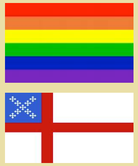
Electroweak Baryogenesis & Higgs Studies

M.J. Ramsey-Musolf

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



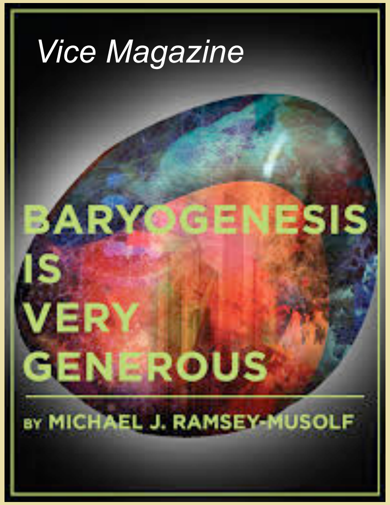
My pronouns: he/him/his

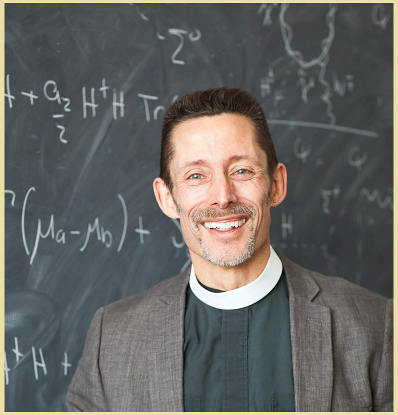
EWPT an Higgs Physics Symposium
IHEP Beijing, July 2020

Michael Ramsey-Musolf

Chair Professor, SJTU & T.D. Lee Professor, TDLI
Professor & Director, ACFI, U. Mass Amherst

Theoretical Physics





- *Why does the Universe contain more matter than antimatter ?*
- *What are the laws of nature beyond those of the Standard Model & General Relativity ?*
- *How do quantum field theories work ? How do they apply to processes in the early Universe ?*
- *How can experiments test our theoretical ideas?*

- *Ph.D. Princeton*
- *Post-doc MIT*
- *美国 → 中国 2019*

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Selected References

- *D. Morrissey & MJRM, "Electroweak Baryogenesis", NJP 14 (2012) 125003 [1206.2942]*
- *MJRM, "The EW Phase Transition: A Collider Target" [1912.07189]*
- *S. Profumo, MJRM, G. Shaugnessy, "Singlet Higgs Phenomenology and the EW Phase Transition", JHEP 08 (2007) 010 [0705.2425]*
- *S. Profumo, MJRM, C. Wainwright, P. Winslow, "Singlet-catalyzed EW Phase Transitions and Precision Higgs Boson Studies", PRD 91 (2015) 035108 [1407.5342]*
- *H. H. Patel & MJRM, "Stepping Into EW Symmetry-Breaking: Phase Transitions and Higgs Phenomenology", PRD 88 (2013) 035013 [1212.5652]*
- *S. Inoue, G. Ovanesyan, MJRM "Two-Step EW Baryogenesis", PRD 93 (2016) 015013 [1508.05404]*
- *V. Cirigliano, C. Lee, MJRM, "Resonant Relaxation in EW Baryogenesis", PRD 71 (2005) 075010 [hep-ph/0412345]*

Key Ideas for this Talk

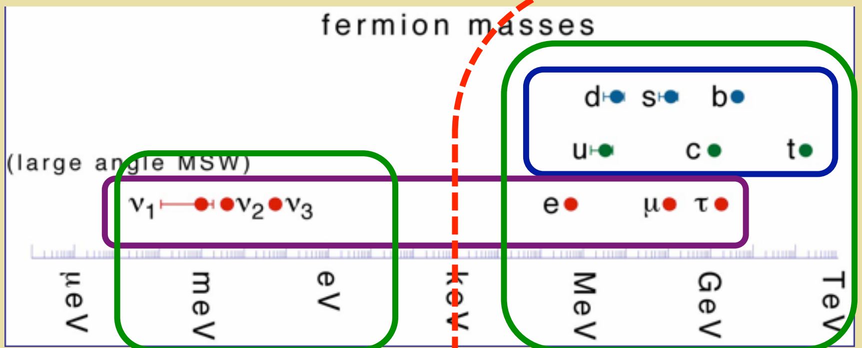
- ***The "electroweak temperature" → a scale provided by nature that makes EWBG/ EWPT a clear BSM target for colliders***
- ***High degree of complementarity and synergy between precision Higgs studies, new particle searches, and low-energy symmetry tests → exciting opportunities for the CEPC!***
- ***Non-perturbative computations essential input for reliable collider pheno***

Ingredients for Baryogenesis

Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	BSM
• B violation (sphalerons)	✔	✔
• C & CP violation	✖	✔
• Out-of-equilibrium or CPT violation	✖	✔

Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

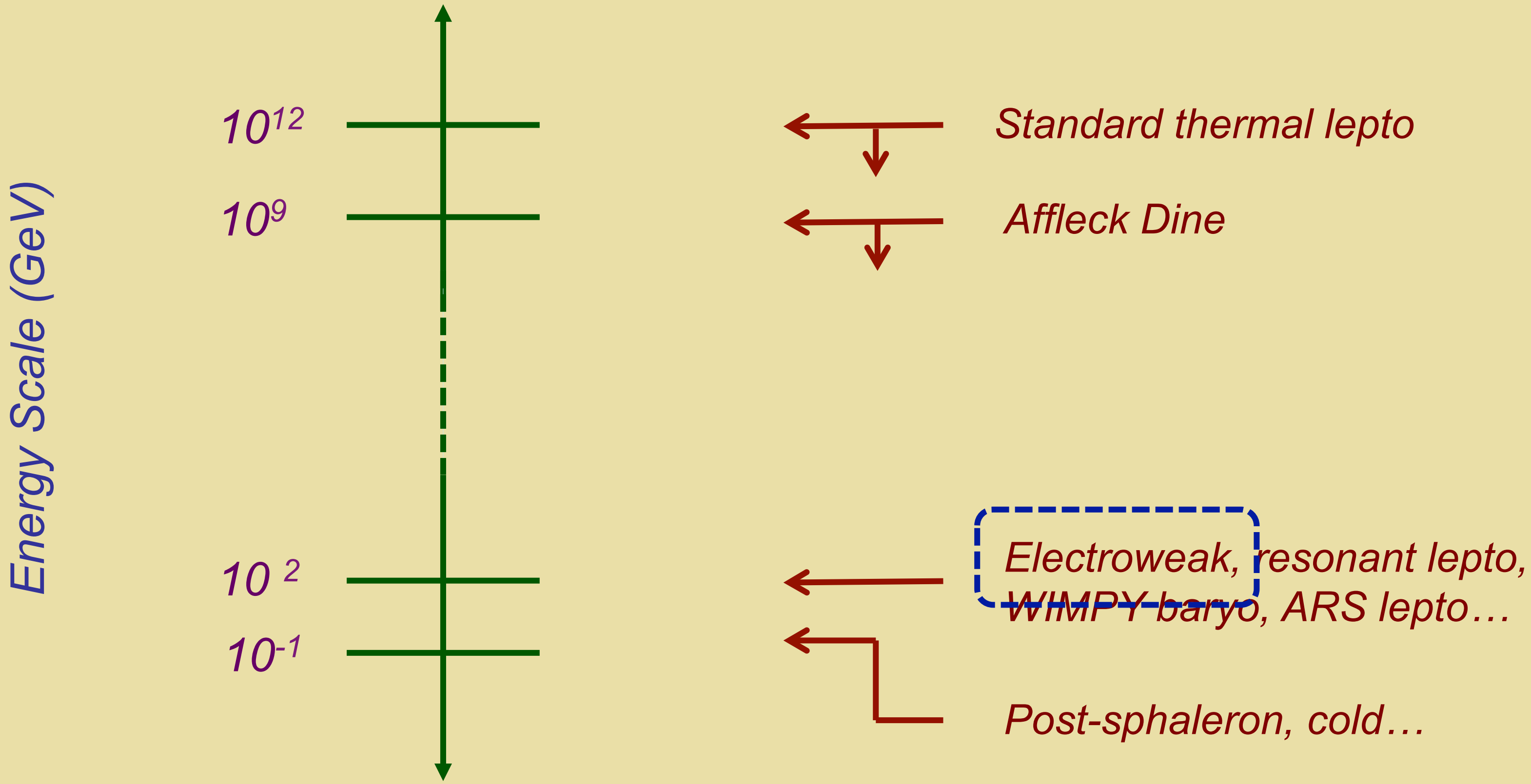
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

This talk

Baryogenesis Scenarios



Outline

I. Electroweak Baryogenesis

II. Electroweak Phase Transition

III. EWPT: Models & Phenomenology

IV. CPV for EW Baryogenesis

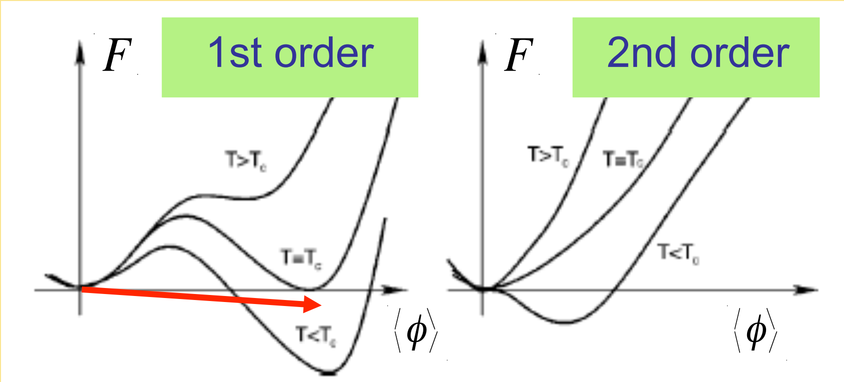
V. Outlook

VI. Back-up Slides:

- *Grav wave - collider interplay*
- *Higgs self-coupling &* σ_{ZH}

I. Electroweak Baryogenesis

EW Phase Transition: BSM Scalars & CPV



Increasing m_h →

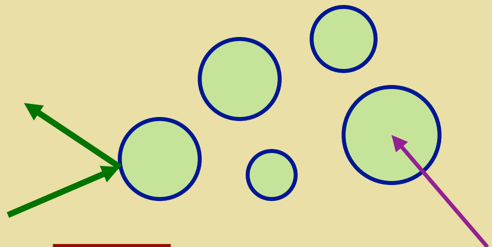
← *New scalars*

Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" *1^{st} order EWPT*

↓

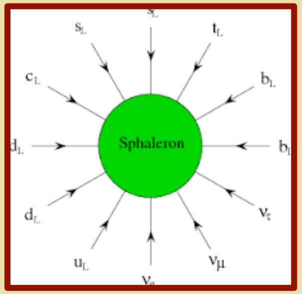
Bubble nucleation



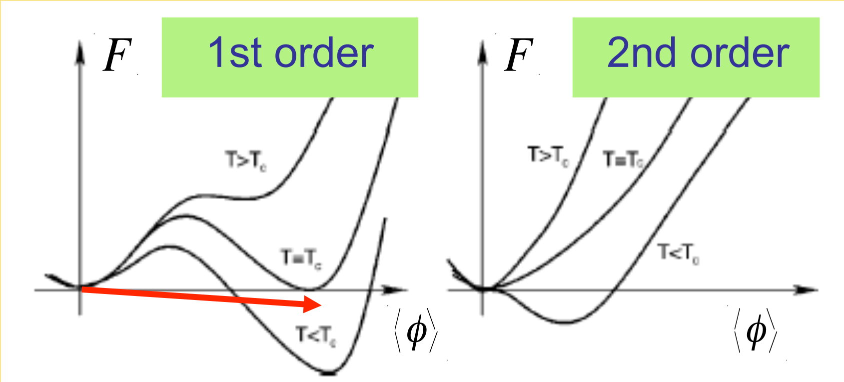
Y_B : CPV & EW sphalerons

EWSB

BSM



EW Phase Transition: BSM Scalars & CPV



Increasing m_h →

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Baryogenesis
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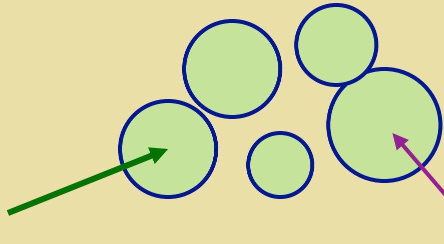
LHC Searches

"Strong" 1^{st} order EWPT

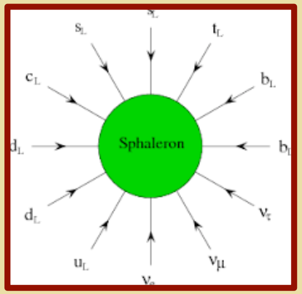
↓

Bubble nucleation

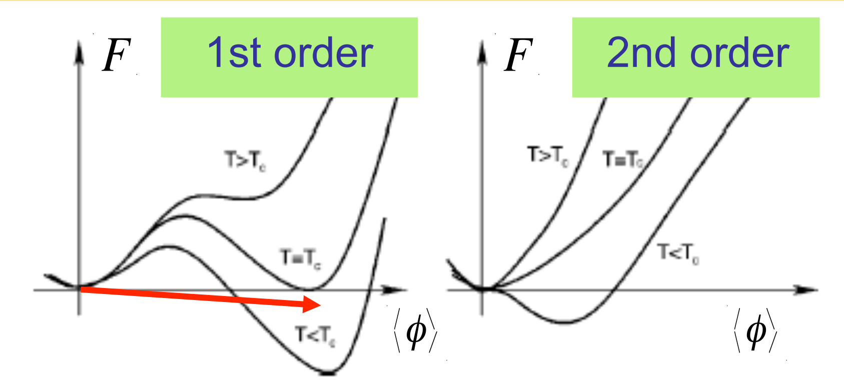


Y_B : diffuses into interiors

EWSB



EW Phase Transition: BSM Scalars & CPV



Increasing m_h →

← *New scalars*

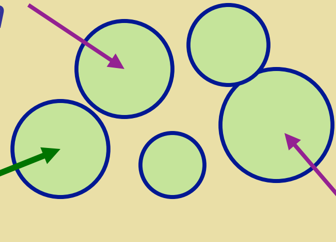
Baryogenesis
Gravity Waves
Scalar DM
LHC Searches

"Strong" 1st order EWPT

Preserve $Y_B^{initial}$

Bubble nucleation

Quench EW sph



Y_B : diffuses into interiors

EWSB

II. EWPT: A Collider Target

MJRM 1912.07189

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

T_{EW} Sets a Scale for Colliders

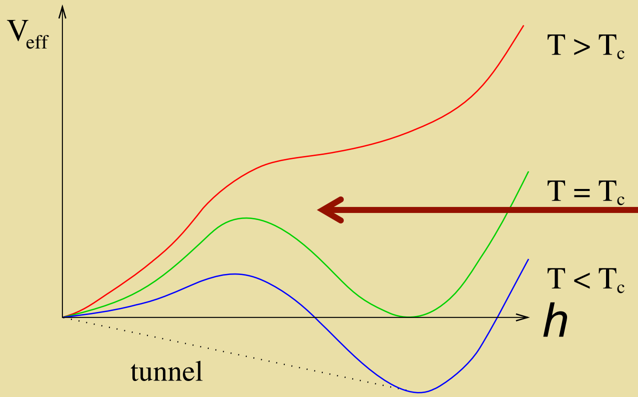
High-T SM Effective Potential

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

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

T_0 ~ 140 GeV **≡ T_{EW}**

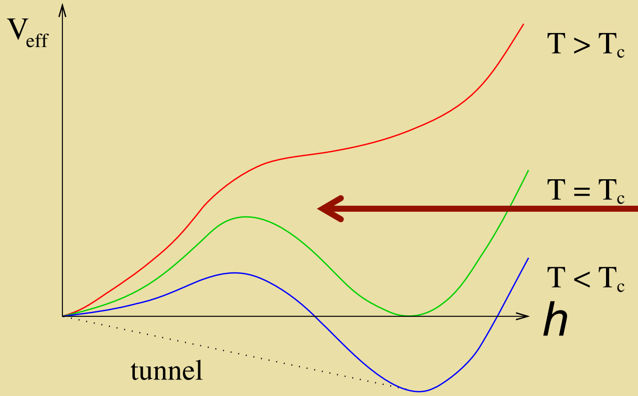
First Order EWPT from BSM Physics



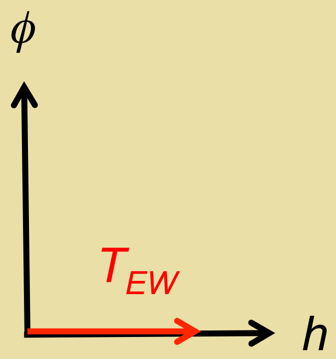
Generate finite-T barrier

Introduce new scalar ϕ interaction with h via the Higgs Portal

First Order EWPT from BSM Physics

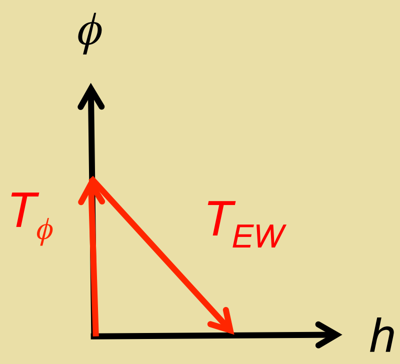


Generate finite-T barrier



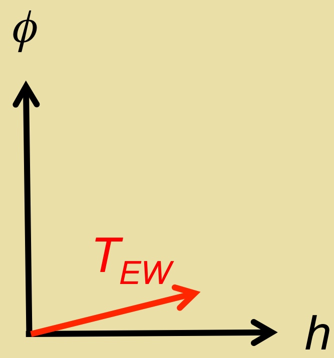
$a_2\, H^2\phi^2$: $T > 0$

loop effect



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

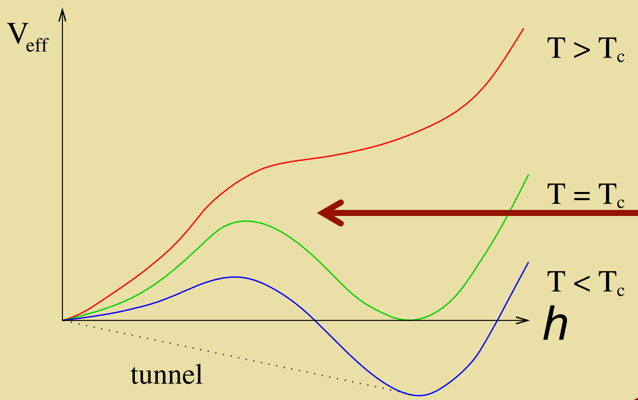
tree-level effect



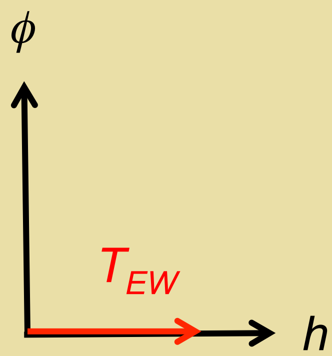
$a_1\, H^2\phi$: $T = 0$

tree-level effect

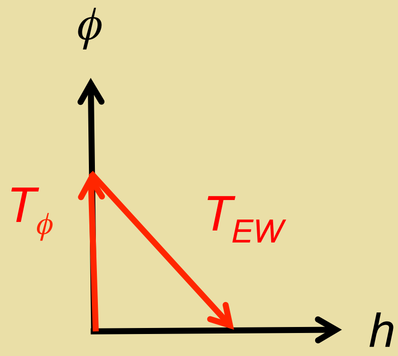
First Order EWPT from BSM Physics



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

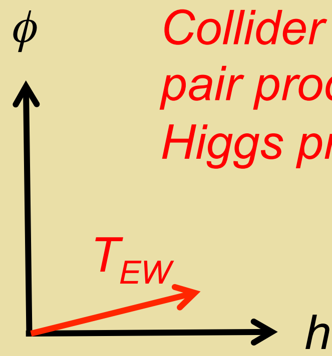


$a_2 H^2\phi^2$: $T > 0$
loop effect



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

Collider Target: ϕ pair production & Higgs precision



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

T_{EW} : Higgs Boson Properties

First Order EWPT from BSM Physics

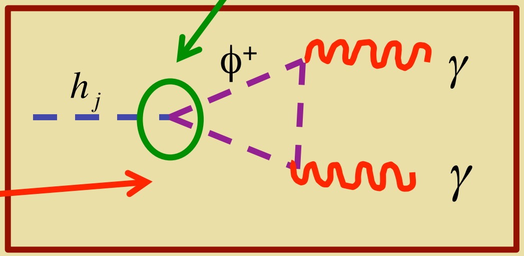
- $\Gamma(h \rightarrow \gamma\gamma)$
- ***Higgs signal strengths***
- ***Higgs self-coupling***
- ***Exotic Decays***

First Order EWPT from BSM Physics

- ***Γ (h → $\gamma\gamma$)***
- ***Higgs signal strengths***
- ***Higgs self-coupling***
- ***Exotic Decays***

$H^2\phi^2$ Barrier ?

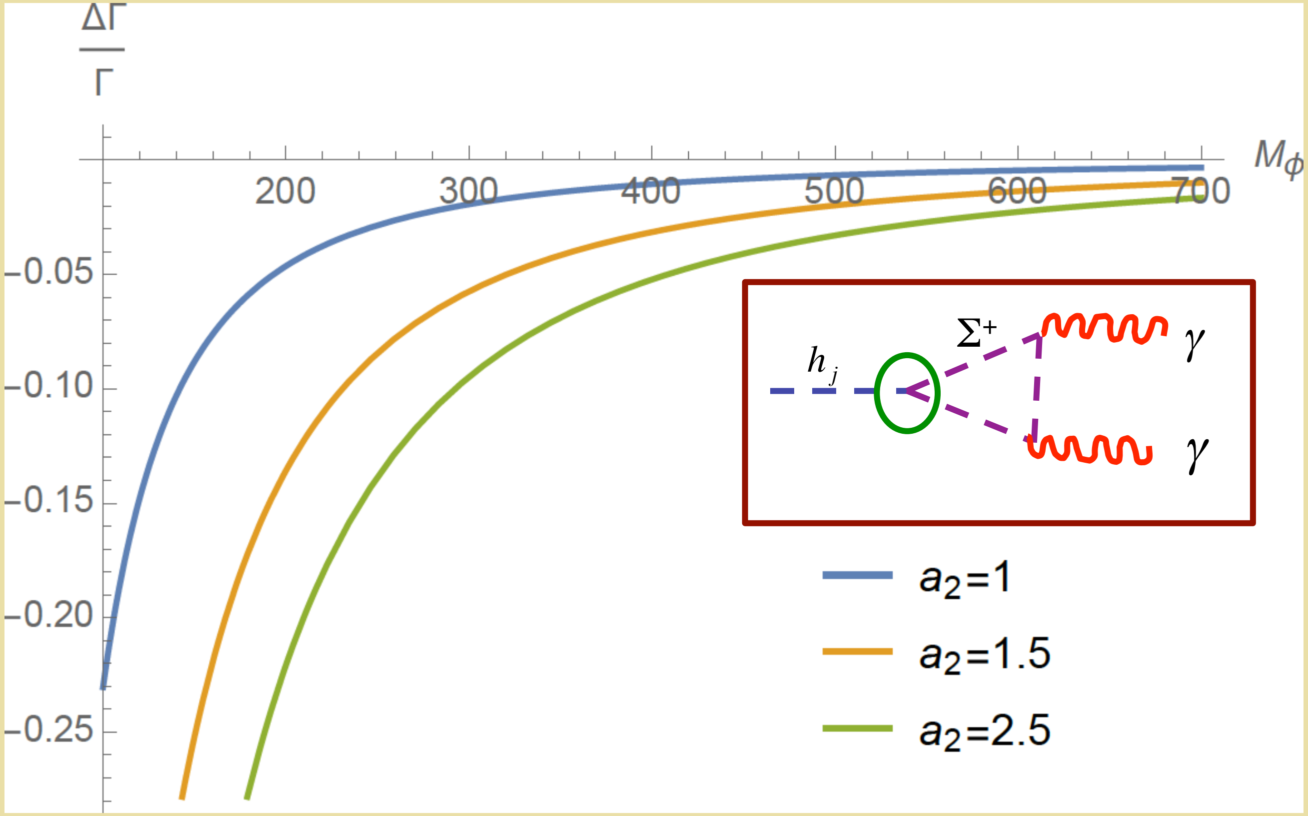
ϕ : EW Multiplet



Collider Target: Precision

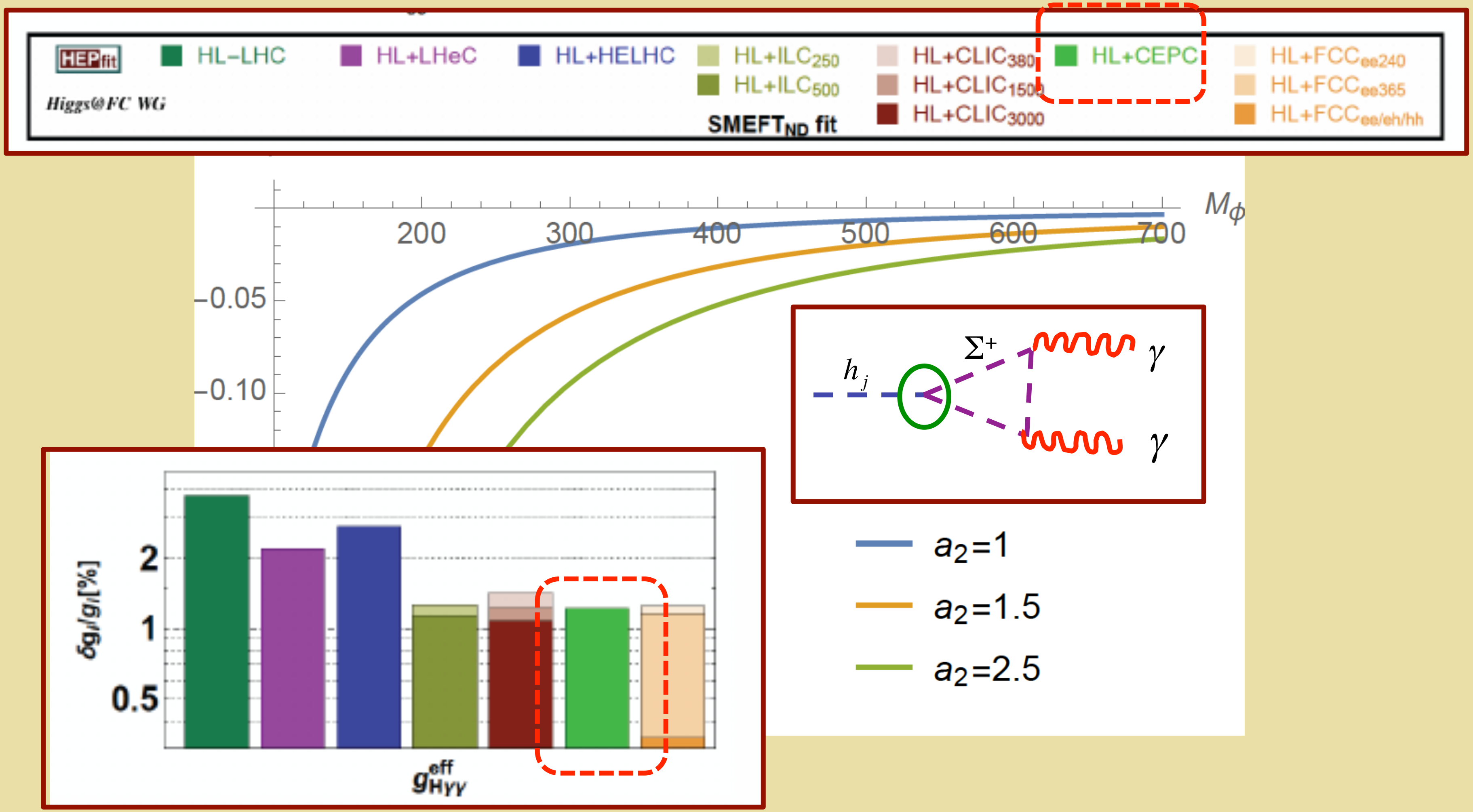
May not have observable ZZH effect

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



EWPT → Decrease in rate

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



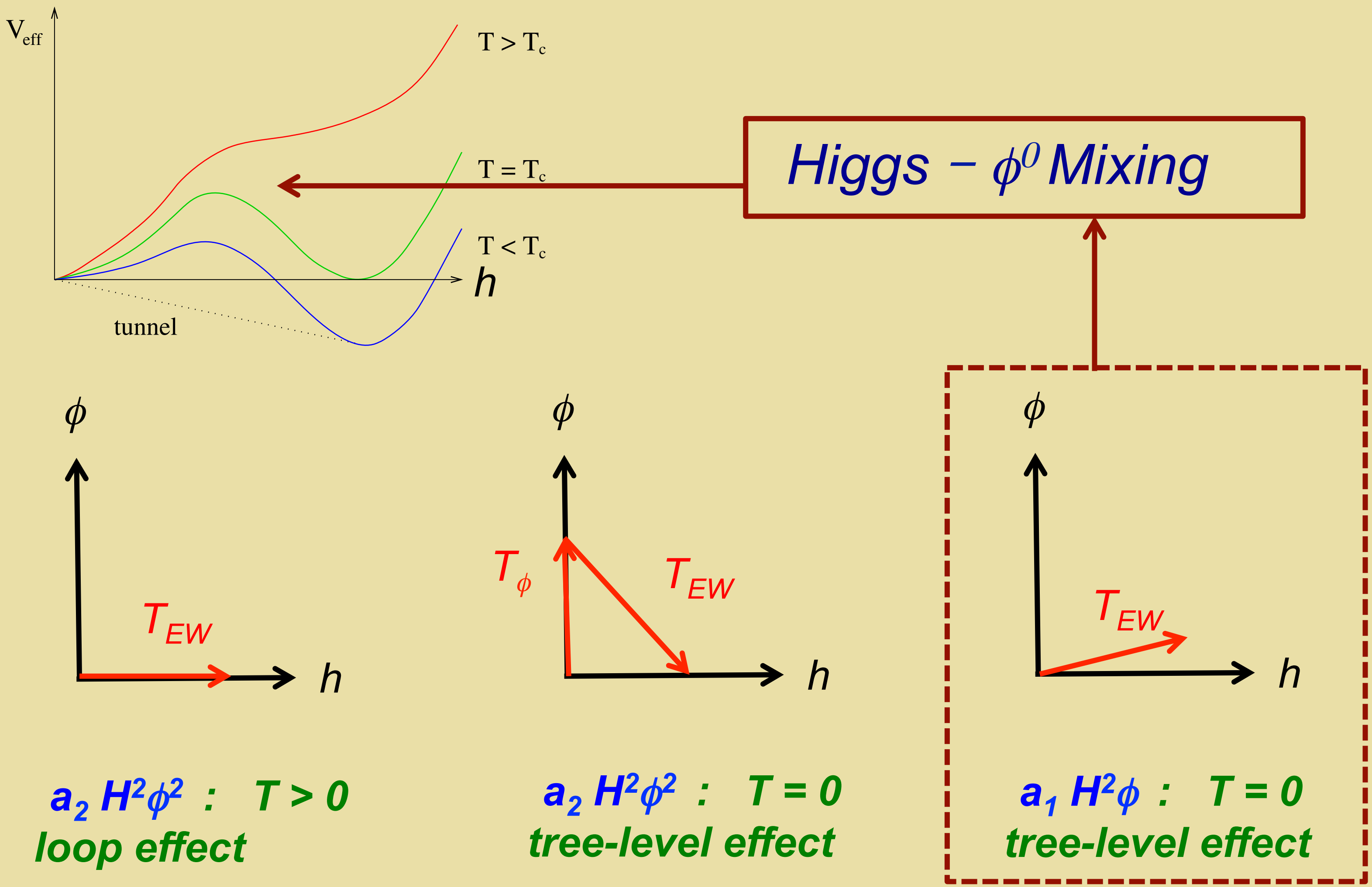
Thanks: M. Cepeda

First Order EWPT from BSM Physics

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

$H^2\phi$ Barrier ?

First Order EWPT from BSM Physics



First Order EWPT from BSM Physics

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

$H^2\phi$ Barrier ?

H-ϕ Mixing

First Order EWPT from BSM Physics

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

Collider Target: Precision and single ϕ production*

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

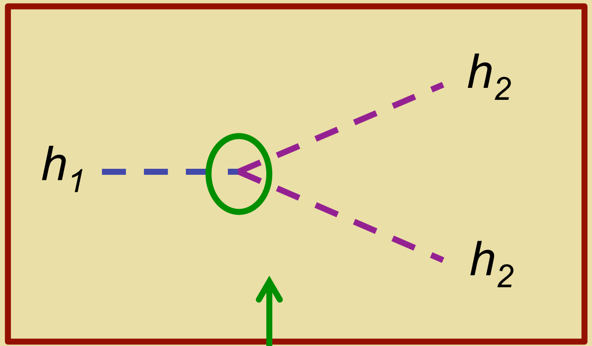
$$|\sin\theta| \gtrsim 0.01$$

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

** Note scale for ZZh coupling deviation*

First Order EWPT from BSM Physics

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



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

* *Visible or invisible*

III. EWPT: Models & Phenomenology

Model Illustrations

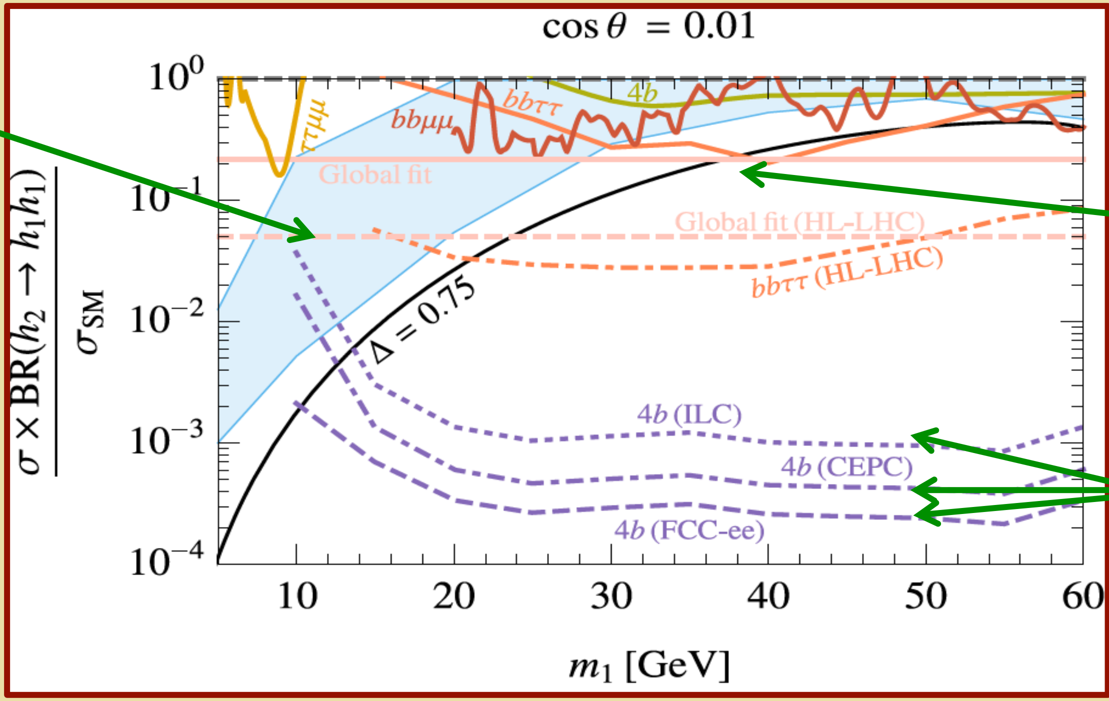
Simple Higgs portal models:

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

Light Singlets: Exotic Decays

$h_2 \rightarrow h_1 h_1 \rightarrow 4b$

EWPT viable: numerical



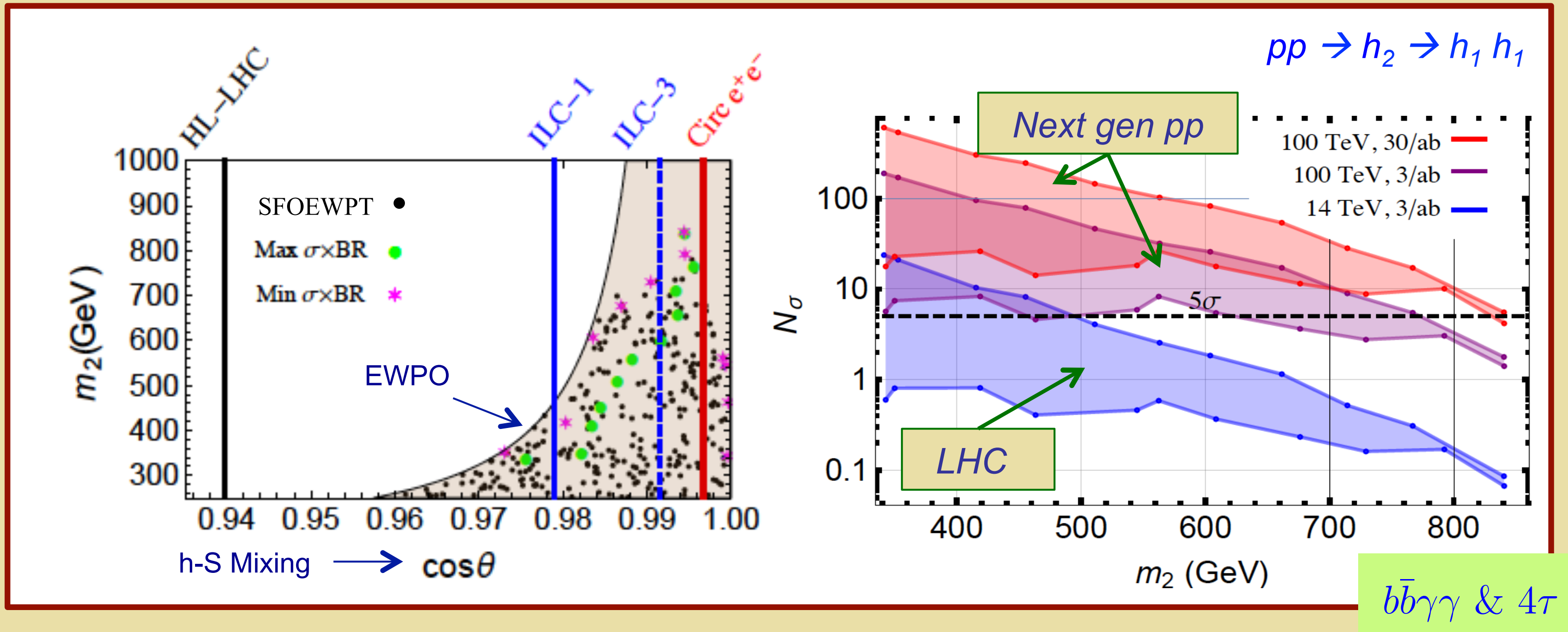
EWPT viable: Semi analytic

Future e^+e^-

J. Kozaczuk, MR-M, J. Shelton 1911.10210
See also: Carena et al 1911.10206

Singlets: Precision & Res Di-Higgs Prod

SFOEWPT Benchmarks: Resonant di-Higgs & precision Higgs studies



Kotwal, No, R-M, Winslow 1605.06123

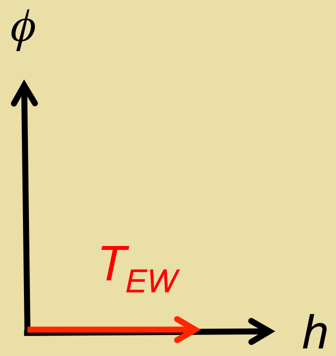
See also: Huang et al, 1701.04442;
Li et al, 1906.05289

Model Illustrations

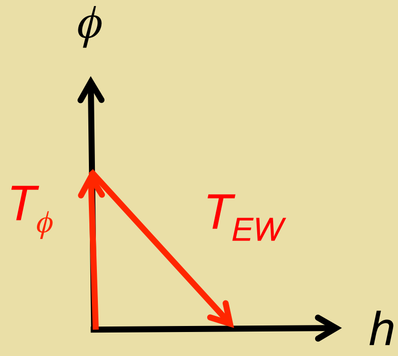
Simple Higgs portal models:

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

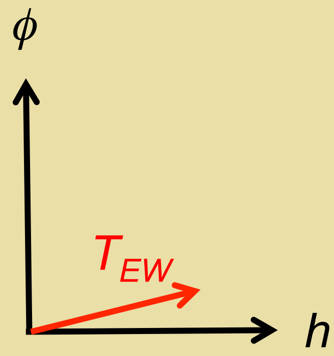
Real Triplet



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



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



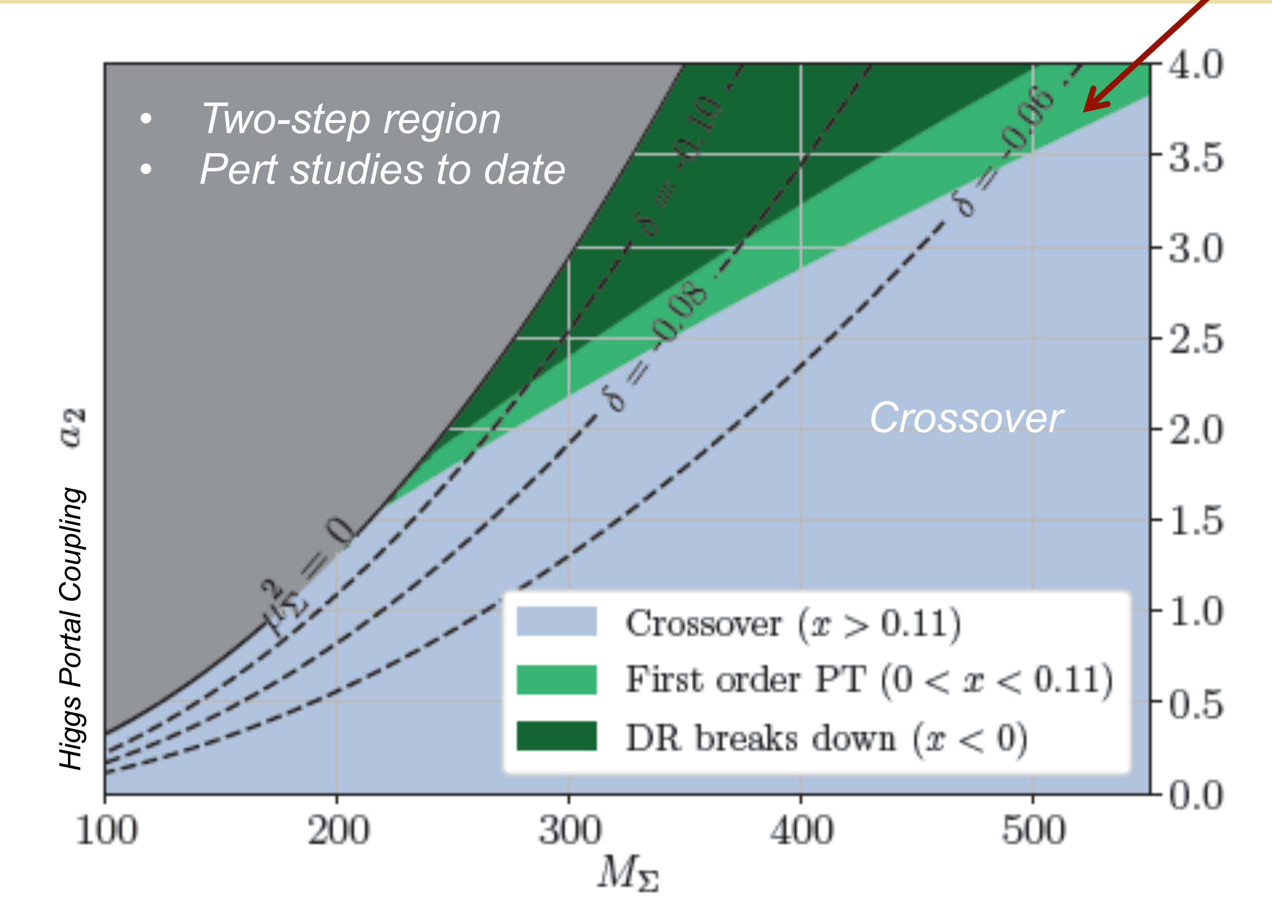
$a_1\, H^2\phi$: $T = 0$
tree-level effect

Non-perturbative results

EW precision tests → too tiny

Real Triplet: One-Step EWPT

FOEWPT

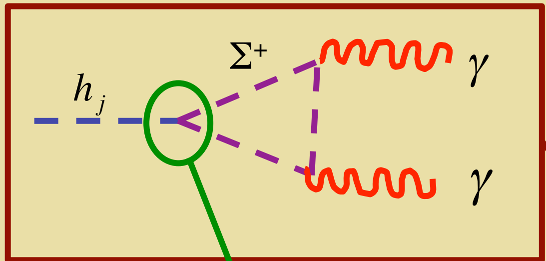


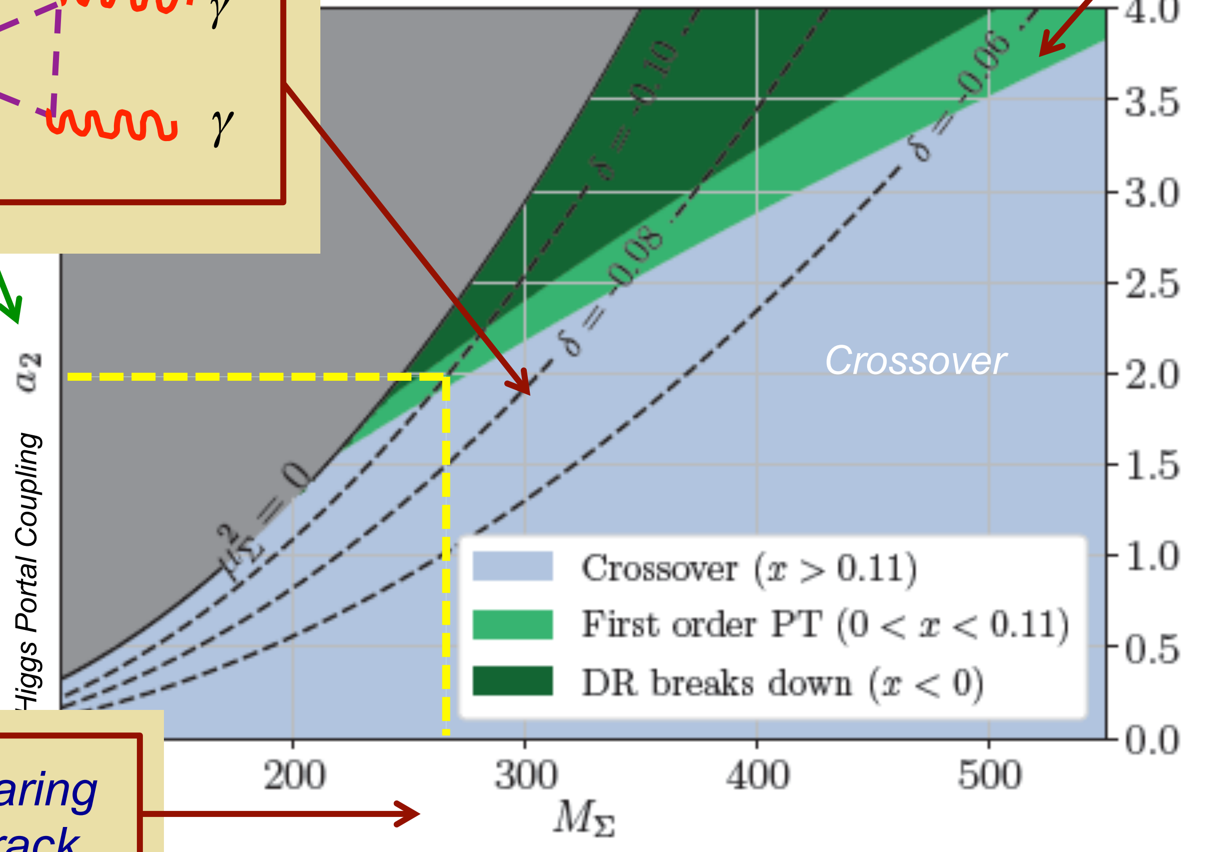
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

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

Real Triplet & EWPT

FOEWPT





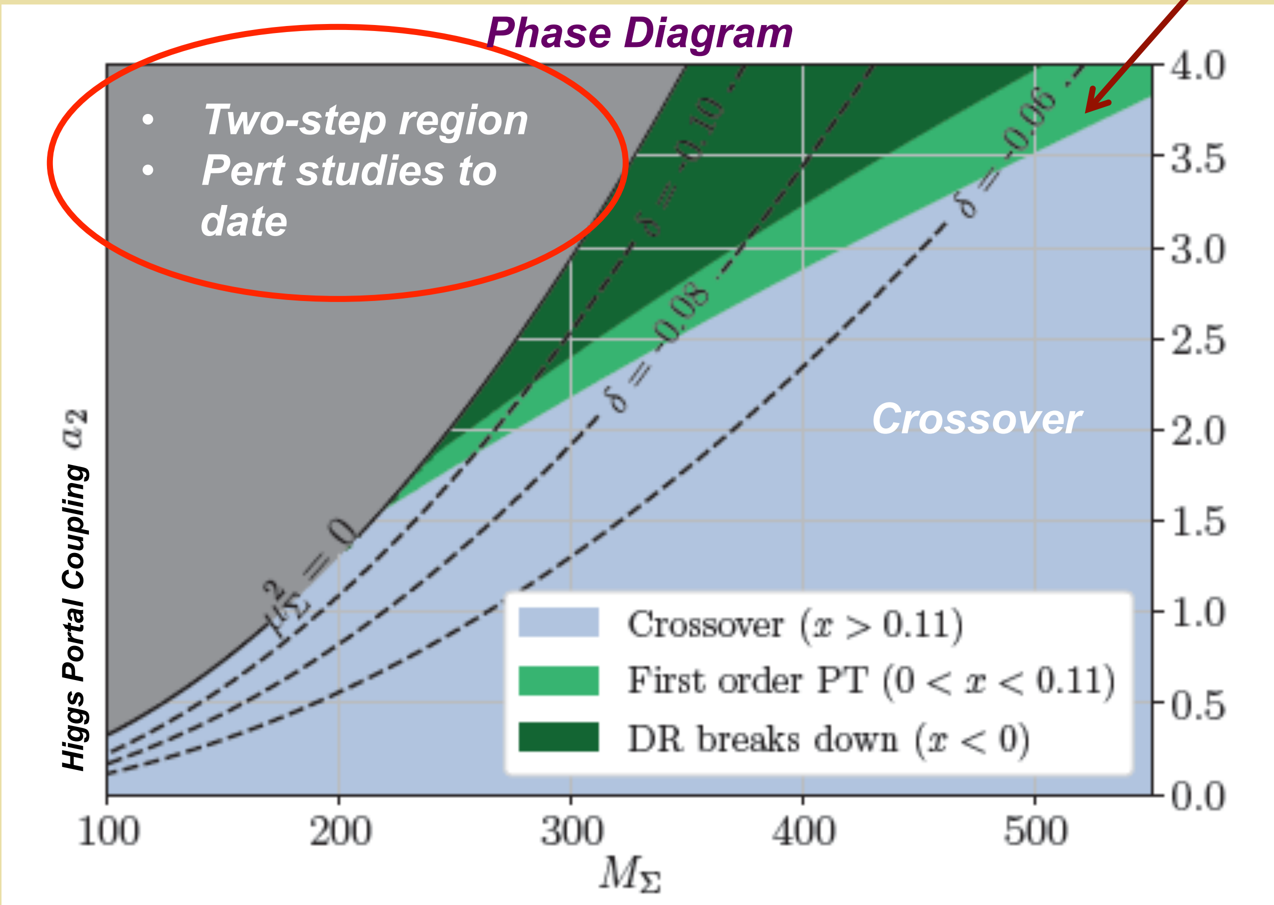
Disappearing charge track

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

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

Real Triplet & EWPT: Novel EWSB

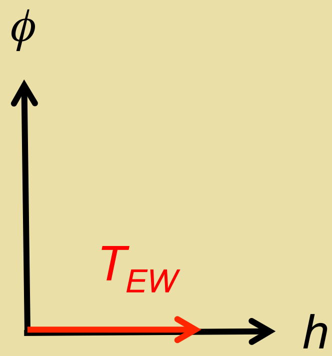
FOEWPT



- One-step
- Non-perturbative

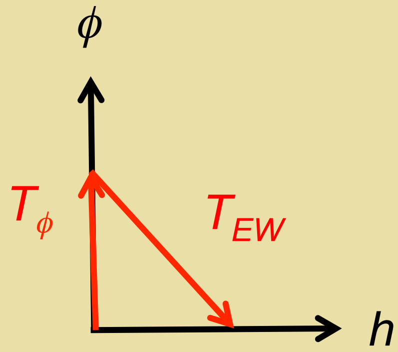
Niemi, Patel, R-M, Tenkanen, Weir 1802.10500

Real Triplet



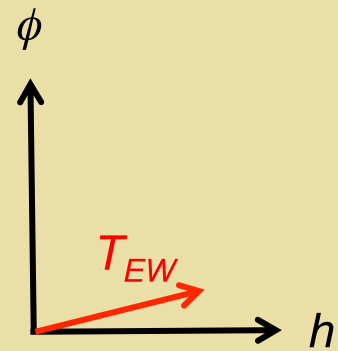
$a_2 H^2\phi^2$: $T > 0$

loop effect



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

tree-level effect



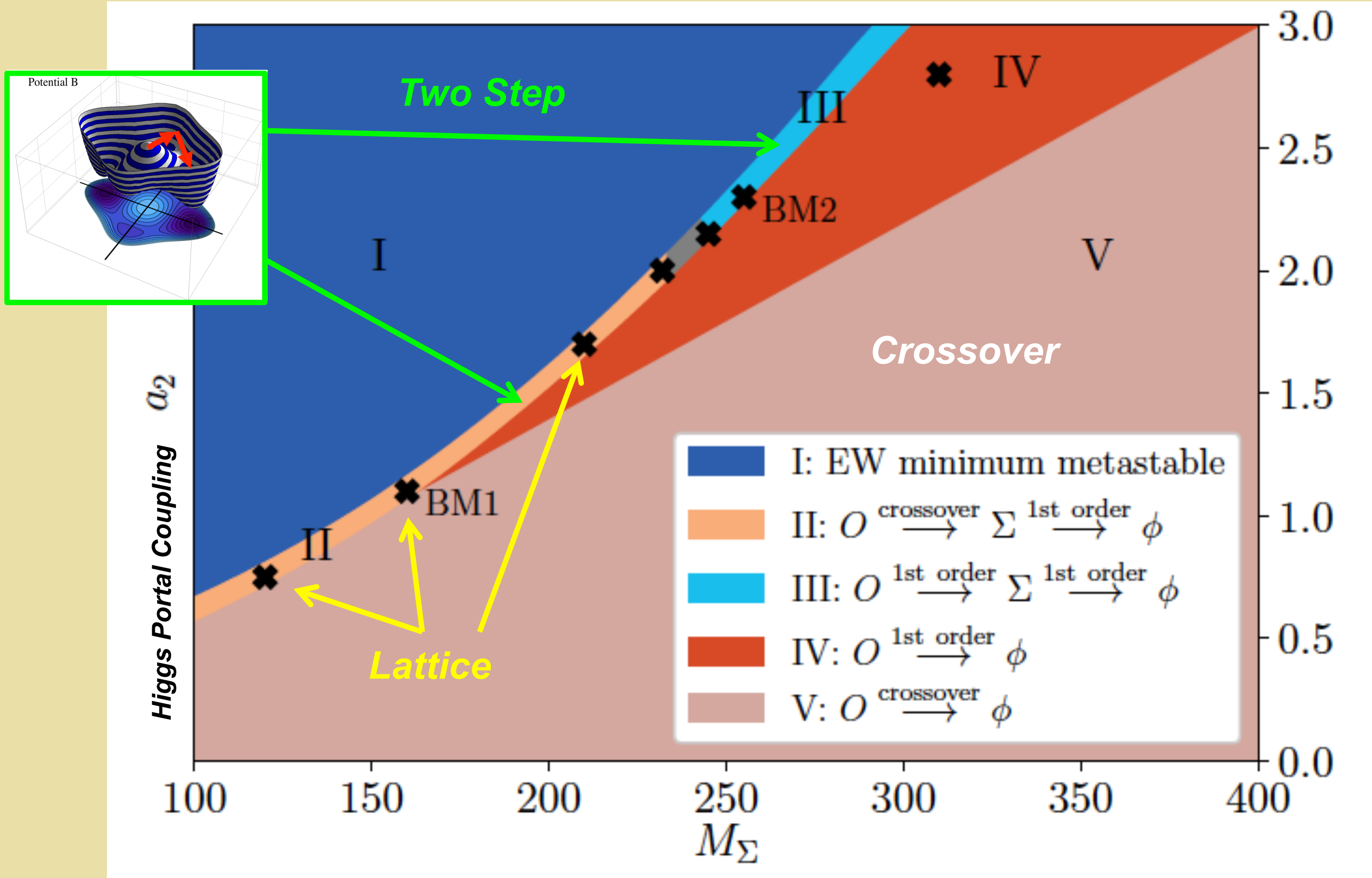
$a_1 H^2\phi$: $T = 0$

tree-level effect

Non-perturbative results

EW precision tests → too tiny

Real Triplet & EWPT: Novel EWSB



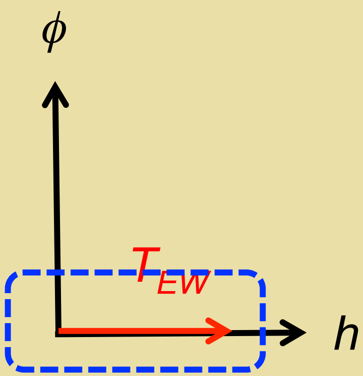
Niemi, R-M, Tenkanen, Weir 2005.11332

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

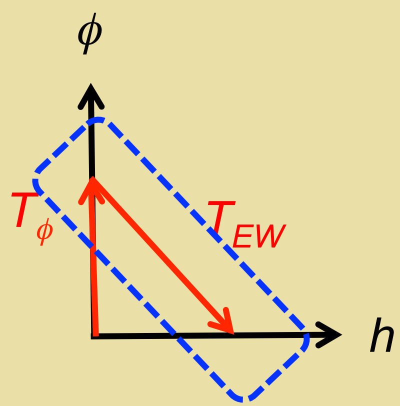
IV. CPV for EW Baryogenesis

EWSB Scenarios & CPV

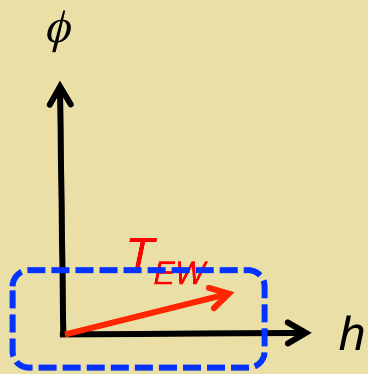
- *BAU generated by CPV during first order transition to Higgs phase*
- *Stringent constraints from EDM searches*



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



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



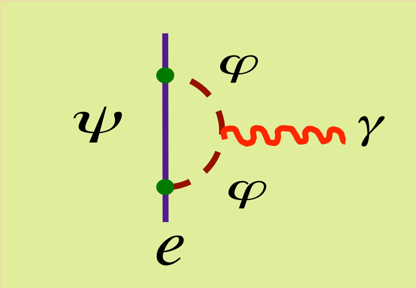
$a_1\ H^2\phi$: $T = 0$
tree-level effect

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
ThO	1.1×10^{-29} **	10^{-38}	10^{-29}
n	1.8×10^{-26}	10^{-31}	10^{-26}

* 95% CL ** e^- equivalent

Mass Scale Sensitivity



$\sin\phi_{CP} \sim 1 \rightarrow$ M > 5000 GeV

M < 500 GeV $\rightarrow \sin\phi_{CP} < 10^{-2}$

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	7.4×10^{-30}	10^{-35}	10^{-30}
ThO	1.1×10^{-29} **	10^{-38}	10^{-29}
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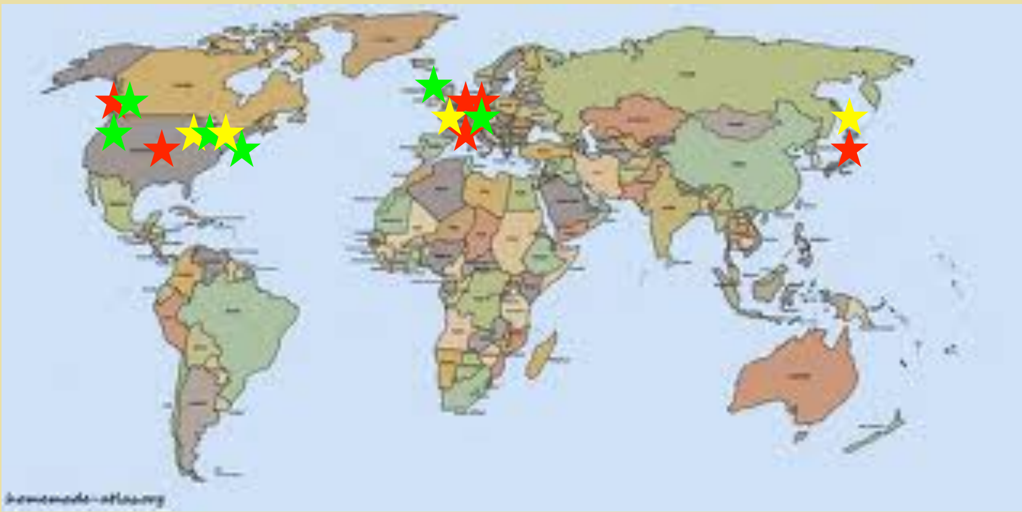


★ neutron

★ proton & nuclei

★ atoms

~ 100 x better sensitivity

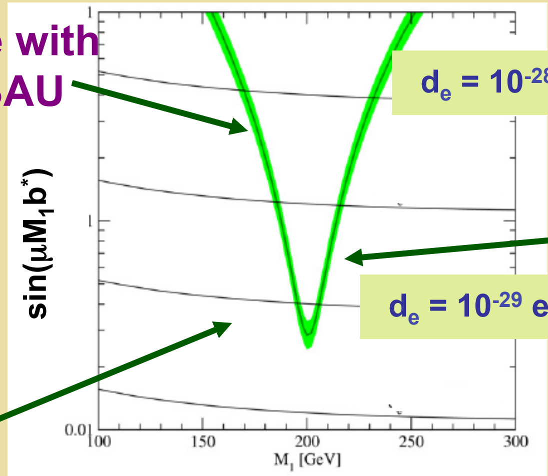
Not shown: muon

EDMs & EW Baryogenesis: SUSY

Electron EDM

Compatible with observed BAU

Previous d_e



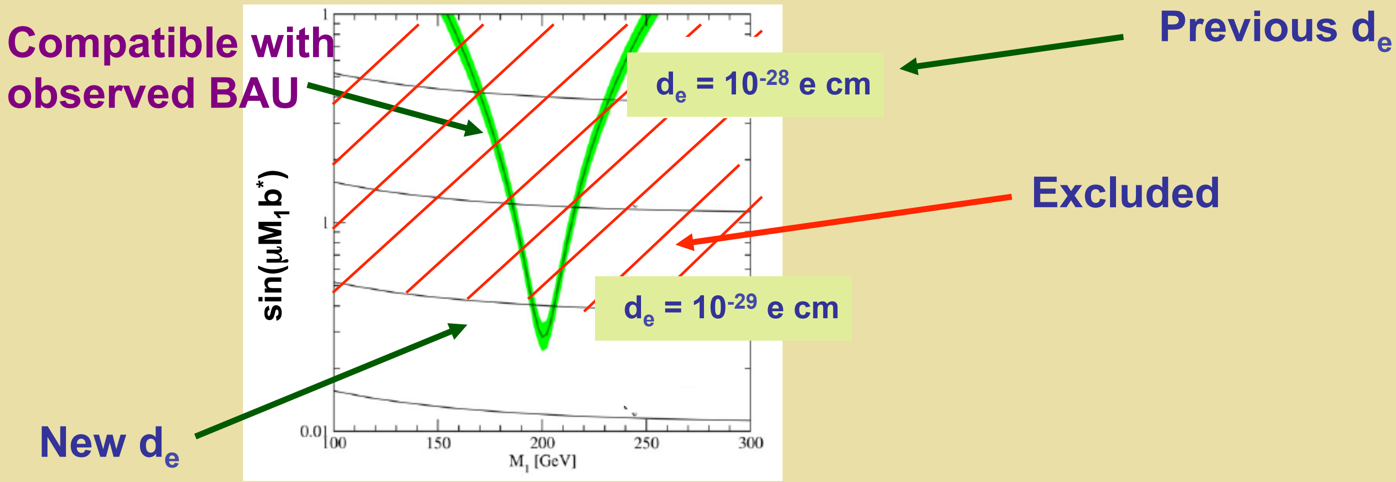
Compressed spectrum (stealthy SUSY)

New d_e

Li, Profumo, RM '09-'10

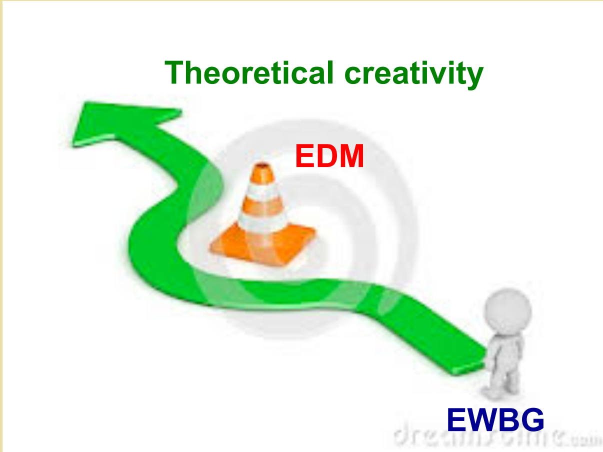
EDMs & EW Baryogenesis: SUSY

Electron EDM

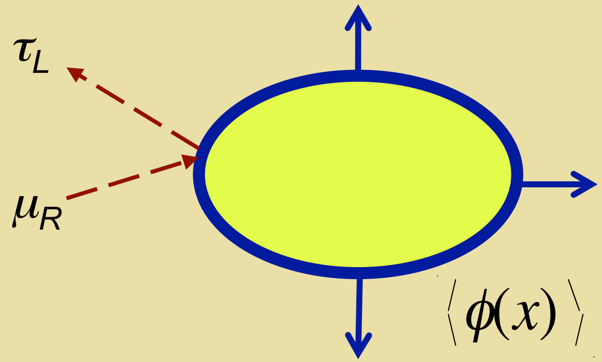


Li, Profumo, RM '09-'10

CPV for EWBG



Flavored EW Baryogenesis



Type III 2HDM

Jarlskog invariant

$$J_A = \frac{1}{v^2 \mu_{12}^{\mathrm{HB}}} \sum_{a,b,c=1}^{2} v_a v_b^* \mu_{bc} \mathrm{Tr}\left[Y_c Y_a^\dagger\right]$$

T=0 Higgs couplings

Im (y_τ) ~ Im (J_A)

EWBG CPV Source

S^{CPV} ~ Im (J_A)

Flavor basis (high T)

$$\mathscr{L}_{\mathrm{Yukawa}}^{\mathrm{Lepton}} = -\overline{E_L^i}\left[(Y_1^E)_{ij}\Phi_1 + (Y_2^E)_{ij}\Phi_2\right] e_R^j + h.c.$$

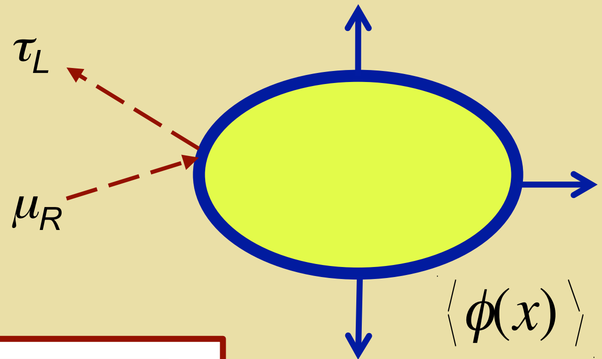
Mass basis (T=0)

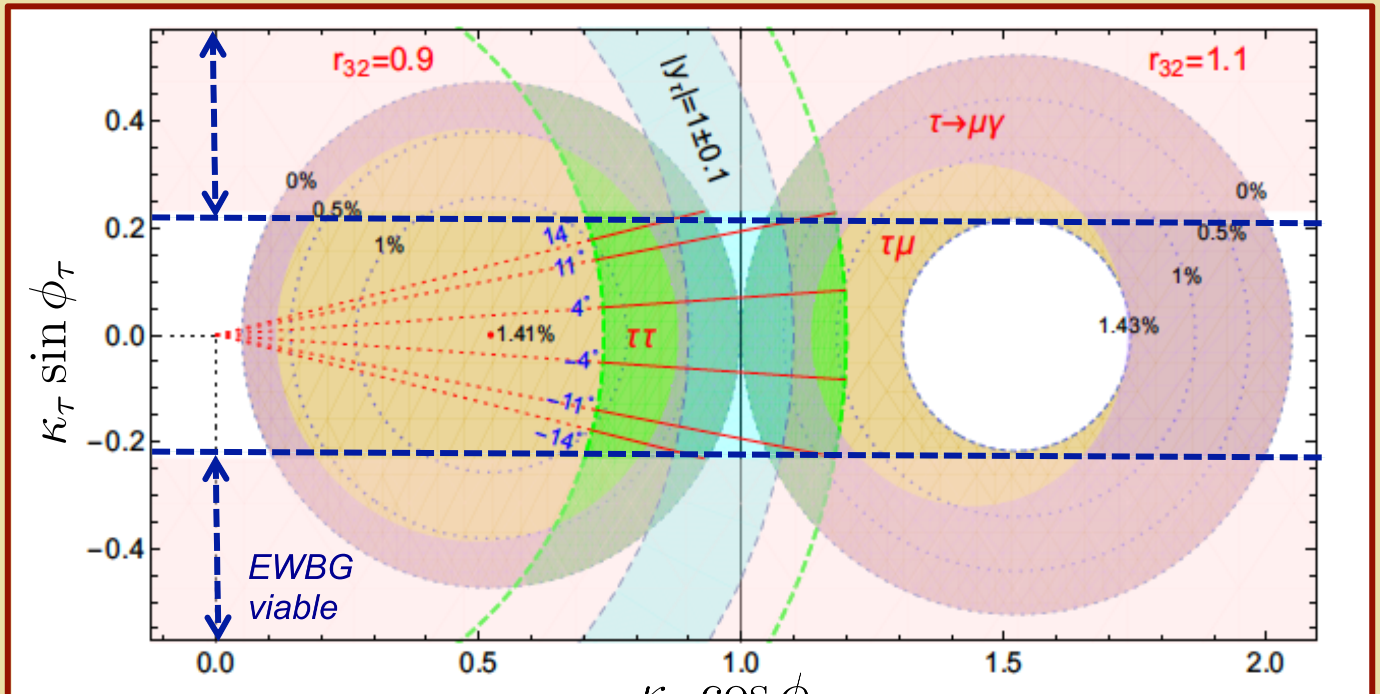
CPV $h \rightarrow \tau\tau$

$$\frac{m_f}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau)h$$

Guo, Li, Liu, R-M, Shu 1609.09849
Chiang, Fuyuto, Senaha 1607.07316

Flavored EW Baryogenesis





Guo, Li, Liu, R-M, Shu 1609.09849

$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14

CPV in $h \to \tau\tau$

PHYSICAL REVIEW D **88,** 076009 (2013)

Measuring *CP* violation in $h \to \tau^+\tau^-$ at colliders

Roni Harnik,[1] Adam Martin,[2,3] Takemichi Okui,[4] Reinard Primulando,[5] and Felix Yu[1]

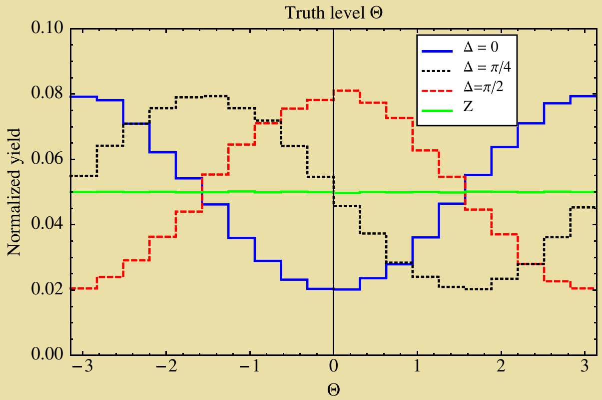
$h \to \tau^+ \tau^-$

$\tau^- \to \rho^- \nu$

$\rho^- \to \pi^- \pi^0$

CPV in h → ττ

Study cos (2Δ − Θ) distribution



$\Delta\phi_\tau \sim 10^o$:

3 ab^{-1} @ LHC 14

What about CEPC?

S.-F. Ge, G. Li, P. Pasquini, MJRM 2008.NNNNN

ILC 250

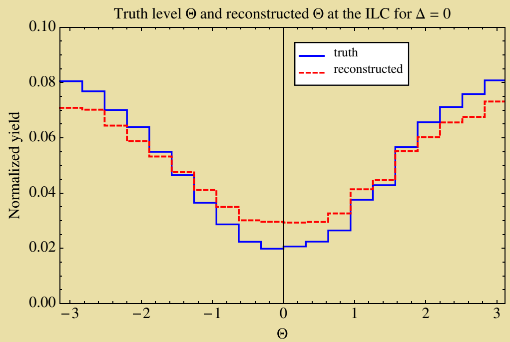


TABLE I. Cross section, branching fractions, expected number of signal events, and accuracy for measuring Δ for the ILC with $\sqrt{s}$ = 250 GeV and 1 ab^{-1} integrated luminosity.

$\sigma_{e^+e^-\to hZ}$	0.30 pb
$Br(h \to \tau^+\tau^-)$	6.1%
$Br(\tau^- \to \pi^-\pi^0\nu)$	26%
$Br(Z \to \text{visibles})$	80%
N_{events}	990
Accuracy	4.4°

Stat only

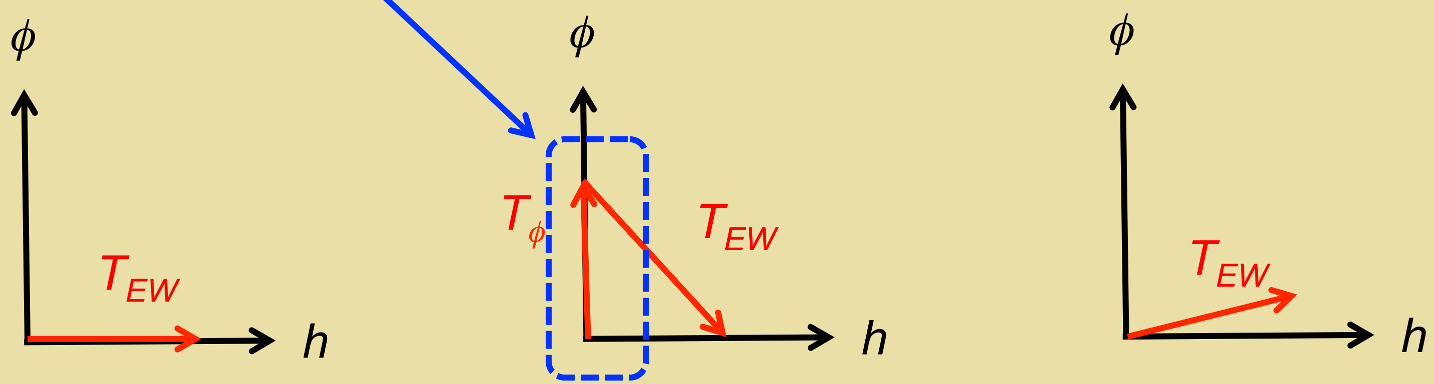
EWSB Scenarios & CPV

- *BAU generated by CPV during first order transition to the ϕ phase → subsequently transferred to Higgs phase*

"Two Step EW Baryogenesis"

- *Inoue, Ovaneysan, MJRM 1508.05404 [CPV]*
- *H. Patel, MJRM 1212.5652*
- *Blinov, Kozaczuk, Morrissey, Tamarit 1504.05195*

"Partially secluded CPV" → evade EDM bounds



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

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

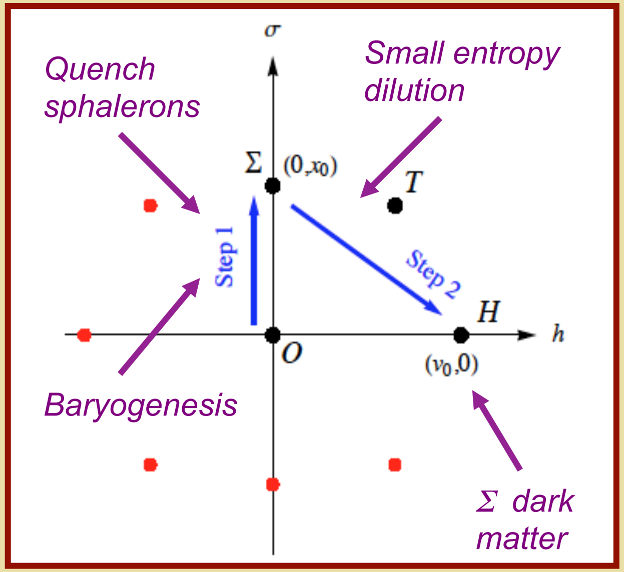
$a_1 H^2\phi$: $T = 0$
tree-level effect

Illustrative Model: Singlets + Triplets

$$M^2 = \begin{pmatrix} m_{11}^2 & m_{12}^2 \\ m_{12}^{2*} & m_{22}^2 \end{pmatrix}$$

CPV: $\theta = Arg\,(m_{12}^2) = \theta(x)$

$m_{12}^2 = a\, v_\Sigma(x) + b\, v_S(x)$



CPV asymmetry generated in SM sector via interactions with the ϕ_j

- *New sector: real triplet (Σ) & real singlet (S)*
- *SM Sector: Z_2 symmetric 2HDM*

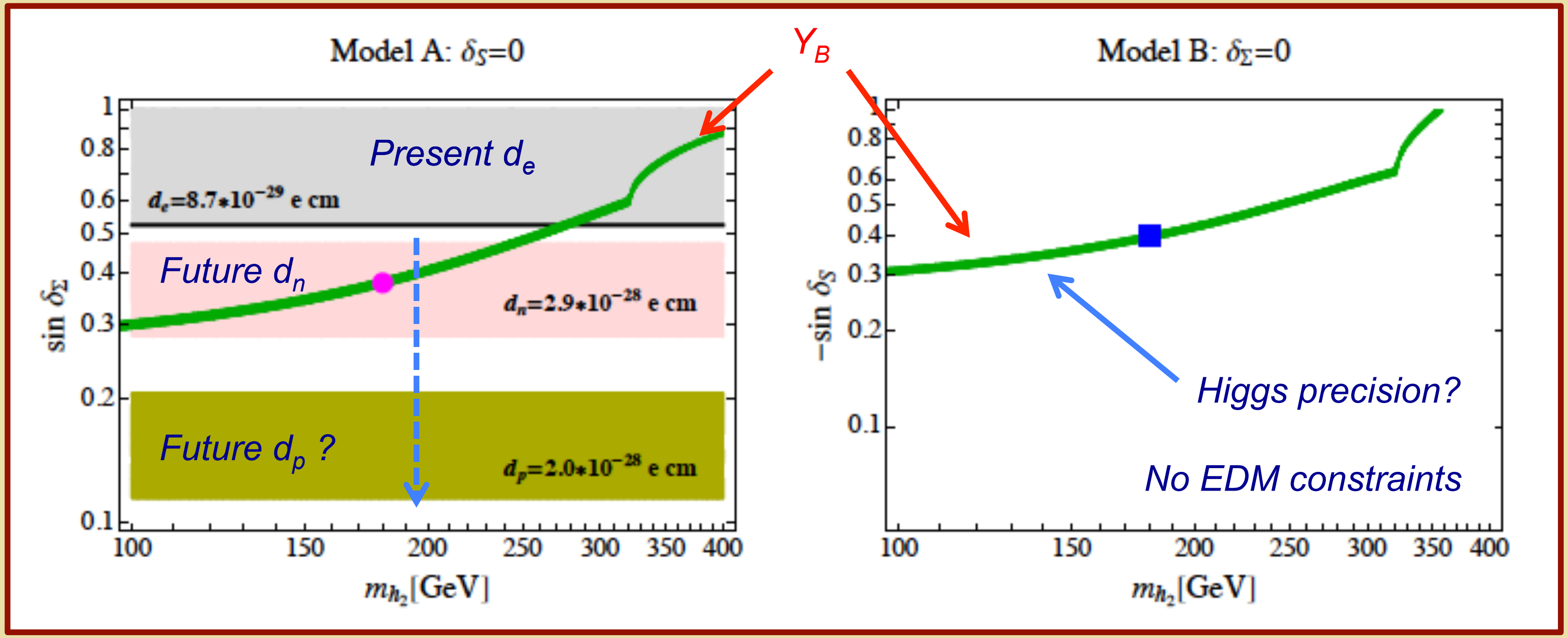
$V(H_1, H_2, \Sigma, S)$ *CPV: $H_1 - H_2$ mixing*

$$= -\frac{\mu_\Sigma^2}{2}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{b_{4\Sigma}}{4}\left(\vec{\Sigma}\cdot\vec{\Sigma}\right)^2 + \frac{b_{2S}}{2}S^2 + \frac{b_{4S}}{4}S^4$$
$$+ \left[\frac{1}{2}a_{2\Sigma} H_1^\dagger H_2 \left(\vec{\Sigma}\cdot\vec{\Sigma}\right) + \frac{1}{2}a_{2S} H_1^\dagger H_2 S^2 + \text{h.c.}\right],$$
$$+ a_{1\Sigma S}\vec{\Sigma}\cdot\vec{\Sigma}\, S + \frac{1}{2}a_{2\Sigma S}\vec{\Sigma}\cdot\vec{\Sigma}\, S^2 + V(H_1, H_2)\,. \quad (5)$$

Inoue, Ovaneysan, MJRM 1508.05404

Two-Step EW Baryogenesis & EDMs

Two cases: (A) $\delta_S = 0$ (B) $\delta_\Sigma = 0$



Inoue, Ovanesyan, R-M: 1508.05404

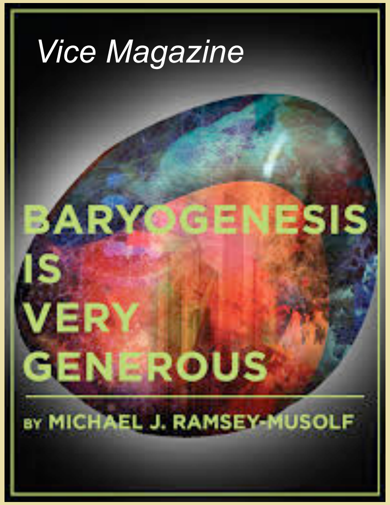
IV. Outlook

- *Generation of the cosmic matter-antimatter asymmetry in conjunction with EWSB -- EW baryogenesis -- is one of the most compelling possibilities*
- *The existence of the scale T_{EW} → BSM ingredients for EWBG are experimentally accessible*
- *There exists a high level of complementarity between experimental probes at the energy frontier, precision Higgs boson studies, and low-energy symmetry tests → exciting opportunities for the CEPC !*
- *A rich opportunities exist for further experimental and theoretical exploration and refined theoretical computations*

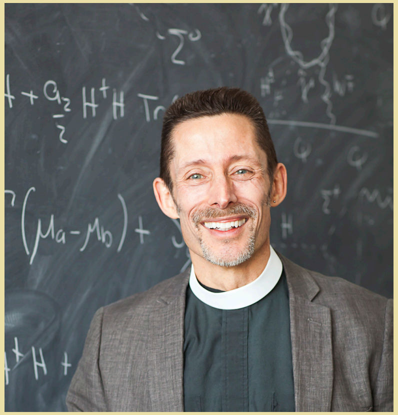
Michael Ramsey-Musolf

Chair Professor, SJTU & T.D. Lee Professor, TDLI
Professor & Director, ACFI, U. Mass Amherst

Theoretical Physics



谢谢

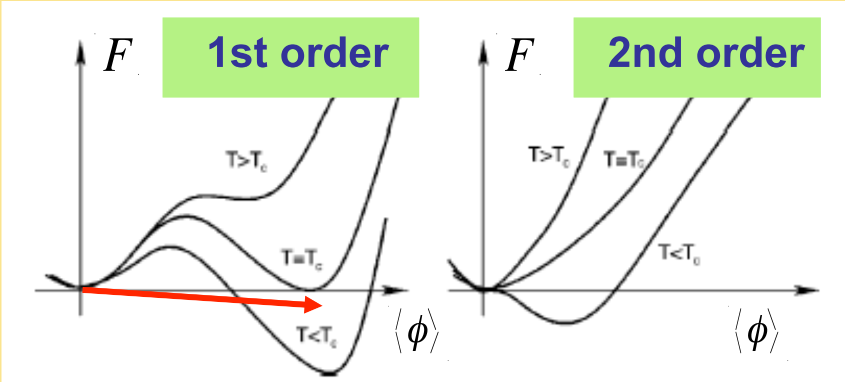


- *Ph.D. Princeton*
- *Post-doc MIT*
- *美国 → 中国 2019*

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

Back Up Slides

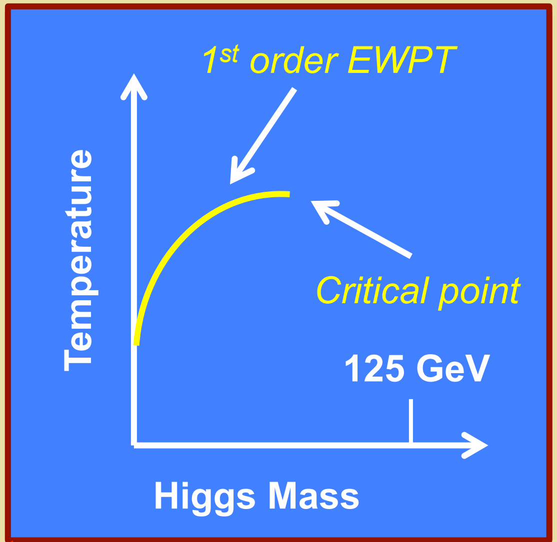
EW Phase Transition: St'd Model



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



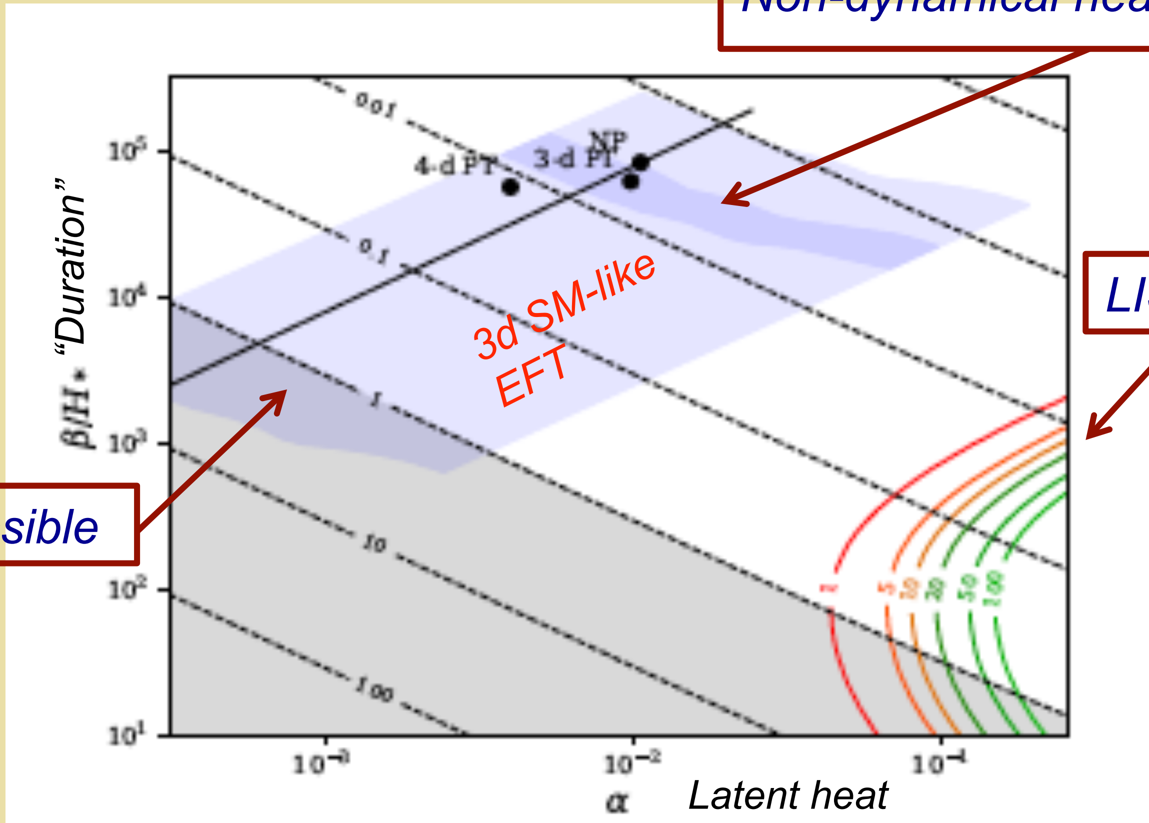
EW Phase Diagram

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

Gravitational Waves

Heavy Real Singlet: EWPT & GW

Non-dynamical heavy BSM scalars



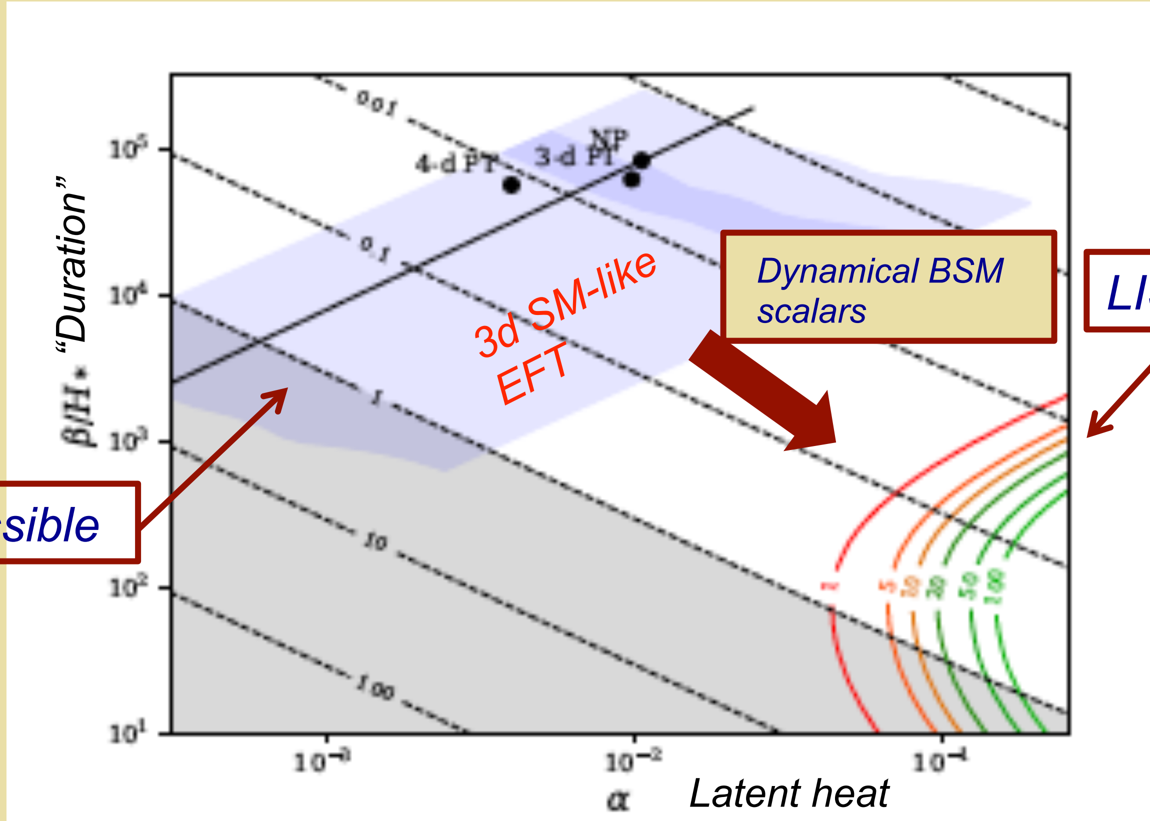
LISA SNR

Collider accessible

- One-step
- Non-perturbative

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

Heavy Real Singlet: EWPT & GW



LISA SNR

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

- One-step
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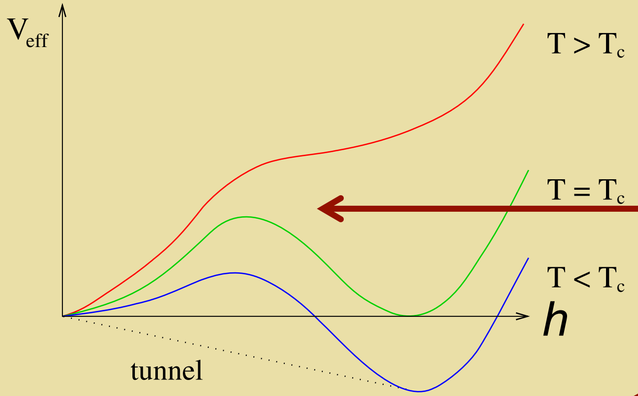
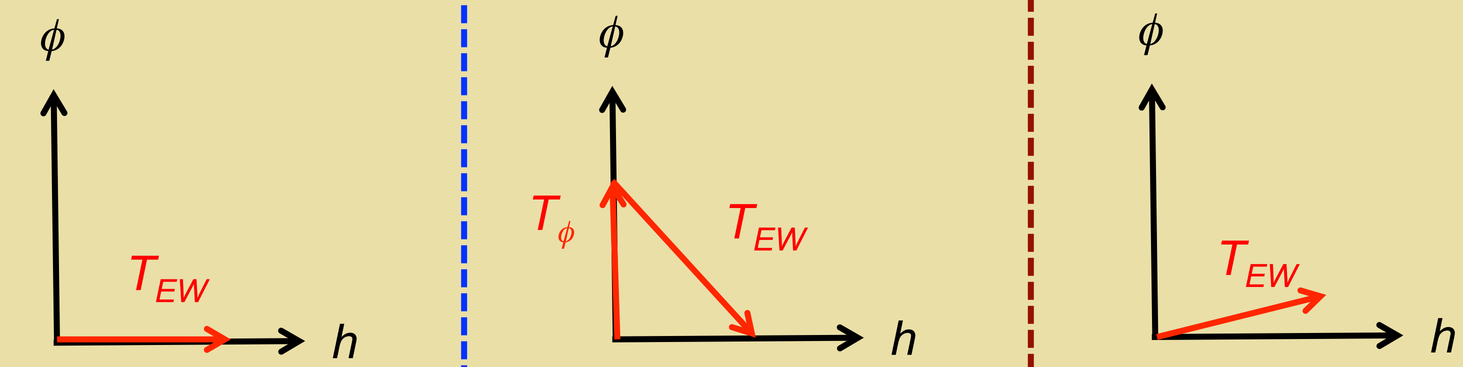
Mass Bound

First Order EWPT from BSM Physics



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

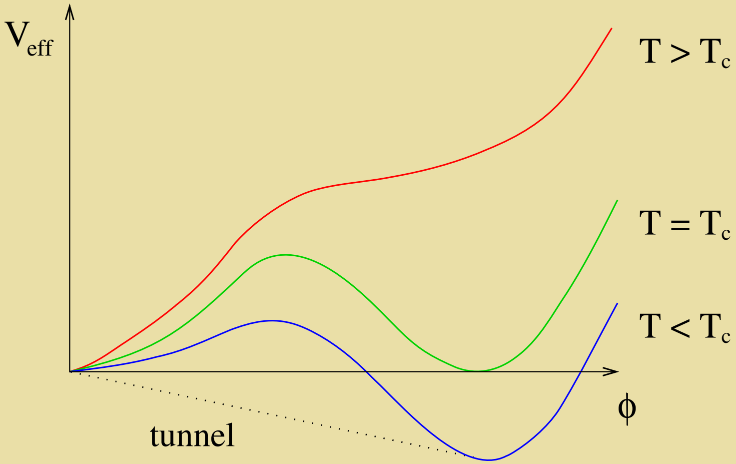


$a_2\, H^2\phi^2$: $T > 0$
loop effect

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

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

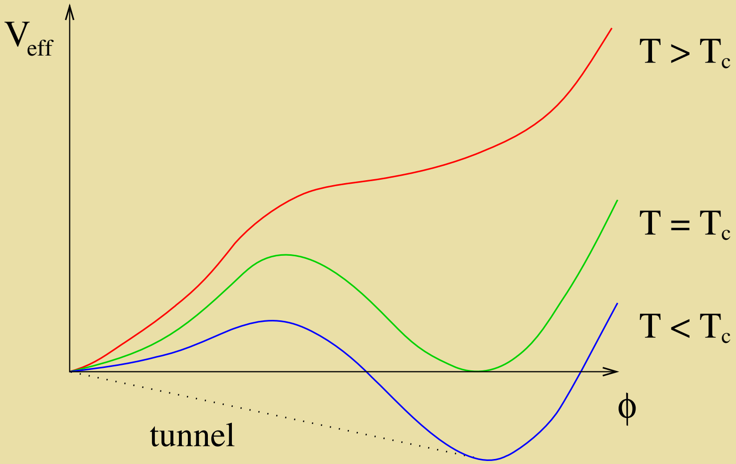
First Order EWPT from BSM Physics



$$\Delta V(h,T) \supset -\frac{T}{12\pi} M_\phi(h,T)^3$$

$$M_\phi(h,T)^3 = \left[\frac{a_2}{6}T^2 + b_2 + \frac{a_2}{2}h^2\right]^{3/2}$$

First Order EWPT from BSM Physics



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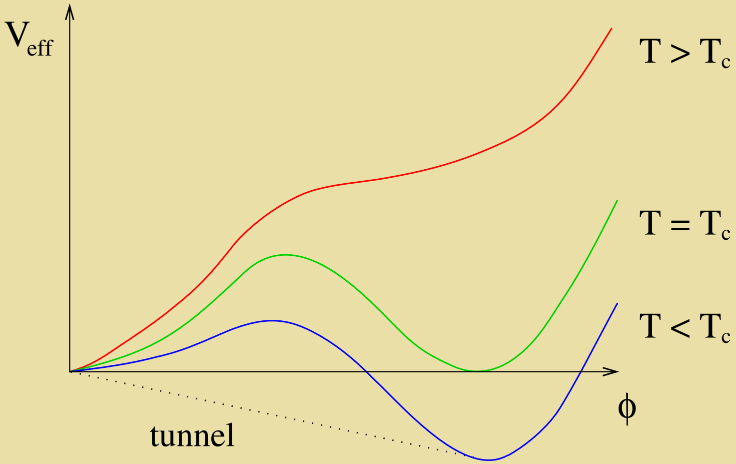
Choose b_2 , a_2 to cancel at $T \sim T_{EW}$

First Order EWPT from BSM Physics



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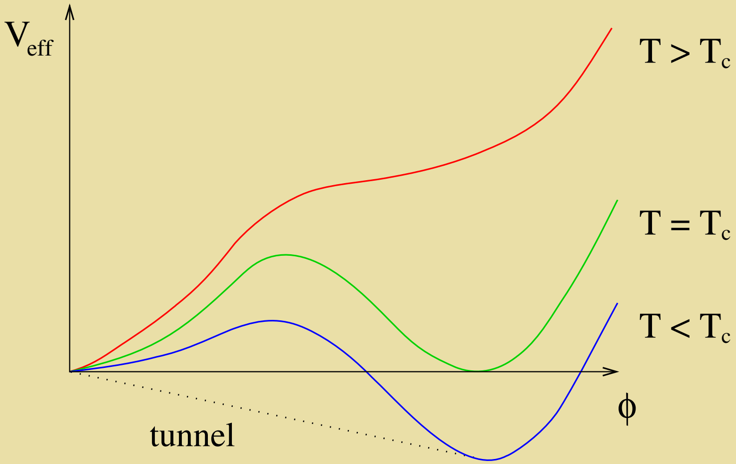
$$\Delta V(h,T_{\rm EW}) \supset -\frac{T_{\rm EW}}{12\pi}\frac{a_2^{3/2}}{2\sqrt{2}}h^3$$

$$M_\phi(T=0)^2 = \frac{a_2}{2}\left(v^2 - T_{\rm EW}^2/3\right)$$

Choose b_2 , a_2 to cancel at $T \sim T_{EW}$

First Order EWPT from BSM Physics



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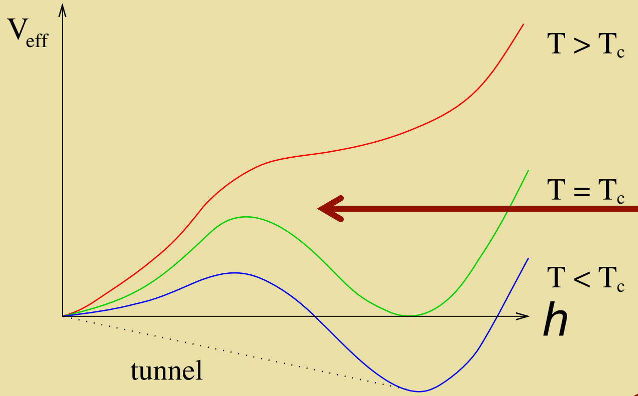
Choose b_2 , a_2 to cancel at $T \sim T_{EW}$

$$M_\phi(T=0)^2 = \frac{a_2}{2}\left(v^2 - T_{\rm EW}^2/3\right)$$

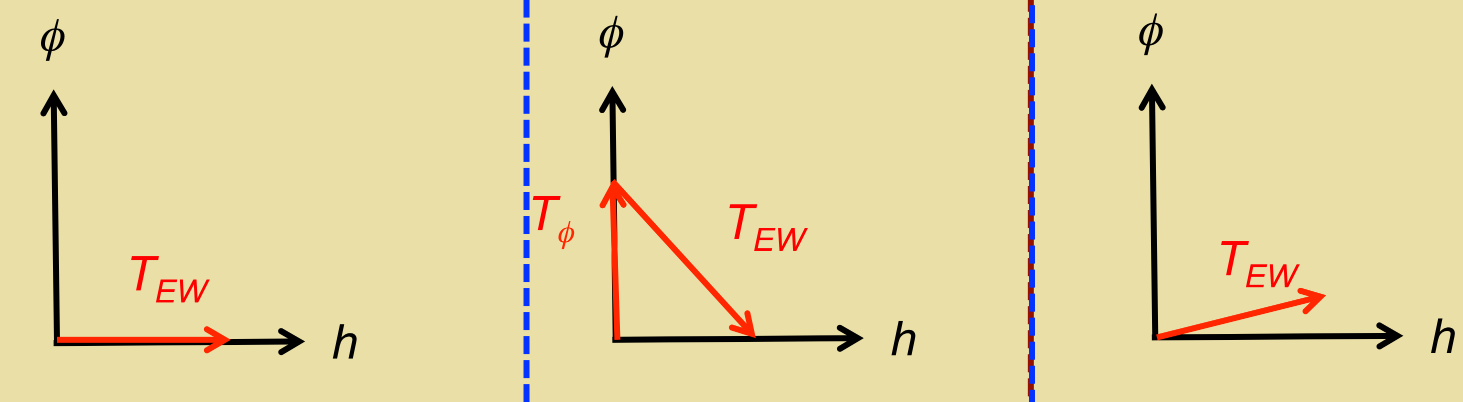
M_ϕ < 350 GeV for perturbative a_2

First Order EWPT from BSM Physics



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

Analogous logic: 1912.07198/back up slides



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loop effect

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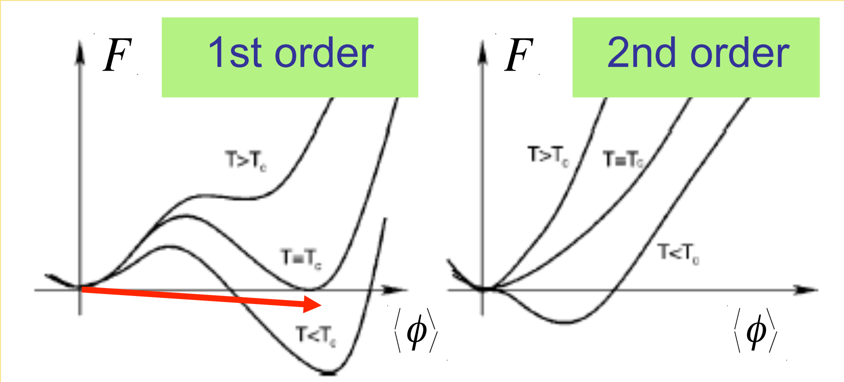
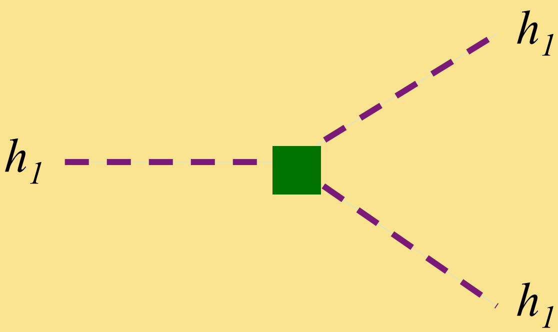
tree-level effect

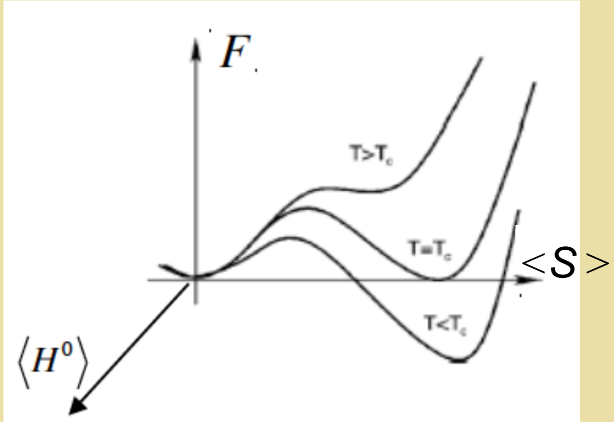
Higgs Self-Coupling & ZH Production

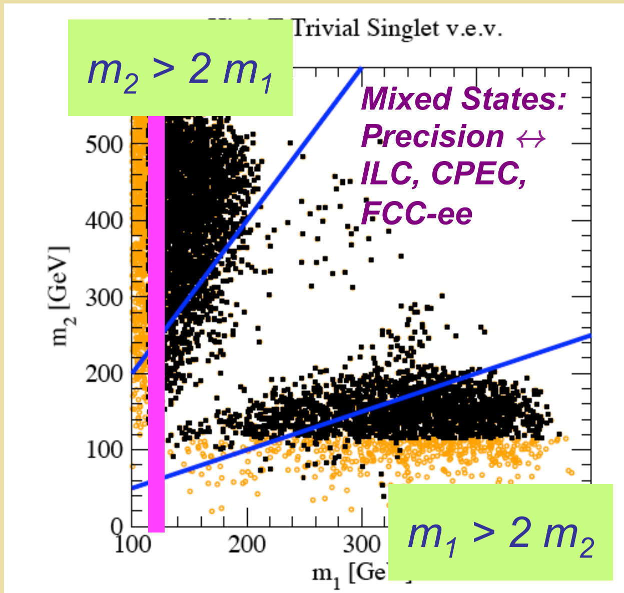
EW Phase Transition: New Scalars



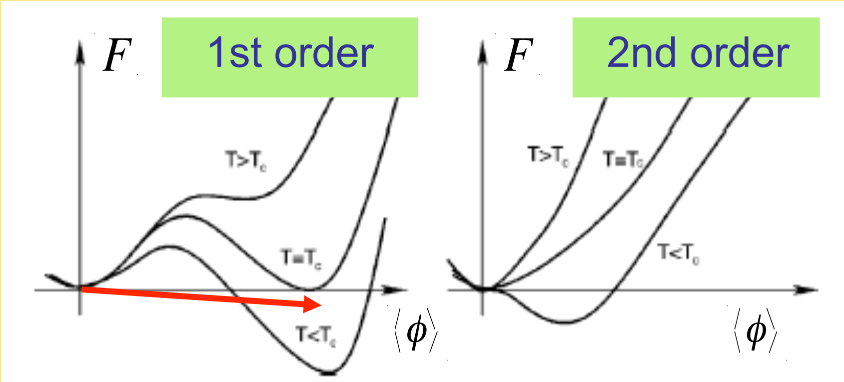
Modified Higgs Self-Coupling

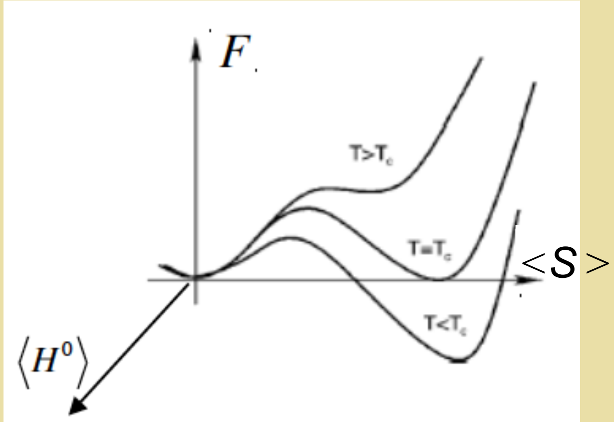




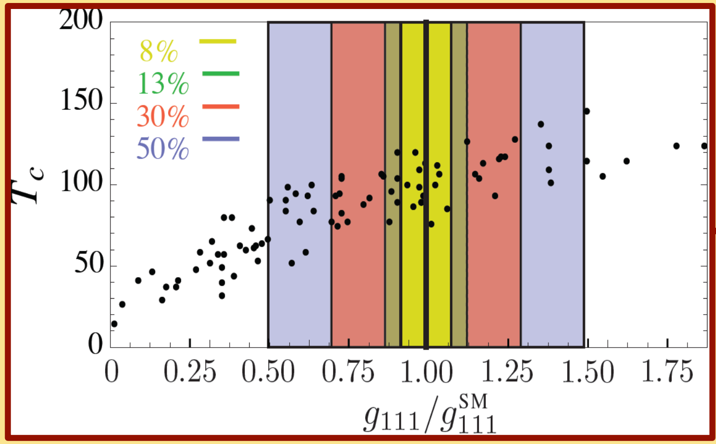


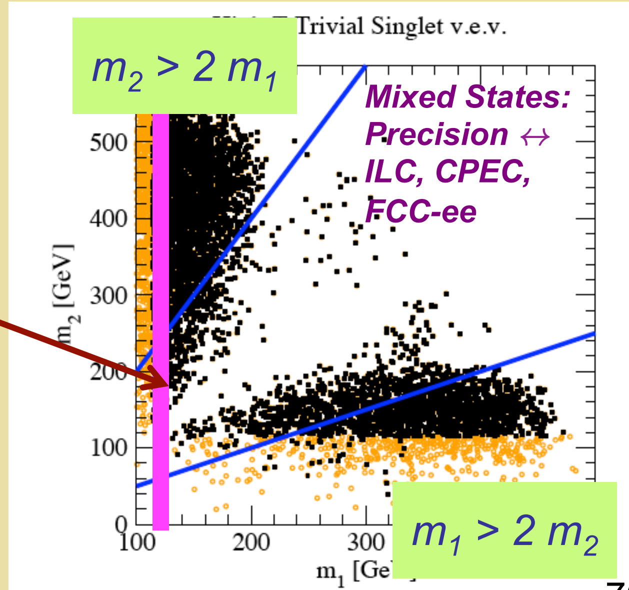
EW Phase Transition: Singlet Scalars





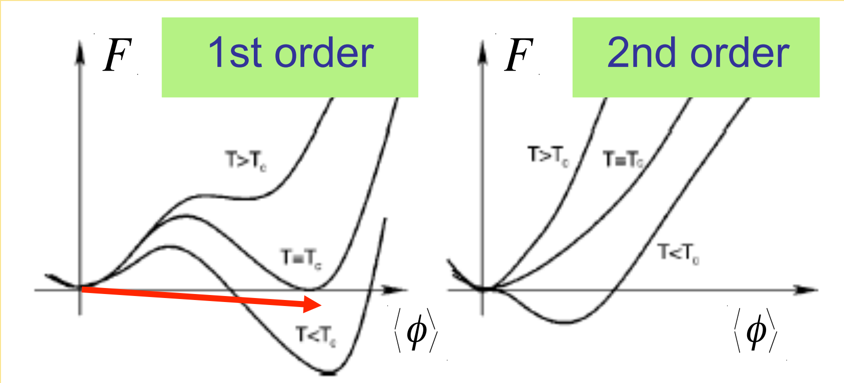
Modified Higgs Self-Coupling



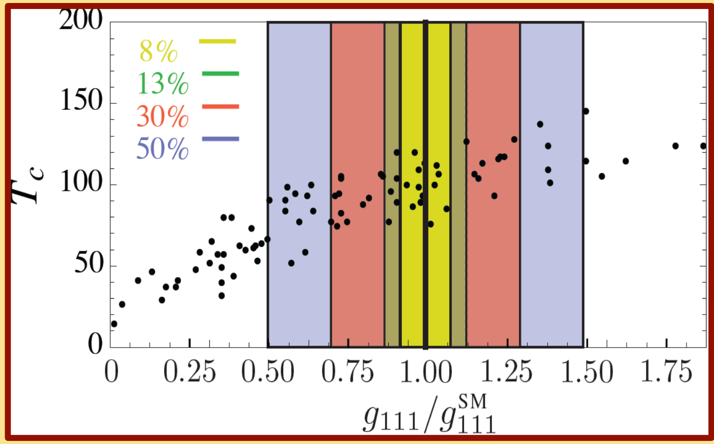


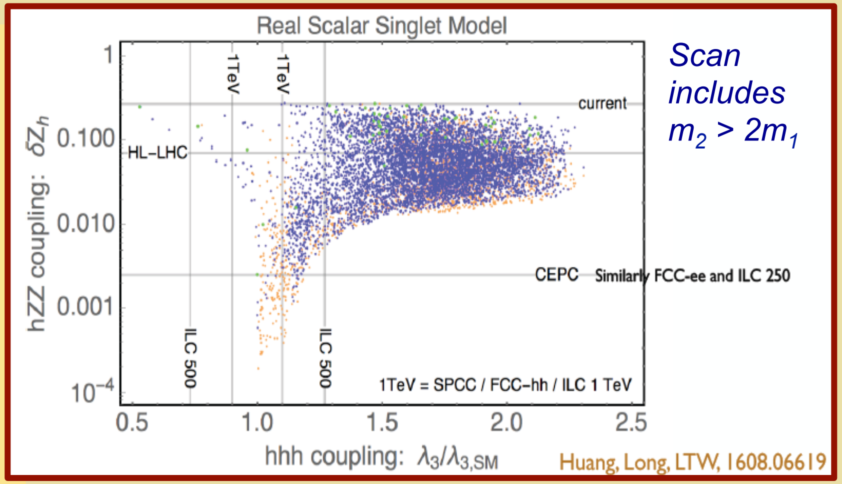
Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

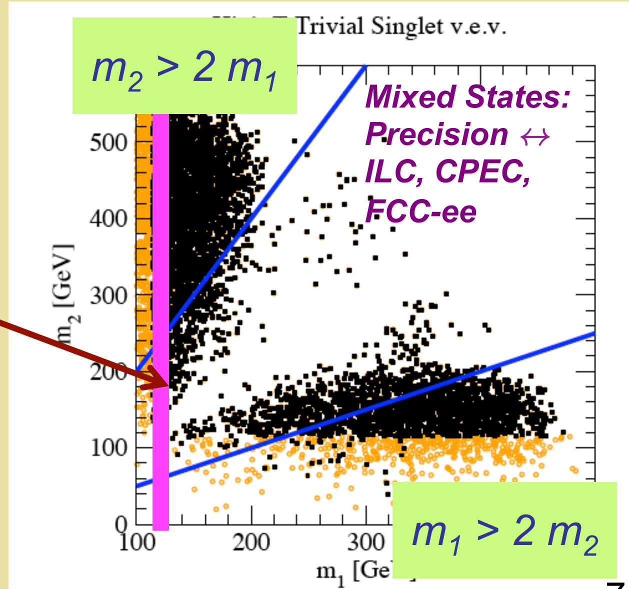
EW Phase Transition: Singlet Scalars



Modified Higgs Self-Coupling







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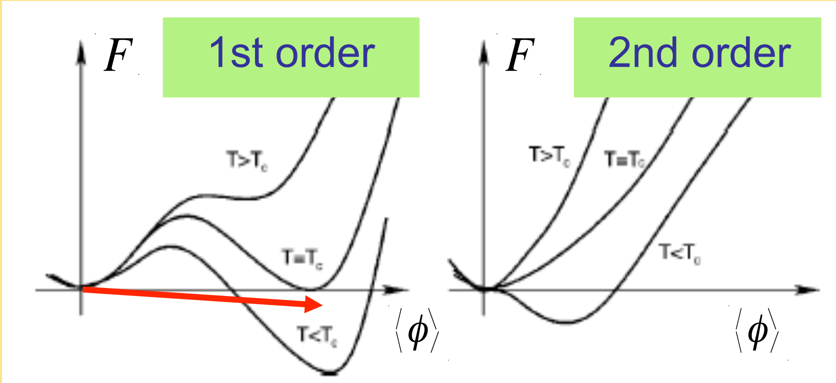
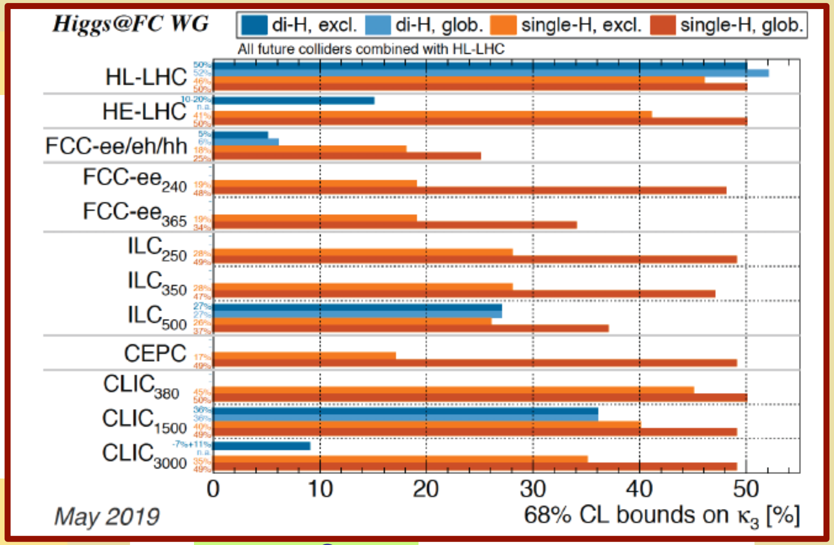
Thanks: M. Cepeda

EW Phase Transition: Singlet Scalars





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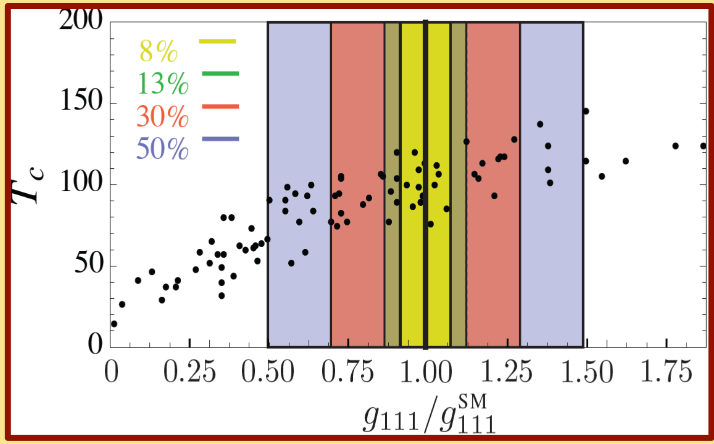

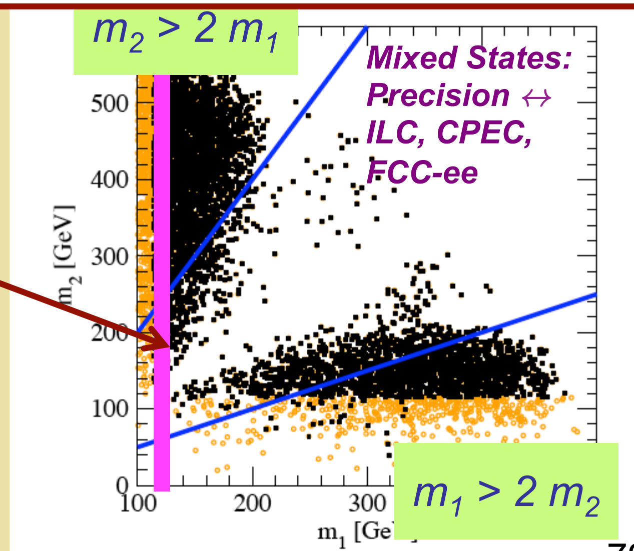

Profumo, R-M, Wainwright, Winslow: 1407.5342; see also Noble & Perelstein 0711.3018

Thanks: M. Cepeda

Higher Dimensional Operators

$$\tilde{V}_0(H) = \lambda\left(H^\dagger H - \frac{v^2}{2}\right)^2 + \frac{1}{\Lambda^2}\left(H^\dagger H - \frac{v^2}{2}\right)^3$$

$$\tilde{V}_0(h) = \tilde{V}_0 - \frac{\tilde{\mu}^2}{2}h^2 + \frac{\tilde{\lambda}}{4}h^4 + \frac{1}{8\Lambda^2}h^6$$

$$\tilde{\mu}^2 = \left[\lambda - \frac{3v^2}{4\Lambda^2}\right]v^2$$

$$\tilde{\lambda} = \lambda - \frac{3v^2}{2\Lambda^2}$$

$\tilde{\lambda} < 0$ → *FO EWPT* → Λ *< 840 GeV*

→ *Implications for* σ_{Zh}

- *Cao, Huang, Xie, Zhang 2017*
- *Grojean, Servant, Wells 2004…*
- *Grinstein, Trott 2008…*

Electroweak Phase Transition

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

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

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

Strong First Order EWPT: Necessary condition for EW baryogenesis