Exotic Higgs Decay Probes of an Electroweak Phase Transition

M.J. Ramsey-Musolf

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

- *mjrm@umass.edu*
- *mjrm@sjtu.edu.cn*
- *微信：mjrm-china*
- *https://michaelramseymusolf.com/*

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

European CEPC Workshop
Marseilles April 8, 2024

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 Electroweak Phase Transition ?

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

→ *First Order EWPT*

Was There an Electroweak Phase Transition ?

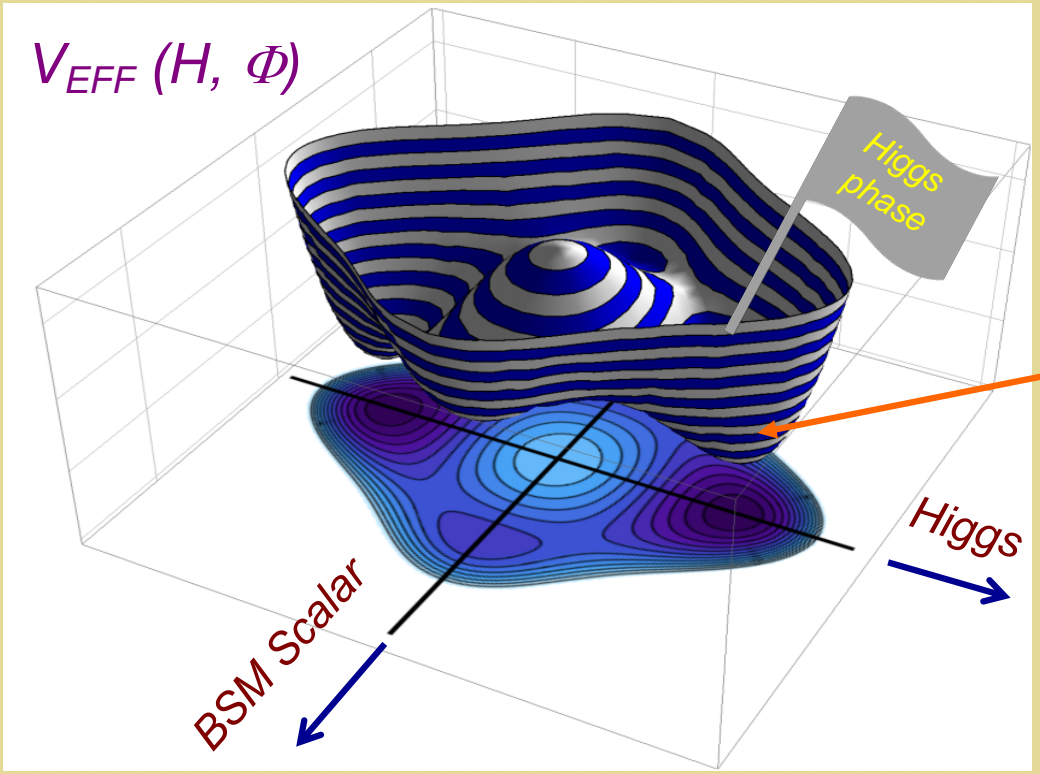
- *Interesting in its own right*
- *Key ingredient for EW baryogenesis*
- *Source of gravitational radiation*

First Order EWPT

SM: $m_H < 70$ GeV

BSM Scalars

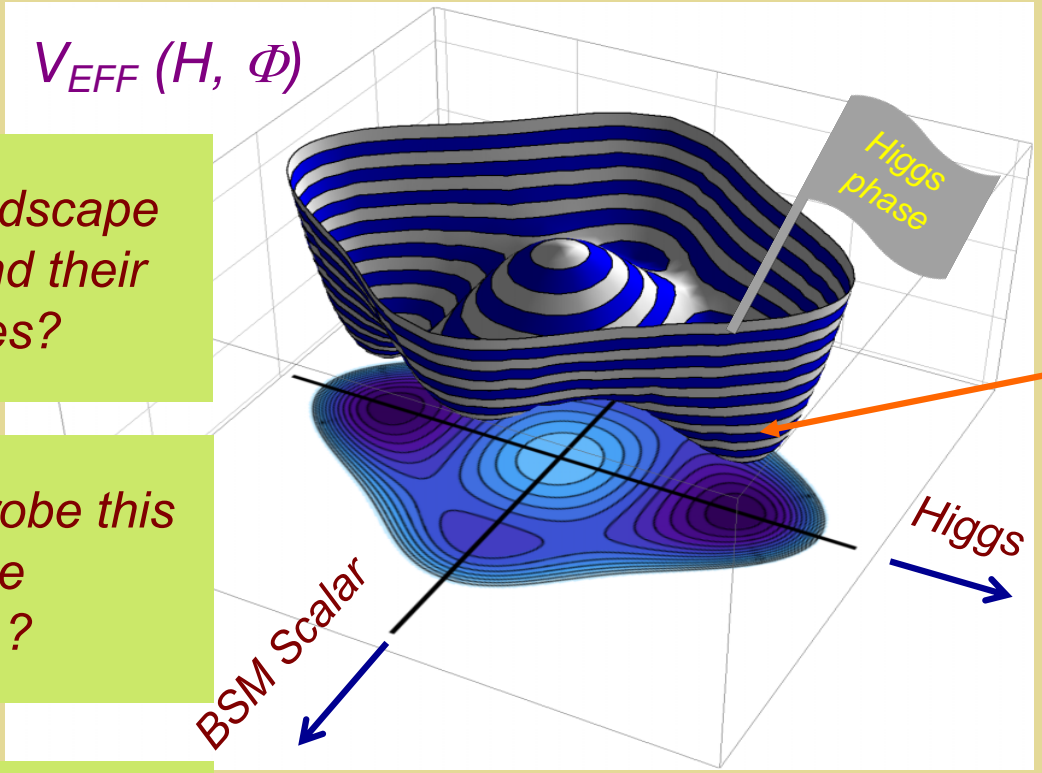
Was There an EW Phase Transition?



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

Was There an EW Phase Transition?

- *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

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

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

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

High-T SM Effective Potential

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

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

FO EWPT → Collider target:

$M_{BSM} \lesssim$ 700 GeV

$\delta\,\kappa_H \gtrsim 0.01$

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

High-T SM Effective Potential

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

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

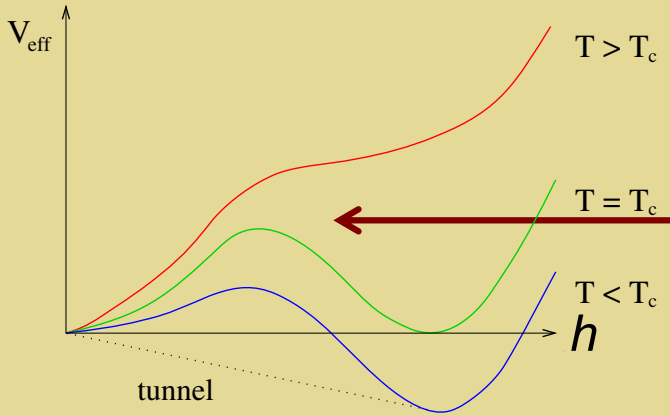
Exotic Higgs decays:
Light BSM scalar ?

FO EWPT → Collider target:

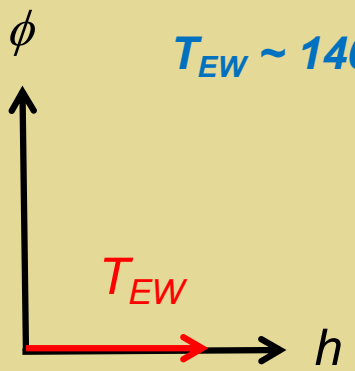
$M_{BSM} \lesssim$ 700 GeV

$\delta\,\kappa_H \gtrsim 0.01$

First Order EWPT from BSM Physics

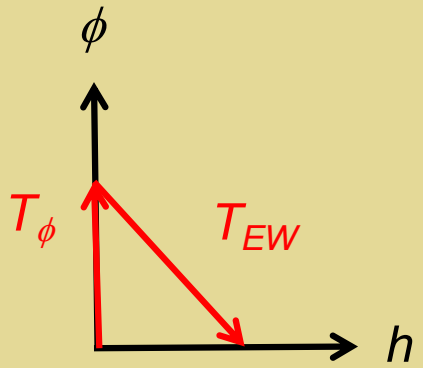


Representative thermal histories → barrier for SFOEWPT

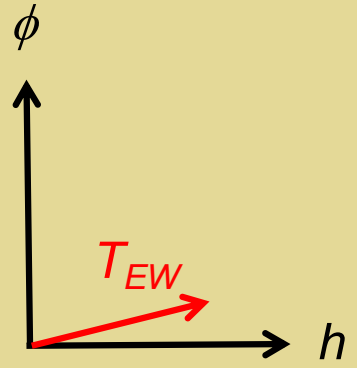


$T_{EW} \sim 140$ GeV

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



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



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

II. Model Illustrations

Simple Higgs portal models:

- ***Real gauge singlet (SM + 1)***
- ***EW Multiplets (SM + 3,4,…)***

II. Model Illustrations

Simple Higgs portal models:

- *Real gauge singlet (SM + 1)*
- *EW Multiplets (SM + 3,4,…)*

Simplest Extension

Standard Model + real singlet scalar

Z_2 Z_2

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

Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

Simplest Extension

Standard Model + real singlet scalar

$\not{Z}_2$ Z_2

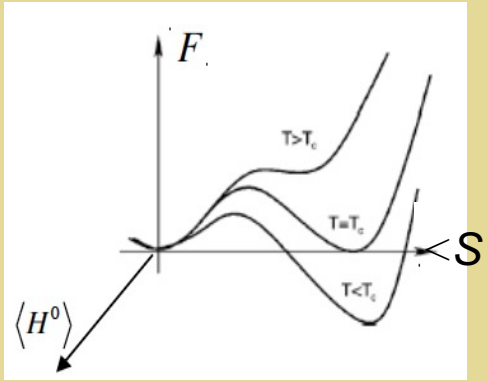
$$V_{\rm HS} = \frac{a_1}{2}\left(H^\dagger H\right) S + \frac{a_2}{2}\left(H^\dagger H\right) S^2$$

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

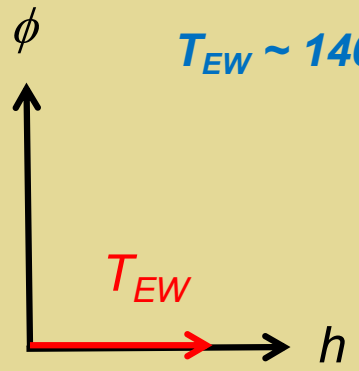
EWPT



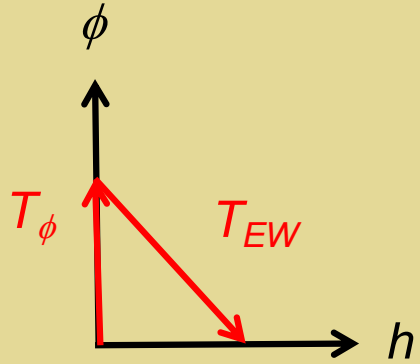
T_C , Γ_N , Γ_{sph} , …

Profumo, R-M, Shaugnessy JHEP 0708 (2007) 010

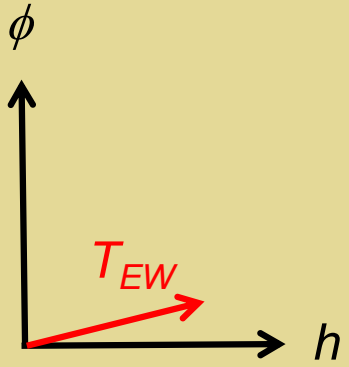
Exotic Higgs Decays & EWPT



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



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



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

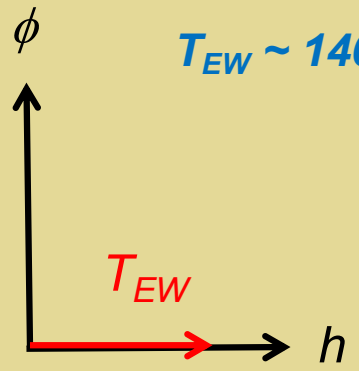
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

Exotic decays

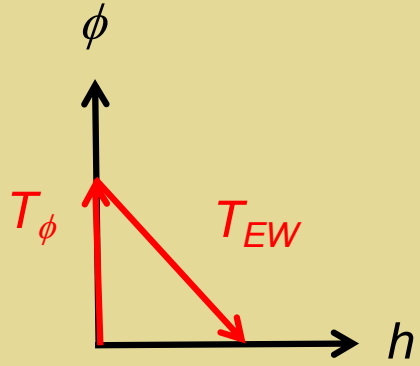
$h_1 \rightarrow h_2 h_2$

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

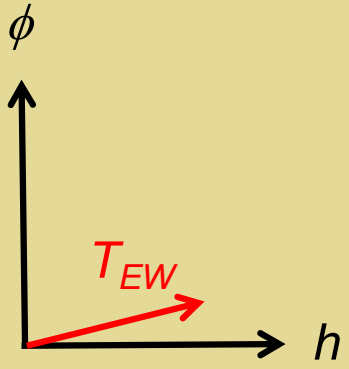
Exotic Higgs Decays & EWPT



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



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



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

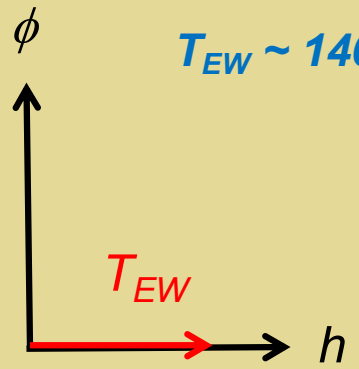
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

Exotic decays

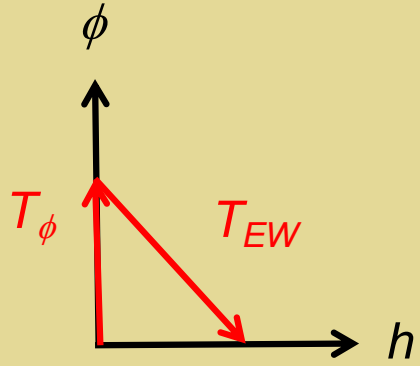
$h_1 \rightarrow h_2 h_2$

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

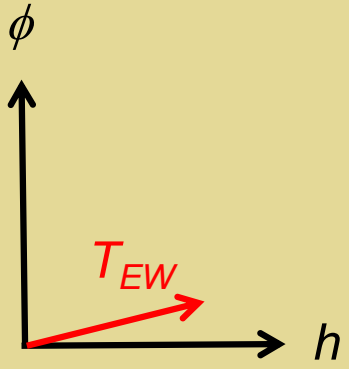
Exotic Higgs Decays & EWPT



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



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



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

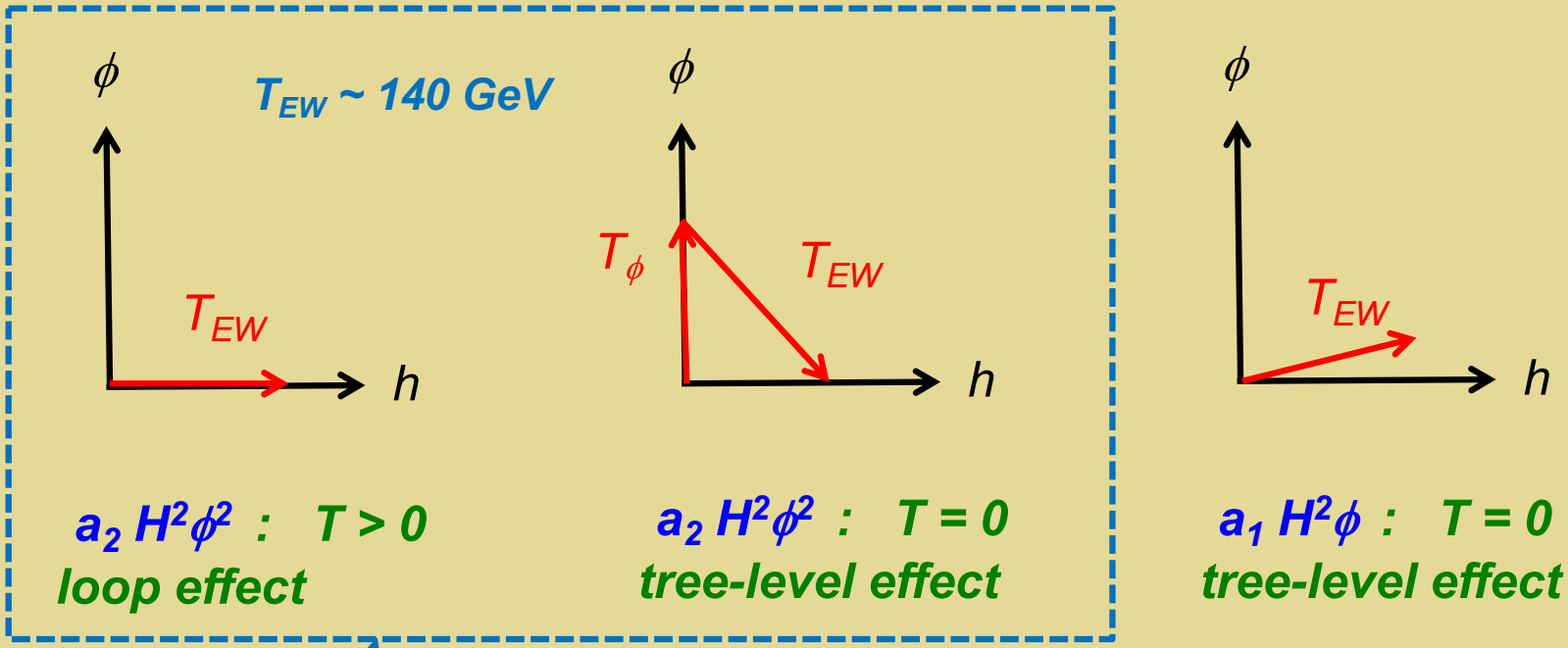
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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



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

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

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

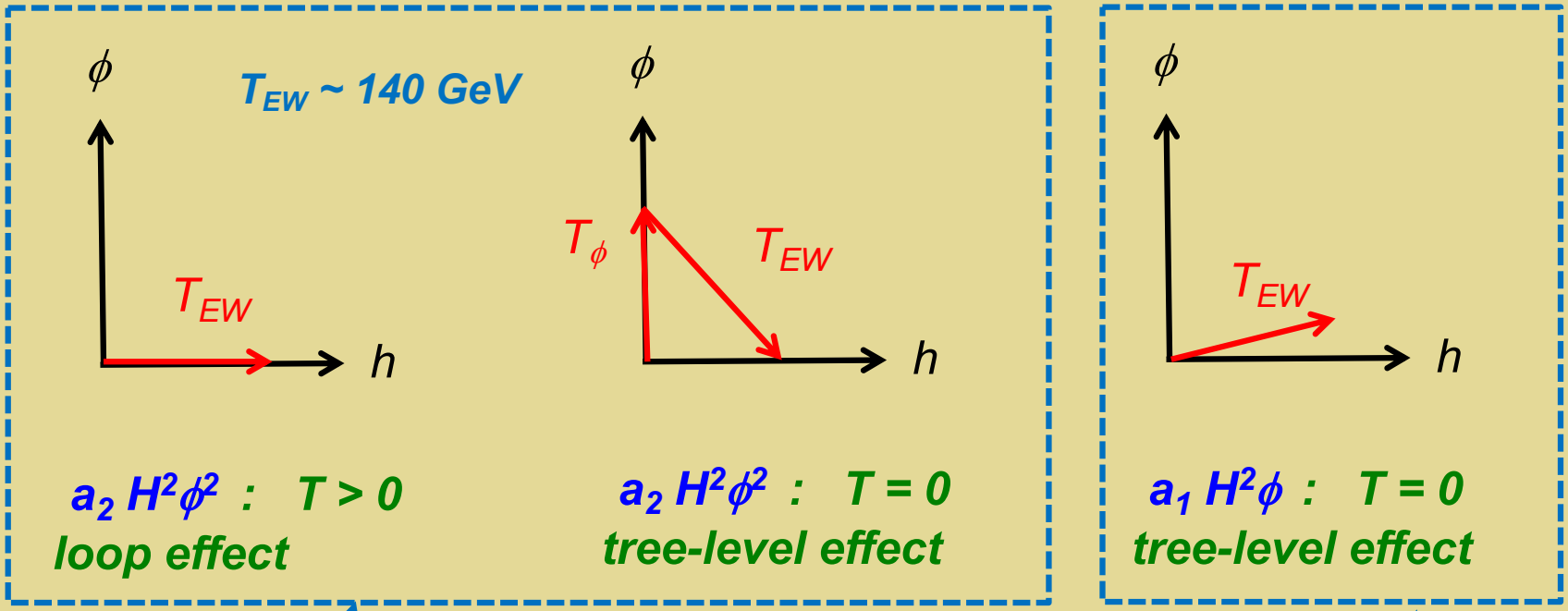
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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



Spont

Explicit

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

Exotic decays

$h_1 \to h_2 h_2$

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

Z_2 breaking

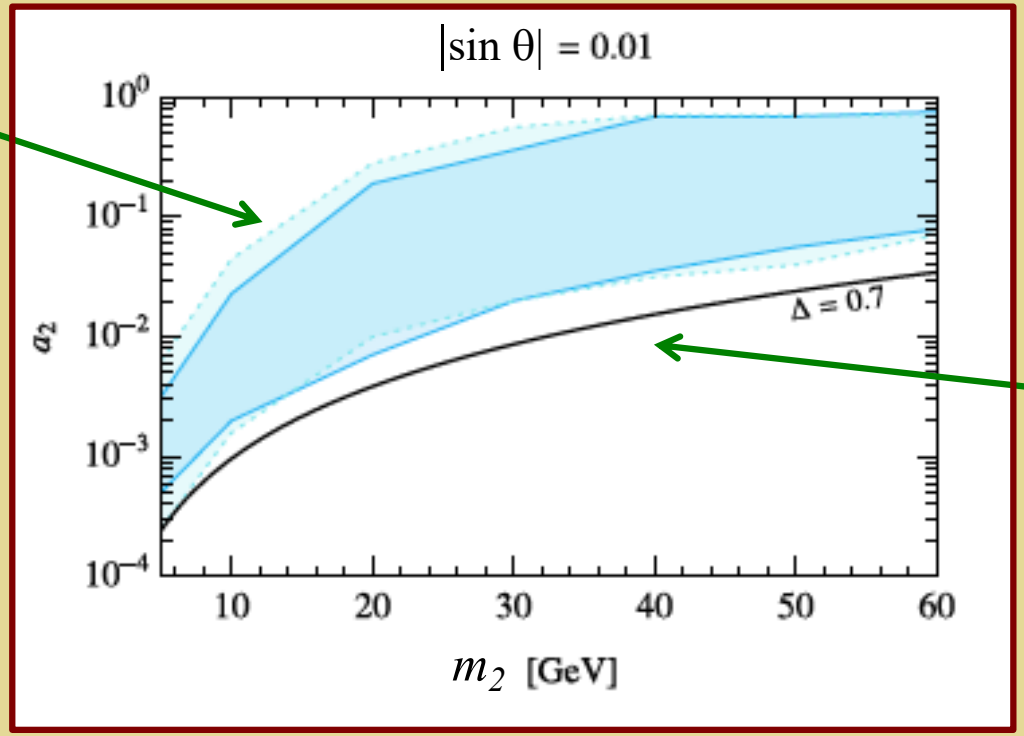
III. Electroweak Phase Transition

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

Light Singlets: Exotic Higgs Decays

One loop perturbation theory

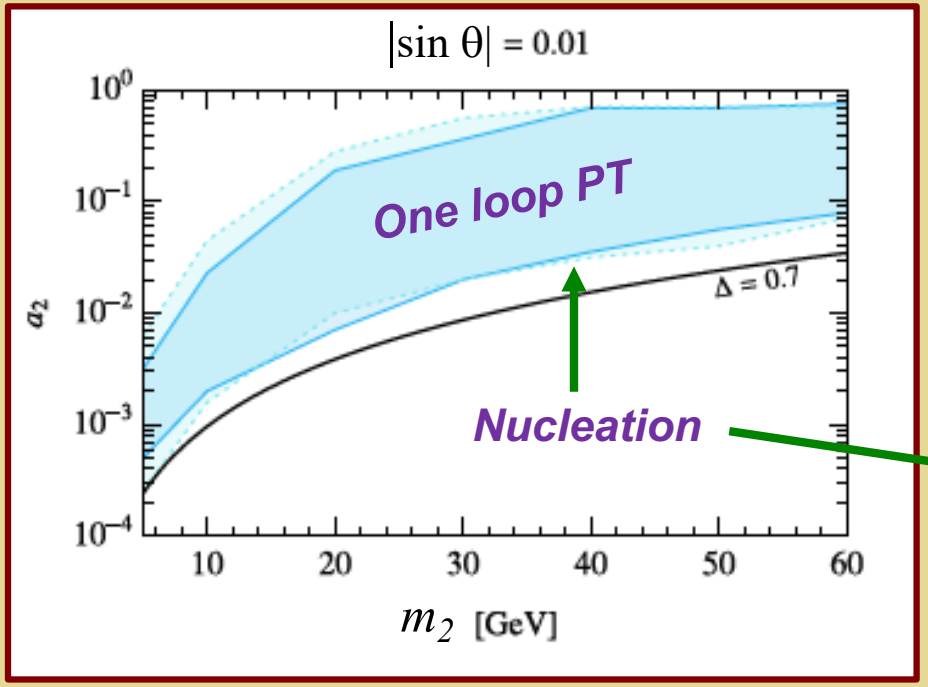
EWPT viable: numerical

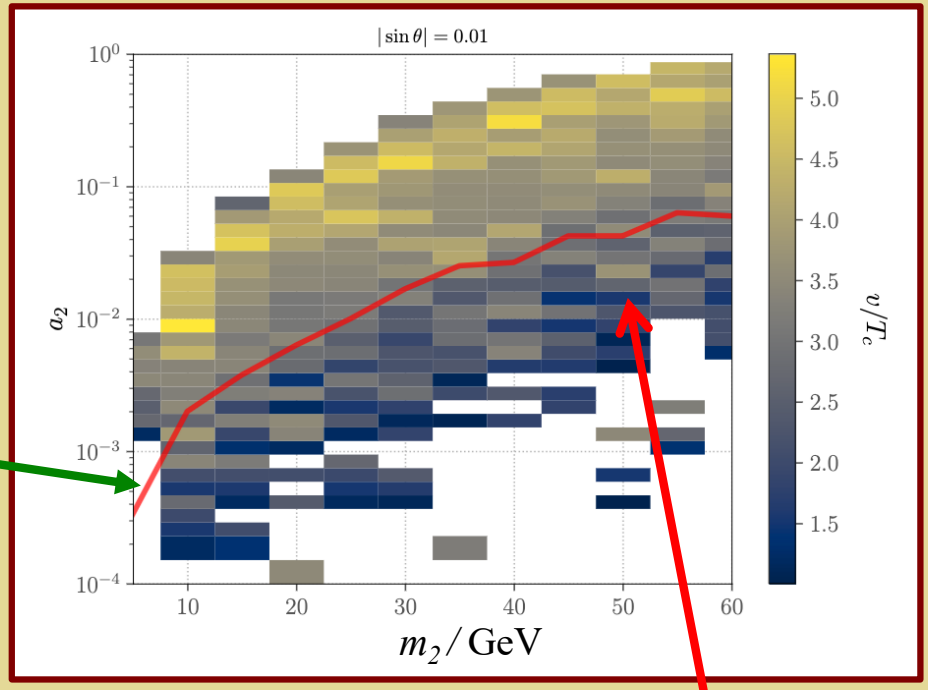


EWPT viable: Semi analytic → nucleation decisive

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



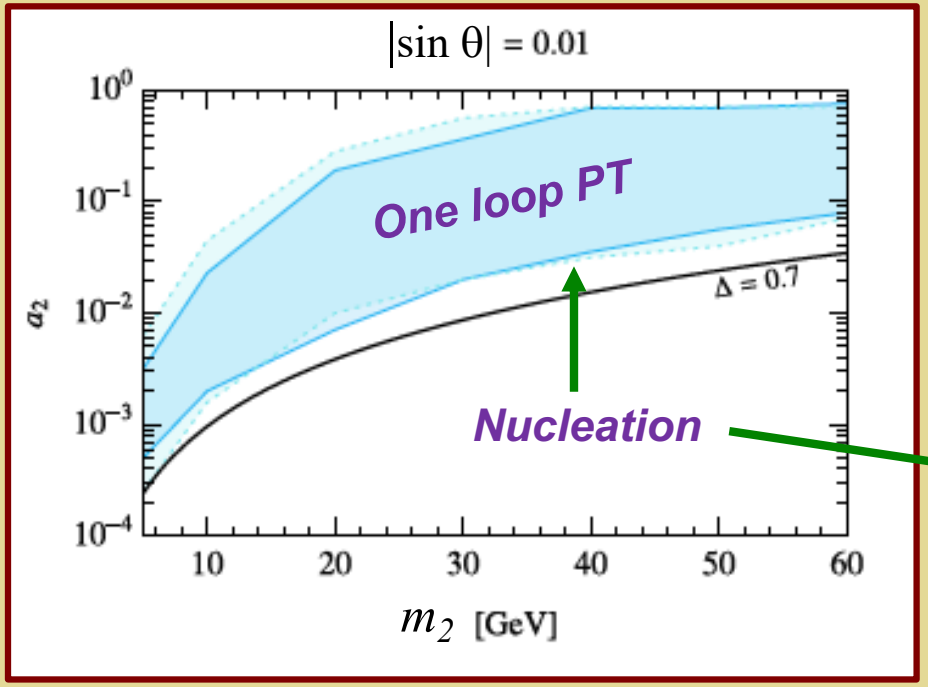


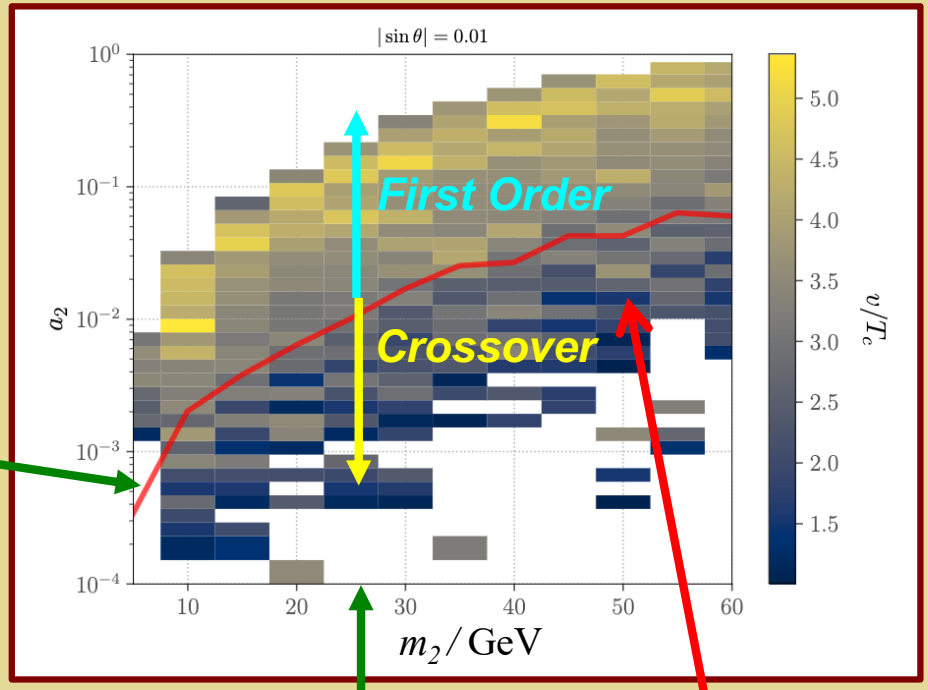
J. Kozaczuk, MR-M, J. Shelton 1911.10210

Two-loop PT: 3d EFT

L. Niemi, MJRM, G. Xia 2404.NNNNN

New: Lattice + EFT @ T > 0





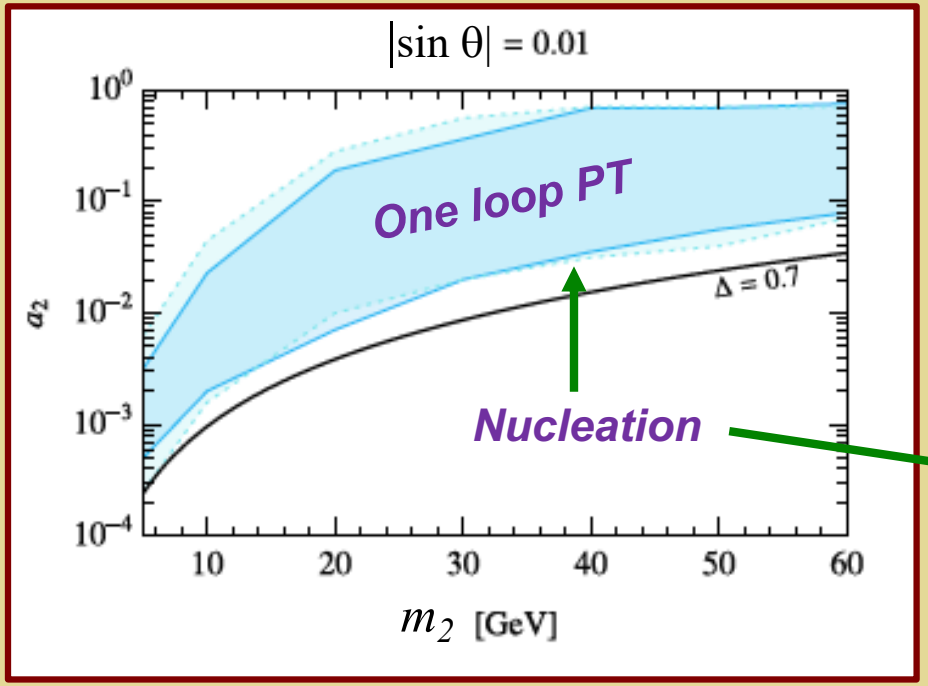
J. Kozaczuk, MR-M, J. Shelton 1911.10210

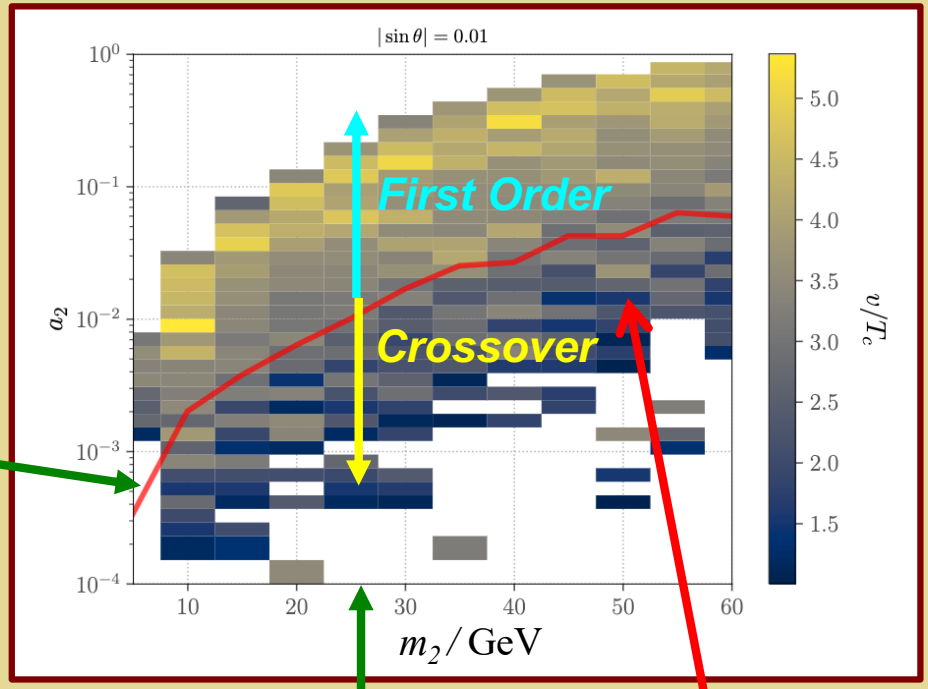
Lattice study

Two-loop PT: 3d EFT

L. Niemi, MJRM, G. Xiao 2404.NNNNN

New: Lattice + EFT @ T > 0





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

Lattice study

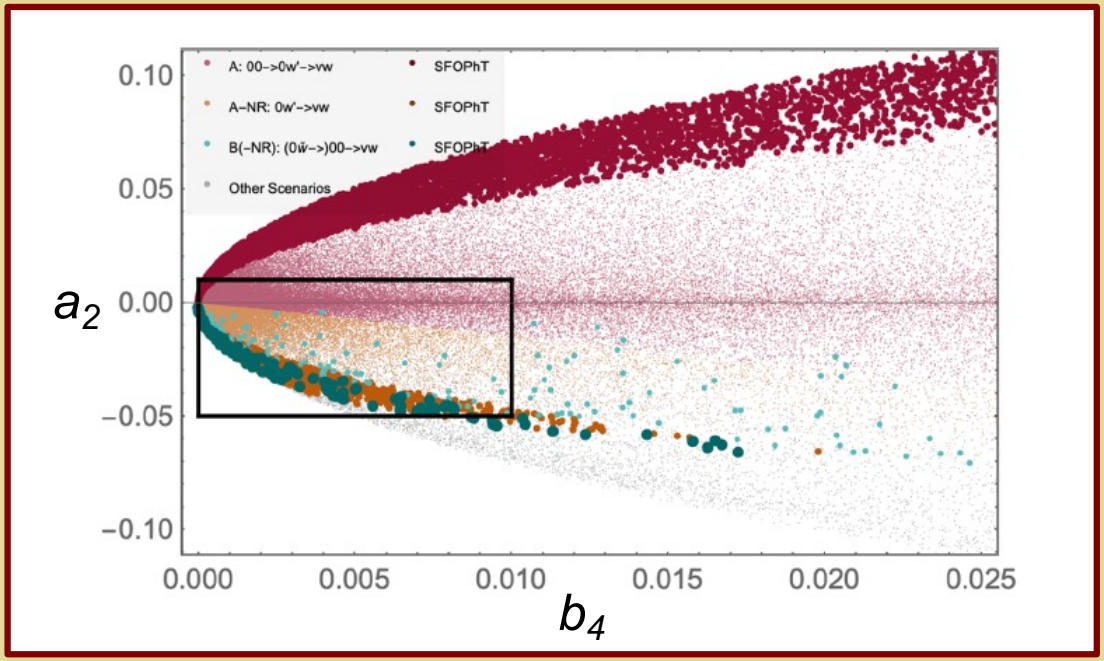
Two-loop PT: 3d EFT

Small portal couplings → FO EWPT unlikely

L. Niemi, MJRM, G. Xiao 2404.NNNNN

Light Singlets: Exotic Higgs Decays

Z_2 breaking *One loop perturbation theory*



Carena et al 1911.10206

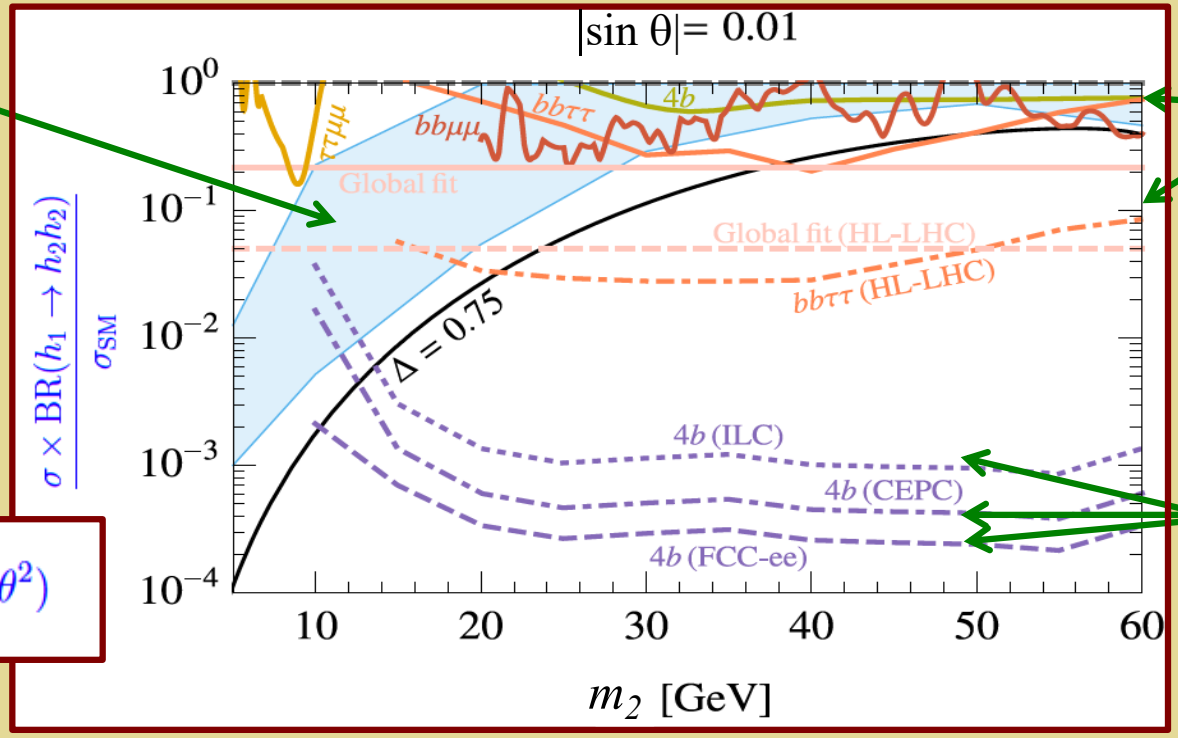
IV. Phenomenology

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

Light Singlets: Exotic Higgs Decays

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

EWPT viable: numerical



LHC: 2019 & HL

Future e^+e^-

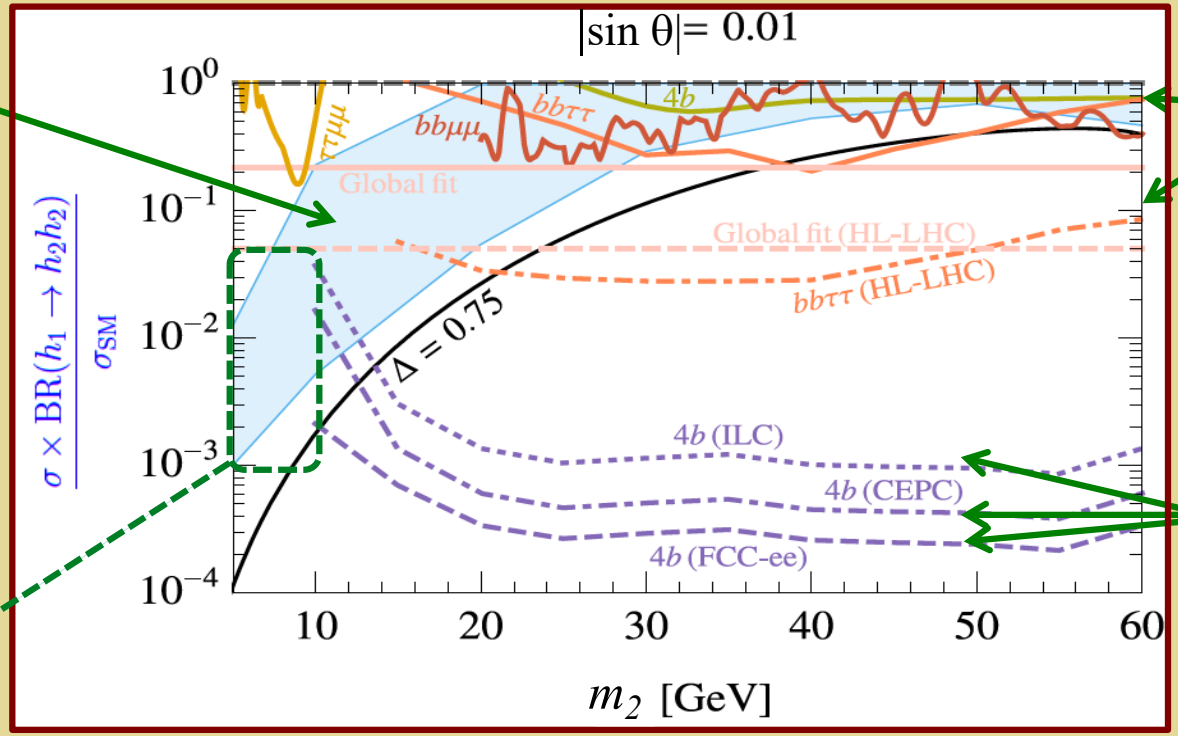
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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

EWPT viable: numerical



LHC: 2019 & HL

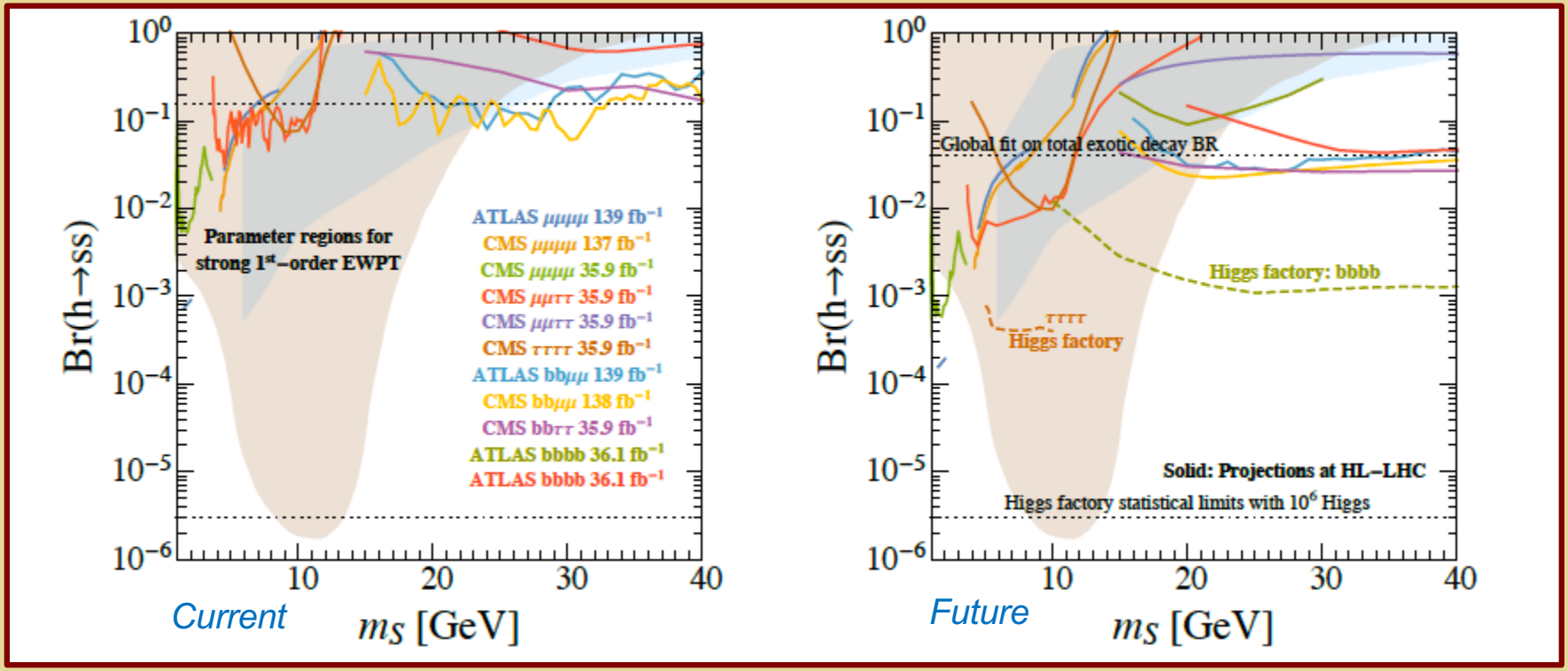
Future e^+e^-

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

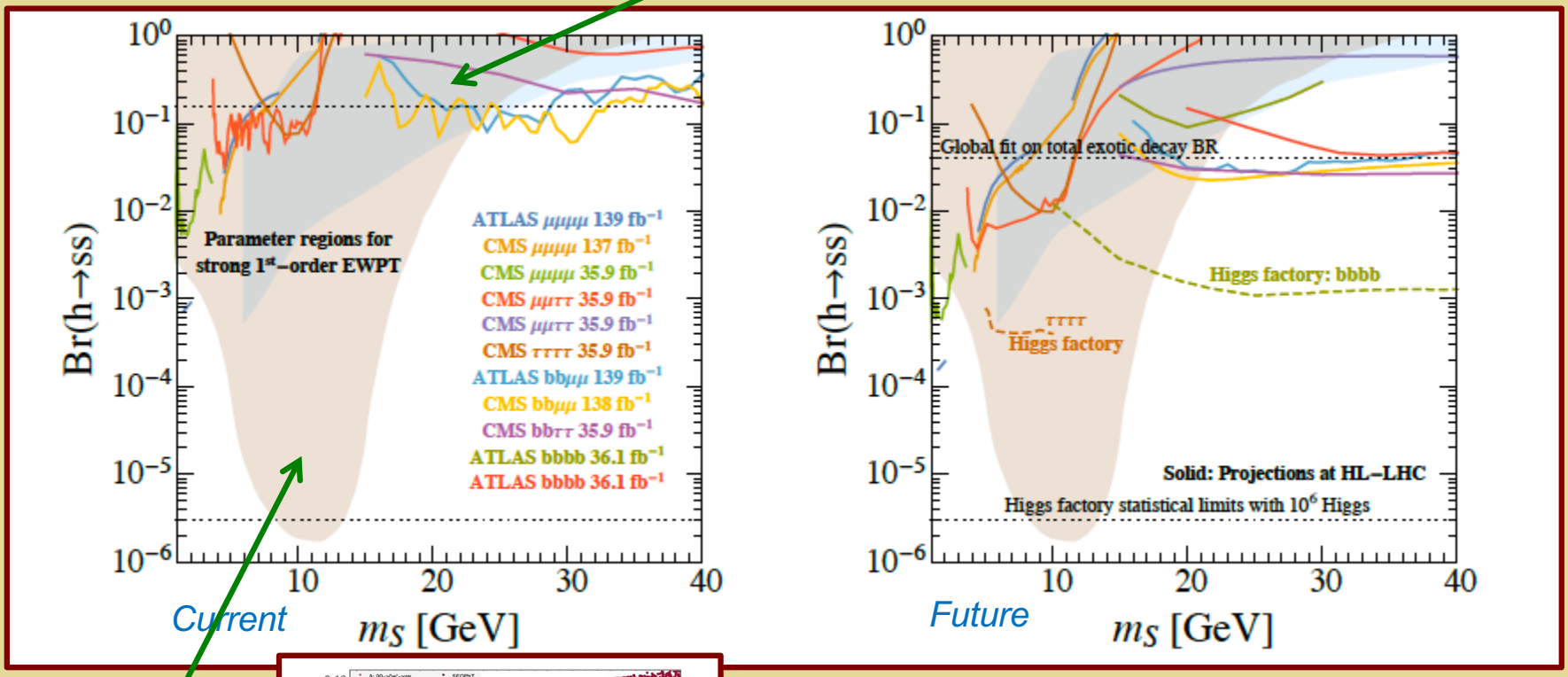


Carena et al (Snowmass) 2203.08206

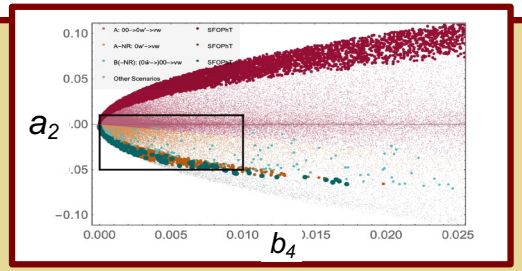
Light Singlets: Exotic Higgs Decays

Z_2 breaking: prompt h_2 decays

Explicit Z_2 breaking



Spont Z_2 breaking



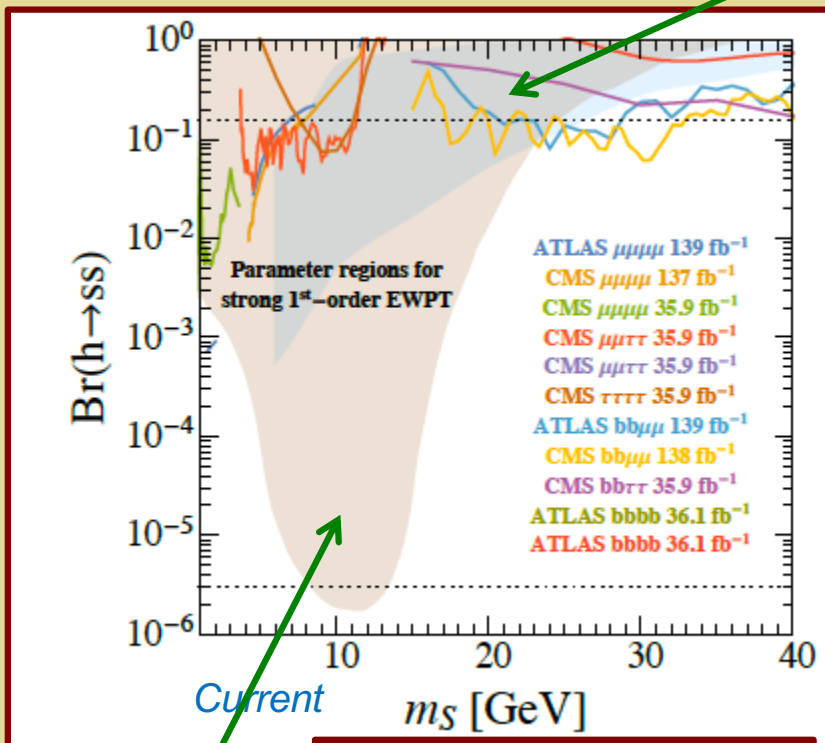
Carena et al (Snowmass) 2203.08206

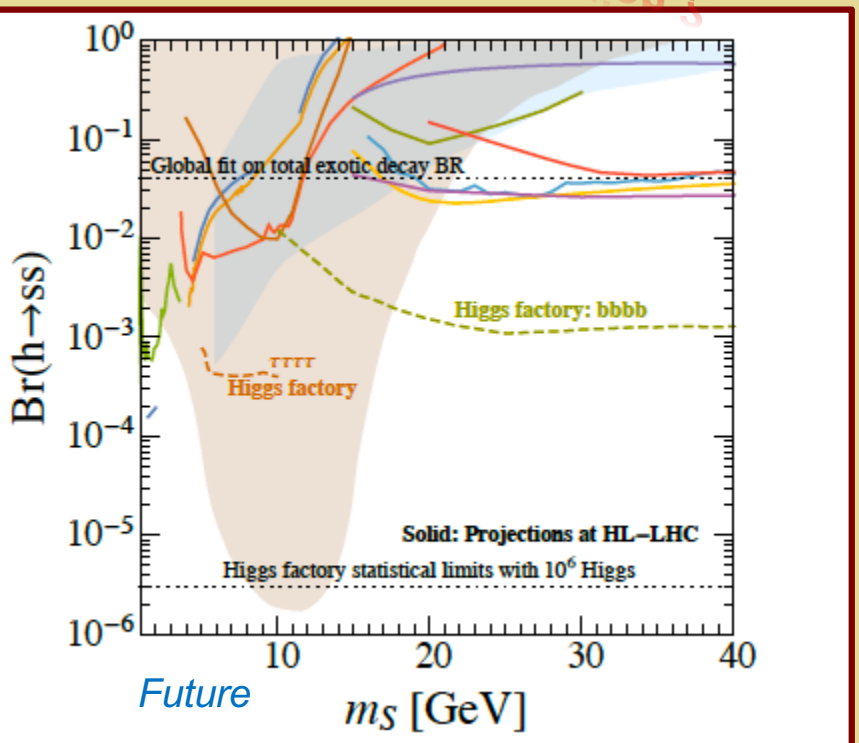
Light Singlets: Exotic Higgs Decays

Z_2 breaking: prompt h_2 decays

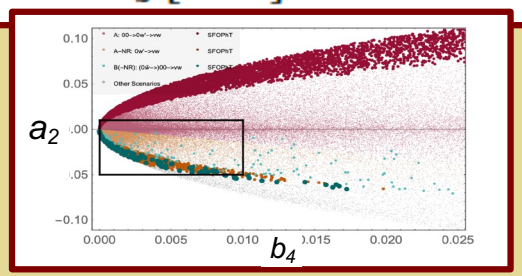
Explicit Z_2 breaking

Consistent w/ EFT + lattice thermo but nucleation ?





Spont Z_2 breaking



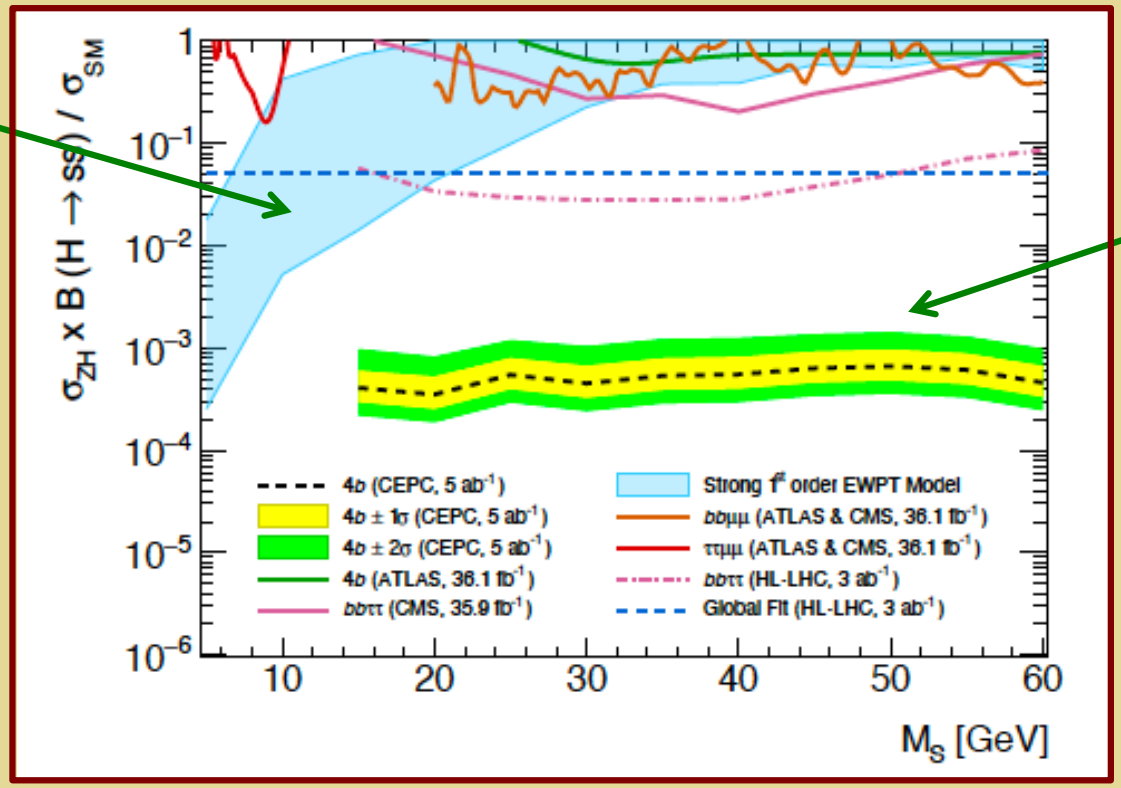
Consistent w/ EFT + lattice ? Tiny a_2

Carena et al (Snowmass) 2203.08206

Light Singlets: Exotic Higgs Decays

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

EWPT viable: numerical



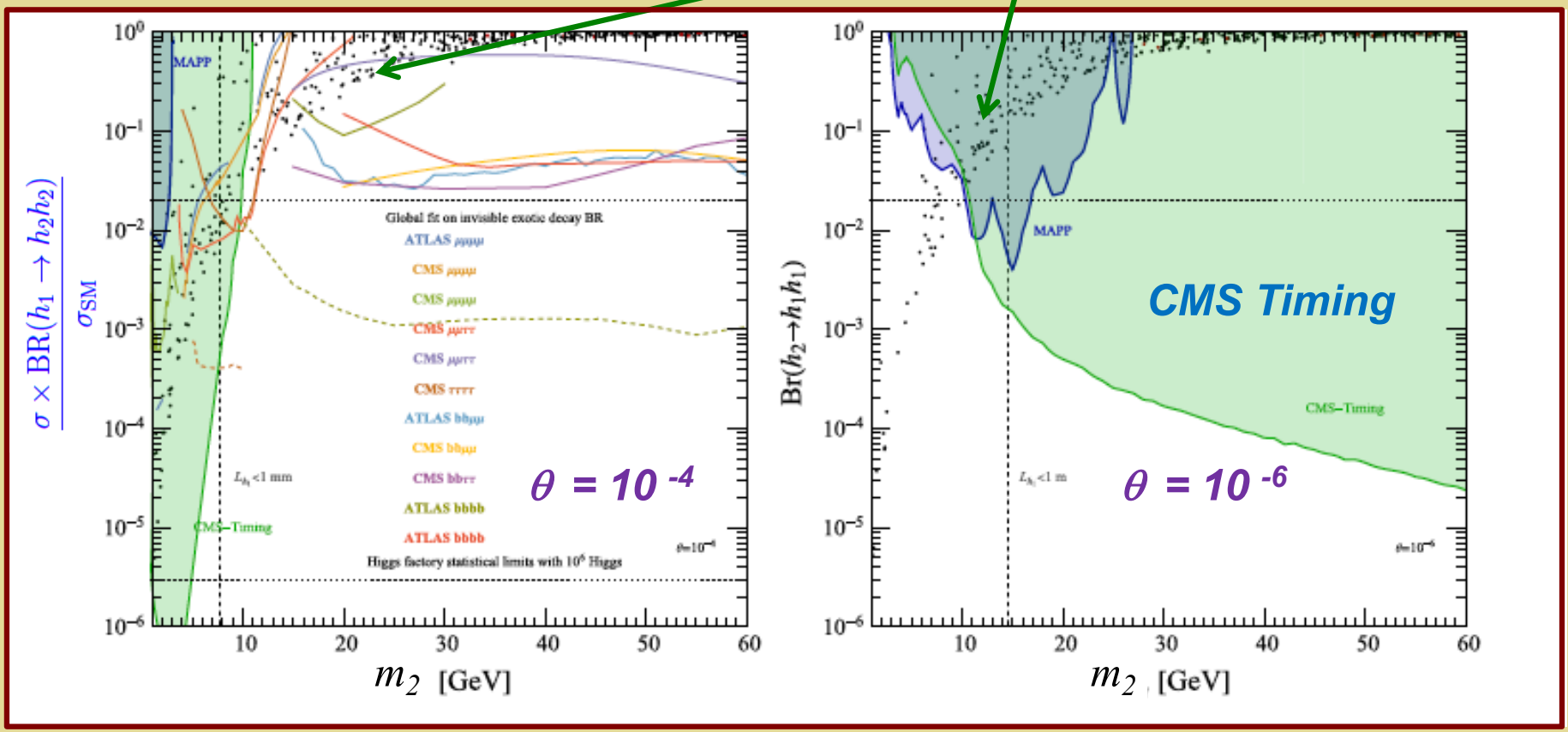
CEPC 4b

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

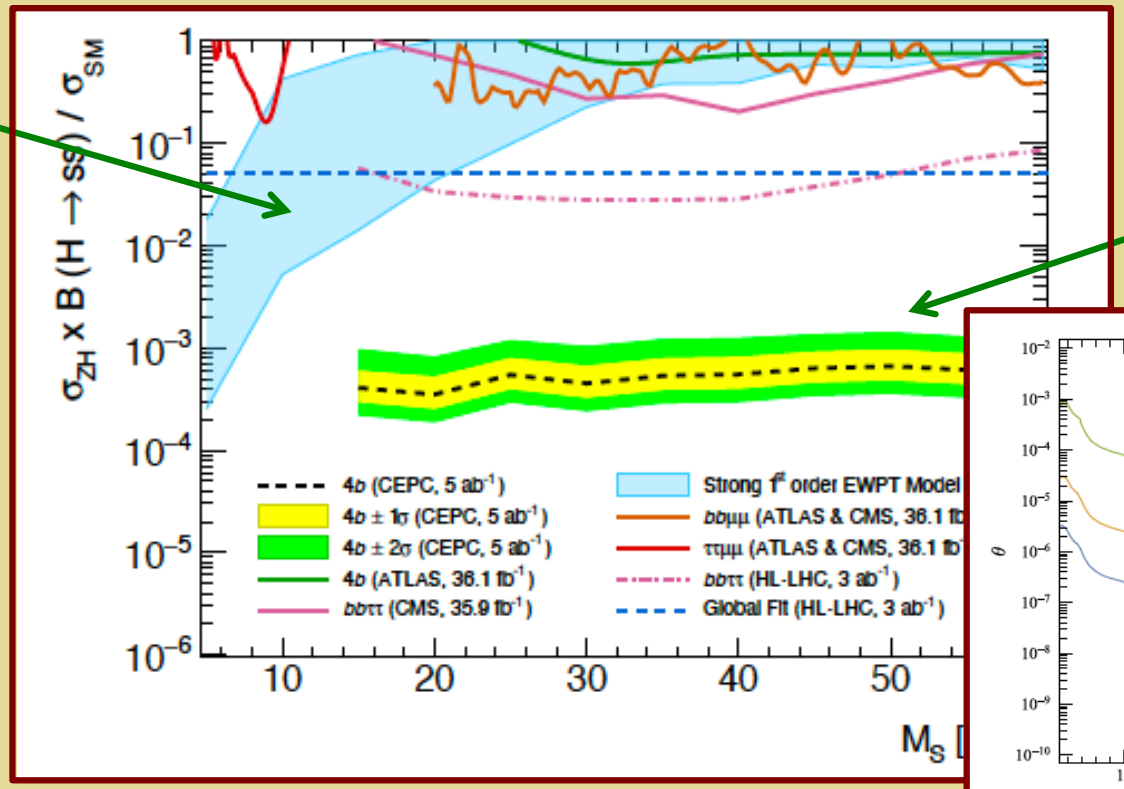


W. Liu, A. Yang, H. Sun, PRD 105 (2022) 115040

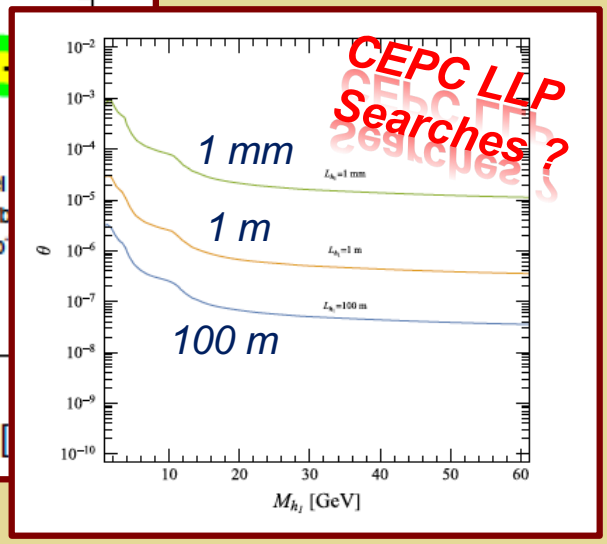
Light Singlets: Exotic Higgs Decays

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

EWPT viable: numerical



CEPC 4b Prompt

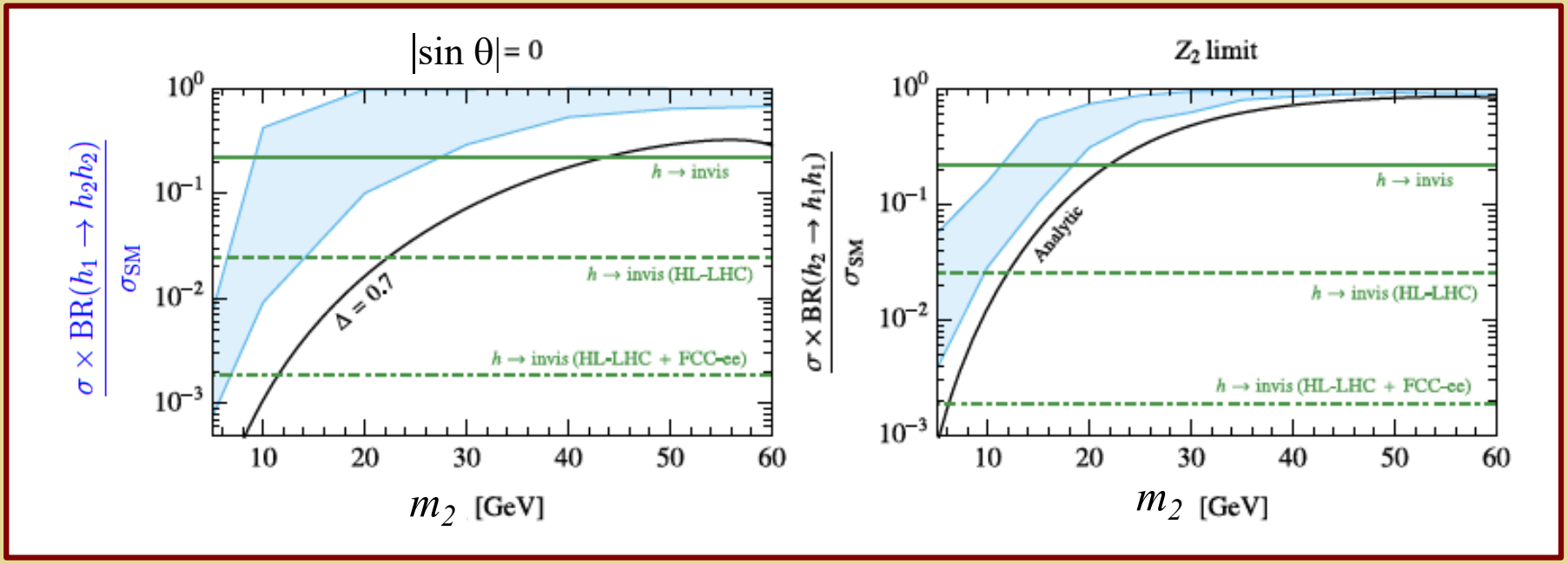


J. Wang et al (Snowmass) 2203.10184

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

Light Singlets: Exotic Higgs Decays

Invisible decays

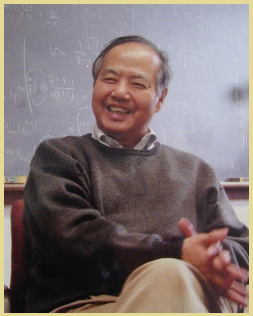


J. Kozaczuk, MR-M, J. Shelton 1911.10210

VI. Outlook

- ***Determining the thermal history of EWSB is key challenge at the forefront of high energy physics & cosmology***
- ***Exotic Higgs decays provide a unique probe of a first order EW phase transition, with implications for baryogenesis and gravitational waves***
- ***Robust theory requires close interplay of lattice computations with state-of-the-art perturbative studies (EFT)***
- ***Exciting experimental prospects ahead with complementary searches at the HL-LHC and future e+e- colliders***

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world famous source of original innovation

Founded 2016

Theory & Experiment

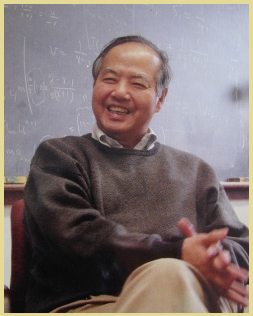
- Particle & Nuclear Physics
- Astronomy & Astrophysics
- Quantum Science
- Dark Matter & Neutrino
- Laboratory Astrophysics
- Topological Quantum Computation

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

https://tdli.sjtu.edu.cn/EN/

T. D. Lee Institute / Shanghai Jiao Tong U.



Director

A point of convergence of the world's top scientists

A launch pad for the early-career scientists

A world-famous source of original innovation

Founded 2016

Welcome to Shanghai!

Theory & Experiment

- Particle & Nuclear Physics
- Astronomy & Astrophysics
- Quantum Science
- Dark Matter & Neutrino
- Laboratory Astrophysics
- Topological Quantum Computation

100+

faculty members from 17 countries and regions, with over 40% of them foreign (non-Chinese) citizens

https://tdli.sjtu.edu.cn/EN/

VI. Outlook

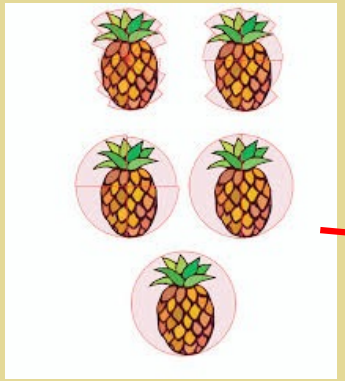
谢谢！

- *Determining the thermal history of EWSB is key challenge at the forefront of high energy physics & cosmology*
- *Exotic Higgs decays provide a unique probe of a first order EW phase transition, with implications for baryogenesis and gravitational waves*
- *Robust theory requires close interplay of lattice computations with state-of-the-art perturbative studies (EFT)*
- *Exciting experimental prospects ahead with complementary searches at the HL-LHC and future e+e- colliders*

Back Up Slides

Was There an EW Phase Transition?

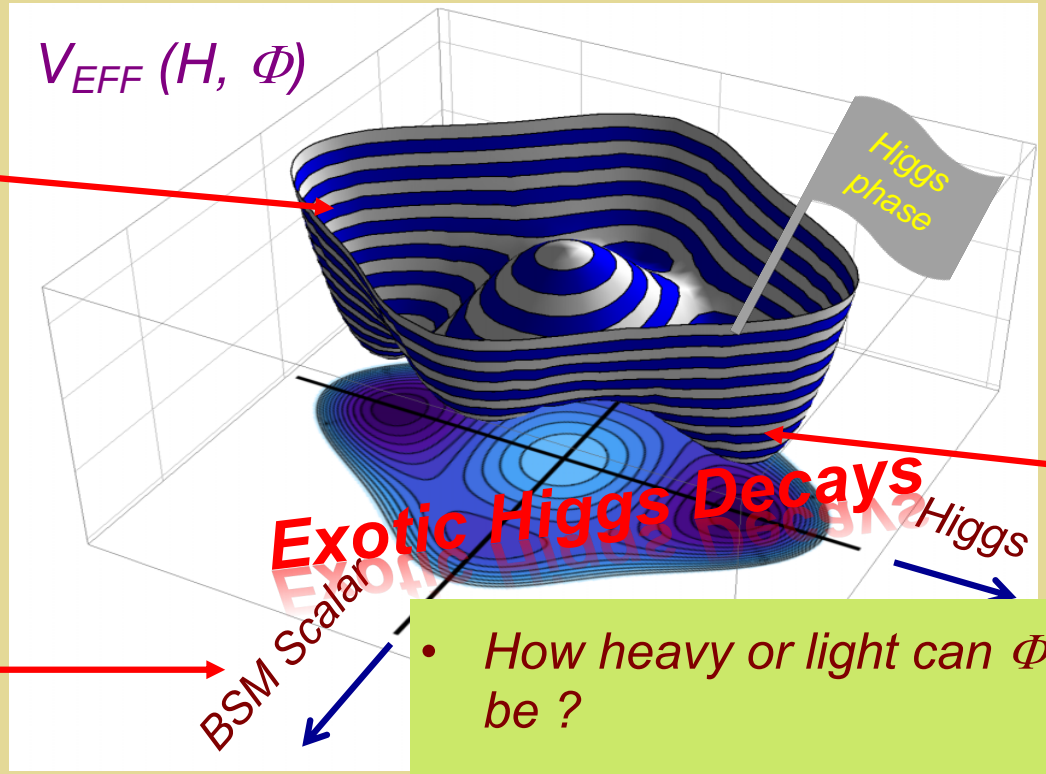
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs



Higgs precision tests

SM Higgs BSM Higgs

Extrema can evolv
rich possibilities fo

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

→

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*

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

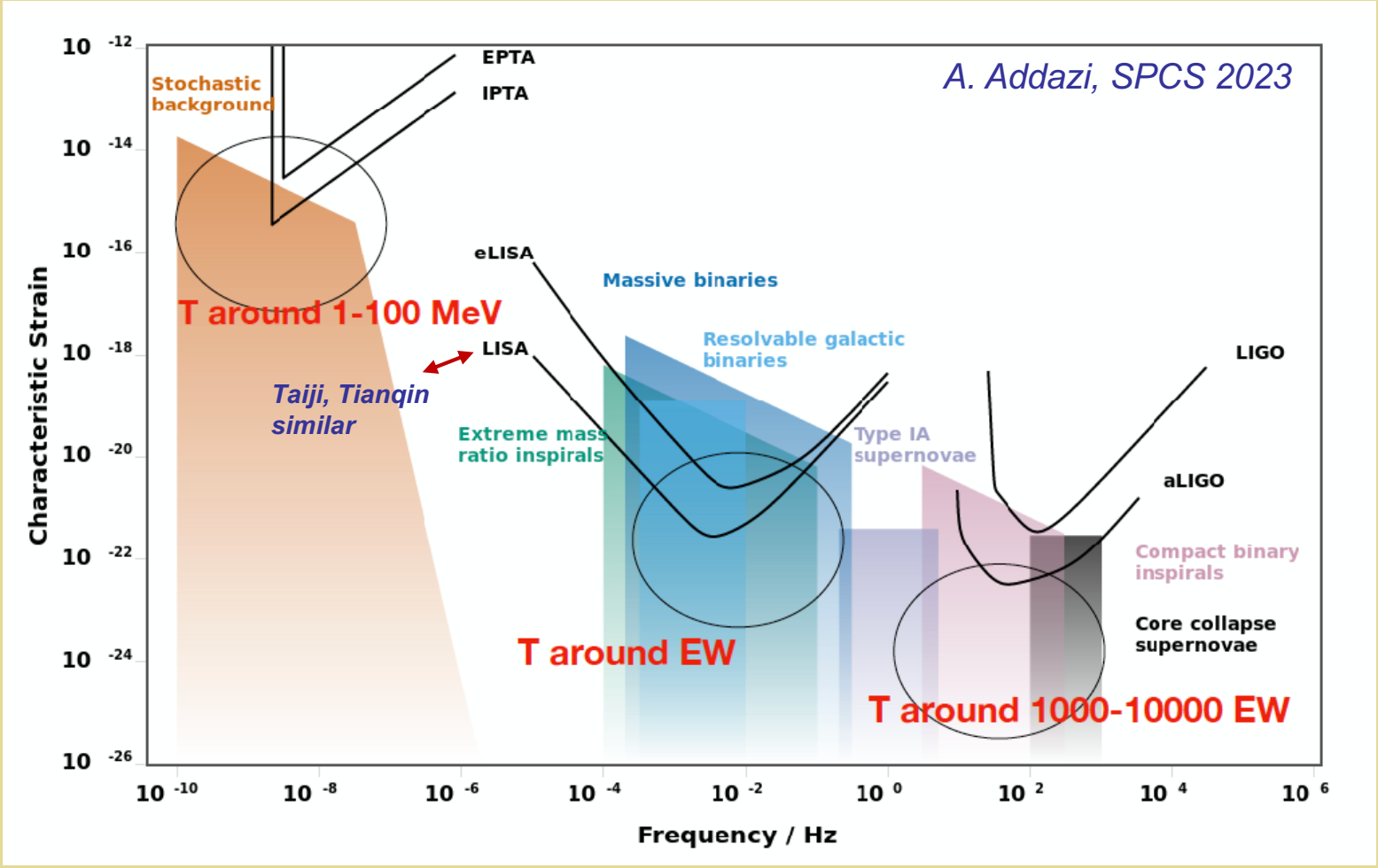
$$\phi^2_{3d} = \frac{1}{T}\left[1 + \hat{\Pi}'_\phi(0,0)\right]\phi^2$$

Field

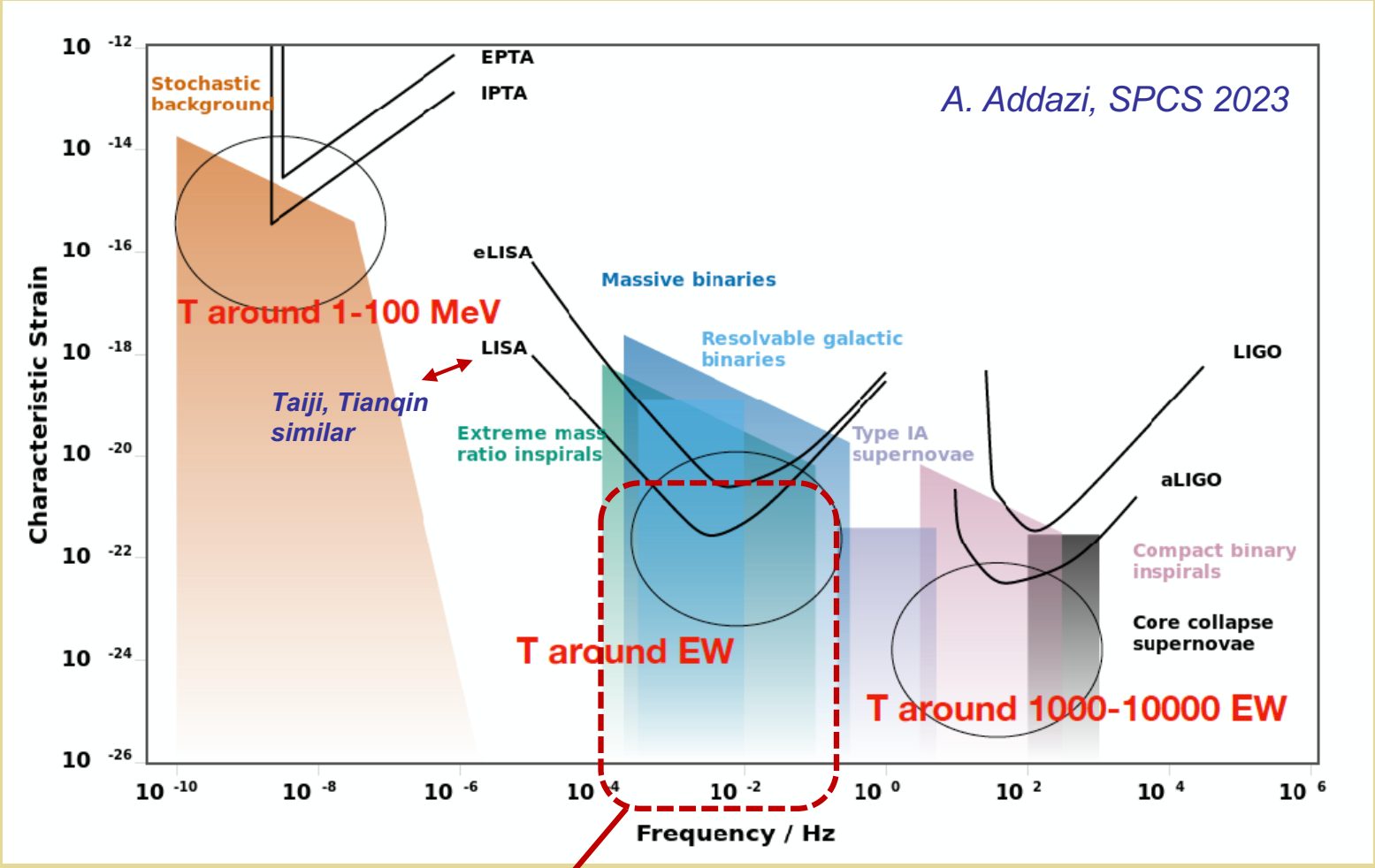
$$a_{2,3} = T\left[a_2 - a_2(\hat{\Pi}'_H(0) + \hat{\Pi}'_\Sigma(0)) + \hat{\Gamma}(0)\right]$$

Quartic coupling

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: Inter-frontier Connections