Electroweak Phase Transition: the Theory Frontier

M.J. Ramsey-Musolf

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

About MJRM:

Science

Family

Friends

My pronouns: he/him/his
 # MeToo

HPNP, Osaka University, March 2021

Key Ideas for this Talk

- ***The "electroweak temperature" → a scale provided by nature that gives us a clear BSM target for colliders***
- ***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 → PRL 2021***

Outline

I. Context & Questions

II. EWPT: A Collider Target

III. Theoretical Robustness

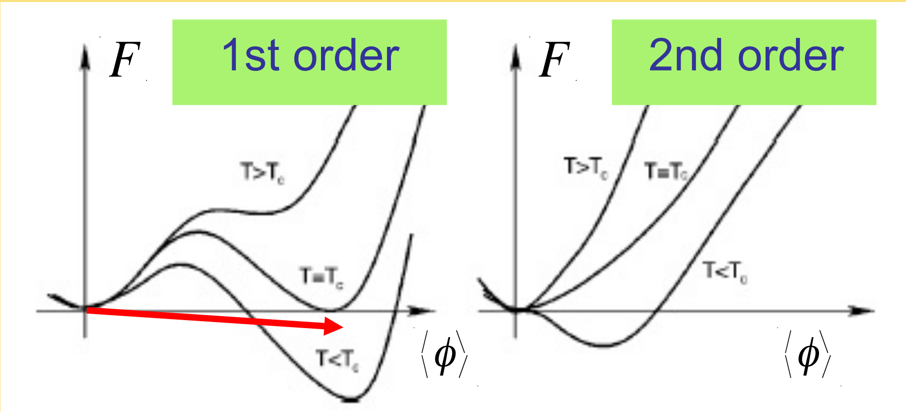
IV. Outlook

I. Context & Questions

Electroweak Phase Transition

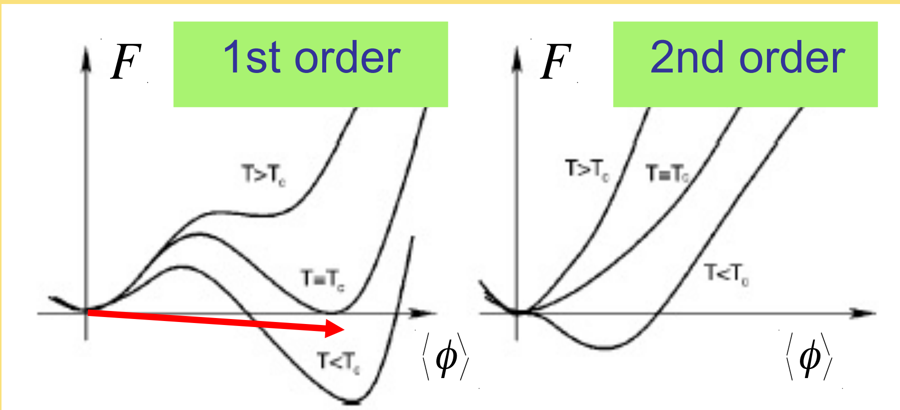
- *Higgs discovery $\rightarrow$ What was the thermal history of EWSB ?*
- *Baryogenesis $\rightarrow$ Was the matter-antimatter asymmetry generated in conjunction with EWSB (EW baryogenesis) ?*
- *Gravitational waves $\rightarrow$ If a signal observed in LISA, could a cosmological phase transition be responsible ?*

EWSB Transition: St'd Model



Increasing m_h →

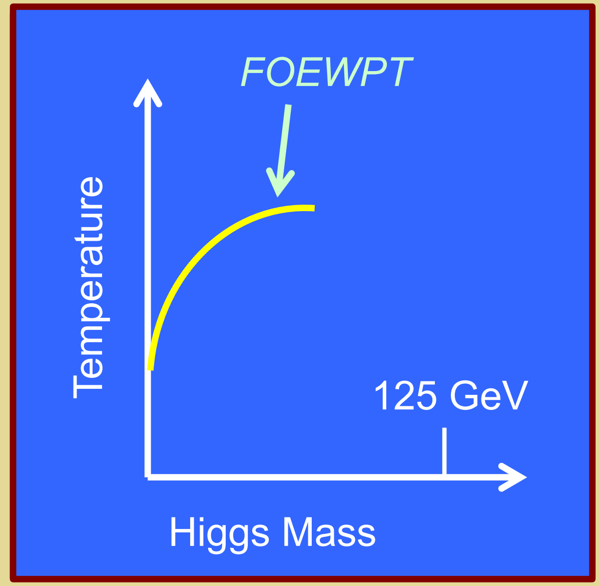
EWSB Transition: St'd Model



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



EW Phase Diagram

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

II. EWPT: A Collider Target

MJRM: 1912.07189

T_{EW} Sets a Scale for Colliders

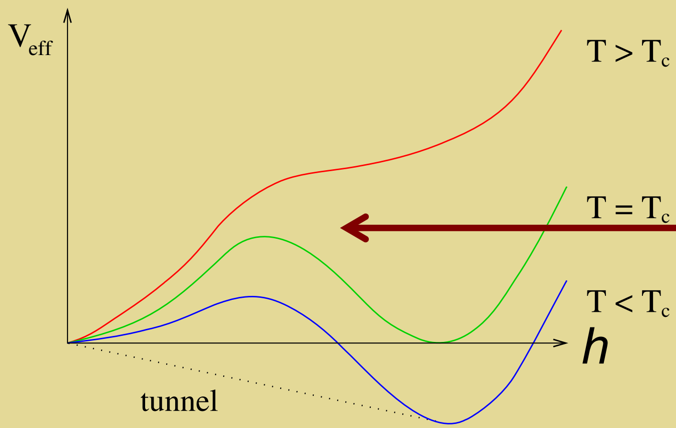
High-T SM Effective Potential

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

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

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

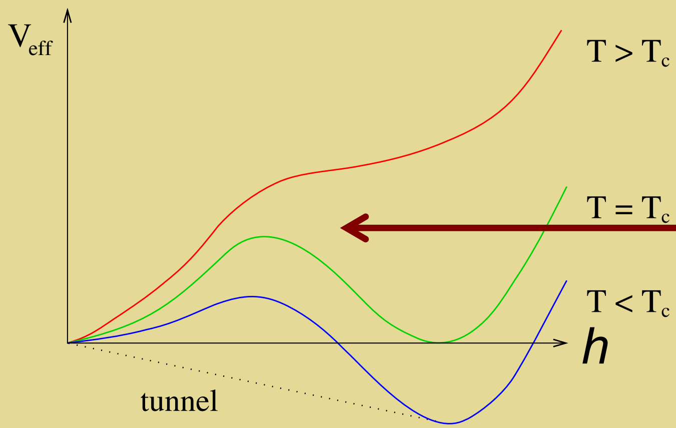
First Order EWPT from BSM Physics



Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

First Order EWPT from BSM Physics



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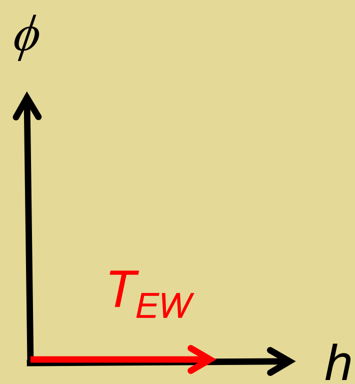
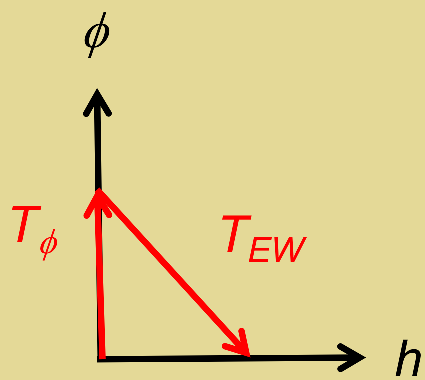


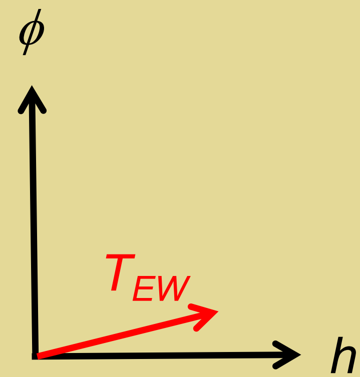
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

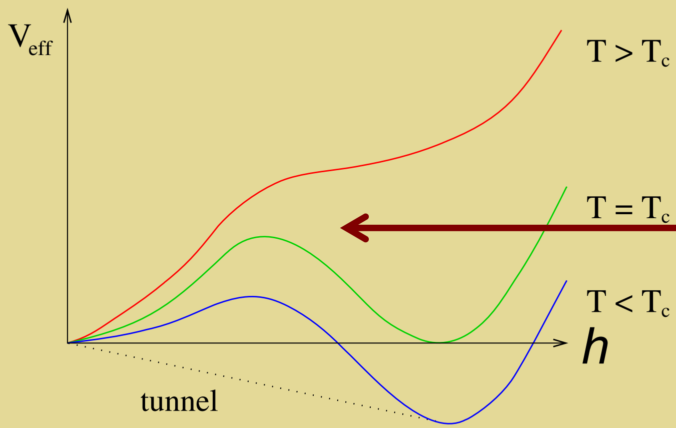
tree-level effect



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

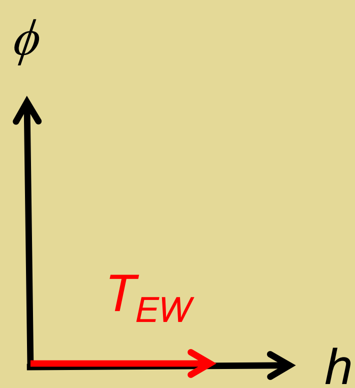
tree-level effect

First Order EWPT from BSM Physics

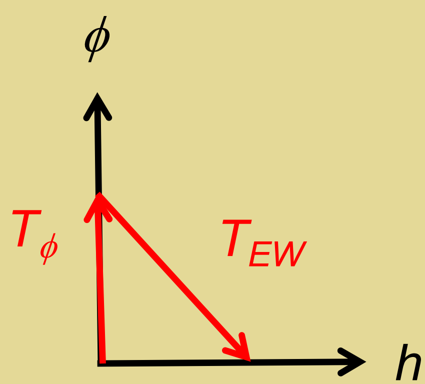


Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

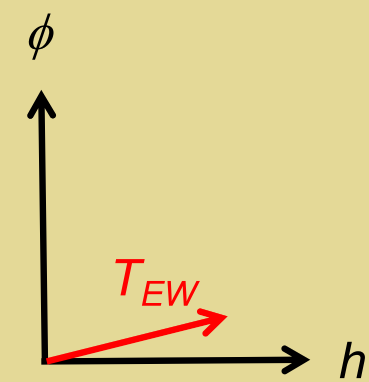
MJRM: 1912.07189



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



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



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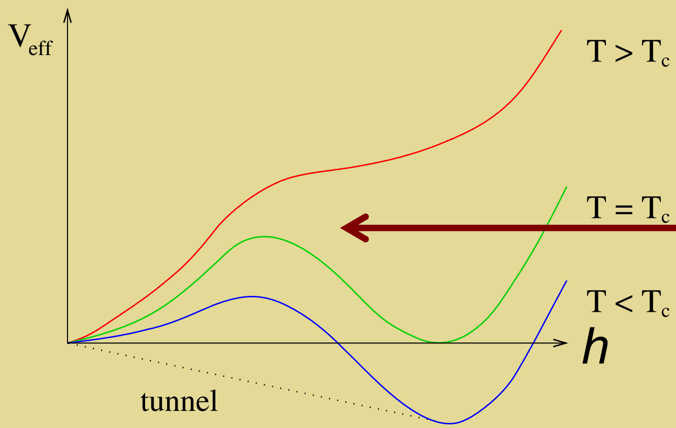
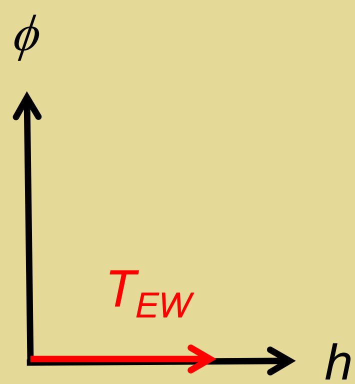
First Order EWPT from BSM Physics



$| \sin\theta | > 0.01$

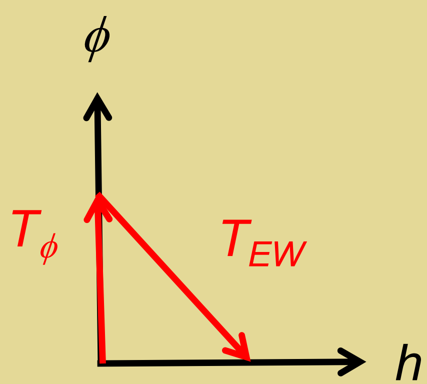
MJRM: 1912.07189

Higgs – ϕ^0 Mixing



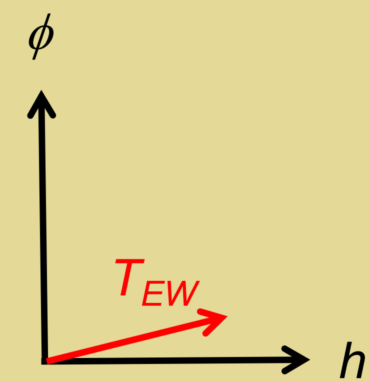
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



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

tree-level effect

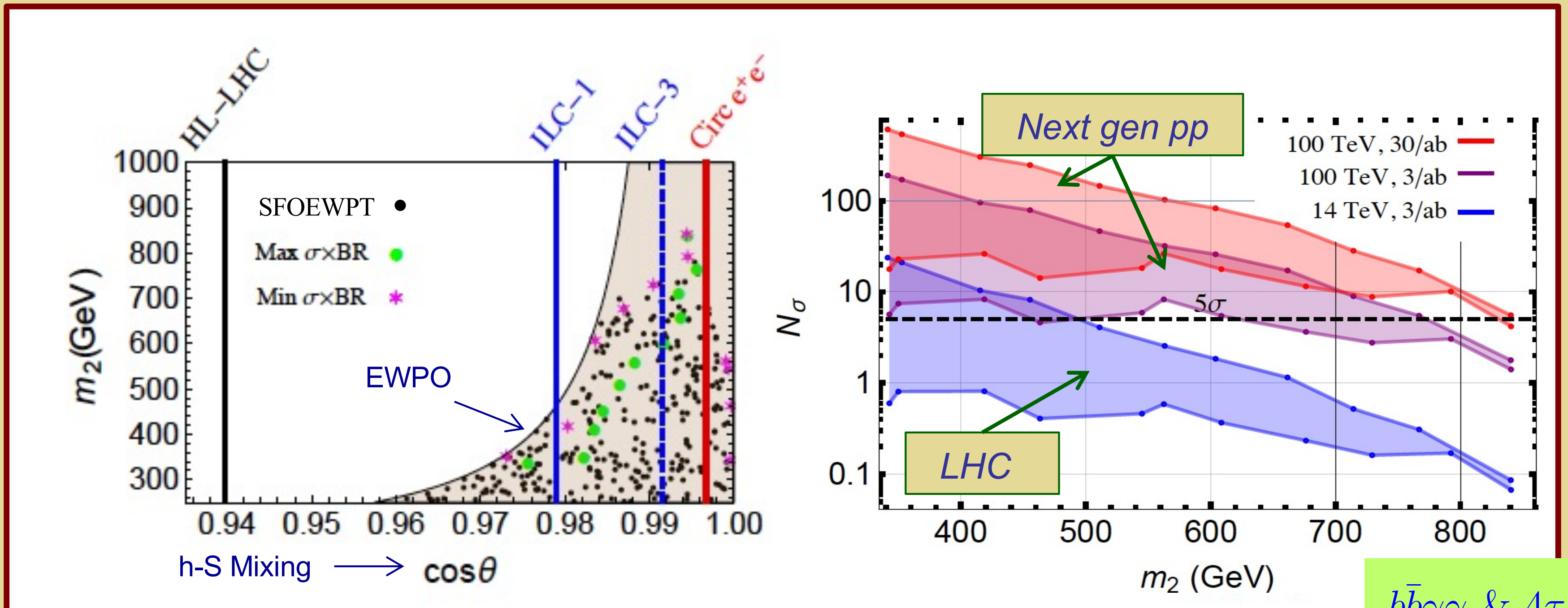
Model Illustrations

Simple Higgs portal models:

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

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



$b\bar{b}\gamma\gamma$ & 4τ

Kotwal, No, R-M, Winslow 1605.06123

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

III. Theoretical Robustness

- *L. Niemi, H. Patel, MRM, T. Tenkanen, D. Weir 1802.10500*
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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

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*

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

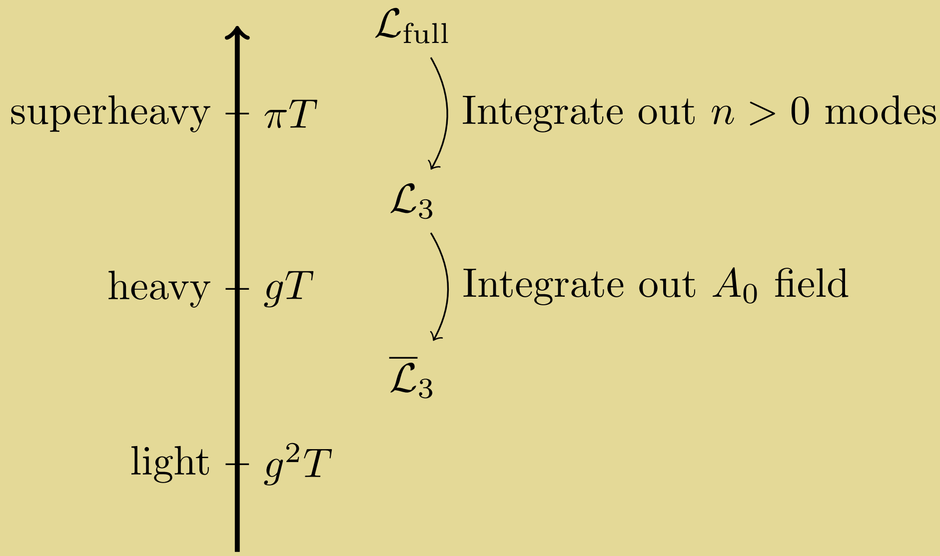
Strategy

- *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*

High-T EFT: Dimensional Reduction

Benchmarking PT: Recent Progress

Meeting ground: 3-D high-T effective theory



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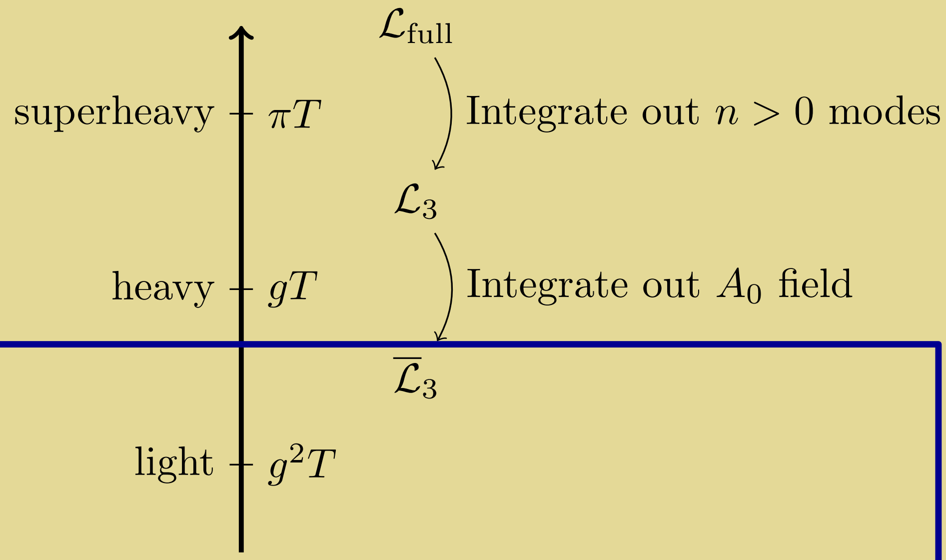

$$V(\phi) = \bar{\mu}^2_{\phi,3}\phi^\dagger\phi + \bar{\lambda}_3(\phi^\dagger\phi)^2$$

Lattice simulations exist

Benchmarking PT: Recent Progress

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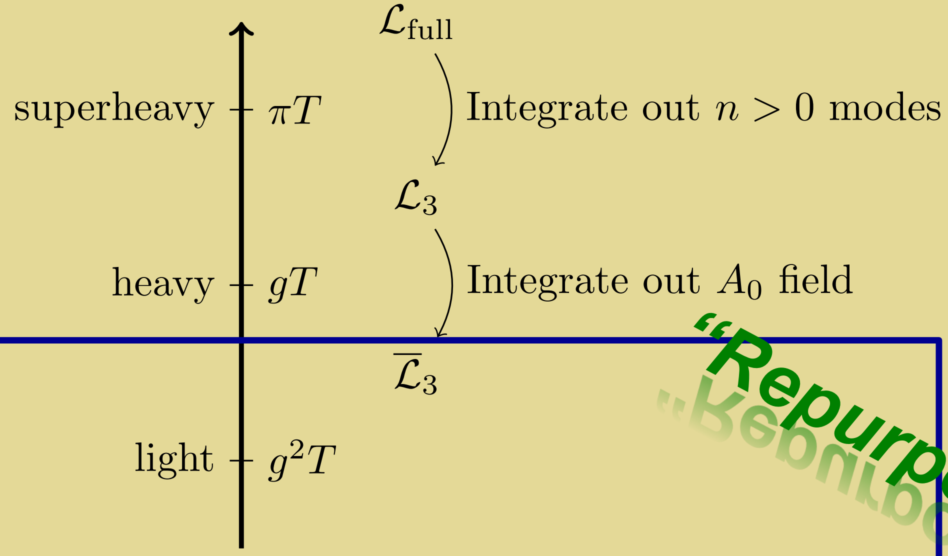

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"Repurpose" lattice results

Lattice simulations exist

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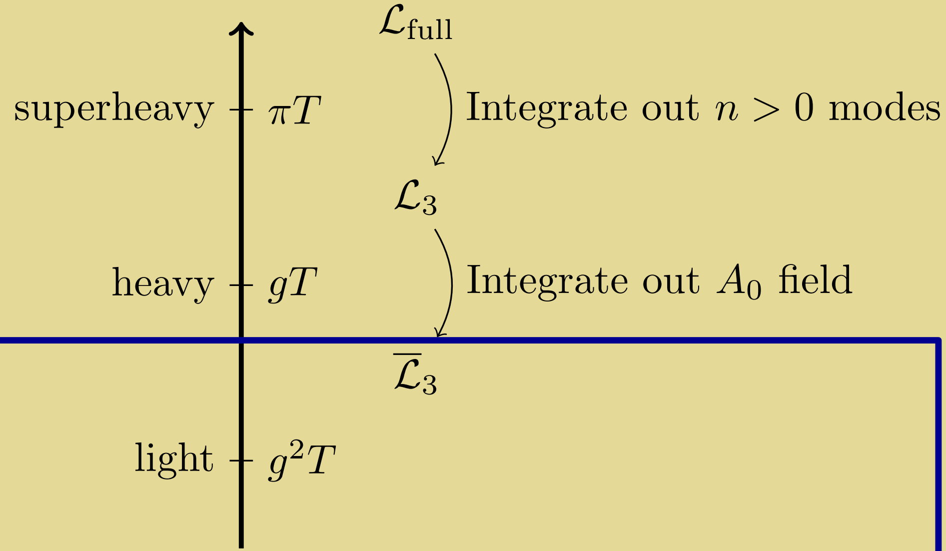

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Lattice simulations exist (e.g., Kajantie et al '95)

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

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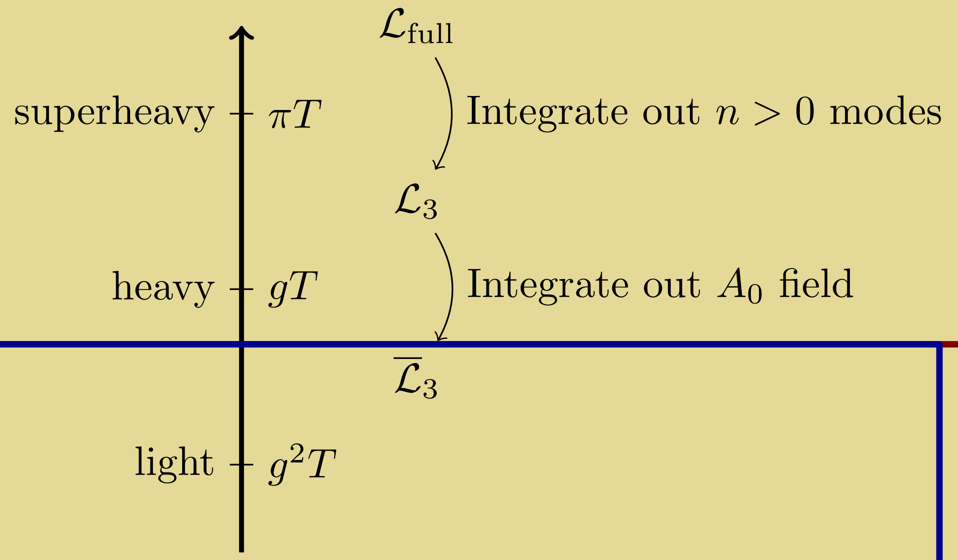

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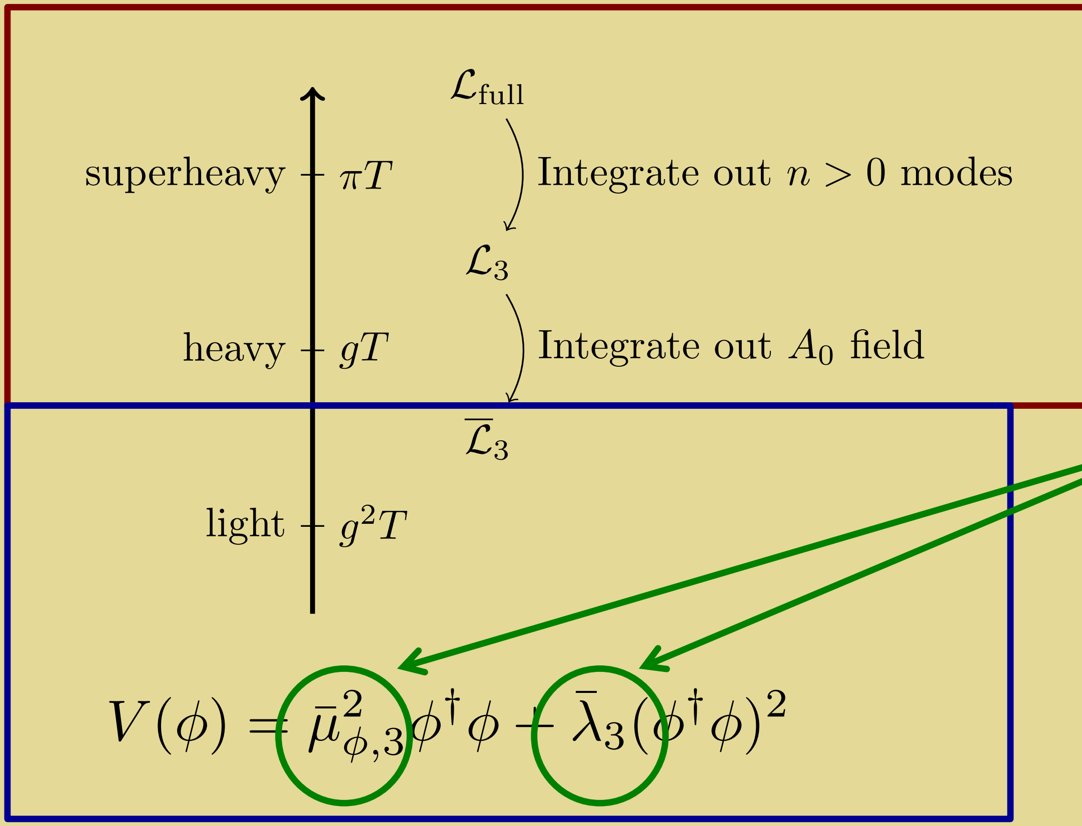

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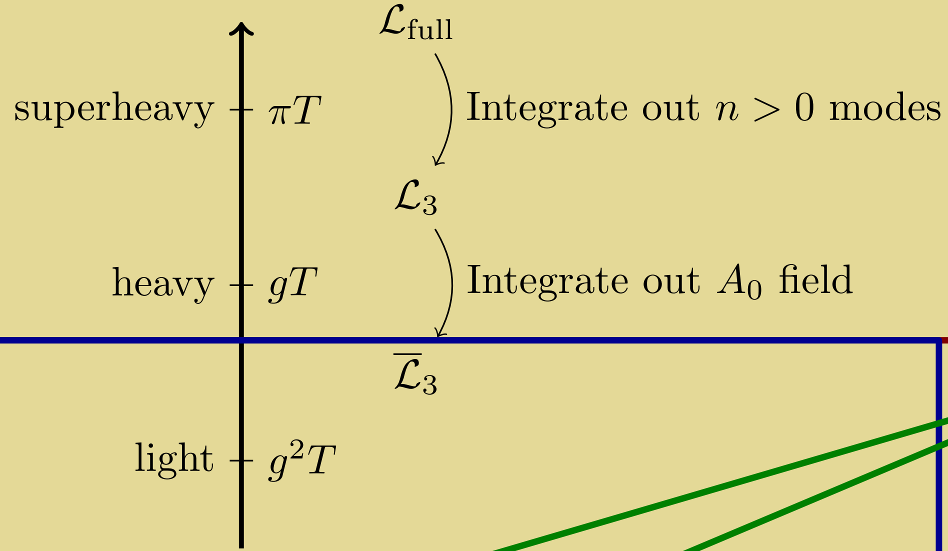

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Model Illustrations

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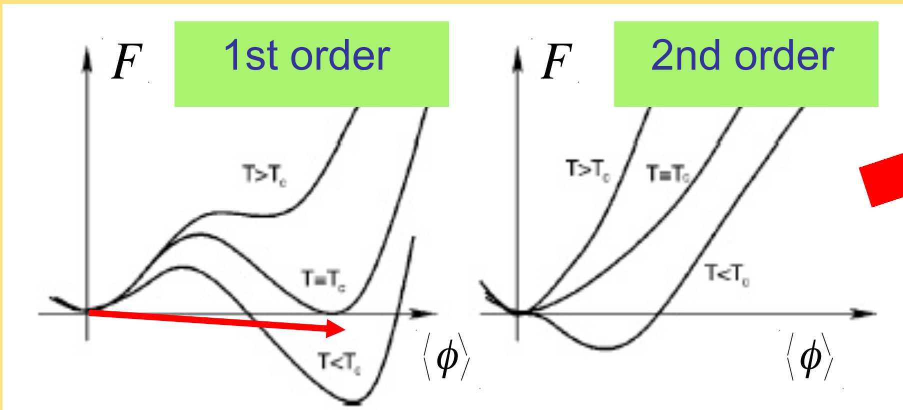
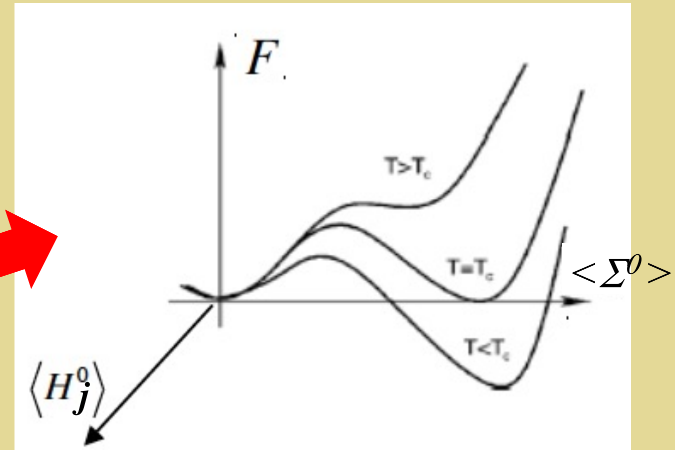
EW Multiplets: EWPT





Increasing m_h →

← *New scalars*

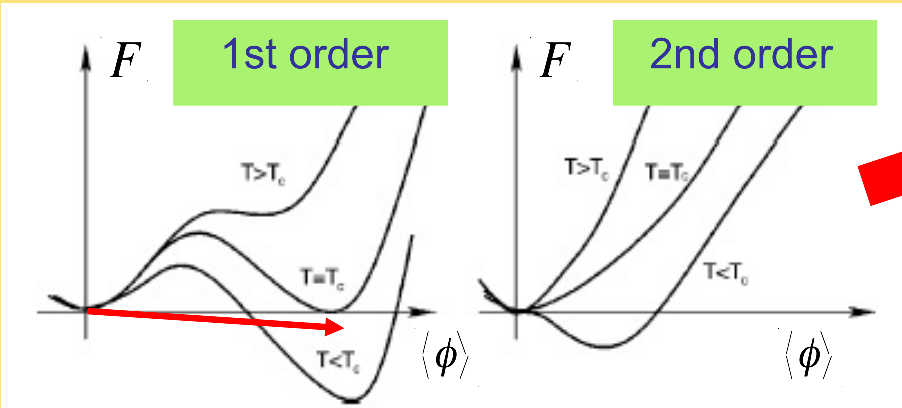
- *Thermal loops*
- *Tree-level barrier*

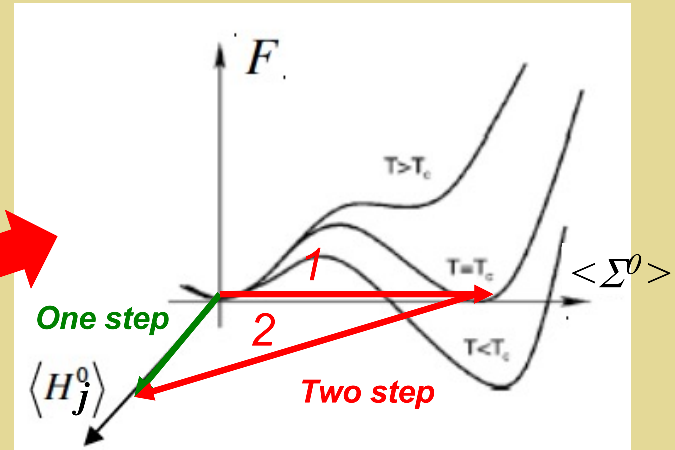
Illustrate with real triplet: Σ ~ (1,3,0)

$H^2\phi^2$ Barrier ?

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

EW Multiplets: Two-Step EWPT





Increasing m_h →

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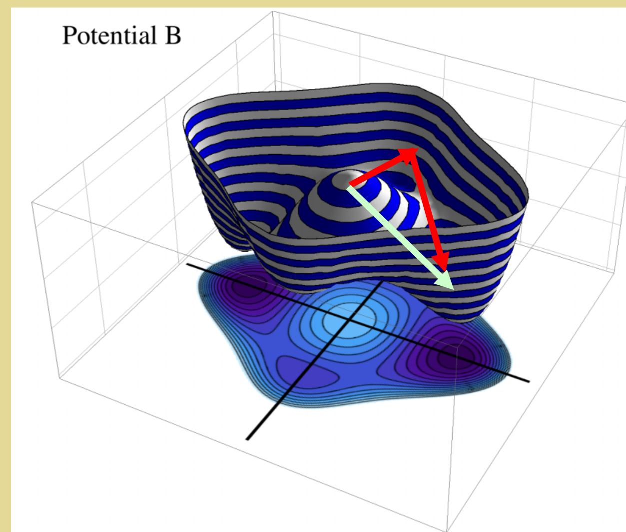
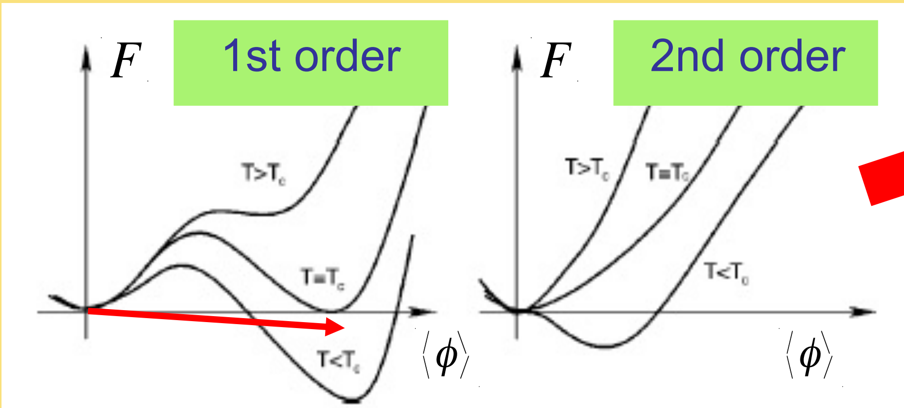
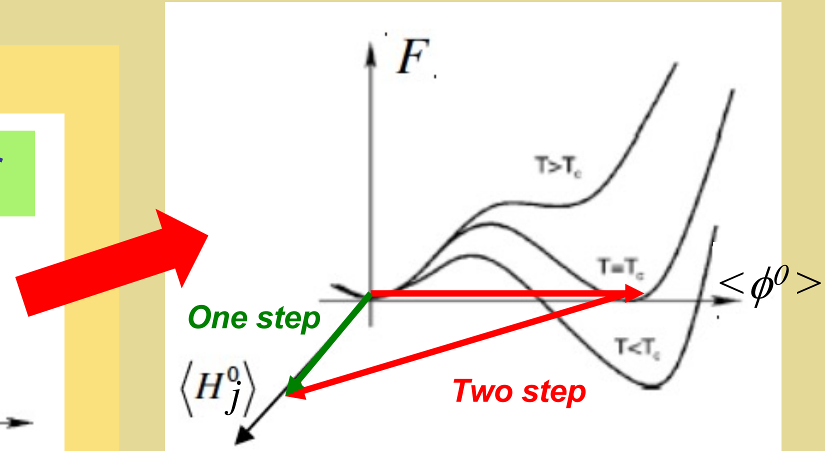


- *One-step: Sym phase → Higgs phase*
- *Two-step: successive EW broken phases*

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

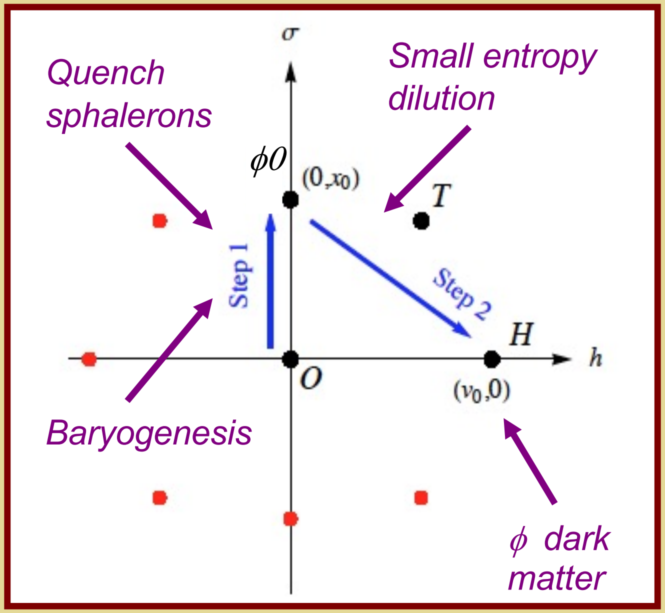
EW Multiplets: Two-Step EWPT





Increasing m_h ⟶

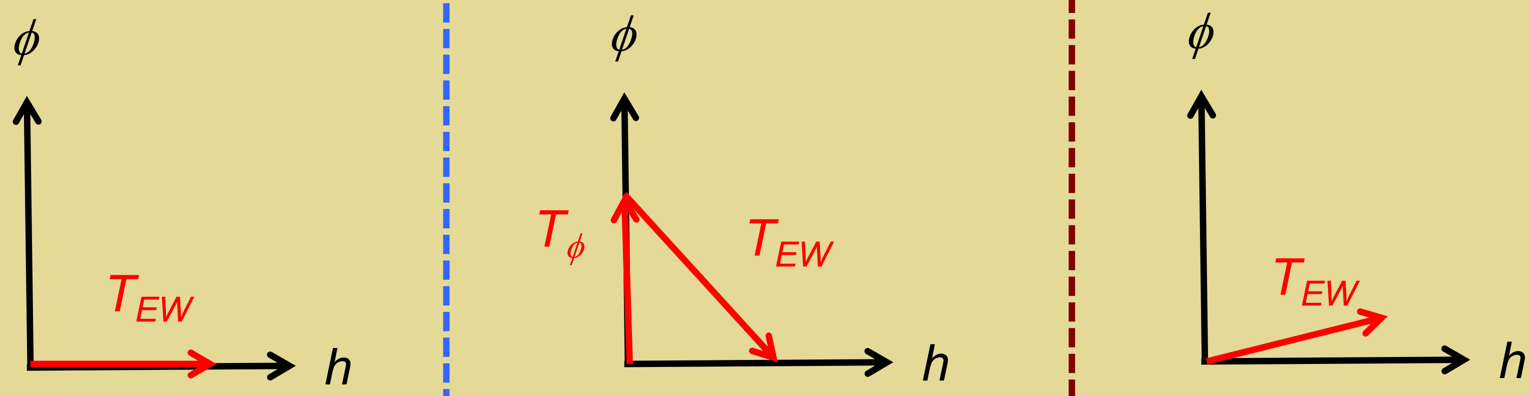
⟵ *New scalars*



- *One-step: thermal loops*
- *Two-Step 1: thermal loops*
- *Two-Step 2: tree-level barrier*

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

Real Triplet



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

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

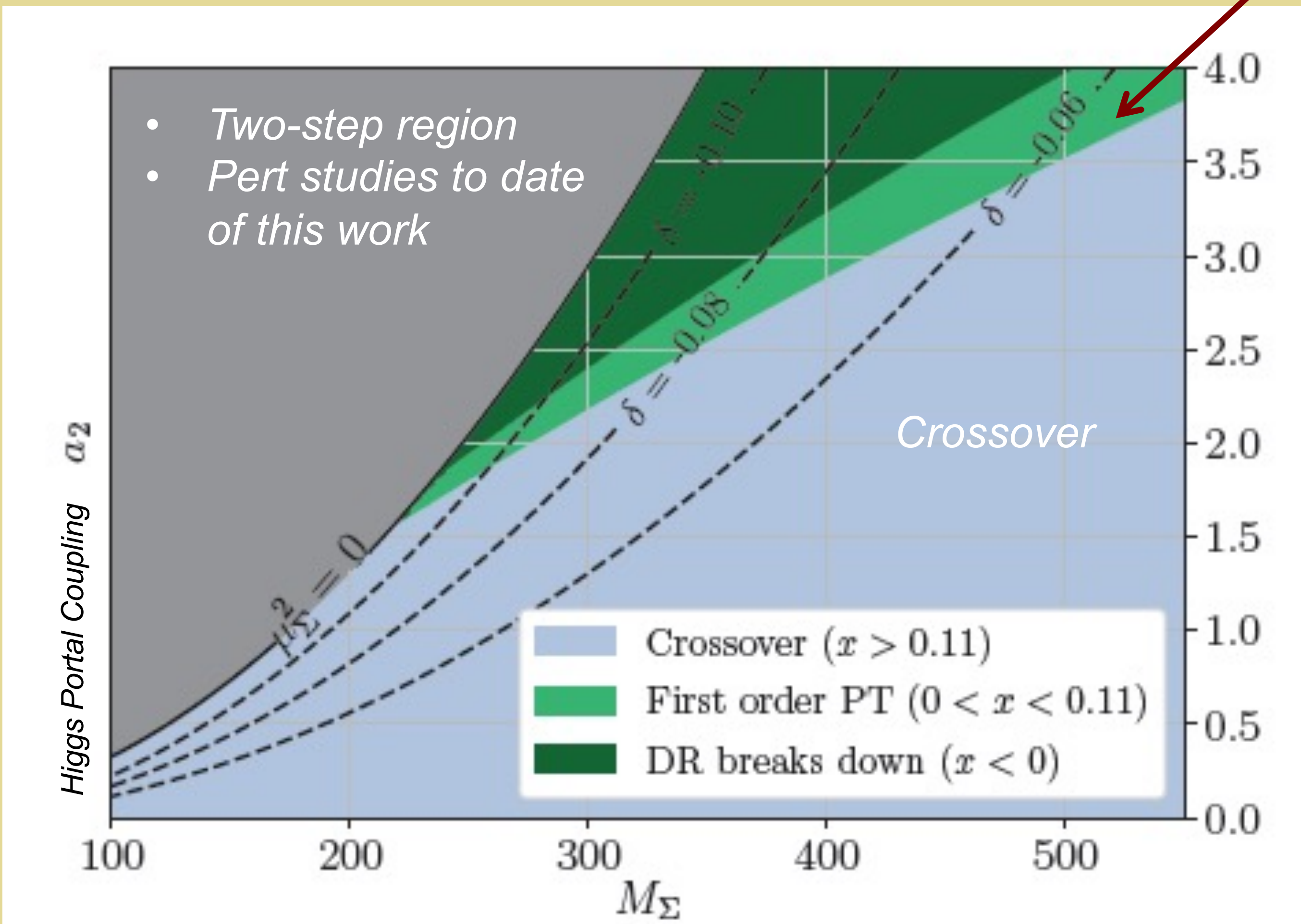
$a_1\, H^2\phi$: $T = 0$
tree-level effect

Non-perturbative results:
Heavy triplet

EW precision tests → too tiny

Real Triplet: One-Step EWPT

FOEWPT

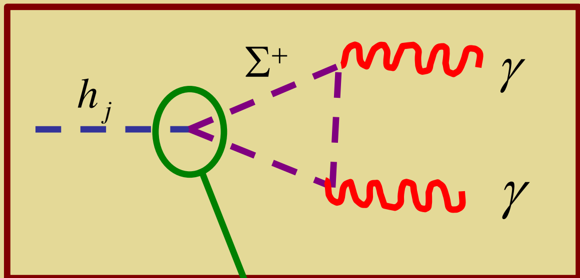


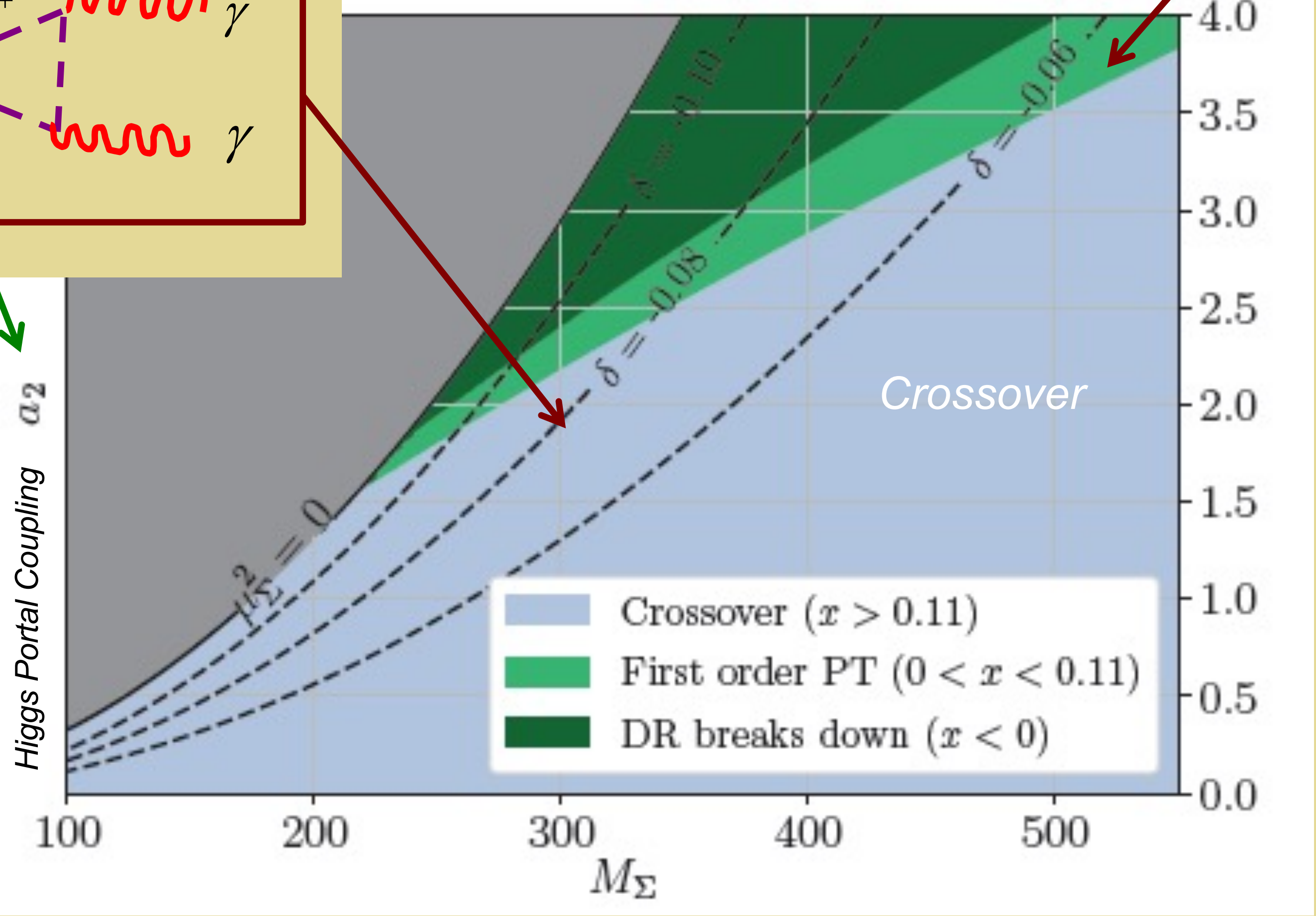
- One-step
- Non-perturbative

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

Real Triplet & EWPT

FOEWPT





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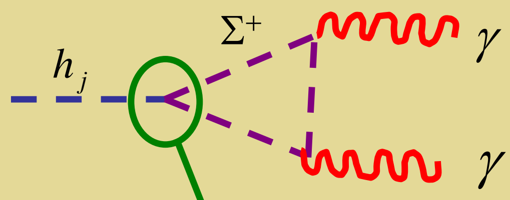
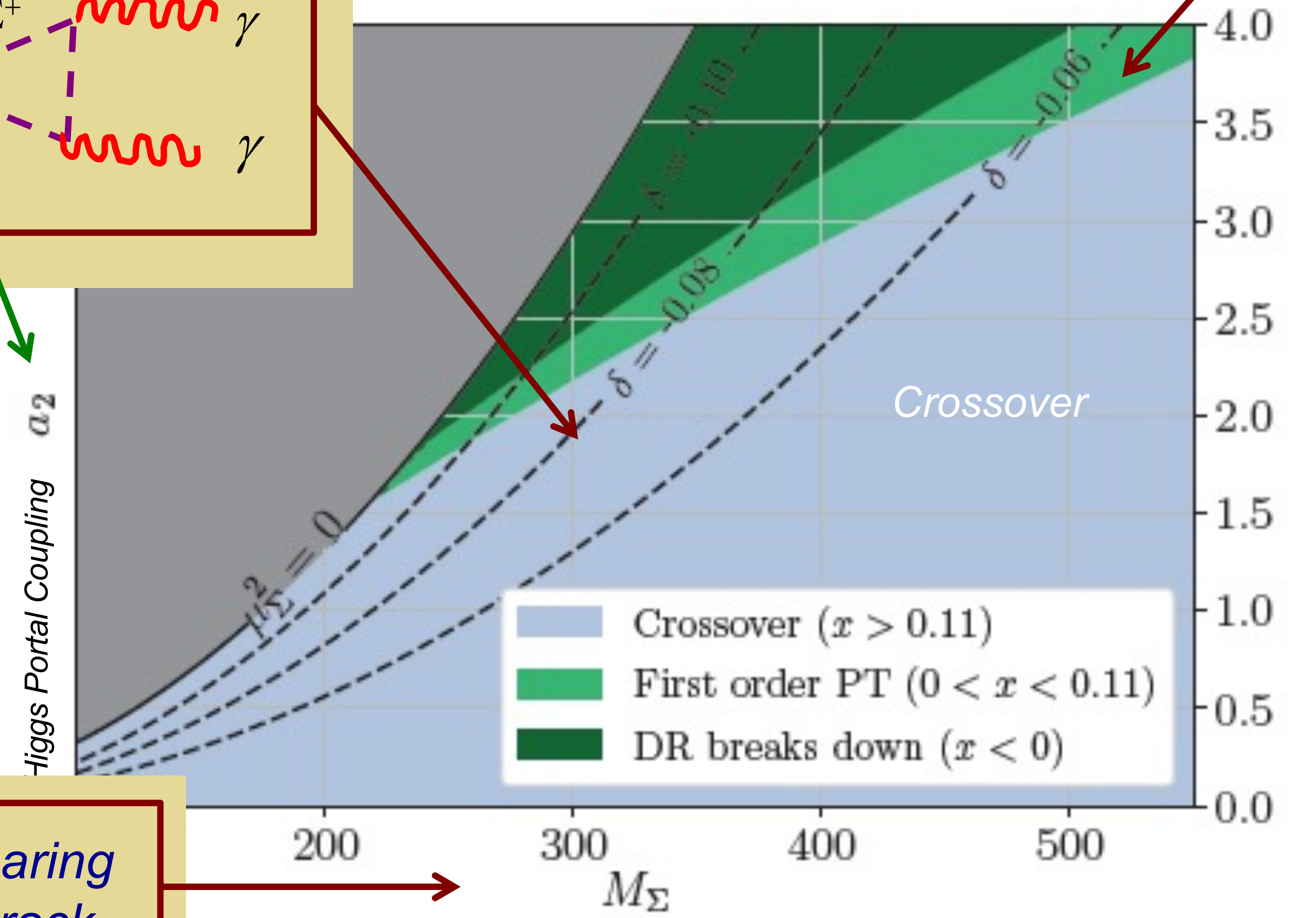
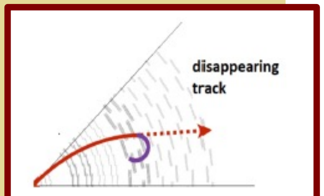
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

FOEWPT







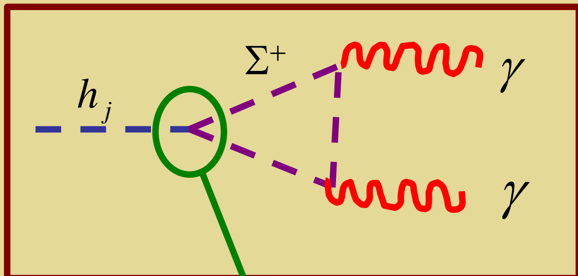
Disappearing charge track

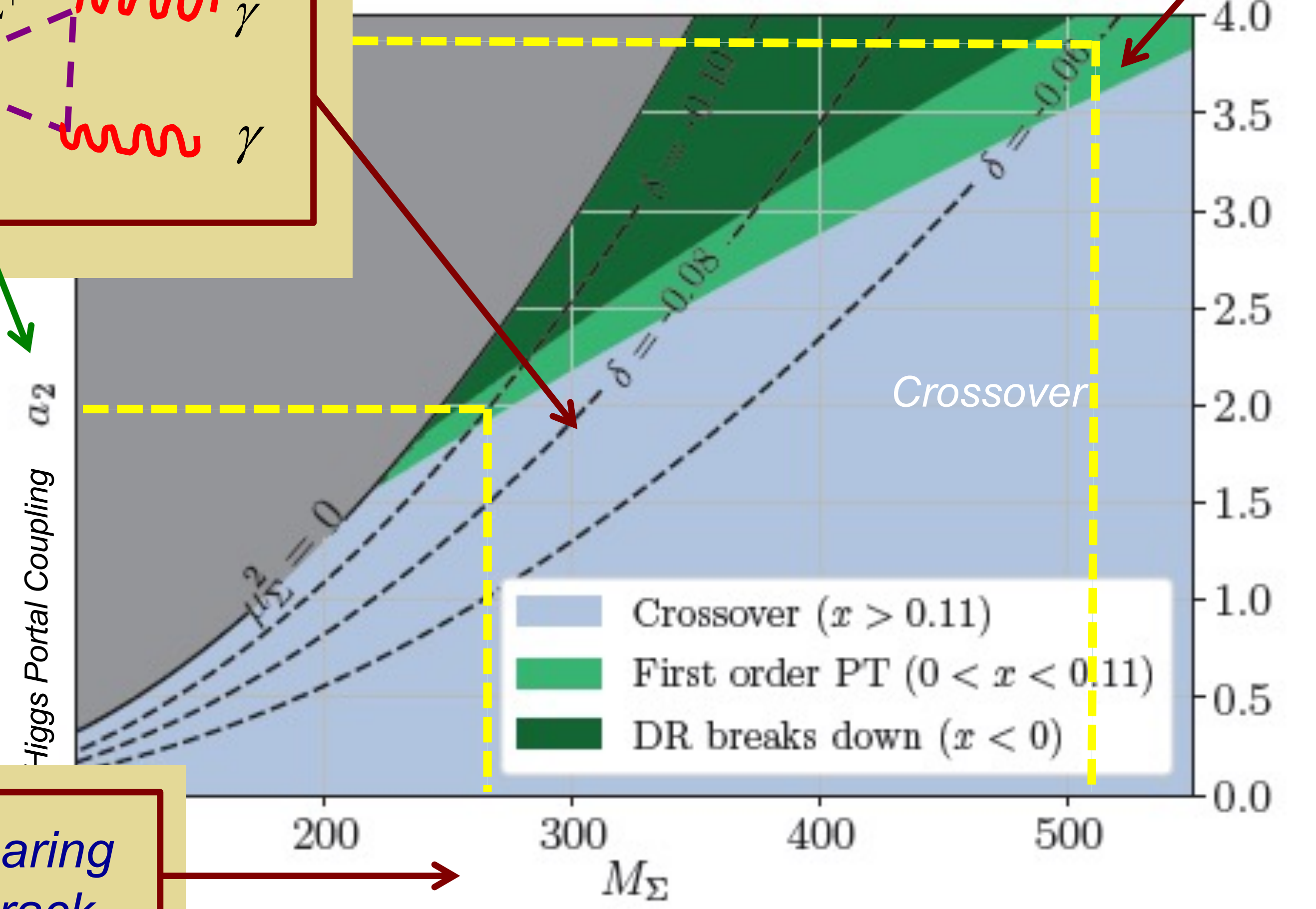
- One-step
- Non-perturbative

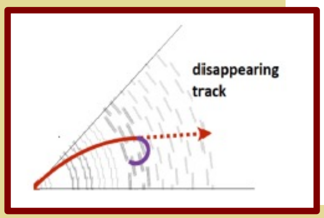
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet & EWPT

FOEWPT





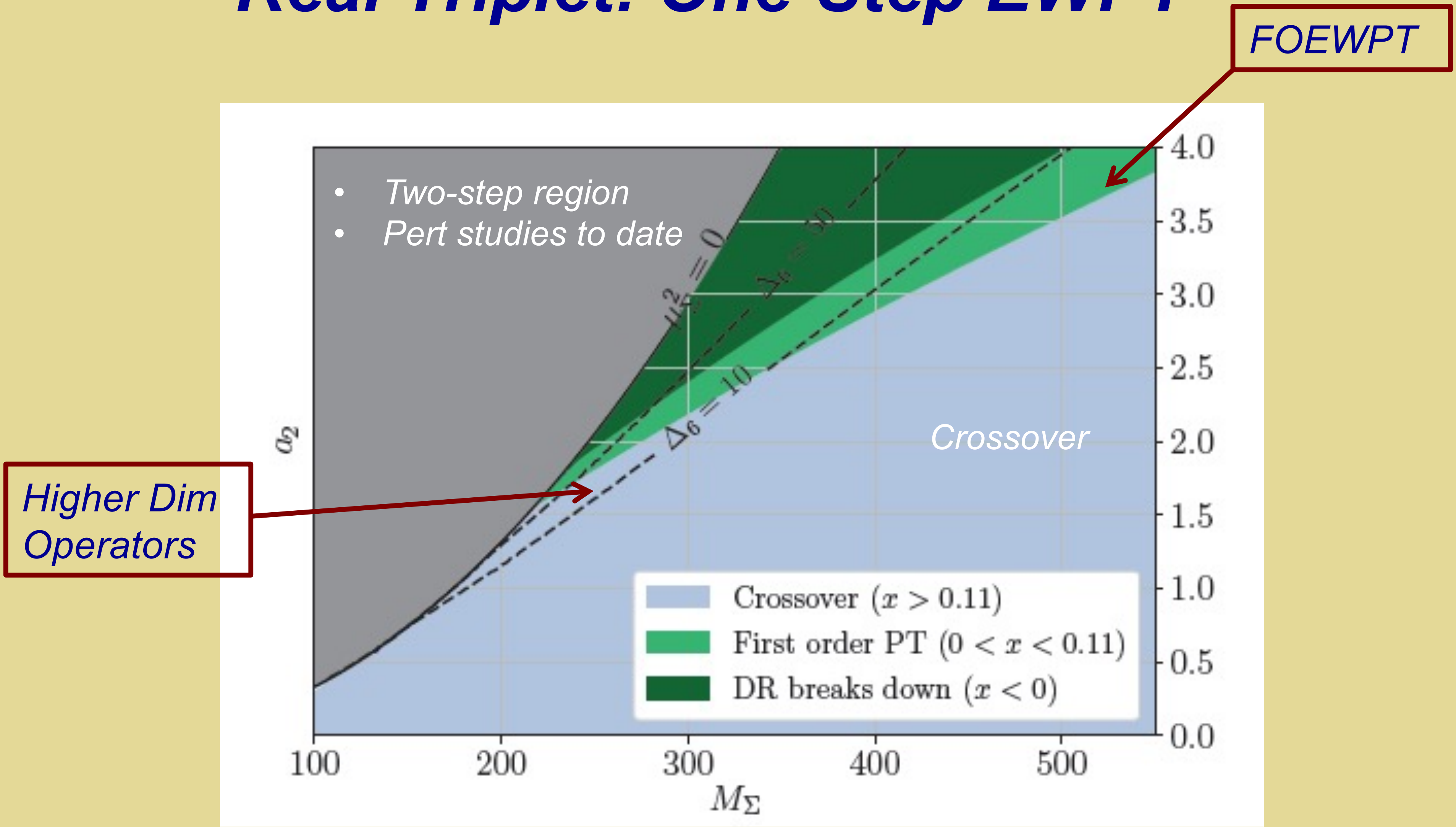


Disappearing charge track

- One-step
- Non-perturbative

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

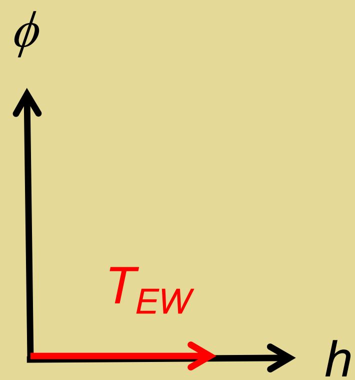
Real Triplet: One-Step EWPT



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

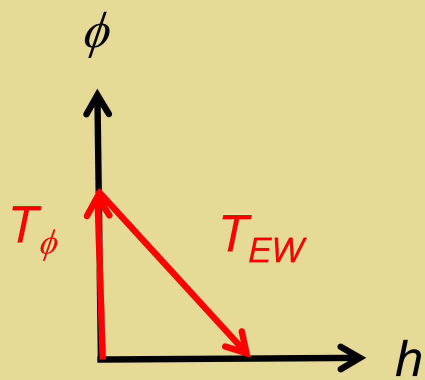
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet



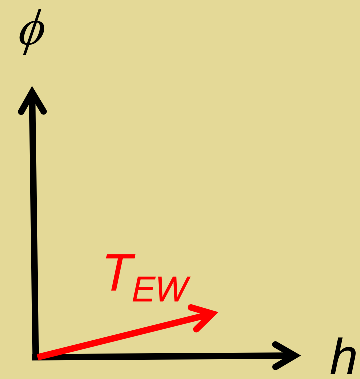
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



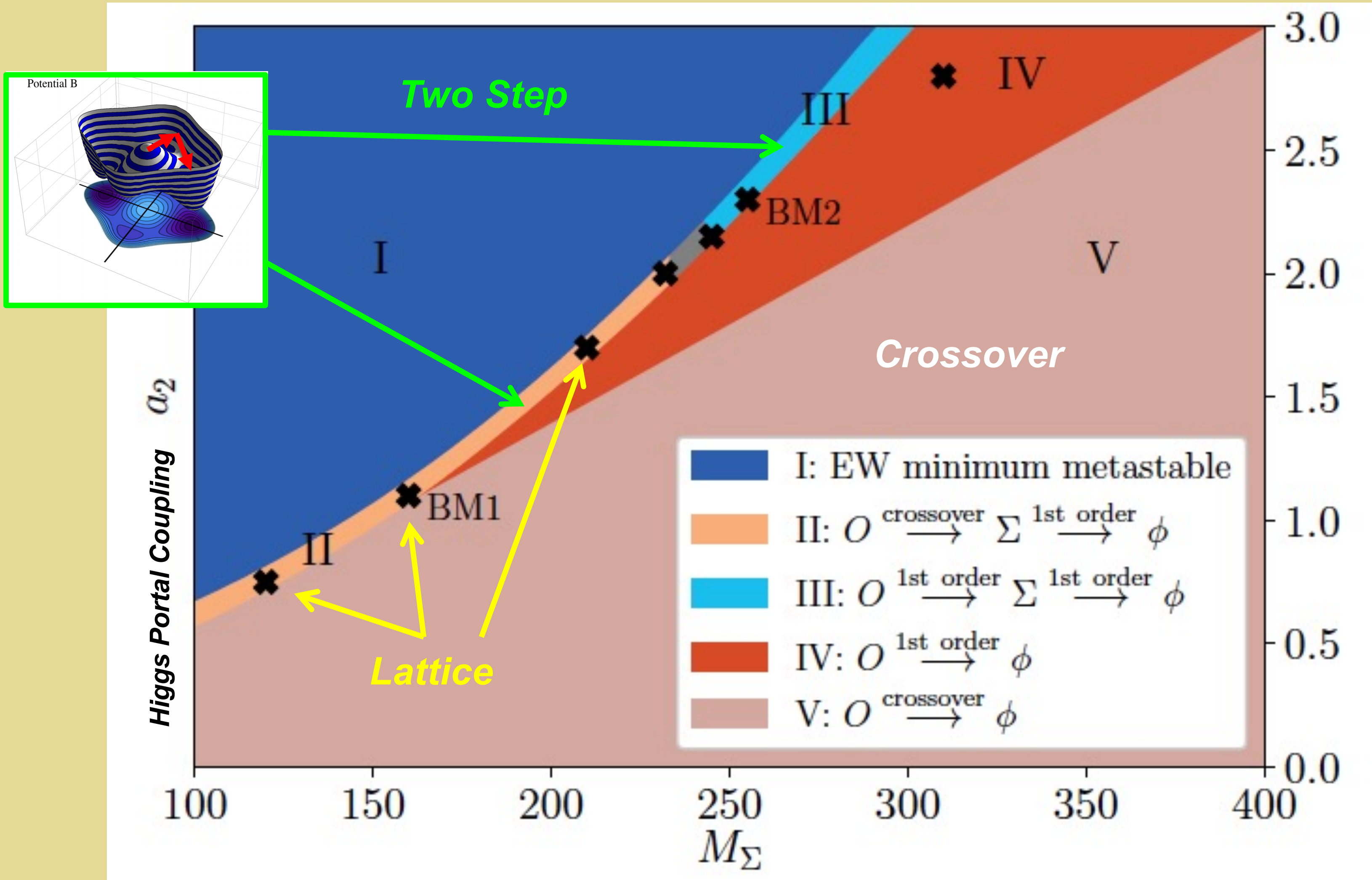
$a_1 H^2\phi$: $T = 0$

tree-level effect

Non-perturbative results

EW precision tests → too tiny

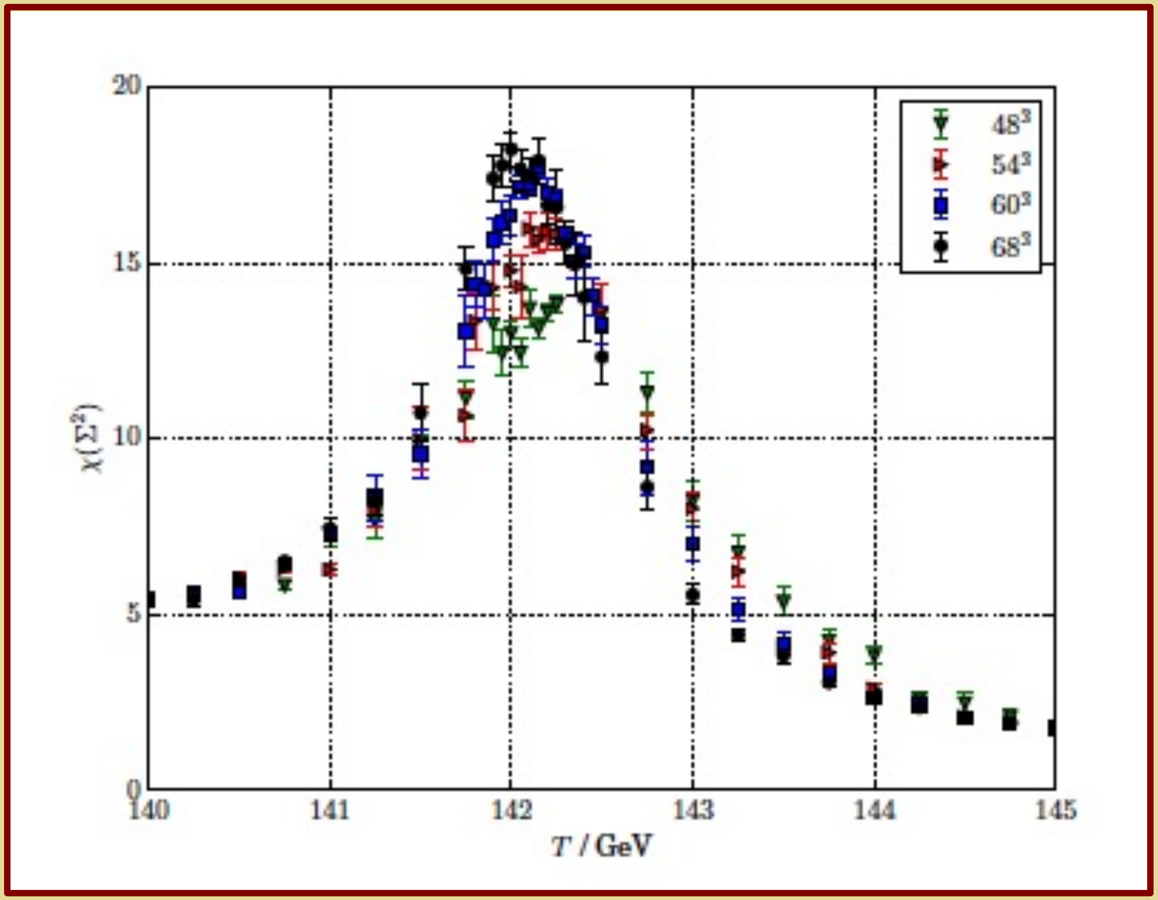
Real Triplet & EWPT: Novel EWSB



Niemi, R-M, Tenkanen, Weir 2005.11332 → PRL 2021

- 1 or 2 step
- Non-perturbative

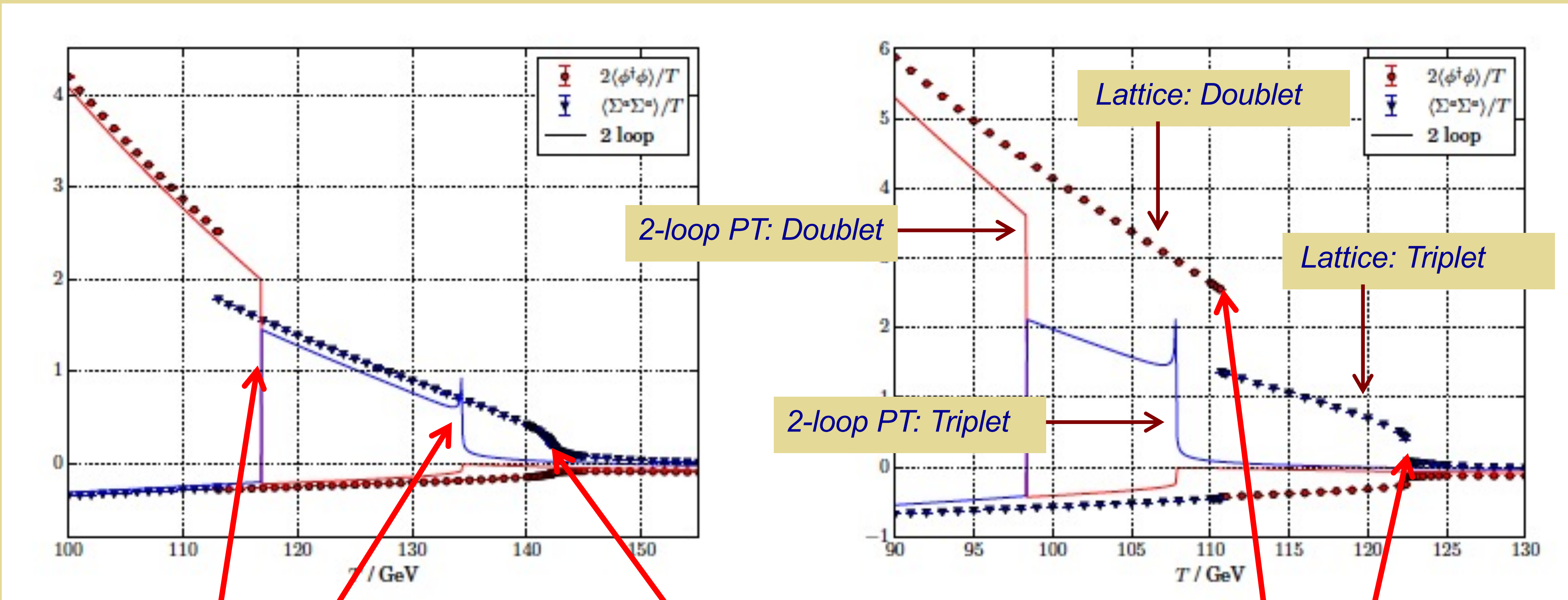
Real Triplet: Crossover vs 2nd Order



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

Niemi, R-M, Tenkanen, Weir 2005.11332 → PRL 2021

Real Triplet & EWPT: Benchmark PT



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

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

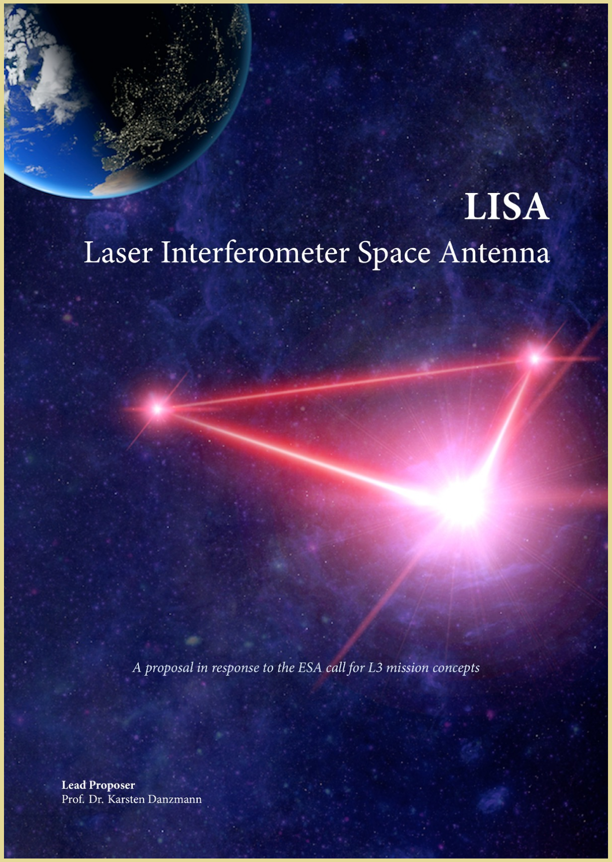
PT Discontinuities: First order EWPT

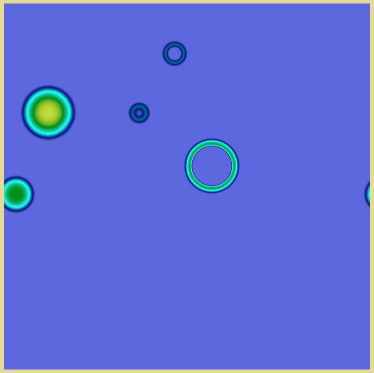
Lattice: Smooth Crossover: No phase transition

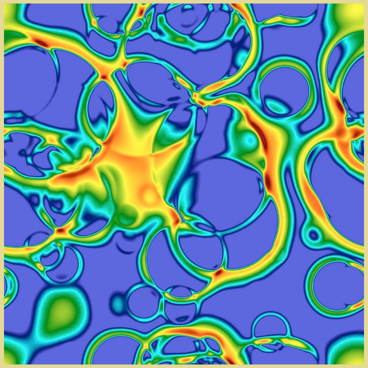
Discontinuities: First order EWPT

Niemi, R-M, Tenkanen, Weir 2005.11332 → PRL 2021

Gravitational Radiation



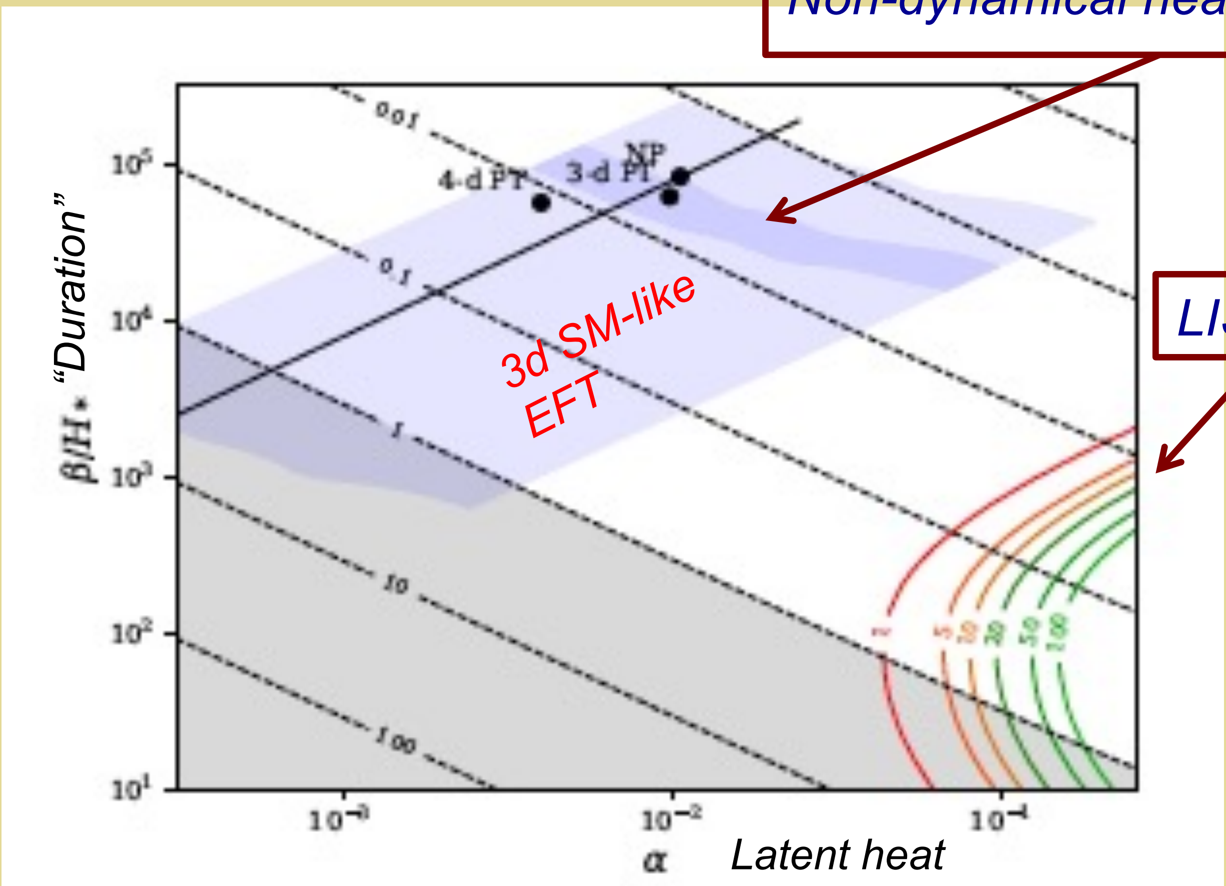




1. Bubbles nucleate and grow
2. Expand in a plasma - create reaction fronts
3. Bubbles + fronts collide - violent process
4. Sound waves left behind in plasma
5. Turbulence; damping

Thanks: D. Weir

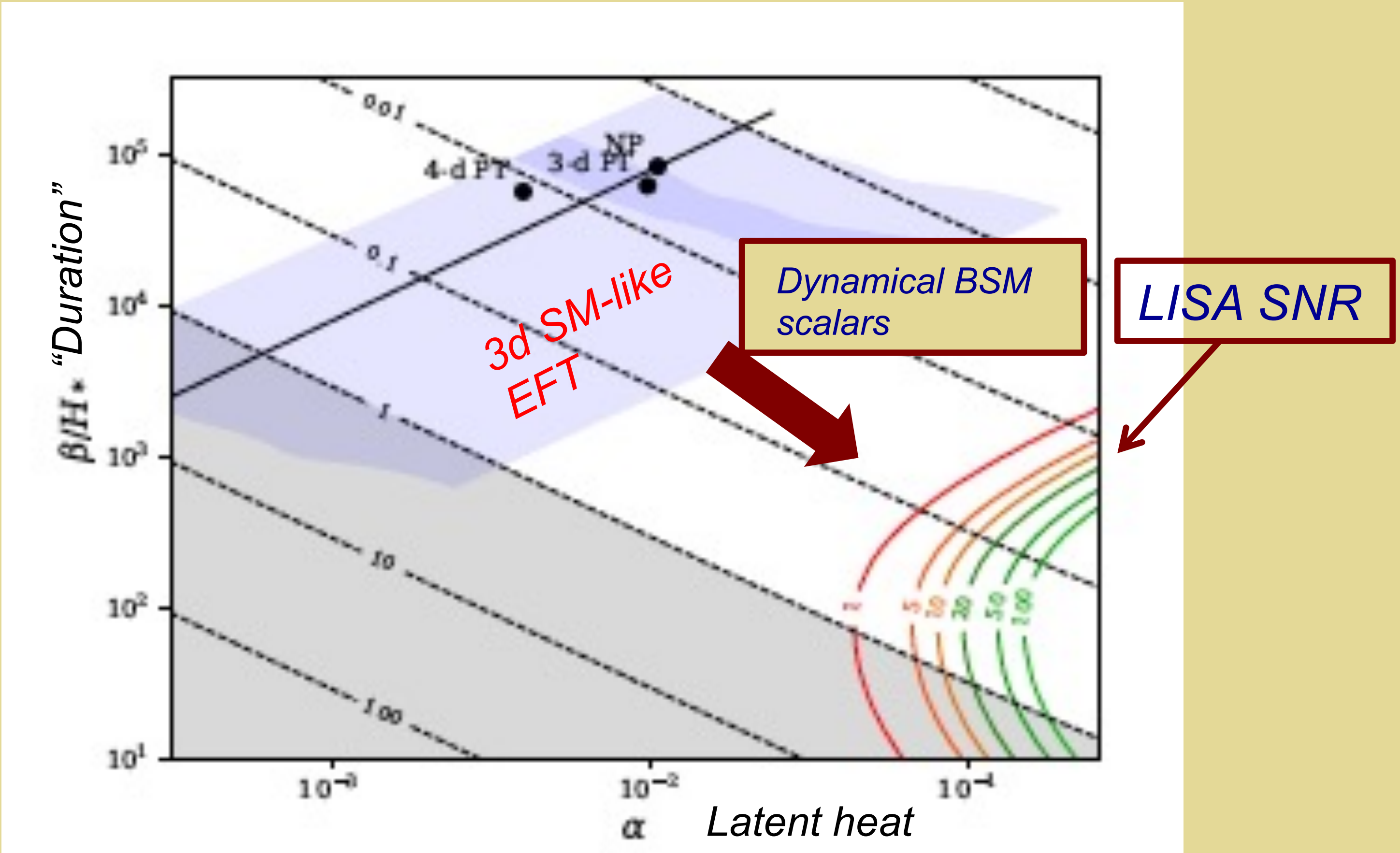
Heavy Real Singlet: EWPT & GW



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

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

Heavy Real Singlet: EWPT & GW



- One-step
- Non-perturbative

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

IV. Outlook

- *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 → EWPT is a clear collider target*

- *Realizing this opportunity requires a new generation of robust theoretical computations, using EFT & non-perturbative methods, to benchmark perturbative calculations*

IV. Outlook

- *There are exciting opportunities for talented and ambitious theorists to make significant contributions to this growing frontier*

谢谢

Back Up Slides

First Order EWPT from BSM Physics

- $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

First Order EWPT from BSM Physics

- *Thermal $\Gamma(h \rightarrow \gamma\gamma)$*
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*

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

First Order EWPT from BSM Physics

- *Thermal $\Gamma(h \to \gamma\gamma)$*
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

- *Thermal $\Gamma(h \rightarrow \gamma\gamma)$*
- *Higgs signal strengths*
- *Higgs self-coupling*
- *Exotic Decays*
- *Single ϕ production*

$H^2\phi$ Barrier ?

H-ϕ Mixing

Strong First Order EWPT

- *Prevent baryon number washout*
- *Observable GW*

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

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

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

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

→

$|\sin\theta| \gtrsim 0.01$

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

Strong First Order EWPT

- ***Prevent baryon number washout***
- ***Observable GW***

Collider Target: Precision and single ϕ production

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

→

$| \sin\theta | \gtrsim 0.01$

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

T_{EW} : Single ϕ^0 Production in e^+e^- & pp

Z ϕ production in e^+e^- :

$E_{\rm CM}$(TeV)	M_ϕ (GeV)	$\lvert\sin\theta\rvert$	σ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	N
340	150	0.01	0.01	5	50
500	150	0.01	0.005	2	10
	240	0.01	0.003	2	6
1500	150	0.01	5×10^{-4}	2.5	1
	400	0.01	4×10^{-4}	2.5	1
	700	0.01	2×10^{-4}	2.5	<1
3000	150	0.01	1×10^{-4}	5	<1
	400	0.01	1×10^{-4}	5	<1
	700	0.01	1×10^{-4}	5	<1

Single ϕ production in pp via GF:

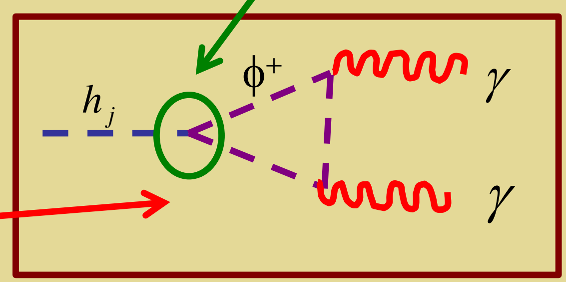
$E_{\rm CM}$(TeV)	M_ϕ (GeV)	$\lvert\sin\theta\rvert$	σ (fb)	$\int dt\mathcal{L}$ (ab^{-1})	$N\times10^{-3}$
14	415	0.01	1	3	3
	714	0.01	0.1	3	0.3
100	415	0.01	59	30	1770
	714	0.01	12	30	360

First Order EWPT from BSM Physics

- $\Gamma(h \to \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

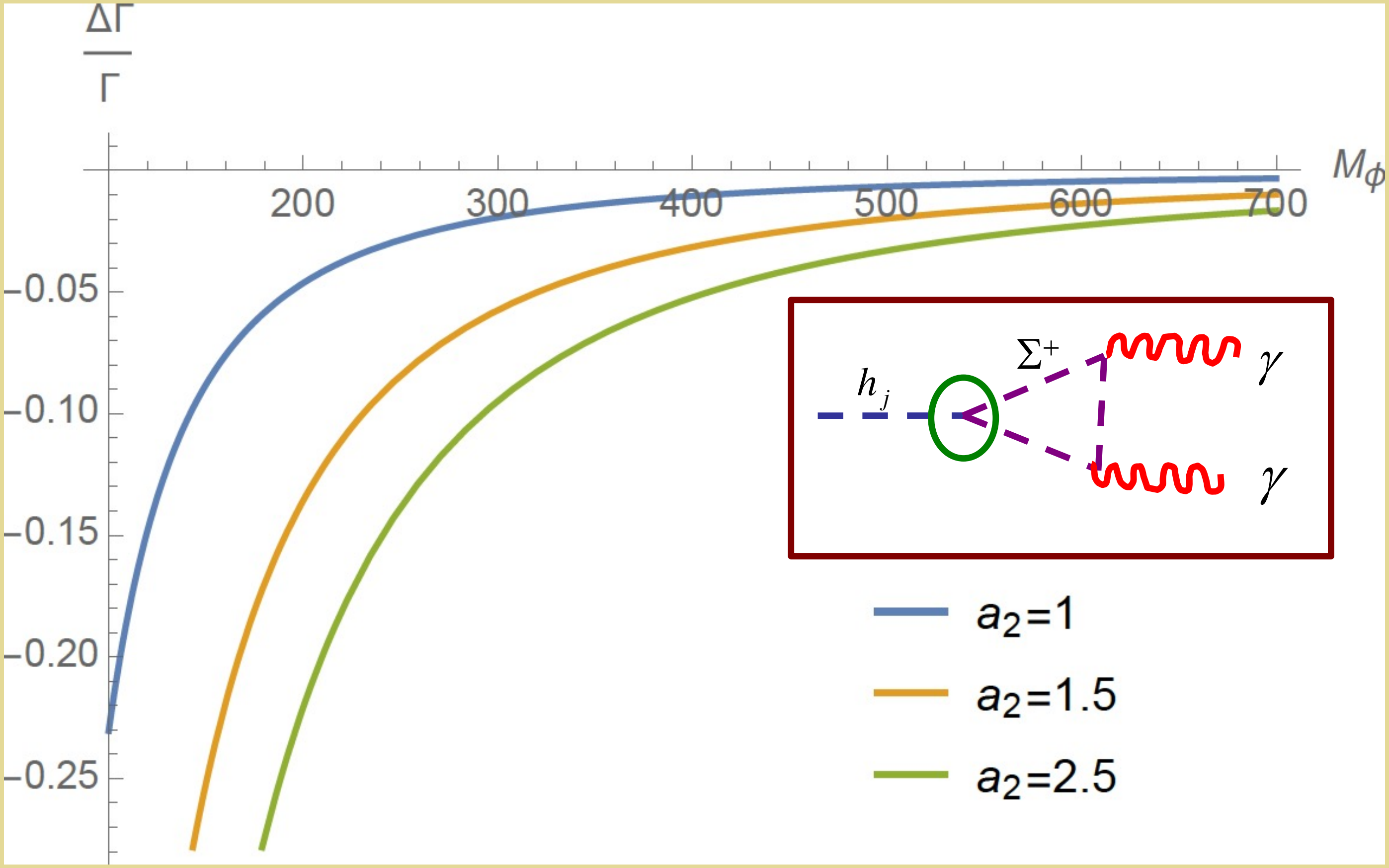
$H^2\phi^2$ Barrier ?

ϕ : EW Multiplet



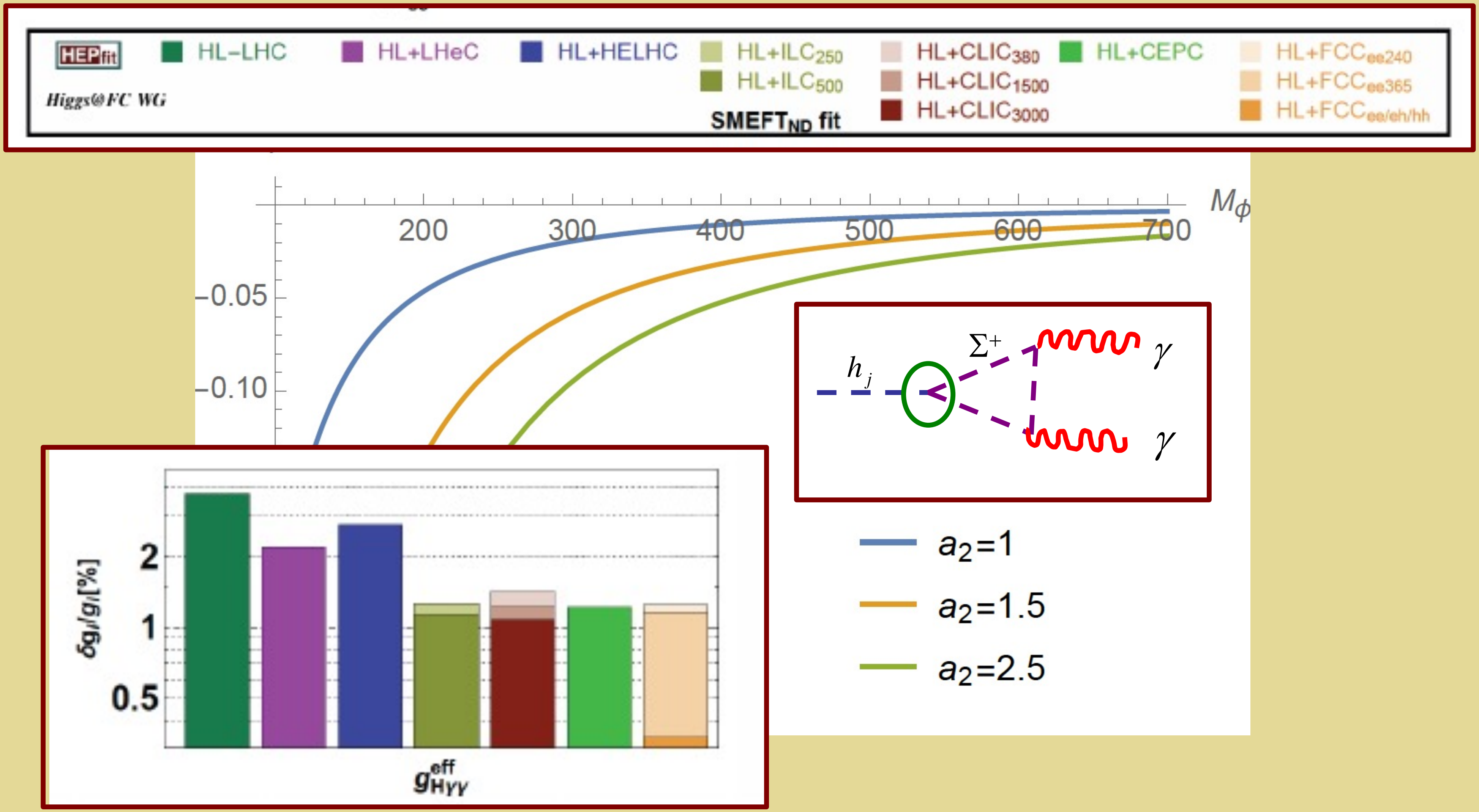
Collider Target:
Precision

$H \rightarrow \gamma\gamma$: Is There a Barrier ?



EWPT → Decrease in rate

$H \rightarrow \gamma\gamma$: Is There a Barrier ?



Thanks: M. Cepeda

First Order EWPT from BSM Physics

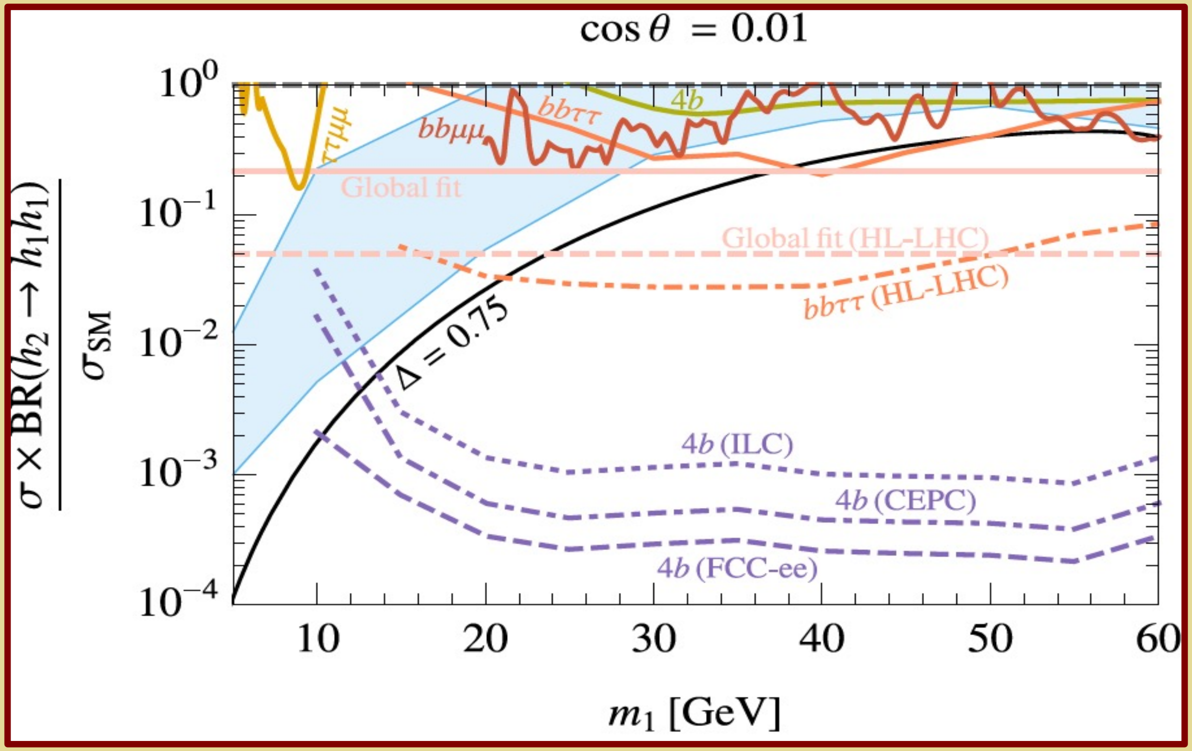
- Thermal $\Gamma(h \rightarrow \gamma\gamma)$
- Higgs signal strengths
- Higgs self-coupling
- Exotic Decays

$H^2\phi$ and/or $H^2\phi^2$
Barrier ?

See ahead

Light Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

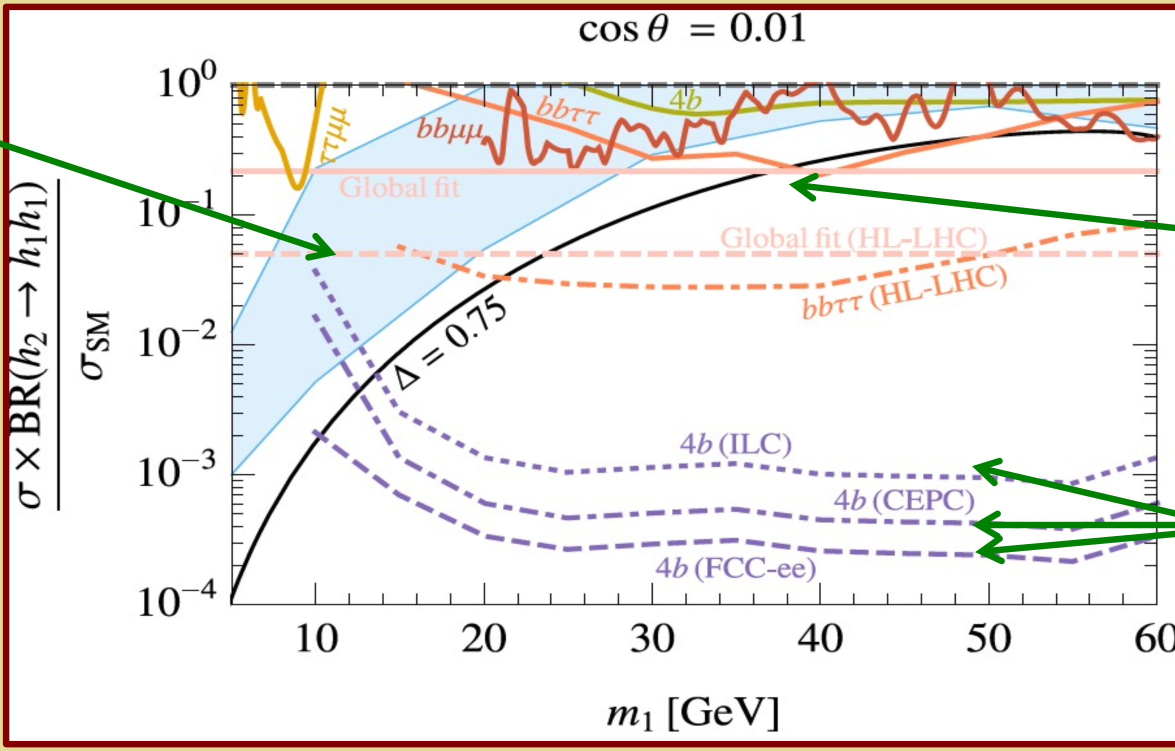


J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206
Z. Liu talk this meeting

Light Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



EWPT viable: Semi analytic

Future e^+e^-

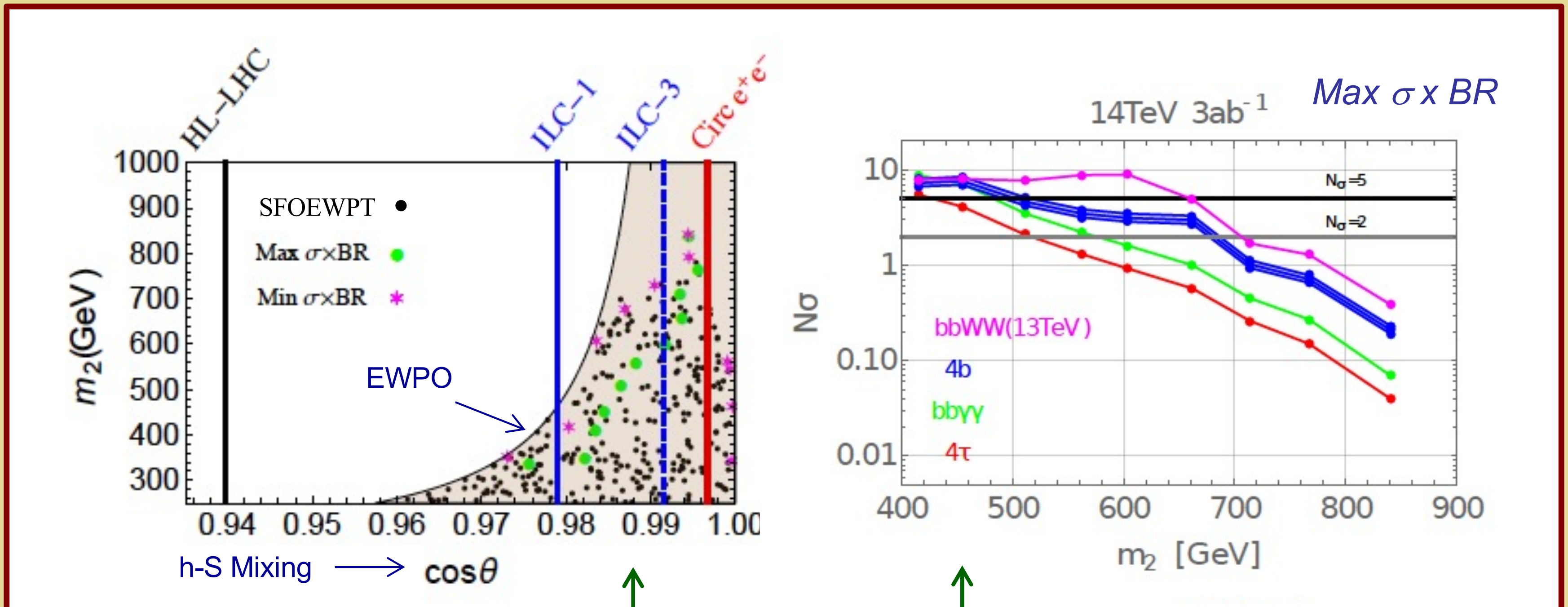
J. Kozaczuk, MR-M, J. Shelton 1911.10210

See also: Carena et al 1911.10206

Z. Liu talk this meeting

Singlets: Precision & Res Di-Higgs Prod

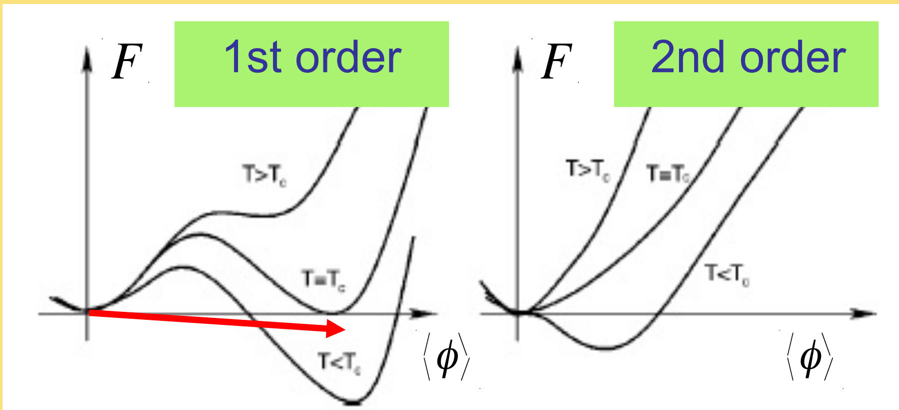
SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



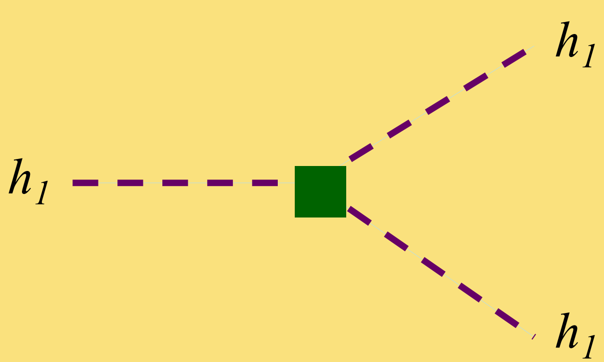
Kotwal, No, R-M, Winslow 1605.06123

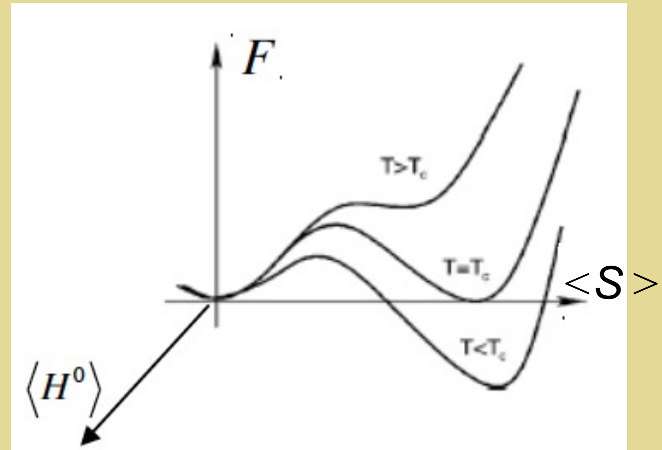
Li, R-M, Willocq 1906.05289
See also: Huang et al, 1701.04442

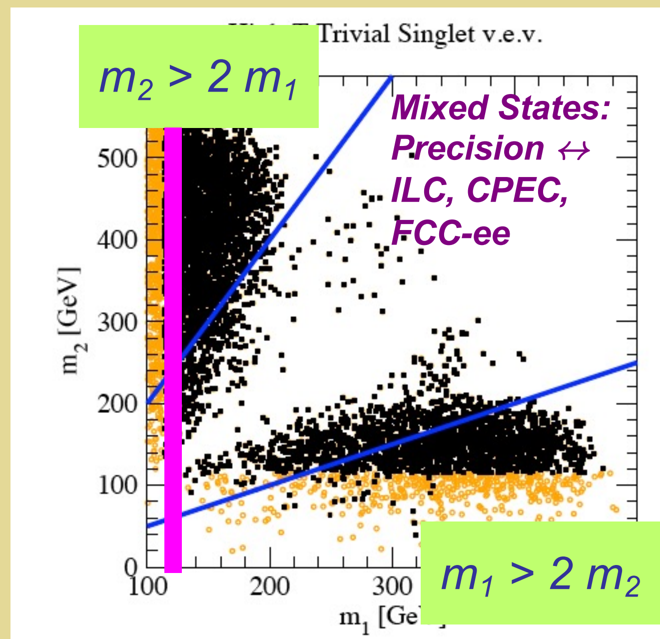
EW Phase Transition: New Scalars



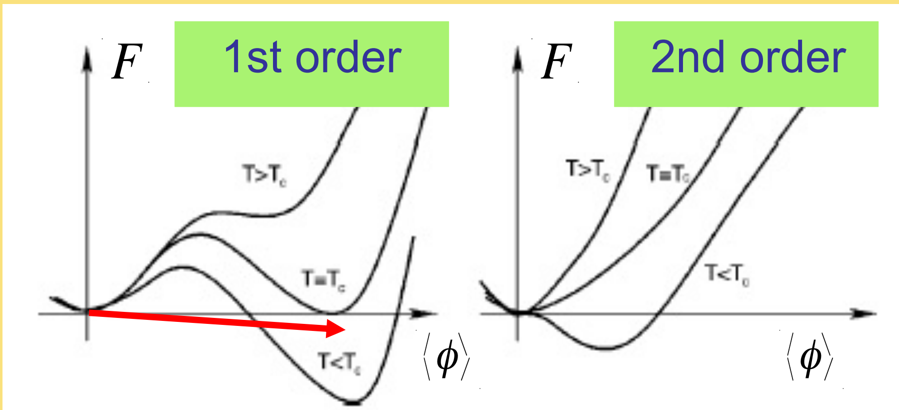
Modified Higgs Self-Coupling

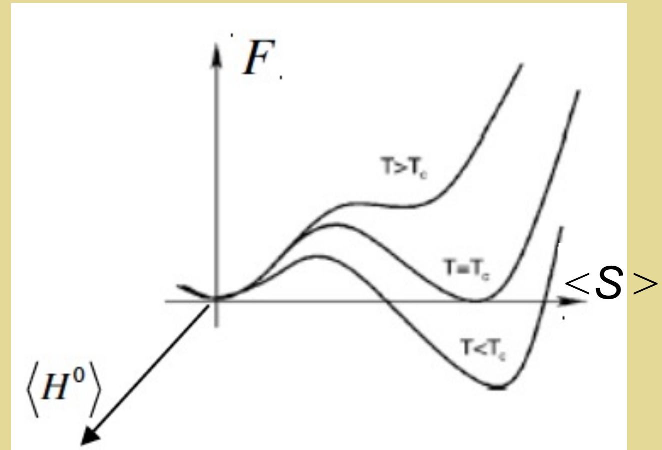




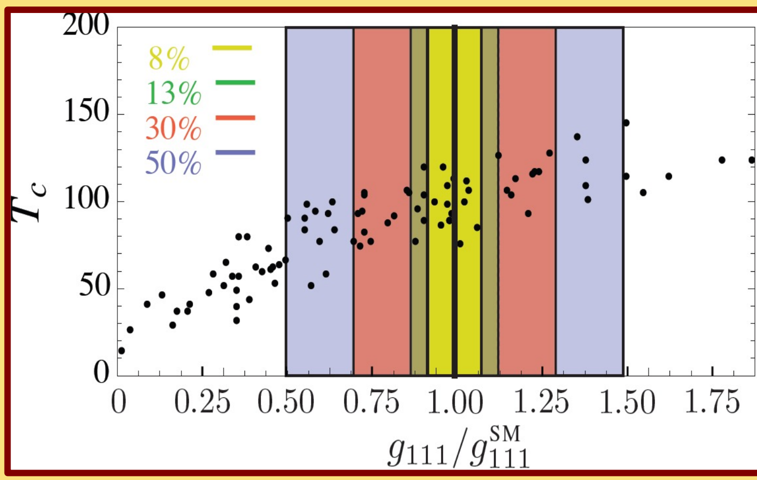


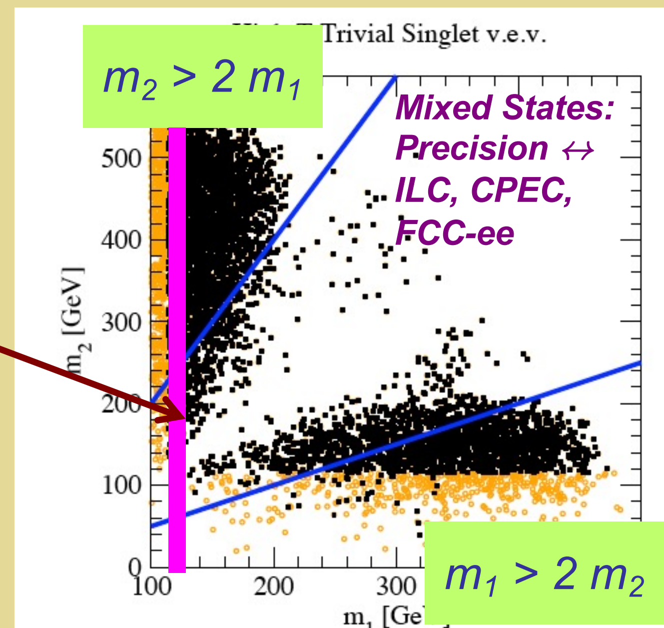
EW Phase Transition: Singlet Scalars





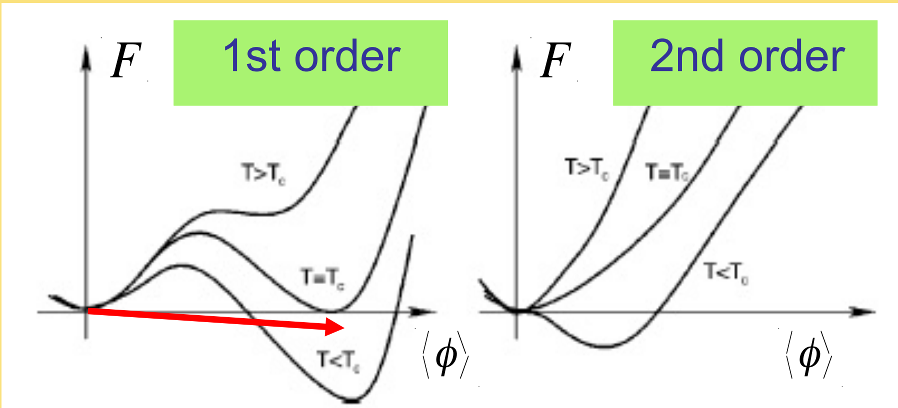
Modified Higgs Self-Coupling

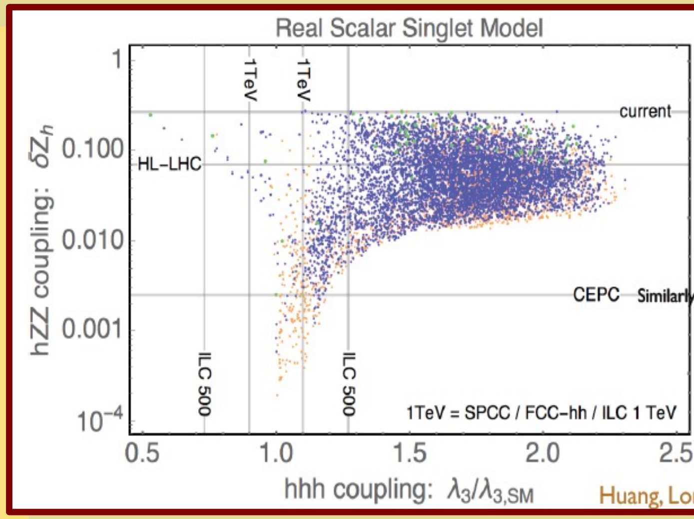




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

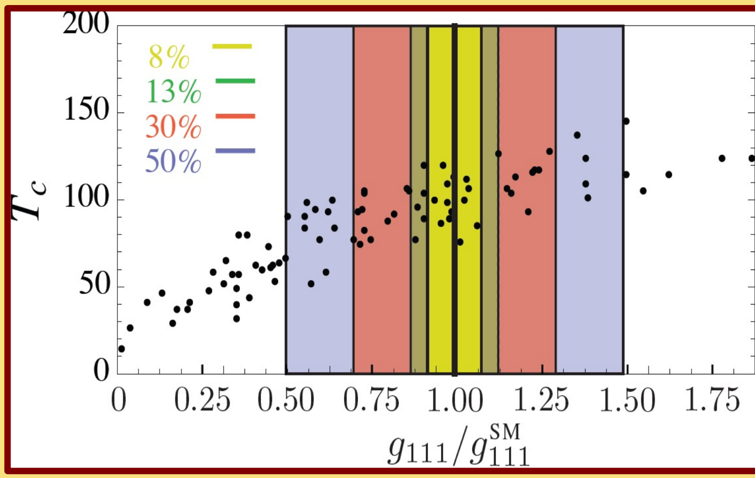
EW Phase Transition: Singlet Scalars

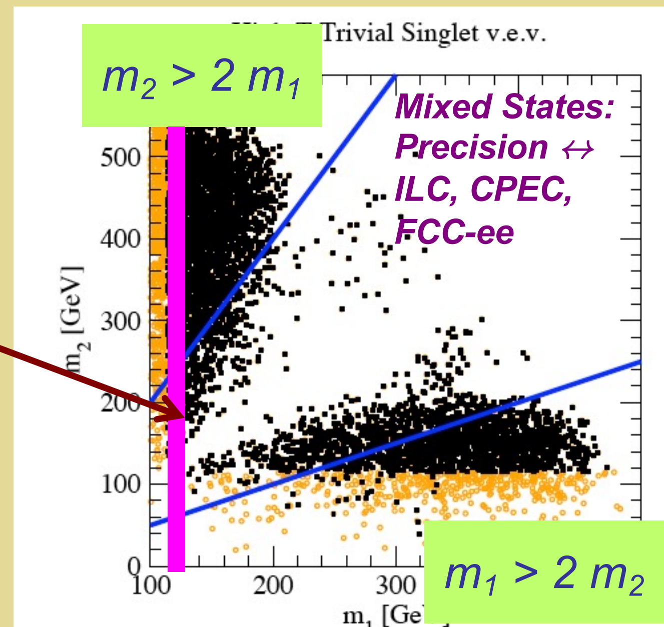




Scan includes $m_2 > 2m_1$

Modified Higgs Self-Coupling

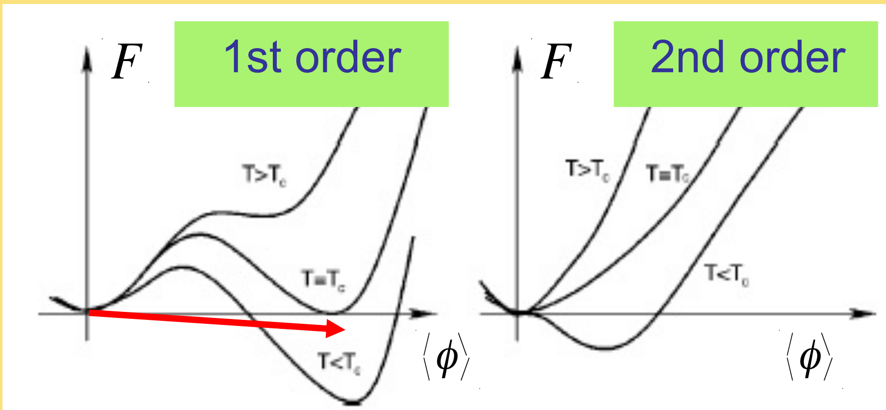


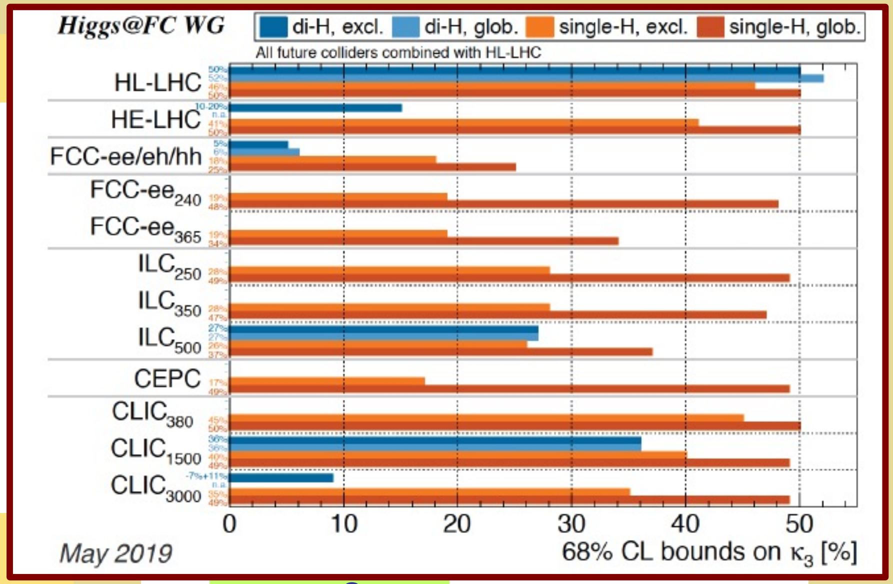


Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

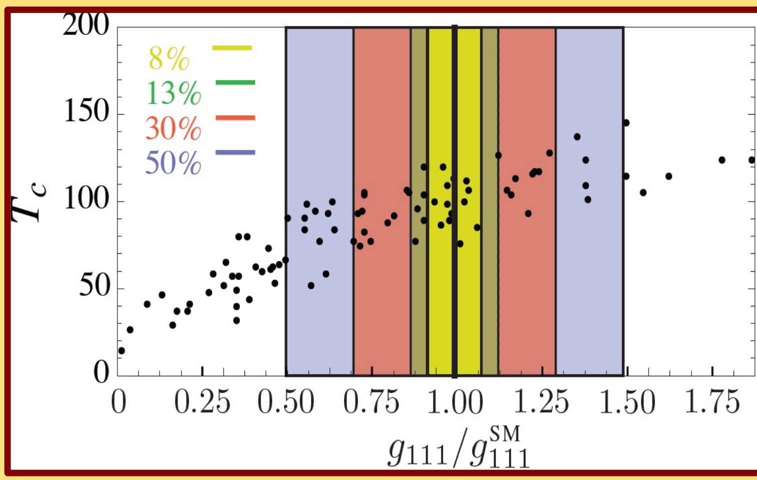
Thanks: M. Cepeda

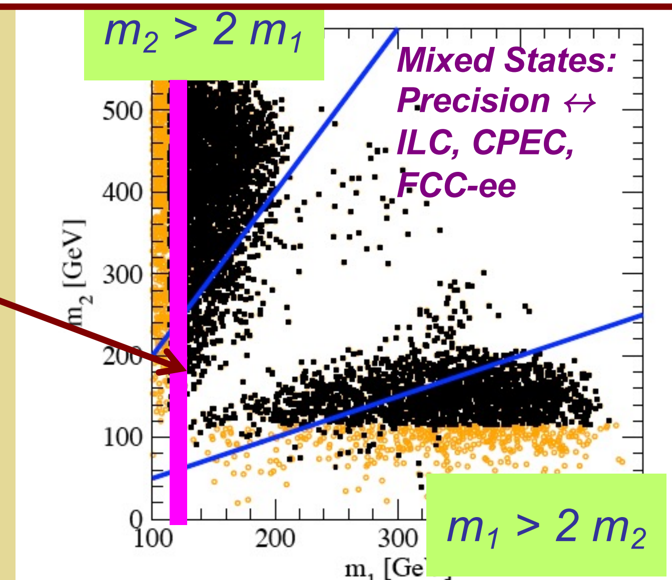
EW Phase Transition: Singlet Scalars





Modified Higgs Self-Coupling

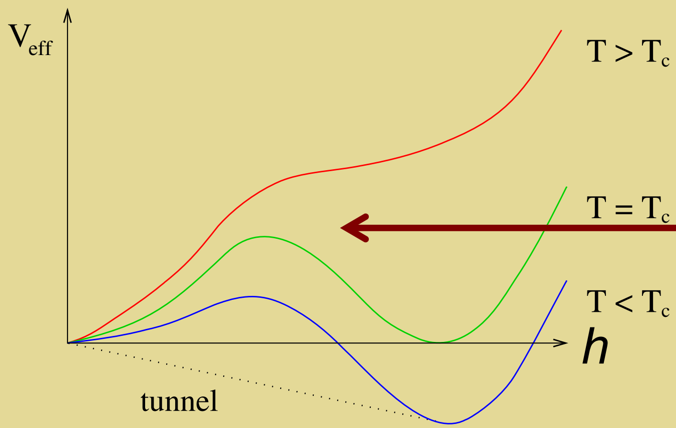




Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

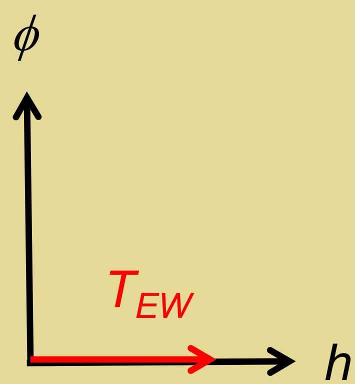
Thanks: M. Cepeda

First Order EWPT from BSM Physics



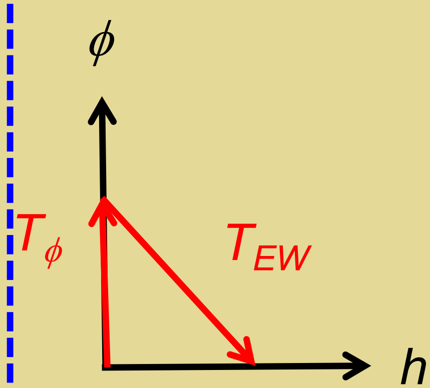
Simple arguments: T_{EW} + first order EWPT → $M_\phi \lesssim 700$ GeV

Illustrate logic



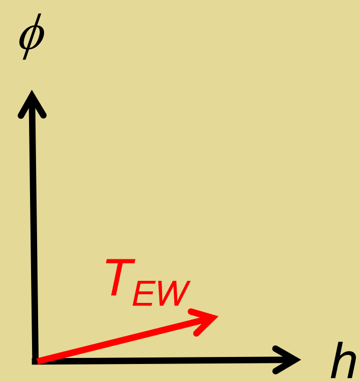
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

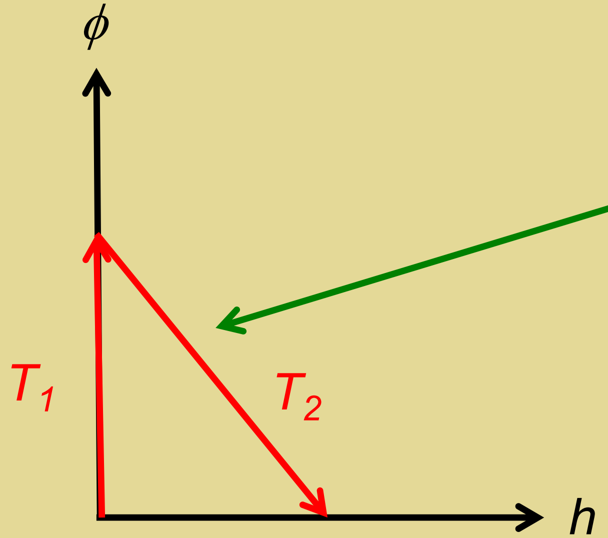
tree-level effect



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

tree-level effect

First Order EWPT from BSM Physics

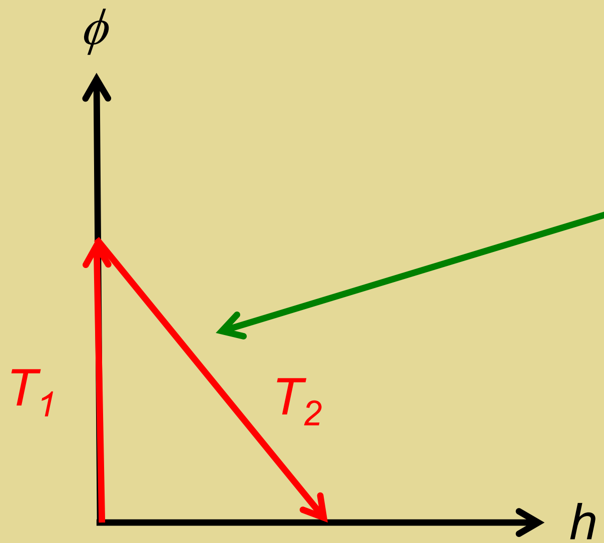


- Tree-level barrier: $a_2\, \phi^+\phi\, H^+H$
- Want $T_1 > T_2 \sim T_{EW}$

Negative for $T_1 > T_2 \sim T_{EW}$

$$V(\varphi, T) = \frac{1}{2}\left[-|b_2| + \frac{T^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]\varphi^2 + \frac{b_4}{4!}\varphi^4$$

First Order EWPT from BSM Physics

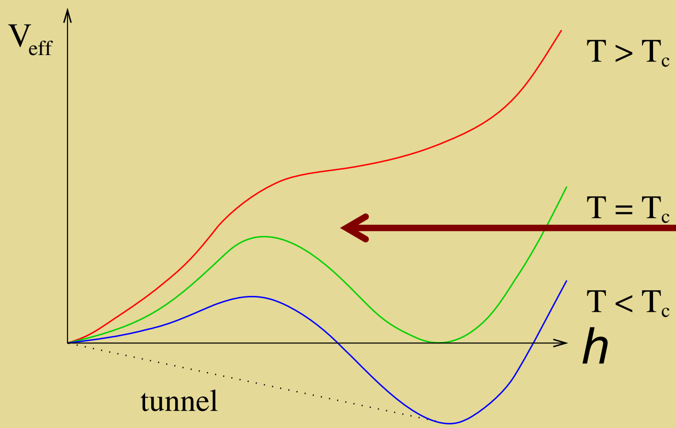


- *Tree-level barrier: $a_2\ \phi^+\phi\ H^+H$*
- *Want $T_1 > T_2 \sim T_{EW}$*

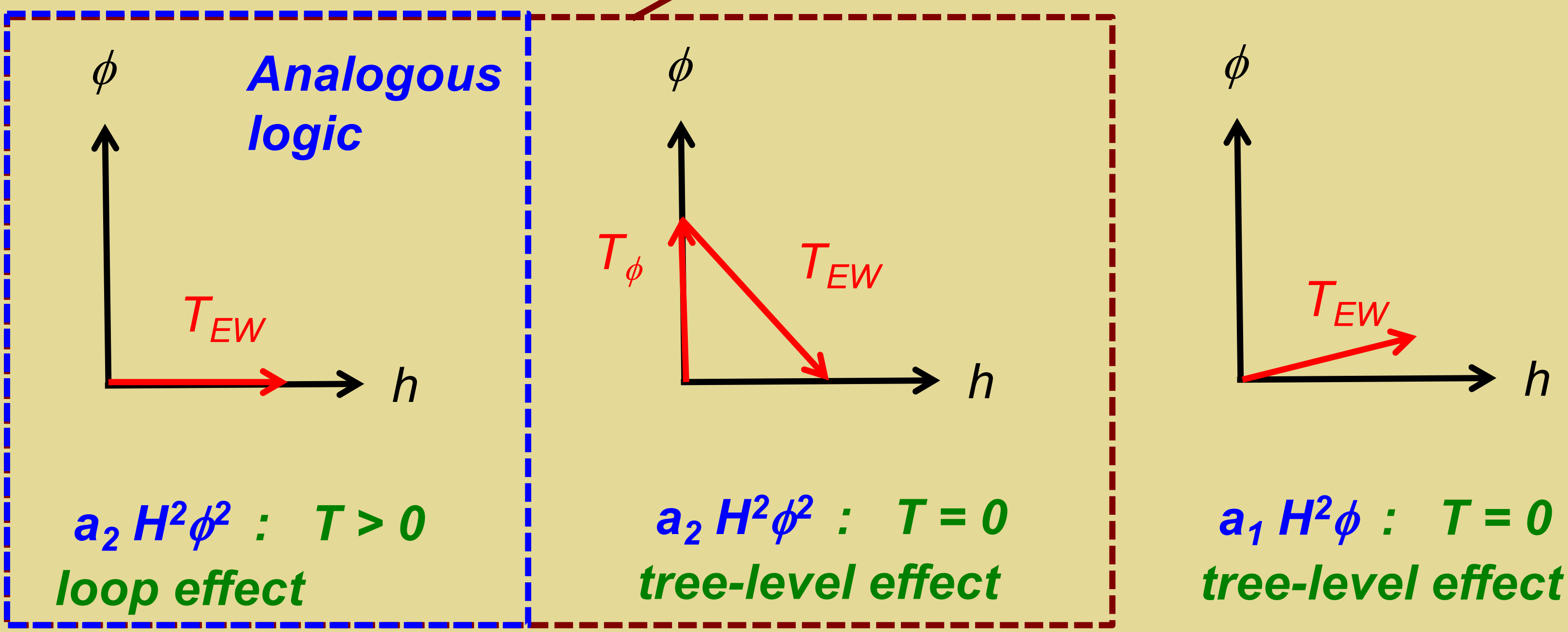
$$M_\phi(T=0) < \left[\frac{a_2}{4}v^2 - \frac{T_{\rm EW}^2}{6}\left(a_2 + \frac{3}{2}b_4\right)\right]^{1/2}$$

M_ϕ < 350 GeV for perturbative a_2 , b_4

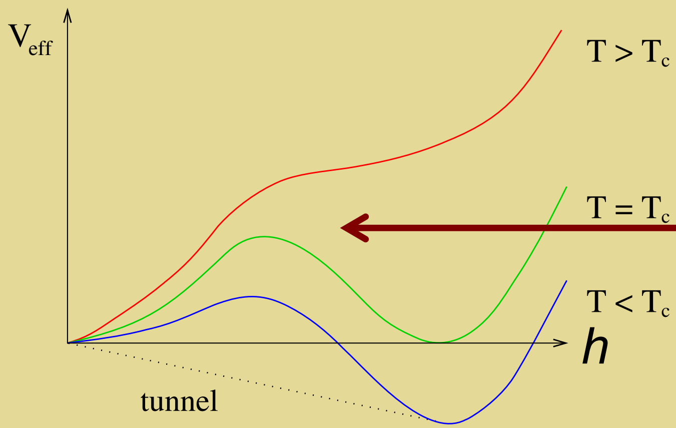
First Order EWPT from BSM Physics



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

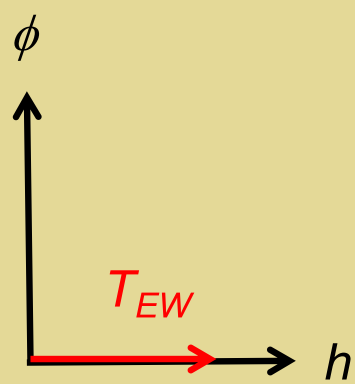


First Order EWPT from BSM Physics

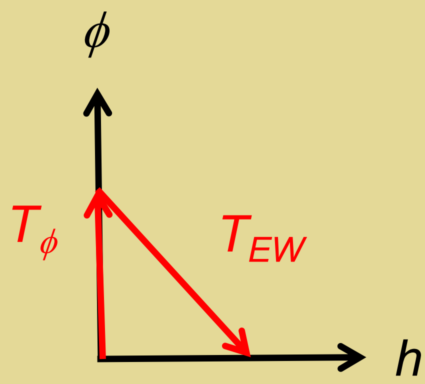


Simple arguments: T_{EW} + *first order EWPT* → $M_\phi \lesssim 700$ *GeV*

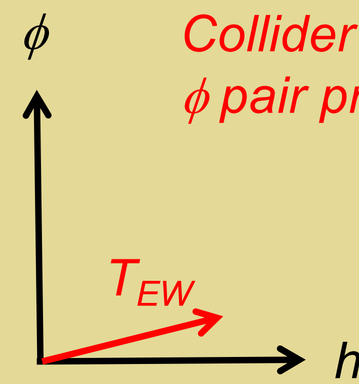
Collider Target:
ϕ pair production



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



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



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