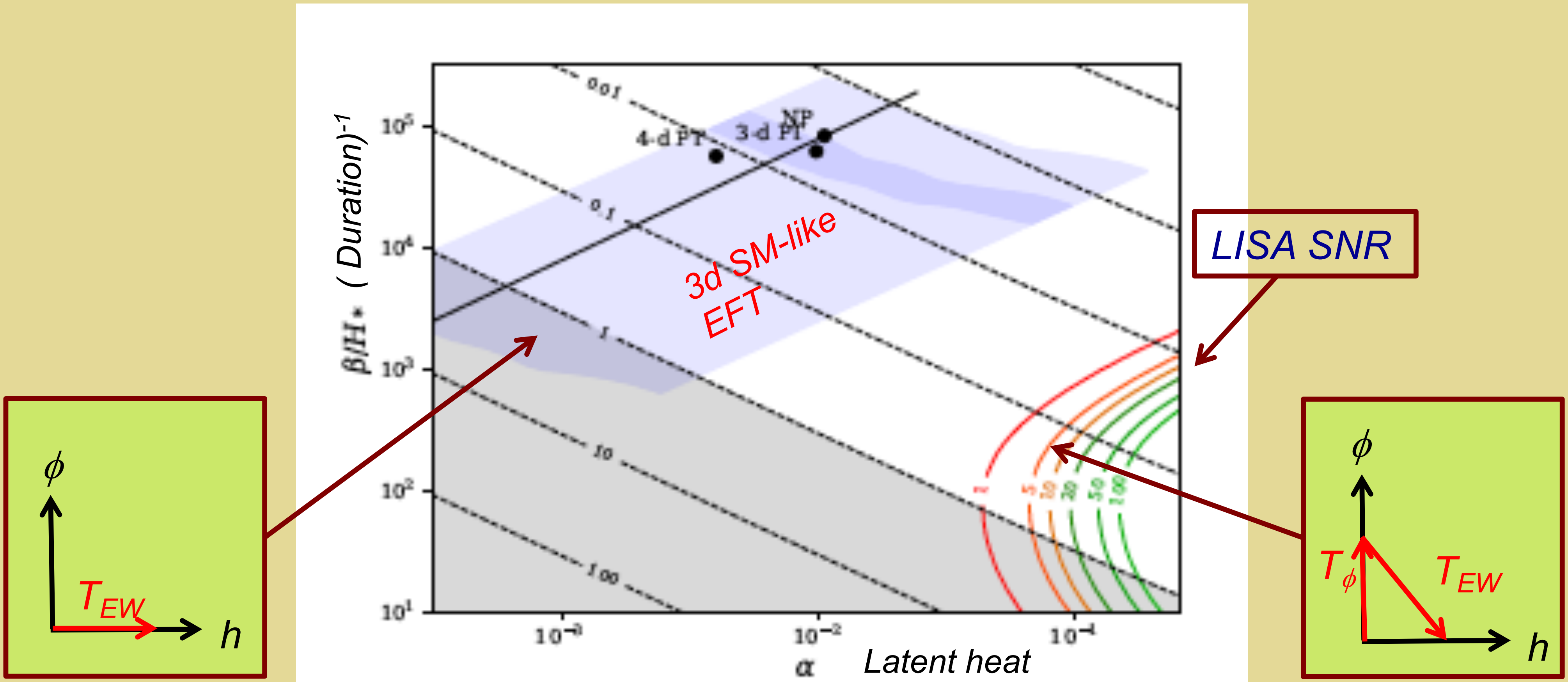
How Reliable?

BSM Scalar: EWPT & GW



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

BSM Scalar: EWPT & GW

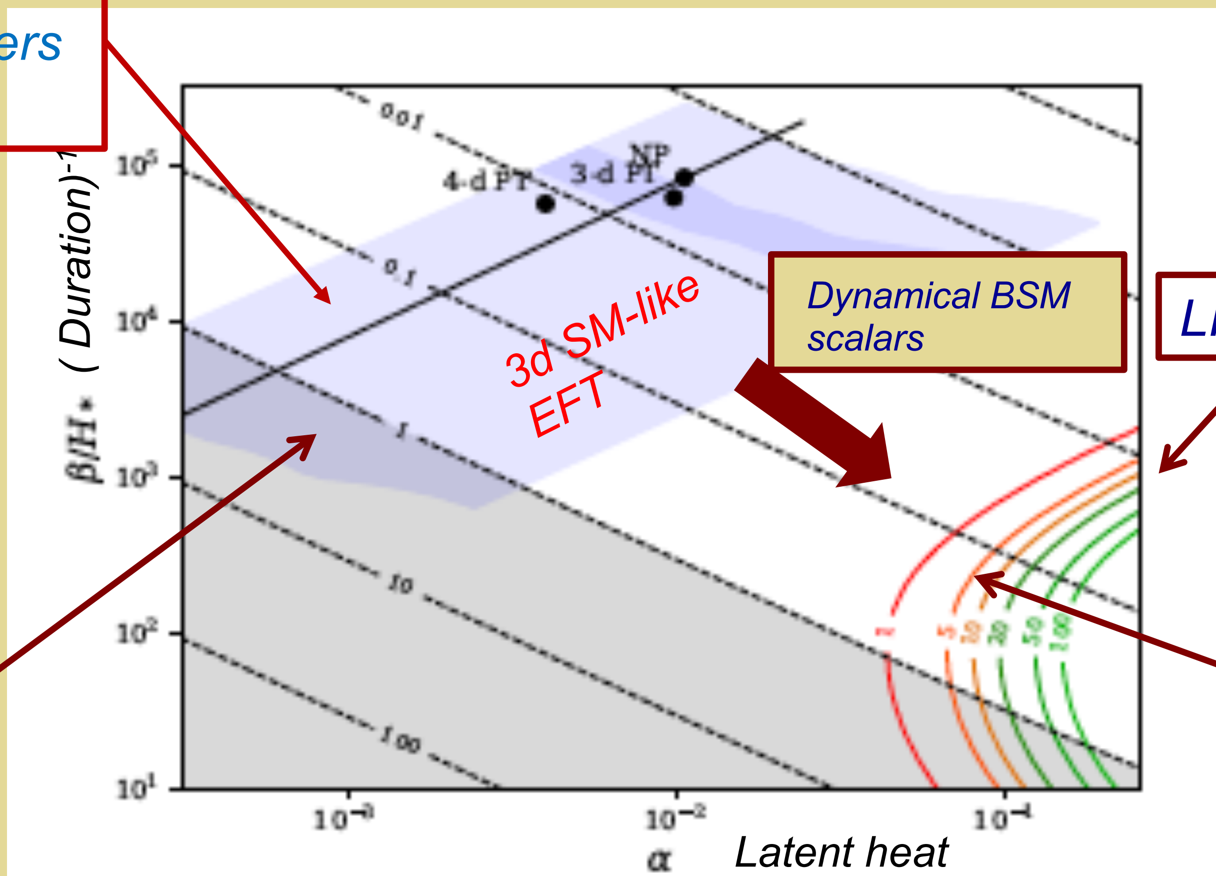


Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

10.2

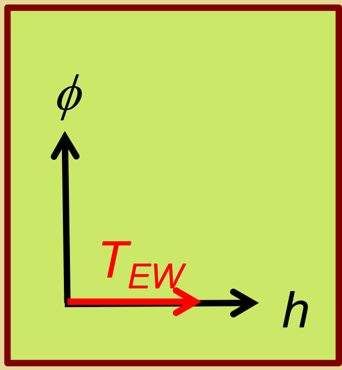
BSM Scalar: EWPT & GW

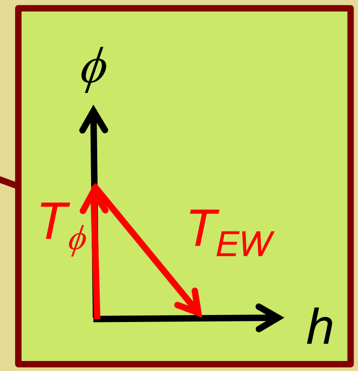
Collider probes of BSM parameters in $\mathcal{L}_{full}$



Dynamical BSM scalars

LISA SNR

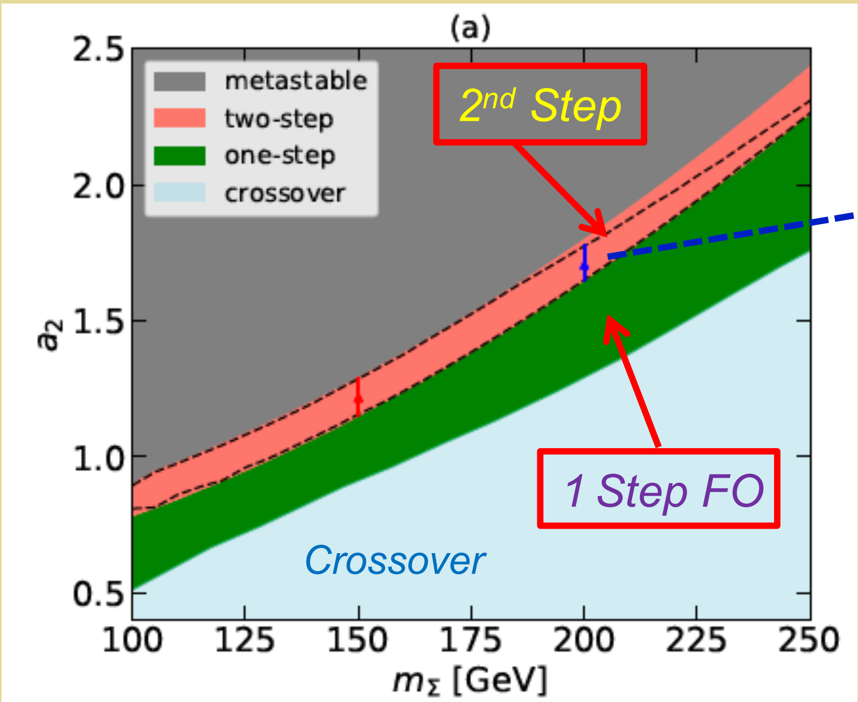


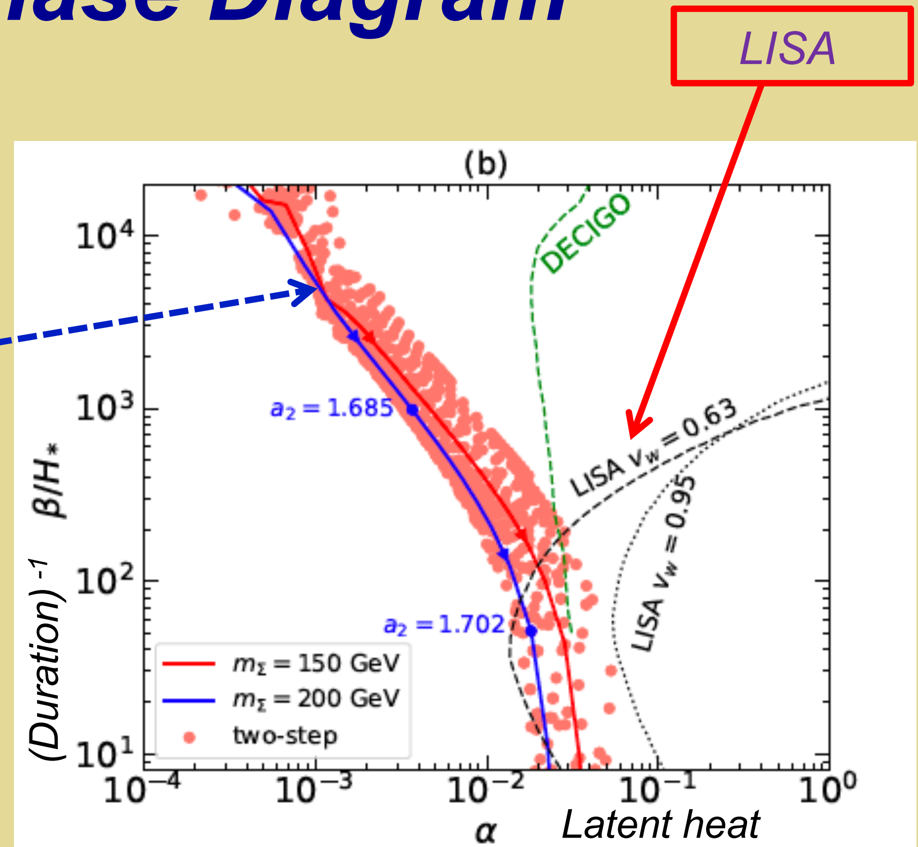


- One-step
- Non-perturbative

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

GW & EWPT Phase Diagram

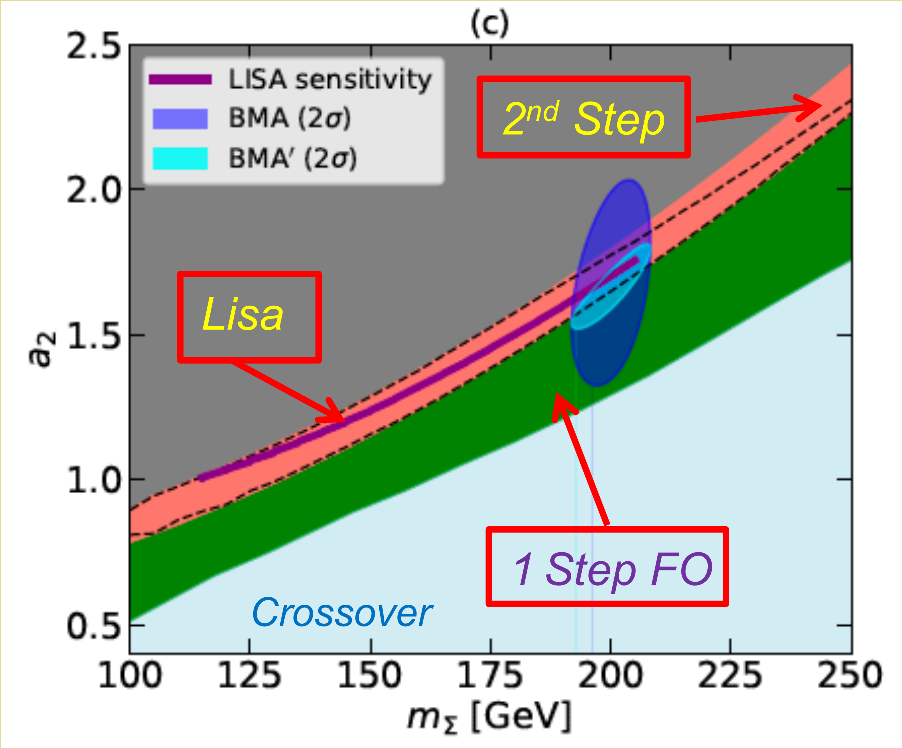


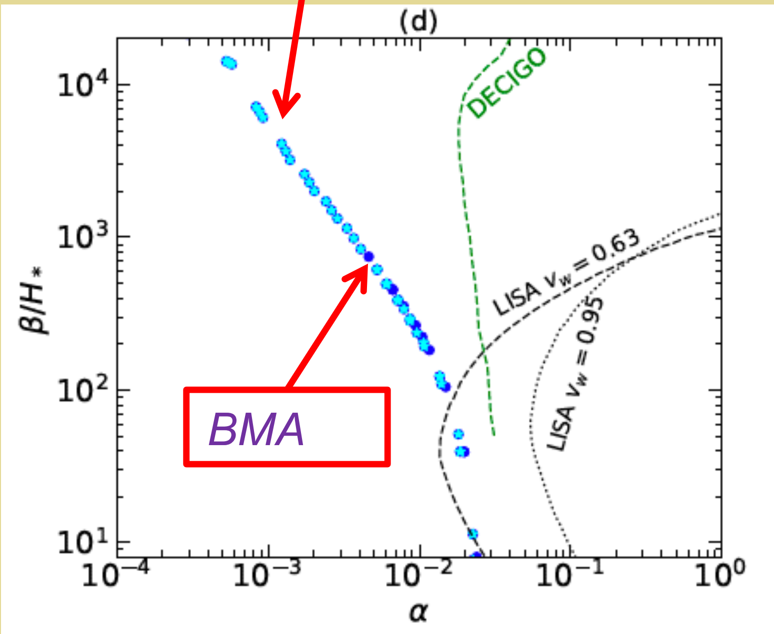


- *Single step transition: GW well outside LISA sensitivity*
- *Second step of 2-step transition can be observable*
- *Significant GW sensitivity to portal coupling*

Friedrich, MJRM, Tenkanen, Tran 2203.05889

GW & EWPT Phase Diagram





BMA: m_Σ + h → $\gamma\gamma$

BMA' : BMA + Σ^0 → ZZ

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

Friedrich, MJRM, Tenkanen, Tran 2203.05889

V. Theoretical Robustness

- ***Thermodynamics: phase diagram, T_C , α***
- ***Dynamics: nucleation, β / H_****

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 ?

EWPT & Perturbation Theory: IR Problem

Bosonic loop at T>0

Bose dist fn

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

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]*

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

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*

A. **Perturbative**

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

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

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

Strategy

- *Employ dimensionally-reduced 3D EFT in two regimes:*
  - *Heavy BSM scalars → integrate out and "repurpose" existing lattice computations*
  - *Light BSM scalars → perform new lattice simulations*
- *Compare with perturbative computations at benchmark parameter points in selected models*

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

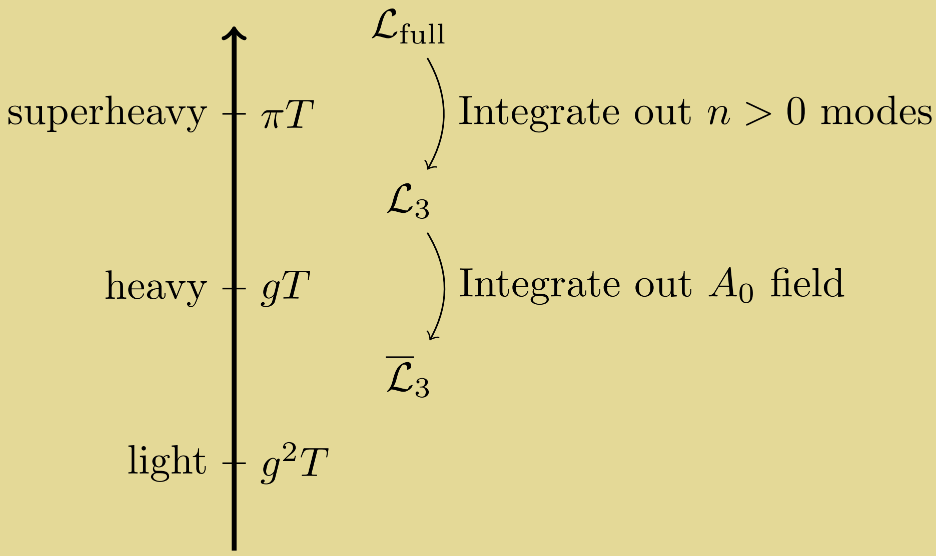
- πT — *Non-zero Matsubara modes*
- M_{BSM} — *BSM mass scale: can be > or < πT*
- $g\,T$ — *Thermal masses*
- M_{NUC} — *Nucleation scale ~ $1/r_{bubble}$*
- $g^2\,T$ — *Light scale*

EFT 2

EFT 1

Thermal Effective Field Theory: EFT 1

Meeting ground: 3-D high-T effective theory

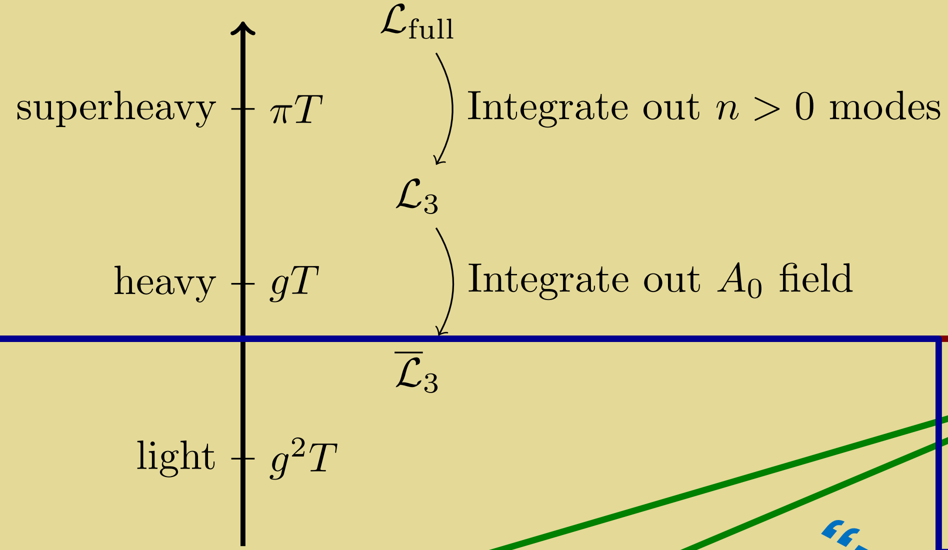


$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$ **+ $V(\Phi) + V(\phi, \Phi)_{portal}$**

Non-dynamical BSM scalars ***Dynamical BSM scalars***

EFT 1-A: Integrate Out All BSM Fields

Meeting ground: 3-D high-T effective theory



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

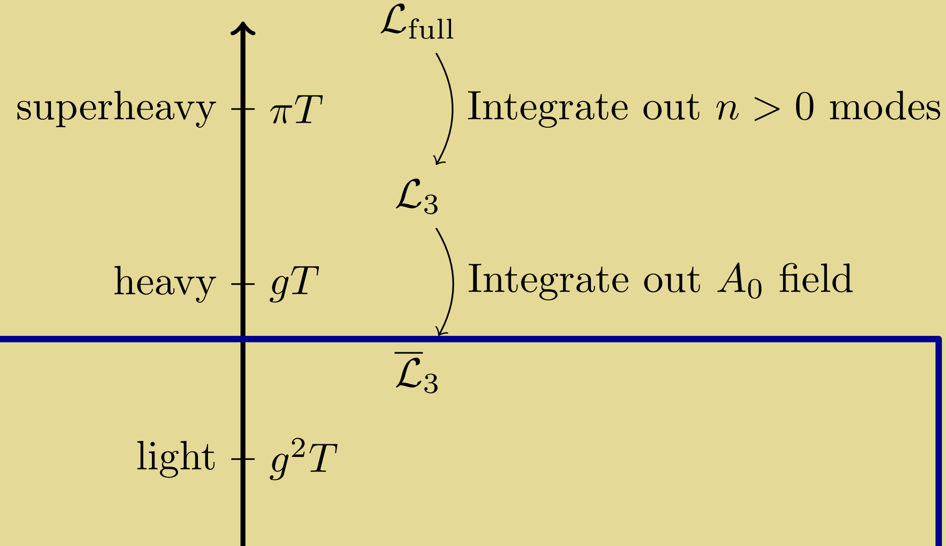
- Assume BSM fields are "heavy" or "supeheavy" : integrate out
- Effective "SM-like" theory parameters are functions of BSM parameters
- Use existing lattice computations for SM-like effective theory & matching onto full theory to determine FOEWPT-viable parameter space regions

"Repurpose" lattice results

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

EFT 1-A: Integrate all BSM Fields

Meeting ground: 3-D high-T effective theory



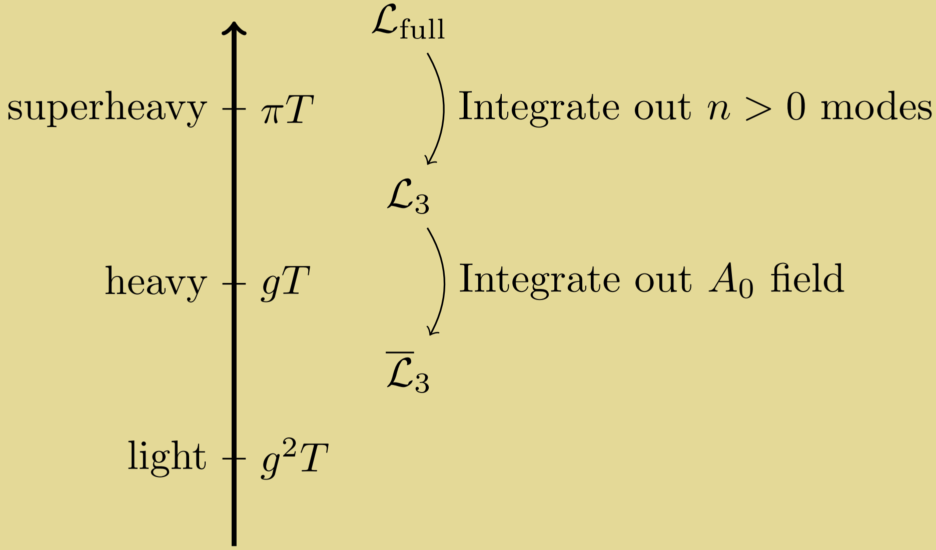
$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

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 (e.g., Kajantie et al ’95)

Thermal Effective Field Theory: EFT 1

Meeting ground: 3-D high-T effective theory

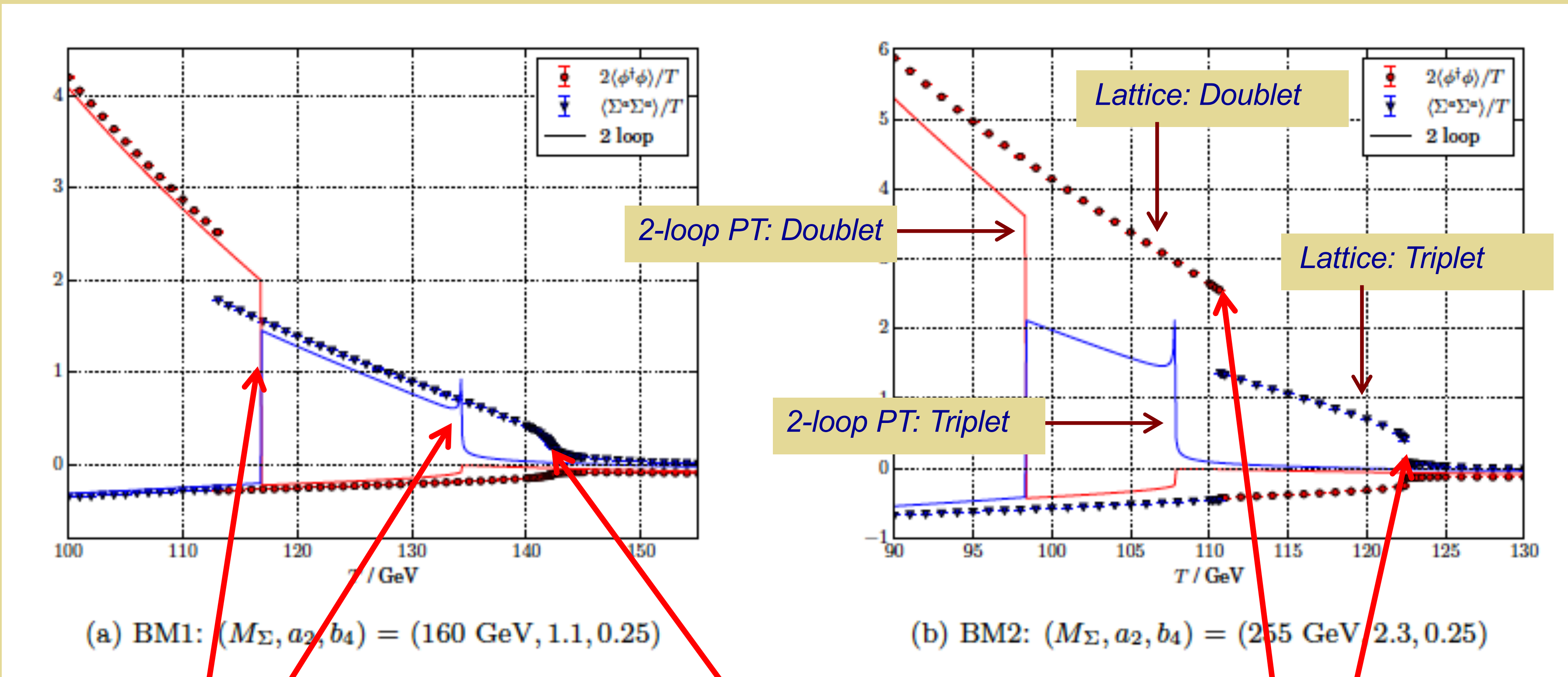


BSM parameters explicit in the light theory EFT used in lattice simulations

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

Non-dynamical BSM scalars ***Dynamical BSM scalars***

Real Triplet & EWPT: Benchmark PT



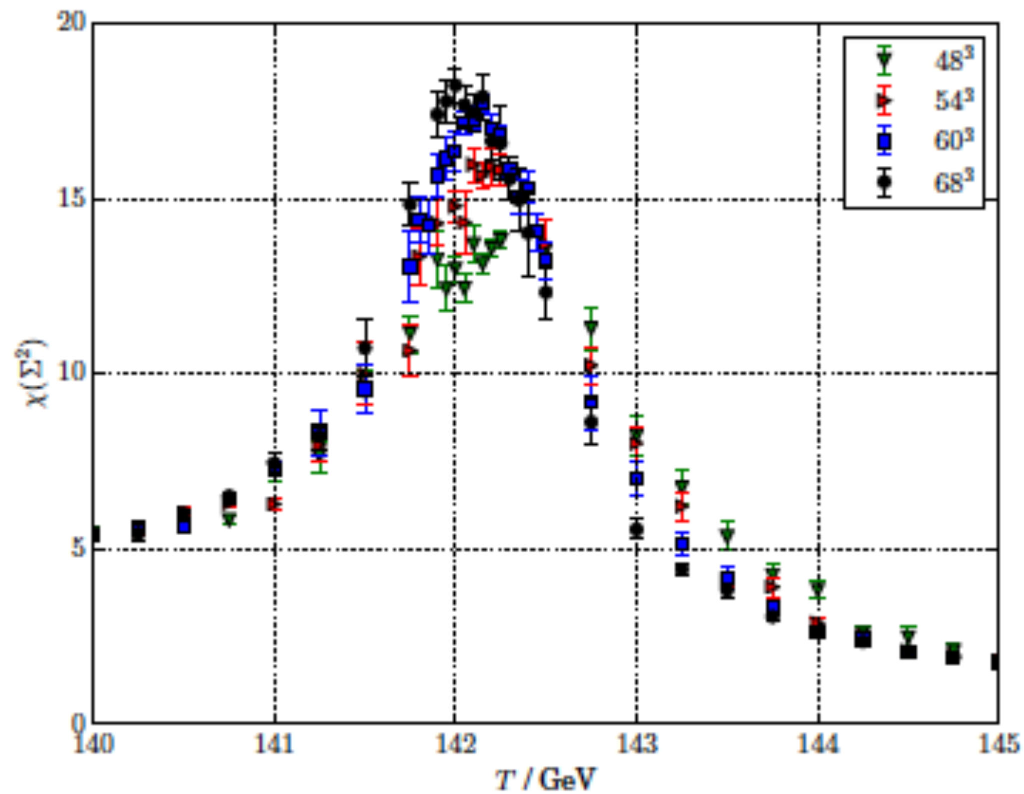
PT Discontinuities:
First order EWPT

Lattice: Smooth Crossover:
No phase transition

Discontinuities:
First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332

Real Triplet: Crossover vs 2nd Order



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

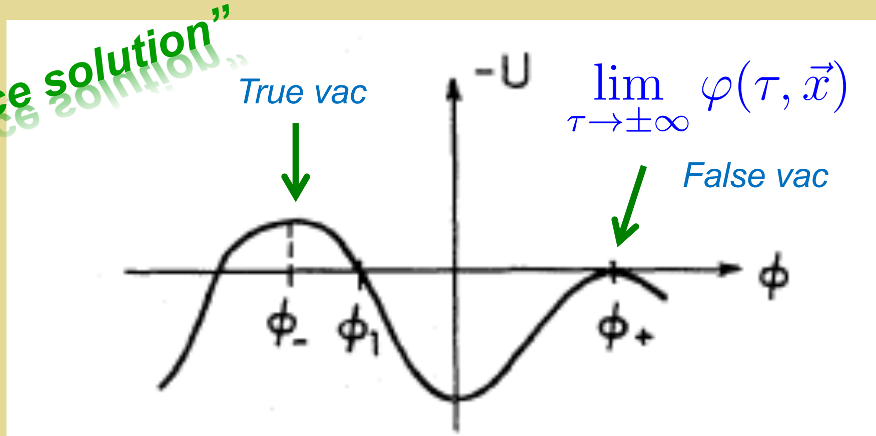
Niemi, R-M, Tenkanen, Weir 2005.11332

S. Coleman, PRD 15 (1977) 2929

Tunneling @ T=0: Coleman

Scalar Quantum Field Theory

"Bounce solution"



Rotational symmetry

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

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

Friction term

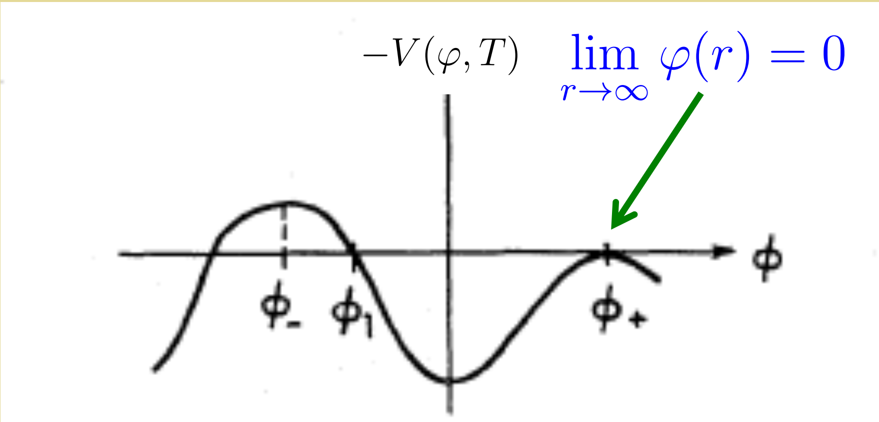
Path: minimize S_E

Ln Γ

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

Tunneling @ T>0

Scalar Quantum Field Theory



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

Path: minimize S_E

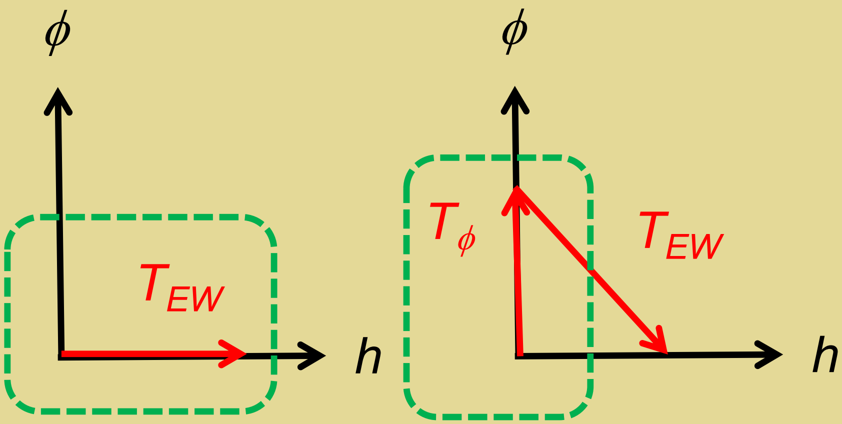
Exponent in Γ

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

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

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



Tunneling rate / unit volume:

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

Exponent in Γ

Path: minimize S_E

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

Friction term

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

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

Tunneling @ T>0

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

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

Illustrate w/ Abelian Higgs

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

Details: back up slides

Full 3D effective action

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

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

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

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*

V. Outlook - 1

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW*

- *The scale T_{EW} → any new physics that modifies the SM crossover transition to a first order transition must live at M < 1 TeV and couple with sufficient strength to yield (in principle) observable shifts in Higgs boson properties*

- *Searches for new scalars and precision Higgs measurements at the LHC and prospective next generation colliders could conclusively determine the nature of the EWSB transition*

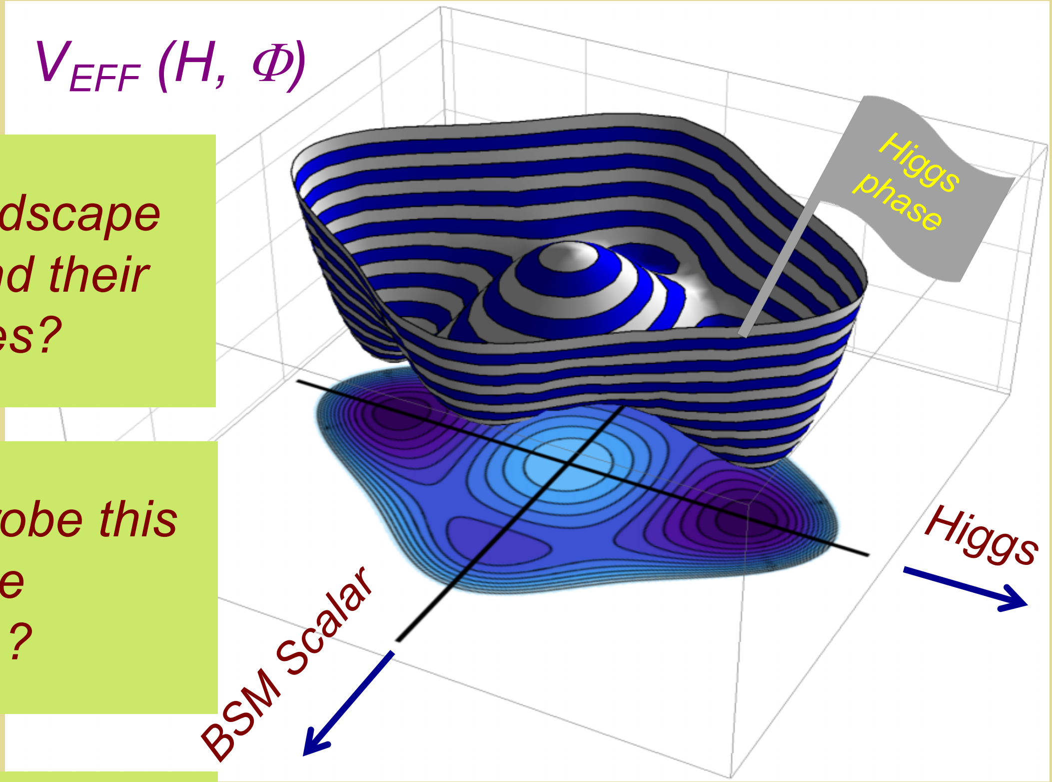
V. Outlook - 2

- *Realizing this opportunity requires meeting several theoretical challenges:*

  - *Performing a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

  - *Mapping out the full landscape of EWPT-viable BSM scenarios and making robust connections with exp’t*

Thermal History of EWSB



- *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 ?*

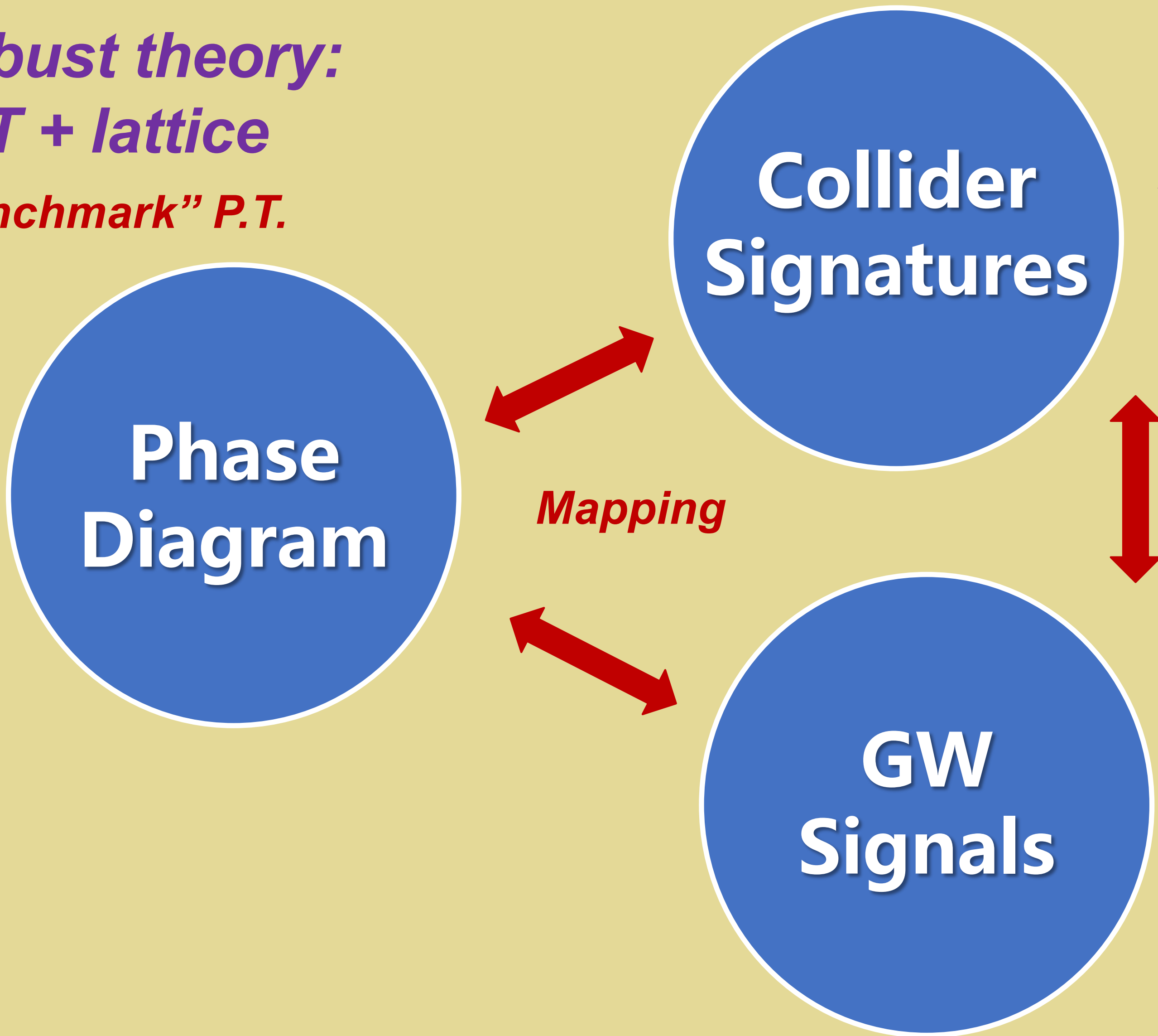
n evolve differently as T evolves →
ilities for symmetry breaking

BSM EWPT: Three Challenges

Robust theory:
EFT + lattice

"Benchmark" P.T.

Observables:
model specific



Combined reach: N_σ vs S/N

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

V. Outlook - 3

- *Realizing this opportunity requires meeting several theoretical challenges:*

  - *Performing a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

  - *Mapping out the full landscape of EWPT-viable BSM scenarios and making robust connections with exp't*

TDLI theory program

V. Outlook - 3

- *Realizing this opportunity requires meeting several theoretical challenges:*
    - *Performing a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*
    - *Mapping out the full landscape of EWPT-viable BSM scenarios and making robust connections with exp't*
- *There are exciting opportunities for talented and ambitious theorists to make significant contributions to this growing frontier*

TDLI theory program

谢谢