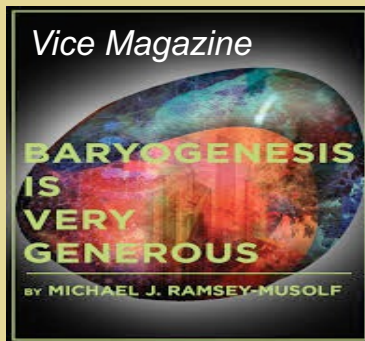# *Electroweak Phase Transition & Higgs Physics*

M.J. Ramsey-Musolf

- *T.D. Lee Institute/Shanghai Jiao Tong Univ.*
- *UMass Amherst*
- *Caltech*

- *mjrm@sjtu.edu.cn*
- *微信：mjrm-china*

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

CLHCP Workshop
Nanjing November 25, 2022

1

Was There an Electroweak Phase Transition?

- *Not in the Standard Model but could be in BSM Universe*

- *Answering this question is one of the few opportunities for collider physics to reach a definitive conclusion*

- *It's an exciting frontier at the interface of particle physics and cosmology with ample opportunities for significant theoretical and experimental advances*

Key Ideas for this Talk

- *Determining the thermal history of EW symmetry breaking is a key challenge for particle physics*

- *The "electroweak temperature" $\rightarrow$ a scale provided by nature that gives us a clear BSM target for colliders to address this challenge*

- *Precision tests and direct searches are vital*

- *Robust test of theory requires a new era of EFT & non-perturbative computations $\rightarrow$ new results highlight this theoretical frontier*

Key Ideas for this Talk

- *MJRM: 1912.07189*

    - *L. Friedrich, MJRM, T.V.I. Tenkanen, V.Q. Tran: 2203.05889*
    - *S. Arunasalam, H.-L. Li, K. Liu, MJRM, Y. Zeng, W. Zhang 2211.NNNNN*
    - *Y. Cai, MJRM, L. Zhang, W. Zhang   2212.NNNNN*

- *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*

4

Outline

I. *Context & Questions*

II. *EWPT: A Collider Target*

III. *Higgs Boson Properties: Model Illustrations: LHC Opportunities*

IV. *Theoretical Robustness*

V. *Outlook*

I. Context & Questions
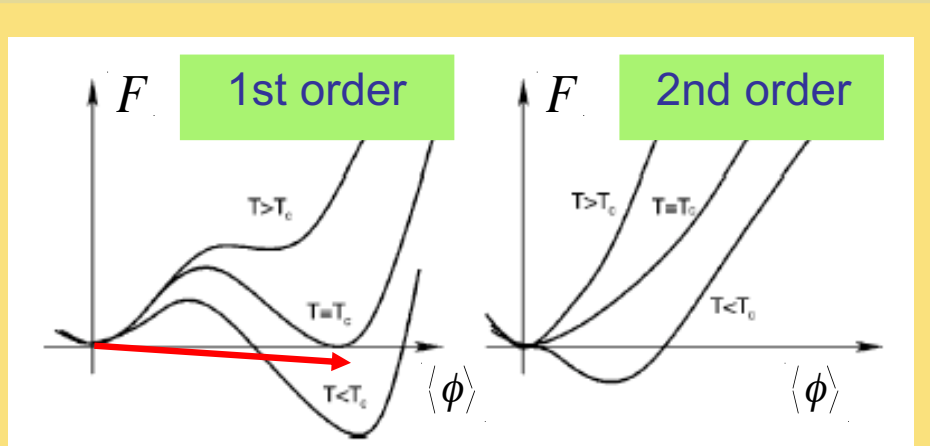
Electroweak Phase Transition

- *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 next generation probes, could a cosmological phase transition be responsible ?*

7

Thermal History of Symmetry Breaking
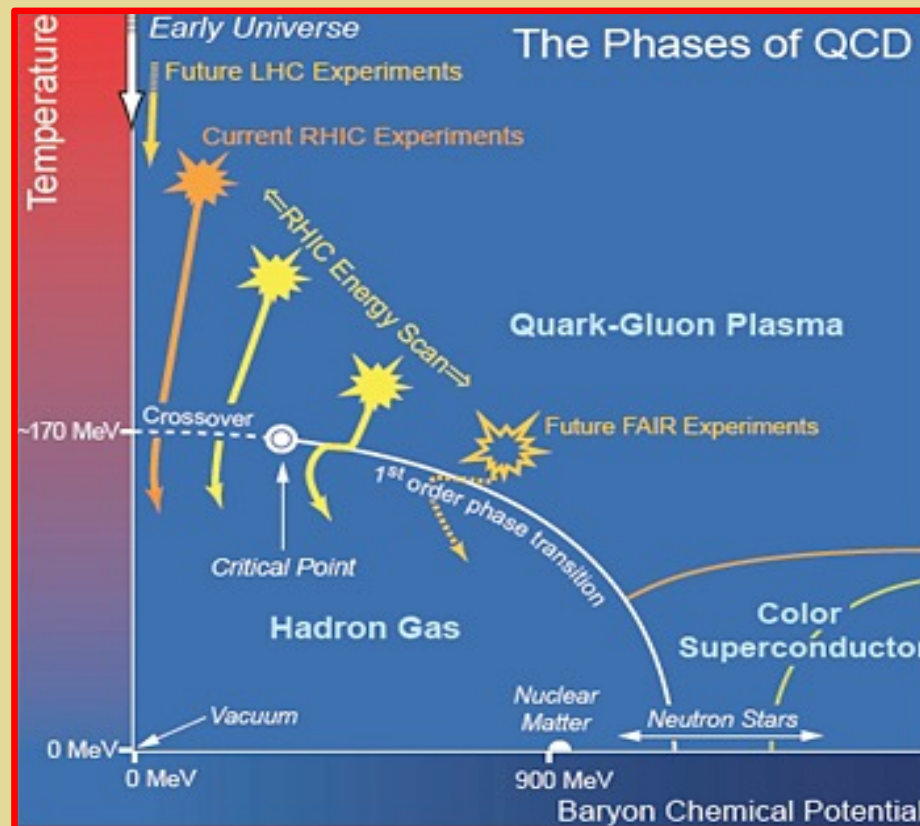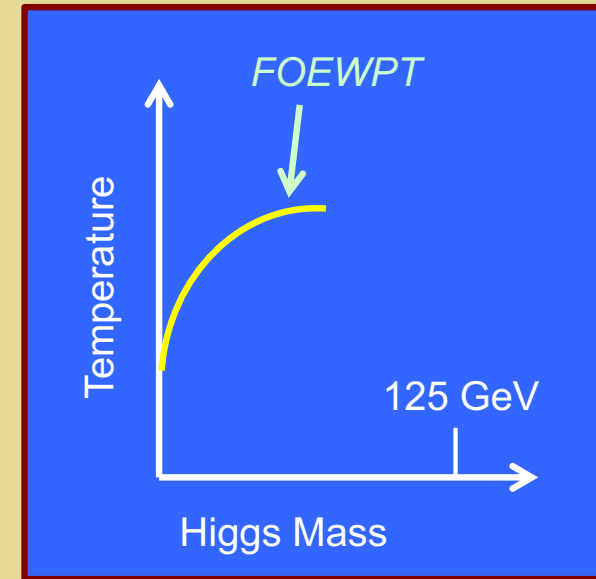

QCD Phase Diagram → EW Theory Analog?

EWSB Transition: St'd Model

F — **1st order**

$T > T_c$
$T = T_c$
$T < T_c$
$\langle \phi \rangle$

F — **2nd order**

$T > T_0$ $T = T_0$
$T < T_0$
$\langle \phi \rangle$

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

FOEWPT

Temperature

125 GeV

Higgs Mass

EW Phase Diagram

How does new TeV scale physics change this picture ? What is the phase diagram ? EWPT ? If so, what kind ?

9

Electroweak Phase Transition

- *Higgs discovery → What was the thermal history of EWSB ?*

- *Baryogenesis → Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*

- *Gravitational waves → If a signal observed in next generation probes, could a cosmological phase transition be responsible ?*

First order EWPT required

Patterns of Symmetry Breaking

BSM Scalar

$V_{EFF}\,(H,\,\Phi)$

Earlier phase

Higgs phase
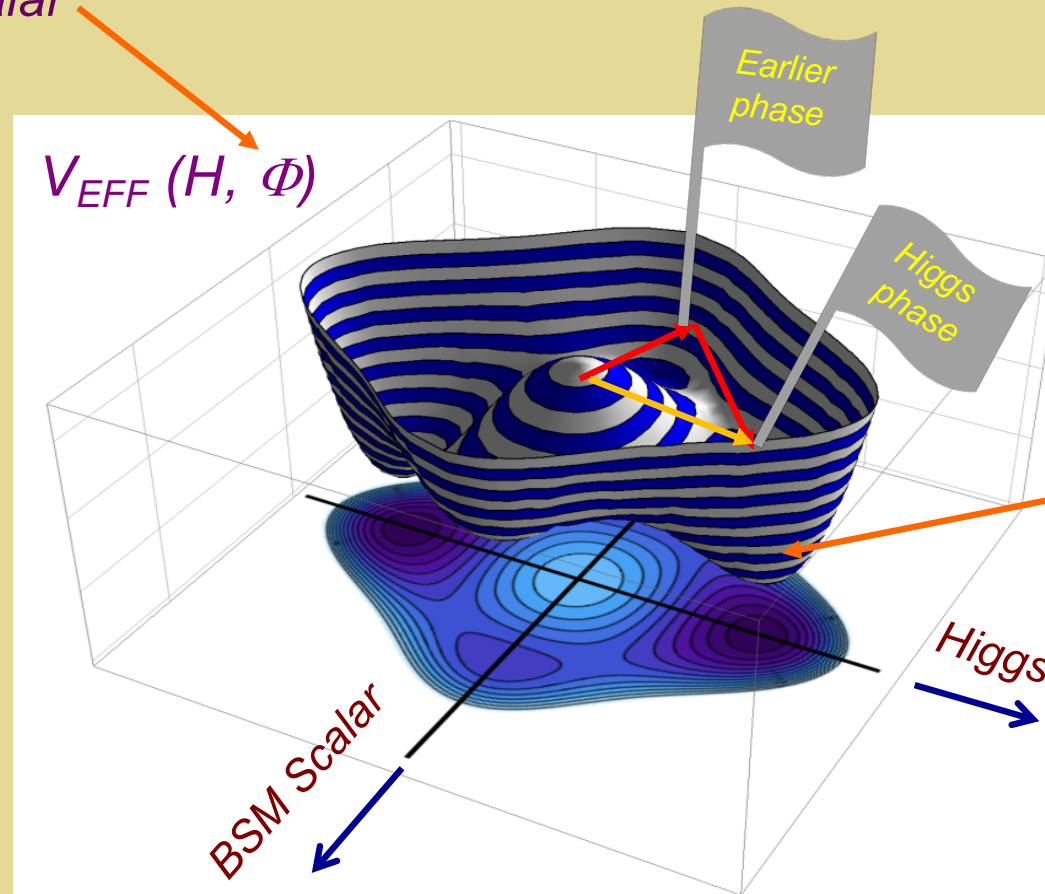
How did we end up here ?

Higgs

BSM Scalar

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

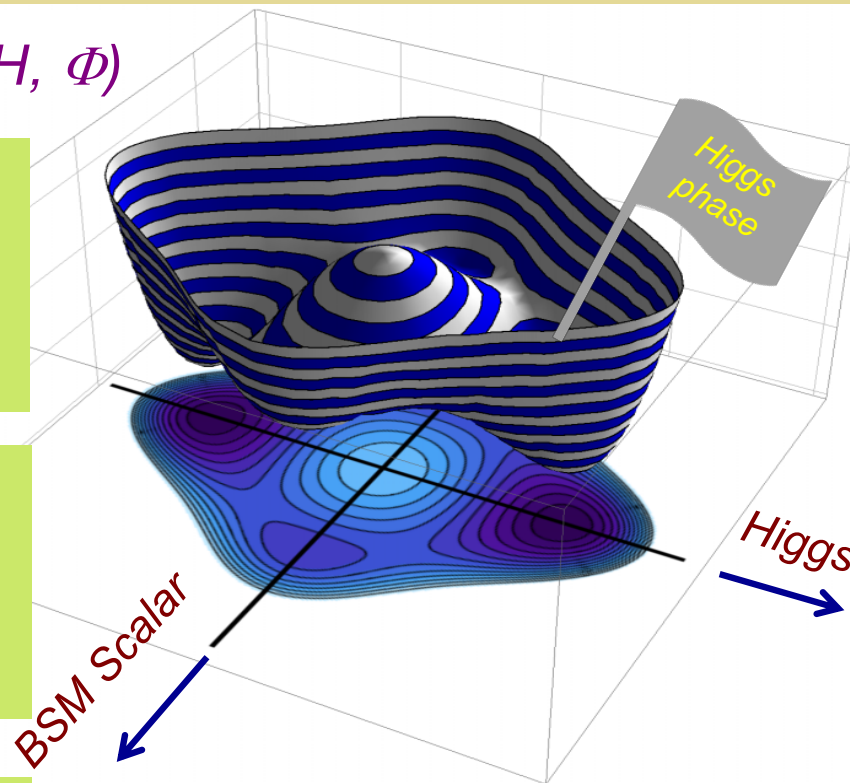# *Thermal History of EWSB*

V_{EFF} (H, Φ)

Higgs phase

Higgs

BSM Scalar

- *What is the landscape of potentials and their thermal histories?*

- *How can we probe this T > 0 landscape experimentally ?*
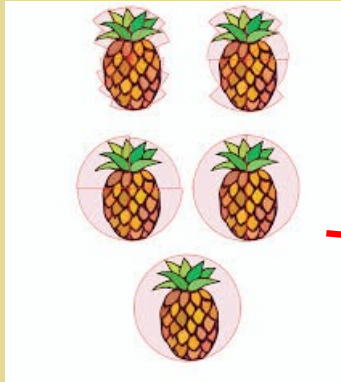
- *How reliably can we compute the thermodynamics ?*

n evolve differently as T evolves →
ilities for symmetry breaking

Experimental Probes

Bubble Collisions

Grav Radiation

Direct Production

BSM Higgs

V_{EFF} (H, Φ)

Higgs phase

Higgs

BSM Scalar
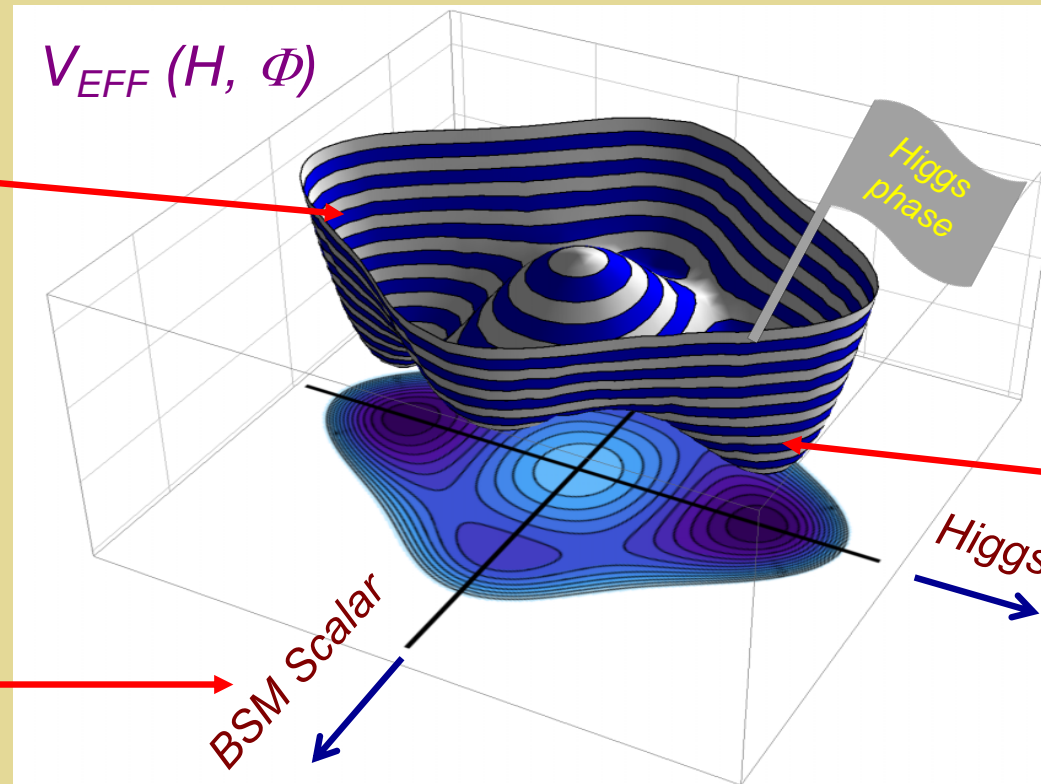
Higgs precision tests

SM Higgs   BSM Higgs

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

13

II. EWPT: A Collider Target

MJRM 19010.07189

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

T_{EW} Sets a Scale for Colliders
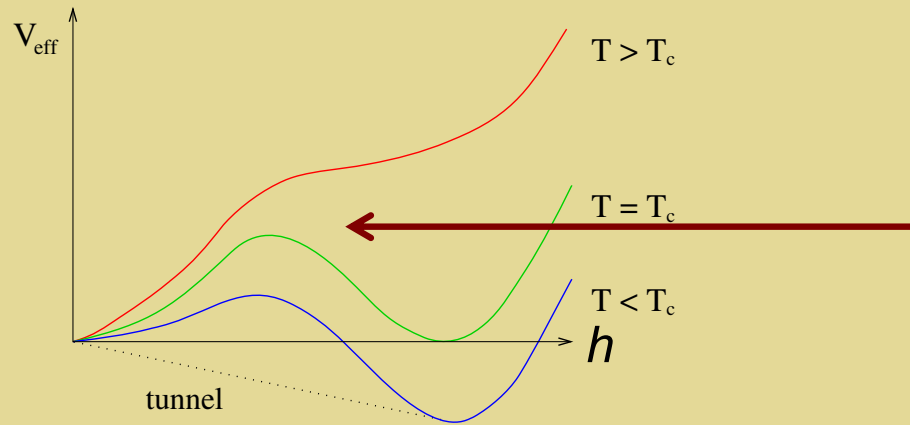
High-T SM Effective Potential

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

$$T_0^2 = (8\lambda + \text{ loops}) \left(4\lambda + \frac{3}{2}g^2 + \frac{1}{2}g'^{\,2} + 2y_t^2 + \cdots \right)^{-1} v^2$$
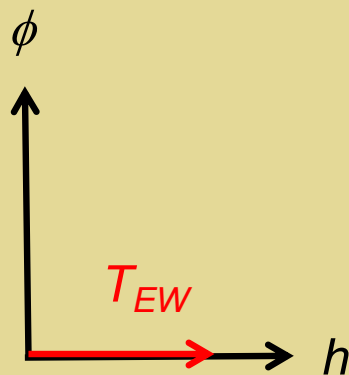
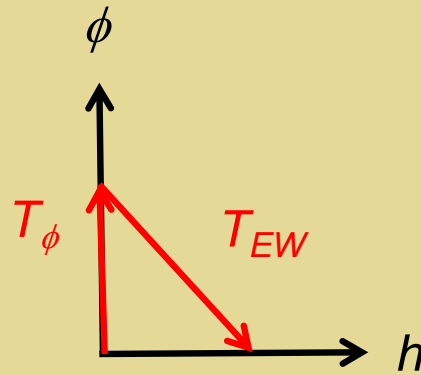$T_0 \sim$ **140 GeV** $\equiv$ T_{EW}
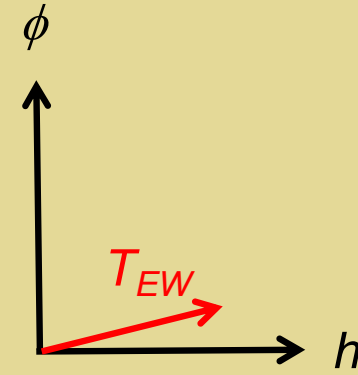
First Order EWPT from BSM Physics

V_{eff}

$T > T_c$

$T = T_c$

$T < T_c$

h

tunnel

Generate finite-T barrier

ϕ T_{EW} h

ϕ T_ϕ T_{EW} h

ϕ T_{EW} h

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

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

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

16

First Order EWPT from BSM Physics

V_{eff}

$T > T_c$

$T = T_c$

$T < T_c$

h

tunnel

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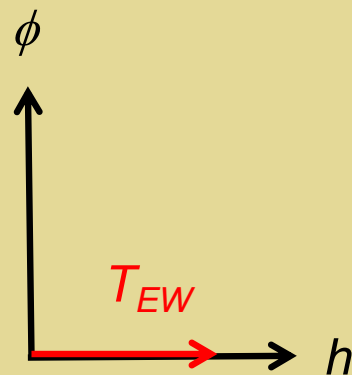
ϕ

T_{EW}

h

ϕ

T_ϕ

T_{EW}

h

ϕ

T_{EW}

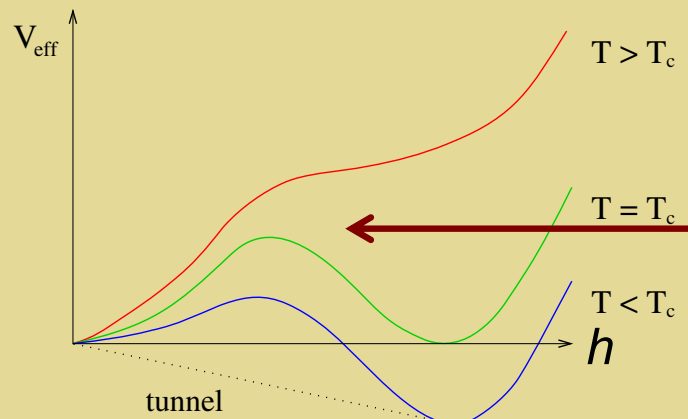h

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

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

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

17

First Order EWPT from BSM Physics
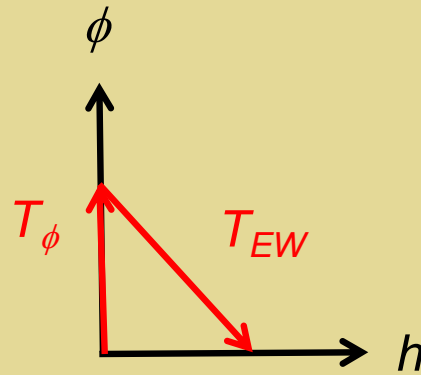

V_{eff}

$T > T_c$
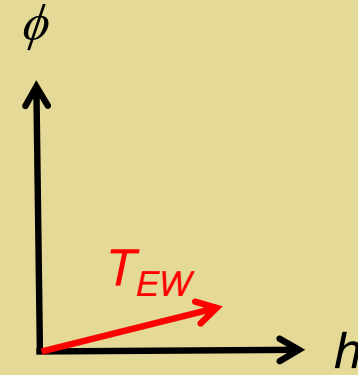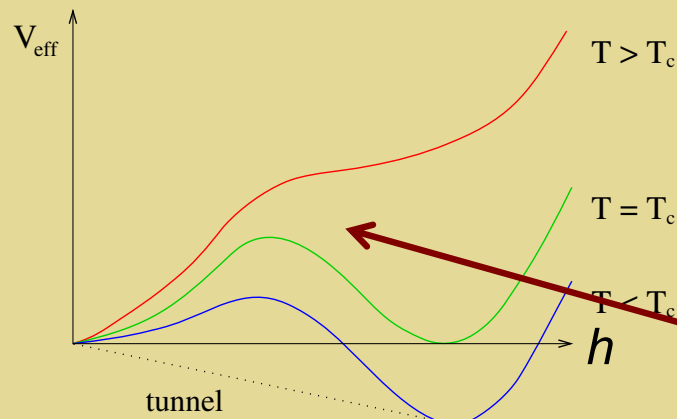
$T = T_c$

$T < T_c$

h

tunnel

Higgs $-$ ϕ^0 Mixing

$| \sin\theta | > 0.01$

ϕ

T_{EW}

h

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

ϕ

T_ϕ

T_{EW}

h

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

ϕ

T_{EW}

h

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

18
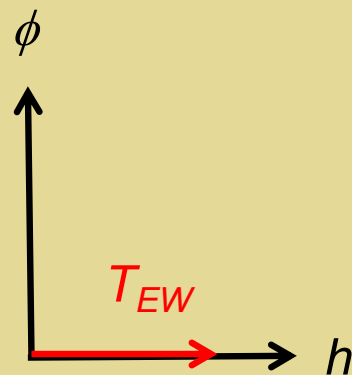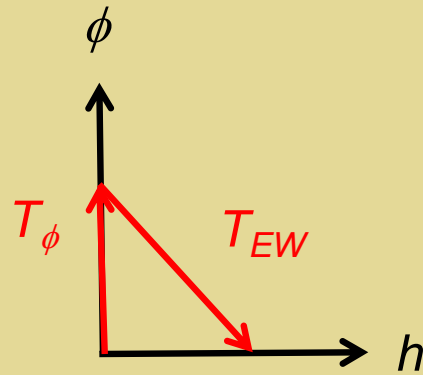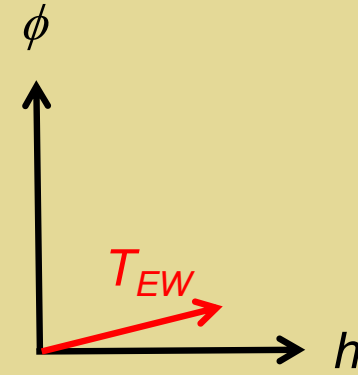
III. Higgs Boson Properties

Model Illustrations

First Order EWPT from BSM Physics

- **Thermal $\Gamma(h \rightarrow \gamma\gamma)$**

- **Higgs signal strengths**

- **Higgs self-coupling**

- **Exotic Decays**

- **Single ϕ production**

First Order EWPT from BSM Physics

- **Thermal $\Gamma(h \rightarrow \gamma\gamma)$**

- **Higgs signal strengths**

- **Higgs self-coupling**

$H^2\phi^2$ **Barrier ?**

- **Exotic Decays**

- **Single ϕ production**

First Order EWPT from BSM Physics

- **Thermal $\Gamma(h \to \gamma\gamma)$**

- **Higgs signal strengths**

- **Higgs self-coupling**

- **Exotic Decays**

- **Single ϕ production**

$H^2\phi$ Barrier ?

H-ϕ Mixing

Higgs Portal: Simple Scalar Extensions

Extension	DOF	EWPT	DM	
Real singlet: $\not{Z_2}$	1	✓	✗	xSM
Real singlet: Z_2	1	✓	✓	
Complex Singlet	2	✓	✓	
EW Multiplets	3+	✓	✓	

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

Singlets: Precision & Res Di-Higgs Prod

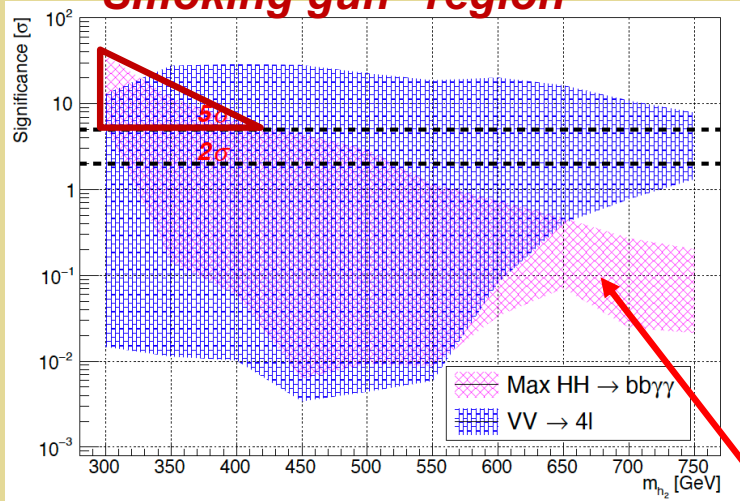*SFOEWPT Benchmarks:* Resonant di-Higgs *& precision Higgs studies*
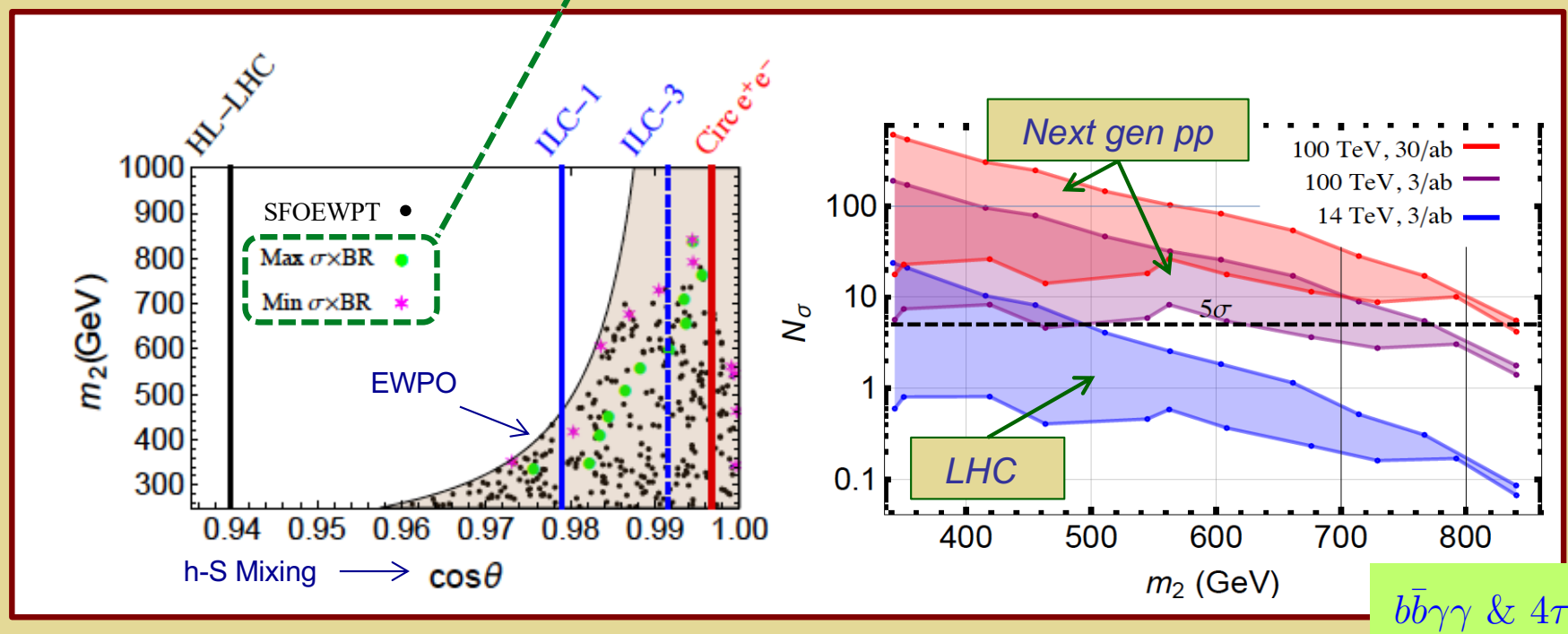
Kotwal, No, R-M, Winslow 1605.06123
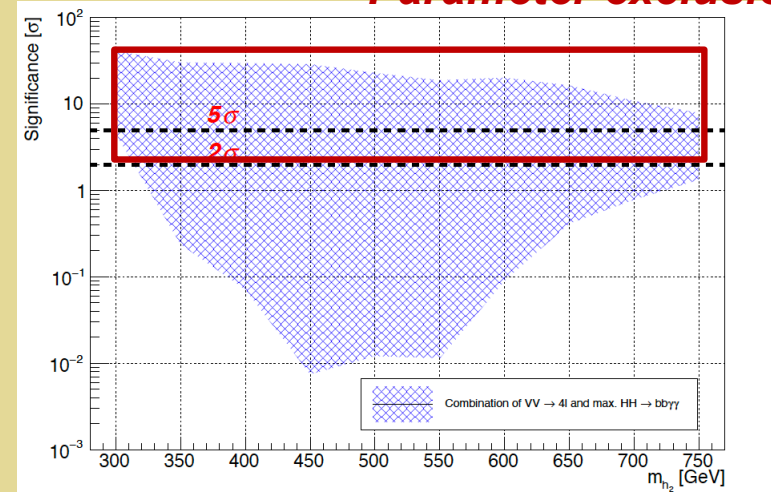
See also: Huang et al, 1701.04442;
Li et al, 1906.05289

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

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

"Smoking gun" region

Parameter exclusion region

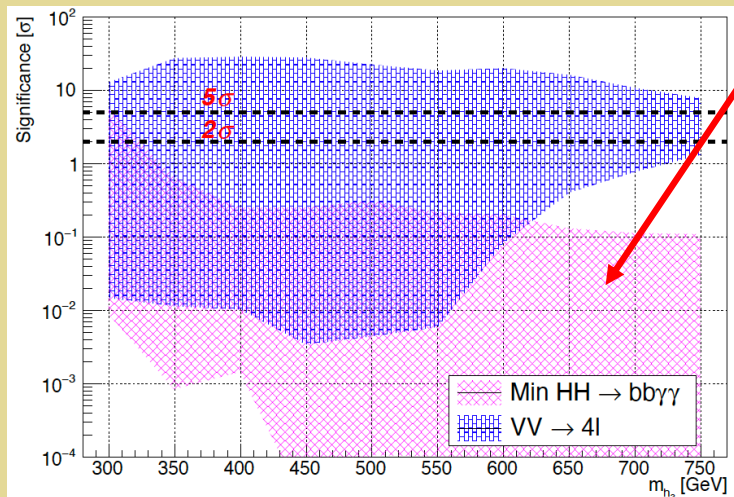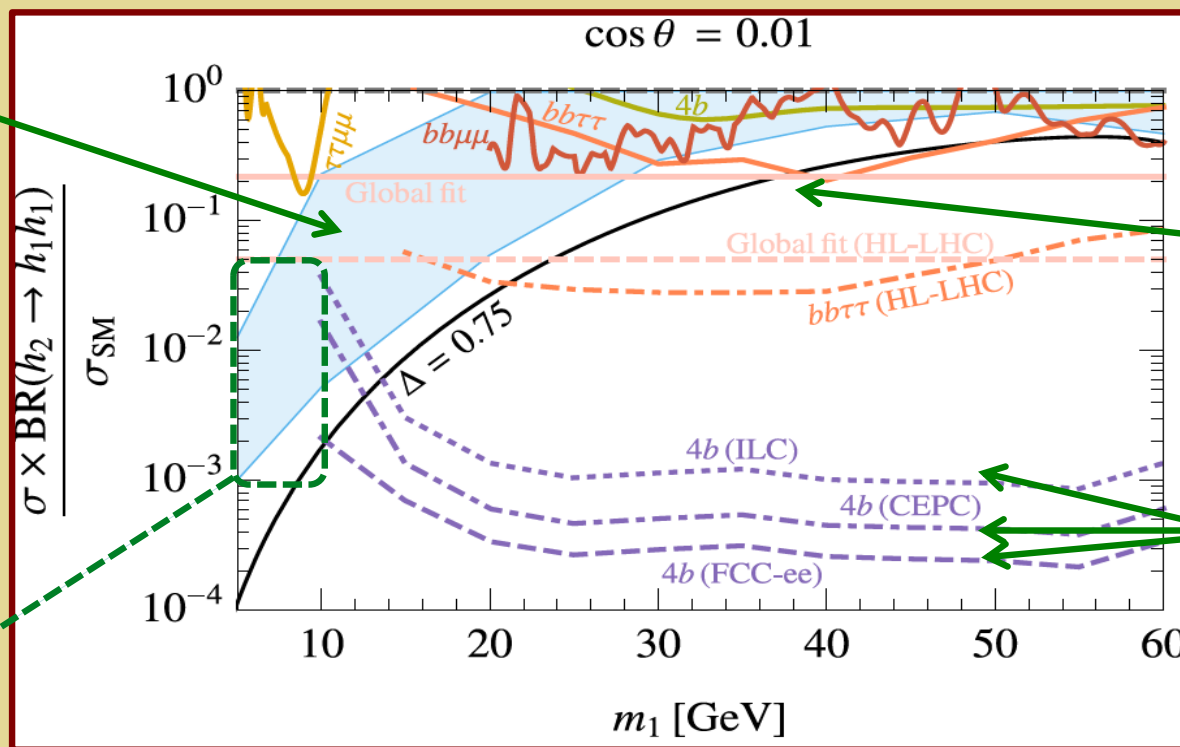**100 TeV accessible**

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.NNNNN

25

Light Singlets: Exotic Higgs Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical

Other probes?

EWPT viable: Semi analytic

Future e^+e^-

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,

26

Higgs Portal: Simple Scalar Extensions

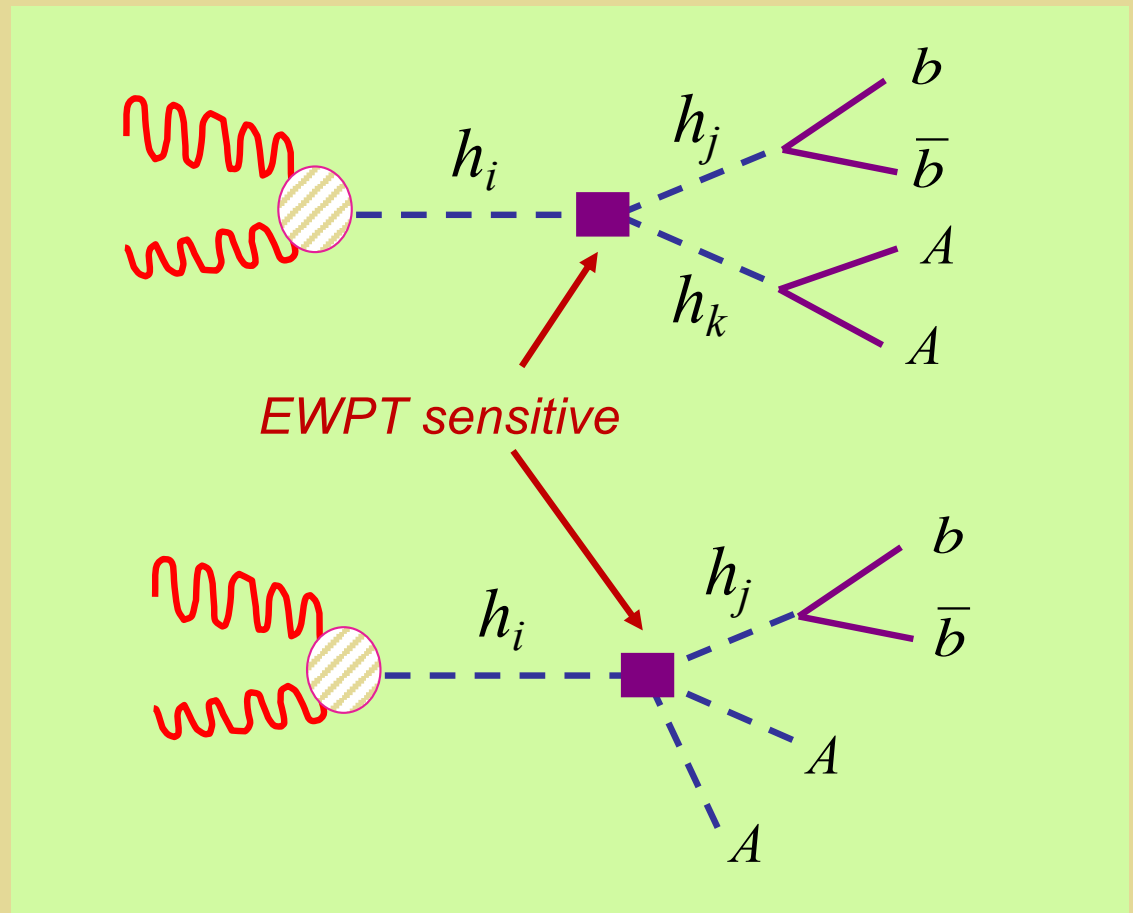| Extension		DOF	EWPT	DM
Real singlet:	~~Z₂~~	1	✓	✗
Real singlet:	Z_2	1	✓	✓
Complex Singlet		2	✓	✓
EW Multiplets		3+	✓	✓

cxSM

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

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

EWPT sensitive

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

Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang   2212.NNNNN

Complex Singlet: DM + EWPT

Search for bb + MET
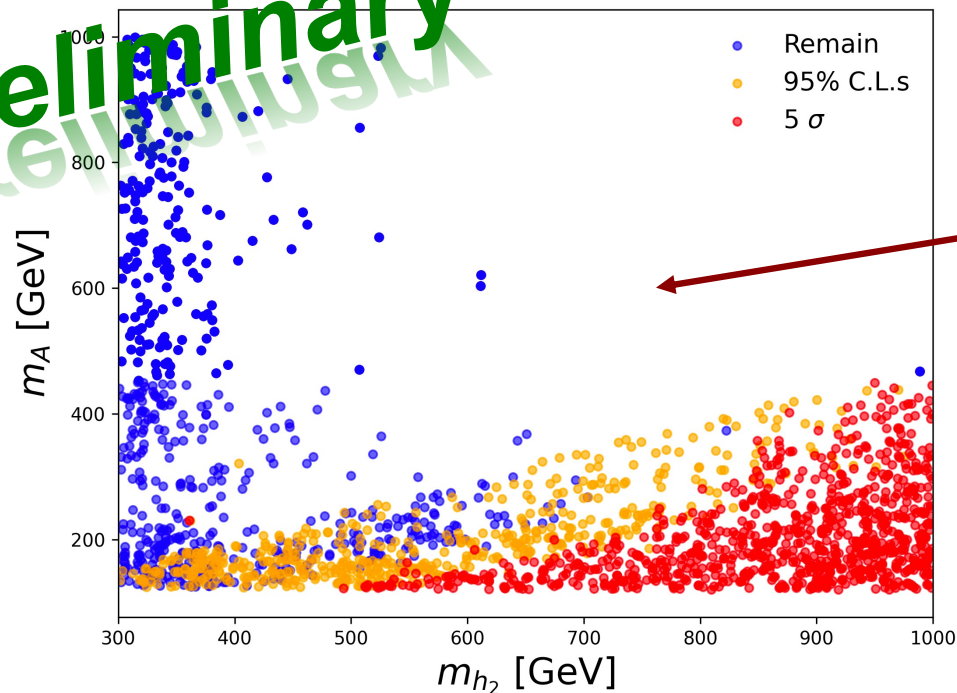
Heavy Higgs → VV exclusion: BR (h_2→VV) larger when $m_{h2} < 2 m_A$
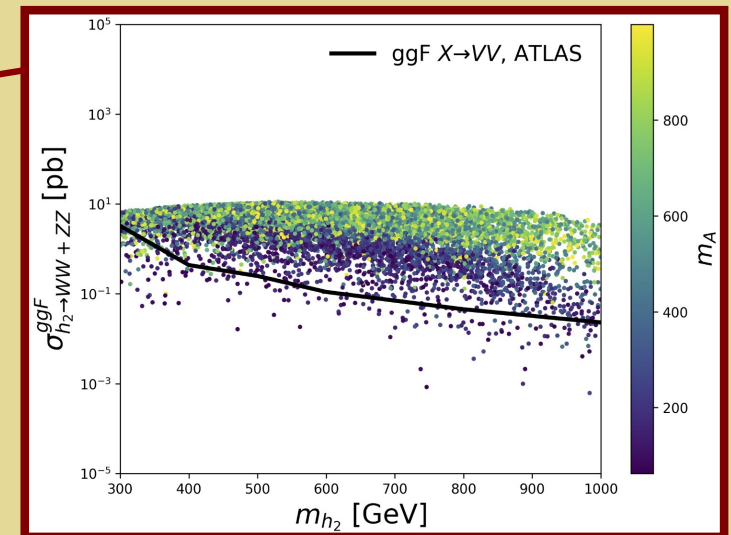
Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang   2212.NNNNN

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

Real Triplet

ΣSM:
Σ ~ (1, 3, 0)

$a_2 H^2 \phi^2$: 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
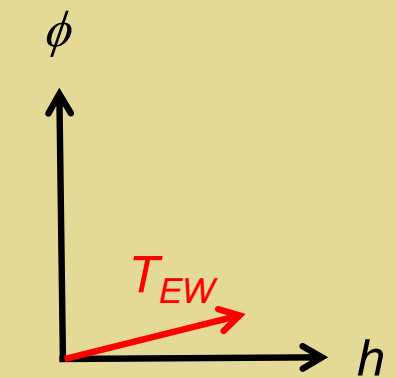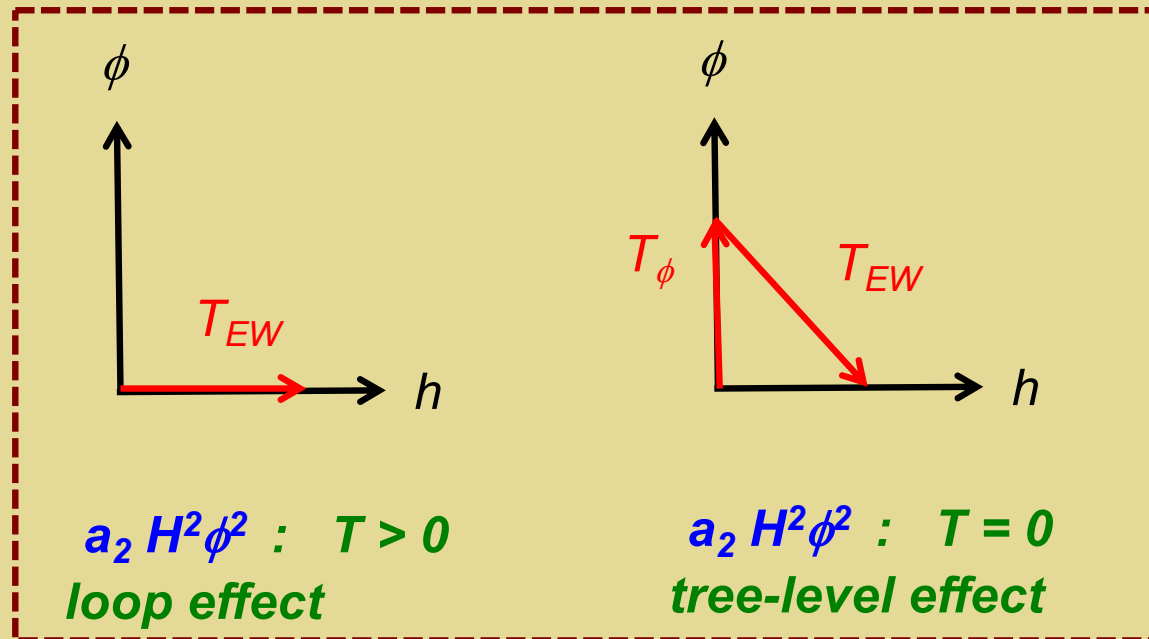
EW precision tests →
too tiny

First Order EWPT from BSM Physics

- $\Gamma(h \rightarrow \gamma\gamma)$

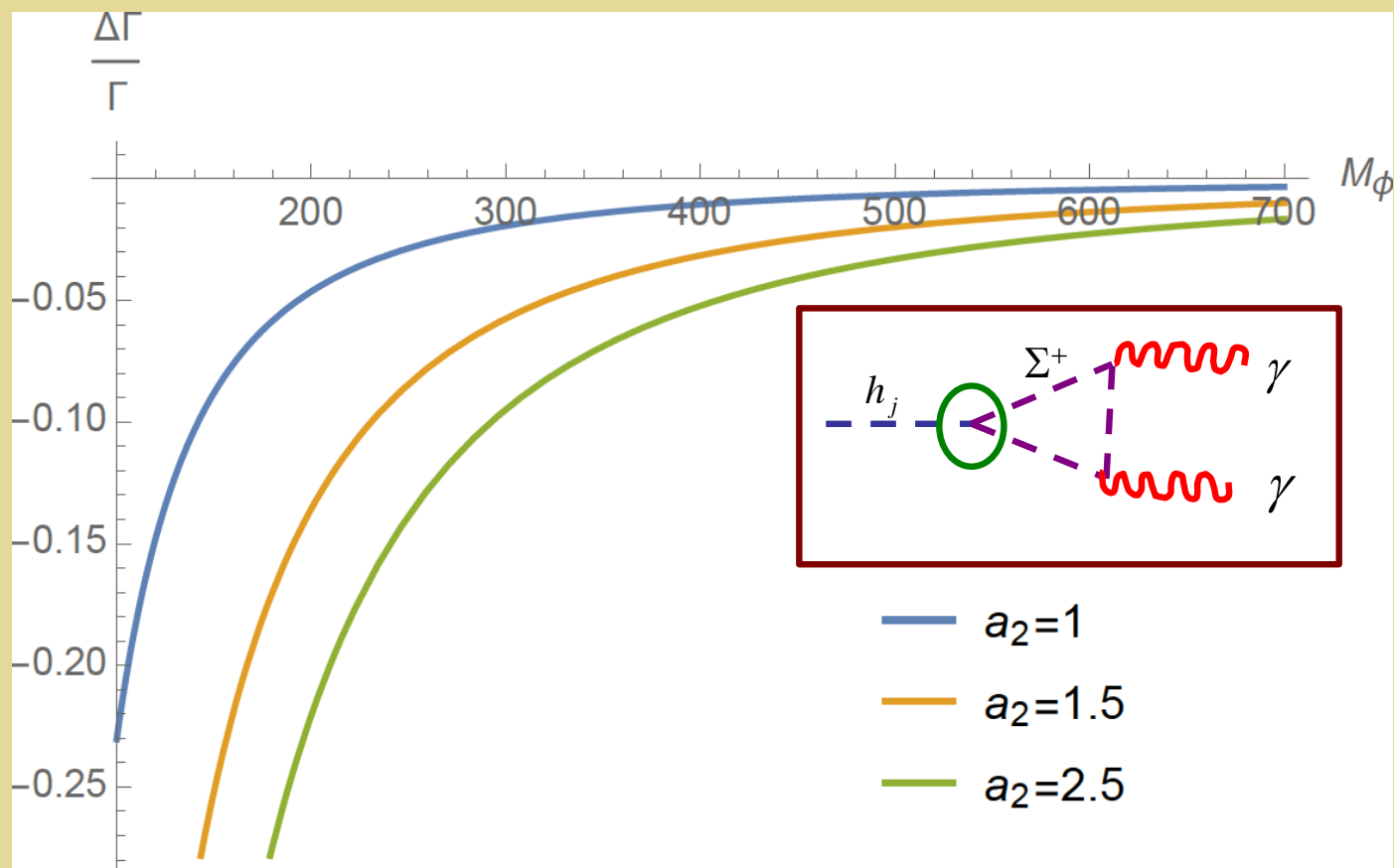- **Higgs signal strengths**

- **Higgs self-coupling**

- **Exotic Decays**

$H^2 \phi^2$ **Barrier ?**

$\phi :$ **EW Multiplet**
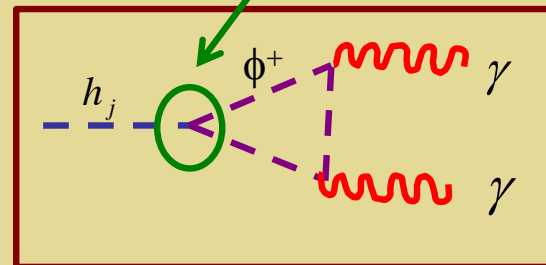
$H \rightarrow \gamma\gamma$: Is There a Barrier ?

EWPT → Decrease in rate

H → γγ : Is There a Barrier ?

34
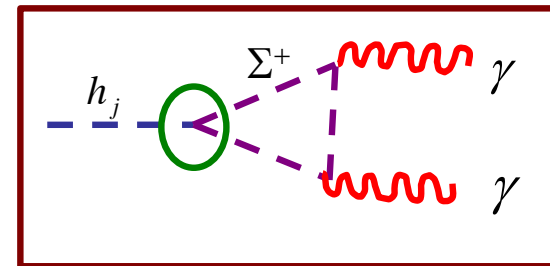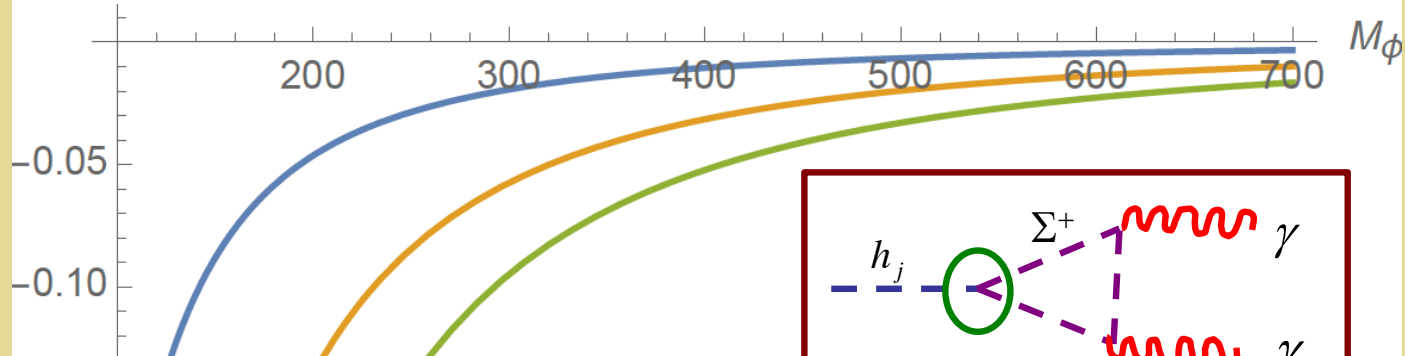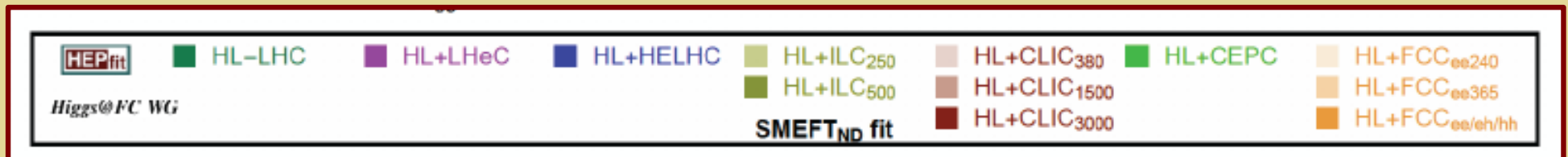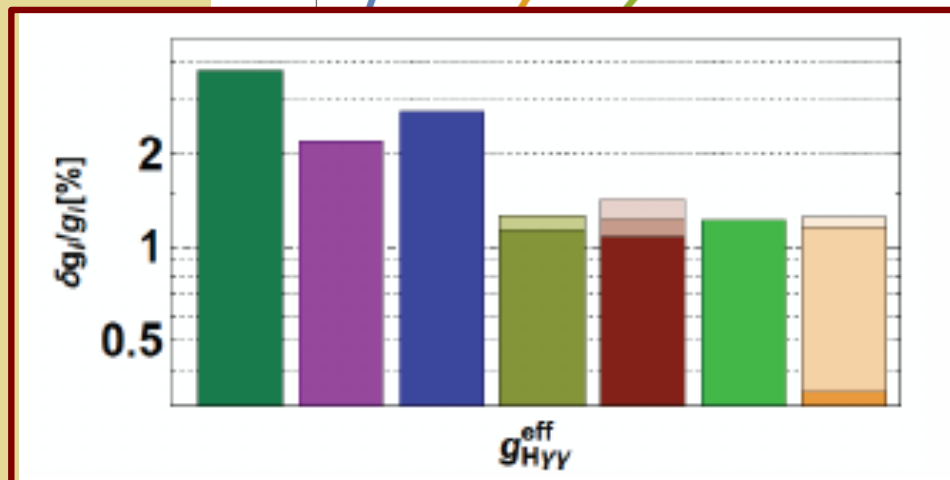
Real Triplet & EWPT

FOEWPT

Σ^+

h_j

γ

γ

Crossover

a_2

Higgs Portal Coupling

$\delta = 0.10$

$\delta = 0.08$

$\delta = 0.00$

$\delta = 0$

$\mu_\Sigma^2 = 0$

Crossover ($x > 0.11$)

First order PT ($0 < x < 0.11$)

DR breaks down ($x < 0$)

disappearing track
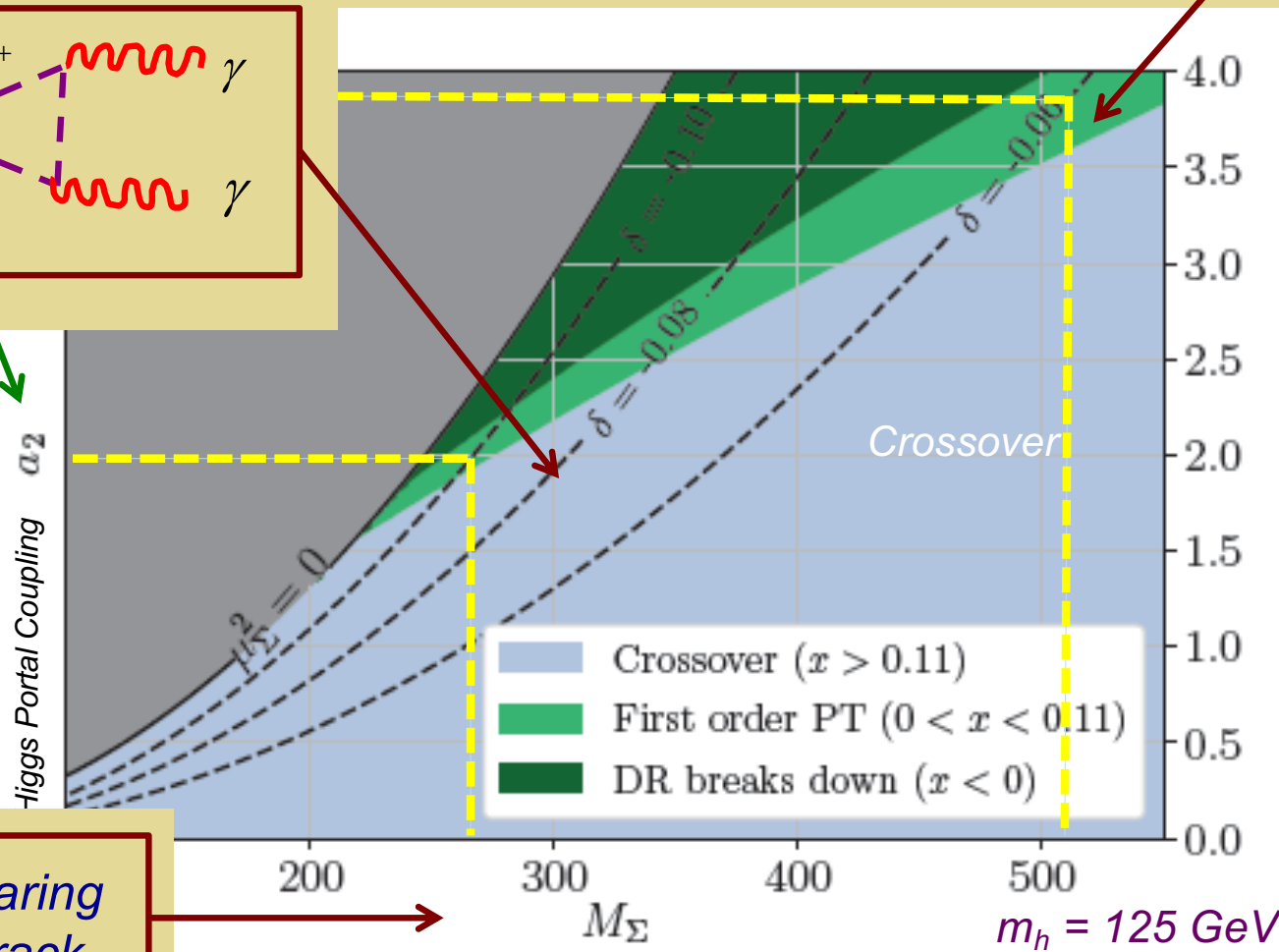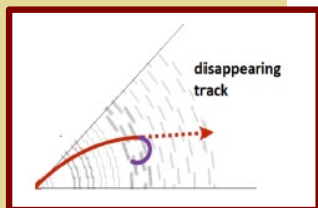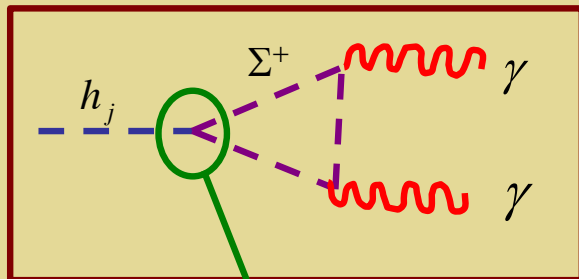
Disappearing charge track

200 300 400 500

M_Σ

$m_h = 125$ GeV

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

- One-step
- Non-perturbative

35

Real Triplet & EWPT: Novel EWSB

Niemi, R-M, Tenkanen, Weir 2005.11332
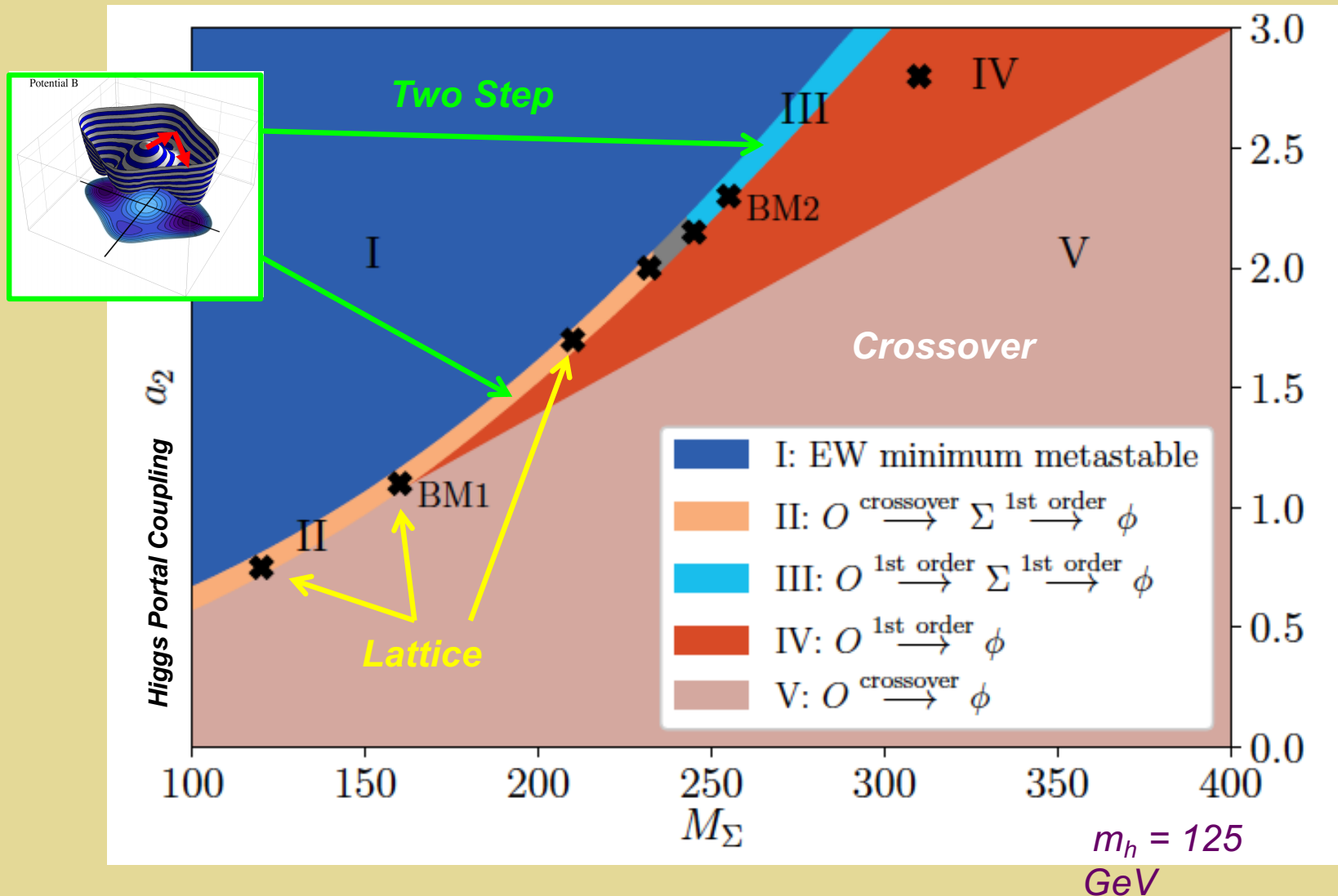
- *1 or 2 step*
- *Non-perturbative*

36

Dynamical BSM Scalar: EWPT & GW

(a) Plot with axes a_2 (vertical, 0.5 to 2.0) and m_Σ (GeV) (horizontal, 100 to 250). Labels: *1 Step FO*, *2nd Step*, *Lisa*, *Crossover*. Legend: BMA (2σ), BMA' (2σ), LISA sensitivity.

(b) Plot with axes β/H_* (vertical, 10 to 10^5) and α (horizontal, 0.001 to 1). Labels: *BMA*, *BMA'*, DECIGO, eLISA, LISA.

BMA: $m_\Sigma + h \rightarrow \gamma\gamma$

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

Friedrich, MJRM, Tenkanen, Tran 2203.05889
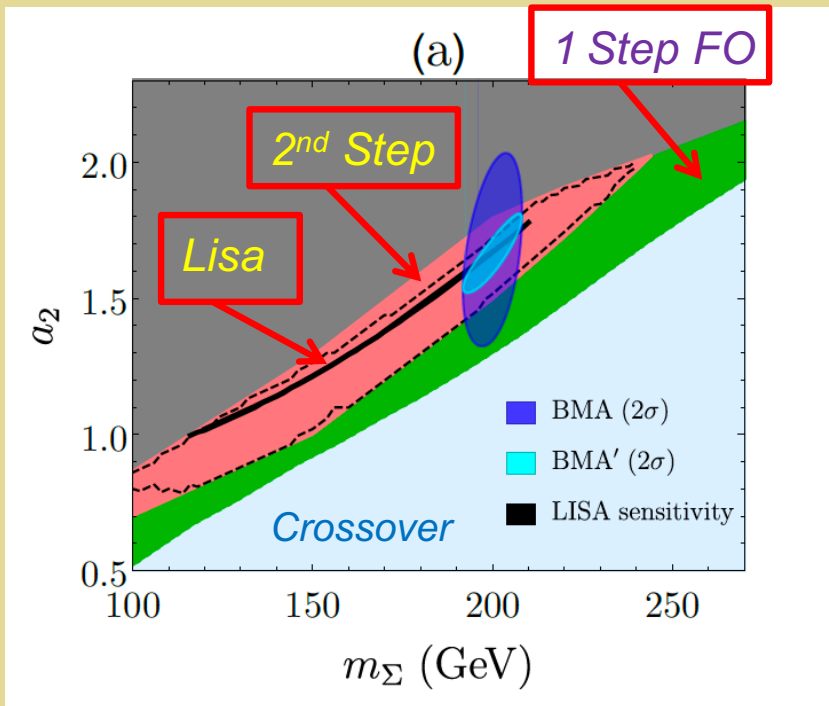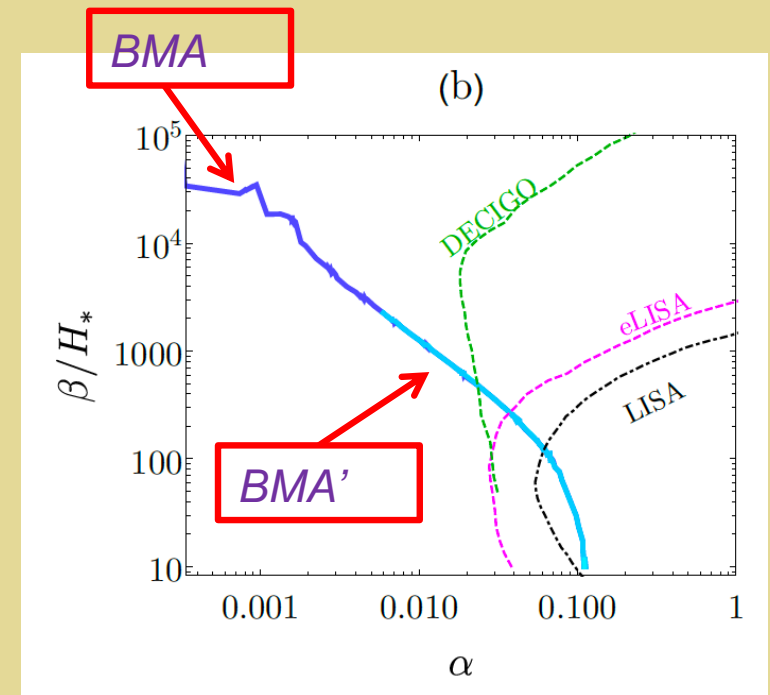
- *Two-step*
- *EFT+ Non-perturbative*

37

IV. Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. 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*

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

Real Triplet: One-Step EWPT

FOEWPT

- Two-step region
- See previous slide

Crossover

Lattice needed

Higgs Portal Coupling a_2

$\delta = 0.10$

$\delta = 0.08$

$\delta = 0.06$

$\mu_\Sigma^2 = 0$

Crossover $(x > 0.11)$

First order PT $(0 < x < 0.11)$

DR breaks down $(x < 0)$

M_Σ

$m_h = 125$ GeV

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

- One-step
- Non-perturbative

41
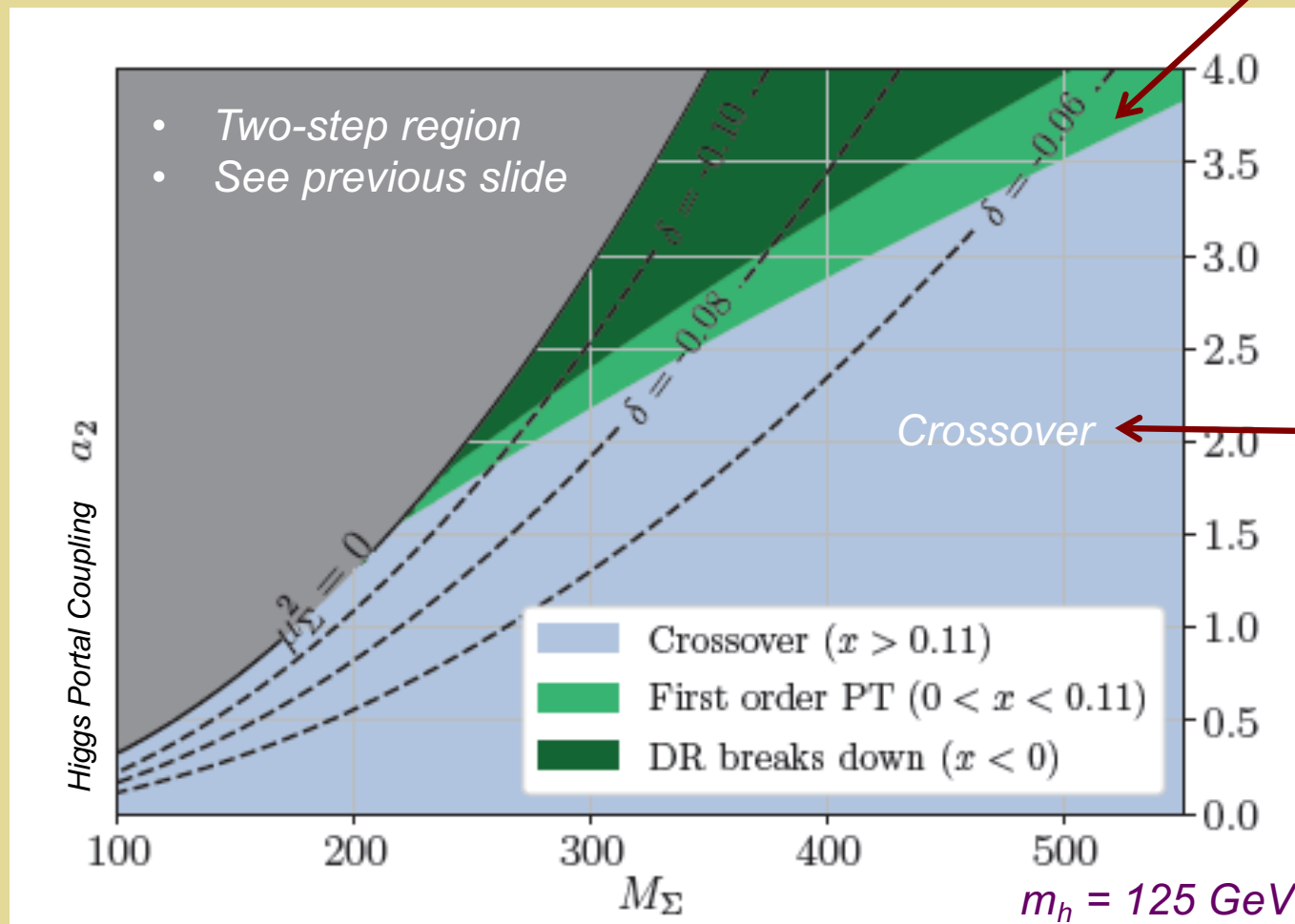
Real Singlet: One-Step EWPT

Condensate change at T_c

Plot axes: $2\Delta\langle\phi^\dagger\phi\rangle/T_c^2$ vs $\sin\theta$

Legend:
- 1-loop
- 2-loop
- lattice $\beta = 40$
- lattice $a \to 0$

Preliminary

Doublet-singlet mixing

Pert Th'y: FOEWPT

Lattice: FOEWPT

Lattice: Crossover

Small θ: Truly FOEWPT ?

Inset plot: m_2(GeV) vs $\cos\theta$, HL-LHC, ILC-1, ILC-3, Circ e^+e^-, Max $\sigma\times$BR, Min $\sigma\times$BR

Lauri Niemi, MJRM, Guotao Xia In progress

42
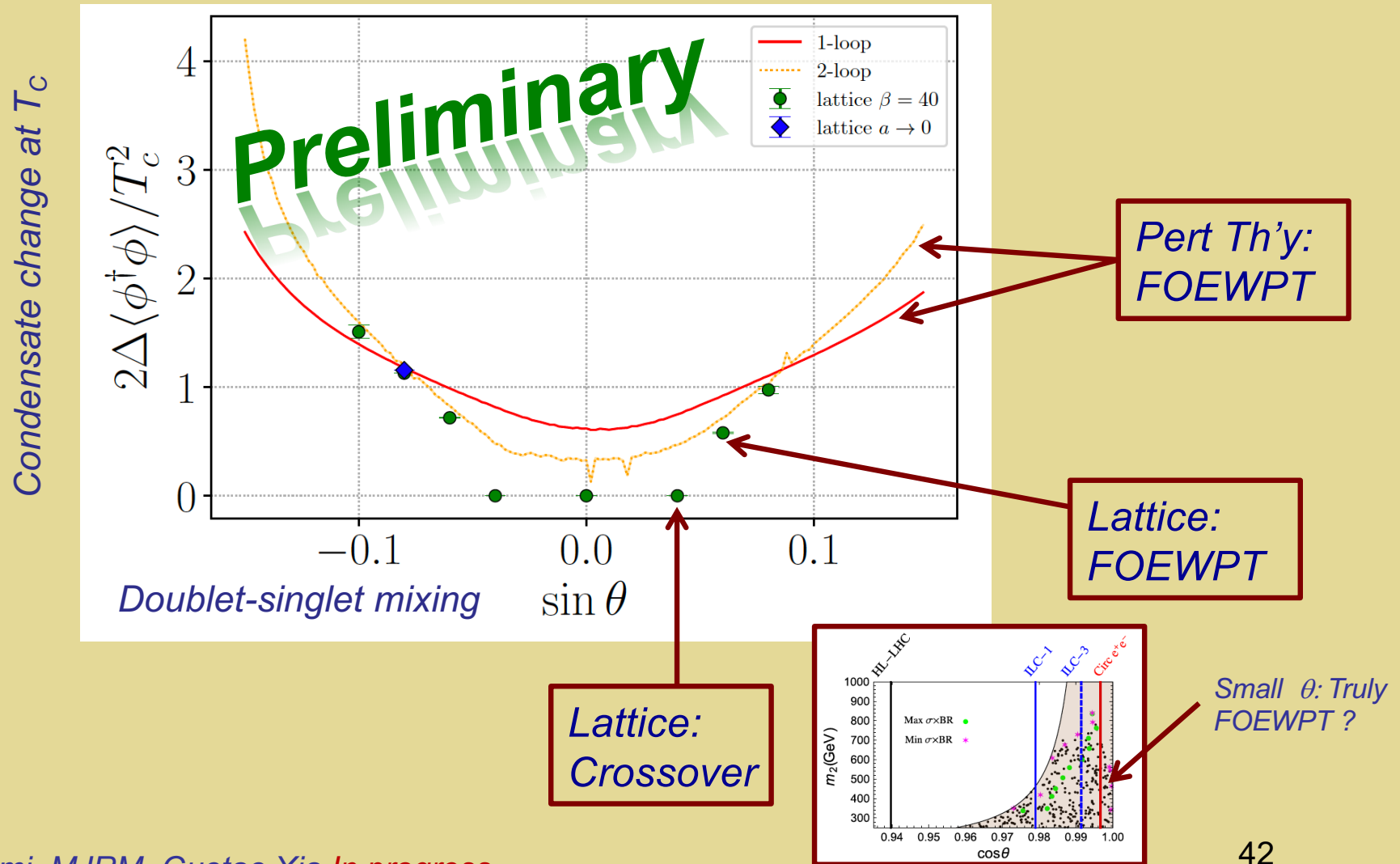
Opportunities

TDLI/SJTU Program

Model building & cosmological scenarios

Pheno: Collider, EDM, Gravitational Radiation

EW Phase Transition & EW Baryogenesis

Robust theory computations: formal "machinery", analytic, non-perturbative

44

IV. Outlook

- *Determining the thermal history of EWSB is field theoretically interesting in its own right and of practical importance for baryogenesis and GW → a key challenge for particle physics*

- *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*

- *A robust confrontation of of experiment and theory requires new level of theoretical rigor combining EFT methods with lattice simulations and new advances in theoretical tools*

Was There an Electroweak Phase Transition?

Answering this question is an exciting frontier at the interface of particle physics and cosmology, with ample opportunities for significant theoretical and experimental advances

谢谢