Was There an Electroweak Phase Transition?

M.J. Ramsey-Musolf

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

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

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

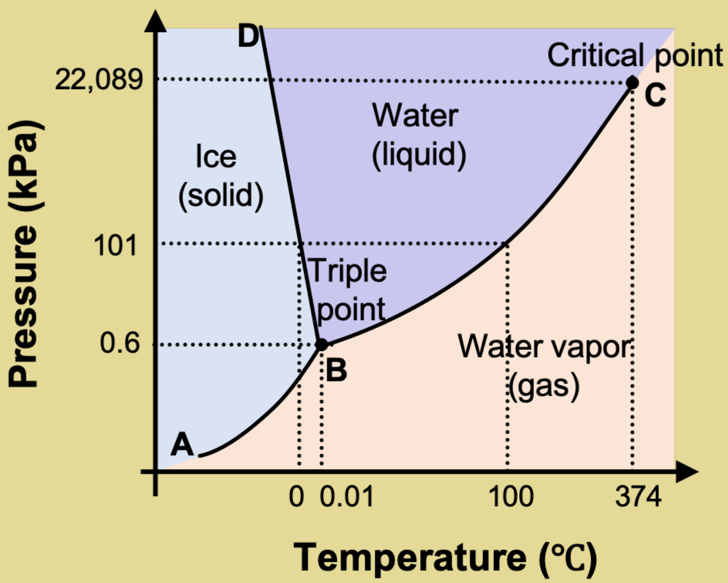
SUSY 2024 Madrid
June 13, 2024

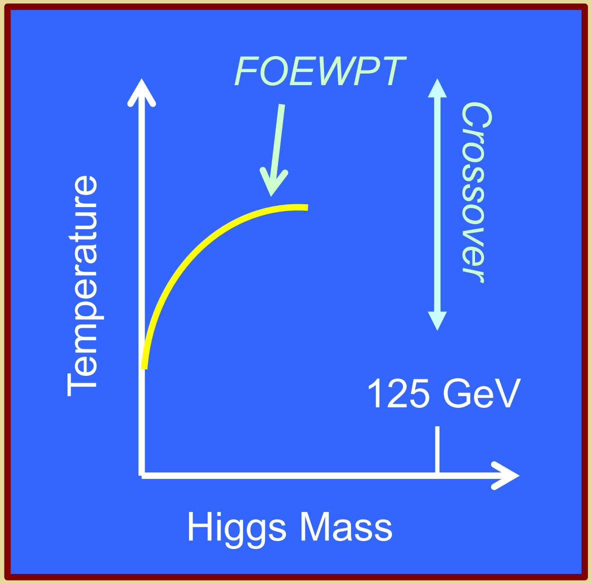
I. Context & Questions

Was There an Electroweak Phase Transition ?

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

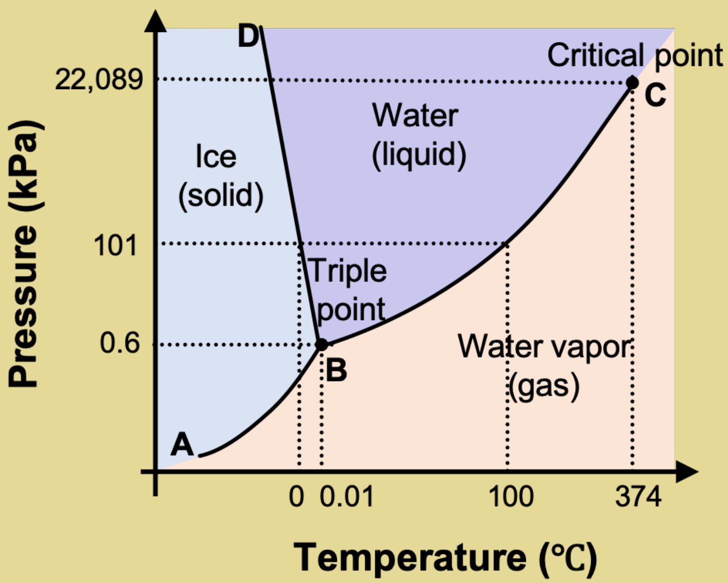
Was There an Electroweak Phase Transition ?

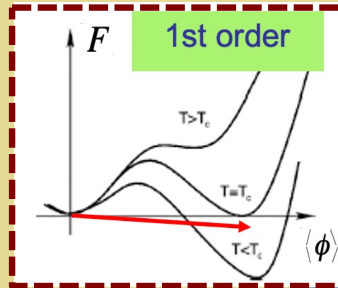


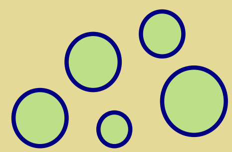


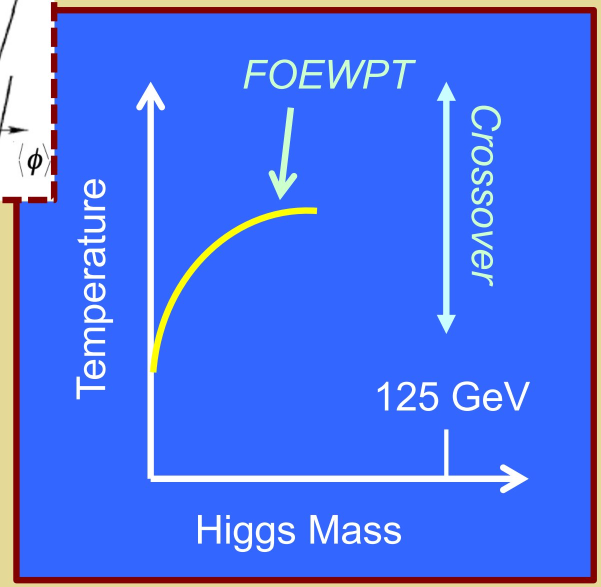
EW Phase Diagram

Was There an Electroweak Phase Transition ?



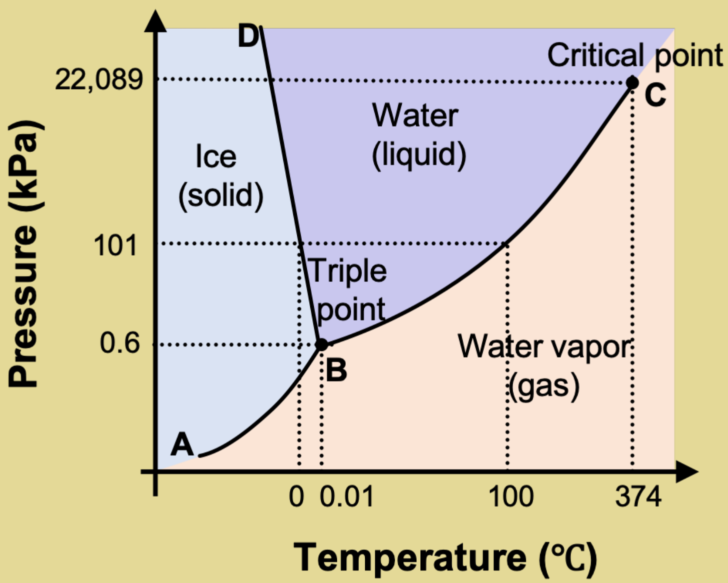


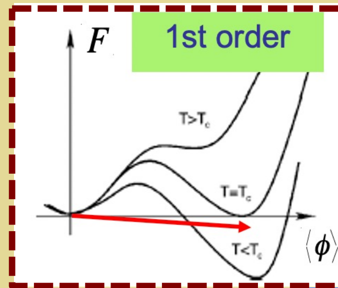


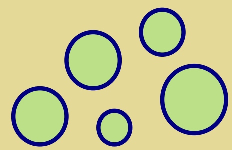


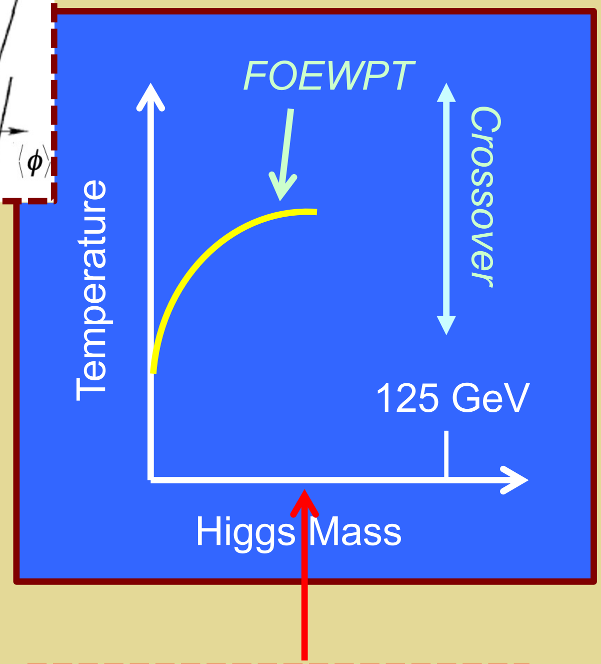
EW Phase Diagram

Was There an Electroweak Phase Transition ?





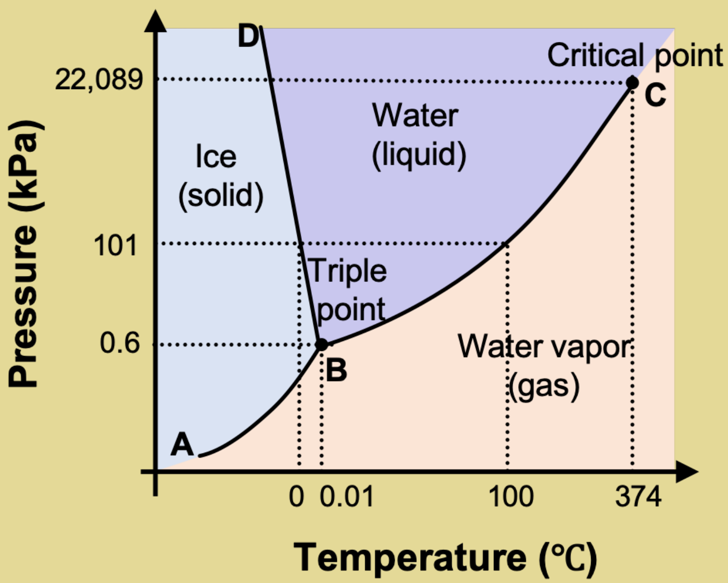


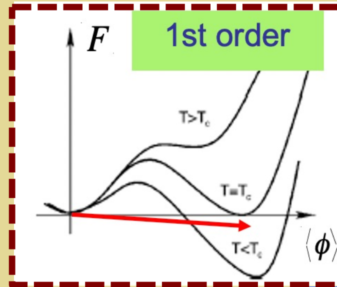


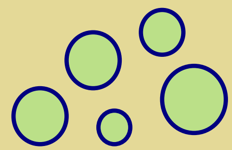
EW Phase Diagram

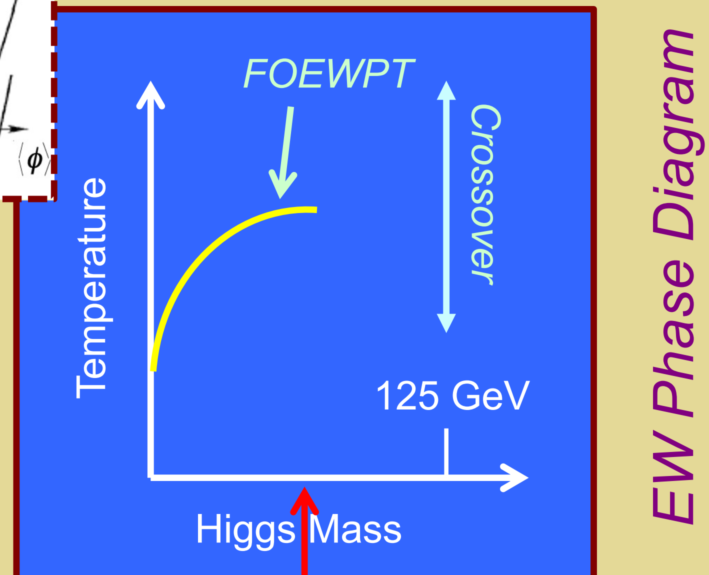
Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

Was There an Electroweak Phase Transition ?





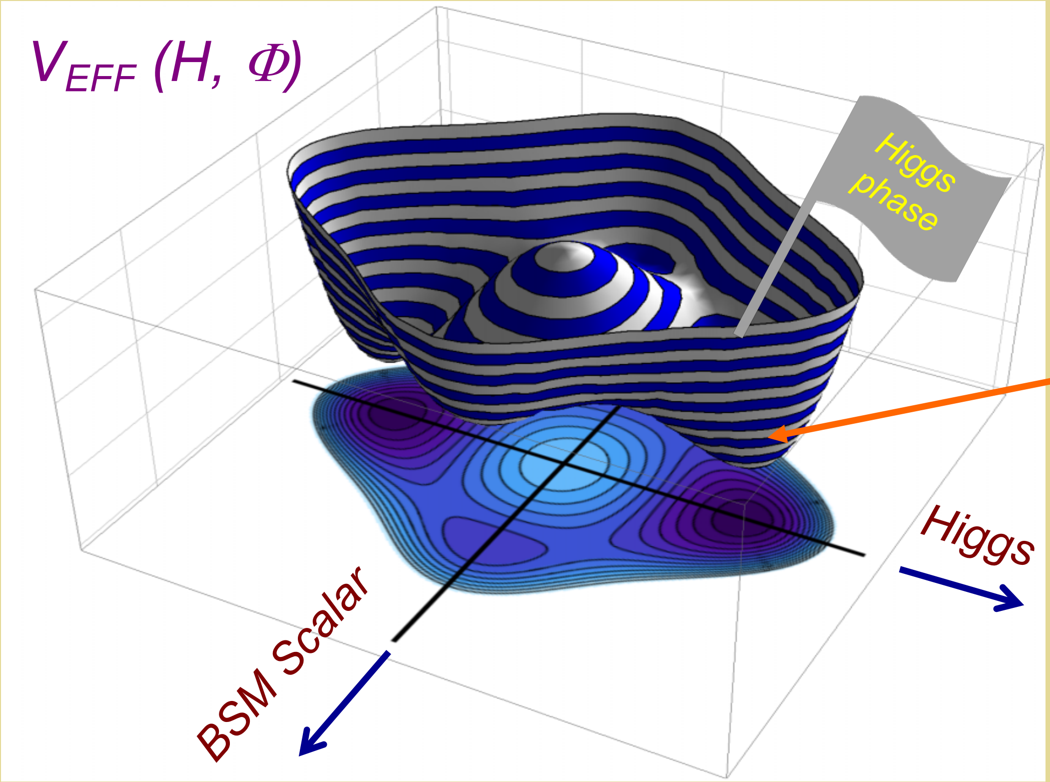




Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

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

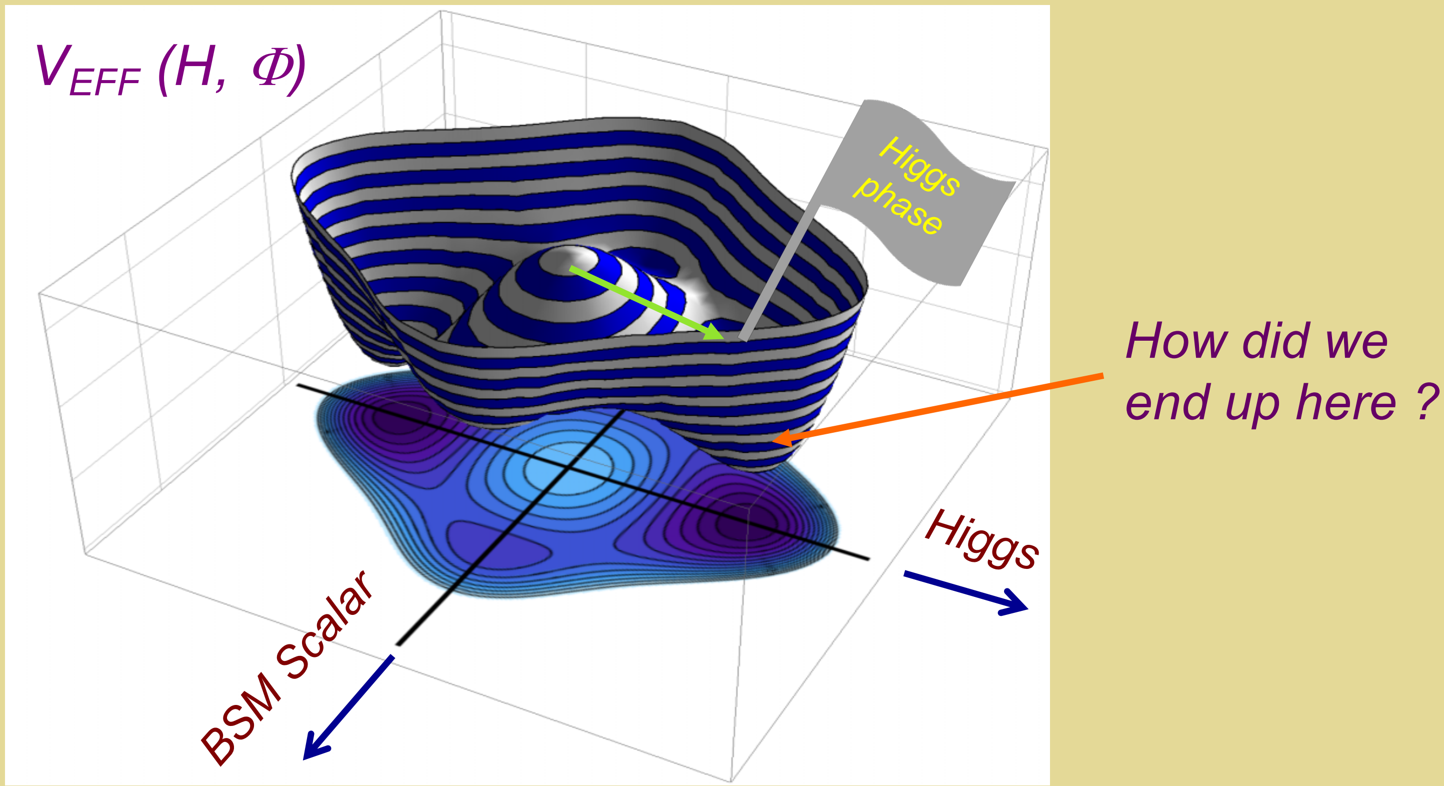
What Was the EWSB Thermal History ?



How did we end up here ?

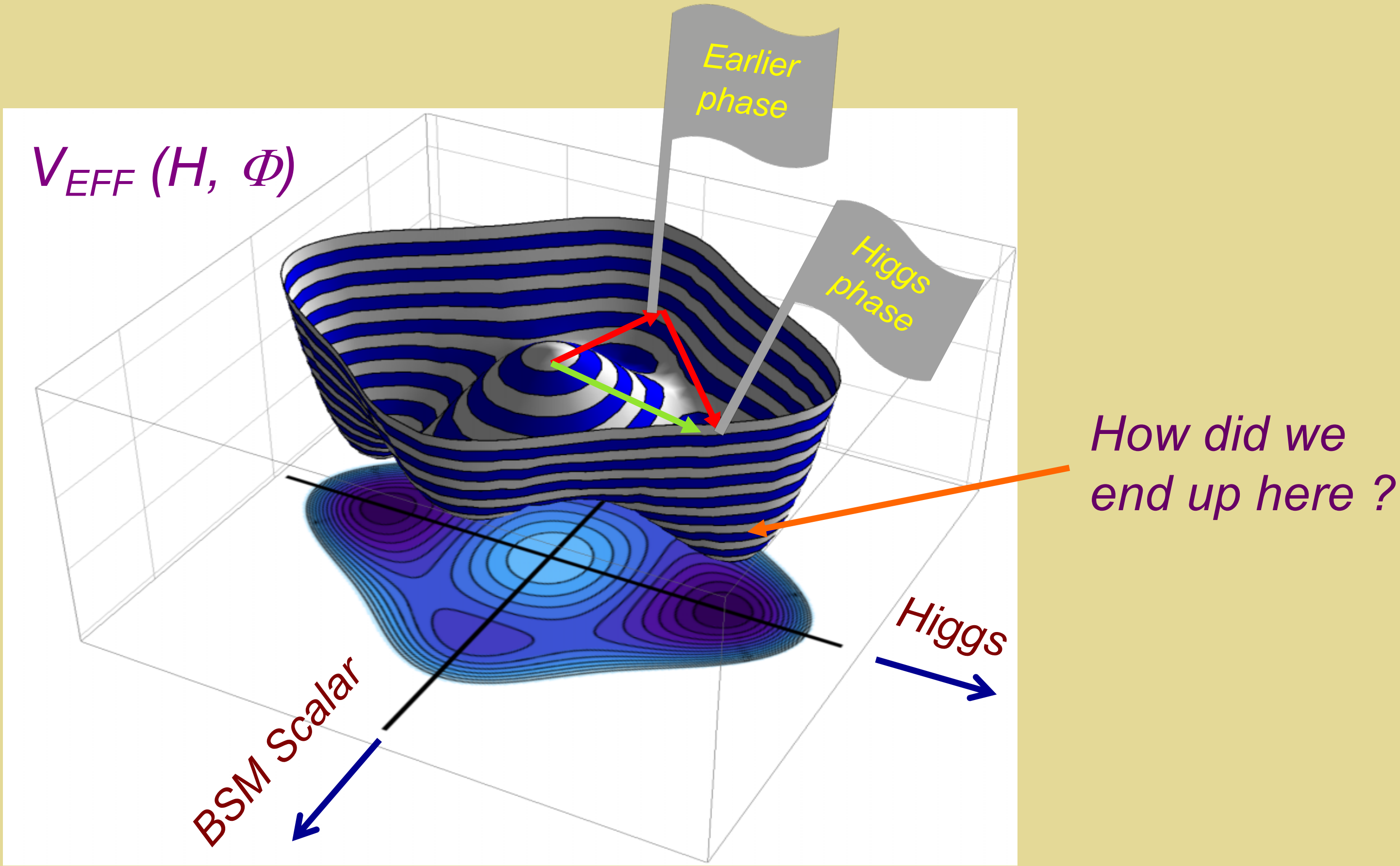
Extrema can evolve differently as T evolves → rich possibilities for symmetry breaking

What Was the EWSB Thermal History ?



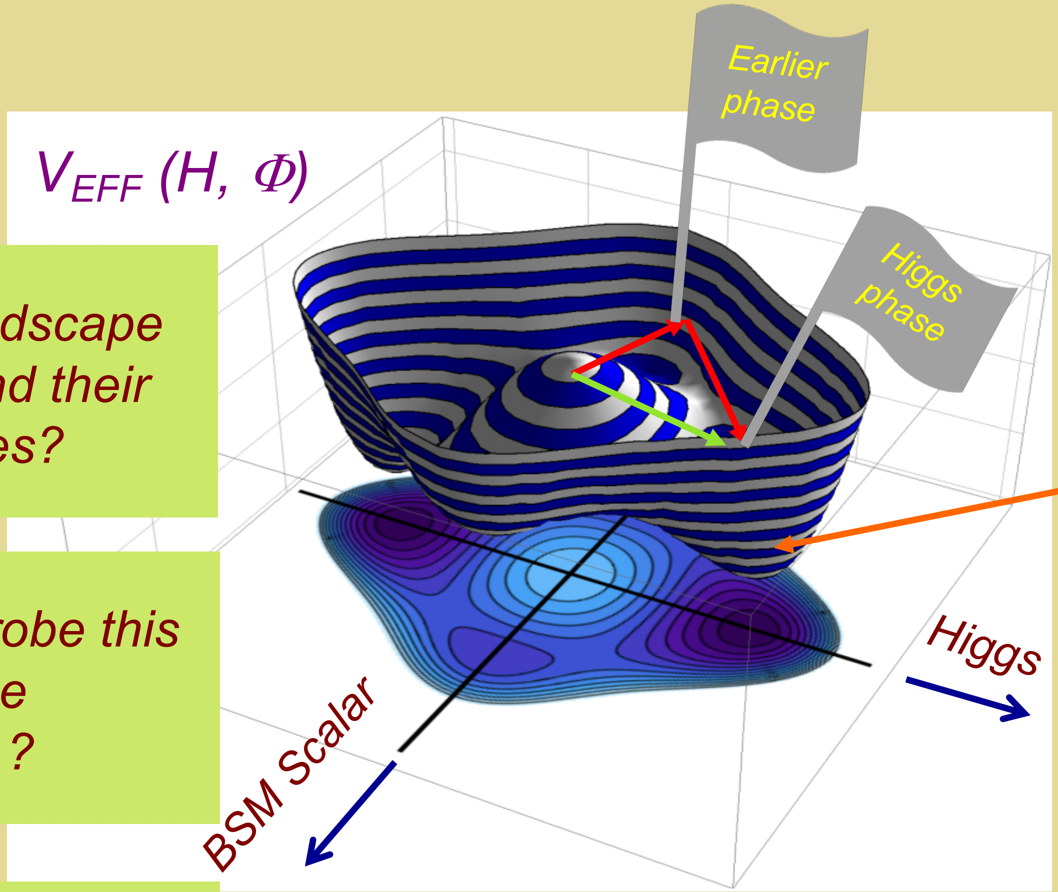
Extrema can evolve differently as T evolves →
rich possibilities for symmetry breaking

What Was the EWSB Thermal History ?



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

What Was the EWSB Thermal History ?



How did we end up here ?

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

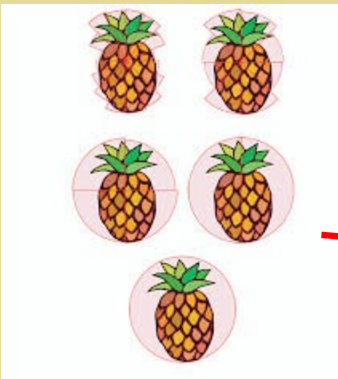
- How can we probe this T > 0 landscape experimentally ?

- How reliably can we compute the thermodynamics ?

n evolve differently as T evolves →
ilities for symmetry breaking

Was There an EW Phase Transition?

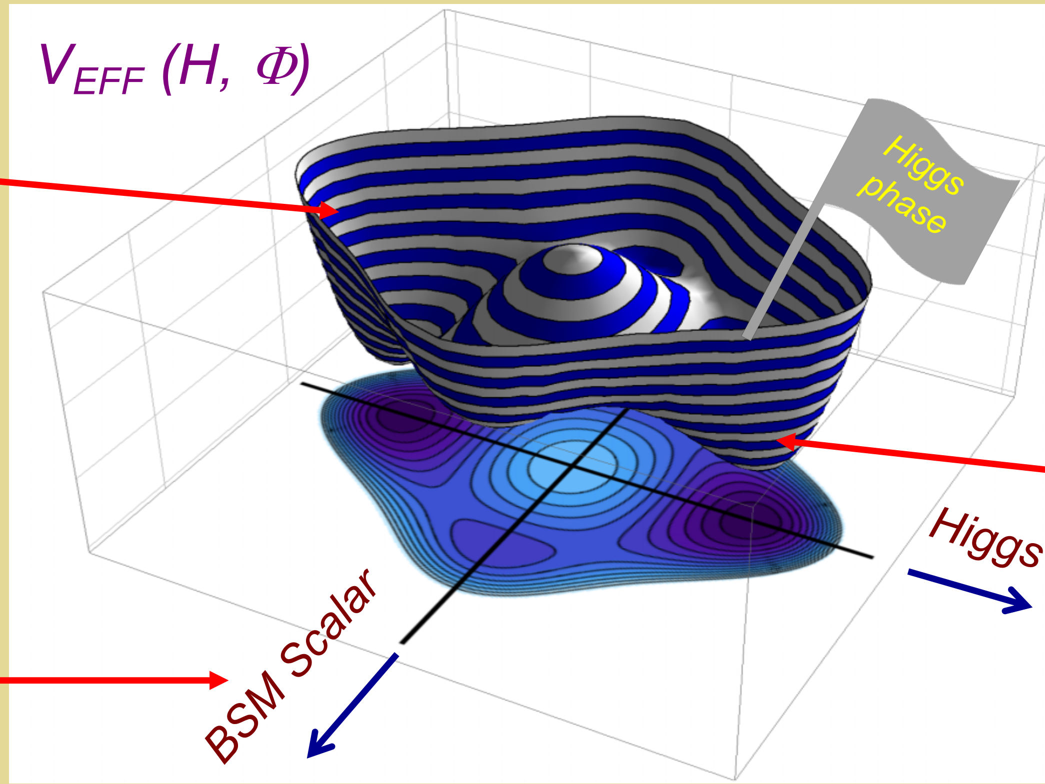
Bubble Collisions



Grav Radiation

Direct Production

BSM Higgs

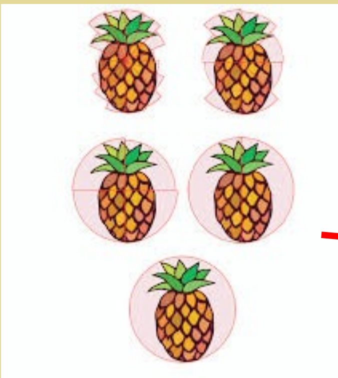


Higgs precision tests

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

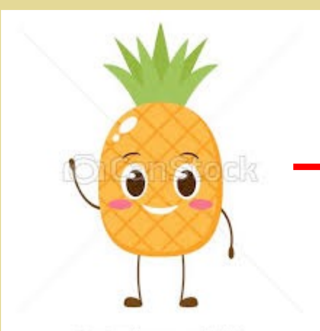
Was There an EW Phase Transition?

Bubble Collisions

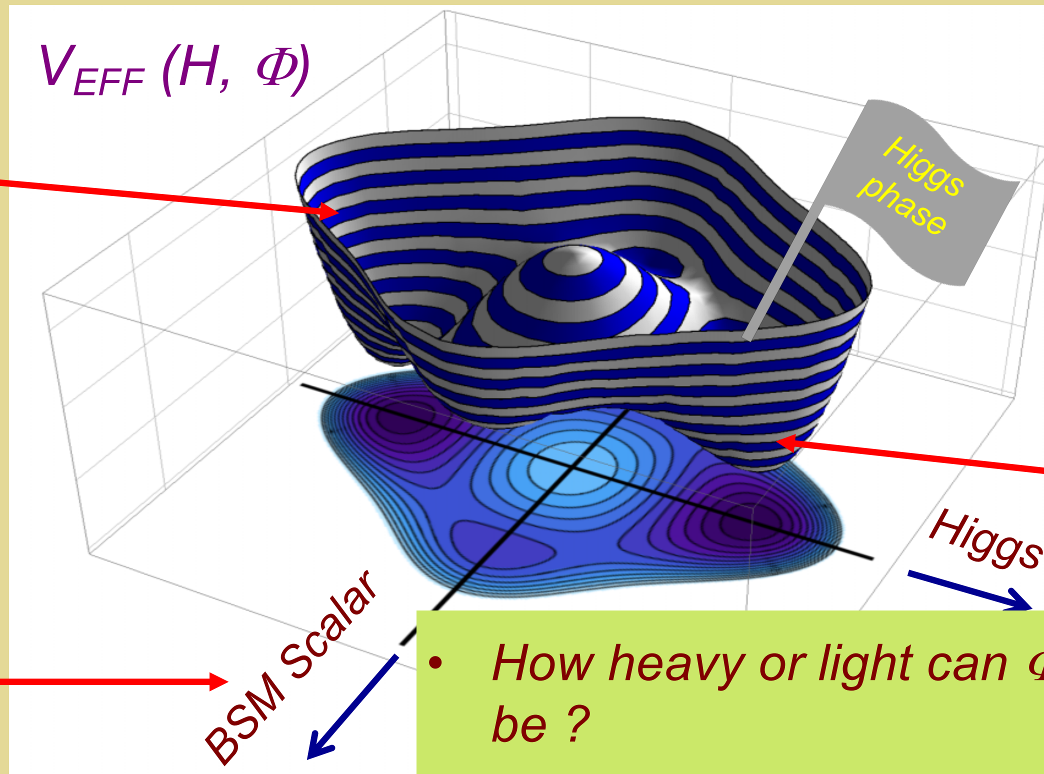


Grav Radiation

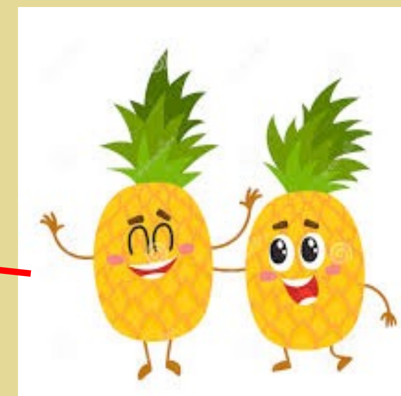
Direct Production



BSM Higgs



Higgs precision tests



SM Higgs **BSM Higgs**

- How heavy or light can Φ be ?
- How coupled to H ?
- Can it be discovered with colliders & GW probes ?

Extrema can evolv →
rich possibilities fo

6.2

MJRM: 1912.07189

T_{EW} → Scale for Colliders & GW probes

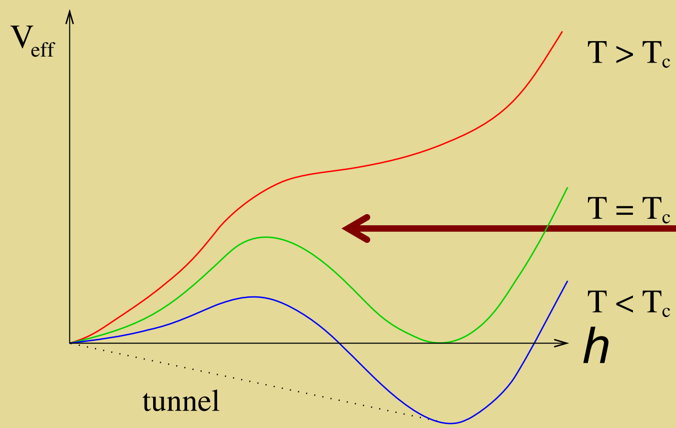
High-T SM Effective Potential

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

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

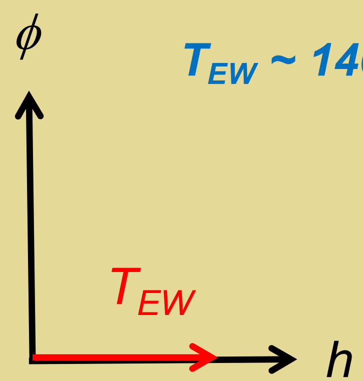
MJRM: 1912.07189

First Order EWPT from BSM Physics



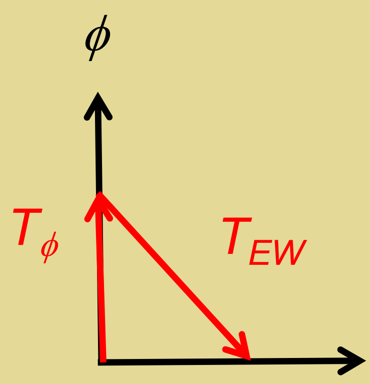
Representative thermal histories → barrier for SFOEWPT

T_{EW} ~ 140 GeV



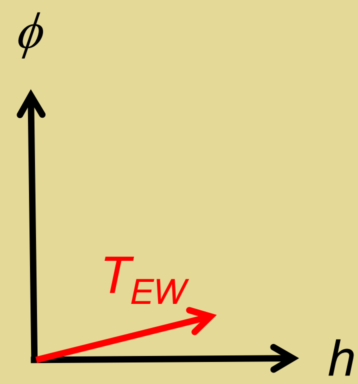
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect

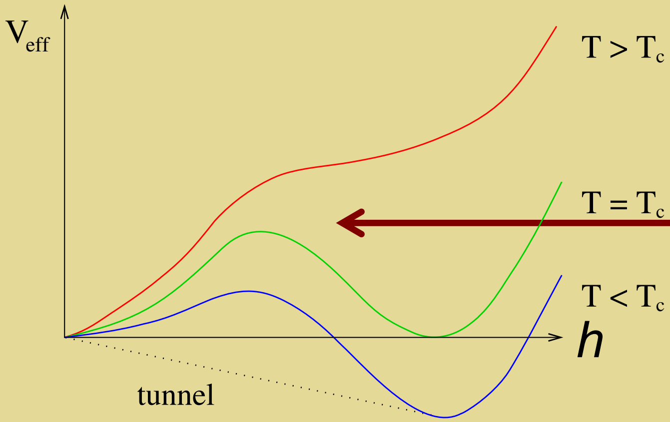


$a_1\, H^2\phi$: $T = 0$

tree-level effect

MJRM: 1912.07189

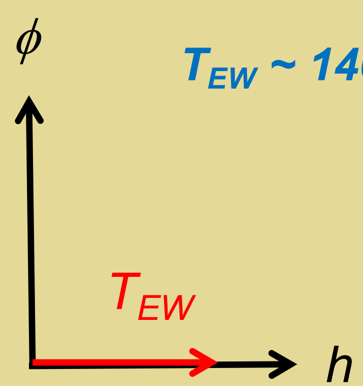
First Order EWPT from BSM Physics



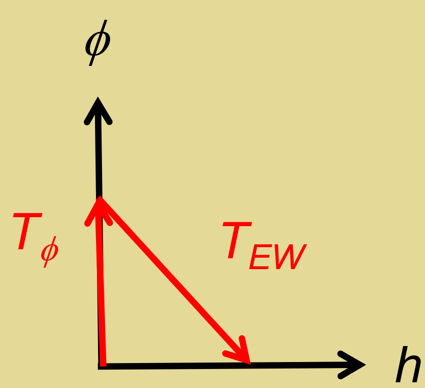
Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

Collider target

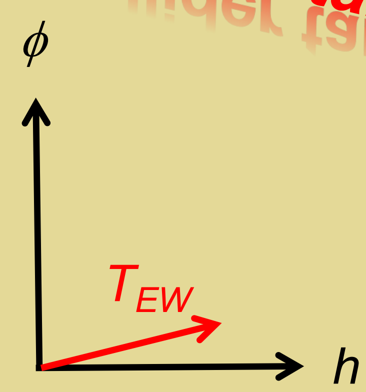
T_{EW} ~ 140 GeV



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



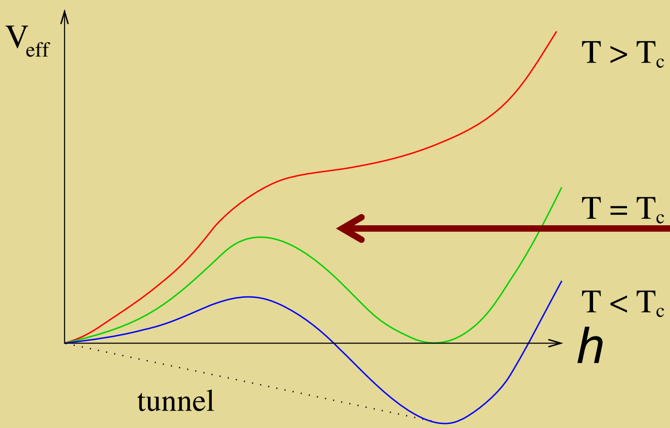
$a_2 H^2\phi^2$: $T = 0$
tree-level effect



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

MJRM: 1912.07189

First Order EWPT from BSM Physics

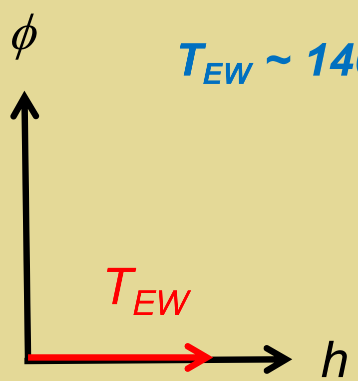


$|\sin\theta| \gtrsim 0.01$ $\quad |\Delta\lambda/\lambda| \gtrsim 0.003$

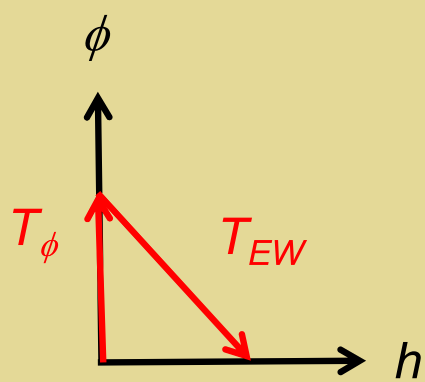
Higgs – ϕ^0 Mixing

Collider target

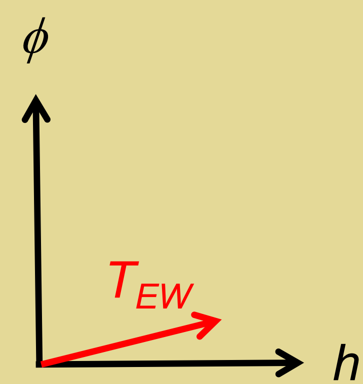
$T_{EW} \sim 140$ GeV



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

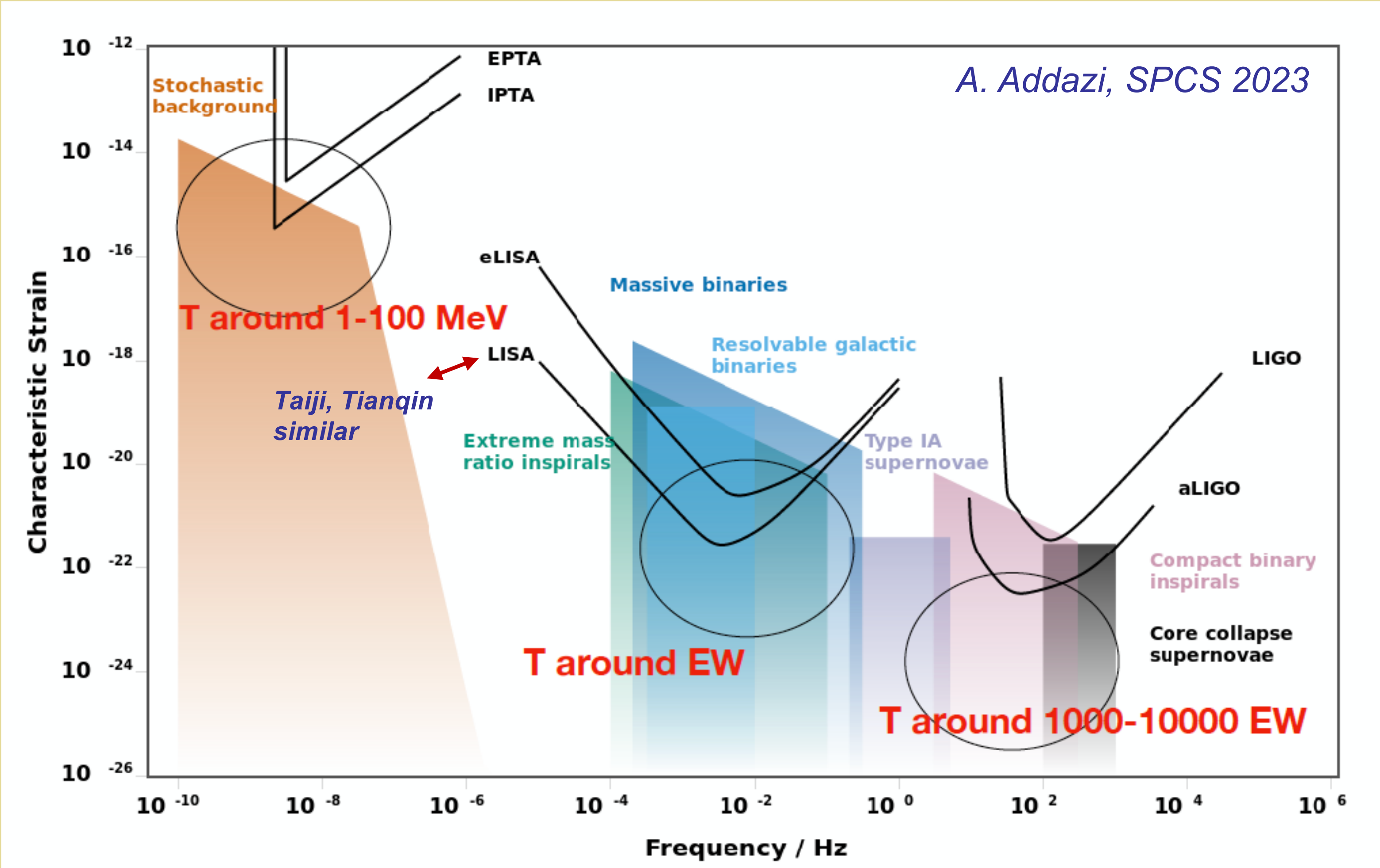


$a_2 H^2\phi^2$: $T = 0$
tree-level effect

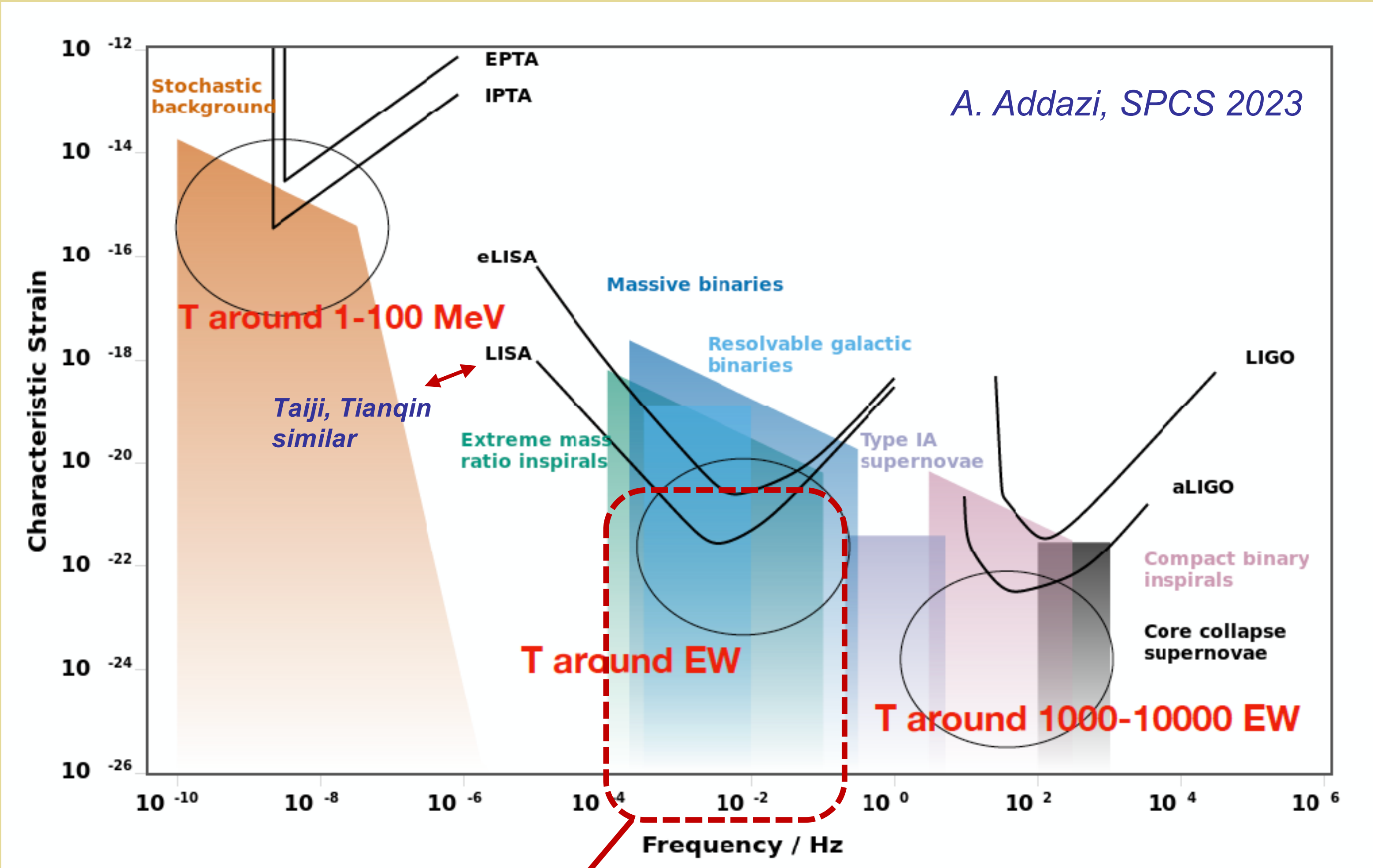


$a_1 H^2\phi$: $T = 0$
tree-level effect

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

II. Theory-Pheno Interface

Theoretical developments → phenomenological implications

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, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...
SM + Scalar Triplet	Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...
MSSM	Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...
NMSSM...	Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

Models & Phenomenology

What BSM Scenarios?

SM + Scalar Singlet

Espinosa, Quiros 93, Benson 93, Choi, Volkas 93, Vergara 96, Branco, Delepine, Emmanuel-Costa, Gonzalez 98, Ham, Jeong, Oh 04, Ahriche 07, Espinosa, Quiros 07, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Das, Fox, Kumar, Weiner 09, Espinosa, Konstandin, Riva 11, Chung, Long 11, Barger, Chung, Long, Wang 12, Huang, Shu, Zhang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14, Jiang, Bian, Huang, Shu 15, Kozaczuk 15, Cline, Kainulainen, Tucker-Smith 17, Kurup, Perelstein 17, Chen, Kozaczuk, Lewis 17, Gould, Kozaczuk, Niemi, Ramsey-Musolf, Tenkanen, Weir 19...

SM + Scalar Doublet (2HDM)

Turok, Zadrozny 92, Davies, Froggatt, Jenkins, Moorhouse 94, Cline, Lemieux 97, Huber 06, Fromme, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17, Andersen, Gorda, Helset, Niemi, Tenkanen, Tranberg, Vuorinen, Weir 18...

SM + Scalar Triplet

Patel, Ramsey-Musolf 12, Niemi, Patel, Ramsey-Musolf, Tenkanen, Weir 18 ...

MSSM

Carena, Quiros, Wagner 96, Delepine, Gerard, Gonzalez Felipe, Weyers 96, Cline, Kainulainen 96, Laine, Rummukainen 98, Carena, Nardini, Quiros, Wagner 09, Cohen, Morrissey, Pierce 12, Curtin, Jaiswal, Meade 12, Carena, Nardini, Quiros, Wagner 13, Katz, Perelstein, Ramsey-Musolf, Winslow 14...

NMSSM...

Pietroni 93, Davies, Froggatt, Moorhouse 95, Huber, Schmidt 01, Ham, Oh, Kim, Yoo, Son 04, Menon, Morrissey, Wagner 04, Funakubo, Tao, Yokoda 05, Huber, Konstandin, Prokopec, Schmidt 07, Chung, Long 10, Kozaczuk, Profumo, Stephenson Haskins, Wainwright 15...

Models & pheno: how reliable ?

Thanks: J. M. No

Extensive references in MJRM: 1912.07189

Theory Meets Phenomenology

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

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

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

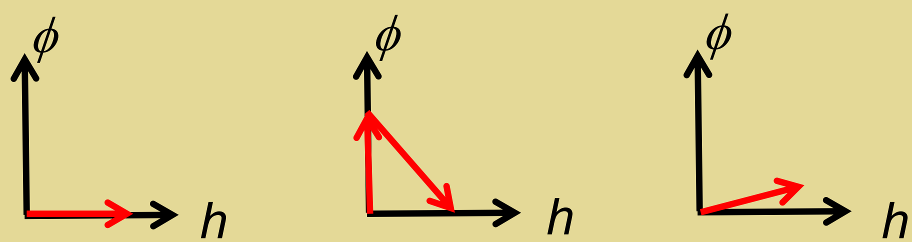
Benchmark pert theory

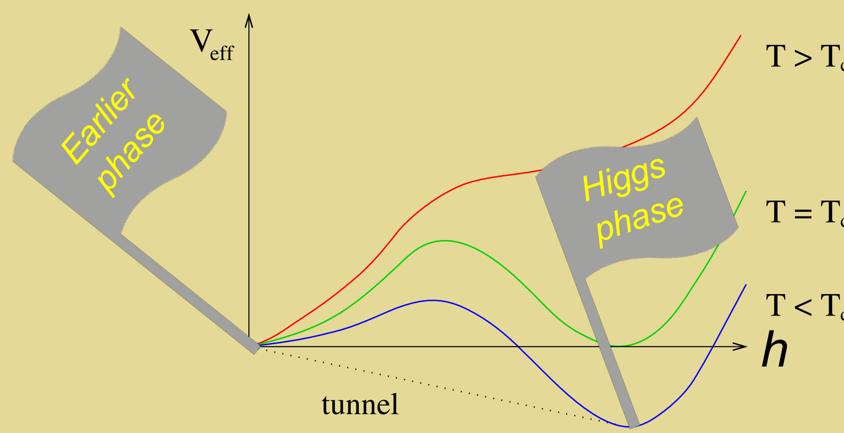
Theory-Pheno Interface

Simple Higgs portal models:

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

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



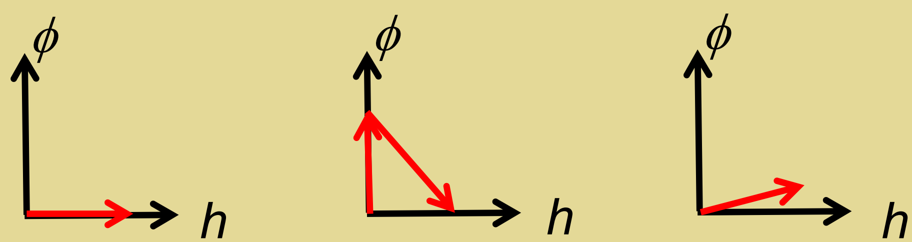


Theory-Pheno Interface

Simple Higgs portal models:

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

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



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*

Collider Probes

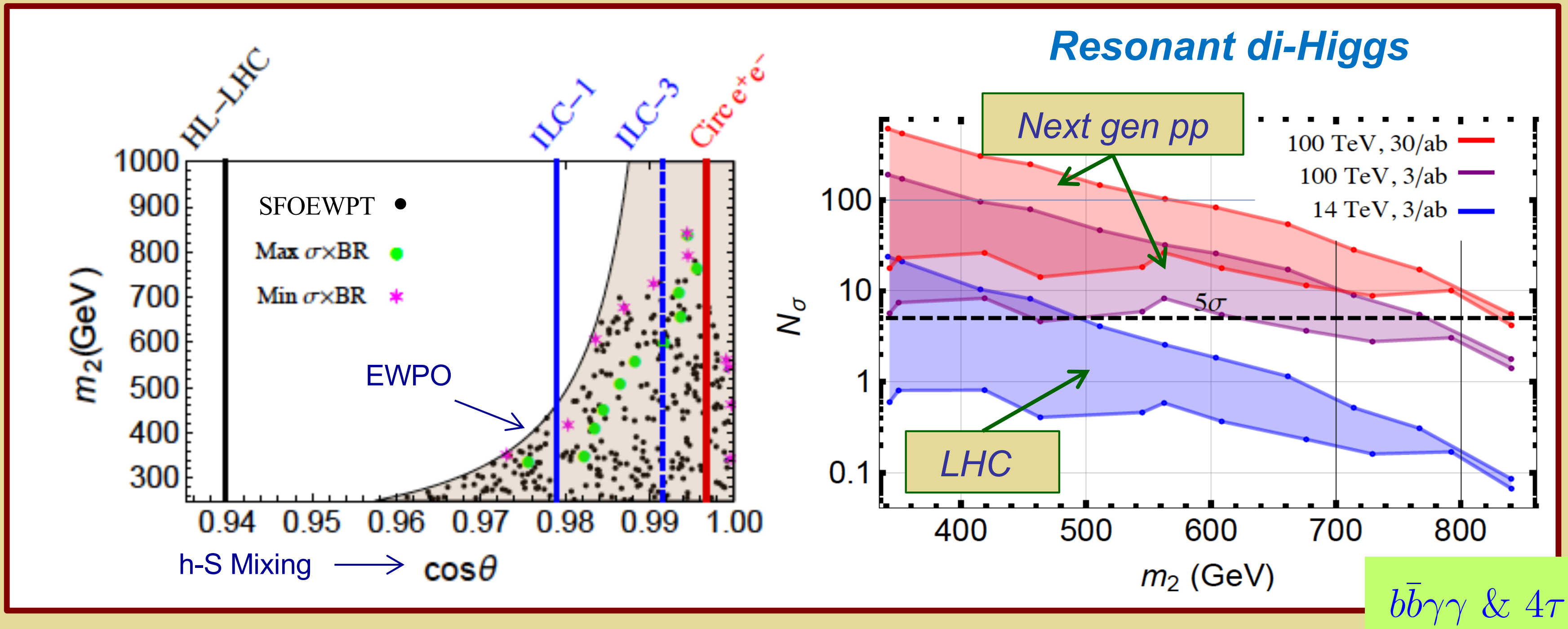
- *Resonant di-Higgs ($h_1\ h_1$) production* *
- *Heavy h_2 production* *
- *Associated production ($Z\ h_1$) and non-resonant di-Higgs production* *
- *Exotic Higgs decays* **

* *Heavy h_2*

** *Light h_2*

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

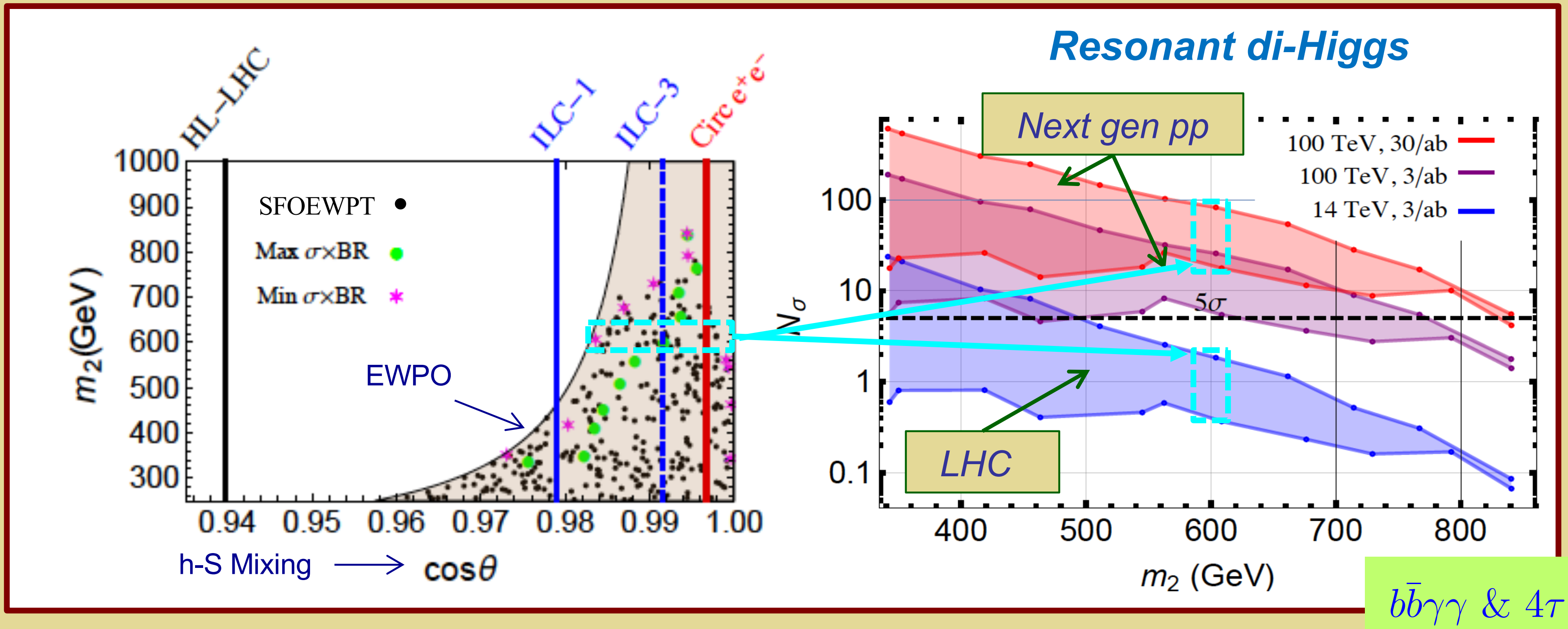


Kotwal, No, R-M, Winslow 1605.06123

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

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

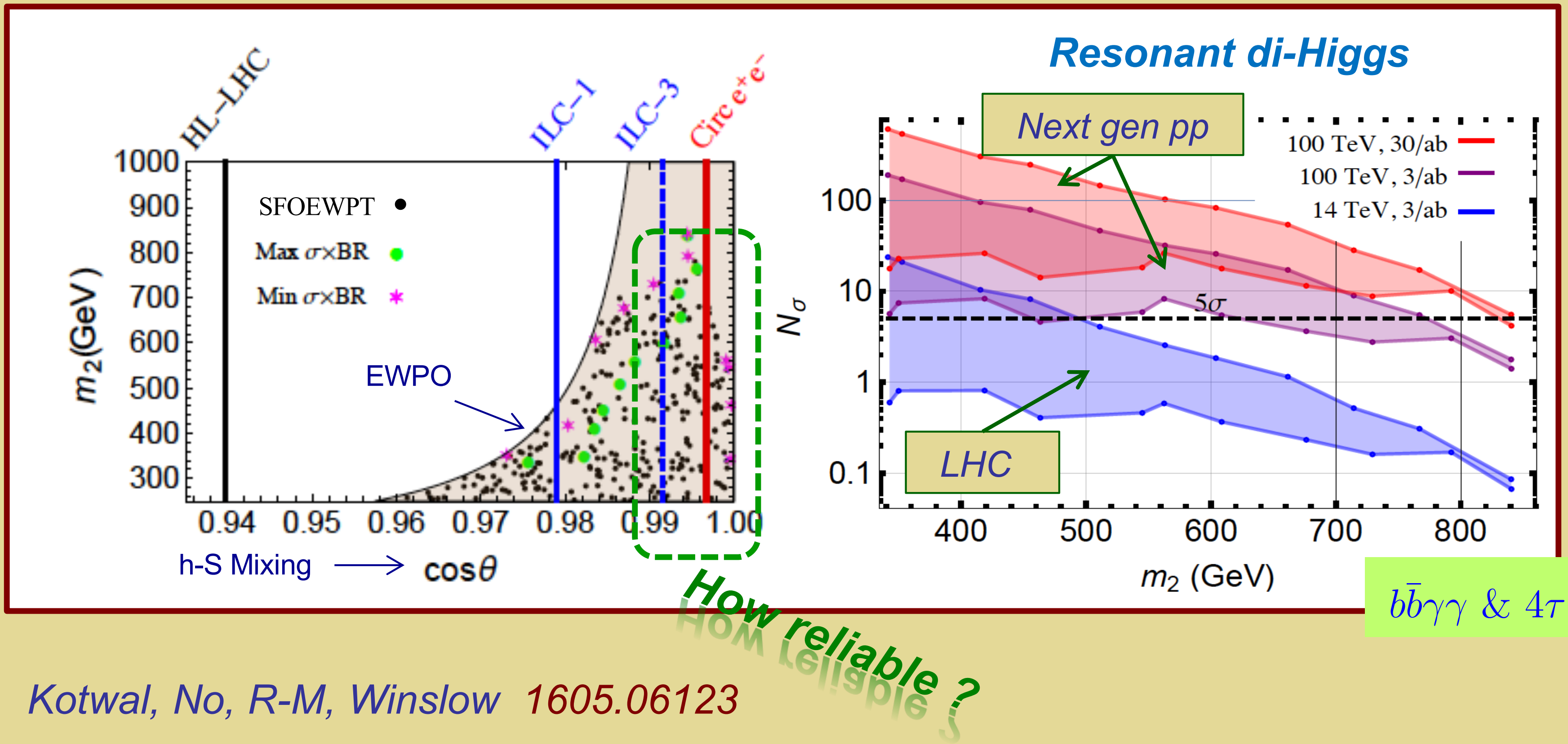


Kotwal, No, R-M, Winslow 1605.06123

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

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies

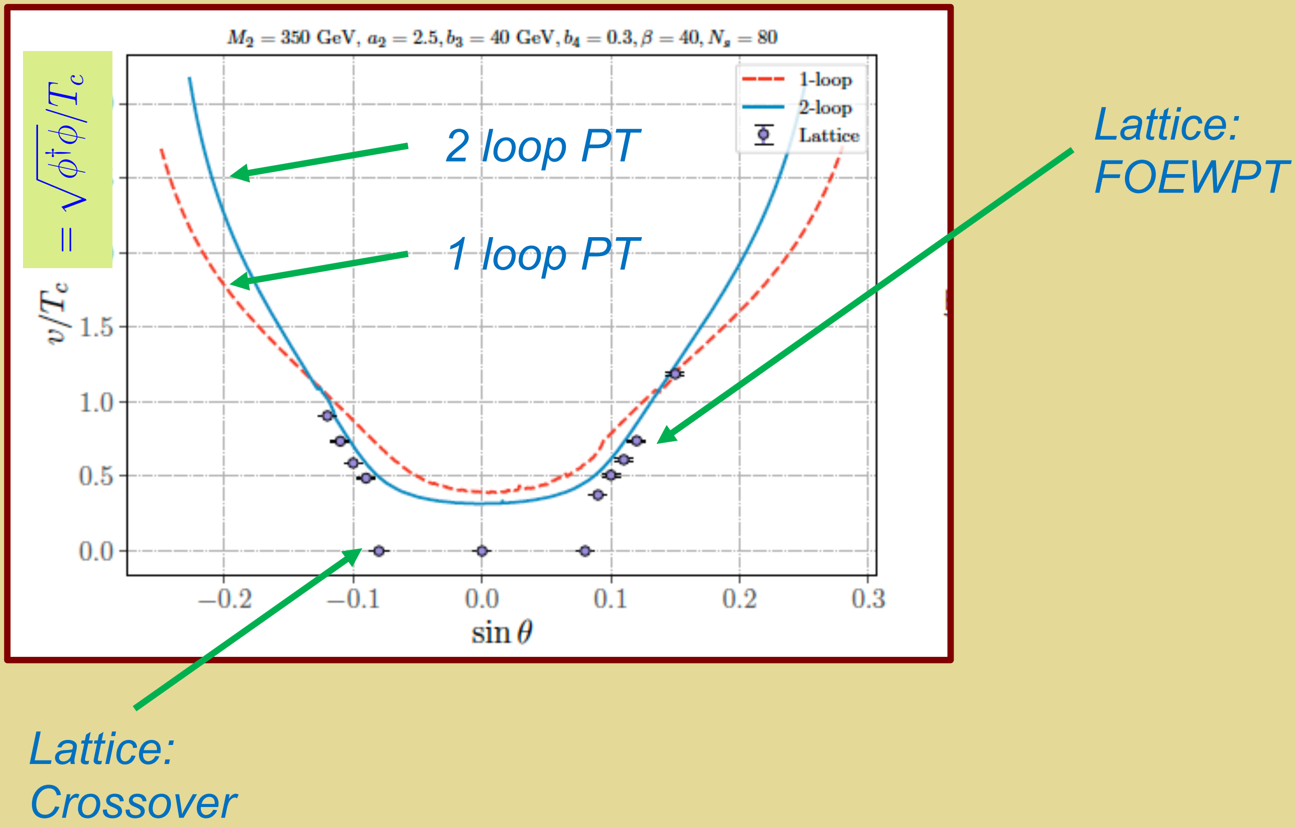


Kotwal, No, R-M, Winslow 1605.06123

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

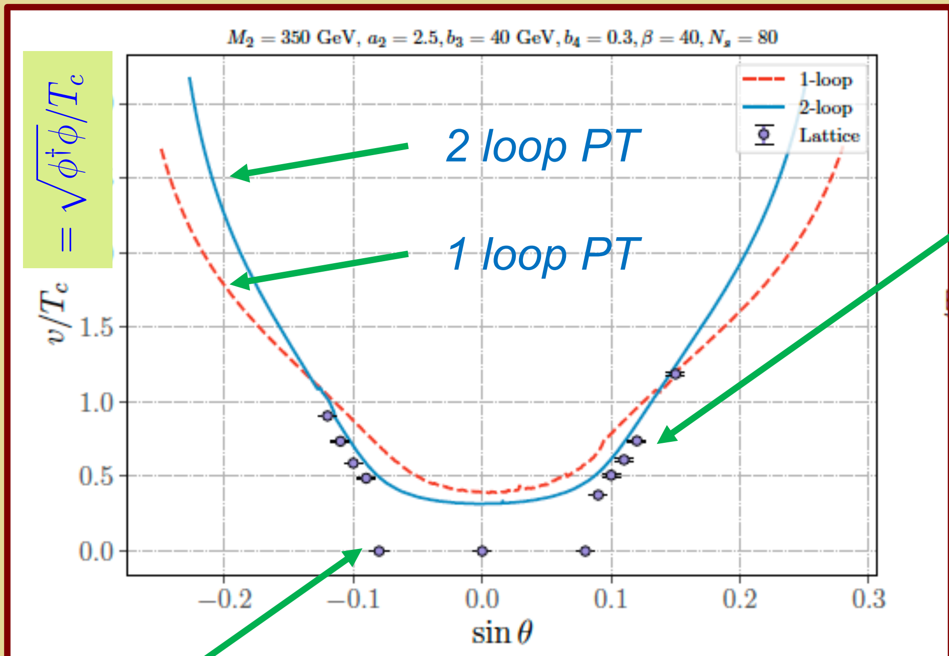
Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



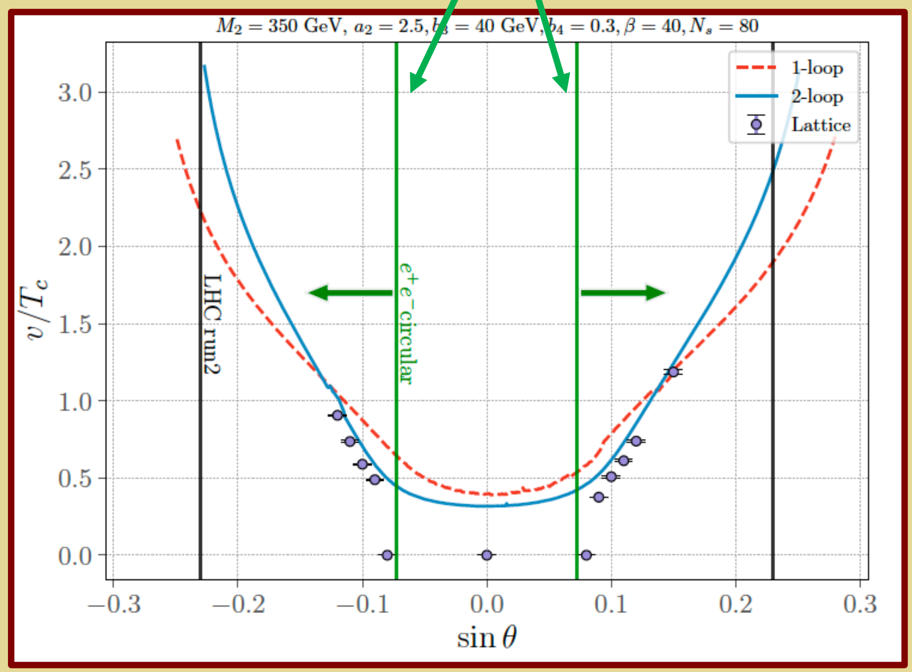
Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



Lattice:
FOEWPT

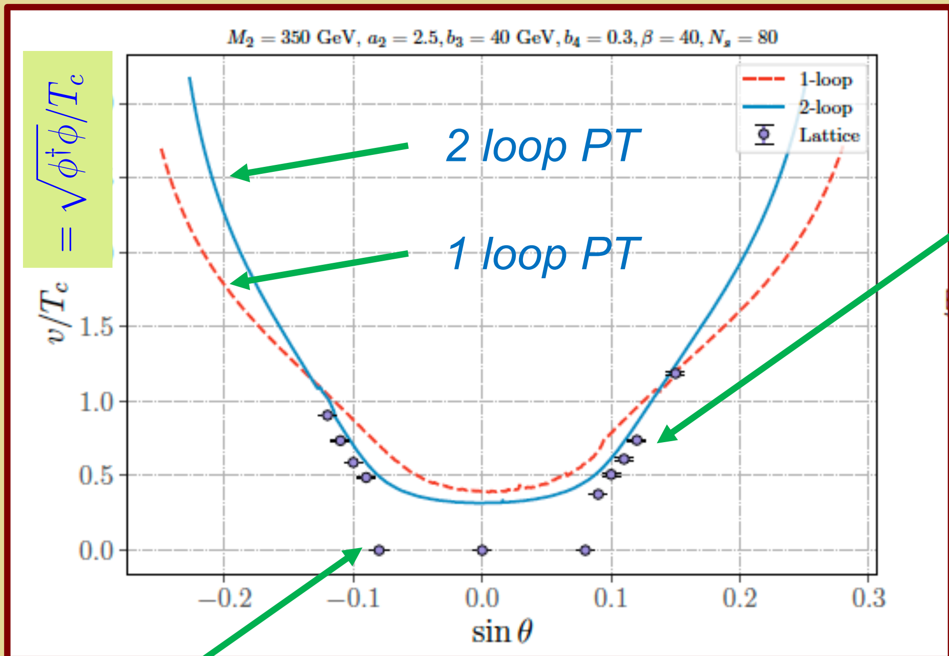
Future e^+e^-



Lattice:
Crossover

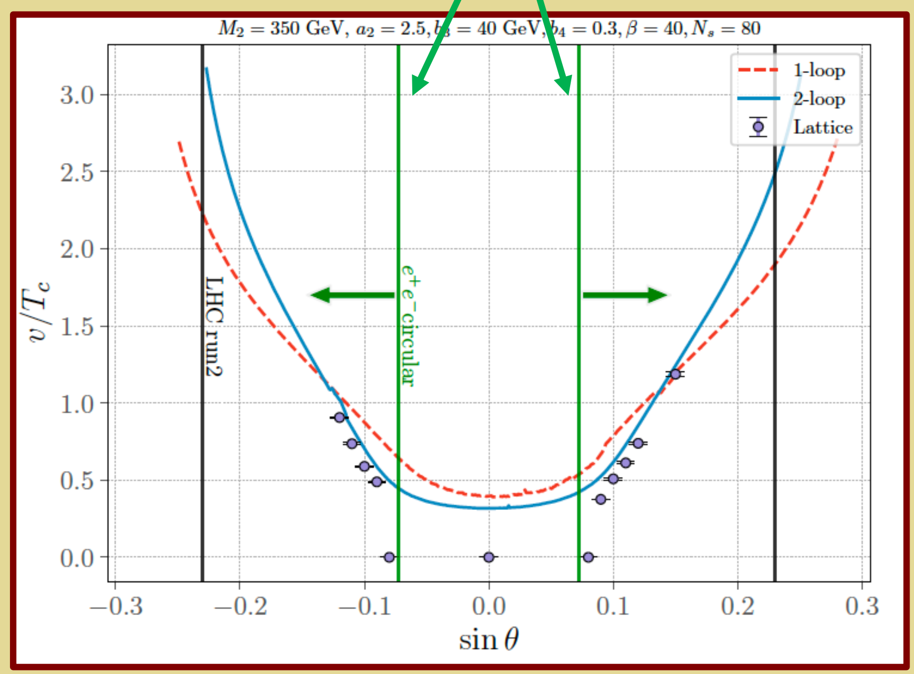
Lauri Niemi, MJRM, Gutao Xia, 2405.01191

Singlets: Lattice vs. Pert Theory



Lattice: FOEWPT

Future e⁺e⁻



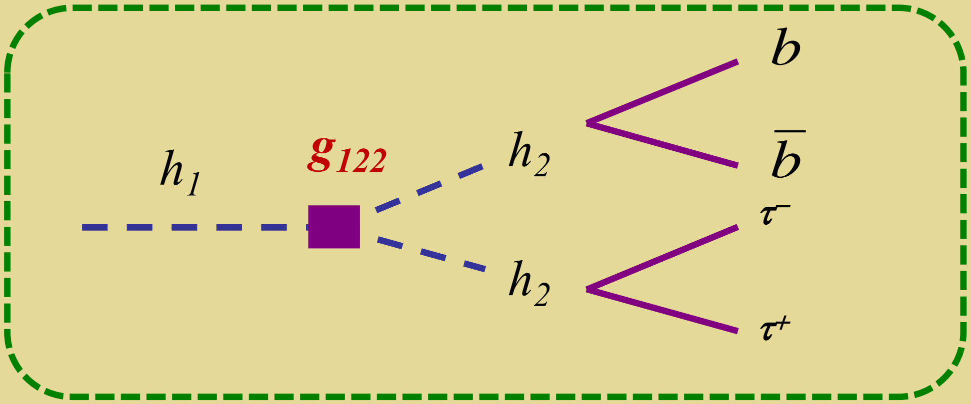
Lattice: Crossover

- *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*

- 16.3

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* **



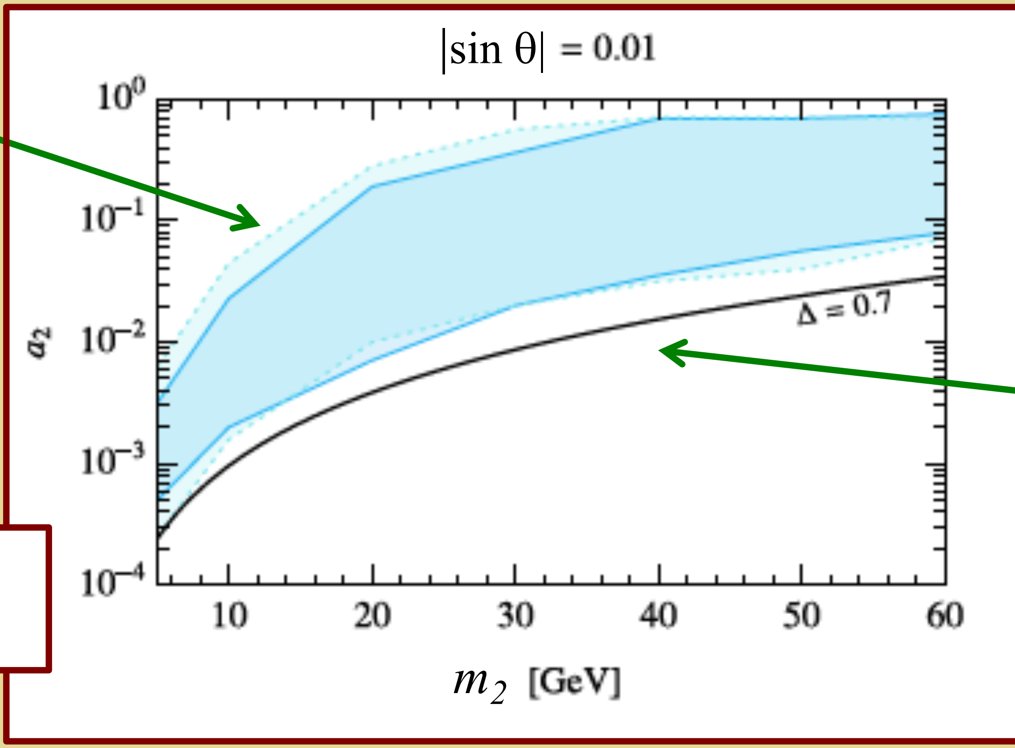
* *Heavy h_2*

** *Light h_2*

Light Singlets: Exotic Higgs Decays

One loop perturbation theory

EWPT viable: numerical

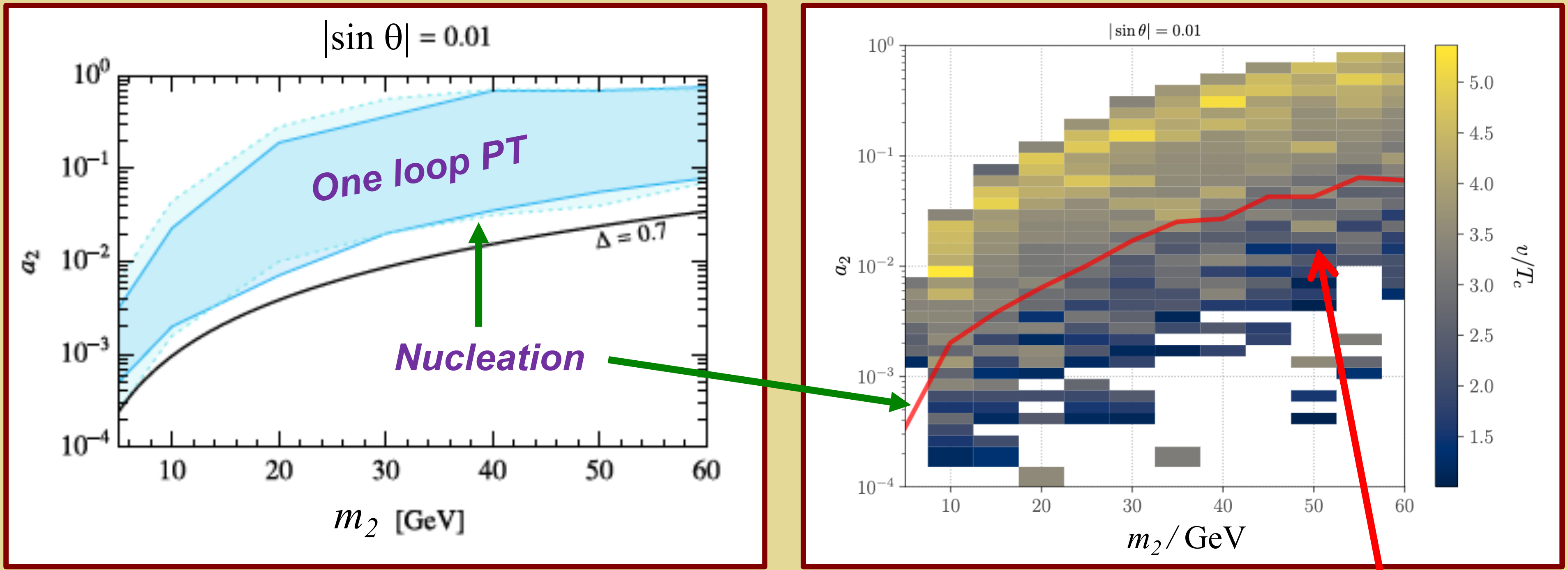


EWPT viable: Semi analytic → nucleation decisive

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

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,

New: Lattice + EFT @ T > 0

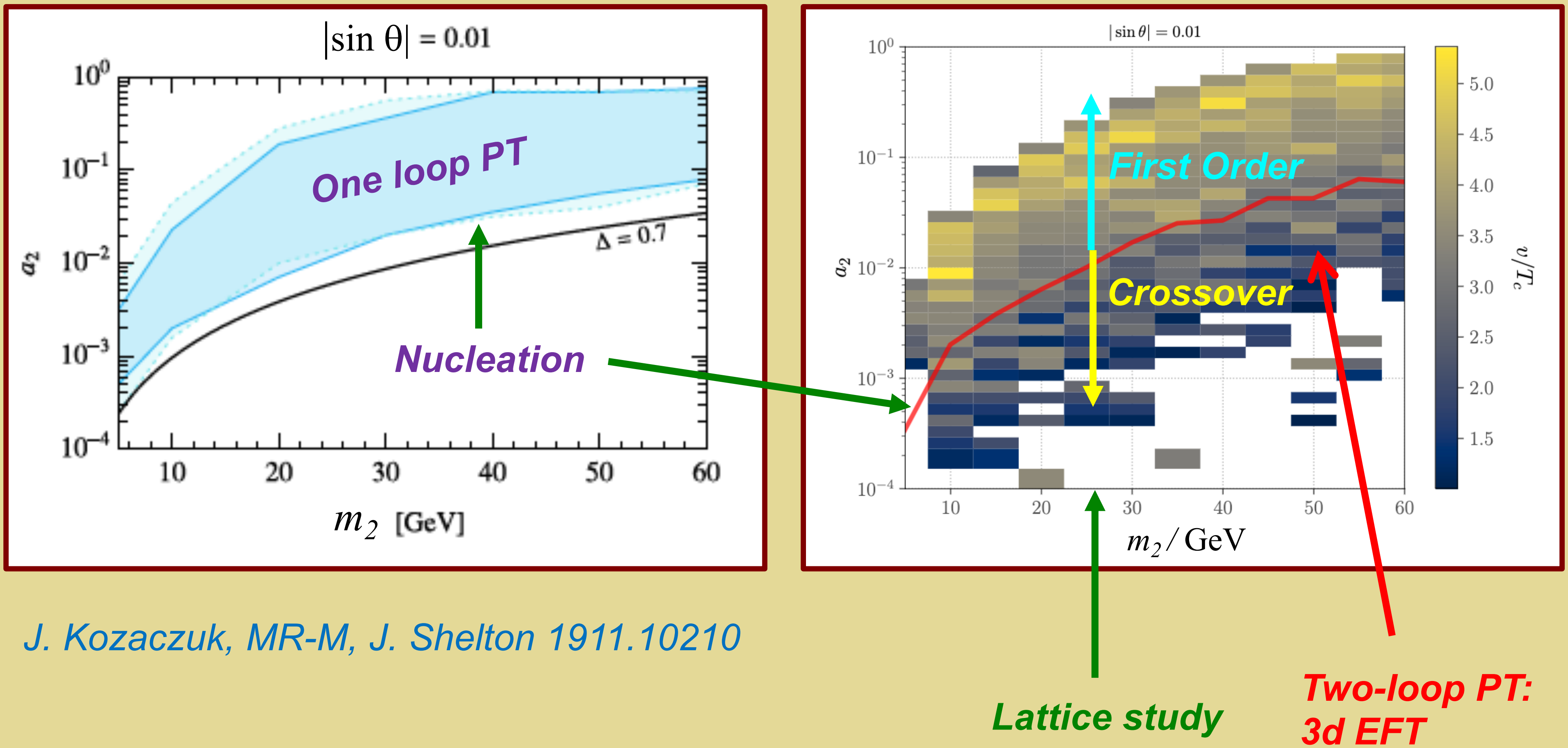


J. Kozaczuk, MR-M, J. Shelton 1911.10210

Two-loop PT:
3d EFT

L. Niemi, MJRM, G. Xia 2405.01191

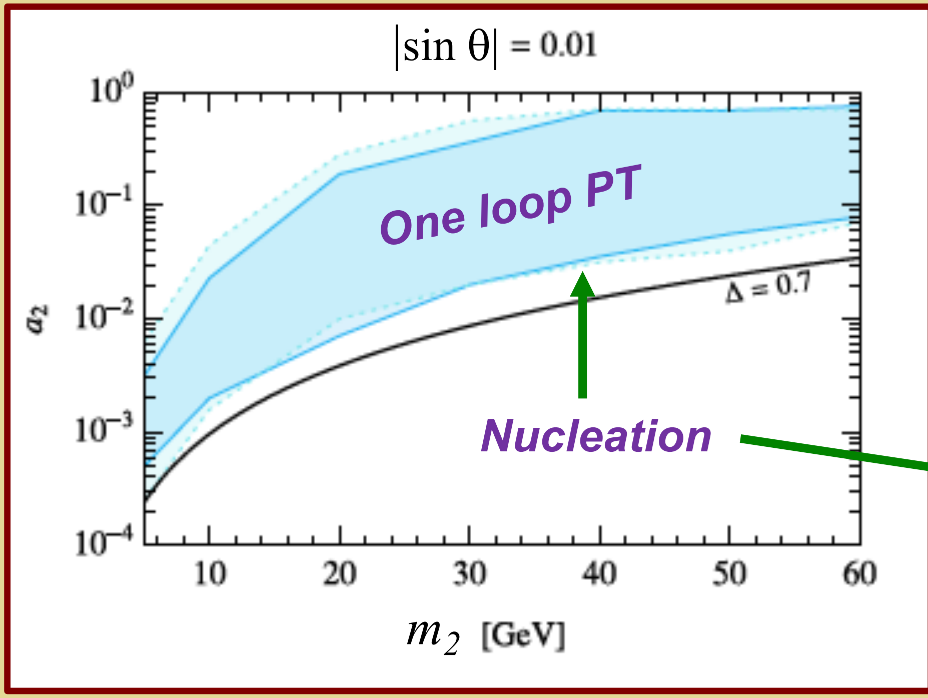
New: Lattice + EFT @ T > 0

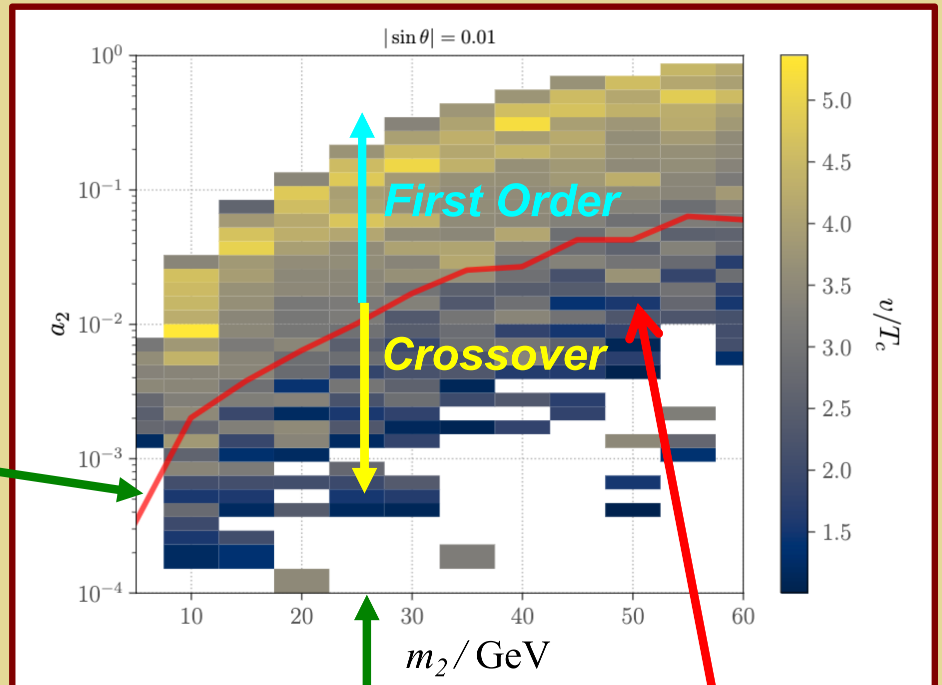


J. Kozaczuk, MR-M, J. Shelton 1911.10210

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

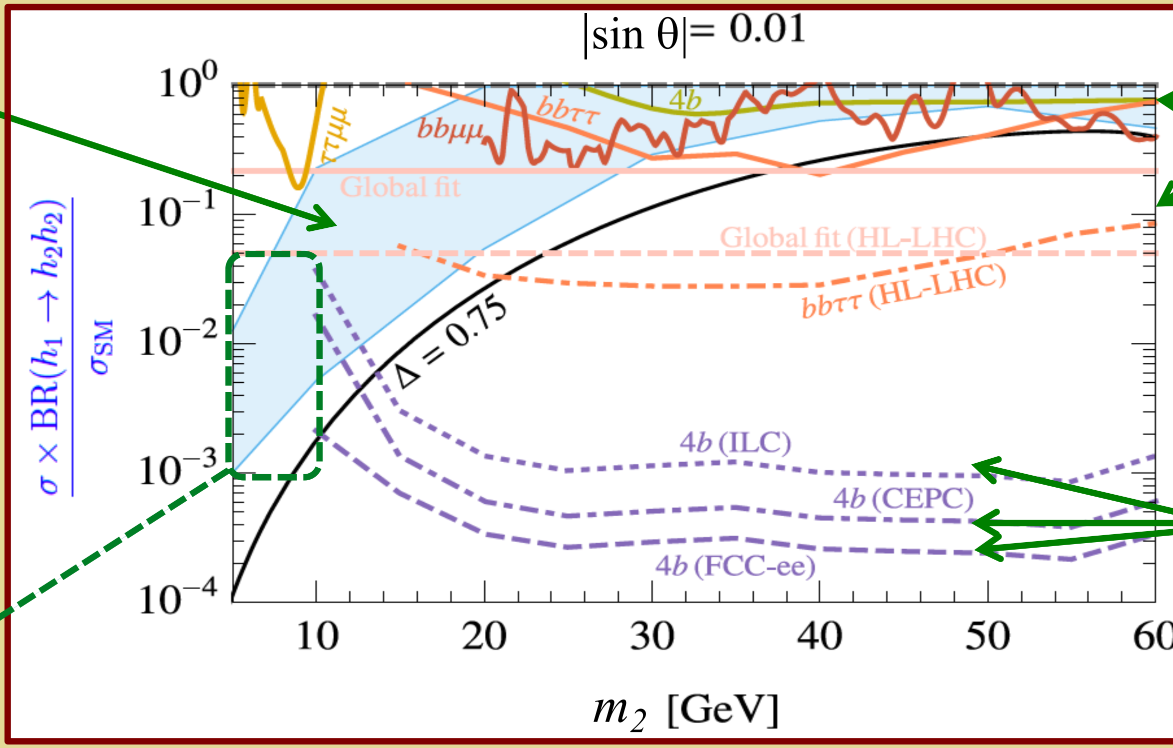
Small portal couplings → FO EWPT unlikely

L. Niemi, MJRM, G. Xia 2405.01191

Light Singlets: Exotic Higgs Decays

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

EWPT viable: numerical



LHC: 2019 & HL

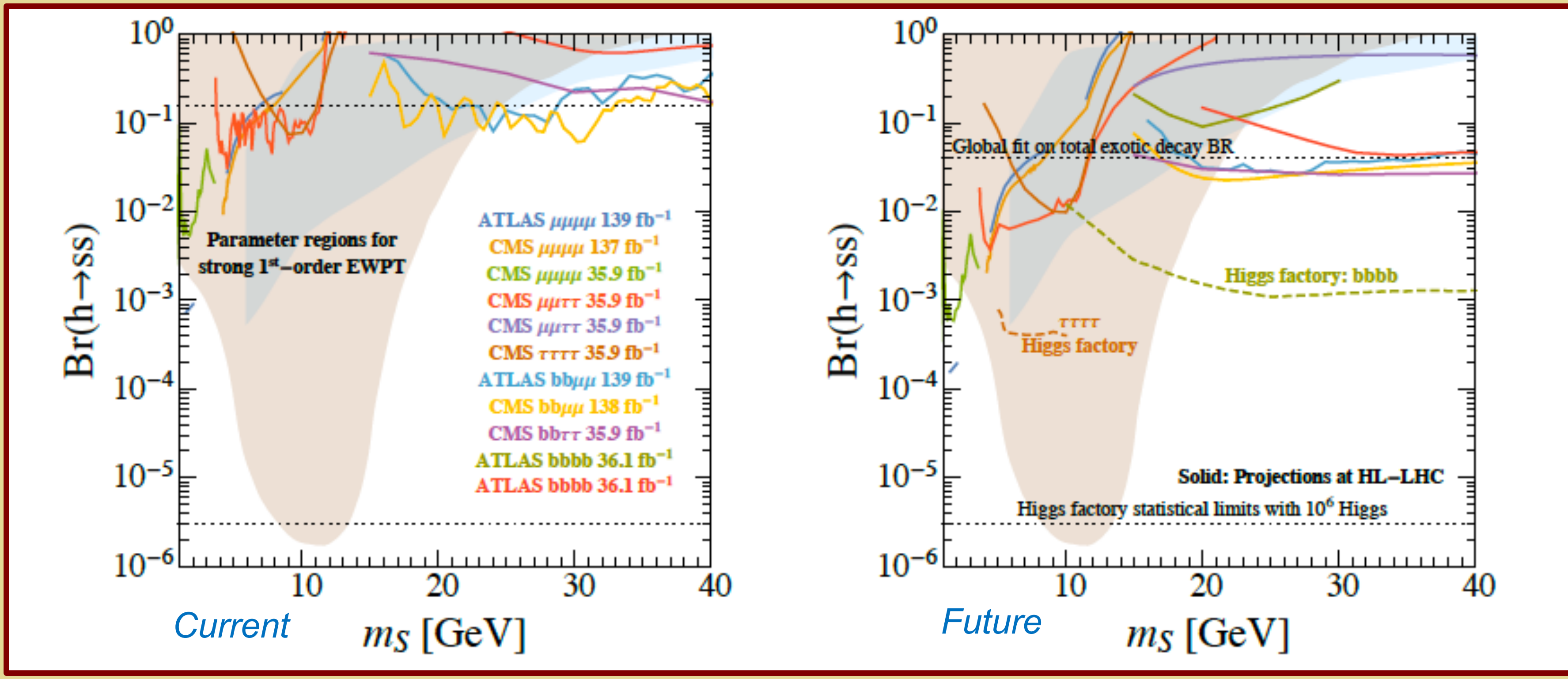
Future e^+e^-

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

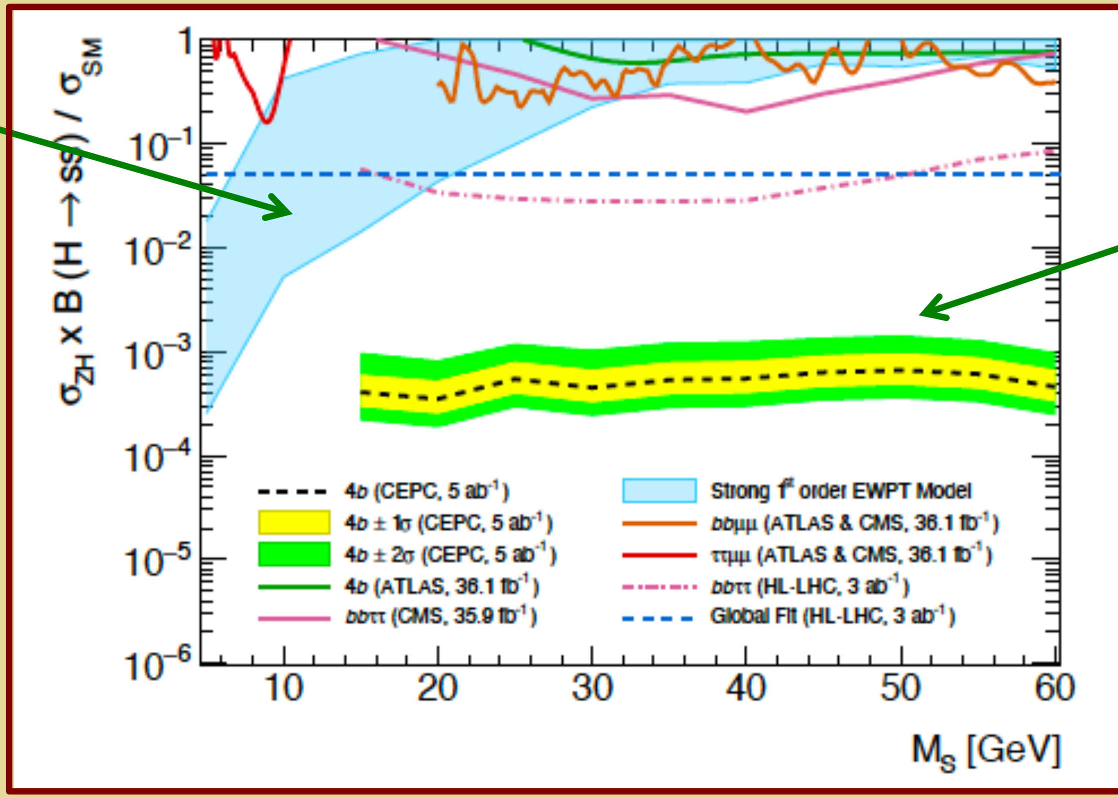


Carena et al (Snowmass) 2203.08206

Light Singlets: Exotic Higgs Decays

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

EWPT viable: numerical



CEPC 4b

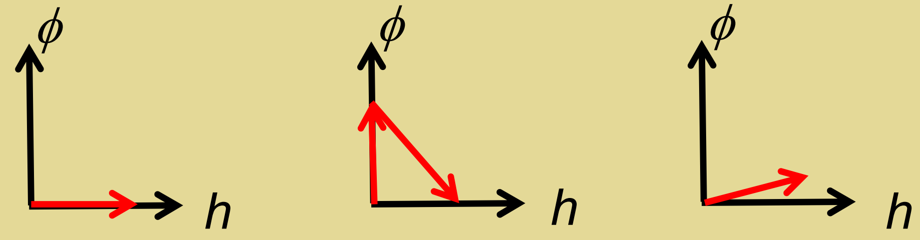
J. Wang et al (Snowmass) 2203.10184

Theory-Pheno Interface

Simple Higgs portal models:

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

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



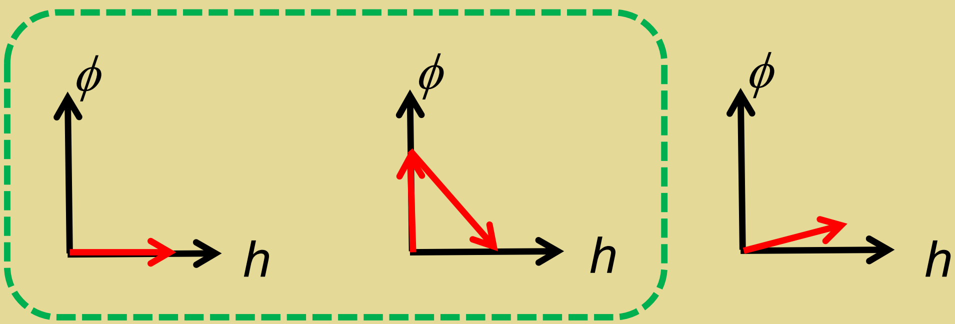
Theory-Pheno Interface

Simple Higgs portal models:

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

Small

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



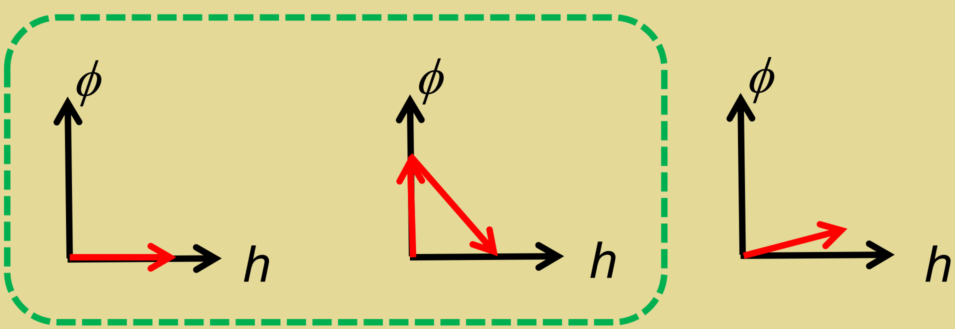
Theory-Pheno Interface

Simple Higgs portal models:

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

Small

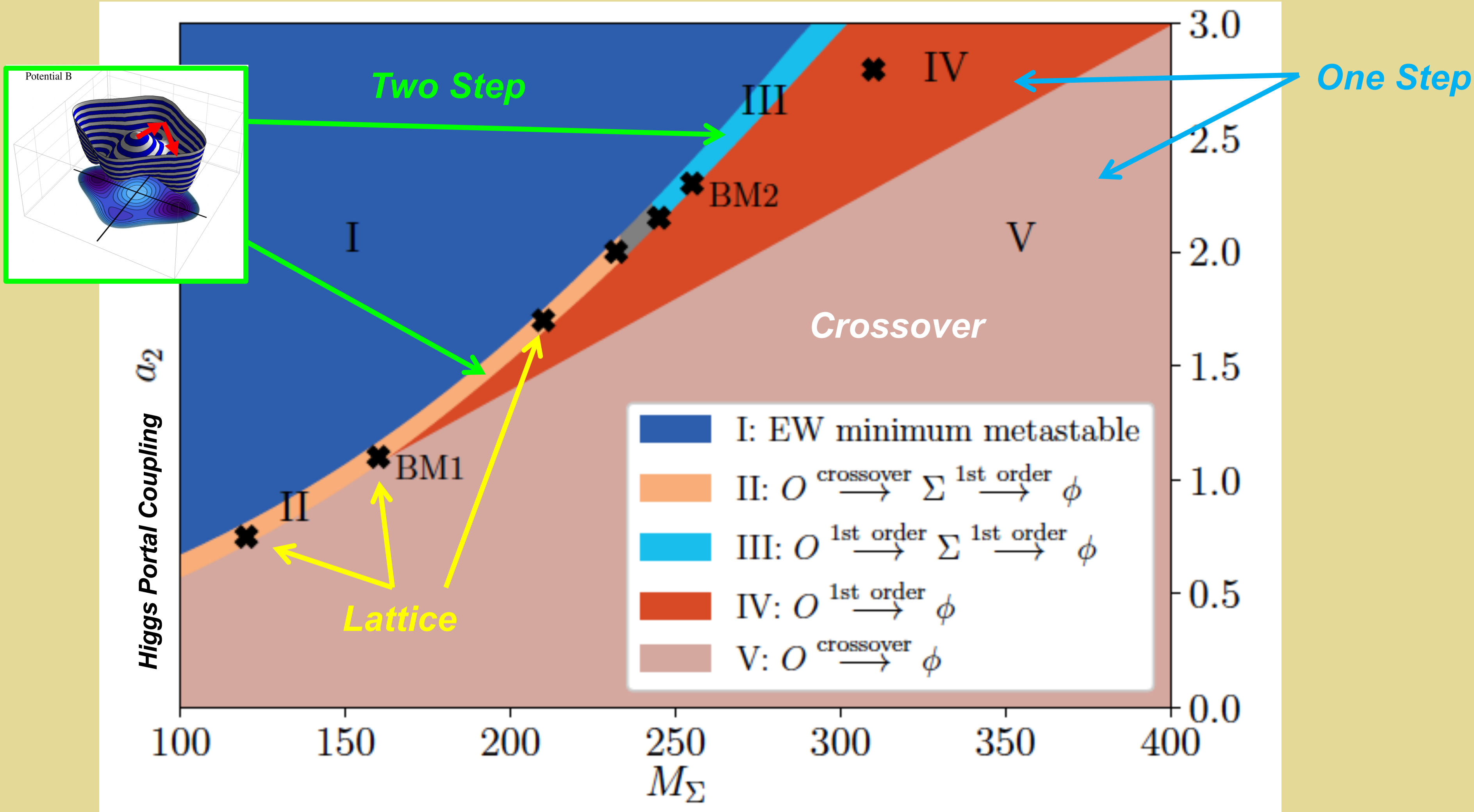
$$V \supset a_1 H^2\phi + a_2 H^2\phi^2$$



Phenomenology

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

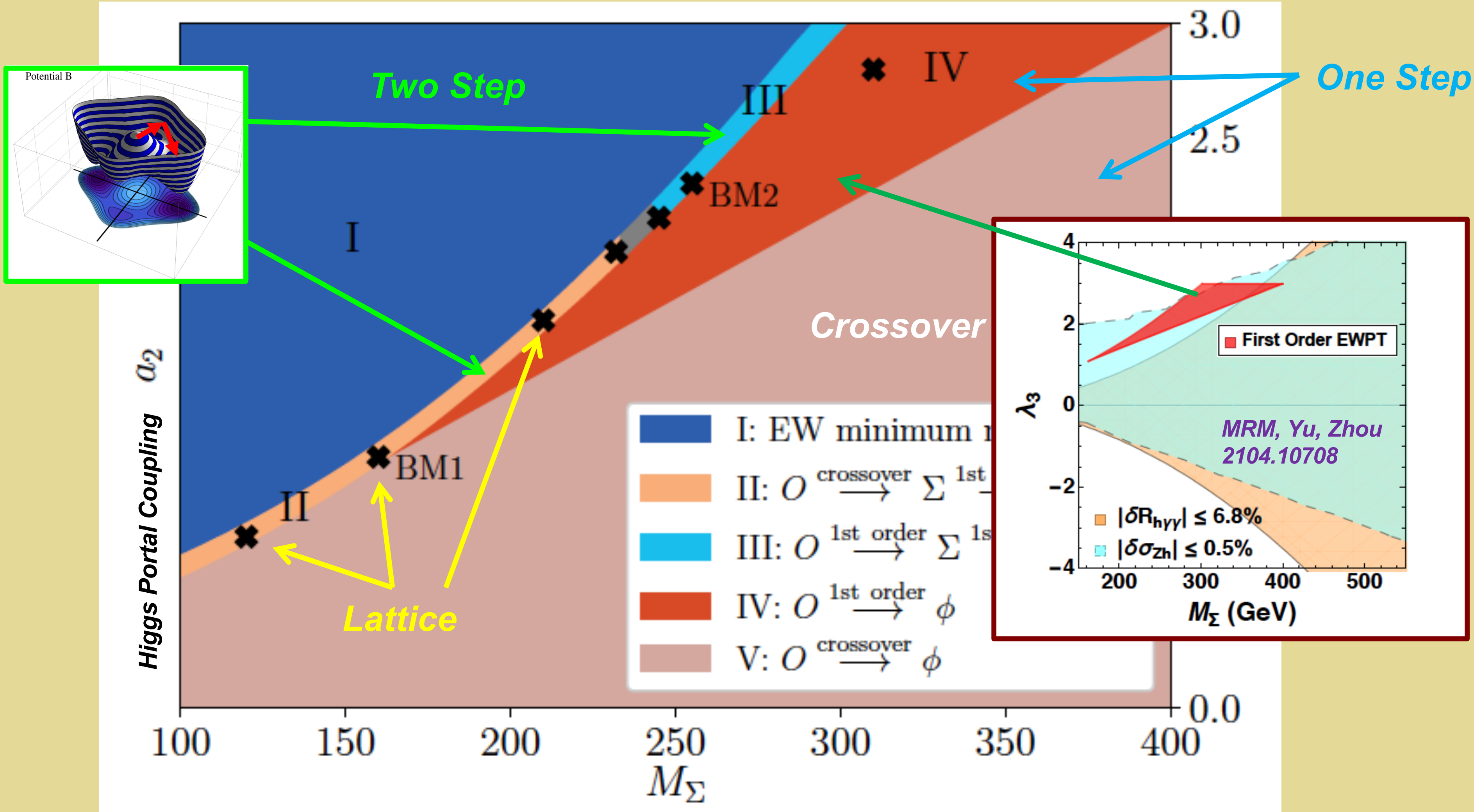
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332

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

Real Triplet & EWPT: Novel EWSB



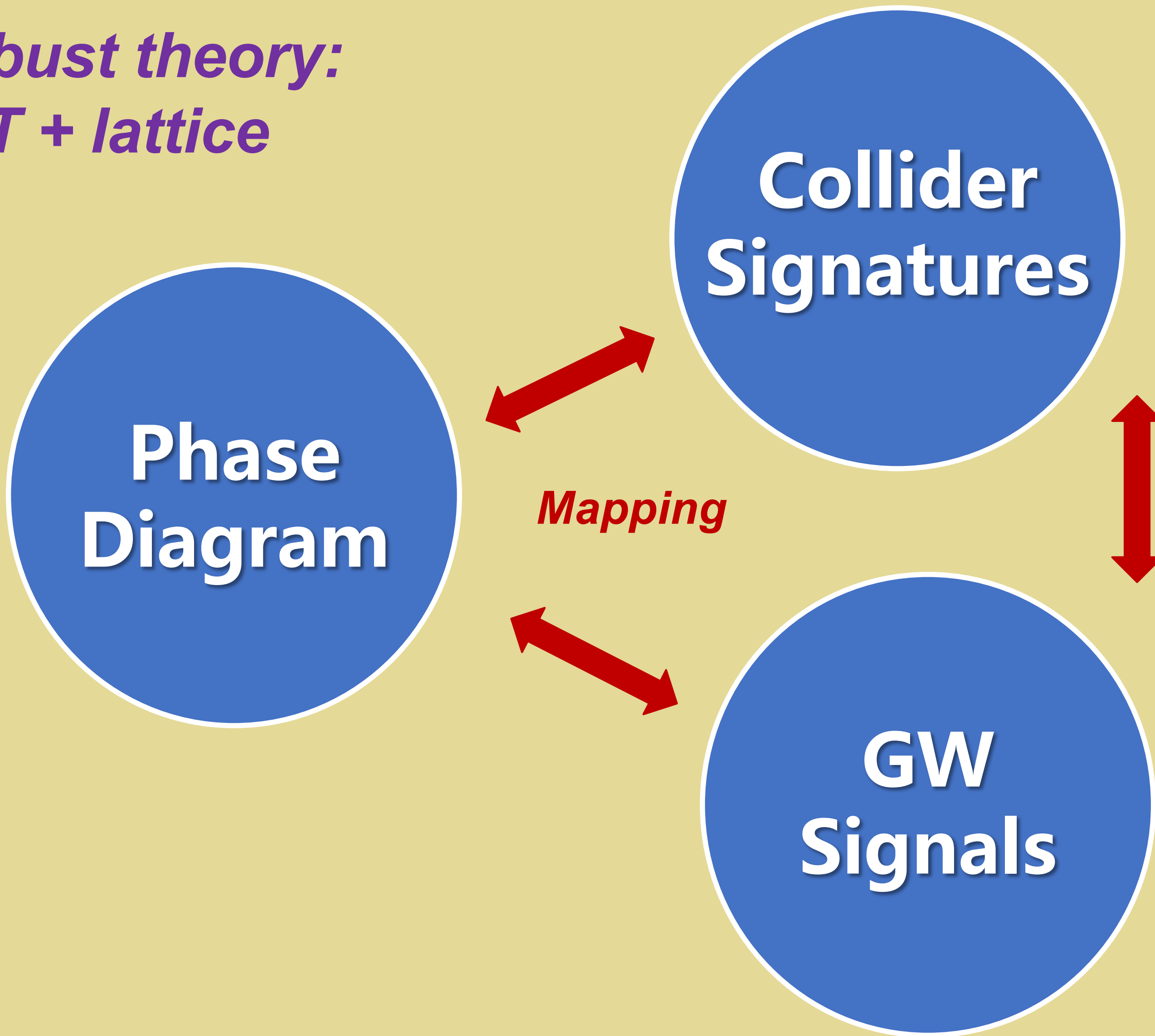
Niemi, R-M, Tenkanen, Weir 2005.11332

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

BSM EWPT: Inter-frontier Connections

Robust theory:
EFT + lattice

Observables:
model specific



Combined reach

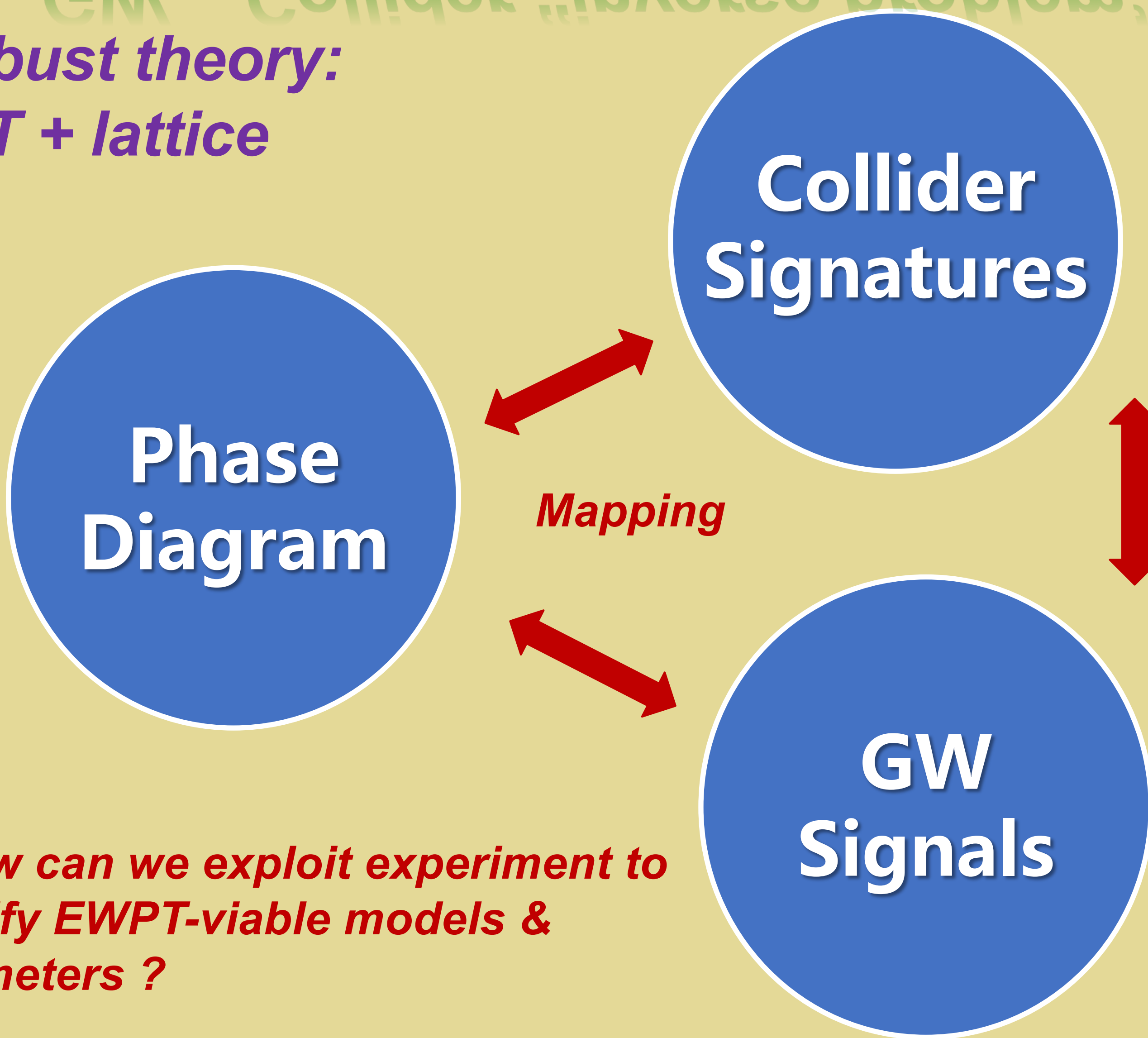
Hydro:
α , β / H_*

BSM EWPT: Inter-frontier Connections

GW – Collider “inverse problem” **

Robust theory:
EFT + lattice

Observables:
model specific

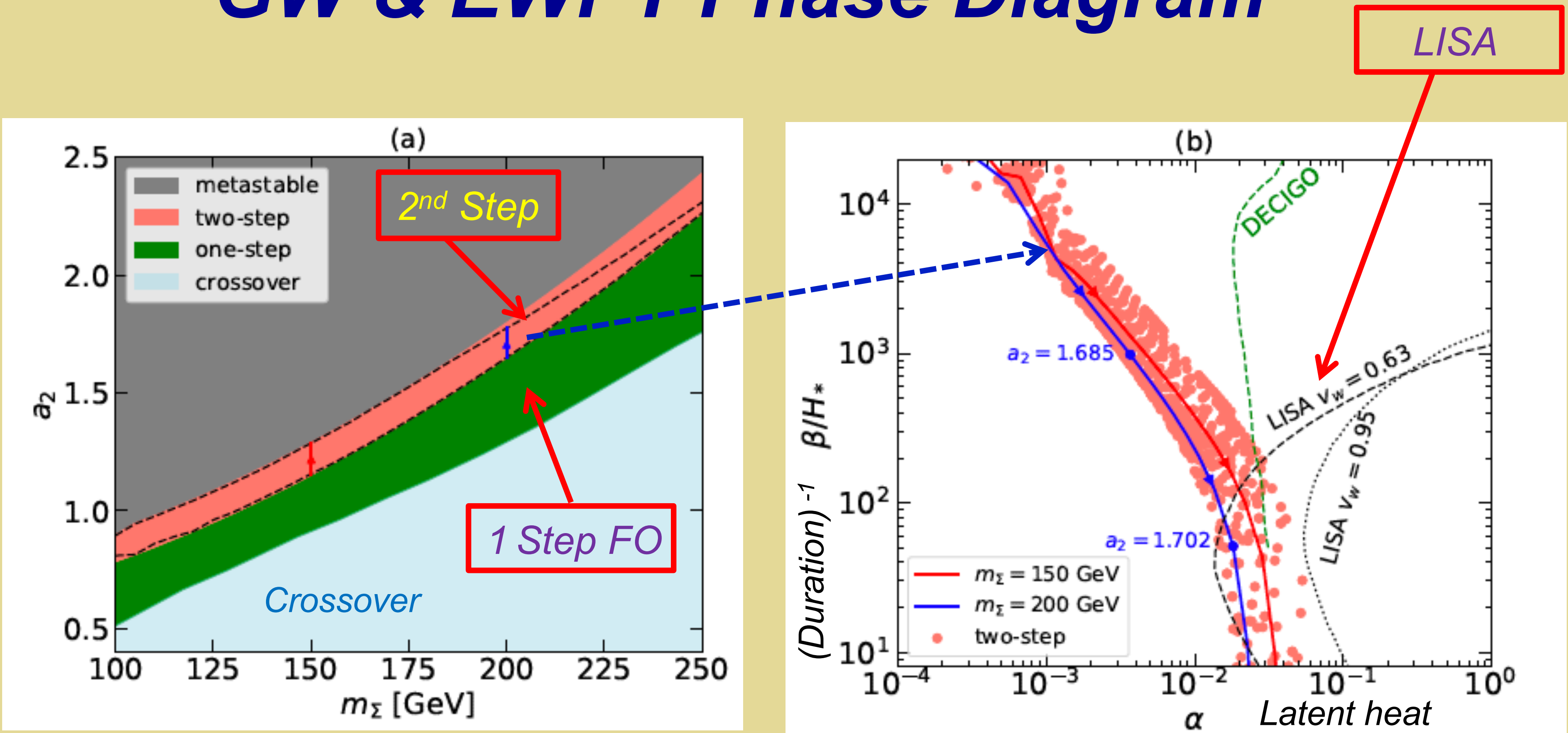


Combined reach

Hydro:
α , β / H_*

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

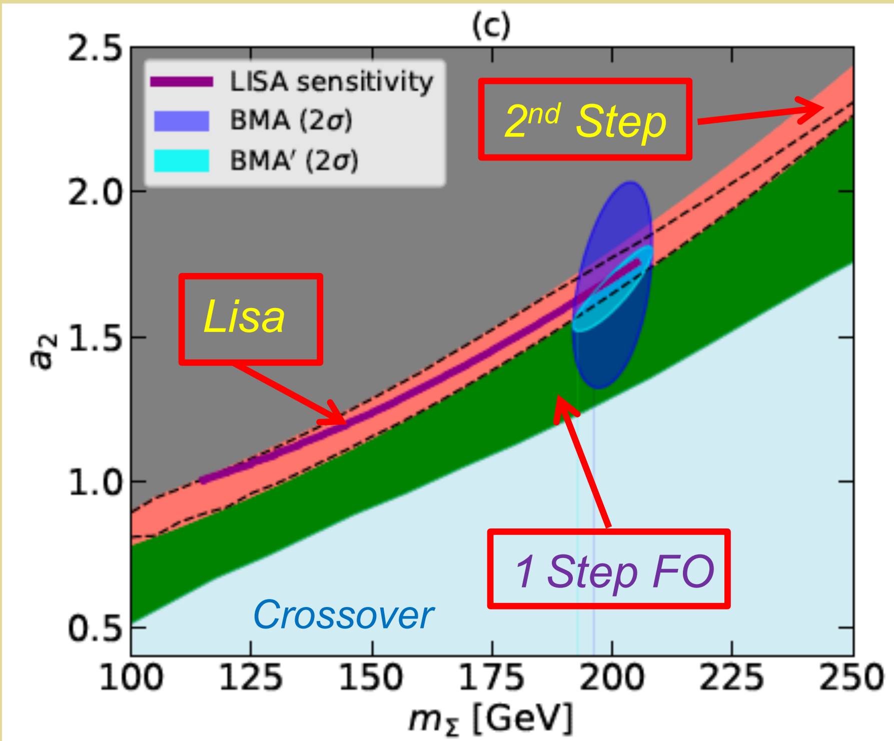
GW & EWPT Phase Diagram

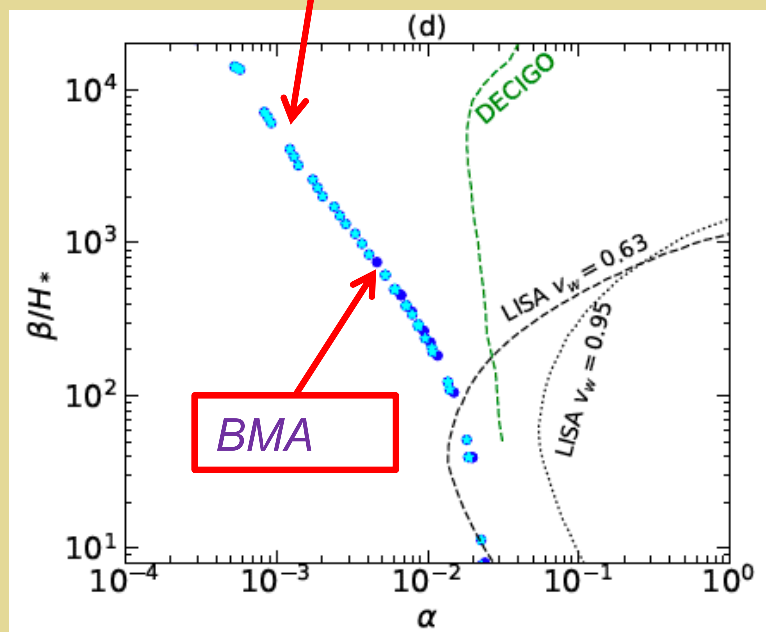


- *Single step transition: GW well outside LISA sensitivity*
- *Second step of 2-step transition can be observable*
- *Significant GW sensitivity to portal coupling*

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*

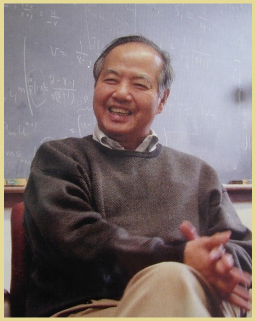
Friedrich, MJRM, Tenkanen, Tran 2203.05889

III. Outlook

Was There an Electroweak Phase Transition ?

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

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

100+

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

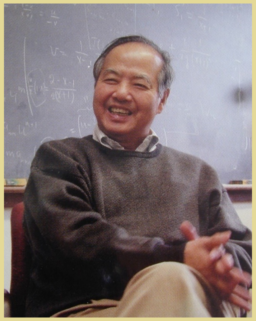
Theory & Experiment

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

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

https://www.youtube.com/watch?v=z0awD6q8FTI

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



A point of convergence of the world's top scientists

A launch pad for the early-career scientists

Director

Founded 2016

Welcome to Shanghai !

A world famous source of original innovation

100+

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

Theory & Experiment

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

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

https://www.youtube.com/watch?v=z0awD6q8FTI

Was There an Electroweak Phase Transition ?

- *Answering this question is an important and exciting challenge for Higgs Physics @ LHC/CEPC/FCC-ee/ILC…*

- *The relevant scale T_{EW} makes this physics a prime target for collider and gravitational wave probes*

谢谢！

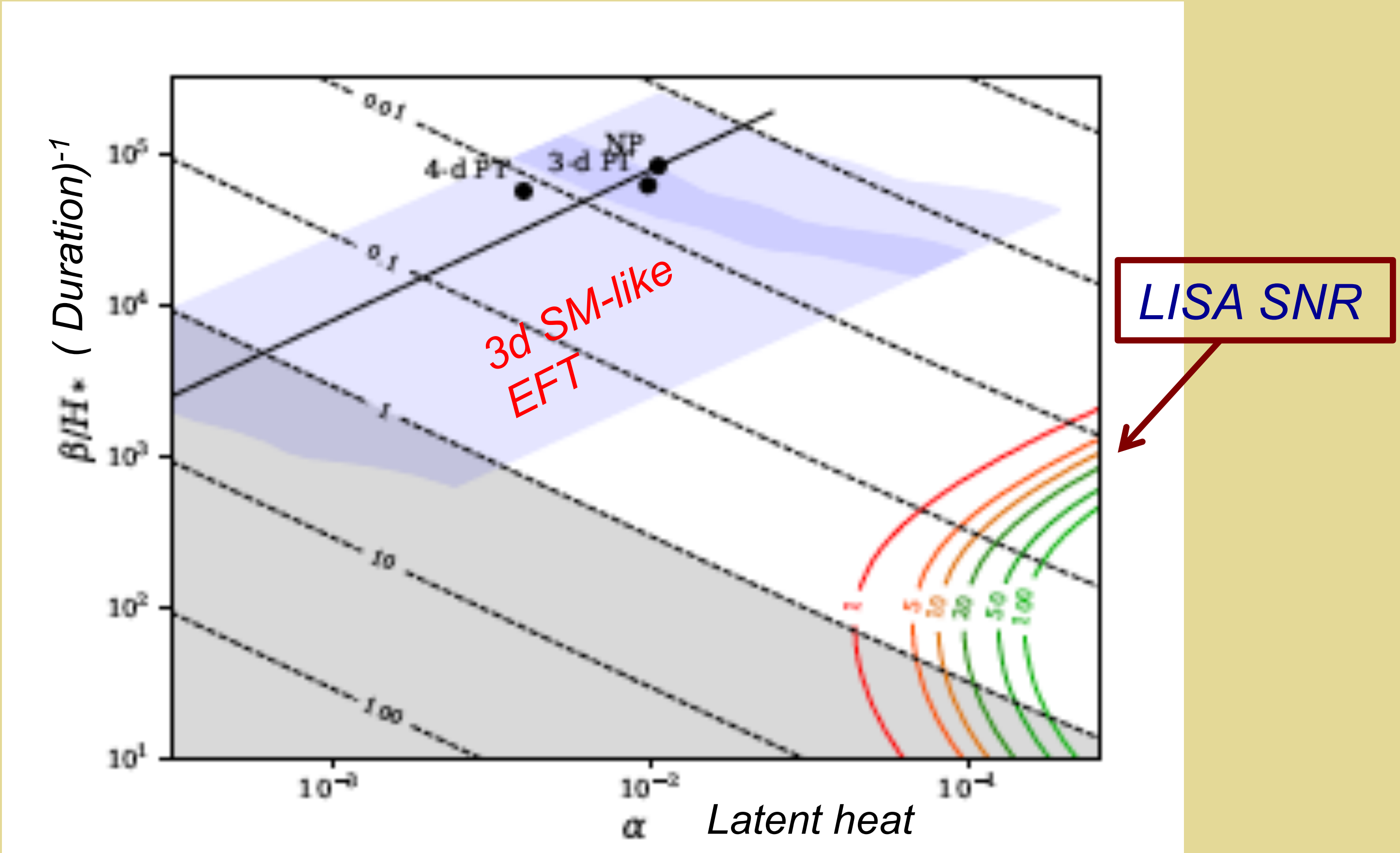
- *The EWPT question entails a rich interplay of model building, thermal QFT, phenomenology & experiment → robust thermal field theory is vital*

- *The collider – gravitational wave "inverse problem" has emerged as a particularly compelling arena for further exploration and opportunity HEP community and beyond*

Back Up Slides

GW-Collider

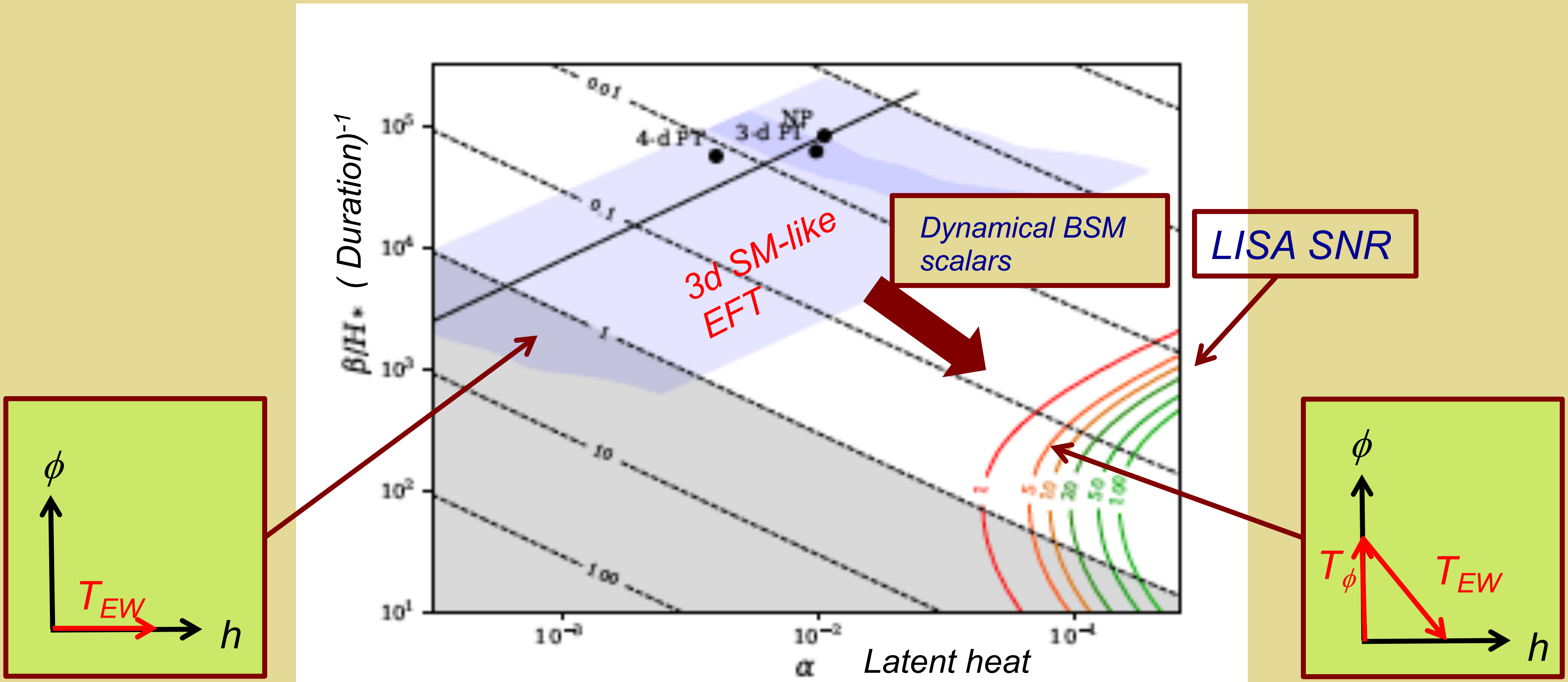
BSM Scalar: EWPT & GW



29.1

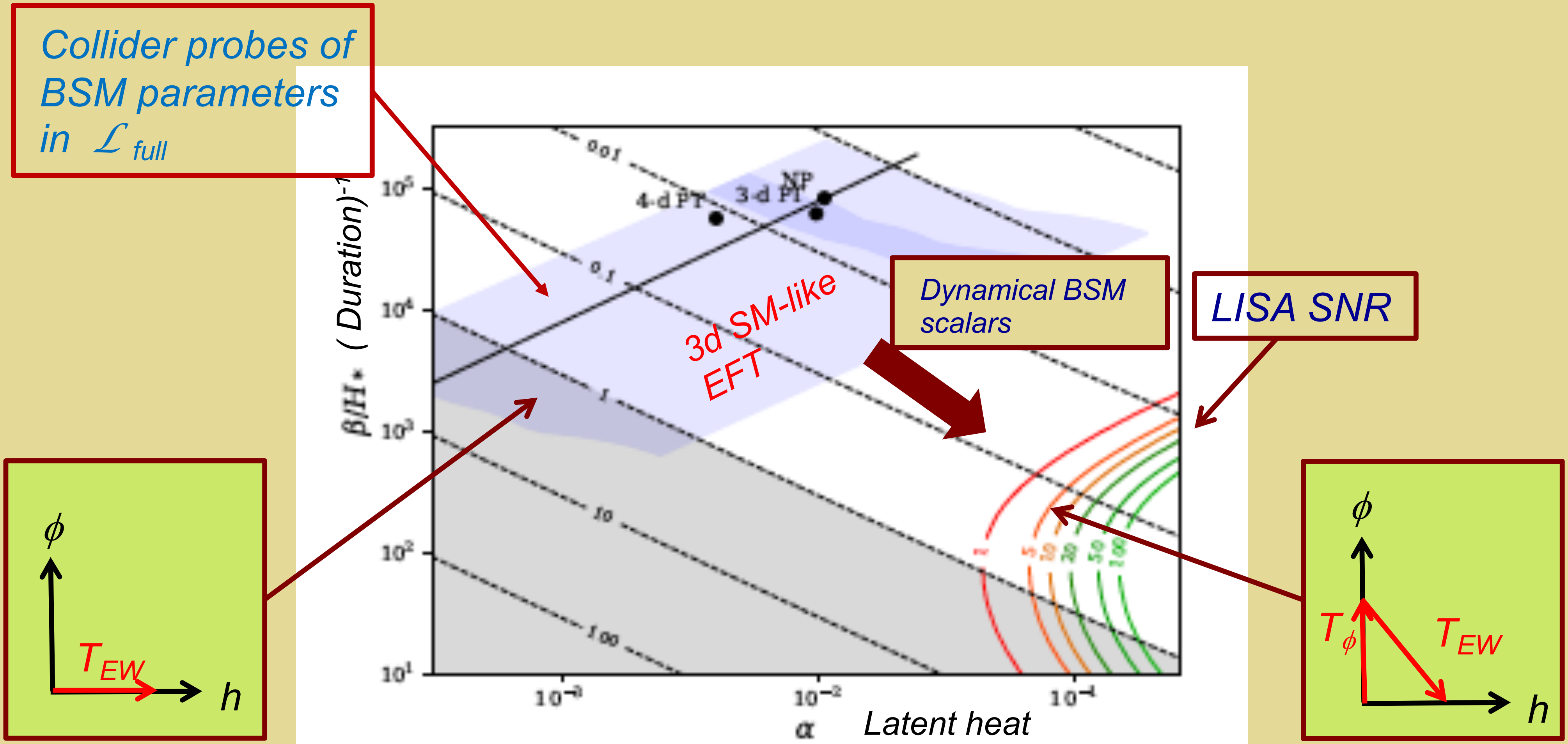
Gould, Kozaczuk, Niemi, R-M, Tenkanen, Weir 1903.11604

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

Nucleation

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

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

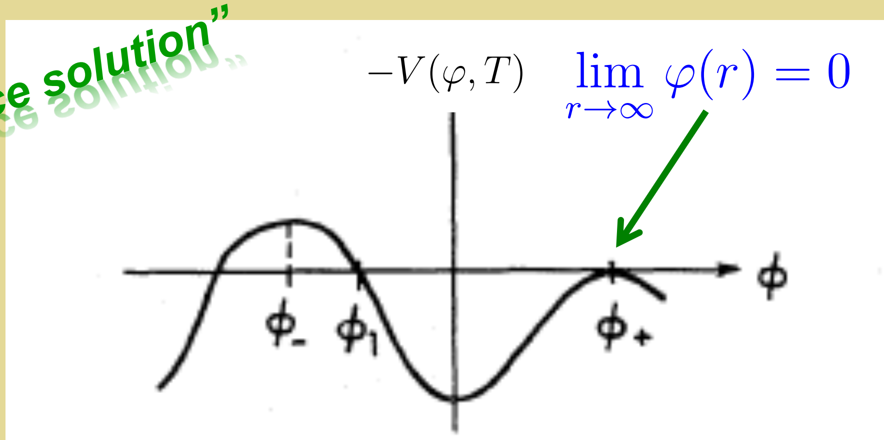
How Reliable?

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

Tunneling @ T>0

Scalar Quantum Field Theory

"Bounce solution"



Tunneling rate / unit volume:

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

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

Friction term

Exponent in Γ

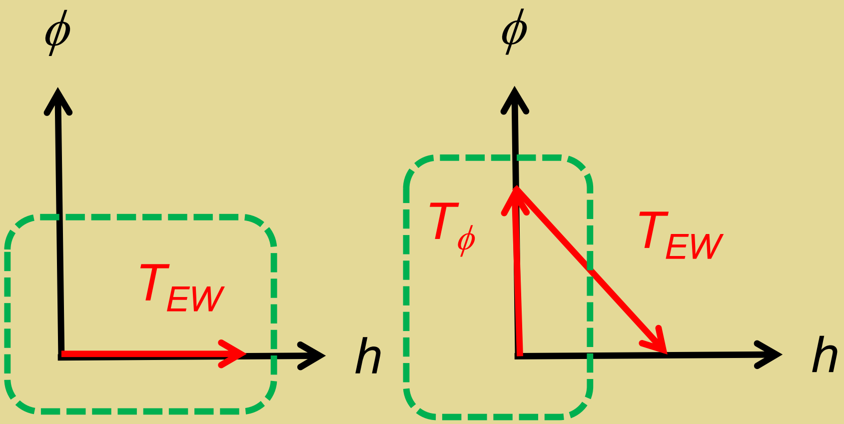
Path: minimize S_E

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

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

Tunneling @ T>0

Radiative barriers → st'd method gauge-dependent



Tunneling rate / unit volume:

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

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

Exponent in Γ

Path: minimize S_E

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

Illustrate w/ Abelian Higgs

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

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

Full 3D effective action

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

Adopt appropriate power-counting in couplings

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

(Re) Organize the Perturbative Expansion

Illustrate w/ Abelian Higgs

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

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

Full 3D effective action

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

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: G.I. & Nielsen Identities

Adopt appropriate power-counting in couplings

Lofgren, MRM, Tenkanen, Schicho 2112.0752 → PRL

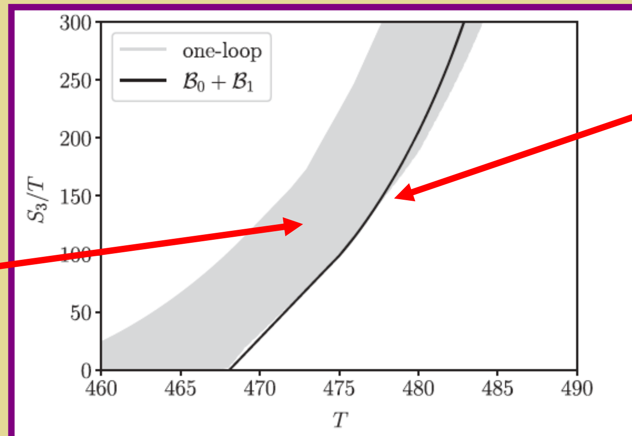
$$S_3 = a_0 g^{-\frac{3}{2}} + a_1 g^{-\frac{1}{2}} + \Delta$$

Order-by-order consistent with Nielsen Identities

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

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

Numerical comparison with conventional approach



Conventional: $0 < \xi < 4$

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

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*

IR Problem

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

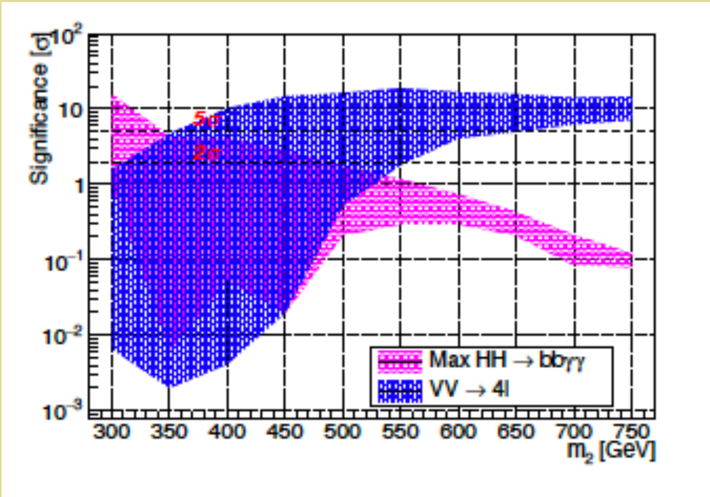
SM lattice studies: *g_{eff} ~ 0.8 in vicinity of EWPT for m_H ~ 70 GeV* *

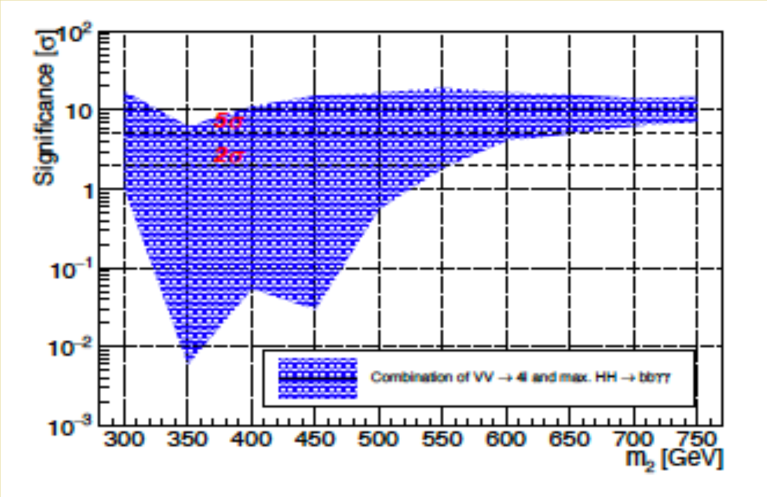
* *Kajantie et al, NPB 466 (1996) 189; hep/lat 9510020 [see sec 10.1]*

Additional Pheno

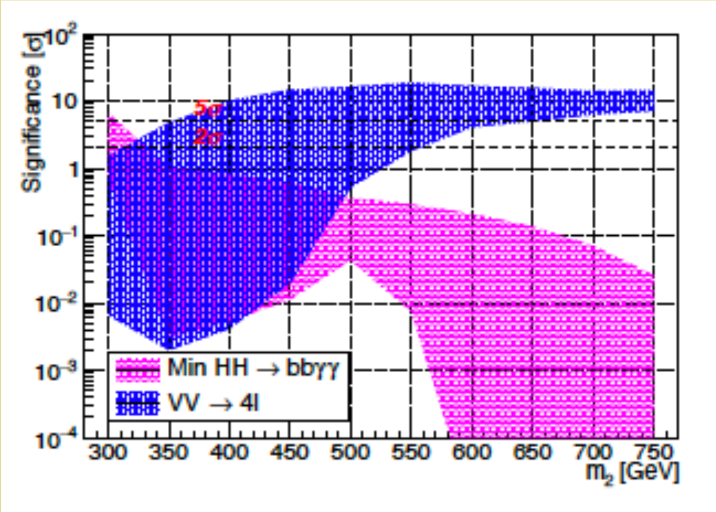
Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

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





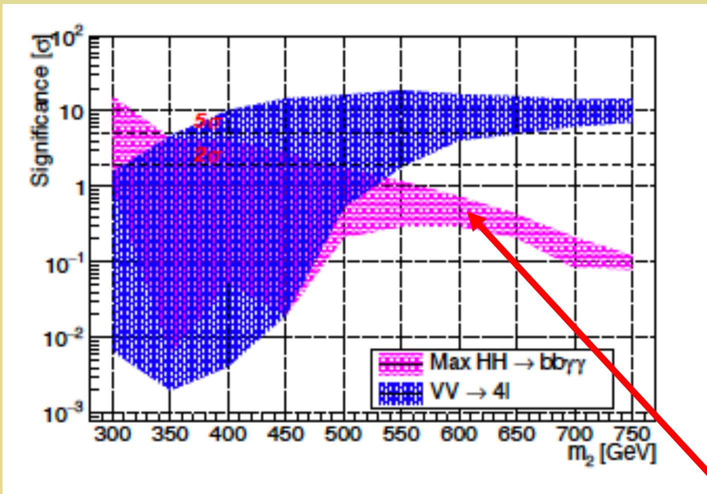
SFOEWPT Min Benchmarks:

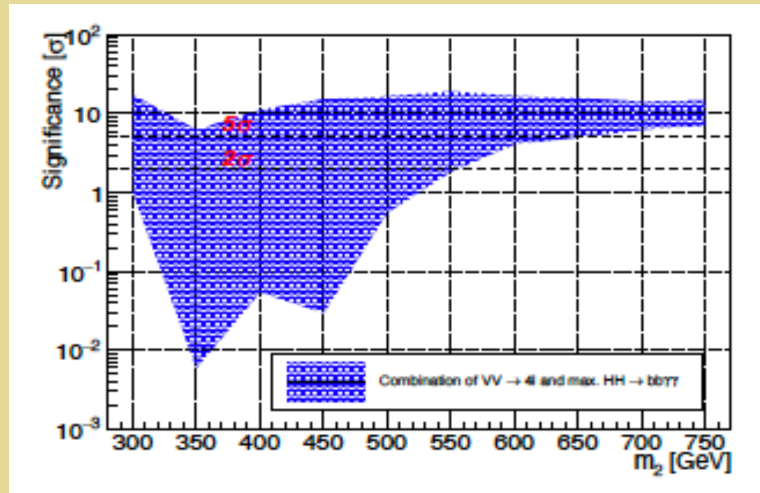


S. Arunasalam, Hao-Lin Li, Kun Liu, MJRM, Yongchao Zeng, Wenxing Zhang 2211.0303612

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

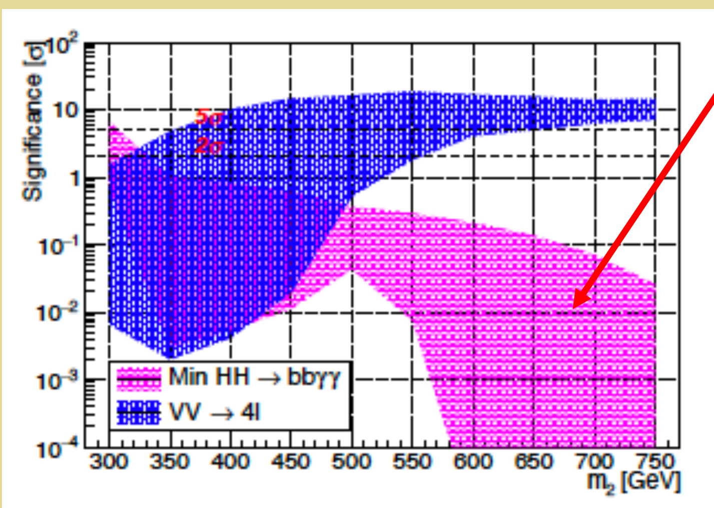
SFOEWPT Max Benchmarks: HL LHC Combination $bb\gamma\gamma$ & 4 lepton





100 TeV accessible

SFOEWPT Min Benchmarks:

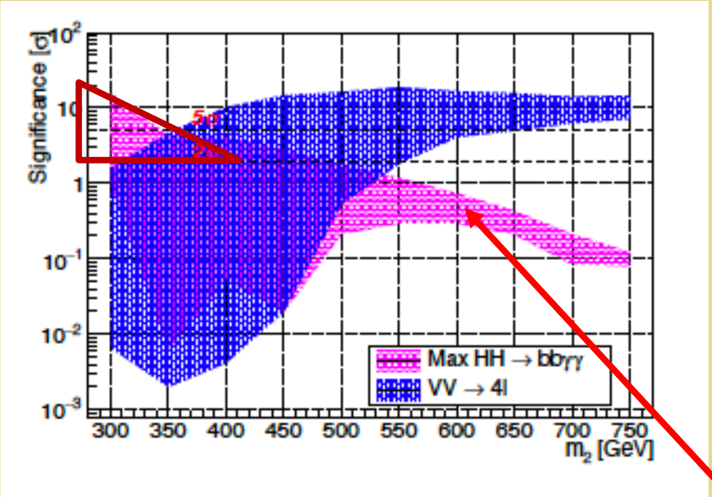


S. Arunasalam, Hao-Lin Li, Kun Liu, MJRM, Yongchao Zeng, Wenxing Zhang 2211.0303612

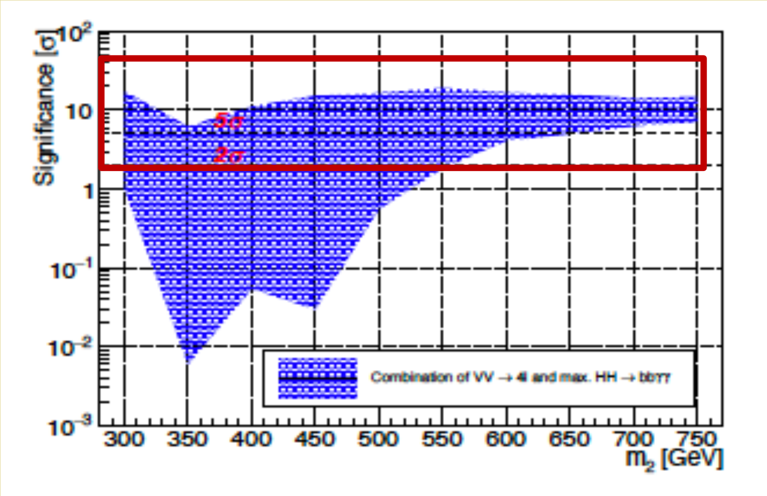
Singlets: Resonant Di-Higgs & $H_2 \rightarrow VV$

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

"Smoking gun" region

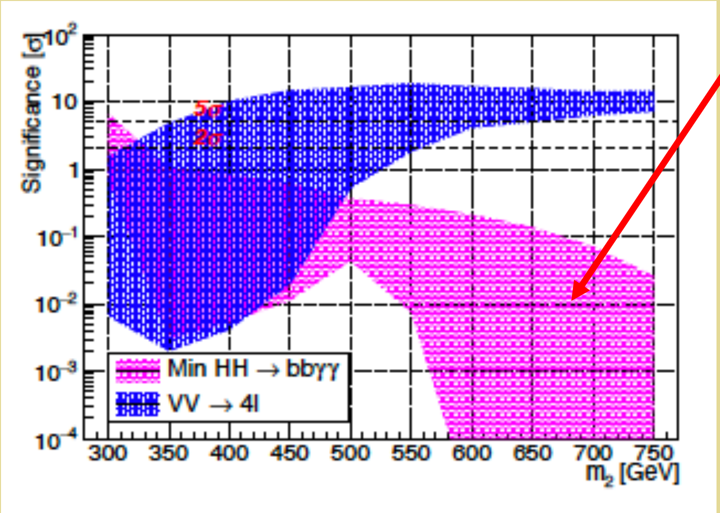


Parameter exclusion region



100 TeV accessible

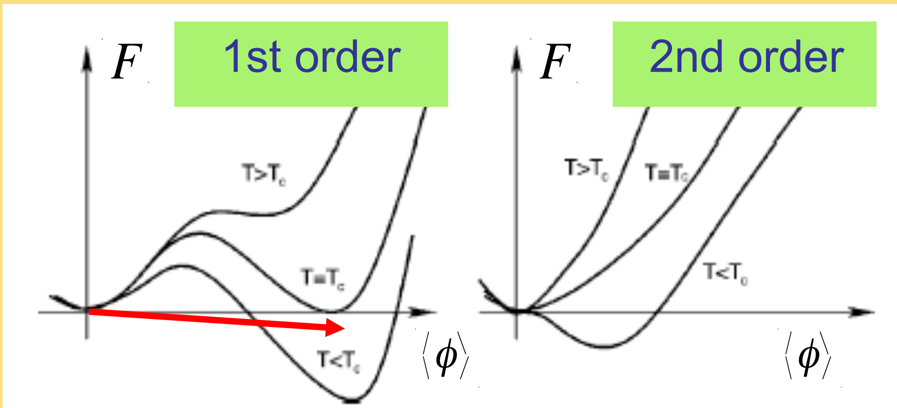
SFOEWPT Min Benchmarks:

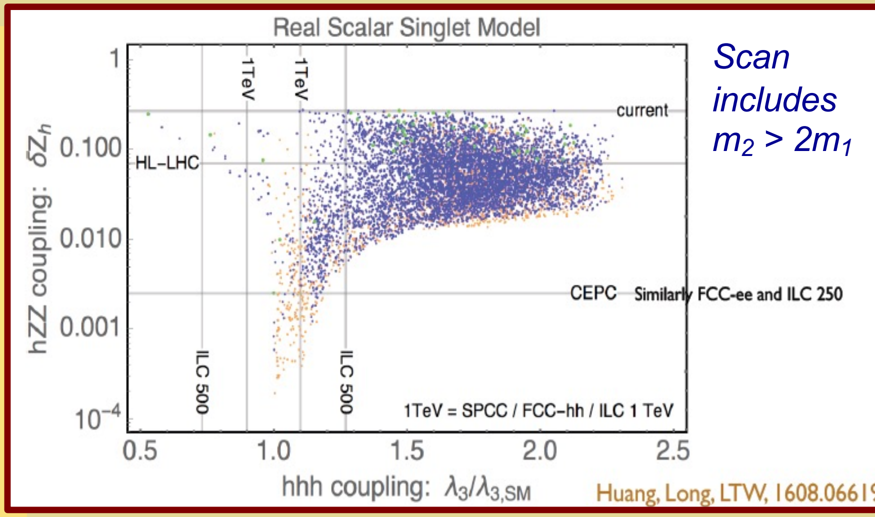


- *Observation of 4l channel would indicate existence of heavy resonance consistent with xSM SFOEWPT*
- *"Smoking gun" region would provide nearly definitive evidence & narrow down model parameter space*
- *Exclusion would leave ample room for 100 TeV pp discovery*

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

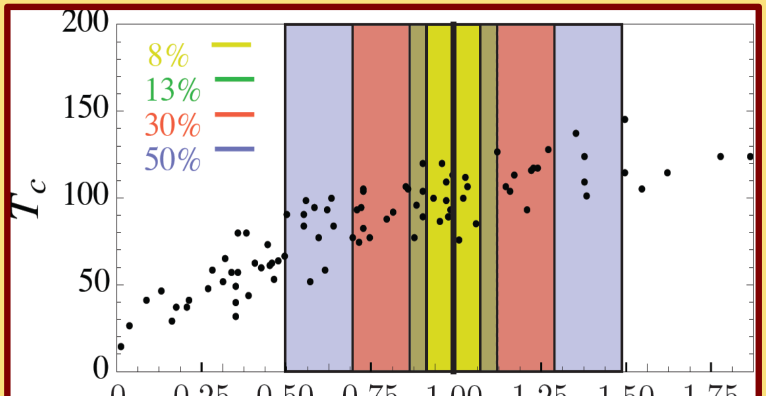
EW Phase Transition: Singlet Scalars



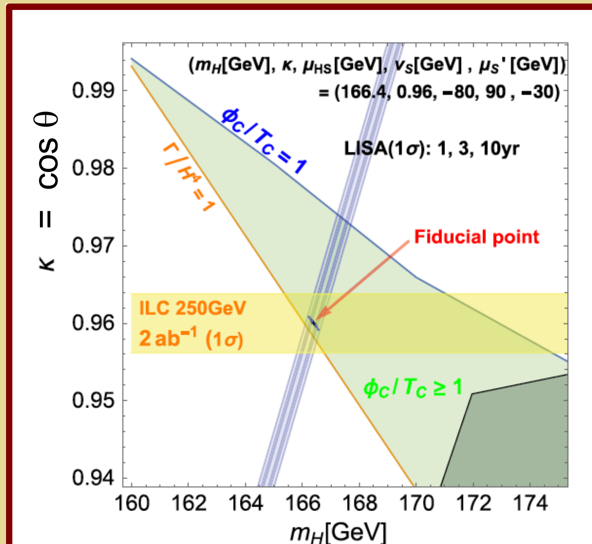


Scan includes $m_2 > 2m_1$

Modified Higgs Self-Coupling



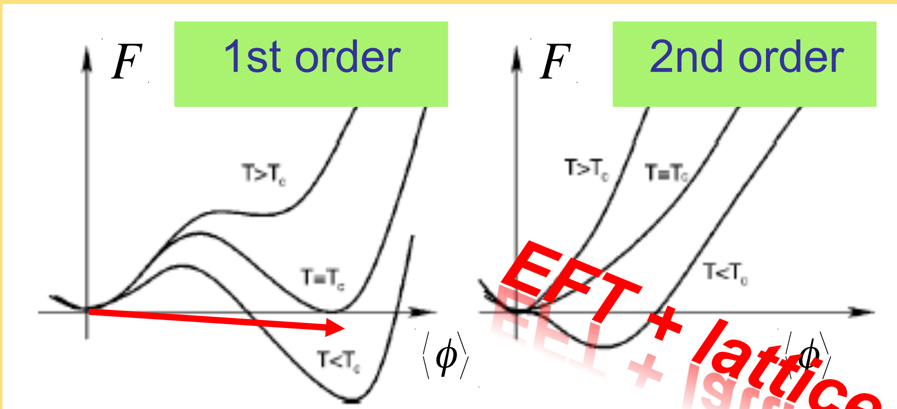
Scan for $m_2 < 2m_1$



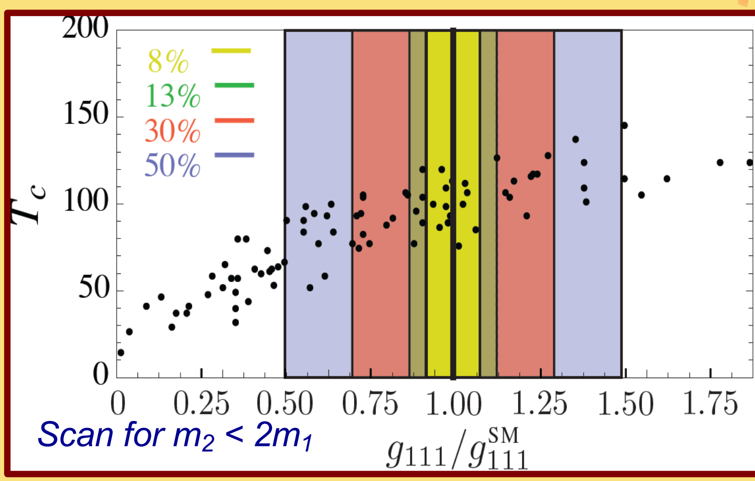
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

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

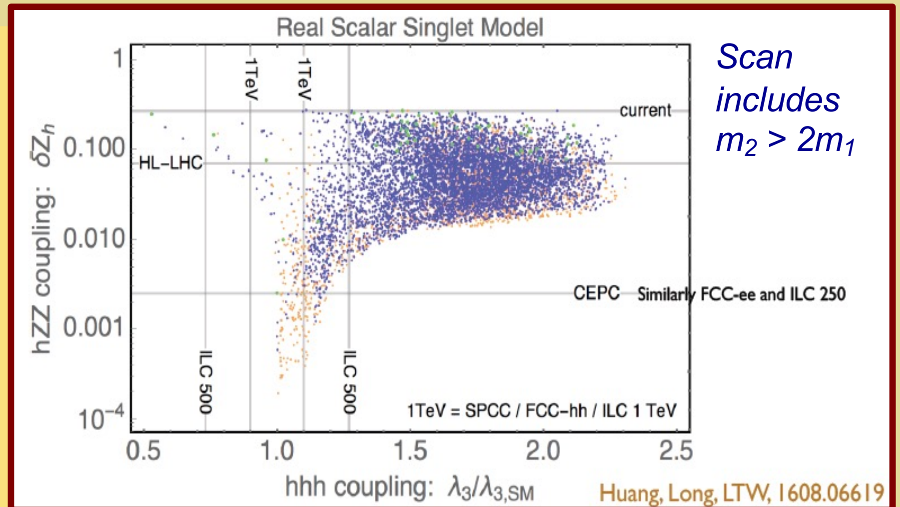
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling

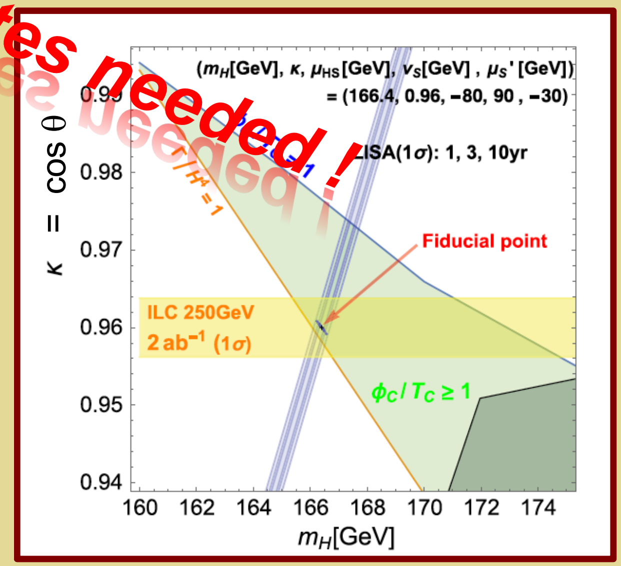


Scan for $m_2 < 2m_1$



Scan includes $m_2 > 2m_1$

EFT + lattice updates needed !



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

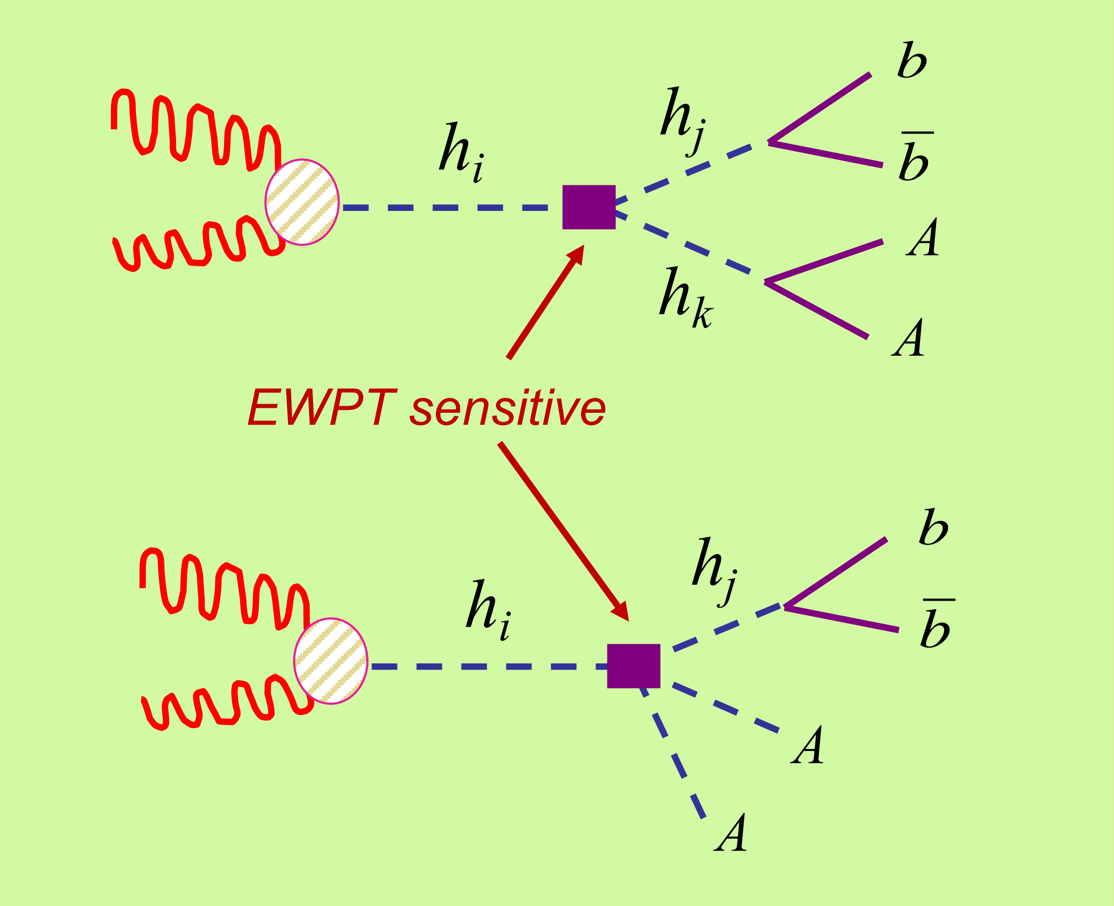
K. Hasino et al, PRD 99 (2019) 075011

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

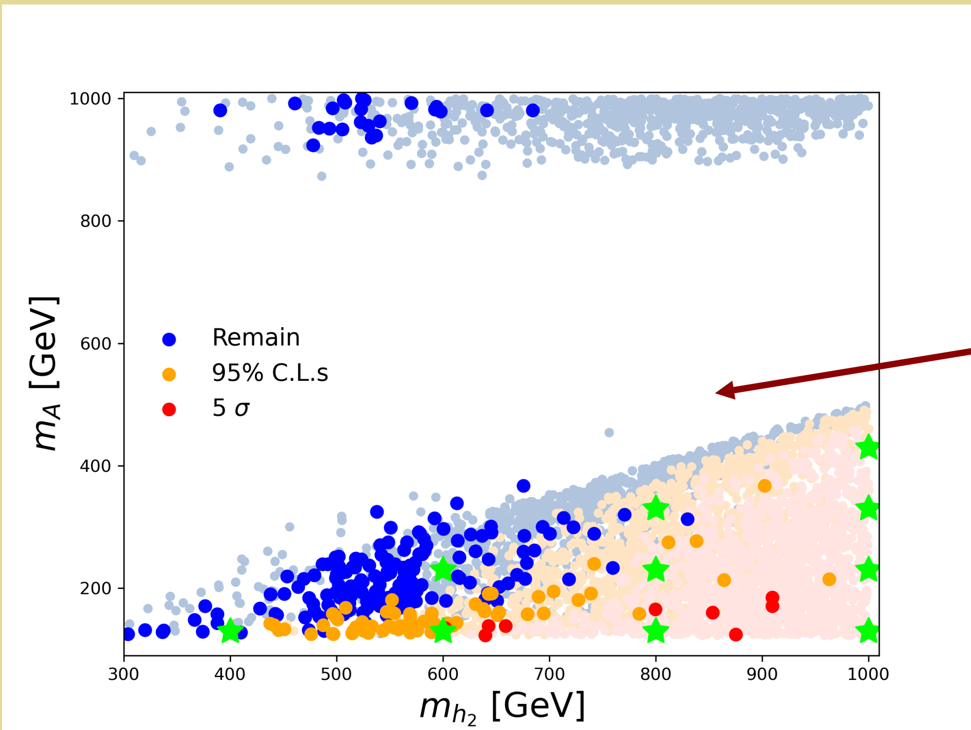


V. Barger, P. Langacker, M. McCaskey, MJRM, G. Shaugnessy 0811.0393

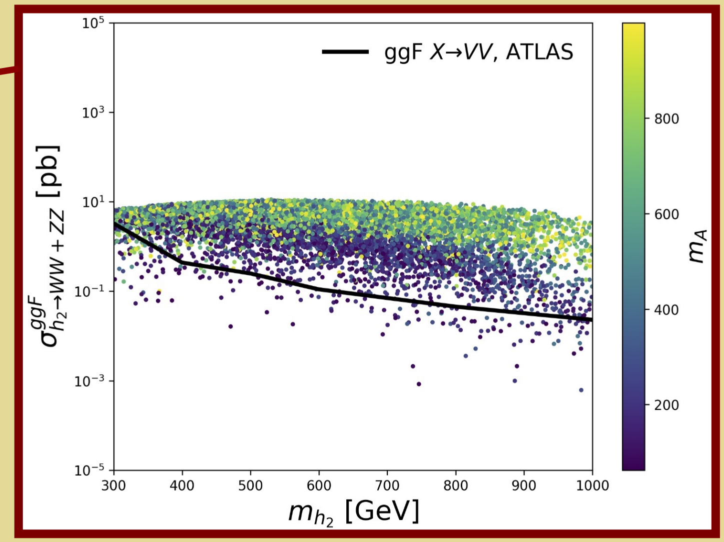
Yizhou Cai, MJRM, Lei Zhang, Wenxing Zhang 2311.NNNNN

Complex Singlet: DM + EWPT

Search for bb + MET

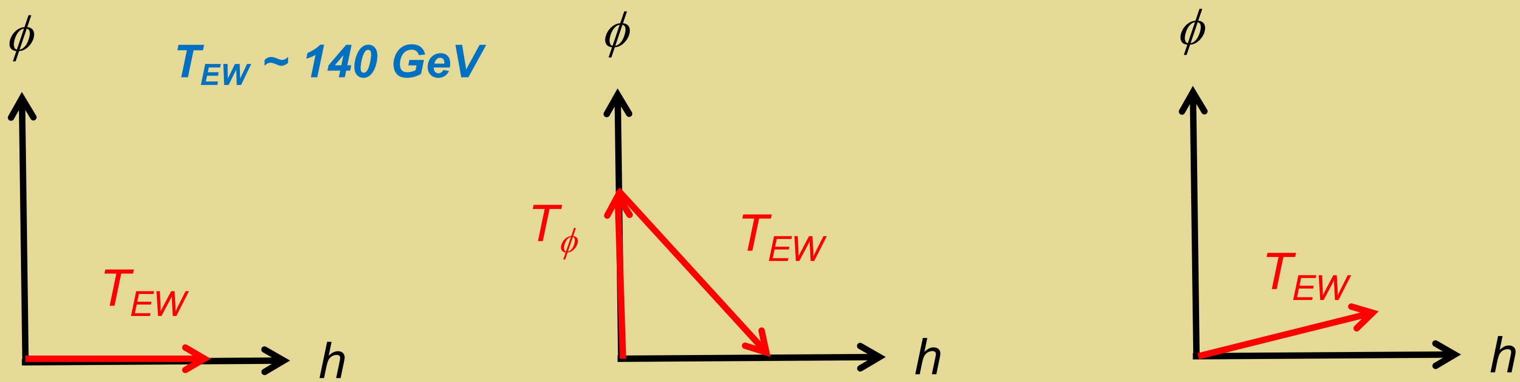


Heavy Higgs → VV exclusion: BR (h_2→VV) larger when m_{h2} < 2 m_A



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

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

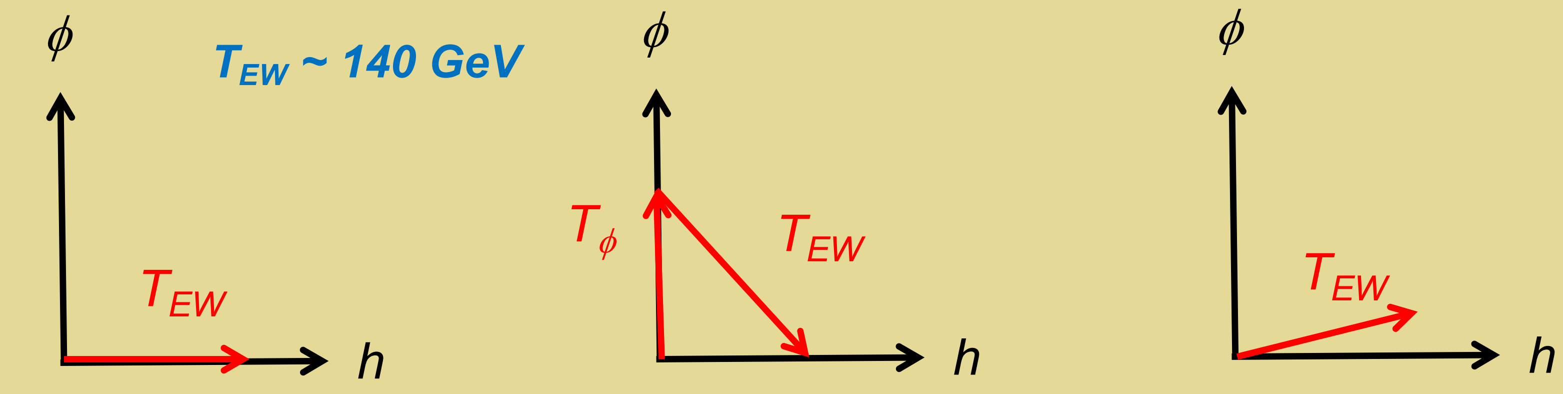
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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

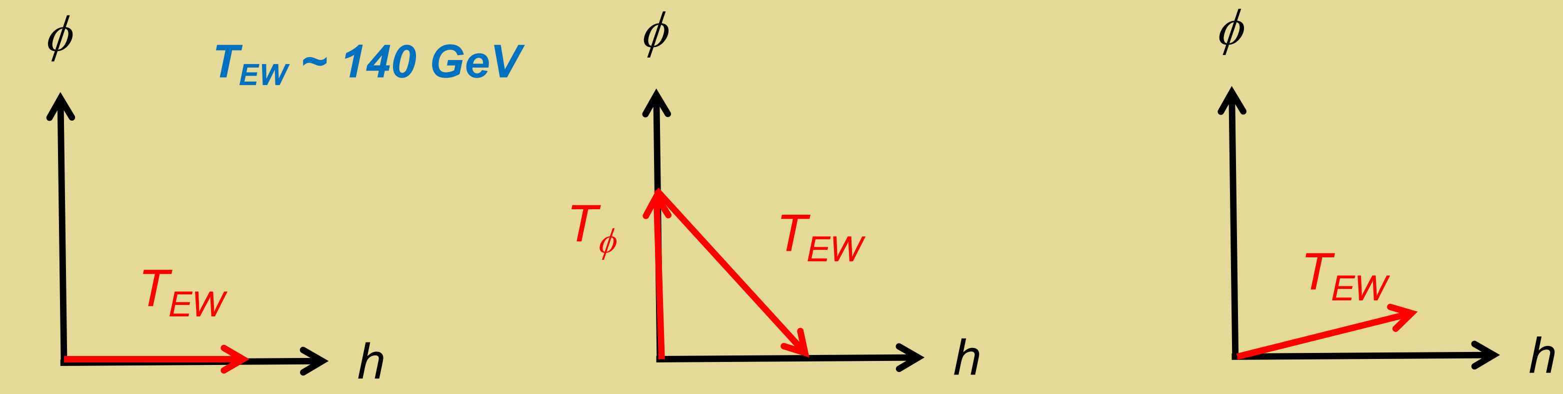
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

Exotic decays

$h_1 \rightarrow h_2 h_2$

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

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

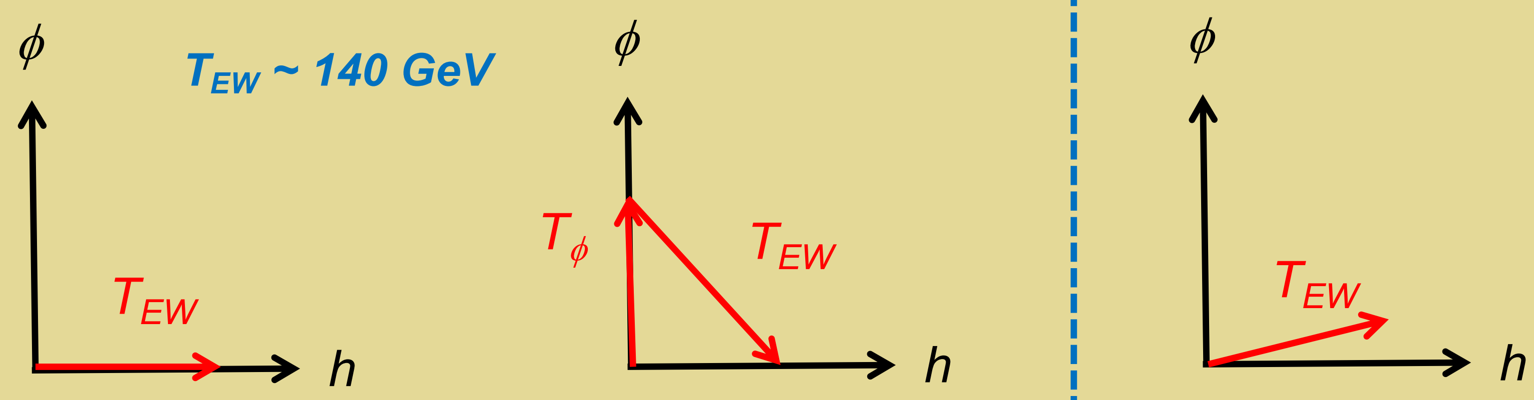
$$g_{122} = \frac{1}{2} v a_2 + \mathcal{O}(\theta^2)$$

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

$h_1 \rightarrow h_2 h_2$

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

Exotic Higgs Decays & EWPT